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The History and Development of Aircraft Instruments - 1909 to 1919

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The History and Development of Aircraft Instruments - 1909 to 1919

Abstract

This is a history of early aircraft instruments and of the scientists who developed them in the First World War. Many, like Lindemann, Tizard, Dobson, Farren, Taylor, Thomson and Wimperis, became better known later in other fields. Most had no knowledge of aeronautics, only the laboratory research and experimental practice of the universities they had left. Farnborough researched the improved aerodynamic performance of aeroplanes and new problems, like cloud flying, while the Testing Squadron at Upavon and later Martlesham Heath, more routinely compared the performance of new machines and equipment. The experimental environment in which both groups worked was hostile, the aeroplane was cramped, noisy, unreliable and suffered severe vibration and acceleration forces, while the accuracy of its instruments was effected by its own passage through the air and the atmosphere conditions in which it flew. New flight test instruments, and methods to calibrate them from the ground, became essential. The instruments developed were simple but effective, often manometric - gyroscopic instruments did not see wartime service. The parallel development of the aircraft compass at the Admiralty Compass Department resulted in bitter controversy with Farnborough scientists. However the parallel development of the bomb sight, by Wimperis at the RNAS Laboratory at Imperial College, was more harmonious as scientists knew each other. The design of reliable recording instruments defeated everyone and the trained observer remained the only satisfactory option to record measurements. Some scientists learned to fly to further their work, some died while doing it. At the end of the war, they left a scientific framework in place for future government aeronautical research. The whole development was entirely British, no French, German and American aircraft instruments were adopted during the war, although many were examined.

The research in this thesis is original, as no previous history exists of early aircraft instruments.

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Editorial Note

Numerous diagrams of instruments are necessary to this thesis. It was felt these were best placed immediately adjacent to the text in which they are described. To achieve this, the reference notes for each chapter have been placed together towards the end of the thesis, except for the Introduction and Conclusions, which contain no diagrams, and footnotes presented no difficulty. Some diagrams warrent technical details and these are placed below the diagram and are not repeated in the text. The notes for each chapter can be quickly referenced by the chapter and page numbers given at the top of each page of notes. Numerous scientists are referenced in this thesis and to assist the reader brief biographical notes are provided in Appendix 3.

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Introduction

History and Development of Aircraft Instruments 1909 to 1919

1. Aircraft instrumentation - a history of its technology

The aeroplane historian has seen the open frame aeroplane, without instruments, evolve to the biplane fighter with a simple panel, and onwards to the modern civilian and military aeroplanes with their complex analog instrument panels, now changing to visual display screens and head-up displays. He has seen the number of flight instruments increase as the operational speed, altitude and range of the aeroplane increased, and multiply as a second pilot and more engines were added. He has seen instruments grouped in different locations to meet changing aircrew responsibilities, then relocated back to the pilot as equipment became more reliable and automatic, and the need for individual crew responsibilities disappeared. He has seen the number of alarms increase, as the potential number of victims per accident and the publicity given to accidents increased. The history of this is the operational use of instrumentation, of its logical arrangement for the safe and economic operation of the aeroplane, determined by ergonomic experience and safety standards and regulations.

There is another history of the aircraft instrumentation technology itself. This started as self-contained, self-powered instruments, actuated by hydrostatic, centrifugal, gyroscopic, magnetic or thermal expansion forces. It became electro-mechanical as aeroplanes became larger and the measurements had to be transmitted to the flight panel, and is now micro-computer based in which the instrument is an image on a computer screen. Accuracy, reliability and weight have been over-riding and inter-related design constraints throughout this development. The technology has always been demanding and was no less so in the first ten years. This thesis is a history of the those early years and of the scientists, particularly those in the First World War, who were involved. Many of these, like F.A.Lindemann, H.T.Tizard, H.E.Wimperis, W.S.Farren, G.I.Taylor, G.M.B.Dobson, became more well known in other fields, while others, like K.Lucas and B.Hopkinson, were killed.

To evolve, the instrument technology required scientists, engineers and technicians, well equipped laboratory facilities, proven experimental methods and reliable components.

Little was in place in 1909, but some progress had been made by 1914, involving the Royal Aircraft Factory (RAF) at Farnborough, the National Physical Laboratory (NPL) at Teddington, the Admiralty Compass Department (ACD) at Deptford, the Advisory Committee for Aeronautics, various instrument makers, and one or two private inventors. The technology was one of adapting existing mechanisms, like the barometer and compass, to withstand the vibrations of the aeroplane.

The outbreak of war in 1914 dramatically increased the development activity as the potential of the aeroplane in warfare became apparent. Existing instrument design was frozen to assist wartime production of aircraft instruments by established makers and non-instrument firms and some university scientists were directed into government establishments to undertake the solution of problems. New aircraft were being designed to meet military and naval requirements, requiring new airborne and ground based instruments to measure their performance. The activity continued to increase up to the end of the war, when it was rapidly wound down. Some scientists remained in aeronautics, while most returned to their former careers. However, a framework of measurement and instrument technology, of laboratory facilities and of scientifically based experimental methods, was in place for future research.

This thesis examines the development of aircraft instruments for normal, cloud flying (later called blind flying), research and performance flying, during that period. Bomb aiming is included because it was closely related to aeroplane stability and the methods used to test sights found immediate application in research and performance flying. The instruments examined in this thesis include,

<u>Normal Flight</u>
Tachometer
Altimeter
Inclinometer
Compass
Manometer Air Speed Indicator (Velometer)
Diaphragm Air Speed Indicator

<u>Cloud Flying</u>
Compass
Static Turn Indicator
Gyroscopic Turn Indicator

<u>Research Flying</u>
Ripograph
Trajectograph
Kymograph and Photo-kymograph
Photo-multi-manometer
Accelerometer

<u>Performance Flying</u>
Climbmeter
Statometer
Fuel Flow Meter
Baro-thermo-graph

<u>Bombsights</u>
CFS
Lever
Equi-distance
Negative Lens
Wimperis Drift and Course Setting
RAF and Gray Gyroscopic

<u>Air to Ground Calibration</u>
Camera Obscura
Robinson Mirror
Ground Speed Timing Course
High Speed Timing Course

The significance of the wartime development was emphasised by Sir E.L.Ellington,[1b] Director General of Supply and Research for the Air Ministry, when he stated that,

> the progress made in aircraft instruments, equipment and communications had been radical, whereas that made with the aeroplane itself was only conventional.

He explained that the impetus of war had increased the number and types of machines, had improved their design and performance and the power to weight ratio of their engines, but the machines were still a direct development of their 1914, wood and canvas, predecessors. Durability was unimportant, as the life of a machine was short due to hostile action, bad aerodromes and poor handling. Structural strength had been sacrificed for performance, because the risk of being destroyed by the enemy was greater than the risk of the machine breaking up in the air. Engine reliability was acceptable if it could carry out a day's work without breakdown. Against this, there had been a significant improvement to the equipment and instrumentation provided for the aeroplane.

This may at first appear a surprising statement. Instrumentation was a minor part of overall aeronautical experimental effort, and had not in itself effected the outcome of the military or naval war. In fact, many military pilots made little use of their instruments, except when in trouble, and then lack of practice and mistrust led to serious mistakes. The short duration of military flights and the need for pilots to concentrate on the control of their machines, while constantly on the alert for enemy machines, made this argument plausible. They had also been taught to fly without instruments in the belief that using instruments would prevent them from acquiring the necessary flying skills. Naval pilots, on the other hand, made much more use of instruments, as their war involved long sea patrols with less enemy opposition.

However, it was not for the pilots, but for the scientists and engineers, who were designing and improving the performance of aeroplanes, that instruments were essential and new ones designed. Measuring this performance at Farnborough and Martlesham Heath was impossible without instruments, and papers by Tizard, Farren and Barlow on testing aeroplanes are devoted entirely to instrumentation and not the aeroplanes involved.[1a] Performance flying introduced additional research instruments, which later found their way into normal service. It also showed that instruments, accurately calibrated on the ground, did not maintain their accuracy in the air, due to density variations of the air itself and the disturbance effect produced by the aeroplane to which they were fitted. This introduced the need to calibrate the instruments from the ground by translating the three dimensional path of the aeroplane into a two dimensional record.

1a. H.T.Tizard, 'Methods of Measuring Aircraft Performance', *Aeronautical Jnl*, **XXI**, August 1917, 445-68. W.S.Farren, 'Full Scale Aeroplane Experiments, *Aeronautical Jnl*, **XXIII**, February 1919, 34-72. T.M.Barlow, 'Performance Testing of Aeroplanes', *Aeronautical Jnl*, **XXVI**, May 1922, 152-76.

1 b. Air Vice Marshall Sir E.V.Ellington, 'The Present Position of Aircraft Research and Contemplated Development', *Proceedings of 1920 Air Conference*, HMSO, 1920, 57-66, and discussion by Sir Richard Glazebrook, 66-70.

2. This thesis in the context of science and technology of the same period.

Edgerton and Gummett conclude that scholarly work on science, technology and research establishments in the First World War, is very limited.[2] Some of this places undue emphasis on the formation of the Department of Scientific and Industrial Research (DSIR) and the various Inventions Departments, while ignoring the major research within the services themselves.[3] This thesis shows that wartime research on aircraft instruments was conducted within the services. The development of early aircraft instruments has not been examined previously and, because it does includes wartime government research, it extends the history of government research in that period.

Sumida examines the optical and gyroscopic technology of naval gunnery control from 1884 to 1914, its dependence on the work of Hungerford Pollen, and the way his patents were utilised without his permission.[4] This thesis extends Sumida's history to show that Pollen also patented an aircraft bombsight to which the same thing happened. Hackmann has examined naval underwater acoustics from 1893-1954, including the contribution of scientists to this technology during the First World War period.[5] Bomb sight design at Imperial College for the naval air service adds a further chapter to wartime naval research. Hartcup gives a general account of the development and use of inventions and technology in the war, which includes poisonous gas, the tank, the aeroplane, artillery sound ranging, signalling and wireless, and anti-submarine warfare.[6] The wide range of topics means that only their major considerations are included, but his bibliography provides a starting point for further research. Terraine had earlier covered the same inventions and technology from

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2. D.Edgerton and D.Gummett, 'Science, Technology and Economics in the Twentieth Century', Chapter XXI in G.Jordan (ed), *British Military History - A Guide to Sources*, (New York : Garland Press), 1988. Edgerton and Gummett should be used for specific war technologies, like gas warfare, submarine detection, the torpedo, artillery and machine guns.

3. I.Varcoe, 'The Early History of the DSIR 1914-1916', *Minerva*, **8**, April 1970, 192-216. R.M.Macleod and E.K.Andrews, 'Scientific Advice in the War at Sea 1915-1917 : The Board of Invention and Research', *Jnl of Contemporary History*, **6**, 2, 1971, 3-40. M.Pattison, 'Science, Inventors and the Military in Britain 1915-19 : The Munitions Inventions Department',*Social Studies of Science*, **13**, 4, 1983.

4. T.Sumida, 'In Defence of Naval Supremacy - Finance, Technology and British Naval Policy 1889-1914', (Boston : Unwin Hyman), 1989 and 'The Pollen Papers', (London : Allen and Unwin), 1984. See also A.McConnell, *Instrument Makers to the World : A History of Cooke, Troughton and Simms*, (York :William Sessions), 1992.

5. W.D.Hackmann, 'Underwater Acoustics and the Royal Navy,1893-1930', *Annals of Science*, **36**, 1979, and *Seek and Strike : Sonar Anti-Submarine Warfare and the Royal navy, 1914 1954*, (HMSO), 1984.

6. G.Hartcup, *War of Invention*, (London : Brassey), 1990.

their strategic employment.[7] Published history of Farnborough is minimal and yields little information on experimental method and instrumentation.[8] Kinsley has written a popular non-technical account of Martlesham Heath and Orfordness, but mentions little of the First War period.[9] Fanning examines the long history of the Admiralty Compass Department, in which the development of the aircraft compass only plays a small part.[10] Hashimoto examines aerodynamic research from 1909 to 1930, covering the collaboration between British scientists and engineers in aeroplane stability and the scale factor controversy between wind tunnel research at NPL and full scale testing at Farnborough.[11] My thesis adds substantial material to these accounts.

General history of aircraft instrumentation is characterised by its neglect. Chorley is most frequently cited, but his paper is limited to a literature search in published aviation journals.[12] Coombs' popular account of the changing layout and organisation of the pilot's instrument panel and controls since the Wright brothers, is limited to commercially available instruments, with no description of them or their development.[13] Text books can provide a history of science and technology as they document established practice at their date of publishing, but again there are few on aircraft instrumentation. Stewart, who was actively involved in wartime developments, is particularly good.[14] Pannell, at NPL, who was killed when the airship R38 crashed in August 1921, covers pressure and velocity measurement in wind tunnels and in flight, Griffiths at NPL extends the scope of Pannell's book, Eaton covers American instruments, and Sloley, Coulthard, Pallett and Siberry cover

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7. J.Terraine, *White Heat : The New Warfare 1914-18*, (London : Book Club Associates), 1982.

8. P.B.Walker, *Early aviation at Farnborough, Vol 2, The First Aeroplane*, (London :Macdonald), 1974. S.Child & C.F.Caunter, *Summary of the Royal Aircraft Factory and its Antecedents - 1887 to 1918*, RAE Report Aero 1280, March 1947. A.Gollin, *No Longer an Island : Britain and the Wright Brothers*, (London : Heinemann), 1984. P.R.Hare, *The Royal Aircraft Factory*, (London :Putman), 1990. *Laboratory of the Air : RAE Farnborough*, (HMSO), 1948; and *Fifty Years at Farnborough*, (HMSO), 1955.

9. G.Kinsley, *Martlesham Heath*, (Lavenham : Terence Dalion), 1983; and Orfordness, (Lavenham : Terence Dalion), 1981.

10. A.E.Fanning, *Steady as she goes - A History of the Admiralty Compass Department*, (HMSO), 1986.

11. Takchiko Hashimoto, *Theory, Experiment and design Practice : The Formation of Aeronautical Research :1909 - 1930*, PhD Thesis : Baltimore, 1990.

12. R.A.Chorley, 'Seventy Years of Flight Instruments and Displays', *Aeronautical Jnl*, **70**, August 1976, 323-42, N.A.Price & C.Robson, *Bibliography - Flight Instruments and Displays 1903-1976*, RID 1551, Smiths Aircraft Instruments, September 1976.

13. L.F.C.Coombs, *The Aircraft Cockpit*, (Wellingborough : Patrick Stevens), 1990.

14. C.J.Stewart, *Aircraft Instruments*, (London : Chapman and Hall), 1930. The book was based on an earlier paper, 'Modern Developments in aircraft Instruments, *Aeronautical Jnl*, **XXXII**, June 1928.

the period from 1934 to 1993.[15] These sources are limited to a functional description of successful instruments and are not concerned with their development. Balloon and airship instruments do not provide a pre-history of aircraft instruments as there was little or no transfer of technology. They shared the same atmospheric conditions, but not the vibration and acceleration forces. Numerous histories examine military and naval flying and squadron histories.[16] Few are analytical and practically none mention instruments. Similarly, except for Jones, bombsight technology is ignored in histories of strategic bombing, or comments are qualitative like 'the sight was not much use'.[17] Aircraft navigation instruments are examined in several histories.[18] Except for the compass, they are hand held instruments and outside the scope of this thesis.

The history of aircraft instruments in this thesis is mainly a British one. American technology had no influence until after the First War, and this thesis will show that even Sperry's aircraft instrument patents were copies of British and French patents which preceded them. French aircraft instruments arrived on French aeroplanes, but none were adopted on British military aeroplanes although some, popular with French pilots, were tested. However, the pocket barograph recorder by Richard was used extensively in British test flying. There is no evidence that German aircraft instrument design had any influence on British instruments, captured instruments and bombsights were examined, but none offered any advantage over British ones.

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15. J.R.Pannell, edited R.A.Frazer, *The Measurement of Fluid Pressure and Velocity*, (London : Arnold), 1924. E.A.Griffiths, *Engineering Instruments and Meters*, (London : Routledge), 1921. H.N.Eaton et al, *Aircraft Instruments*, (New York, Roland Press), 1928. R.W.Sloley, *Aircraft Instruments*, (London : Pitman), 1934. W.H.Coulthard, *Aircraft Instrument Design*, (London : Pitman), 1952. E.H.J.Pallett, *Aircraft Instruments*, (London : Pitman), editions 1972-1993. M.Siberry, *Instruments of Flight*, (Newton Abbot : David and Charles), 1974.

16. Sir Walter Rayleigh & H.A.Jones, *The War In the Air : Being the Part played in the War by the Royal Air Force*, Six vols, (Oxford University Press), 1922-3. S.F.Wise, *Canadian Airmen and the First World War*,(Toronto), 1980. M.Paris, *Winged Warfare - The Literature and Theory of Aerial Warfare in Britain 1958-1917*, (Manchester University Press), 1992. L Kennett, *The First Air war 1914 1918*, (New York : Free Press [Macmillan]), 1992. D.Devine, *The Broken Wing : A Study in the British Exercise of Air Power*, (London : Huchinson), 1966.

17. N.Jones, *The Origins of Strategic Bombing : British Air Strategic Thought and Practice up to 1918*, (London : Kimber), 1973. J.Sweetman, *Strategic Bombing and the Origins of the Royal Air Force*, PhD Thesis, University of London,1983. B.D.Powers, *Strategy without Slide Rule : British Air Strategy, 1914-1918*, (London : Croom Helm), 1976.

18. E.B.Williams & W.J.V.Branch, *A Short History of Navigation*, (School of Navigation, Southampton University, Weems System of Navigation, Maryland), 1942. A.J.Hughes, *History of Air Navigation*, (London : Allen & Unwin), 1946. N.B.Harbold, *The Log of the Air Navigator*, (USA : Naylor Company), 1970. A.J.Hughes, *The Book of the Sextant*, Glasgow : Brown, Son and Ferguson, 1938. C.F.Cotter, *The History of the Navigators Sextant*, (Glasgow : Brown, Son and Ferguson), 1983. H.E.Wimperis, *Primer on Air Navigation*, (London : Constable), 1920. D.C.T.Bennett, *The Complete Air Navigator*,(London) : 1936. P.V.H.Weems, *Air Navigation*, (London : McGraw Hill), 1931 and revised and edited by H.A.Hughes and P.F.Everitt in The British Empire Edition, 1936.

3. Thesis in Context of the Sociology of Science and Technology

The development of aircraft instruments has continually demanded intensive research by individuals or groups of people. No instruments mysteriously appeared or had the inertia to evolve by themselves, and both instrument technology and its social construction are examined in this thesis. Examining laboratory working practice to follow how science is constructed is well established.[19] This thesis does not discuss the relative merits of the different historiographical approaches, but freely adopts those concepts which produce a meaningful history, and like classical history, is written in the context of the period when the technology itself was evolving.

The framework of this thesis consists of reports and papers by those involved, which were published by the Advisory Committee for Aeronautics and Royal Aeronautical Society respectively. However, the main material of this thesis is from their unpublished reports and correspondence in the Public Records Office and various museum archives, together with their private papers and diaries (See Bibliography). Biographies exist for some of those involved, but these provide little technical information.

4. Objectives.

The objectives of this thesis are to examine the technology involved in the development of early aircraft instruments, the way the development evolved and was organised in peace and war between 1909 and 1919, and the role played by various scientists and technologists, many of whom later became more well known in other fields and their contribution to aircraft instruments ignored.

It is not intended as a business history of aircraft instrument makers, although commercial aspects are examined when relevant to the development of specific instruments.

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19. S.Shapin, 'History of Science and its Social Reconstructions', *History of Science*, 20, 1882, 157-211. J.Golinski, 'The Theory of Practice and the Practice of Theory : Social Approaches in the History of Science', *Isis*, **81**, 1990, 492-550 provides a summary of the papers by Collins, Garfinkel, Gooding, MacKenzie, Pickering, Schaffer, Latour and Woolgar.

Chapter 1.

Aircraft Instruments

A Scientific Footing - Politics, People and Places

This chapter outlines the formation of the Advisory Committee for Aeronautics, which placed the developing science and technology on a scientific footing. By 1913, the environment in which aeroplane instruments had to work was very apparent and Horace Darwin's description of this and the design practices he recommended is used to introduce the problems faced by the aircraft instrument designer. The aeronautical research establishments and the scientists working in them are then introduced to provide the social framework of the development and avoid unnecessarily interrupting the technical history of a particular instrument in subsequent chapters.

1.1. The Advisory Committee for Aeronautics.

In 1909, when aviation in this country was just starting, the Advisory Committee for Aeronautics was set up by the Secretary of State, Richard Burdon Haldane, to ensure that all government funded aeronautical development was on a sound scientific basis. The events leading up to the formation of this Committee will be briefly examined as an introduction to the main thesis.[1]

Orville and Wilbur Wright had made their first powered flight in 1903. This success was helped by several years of gliding experiments to build up design and flying experience and to the 70% efficiency of their propeller, which enabled them to take off with a 12 horsepower engine along a monorail track, augmented by the impetus of a falling weight. They designed and flew new machines in 1904 and 1905, after which the machines were dismantled and kept them from public and military view while they endeavoured to sell their invention first to the American, and later to the British, French, German and Russian Governments. They were concerned that their patents were not comprehensive and that their invention could be easily copied and result in protracted litigation. However, no government contracts were forthcoming and they decided to demonstrate their machine to achieve private orders. Wilbur undertook the European demonstrations, where his flights in 1908 completely eclipsed Henri Farman's one kilometre closed circuit flight earlier in the year and any achievement in Britain. S.F.Cody had managed to get airborne in Army Aeroplane No.1 at Farnborough, using the engine from a dismantled airship. A second

machine at Farnborough, designed by Lt. J.W.Dunne, was being rebuilt after failing to get airborne. At Brooklands A.V.Roe had achieved a short flight by taking off using a down hill slope on the racing circuit.

In the same year, the Prime Minister Mr. Asquith, asked the Committee of Imperial Defence to report on;

a) The dangers to which the country would be exposed on sea and on land by any development in aerial navigation reasonably probable in the near future.
b) The naval or military advantages that we might expect to derive from the use of airships or aeroplanes.
c) The amount that should be allocated to expenditure on aerial experiments, and the Department to which it should be allotted.

On the Committee, Haldane, who was familiar with the developments at Farnborough, made it clear that he believed that the problems of flight were too complex for non scientific enthusiasts like Cody and Dunne. He wanted to secure for the Government the services of qualified scientists, who could discover the principles of flight to develop efficient military aircraft. The hydrodynamic problems of marine navigation were worked out with models in an experimental tank before a ship was built, and he saw that aerial navigation required similar techniques. He also felt that an advisory committee, similar to the Explosive Committee under Lord Rayleigh, would be desirable. However, General Sir William Nicholson's view prevailed that, provided advantage was taken of private enterprise in aviation, there was no necessity for the Government to continue experiments in aeroplanes, and those at Farnborough should be discontinued. Therefore, a sum of £35,000 was included in the Navy Estimate and only £10,000 in the Army Estimate.

This was not what Haldane wanted, but it enabled him to dismiss Cody and Dunne in January 1909, although both were allowed to keep their aeroplanes in order to continue their research privately. As Farnborough was reluctant to lose their aeroplanes, Cody was given permission to remain on site, providing he erected his own shed and financed his own experiments. By May, he succeeded in flying a mile and by year end, he was able to carry a passenger over the same distance. Dunne and his machine, with money from wealthy supporters, became the Blair Atholl Syndicate and latter flew successfully at Eastchurch. Haldane's second step was prompted by the maiden flight of Imperial Airship Zeppelin 1 in March, and the resulting censure of the government for the inadequate arrangements at Farnborough and for its policy of leaving aviation development to private enterprise. He had already asked Lord Rayleigh, chairman and director of the National Physical Laboratory, and Dr. R.T.Glazebrook to prepare a scheme that would secure the co-operation of the laboratory with the embryo aeronautical services.[2] Following approval of the proposals by the Admiralty, Asquith agreed to the formation of the Advisory Committee

of Aeronautics under the presidency of Lord Rayleigh on 30 April and Haldane made the following announcement of the Government policy to the House on 5 May,

> With the view to securing that the highest scientific talent shall be brought to bear on the problems which will have to be solved in the course of work of the two departments, the National Physical Laboratory has been requested to organise at its establishment at Teddington a special department for continuous investigation, experiment or otherwise, of questions which from time to time must be solved in order to obtain adequate guidance for construction. For the superintendence of the investigations at the national Physical Laboratory and for general advice on the scientific problems arising in connection with the work of the Admiralty and War Office in aerial construction and navigation, I have appointed a special committee. . .

The Committee consisted of two service members and eight civilians, all of who had considerable experience in various branches of science.

Lord Rayleigh, FRS.	R.T.Glazebrook, FRS.
H.Darwin, FRS.	Sir A.G.Greenhill, FRS.
H.R.A.Mallock, FRS.	W.N.Shaw, FRS.
Prof J.E.Petavel.	F.W.Lanchester.
Capt. R.H.S.Bacon.	Maj. Gen. Sir Charles Haden.

To these shortly were added Capt. Murray F.Seuter, Captain Inspector of Airships, and M.O'Gorman, Superintendent of the Army Balloon Factory. The FRS members were friends of long standing, formerly from Trinity College, Cambridge, with the exception of Shaw from Emmanuel. Glazebrook and Shaw had written text books while at the Cavendish under Rayleigh and Shaw was now with the Meteorological Office and Greenhill at the Royal Naval College, Greenwich. Horace Darwin was chairman the Cambridge Scientific Instrument Company, which he had founded for the design and manufacture of scientific apparatus for research laboratories, and where Shaw was also a director.[3] Petavel was carrying out aerodynamic research at Manchester University, having previously worked at the Royal Institution Davy-Faraday Laboratory, of which Rayleigh was chairman. Lanchester, in spare time while founding and running the first British motor car company, had experimented with model aeroplanes and had published a two volume book on aerodynamics and also a paper, which criticised the inherently unstable design and weak structure of the Wright Flyer.[4]

1.2. Farnborough - balloons to aeroplanes.

O'Gorman was appointed Superintendent of the Army Balloon Factory in October 1909. He had been a partner with the consulting engineers, Swinburne, O'Gorman and Baillee, and was a classics and science graduate from Dublin University, with post graduate training in electrical engineering at the City and Guilds Institute, London. Work at Farnborough at this time was on airships, particularly their engines, and O'Gorman recruited F.M.Green from Daimler as his chief engineer in January 1910. The Factory had been given a Wright Flyer by Charles Rolls, but had no pilot or funds to experiment with

it. By coincidence, Geoffrey de Havilland had designed and built his own aeroplane and its engine with £1,000 borrowed from his grandfather, but had run out of funds.[5] O'Gorman met de Havilland and impressed with his potential as both designer and pilot, persuaded the war Office to recruit him and his assistant Frank Heal and also to purchase de Havilland's aeroplane for £400, provided it successfully completed a test flight of one hour's duration.

Green's acceptance report for de Havilland's aeroplane on 14 January 1911, showed that no instruments were used for Farnborough's first official test flight.

> Trial was made of the de Havilland Biplane, driven by Mr de Havilland, to test the suitability for flying and its power for remaining in the air. It was decided that a test of one hour continuous flight was advisable, carrying only the pilot, and that shorter flights should be made afterwards to test its passenger carrying capacity.
> The flights were entirely successful, the pilot showing very good control over the machine and all landings were accurately made. Up to the present no accurate determination has been made of the speed of the machine, but it appears faster than the usual type of Farman and the speed is probably between 40 and 50 mph, but the exact determination must be made later.[6]

The situation had improved a little by March 1912, as de Havilland used pocket instruments when he tested the BE 1 along a measured course with timing huts at each end, followed by a climbing test. He carried an aneroid and stop watch, with a pocket barograph as a check and the official report records,

> the mean speed over a three quarter mile course with a live load of 25 stones and sufficient petrol for one hour's flight is 58-59 mph. The rate of rising loaded as above has been tested up to 600 feet and found to be at the rate of 155 feet per minute.[7]

The development of aeroplane instruments at Farnborough can be considered to start at this time. The aim was now to clean up the lines of de Havilland's aeroplane to reduce its head resistance. There was a desire for recording instruments 'since pilots recollections are not always reliable', but vibration and acceleration forces seriously affected indicators, let alone recorders. The Army Balloon Factory became the Army Aircraft Factory in April 1911, and the Royal Aircraft Factory (RAF) three years later. The abbreviation RAF was used to reference Farnborough designed equipment and personnel, hence O'Gorman as Superintendent was SRAF. It was only after the formation of the Royal Air Force in April 1918, that this abbreviation took on a different meaning, at which time Farnborough became the Royal Aircraft Establishment (RAE) to avoid confusion.

1.3. Instrument problems and design considerations - Darwin's views.

Horace Darwin's appointment to the Advisory Committee put aeronautical instrumentation on a scientific footing at an early date. For the next 10 years, he would make a significant

contribution to its development, not so much from design and manufacture, but from the support he gave to others. O'Gorman recalls,

> H Darwin didn't think he earned his £5-5-0 per meeting on the Aeronautical Advisory Committee - and asked in what way he could help me. I never knew any more naïve proof of his humility - of course he was always useful on the Committee and indeed I thought him by far the most useful member.[8]

This help and support to aeronautics will be documented throughout this thesis, although it is mainly ignored in the history of the Cambridge Scientific Instrument Company, probably because the company never became a major supplier of aeronautical instruments except for wartime radiator thermometers.[9] Darwin produced many experimental instrument designs and some specialist research instrumentation, which after all was the work of his company and what interested him personally. He usually acknowledged the help in this work of C.C.Mason, a former mathematical and mechanical sciences tripos man from Trinity Hall, who was joint managing director with R.S.Whipple.

In May 1913, Darwin was asked to give the first Wilbur Wright Memorial Lecture.[10] The fact that an instrument designer was chosen to give the first lecture, indicates the interest in the subject at this time and he chose as his subject *Scientific Instruments : Their Design and Use in Aeronautics*. The paper examined the compass and air speed meter as an introduction to the environmental problems encountered in aeronautics and to the Geometric Design practices Darwin believed should be adopted. Instruments had to cope with the problem that,

> The aeroplane shakes, it does not remain level, and is subject to acceleration in all directions. The instrument should be designed to be unaffected by any of these disturbances. A vertical acceleration has the same effect as an increase in the downward pull due to gravity. A lateral acceleration has the effect of both altering the direction and amount of gravity. But vibration is the greater difficulty. The hand of an instrument may move so much and so rapidly that it is difficult to estimate the mean reading on the scale, and sometimes quite impossible to do so, and this may happen when the quantity which is indicated by the hand varies only slowly and by small amounts.

The effect of a sudden lateral movement on an unbalanced part of an instrument produced a moment about its vertical axis, which tended to rotate it and the further the centre of gravity was from the axis, the greater the tendency to rotate. Reducing the mass of the unbalanced part would reduce the rotation, but it could then bend and vibrate under the forces on it. Good balancing and lightness wereessential and damping should also be provided, which according to Mallock should be proportional to the velocity of the movement of the index. This could be provided by magnetic damping, where a copper plate moved between the poles of a magnet, but more often air or liquid damping was being used, which was proportional to the square of the velocity.

Darwin believed good instrument design should be Geometric, a principle he tried to adopt with all scientific instruments. He stated James Clerk Maxwell's self-evident, but frequently ignored, *General Principles of the Construction of Apparatus*,

> that the construction of the instrument should be adapted to the use that is to be made of it, and in particular, that the parts intended to be fixed should not be liable to become displaced; that those parts that ought to be movable should not stick fast; that those parts which have to be observed should not be covered up or kept in the dark; that the pieces intended to have a definite form should not be disfigured by warping, straining or of wearing.
>
> Each solid piece of an instrument is intended to be either fixed or movable, and to have a definite shape. It is acted on by its own weight and other forces, but it ought not to be subjected to unnecessary stresses, for these not only diminish its strength, but they alter its figure, and may by their unexpected changes during the course of an experiment, produce disturbances or confusion in the observations we have to make.
>
> We have, therefore, to consider the methods of relieving the pieces of the instrument from unnecessary strain, of securing for the fixed pars a determined position, and ensuring that the movable parts shall move freely, yet without shake.
>
> This we may do by attending to the well known fact in kinematics - *A rigid body has six degrees of freedom.*[11]

These six degrees of freedom were the three axes at right angles to the body and rotation about these axes. A minimum of six points of contact were required to hold a body rigid. Darwin gave as example, that a three legged stool was a geometric design, while a four legged table was not as it could rock on two legs. The three legged stool had three points of contact, which prevented three degrees of freedom, i.e. they prevent it from moving vertically or rotating about two horizontal axes. A transit telescope, with its trunnions resting in two V-shaped groves, was another geometric design. The four points of contact still left two degrees of freedom, rotation about the axis of the trunnions and movement along the axis. Points of contact in reality were the contact between two surfaces, the area depending on the hardness of the material, the forces between them, and the amount of wear that will take place. In many cases, the contact between two surfaces had to be ensured by pressure from a spring.

Darwin used a wheelbarrow to illustrate two principles of geometric design, firstly that the instrument shall still function well when the working parts get worn or bent; and secondly, that a better deign can often be made by reversing the relative position of two parts of the instrument. Wheelbarrow (a) had the normal arrangement of an axle rigidly fixed through the wheel and rotating in holes in the frame of the wheelbarrow; while in wheelbarrow (b), the wheel rotated on an axle which was held rigid in the frame. When new, both wheelbarrows would work well, but as the axle wore the

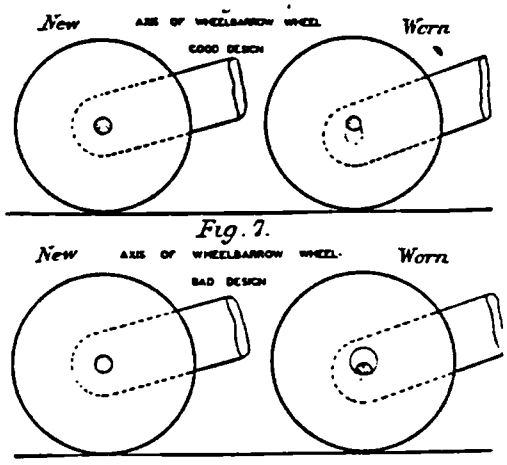


Fig. 7.

bearing, the normal design (a) would continue to work satisfactorily, but in (b) the wheel would become more and more loose and shaky. This example also illustrated the concept that reversing the arrangement of links in an instrument could improve its design and he would suggest to Farnborough in 1915, that they try reversing the cup and pivot of aircraft compasses to reduce the effect of vibration, a suggestion which immediately improved compass behaviour. In his paper, he added that reversing the parts could also lead to a different instrument. In a clock for example, the clockwork mechanism was fixed to the case and the hour hand rotates, but if the hour hand was fixed, the clockwork and the case would rotate. A chart recorder can be designed this way, with the clockwork fixed inside the drum carrying the paper chart.

The liquid U-tube manometer, which Farnborough used as an air speed indicator, was given as a example of geometric design, and will be examined in the next chapter. Darwin concluded that the principles of geometric design were important to the instrument designer, and even more important to those *designers in laboratories who make the wind, cork and sealing wax class of instruments.*

1.4. Scientists at Farnborough.

Edward Teshmaker Busk joined Farnborough as Assistant Engineer-Physics in July 1912, aged 26, well ahead of the main influx of wartime scientists.[1 2] He had graduated from Kings College, Cambridge, with a First in the Mechanical Sciences Tripos under Professor Bertram Hopkinson, after which he worked in industry for two years and learned to fly at Hendon. He then spent a year attempting to build an aeroplane, but handicapped by limited finances, he looked for work through the Cambridge Appointments Board and he was recommended to O'Gorman by Hopkinson and encouraged to accept the post by Glazebrook. His spent a training month at NPL, where his close friend B.Melvill Jones from Cambridge was completing an aeronautical research scholarship from Imperial College. On returning to Farnborough, he was given flying instruction by de Havilland on a BE 2, and made head of the small H-Department. An account of Busk's work is provided by R H Mayo, a Cambridge graduate who became his assistant in June 1913, H-Department was still small in June 1914 and consisted of,[1 3]

Calculations	3 men
Materials testing	1 man
Instrument testing and design	1 man
Instrument making	1 man, 1 boy
Fabrics testing	1 man, 1 boy
Chemistry	1 man, 1 boy

Five months later in November 1914, after Busk was killed when his machine caught fire, 42 members of the department signed a letter of condolence to his mother. Post war, the Busk Scholarship was set up and administered by Melvill Jones, Professor of Aeronautics at Cambridge. Busk's work on aircraft instruments will be examined in the next chapter.

The war brought F.Aston, W.S.Farren, H.Glauert, B.Hopkinson, F.A.Lindemann, K.Lucas, B.Melvill Jones, R.McKinnon Wood, G.F.C.Searle, R.V.Southwell, H.L.Stevens, G.I.Taylor and G.P.Thomson among others to Farnborough. They arrived by different routes, but the starting point was often Trinity College, Cambridge. McKinnon-Wood and Stevens, both Mechanical Sciences Tripos 1914, met O'Gorman when he visited Darwin to recruit staff. Stevens was offered £1 per week, providing he got a good place in the Tripos, and started in Busk's group on 1 August.[14] Darwin recommended Lucas, aged 35, to O'Gorman and he joined Busk's group in September, together with McKinnon-Wood.[15] Taylor, aged 28, was already there, having offered himself directly to the War Office as a meteorologist, only to be directly routed to Farnborough by Lt. Col. Sefton Brancker, Head of Military Aeronautics, who was looking for any scientists he could find. Taylor later joked that the War Office told him that the army had no need for a meteorologist, as it fought whether it was raining or not.[16] Similarly G.P.Thomson, J.J.Thomson's son aged 22, arrived after offering himself and his motor bike to the War Office as a dispatch rider. Melvill Jones, aged 27, Mechanical Sciences Tripos 1909, now a 2nd Lieutenant in the Royal Engineers, was transferred to Farnborough in October, because of his previous experience at NPL and Armstrong Whitworth. Major Hopkinson, aged 40, who as Professor had commanded the Cambridge Corps of Electrical Engineers, joined former students at Farnborough for a short time between instructing at Chatham and moving to the Department of Military Aeronautics at the War Office.[17] Farren, aged 23, joined Farnborough on 1 May 1915 from BTH* at Rugby to work under Green on full scale testing. David Pincent, a Cambridge mathematician, joined late 1916 and when he was killed, H.Garner from St. John's College took his place.[18] Southwell served in the Service Corps in France and then on rigid airships with the RNAS before joining Farnborough in 1917.

Most were civilian when they arrived, but in November 1915 the Hampshire Aircraft Park was formed and some 30-40 scientists and engineers received commissioned rank, their uniforms the only visible evidence the unit existed. Rank, based on position in the Factory, education and financial means and without formal military training, was questioned at the end of the war, but dealt effectively with the mistaken patriotism of young ladies, who presented white feathers to men out of uniform.[19] Accommodation for the main Trinity College group was Chudleigh House on the Fleet Road, which although an official military mess, was run very much like a senior common room. One non-Factory

*. British Thomson Houston

member of the Chudleigh Mess was Captain Edgar Adrian, formerly of Trinity College and a physiology research student of Lucas, who was now working in at the Aldershot Military Hospital a short distance away. Lucas was made president of the Hampshire Aircraft Park mess and lived in a hut within the Factory perimeter and other Cambridge graduates like S.B.Gates, not in the main group, had similar humble accommodation.[20]

Few brought any aeronautical experience with them. Their experience was predominantly Cambridge University laboratory practice, except Lindemann whose research experience had been with Nernst in Berlin. Many would learn to fly to conduct their own experimental work, Taylor being first, followed by Lucas, Lindemann and Farren. This group of wartime scientists at Farnborough is referenced in several books, because many received Nobel prizes and knighthoods for post war achievements, although the references are usually anecdotal and sometimes inaccurate. However, several were involved in the design of aircraft instruments and their work is examined in this thesis. Brief biographical notes on all the scientists in this thesis are provided in Appendix 3 for quick reference. Lindemann's involvement was significant and additional material on his technical activities at Farnborough is provided in Appendix 1 to supplement his biographies.[21]

1.5. The Experimental Flight at Upavon.

The war established another group of scientists at the Central Flying School (CFS) at Upavon in Wiltshire. In 1914, the CFS consisted of four flights for the sole purpose of training RFC and RNAS pilots on a mixture of privately built and RAF built machines, but with a need to evaluate aeroplanes and equipment, Brancker at the War Office formed the Aeroplane Experimental Flight at Upavon in November 1914. Captain A.H.L.Soames of the 3rd Hussars, who was serving with the RFC in France, was put in charge and given two BE 2 aeroplanes and 2nd Lt. G.M.B.Dobson as assistant. Prior to the war Dobson, from Caius College at Cambridge, was civilian meteorological officer at the CFS, and after the war would join Lindemann's staff at the Clarendon Laboratory. At this time, R.H.Mayo was learning to fly at the CFS to order to take over Busk's work and his course timetable shows that part of Dobson's duty was to give weekly lectures on instrumentation to trainee pilots.[22]

The original terms of reference of the Experimental Flight were to develop devices for mounting guns, for visual signalling from aeroplanes, and for bomb dropping apparatus and sights. On 20 December 1914, 2nd Lt. Robert Bourdillon, a tutor in Chemistry and Fellow of University College Oxford, joined the Flight. He had requested transfer to the RFC to develop an experimental bomb sight, that he had designed in his spare time

while serving with the Intelligence Corps in France. Soon more staff were required and Bourdillon wrote to Henry Tizard, another Oxford chemist formerly at Oriel College and now serving as a training officer in the Royal Garrison Artillery at Portsmouth, asking if he would consider joining them if transfer to the RFC could be arranged.[23] Tizard agreed and was posted to Upavon on 2 July, 'on probation for appointment as Assistant Equipment Officer in connection with experiments'.[24]

Dobson knew Tizard well, as he had attended Tizard's wedding in April 1914, at which Boudillon was best man. After graduating at Oxford in 1908, Tizard had spent two years as a research student under Nernst in Berlin, where he worked with Lindemann. On his return, he worked for a few months as a science master at Eton and then for a year at the Royal Institution Davy-Faraday Laboratory, where he produced a revised English edition of Nernst's *Theoretical Chemistry*. In 1911, he was offered a Fellowship and Lectureship by Oriel College and returned to Oxford, where in addition to lecturing in chemistry he also lectured and demonstrated in the Electrical Laboratory.

Boudillon and Tizard next persuaded a physics colleague, I.O.Griffith from the Clarendon Laboratory, to join Upavon. Griffith was gazetted 2nd Lieutenant in the Experimental Flight at Upavon as Assistant Equipment Officer in September 1915 and promoted Lieutenant in January 1916. Afterwards two more Oxford chemistry graduates, R.T.Lattey and H.R.Raikes, were also persuaded to join Upavon. Lattey and Tizard had toured the Black Forest together in the summer of 1911, after Tizard had returned to Oxford.

Tizard worked initially on bomb aiming experiments and soon came to the conclusion as did others, that it would be difficult for any scientific man to undertake aeroplane experiments without himself learning to fly. He received permission to learn providing that he was only taught on days when the weather was too bad for normal pilot instruction and obtained his Royal Aero Club Aviators Certificate on 18 January 1916 and his RFC Certificate of Completion of the CFS course on 23 May 1916.[25] Ten days after qualifying, he logged a 60 minute flight to Salisbury and Stonehenge with F A Lindemann as passenger, which no doubt prompted Lindemann to make his own request to learn to fly, though permission was not granted until after O'Gorman left Farnborough two months later. Like Lindemann, Tizard had poor eye sight, but wore his glasses under his flying goggles until he had lenses fitted into them.

Tizard,Bourdillon and Griffith were not happy about their rank of Lieutenant compared with their colleagues at Farnborough and wrote jointly to their commanding officer that,

> their present rank is inconsistent with the amount and nature of the work we are called upon to perform, and also with our positions in civilian life; also that this work, responsibility and initiative, cannot be carried out by officers of the lowest rank. Further, officers occupying scientific posts in other branches of the army are given ranks more consonant with their attainment, for example we know of officers of similar or inferior positions to ourselves in civilian life being gazetted as Captains immediately on joining the Army.[26]

There was no immediate response and Tizard was not promoted until the end of the year. The second part of the letter listed their technical responsibilities and concluded by saying they had also drawn up the scheme for the establishment of the proposed new experimental station at Orfordness, to which the armament activities at Upavon were transferred later in the year. Tizard remained at Upavon as Chief Experimental Officer of what was now the Testing Squadron, but was apparently unhappy with the situation. He wrote to Lindemann that he would like to work at Farnborough, enquiring about the Scientific Flight he had heard was being formed there and which he would like to command.[27] He said his work in the Test Flight was very unsatisfactory at present, it was a non-flying job as they could get no one else and he felt he was in a blind alley. He was thinking of applying to go to the Front as an ordinary flying officer if they would let him go, but he would prefer a home job where he could really do something, particularly as he could not imagine what would happen to his family if he were taken. This was a strange letter to write, unless he was exploring the Farnborough post, because his Pilot's Log showed he flew continuously until he moved to martlesham Heath the end of the year, by which time he had totalled some 100 flying hours for the year.

1.6. Orfordness and Martlesham Heath.

Testing new aeroplanes and developing bomb aiming and gunnery techniques at a flying school grew untenable due to the priority of instructors and aircraft for training and the congestion over the airfield. Hopkinson persuaded the War Office that new facilities were essential and Orfordness and Martlesham Heath were established adjacent to each other on the East Coast near Ipswich.[28] Towards the end of 1915, the Armament Experimental Unit started work at Orfordness, with Melvill Jones from Farnborough in charge of experiments and Boudillon, Lattey and Raikes from Upavon. Dobson did not move to Orfordness, instead he was posted to Farnborough to replace Lucas and found himself responsible for instruments, chemistry, physics, fabrics and instrument repair, and the small physical laboratory of Lindemann and T.C.Keeley.[29] Hopkinson and Tizard next based themselves at Ipswich, to look for a suitable site for performance testing and a site on Martlesham Heath was chosen. Building work began in the Winter 1916 and Tizard

moved his equipment from Upavon to the new Aeroplane Experimental Unit in January 1917. Tizard, now Scientific Officer with the rank of Captain, was in charge of the technical developments, assisted by Lt. Chivers on instrumentation and mathematics, and by Lieutenants Inton and Gore on calculations and the reduction of experimental measurements. Mayo moved from Farnborough to be one of the test pilots. Except for Tizard's own paper, this test work has not been published and is not mentioned by Kinsey in his histories of the two establishments, which in 1924 merged as the Aeroplane and Armament Experimental Establishment (A&AEE).[30]

1.7. RNAS Laboratory - Imperial College

The new buildings at Imperial College had only just been completed when the war started and the fully staffed and equipped laboratories and workshops were empty of students. In 1915, Harry Egerton Wimperis, aged 39, a graduate in Mechanical Sciences at Gonville and Caius College, Cambridge, arranged for the RNAS to establish a laboratory in the Physics Building.[31] The College Governors generously agreed to place the physics workshop and such laboratory room as required at the disposal of the Admiralty, free of rent and any charge for salaries or wages other than overtime, war bonus and materials consumed. This laboratory under Wimperis became the centre for bomb aiming research during the war, and the Air Ministry Laboratory after it. There is no biography of Wimperis or published history of this laboratory to date, but its importance will become apparent in Chapters 7 and 8, where it will be more convenient to merge its history and technical achievements.

1.8. Air Inventions Committee

Until 1917, inventions relating to the Navy were reviewed by the Admiralty Board of Inventions and Research (BIR or sometimes as the Board of Intrigue and Revenge) under Lord Fisher, with scientists like E.Rutherford and J.J.Thomson as members.[32] Inventions relating to the Army, were reviewed by the Munitions Inventions Department.[33] Responsibility for aeronautical inventions was split between the two groups and the division became more acute as the war progressed. In June 1917, the President of the Air Board Lord Cowdrey, formed the Air Inventions Committee as a sub committee of the Aeronautical Advisory Committee, with Sir Horace Darwin as chairman, now aged 66, to handle more effectively the thousands of air inventions which were being received. Cowdrey believed that a specialist inventions committee, exercising independent judgement on their merits, would be more conducive to public confidence than a section of a government department.[34] The organisation of the Air Inventions Committee would be

similar to the Munitions Inventions Department, except that decisions would be made by the committee rather than a Controller. Being a sub committee of the Advisory Committee would avoid any delays in setting it up or providing links with experimental resources, while overlap and communications with the other two inventions departmentswerecovered, as members of the Air Inventions Committee were also members of these bodies. This at any rate was the official statement by the new chairman. Correspondence shows that Cowdrey was willing to approve anything agreed between Rayleigh and Darwin.[35] Darwin defined engines, armaments and instruments as specialist sub committees, while he chaired the Instrument Sub Committee with R.T.Glazebrook and L.Bairstow (NPL), H.L.Callender (Imperial College), Major G.I.Taylor and Captain B.M.Jones (RFC) and Lt. Cdm. H.E.Wimperis (RNAS) as members. Callender was Professor of Physics and had received first class degrees in classics 1884) and mathematics (1885) while at Trinity College, after which he developed the platinum resistance thermometer as assistant demonstrator in the Cavendish under J.J.Thomson, and for which Darwin obtained sole manufacturing rights. The instrument sub committee was a tight knit community!

In the first seven months, upwards of 5000 inventions and suggestions relating to the Air Service were examined. The sheer quantity forced Darwin to publish guide lines in numerous journals and periodicals.[36] He explained that he appreciated the patriotic motives of inventors and that those not connected with air services or manufactures were at a disadvantage, but it was useless for inventors to submit ideas that would take a long time to develop. Radical changes in shape of aeroplane bodies and wings were only possible after long and patient research, while minor improvements could only be justified by some very marked superiority over present standardised fittings, and safety devices usually involved a weight penalty that effected the war performance of the machine. The exacting performance of the aeroplane engine running continually at maximum power also meant that ideas, based on a knowledge of the motor car engine, were usually impractical. Regarding instruments, he thought it scarcely likely that anyone without the necessary scientific and mechanical knowledge could improve the efficient and well designed instruments already available - many suggestions disregarded centrifugal action on pendulum and spirit level devices or showed little understanding of the application or limitations of the gyroscope. In fact, no instrument suggestions proved worthwhile.

The Air Inventions Committee was also responsible for the procedures for patenting and disclosing inventions.[37] Secret patents had tobe assigned to the Government, who would bear expense and agree remuneration. Patents taken out by Government Officials, which were not to be kept secret after the war, could be communicated to others with the permission of the Department concerned and the Inventor given permission to take out patents in foreign countries, providing the Government retained free right of use of the

invention in those countries. Patents to be kept secret after the war, could be disclosed to Allied Governments, providing they were 'material to the conduct of the war' and manufacture was in a government factory. Restrictions were placed on private firms collaborating on developments which were the property of the British Government - all matters and instructions submitted by a Department to a collaborating firm were the property of the Department and no independent patents could be taken out without its approval. In the case of invention by a person or a firm in connection with information supplied by a Department, the Department would have the right to join in the application for the patent.

1.9. Instrument inspection and repair facilities at Farnborough.

The work of the instrument inspection and repair departments and the test equipment that they designed and used, which provided extensive instrument facilities for Farnborough scientists during the war,are well documented.[38] However, as the detail is not considered essential to this thesis, only a brief description will be provided. From 1910-1917, all principal RFC aeroplane instruments were inspected and in some cases designed at Farnborough and after 1917 repair facilities were also provided. The Inspection Department was responsible for designing bench and air tests for proving instruments and for writing standard specifications in time for the war, for the design of special test instruments and for the wartime arrangement to manufacture thousands of aneroid movements by Zenith in Switzerland, and in time grew under Lt. Harrision to 14 men and 104 girls. This centralised inspection was not favoured in America, instead government inspectors resident at the instrument makers returned random samples to the Bureau of Standards.[39] The Repair Department under Mr. Whidbourne consisted of 122 men and 66 girls, divided into sections covering each type of instrument plus machine, finishing, engraving and painting shops. Equipment for simultaneously testing batches of instruments in these departments included 8 sets for air speed indicators, 23 sets for aneroids, 11 sets for pressure gauges, 15 sets for revolution indicators and 12 sets for thermometers.

Repair was an expedient and eccohomic way to meet the shortage of instruments for new aircraft.

The repair cost for most instruments was only 7-10% of the new cost, the exception being 45% for watches and 25% for the mechanical drives and gearboxes of revolution indicators. The Repair Department was able to increase overall instrument repair from 240 in February 1917, to 600 in December that year and finally to 7,083 in October 1918 during the last full month of the war, by which time 73,837 instruments had been

repaired. The Air Board had set them a target of 8,000 per month, which they would have achieved if hostilities had continued.

The centralised inspection and repair departments had good relations with Lt. Cmdr. Hull in Supply Department at the Air Board and with Major Stewart at Martlesham Heath. No mention was made of Major L.N.G.Filon at the Air Board Technical Department, who was technically responsible for the two departments at Farnborough and had been the subject of complaint from them.[40] Filon was a mathematician with little experience of the work in which he was involved and who never visited Farnborough although repeatedly asked to do so, a situation which resulted in the staff at Farnborough, Supply Department and Martlesham Heath establishing direct links to bypass him. Centralised inspection and repair enabled Farnborough ... to make experimental instruments, or manufacture short runs of instruments for themselves or Martlesham Heath before placing orders with a commercial maker. Martlesham Heath developed test and calibration equipment for single instruments, which is equally well documented.[41]

Conclusions

The Advisory Committee for Aeronautics established British aeronautics on a sound scientific footing from an early date, and the presence of Horace Darwin on the committee ensured the same for the instrumentation involved. He helped Farnborough significantly in their early days and this help and advice to others will be noticeable throughout this thesis. That the first Wilbur Wright Lecture was on aircraft instruments, showed the subject was gaining importance and that vibration and acceleration presented demanding scientific problems. Pre-war, Farnborough had a Cambridge graduate as both test pilot and head of the experimental department. However, war brought an influx of university scientists, most of whom had no aeronautical experience, only the laboratory research and experimental practice of the universities they had left. They were led initially by Mayo, another Cambridge graduate who also doubled as experimental test pilot. The war established another group of scientists at Upavon under Dobson from Cambridge, while the RNAS established their own laboratory at Imperial College under Wimperis, another Cambridge graduate. This thesis examines the instrument activities of these groups of scientists. Many later become well known in other fields and brief biographical notes are provide in Appendix 3 for quick reference.

What becomes very apparent is that the various aeronautical committees and groups of scientists were not a haphazard collection of interested individuals, but hand picked communities based on former academic relationships. We shall also see that in addition to

Professor B.Hopkinson, a notable contribution was made by Professors H.L.Callendar, J.B.Henderson and J.G.Gray.

Wartime research was mainly conducted within the services. It was sheltered from the flood of suggestions and inventions of the general public by the naval Board of Invention and Research, the military Munitions Inventions Department and eventually the Air Inventions Committee, which was formed under Darwin to co-ordinate aeronautical matters in both services. However, few inventions outside the services had any strategic value - certainly no aeronautical instruments. The development of aeronautical instruments during the war was entirely British, with no European or American influence.[42] The next chapter will examine pre-war development of aircraft instruments to show the technology that existed when the wartime scientists arrived.

Chapter 2.

Aircraft Instruments

Early Commercial and Government Developments

Summary - Instrumentation slowly added to aeroplanes - the potential for commercial development - development without research, the example of J.J.Hicks - development of revolution indicators - altimeters - Darwin's 1913 paper 'Scientific Design of Aeronautical Instruments' - The RAF Velometer - Darwin's yaw and ascending speed meters - stability and acceleration measurement - Ripograph and Trajectograph - problems with photographic recording - use abandoned in favour of qualitative observations - Thurston's 1914 paper 'The Measurement of Air Speed' - three methods to measure air speed, (i)velocity, (ii) velocity density and (iii) velocity squared density - pressure plate air speed indicators - Darwin, Clift and Ogilvie air speed indicators - Pitot-static and pitot-suction heads - gravity versus spring control - hot wire anemometers - Clift and J.W.Munro - Griffith Brewer and the British Wright Company - development of Ogilvie indicators - the Aeronautical Instrument Company and its patents - the Royal Commission for Awards to Inventors - conclusions

This chapter examines the development of the revolution counter, altimeter and air speed indicator, together with some specialised instruments like the accelerometer. Engine revolution indicators received early attention, as sustained flight depended on low powered and unreliable engines. The narrow safety margin between stalling and structural damage created the need for the air speed indicator and then as aeroplanes struggled higher the altimeter was added. The main problem facing the instrument designer was engine vibration. Successful balloon or mountaineering barometric instruments proved useless in the close proximity to an aeroplane engine, except as hand held instruments. We shall see that most of this early development was commercially based, but that Farnborough were designing aircraft instruments for their own use. Commercial design was frozen during the war to assist the production of instruments, but some makers showed inventiveness during it although they received little reward later.

2.1. Commercial Development without Research - example of J.J.Hicks.

The instrument trade followed two paths as interest grew in aeronautical instruments. Some makers took the development seriously and endeavoured to overcome problems, while others saw aeronautics as a new outlet for existing instruments, which required little effort other than creative advertising. The second policy had some initial success with

simple instruments and inexperienced pilots, but was short lived. Trade journals were aware of the potential of the new field. The Optician and Photographic Trade Journal [6 August 1909] was prompt to alert its readers to the formation of the Advisory Committee for Aeronautics, which included 'eminent mathematical opticians', and of the Government's intention to devote a large sum of money to aeronautical development for military and naval purposes. The writer thought it unlikely that meteorological instruments would be required in an aeroplane, but saw great scope for the instrument maker to design small gyroscopic movements and compasses similar to the larger versions used on ships. He believed that a proportion of the money voted for the development of the aeroplane might be used to purchase inventions of this type. Regarding the protection of ideas and complaints at their theft, the Government required a patent application to be made prior to any invention being submitted to them .

The advertisements of J.J.Hicks of Hatton Garden in the same trade journal showed how one established instrument maker attempted to meet the challenge. Hicks claimed to employ unfailing ingenuity and resource in the design of his aeronautical specialities, but his advertisements were more ingenious than his designs. In October 1910 he claimed his 2 inch Aero Liquid Compass, in its brass oxidised hunter case (Fig 2.1), was especially suited to meet the trying ordeals of man-flight, but to increase its market he suggested that opticians might advantageously state in their window display, that although it had been designed for aerial adventures, it was also suitable for travellers on horseback, trains, yachts or ships. He employed the opposite argument for his altimeter, where its use for meteorological kite flying and by military balloonists, motorists, cyclists and hill climbers, made it ideally suited for aeroplanists. It weighed only 7 ounces in its aluminium case and, as its hand only moved in one direction, it stopped and recorded when the aerial machine had attained its greatest height. His altimeter was an instrument of achievement, rather than one to assist the pilot return to earth and, although it had been structurally improved to withstand vibration, it was intended to be carried in the pocket.

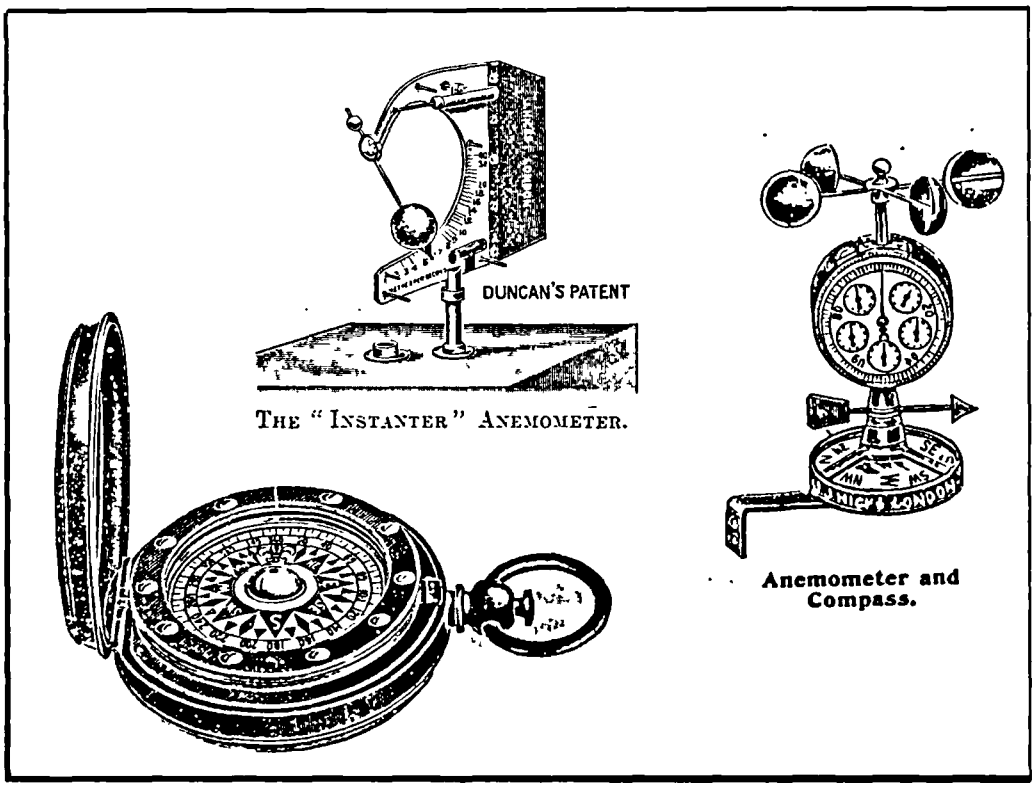


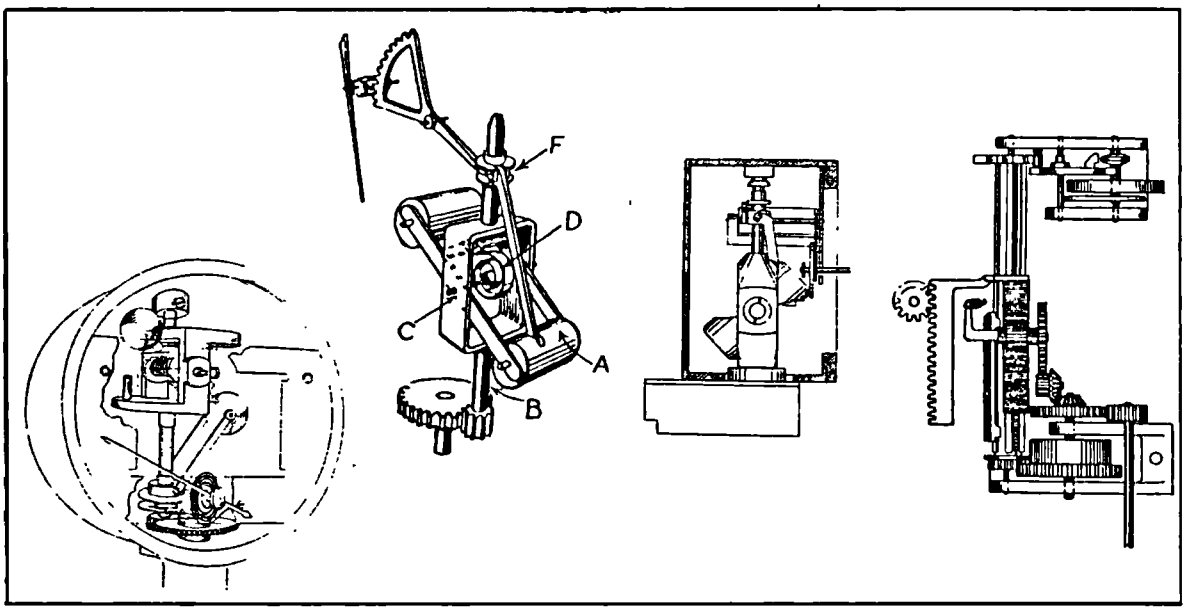
Fig 2.1 Some Hicks "Aero" instruments.

His most impractical instrument was a combined anemometer, wind vane and luminous compass, complete with bracket to fix it in any desired position in the aeroplane. The anemometer had six separate circles, reading from *0.1 to 10,000 miles and could be reset back to zero.* An arrow was provided beneath the dial to indicate wind direction and the compass was luminous for night flying. In 1912, he advertised the Aero Clinometer and Instanter Anemometer. The clinometer was a disc shaped instrument with a circumferential glass tube half filled with mercury, based on his marine clinometer patent 14,724/11, which was popular with both ship's officers and passengers. The Instanter was a pressure plate air speed indicator which gave the wind velocity on sight.

Hicks was a long established instrument maker with a good reputation, but is given as an example of a maker who did not undertake any serious aeronautical research, adopting instead, the type of empirical approach to aeronautics that Haldane had anticipated and wished to avoid. This was surprising in Hick's case as previously he had undertaken important research to reduce the hysteresis of the aneroid barometer when ascending and descending mountains.[1]

2.2. Engine Revolution Indicators

Automobile revolution indicators were designed for vibrating service and were adopted for aeronautical use with little modification, other than reducing their weight. Elliott Brothers, S.Smith & Sons, North & Sons and Haslar Telegraph Works, all London makers, were the main suppliers.[2] The first three companies made centrifugal type indicators, containing spring-constrained revolving weights, which assumed a horizontal position as the speed increased and moved a collar on the central shaft to actuate the pointer - Elliott Brothers and Smith designed their own, North at Watford made the Nicole Neilson under licence. The TEL indicator of Haslar Telegraph Works, 26 Victoria Street, was the more accurate, but the more expensive as it used the more complicated chronometric principle, which measured the revolutions performed in successive time intervals of fixed length.



(a) Elliott Bros. (b) Smith & Sons (c) North Watford (d) Haslar TEL

Fig 2.2. Engine Revolution Indicators.

Revolution indicators were in use at Eastchurch in 1910, when Dunne logged his engine revolutions as 1400 to demonstrate to Orville Wright that his machine was sufficiently stable for him to release control and write a brief note, a feat impossible with Wright's own machine.[3] Both Smiths and Elliott indicators were in use by 1911.[4] Elliott's received praise from Sopwith, after his record breaking long distance flight to Belgium,

> I should like you to know how essential your revolution indicator has been to my flying. I would not be without it for anything. I practically 'drive on it' the whole time, as well as do my engine tests with it. During my flight to Belgium, it worked magnificently, never giving a moments trouble and showing a perfectly steady reading.[5]

He could not write a similar letter to his compass maker as his compass card never stopped rotating during the flight and was the reason he ended in Belgium. There was little innovation in mechanical revolution indicator design until replaced by electrical ones.

2.3. Altimeters

The altimeter, like the revolution indicator, was a commercial development. The aneroid barometer was well established for mountaineering, ballooning and meteorological research

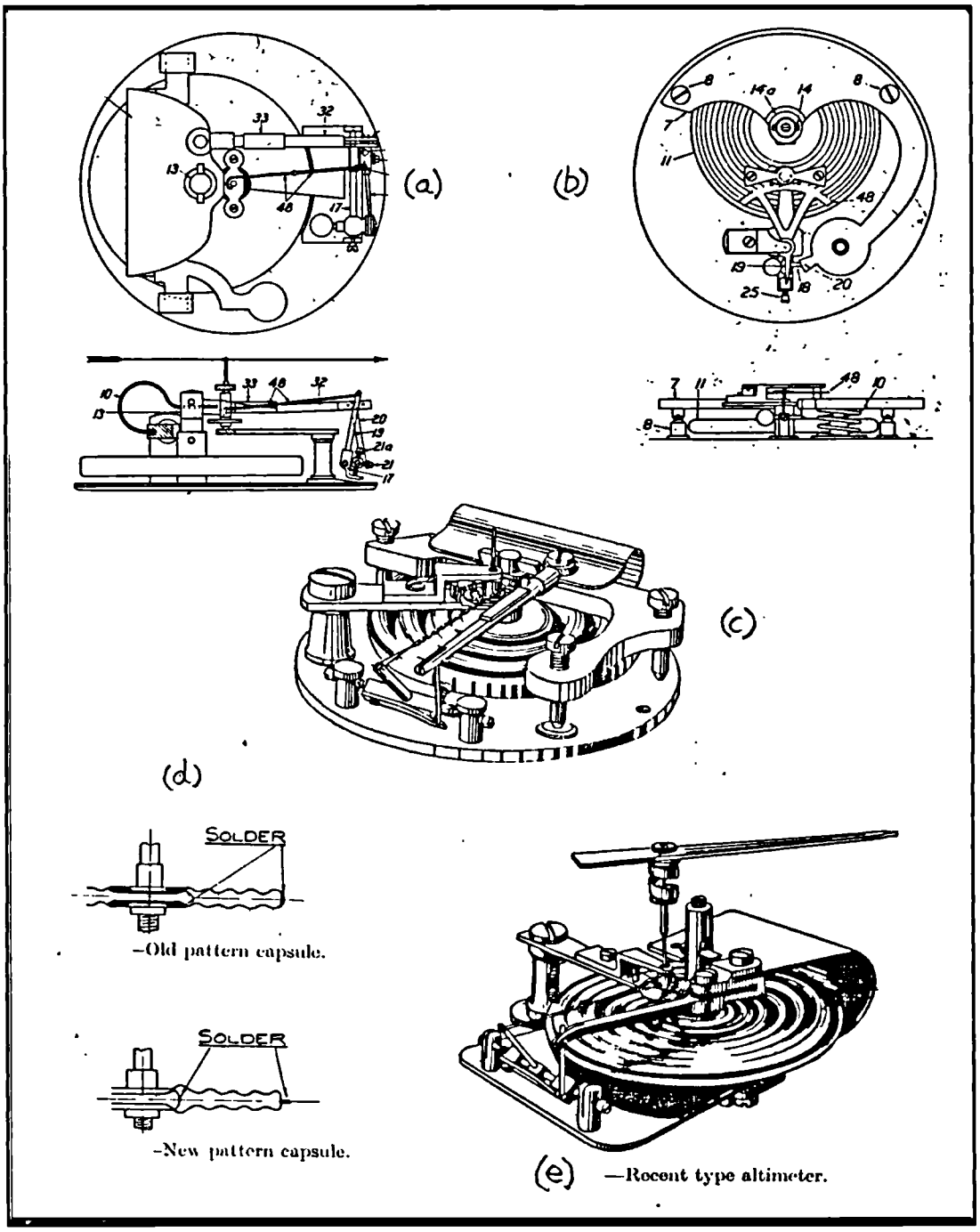


Fig 2.3. Altimeter design.

(a) Aneroid barometer - C-spring design. (b) Aneroid barometer - helical spring design. (c) British wartime altimeter - C-spring with 3 point geometric mounting. (d) Reduction of solder to reduce hysteresis. (e) Post-war altimeter to avoid C-spring mounting block.

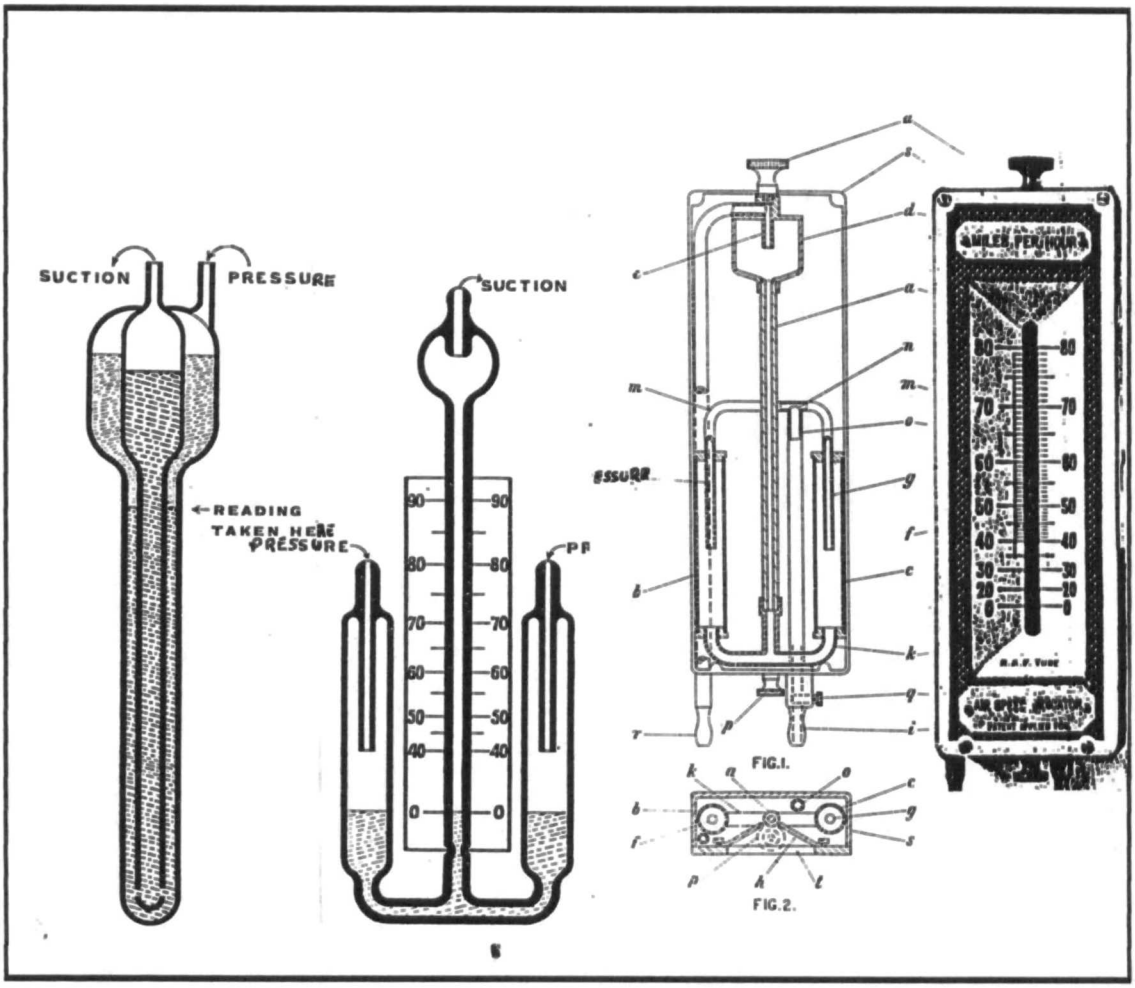
and was available from Casella, Elliott Brothers, Munro, Negretti and Zambra, Short and Mason, as well as Hicks.[6] However, existing instruments proved useless when fixed to a vibrating airframe as the mechanism, which magnified the 2 millimetre movement of the vacuum capsule into a 300° pointer rotation, also magnified the vibration.

In the aneroid instrument, the evacuated capsule has to be prevented from collapsing by spring pressure. There were two basic designs. One used a strong C-shaped leaf spring, clamped to side pillars and latched under an inverted knife edge on a short pillar attached to the top surface of the capsule (Fig 2.3a). The moving parts in this design had little mass. The second used a helical spring, positioned under a curved arm of a bridge, which extending across the capsule from two pillars on the opposite side and latched under a pin on the capsule pillar to prevent the capsule from collapsing (Fig 2.3b). The bridge plate in this design was a moving part and therefore prone to vibration. Both designs were used in French altimeters.[7] However, the British altimeter adopted the leaf spring design, but secured it more firmly with three point geometric mounting, modified the linkage to provide an evenly divided height scale, and provided a racked periphery and pinion knob to allow the pilot to rotate the dial before take off to set the pointer to zero (Fig 2.3c). The resulting design was tolerant to vibration, but as ascents and descents were more rapid than in mountaineering, its lag and hysteresis were very noticeable. Nevertheless, it remained in service throughout the war period and it was 1922 before Farnborough found that it was the relatively large amounts of solder on the edges and stud of the capsule, that seriously effected its elasticity and caused the lag and hysteresis.[8] The amount of solder was reduced by using a larger stud and providing flat edges on the capsule pressings (Fig 2.3d) and hysteresis was further improved by modifying the way the C-spring was fixed into the bridge. In its manufacture, any looseness was removed by hammering the edges of the spring slot together, which resulted in the spring being held at points along its edge, but still being able to rock in the slot. In the re-design, the spring was supported between two knife edges (Fig 2.3e). These improvements were empirical and it was 1927 before the theory of the pressure capsule was examined by Farnborough.[9]

2.4. Velometer and Yaw Meter

The forward speed of an aeroplane is equal to the speed of the air flowing past it. Initially for low speeds, meteorological instruments like the Robinson cup anemometer were used, which could be placed outside the slipstream from the propeller and still be read by the pilot. The pressure plate provided another method, but still had to be placed outside the slipstream and be readable at a distance from the pilot. Farnborough adopted the Dines pitot tube anemometer as the solution, as the head could be placed well away from the slipstream and the readout could be placed in front of the pilot. The accuracy of the pitot-

static measurement in wind tunnels had been determined in 1903 by Stanton at NPL and confirmed for aeroplanes by Melvill Jones and Harris Booth at NPL in 1913.[10] The following month, Horace Darwin described the use of the pitot tube and manometer in the First Wilbur Wright Memorial Lecture, *Scientific Instruments - Their Design and Use in Aeronautics*.[11]



(a) (b) (c)

Fig 2.4. RAF liquid manometer air speed indicator.

(a) Short concentric air speed indicator. (d) Short 3 limb air speed indicator or Velometer.
(c) Short's 1912. Patent 14,749.

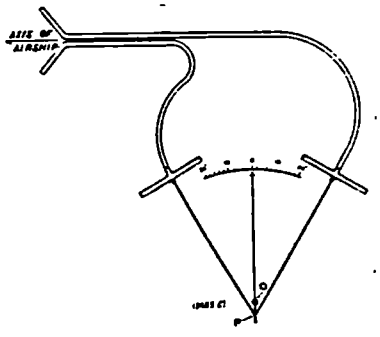
The principle was simple - as the air speed increased, the pressure in the pitot tube increased and the difference between this pressure and the static pressure outside the tube measured air speed. By experiment, it had been found that the size or shape of the opening of the pitot tube made little or no difference to the pressure in it, although the design of the static openings was critical. The simplest manometer was a U-tube, but on an aeroplane it suffered errors due to tilting the tube and the scale was not open enough. Frank Short at Farnborough designed two ways to minimise these difficulties - a concentric tube version with two liquids of different density (Fig 2.4a) and a single-liquid three-limb U-tube

version (Figs 2.4b and 2.4c), which he patented, Patent 14,749/12. The concentric tube version was very similar to 'Dines' portable anemometer, with which Short would be very familiar as J.C.Dines was at the Meteorological Office, South Farnborough at this time. The three limb U-tube version possibly evolved by 'opening out' the cross sectional view of the concentric tube.

The three limb U-tube version became the standard service air speed indicator for the next two years and was manufactured by Elliott Brothers and Casella as the Velometer.[12] The three limbs reduced the effect of tilt, while the smaller diameter middle limb magnified the reading to give a more open scale and only this limb was visible to the pilot. The instrument had a fast response as only a small volume of liquid had to be displaced when the speed of the machine changed and it could be inverted during a loop without loss of liquid. However, it was not an convenient instrument to read and by 1914 the more 'user friendly' dial indicators were preferred.[13] Nevertheless, Farnborough continued to use the velometer in research flying until 1920, as its accuracy and small measurement lag were more important than its ease of reading. The concentric tube manometer was not used in service aeroplanes, but found favour to indicate gas pressure in airships.

Darwin had introduced the instrument in his paper as an example of a design with a high tolerance to vibration, but also drew attention to the effect of acceleration on its accuracy in an aeroplane. He gave the example of an aeroplane flying at 100 mph in a circle of radius 1400 feet at a bank of 26° to prevent side slip. The increased vertical acceleration on the manometer due to the turn would decrease the manometer reading to 94.5 mph. No one commented on this error at the time and its real implication did not become apparent until later.

Darwin next reviewed two instruments of his own design, the yaw meter and the ascending speed meter. His yaw meter consisted of two pitot tubes inclined at about 120° to each other, and connected to a differential pressure device.[14] In normal flight, the wind would blow symmetrically onto the two tubes, but with yaw or sideslip, the wind direction would be oblique and produce more pressure in one tube than the other. The indicator suffered from vibration, not surprising as the mechanism was taken from a letter balance.[15] However, the method of measuring yaw worked and its successful use by others will be discussed later. Darwin said that his ascending speed meter was experimental and needed to be remodelled to make it smaller. He described the instrument as a vessel with a clockwork driven valve connecting it to the open air so that with the valve open, the air in the vessel was at the same pressure as the air outside. Closing the valve trapped air in the vessel and, as the aeroplane climbed, this air was at a



higher pressure than the air outside and the difference in pressure measured with a manometer gave the change in barometric height between the two movements of the valve. Darwin did not make a second model, possibly he found the design was not novel as Horace Short of Short Brothers had patented a similar device for balloons in 1910, Patent 29874. The ascending speed meter or climbmeter was developed as a practical instrument in 1916 by the Testing Squadron at Upavon and is examined in Chapter 3.

A typical experiment using two velometers was described by O'Gorman and Busk.[16] To measure the effect of slipstream on a rudder, one manometer was connected to a pitot head on a forward wing strut, and the second to a pitot head on a beam just ahead of the tail plane, which could be moved to take readings at various distances from the centre line of the body. The velometers were checked by a timed flight on a speed course, the tube on the wing giving air speed, the one on the tail giving the sum of air speed and slipstream. The same method was still in use in 1917.[17]

2.5. Aeroplane Stability and Acceleration.

A useful feature of the liquid U-tube was that the shadow of the liquid could be photographically recorded, which Farnborough made use of in the Short-Dines tetra-nemograph, a device for recording wind gusts at 4 locations onto a single recorder.[18] They tried to use the same feature during stability experiments to measure the motion of the aeroplane along three axes, mutually at right angles, and its rotation about these axes. Nine in-flight measurements were synchronously recorded into a single instrument called the 'Ripograph' (Greek for rush or flow of air), which was developed by Busk's department and made by the Cambridge Scientific Instrument Company.[19]

The instrument was intended to replace earlier experiments, where the movement of the controls was recorded on a chart by a pencil attached to the controls, while the movement of the aeroplane was followed with two theodolites.[20] However, this attempt to measure the response of the aeroplane to its controls in one instrument proved to be outside the scope of the instrument designer. The instrument was heavy and cumbersome and mechanical problems resulted in wasted test flights, as any failure was not apparent until the photo-record was developed after the flight. A simpler instrument called the 'Trajectograph' was produced using only the U-tube altimeter and air speed indicator, which proved more practical as there was less to go wrong. Nevertheless, the record still had to be developed to know the test was successful and this problem was to remain with all aircraft photo-recording instruments and led to the universal agreement in aircraft research establishments in 1919 that ***a trained observer was superior to any recording instrument.*** Recorders were only used in single seater aeroplanes, where the

pilot was unable to log readings himself, or as secondary instruments when an observer was present. Both the ripograph and trajectograph were amongst instruments exhibited earlier in May at the Royal Society Soirée by O'Gorman and Busk.[21]

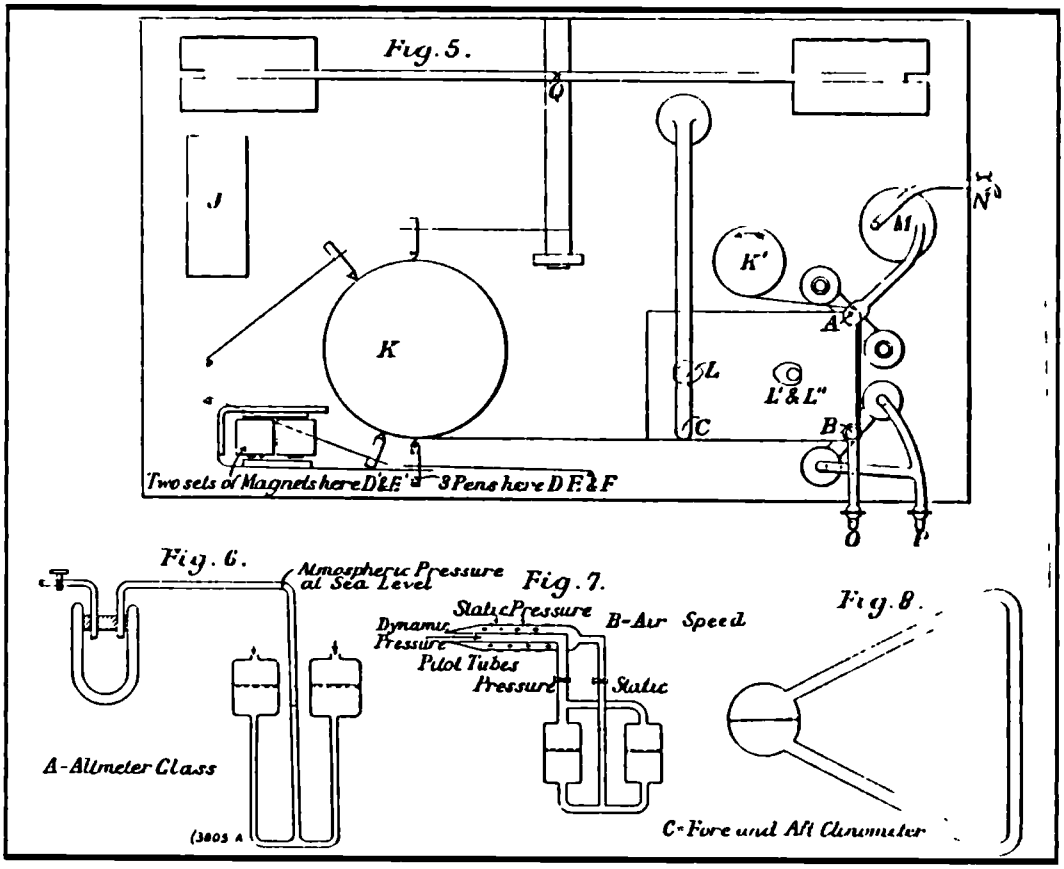


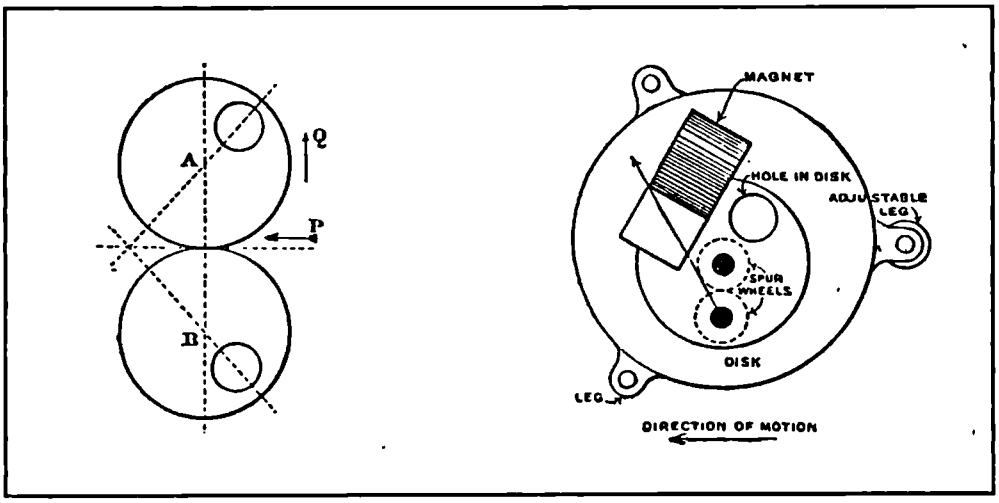
Fig 2.5. The Ripograph

The wooden light tight box housed the recording equipment for nine measurements - rudder, elevator and wing flap movement, height, air speed, engine speed, horizontal and lateral inclination, and time. A clock-work driven drum *(K)* unwound bromide paper strip chart from a second drum *(K)'* and along two sides of a lamp box *(L)*. Three shadow photographic records were taken on the inside of this chart paper and six pencil records on its outside. The shadow recordings were obtained from liquid columns in a U-tube altimeter, air speed indicator and inclinometer, (Fig 2.4c, d and e). The six pencil records were the three control surface movements, the engine revs, roll and time. The elevator, rudder and warp movements were recorded by cables connected to the stick and pedals. The roll the aeroplane was recorded by a large weighted lever *(Q)*, which constituted a short pendulum of long time period. The engine speed was recorded through a 100:1 reduction gear mechanism, which marked the chart every 100 revolutions. A time base for the recordings was provided the electric motor *(J)* and electro-magnet *(D)*, which marked the chart and flickered the lamps to mark the shadow recordings every 15 seconds.

By early 1914, lack of suitable instruments forced Farnborough to use qualitative methods to assess stability by observing the effect of allowing disturbances to go uncontrolled. Busk would start a turn and observe whether the rate of turn increased or diminished with the rudder free.[22] The report mentioned that the manoeuvres were all performed at a good height above the ground, to warn others that Busk had damaged one machine when he

crashed into a small hill while his attention was diverted by qualitative observations.[23] It also mentioned that some stability measurements were possible by separately examining the movement of the aeroplane about each axis using Darwin's yaw head and Wimperis's accelerometer. Because Darwin's indicator mechanism was unusable, each pitot tube was connected to a Short Velometer - the average of the two readings gave the air speed, while the difference gave the yaw or sideslip. However, this was only a partial solution, as the constant movement of the instruments due to wind gusts and pilot corrections made it too difficult to read them with sufficient frequency to obtain sensible averages. Acceleration forces also put a strain on the aeroplane rigging and O'Gorman designed a tautness meter to measure and record the strain, which Darwin manufactured.[24]

The Wimperis accelerometer was an interesting use of an instrument designed for rail and road vehicles. It consisted of pivoted masses constrained by a spring (Fig 2.6), the distortion of which measured acceleration and ingeniously registered forward acceleration, whether level or inclined, but ignored sideways acceleration on a curve. Wimperis jointly patented it with K.Elphinstone of Elliott Brothers in 1909, Patent 20,231, and later published a book to explain its use for road transport.[25] It was made by Elliott Brothers, with certain improvements added by Frank Short to make it successful in flight. Darwin



(a) (b)

Fig 2.6. The Wimperis Accelerometer 1909.

(a) shows the design concept looking from above. The un-balanced discs are geared together, so they revolve if acceleration is in the direction of motion P, but not for acceleration Q at right angles to it. (b) The actual instrument had only one disc, the mass of the pointer replacing the second disc. The disc was copper and the magnet provided eddy current damping.

designed a constrained mass accelerometer in 1914, Patent 13,776, in which a torsion rod provided the constraining force, and another post-war in which the mass was constrained by leaf springs, but there are no reports of their use.[26] A spring constrained accelerometer was also used in the RNAS Recording Wavemeter, which was designed to measure wave height and assist inexperienced seaplane pilots determine if take off was feasible.[27]

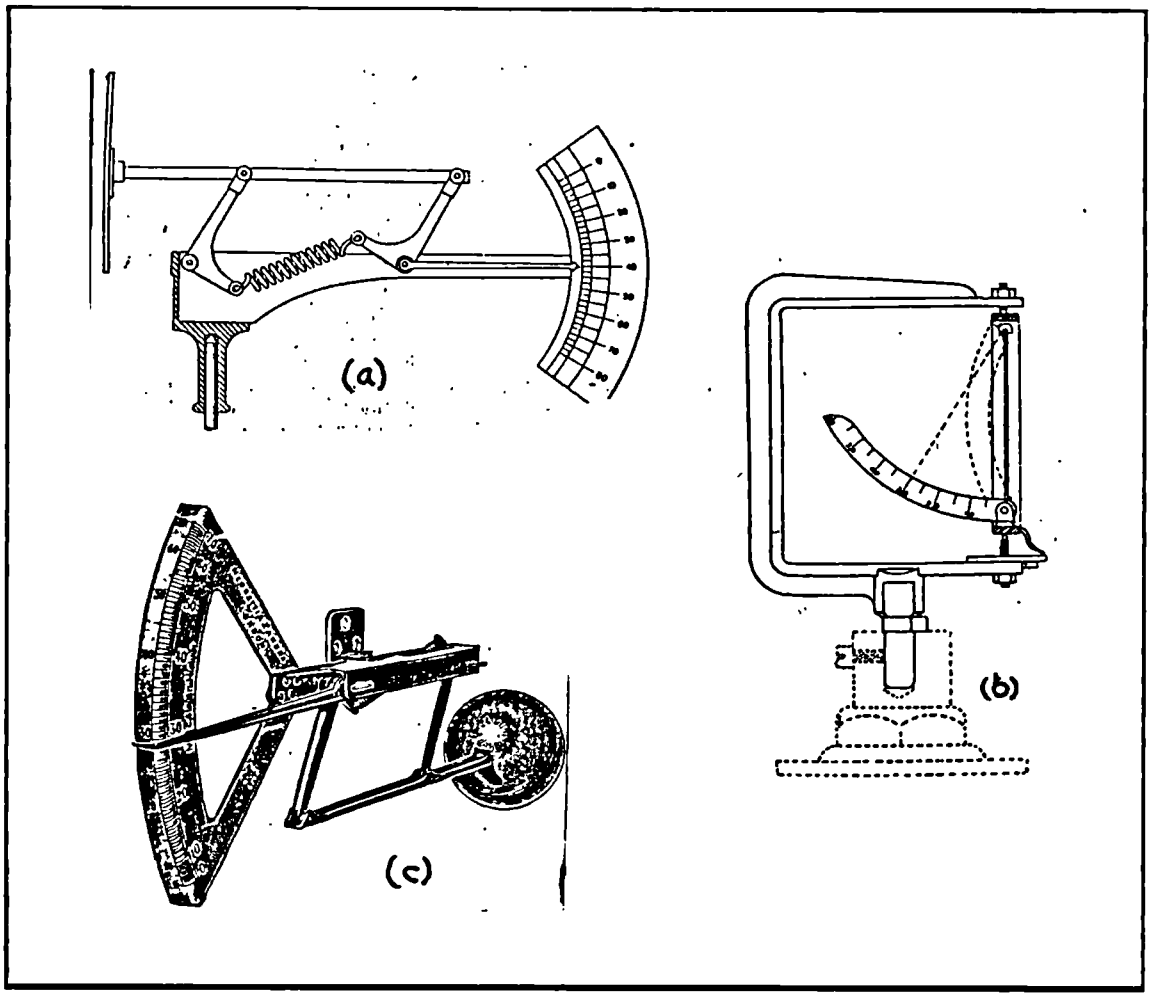
The simple methods used by Farnborough to measure aeroplane stability proved successful and increasing the rear fin area and the wing dihedral improved lateral and directional stability, while staggering the lower wing back from the upper wing improved longitudinal stability. With these changes, the BE 2 could be flown 'hands-off' for long distances.

2.6. Air Speed Measurement

The velometer was not a convenient instrument to read and dial type air speed indicators were developed commercially in parallel. A.P.Thurston gave a paper on the position in May 1914 to the Royal Aeronautical Society, with Darwin presiding.[28] Thurston lectured on aeronautics at East London College, one of two London colleges to have an aeronautics department and laboratory - the other was Northampton College, where Handley-Page lectured. Thurston saw the measurement of air speed as a matter of extreme importance to guard the pilot against the risk of stalling his machine, or of attaining a higher speed than its structure could withstand.

He explained that three methods could be used to measure air speed, (i) the velocity method v, (ii) the velocity-density method ρv, and (iii) the velocity-squared-density method ρv^2. In the first method, the velocity is determined by the time taken by an object, floating or dragged along by the air, to travel from one point to another - rotating cup or vane instruments are of this type. The useful feature that the velocity was independent of air density and needed no correction for altitude, was little use to early aircraft, which did not fly high enough to take advantage of it and when they did, their speed was too great for the instrument. In the second method, the velocity is determined by the mass of air passing a certain point, and is therefore dependent on density and velocity, or ρv. Instruments measuring the cooling effect on an electrically heated wire fall into this group, but the relatively large weight and complexity of such instruments made their airborne use as air speed indicators impractical, although the Testing Squadron later used the principle to measure the mass air flow into engine carburettors and super-chargers.

Practical air speed indicators fall into the third method ρv^2, where velocity is determined by placing an obstruction in the air stream and measuring the force exerted on, or the pressure generated by the obstruction.[29] In the simple but least accurate air speed instruments, the pressure was generated on a flat plate or sometimes a piece of string was used as an effective alternative.



(a) Maxim (c) Negretti and Zambra (b) Scattergood

Fig 2.7 Airspeed Indicators.

In the 1894 Maxim indicator, the linear deflection of a circular plate was resisted by a spring. Negretti and Zambra still using the same principle in 1913.[30] The rectangular plate in the Scattergood was pivoted at its upper end and the resistance balanced by gravity.

The more accurate velocity-squared-density instrument was the pitot-static tube, where the differential pressure h, produced by a pitot-static device, is given by $v^2 = 2gh/\rho$. The pitot and static tubes could either be connected to two limbs of a liquid U-tube or to compartments of a chamber divided by an elastic diaphragm. The mechanical arrangement of the indication gave two important instrument sub-classes, gravity controlled and spring controlled instruments. The U-tube was a gravity controlled instrument, in which the differential pressure was balanced by the mass of the liquid in the differential head between the two limbs. The diaphragm instrument was spring controlled. Thurston ignored the liquid manometer, but the discussion following the paper gave J.L.Hodgson, from the instrument maker George Kent, the opportunity to introduce one he claimed was suitable for aeroplanes. The patent feature was the equation of curvature of the curved tube to

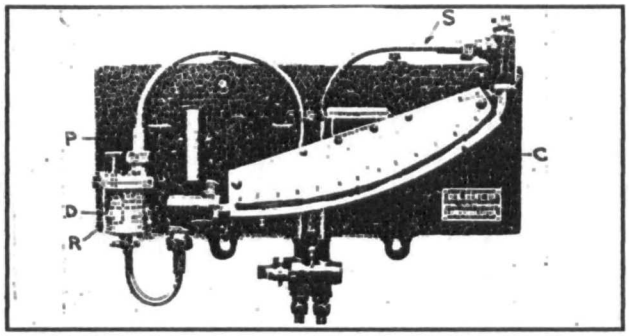


Fig 2.8. Hodgson Manometer
The pitot and static tubes were connected to P and S respectively, zero adjustment was provided by the displacer D in the reservoir R.

give a linear scale. However, this manometer would have been sensitive to tilting and acceleration, heavy and awkward to locate and is another example of an established instrument maker proposing an aircraft instrument with little appreciation of the requirements.

2.6.1. Diaphragm Air Speed Indicators - Darwin, Clift and Ogilvie.

Thurston described the spring controlled air speed indicators by Clift and Ogilvie, because 'they had proved their worth and deserved to be better known'. Both were elastic diaphragm instruments, using pneumatic amplification for increasing the magnitude of the force. The pitot tube was connected to one side of the diaphragm and the static tube to the other. The force due to the difference in pressure between the pitot and static tubes was multiplied by the ratio of the diameters of the diaphragm and the pitot tube. This high amplification provided a powerful force to operate the indicator, although the volume that had to be filled meant that the instrument had a long lag.

Thurston did not mention Darwin's diaphragm air speed indicator, probably because it was no longer in use, but it was the first aircraft diaphragm air speed indicator. Darwin had made it in 1911 and he and O'Gorman had tested it in O'Gorman's car at speeds of 70 mph along Hartford Bridge Flats near Cambridge.[31] The prototype was housed in a wooden box, while production ones were similar in shape and design but in a metal case (Fig 2.9a).[32] The shape of the instrument would make it inconvenient to locate on an instrument panel and it probably suffered from vibration, as Darwin described Short's velometer as a good vibration tolerant design without mentioning his own in his 1913 paper discussed earlier. Darwin's was not the first diaphragm indicator per se, NPL had designed a ground based one in 1912 to measure wind gusts.[33]

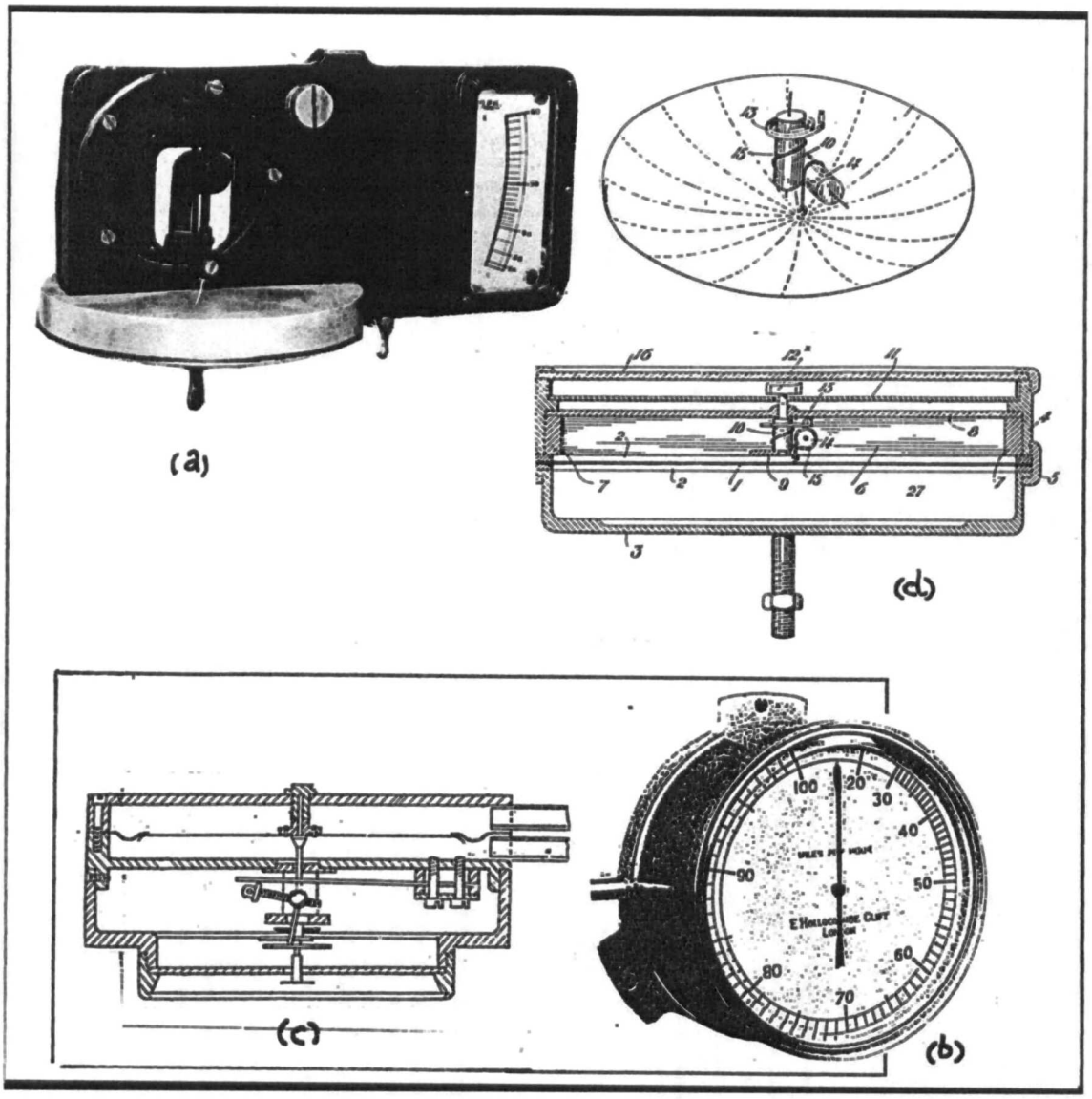


Fig 2.9. Diaphragm Air Speed Indicators.

(a). 1911 Darwin Indicator [no sectional view available]. (b). 1913 Clift Indicator general view and (c) cross section. The air chamber was divided by a very light flexible diaphragm of specially prepared thin leather skin. A light spindle, guided on either side of the diaphragm, pressed against the free end of a cantilever leaf spring, the deflection of which was transferred to the pointer mechanism by a rocking lever and quadrant plate. A spiral hair spring on the pointer provided the restoring force. (d) 1913 Ogilvie Indicator cross section. A thread, connected to the diaphragm, passed round an intermediate spindle before making two ascending turns on the pointer spindle. The pressure difference across the diaphragm, caused a pull to be exerted on the thread, which rotated the spindles against the action of a spiral hair spring mounted on the pointer spindle.

The Clift air speed indicator was manufactured by R.W.Munro (Fig 2.9b and c). Thurston said Munro calibrated each instrument to the equation $v = 57.7\sqrt{h}$, where v is the velocity in feet per second and h the inches water gauge, using a delicate tilting manometer.[3 4] He had tested the instrument in his laboratory and found a small hysteresis between ascending and descending readings, varying from 1.5% at top and bottom of the scale to 3.0% in the

middle. As greater accuracy in a flying machine was required on decreasing speed, he recommended the instrument be calibrated on the descending scale so that the error did not exceed 0.25 mph. The Clift indicator was provided with a Clift pitot-static head, consisting of the usual pitot tube, but the static tube was provided with a conical cap to increase the suction in the lateral holes in the tube under the cap. A disc, of the same diameter as the base of the cone, was mounted on the tube to leave an annular opening round the cone. Thurston found the constant *57.7* in the equation was very sensitive to the manufacturing tolerance of this annular opening.

The Ogilvie instrument was characterised by its simplicity (Fig 2.9d). The air chamber was divided by a stretched rubber diaphragm, which had little hysteresis providing it was given an initial tension when installed. It worked between wide ranges of temperature with no deterioration of the diaphragm, provided it was in continual use. Blowing into the instrument was to be avoided, as this upset the calibration and could damage the indicating mechanism.

Pannell at NPL determined the constant of the Clift as 57.3 and the Ogilvie as 66.7.[35] Martlesham Heath found the Clift more accurate.[36] Both instruments were described after the war by Pannell and Griffith, but neither comment on performance.[37] By the end of the war, metal diaphragm instruments were becoming available. Farnborough produced their own design using two single capsules, later modifying it to a single capsule, which was made by Munro.[38] They also examined one made by the Foxboro Company in America, British Patent No.111,615/17.[39] After the war Smiths replaced the conventional corrugated surface capsule with a fluted surface, making it more sensitive.[40]

2.6.2. Pitot-Static Heads

In the discussion following the paper, F.H.Bramwell described his recent work on pitot-static heads at NPL and emphasised that a sharp distinction should be drawn between tubes that measure the true static pressure, like the Ogilvie, and those that measure suction, like the Clift. He had found that every shape of pitot tube, ranging from the hole in the centre of a flat plate to a thin walled tube only one millimetre in diameter, gave a pressure of $^1/_2pv^2$ to the degree of accuracy of the experiments. So the problem resolved itself into determining the form of tube that would register the atmospheric pressure and he found this was best done with a tube, parallel to the wind direction and having a circumferential row of small holes some four or five diameters distant from the end. The advantage of this tube was that the correct reading was always obtained in spite of indifferent workmanship; whereas a tube that measured suction had to be made with great care, and even then there were small differences between apparently similar tubes. Tubes measuring suction also

departed from the square of the speed below 14 mph which, although of no importance to aeroplanes, meant they could not be used as a standard of velocity. However, they did have the advantage that were less sensitive to yaw.

Bramwell had conducted his experiments with a whirling arm in which the actual speed was obtained by measurement of time and distance travelled by the arm. Taking into account the velocity of the air set in motion by the whirling arm, he claimed an experimental accuracy of one part in a thousand. He also described the method of determining the velocity of air in a wind tunnel using a manometer connected to a small hole in the side of the tunnel. This was first calibrated by placing a standard pitot-static tube in the position to be occupied by the model under test. This tube was then removed during the actual tests, leaving the tunnel free from obstruction. He also mentioned that NPL used pitot-static tubes of 1 mm diameter for exploring velocities around models. Thurston commented that initially he had been sceptical about using a manometer connected into the side of the wind tunnel to measure velocity, although it was common practice for measuring the velocity of fluids in pipes. However, following advise from NPL, this method was now used by East London College, but care had to be exercised with large bodies placed at excessive angles, which effected the pressure at the wall of the tunnel.

2.6.3. Gravity versus Spring Controlled Instruments

Thurston next examined acceleration forces on gravity and spring controlled air speed instruments, as these effected any unbalanced moving part in the instrument. A gravity controlled instrument like the U-tube manometer will only read correctly when the machine is flying straight and level as its liquid column was an unbalanced mass and any vertical acceleration would effect its reading. If the machine had an upward acceleration, the effective 'gravity' was increased, requiring less liquid head in the U-tube to balance the differential pressure across it, making the indicated velocity less than the actual velocity. The same was true for acceleration due to a sharp turn. In early flying, this decrease in indicated air speed in a turn was considered an advantage as pilots would increase speed in a turn to avoid any loss of lift, which could result in a fatal spin. However, when the machine had a downward acceleration which decreased the effective 'gravity' - requiring more liquid head in the U-tube to balance the differential pressure across it - the indicated velocity was greater than the actual velocity. This effect could be fatal near the ground, if the downward acceleration was due to the machine approaching its stalling speed, because as it lost lift, the effective 'gravity' decreased further and in turn increased the indicated velocity, telling the pilot he was above the stall velocity when he was actually dropping to the ground.

Thurston pointed out that 'these effects were so well known that it is difficult to realise that it required a lengthy discussion in the technical Press to establish them'. Darwin had certainly pointed them out in his 1913 lecture, but Thurston's referred to an article by Harris Booth, now in the Admiralty Air Department, and to the subsequent correspondence. This showed the effects were apparently unknown to those who should have known.[41] In fact, not only were the effects unknown, they were disputed - possibly due to the confused way that Booth had approached the difference in behaviour of the two types of instruments. Instead of considering the simple case of the aeroplane subjected to an upward vertical wind gust, he considered the more complicated case of a horizontal wind gust, when the pressure down the pipes of both instruments and the lift on the aeroplane, were both proportional to the square of the relative velocity. This meant that when the machine met a head gust equal to its own speed, the gust would double the relative velocity and increase the lift fourfold, and this increased lift made all bodies on the aeroplane appear to be four time heavier than normal. At the same time, the twofold increase in relative velocity increased the differential pressure across the manometer four times, with the result that the liquid in a manometer did not move and no change in velocity was indicated. A spring controlled instrument in the same circumstances would have indicated the increase in relative velocity, as it would be unaffected by gravity. To add to the confusion, had the machine been sitting on the ground, the same horizontal wind gust would have produced an indication on both types of instrument.

In the resulting correspondence, the effect was certainly unknown to Clift, who replied that Booth deserved thanks from all interested in aviation and that liquid air speed gauges must go, although he said he felt a little embarrassed about saying this as he had just placed a spring controlled indicator on the market.[42] Bairstow at NPL missed the whole point of Booth's argument and discussed relative lags in the two type of instruments, concluding that there did not appear to be anything in principle which favours one instrument more than the other on Booth's calculations.[43] In the same issue, Busk at Farnborough wrote a short article on gravity controlled velometers, also disagreeing with Booth.[44] However, Busk got real weights and apparent weighs confused in his argument. Even ignoring theory, one would have thought that Busk would have observed the effect of gravity on a velometer, but apparently not. The fact that he wrote the article also meant that no one else at Farnborough was aware of it either. Booth replied to both comments, pointing out the errors in their arguments and by this time his paper had also been published.[45] There was no further correspondence in this remarkable public argument between the key government aeronautical departments, on a topic which should have been self obvious to most scientists. O'Gorman asked Short to find which type was preferable, but no report was published.[46] A year later, Bairstow published a paper in which he generalised Booth's equations to apply to an aeroplane in any position and with accelerations in any direction.[47]

2.6.4. Hot Wire Anemometers

Thurston had mentioned that hot wire anemometers were velocity-density instruments. He gave the example of one with which he was familiar, as it had been designed and used by Professor Morris, a colleague at East London College. A paper by Professor Morris on the instrument and its use had been given at the British Association meeting at Dundee in 1912.[48] The instrument used the knowledge, that the electrical resistance of a wire varies with its temperature, that different materials have different temperature coefficients, and that radiation of heat from a hot wire is related to the velocity of the air passing it.[49] Morris used a Wheatstone bridge circuit to measure the change in resistance and hence air velocity. We shall see in Chapter 6 that Darwin would suggest to Farnborough in 1918 that they try

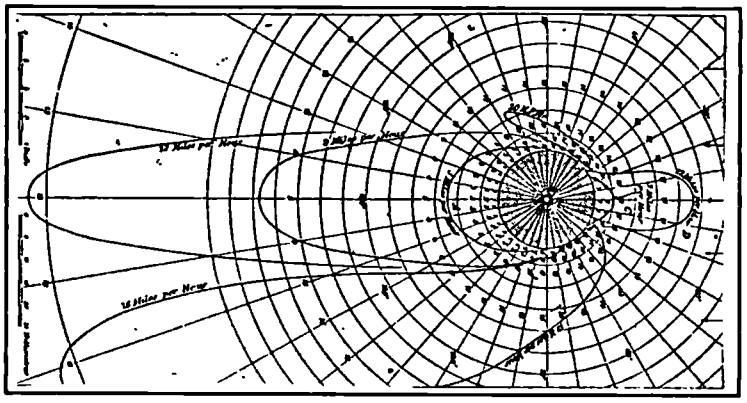


Fig 2.10. Velocity contour lines round circular rod

this instrument as a turn indicator. The laboratory use of the instrument was illustrated with the contour diagram of the distribution of wind velocities round a circular rod of diameter 0.825 inches in a uniform air current of 15 mph. Thurston drew attention to the 'cushion' effect in front of the rod and the 'shadow' behind it, indicating the need for extreme care when positioning air speed indicators on aeroplanes. It was necessary to go at least two diameters in front of the rod to get in air at a velocity equal to the air current.

The importance of correctly positioning the pitot tube was confirmed by Monsieur A.Delaunay from the Aeronautical Laboratory at Saint Cyr, who was present in the audience. He said that Aviator Lieutenant Gouin, engaged in this work, had found it necessary to place the pitot tube 5 feet in front of the wings on a Bleriot monoplane, because the disturbed air extended far ahead of the wings. Lindemann would find the same requirement in 1917. Delaunay also described a hot wire instrument they were using, which consisted of two wires placed a fixed distance apart and connected in circuit to a two-pen recording ammeter, which was sensitive enough to detect the movement of the pendulum of a clock.

2.7. Clift and R.W.Munro Ltd

The Clift and Ogilvie air speed indicators became the standard air speed indicators during the 1914-18 war. Thurston had described how they worked, but not their development. The Clift air speed indicator was in fact patented jointly by A.J.Munro and his chief engineer F.J.Rooker in January 1913, Patent 1518. Clift had approached R.W.Munro Ltd. for assistance to produce an improved form of air speed indicator and Rooker's Calculation and Sketch Book records his design of the instrument details and the calibration of its scale.[50] A brief Company history records that the design bore little resemblance to *the liquid type gauge Clift had proposed.*[51] However, the patent was later assigned to Clift, probably under some business arrangement as subsequent orders for indicators from Munro were always placed through Clift, and the instrument dial carried Clift's name.[52] In 1916, Clift's brother Frederick Hollocombe Clift, modified the movement to work in both direction, to allow the spring to deform without undue stress and provide a more open scale (Patent 111,565). In 1917, Smiths bought out Clift to acquire his patent and manufactured the indicator for the remainder of the war, although we shall see that the Ministry of Munitions placed orders directly with sub contractors without telling Smiths.[53]

2.8. British Wright and the Aeronautical Instrument Company

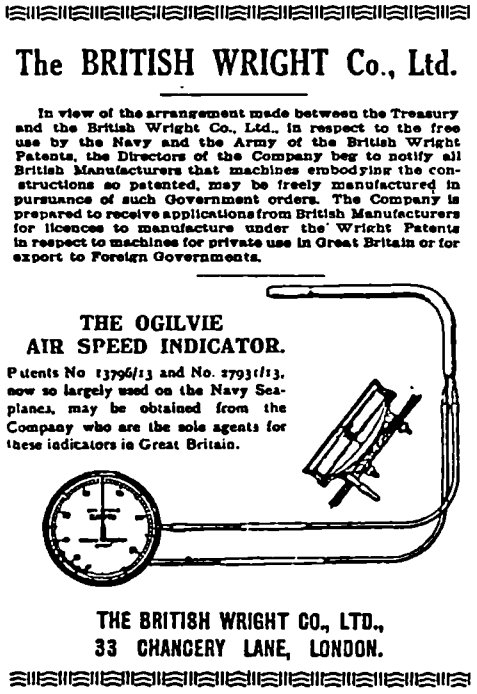
Ogilvie provided an account of the development of his air speed indicator.[54] After Wilbur Wright had demonstrated the Wright Flyer in France in 1908, Charles Rolls, Sir Maurice Edgerton, Frank McClean, T.P.Searight and Ogilvie arranged to have six Flyers fabricated for them by Short Brothers - Rolls ordered two, so he could present one to Farnborough. The Wrights had no drawings of their machine and Shorts visited France to measure the machine and make their own construction drawings. Ogilvie and Searight initially set up some facilities at Camber near Rye, but later moved to Eastchuch adjacent to Shorts. Towards the end of 1912, Harris Booth left NPL to replace Ogilvie's assistant Vyvian le Cren, who was returning to New Zealand. With Booth's knowledge of measurement, Ogilvie was able to develop a spring controlled air speed indicator, that he had had in mind for some time. The development effort was considerable and the first production instrument was fitted to McClean's aircraft when Ogilvie accompanied him on his flight up the Nile in 1914. When Ogilvie returned in April, Booth had received an appointment with the Admiralty Air Department and recommended as his replacement Frank E.Cowlin, who had been with him at school and Cambridge. Ogilvie and Cowlin spent the next ten months improving and manufacturing the instrument. Cowlin recalls they had a first class instrument maker and his mate to make them, while he and a draughtsman calibrated them, but they were only able to cope with a few initial orders for Sheerness Dockyards as they were undertaking other work, including the servicing of two Wright aeroplanes.[55] The

main bulk of the orders, totalling some 190 instruments, were made by Elliott Brothers.[56] With the outbreak of war, Eastchurch was taken over by the RNAS. In the spring of 1915, Ogilvie was commissioned as Squadron Commander of the Eastchurch Flying School, Cowlin joined Booth at the Admiralty Air Department, and production of the air speed indicator was handed to Griffith Brewer at the British Wright Company, who had been handling all sales since production started. Ogilvie later moved to the Admiralty Air department as Head of Aircraft Design, and was one of two survivors when the prototype HP V1500 crashed.[57]

The sales and production of the Ogilvie air speed indicator by the British Wright Company appear unusual, until the history of the company is examined.[58] Griffith Brewer was a patent agent, whose interest in aeronautics through ballooning - he held Aeronautical Certificate No. 5 of 1907 - led to a life long friendship with Orville and Wilbur Wright. Educated at Kings College, London, he had joined the family firm of Brewer and Sons, Patent Agents, at 33 Chancery Lane, London. At the time of Wilbur Wright's death in 1912 the brothers had received no income from their foreign patents, in spite of the aggravation of litigation and repeated visits to Europe, which had hastened Wilbur's early death at 45. No action had been taken to restrain the infringements of their patents in England and on a visit to Orville, Brewer suggested that he would be glad to form a company amongst Wright's British friends, who were concerned with the lack of recognition of the Wright's achievements, which would enforce the recognition of the Wright's inventions in England, especially with the British Government. With the support of Ogilvie, McClean, Egerton and Percy Grace, Brewer formed the British Wright Company in 1913 with Wright as chairman and himself as managing director, using his own office at 33 Chancery Lane as its registered address. The shareholders subscribed £3000 for half the shares and Orville Wright received the other half of the shares in exchange for his British patents, giving the company a capital of £6000, the agreement stating that 'Wright sold to the British Wright Company for £3000, the rights and interest in the infringement of his British patents'.[59] Brewer said the enterprise was a sporting effort and shareholders were prepared to risk £3000 to 'twist the lion's tail'. The problem they faced was the Crown could not be sued for a patent granted by the Crown, but they made formal application to the Government for the infringement of the British Wright patents. When a year passed without any progress, they applied for permission to sue the Crown through a nominee, and O'Gorman at Farnborough was named by the Government as its defendant. However, the war intervened before any litigation was started and Brewer's fellow directors joined up - except Grace, who had lost his lifewhileflying across the Channel from France in poor visibility and had veered out over the North Sea, possibly because his compass was not working due to vibration. As it seemed unreasonable to sue one's country for infringement while fighting for it, Brewer visited General Henderson at the War Office and secured a settlement of £15,000. The result of this, as he summed up

later, was that no British company was called on to pay royalties, none were ever refused a licence, and none ever thanked the British Wright Company for the immunity they enjoyed.[60] The history of the British Wright Company is ignored by both Walker and Gollin in their accounts of the Wright's influen ce on British aeronautics.[61]

Production of the Ogilvie air speed indicator was undertaken by The Aeronautical Instrument Company, of 33 Chancery Lane, with manufacturing facilities at 9 Galen Place, Bury St, WC1. The Memorandum of Association of the Company states the object of the Company as the purchase of the business of the Aeronautical Instrument Manufacturer and Vendor, hitherto carried out by Alec Ogilvie of Eastchurch, Sheppey.[62] Managing this company and giving training lectures on ballooning at the RNAS Station at Roehampton, occupied Brewer full time throughout the war. When the British Wright Company was wound up after the war, shareholders were paid £24,000 in dividends and share redemption. At the peak demand for aircraft instruments in 1917, Elliott Brothers met orders for 550 Ogilvie indicators.[57]



The Aeronautical Instrument Company took out other patents involving the Ogilvie indicator - Ogilvie's Patent 9102 of June 1915 measured yaw and Brewer's Parent 9100 of

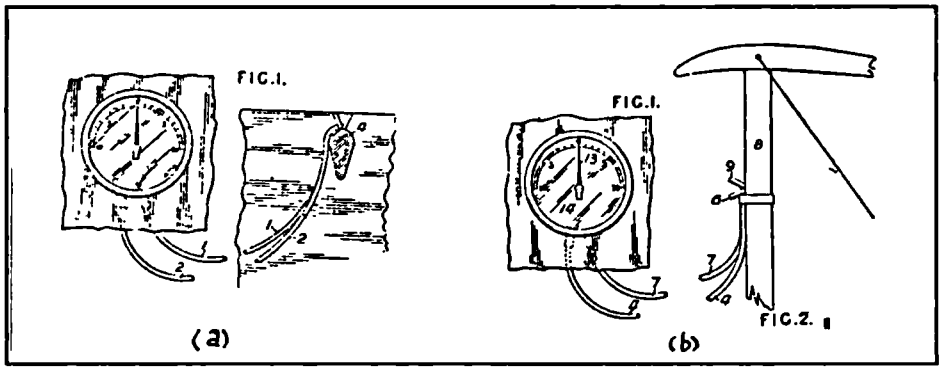


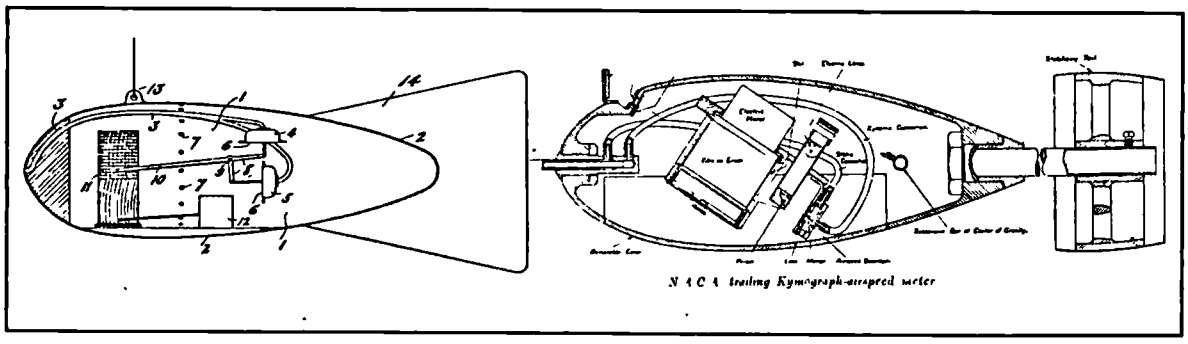
Fig 2.11. (a) Ogilvie Yaw Indicator and (b) Brewer Incidence Indicator

the same date measured inclination of an aeroplane. They acknowledged that these applications were based on Darwin's 1913 yaw meter in the discussion following his 1919

paper on the static turn indicator, which incorporated an Ogilvie indicator.[63] Ogilvie, then at the Air Ministry, said that it was obvious to him that Darwin's differential pressure indicator was insufficiently sensitive and that his own more sensitive instrument could be used instead. This had been designed when airspeeds were 40 mph, and the differential pressure to be measured was small. For the diaphragm, he used a material called "rubber dam", but for speeds of 120 mph ordinary bicycle tube patching material was satisfactory.

In this same discussion he also gave some background history to his pitot-static head which he designed after Harris Booth brought the NPL pitot head to his attention. In this head, the pitot and static tubes were concentric, with a long taper between the smaller pressure tube and the outer and larger static tube. The static holes were a long way back from the nozzle in order to get a true static reading. This long nozzle made the head fragile, and attempts were made to reduce the length by streamlining the end of the outer tube. Ogilvie had a head made and sent it to NPL, asking them to drill rings of holes at different distances from the streamlined end and test the static pressure at each ring of holes. NPL found that the ring of holes could be placed quite near to the streamlined end without detriment to the accuracy of the static pressure and this short robust head was patented in December 1913, Patent 27,931.

Submitting patents was no problem to Brewer as a patents agent and several he took out for the Aeronautical Instrument Company will be briefly examined. Patent 125,638/16 provided a method of layering several stretched sheets of thin rubber, when a diaphragm of exceptional strength without diminution of sensitivity was required. Patents 131,333 and 131,338 of 1918 covered various swivelling static heads for use with the Darwin static turn indication (Section 6.3). Patent 109,365 in 1917 adapted the Ogilvie gauge to record hydrogen pressure in airships, but vibration prevented the use of pen recorders on aeroplanes. A 'flying' or 'trailing' air speed recorder to suspend below an airship was



(a) (b)

Fig 2.12. (a) Brewer air speed meter (b) N.A.C.A kymograph air speed meter

described in Patent 124,783 of 1916. Flying or trailing air speed meters were used when measurement accuracy was effected by the disturbance caused by the craft whose speed was being measured, particularly true of airships, and to a lesser extent with aeroplanes. Fig 2.12(a) shows Brewer's patent, together with the way it was brought back to this country by Joseph Ames, Professor of Physics at John Hopkins University, in his 1923 Wilbur Wright Lecture,[64] The N.A.C.A. (National Advisory Committee for Aeronautics) trailing kymograph air speed meter was a combination of Brewer's air speed recorder (Fig 2.12b) and Keith Lucas's kymograph (Fig 7.5). Ames gave no acknowledgement of its origin and there was no published discussion of the paper.

2.9. Awards for Invention - Clift and Ogilvie air speed indicators

The Treasury files of the Royal Commission for Awards to Inventors provide more information on the Clift and Ogilvie air speed indicators. S.Smith and Sons claimed £3000 in June 1919 for the British Government use of the Clift air speed indicator, as they now owned the Clift patents.[65] The amount was an estimate of the royalties on Clift indicators ordered by the Ministry of Munitions from other companies from whom Smiths received no benefit. In a letter dated 5 July 1919, Smiths identified some of these other companies and the quantities as;

Maker	Quantity
C H Kemp Ltd, Ilex Works, Northwold Rd, Hackney, E.	1655
W Faraday Esq, Crownstone Rd, Brixton, SW2.	not known
Newman and Gardia Ltd, 17-18 Rathbone Place, W1	4000
Stuart and Moore, Packington Rd, Acton, W3	955
C F Casella, 73 Gurney St, SE	not known

The Treasury counter statement gave wartime production of Clift indicators from Smiths as 35,000 at a total cost of £200,196, while other manufactures had produced 18,000 at a cost of £67,000, that is £4 per instrument less than Smiths. They considered the inventive merit small, as Budenburg and Harters had patented a differential pressure gauge in 1877, Patent 2085, and the principle was common in air speed indicators. The claim was therefore considered excessive and a minor ex-gratia award, based on small inventive merit and the profit already made by Smiths, was proposed instead. This approach to minimise the merit of any claim, and hence the award to be paid, was the standard approach of the Treasury as will become apparent when award claims for other instruments are discussed. Most inventors based their claims on lost royalties and did not appreciate that the Royal Commission was appointed to consider award for inventiveness.

Smiths 'strongly protested' against this view claiming that the inventive merit was considerable, as the design had allowed the company to meet Government shortages and the Government would not have ordered so many had it not been one of the best available. Neither did they

believe that their claim was excessive as they had anticipated the extensive 1917 requirements for air speed indicators, but could not persuade the Government to increase orders to meet them. When orders were placed, Smiths had to increase output at short notice, incurring costs they were unable to recover and a direct loss when supply shortage forced the Ministry of Munitions to go elsewhere. Smiths pointed out that the cost of instruments made by other manufactures did not represent the true cost, as material was free issue from the Ministry of Munitions, and the production figure of 35,000 by Smiths included orders that were cancelled at the end of the war. To ignore the cost of free issue material and to include cancelled orders, was standard Treasury strategy to minimise a claim. The Royal Commission finally awarded Smiths £950 on 17 November 1919 for air speed indicators supplied by themselves *and* for 18,000 supplied by others. The inclusion of indicators supplied by others effectively prevented Smiths from claiming royalties from these suppliers, which they in turn would have been passed on to the Ministry of Munitions and hence to the Treasury.

The British Wright Company made no claim for use by the British Government of the Ogilvie air speed indicator, because of their earlier agreement for the use of patents. However, Griffith Brewer as Managing Director claimed for the use by the American Government of British Patent 13796/13 - for which American Patent 1,146,202 had been granted on 13 July 1915. The claim was on the basis that the American Government had 600-700 'chinese copies' made by the National Cash Register (NCR) of Dayton for the U.S.Navy.[66] The Treasury counter statement disclaimed any British Government involvement, before minimising the actual claim. It said that the invention was available in America before America entered the war, so that the Bolling Agreement of 1917, by which the British Government assumed liability for British Patents used by American Government, did not apply. The invention had not been communicated by the British Government, and if it had been, the use by the American Government was not due to that communication. A sample had been sent by the British Wright Company on 4 May 1916, but no promises had been made to the claimant at that time.[67] Neither was the invention considered novel - there had been other air speed indictor patents like Eckhard 16164 of 1911, Short 14749 of 1912 and Munro 1518 of 1913, there had also been publication of a similar indicator before the letters patent appeared (La Technique Aeronautique Vol 1, page 77, figure 9), and an air speed indicator with a silk diaphragm had been made by H.Darwin and used at Farnborough about 1910-12. Finally, the invention was not useful and the claim was excessive.

The claim dragged on for three years before the Adjutant General of U.S.Army cabled in March 1923 that,

> Ogilvie infringement and validity not contested. 697 built and scrapped in 1918. No subsequent use made or further use desired.

However, this statement did not agree with the fact that the British Wright Company had received an order from McCook Field at Dayton in March 1920 for 11 diaphragms for instruments made by NCR, which they were more than willing to supply. Eventually, the Royal Commission accepted the claim and made a settlement of £150 for war use, but nil for post war use, on the basis that no promises were made by the British Government and that The British Wright Company had made the negotiations themselves. Some pencilled notes by the Treasury solicitor suggests this low settlement was based on the fact that Smiths had received £950 for 18,000 instruments made by others, while the British Wright claim was only for 700 by others.

Conclusions

The growing importance of instruments for aeroplanes was shown when Darwin was asked to give the First Wilbur Wright Lecture on this subject. Progress had been made from 1910 to provide aircraft instruments and although the technology was not high, it was sufficiently robust to provide the basic flight instruments for military and naval aircraft during the war. The development was by those makers who took a serious interest in the new science, rather than casually rely on the power of advertisement. Early engine revolution indicators were adapted from existing mechanical designs, reliable electrical versions were a post-war development. An acceptable altimeter was available at the outbreak of war and remained in service during it, but it was several years before its lag and hysteresis were understood and a more suitable construction emerged. Measuring air speed was a new requirement and considerable research and development were required to accurately measure the small differential pressure from the pitot-static head. The liquid manometer was the first practical device, but was not an easy instrument to read and the need to replace it brought new thought to the problem. Extensive effort by Ogilvie with the assistance of Booth and Cowlin, two other Cambridge graduates, produced a remarkably simple but sensitive diaphragm indicator, which had a high tolerance to vibration and was cheap to manufacture. Darwin summed the instrument up when he said,

> There were two classes of instrument, the first which led to the remark, 'What a fool I was not to have thought of that', and the second to the remark, 'What a fool the man must be to think the thing will ever work'.

and that he would have put Ogilvie's indicator into the second class, had he seen the instrument before it had been proved.[68] The formation of the wartime Aeronautical Instrument Company specially to make it was a unique enterprise, freeing established instrument makers to meet other government orders. Less is known of Clift, who appears more of an inventive entrepreneur than inventor. His indicator was more accurate, but was the product of Rooker at Munro, who changed Clift's idea from a liquid manometer to a diaphragm dial indicator.

The comparison of manometer and diaphragm air speed indicators introduced the effect of vertical acceleration on the accuracy of the liquid manometer, which was generalised by Booth in his discussion on the advantages of spring controlled instruments over gravity controlled instruments. However, although the elastic diaphragm instrument became the standard air speed indicator during the war, its measurement lag was a disadvantage to research flying at Farnborough. Another problem faced by test flying was the lack of suitable recording instruments and the trained observer became universal. Except for the Richard pocket barograph, existing pen recording devices could not withstand aircraft vibration, while photographic recording wasted many flights as poor results were not apparent until the chart was developed. Test flying became more important as the war progressed and the development of instruments for this purpose is the subject of the next chapter.

The post-war claims of the Aeronautical Instrument Company and Smith & Sons to the Royal Commission for Awards to Inventors, portray the Government's attitude to invention once hostilities had ceased, as one of disclaiming the utility of the invention, depreciating its inventive merit, manipulating costs and disadvantaging the status of the claimant. The fact that British makers were claiming infringement of their patents by the American Government also shows that their was no American influence on British aircraft instrument design at this time, but that the reverse was true. More on this subject will appear in later chapters.

Chapter 3.

Performance Measurement

Summary Tizard and aeroplane performance - measuring speed and rate of climb accurately - his 1917 paper, discussion and preparation - the move to Martlesham Heath - Farren and full scale aeroplane testing at Farnborough - the unfriendly experimental environment - measuring air speed - speed courses at Farnborough - velometer or diaphragm asi - measuring stability - the principle of the camera obscura - new test instruments - climbmeter and statoscope - barothermograph - petrol flowmeter - electric timing apparatus for speed course - Taylor's photomulimanometer - direct measurements - post war test methods - conclusions.

Superior aircraft performance is the keynote of success in air warfare, but the comparative performance of different aircraft using manufactures figures becomes meaningless, if the accuracy of the instruments used is unknown. Even for instruments that were accurately calibrated on the ground, the accuracy in flight was not guaranteed. The routine measurement of aircraft performance was the main work of the Testing Squadron at Upavon, and later at Martlesham Heath. Farnborough were more involved with research flying to examine how performance could be improved and, although measurement at the two establishments had much in common, each developed special instruments for their particular purposes. Speed and rate of climb were the basic parameters of performance initially and were calculated from the air speed indicator and altimeter introduced in the previous chapter, but we shall see that the accuracy of these basic instruments made the calculation complex. Leading scientists, such as H.T.Tizard and W.S.Farren gave papers on government methods of testing aeroplanes. These papers, together with a slightly later one by T.M.Barlow, will be discussed as a introduction to a more detailed examination of the instruments to which they referred.

3.1. Tizard and Aeroplane Performance Measurement - 1917.

In March 1917, three months after the Testing Squadron had moved to Martlesham, Henry Tizard described the routine testing of new aircraft to the Royal Aeronautical Society.[1] He explained that for some months after the war began, a climb from 3000 to 5000 feet by aneroid and a run over a speed course was considered sufficient to test a new aeroplane. However, more scientific methods were soon adopted, based on those used at the Royal

Aircraft Factory at Farnborough. These were modified as performance requirements increased, and *military and naval test methods had recently been coordinated.* The methods were complex, but he emphasised that once they had been thought out scientifically, it did not require a high degree of scientific knowledge to carry them out. In the end, the accuracy of the final results depended on the flyer - the task was comparatively easy with careful flyers, whose judgement and reliability could be trusted, but with careless flyers it was impossible.

3.1.1. Measuring Rate of Climb

Tizard approached his subject by comparing the speed and rate of climb of an aeroplane at 10,000 feet on two different occasions. What does 10,000 feet mean? Did it mean the aneroid read 10,000 feet, or that you were 10,000 feet above the spot you started from, or 10,000 feet above sea level. Were the conditions of atmospheric temperature and pressure on the two occasions the same? An aneroid instrument did not measure height, but was calibrated to measure air pressure at some fixed temperature, originally chosen as 10°C, which meant it only read height correctly if the atmosphere had a uniform temperature of 10°C. As this was not the case, the real variable to measure was air density, which was also important because the power developed by the engine, the lift on the wings and the resistance to the movement of the aeroplane through the air, were all proportional to the density of the air. Therefore, the performance of machines should be compared at the same conditions of *atmospheric density.*

However, this was not straightforward, as the density of the air at the same height above the earth may vary considerably on different days, and at different places on the same day. It was also meaningless for the pilot to be told the speed of the aeroplane was 70 mph at 0.8 kg/m^3. He wanted to know the height, posing the question, what was the relationship between atmospheric density and the height above sea level? This was obtained by averaging out a long series of meteorological observations, taken by W.H.Dines, to provide a table of the average density at 1000 foot intervals. The table was then made more convenient by expressing density as a percentage of a standard density and it was decided this standard would be 1.221 kg/m^3, which was the density of dry air at 760mm pressure and 16°C temperature, the same standard density p used in pv^2 to calibrate pitot tube air speed indicators.

Table of Height and Standard Density

Height in 1000's of feet	% of Standard Density	Height in 1000's of feet	% of Standard Density
0	102.6	11	71.7
1	99.4	12	69.5
2	96.3	13	67.3
3	93.2	14	65.2
4	90.3	15	63.0
5	87.4	16	61.1
6.5	83.3	16.5	60.1
7	81.9	17	59.1
8	79.7	18	57.1
9	76.5	19	55.2
10	74.1	20	53.3

Heights of 6,500 and 16,500 feet made the table easy to convert from 0 to 6000 metres, for comparison with French performance tests. However, a standard based on the average English day from meteorological observations, which placed 100% standard density at a height of about 800 feet, conveniently the height of Martlesham above sea level, was not popular with the RNAS, let alone the basis for an international standard.

Tizard explained how a rate of climb curve was produced. The aneroid was treated solely as a pressure instrument, with 760mm of mercury as the zero point of its 'height' scale. As the aeroplane climbed, air temperature and height (i.e. pressure) were logged against time, as each 1000 foot height indicated on the aneroid was passed. Temperature was read on a thermometer attached to the wing strut, well clear of warm air from the engine. The indicated height was corrected for temperature to give the standard height, which due to the correction would not be an exact number of thousand feet. The standard heights were then plotted against observed time, and a curve drawn through the points. The rate of climb at any height was the tangent to this curve at that height, and by taking tangents at each thousand feet of standard height gave rate of climb performance against standard height. These curves also showed why the rate of climb when taking off on a hot summer day could be half that on a average day, as on a hot day the air density at ground level may decrease to 85% of the standard density, corresponding to a height of 5,000 feet. This analysis of measurements showed that the simple aneroid needed considerable correction to provide an accurate standard measurement of altitude in flight test work. For normal flying, this accuracy was not required and the aneroid scale was graduated by assuming a uniform fall in temperature for increasing height. Tizard described the climbmeter used to assist the pilot determine the maximum rate of climb, which was not easy by aneroid and stop watch (See 3.5).

3.1.2. Measuring airspeed accurately.

Air speed was usually measured at regular intervals of height, generally every 2000 feet from the highest point downwards, with the aeroplane flying level. Care and concentration were needed to fly level, particularly when conditions were bumpy. The aneroid was not sensitive enough to show the pilot he was flying level, and a bubble statoscope made by the British Wright Company was used for this purpose (See 3.5).

Measuring air speed accurately, had much in common with measuring height accurately, both the air speed indicator and the aneroid were really pressure gauges. The air speed indicator measured the difference in pressure between the pitot and static tubes, which was proportional to pv^2, where p was the standard density of the air (1.221 kg/m^3), and v the air speed. Therefore, the observed air speed had to be divided by the square root of the density to give the true air speed. Even then, this was only the true air speed if the pitot tube was located where its pressure was not disturbed by parts of the machine. It was therefore necessary to measure the true air speed of the machine by timed observations over the ground, to check the calibration the air speed indicator. The Testing Squadron used two methods, either speed trials close to the ground along a measured course, or at some considerable height above the ground using camera obscuras. The ground course was used when an aeroplane had to be tested quickly, or poor visibility prevented the camera obscura method from being used.

On the ground course, the aeroplane was flown at 50 feet and timed by observers at each end of the course. As it passed over the first observer, he started his stop watch and signalled the second observer by a bell circuit to start his. When the aeroplane passed over the second observer, he stopped his stop watch and signalled the first observer to do the same. The mean of the two times was taken as the time of the run, as the observer at the end of the course tended to start his watch late, while the observer at the beginning of the course tended to stop his late. Four runs, two up and two down the course, were made at each planned airspeed, while the pilot or his observer carefully noted the indicated air speed during each run. Observations of the atmospheric pressure and temperature, wind speed and direction were noted by the ground observers. The use of the ground course was restricted to calm or light wind conditions, as varying wind speeds made accurate measurement impossible. Accuracy was also suspect with single seater aircraft, as the pilot could only glance at his instruments while endeavouring to fly at speed only 50 feet above the ground. To fly at high speeds also required space in which to accelerate up to speed before reaching the course, space which was not available with their present course and the Testing Squadron preferred to calibrate air speed by the camera obscura method (See 3.4).

Having calibrated the air speed indicator, speeds at full throttle at various heights were logged and first corrected for density, calculated from readings of height and temperature, and then for instrument errors by adding or subtracting the correction found from the cameras or speed course. True air speed against standard height was then plotted.

Tizard concluded his paper with his views on instrumentation for measuring aircraft performance, which like other work connected with aeroplanes was only in its infancy, but as time went on better methods and instruments would be evolved. It was argued that more emphasis should be placed on using self recording instruments, but this had disadvantages, including the immediate one of getting new and elaborate instruments made at a time when manufacturers were fully engaged on other important work. More reliance can be placed on direct observation, the observer was aware of the behaviour of the instruments and no time was lost because the recording instrument failed to measure or failed to record. The Testing Squadron used them only as a check against direct observation, although there were plans to adopt recording air speed indicators on single-seaters. But whether direct reading or self recording instruments were used, he hoped that he had shown that it was the flyer on whom the accuracy of the tests depended, and like experimenters in other branches of science, he required training and a great deal of patience. It was only by accurate full-scale testing that a steady improvement in the efficiency of the aeroplane could be achieved.

3.1.3. Discussion following Tizard's Paper.

The Royal Naval Air Service made the first comments after Tizard's paper. Squadron Commander Busteed regretted that the Naval Testing Department were not as far advanced with their testing as they would like to be, but some good work had been done. He fully supported the view that readingstaken by the pilot or observer were preferable to self recording instruments, which were a source of trouble even in single-seaters, where once the pilot had got in, there was little room for instruments. Lieutenant G.H.Millar, RNVR, expressed his admiration for the thoroughness with which the RFC conducted their testing, but he did not agree with the standard density that had been adopted. He would have preferred one based on a 760mm pressure and 15°C temperature at sea level, and a uniform rate of fall of temperature of 1.5°C per 1000 feet rise. The curve of density against height did not differ greatly from the empirical one adopted, and reducing the assumed ground temperature in the adopted standard would bring them into line. No advantage was gained by using the density for which air speed indicators were initially calibrated, since the instrument had to be calibrated in the machine in any case. He preferred ground course speed testing, as testing at height reducedthe higher speeds that could be tested, unless the

machine was flown slightly downhill. He had found that four pairs of runs at different speeds fell on a straight line, even with rough timing methods.

Captain Harry Grinstead from Farnborough said the next step towards improved accuracy was to improve the instruments with which the measurements were made, to accept an aneroid as a accurate pressure measuring instrument was to give it too good a character. Owing to its lag, it does not give the correct measurement of pressure when the rate of pressure was changing rapidly. Measurement of performance was confined to tests of speed and climb, but manoeuvrability was equally important to the service pilot. Captain William Farren, currently responsible for full scale aeroplane experiments at Farnborough, confirmed that performance methods at the Royal Aircraft Factory and the Testing Squadron had been arrived at by joint discussion, that the same standards of density were used, and that both agreed on the superiority of ordinary instruments and good observers over automatic recording instruments, particularly as the Factory were not usually involved with single seat machines. They did not use the statoscope for level flying to the same extent as they found the aneroid gave control over height within 100 feet and, as their runs were 12 miles, this amount of error averaged out. The Factory statometer was similar to the one described, but much smaller, occupying a space of 1 inch by 1 inch by 6 inches, and their rate-of-climb meter was also of similar size. He referred back to the time when Captain Dobson of the Testing Squadron brought the first rate-of-climb meter to Farnborough, where it became known as the 'coffee-ometer' by the pilots on account of the thermos flask used for the first instrument. A search of the Instrument Stores brought to light an similar German balloon instrument, but the credit for introducing it onto aeroplane testing must go to the Testing Squadron. The rate-of-climb meter suffered badly from vertical acceleration when changing speed, which caused the indicating column to move with change of effective gravity, and consequently only gradual changes in speed could be made when searching for the best climbing speed. They had attempted to develop a alternative dial indicator version, but this had considerable lag due to the large volume of air enclosed in the diaphragm chamber. He concluded with some professional and patriotic flag waving remarks on who should test aeroplanes. Satisfactory results required the highest training, but it occupied no special place by virtue of this, it merely brought it into line with the rest of engineering.

> One can learn to fly in a month, but an engineer's training required years. It was evidently necessary, therefore, that engineers - men with scientific training and trained to observe accurately, to criticise fairly, to think logically - should become pilots, in order that the development of aeroplanes may proceed at a rate it must proceed if we are to hold that place in the air to which we lay claim - the highest.

3.1.4. Preparation of Tizard's Paper.

Tizard's paper provided a confident statement on aeroplane performance testing, the standardisation of results and the coordination with other groups. However, a diary he kept for January and February 1917, during the hectic seven day week when Martlesham Heath was being equipped, questions this confidence.[2] On Tuesday, 6 February, Tizard went to Hendon to get his flying boots and coat, had lunch with Dobson,Bourdillon, Grinstead and Jones, and saw O'Gorman to discuss the proposed paper on Testing before returning by train to Ipswich. On Friday morning, 9 February, he started writing the paper and checking density figures, but in the afternoon went to Ipswich and walked back. He continued writing the paper on Saturday, finished it the following day and sent it on Monday to O'Gorman; curves were to follow as he was recalculating the height-density curve. He received O'Gorman's comments on Wednesday, and on the following day went through the paper, made some new diagrams and sent the 10,000 word script to the Aeronautical Society. He had earlier written to Dobson on Saturday, 27 January, about the standard density curves and Dines results, in preparation for a conference at the Admiralty the following Thursday on aeroplane testing, reduction methods and report forms, at which no one from the RNAS Testing Squadron was present.

This means that the curves in his paper, that he said were in use by the Testing Squadron, had never been tried, and the agreement with the Admiralty on the method of reduction was a one day meeting which did not involve the people concerned. The first chance they had to comment was when Tizard presented his paper. Although written quickly, the paper was based on earlier notes with the new curves added.[3] These notes provide instrument reliability detail, which he omitted in the more general paper. The RAF petrol flow meter was still unreliable, but experiments were continuing because it would do away with prolonged fuel consumption tests. Measurements with the air speed indicator and the statometer were unreliable in anything but still air, usually found at 4-6,000 feet, early morning and late evening. Engine revolutions were a good check on the instruments, but revolution indicators themselves left much to be desired, and an order had been placed for a Jaeger, a Swiss instrument of the chronometric type. Speed tests were performed with the air speed indicator supplied with the machine, which was always calibrated on the ground and checked to see it was in good working order. The Clift was the more reliable, the Ogilvie was unreliable at low temperature, and the liquid manometer was not used when it could be replaced. The British Wright statometer was satisfactory and the climbmeter being constructed looked promising. The Short and Mason aneroid was reliable, but readings must always be corrected for temperature since their aneroids 'for some unknown reason are calibrated to 50°F'. The accuracy of the Richard recording barographs had been

improved by running them faster, and the Hicks strut thermometer had been modified by cutting a groove in the wood backing to allow better circulation of air round the bulb.

Nevertheless, the paper was important as the first paper on wartime aeroplane testing by a leading scientist involved, and its presentation was remarkable in that it was given during the war. Two years later, Farren was invited to describe methods used at Farnborough, but first Tizard's account of setting up Martlesham Heath will be examined.

3.2. Organising instrumentation at Martlesham Heath - Tizard's diary.

Tizard's diary for January and February 1917 recorded instrumentation aspects, as well as carburetter testing, aeroplane deliveries, test flying, designing test report forms, visits to London and general organisation. Except for Wimperis' this appears to be the only day to day account kept by a leading scientist involved in aircraft instrumentation.

The Upavon camera was taken down on 2 January and moved to Martlesham Heath five days later. He arranged for the instrument workshop to be fitted out and for the supply of flight test instrumentation. He wrote to Dobson about the new baro-thermograph, to Short and Mason about the supply of 20,000 foot aneroids, to British Wright about the supply of statometers and climbmeters, to C.I.A. about the ball flow meters and to the Aircraft Investigation Department (A.I.D) about testing them, following it with a visit to their Experimental Station at Esher. Work started on 23 January to set up the slate table in the vertical camera obscura, but frost prevented cementing it in. The distance between the cameras was accurately measured, as was the speed course. The following day the table in the vertical camera was half set in, and the speed huts set up. The Sperry engineer Titterington arrived with their new rudder control gyro, the same engineer who had taken the gyro stabiliser to Upavon. This was to be installed in BE 2c 4447, a machine Tizard often flew at Upavon according to his log book. The slate table in the vertical camera was completed on 25 January, and the sloping table was temporarily set up in the other camera the following day. It fitted satisfactorily and special fittings were designed for the lens carrier. On the same day, he inspected the speed course with R.H.Mayo, who had been transferred to him from Farnborough, and the hut at the far end was resited. On Saturday, 27 January, he started calculation work on the cameras before continuing with his paper. On Monday, he went to the War Office to get the address of the Electric Heating Clothing Company and visited them to arrange for two flying suits to be made. In the afternoon, he purchased a large builder's level and protractor and set up the sloping table the next day, making additional supports as it showed signs of warping. He discussed new standard test reports with Filon and Hopkinson.

On 30 January, temporary sights for the speed course were provided, and the communicating telephone line laid. Tizard flew on the speed course to see how much clearing was still needed, finding he could fly no lower than 20 feet. He went to the British Wright Company on Monday, 5 February, but as they were unable to supply any statometers, he arranged for them to sell him the glass traps, so that he could get the instruments made elsewhere. Two days later, he wrote to Cowey at Alexander Works, Kew, about making up a combined statometer-climbmeter, and ordered some a week later. On 13 February, he arranged for the speed course to be better marked out and for the camera huts to be finished. During this period test flights with the flowmeter and the Sperry rudder gyro proved unsatisfactory. The rudder gyro remained jerky in spite of modifications, and the servo gearing would have to be changed. The electrically driven gyro was also effecting the compass and had to be moved into the tail. The final entry in the diary was 21 February, when he checked all instruments in the instrument workshop. Probably after this date, work was too hectic to keep a record of it, but this short account does provide some idea of the work in setting up a new test establishment.

He must also have started a new pilots log book at Martlesham Heath, as there are no entries after 26 November 1916 in his surviving log book.[4] This log book gives some indication of the actual experiments he undertook at Upavon, including 14 in June and July 1916 on testing rate of climb at different air speeds, speeds over camera, and testing statoscope and climbmeter. The flights were usually an hour or more and sometimes Dobson flew as observer.

3.3. Full Scale Aeroplane Experiments at Farnborough in 1918.

On 18th December 1918, the war having just ended, Captain W.S.Farren read a paper to the Royal Aeronautical Society on flight test experiments at Farnborough, for which he was responsible.[5] This was the first account on the subject since O'Gorman's in 1911.[6] Farren said *'the whole essence of experiment is measurement'* and his paper was devoted entirely to the measurements involved. He drew out the differences between *research* measurement at Farnborough and *routine* performance measurements at Martlesham Heath, and the interaction between *full scale* aeroplane experiments at Farnborough and *model* work at NPL. Both these areas had recently provoked active discussion between the establishments concerned. Martlesham Heath had not appeared to understand the need for the accurate measurements that Farnborough were carrying out, and NPL had held the view that model experiments established better full scale design, without accepting that validation of the model by careful full scale experiments was required. Lieutenant-Colonel O'Gorman, who was chairing the meeting, mentioned that it had taken a joint committee

two years to establish the relationship between full scale and model experiments, a relationship fundamental to aeronautical progress. Farren had been one of the moving spirits in that debate and by the time they had finished, the disagreeing parties had not only agreed, but discovered more information and established more esteem for each other. It was now accepted that model work derived much of its value from the validation of subsequent full scale work, and could not just be applied to the full scale by *a priori* logical thinking.

Farren introduced the scale effect at the beginning of his paper. Aeroplanes now had wing areas between 1000 and 2000 square feet, while the wing area of the largest model was only 6 square feet. The purpose of full scale research in any branch of engineering was to establish satisfactory design formulae and investigate phenomena in terms of existing or new formulae. Referring to H.Levy's work at NPL, he said design formulae derived from model experiments could not be considered as established until checked by full scale work.[7] Unfortunately, aeroplanes were somewhat unsuited by nature for accurate experiments and in no engineering structure was there so little room to spare as in an aeroplane. Full scale experiment faced immeasurably greater difficulties than those of model experiments, and statistical methods of analysis had to be adopted where the model man could use direct methods. In full scale work, there was no obligation to make answers *agree* with model experiments, experiments were designed to provide results that could be *compared* to the model results.

The so called 'Scale Effect' had long caused contention. NPL argued that wind tunnel measurements were very accurate, while measurements taken in full scale testing were not. The calculated scale factor between a model and full scale aeroplane was therefore dependent entirely on the accuracy of the full scale testing. Farnborough did not agree that their testing was inaccurate and the Scale Effect Committee was set up, which only resolved the problem after the war, when the real effect of the walls of the wind tunnel on the model was realised. This was determined when the same airship model was tested in several European wind tunnels, with differing results.[8]

3.3.1. The Experimental Environment

Farren explained they had no control over the physical conditions of the atmosphere in which the experiments took place. It was a unsatisfactory medium in which to conduct experiments, particularly in making the assumption that it was a uniform fluid. They could measure temperature and pressure of the free air near the aeroplane, but for accurate experiments, the whole atmosphere over a considerable area was required in a steady state,

with temperature changing uniformly with height and no up or down currents. A calm region for stability experiments could usually be found just above a cloud layer, but this usually made observation from the ground impossible. This meant, that if the weather was suitable for test flying on 70% of the days, then it dropped to 35% for research flying, although in practice they flew for 60% of the days, resulting in some loss of accuracy.

3.3.2. Speed Courses at Farnborough

Farnborough used three methods of speed measurement, the ground speed course and camera obscura methods adopted from the Testing Squadron, and a third method, which they called the High Speed Course. The Farnborough ground speed course was 1000 yards long, marked out on fairly level round, along which the aeroplane was flown within a few feet of the ground, so near that sometimes the wheels touched. Timing was stop watch and bell signal by observers with simple sights at each end of the course. It was easy for the pilot to keep his course and fly level, but it was difficult to maintain a steady speed, because of the need to watch the ground. The course could be used on cloudy days and, because the wind near the ground was less that higher up, it could be used on more days than the higher altitude courses. Wind speed could be accurately measured at several points along the course and the effect of cross wind eliminated by flying in each direction and letting the aeroplane drift, but keeping parallel to the course. It had been difficult to find a course of good length, which meant that the actual course was shorter than they would have liked, reducing the measurement accuracy for fast machines and making it dangerous if the engine failed when coming off the course, as little clear space was left.

With the camera obscura and high speed course methods, it was only necessary to pass across a line between two defined points and at roughly right angles to it. The camera obscura method was identical to that at the Testing Squadron. It was safer than the ground course, easier for the pilot to keep straight at constant speed and height, and could be varied to suit wind direction. Wind speed was measured by observing the drift of puffs of smoke from Very parachute smoke cartridges. The camera obscura method had two disadvantages, it took time to reduce the observations and its definition was materially less than a good optical sight on misty days. These disadvantages led to Farnborough developing the so called 'high' or 'upper' speed course described in Fig.3.1.

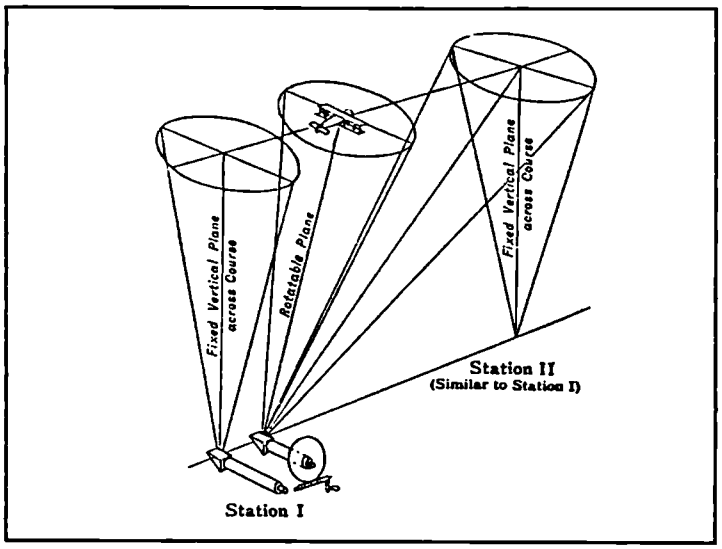


Fig 3.1. Farnborough Upper Speed Course.

Optical sights were provided about 4000 yards apart. One station was permanent while the second was moved to make the course approximately at right angles to the light wind. The sights were horizontal and of the Aldis type with no magnification. Reflecting prisms provided a vertical field of view, which was about 30° so that at 3000 feet an aeroplane could be 800 feet off course laterally in each direction and still be in the field of view. The aeroplane was kept in view by rotating one reflecting prism by a mechanism, which could be thrown out of gear by an electrical signal, sent from the other end of the course as the aeroplane passed. A Veeder counter on the mechanism gave the angular height directly and so avoided the error of attempting to read it instantaneously. Flight times were recorded at one end by electrically operated styles moving over a metallic paper chart.

Wind speed was still measured by observing the drift of puffs of smoke and a squared graticule in the optical sight for this purpose was being tried. They were also considering a more permanent course with three stations arranged in an equilateral triangle, which would allow one leg to be used whatever the wind direction, and avoid the time spent setting up the distant station.

3.3.3. Air Speed Measurement.

Farren explained that an air speed indicator was only accurate when the aeroplane caused no interference to the air near the pitot head, which could only be achieved with cumbersome gear to place it well in front of the aeroplane. A standard pitot head on a wing strut was only accurate when it had been calibrated on a speed course, and this took considerable time. To reduce this time, Farnborough were considering having a standard machine, carefully calibrated on a speed course on an ideal day, alongside which other machines could be flown later to calibrate their air speed indicators.

U-tube or diaphragm instruments was the next question. Undoubtedly the latter was the more convenient and easier to read, but for accurate work it required frequent calibration and periodic inspection, and could not be left unused for long periods. Farnborough had established a simple routine procedure to give more regular results. The diaphragm indicator was connected to a piece of rubber tube bent to a U-shape. This was placed under an ordinary water tap, which partially filled one leg with water and compressed the air in the other leg of the tube to operate the diaphragm indicator. The tap was then left running so that the broken stream of water caused continual and irregular changes of pressure in the instrument to effectively shake up the diaphragm. It was elementary, but extremely effective.

The disadvantage of the diaphragm indicator for accurate measurement was its lag and Farnborough preferred the differential liquid manometer for accurate work. Farren mentioned that Farnborough were fortunate in having two aneroids, which were probable the finest in existence. He did not name the manufacture, but said that the head of the firm had made a large number of diaphragms with his own hands, before selecting the best two. They also used the climbmeter, which had been made more compact by Lindemann, but it still had the problem that the scale was dependent on air density, and that making the instrument sensitive for small rates of climb or descent increased its lag. The manometer was also employed in G.I.Taylor's photo-multi-manometer to measure the distribution of pressure over wing surfaces.

He explained that research flying was not so interested in the maximum rate of climb at each height in which engine revolutions and propeller efficiency were varied to achieve it. In research work, the more variables that could be kept constant, the easier it became to examine others. The usual method was to measure the rate of climb at various heights by varying the speed in steps of 5 mph, while keeping the engine at full throttle, a practice known as partial climbs.

3.3.4. Stability and Controllability

Farren said that he had covered experiments in which there were measurement difficulties, but there was a class of experiment, where the difficulty was to know what to measure and how to interpret the results. After four years of wartime research, stability and controllability were still confusing and even contradictory subjects. Busk had applied the aerodynamics of stability and produced the stable BE 2c for aerial reconnaissance, but when the war came along the chief use of the aeroplane was fighting, where controllability

was more important than stability, although post-war development on civil aeroplanes may change this perspective. When a stable body was displaced from its position of equilibrium and released, it oscillated about this position with steadily decreasing amplitude. The period and the amplitude of the oscillations determined stability. With fore and aft stability, any measurement, such as speed, engine revolutions, magnitude of apparent gravity or attitude, could be used to measure period and amplitude, but with lateral and directional stability, only attitude could be used. The most convenient way to measure the attitude of an aeroplane was to use the photo-kymograph, a method originally due to Dr Lucas.

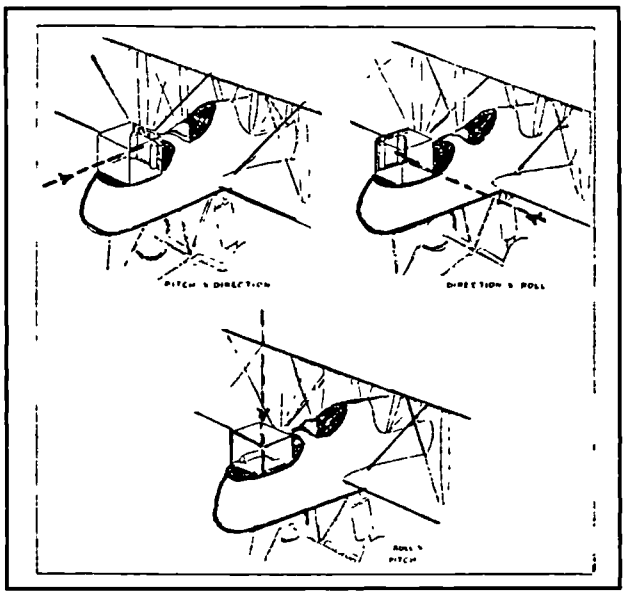


Fig 3.2. The Photo-kymograph.

The apparatus traced the image of the sun cast by a pin hole on a moving band of photographic paper. The experiment was usually initiated by releasing a weight from a wing. Farren suggested that half the difficulties of interpreting stability experiments was due to the asymmetry produced by the propeller and slipstream. Some aeroplanes were unstable with the engine on, but stable at the same speed in a glide with the engine off. Controllability was even more difficult to measure and interpret. Comparative experiments had been made on different aeroplanes to measure the time to bank to 45°, or the minimum radius of turn achieved with the aeroplane banked vertically. He expected more valuable results to be obtained with the accelerometer designed by Dr. Lindemann and modified to simultaneously record air speed by Dr. Searle.[9] The accelerometer consisted of a quartz fibre loop, the shadow of which was recorded on a light sensitive chart. It was also used to time rapid manoeuvres, such as those in a dog fight. As the apparatus was strapped to the leg of the pilot or observer, it was not strictly and aircraft instrument, nevertheless it was an interesting development by Lindemann, it is discussed in Appendix 1.

The discussion which followed the paper centred mainly on stability and controllability and was between those scientists, whom the chairman pointed out to the audience, had carried out the experiments described in the paper at the risk of their own person. Major B.M.Jones pointed out that a single seater Sopwith Camel was more manoeuvrable than the two seater Bristol Fighter, but he had seen a pilot in a Bristol Fighter out-manoeuvre a Camel. One had to be careful not to take too scientific a standpoint on the subject of controllability, where different pilots could produce different results in the same experiment. Lindemann took the more scientific view that until controllability could be measured, there was little prospect of any advance in the subject, as vague expressions of *feel* of the machine were not acceptable in physics or any other science. Lt. McKinnon-Wood, now working on model experiments at NPL, said that full scale experiments were essential to investigate stability and controllability, as unconstrained motion was not possible in wind tunnel experiment and he also suggested that the gyroscope might eventually prove the best replacement for the photo-kymograph. H.L.Stevens from Farnborough showed slides of apparatus that measured the movement of the aeroplane in the air, the position of the controls, and the forces applied to them. It obviously had some commonality to the abandoned ripograph, but unfortunately he gave no information about it nor is it mentioned in other reports.

Finally, Major R.V.Southwell said he taken over the full scale experimental work were Farren had left it. He thought that a new procedure of photographing a group of standard indicating instruments and a chronometer at equal intervals of time, would prove the solution to the problems of the recorder.[10] Farren said he had considered this method, but still felt that it was only when the observer had to read the instruments and note anomalies, such as a sudden change in the rate of climb that indicated a vertical air current, that the experiment could be stopped without wasting further time. It was surprising how much fresh information had been gained this way, which would have been rejected with a automatic measurements as an instrument error. He concluded that the paper was a summary of the work of RAE staff over three years, and he was sorry he had not been able to make it more personal.

3.4. The Camera Obscura

The accuracy of Bourdillon's bomb sight could only be quantified if the relationship between the release of the bomb from the aeroplane and its point of impact on the ground could be measured and it was for this purpose that the the camera obscura was first introduced. There is no reference as to who suggested using it in the first report of its use at

Upavon by Dobson, Tizard and Mackie.[11] The report mentions the first installation was similar to the Darwin-Hill Position Finder (also called Darwin Tilting Mirror or Gimballed Mirror) . This was an attempt to measure the height and speed of aircraft for anti-aircraft gunnery by H.Darwin and A.V.Hill. Hill had been one of Keith Lucas's research students before the war, but as an officer cadet had been immediately posted to the Cambridge Regiment, where he had survived to become Battalion Ballistics Instructor before Darwin rescued him. Darwin, as a member of the Munitions Inventions Department, chose Hill to run the Ack-Ack Experimental Station, who then recruited several other Trinity College graduates.[12] A.P.Rowe, in the group, submitted Secret Patent 2153 for a Camera Obscura in 1915, but this patent has not been traced. However, Darwin had produced a scheme in 1884 for George Whipple, Superintendent of Kew Observatory, for using two photographic cameras with plotting table and strings, to measure the height and speed of clouds, and before that a multi-camera system for photographing explosions at Chatham called the 'photobustoscope', so optical position finding methods were familiar to him.[13]

The first Upavon camera was mobile and assembled quickly, because within two months of arriving, Tizard wrote to Lindemann asking him when he was coming up for a visit as 'the mobile camera obscura will be finished in a day or two, in fact I am really only waiting for the lens to come back from the repairers'.[14] The path of the aeroplane and the bomb were plotted on the table of the camera obscura, the pilot signalling by wireless or Very pistol, that he had released his bomb. The known distance between the wing tips of the aeroplane and the width of its image on the table, gave the scale of the plot, from which the height and speed of the aeroplane could be calculated. The field of view of the camera obscura did not include the local ground, but the top of a flagstaff and wireless mast were visible and a theodolite was used to fix the ground impact of the bomb with reference to the flagstaff and wireless mast, to allow the deviation of the bomb fall to be calculated. This use of camera obscura and theodolite was complicated and led to the installation of two camera obscuras, in which the distance between them provided a fixed base line for the observations.

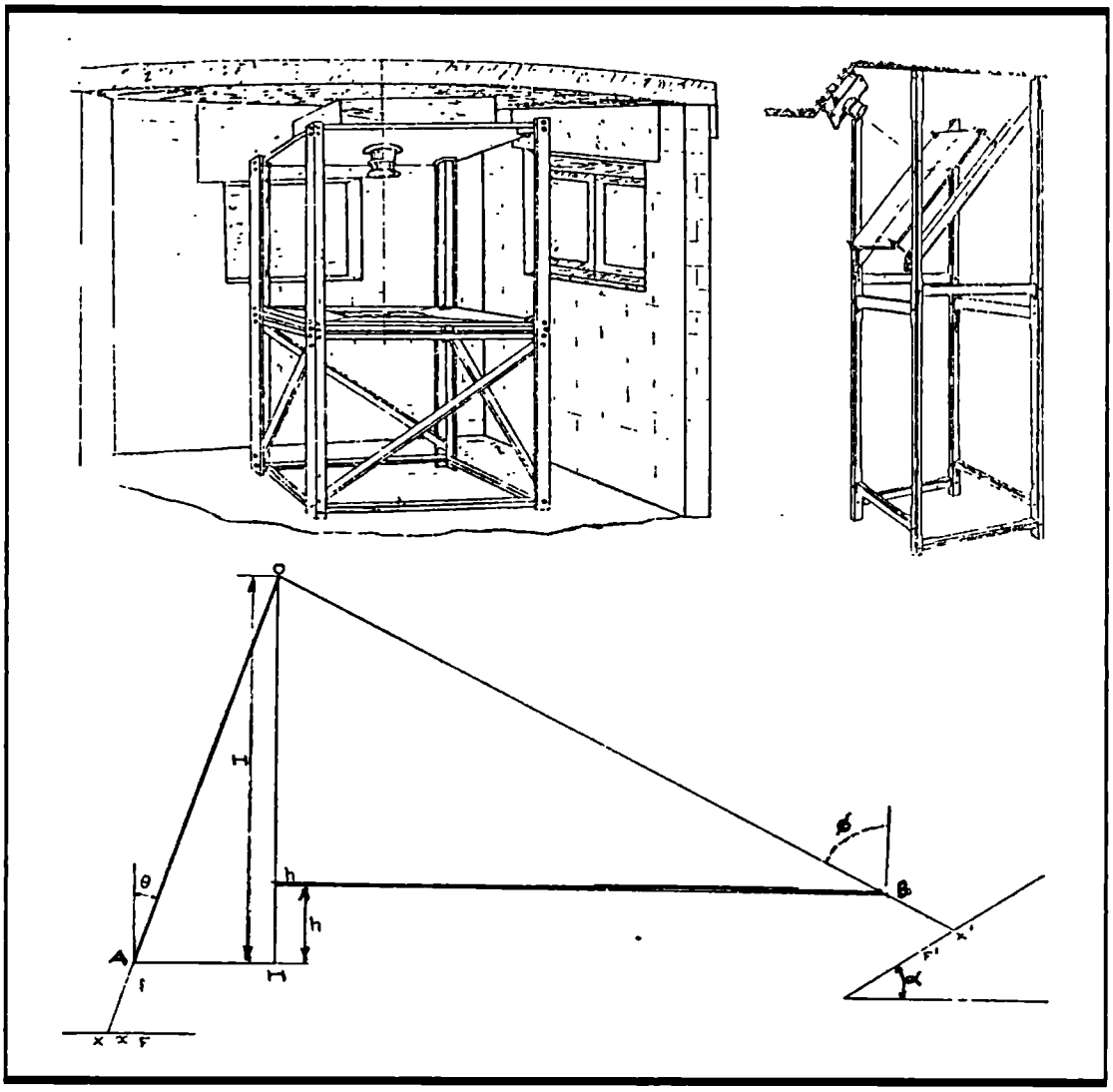


Fig 3.3. Camera Obscura Method.

O represents the position of the aeroplane as it crosses the line between the two lens A and B. The inclined lens at B is higher than the vertical lens at A due to the contour of the ground, X and X' is the image of the aeroplane in each camera., F and F' are the centres of each table and AF and BF' are the focal length of the lens A and B.

Let OH = H ; AF = f ; BF' = f' ; XF = x ; X'F' = x' , and L = distance AB.

Then AH = $H \tan \phi$

Bh = Oh tan φ = $(H - h) \tan \varphi$

L = AH + BH = $H (\tan \varphi + \tan \phi) - h \tan \phi$

i.e. $H = \dfrac{L + h \tan \phi}{\tan \varphi + \tan \phi}$ where $\tan \varphi = \dfrac{x}{f}$ and $\tan \phi = \tan (X'BF' + \alpha)$

and where α is inclination of table

Hence tan φ and tan ϕ can be calculated from x and x' using tables constructed for the purpose, and substituted into the equation to give height of the aeroplane. The ground speed was then calculated from

$\dfrac{\text{Distance travelled on chart} \times H/h}{\text{time taken}}$ where H/h is the scale factor of the table plot.

The camera obscuras were set up 5850 feet apart, one with its axis vertical and the second with its axis inclined at 45° towards the first. The pilot flew straight and level and at

constant air speed directly towards the vertical camera, and approximately at right angles to a line joining the cameras. Observers at each camera traced the image of the aeroplane on the table, by dotting its position every second. A line was drawn on the table at each camera pointing directly towards the other camera, so that when the image of the aeroplane crossed the line on one camera, it crossed the line on the other camera simultaneously. This enabled the two tracks to be synchronised without the need for the observers to dot simultaneously, so avoiding the need for communication between the cameras. Another line, called the cross line was drawn on each table at right angles to the line joining the cameras.

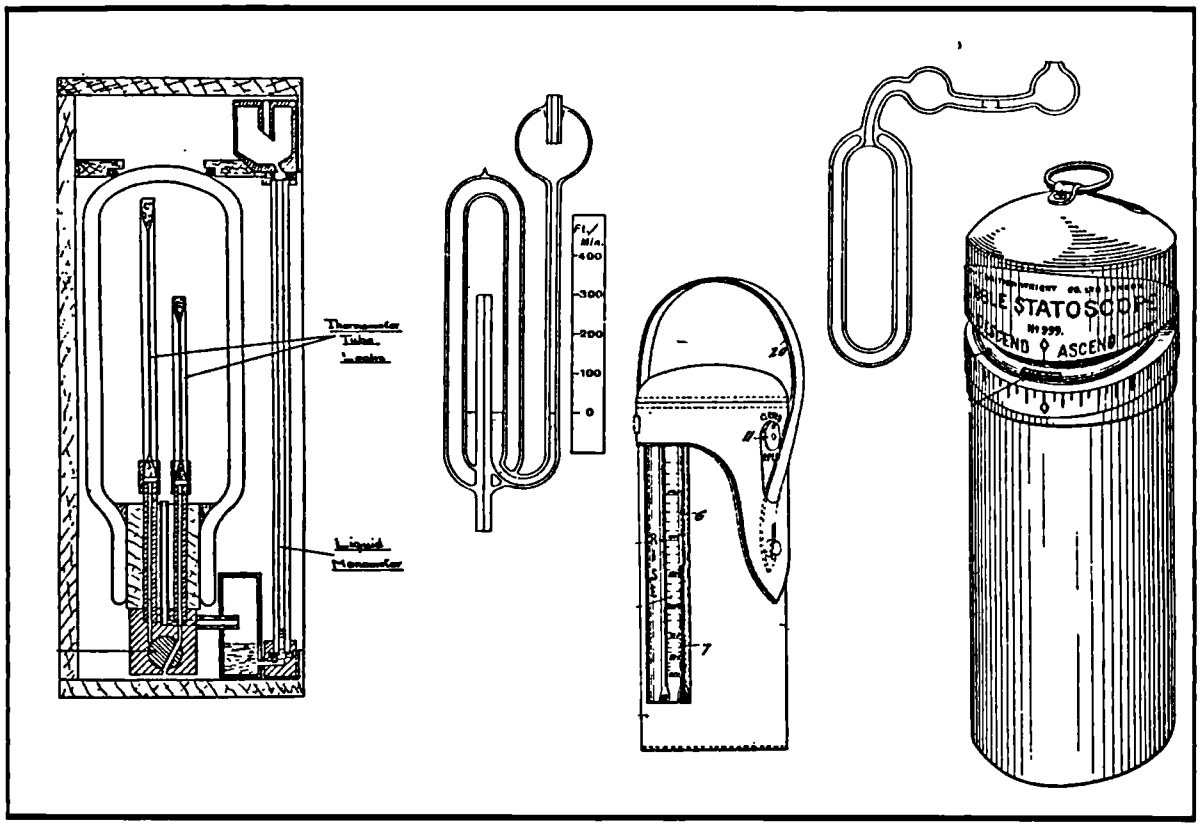
The height of the aeroplane was then be found at any moment by the distance of its image from the cross lines at each camera and knowing the height, the speed of the aeroplane over the ground was calculated from the distance its image moves in one second. However, to find the actual air speed of the aeroplane, the wind speed and direction at the height of the aeroplane had to be known. This was found by dotting in the track of a smoke signal fired by the pilot while in view of the camera. As set up, the limits of the equipment were 1500 feet to 10,000 feet on a clear day. Tizard's papers contain 12 records of bomb aiming experiments using this equipment.[15]

The camera obscura was a very important device for translating three dimensional motion into two dimensional measurement. It use declined with time, but a mobile version was still in use for bomb aiming practice by the Australian Air Force in World War Two.[16]

3.5. New instruments at the Aeroplane Testing Squadron.

The new instruments for measuring aeroplane performance, that Tizard mentioned in his paper were the climbmeter, statometer, baro-thermograph, petrol flow meter, and electrical timing apparatus for the ground speed course.

Rate of climb and speed performance flying werenot easy for pilots as the first involved the altimeter and stop watch and the second involved flying level by reference to the altimeter. The Testing Squadron developed the climbmeter to assist the pilot climb at maximum rate, whereby the pilot varied his air speed until the liquid in the manometer tube was as high as possible.[17] The prototype in its wooden box was replaced by a more practical design by the British Wright Company, patented by Lt.T.G.Hull, RNVR, and Griffith Brewer, No.125,440/16.



(a) (b) (c)

Fig 3.4. (a) Testing Squadron Climbmeter. (b) British Wright Climbmeter. (c) British Wright Bubble Statoscope.

The climbmeter thermos flask communicated with the outside air through a leak made from a piece of thermometer tube. A small bore manometer measured the pressure difference between the inside and outside of the flask. As the aeroplane climbed, the atmospheric pressure diminished, pressure inside the vessel became greater than the outside atmospheric pressure, forcing air out through the leak tube, at a rate equal to the rate of change of atmospheric pressure due to climbing. The statometer was similar with the manometer replaced by a horizontal curved glass tube with liquid traps at each end.

The statometer was similar to the climbmeter with the manometer replaced by a curved horizontal glass tube. A drop of liquid was placed in the tube, and at either end of the tube were glass traps which prevented the liquid escaping either into the outside air or back into the thermos flask. When the machine ascended, the air in the flask became higher than the external atmospheric pressure, the liquid bubble was pushed to the right hand trap, where it broke allowing the air to escape. On descending, the reverse happened, but when flying truly level, the bubble remained stationary. Various versions of the statometer had been made for balloons and airships, but the one used for aircraft was made by the British Wright Company. Fig 3.6 shows one 'wired' to the instrument panel.

The Testing Squadron designed a clever baro-thermograph to attempt to record the distribution of temperature with height.[18] A Dines balloon-sonde barograph had been

tried, but its movement was not balanced and suffered from vibration and a microscope was needed to examine the record.

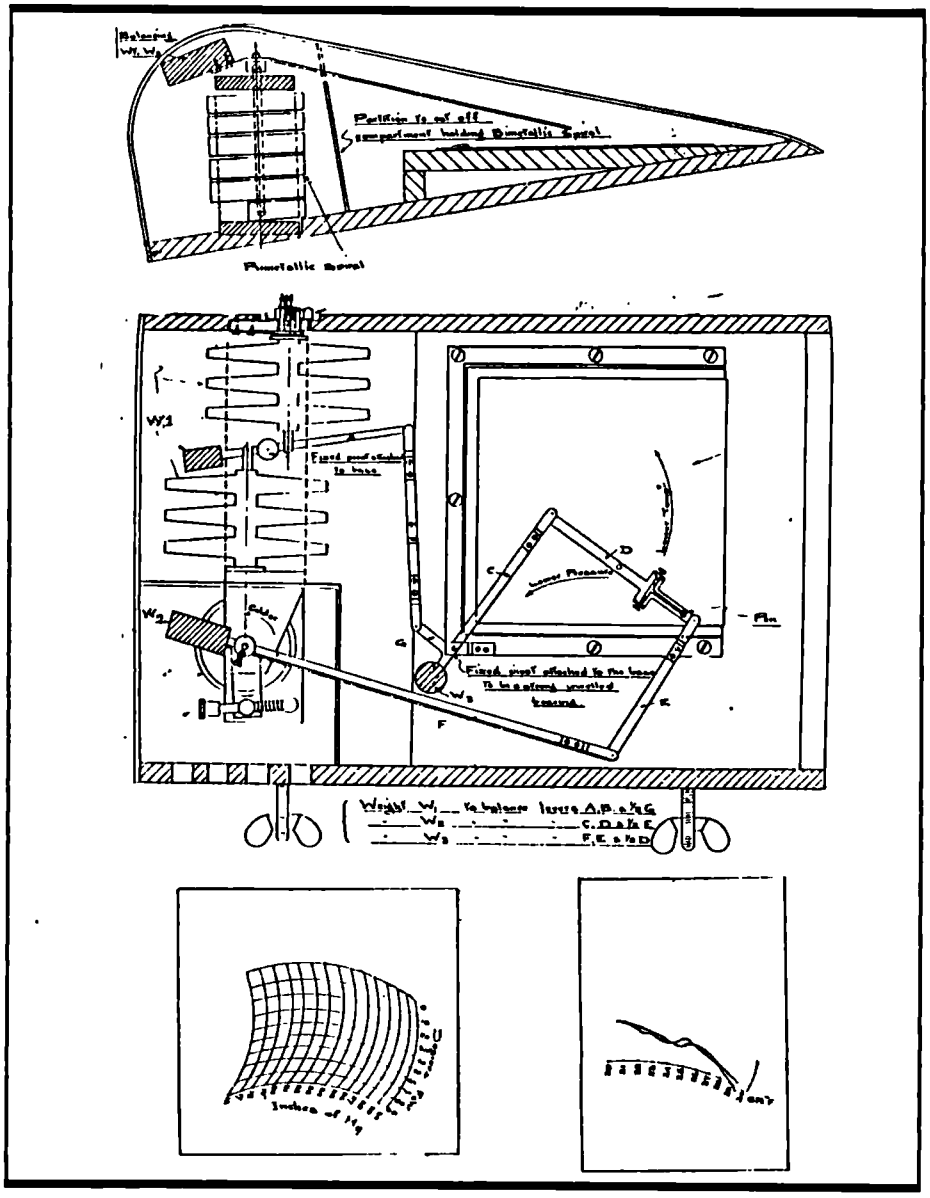


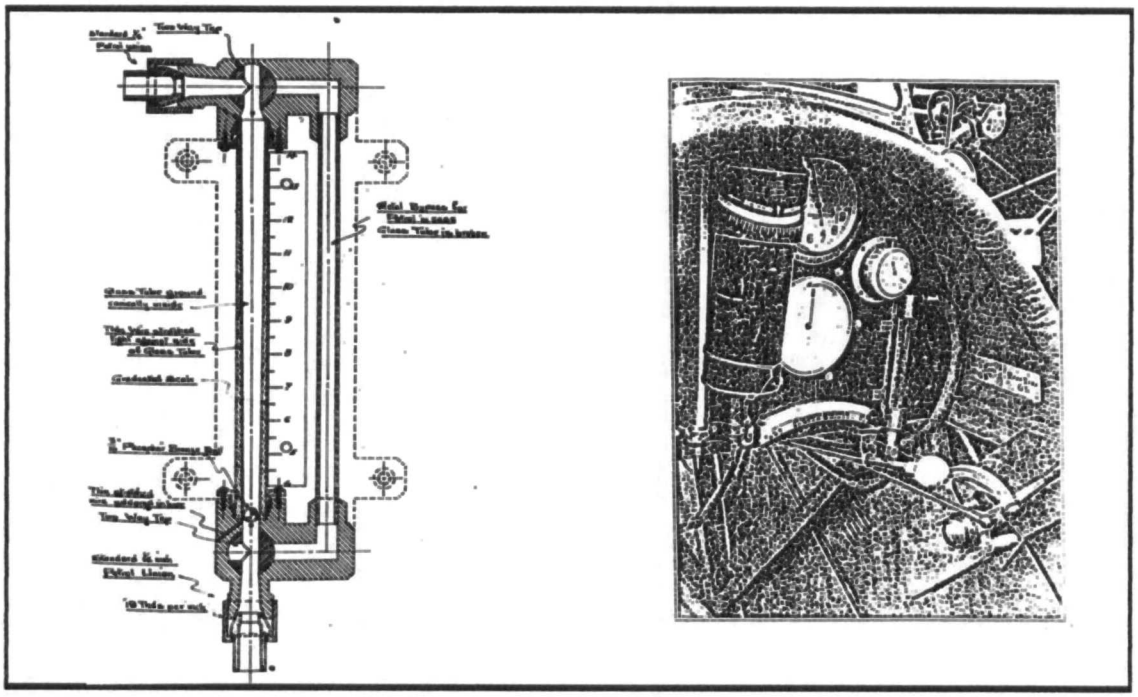
Fig 3.5. Baro-thermograph with typical record.

Bi-metallic thermometer and twin aneroid elements, with weights on the linkages, balanced vibration effects. Pen was a metal point moving on a smoked sheet to avoid friction, the sheet being fixed afterwards with dilute shellac varnish. The whole assemble was placed in a streamlined housing, which could quickly be clamped or removed from a special cradle mound on the lower wing.

Tizard got the device made at Farnborough using standard maker's bi-metallic thermometer and aneroid box to simplify manufacture.[19] The baro-thermograph looked a practical instrument and was reasonably accurate on test, but its use does not appear in any

subsequent reports. It probably suffered from vibration if its balance was disturbed, and the smoked recording plate would not be very practical in mist and rain.

Another instrument, whose use was introduced by the Testing Squadron, was the variable area tube flowmeter to measure the instantaneous fuel consumption of an engine in flight.[20] The alternative was a small calibrated test tank that could be switched in during a test, but this only gave average consumption over a period of time. The petrol flowed up through a vertical glass tube, ground internally so that its inner surface was slightly conical, the smaller end being at the bottom. Flow was indicated by the position in the tube of a phosphor bronze ball, which was in equilibrium under its weight in petrol and the difference in pressure between the upper and lower side of the ball. The flowmeter was



(a) Section (b) Installation

Fig 3.6. Variable Area Petrol Flowmeter.

screwed to the pilot's panel and connected between the petrol tank and the engine using flexible tubes, fuel entering at the bottom connection. Some provision for safety was provided by two ball valves on the inlet and outlet, which could be turned to divert the fuel through a metal bypass tube if the glass tube fractured. Bringing flexible tubes carrying petrol into the cockpit area was a serious hazard, acceptable in research to obtain measurements that would otherwise be unobtainable, but not for active service. Readings up to 10 gallons per hour were steady, although above this the ball oscillated about 0.3 gallons per hour on the scale.[21]

The stop watch method of timing the ground speed course at Martlesham Heath was replaced by electrical timing equipment by the end of the war.[22] The construction described how 'the apparatus was made from various pieces of apparatus which happened to be at hand', a practice very typical of university and research laboratories. It consisted of a tape machine taken from a Brown Automatic Wireless Receiver, and two recording pens, operated by electro-magnets taken from electric bells.

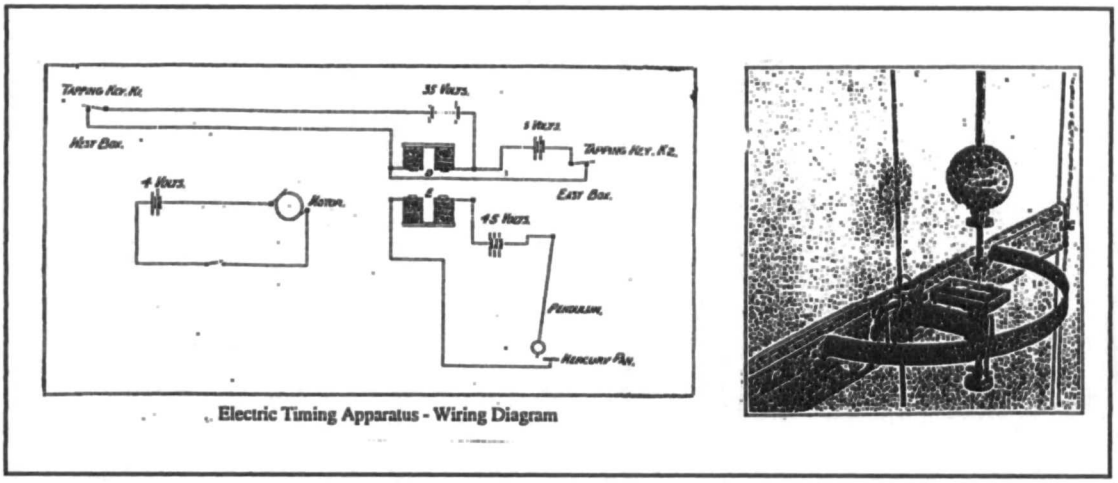


Fig 3.7. Electric Timing Apparatus - Wiring Diagram and timing pendulum.

The electro-magnet D was excited by keys operated by the observers at each end of the speed course. The timing apparatus was installed in East Box, where the key K2 was connected in series with two Leclanché cells and the electro-magnet D. The key K1 in West Box was connected to the same electro-magnet D in East Box, via 35 volt dry batteries, to overcome the line resistance. The electro-magnet E was connected in series with a pendulum, which made contact every second with a mercury surface to completed the circuit and mark the recording tape.

The method of using the apparatus was similar to the stop watch method.[23] A sighting device in each box allowed the observer to sight along an imaginary vertical plane. About half a minute before the aeroplane passed the starting end of the run, the tape machine motors were started. The observer at this end pressed his key a second or two before the aeroplane crossed his plane of observation, and broke the contact as the tail of the aeroplane crossed this plane. The observer at the finishing end repeated this process. Timing was provided by a pendulum making contact every second with a mercury surface to complete a circuit and mark the recording tape. The method was considered accurate to one twentieth of a second. The period of oscillation of the pendulum was tested from time to time against the Eiffel Tower time signals, using the 4 minute time interval between the dots at 10.45 and 10.49am.

3.6. New instruments at Farnborough

Farren described G.I.Taylor's photo-multimanometer for measuring the distribution of pressure over wing surfaces. Taylor said,

> much of the work at Farnborough consisted of designing instruments for use in aircraft, and it soon became obvious to me that many of our difficulties arose because we had no clear picture of experiences that pilots tried to explain.[24]

As O'Gorman was reluctant to upset the Factory pilots, Taylor asked O'Gorman to release him to the RFC, where he learned to fly between May and July 1916. He had complete faith in his instruments, would do violent manoeuvres near the ground by concentrating on them and on one occasion he managed to safely land down wind without stalling, when his engine failed after taking off.

Taylor's best known work at Farnborough was his development with A.A.Griffiths of the soap film apparatus to analyses stress profiles in various objects. The apparatus consisted of a chamber with a thin plate dividing it into two compartments. A cut out of the model of the object under analysis, say a propeller shaft with key way, was made in the plate and a soap film formed across the cut out. Then the air pressure on one side of the plate was gradually increased and the profile measured with a microscope. It produced 'rule of thumb' design concepts without recourse to solving difficult equations and would now be called an analogue computer and it was often used to reduce the stress at a corner by determining the best radius of curvature. Taylor never mentioned where the idea came from, but there would be many indicators around the department, which measured air speed by the change in profile of a thin elastic diaphragm when a differential air pressure existed across it.

Taylor used his meteorological training to analyse the inaccuracy of altimeters.[25] Aneroid barometers in service at that time were calibrated to read height assuming the atmosphere to have a uniform temperature of 50° F. He analysed the temperature record of a hundred balloon ascents up to 6000 feet, taken at random time and place, to calculate the greatest error in height that a standard uncorrected aneroid barometer would have given, had it been used in each ascent. He also plotted temperature against height for each ascent, and by measuring the area under each curve with a planimeter found the average temperature up to 6000 feet for each ascent was 7°F. For the 100 cases, he found the following errors,

Errors between	0-50	50-100	100-150	150-200	200-250	250-415 feet
Uncorrected - no. of cases	22	16	20	16	12	14
Mean 7°F correction "	80	16	4			

The improvement was very obvious, but this inaccuracy due to the scale remained throughout the war on service altimeters, and became known as the 'trade scale' and the problem worsened when operational heights increased to 10,000 feet. Dobson repeatedthe

exercise four years later and showed the improvement was greater if the altimeter was corrected for temperature uniformily decreasing with height.[26]

On return to Farnborough after learning to fly, Taylor designed the photo-multi-manometer to measure the pressure distribution over the wing of an aeroplane in flight to compare it with the wind tunnel model predictions.[27] Although this was a recording instrument, the alternative of trying to read 20 pressure indicators simultaneously was beyond the power of an observer and the method proved very satisfactory except for the time spent in detecting leaks and blockages.

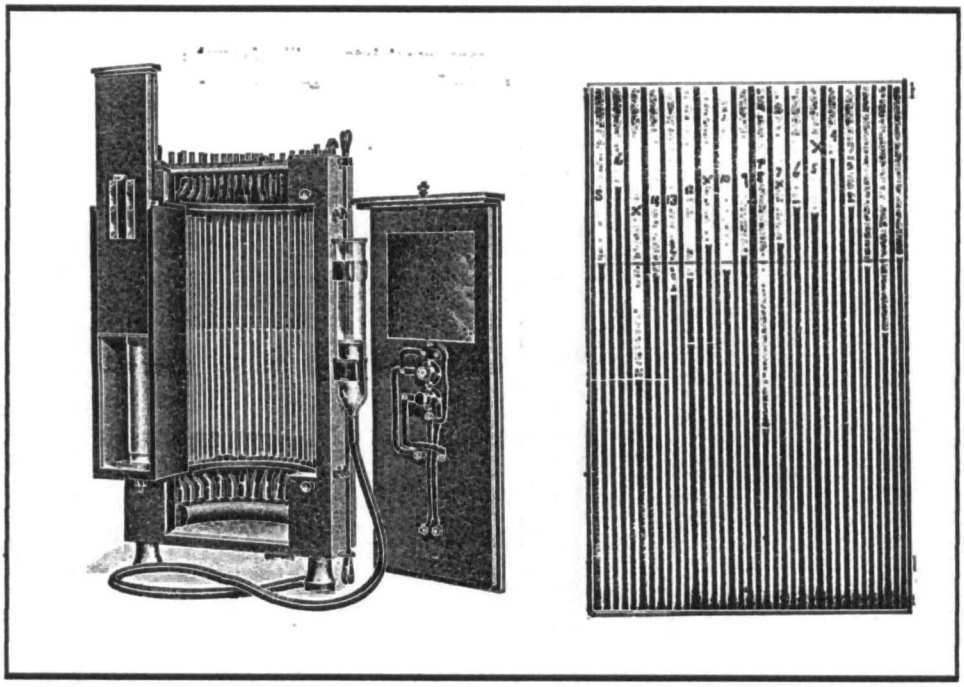


Fig 3.8. Taylor Photo-multi-manometer.

The 20 manometer tubes with their lower ends connected to a common alcohol reservoir, looked like a radiator. The upper ends of the tubes were connected by rubber tubing to flush holes in a brass wing rib, so the liquid height in any tube measured the pressure at the respective hole. The shadow, cast by a light in front of the tubes, was recorded with a half second exposure on bromide paper wound behind them, and the paper wound forward for another record. Damping was provided by an adjustable orifice in each rubber before its connection to the reservoir. The two outside tubes were connected to yaw heads, arranged vertically to give incidence, and the centre tube was connected to a pitot line to recorded air speed reading. In the laboratory the apparatus was accurate to 1mm Hg.

The concept of the recorder was not new as similar equipment and experiments had been published two years earlier by Ellis Williams in Professor Bryan's department at Bangor University, although Taylor gave no acknowledgement to this at the time or later. Williams had conducted his experiments above Llanddona Beach in Anglesea to compare a an actual Eiffel No.7 wing section with its wind tunnel model, using a monoplane that he had constructed for purpose.[28] He used 12 petrol filled, U-tube manometers and their

shadow on bromide paper was illuminated by daylight from a flap, mirror and slit arrangement at the front of the box, with damping provided by a plug of cotton wool in the bend of each U-tube. A manometer was also provided to record air speed from a pitot tube mounted 6 feet above the body out of the slip stream. An even earlier method had been patented by C.J.Lane and C.J.T.Birt in 1910, Patent 17,727, in which spring contacts, attached to small flaps at each hole, were in circuit with resistances and an ammeter.

Although Farren had said that the photo-manometer was used in preference to the observer trying to read several manometers simultaneously, the latter method was still used with 8 manometers to examine the forces on the tail plane of a BE 2c after a more powerful engine had been installed (Fig 3.9a).[29] To measure slip stream from a FB-9 pusher, which had a considerable turning tendency, a moving vane instrument was developed.[30]

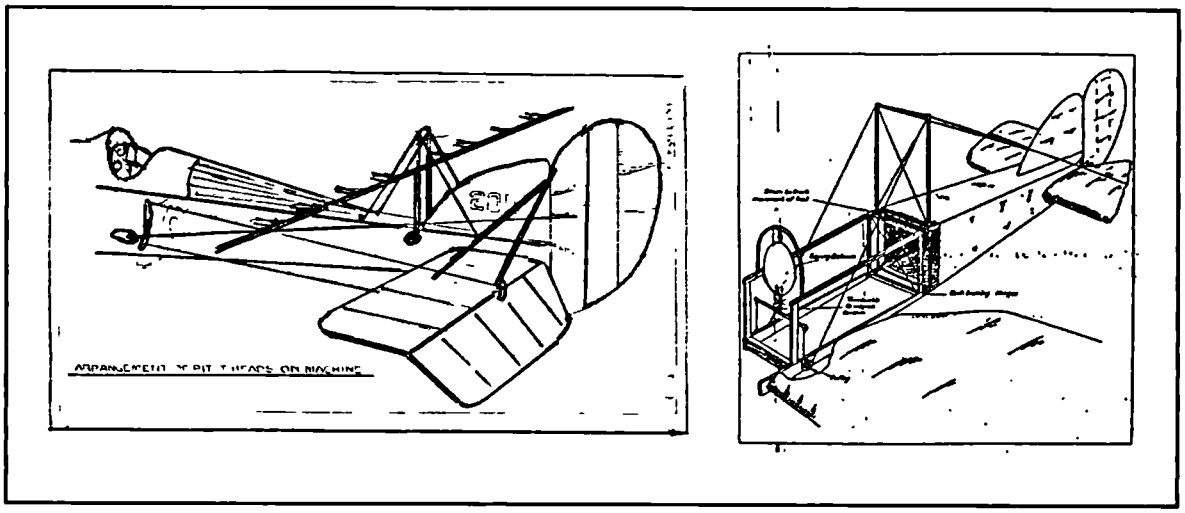


Fig 3.9. Measuring (a) slipstream velocity (b) load on tail.

Farnborough also used a direct a method to calculate the centre of pressure of the wings, in which the aeroplane was cut in two just behind the pilot's seat. The rear of the fuselage was hinged to the front by two ball bearings at the meeting point of the lower longerons, with stops to limit angular movement, while a framework arrangement of wires and spring balance determined the bending moment on this point. Farren said that many wings arrangements were tested this way, without any problem in flight regarding control of the aeroplane. This was true regarding the control of the aerolane, but he did not add that Captain Renwick and his observer David Pincent, both of whom had often flown as Lindemann's observers, were killed when the aeroplane in which they were conducting this experiment broke up in flight.[31]

3.7. Post-War Performance Testing at Martlesham Heath.

In 1922, Squadron Leader T.M.Barlow delivered a paper to the Cambridge University Aeronautical Society, in which he described the current performance test methods at Martlesham Heath.[32] It showed they had remained relatively unchanged since Tizard's 1917 paper, though the hastily adopted British Standard Height had been dropped and some new instruments were being tried.

Britain had now adopted the standard atmosphere established in France, based on a straight line law for variation of temperature from initial ground conditions of 15°C, 10.33 kg/m^2 (760 mm Hg), to a height of 11,000 metres, above which temperature was considered isothermal. These were the initial conditions that the RNAS had wanted to see in 1917 and gave a standard density of 1.225 kg/m^2. The strut thermometer was being replaced by the vapour pressure thermometer, which allowed the capillary tube to be taken to a dial in the cockpit. This had the advantage that the pilot or observer did not have to move his head and re-focus his eyes from the other instruments, but the vapour pressure thermometer, like the strut thermometer still suffered from lag and it was necessary to observe how far the temperature dropped after the end of the climb - usually about 0.5° C. The pocket Richard barograph was still standard, but a new photo-barograph was being tried in which the usual linkage from the aneroid was replaced by a mirror and a beam of light, reducing backlash and lag to a minimum. This had been designed by Professor S.Smith of Alberta University, when a Captain on the technical staff at Martlesham Heath. An air speed recorder by Munro was also being tried, but the official view on recording instruments was unchanged.

Conclusions

Aeroplanes testing is about the experimental methods and instrumentation used to test the performance of aeroplanes, not about the aeroplanes themselves. The Testing Squadron were concerned with the routine but accurate measurement of air speed and rate of climb to compare the performance of different aeroplanes. Farnborough conducted research flying to compare the performance of a full scale aeroplane with the prediction of its wind tunnel model to understand and improve its aerodynamic performance, and where it was better to keep as many variables constant and examine the remainder. Taylor, who was involved in both, agreed with Tizard that experimental work which recorded measurements on pre-printed forms was not pure research, but did required a scientific basis to establish the tests in the first place.[33] Nevertheless, Farnborough and Martlesham Heath shared the same

experimental environment and used similar measurement methods and instrumentation, althought they had their own preference for some instrumentation. The aeroplane was a unique and unfriendly laboratory, it vibrated the test instruments fitted to it and provided little space for them, it was noisy and cold, its altitude often deprived the experimenter of oxygen and engine failure could terminate experiments prematurely. But more importantly, the passage of the laboratory through the air affected the accuracy of the height and air speed instruments in it and methods and instrumentation had to be devised to calibrate its movement from the ground. Further, because height and air speed were measured indirectly by differential air pressure, comparative readings had to be laboriously reduced to a standard density to be meaningful. The test instruments used were simple scientific devices, an improvement on the string and sealing wax apparatus of the university laboratory, but often still housed in wooden boxes, and the liquid manometer was basic to many. Suitable recording instruments defeated both groups and the trained observer became universal.

This thesis is based predominantly on published and unpublished reports written by the scientists concerned as edited and organised accounts of their work. The diary that Tizard kept for two months shows that more personal material provides an insight into experimental uncertainties that are hidden in the published paper. Wimperis kept a diary for every day of the war and this will be used extensively in Chapter 8.

The work by wartime scientists established the experimental methods to measure aeroplane performance on a sound scientific basis. The wartime facilities, resources and urgency advanced test flying far quicker than would have occurred in peacetime and provided a sound basis for post-war research. Instruments to accurately measure aeroplane performance were more important to the scientist than to the normal service pilot, who only glanced at them occasionally. However, the service pilot did need a good compass and its development is the subject of the next chapter.

Chapter 4.

The Aircraft Compass - Part 1
Development from 1909 to 1916

Summary : Pre-war empirical developments - Creagh-Osborne and Clift compasses - wartime developments at Farnborough by Lucas and Lindemann - vibration, acceleration and northerly turning error - Lucas Spherical compass - parallel development by Creagh-Osborne at the Admiralty Compass Department.

This chapter examines the problems with the aircraft compass in the pre-war and early wartime period. As aeroplanes remained in the air for longer periods and flew further distances, the instrument assumed increasing importance, but engine vibration caused the compass card to rotate continuously. The Admiralty and a private inventor attempted to overcome the problem, but by the outbreak of war the aircraft compass was still in trouble, as engine power and hence vibration had increased, acceleration effects were becoming noticeable as aircraft manoeuvred more quickly, and pilots were trying to use it to fly through cloud. At Farnborough, Lucas examined the problem and designed a new military aircraft compass and Lindemann continued his work, while Creagh-Osborne at the Admiralty Compass Department developed compasses, which would result in contention between the two groups. We shall see that a significant development effort was required to transfer an apparently simple and well established instrument into a new environment.

4.1. Creagh-Osborne's Compasses

Captain F.Creagh-Osborne at the Admiralty Compass Department was the first person in Britain to be involved with aeroplane compasses.[1] Creagh-Osborne wrote to Cody at Farnborough in August 1909 suggesting a Navy liquid filled compass, which could withstand gunfire shock, might be suitable for an aeroplane. He flew with Cody on 2 September and found the compass spun due to the engine vibrations, but he was able to reduce this by placing the compass in a box filled with cotton waste, first proving it on the floor of a car driven by a single cylinder engine. In May 1910, he visited the aviators at Brooklands and formed the general opinion that flyers would like a compass in an aeroplane, but thought it hopeless on account of vibration and magneto interference. He

wrote to F.W.Clark, managing director of the compass makers Kelvin and James White, discussing compasses and methods of mounting them in aeroplanes and encouraging them to be first in the new field. They produced their first aeroplane compass the following year, which was a reduced diameter Chetwynd naval type, mounted in a container filled with horse hair, with four trunnions in rubber sockets to reduce the effect of engine vibrations.

The designers, Field and King described the design basis they adopted for this compass.[2] The use of the dry card compass system was discarded, because it was only effective for compasses of 10 inch diameter. This had been Kelvin's original design, which balanced the conflicting requirements of lightness to reduce pivot friction, sufficient magnetic moment to restore the card after small deviations, and a long period of oscillation to provide steadiness. The liquid system allowed a small steady card to be provided, which had a hollow dome section to provide buoyancy to reduce pivot friction. Sufficient gap between the card and the bowl was provided to reduce the frictional effect of the bowl dragging the liquid, and hence the card, round with it, while the bottom of the bowl was flexible to allow the liquid to expand and contract. Horse hair packing was provided to reduce the shock on landing from damaging the iridium pivot and the outer case was mounted to the aeroplane in a novel way. It had a circumferential groove in which a girdle of stranded wire was wound, from which three ligaments of stranded wire, 120° apart, attached the case to suitable parts of the aeroplane so that the springiness of these ligaments acting as a shock absorber. The compass was 5.5 inches diameter by 3.5 inches deep, and weighed 3 lbs. 3 ozs. The designers stressed the importance of mounting the compass away from ferrous objects or substituting them for phosphor bronze, drawing particular attention to the steering gear which was constantly changing position in flight. Compass deviation due to fixed objects like the engine could be corrected with brass cased magnets supplied with each compass. They finally mentioned that the compasses had been adopted by the Admiralty, Royal Flying Corps, Central Flying School and Royal Aircraft Factory.

This compass did not apparently meet all the military requirements as O'Gorman asked Darwin if he could make a compass on the basis of the Kelvin and White, but Darwin was not successful.[3] A conference was eventually held on 5 December 1912 to discuss the standard features required for the aeroplane compass. Present were Cmdr. Creagh-Osborne (ACD), Cmdr. O.Schwann (Naval Flying Wing), Maj. F.N.Sykes (5th Hussars, for War Office and Military Flying Wing) and Maj. E.L.Gerrard (CFS) and a specification, based on the Kelvin and White compass, was produced and given to manufacturers on the

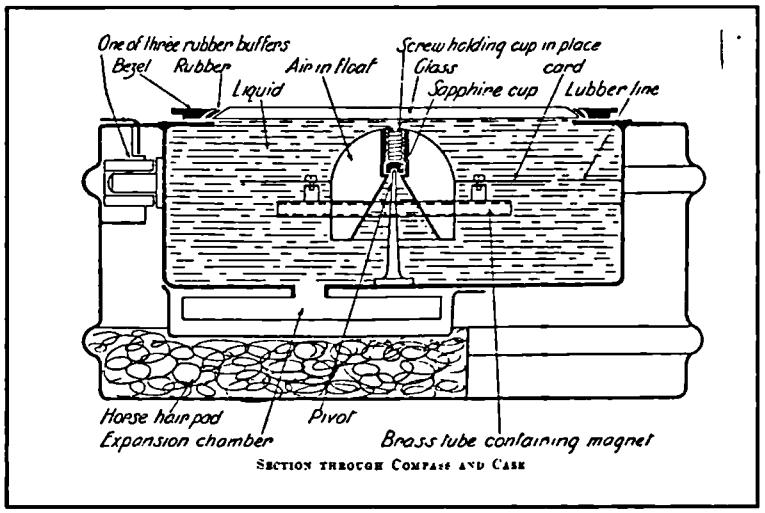


Fig 4.1. Admiralty pattern 200 aircraft compass 1913.

Admiralty List. The resulting Pattern 200 compass became the standard military and naval compass for the next two years.

4.2. Clift Compasses

The private inventor E.H.Clift was critical of the Kelvin and White aircraft compass as he felt an aircraft compass should be in gimbals to keep it level, especially when gliding down, and that horse hair suspension to overcome shock and vibration was useless.[4] He explained the design, construction and use of his own compass in march 1912, which also provided a good account of compass problems at this time.[5] He retained the reduced diameter, slightly negative buoyant card, expressing that care was needed to prevent eddies in the liquid, but giving no details of how he prevented this. He rejected the older marine methods of marking the card with 32 cardinal, half and quarter points, or 4 cardinal points with 0° for north and south and 90° for east and west, in favour of the newer and less confusing marine method of marking 0-360° progressively round the card from north. He was aware of the importance that,

> if the period of the card in any way agrees with the rate of vibration of the aeroplane, the matter becomes hopeless, and although a special type of suspension was practically always required, it will rarely remedy this defect, although on the ground it may appear to be satisfactory.

Determining the correct period for aircraft compasses is crucial and we shall see this considered again by Lucas at Farnborough in 1916 and more systematically by Wimperis and Rowe at the Air Ministry Laboratory at Imperial College in 1920.

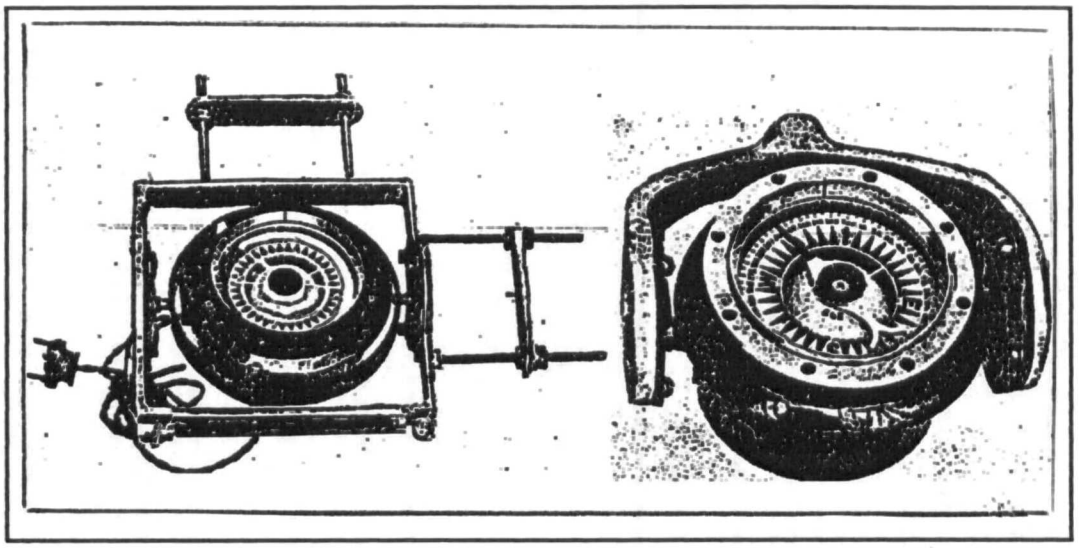


Fig 4.2. Clift Compass 1912, showing rubber anti-vibration mountings.

Clift was also aware of the importance of anti-vibration mounts for a compass in an aeroplane and used fairly rigid cross-shaped rubber mounts to secure the outer gimbals to the frame. He recommended the compass should be mounted centrally in front of the pilot to avoid parallax in reading the bearings, as it was well known that the aviator who had constantly to put his head to one side to observe his compass, never looked at it sufficiently to steer a correct course.

He recommended that the compass was swung by turning the heading of the aeroplane round on the ground and noting the error between the observed compass heading and that of a fixed landmark every 10 degrees of rotation. The deviation was produced by the proximity of ferrous metal to the compass and could be reduced to a small amount by compensating magnets placed close to the compass. However, he said that aviators failed to understand that a small piece of iron close to the compass could have a much greater effect than the engine at some distance from it. He explained that iron and steel had different effects. Soft iron became magnetic by induction in the earth's magnetic field and if horizontal would vary with the machine's head and have a varying action on the compass. However, magnetism induced in vertical soft iron remained constant with heading, but its effect on the compass varied from nothing when in line with the needle to maximum when at right angles. Steel hardened by hammering, on the other hand, became permanently magnetic and the magnetic poles were not reversed whatever the direction of head of the machine.

Clift recommended that the engine should be run first to see if the magneto had any effect on the compass and if it was a rotary engine, the engine should be rotated to three or four

different positions to see that the cylinders were not effecting the compass more in one position than an other. One should also be alert to brass control levers provided with steel tubes for strengthening, to adjacent brass instruments fixed with steel screws, and to energetic assistants who lean over the cockpit with tools, bolts or spare parts in their overalls, while the whole swinging effort could be wasted if the pilot later carried a steel map case or a bag of tools with him. He also showed that the deviation curve on two similar machines was different, indicating that a compass could not be transferred from one machine to another without swinging the machine first.

He concluded that his article would have fulfilled its purpose, if aviators, manufactures and mechanics now understood that no alterations should be made in an aeroplane after the compass was adjusted. His compasses and associated navigational aids were made by Henry Hughes and Sons of 59 Fenchurch Street, London.[6]

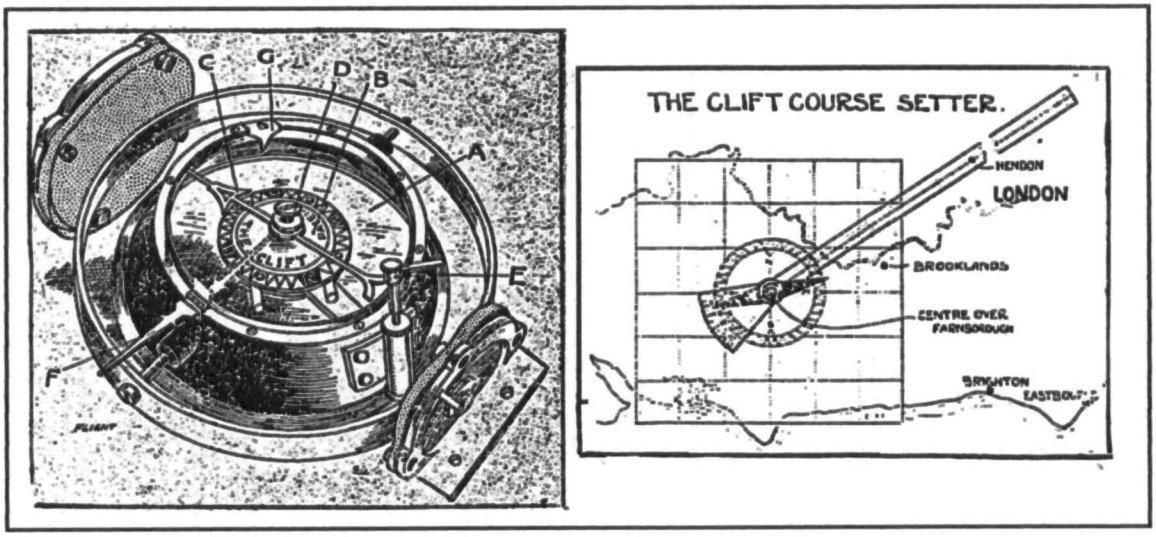


Fig 4.3 (a) Clift Leeway Compass 1912 (b) Clift Course Setter

Transparent bowl allowed pilot to observe direction traversed by objects on the ground and correct his drift.

Clift introduced his Leeway Indicating Compass the same year, in which the bottom of the bowl was transparent. This allowed the aviator to observe the direction traversed by objects on the ground and correct drift due to a beam wind by altering the direction he was flying until the objects on the ground moved parallel to the desired course.[7] The diameter of the compass card in relation to the diameter of the bowl had been reduced to provide a clear view and the anti-vibration mounts were now solid rubber discs, the tension of which could be adjusted to minimise vibration. Clift also tried to simplify navigation for the pilot, which at this time he saw was predominantly flying a *pre-planned fixed course between two locations*. He therefore prepared individual strip maps for popular routes between two

airfields and this fixed course between the two airfields was set into his compasses *before the flight*. To complete his navigation package, Clift also designed a course setter to allow the magnetic course to be instantly laid off a standard ordnance survey map, when the flight was not covered by one of his own maps.

It was obvious from his advice and caution that Clift had considerable experience with the design, installation and use of aeroplane compasses. His articles were certainly not the casual comments of someone on the fringe of the work. However, we saw in Chapter 2 that the air speed indicator that bore his name had been designed by someone else. It is likely that the same was true of his aeroplane compass, but there is no documentary evidence to support this. Henry Hughes, who made his compasses were established compass makers and Clift may have encouraged or sponsored their involvement with the aeroplane compass. Hughes certainly had considerable experience with aircraft compasses when they assisted Creagh-Osborne with his range of wartime ones.

Compasses were advertised by other makers like Batty & Sons, Elliott Brothers and Smith & Sons.[8] It is doubtful whether any of these worked in the air as none had any form of anti-vibration mounts. They would look practical on the ground, but would cease to point north once the engine was started. Elliott Brothers had also made a sun compass since 1910, which avoided the difficulties of deviation and vibration. The aeronautical shadow plate consisted of a 10 inch diameter, circular celluloid plate, with a 10 inch vertical gnomon on its centre. In flight, the plate was adjusted every 15 minutes according to a set of tables supplied, and the course maintained by keeping the shadow of the gnomon at a fixed mark.[9] The real use for the sun compass came after the war when Byrd used the Blumstead sun compass, in which the plate was rotated by clockwork, to navigate in polar regions where the magnet compass is unusable.

4.3. Wartime Compasses development by Keith Lucas at Farnborough.

As service flying increased, it became obvious the aircraft compass still had problems as increased engine power had increased vibration and acceleration forces since the first compasses had been designed. Even before the war, reports said that Clift compasses were unsatisfactory and that although the Pattern 200 from Kelvin and White was preferred to the older Chetwynd type, it ought to be mounted in gimbals as it jammed in bumpy weather.[10] There were reports of compasses sticking in turns and of errors caused by the electrical field from not twisting the wires of the compass lamp. There were also reports of compass deviation in cloud and of balloon ascents to measure whether the magnetic angle of dip varied with height, that might explain the deviation.[11]

Keith Lucas, working in Busk's department at Farnborough, initiated the next development in September 1914. R.H.Mayo recalled that Lucas,

> arrived quietly and, after a brief inspection of the department, was given a stool at a bench and handed some papers to look over. The first was a report on various matters from the Royal Flying Corps in France. One sentence was *'The compasses are useless'*, no explanation of the nature of the trouble was given. Although he had no special knowledge of compasses, this aroused his keen interest, and he began at once a most brilliant research, which resulted not only in him finding out why the compasses were useless, but in the production of a new compass.[12]

Mayo added that the simple direct methods which Lucas applied in his investigation and the immediate success he achieved made a profound impression on the whole of the staff at Farnborough, and he became regarded as the chief authority on all matters that arose for investigation. Melvill later commented that it was Keith Lucas, who convinced him to accept what pilots told him and then fly with them to understand the problem for himself.[13].

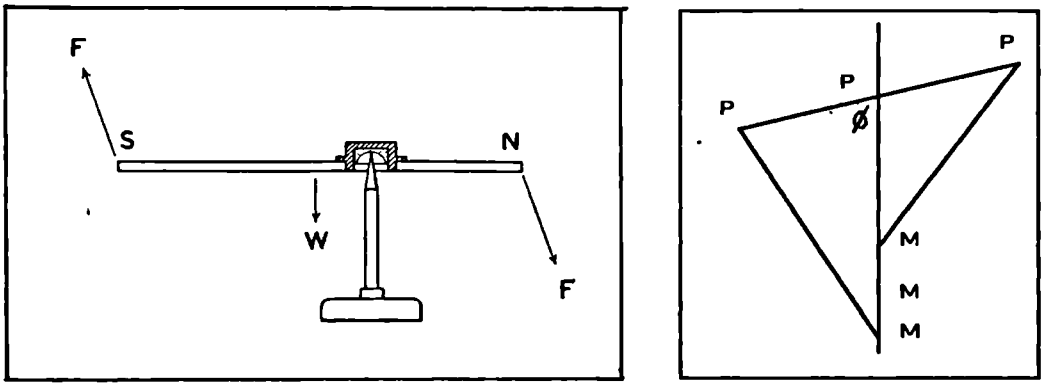
Lucas fully documented his compass investigations and the design basis of the resulting compass.[14] The complete report also included the theoretical investigations of the subject by Mallock, Greenhill and Darwin, who approached the problem as a Mathematical tripos question.

4.3.1. Theoretical investigations by Mallock, Greenhill, Darwin and Baker.

Mallock examined mathematically the problem as the friction between the cup and the pivot, which had different radius of curvature. This friction provided a couple on the magnet to turn it in the same direction as the 'closed curve' followed by the point of the pivot due to the imposed vibration. Later, Mallock suggested a compass design with pivots above and below the card to allow the centre of gravity to be at the point of rotation, while the card floated on an interface of ether and water.[15] Greenhill provided a mathematical solution, regarding the magnet as a balanced pendulum with a vibrating suspension, explaining his theory was developed from a problem of vibrating the suspension of a pendulum set by Clerk Maxwell in the 1869 Mathematical Tripos paper.

Darwin approached the problem as he had done in his 1913 paper by assuming the magnetic needle of a compass was weighted on the south arm to balance the vertical component of the earth's magnetic field and so keep the needle horizontal.[16] He saw the compass as a mechanism of linkage and couplings, and drew the analogy with the connecting rod of a steam engine, where the pivot was the rotating big end of a

connecting rod, and the centre of mass of the magnet along the south arm was the little end of a connecting rod, constrained to move in a guide.



(a) (b)

Fig 4.4. (a) Darwin's compass needle and (b) vibration diagram

P is the support of the needle moving with simple harmonic motion between P_1 and P_3. M is the centre of mass of the needle constrained to move in a guide. PM is the connecting rod and is assumed to have no mass. As P accelerates from P_1 to P_2 to P_3 and back again, M continually exerts a pressure on the same side of the guide, i.e. the vibration produces a couple which tends to diminish the angle Ø and cause rotation.

The solution he proposed was to reverse the cup and pivot so that the pivot was on the magnet and rested in an inverted cup in the bowl of the compass. He gave no explanation of why the inverted arrangement would reduce the error, though it must be analogous to a conjurer spinning a plate on a stick, a feat difficult if the stick was fixed to the centre of the plate. Reversing the coupling between two elements of a mechanism to provide better performance was a technique in the geometric design of instruments practised by Darwin. He proved that the inverted support did reduce the vibration error by testing it on a vibrating table and also found that any error was in the opposite direction to that with the normal support.[17] He also obtained the same result by replacing the compass magnet with a brass rod, indicating that the cause looked like friction. He then conducted other experiments to identify the cause of the error, but was sceptical of the results, because the vibration table was roughly made and moved in two closed loops. As usual in his investigations, he acknowledged the help of his director and former wrangler, C.C.Mason.

The solution offered by Oxford trained H.B.Baker, Professor of Mechanical Engineering at Imperial College, was similar to Darwin's and was not published.[18] He examined the forces imposed on the sides of a slot by the centre of gravity of a rod, which was constrained to move along the slot, as the rod moved harmonically on a smooth table. He then examined the couples that would be required to maintain the same motion if there was no slot, explaining that his solution was based on a similar one in Volume III of

Rayleigh's papers. It would seem that older scientists still examined problems as they had done many years earlier.

4.3.2. Experiments by Lucas on compass error due to vibration.

Lucas first examined the effect of vibration on the Admiralty Pattern 200 and Chetwynd compasses currently used on aircraft. Positioning a Pattern 200 compass in the observer's place in a BE 2c, directly behind the 70 hp Renault engine, gave the following errors when the aircraft was pointing in a known heading on the ground and in flight,

Engine rpm	1400	1500	1600	1750
Ground Test Deflection	7°	20°	42°	
Flight Test Deflection				40-50°

This confirmed that the standard pattern compass was useless in the observer's position. In the flyer's position however, where the vibration from the engine was less, the error was smaller and within 10° by ground course observation.

He then compared the vibration errors of each compass, and the effect of inverting the pivot and cup, using Darwin's vibrating table with a 0.05 mm orbital radius.

Vibrations/min	500	1100	1600
Deflection with standard pivot-cup	10°	16°	6°
Deflection with inverted pivot -cup	1°	1°	4°

The reduced deflection with the inverted cup confirmed Darwin's vibration table experiments, including that the deflection was in the opposite direction to that with the standard pivot. However, the inverted pivot-cup was not the answer by itself as a flight test showed the card still could not be read as the aircraft vibrations were greater in amplitude than the table vibrations.

Lucas next examined the effectiveness of the Admiralty anti-vibration compass mounting using Darwin's vibrating table. The Pattern 200 compass had three rubber trunnions clamping the bowl to the case, with a horse hair pad beneath the bowl.. He found that not only was the mounting ineffective, but there was little difference when he replaced the rubber trunnions with wooden wedges.

Vibrations/min	500	1100	1600
Deflection - rubber clamp	19°	22°	9°
Deflection - wooden clamp	16°	22°	8°

When he replaced the trunnions with four leaf springs arranged round the bowl, a geometric design technique, a ground test showed the deflection was dramatically reduced,

Rpm	500	1000	1200	1400	1500	1600
Deflection - ground test	0°	0.5°	0.5°	1.5°	3.0°	1.0°

and a flight test at 1750 rpm showed the card was perfectly steady. He repeated the tests with a standard pivot compass and found that the spring mounting again made a dramatic improvement, but not quite as good as with the inverted pivot.

He concluded that vibration error was serious but that the compass could be made reasonably free of vibration by a stable suspension of the compass card and of the compass bowl. He mentioned that Lt. Dobson at Upavon had also examining the problem and had made similar improvements with a neutrally floated, double pivoted card, but this involved careful design to obtain neutral buoyancy and the manufacturing complication of double pivots.[19]

4.3.3. Experiments by Lucas on compass error due to tilting.

With a few simple experiments, Lucas had explained the vibration problems that had plagued the aircraft compass for 5 years and he next turned to the error due to tilting the axis of the card. He used the term *tilting error* for compasses in aeroplanes to avoid confusion with *heeling error* in ships, which was due to the inclination of the ship under the compass and not from the inclination of the axis of the card. It was well known, that if the axis of compass card was gradually inclined over westwards into the E-W plane, the vertical component of the earth's magnetic field produced a moment about the axis to pull the North point of the card downwards, i.e. towards West, giving a westerly deviation. For an angle of magnetic dip of 65°, the laboratory errors due to inclining the axis of the compass to the vertical were,

Angle of inclination to vertical	10°	30°	50°	70°	90°
Angle of error of reading	21°	47°	59°	63°	65°

Had the axis been tilted in the N-S plane, the card would not have changed direction. Lucas explained that these well known results were important as the axis of a compass card becomes tilted when the aeroplane accelerated or deceleratedwhile flying straight and level, or when banking into a turn

Lucas also realised that the error in flight did not simply depend on magnetic forces as tilt could be caused by acceleration or deceleration force on the unbalanced mass on the south side of the card. Therefore for an aircraft flying magnetic West - its compass card pointing North at right angles to the heading - a deceleration force that caused the axis to tilt forward and allowed the North point of the card to be dragged downwards in a counter clockwise direction, would also cause the weighted south side of the card to move West in a clockwise direction. Proving this example by flight test, Lucas found errors of 20° - 25° as the aircraft was accelerated or de-accelerated between 48 mph and 70 mph.

Although the error was significant, Lucas was aware that such transient error while flying a straight course had little practical disadvantage to the pilot and the real problem was the resultant of the magnetic and acceleration forces in a turn. It was during turns that pilots complained that the compass was *sticking*. There were also many reports that the compass went wrong in clouds, and the pilot found himself coming out of the cloud on the same side that he entered. These were the lucky ones as some pilots, who lost orientation in cloud, got into a fatal spin as the procedure for recovering from a spin was unknown at this time. In fact, it was unwise to fly a rotary engined scout type aircraft into cloud, as the gyroscopic torque of the rapidly rotating cylinders invariably produced a spin once the pilot lost sight of the visible horizon. It should be remembered also that there were no turn indicator instruments at this time and the compass was the only instrument available to tell a pilot that he was deviating from a straight course in cloud.

Lucas and Mayo carried out a series of tests using the modified compass, in the course of which they observed that the compass appeared to stick in turns off north and south, but never in turns off east and west, and the effect became worse as the angle of bank increased. Perhaps the best way to visualise these results is to realise that the card should continue to point North throughout any turn, if the true heading of the aircraft is to be known. If the pilot is flying due north and begins a turn towards the east, and the card happens to turn at exactly the same rate as the aeroplane, the pilot will be given the impression that the aeroplane is not turning or that the card has stuck. If on the other hand, the compass card turns more rapidly than the aeroplane, the impression will be that the turn is in the opposite direction to that which is actually occurring. In cloud flying with the horizon invisible, this would lead the pilot to further increase his rate of turn eastward to correct the apparent turn towards the west and result in a spin. This phenomenonof indicating a turn in the wrong direction, was given the name **Northerly Turning Error.**

Lucas concluded his report with an short analysis of his findings. The only complete solution would be to mount the card so that its axis cannot be inclined under any conditions. This could be done using a double pivoted card, i.e. one with pivots above and below the card as both Dobson and Mallock had suggested or by mounting the compass on a gyrostat. However, a double pivoted card introduced manufacturing difficulties, and the gyrostat was an impractical solution due to its weight and reliability. Therefore, accepting that there was no alternative to the single pivoted card, the most likely improvement to acceleration and tilting errors would be to increase the period of the card.

4.3.4. A New Type of Compass - The RAF Mk II

Lucas found the best period for a compass card was 17 seconds, but that this could only be achieved by reducing its magnetic moment to about half the customary value,and adding damping vanes, and he needed to determine whether reducing the magnetic control produced any unwanted secondary effects. For example, would the card be more easily disturbed by vibration or by movements of the liquid in the bowl and his report showed how these secondary effects were reduced in the design of his new compass.[14]

Vibration could be rectilinear as considered by Darwin and Greenhill, or in a closed path as considered by Mallock. The rectilinear effect varied with the distance of the centre of mass of the card from the centre of support and reducing the magnetic moment by half, reduced the balance weight by half, and consequently reduced its disturbing force. The effect from vibration in a closed path was dependent of the friction between the cup and pivot, and therefore on the weight of the card. Reducing the magnetic moment, reduced the weight of the card from 25 to 15 grams, because smaller magnets were used. However, there was a minimum to which the unfloated weight could be reduced, as the card would float off the cup as the density of the compass liquid increased when its temperature decreased at high altitudes. Experience showed that the floating weight of the card should be between 1 and 1.5 grams.

However, although reducing the magnetic control directionally helped to reduce vibration errors, the same was not true for errors caused by the movement of the liquid in the bowl. If the card was carried round with the liquid, reducing the magnetic control reduced the restoring moment and flight experiments on 1st June proved this to be true. The disturbance of the liquid was found to result from two causes. Firstly, when the bowl was rotated about a vertical axis as the aeroplane turned, skin friction caused the liquid in the bowl to rotate with it. Secondly, when the aeroplane pitched and rolled about a horizontal axis, the card did also and this second disturbance was much more severe than the first. If these movements were so timed that the pitch forward was followed by a roll to the right, and the pitch back was followed by a roll to the left, the card could be made to rotate continuously clockwise. Filling the bowl with a liquid, which had visible particles in suspension, showed this movement was caused by the flat glass on the upper surface of the bowl. As the bowl was pitched forwards or sideways, the flat glass deformed the liquid contained in the bowl by forcing down the flat surface of the card.

Lucas incorporated several design features to reduce these effects. He reduced the movement of the card due to the rotation of the liquid by increasing the clearance between the edge of the card and the inner surface of the bowl, the zone where the liquid was being

moved by skin effect. The bowl was spherical so that the contained liquid was not altered in shape when the aeroplane pitched and rolled, but merely had its outer layer set in motion by skin friction on the inner surface of the bowl. Lucas tried mounting a compass card in the case of a spherical liquid level that he had been experimenting with a few months earlier and found that the deviation caused by roll and pitch was small, showing that the motion which caused the card in the flat-topped bowl to rotate continuously, did not move the card in the spherical bowl more than 10 degrees.

While Lucas was doing this work, Darwin asked Professor Baker to investigate the conditions under which errors with a card from this source could be minimised and Baker subsequently wrote to Lucas, that the damping of the card about its horizontal axes in the liquid should be as small as possible. This meant that a flat card was wrong and a better one for minimum damping would be a short vertical cylinder, concentric with the pivot, so that any movement of the card about a horizontal axis through the pivot was edgewise through the liquid.

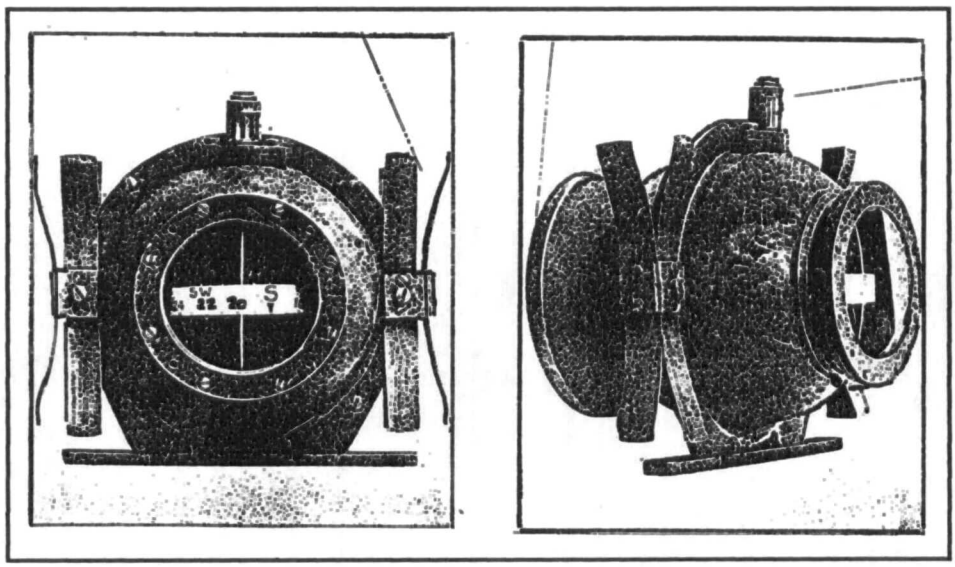


Fig 4.5. Lucas Experimental Spherical Compass 1915 - RAF Mark I.
The window was placed on the side of the sphere and the card had to be read on the outer face, which was not convenient. The leaf springs can be clearly seen.

Lucas placed the window on the side of his prototype spherical compass (Fig 4.5) to read the lettering and divisions on the *outer* face of the short cylindrical card. This meant that the pilot was reading the point of the card nearest to him, instead of the point furthest away from him as on a disc card. Therefore, when he was flying south, the letter **SW** on the card was to his left. To avoid this confusing reversal he moved the window higher

allowing the divisions to be printed on the *inner* surface of the cylindrical card, so that the pilot read the card in the normal way (Fig 4.6).

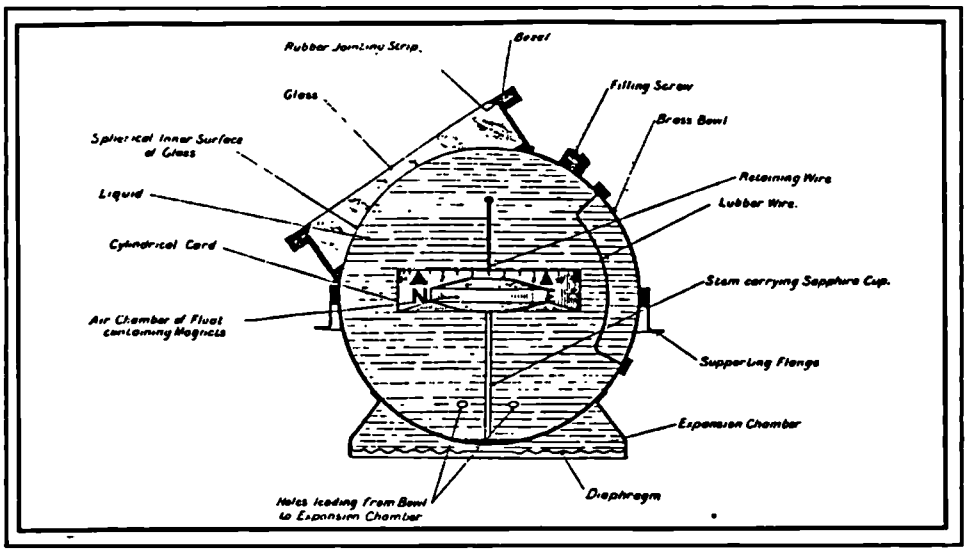


Fig 4.6. Cross section through second version of Lucas spherical compass.
The window is in the new position so inner edge of card can be read. The expansion chamber is in the base, but there is no air trap to collect bubbles at the top of the bowl.

The basic design of the compass card and bowl was now complete, but it still needed to be mounted in a case, which would also house the compensating magnets. The benefit of the

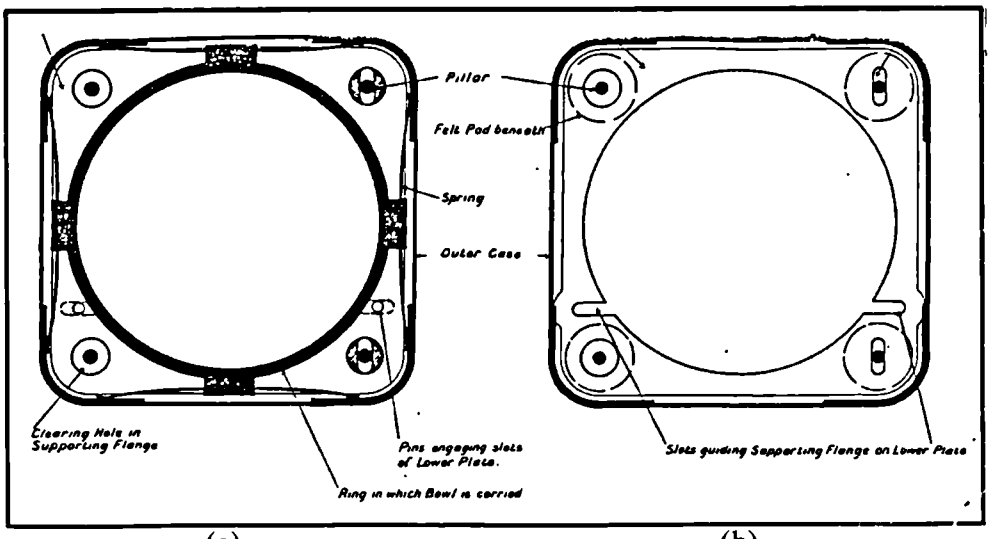


Fig 4.7. Anti-vibration mounts for spherical compass.
Section (a) shows the compass support flange, which has four leaf springs to keep the bowl central and is allowed to move laterally by two pins which engage in the plate (b) below. The brass plate (b) rests on four felt washers and is constrained to move fore and aft by the elongated slots on the right hand pillars. he compass can therefore move laterally or fore and aft, but not in a closed path.

leaf-spring anti-vibration mounting had been shown in the early compass test flights and needed to be incorporated in the new compass. This was achieved with four leaf springs, with an arrangement of pins and slots which allowed the bowl to oscillate laterally or fore and aft, but not in a closed path. Friction between the sliding parts of the mounting was sufficient to damp out any resonant oscillation that might develop. The final design became the Royal Aircraft Factory (RAF) Pilots Compass Mark II (Fig 4.8).

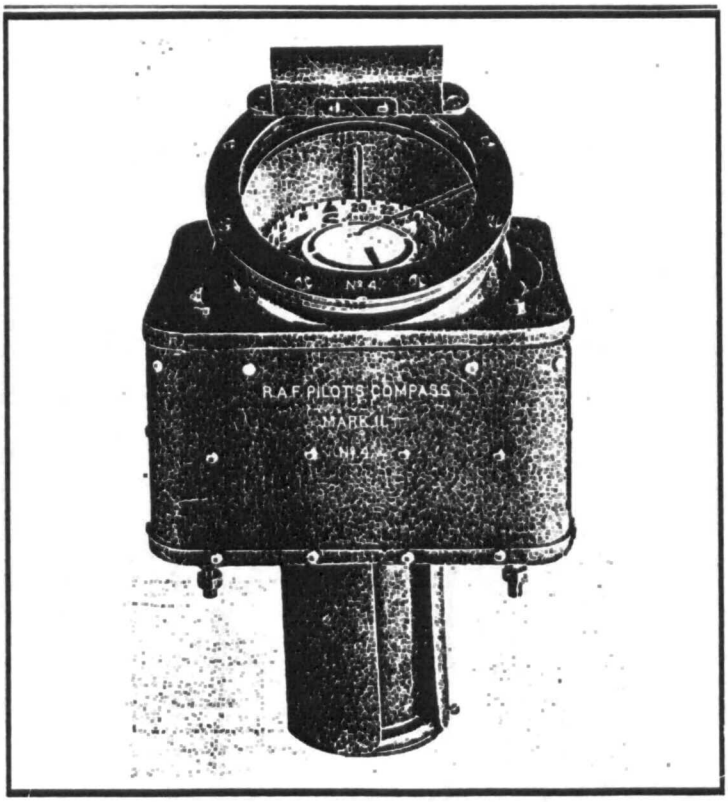


Fig 4.8. RAF Pilots Compass Mark II.

Showing assembly of spherical bowl in square support flange with cylinder beneath containing compensating magnets.

This compass proved to be the first instrument developed during the war to make cloud and night flying practical with training, but although standard for the RFC, we shall see that the Admiralty developed its own compass. Later, demand developed for a smaller version of the compass in which the diameter of the bowl was reduced from 4.38 to 3.5 inches and the weight from 4.75 to 2.25 pounds.[20] Flight test showed its the northerly turning error was nearly as good as the original compass, but its smaller card was more difficult to read accurately. A convex window was fitted to magnify the card, but was abandoned as this increased the sky reflection and made reading more difficult.

After the compass work, Lucas went on to measure aeroplane stability and examine the need for gyroscopic bomb sights (Chapter 8). Regrettably, Lucas was killed on 5 October 1916 in a mid air collision, when learning to fly at Upavon.

4.3.5. Lindemann and Northerly Turning Error

Lindemann, who was learning to fly at the same time, took over Lucas's work and published his own approach to northerly turning error.[21] He saw the errors that Lucas had called tilting error and acceleration error as being complementary and not additive. His explanation involved a detailed analysis of complex equations of motion, but only the results of his analysis will be given here. The equations of motion were developed by David Pinsent, a Trinity College mathematician, who had recently arrived at Farnborough.

Lindemann explained that a magnet freely suspended at its centre of gravity will align itself in the dip angle of the earth's magnetic lines. The magnetic meridian is defined by the plane through the magnet and its plumb and a small weight is added to the south side of the magnet to balance the vertical component of the earth's magnetic field and keep the card horizontal. This means that *a compass uses both the earth's magnetic and gravitational lines to define the magnetic meridian.* He saw the easiest way to explain the error was to separate the magnet and its balance weight and consider how the magnetic, gravitational and acceleration forces acted on each, that is,

1. Gravity on the pivoted magnet.
2. Centrifugal force on the pivoted magnet.
3. Gravity on the unbalanced mass on its south side.
4. Centrifugal force on the unbalanced mass on its south side.
5. The earth's horizontal magnetic field.
6. The earth's vertical magnetic field.

Any movement of the card can only be caused by forces which produce a couple about the axis of the card. In the list above, forces 1 an 2 on the pivoted magnet produce no couple about its axis, while forces 3 and 6 balance out. However, the centrifugal force on the unbalanced mass of the south side (force 4) and the horizontal magnetic field (force 5) will produce a couple about the axis of the card. The centrifugal force 4 would be constant during a steady turn off north, but the restoring force due to the horizontal magnetic field would start at zero with the card pointing north, and increase as the card was carried round east or west.

This also showed the error depended more on the speed of the aeroplane, than on the angle of bank. Lindemann found the critical period in England was 26 seconds for 67 mph, if it were not for the rotation of the liquid in the compass, but as the liquid appeared to rotate at

75% of the rate at which the aeroplane was turning, the critical period was 35 seconds. When the speed increased to 135 mph, the critical period increased to 50 seconds. He confirmed this with fight tests in a BE-2c with three compasses, using the sun as reference. The RAF Mk II, with a 54 sec period, was satisfactory, while the early CO 200 and latest CO 259, with a 36 and 24 second period respectively, indicated a turn in the opposite direction to that of the aeroplane. (Although the Admiralty referred to their compasses by the pattern number, the compasses were engraved with the patentee's initials C.O.)

All this involved flight test work. Both Lindemann's pilot log book and the Farnborough Flight Log record that he made nearly forty flights in connection with compass work between late November 1916 and mid January 1917, with Lieutenant Renwick as observer. The flights varied in length, but averaged around 45 minutes and two were curtailed with engine failure and one with severe engine vibration caused by a leaky carburetter.

4.4. The Admiralty Aircraft Compass : Creagh-Osborne's Account

In February 1916, F.W.Lanchester of the Advisory Committee for Aeronautics, wrote to Rayleigh to forcibly draw his attention to the **flagrant case of piracy on the part of the Admiralty, concerning the compass work of Darwin and Lucas.**[22] He felt strongly that the absence of publicity under wartime conditions must not allow others to attach their name to things, to which no credit is due them. Lanchester's statements are in sharp contrast to the straight forward accounts of the Admiralty aircraft compass given by Fanning, Bastin and Dunnicliffe, which are limited to Admiralty records.[23] However, a different history emerges if the development is examined in documents from Air Board, Department of Industrial and Scientific Research (DSIR) and Treasury Files. These files include Creagh-Osborne's own account of his work, his relationship with Farnborough, and the commercial problems faced by Hughes & Sons in supplying Admiralty compasses. This section will examine Creagh-Osborne's own account, which was written for the Advisory Committee of Aeronautics at the time when the Admiralty Compass Department was at 47, Victoria Street, and consisted of the Superintendent Captain Creagh-Osborne, the Assistant Superintendent, Commander S.B.Norfolk, a naval assistant and a clerk.[24] He divided the development of the aircraft compass into two periods; from 1909 to Lucas's work in September 1914, and from then until March 1916. The controversy which subsequently developed is the subject of the next chapter.

He confirmed his interest to air compasses had been drawn initially on seeing the compass in Cody's first machine revolving rapidly directly the engine was started. A few experiments, however, with a liquid compass damped in a box of cotton waste, enabled a

considerable improvement to be made and, during a flight in September 1909, only slight oscillation was noted. Early machines were mainly fitted with compasses according to the individual tastes of the pilot, which were generally placed in impossible positions from the magnetic point of view and he had provided some installation guidelines.[25]

The Pattern 200 was the first attempt to standardise a compass for an aircraft, vibration was damped by placing the bowl on a bed of horse hair and the card was allowed a 20° heel. From his personal experience, this was a fairly efficient instrument for the machine of the day and was standard for service machines until the beginning of the war. The machines were relatively slow and turns were negotiated carefully in large circles without banking. When initial compass contracts were completed, the opportunity was taken to make some improvements. The Pattern 250 allowed the heel to increase to 30° as gimbals were not provided, the Pattern 251 added the inverted pivot suggested by Horace Darwin to reduce vibration error, and the Pattern 252 added improved lighting. Although the inverted pivot had been tried in the naval compass, it had not been adopted because sediment settled in the cup. However, this was no problem with aircraft compasses, where the service life of the compass was short and vibration kept the card lively. He would also have improved the vibration mounting if he had been aware of Dr. Lucas experiments.

After the war started there was an enormous increase in speed and performance of machines and the need for a more reliable compass was soon recognised. Beyond vague rumours of cloud errors he had no time to keep in touch with development until Dr. Lucas's Report, T-505 in September 1915 brought to his notice that serious new errors had been found. These errors were claimed to be eliminated in the RAF spherical compass, a few of which he was asked to make for test in both wings of the Air Service. On the occasion of a visit to the RAF, he had the opportunity to observe the effect in a heavily banked turn on the old pattern compass. He understood from the Superintendent of the Royal Aircraft Factory (SRAF) and Dr. Lucas that an independent attempt to solve the problems would be welcome, and that an amalgamation of desirable features of the RAF and his own instrument would be a public service. With this objective, results of future experiments would be exchanged. He attached extracts from letters he later sent to Farnborough to provide the Advisory Committee with a history of the Pattern 255 compass, which **as regards features of bowl and card was simply a modernised Reynold's yacht compass with a new directive system to suit aircraft** and he provided a drawing of the Reynold's yacht (Fig 4.9) to show the similarity. The importance of this view will be very apparent in the events which followed.

Extracts from Letter to Dr. Lucas, 29 September 1915

> Congratulations on your work. It is unfortunate that we work in watertight compartments as your time has been used in threshing out points which we (ACD) could have settled in five minutes, although we are quite without your opportunities for experiment at Farnborough. For example, the advantages and disadvantages of inverted pivots, baffled plates, horizontal or vertical card readings and use of more than one magnet have been threshed out years ago and the relic of the 19th Century compass you saw at Deptford had an inverted pivot and spherical bowl.
> The question is how to make up for lost time without delaying deliveries. Makers will not be able to provide a new type of compass, but I think it is a simple matter to improve steadiness with side springs as you suggest. The reduction of the directive force of the needle can be easily arranged also, but I think that we should try to avoid doing this, as low directive force leads to other troubles as shown by nautical experience. I will let you have the results of the three compasses Hughes are making up. The period will be 25-30 seconds.

He also included page 12 from 'Magnetic Compasses in Aircraft', which was to be supplied with every compass. He proposed to insert words to the effect that,

> It is advisable to call attention to the results of exhaustive trials carried out by Dr. Lucas at Farnborough, which indicate present compasses may be a source of danger under certain circumstances, when anything but moderate banking is indulged in. When steering off north, the north point of the compass will follow the head of the machine round until steady on a new course when it will return to the correct position. This is not a serious matter when landmarks are available, but may be vital in darkness or cloud, when it is quite possible for the pilot to be rapidly turning without being aware of it.

Creagh-Osborne found that it was possible to introduce the side springs, designed by Lucas, into Pattern 250-252 compasses as they were manufactured or came in for repair. Farnborough ground tested these for him on 12 October 1915. The vibration error at 1500 rpm was 5°, an improvement on the results with horse hair damping.

Extracts from Letter to Dr. Lucas, October 1915

> I have used for experiment at Chingford, the ordinary 250 bowl and the spherical ones, which Hughes had in stock. The best results are obtained with a 35 second period. The spherical bowl and sliding anti-vibration mounts are a step in the right direction.
> A good place for the compass on a BE 2c would be in a streamline case on the first strut, where vibrations are slight, no compensation is required and it can be made easily visible.
> Thank the SRAF for the drawings, but I will not have any made up until my present experiments are completed.

The spherical bowls that Hughes stocked were for Reynold's yacht compasses. Creagh-Osborne said that he received no acknowledgements from Farnborough of his letters.

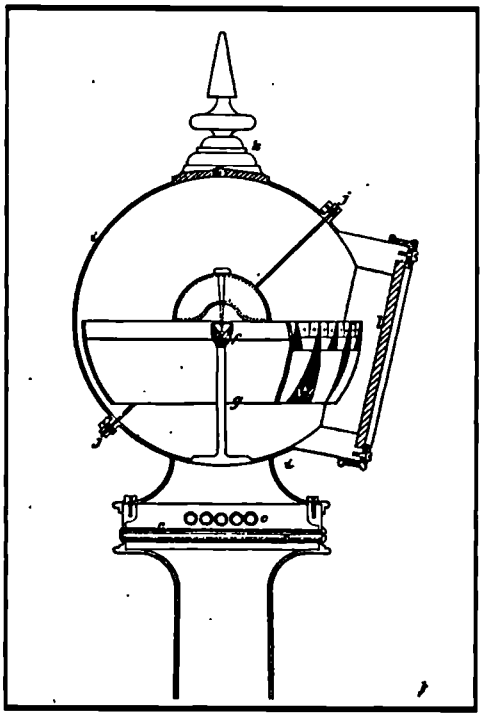


Fig 4.9 Reynold's Yacht Compass.
Similarity with the RAF Mk II compass is evident. It also had a better float and the window could be mounted above or below the centre line.

Extracts from letter to SRAF, 23 November 1915

Have forwarded your sketches to Messrs Heath, and I would advise that you keep in touch with them directly.

Tell Dr. Lucas, the compass that I have made up showed no movement of card when running the engine of a BE 2c on the ground from 480-1,800 rpm, and an air test is planned. Compass is quite visible on rear strut.

After much toil on and off terra firma, I have completed my design of aero compass and Hughes are making six for each Service. Delay has been due to trying various needle systems and periods. The results from air tests (Two pilots with Finch-Dawson and myself) show the period needs to be over 30 seconds and 40 seconds seems ideal. Longer period introduces objectionable features. A system of eight small magnets found beneficial.

Providing the machine is flying straight and steady and not yawing before changing course, the turn is indicated exactly. (Attached tests results dated 22 November 1915 showed that card held up for 5 seconds after turning 60° if machine was not steady at start of turn.)

I think your card is too light. A floated weight of 2-3 grammes avoids *pumping*. Have tested a bowl with two windows, so that observer can see compass on wing strut as well as pilot, where he is in front of pilot on BE 2c.

Compass adjustment arrangements are within casing and use as many $1^1/_2$ needles as necessary.

Have shaken up Heath at Crayford about your six compasses; advisable that you contact them as well to keep them on the mark. I have personally driven Hughes, including sending young Hughes up to observe results.

He said the directive system used a card with eight diamond shaped needles, which Lamont (1851) and Starling (1916) amongst others considered an effective shape.

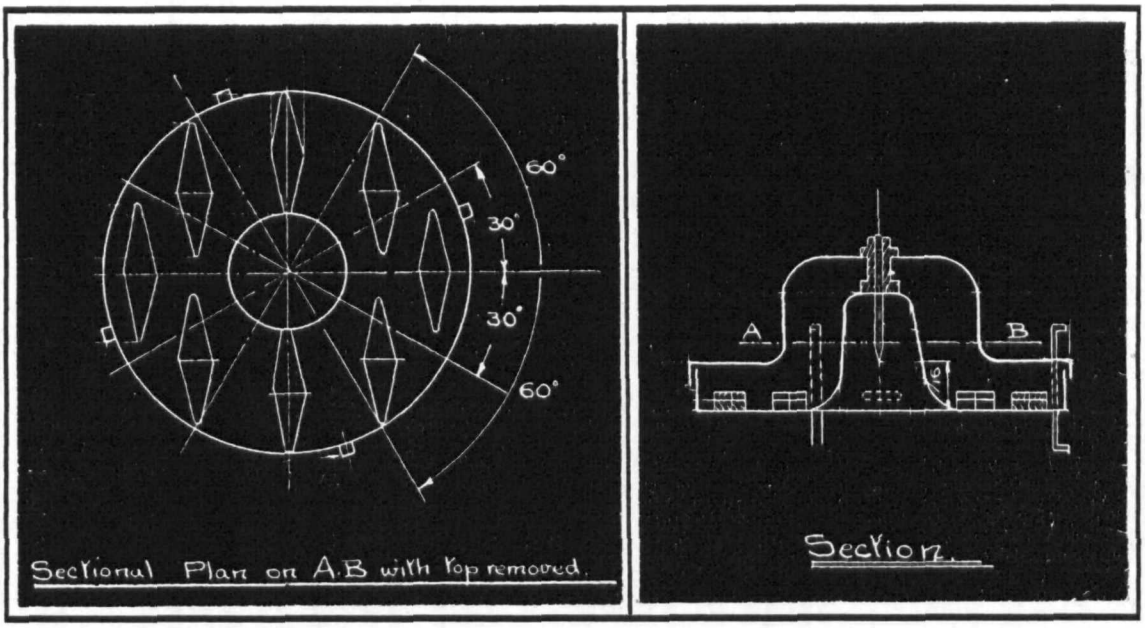


Fig 4.10 Compass card with 8 needles and low centre of gravity used in Pattern 255.

This arrangement gave magnetic stability, systematic distribution of mass, better retention of magnetism and allowed the relationship between magnetic moment and moment of inertia to be varied, which he had made large. The features of the card were,

Period in air	27.8 secs	Weight in air	36 gms
Period in liquid	45.0 secs	Weight in liquid	2-3 gms
Moment of inertia	187 cgs	Magnetic moment	51.4 cgs

He explained that this card system, with iridium pivot and sapphire cup, was eventually used in the Pattern 255, although he was also testing the float from the Pattern 200, which had six needles, three on each side arranged vertically above each other. He was not aware at this time that the RAF had discarded the vertical window, until he saw report T-634. From the seaman's point of view, he agreed with the objection to reading the card in an unaccustomed way, but it had the advantage that it could be clearly read and RNAS pilots had quickly got used to it and expressed no objection. The Pattern 255 had two vertical windows, one for the pilot and one for the observer, which used flat triplex instead of plano-concave glass (Fig 4.11). Compensation was provided by soft iron correctors fitted in four tubes inside the supporting ring, although this left a certain amount of quadrangle error. The base plate was fitted to the support ring and could be moved round to the sides or top to provide universal mounting. Two flat chambers in the spherical bowls

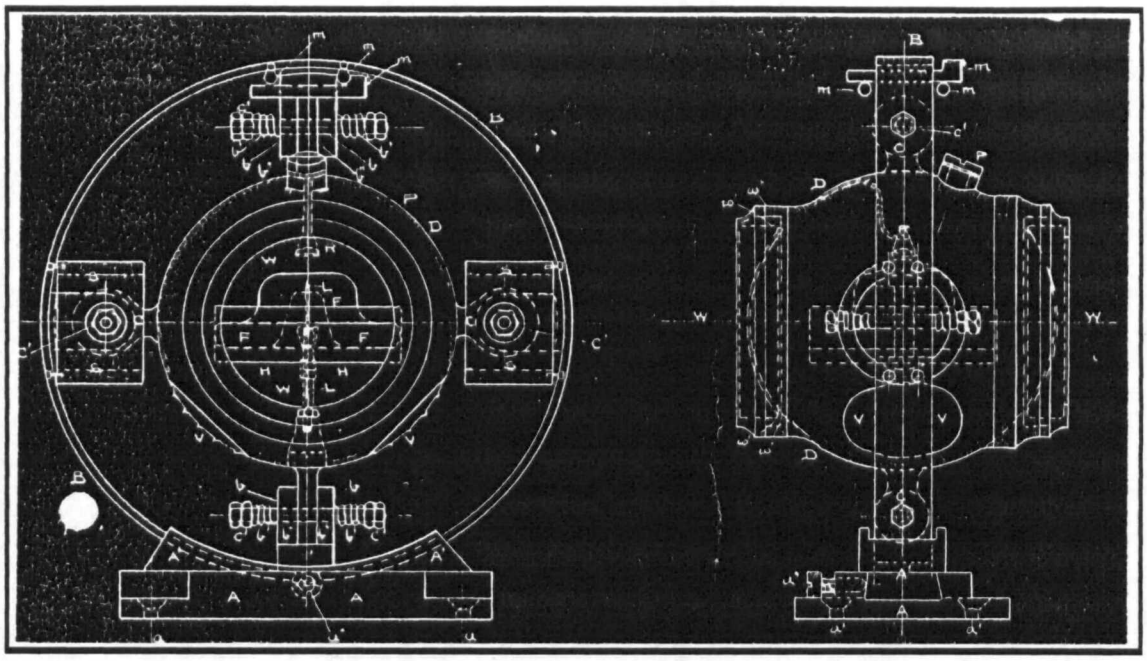


Fig 4.11 Pattern 255 Admiralty Aircraft Compass.
The similarities with the Reynold's yacht compass and RAF Mk II compass which led to the controversy on its origin are evident.

allowed liquid expansion. He gave these details to Farnborough in his next letter.

Extracts from letter to SRAF, 6 December 1915

> Enclosed print of aero compass, which I have evolved with view to getting over the troubles to which Dr. Lucas drew attention in his report. I have kept him fully informed of my experiments as promised.
> It will be obvious that I have proceeded on quite different line as regards damping vibrations, adjustment and general design to the RAF instrument, the 'compass' itself more or less follows the general features of the instrument, which are however by no means novel, as a visit to the Museum at Deptford will show. The compass follows the general principles laid down by Lord Kelvin, especially as regards the large moment of inertia to magnetic moment, and uses eight small needles as frequently tried in the past and now used by the German Merchant Service. I have tested various arrangements, but have not been able to improve on this. The spherical bowl is not strictly essential, providing there is plenty of space above and below the card and is used principally in the 255 for convenience of manufacture.
> I quite agree with your remarks at our interview in September as regards keeping the type confidential as long as possible, but I had not considered the question of protecting the design in any way until I received notice re secret patent of RAF instrument, as far as I am concerned I have left the matter as regards the Pattern 255 in the hands of the Admiralty. Neither 'compass' is in my opinion, in any single feature or in all combined, capable of protection. On the other hand, both system of anti-vibration mounts are, as is my system of adjustment. The anti-vibration fitting is Mr A Hughes design, but he has placed the protection or not of it with the Admiralty.
> I trust that I have made myself quite clear, and there is no doubt that what ever type is finally selected, a great advance will have been made as a result of Dr. Lucas's tests.

He also enclose his latest 'Magnetic Compasses in Aircraft', amended as desired in the September interview. He thought it unlikely now that it would be reprinted as it was not

proposed to supply it with compasses any more and the gist was being included in a book on Aerial Navigation for the RNAS.

Extracts from letter to SRAF, 18 December 1915

> The first six Pattern 255 were delivered on Wednesday evening and sent to MA2. Three others are being fitted to RNAS machines and the remaining six are promised next week and presume you will get one, unless one from the first six has already been sent to you. Regarding secret patents, Admiralty have decided not to patent the 255 and under usual restrictions as regards government orders, Messrs Hughes and I will take out a provisional protection for it as this will keep it under Government control when authorising supply to Allies.

He also enclosed sketches of Pattern 257, which was a 255 with a flat glass at the top as with conventional compasses. Other patterns followed quickly over the next few weeks. The 256 was a large version of the 255 for flying boats, but had one window. The 259 was a small version of the same design for land planes, which became the more popular design and some 55,000 were made.

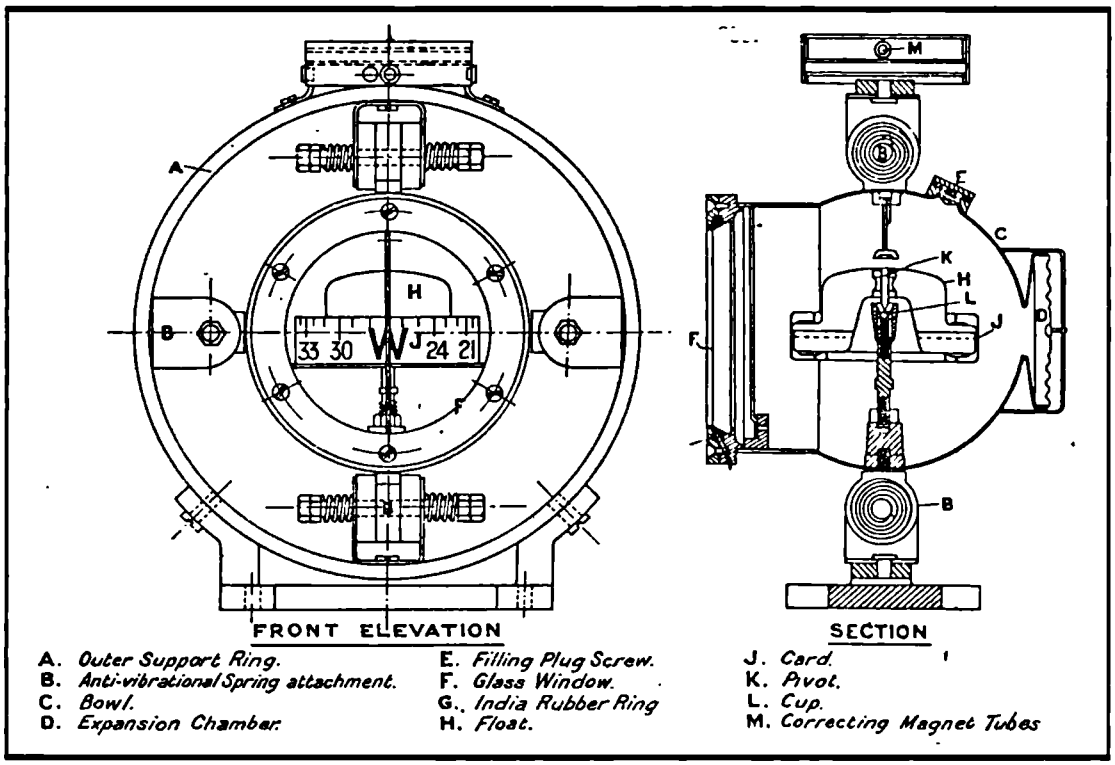


Fig 4.12. Pattern CO 259 Admiralty Aircraft Compass made by Hughes.

For the information of the Advisory Committee, he attached a copy of a paper by S.G.Starling of West Ham Municipal Institute, a consultant retained by Hughes, which examined the deviation of the card for varying angles of tilt, but did not consider the asymmetrical centre of gravity of the magnetic needle.[26]

However, subsequent operational experience with the Pattern 255 to 259 over the next few months changed Creagh-Osborne's attitude to the long period of the card. He wrote to all RNAS stations in August 1916 that the aircraft compass should,

> (1) have good directive power.
> (2) be easy to read day and night.
> (3) be steady under vibration.
> (4) be easy to manufacture economically in large quantities.
> (5) be installed in a good magnetic position in the aircraft.[27]

He explained that the flat nautical compass Pattern 200 proved unsuitable as it had a 40-50° vibrational error, a northerly turning error and its awkward shape made it unsuitable for the aircraft instrument board. These problems had been mitigated in the RAF Mk II and Patterns 255-259 by giving them a slow period of swing, but the weak magnetic moment made them sluggish and more susceptible to damage as the effect of pivot friction was more pronounced. He *now considered that the problem of northerly turning error was remote* and short period versions were now being introduced, although production problems meant that there were still some long period compasses in service.

Conclusions

The compass gradually assumed importance as the duration and distance travelled by aeroplanes increased. Pre-war development was mainly trial and error, with little flight test experimentation. Vibration was the main problem, one pilot ironically commenting that,

> Life is at its darkest hour when the compass shows signs of settling down and at last gives more or less a steady reading.[28]

when his engine had failed. Darwin's suggestion to reverse the cup and pivot was the single most important modification to improve the behaviour of the compass under conditions of severe vibration. As the aerodynamic performance of machines increased, the resulting acceleration forces produced compass effects that had not been apparent on slower machines. The effects were pronounced when pilots attempted to use the compass to navigate through cloud, when the pilot's loss of orientation led to apparent incredulous reports of compass behaviour. The effects were present in normal flying, but with the visible horizon to provide a level reference, the pilot was no longer concentrating on his compass. The work of Lucas explained these effects, particularly the northerly turning error, and produced a compass that would correctly indicate the direction of turn to enable a trained pilot to fly through cloud. His work quickly made others appreciate the advantages of developing aircraft instrumentation on a scientific basis. It was no longer sufficient to try a pad of horse hair to improve performance, instead, observed facts were replicated and analysed to identify each factor, and only when they were identified was a new instrument

designed. In six months, Lucas produced a new compass which was used by the RFC throughout the war. There was nothing remarkable in the way he examined compass behaviour, the significant fact was that he flew to observe the effects for himself. To him this work was just a problem requiring an instrument solution, no different to his pre-war physiology experiments. His simplistic approach to experiment illustrated that an experienced research scientist could quickly analyse a problem and develop a solution in an unfamiliar field and undoubtedly went some way towards the scientific method that Haldane had envisaged in 1909. However, it was still based on short tables of discrete experimental flight test observations. Lindemann provided a mathematical explanation of the effects, but the complex behaviour of the aircraft compass would not be reproduced in the laboratory until after the war. Farnborough felt the long period compass met the immediate needs of any service pilot, but had not considered that the most of them simply required a responsive compass for routine navigation. The Admiralty Compass Department appreciated this need and moved to a short period compass, retaining some features of the Lucas compass but attributing them to an earlier yacht compass. The controversy this caused and developments which resolved it are examined in the next chapter.

Chapter 5.

The Aircraft Compass - Part 2
Development from 1916 to 1920

Summary : The situation in 1916 - controversy between the Admiralty and Farnborough - the development of the Pattern 5/17 compass - Hughes claim to the Royal Commission for Awards to Inventors - the development of the Pattern 6/18 aperiodic compass - Flight tests with long, short and aperiodic compasses - compass research at Air Ministry Laboratory by Capon, Lee and Rowe under Wimperis - the problems solved - conclusions.

It is worthwhile pausing to consider why the Admiralty was developing exclusively short period compasses, while Farnborough still encouraged the RAF Mk II long period.

5.1. Summary of aircraft compass situation 1916.

Creagh-Osborne had been involved with aircraft compasses from 1909, but had not really appreciated the vibration and acceleration errors until reading Lucas's report in 1915, which he constantly acknowledged as a significant contribution to the development of the air compass after his initial scepticism was disproved by a flight at Farnborough. From his own compass design experience he immediately appreciated that Lucas's spherical compass would overcome the problems, although part of Lucas's effort had been to establish design practice that was well known by the Admiralty. He also offered to consider the design problems himself and to get some Lucas compasses made by Messrs Heath, who were not at that time involved with air compasses. Creagh-Osborne himself was working in close collaboration with Messrs Hughes, who were making his Pattern 250 type and who showed him that the Reynold's yacht compass they stocked had very similar features to the Lucas spherical compass. Hughes were also able to introduce Lucas's spring mounting to the Pattern 250 type in production, while suggesting alternative anti-vibration, air trap and compass adjustment features for the new Creagh-Osborne compass. Hughes also suggested the use to Creagh Osborne of radium compound paint on certain bearings to make it clearer to read at night, and managed to incorporate this after considerable experiment with protective paint and varnish.

This new compass was simpler than the Lucas compass and would cost less to manufacture. So although Creagh-Osborne needed to acknowledge Lucas's seminal work

on air compass errors, he did not need to acknowledge Lucas's spherical compass design, as this had been anticipated in the Reynold's yacht compass. In fact, he did not believe that the new compass Pattern 255 was patentable, but provisionally protected the design and new features as standard practice. He kept Farnborough informed of his work, but they did not reciprocate, probably because they already felt he had plagiarised Lucas's ideas and patented them himself and was broadcasting his own views by including a copy of 'The Magnetic Compass in Aircraft' with every compass dispatched by Hughes.

At this time, he believed that the northerly turning error was important and that the long period compass was the solution. But in early RNAS service reports on the new Pattern 255 the sluggishness of the new compass was severely criticised by pilots using it for normal navigation, while their need to use its northerly turning feature for cloud flying hardly occurred, even if they understood it. Later, he continually referred to northerly turning error in *heavily banked turns*, ignoring that the effect was present in gentle turns and it was gentle turns in cloud that made cloud flying impossible, not heavily banked turns when the horizon was visible. Most military flying at this time was usually of relatively short duration and distance,and navigation was by landmark and compass, for which a quick responsive compass was better. Military flying in low visibility was avoided, because of the danger of hitting objects on the ground. However, military pilots needed to be able to fly through a cloud for a short period of time when they had to, without spinning out of control, which would usually be fatal to inexperienced pilots and leave few to explain to others the difficulties they had experienced. Cloud flying was only possible by pilots trained to use a RAF Mk II long period compass, but the occasions on which they needed to do it at this time were limited, and even then it was not easy. The machine had to be kept straight and any small tendency to turn corrected by the *rudder without banking*, but once control was lost it was impossible to recovery orientation within the cloud. The problem was compounded by the gyroscopic torque on machines with single rotary engines. The Navy were involved with two kinds of flying, that of RNAS squadrons supporting the RFC in France using similar machines and in similar conditions, and long distance sea patrols in large multi-engined flying boats. The latter flew in low visibility for long periods, but as they could do this at wave top height with the sea providing the horizon plane, a quick responsive compass for navigation only was required.

It was the this difference between the small but vital requirement for cloud flying and the more general routine navigation requirements that contributed to the different views. In hindsight, it may have helped if the MK II compass had been called a turn indicator rather than a compass.

5.2. Aircraft Compass Design - Farnborough versus Admiralty

Farnborough did not agree with the Admiralty Compass Department, that the short period compass was a better design. They still saw that a long period compass was needed for cloud flying and their views can be followed in an Air Board file on the subject.[1]

The new CO 259 short period compass by Hughes was introduced into service towards the end of 1916. When Farnborough received one in early 1917 they compared its operation to the Lucas RAF Mk II compass, particularly its northerly turning characteristic and flight experiments showed that the CO 259 had a severe northerly turning error, indicating a turn in the wrong direction. In one experiment, with the observer continually reading the CO 259 and directing the pilot by signals, the aircraft turned through 720°, while the observer saw the card steadily pointing north. The report stressed that the problem only existed when the horizon could not be seen, as normally the military pilot would only glance at the compass and steer by the ground or the sun. The northerly turning error was stated to be due entirely to the unbalanced weight fitted to the south pole of all single pivoted compasses, as Lindemann had reported. For the same reason the CO 259 also showed more acceleration error than the Mk II when the speed of the machine was increased or decreased while flying east or west. It also suffered from vibration and had a 15° error compared to the 2° error of the Mk II. However, it had two distinct advantages, the period was short and it settled down more quickly than the Mk II after a turn, and it weighed only 2 pounds compared with 5 pounds for the Mk II, which was equivalent to 5 minutes of petrol.

Farnborough issued report H-531 on their findings, circulating it in the usual way to all interested parties, including a copy to Creagh-Osborne.[2] Creagh-Osborne, incensed by the adverse comments on his compass design and the method by which they were publicised, asked Norfolk to analyse the report. Norfolk's analysis showed he did not appreciate the difference between brief duration military cloud flying and long duration sea patrol navigation. He said that the RAF report was directed solely at northerly turning error, so that experiments were biased in favour of the RAF compass with little mentioned of the benefits of the 259. The 259 originally did have a long period to indicate a turn off north, but it was so sluggish for normal navigation that the period had been reduced. Norfolk felt that the method of navigation of the RFC was dangerous, and it was not surprising that they got lost or killed when they got into trouble in poor visibility. Steering by the sun was *ludicrous*, as the sun could change direction by 1° in 4 minutes at some times of the year. Pilots should be taught to habitually steer by the compass, only using landmarks to assess drift. Norfolk said that *it was possible to hold a northerly course with*

a 259, (which of course was true if you could see the horizon). He also commented on the curious way the report said the turns were indicated by the card, when in fact the card was steady and it was the bowl that moved. Finally, he disagreed that *the Pattern 259 copied the RAF Mk II fairly closely.* They were designed independently and the spherical bowl had been patented by Reynold in his yacht compass of 1874. He stated that **it was not a fact that the modern compass had a weight fixed to the south pole**, but that the vertical component was overcome by the method of suspending the needles. Any theory evolved from this fact was therefore erroneous.

This said Lindemann was wrong, as this was part of his explanation of northerly turning error. Norfolk offered no further detail, probably because he thought it so obvious it did not need any, while Farnborough believed the statement was inconsistent with the elementary laws of physics. However, what Norfolk said was true, as the Pattern 259 card **had no weight on the south side.** Instead, it had a low centre of gravity with the magnets placed below the pivot. The vertical component of the earth's magnetic field still produced a couple to tilt the card, but as it tilted, the centre of gravity of the card moved away from the vertical centre line of the pivot, until it balanced the magnetic couple. The tilt was about 3° and not noticeable. The Admiralty had established this practice with their compass cards to avoid having to re-balance the card as the angle of magnetic dip changed on long voyages. The practice is now common on aircraft compasses, but the RAF Mk II card had a high centre of gravity. Without a balance weight, it would tilt until it aligned with the angle of dip, when the couple due to the vertical component was zero. A great deal of subsequent misunderstanding at the time would have been prevented, if this fact had been stated clearly.

Creagh-Osborne wrote on 2 February 1917 to an independent expert, Captain E.W.Creak, considered to be the greatest living expert on compasses, asking his opinion of the relative merits of two compasses of similar design, the first with extremely low directive force, a period of 50-65 seconds and light on pivot, the second with normal directive force, a period of 20 seconds and heavier on pivot. Creak replied that, based on his own experience over several years and also on American, Italian and German naval practice, the second compass with the strong directive force was the better. This was true, as Creak assumed his opinion was being sought on normal marine navigation.

Creagh-Osborne then wrote on 6 February 1917 to the 5th Sea Lord, with a copy to the Director of Military Aeronautics (DMA), General Henderson, attaching copies of Farnborough Report H-531, Norfolk's comments and Creak's reply. He sought support from them, that carrying out the tests and the compilation and circulation of the report without reference to himself first, *was not conducive to war efficiency, and lacked the*

courtesy which would have occurred if control had been in the hands of brother officers in the sister service. He drew attention with 'unconscious humour that the 259 copied the Mk II fairly closely' and that a 'single pivoted compass had a weight on the south pole'. He said the question to be answered was whether a compass was required to register a heavily banked turn off north or for general navigation. If the first purpose was required, then the 259 can be given a long period; if the second was required, then the Mk II can be given a short period. He submitted that the Director of Military Aeronautics should be directed to recall all copies of the misleading report.

Creagh-Osborne also sent a copy of the letter to the new Superintendent of the Royal Aircraft Factory (SRAF) and followed it three days later with a remarkably impersonal letter addressed *My Dear Sir*, explaining that he,

> was not making an personal attack on the SRAF (I do not even know his name at present), who probably knows nothing whatever about the matter, but the branch of the RAF which issued the report and circulated it in the manner objected to. I trust you will excuse me writing directly, but now that my department is to take over the compass work, I consider you should be fully cognisant of the matter. When official confirmation of the above is received I will come down and see you.

Sir Henry Fowler, the new SRAF, who had recently taken over from O'Gorman, replied briefly the same day,

> I have not yet received instructions with regard to the compass work being handed over to your department, and when this is received I will make the necessary steps and there will be no need to trouble to come down here.

Fowler also wrote to the DMA*, General Henderson, on 19 February 1917 to explain that, as most of the experts on the controversial question had preconceived ideas, he thought it would not be possible to obtain an independent report. He regretted that the Superintendent of the Compass Department had taken such exception to report H-531, which was a simple statement of the fact obtained from the same experiments on both compasses, and gave Farnborough's view of the statements of Creagh-Osborne and Norfolk.

Regarding Creagh Osborne, he said,

> 1. We cannot accept statements with reference to aeroplane compasses from the Superintendent of the Compass Department simply upon his authority. He seems never to have understood the difference between a fast moving aeroplane and a slow moving airship. On 11 March 1915, Creagh-Osborne had written to the SRAF saying he was unacquainted with the northerly turning error and was only convinced by actual demonstration at the RAF on 21 September 1915. Further, the statement that the vertical magnetic component in the single pivoted compass is not balanced by a weight on the south pole is clearly wrong in aircraft compasses. It was also unfortunate when asking Captain Creak's opinion, he had not mentioned the compasses were for use on aircraft.
>
> 2. We would prefer not to discuss whether Captain Creagh-Osborne copied the Mk II when designing his own patented compass, since it does not affect the present controversy on which compass is the best for the RFC.

*. Director of Military Aeronautics

3. We feel H-531 should not be withdrawn as the facts should be made known and for this reason the theory of the northerly turning error is set forth in the Advisory Committee for Aeronautics Report T-902 by Dr Lindemann. We strongly recommend that the tests be repeated at Orfordness or Martlesham, that the true facts are widely circulated to the RFC as the mistrust of compasses engrained in a large number of pilots is caused by error inherent in compasses such as the CO 259.

Comments on Commander Norfolk's remarks were added at the end in note form,

Observed facts cannot be accused of being a biased report. The northerly turning error applied to 5° bank as well as heavily banked turns.
Regarding Norfolk's exception to the remark that *the 259 copies the RAF Mk II fairly closely*, Creagh-Osborne himself stated in the same letter to the SRAF that *the compass itself follows the general features of the RAF Mk II.*
Regretted that Norfolk felt that the acceleration tests were not convincing and that the aircraft had probably deviated from its heading, but the acceleration tests were made by keeping the shadow of one strut on another. There was no deviation from heading.
Military pilots needed to look around them and not have their eyes glued to the compass. In fine weather, the course was checked by glancing at the compass ever few minutes and the apparent motion of the sun did not matter. In cloud or at night, the pilot must of cause steer entirely by is compass.
Norfolk asserted that on no modern compass is the vertical component of the earth's magnetic force neutralised by the unbalanced weight on the southern half of the card and claimed 'the method of suspension of the system of needles overcomes the effect of the vertical component'. This statement, which was clearly endorsed by the Superintendent of Compasses, was clearly inconsistent with the elementary principles of physics.

At this crucial moment in the history of the air compass, there is no further correspondence in the Air Board File, nor any indication that differences between the two departments were resolved officially. In 1917, Hughes and Creagh-Osborne designed a new Pattern 5/17 compass, so called because the patent application was May 1917. Creagh-Osborne's 'Magnetic Compasses in Aircraft' was still sent with each compass, supplemented with an 'Additional Note', dated 10 August 1917. This explained that *long sea patrols had shown northerly turning error was a bogey which, while its existence was known, need not effect the pilot*. He conceded that the short period Pattern 259 did have a vibration problem, but that this had been overcome in the improved Pattern 5/17 compass, which was being introduced. The 5/17 had a period of 12 seconds, was practically dead beat, had a light card which dispensed with the need for a float, and a 20° sloped window which allowed the compass to be placed below the pilot's eye level and the card read 'inside'. He accepted that the short period gave the card both a northerly turning error and an acceleration error, but though the northerly turning error could be ignored, while the acceleration error only meant that the suspended needle lagged behind the true vertical during acceleration to hang aft of the pivot. He suggested the pilot remember a simple guide line, *easterlyacceleration gives easterly deviation, westerly acceleration gives westerly deviation.*

This memo and additional notewere later published as the compass section of 'Aeroplane Instruments', dated 10 August 1917, by which time Creagh-Osborne was Director of

Compasses following the establishment of the Admiralty Compass Observatory at Ditton Park near Slough. Norfolk was Assistant Director and there were three sections, each under a superintendent, dealing with air compasses, marine magnetic and marine gyro compasses. The air compass section was responsible for the compass requirements of both the RNAS and RFC and with this combined responsibility, Creagh-Osborne decided to stop production of the RAF Mk II in favour of the 5/17. This decision would not have endeared him to Farnborough, but by this time they were experimenting with static and gyroscopic turn indicators for cloud flying. However after the war, resentment still showed when Dobson, still at the RAE, wrote to Lindemann asking *if he could get the Oxford member to ask the House whether Captain Creagh-Osborne drew a royalty from the Government amounting to some £200-300 p.a. for his aircraft compass.*[3]

5.3. Taylor, Starling, Pierron and Hughes on the aircraft compass.

The Admiralty was not alone in their views on short period aircraft compasses. G.I.Taylor was examining compass behaviour at the Testing Squadron in May 1917 and wrote to Lindemann suggesting that a short period compass was acceptable, as it more quickly returned to the correct heading after a northerly turn.[4] This was the same argument used by the Admiralty Compass Department, which was true providing the horizon was visible, but if it was being used to navigate through cloud its northerly turning error would aggravate any heading correction.

A similar discussion followed a lecture by Starling to the Optical Society at Imperial College in June 1917.[5] Starling had examined the equations of motion and the deviation of a static tilted compass and had proposed a mechanical arrangement to cancel the vertical component of the earth's field in a dynamic turn. The device consisted of a spring restrained mass, which detected centrifugal force in a turn and moved magnets to counteract the vertical component. Lindemann was one of the first to speak and gave his views on the uselessness of any compass which indicated the wrong direction of a turn for any angle of bank and said the problem to be solved was to maintain a straight course when the horizon was invisible. He thought Starling's device ingenious and had flown with it, but found random acceleration in normal flight continually adjusted the compass and this problem would exist with any mechanical correction actuated by gravity. He believed the solution to cloud flying lay in designing the magnetic moment and inertia of the compass card to provide a sufficiently long period, and *prompt course correction with the rudder*. He also commented that the liquid damping coefficient in the equations of motion was dependent on the compass used. With the 259, the liquid rotated as if it were fixed to the bowl. These views were endorsed by Major Grinstead, Lindemann's head at Farnborough, but he added

that a more responsive compass was required for sea plane work, where navigation was by dead reckoning and long straight legs had to be held accurately. Dr G.T.Bennett from Cambridge, who was working at the Admiralty Compass Department gave more comments on the equations of motion that Starling had used.

Captain Pierron gave some very relevant views as a pilot who had made some sixty flights between London and Paris, which included the Dover to Gris-Nez leg that was almost magnetic north and often made in bad weather. He had been using a compass with a very short period of 13-14 seconds (which meant it was a 5/17 made by Hughes), and on no occasion, while he was trying to hold a straight course, had it indicated a turn in the wrong direction, but *'he made course corrections by side slipping so that the earth's vertical magnetic component had little effect on his compass'*. Although theory said the long period card was better, he found the *'card never appeared to come to rest.'* His flying experience also included the Western Front and he confirmed that ninety-nine pilots out of a hundred never looked at their compass unless they were in trouble.

The comments of A.J.Hughes, *'as only a compass maker'*, were probably the most valuable. He said that Lord Kelvin had not been able to design a marine compass card with a period less than 24 seconds, but as this coincided with the period of roll of a ship, Kelvin recommended that the period of the card should be increased to 30 seconds. He thought that if Kelvin was alive today, he would have endorsed the quick period card which was now available with lighter and more powerful needles. The important aspect today was *'not the time for one swing of the card, but the time it took to come to rest.'* The long period card may be the solution to cloud flying, but the time it took to come to rest made it difficult to hold a long straight course for ordinary work in the air and a compass that came to rest quickly had a great advantage.

This discussion showed the advantages and disadvantages of both types of compass, and that there were ways to use the quicker response compass safely when the horizon was not visible. However, arguments on the merits of each continued for another year, and only ended when Dr. Bennett and Commander Campbell at the Admiralty Compass Department produced the Pattern 6/18 aperiodic compass. This had a long period, but came to rest without swinging - the feature Hughes advocated.

5.4. Earlier plagiarism at the ACD

The official history of the Admiralty Compass Observatory, condenses the development of the Admiralty aircraft compass as follows,

> At about the same time that Creagh-osborne designed the 259, the RAF at Farnborough designed a similar compass known as the RAF Mk II, which had a very slow period designed to counter the effects of northerly turning error, which had recently been identified by Dr. Lucas. The error occurs when the aircraft banks steeply. However, the Compass department and the Navy proposed to use a compass with a quick period, which although subject to northerly turning error, more rapidly took up the correct heading after the turn. The two schools of thought persisted until 1917, but many of the RFC pilots also came to prefer the short period instrument and eventually the RAF Mk II (Quick Period) was introduced.[6]

There is no hint of the previous controversy, but interestingly a similar incident which occurred around the same time is mentioned. This happened when Cmdr. G.B.Harrison and Dr. A.L.Rawlings at the Admiralty Compass Department patented a gyro-compass, which was based on similar work by S.G.Brown and J.B.Henderson with which they were acquainted, and which therefore disqualified them from making any claim for originality themselves. Both survived a subsequent law suite and appeal by Brown and Henderson, but were dismissed later following an Admiralty enquiry (Philpot Committee). The enquiry must have had some concern about the Admiralty Compass Department, as their report stated *that Henderson was anxious to keep his invention secret from the Compass Department and events justified his suspicion.* However, the aircraft compass incident was not public and involved only government research departments. Any accusation of plagiarism or 'piracy' would be pointless, as the RAF compass had unknowingly been anticipated by an earlier yacht compass patent.

5.5. Development of the Pattern 5/17 Compass.

The joint development of the Pattern 5/17 compass by Creagh-Osborne and Hughes can be followed in the Treasury file for the Royal Commission for Awards to Inventors.[7] This shows the air services gained a good navigation compass, for which Creagh-Osborne received significant royalties and Hughes & Sons almost went bankrupt.

On 13 September 1919, Hughes submitted a claim for the British Government use of their air compass, and later for American use on 30 December 1922. The British claim was based on Patents 1148/15 and 17736/15 for the inverted pivot, radium compound paint, and other features of the Pattern 255 compass, later used in the Pattern 5/17. Hughes claimed £10,000, being 2% of their total British orders, as like other claimants they were unaware that they were claiming an award for inventiveness, and not a royalty for utility

and usage. A letter with the claim said that although Creagh-Osborne was co-patentee and his name appeared on the claim, he was not personally involved in any way as he had surrendered his rights. He had in fact sold his rights to Hughes for £2000, shortly after receiving £3571 as his half share of royalties for compasses made under licence by Sperry.

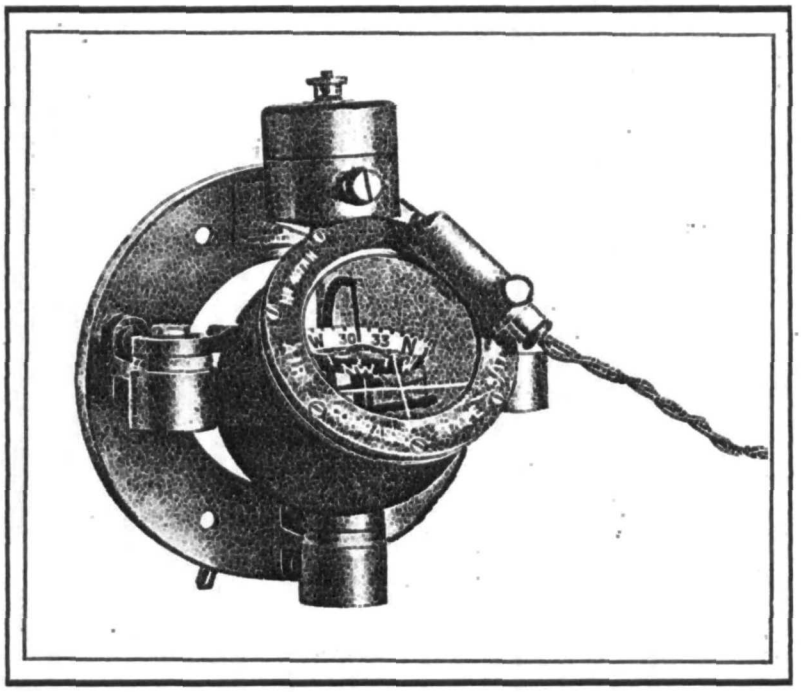


Fig 5.1. Pattern 5/17 Compass 1917
Similarity with RAF Mk II and earlier Creagh-Osborne-Hughes compasses is evident.

The Treasury were dealing with many other claims and did not prepare a counter statement until August 1920. This statement examined the legitimacy, novelty and utility of the claim and the status of the claimant. Hughes' claim was legitimate as they were co-patentees. The compasses had marked utility and were extensively used, some 1000 of Pattern 255, some 1000 of Pattern 256, some 500 of Pattern 258, some 10,000 of Pattern 259 and some 55,000 of the Pattern 5/17 were ordered. However, there was no inventive advance over known compass practice, in particular no novelty in the proportion of magnetic moment to moment of inertia, multiple magnets, domed float, inverted pivot, spherical bowl and vertical reading marking on cards. They listed similar features could be found in 19th Century compass patents by Daniel (10366/85), Reynold's (10053/88), Morton(15787/91) and Smith and Heath (418/90); and in more recent patents by Wilkie (47/05), Chetwynd (4761/12) and Kelvin and White (25718/09), without considering the RAF Mk II. Interestingly, they also listed Patents 13998/02 and 26963/03 by G.C.Lilley, a London optician in Fenchurch Street, which anticipated the spring slip suspension of Lucas and the helical spring suspension of Hughes respectively.

However, the greatest drawback to the claim was the status of Creagh-Osborne whose duty it was to design compasses for the Government and to be familiar with existing compass practice. He had communicated this knowledge to Hughes, making them in reality a service inventor. But before this verdict was given to Hughes, the Admiralty forwarded a letter to them from Hughes, dated 20 October 1920, explaining the financial hardship they were facing and asking when their claim would receive attention. They had received no assistance from the Government and had raised £40,000 from friends and relations during the war to build and equip a large factory for making compasses and other instruments requested by the Admiralty. Since the war, they had an output of £100,000 per year, but discouragement was so great that the factory would close at the end of the year.

More details of this venture appeared during the hearing in July 1921. A letter from Hughes to Creagh-Osborne, dated 3 November 1917, reported that production of the Pattern 5/17 at their Slough Works had increased from 400 to 500 per week, and was expected to reach 800 per week when the new factory was completed. They asked for an advance of £5000 now and at year end to finance the outlay and they planned to drop the price of the compass from £7 to £5 as production increased. Creagh-Osborne wrote to congratulate them, accepting that he was largely responsible for their financial position having urged them to greater effort, and knowing that their pre-war private connections were exhausted said he would put the fact to the notice of the Treasury.

At the hearing, Hughes' solicitor read out a letter from their auditor at this time;

> I have repeatedly pointed out to you and to the Ministry of Munitions the extremely hazardous financial position in which you are placing your company in incurring this heavy additional financial outlay, which is more than three times in excess of the capital of the company, and which was being financed on borrowed money. It is true that 35% of the plant and 40% of the building can be written off against profits, but I doubt that even this covers the excess cost compared with pre-war prices.
> I have also pointed out that you will experience great difficulty in raising fresh capital to repay these loans in view of the fact you have paid only 6% dividend since the war started, which offers little inducement for speculative investment. The result of this expenditure has undoubtedly been the creation of a works which are very efficient for present requirements, and the general organisation and development of a skilled body of workers, mainly female, and that does not overcome the great danger of your eventually being left with the buildings, machinery and equipment, which will be far in excess of your requirements when trade again becomes normal.

The transcript of the Royal Commission hearing on the 18 and 25 July 1921 makes it clear that the Commission were very concerned about the financial risk that Hughes had taken to meet wartime demands. The hearing was chaired by the Hon. Mr. Justice Sargent, with Lord Rayleigh and Mr. Norton K.C. present. Hughes were represented by Sir Duncan

Kerley and the Treasury by Mr. Moritz.

> *Kerley:* Creagh-Osborne put all the resources of knowledge of the Government at the disposal of Hughes, and this was more than reciprocated by Arthur Hughes putting the full use of their factory and their skill and material at the disposal of Creagh-Osborne.
> *Chairman:* Leaving the balance due to Hughes.
> *Kerley:* Yes, My Lord. Hughes manufactured £600,000 of compasses, but their profit was only £20,000 and this went to paying off capital of £70,000 for the factory they built specially to produce them, still leaving them £50,000 debt to dispose of. One compass was originally ordered for £7, based on the experimental work that had to be done. This was reduced to £5 as the orders increased, but Hughes had to ask it increased to £6, because they were making a loss. Royalty was excluded from the price of things made by Hughes themselves.

Kerley also explained that Hughes received £12,570 in royalties from Sperry, who manufactured the compass under licence in America. This was reduced after tax to £7,142 and half of this, £3,571, was given to Creagh-Osborne. Hughes bought Creagh-Osborne out for £2000, so he received a total of £5,571, while Arthur Hughes reinvested his share in the company and made nothing from it.

However, although the Commission saw the hardship claim was substantial, they were only empowered to make an award for inventiveness and most of the hearing was devoted to establishing this. Hughes had also modified their claim on 28 February 1921 to include £3,102 for experimental expenses. This included the cost of experiments to compare non-freezing liquids, to replace iridium on pivots and to protect radium compound paint, the loss of radium during experiments, fees to S.G.Starling and A.G.Salaman, awards to workers, drawing and patent costs and of making experimental models. The experimental costs were high, because wartime urgency meant that large batches of compasses were dispatched before experiments were completed, and had to be returned and replaced. However, although these additional hardship claims were examined during the hearing, their influence on inventiveness was minimal. The counter statement prepared by the Treasury on 15 July 21, argued that every feature of merit contained in the compass had previously been embodied in the RAF Spherical Compass of the late Capt. K.Lucas, and a specimen of this compass together with a complete set of working drawings were given to Capt. Creagh-Osborne, and by him to the claimants prior to the design of the compasses in question.

The hearing centred on substantiating this fact and on establishing which features developed by Hughes, such as the light floatless card and radium marking, were novel. Several witnesses were called on the second day. Creagh-Osborne would have been the key one, but had suffered a heart attack the previous day. Lord Rayleigh was also ill and the Treasury solicitor tried to postpone the hearing, but the chairman was anxious to complete the hearing and felt they could proceed. The hearing then retraced the history of developments from when Creagh-Osborne visited Lucas, and the SRAF at the time,

M.O'Gorman, was called to confirm events and dates. It was agreed that up to the Pattern 255, there was no novelty. This, it turned out, also included the use of radium paint, as the same work had been done by Frank Short at Farnborough on airship compasses in 1911-12, although he had never mentioned it to Arthur Hughes whom he knew well.

Lt. Alexander, an Admiralty compass examiner, considered the 5/17 novel.[8] It was the Hughes card that enabled the period to be reduced as *'only by eliminating the float to remove weight at the rim, could the moment of inertia of a card be reduced to 15 seconds.'* All previous aero compasses had a float. He said that in his opinion the Mk II was not a compass but a northerly turning indicator, and it had such a high centre of gravity that it would need re-balancing if used in Egypt.

Major Wimperis, now in charge of the Air Ministry Laboratory at Imperial College, was also called. He explained that he was not involved with compasses during the war, but was very familiar with them now and with the reports written at the time. He had also visited Lindemann to gather background information.[9] Wimperis favoured the Mk II, because it had no northerly turning error to indicate a turn in the wrong direction. He felt the compass problems experienced during the war were due ***'to the northerly turning error not being understood at the front, while their opinion on the response of compasses was not corrected back in England.'*** He said the 5/17 was easier to manufacture and its air trap was better than the expansion chamber of the Mk II, but the Mk II had better spring anti-vibration mounts, and they were going back to these again now. The aperiodic compass Pattern 6/18 by Campbell and Bennett was now the preferred compass. It had a longer period than the Mk II, but came to rest more quickly, because it did not over swing. He felt that Hughes had solved a difficult light card problem with rare skill, and the 5/17 was the best all round design for a short period compass. Questioned on whether this was instrumental skill or inventive capacity, he replied instrumental skill.

In all some 66,424 Pattern 5/17 compasses were made, 55,636 of them by Hughes and 10,788 by other British companies.[10] The Royal Commission hearing decided to take up the hardship case with the Treasury and to decide the amount of award after the vacation. However unaware that this vacation lasted three months, Hughes wrote in desperation to the Royal Commission on 9 September 21, that he was at a loss to understand the delay in making an award. The letter was forwarded to Sargent, who replied, that if Rayleigh and Norton agreed to £2000, the claim could go forward. Hughes received £2000 shortly afterwards, which did little to reduce their debt, and on 19 October 1923 they wrote to say that the Inspector of Taxes was trying to prove that the £2000 was liable to Excess Profits Duty. They had fared no better or no worse than other inventors who made claims, believing they were claiming for their service to the country in its hour of need, while the

Government only wished to acknowledge their inventiveness within a very limited budget. Capt. Creagh-Osborne appears to have been the main beneficiary, as he had profited from the Sperry royalties and had sold his patents rights to Hughes, when he knew the short period compass was to be replaced by the new aperiodic compass. He retired in 1921, retaining an interest in instrumentation as a member of the Technical Optics Committee at Imperial College.

5.6. Hughes Claim for American Government Use.

Hughes made a claim on 30 December 1922 for use of their patents by the American Government.[11] In 1916, Lt. Towers, the American Naval Attaché in London, bought some Hughes aero compasses through the Admiralty on the understanding they were patented, and could be manufactured under licence by Sperry. Hughes sent their foreman, Mr Elliott, over to Sperry to instruct them. In 1917, detailed information and models were given to Major Horner of the American Signal Corps and to Major Mendenhall of the National Advisory Committee for Aeronautics (NACA), with the view to devising compasses for the American Air Services. This information was subsequently given to the General Electric Company (GEC) of Schenectady N.Y. and orders for 11,200 compasses, identical to the 5/17, were placed without the consent of Sperry or Hughes. Hughes claimed £5,600 (10/- for each compass), plus £250 for expenses. Later Hughes found that more compasses had been made, but were only able to identify 15,000 by GEC and 1000 by Durkee of Staten Island N.Y. On 8 February 1923, Hughes increased the claim to £14,000, based on 15/- per compass, and £1000 legal fee expenses.

The American Government dismissed Hughes claim for royalties, as the Bolling Agreement made their use an extension of that of the British Government, placing the claim back to the Royal Commission, who met on 6 March 1923 to discuss the new claim. The same people were at the hearing, together with representatives of the American Government. Kerley tried to argue that as their British claim was based on £2000 for 10,788 Pattern 5/17 compasses made by other British companies, the American claim for 16,000 by companies other than Sperry, should be on a pro rata basis. However, although the Commission were still very sympathetic to the Hughes claim, similar claims for American use had not been on this basis, and the argument was rejected. The Commission finally agreed £2,250 for compasses supplied and £750 for future use, a total of £3000 which again did little to alleviate Hughes' financial difficulties, although itself a large award compared with other inventions.

5.7. The Pattern 6/18 Aperiodic Compass.

The patent application for the Pattern 6/18 compass was submitted by Cmdr. Campbell and Dr.Bennett in June 1918 as its reference suggests and its dead beat movement overcame the argument between the relative merits of the long and quick period compasses.

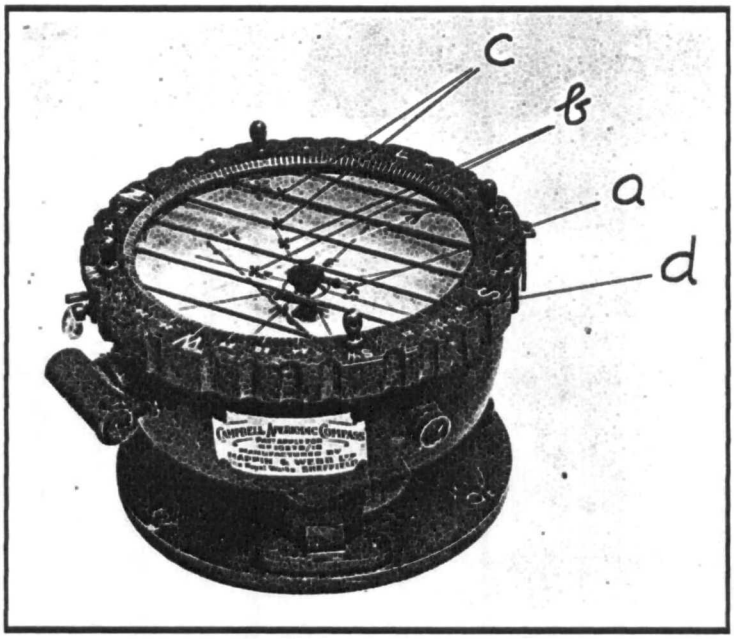


Fig 5.2. Pattern 6/18 Aperiodic Compass
Showing use of wire filaments instead of a card.

It combined strong magnetic moment which got it quickly off the mark, with low inertia and high damping which avoided any overswing. The low inertia was achieved by dispensing with a card altogether, retaining only cross wires to indicate the cardinal points, which also provided the relatively high damping for the 3 gramme weight of magnets and movement. This damping gave it a long period, but as it returned after displacement without overswing, it did not exhibit the slowly diminishing swinging of the long period compass, which had made that compass unpopular. A rotatable parallel grid line and 360° scale were provided on the case. An alternative centesimal scale was also available (Fig 5.3). This 100° counter clockwise scale was provided inside the bowl. The four filaments were not arranged at right angles, but had filament **1** at 100°, filament **2** at 200°, and filament **3** at 300° from the north pointing (zero) filament.. The full circle scale was replaced by one for 100°, and 100, 200 or 300 was added to the scale reading depending which filament was within its arc.

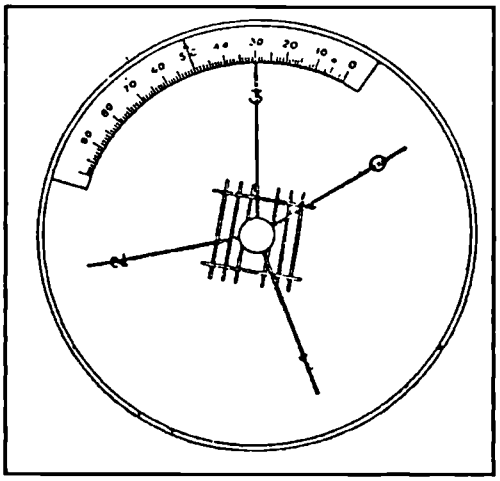


Fig 5.3. Centesimal Scale.
(Heading = filament plus scale, e.g. 300+30=330)

5.8. Fight tests with long period, quick period and aperiodic compasses.

At the end of the war, the long period compass was still the only recommended method of cloud navigation in the RFC. Trials using two formations of five aircraft, one with qualified pilots and the second with student pilots, were conducted at Orfordness.[12] Before entering cloud, the leader fired a Very light warning the other pilots to note the course and 30 seconds later he started to climb at full throttle into the cloud. Pilots 2 and 3 then timed 30 seconds before they also climbed at full throttle, but on a slightly diverging course to reduce the risk of collision, and 30 seconds later still, pilots 4 and 5 did the same. Each pilot then maintained his course until he emerged from the cloud and the formation reformed. Course was maintained with a smart kick on the rudder to correct any deviation in heading, as the compass continued to turn with a banked correction. Initially, none of the pilots understood compasses, particularly its northerly turning error, but managed satisfactorily once this was explained. Orfordness concluded that *only* the RAF Mk II (Long Period) compass could be used for cloud flying, and the compass, air speed indicator, inclinometer and rudder indicator *must* be placed close to each other so the pilot could observe them all simultaneously.

At the same time, the RAF Mk II (Quick Period) compass was being tested by Capt. G.P.Thomson at Orfordness, who found that its performance was by far the most satisfactory quick period compass yet tested, and it was adequate for cloud work *until the turn indicator came into service.*[13] He recommended further tests to compare it with the Mk II (Long Period), together with prolonged trials with pilots of varying skill. The Admiralty Type 5/17 compass performed badly in the same tests.

However, within three months, Lt. J.H.Mackie at Orfordness was recommending the adoption of the Admiralty 6/18 aperiodic compass, again conditional that the compass was used *in conjunction with a turn indicator.*[14] The card turned in the wrong direction during 180° turns faster than 20 seconds, and showed no turn for those between 12 and 20 seconds. However, good navigation was possible in long straight courses in conjunction with a turn indicator. It suffered no vibration problems, had a better scale than the Mk II, and the variable lubber line relieved the pilot of considerable strain in flying a long distance course.

5.9. Transferring compass development to the laboratory

Probably, the compass and its use for normal navigation and cloud flying was the most misunderstood aeronautical instrument of the war. Normal navigation required a short period compass and cloud flying a long period one, while the arguments for each use confused both scientists and pilots. The RNAS pilots, who frequently flew in conditions of poor visibility, had preferred the short period Admiralty compass, but were now starting to use the longer period aperiodic compass. At the same time the RFC, who had used the long period Lucas compass, were asking for one with a shorter period for normal navigation. Besides the different philosophies of military and naval flying, another difficulty was that all experimental work involved laborious test flying to provide the necessary magnetic and mechanical forces. To resolve this situation, compass research was one of the first problems to be examined by the Air Ministry Laboratory at Imperial College, under the directorship of H.E.Wimperis. Imperial College also had on its staff, Professors F.J.Cheshire and A.F.C.Pollard, who had both been involved in the production of aircraft and other instruments during the war.

Wimperis organised a systematic laboratory research programme to compare the theoretical equations of motion of the compass card with its actual behaviour. The Lindemann-Pincent equations of motion were re-examined and simplified to a form in which the constants had more meaning to a compass designer and the actual behaviour of existing compasses was then shown to agree with the new equations. The significant innovation in this research was the laboratory apparatus, which simulated the magnetic forces that would be imposed on a compass in an aeroplane flying and turning on a northerly course. This apparatus was used to examine the performance of the main wartime compasses, and to modify their damping for northerly flying by attaching the radial filaments, developed by Campbell and Bennett, to the magnetic system of each compass. These filaments increased the damping of the system without increasing the inertia of the system or reducing its magnetic moment.

Wimperis generalised the forced vibration problem, considering *all aircraft instruments as having pivotally mounted parts, which were elastically controlled in such a manner as to form a vibrating system.* He divided them into two groups, those with *elastic attachment to the aircraft,* and those with *elastic attachment to the earth.* In this way, the previous descriptions of *spring, magnetic and gravity control* became generalised as *elastic attachment to aircraft or earth.* Most aircraft dial instruments were in the first group, while the compass, pendulum type instruments and bubble sextants fell into the second group. Damping to reduce vibration was assumed to be proportional to angular velocity and also divided into two groups, that relative to the case containing the instrument, which was fixed to the aeroplane, and that relative to space. Wimperis published this mathematical analysis in April 1920, concluding that the best level of damping was about 70% of that which made the motion aperiodic.[15] This reduction in damping also made the aperiodic compass suitable for cloud flying.

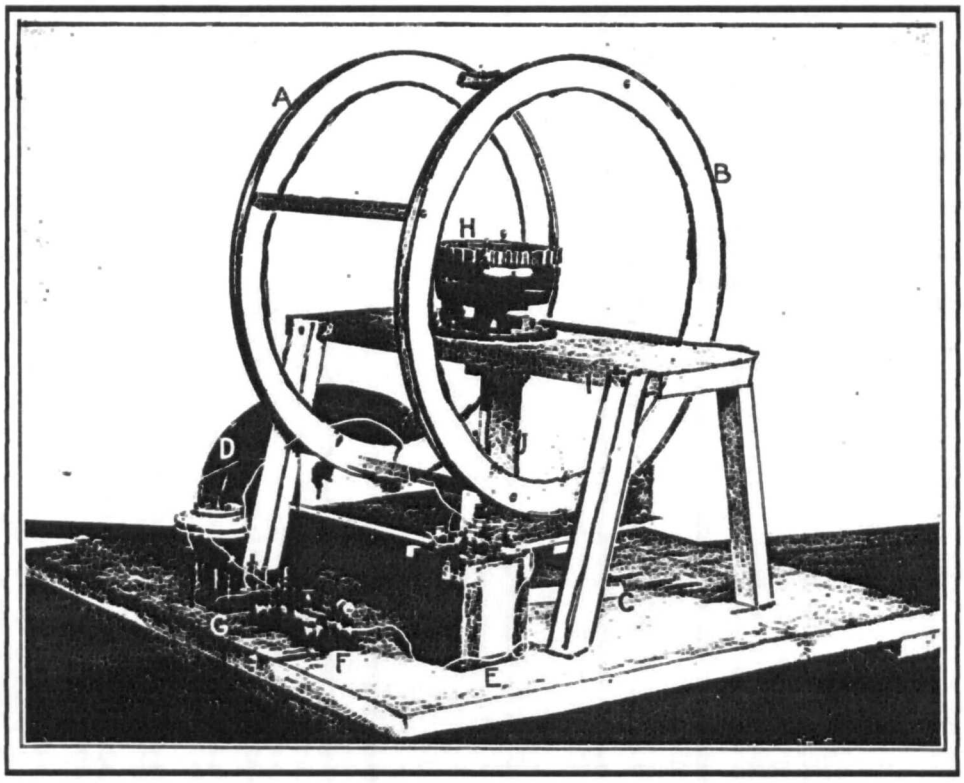
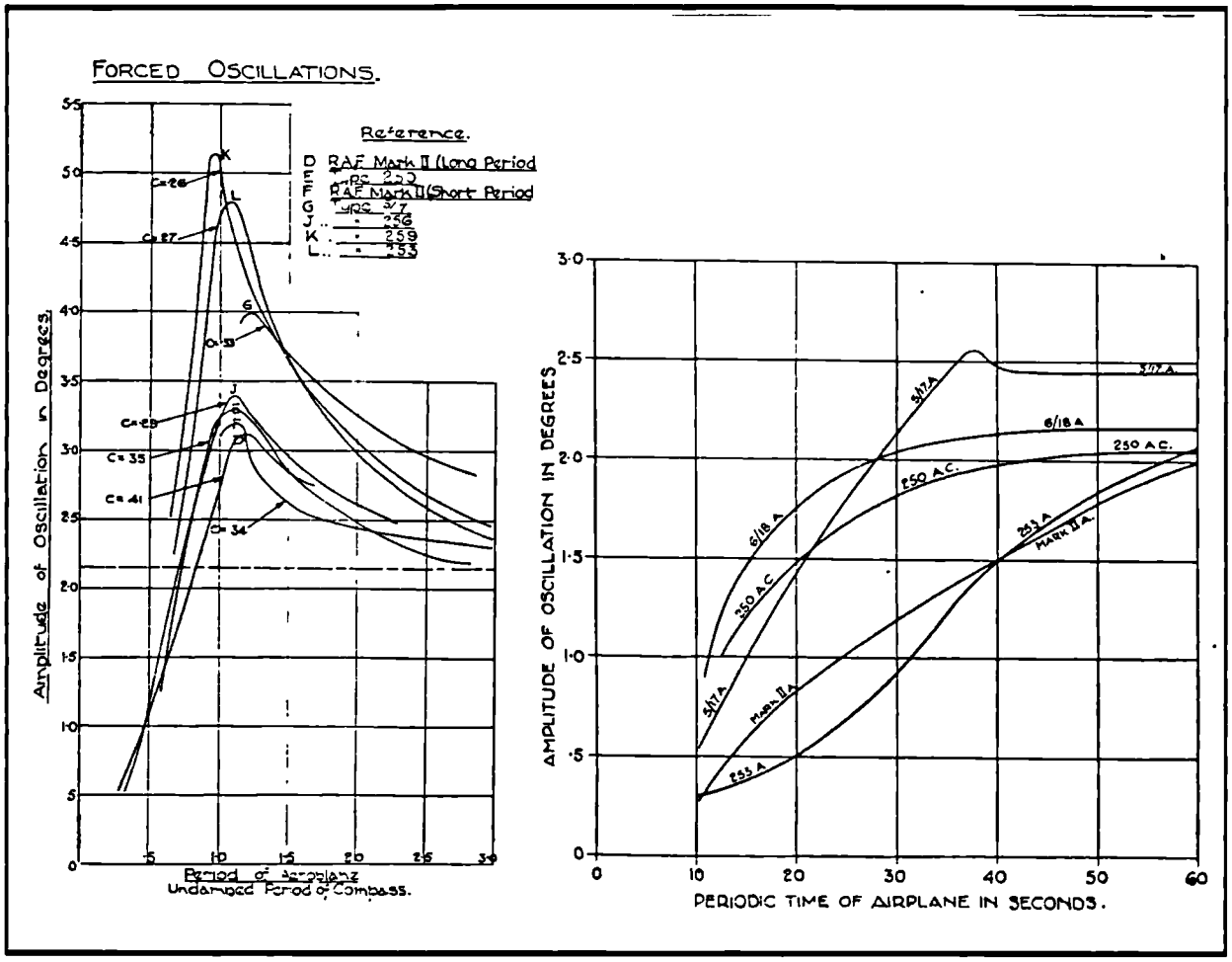


Fig 5.4. Compass test apparatus of Capon and Lee in 1920

The compass *H* to be tested was placed on the fixed table *I*, between the two coils *A* and *B*. The distance between *A* and *B* was equal to their radius, and their axis was on a north-south line. The compensating magnets were inserted in the wooden projection *J* below the compass table. An electric current was passed through both coils in such a way, that their magnetic effects neutralised each other. One coil was then kept stationary and the other coil oscillated in simple harmonic motion through a few degrees on each side of its mid position. This produced a fluctuating magnetic field at the compass to simulate the fluctuating component in the plane of the card of the vertical magnetic force due to a banking turn in flight.

The research to develop more meaningful equations of motion and design apparatus to simulate the aerial behaviour of the compass in the laboratory was carried out by Ft. Lt. R.S.Capon and Dr. Alice Lee in July 1920.[16] Forced oscillations were imposed on a compass to simulate an aeroplane flying on a northerly course with up to 10° roll, varying in period from 7-50 seconds. Behaviour included the effect of the compensating magnets, mounted below the compass to correct its deviation due to ferrous objects when flying level.

The apparatus was later modified by A.P.Rowe so that both coils turned about a vertical axis passing through the centre of the compass. The movement of the coils was controlled by a cord wound slowly on a brass spiral, so shaped that when rotated a constant speed, its angular velocity represented the gradual building up of an aeroplane turn. The brass spiral also operated a sliding contact on a resistance to increase the current in the coils to correspond with a steady increase in the banking angle. The apparatus was used in both forms to examine the behaviour of the wartime compasses and the results were published by Wimperis and Rowe.[17] Rowe later extended the theoretical treatment of the periodic compass by Lindemann and Pincent to the aperiodic compass, including the behaviour when the damping was increased beyond aperiodicity.[18] These compass experiments were the first aeronautical research work by Rowe, who had worked on the control of anti-aircraft guns under A V Hill during the war.



a) standard damping b) aperiodic damping

Fig 5.5. Forced oscillation behaviour of wartime compasses.

Curves plot amplitude of compass card oscillation against a simulated 1° roll of aeroplane of varying period to compare compass behaviour while flying a northerly course. The reduction of oscillation with the aperiodic damping is evident. In curves (b), *A* indicates the magnetic system has been modified towards aperiodicity, *C* indicates the scale is centesimal.

Wimperis also simulated the behaviour of the wartime compasses, when subjected to the forced oscillation that would be induced by a 1° periodic roll of varying frequency for an aircraft flying a northerly course.[19] The short period pattern 259 had the poorest performance, 5° compared to 3° for the RAF Mk II (Long Period) for the critical roll period of 10-12 seconds (Fig 5.5a). With filament damping, the performance of all compass became acceptable(Fig 5.5b).

Similarly the northerly turning error of all the wartime compasses was significantly improved with filament damping (Fig 5.6a and 5.6b). The dotted lines in the upper curves show the reading of each unmodified compass card during simulated turns off north. Only the Mk II turned in the right direction, as would be expected from the previous history.

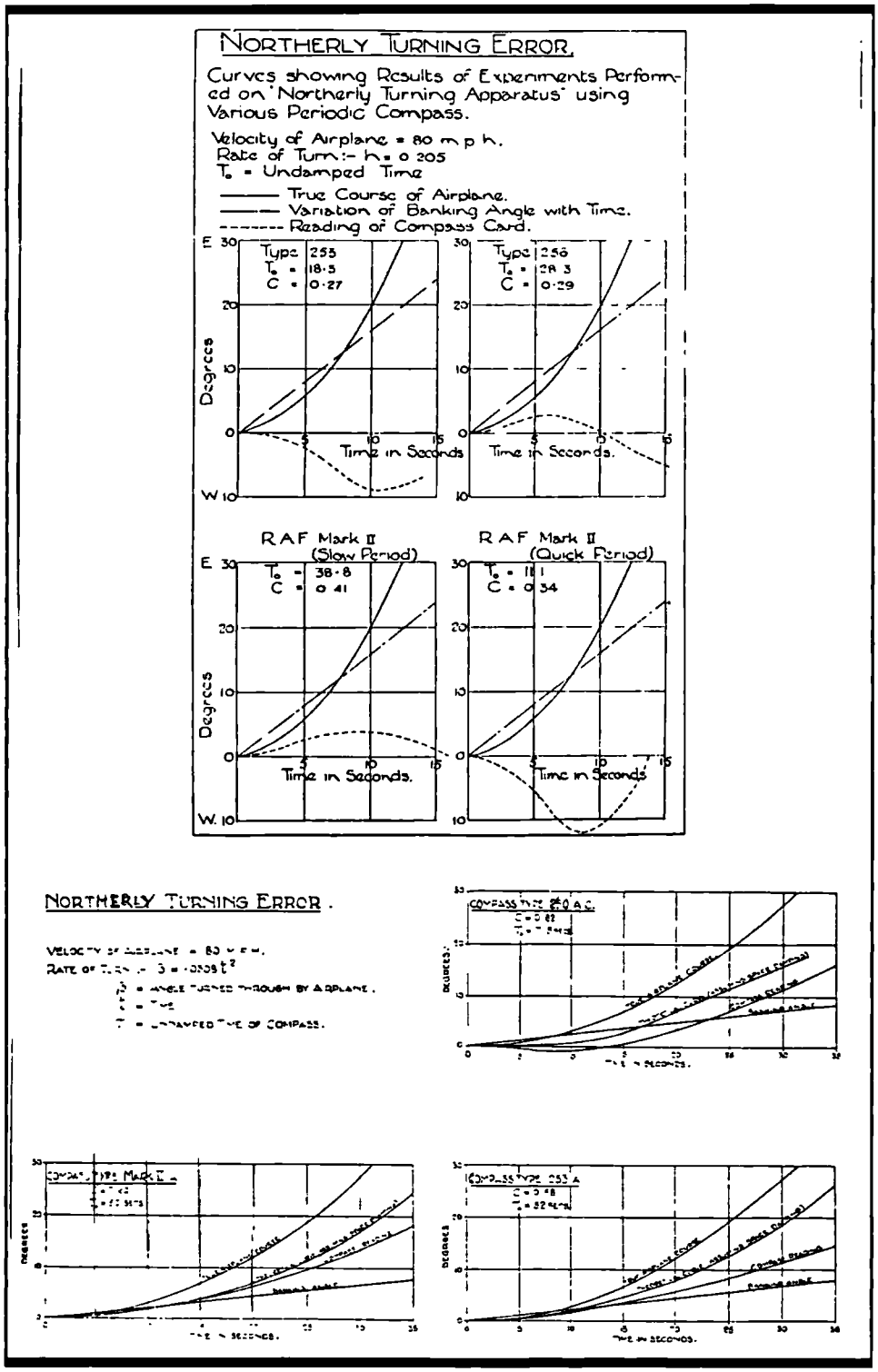


Fig 5.6. Northerly turning behaviour of wartime compasses.

Compass reading (dotted lines in upper curves) below abscissae indicates Northerly Turning Error.

The cards of the other compasses either immediately or eventually turned in the wrong direction, making them useless for cloud flying, as had always been argued. This included

the Mk II (Short Period), which G.P.Thomson said he had found satisfactory at Orfordness, although he added it should be used with a turn indicator. With aperiodic damping, the compass reading (shown full line in the lower curves) of the Mk II was further improved and the Admiralty compasses behaved almost equally as well.

The conclusion was obvious, all the wartime compasses could be modified to have good forced oscillation and northerly turning characteristics, allowing the large stock of wartime compasses could be used up. The Air Ministry Laboratory modified the Mk II to become Pilots Compass P-1, and designed two new compasses, the P-2 with a flat card and the P-3 with a vertical cylindrical card, which became the basis for future aircraft compasses. When Wimperis presented this work in a general paper, he drew attention to the fact that *the new compasses were built by the Admiralty Compass Laboratory - an interesting example of co-operation between the two departments.*[20]

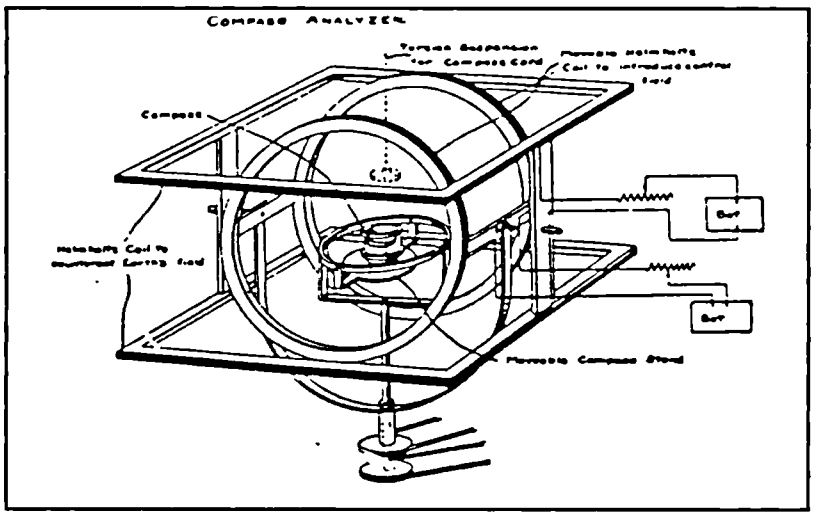


Fig 5.7. MIT compass test apparatus of Draper, MacKay and Cook 1937.

This laboratory apparatus appeared again when Draper, Mackay and Cook examined current aircraft compasses at MIT in 1937, to see if they could be improved. They acknowledged the work of Lucas, Lindemann and Wimperis, but did not mention that they based their apparatus on that of Wimperis, or that their findings only confirmed his of 15 years earlier.[21]

Conclusions

A.J.Hughes writing in 1947 considered that the work of Keith Lucas was the most important scientific contribution to air navigation during the 1914-18 war; that Commander Finch-Dawson's efforts in compass swinging had reduced mistaken landings behind enemy lines, and the introduction of the 6/18 aperiodic compass gave the navigator implicit confidence in the magnetic compass for the first time.[22] He made no mention of his own contribution to the aircraft compass, which provided the link between the work of Lucas and of Campbell and Bennett and which was only recognised with reluctance by the British government. However, this chapter has shown that Hughes' work was significant and that his concept of a strong magnetic moment and light floatless card to reduce inertia was an important intermediate step in aircraft compass design.

The controversy associated with military and naval aircraft compasses was not of his making, nor should it detract from his contribution to compass design. When new responsibilities are established it is not unusual for the relationship between the people involved to become strained as recognition for early work is lost or marginalised in the new organisation. Transferring the responsibility for the military aircraft compass to the Admiralty was no exception and the relationship was aggravated as it involved an older officer in the senior service and young university scientists, temporarily mobilised into a new service. Neither was the situation helped when the career officer apparently benefited financially from the inventive work of one of the scientists and stopped production of the rival instrument. However, it is a narrow line between influence and plagiarism. Farnborough doggedly stuck to the cloud flying work of Lucas and Lindemann, although one feels Lucas may have been adaptive to the situation had he survived. Wimperis summed the real problem when he said that,

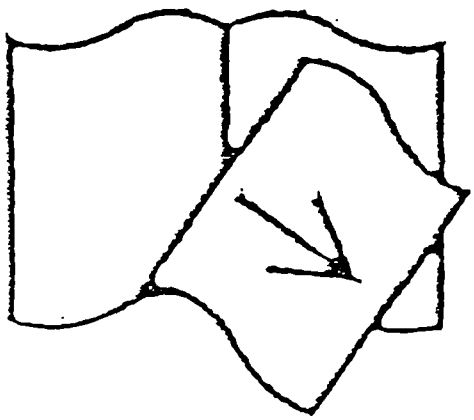
> the northerly turning error was not understood at the front, while their opinion on the response of compasses was not corrected back in England.[23]

This lack of systematic feedback from active service operations to government research and development handicapped the successful introduction of other devices during the war. However,the lesson was well learned and the situation was not repeated when the young scientists of the First World War became the senior scientists of the Second World War.

The history of the air compass has shown that the behaviour and development of an apparently simple instrument can be complex and the misunderstanding and confusion of scientists, designers and pilots at the time is not difficult to appreciate. However, it is difficult to understand why no one in 1917 identified the small but significant difference between the centres of gravity of the RAF and Admiralty compass cards, which contributed

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Chapter 6.

Cloud Flying
Static and Gyroscopic Turn Indicators and Rudder Gyro

Summary : Cloud flying - Darwin's Static Turn Indicator - Flight testing by Lindemann - Testing it at Orfordness - How it was developed - Related patents by Brewer and Sperry - Pendulums and Tops - Development of the gyroscopic turn indicator by Henderson's and Lanchester - Lindemann's turn indicator - Rudder gyro control by Lindemann and Dobson - Kingsway Turn Indicator - Sperry Turn Indicator - Jones on commercial cloud flying - Conclusions

The ability to navigate safely through cloud was essential if aircraft were to fly in any weather. The previous chapter introduced the problem and the attempt to navigate with a long period compass. To look back at the problem today, with the advantage of modern flight instrument and control systems, requires considerable imagination. Gen. Brooke-Popham's experience was of loosing orientation in a cloud and emerging to find himself flying towards a vertical green wall, and only when he distinguished trees and a church sticking out of the wall, did he realised what was happening.[1] Capt. B.C.Hucks, another experienced pilot, gave a more technical account,

> On reaching 1,200 feet we got into a dense rain cloud, but carried on to beyond 5,000 feet, still in cloud, when the compass apparently began to swing (really its the machine that begins to swing, not he compass), and efforts to check the compass had the effect of causing it to swing more violently in the other direction. The air speed then rushed up far beyond normal flying speed; all efforts to pull her up checked her only slightly; then the rudder was tried, back went the air speed to zero; there was an uncanny feeling of being detached from the machine, and I knew her to be literally tumbling out of the clouds. All efforts to settle down to a straight flight seemed to be unavailing, until we emerged from the cloud very nearly upside down. Assuming control again was then a easy matter.[2]

The full account of his loss of orientation resulting from the confusion in trying to interpret the readings of his compass and air speed indicator, and the technical explanation of what in fact was actually happening, is well worth reading and is given in Appendix 2. It was this kind of experience that produced the urgency to develop a turn indicator. Following Hucks' paper, the Superintendent at Farnborough, Sir Henry Fowler, wrote a short article on the Lucas compass to reassure pilots, but could not disclose publicly that what Hucks wanted was already being developed at Farnborough.[3]

6.1. Lindemann's work on the Static Turn Indicator.

In 1917 work on compasses and turn indicators were complimentary. Although the RAF Mk II compass assisted navigation in clouds, it was far from being the answer. Lindemann found it to be,

> a matter of considerable difficulty to steer a definite direction with a compass when in cloud, where no horizon, nor any fixed object is visible. It is scarcely possible to recover one's direction in cloud once a turn has been allowed to develop so that it seemed advisable to examine the relative advantages of certain methods of showing turns.
>
> Only three methods have been suggested to date which merit serious consideration. The first method is due to Mr Horace Darwin and is described in a report to the Advisory Committee in 1912. This method measures the difference in *static* pressure at two points as far apart on the two wings as convenient. The other two take advantage of the difference in the *airspeed* of the two wing tips on a turn. This difference in velocity may be shown by two (pitot) Venturi tubes mounted near the wing tips and connected to a differential pressure gauge, or by a hot wire anemometer suggested by Prof. McGregor-Morris.[4]

In Darwin's method, since properly aligned static heads indicated the true static pressure independent of velocity, the pressure p on the membrane of the gauge during the turn was due to the centrifugal force acting on the column of air in the connecting tubes. This calculation reduces to $p = \rho g l \sin\emptyset$, where ρ was the density of the air in the tube, l the length of the tube and $\emptyset$ the angle of bank. This expression is also conveniently the barometric pressure difference between two static heads on a wing of length l, banked at an angle $\emptyset$.

The mathematical theory behind this calculation is given at the end of the chapter and also shows why the second method to measure the velocity at the wing tips, instead of the static pressure, would not work. The pressure in a pitot head and the centrifugal force in a turn are both proportional to the square of the velocity. More pressure is induced in the pitot on the outer wing because it is moving faster than the inner wing, but is nullified by the centrifugal force in the connecting tubing.

In the third method, a loop of wire was fixed on each wing and heated by a electric current at constant voltage. As the loop on the outer wing in the turn was travelling slightly faster through the air than the loop on the inner wing, it cooled more and the difference in current in the two loops was a measure of the angle of turn. However, the measurement proved sensitive to wind gusts and had the disadvantage that the electrical equipment was heavy and inconvenient.

Lindemann also tested a static head, shielded by a venturi, which would increase the apparent static head and increase the manometer reading, but although this was an advantage, it also increased the effect of wind gusts. He made thirteen flight tests during the autumn of 1917 with the static tube turn indicator in a SE 5a, finding the sensitivity was about 1mm of water gauge for 10° of bank.[5] This low pressure differential made the correct alignment of the static heads imperative, otherwise the slightest out of parallel made the scale of a right and left turn different. Flight tests also showed that a difference of pressure was indicated when the machine was side-slipping, the static head on the side towards which the machine was pointing showing the higher pressure. He tried two swivelling static heads, mounted in gimbals and supplied with a wind vane to keep them head into the wind, but these also indicated side-slip, suggesting the difference was probably due to the shielding effect of the fuselage. Mounting the fixed heads on the inner struts produced an even greater effect to confirm this. Lindemann found the only way to avoid side-slip error completely was to mount the two static heads some 8 feet in front of the wings, but 2 feet above and 1 foot in front of the upper wing of the SE 5a. proved a practical compromise.

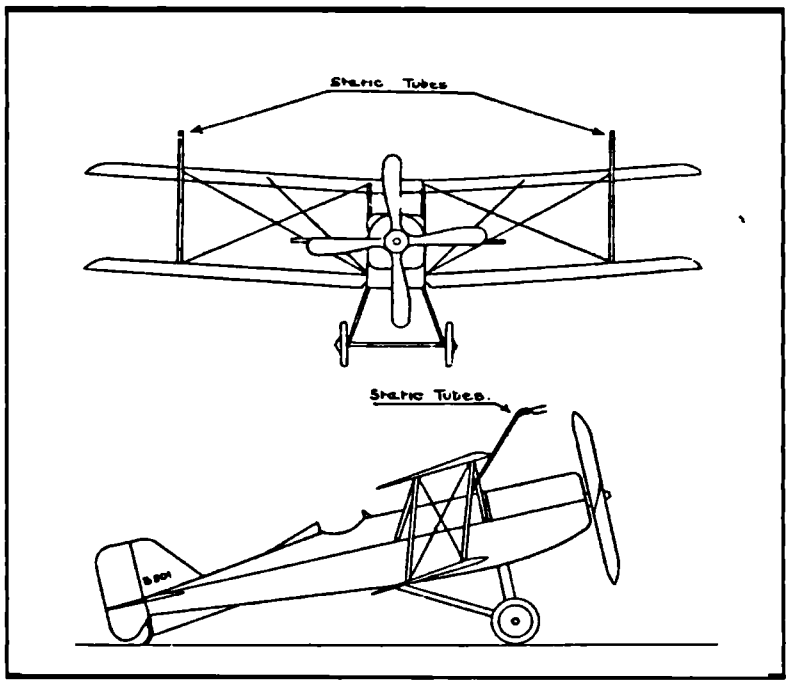


Fig 6.1. Static Tube Position on SE 5a.

He found that with practice, irrespective of whether the static heads were mounted on the struts or above the wings, he could manœvre without difficulty in clouds, and could start a steep turn and flatten out at will. The name Static Turn Indicator or STI was adopted for the arrangement of RAF Mk IVa static heads and an Ogilvie air speed indicator.

6.2. Testing Turn Indicators at Orfordness

Captain G.McKerrow at Orfordness repeated Lindemann's experiments in their entirety, reaching the same conclusions except that 1 foot in front of the mid wing was a safer location for the heads in service use.[6] After a large amount of test flying he concluded the STI was acceptable as an **emergency** instrument for cloud flying to enable the pilot to recover an even keel after a disturbance. This qualification was based on two difficulties he had experienced - the static heads could freeze up in clouds rendering the STI useless, and the large lag in the instrument when making an S-turn, left it still registering the first part of the turn while the machine was in the second part. To avoid the multiplicity of static heads, McKerrow also tried utilising the static head of the air speed indicator on one wing. This did not work as the air speed indicator measured a large differential pressure between pitot and static tubes and could work with a leaky diaphragm, but the slightest leak in the small differential pressures between the static tubes of the STI stopped it registering. He tried a silver diaphragm, but this was not sensitive enough for the small differential pressure measurement required in the STI.

The static turn indicator was a simple instrument and was used until the gyroscope turn indicator became reliable. However, its war service was minimal. In October 1918, 150 were ordered for France, where Capt. Hepburn successfully used one to ascend through several thousand feet of cloud to attack trains at Touraine, but with the end of hostilities only 72 were eventually delivered.[7] Farnborough continued their research after the war and were still trying to reduce the effect of yaw on static heads at the end of 1919.[8] R.V.Southwell designed a tubular head, 1.5 inches diameter and 11.4 inches long, inside which an annular milled groove led away to the measuring device. R.McKinnon Wood designed two disc versions, both 2.5 inches diameter, of which the 'paddle' version with the stem attached to the edge of the disc proved better than the 'sunflower' version, with the stem attached to the back of the disc.

6.3. The Darwin Static Turn Indicator

Horace Darwin provided more information about the development of the static turn indicator in a paper to the Royal Aeronautical Society, which was read by Wimperis as Darwin was ill.[9] Darwin said he had taken up a proposal to use pitot tubes, rejecting them in favour of static tubes, but the eventual success was due to experimental work at Farnborough and Orfordness and to the design of the sensitive Ogilvie pressure gauge

manufactured by the British Wright Company. He gave details of the installation and operation of fixed, swivelling and venturi shielded static heads, explaining that the static

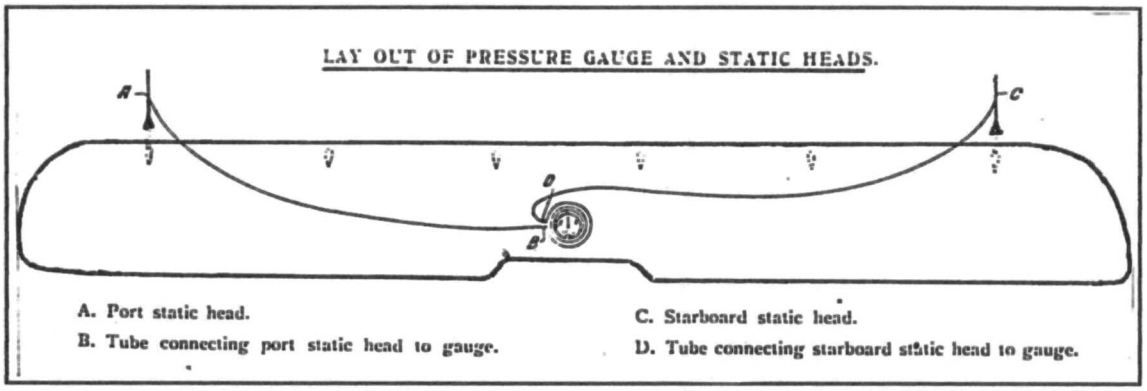


Fig 6.2. Ogilvie Gauge adapted as Static Turn Indicator.

tube was designed to move through the air so that its stream-lined head disturbed the air as little as possible, and the air passed over the holes at right angles to their direction making the pressure in the holes almost identical to that outside the tube. From his family interest in natural evolution, he drew the analogy with the arrangement of a bird's nostrils on its beak, which were positioned to enable the bird to breath easily while in flight, by making the air in its lungs the same pressure as the air outside. He was in favour of using swivelling static heads in the standard position, as tests showed they reduced the effect of

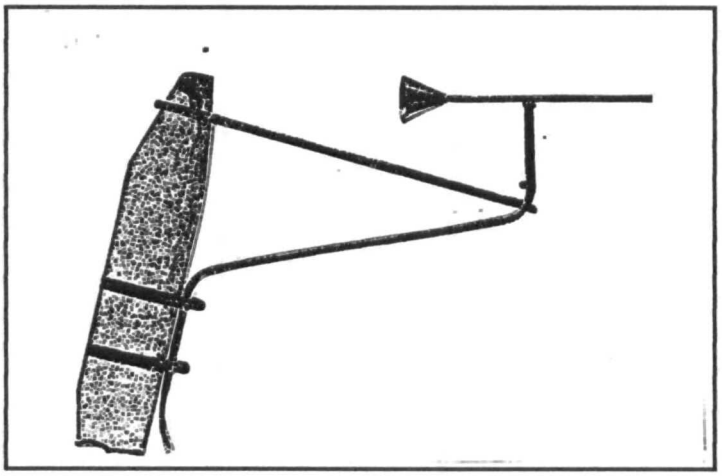


Fig 6.3. Swivelling Static Head mounted on Wing Strut.

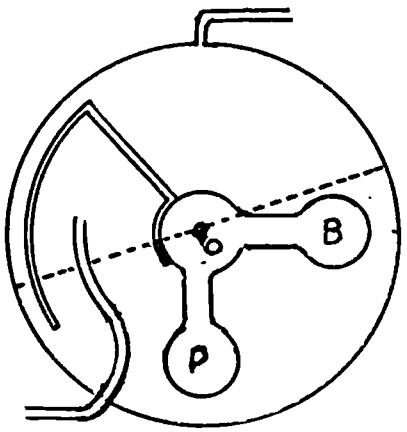
side-slip and were more convenient than fixed heads placed above the wings. He concluded with extracts from favourable reports by pilots who had used the static turn indicator, including one of which said it was now possible to fly scout aircraft with a rotary engine through thick layers of cloud, a feat practically impossible without the instrument.

After reading Darwin's paper, Wimperis opened the discussion, which provided more background to the development and utility of the instrument. He compared the static turn indicator with the gyrostatic turn indicator, which was now being tested. He said that Professor Henderson at Greenwich had invented the gyroscopic turn indicator in 1908 and it should be known by his name. It was subsequently re-invented by himself (Wimperis) in 1910 and again in later years by Sperry, Mendendall and Lanchester. Wimperis said he had recently flown in a Handley Page in which both instruments were installed and found it almost uncanny how they did the same thing, the only difference being that the Darwin type had a small lag due to compressibility of the air in the tubes. He added that Major G.I.Taylor had recently carried out navigational trials in Newfoundland in preparation for a trans-Atlantic flight and found that the accuracy of sextant observations were materially increased when the aeroplane was flown level by the static turn indicator.

Alec Ogilvie described, that while he was at the Air Board, he began work on the static indicator when he visited Tizard at Martlesham Heath about June 1916 and was told of the difficulty experienced in cloud flying, in fact of flying any straight course at all. He and Tizard thought that by putting a pitot head on each wing they had the basis of an idea to fly a straight line, but experiments carried out at Martlesham were not satisfactory. Bertram Cooper, who had previously worked with the British Wright Company and was in charge the Instrument Branch at the Air Board at this time, tried to encouraged him to arrange more experiments, but he was too busy on other projects.[10] Eventually it was Horace Darwin at the Air Inventions Committee, who was very interested in the subject and offered to take the whole job over. Up until that point, he (Ogilvie) and Martlesham Heath were working on pitot tubes rather than static tubes at the wing tips and did not appreciate that centrifugal action overcame the differential measurement from the pitot tubes in the turn.

Who noticed this problem? Both Lindemann's report and Darwin's paper said that Darwin had submitted the idea of the static turn indicator to the Advisory Committee for Aeronautics in a memorandum from himself and C.C.Mason in June 1912. This was incorrect as that memorandum referred to his yaw indicator which used pitot tubes angled 120° apart. The reference they should have given was a memorandum in May 1915 when Darwin and Mason suggested an instrument to indicate the true vertical in an aeroplane.[11] This was a theoretically ingenious but hopelessly impractical instrument for an aeroplane, which empolyeda pendulum consisting of a frictionless piston in a curved tube across the aeroplane. The pendulum would respond to centrifugal force if the aeroplane deviated from a straight course, but if the movement could be counteracted by another force due to the same centrifugal effect, the pendulum would remain vertical. This second force was the differential pressure across air tubes taken out to each wing tip, but the practical difficulty was to design an instrument which was sufficiently sensitive to measure this. The

suggested design was a 'bell jar' dipping into oil, in which the pendulum P, the bell housing and its balance weight B were pivoted at O. One static tube was connected under the bell housing and the other into the top of the instrument case so that the differential pressure between them moved the pendulum. Mason, as a former wrangler, was probably mainly responsible for this 'elegant solution. However, both he and Darwin were aware of the impractical nature of the instrument, which they called an *orthoscope*, and suggested that a sensitive manometer may be more practical for an aeroplane. They had conceived the principle of the static turn indicator, but were diverted by trying to balance the movement of a pendulum instead of move an indicator. When Cooper approached Darwin a year later, he would naturally be very interested, but the problem was still to find an instrument sensitive to static differential pressure, which is much smaller than pitot differential pressure.



In the discussion following Darwin's paper, Dobson explained that Darwin eventually passed the research over to Farnborough where they improved the sensitivity of the Ogilvie gauge to measure a few millimetres differential pressure. Regarding fixed or swivelling heads he said both were affected by side-slip, the only advantage of swivelling heads was that they remained parallel to each other, other than that, fixed heads were extraordinarily good. He also commented that one pilot he knew had deliberately spun and recovered a BE 2c in thick cloud with the instrument. (This was probably Lindemann, who by this time had established his name for spinning.)[1 2]

Before Farnborough improved the sensitivity of the Ogilvie indicator, several alternatives were considered according to Air Invention Committee files.[1 3] G.I.Taylor suggested the use of venturi shielded static tubes to increase the measured differential pressure and Darwin had some made at Cambridge Scientific Instruments for calibration and trials at Farnborough, but Lindemann quickly found these were sensitive to wind gusts. Following a visit with Callender and Taylor to East London College, Darwin thought that the hot wire anemometer of McGregor-Morris might act as a turn indicator, and he supplied Morris with sufficient platinum wire to make the prototype and arranged for him to visit Farnborough to witness the tests on 29 November. A.V.Hill suggested that the change in magnetism detected by two wire loops, one along top and bottom wings and one along the fore an aft line of fuselage and switched in as appropriate, might be used. There was no discussion on this matter, but any airborne instrument for measuring very small electric currents would have presented serious difficulties. Nor was there any discussion on a suggestion to use

the centrifugal effect of liquid filled tubes, probably because any leakage or air bubble would effect the calibration.

6.4. Static Turn Indicator Patents - Darwin, Brewer and Sperry.

The static turn indicator was a new idea and obviously worth patenting, but instead of patenting his proven indicator Darwin patented a more complicated instrument, which he called the Leeway and Curvature of Path Indicator and which combined his static turn and yaw indicators. The differential pressure between two pitot heads measured the leeway or yaw, while the pressure difference between two static heads measured the rate or radius of the turn. The patent claimed the device was suitable for both ships and aeroplanes and the figure (Fig 6.4) in Patent 123,996 of 20 March 1918 illustrated the system for a ship.

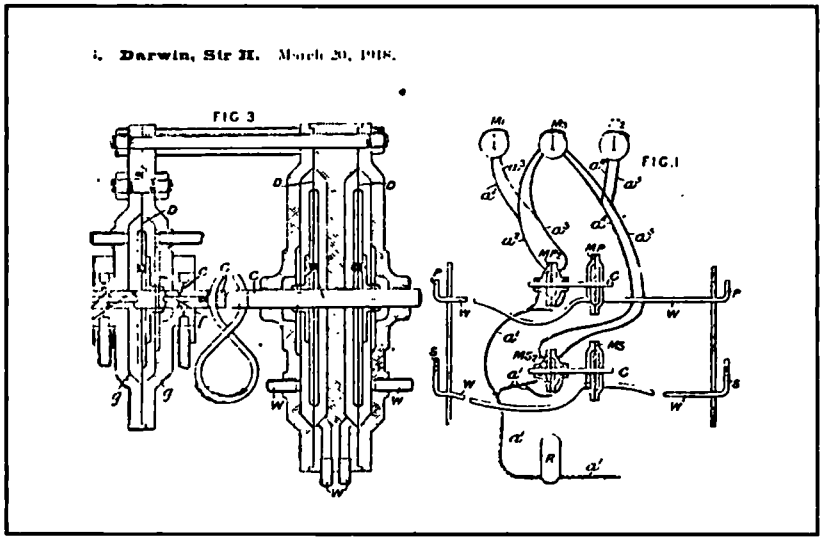


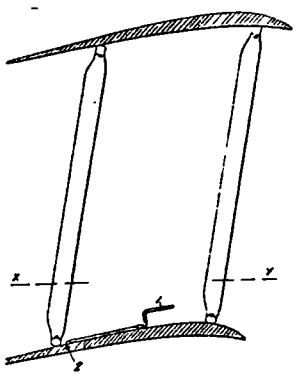
Fig 6.4. Leeway and Curvature of Path Indicator.

Pitot heads P and static heads S were fitted on either side of the ship and connected by pipes W to differential manometers MP and MS. The diaphragms D of the manometers were coupled to a co-axial manometer MP2 and MS2 by rods C. The tendency of the diaphragm of the manometer MP, to depart from the central position due to the differences in water pressure, was neutralised by compressed air admitted on the opposite side of the diaphragm of the manometer MP2 through air pipes a^1, grooves d and c on the coupling rod C and bush in which it slid respectively, and air ducts f in the rod. The resultant pressures in the two compartments of the manometer MP2 were transmitted by air pipes a^2 to the manometer M1, which indicated leeway. Each compartment had a small vent hole g to allow air to leak out slowly. Manometer MS2 was similarly controlled by manometer MS and connected to manometer M3, which indicated leeway and curvature of path combined.

The system was an early example of a forced-balance servo in which the measured pressure is balanced with an equal and opposite pneumatic pressure to avoid any movement of the mechanism and so eliminate errors due to friction and non-linearity of the diaphragm. It

also allows the measurement to be transmitted to a distant indicator and separates the measured fluid from the indicator. Although it used sound servo-dynamic principles, the actual invention would have been impractical. It would be too heavy and complicated for an aeroplane, while the protruding pitot and static heads on a ship would be prone to damage or fouling by seaweed and access for repairing or cleaning difficult.

Brewer also took out Patent 128,757 of 5 July 1918 for the Aeronautical Instrument Company to improve Darwin's basic static turn indicator by locating the static heads in the area of reduced pressure above the lower wing. This was intended to augment the measured static pressure, as Taylor had suggested with a shielded venturi, but this location would be even more sensitive to side slip. Patent 131,396 of 20 June 1918 covered the modifications to give the Ogilvie gauge a mid scale zero and the drawings in this patent document were those Darwin used in his paper. Darwin had not mentioned this, or that he had assigned his static turn indicator patent 4878/18 to the British Wright Company for a royalty of 10/- per instrument.[14]



In October 1918, E.A.Sperry took out an American patent for a static turn indicator, using the venturi shielded static heads to augment the measurement that Lindemann had found velocity and wind gust sensitive, and patented it in Britain a year later. However, he added

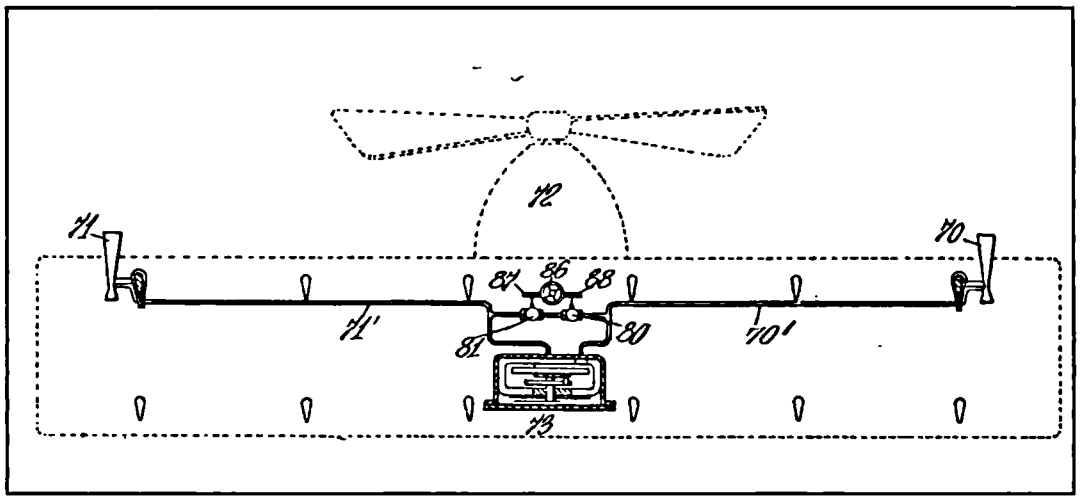


Fig 6.5. Sperry's Static Turn Indicator, using impractical venturi shielded static heads.

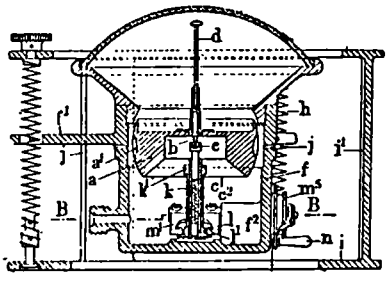
the feature that the indicator should move in the *opposite* direction to the turn so that the pointer remained vertical during it. The pointer of the Ogilvie gauge moved in the same

direction as the turn to show the turn was to right or left. The patent indicates that Sperry was alert to non-gyroscopic inventions, and one wonders if the information came from Titterington, Sperry's representative who was working on their rudder gyro at Martlesham Heath at the time Darwin's static turn indicator was being tested.

6.5. Pendulums and French tops.

Numerous patents were taken out by inventors during the war to indicate the true horizontal or true vertical in an aeroplane. Most were based on the pendulum, as the inventors did not appreciate the acceleration forces experienced by a pendulum when mounted on an aeroplane, and if they did they thought that enclosing it in a can of liquid would reduce the forces. The inventions usually adopted some gravity sensitive element in a liquid filled sphere, hemisphere or annular ring. The element could be a ball at the bottom, or a bubble or float at the top, or a weighted plummet combining both principles, or the interface surface between non-miscible coloured liquids, or an ascending stream of bubbles, to mention a few. Some inventors tried to overcome the impracticality of locating a sphere on the instrument panel by flattening its shape or viewing it through mirrors, and to assist night flying proposed lamp circuits switched by a mercury surface.

Those who were involved in aeronautics knew the pendulum was fundamentally flawed as a turn indicator and that the gyroscope was the real answer if it could be made small and reliable. While the British pursued the Lucas long period compass and the Darwin static turn indicator, the French were developing spinning top gyros. These were unconstrained gyros, similar to a child's spinning top, and those by the Garnier and Hebrard companies were two of several tested at Orfordness.[15] McKerrow compared the Garnier Gyrostatic Level, granted British patent 127,007, 15 May 1917, with a static turn indicator.[16] The vertical axis of the Garnier spinning top gyro had its lower end in a small cup, with its centre of gravity near this point of support to provide gravity control. The indicator arm was the upper extremity of the gyro axis, and moved under a graduated glass dome. McKerrow found that the Garnier,



a) indicated bank rather than turn, and was insensitive to shallow turns.
b) ceased to function when the top struck the case, if bank exceeded 45°.

and was much courser than the static turn indicator. As it did not indicate gradual turns it was unsuitable for cloud flying and was never adopted into British service, although it remained popular with French pilots through out the war. Britain therefore developed its own gyroscopic turn indicator.

6.6. Gyrostatic Turn Indicators - Henderson, Lanchester and Lindemann.

The development of the British gyrostatic turn indicator commenced when Professor Sir J.B.Henderson claimed an award for his 1918 invention in 1931.[17] The fact the claim was still being considered in 1931 is another example of the marginalisation of invention by the government when the wartime emergency has passed. By 1931, James Blacklock Henderson's career had spanned 40 years. From 1891 to 1901, he had worked for the Glasgow instrument makers Barr and Stroud before being appointed lecturer at Glasgow University. In 1905, he obtained the chair of Applied Mechanics at Greenwich Royal Naval College, with an unpensioned salary of £700, which increased to £800 after 1910. In 1920, he received a five year contract as Advisor of Gyroscopic Equipment to the Admiralty and his salary rose to £3000 per annum plus any award for invention.

His earlier inventions were numerous. He had 34 patents for gyroscopic devices, most of which were for stabilised gun control and director firing gear and most wartime naval actions between capital ships had been fought with his control systems. He started negotiating for some financial recognition in 1914 and turned down an award for £6500 in 1917. His problem was status as the Treasury considered that the design and development of mechanical devices for the navy were part of his job. Status was still a problem when he re-applied to the Royal Commission in 1921 and to this was now added the fact that the Admiralty was the only body who could develop his costly equipment and test it anyway, the Treasury providing estimates of the cost of firing the guns to test his equipment on HMS Hood. However, they eventually agreed to an award of £12,500 on the basis that some of his inventions were optical devices, and as Professor of Applied Mechanics he could be regarded as an 'outside inventor' for these inventions.

Although this was a substantial award compared with those of other claimants, Henderson felt that the originality and utility of his inventions to the country were still not being fully recognised. One letter from his solicitors in 1923 suggested, as some of his patents were applicable to aeroplanes, he could be regarded as an outside inventor for these. Eventually, all his claims were re-considered in 1931, during a five day hearing. The Commission's decisions are not recorded in the Treasury files, but the transcript of the last day on 16 December examined the development of the aeroplane gyroscopic turn indicator in 1918. Henderson was claiming that the Government had used the principle of his gyroscope in the RAE Turn Indicator, patented by Lindemann and Smith; somewhat similar to his case

against the Admiralty when Harrison and Rawlings had patented his gyro compass principle (See 5.4).

At the hearing, C.J.Stewart spoke for the Air Ministry and E.L.Pickles for the Air Inventions Committee. In January 1918, Stewart had moved from Martlesham Heath to the Air Ministry, where he was responsible for instrumentation until he became Superintendent of Technical Development at Farnborough in July 1925. In 1918, Pickles was Examiner of Inventions on the Air Inventions Committee and was involved with Lanchester's turn indicator, which the Treasury were using as a counter claim. Henderson explained he had assembled a prototype of his Rate of Turn Indicator for test, because he could not understand why the Static Turn Indicator was being used, unless it was for weight reasons. His device was a constrained gyro, belt driven via a shaft and universal joint, and weighed some 20-24 pounds (Fig 6.6). Henderson gave it to Stewart at the Air Ministry, who sent it for test at Martlesham Heath on 1 August 1918, where it was the first British gyro to be tested. Initially, it was over sensitive until the spring control was modified, after which it proved very positive and indicated the start and end of turns, including flat turns. G.M.B.Dobson, then at Martlesham, sent drawings and photographs to Farnborough on 26 August and wrote that the instrument seemed based on ideal principles, but it was unsuitable for aircraft in its present form and should be redesigned to half its present size and the gyro driven by air. He returned the prototype to the Air Ministry and wrote to the Air Inventions Committee that, as the device was similar to others, Henderson should officially submit his design to the Committee in case any

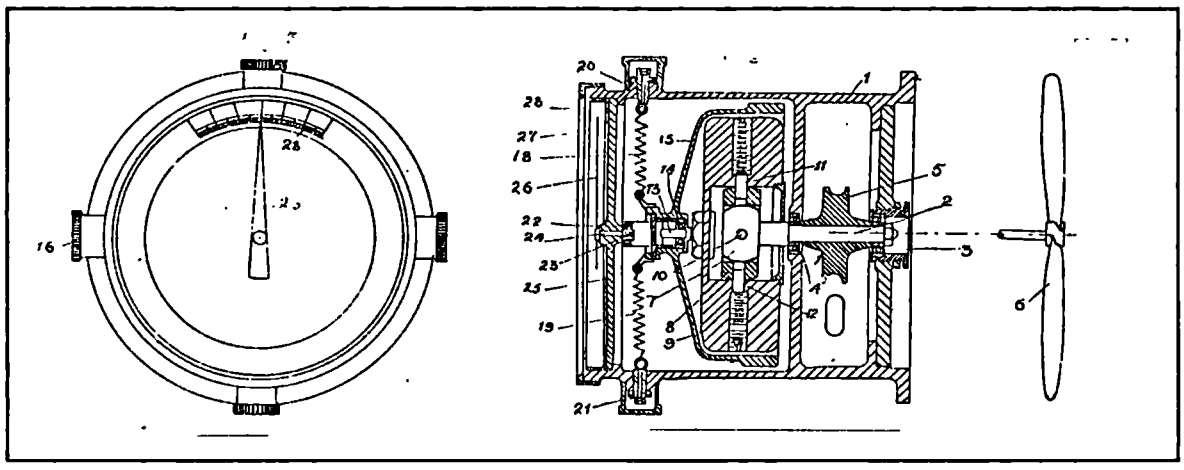


Fig 6.6. Henderson's Gyro Turn Indicator - original shaft driven version 1918
The pulley wheel *5* or air screw *6* drive to shaft *2* spins the gyro flywheel *9*. The Hooke or universal joint *10* allows the gyro and case to pitch about the horizontal trunnion axis *16* against the constraint of springs *18 and 19* and cause movement of the pointer.

question of priority arose. At Farnborough, Henderson's gyroscopic turn indicator was redesigned by Lindemann and Squadron Leader Norman to a more practical instrument, weighing only 4 to 5 pounds, by placing the gyro outside the fuselage and driving its rotor with the slip stream. Henderson included this design in his full patent specification 131,992 of August 1918 (Fig 6.7), as he believed Farnborough had given him permission to do so, but was later directed by the Controller General of Patents on 31 July 1922 to disclaim the construction shown, as he had made no contribution to them.

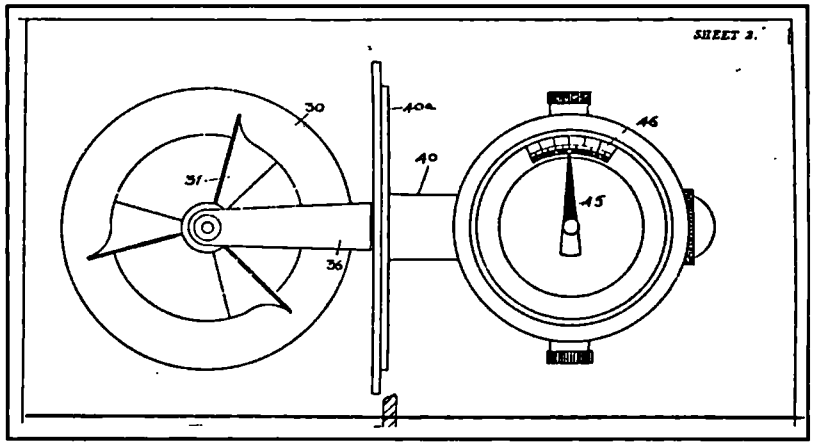


Fig 6.7. Lindemann and Norman's redesign, which appeared as Figure 5 in Henderson's Patent 131,992.

The hearing was told that the redesigned gyro was sent to Orfordness, who compared it with a Darwin static turn indicator, reporting on 25 August 1919 that the 'Henderson' turn indicator was far better than the static turn indicator. It showed a complete absence of lag, allowed the aircraft to be flown sufficiently straight in cloud to allow the compass to settle down and was easy to install and less liable to damage. The sensitivity of the gyro turn indicator for different size aeroplanes was easily adjusted by spring tension, while the sensitivity of the static turn indicator could only be adjusted by varying the spacing between the heads, which was difficult if the static tubes were mounted on the wing struts. The report concluded that the 'Henderson' turn indicator was the best gyro tested at Orfordness and was a great advance over the static turn indicator and had the additional advantage that it could also be used on aeroplanes with folding wings. It was returned to Farnborough with the recommendation to provide better tolerance to vibration, a larger dial and an adjustable zero. Subsequently, Farnborough made 70 of these turn indicators at £23 each and Hughes & Sons made 3 at £16, but they were only used experimentally and never entered squadron service.

At the end of his evidence Stewart agreed, 'that by introducing his instrument, Sir James Henderson had set the inventiveness of the Air Ministry at work'. When asked the difference between the Henderson and Lanchester instruments, Stewart replied that the Henderson was available to put on an aircraft, the Lanchester was not. Pickles was then asked to review the development of the Lanchester turn indicator, which F.W.Lanchester had patented as an *Improved Lateral Plumb Indicator for Aircraft*, (Application 18,292 of 1917, Patent 129,727 awarded 1919).

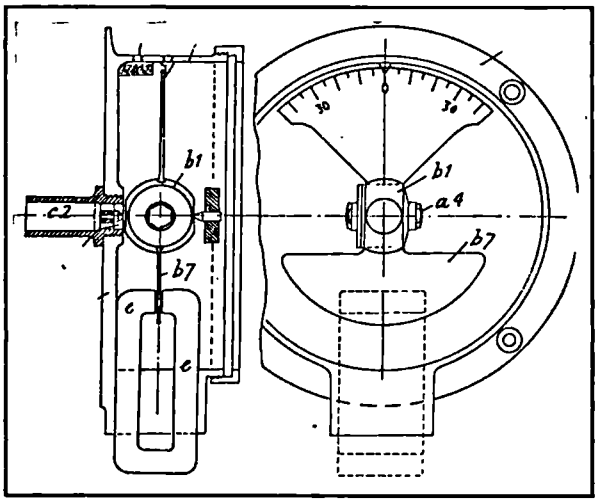


Fig 6.8. Lanchester's Lateral Plumb Indicator.

Lanchester was a member of both the Air Inventions Committee and the Gyroscopic Sub Committee and had communicated his invention to them on 13 December 1917. Various gravity controlled gyro designs were discussed at a meeting on 7 March 1918, at which it was decided to progress the Lanchester gyro rather than an alternative by a private inventor A.A.Macgregor. Lanchester produced the manufacturing drawings and two instruments were ordered for delivery in October 1918 and sent to Martlesham Heath for test. However, the war ended about this time and there is no record of the tests, except that Martlesham thought that the 'tiny' gyro was not large enough. The use of this small gyro becomes obvious if Lanchester's fuse Patent 129,026 of September 1917 is examined. This shows that he had designed the small gyro to bring the firing pin into action on a shell after the projectile had made a predetermined number of revolutions. Re-using the gyro design for an aircraft instrument would seem very practical.

Henderson explained to the hearing that a gravity controlled gyro was scientifically wrong for a turn indicator. Spring control constrained the gyro movement from precessing so that it indicated rate of turn, while the gravity controlled gyroscope was free to precess and

indicated the true vertical in a turn. A gravity controlled device, like the spinning top, was an angle of bank indicator rather than a rate of turn indicator, but it also had another undesirable property. In curvilinear flight, when the resultant force impressed on the aeroplane is continuously displaced from the vertical, the gyroscope wanders away from the vertical and the slower the growth of this disturbance the longer the gyroscope takes to recover.[18] Lanchester reduced this by maintaining gyro rotor speed proportional to aircraft speed, while Gray provided variable friction at the pivots by rotating them. Professor J.G.Gray's gyro was being used in 1918 to stabilise a RNAS bomb sight, where the requirement was true vertical (See 8.1 and 8.5). When Gray later gave a paper on his gyroscope, Henderson commented that it involved a discontinuity, which did not lend itself to easy computation.[19]

In summary, it would seem that Henderson's spring controlled gyro patent for measuring *rate of turn* was the precursor of those that followed. Although Lanchester communicated his invention in December 1917, Henderson's instrument was the first gyroscopic turn indicator tested by the Air Ministry. It was then completely redesigned by Farnborough, but never entered service although 73 instruments were made. As the Royal Commission summarised,

> It seems that there was some communication of something and that communication was made use of, although there had been a previous communication from another quarter.

What happened was that Farnborough further improved the slip stream driven turn indicator, and it was this instrument which entered squadron service as the RAE Turn Indicator and stayed in service until 1924.

6.7. Lindemann and Smith's Gyrostatic Turn Indicator

The improved design was completed by Lindemann and W.S.Smith in November 1918.[20] Lindemann's Pilots Log shows three flights in December 1918 as 'Henderson Turn Indicator', showing he had the opportunity to flight test this instrument before going to Oxford in January 1919. The Lindemann-Smith Patent 147271, which is dated 14 April 1919 after Lindemann had left, and shows the construction (Fig 6.9).

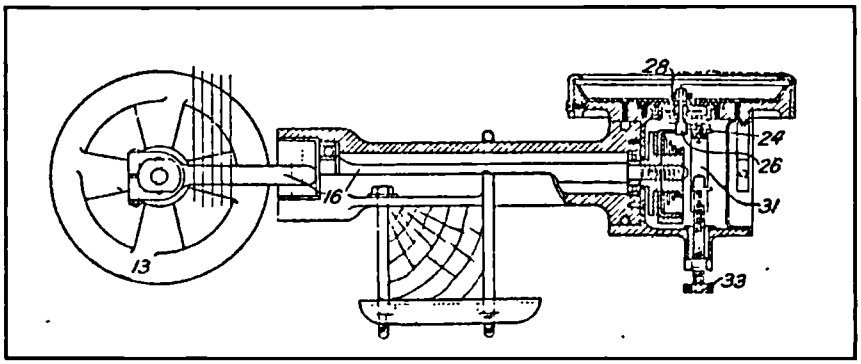


Fig 6.9. The Lindemann-Smith Gyroscopic Turn Indicator

The gyro was spring controlled and designed so that the rotor was outside the fuselage directly driven by the slip stream, and the indicator was inside the fuselage in front of the pilot. Vanes forming the web of the rotor produce a high driving torque. The axis of the rotor was parallel to the fore and aft axis of the aeroplane was mounted in a fork secured to a rotatable spindle. A turn to the right with this configuration caused the fork and spindle to rotate in a clockwise direction and the movement was transmitted to the pointer by gearing. Similarly, a turn to the left would produce an anticlockwise rotation of the spindle.

The instrument was further improved before it went into service by replacing the rotor vanes with obliquely drilled holes and making the sensitivity adjustable (Fig 6.10), and it

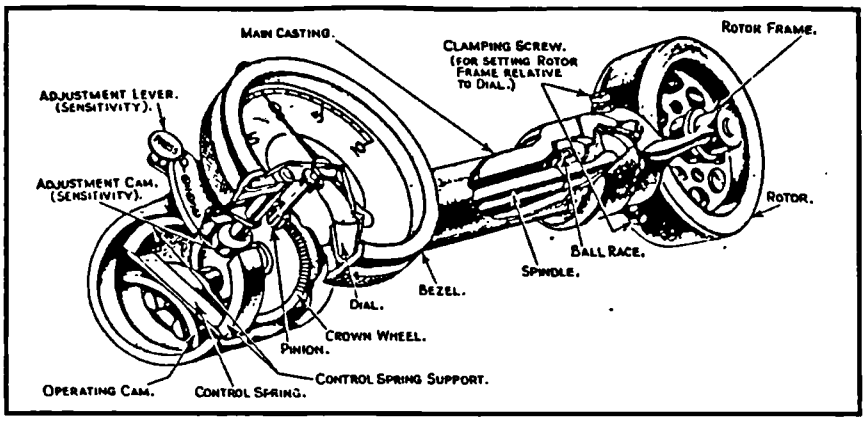


Fig 6.10. The RAE Gyroscopic Turn Indicator.

The web of the rotor was drilled with a series of oblique holes to produce a high driving torque and which proved more robust than the vanes originally tried. The sensitivity of the instrument for different aeroplane was adjustable by a flat control spring which pushed against an operating cam at the end of the spindle remote from the fork. The spring was arranged so that the instrument was most sensitive near its zero reading and became less sensitive as the rate of turn increased. The bearings were of the self aligning type and were protected from dust by small discs. Bearing wear proved excessive and was reduced by providing a brake to hold the rotor fixed when the instrument was not in use.

was exhibited at the Royal Society soirées in 1919 and 1920 together with several other Farnborough instruments.[21] It was later converted for night flying by rotating the

indicator through 90°, so it became an edgewise indicator which could be illuminated from behind.[22] However, bearing failure appeared under service conditions. The slipstream that provided ample thrust to drive the rotor also exposed the bearings to dirt, proving particularly troublesome on long distance flights like that from the Cape to Cairo on 26 February 1920.[23] In addition to the bearing problem, the instrument had to be carefully made to avoid needle vibration.[24] Modifications failed to overcome the problems and after exhaustive tests it was finally abandoned in February 1923 in favour of a more reliable and convenient gyroscopic turn indicator contained within the fuselage.[25] Nevertheless, the exposed rotor turn indicator, like the static turn indicator that preceeded it, had served its purpose as an intermediate step towards a more effective instrument.

Sperry took out patents for static and gyroscopic turn indicators, but they were later than the British ones. His static turn indicator has been discussed earlier. His first gyroscopic patent (American patent 1,309,489 of 8 July 1919) adopted the French spinning top gyro and overcame the wander by providing two tops spinning in opposite directions, leaving it to the pilot to decide which one to use![26] His gyroscopic turn indicator (American Patent 1,433,102 of 24 October 1922) was gravity controlled with springs to prevent it precessing too far and to simulate the pilot's normal view the outline of a radiator and its cap was painted behind the pointer. According to Hughes, this instrument suffered problems of acceleration and of being air driven.[27] He does not mention the Sperry static turn patent in his review of Sperry aircraft instruments, probably because its relevance to aircraft gyroscopes was not obvious to him.

6.8. The RAE Rudder Gyro and new turn indicators.

Sperry had developed an aeroplane autopilot for the Glen Curtiss flying boat before the war and Curtiss demonstrated that the flying boat could be flown 'hands off'. However, what he really demonstrated was that his machine was inherently unstable without the autopilot. The land version of this machine was sent to Farnborough and then to Upavon in 1915. It was found to be structurally weak, difficult to fly in anything but calm weather, and required a 600 pound weight in the nose to make it stable and was returned to its packing crate after the propeller shaft sheared.[28] Elmer Sperry visited Upavon and his representative Titterington was present during trials with the stabilizer, but the autopilot was not adopted as Factory aeroplanes were inherently stable, and it was too heavy to stabilize a machine for bomb dropping.[29] We shall see later (Section 8.2) that Keith Lucas salvaged the gyro units out of this Sperry autopilot for the first British stabilised bombsight.

However, although any stable aeroplane will fly straight and level 'hands off', there is nothing in its aerodynamic stability to ensure it will return to a given course following a disturbance. Interest in the automatic control of the rudder surfaced at Martlesham Heath when Tizard wrote to Titterington on 17 January 1917, inviting him to bring the Sperry Rudder gyro for test a week later.[30] After overcoming installation difficulties, flight tests in February showed the control to be 'jerky' and that the gearing (amplification) of the servo needed to be redesigned. There are no more reports about it after this time, but the aircraft was still there two years later when it was taken to Farnborough for its performance to be compared with that of the RAE rudder gyro control system, which Lindemann and Dobson were developing.

Although a rudder gyro is a servo mechanism rather than an gyroscopic instrument, both devices contain gyros and their development was related. The rudder gyro is a simple control system in which the precession of the gyro is used to actuate the rudder controls via compressed air cylinders to return the aeroplane to its former heading (Fig 6.11)..

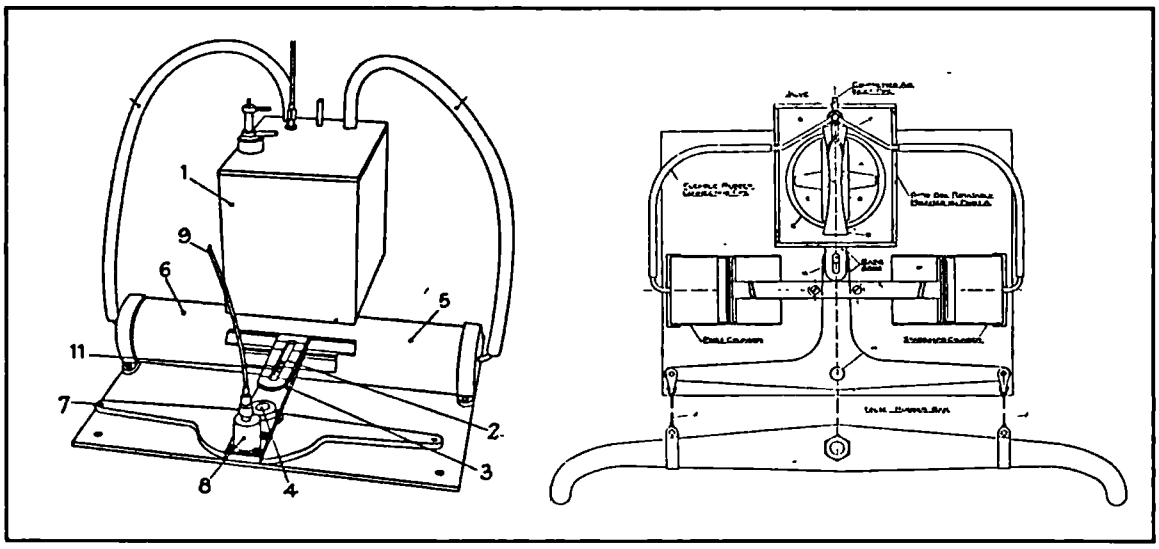


Fig 6.11. RAE Rudder Gyro control.

Gyro box 1 rotates about pivot at geometric centre. Link 2 is rigidly fixed to gyro box. Movement of gyro within box diverts compressed air to one of the cylinders to move axillary rudder bar 7 via torque arm 3. The axillary rudder bar 7 can be disconnected from the torque arm 3 by withdrawing pin 8 with Bowden cable 9 on malfunction. Normal disengagement was isolating the compressed air and linking the cylinders pneumatically. Feed back is via pin 11 to cause rotation of gyro box. Figures taken from Stewart book and Dobson paper.

Lindemann made six test flights in July, and 13 in August, with the RAE Rudder Gyro and he and Dobson were agreeably surprised to find that the very first device flew the plane about twice as accurately as a good pilot.[31] Their experiments renewed interest in the

Sperry version. Bourdillon flew down from Martlesham with their Sperry rudder control, which Lindemann tested on 17 December and again on 3 January, with Stewart as passenger. This was Lindemann's last flight at Farnborough before leaving for Oxford and there is no report on these tests.

The inability to disconnect any control system when it malfunctions is one of the worst problems that can arise with its use. With a rudder gyro control, if the rudder locked over and the emergency disengagement jammed, the situation could be fatal and Lindemann was well aware of this when he commented,

> Although there was a safety plug to free the gyro and another to disconnect the air pressure, my real faith was placed in a wire cutter I carried in my pocket and with which I could sever the cables leading to the rudder if everything else failed.[32]

This certainly showed a better understanding of control mechanisms than Kerr, an Imperial Airways pilot who was trying out the RAE rudder gyro on the Croydon to Paris run in 1925,who reported that after he engaged the rudder control he was able to walk back and talk to his passengers for twenty minutes.[33] Had the rudder gone hard over due to a malfunction, the gyroscopic torque of the spinning aeroplane would have prevented him regaining his seat. (Even today, one pilot must be 'strapped in' when flying on autopilot.) However, Kerr's report highlighted that the real advantage of the rudder gyro was to fly the machine when one engine failed. On two occasions, it saved having to make a forced landing, as he could not exert sufficient force on the rudder controls to hold course for more than a few minutes under these circumstances. Besides making the pilot's work less fatiguing under normal conditions and supplementing his physical strength when flying with a failed engine, the rudder gyro also made cloud flying easier as it continuously made small adjustments to heading without banking the machine. The rudder gyro was certainly a more practical and safer way to steer a twin engined aeroplane than attempt to control each engine throttle with a separate gyroscope, as Henderson frighteningly proposed in his Patent 135,267 of November 1918.

In 1920, Dobson exhibited the RAE Turn Indicator and the Rudder Gyro at the Geographical Society, together with a new Turn Indicator.[34] This was the Kingsway turn indicator, which had been designed by Stewart, W.W.Stainer and L.Burn at the Air Ministry in Kingsway, London. It was a panel mounted instrument with an electrically driven gyro to replace the Hooke joint of Henderson's original turn indicator, but the generic similarity is obvious (Fig 6.12).

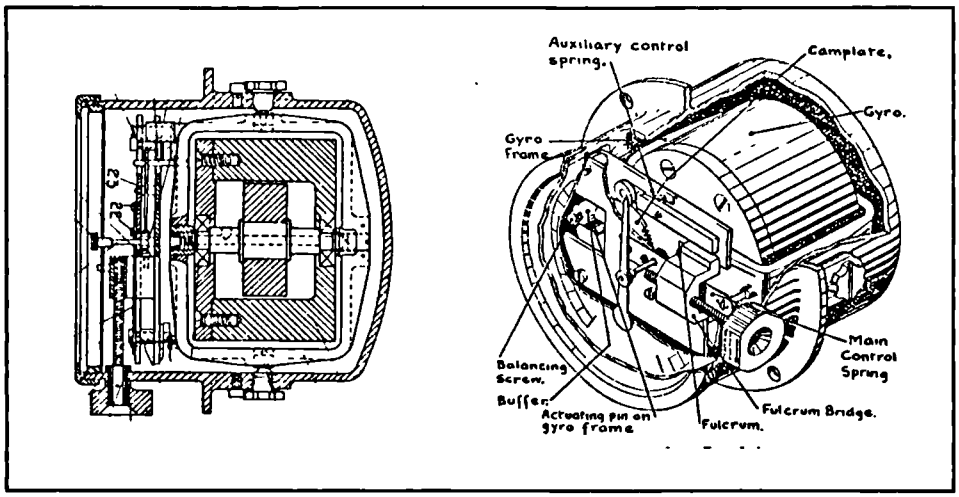


Fig 6.12. Stewart, Stainer and Burn's Kingsway turn indicator - 1920.

The new turn indicator proved successful and was manufactured first by S.G.Brown and later by Smith & Sons. This panel mounted type of integral instrument is still used on light aircraft today, and provides an appropriate point to conclude the history of early turn indicators. However, although they were available for military cloud flying, their reliability for early commercial use was still questioned.

6.9. Jones on cloud flying for commercial aviation

Commercial aviation in 1920 was very interested in cloud flying to maintain schedules in poor weather, but Melvill Jones, by then Professor of Aeronautics at Cambridge, considered the risk involved for commercial purposes was too great. This opinion was based on a review of instruments available for cloud flying. The static turn indicator had an excessive lag and relied on measuring small differences in the presence of possible violent pressure disturbances, which could easily put it out of order, while a kinked tube could prevent it working and the static heads could freeze up in winter conditions. The spinning top was a more responsive instrument, but could topple in a violent manœuvre and cease to function. The gyro turn indicator was the best instrument, but even with this he felt cloud flying was a difficult and dangerous operation and unsuited to commercial work. The particular gyro turn indicator he described was Lindemann's. No one argued with Melvill Jones' opinion, after all he had been in charge of wartime development of cloud flying at Orfordness. Bourdillon supported his view that the gyro turn indicator was now the best instrument for cloud flying, while General Sir Sefton Brancker took the opportunity,

> to praise the scientists who did the wartime research, who put danger aside and thought of nothing but progress and improving the conditions governing the use of aircraft.

Ironically, Brancker's own career ended abruptly ten years later when he died in the R-101 disaster, having failed to convince the authorities to cancel the flight to India as the airship was not ready.[35]

Conclusions

Cloud flying required a turn indicator or artificial horizon to judge orientation when the visible horizon was hidden to the pilot. Those involved in the development saw this to be gyroscopic, but there was no reliable small gyroscope technology or the resource to develop it. Lucas had developed a compass for cloud flying, which although it enabled a trained pilot to fly through cloud, did not allow him recover control if he lost orientation. The static turn indicator overcame this difficulty, but although it was simply a differential pressure gauge connected to static tubes on each wing, it required considerable research time and effort, first by Ogilvie and Tizard, then by Darwin and Mason and finally by Dobson and Lindemann, before it was successful. The ability to measure hydrostatic head of a few millimetres between the wing tips of an aeroplane travelling at over a 100 mph made the static turn indicator a remarkable instrument, but its real value was to separate the development of the turn indicator from the development of the compass, allowing the compass to revert to a navigational instrument.

Henderson pioneered gyroscopic rate of turn measurement at Greenwich Naval College to provide Farnborough and the Air Ministry with a design basis for their own turn indicators, and also established that spring control was better than gravity control, reflecting a similar argument with air speed indicators some years earlier. The gyroscopic turn indicator was a fast spinning, pivoted mechanism, requiring power to drive it, and was significantly different from other aircraft instruments, which were simple, self powered, acceleration tolerant devices. The first gyroscopic turn indicator was not tested until the war had almost finished and none saw active service. Lindemann played an important role in the whole development, test flying and improving the long period compass, the static turn indicator and the gyroscopic turn indicator. This two year wartime effort is ignored by his biographers in favour of his more controversial work on spinning, which took little more than two weeks. His association with Dobson during this work must also have influenced his decision to ask Dobson to join him at the Clarendon Laboratory.

The development of the static and gyroscopic turn indicator was a British one, funded entirely by the Government. The research and development were undertaken by the RFC with no RNAS involvement as they did not share the same interest in cloud flying. Like the development of the aircraft compass there was an element of plagiarism, but this time it was

by Farnborough rather than against them. Again, as with the compass the private sector was involved, but unlike Hughes, Darwin and Mason only provided the theoretical design and Cambridge Scientific Instruments were not involved commercially. In fact, the static turn indicator was the assembly of two RAF static heads and an Ogilvie indicator, which was being manufactured by the Aeronautical Instrument Company, formed exclusively for the wartime production of the indicator, and this use of the indicator came too late in the war to materially increase their production.

The French spinning top gyros proved insensitive and of limited use to the pilot, but testing them was useful to British research by proving with little effort that this form of gyroscope was not the way to go. In America, there was no research on aircraft turn indicators at this time and Sperry's first instrument patents were to copy the British static turn indicator and the French spinning top gyro.

Military cloud flying prepared the way for commercial cloud flying, where the question was no longer one of *safely* flying through cloud, but of the *safety* of flying through cloud, a subtle difference between military and commercial flying and one which is still significant today. The parallel development of the gyroscope to stabilise the bomb-sight will be examined in Chapter 8, while the next chapter examines the initial military and naval research on bomb-sights.

Equations for Static Turn Indicator

In Darwin's method, since properly aligned static heads indicated the true static pressure independent of the velocity, the pressure p on the membrane of the gauge during the turn was due to the centrifugal force acting on the column of air in the connecting tubes,

$$\text{i.e. } p = v^2/r \,.\, \rho l \cos\varnothing$$

where v was the velocity of the aeroplane, r the radius of the turn, ρ the density of the air in the tube, l the length of the tube, S the cross section area of the tube, and $\varnothing$ the angle of bank. With the correct angle of bank, the resultant acceleration force is at right angles to the wings and therefore $\tan\varnothing = v^2/rg$. Substituting this in the first equation gave the pressure p read by the manometer as $\rho g l \sin\varnothing$. This expression is also the same as the barometric pressure difference between two static heads on a wing of length l banked at an angle $\varnothing$.

The reason why pitot heads would not work can be seen by considering the equations involved. Pitot heads indicate a pressure $^1/_2\rho v^2$ in excess of the static pressure. The outer pitot would be moving faster than the inner by an amount $v.l\cos\varnothing/r$. The pressure difference due to this is $\rho v\Delta v = v^2/r \,.\, \rho l \cos\varnothing$, which is the same expression as the centrifugal force on the column of air between the heads and would nullify it.

Chapter 7.

Bomb Aiming Research Part 1
Commercial and Government Research to 1917

Summary : Pre-war development of impractical sights - evolution of simple sights from the block of wood and two nails - RAF Lever, Low Altitude and Periscopic sights - analysis of bombing errors by Lucas with Kymograph - development of practical CFS 4b sight for RFC by dedicated group at Upavon - Wimperis and the RNAS Laboratory at Imperial College - development of Attack Director, Batchelor Mirror, Trombone, Equi-distance, Drift and Negative Lens sights - adoption of some sights by RFC - some limitations overcome but the general problem to bomb in any direction remained.

Bomb aiming research formed a important part of military and naval aeronautical instrument research during the First World War period when the RFC at Upavon and the RNAS at Imperial College designed sights acceptable to their own service. It was closely integrated with the design of the aeroplane and the operational use intended for it.. On a tractor aeroplane, it was only possible to see the target ahead over the side of the aeroplane by removing a narrow section of the canvass on the lower wing, and only then if the aeroplane was not flying obliquely to its ground course due to cross wind. If the observer did the sighting, he needed some method to direct the pilot as voice communication over the noise of the engine was impossible, and he could not defend the aeroplane while he was aiming. If the pilot did the sighting, he could not hold the aircraft level without reference to the visual horizon. The rear engined pusher aeroplane with good forward view was seen initially as the solution, but this type of aeroplane could not ward off attack from behind and was generally restricted to night flying where danger was less. Many tractor machines carried a sight for both pilot and observer and let the circumstance determine who did the aiming. In June 1918, it was decided that individual bomb aiming from two seater aircraft would be discontinued where enemy formations were met and replaced by formation bombing, where the observer in the leading machine did the aiming, while all other observers defended the formation.[1] The pilots in these machines released their bombs when the formation leader fired a Very signal. These factors limited the RFC throughout the war to bomb up or down wind, as the heavy bomber with a forward view and separate gunner saw little active service. This limitation was unacceptable to the RNAS, who needed to attack a moving target like a submarine, but their flying boats had the advantage of a forward view, a crew of three or four, and did not fly in heavily defended areas.

The actual bomb sight appears of little interest in histories of strategic bombing or operational flying, and Jones is one of the few to describe them.[2] Sweetman's thesis on the First World War period ignores them completely, as does Kingsford when recounting two years as a bomber pilot, and Wise limits any reference to *not much good*.[3] The same is true of RFC wartime reports on the assessment of damage after raids - height, weather and accuracy figure prominently, but what sight was fitted and whether it was used, appear immaterial.[4] In this thesis the development of the sight is examined from the research reports of the scientists involved at Farnborough, Upavon, Orfordness, Isle of Grain and Imperial College. Many of these scientists have appeared in earlier chapters and to them bomb aiming was just another instrument problem to be solved.

7.1. Pre-war bomb aiming activity

Two pound bags of flour hurtling down at the squadron flagstaff in 1913 marked an early attempt at bomb aiming without the use of sights.[5] Pre-war accounts of bomb aiming are few, because aeroplanes were under-powered open-frame structures and military use was seen mainly as reconnaissance. However, reports like this did raise the question of bomb aiming at the Advisory Committee for Aeronautics and in response Horace Darwin proposed a liquid damped pendulum sight to view a target vertically below the aeroplane.[6] Such a sight allowed advantage to be taken of a German patent for projecting the bomb backwards from the aeroplane, with a velocity equal to the forward speed of the aeroplane, so that it fell vertically. Darwin obtained his vertical with a pendulum bob, made as a ring with cross wires, at the bottom of a 5 inch deep, liquid filled, transparent tube.[7] A concave-convex lens system allowed the eye to focus the cross wires and the ground simultaneously by drilling a small hole through the centre of the concave lens so that the convex lens, of focal length of 5 inches, focused the cross wires.



It was not the first time that releasing bombs vertically over the target had been considered. In May 1913, a plumb line had been used to sight a target vertically below the dirigible HMA Beta, from which 56 small practice bombs were released.[8] The intention was not to hit the target, which would have been impossible on a target vertically below a moving craft in a fairly strong wind, but to observe where the bombs landed in relation to it. This rather strange experiment is explained by the fact that the forward-downward view from the Beta was very restricted and prevented the target from being seen until directly above it.

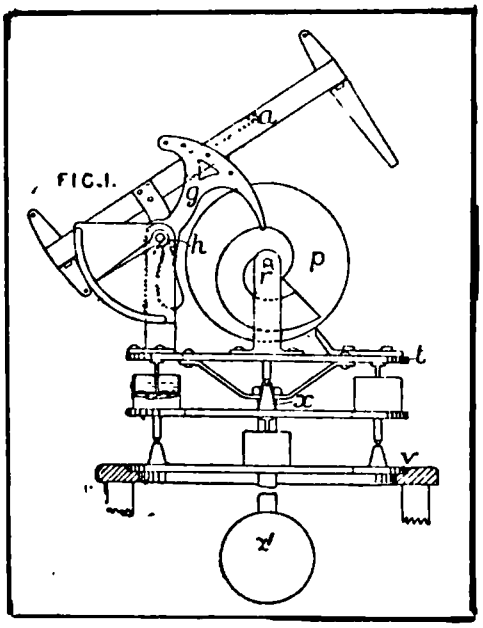


Fig 7.1 Kennedy Sight.

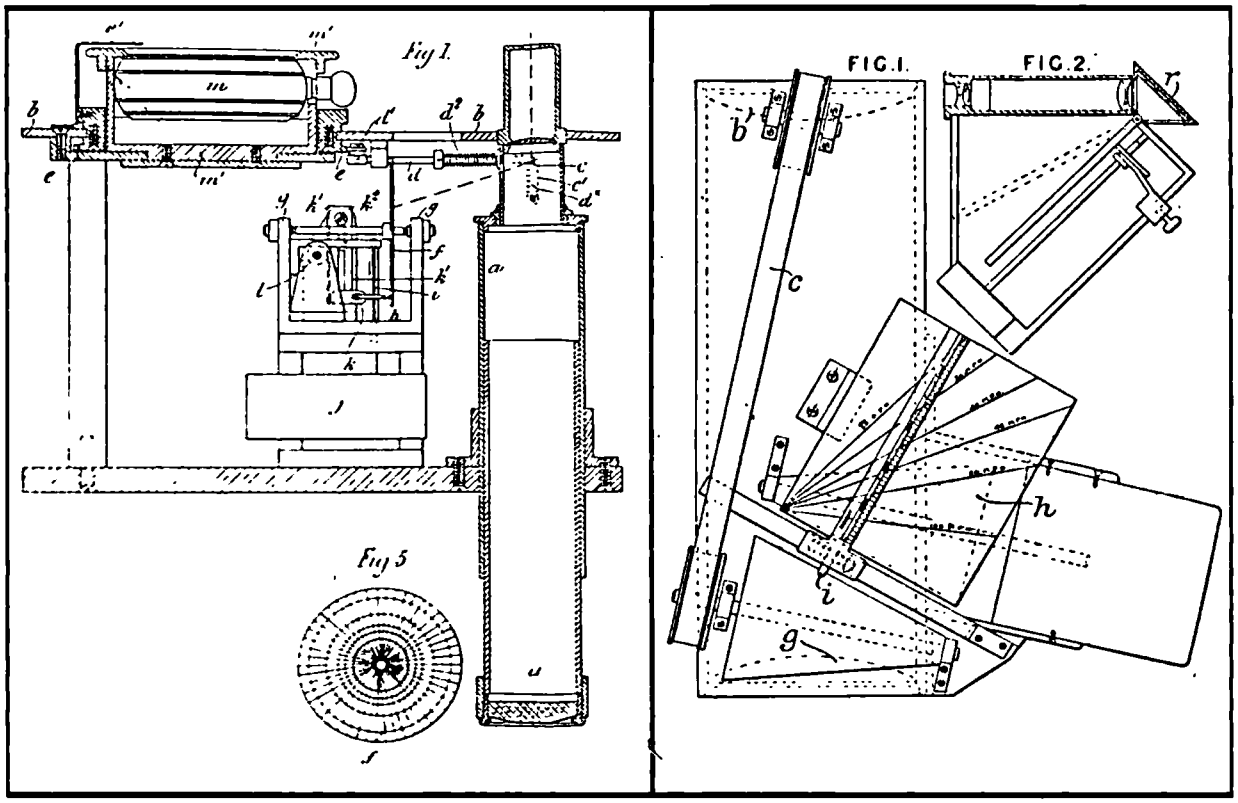
Early military bomb aiming experiments were also conducted by Major Musgrave in 1914, using C.J.Kennedy's aircraft bomb sight, Patent 27,940 of 1909.[9] This device was pendulously mounted in gimbals and the sighting arm angle set for height and ground speed by a style and cam arrangement. The instrument was more suitable for surveying than for aeronautics and Musgrave found it completely impractical and designed his own. This was made and patented by the British and Colonial Aircraft Company at Bristol, but he had no time to test it before the war started and he left for France taking it with him.[10] The Bristol sight was later tested at the Central Flying School (CFS) Upavon, but found unsatisfactory.[11]

In the pre-war period, Wimperis satisfied much of the ad hoc interest shown by the Admiralty in bomb aiming. At this time he was working for the Crown Agents for the Colonies and supplemented his civil service income with royalties from inventions and writing articles for the Times and Nature. After obtaining firsts in Mathematics and Mechanical Sciences at Caius, Cambridge in 1901, Wimperis had worked for the London, Brighton and South Coast Railway and for Armstrong-Whitworth. In 1909, he patented an accelerometer, jointly with Keith Elphinstone of Elliott Brothers, for use on rail and road transport, which was unaffected by directional change or track gradient.[12] Farnborough adapted it for use on aeroplanes (See 2.5) and Wimperis later wrote a book to publicise its use.[13] This early association with Elliott Brothers resulted in many instruments invented by Wimperis being made by them.

Their work on bomb aiming was not so rewarding. Wimperis kept a diary from 1907 to 1941, which each day briefly recorded briefly his work, where he went, who he met and wrote to, and personal social and financial comments.* He first mentions bomb aiming on 30 November 1912, when he lunched with Elphinstone and explained his idea of a device consisting of an Optical Speedometer and an Aerial Sight.[14] Agreeing that it was worth offering to the Government, they submitted a provisional patent in December, Patent 28,596, at about the same time J.L.Travers submitted a similar one (Patent 28,673). They met Travers in February 1913 with the view to combining their activities, but finding this

* The diaries have been condensed in this thesis by combining related events over short periods of time, usually a month. It would be confusing to attempt to reference the dates on which all the event occur and few actual dates are significant to the narrative. Referencing back to the Diary, knowing the year and month of an event, is relatively quick.

would be complicated as he was connected with the Admiralty Flying Wing, they decided to concentrate on the Optical Speedometer (Fig 7.2a). In April, Elphinstone took a model of it to show Capt. Seuter at the Admiralty, who thought it a valuable idea which should be kept secret. The patent specification was completed and a model made from it in July before Elphinstone discovered that R&J Beck, the optical instrument makers in Cornhill,



(a) Wimperis-Elphinstone (b) Beck-Marks

Fig 7.2 Ground Speed Indicators 1913

(a) The ground is viewed through telescope *a*. The aneroid *m* is linked to mirror *d* and adjusts it to reflect the correct graduations on the rotating disc *f* consistent for that height. Varying the speed of rotation of the disc until the graduations coincide with passage of ground objects gives ground speed. (b) The ground speed is measured by adjusting the speed of belt *c* to coincide with the passage of ground objects.

already held a similar patent jointly with A.S.Marks, Patent 3644/13 (Fig 7.2b). However, Beck's were happy to abandon their interest in this patent providing they could design and supply the optical parts for Elliott's device and further, as Beck's patent was open, there was no point in keeping Wimperis' patent secret. The new speedometer, now the Ground Speed Indicator was ready in August, Wimperis recording that *it looked rather heavy*. The Patents Office then drew their attention to Coursin's sight (Patent 9181/13), which Wimperis examined but felt that there was no infringement. The first Wimperis-Elphinstone Rate of Roll Indicator was also ready at this time, Patent 7285/10, but when Elphinstone took it to the Admiralty, he discovered that Professor Henderson at Greenwich

Naval College had invented one 4 years earlier, which had been made a secret patent, but nothing done with it. So while Elliott's continued with the Ground Speed Indicator, Wimperis started to think about a gyroscopic True Vertical (TV) Sight. In April 1914, Elphinstone and Wimperis went to the Admiralty to meet Harris Booth, who thought the Ground Speed Indicator was *forward for its purpose* and the TV sight looked promising, but neither was mentioned again until October, two months after war was declared.

7.2. Military bomb sight research at Farnborough - 1914-1916.

Farnborough tested a Marks-Beck ground speed indicator in May 1914 and found it useable but needed to be reduced in size.[15] In July 1914, they obtained a Cousin-Chaurviene sight , which had won the 1913 Michelin Bomb Throwing Competition, from The Integral Propeller Company Ltd of Elthorpe Road, Upper Holloway, North London. It consisted of a camera box arrangement, in which a wide-angle lens projected the image of the ground image onto a glass screen, together with the shadow of a variable speed electrically driven knotted cord, which was synchronised to calibrate ground speed relative to height. Hopkinson tried to locate this device later, but found that it had been taken to France where it proved impractical.[16] In March 1915, 50 Gould sights with the same projection principle were dispatched to France, and in August, the Quarter Master General tried unsuccessful to buy 25 similar sights from Taillefern in Paris.[17] There is no mention of their use, but any sight based on a camera box and variable speed electric motor would be heavy and cumbersome, the projected image of the ground on a screen would only be distinct in bright daylight conditions and the observer would need to shroud his eyes to view the screen, a risky procedure if enemy aircraft were about.

Such unsuccessful attempts to use commercially available sights were a desperate stop gap measure to meet operational requirements until a practical sight could be developed. The first service bomb sights were improvised from two nails driven into a piece of wood.[18] The device was fitted to the side of the aeroplane and adjusted to give the bombing angle when the target lined up with the two nails. Two wires stretched along the side of the fuselage, parallel with the centre line of the aeroplane and one vertically above the other, allowed the correct line of approach to be judged. The bombing angle was obtained from tables of the estimated height and ground speed of the aeroplane. Height could be taken from the altimeter and ground speed obtained by adding or subtracting wind speed to the indicated air speed, but the more usual practice was to assume values for them before take off. Variations of this principle would be adopted on most wartime bomb sights, different scales determining the version or mark of the sight. In the RAF Mark 1 Lever Sight (Fig 7.3), Farnborough replaced the block of wood and nails with a lever assembly to more

easily adjust the angle, but the device was soon rejected in service as the force of the slip stream could move the lever and the use of tables was inconvenient.[19] Simple sighting

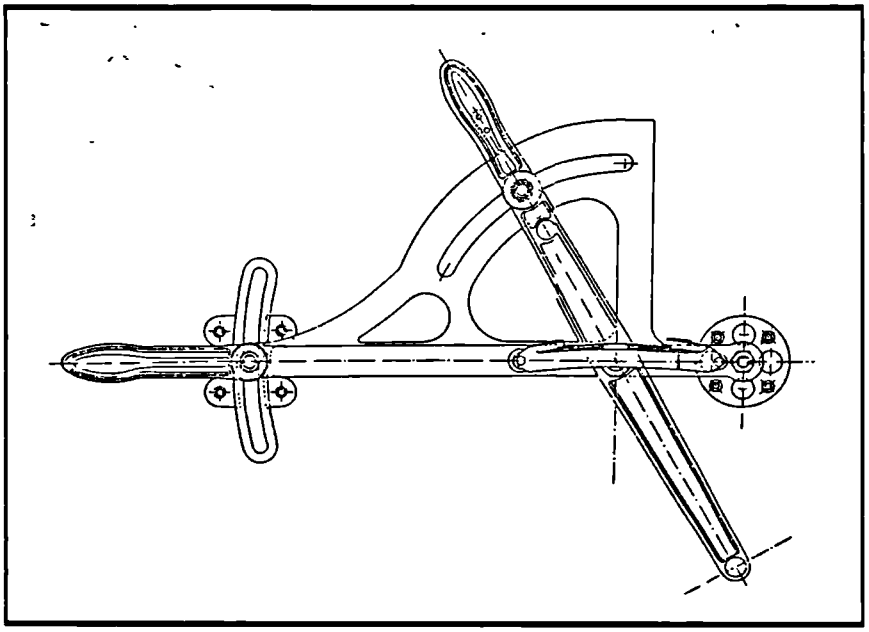


Fig 7.3. RAF Lever Sight Mark 1.

theory assumes the bomb is falling in a vacuum and the effect of air resistance, which makes it lag slightly behind the aircraft as it falls, is built into the scale.

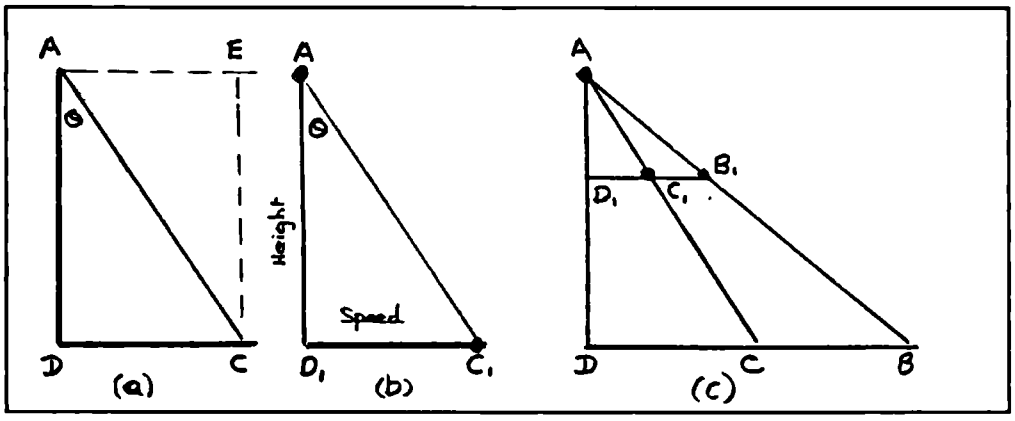


Fig 7.4. Simple Bomb Aiming Theory.

If an aircraft flying steadily from A to E releases a bomb at A, it will explode at C directly below the aircraft, which is now at E (fig a). The time taken for the bomb to fall to earth is equal to the time for the aircraft to fly from A to E. In a simple sight, the fore-sight C_1 slides along D_1C_1, scaled to ground speed and the back-sight A slides along D_1A, scaled to height (fig b). Ground speed is obtained, either by timing the passage of objects on the ground, or by adding or subtracting the wind speed to the air speed indicator reading. The former could be achieved by fitting a second fore-sight B_1 and note the time an object on the ground takes to pass between the two sights B_1 and C_1 (fig c). From similar triangles, the actual ground distance BC = Height AD x B_1C_1/AD_1, and dividing distance BC by the time gives ground speed.

Bomb aiming research at Farnborough was initially undisciplined. H.L.Stevens was assigned to help T.W.K.Clarke, who redesigned his sight every weekend.[20] This was a type of lever sight where the lever was placed across the diameter of a circular fibre tube, partially filled with mercury, which behaved as a heavily damped pendulum to counter the pitching motion of the aeroplane, but did not improve accuracy. Lucas produced his *space-damped pendulum.*[21] This had a pendulum with two cross bars floating neutrally in a transparent spherical liquid-filled container, which was viewed through Darwin's optical system. Being spherical like his compass, the liquid did not follow the oscillations of the aeroplane and the pendulum could be viewed at any angle. The aeroplane was first flown into wind by observing the passage of objects on the ground between the bars until no drift was observed. The sight was then turned at right angles and the ground speed found by timing the passage an object on the ground took to cross the two bars and tables used to set the correct bombing angle. The sight was scientifically clever, but asking an observer to sight targets through a transparent ball over the side of an aeroplane would be impractical, and Lucas would address bomb aiming more systematically later.

In June 1915, Professor Bertram Hopkinson was consulted on bomb sights and stayed at Farnborough four months. He had spent the early part of the year experimenting for the Admiralty on the effect of explosive forces on sections of merchant ship and cruiser plating, the test sections being floated on the Granta. This research was patented and his *bulge* was added to the waterline of all capital ships. During the spring, he conducted experiments to bomb a factory, specially constructed to $^1/_6$ scale at Hastings Field at Cambridge, to determine the best proportion of case and charge and the best material for the case.[22]

He conducted experiments with two bomb sights that Farnborough were developing, a simple low altitude sight and a periscopic sight. The low altitude sight was a re-engineered version of the lever sight and intended for use below 1000 feet (Fig 7.5).[23] The vertical height scale and horizontal ground speed scale were on the upper part of the instrument, easily seen by the pilot sitting centrally in his seat, and the sight bars were adjustable by notches for rapid movement with cold hands. The whole instrument could be moved along two slide rods for the convenience of viewing, and levelled and clamped to the trim angle of the aeroplane. No tables were needed and no help was provided to estimate ground speed. More importantly, below 1000 feet the aeroplane was very vulnerable to small arms fire and military bombing altitudes soon rose to 6000 feet making the sight obsolete.

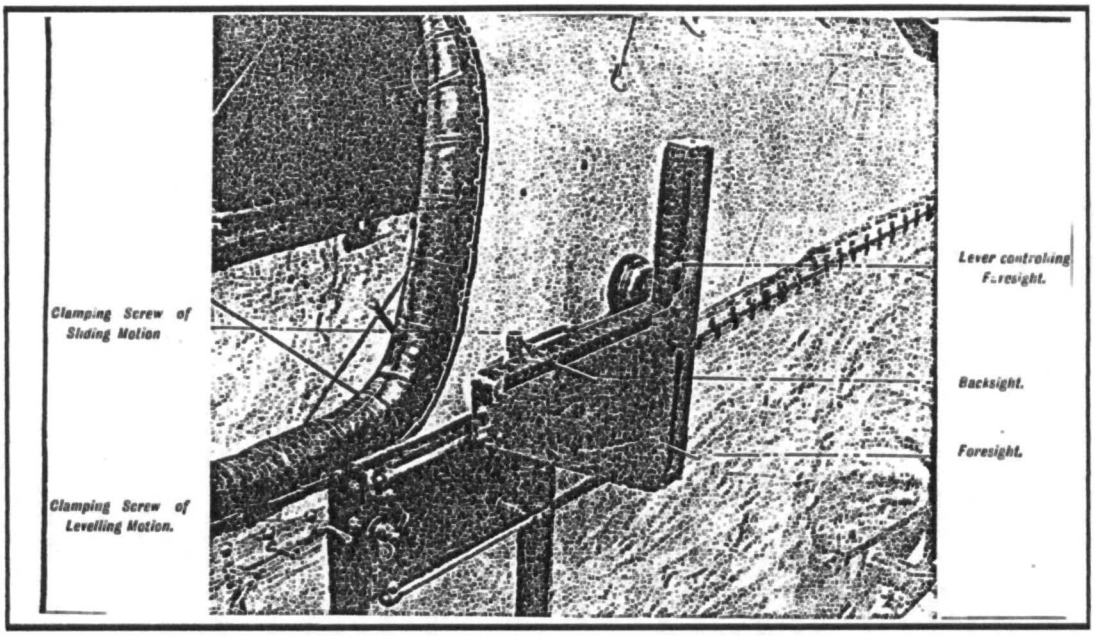


Fig 7.5. RAF Low altitude sights 1915

The periscopic sight was developed to compensate for the poor forward and downward view on tractor aeroplane by protruding below the fuselage (Fig 7.6). To control the angle of view, the lower prism was turned by an external drum, marked with height and time scales. The height scale on the drum set the angle of view to sight a ground object, the

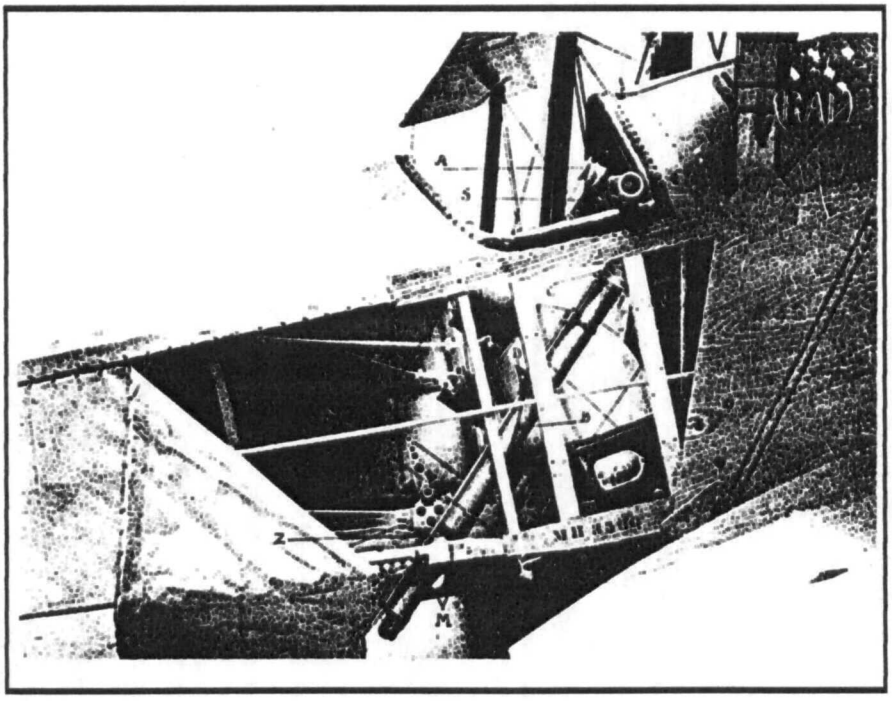


Fig 7.6 RAF Periscopic sight 1915.

drum was then turned back to its stop to direct the field of view directly down, and the time was recorded until the object was seen again directly below the machine. Setting the time scale on the drum to this recorded time gave the correct bombing angle to sight the target.

Notes by Mayo, as pilot and former student of Hopkinson, record a typical experimental flight across a camera obscura target,

> Attempting to fly over camera obscura, being directed to make various angled (course) settings by Professor Hopkinson, who was using a periscope. The angles to be turned through were signalled by an indicator moving over a scale marked in degrees. I had a rough sight for measuring angles of flight path fixed to the side of the machine. Attempts were failures because of difficulty of measuring angle turned through with such a crude sight. Professor Hopkinson's idea was to give one correction when the machine was 40° from the vertical above camera. This system seems to be hopeless. Correction should be continual until machine is approaching target within say 20° of vertical.[24]

In a later experiment, the limited field of view of the periscope and its alignment with the fore and aft axis of the aeroplane gave problems. The notes show the difficulty the observer had to direct the pilot, but the alternative was no better. If the pilot did the sighting, he could not fly the aeroplane level without reference to the visible horizon.

With compass errors explained and a new compass designed, Lucas took over the responsibility for bomb aiming experiments in November 1915 and on 11 November logged the first of many flights he would make with Mayo as pilot in BE 2c No.1688. As with his compass research, he first quantified the basic problem, determining that the accuracy of bomb dropping was linked with the oscillations, whether free or forced, which the aeroplane underwent in flight.[25] With any aiming device, the roll of the aeroplane made the target appear to move from side to side. As the pilot could not be sure whether this movement was due to roll or a heading change of the aeroplane, he instinctively banked to correct the aim. If the movement of the target in the sight was due to roll, the pilot made a series of unnecessary heading changes as he approached the target. Changes in pitch of the aeroplane involved no changes in heading, and were less problem.

To
Lucas devised a simple instrument recorded the roll and pitch oscillations manually (Fig 7.7), which ensured that a record was always obtained, which was not the case with photographic recording devices, like the ripograph. The instrument was called a Kymograph, from the Greek *kym* or wave, the name given by the physiologist Karl Ludwig to an instrument to record nerve fibre response.

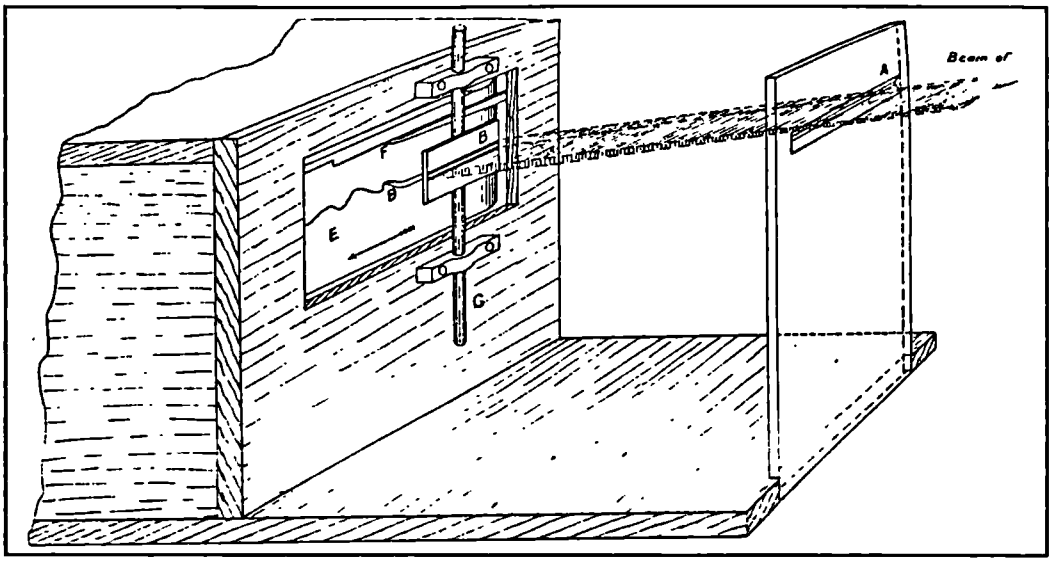


Fig 7.7. The Lucas Kymograph.

Sunlight passed through a slit in brass plate A to a moveable plate B, on which was painted a horizontal black band. The observer kept the band of sunlight on the black band by moving the plate B up or down with rod G, causing pen D to record the movement on a clockwork driven chart E. Timing was provided by pen F, which moves up for one minute and then down for the next.

Pitch tests were made heading away from the sun and showed an average variation of 0.6° in smooth air for a BE 2c, equivalent to 60 feet of target at 6000 feet. If the pilot tried to control pitch, the deviations grew worse as the small variations in indicated speed lagged 45° behind the change in inclination, and the pilot was therefore late with his corrections. Roll tests were made heading at right angles to the sun and showed a 2.5 second oscillation in bumpy air. However in still air, a slower 20 second time period was unmasked, which could not be changed by control. Lucas questioned if this was 'want of stability of heel, or the result of inaccurate steering; the aircraft really being on a banked curve when inclined'. The pilot had steered to keep the shadow of the struts along the wing, but had not attempted to keep the heading constant within 5°. He was provided with a more adequate steering device consisting of double reflecting mirrors, set 22.5° one to the other, which reflected a vertical beam of light on a paper screen on the instrument panel. This could be used as a compass card as the reflected beam in this optical arrangement did not change direction as the aircraft banked. The pilot was now able to control the heading within 1°, but the long period roll oscillation was only slightly improved. The research convinced Lucas that stabilising a sight for lateral error was the only way to provide an accurate sight and directed his research to experiments with gyroscopes.

7.3. Military bomb sight research at Upavon - CFS sights.

While this research work was progressing at Farnborough, the CFS at Upavon designed a sight to meet the immediate operational needs of the RFC. The development was initiated by RobertBourdillon, who gave a brief account of the work when he claimed an award for his sight after the war.[26] He conceived the sight while in the Intelligence Corp on the Western Front and was posted to the Experimental Flight at Upavon to develop it , but found Captain Soames reluctant to devote time to it. However, Lt. Dobson was more enthusiastic andBourdillon was given permission to make purchases up to £5, to use their 3" lathe and an air mechanic second class, and to travel to London if necessary. His initial design used clockwork to measure ground speed, but he and Dobson decided that the only practical clockwork available was a stop watch. The development resulted in the CFS sight, which is described in Fig 7.8. The height and time scales for the sight were both

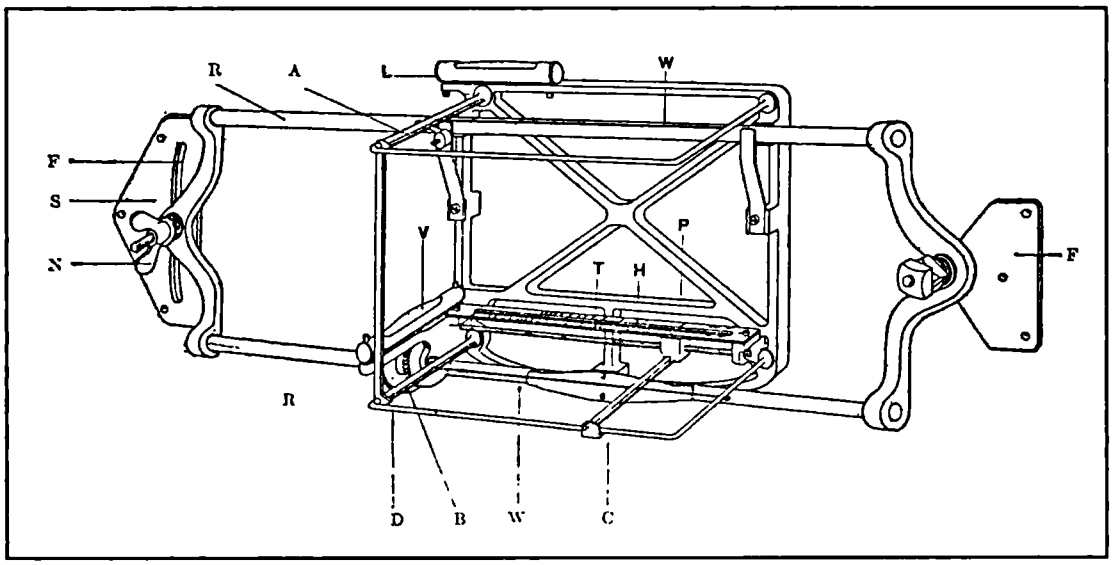


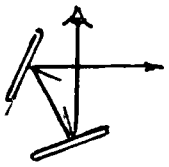
Fig 7.8. CFS 4b bomb sight 1916.

WW are two sighting wires, A is a fixed backsight, B is a fixed foresight and C a moveable foresight with index P, which moves along height scale H and time scale T. The ground speed calculation was simplified by making BC on the ground in Fig 7.4 the same distance irrespective of the height. This was done by placing the height scale on B_1C_1 which adjusted the distance between the two fore-sights so that BC on the ground was 1000 feet. With ground distance BC fixed, ground speed now became a time scale and was used to reposition fore-sight B_1 to give the correct bombing angle.

horizontal and this arrangement became known as the CFS scale. The sight went into production as the CFS 4b and was made by Cassella. Hopkinson rushing the first nine to France, followed by 25 RAF periscopic sights.[27] Although one of the best wartime

sights, it was never patented. Bourdillon's post-war claim was straight forward and was dealt with by the Air Ministry Inventions Committee. Dobson, then at Farnborough, wrote thatBourdillon was entirely responsible for the design although Casella helped with details. Wimperis, representing the Inventions Committee, said the sight was entirely novel in 1915 and although it was called the CFS 4b, he had never come across a CFS sight bearing an earlier number. In March 1921Bourdillon, back at Oxford, received £400 for his design.

Course or line with the CFS sight was provided by its framework of two horizontal rods mounted one above the other, but an optical alternative was sometimes fitted. This



consisted of two mirrors set 45° apart, which allowed the observer to check his level by the side horizon. It was patented by L.C.Cowey of Alexander Works, Station Avenue, Kew Gardens, Patent 5750/15, as one of many patents he took out.[28] A questionnaire in 1916 to determine the usefulness of this optical system was inconclusive - answers varied from 'very useful', 'no instructions provided', 'not used', and 'not supplied'.[29]

The CFS 7 produced in 1917 was a modification of the CFS 4b specifically for the FE 2b pusher night bomber, which usually made a diving approach to its target.[30]

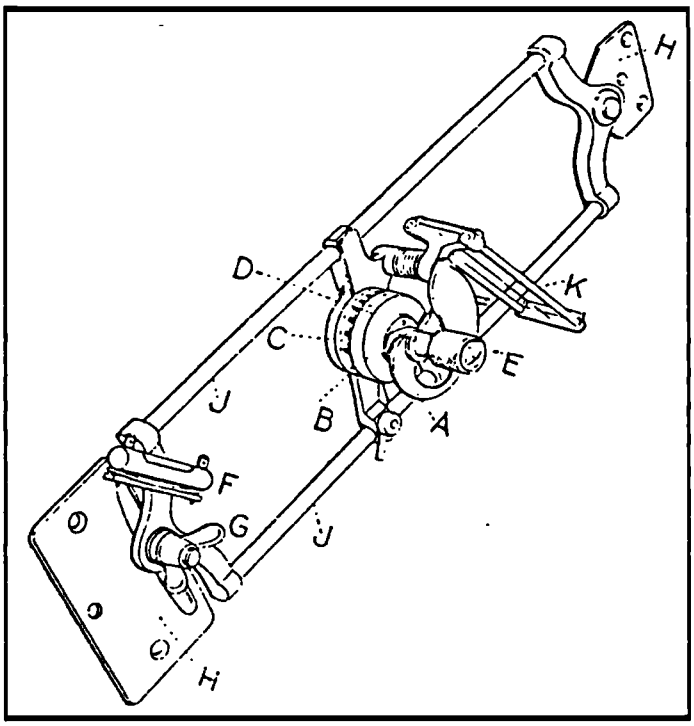


Fig 7.9. CFS 7 Bomb sight for FE 2b - 1917.
The line of sight is given by frame K, which also carried the fore-sight and back-sight wires. The frame is adjusted to the correct bombing angle by the cam A, which is controlled by the height and ground speed scales on the drum B and C.

It was designed to be fitted to the side of the fuselage, which was pointless as the observer in a FE 2b had an uninterrupted forward view. The sight was modified in the field so that only the cam assembly was mounted on the front of the nacelle. However, this was still unsatisfactory and observers found the slope of the nacelle was just as accurate and trials to replace the sight were abandoned when the war ended.

The use of the camera obscura by Tizard, Dobson and Bourdillon at the CFS has been discussed in an earlier chapter. While Lucas was measuring the dynamics of a bomb dropping aircraft with his kymograph, the camera obscura allowed the CFS group to quantify the dynamics of bomb dropping from the ground. Both devices allowed movement in three dimensions to be recorded in two dimensions, both were simple and accurate and their importance to research at this time was significant. The camera obscura was initially used to monitor the path of the bomb after leaving the aeroplane, but once a sight was developed the camera obscura was used also to train pilots on bomb aiming without having to drop actual practice bombs. Seen from the aeroplane, the bomb appears to remain vertically below the aeroplane or lag a little behind it due to air resistance as it falls to the ground. Knowing the altitude and ground speed of the aeroplane, the point at which the bomb would strike the ground can be estimated. The method involved the pilot flying towards a target near the camera obscura, setting his sight as described and transmitting a wireless at the moment he would have released his bomb. Plotting the path of the aeroplane on the camera obscura and marking the point at which the wireless signal was transmitted, allowed the point of impact of the bomb to be estimated. Accuracy was found to be very dependant on the commitment of the operators.[31]

7.4. Wimperis and bomb sight research : 1914-1915.

Wimperis started his war by taking a holiday with his family which had been planned earlier, but in October he discussed three ideas for bomb sights with Elphinstone and Conrad Beck, who agreed the best idea was still the TV sight and War Office and Admiralty versions were planned with gyroscopic experiments at Elliott Brothers Lewisham Laboratory. Almost immediately, Wimperis thought of a simple optical TV sight based on binocular field glasses, which Elphinstone had made in six days and showed to Col. Brancker at the War Office. Brancker took it to Farnborough and Wimperis wrote to O'Gorman suggesting that Farnborough should ask the Crown Agents for his service to develop the apparatus. Wimperis and Elphinstone visited Farnborough at the end of October to see what progress had been made with the binocular sight, only to find that nothing had been done. Wimperis recorded that O'Gorman was *ludicrously*

emphatic against any co-operation in research with the Admiralty, however, he arranged for Wimperis to fly with Busk to test the sight for himself. This was the first time that Wimperis had flown and made aware of engine vibration, noting that *the TV Sight promised well, but the practical difficulties due to vibration were great.* He was begining to realise the problems faced by any aircraft instrument.

The Crown Agents reluctantly agreed to Wimperis spending a few days at Farnborough and he asked O'Gorman to tell Elliott Brothers to make models of his instruments at once. During the first two weeks of November, he visited Farnborough three times, one on the day following Busk's death. He had discussions with T.K.W.Clarke and R.H.Mayo on their damped mercurial pendulum, took measurements on a BE, and returned with a wooden model of his ground speed indicator, only to confirm his original fear that it was too heavy. Between these visits, he discussed acceleration forces on aeroplanes with Bairstow at NPL, bomb dropping with Darwin, Whipple and Mason at Cambridge, and had design reviews with Elphinstone and Beck, who suggested fixed magnification would halve the weight of the optics. Visiting Darwin to discuss bomb dropping was probably associated with a bomb sight that Darwin patented with Booth at the Admiralty Air Department.[32] This was a carefully balanced optical version of the lever sight in which the target was viewed through a half mirror on a lever arm, that also reflected the sighting angle from a graduated circular scale, the correct sighting angle being taken from tables of height and ground speed. Darwin referred later to an elaborate sight he designed at this time that was too difficult to manipulate and abandoned in favour of research by Dobson at Upavon.[33] During the second half of November, he worked out the theory of damped mercurial pendulum, discussing it with Clarke, Mayo, Lucas, Short and McKerrow at Farnborough. He also carried out gyro experiments at Lewisham, sometimes with Booth and Bramwell in attendance. In December his work load reduced when Farnborough decided to abandon the damped pendulum, but was replaced by a request from the Admiralty for help with their sights.

In the first half of 1915, Elphinstone asked Wimperis to help Professor Henderson at Greenwich Royal Naval College with his gunnery gyroscopic fire control equipment, which Elliott Brothers were making for the Admiralty. To meet this request, Wimperis regularly visited Greenwich in the morning for discussions and lunch with Henderson and then travelled by tram to Lewisham for gyroscopic experiments, some of which were witnessed by Booth and Bolas. Booth also asked his help with stress calculations to determine the source of resonance being experienced on a large flying boat, and Upavon asked for his help on bomb dropping apparatus. Wimperis tried to meet all these demands with the result he became seriously ill and was confined at home for most of May and June.

7.5. Naval bomb sight research at Imperial College 1915.

In July 1915, the Admiralty realised that the only way to secure his services was to offer him a commission as Lt. RNVR, under Cmdr. Finch-Noyes on air invention work at the Admiralty Air Department, knowing that the Crown Agents could not refuse to second him. Before his commission came through he visited Farnborough once more, where Hopkinson was now involved on bomb aiming. He started work at the Admiralty on 30 August 1915 and on the following day went with Booth and Bolas and others to the Army Flying School at Northolt to examine the Sperry Stabiliser. Finch-Noyes' group was temporarily housed at Victory House in Cockspur Street, but was anxious to move to the main Admiralty building as Victory House was also the address of Lord Fisher's Board of Invention and Research. Wimperis was to work for Lt. Batchelor, but was first sent to Calshot Air Station for *air experience*, involving bomb dropping with Cmdr. Travers, whom he had met two years earlier. The experience brought home to Wimperis that **naval bomb aiming had no scientific basis** and that experimental flights could be curtailed by rough weather, engine failure, a broken propeller, the wrong pitch on the replacement, or diverted into a real mission, when a German submarine was sighted off the Nab. He spent any non-flying days getting a Sperry stabiliser to run.

He returned to London in late September and was able to continue discussions with Elphinstone and Henderson amongst his new work. However, lunch at the Royal Automobile Club with Dugeld Clark on 29 September proved an important meeting, recording in his diary that 'Clark thought Dalby's Lab will be at our disposal for the asking'. Clerk was a consulting engineer, who Wimperis frequently met and had known for many years and who had just turned down an offer to join Fisher's Board. Wimperis went to Imperial College the following day to see Professor Dalby (Mechanical Engineering) and Professor Callendar (Physics) and found the latter very willing to help with the construction of apparatus. This help was immediately accepted and within two weeks Callendar's technicians had made a Course Recorder, which was also referred to as Callendar's Mirror and must have been similar to the mirror designed by Batchelor for bomb aiming practice, known at this time as the Instructional Mirror, several of which were being made at the RNAS Depot at White City. Batchelor and Wimperis visited Dobson and Bourdillon at Upavon to find out more about camera obscuras, which they were using for the same purpose, and left them a Batchelor Instructional Mirror for experiment. Wimperis met Hopkinson on two occasions during October, the second time when Hopkinson was dropping bombs from the airship SS-14 'with a useless sight of his own'.

On 28 October, Callendar showed Batchelor and Wimperis the private laboratory he could place at their disposal. The new buildings at Imperial College had been completed just prior to the war and were empty of students. The Governors were agreeable to the Physics Workshop and such rooms as required being placed at the disposal of the Admiralty, free of rent and of the salaries or wages of any college staff involved. The only cost to be paid by the Admiralty was for materials consumed, overtime and war bonus payment and the total cost to the Admiral was only £627 over the next two years.[34] The generous arrangement agreed by the Governors was probably influenced by two factors. They were anxious to involve the college directly with government research as it was already proposed to make Imperial College the centre of aeronautical education and research after the war; and the original letter from the Admiralty was so worded that they *might* reimburse the College before asking the cost, implying that only a very reasonable cost would be met.[35] Wimperis had also been offered A.P.Trotter's Laboratory at the Board of Trade, but did not accept it.[36] Dalby's mechanical engineering laboratory would later undertake predictor design for A.V.Hill's Anti-Aircraft Experimental Station as well as other government work.

Two days after being shown the laboratory facilities, Wimperis invented his Attack Director, which was a linkage to determin the course to steer to reach a submarine sighted on the surface, assigning the patent to the Admiralty on 23 November three weeks later.[37] Callendar immediately started work on the prototype model, while Wimperis used Mecanno to experiment with its use. He moved into the laboratory on 26 November, after which his diary each day was usually *Admiralty and Lab*, or *Lab and Admiralty*. During December, he designed a low height bomb sight. Batchelor was at Grain testing his Instructional Mirror, but was replaced by Wells when Batchelor went to Upavon to learn to fly. On one of his visits back to the Laboratory, Batchelor hit on the idea of superimposing the CFS scale onto his mirror, which turned it into a very practical training device. Wimperis had discussions with many people, including Sir Napier Shaw and Professor Frewen Jenkin, Professor of Engineering Science at Oxford and now also Lt. RNVR .[38] Jenkin was in the Materials Section of the RNAS Technical Department, who were taking advantage of laboratory space at Birmingham and Manchester Universities and at the Royal College of Mines. David Pye, formerly on his staff at Oxford, would later work for Tizard at Martlesham Heath.

7.5.1. The Batchelor Mirror.

The RFC were using camera obscuras for practice bombing in 1915 and the RNAS had been considering the use of the same relatively expensive and calculation intensive equipment. Bachelor's Mirror was a more simple and portable optical system, consisting of a horizontal mirror with a hole sight fixed 10 inches above one edge (Fig 7.10a).[39]

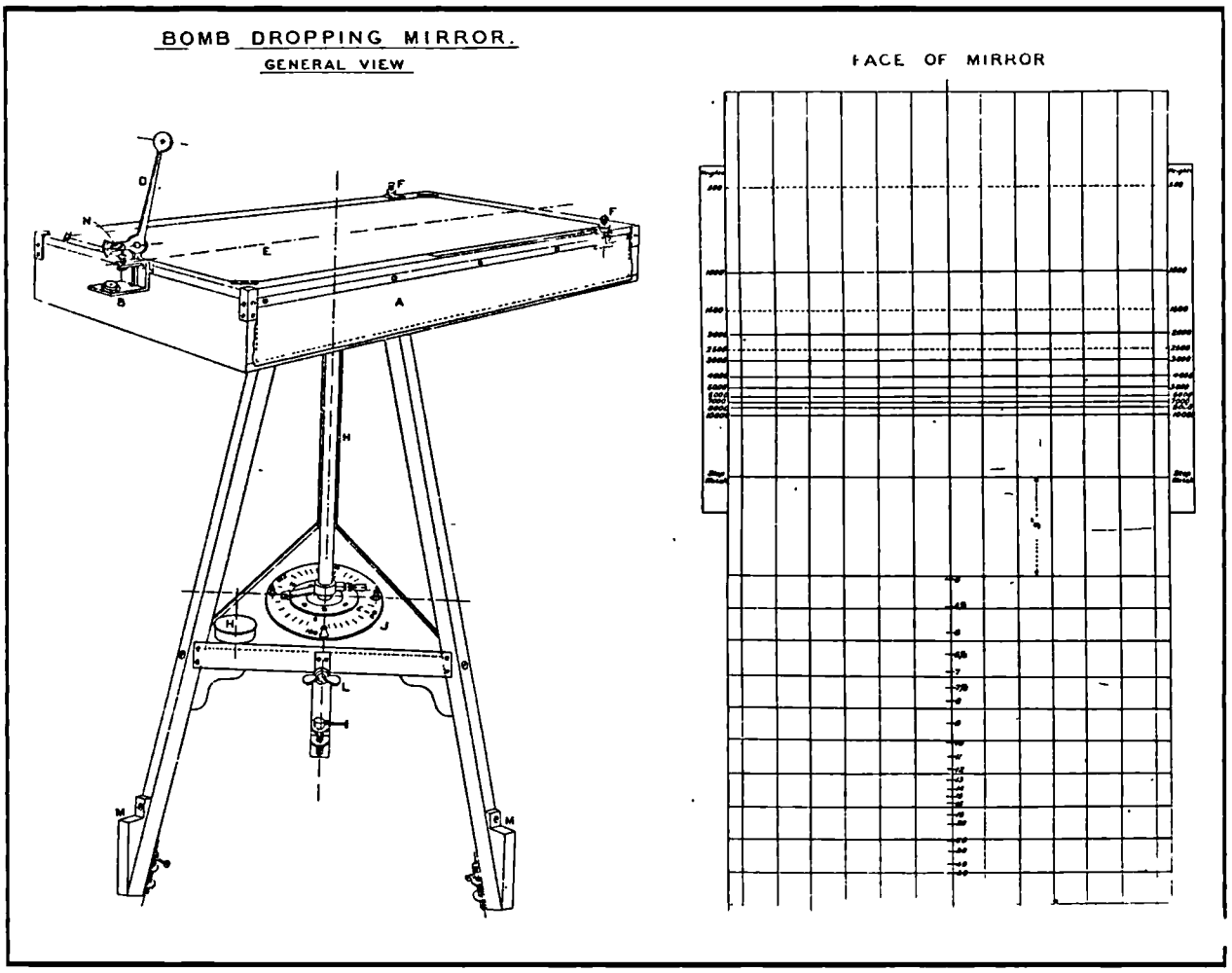


Fig 7.10. (a) Batchelor Mirror (b) CFS Scale on mirror.

The mirror was positioned at the target point and the reflection of the approaching aeroplane in the mirror was viewed through the sight hole. The pilot flew at a pre-arranged height and signalled by wireless or Very pistol when he judged he was correctly positioned to release a bomb at the target. Adding the CFS scale to the surface of the mirror (Fig 7.10b) allowed the bombing accuracy to be determined without calculation. Lines were drawn across the mirror for each 1000 foot height, scaled so that the actual distance travelled by the aeroplane as its reflection passed between the any height line and the base line was the same

at any height. Therefore, the time in seconds for the reflection to move between a height line and the base line gave the ground speed of the aeroplane, and the mirror operator had only to keep the centre line of the mirror parallel with the course of the aeroplane, note this time, and mark the point when the pilot signalled the release, to locate a marker at the estimated point of impact.

Bachelor also designed a Bomb Dropping Teacher or what would now be called a simulator. The nacelle of a bomber, with a CFS 4b sight fixed to the side, was positioned 25 feet above an endless belt of simulated ground scenery, driven at a speed consistent with the bombing height being simulated. A lamp directly below the sight was flashed on, after a timed delay representing the fall of the bomb to illuminate the range error.[40]

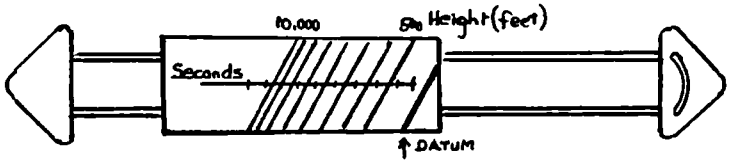
The Bachelor Mirror was secretly patented (17082/15) and 273 were made in the U.K. at a cost of £145 each. Of these, 16 were sent to America and another 41 were made over there. The Admiralty awarded him £100 for his invention in February 1917 and he received a further £400 from the Air Ministry in October 1919. In 1921, Major Bachelor crashed in a Handley-Page bomber he was piloting and was killed, and Wimperis suggested to his widow that it might be possible to claim for the American use of this invention and that he would represent her at the hearing to save solicitors fees.[41] The Treasury argued that the invention was little more than a nephoscope used by the Meteorological Office to measure cloud speed and coverage, that the CFS scale was not Bachelor's invention, that he was employed to carry out experiments on bomb sights and bomb dropping and that the development had been at government expense. Wimperis contended that they had never heard of a nephoscope in 1915 and Bachelor alone had thought of adding the CFS scale to the mirror. The Commission finally awarded £50, based on the fact that awards for British use had already been made and that the extended use in America was not pro rata.

7.6. Research at Imperial College 1916

In January 1916, Callendar finished the first Attack Director and first Instructional Mirror with the CFS scale and Wimperis and Wells took both for trials at Grain. Wimperis was also transferred from the RNVR to the RNAS Armament Department during the month. February saw two new inventions, Wimperis conceived the idea of a sight using the measurement of drift instead of turning into the wind, and he and Wells thought up the idea of a plano-convex lens mounted in the floor of the aeroplane. Wimperis immediately visited Beck, who got Bisacre in the company to make the first one a week later. This 'glass eye' provided the pilot with a forward view that was otherwise obscured by the

engine. It was initially called the Porroscope, an instrument for looking forward, and when provided with sights became the Negative Lens bomb sight. Both these ideas were significant, the resulting sights would be made in their thousands and the drift sight would set the future path for sight design. O'Gorman visited Wimperis at the beginning of the month 'to bury the hatchet', but whether this was because Wimperis had cast his lot with the Admiralty is not recorded. At this time, Wimperis and Batchelor were also working on a camera obscura lens for Eastchurch, where there was urgent need to improve the speed course, which at this time was along rising ground and used still using flags and stop watch.[42]

The next three months were busy ones. In March, Batchelor was posted to Cranwell and Wimperis was given control of the Laboratory, with Lt Childers as a new assistant. This released Wells to go to Grain for ten days to carry out trials with the Porroscope and new Bomb Dropping Mirror. He returned briefly to remove the lens from the Porroscope and use the housing to provide a quick prototype for Scarff's Equi-Distant bomb sight. The new Bomb Dropping Mirror was most likely a sight which Wells had designed to avoid leaning out over the side of the fuselage to sight the target.[43] It consisted of a long narrow mirror fitted on slides to the side of the fuselage, roughly at eye level and forward of the observer. It was angled at 45° to the horizontal plane to reflect the ground while the observer remained seated and had height lines etched obliquely across the mirror and a timing line along its centre line. To use the sight the time in seconds was noted for the reflection of a ground object to pass between a datum line and the appropriate height line on the mirror. The bomb was then released when the reflection of the target reached the appropriate seconds mark. The device was in fact a Batchelor mirror mounted in the aeroplane, but although the idea was good one, the sight was rendered useless by the mirror misting up.



Travers was still conducting bombing trials and Wimperis visited Calshot to examine a sight he had just made, but found it useless. Wimperis was also given wider research as he was in the Armament Department, which included the theoretical calculations of bomb trajectories, timing the fall of different sized bombsdown a coal mine near Doncaster, and work on a sight to aim Ranken's Firey Darts at Zeppelins. He was also involved with machine gun sights and asked Elliott Brothers to make 100 Le Prier sights, as well as patenting his own gun recoil method. On top of all this, he was made a member of the Advisory Committee for Aeronautics and was grateful when Lt. E.C.Horsley was added to his staff. In May, Wells completed successful trials with the drift Sight and Wimperis was given permission to proceed with it. His own Gyro True Vertical Sight of a year

earlier, now re-named Gyro Director Sight, also turned up at last from Elliott Brothers, who were now also conducting gyro experiments with Dr Gray of Glasgow University.

Callendar was very keen to expand the Imperial College work and in June 1916, Wimperis discussed it with Sir Alfred Keogh (Rector) and Professor S.M.Dixon (Civil Engineering) before taking Captain Davis and Commander Seuter round the laboratories. Seuter asked Wimperis to write a report on the whole plan to use the college for training, research and administration of both air services. This report was issued under Seuter's name and contained dramatic proposals, which had they materialised could have changed the future of Imperial College.[44]

It supported the view of Haldane and Churchill that the Sea Lords had given no assistance to create the naval air service, and had on the contrary hampered it in every possible way and this attitude continued. The organisation of the RNAS was a jig-saw puzzle. It was administered by the Air Board, the Admiralty, the Commander-in-Chief Western Front and Senior Naval Officers. Research was carried out mainly at NPL and Imperial College, but also at Greenwich Royal Naval College, London University Laboratory, Finsbury Central Technical College and Oxford University; while inventions were handled by the Air Department, the Air Board, the Advisory Committee for Aeronautics and the Naval Board of Inventions and Research. The report proposed that the Naval and Military Air Services should be amalgamated and that their research should be brought together under one roof at Imperial College. The buildings of the Physics and Chemistry Departments were sufficient initially for bomb sighting, signalling, air speed measurement, navigation, gyrostats, W/T, gun sighting, magnetic and gyro compasses, engines, dopes, propellers, and wind tunnel and water tank experiments. As research increased, it could expand into the Civil and Mechanical Engineering Departments, the latter currently occupied by part of the War Office Pay Department. At the end of the War, the Air Services could retain the buildings and a new Imperial College built elsewhere. All other research would be at Farnborough, which would become the National Experimental Factory. Wimperis further proposed to *'comb out the Advisory Committee for Aeronautics and place new scientists to refresh it and hold all meetings at Imperial College.'*

However, these proposals were not adopted, probably because War Office and Admiralty were not ready for such a dramatic centralisation at that time. Except for meetings of the Advisory Committee for Aeronautics, there was little contact between the RNAS and RFC at this time. Bourdillon visited Wimperis' Laboratory, the first of many visits and the start of a long friendship between the two scientists.

In August 1916, Callendar arranged for Wimperis to have Room 19 as a larger private laboratory and Lts. Fellowes, Darwin and Smith joined the Laboratory. Sometimes there were panic jobs, such as making a Zeppelin Dart Sight over one night, Wimperis taking it to HMS Vindex the following day to find there was general approval for his sight but there was grave doubt that Ranken's darts would ignite an airship. In the last quarter of 1916, Wimperis arranged for Casella to make some drift sights and the first arrived on 30 October. He visited the Optical Department of the Ministry of Munitions and other instrument makers, T. Cooke, Adam Hilgar Beck and British Wright. The laboratory examined several German bomb sights removed from crashed Zeppelins, from which he was able to give the Anti-Aircraft Authorities information on their bombing height and speed. He was also giving work to mathematicians Arthur Berry at Kings College and Karl Pearson at University College and they were visiting his laboratory.

7.6.1. The Trombone, Scarff, Drift and Negative lens sights

Before Wimperis had established his laboratory at Imperial College, the RNAS has already ordered some CFS sights from Casella as no others were available, but in addition to its restricted use up and down wind, they found another limitation. On sea patrols, the only object visible to measure 'ground' speed was usually the target itself. If they used some earlier object in the flight, the wind speed there could be different from that at the target. The solution was to provide addition foresights to allow the passage of the target between them to be used to measure ground speed and this used to set the bombing foresight. As these addition sights were fitted to a tubular U-shaped extension, the sight was known as the trombone sight. However, although it allowed the target to be used to measure ground speed, it still involved setting the fore-sight once this was found. An improved sight, called the Equi-Distant sight, was suggested and patented by F.W.Scarff, better known for his machine gun mounting.[4 5] It had a fixed back-sight and two fore-sights sliding along a height graduated scale so that the distance on the ground, subtended by the upper and lower fore-sights and between the lower fore-sight and a point directly below the aeroplane, was the same (Fig 7.9). The sight employed a special reversible clock, which was started as the target lined up with the first sight and reversed when target passed second sight. The bomb was automatically released when the time from the target was the same as the time the bomb would take to fall from that height.

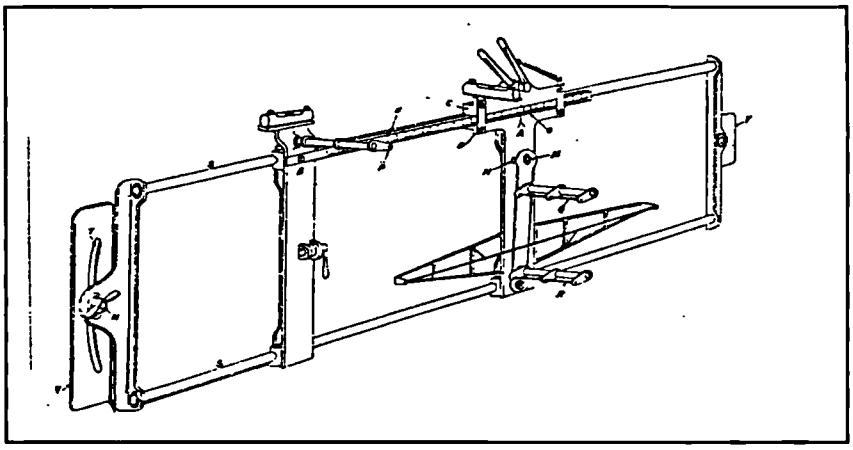
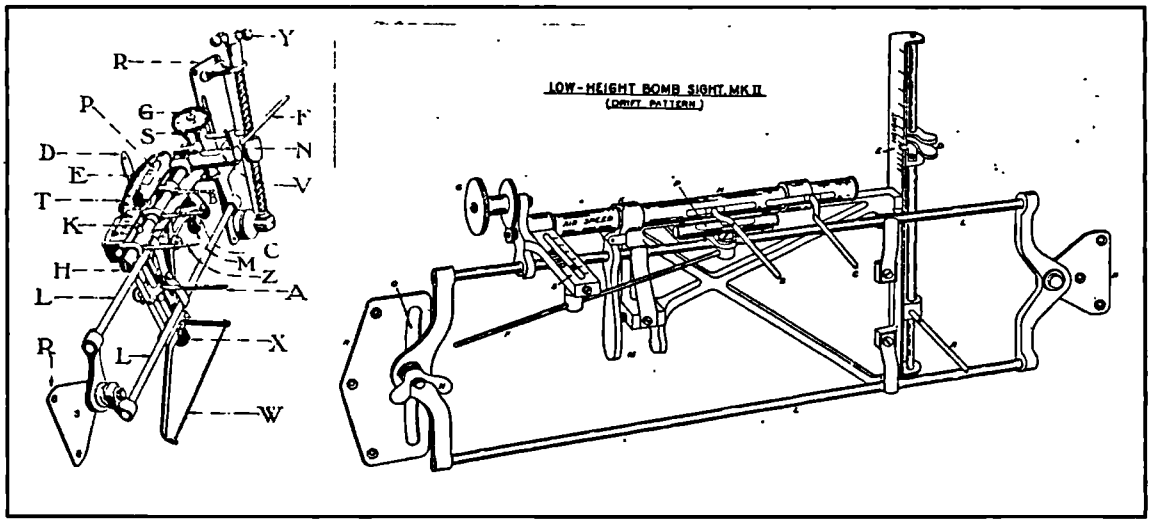


Fig 7.11. Scarff Equi-Distance Sight 1915.

RNAS pilots preferred the equi-distant sight to the trombone sight, but Wimperis still believed that no sight should use a stop watch or tables or require last minute adjustments. His Drift Sight was designed with this in mind and the new feature was the drift bar.[46] It had one fore-sight adjustable to height and two back-sights adjustable on an air speed scale, one for up-wind and one for down-wind use (Fig 7.12).



(a) High Altitude version (b) Low Altitude version

Fig 7.12. Wimperis Drift Sight 1916.

Having set the sight to air speed, the aeroplane was flown at right angles to the wind and the drift bar adjusted until parallel with passage of objects on the ground, the opposite side of the right angled velocity triangle gave the wind speed. The ground speed on the bombing run was therefore the air speed plus or minus this measured wind speed. Although the drift sight avoided a timing run, it still involved a calibration run at right angles to the wind near the target. This was awkward and took time, because flying at

right angle to the wind was determined by slowly changing course until the angle of drift was maximum, not easy in gusty weather. Nevertheless, this was considered preferable at the time to using a stop watch and low and high altitude versions were made and used in large numbers by the RNAS and RFC. However, Mckerrow found that when formation bombing was introduced later in the war, setting the wind vector by flying at right angles to the wind became a severe problem.[47] Only the leader's observer could direct a formation to fly at right angles to the wind. All the other observers then tried to set their drift bar, taking different times to do it and setting it differently. Even the leader had great difficulty at 12-16,000 feet due to the oscillations of the aircraft, objects never appeared to move down the drift bar, but rocked from side to side. He saw the gyroscope to be the only solution, but as he knew from his work at Orfordness (See 6.5) that this was impractical in its present form, and so he recommended setting the drift bar before take off by observing the drift of Ack-Ack bursts with a Bachelor Mirror.

Some problems were being solved, but there still remained the difficulty of keeping a target in view with any sight fitted to the side of the fuselage. Farnborough had produced the RAF periscopic sight to provide a forward view of the target area from below the aeroplane, which was fitted to Martinsydes, RE 7's and Sopwith $1^1/_2$ Strutters, but was expensive. Wimperis and Wells jointly proposed the Porroscope or Negative Lens sight, which was a less accurate, but cheap to manufacture. Originally conceived as a glass eye to provide a wide-angle view of the ground below the aeroplane, sights for two and three fixed altitudes were added later. The sight consisted of a tin-box housing, 6 inches deep, with the 6 x $5^1/_2$ inch plano-convex lens at the top (Fig 7.13).

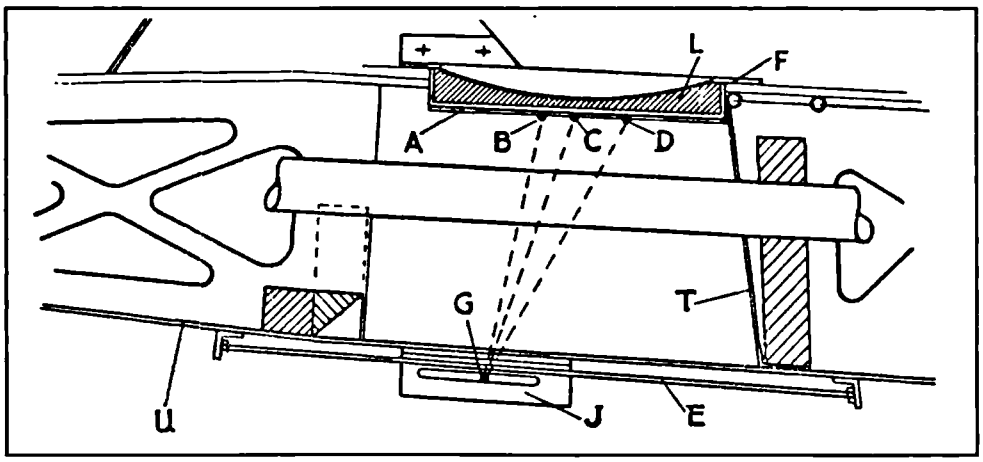


Fig 13. Wimperis-Wells Negative Lens Sight 1916.

L is plano-convex lens, G is single foresight adjuctable along wind speed scale J, B is backsight for 90 mph at 6000 feet, C is backsight for 80 mph at 10,000 feet and D is backsight for 70 mph at 15,000 feet.

The housing was fitted in the floor of the aircraft at a suitable position for the pilot to see through. Two longitudinal wires, one below the lens and one along the bottom of the housing gave line and level. Sighting for 90 mph at 6,000, 80 mph at 10,000 and 70 mph at 15,000 feet altitudes was provided by three fixed back-sight wires at right angles to the top steering wire. A single fore-sight wire across the bottom of the housing was adjustable on scale graduated for wind speed, forwards for down-wind and backwards for up-wind aiming. There was nothing novel in the lens or the three sights, but the combination of them was patentable. It was a rough sight, costing only £3, which proved so popular with the RFC that 19,750 were ordered, although 6600 were cancelled when the war ended. Some of this popularity was apparently due to Hopkinson's own flying experience and earlier bomb aiming experiments which gave him a belief in simplicity and dislike of gadgetry.[48] A version with the sighting wires mounted pendulously was also introduced for use if the aircraft was losing height while approaching the target.[49]

7.7. Research at Imperial College 1917

January 1917 started with Wimperis designing an alternative Pilot's Periscope for the Sopwith $1^1/_2$ Strutter used by the RNAS and ended when he borrowed a French instrument to measure depression angle and invented a much better one in the afternoon. During the month some time was spent working on collimation theory; Lt. Shaw joined the laboratory; Meadows was promoted to warrant officer; and Wimperis visited T.Cooke's works at York to discuss the manufacture of the Zepplin Dart Sight and his own periscopic sight, meeting both directors Denis and Wilfred Taylor and Wigglesworth. In February, Wimperis was promoted Lieutenant Commander with a special technical allowance of 10/- a day. He noted that this would lighten the burden on the Crown Agents, who were making his military pay up to his previous civilian rate, and was pleased when they told him they would not take the special 10/- a day into account. The administration of the two air services under the new Air Board took place by moving the Admiralty Air Department to the Hotel Cecil, where the new Technical Department covered both air services and Wimperis would now usually be at the Air Board in the morning and the Laboratory in the afternoon.

In March 1917, trials with the drift sight at Grain proved successful, in April the Advisory Committee for Aeronautics considered it could be a standard for both services and 500 were ordered from Casella. In May, Felixstow claimed three submarines sunk with drift sights they had for evaluation and Calshot claimed two submarines with theirs. Although, these sinkings were never officially confirmed, 700 more drift sights were immediately ordered from Casella due to the advertisement provided by them. Casella made Wimperis a

miniature drift sight for demonstration and he visited several aircraft manufacturers to explain how to fit the new sights. Although he saw himself more and more involved with anti-submarine work, more general armament experiments continued to be given him, such as rifle fire through petrol tanks, after which he submitted a patent for a new type of tank. In July, he went to France to discuss bombing and explain his drift sight, meeting Bourdillon at St. Omer and back in England he visited air stations in Cornwall and the Isles of Scilly, and Dobson at Farnborough for the same purpose.

Some problems were being solved, but Wimperis personally was not happy with any of the sights, as none solved the general attack problem of approaching the target in any direction, which was certainly necessary when the target was submarine. In addition, both the RFC and RNAS felt bomb sights should be stabilised. This development will be examined in the next chapter.

Conclusions

Pre-war bomb-sights were elaborate scientific instruments which assumed the aeroplane was a stable platform, that it did not vibrate and would not fly in the rain and cold, that the observer could devote full time and concentration to the aiming procedure, and that the size and weight of the sighting device were immaterial. Farnborough, with Darwin's help, attempted to produce more simple sights but with no better success. No real thought was being given to active service conditions by either the private or service designers. Private inventors were handicapped by having no aeronautical experience and it only needed one flight to make Wimperis aware of his ignorance of the difficulties faced by any design. When the war started Farnborough initially experimented with several ideas, until Lucas systematically examined the fundamental problems of aiming by observing the oscillations of the aeroplane with respect to the ground, as he had earlier observed the oscillations of the compass card with respect to the aeroplane. His research quickly showed that bombing accuracy would depend on stabilising any sight and he salvaged a Sperry gyrostat for his experiments.

Within months of the war starting, there was an urgent need for a practical sight for both military and naval use. Farnborough's Lever Sight replaced the board and two nails but proved unsuitable, the maximum altitude of 1000 feet for the Low Altitude Sight rendered it unpopular when attacking a defended target, and any commercially available sights had problems. At Upavon, a dedicated group of scientists turned Bourdillon's ideas into the CFS 4b Sight, which became the first practical sight for military use. However, it did not meet the requirements for naval flying and Wimperis established experimental facilities at

Imperial College to develop more suitable devices. His research group produced a range of new sights, all simple in concept and practical in operation. The Drift Sight avoided the use of stop watch timing and was the most widely used sight during the war. It was also adopted by the RFC and the American Air Service and produced in large numbers. The RFC also adopted the less accurate Negative Lens Sight in very large numbers, because it was cheap and suited their style of bombing.

The research at Farnborough, Upavon and Imperial produced the camera obscura, the Batchelor mirror and the kymograph, instruments which were able to record three dimensional movement in two dimensions, and which later became essential instruments to measure aeroplane performance and stability. The wartime scientists were primarily responsible for placing government bomb aiming research on a scientific and practical basis. The RFC facilities at Upavon expanded rapidly and moved to a new location at Orfordness. At Imperial College, Wimperis suggested that the college buildings should become the future centre of government aeronautical research and its academic function relocated elsewhere after the war, but this radical proposal was not adopted. Nevertheless, research cooperation existed between the military and naval air services based on personal friendship between the scientists involved. Although bomb-sights were improving, they were still limited to bomb up and down wind. The way this was overcome by Wimperis, the attempts to produce a stabilised sight and the later amalgamation of military and naval research under the Air Ministry is examined in the next chapter.

Chapter 8.

Bomb Aiming Research Part 2
Course Setting and Stabilised Sight Research

Summary : Wimperis' account of his bomb aiming research at Imperial College - commercial production of Wimperis sights by Casella and Cooke - The Air Ministry Laboratory established - Professor Gray joins Wimperis to research gyro sights - research on gyro sights at Farnborough by Lucas and Lindemann - gravity versus spring control - Lindemann's aerial rangefinder - Awards to Inventors, Gray, Wimperis and Pollen - post war research at the AML.

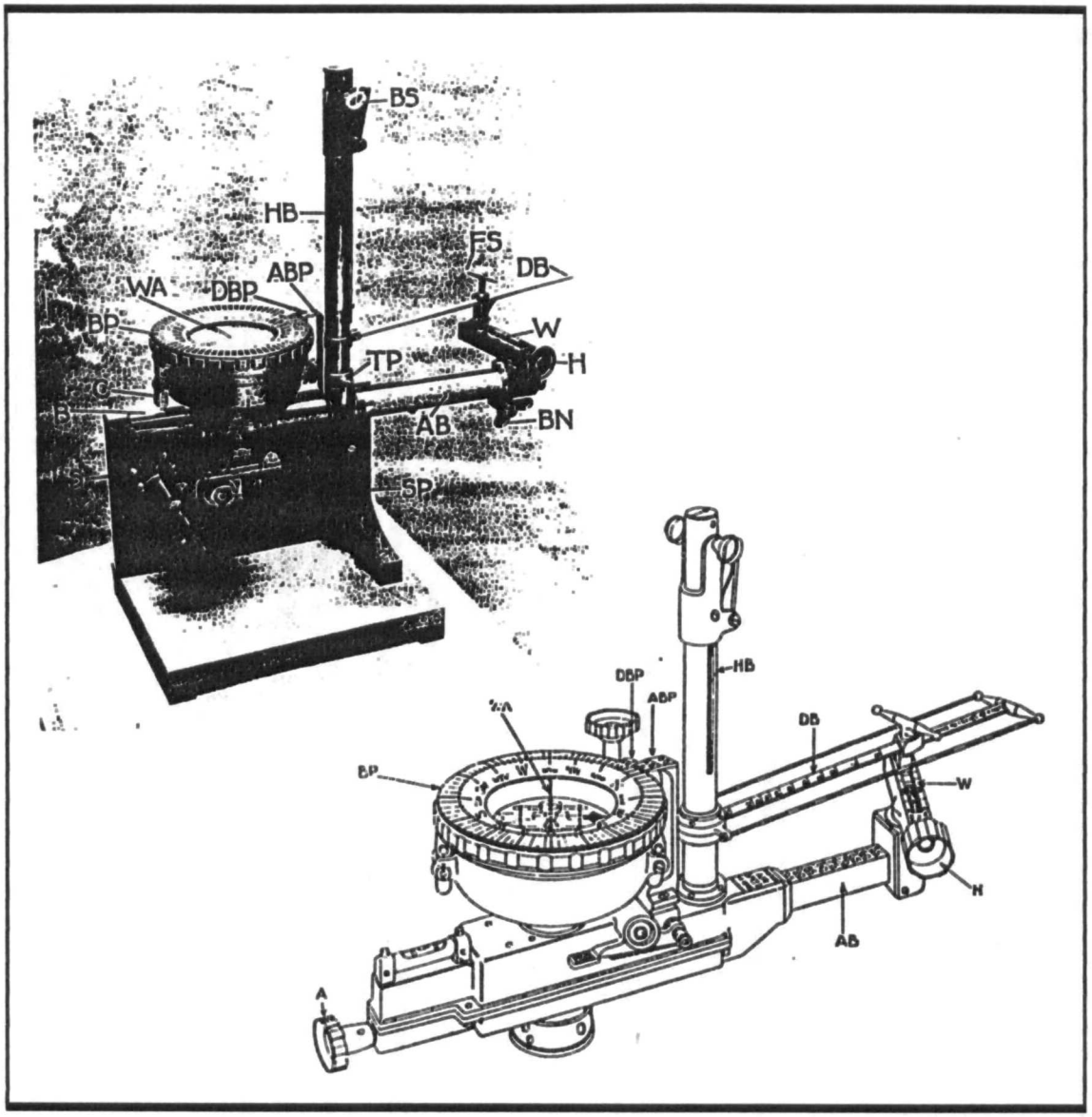
The RFC found the Wimperis drift and negative lens sights met their needs and discontinued their own unstabilised bomb-sight design. However, Farnborough considered that a stabilised sight was the only way to improve accuracy and Lucas and Lindemann conducted experimental research in this direction. Wimperis shared the same conviction and conducted his own research, but in the end the absence of a small reliable gyroscope defeated both groups. His first priority, however, was to complete his Course Setting Bomb Sight to attack a submarine from any direction, as it was difficult enough to reach the target before it dived without having to turn into wind as well.

8.1. Research by H.E.Wimperis - his own account.*

Although Wimperis noted this need on 11 May 1917, the first one was not made at Imperial College and shown to the Air Ministry until 18 August. It was then taken to Felixstow for initial trials with its name changed from Drift Sight Mark IV to Course Setting Bomb Sight Mark I or CSBS.1. More extensive trials at the Scillies Air Station produced an enthusiastic report in December and Wimperis received authority for 20 to be made, which he arranged with Cooke's at York, but increased the order to 40 as he was confident of its success.

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* The following account is condensed from the Wimperis Diaries for 1917-1920, unless referenced otherwise.



(a) First version (b) Later version

Fig 9.1. Wimperis Course Setting Bomb Sight

The triangle of velocities is formed by the air speed bar AB, the wind bar W and the drift bar DB. The innovative feature of the device was to repeat this triangle of velocities at the compass by rotating the compass by gearing so that its wind arm WA was parallel to the wind bar W and gearing the drift bar pointer DBP to be parallel with the drift bar, while the lubber mark ABP was the axis of the air speed bar. The vertical wind gauge bar WGB folds down across the compass and has a bevelled edge to rule a line with a glass-marking pencil. In its vertical position, its height scale allows is use for bomb aiming.

Meanwhile, Casella were in full production with his drift sights, 1375 Low Height Drift (LHD) and 1800 High Altitude Drift (HAD) Sights were on order by year end. Wimperis also gave thought to foreign usage and although his patents were still secret, he obtained permission in November to make his own terms with allied governments for the drift and negative lens sights; and in early December was offering the designs free to Canada and

Italy, and at a royalty of $4.5 each or $22,000 the lot to the American Government. Almost immediately he heard the American Government had asked for 100 LHD Sights and would probably want HAD's as well. He also hoped that the British Government would give him £2,000 for all of theirs, although he would have been happy with £1,000.

During this period, gyro experiments were progressing slowly and it would appear that Wimperis had abandoned his own stabiliser in favour of one jointly patented by Professor Gray and his brother, which he saw was more suitable for the CSBS. James Gordon Gray was Professor of Applied Physics at Glasgow, where his father Andrew Gray had succeeded Kelvin as Professor of Natural Philosophy and also wrote papers on gyrostats. Wimperis had met Gray at Elliott Brothers, where his first models were being made, and in early September visited Gray at Kingsworth Air Station, where they were being tested. He flew to see the stabiliser in operation and offered Gray a room at Imperial College to continue his work. Wimperis was now a member of Darwin's Air Inventions Committee, although he would rather not have been involved. Over the Autumn months, he meet both Dobson and Bourdillon on several occasions, each staying for a weekend at his home at Goring, so communication between the two services was improving, if only through personal friendship.

Wimperis started 1918, as he had started 1917, with an invention, submitting a patent application on the first day for a Compass Course Setter, which he had designed the previous day and immediately planned the workshop to make the prototype. He visited Cooke's at York on 22/23 January to discuss the final details of the CSBS so they could start production. On 29 January, he filed the provisional specifications for it and the Compass Course Setter and two days later designed the CSBS.2 for high altitude work. The RNAS were taking more advantage of the Imperial College facilities and had recently moved their Engine Test Section and Wireless Telegraphy Section (formerly T-3 Section) into the laboratories, the latter section having been bombed out of their accommodation at the Institution of Electrical Engineers at Savoy Hill in a Gotha raid. The W/T Section had quickly taken advantage of the glass blowing and exhausting equipment in the workshop to manufacture their own valves and set up a small production line for helium indicator tubes, which they produced for 1/- compared with 6/- commercially.[1] The section was under the care of Lt. S.R.Mullard, who would later form Mullard Valves Ltd. However, Callendar wanted these sections to come under Wimperis and in early February was also urging the Governing Body to consider Wimperis for the chair of aeronautics; Wimperis noting 'Nice, but nothing will come of it'.

The RNAS had now ordered 2250 drift sights and 100 negative lens sights and the RFC 1800 and 3300 respectively, which at £9-0-0 and £2-10-0 each would provide a

worthwhile royalty, if this could ever be negotiated. He considered the idea of measuring drift over the sea with the CSBS.1 by firing ahead with a machine gun and observing the splashes, and flew twice with Rea at Grain to try it out, later adding the method to his patent. Compass work brought him into contact with Creagh-Osborne at the Slough Compass Observatory, he visited Dobson and Lindemann at Farnborough, and met Lt. L.C.Bygraves, who had just invented his own drift sighting method and would become a member of the Laboratory after the war. Creagh-Osborne got King at Kelvin, Bottomley and Baird to provide the first ACO bomb sight compass. The limited space for the compass on the Wimperis sight made it impossible to fit an expansion chamber, and the compass suffered from bubbles until the 1932 version.[2] Several versions also had double pivots to avoid acceleration error.

In March, there was welcome news from Horsley that Gray's gyro sight was now performing better using a wind spun gyro that Horsley himself had designed (Patent 123,836/18). Wimperis flew at Grain the following day to see it work, noting that he *had never enjoyed a flight some much.* The next problem was who should make the new sight. Although Elliott Brothers had made the first Gray gyrostats, they were committed to so many other government orders that they could not undertake production and neither could Cooke's, who were producing the CSBS. Wimperis first visited Greenwood & Bately of Leeds, but decided after lunching with Mr., Mrs. and Miss Reavell, that Messrs. Reavell of Ipswitch, who manufactured sheep shearing equipment, would be *splendid* for the purpose. During the month, he also received the OBE at Buckingham Palace, in recognition of his work, and there was promise of financial reward in a minute from the Director of Armaments;

> Lt. Cdr. Wimperis has rendered most valuable service in the invention and perfecting of devices of great practical value in Aerial Warfare and it is considered that a substantial award should be granted to him.

There were significant organisational changes through the Winter and Spring of 1918. In January, the Air Board was replaced by the Air Ministry and his diary would routinely record *A.M. and Lab* or *Lab and A.M.* Wimperis wanted the laboratory to come under Bertram Hopkinson at the Air Board Technical Department, as he was concerned that members of the Air Inventions Committee were also trying to gain executive control, though his immediate superior was more concerned that the Admiralty did not claim it for naval research.[3] When the laboratory was placed under the Air Ministry Technical Department, Professor Callendar wrote to say that if the three sections were under the control of one officer, and that this was Lt. Cmdr. Wimperis, Imperial College was willing to continue with the present financial arrangements.[4] Hopkinson agreed, but explained that under the new organisation engine research might be moved to Farnborough.[5] When the

arrangements were confirmed on 16 February 1918, Wimperis decided to name his combined department,

Air Ministry Laboratory (AML) - Imperial College of Science

At this time, he listed his staff as seven naval personnel, Dr Gray, two instrument fitters, two fitter improvers, two boy learners and the valuable assistance of Professor Callendar and his staff.[6] The formation of the Royal Air Force from the RFC and RNAS on 1 April 1918 forced the Air Ministry Technical Department to move from the Hotel Cecil to bigger offices in Kingsway, and meant that Wimperis was now a full major.

The prototype CSBS.1's which were made in the Laboratory, were gaining service acceptance and Hopkinson thought it a beautiful piece of design, welcome praise from a former Professor of Mechanism. The first production sights started to arrive from Cooke's and Wimperis took them personally to various air stations and training schools to explain their operation and installation and in April, 600 more were ordered to provide sufficient for all large flying boats and land bombers. Successful reports, like the Log of 15Y, were not long in coming in,

> We had just been fitted with the new compass bomb sight, which allowed one to bomb from any direction, not only up and down wind. One had to set up wind direction and speed and one's own speed, direction and elevation, all done as an early routine and only adjusted if required. So I fused the bombs and we claimed a perfect straddle of the submerging conning tower, but had no camera to record it and in any case the light was bad. Having circled for half an hour we made for home. Despite a fine welcome and the DSC for the first pilot, the Admiralty would not allow a hit.[7]

At the end of May, Wimperis went to France again, this time as a passenger in a DH-4 and gave a talk on the CSBS in Paris and then travelled by train to the Centre d'Aviation Maritime on the Mediterranean to give them a CSBS and discuss submarine attack, meeting Montagne, who had invented a form of course setting sight himself. In June 1918, he was elected to the Athenaeum, years before he expected, later finding he had topped the elections. From now on, he would frequently dine there with Dugeld Clerk, Darwin, Glazebrook, Schuster, O'Gorman, Sir Alexander Kennedy and others. He settled the arrangements and equipment for the engine laboratory with Hopkinson and was also meeting Tizard, whose ability impressed him very much - on one occasion he took Tizard to dine at the Athenaeum, on another Tizard flew him through rain and hail from Hendon to Martlesham. There were also visits to Dobson and Lindemann at Farnborough and Griffith at Martlesham. Committee meetings too were on the increase, he attended the Advisory Committee for Aeronautics, the Air Invention Committee, the Bomb Sight and Navigation Committees and his own Gyro, Engine and Wireless Committees at the Laboratory, where his staff had further increased and Callendar was urging the Governors to consider Wimperis for the chair of aeronautics.

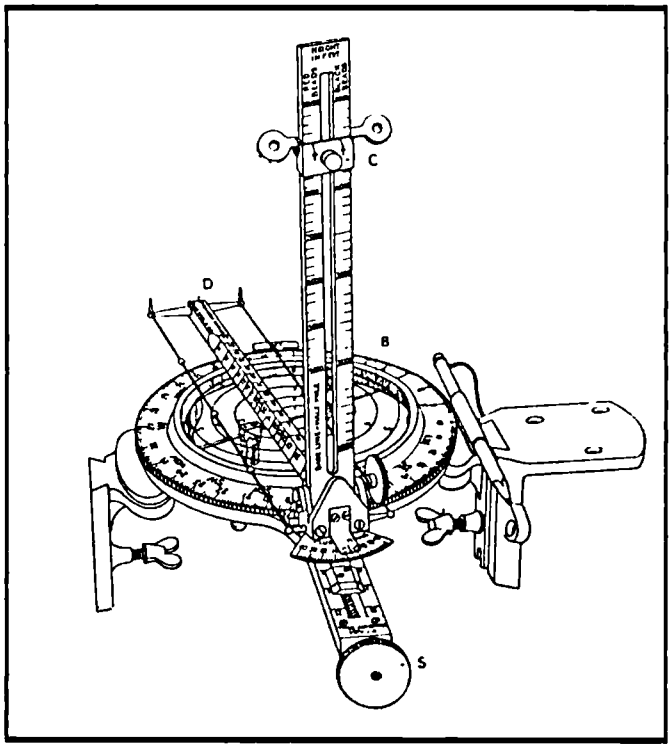


Fig 9.2. Wimperis Wind Gauge Bearing Plate 1918.
The diagram at the top shows how the wind vector was found by flying two courses AC and DC. The drift lines AB and DE for these course intersect at P to give PC as the wind vector. The same principle was used on the CSBS.

Wimperis was on leave in Devon at the end of August when he received a telegram that Hopkinson had been killed. On return to London, Wimperis visited an exhibition at Kings College on 7 September and was surprised to see a HAD, a negative lens and a CFS sight on public display. A week later he filed the provisional specification for his Compass Course Setter, which would be renamed Wind Gauge Bearing Plate and be extensively used for navigation over the next 10 years. The instrument was basically a more simple triangle of velocities than the CSBS, it did not have the compass incorporated, but could still be used as a bomb sight (Fig 9.2). The final specification was not completed until September 1919, Patent 131,757.

In October, the Conrady Depression Indicator was tested and Wimperis had his first experience of the rocking seasickly motion of a kite balloon. This instrument was probably a version of his own depression indictor, last tested at Grain in July, which Professor Conrady in the new Technical Optics Department at Imperial College had now improved. Wimperis heard that the American Government had ordered 3500 CSB Sights from the National Cash Register Company at $400 each and was getting them at the rate of 45 per day. Just afterwards, Wimperis went to Grain to test the CSBS.1A on a DH-10 and was

there again a few days later testing Gray's stabiliser with a Double Bubble Level Sight on a NE-1. The CSBS.1A had been made in the Laboratory at the beginning of the month, but it is unclear what the modification was. Next day he visited Martlesham to see I.O.Griffith. and also saw a HAD-1A sight on a Handley Page bomber ready to bomb Berlin. Wimperis was also involved in several discussions with Pollen about their respective patents and had agreed that his CSBS patent had priority over a similar device by Pollen. However, this issue resurfaced later when determining the award Wimperis received for his CSBS.

There were now rumours of peace. Elphinstone met Wimperis to say that Elliott Brothers were willing to take up the CSBS and its derivatives after the war and deal with foreign rights. On 8 November, Wimperis took a high altitude CSBS.2 to be fitted to a Handley-Page and three days later it was all over - Armistice was declared. Wimperis had already decided he would like to continue with his present work, if that could be arranged. Therefore as soon as the celebrations had died down, Wimperis discussed the future of the Laboratory with Callendar and Sir Alfred Keogh - both were very much in favour of it continuing - but on 30 November, Wimperis was startled to find The Crown Agents were asking the Air Ministry for his return. Stoppard immediately promised to try to get him into the Air Ministry on a permanent basis and meanwhile arranged for him to visit America, where he was away for six weeks, including 19 days at sea, in which the outward voyage was extended when the engines of the SS Carronia were damaged by very rough seas and the ship drifted for a day while they were repaired. In America, he visited flying fields, laboratories and manufacturers, including Sperry, and was taken to the International Cash Register Company by Lt. Boettcher to see his Pilot Directing Sight. Boettcher's sight was remarkably similar to the CSBS, but Wimperis made no comment about it, although it would later be granted a British patent. On his return, he found his personal arrangements were still unconfirmed. The Crown Agents asked him to prepare a report on the organisation of economic development work, which he did while Stoppard wrote to them to ask that his return be delayed until early April. Gen. Brooke-Popham told him they planned to put him in charge of research in navigation and meteorology and this was confirmed when he met Brooke-Popham, Ellington and Sir W.Robinson on 24 March. He tried to negotiate £1,200, but accepted £1,000 plus any awards for inventions, although on the following day he found that any award above £1,000 was now to be referred to the Royal Commission for Awards to Inventors.

Wimperis had already started to plan the Laboratory, while these arrangements were progressing. He had discussed possible staff with Tizard and they had visited Martlesham Heath to see if I.O.Griffith would 'stay on' as assistant to Wimperis. After Wimperis' position was confirmed, he went back to see Griffiths and persuaded Roche, Capon,

Bickerton and Mackie provisionally to join his staff. Stewart, in charge of instruments, had already accepted a 3 year contract at £800, rising to £1,000, to remain at Martlesham, so was not available. Eventually, only Capon joined the AML, Griffith and Mackie returning to Oxford to join Lindemann. There was talk with Dobson of losing Capon to American Astronomy, but this did not happen and Horsley and Capon were shortly joined by Bygraves. Wimperis next met Sir Napier Shaw at 'South Ken. Met. Office' and visited Dines Observatory at Benson to start looking for suitable meteorologists; Morris and Murray later joining the AML. Wimperis also met Ernest Gold, a Cambridge mathematician, who had set up the War Office Meteorology Laboratory in France, ending as Lt. Col. with a staff of 28 officers and 187 other ranks.[8] The attitude of the War Office to meteorology had changed since 1914, when they turned Taylor down and sent him to Farnborough.

On the patent front, Elphinstone had submitted French and American patents for the Drift Sight and CSBS. His prototype Wind Gauge Bearing Plate was also proving successful at Martlesham and he agreed the final design with Elphinstone, who fixed the cost at £20 each with 15% to Wimperis. New laboratory work was initially directed at navigation calculators, sextants and compasses, Wimperis and Horsley patented a mechanism for solving spherical triangles, Wimperis designed the AML sextant while examining a Cary sextant, but this work was later dropped when Booth at Farnborough designed the first of his RAE sextants. Dobson was the main contact at Farnborough until August 1920, when he left to join Lindemann. The laboratory research was next directed at the aircraft compasses and the laboratory simulation of their behaviour in flight (See 5.9.), Wimperis and Capon making frequent visits to Creagh-Osborne at the Admiralty Compass Observatory at Slough. At home, Wimperis was writing his Primary of Air Navigation, designing a pocket watch-sized accelerometer and building Mecanno models.

Membership of the Advisory Committee, shortly reformed as the Aeronautical Research Committee, the Meteorology and Navigation Committee and the Royal Aeronautical Society Council provided regular meetings with Tizard, Lindemann, Taylor, Ogilvie, Bairstow, Pippard and Melvill Jones. Socially, Wimperis met Taylor at Cambridge, visiting Rutherford's and Jones' Laboratories, and Tizard and Lindemann at Oxford, Tizard complaining that his salary was now only £550. The Athenaeum also kept him in regular contact with Rayleigh, O'Gorman and Dugeld Clerk. At Imperial College, he involved Callendar and Conrady in his work and Glazebrook, now Professor of Aviation, arranged for him to give a series of lectures on navigation and aircraft instruments. Casual wartime associations had become regular peacetime ones.

8.2. Stabilised bomb sight research by Lucas and Lindemann.

Bertram Hopkinson, Deputy Assistant Director of Aircraft Equipment (DADAE) held meetings in April 1916 to co-ordinate RFC and RNAS gyroscopic bomb sight development. Present at the first meeting were Lucas, Dobson, Tizard, Wimperis and Phear.[9] Tizard discussed experiments conducted at the CFS with the Sperry Stabiliser on a BE 2c to see if it assisted bomb aiming. Their results showed that control with the stabiliser was little better than the natural oscillations of the machine as Busk had found in 1914, but more importantly the distortion to the airframe imposed by the stabiliser was so severe that the machine had been declared unsafe and experiments discontinued. Wimperis said that Cmdr Porte at Felixstowe had experienced the same problem on a flying boat and the RNAS had also decided to discontinue these experiments, but planned to try the Sperry platform with a CFS bomb sight. Lucas was able to save them the trouble, because he had already examined the stability of the Sperry platform at Farnborough and found that at 15,000 to 17,000 rpm it only remained steady within 1°, so they had made no attempt to couple it to a bomb sight. However, he had found that an individual Sperry gyrostat with neutral gravity control (centre of gravity at the intersection of axis of gimbals) did remain steady within $^1/_2$° for 4 to 5 minutes after release. He now planned two sets of experiments, one to use the gyrostat to provide a stabilised 'line of sight' with a bomb sight, the second to provide the gyrostat with electrical contacts to control the rudder to keep the aircraft straight and make it easier for the pilot to use the sight and avoid stabilising it.

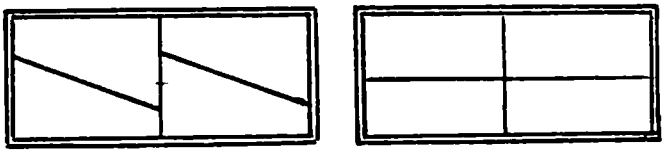
Hopkinson decided that Lucas should continue his experiments, while Tizard, because of the experience he had gained with automatic control, should design the steering gear to fit a BE 2c. Initially they would use the Sperry air propeller driven generator for the experiments until these could be replaced by 50 watt rotary converters which were being designed by Professor Field at Manchester University and made by Joseph Lucas in Birmingham. Hopkinson also proposed to find out more about a stabilised bomb sight that Mallock had apparently designed, though this turned out to be a pendulum controlled sight together with a trajectory calculator.[10] Wimperis wrote his own minutes of the meeting adding that the RFC proposals were still to bomb up or down wind and were not attempting the general attack problem.[11] Hopkinson subsequently arranged that Tizard's steering gear should be fitted to a BE 2c at Farnborough, that the trials should take place at Orfordness, using a new 4 watt alternator designed at Farnborough weighing 4 lbs ,and capable of running the Sperry gyrostat up to 10,000 rpm in $2^3/_4$ minutes.[12]

The trials were held at Orfordness four month later on 11 August 1916. Lt Courtney piloted Capt Lucas in a machine fitted with the gyro sight, while Capt Bourdillon and later Capt Gribble piloted a second machine with a CFS 4b sight. Lucas judged when the machine was level and the gyro could be released by reference to bubble inclinometers. All bombs were dropped from 6000 feet and the average error of 137 feet achieved with the gyro sight showed a marked improvement over 353 feet with the unstabilised sight[13]. Lt. Cmdr. Pulford witnessed the trials for the RNAS and Wimperis visited him at Orfordness to discuss them two days later taking with him Lt. Daman, who was developing a wind spun gyro which only weighed one fifth that of the Sperry[14]. Even before the Orfordness trial had taken place, Farnborough were asked to make twelve Lucas gyro sights for fitting to DH 4 pushers.[15] It seems after this time that the RFC and RNAS continued bomb aiming research separately.

Following Lucas's death in October 1916, Lindemann picked up his compass and bomb aiming experiments. The Farnborough Log shows that as a pilot Lindemann carried out some thirty flights on the Lucas compass in December and January and thirty five on bomb aiming from March to June 1917. Renwick flew as his observer on the compass flights, but he had thirteen different observers during the bomb aiming experiments as he was doing the aiming himself. On two occasions, his observer was Capt. A.C.G.Egerton, who would later join him at Oxford. Some fights ended abruptly - broken tail skid, smashed undercarriage, machine ran into fence, collision with FE 2e on ground - as although Lindemann was able to aim with his good eye, his lack of stereoscopic vision made it difficult to judge distance.[16] During May, he was testing his accelerometer. Flights were not always strictly experimental. One on 16 August logged *Calibration to Cambridge and back*, hides the freedom enjoyed by Farnborough scientists at this time, when Lindemann and Renwick flew to Cambridge to drop a boot by parachute over the church as Farren and his wife emerged after their wedding, although the accuracy of aim is not recorded.[17] On 14 October, a short flight logged 'trim and engine test' disguised a joy flight for Edgar Adrian (later Lord Adrian), who as a Captain at Aldershot Military Hospital, was able to live in the Chudleigh Mess with his former colleagues from Trinity College Cambridge.

In June 1917, Lindemann experimented with a diving bomb sight on a BE 2c.[18] It consisted of two wires on the right hand side of the fuselage - the lower one stretched horizontally from behind the pilots position to a front engine bearer, the upper one from the same rear position to a strut in front of the pilot. However, the accuracy of aim was not improved, as he found it difficult to judge that the machine was level while diving as he could no longer see the horizon, and the engine smoked badly in the dive and flying oil clouded his goggles.

During the same month and again in September, Lindemann flew to Orfordness with the Lucas gyro sight to compare the results of bombing from a single aircraft with that from a formation and was given one hours practice to lead the formation. The BE 2c was not a good machine on which to use the gyro sight, as this was fixed outside the fuselage forcing him to rise half out of his seat and lean outside the fuselage. When flying alone, his machine was trimmed to fly 'hands off', but he could not do this in formation as his machine was trimmed to fly faster than the formation could fly with safety. Instead, he was forced to control the machine with one hand while he leaned over the side to sight the target, reducing the accuracy he achieved in formation to half of that he achieved in individual trials. Lindemann determined when the machine was level with a split mirror. This was fixed in front of him so that it reflected the horizon on each side of the machine as a continuous line when the machine was level, a more convenient and accurate method than the bubble levels used by Lucas.[19]



8.3. Comparison of military and naval designed stabilised sights - 1918

The next bombing trials at Orfordness were in May 1918. This time the Lucas gyro sight was fitted to a NE-1 (Night Experimental) pusher. The trials were to compare it with a Gray gyro sight fitted to a RNAS machine piloted by Wells. The stability of the Gray sight had been tested in March by using the shadow of the sun along the sight and looked promising[20]. Both devices used the stabilised 'line of sight' principle, the Lucas fitted to a CFS 4b sight and the Gray to a Wimperis course setting sight. All the bombing was from 15,000 feet and Lindemann was both pilot and bomb-aimer.[21] Although the Lucas sight appeared the better device, the results were inconclusive as Wells and his observer were relatively inexperienced and the Gray sight was found to be defective and had to be repaired by Professor Gray's brother Captain Gray, who was present at the trials.[22] The NE-1 was left at Orfordness for further trials, but these were never completed as Lindemann crashed in it on 2 June just short of Orfordness aerodrome, when trying to return with engine failure.[23] For a second time, Lindemann was unhurt, having also crashed in a RT-1 at Orfordness during trials on his aerial rangefinder three weeks earlier.[24]

8.4. Lindemann's aerial rangefinder

Lindemann's aerial rangefinder was not a bomb sight, but shared many design features and deserves mention. It had been developed to use an aeroplane to direct the fire of a naval shore battery on a target beyond their view - measuring the declination and bearing of the target and shore battery from the aeroplane and using the height of the aeroplane as the base line, the range and bearing of the target from the shore battery could be calculated geometrically. Lindemann designed his instrument after carrying out trials on one designed by Maj. Horsefield, who had used a single telescope, with horizontal and vertical degree scales, above a compass.[25] Sighting first the target and then the shore battery took time, during which the aeroplane had flown a considerable distance to rendered any calculations inaccurate. Lindemann retained the same principle, but used two Aldis rifle sights so that readings could be shared between the observer and the pilot, who fly the machine towards the target. The readings and the altimeter reading were then sent by wireless to the shore battery, who used a station pointer calculator designed by Lindemann to work out the range and bearing of the target. Lindemann calculated an accuracy within 2% for a maximum range of 20,00 yards and said the purpose of the instrument was to get the first shots close to the target and then use the aircraft as a spotter for the fall of shells afterwards. Tizard thought that Lindemann's claim of 2% was somewhat remarkable, but trials would demonstrate this.[26] Flight experiments during May and June 1918, first on the RE 1 in which he crashed, then on a Sopwith $1^1/_2$ Strutter and later on a RE 9 with better forward visibility, showed numerous problems.[27] Spirit level clinometers were added to the sights in an attempt to cope with the pitch oscillation of the aeroplane and the heavy wireless equipment was replaced by an Aldis daylight signalling lamp, which allowed the height of the aeroplane to be calculated from two shore batteries more accurately than the observer's altimeter. Farnborough arranged for 12 rangefinder sets to be made by Troughton and Simms. Trials with the prototype were carried out at Orfordness with Lindemann as pilot, but accuracy was marred by the vibration of the clinometers, difficulty in communication between pilot and observer, difficulty in keeping the Aldis lamp trained on the shore battery due to the slipstream, and failure of the shore battery to read the signals, which were sometimes obscured by the tailplane. Even after finding the charts used were inaccurate, the average overall accuracy was 8.1%. Trials continued during June without Lindemann, but concluded that too many readings had to be taken by too many people, and that visual signalling and the time to transmit and calculate the range were the main problems.[28] Wimperis supported this view a year later, adding that the accuracy of any system using an aeroplane compass and altimeter was suspect.[29] Lindemann's aerial rangefinder was not the first to be tested, I.O.Griffith at Orfordness tested an Artillery Spotter in 1917, based

on a graticule projection above a compass, but found vibration a problem if the instrument touched the aircraft.[30]

Lindemann's rangefinder was patented after the war. As his attitude to patents was in sharp contrast to that of many other scientists who wished to patent their inventions, and was both amusing and illustrative of the communication network between scientists in the face of bureaucracy, it is described in Appendix 1. However in 1925, Lindemann was still apparently unconcerned with the difficulty of optical communication when he carried out work at the Clarendon Laboratory on the remote control of an aeroplane by a light beam; a proposal which Wimperis at Imperial College and Capon at Farnborough considered impractical.[31] The apparatus used a photo-cell via amplifiers and relays. It had the advantage over wireless transmission that it could not be jammed, but it was only possible to direct a narrow beam of light at the aeroplane at night, when it was difficult to see the aeroplane.

8.5.1 Awards for invention - Professor Gray's stabilised sight

With the urgent demand in 1918 for an accurate service bomb sight for the heavy Handley-Page bombers, orders were placed for 20 Gray sights for further trials at Orfordness and 550 for service use. However, Reveall's were only able to produce 370 before hostilities ceased and received £600 compensation for the cancellation of the remainder.

These details were given to the Royal Commission for Awards to Inventors in 1923, when Professor Gray claimed royalties for Government infringement of his 1915 patents and expenses for his wartime assistance to the Government.[32] He said that some credit should be given to Elliott Brothers, who had cleverly designed the gyroscope for the original trials so that different erection mechanisms could be quickly inter-changed. His claim was based on royalties owed him by Reavell for the use of use of his erection method in gyroscopes manufactured by them, the right of use of his patents given by the Government to France and America, and improvements to his patent taken out by Reavell and by Horsley. Expenses were £3000, based on some 600 days he worked 'at the request of the Government', £736 patent fees and £1200 for rail tickets between Glasgow and London. These expenses were to repay the cost which had been borne by Glasgow University at the time. The problem faced by Gray, as with other inventors, was status. However, Gray's case was different, it was not that he was employed by the Government to invent, but that there was no record that the Government had ever requested his help. Gray claimed that Brancker and Robinson at the Air Board had asked him to 'father' his invention by working with Wimperis. Wimperis said that he had not made the original request and had only offered Gray accommodation. In the end the hearing accepted that

without his help the invention would not have been so useful to the Government, but the Treasury contended that extensive use would not have been made of it unless he had provided the help. Wimperis also pointed out that of the 370 devices manufactured, few were ever actually used. The Commission finally made an award to Gray of £2900. It was not the Commission's policy to disclose how this figure was reached, but they were faced with this when Gray later had to separate earnings from expenses to the Inland Revenue. They finally agreed £2000 'royalty' and £900 'expense'. How much Glasgow University finally received is not recorded, but they had certainly financed the Gray stabilised bomb sight.

8.5.2 Awards for Invention - Wimperis and Pollen course setting sights

The transcripts of the hearings by the Royal Commission for Awards to Inventors provide a valuable insight into the design of aircraft instrumentation and
who was responsible for its novelty. In the case of the course setting bomb sight, Wimperis was the main claimant, but there were counter claims by others. Captain Mathews and Commander Gregory claimed for similar devices earlier, the British and Colonial Aircraft Company asked for consideration of the Bristol Sight before withdrawing it, but the more serious claim was from the Argo Company, who alleged that Wimperis had infringed their patent after it had been disclosed to him.[33] If infringement was proved, the Treasury was worried that Argo had an agreement with the Admiralty that the use of their inventions was on a royalty basis, not an award. The hearing was chaired by Mr Justice Sargent, Moritz appeared for the Treasury, Bousfield for the Argo Company and Whitehead for Gregory. Mathews and Wimperis represented themselves and Moritz had asked that Lord Rayleigh be present because of the technical nature of the claims.[34]

The main problem Wimperis faced was his status. As Moritz said after admitting the value of his inventions in the war,

> Wimperis was responsible first under Bachelor and then himself for all the (RNAS) work in connection with bomb sights. If ever there was a case for which the status of an Officer precluded his getting an award - this was it.

Wimperis explained that he had made his claim on the suggestion of General Hetherington of the Air Ministry, but the significance of this statement did not appear until much later. He was claiming for his Drift Bomb Sight, Porroscope or Negative Lens Bomb Sight and Course Setting Bomb Sight.[35] There were no counter claims for the first two, only for the

course setting sight, as Moritz summarised,

> All the inventions but one turn on the use of vector linkage for the reduction of the triangle of velocities - given two of the vectors air, ground and wind speed, find the third. This had been worked out at sea in the 1903 Battenburg drift indicator using three deformable linkages. In 1911, Gregory proposed the same instrument for air purposes (Secret Patent 7471/12). At the same time Faccioli proposed practically the same instrument.[36] At the outbreak of the war, Mathews set out the same idea mathematically and introduced the new idea that the air speed arm of the linkage could be used as a direction or sighting arm. None of these ideas was used in service.
> In 1916, Wimperis developed the drift sight, mounting on the air speed arm a fore and aft sight, ingeniously geared to the linkage so that they automatically corrected themselves for the wind vector. Later he combined the sight with a compass, with a rotary bearing ring and three lubber marks to make it possible to bomb off wind.
> The Argo Company claim they invented this sight, but their device allowed an observer, armed with compass and vector linkage and keeping the air speed arm directed at the target, to get the bearing to be steered to the pilot's compass by gearing.

Gregory had been a navigating officer before learning to fly at Eastchurch when it opened on 1 March 1911 and, being familiar with the Battenburg Course Corrector, had made a patent application for its aerial equivalent in celluloid. Two devices were made by Elliott Brothers about March 1912. Gregory was claiming £250 ex gratia payment as his patent had been thought important enough to make it secret, which it has remained ever since. Moritz felt that Gregory's case rested on whether in putting his patent before his superiors he had hastened the later adoption of other course setting methods.

Mathews' claim was based on a proposal he made to the Ministry of Munitions. He had the idea of bombing Rhine bridges to disrupt supplies as one way of shortening the war. He knew nothing about aeroplanes except that they were too shaky to attach a sight to them. His method was to manoeuvre the aircraft until the air speed vector and ground speed vector were at maximum angle, when the wind vector would be at right angles to the ground vector. His letter was reviewed by Glazebrook, Thomson, Darwin, Kennedy and Indell, who thought the device too elaborate for war service. Their reply never reached Mathews, who next sent a second copy of his proposal to Upavon. Captain Griffiths at Orfordness replied, explaining that it was not easy when flying to find the maximum angle between air and ground vectors, but more importantly the RFC practice was to bomb up or down wind because it was not possible in a tractor aeroplane to see obliquely down if trying to bomb across wind. Again Moritz pointed out that Mathews' case rested on whether his idea was used by the authorities, but there was evidence that the authorities had read and were aware of his ideas, instead of just putting them in a pigeon hole.

The Wimperis drift sight used the same principle as Mathews', with gearing replacing the mathematics, but as Wimperis pointed out, the principles of navigation were a truism - commonplace knowledge, the mechanical detail was the invention. He had not seen Mathews' paper until the hearing and said it had great credit for anyone who had not been

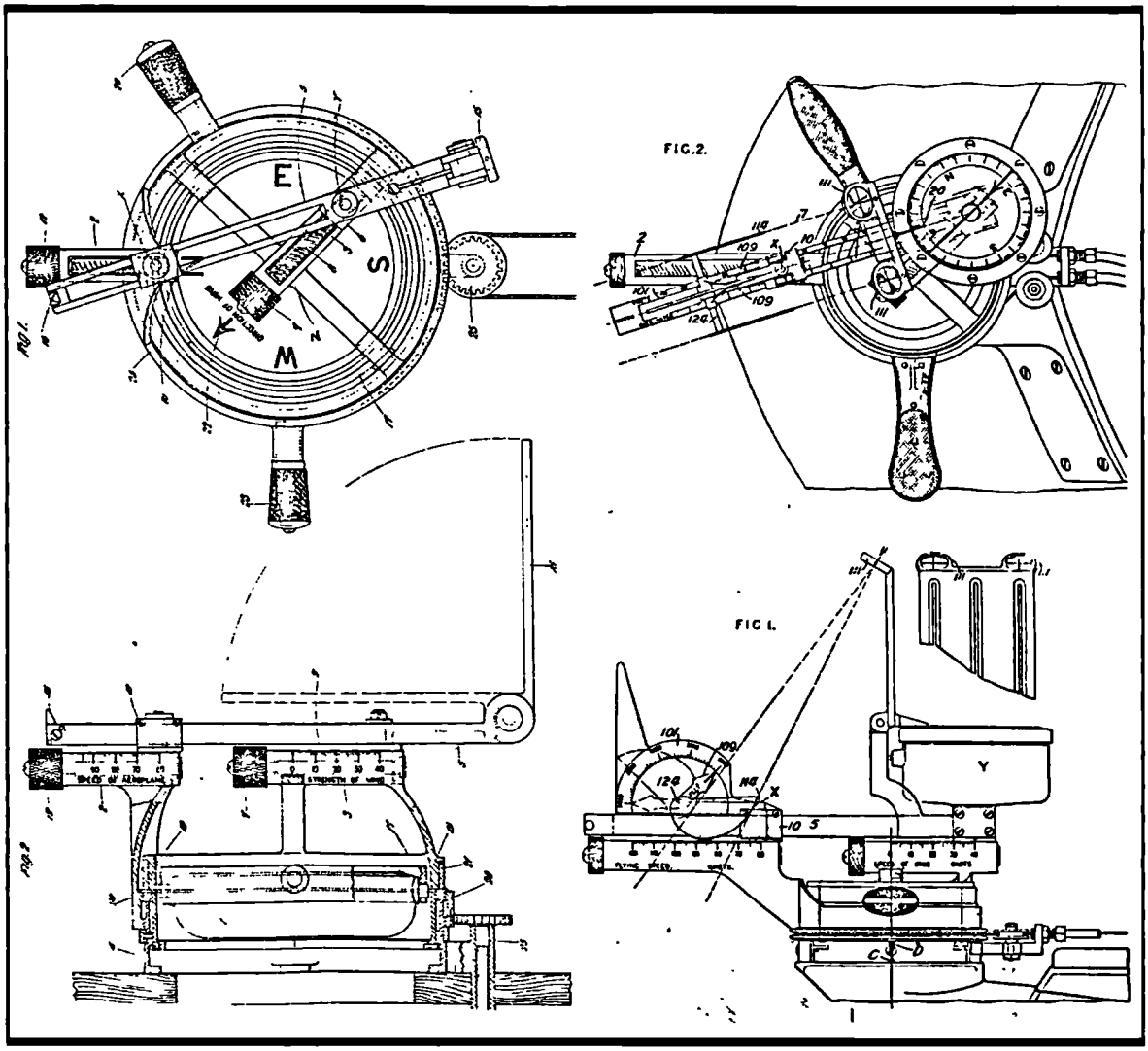
in the air, adding interestingly that although he saw all RNAS papers, he only saw RFC papers through personal friendship. He then gave a review of his own career and the history of the development of his sights. The drift sight was developed to avoid the violent prejudice of pilots to use a stop watch on active service. With it, the component of the wind speed in the direction of approach to the target was added or subtracted from the air speed. Indicated air speed could be used because the air density correction was incorporated in the altitude scale of the sight. With a touch of humour, he said that the RFC did not like his new sight any more than they appeared to like Mathews' proposals, probably because they operated over land, but adopted it eventually when the RFC and RNAS amalgamated.

The course setting sight avoided the need to find maximum drift angle by flying at right angles to the wind, something O'Gorman thought impossible. He had informed the Air Inventions Committee of the new sight on 7 February 1916, just prior to the Admiralty patent application. It was only later when preparing production drawings dated 2 June 1915, that it occurred to him to add another bar to convert it into a navigation instrument. This was after he had visited Pollen on 5 January 1917 with Major Bourdillon, when they were shown three sights. Two used stop watches, which did not interest him, and he saw nothing new in the third. He did not disclose his own invention to Pollen, because it was a secret patent.

Infringement of the Argo patent rested on the interpretation of a paragraph in its specification;

> This invention relates to a linkage by means of which the course to be steered by the pilot of an aeroplane so that he may pass over a given position on the ground is automatically indicated to him so long as the observer keeps a sight on the said target.

It assumed the observer knew the air speed and wind speed. In August 1918, Argo's Patent 131,706 added bomb sights to the original patent, but this was not involved in their claim. Argo's case presented by Bousfield was that the Wimperis course setting sight infringed the Pollen-Landstad Patent 127032 of 21 March 1917, that Wimperis was ignorant of its principle when it was shown him on 5 January, and that his bomb sight only became a course setting sight during its development after visiting Pollen. For Wimperis to say that he saw nothing new, was not true as the combination of a deformable vector course setter with a linkage to the pilot was certainly novel to him. Under the Patents Act this was not a disclosure. Pollen always communicated his inventions to the Admiralty before taking out a patent, and any subsequent use by the Admiralty was on a royalty basis. In short, his case was that Pollen's instrument had put ideas into Wimperis' head to solve the general attack problem. Nothing of this claim is mentioned by Sumida.[3 7]



(a) Patent 127032 of 1917 (b) Patent 131,706 of 1918

Fig 9.3. Pollen Course Setting Sight.

(a) Pollen's arrangement of the triangle of velocities above the compass is shown in the top diagram and is the patent that Wimperis supposedly infringed. (b) is Pollen's later redesign incorporating a bomb-sight, which closely followsWimperis' design.

Arthur Joseph Hungerford Pollen was called and explained that his setter had been designed with submarines in mind. With bomb dropping, it was essential to be on the exact course - any error resulted in a miss - exactly like aiming a gun. When Wimperis had visited him, Pollen's chief engineer H.F.Landstad had shown and explained their Drawing No. 3015 to him as they had no model of their setter at that time. Wimperis had said the device was both new and important and asked if they were going to make a model. Pollen had explained that his manufacturer was a controlled firm and he could not ask them to carry out experimental work without an order from the Admiralty; that is from Wimperis.

Moritz unsuccessfully tried to get Pollen to say that his patent was 'a communication between observer and pilot', a much narrower interpretation than the infringement they were claiming. Wimperis had no questions to ask Pollen, but 'congratulated him on his memory'. Bousfield then called Major Charles Edward Fairburn, who had been in charge of bombing experiments for two years, as an expert witness. He said that he had seen many drift indicators, but in his opinion the Argo patent would be a great advantage to the pilot to reach the target quickly. For Fairburn to appear as an expert witness for Argo is surprising and raises the questions; was it for the fee, was it to argue RFC technology versus RNAS technology or was it personal?. There is no clue in the evidence, but under questioning Fairburn probably wished that he had not appeared. Moritz first got him to admit that he was only giving his opinion of the Argo sight as he had no experimental evidence to support it. He then got Fairburn to agree to the narrow interpretation of the infringement paragraph by agreeing that there was nothing new in using a vector linkage for steering but that only the particular linkage was novel. Wimperis in turn led Fairburn through the design of a course setting sight, getting him to agree that he would use an aero bearing link to find drift and a compass to measure the drift relative to the earth's magnetic field, that he would place these together to be able to read them in quick succession, that it was better to place the compass behind the vector linkage rather than in the middle of it. In turn Moritz called Edward Llewelyn Pickles from the Air Inventions Board at the Air Ministry to support all that had been said.

Moritz summed up - in the Argo patent the air bar was variable, in the Wimperis it was fixed fore and aft, so that Argo indicated the course *to be steered* while Wimperis indicated the course *being steered* - two totally different things - with Argo the hypothetical triangle was set and continuously corrected, with Wimperis a fixed triangle was set based on initial observation - as Pollen said 'His was more accurate'. If the broad construction of the Argo patent was taken, then two prior documents by Faccioli and Mathews prevented it being novel. The question to be answered was ; did the junction of a vector linkage and compass which Wimperis has admitted was novel to him, set him on the way to design the course setting bomb sight? In reply, Bousfield said that he was not concerned whether Wimperis had used the idea, the important thing was that the Argo communication had been to the right fountain head, and that there was a case for infringement based on previous patent law as Wimperis had admitted that the combination of linkage and compass was novel to him at the time.

On 16 July 1920, the Royal Commission awarded Wimperis £500 for his drift sight, nil for his negative lens sight and £500 for his course setting sight, based on his 'bad' status as a serving officer who had been responsible for development of bomb sights. Argo was awarded £500 for their 'suggestion' to Wimperis as their patent was not novel if read

broadly and there was no infringement if read narrowly. Gregory received £100 and Mathews nothing. But this was not the end of the story as Wimperis submitted a claim in 1923 for the American use of his patent.

8.5.3 American use of Wimperis course setting sight

The Royal Commission hearing for the American use of Wimperis' patents was again chaired by Mr Justice Sargent.[38] Wimperis was represented by his solicitor Whitehead, who explained why Wimperis was pursuing another claim in view of his 'bad' status in the earlier claim. He revealed the curious circumstances of Wimperis's employment, which had not been known to the Royal Commission until he had questioned the meagreness of his award. Wimperis had asked for a salary of £1200 to run the Air Ministry Laboratory, but the Treasury would only pay £900 rising to £1000, his previous salary with the Crown Agents. However, Major Ellingham and Sir William Robinson at the Air Ministry suggested he accept this and they would make a strong recommendation to the Air Inventions Committee for special monetary award for his inventions, and would write to the Crown Agents to say he would not be returning to them. The Air ministry file on this had since been lost, but Wimperis still had a copy of the minutes of the meeting. The Commission saw this as a 'wangle' and were concerned at the implications it placed on them. However, as there was no binding contract they agreed to proceed.

The evidence at the hearing was a complex commercial issue rather than a technical one. Whitehead explained that assigning patents to the Crown did not make the patents the property of the Crown under the Patent Act that existed during the war. It only gave the Government the right of use of the patent. This had since been amended in the 1919 Patents Act to give the Government the right to 'make, use, exercise and vend'.

Under the old act, Wimperis received permission to patent his invention abroad, provided the British Government retained the right of use. Initially permission excluded America, but this exclusion was withdrawn on 28 September 1918 and Wimperis started correspondence on 28 November to try to negotiate a royalty of 7·5-10% for wartime use and 12% for use afterwards. The claim was substantial and based on 15,044 drift sights made during the war at a cost of $659,000, but for which no future use was foreseen, and for 2200 course setting sights on order with the International Cash Company of Chicago at a cost of $265,000. He also applied for and was granted American Patent 1,313,934 for his drift sight and 1,315.065 for the course setting sight in 1919. Negotiations proceeded for some time before the American Government realised that their use could be considered as an extension of the British Government use under the Bolling Agreement, an agreement

of which Wimperis had not been made aware. Neither was he aware that the Admiralty had given an early course setting sight to some American officers on a wartime visit and that one of them had since patented the embodiment of the Wimperis sight by the 'substitution' of the sighting arm below the compass and the addition of electrical means to transmit the course to the pilot, while carefully avoiding any claims made in the Wimperis patent. The

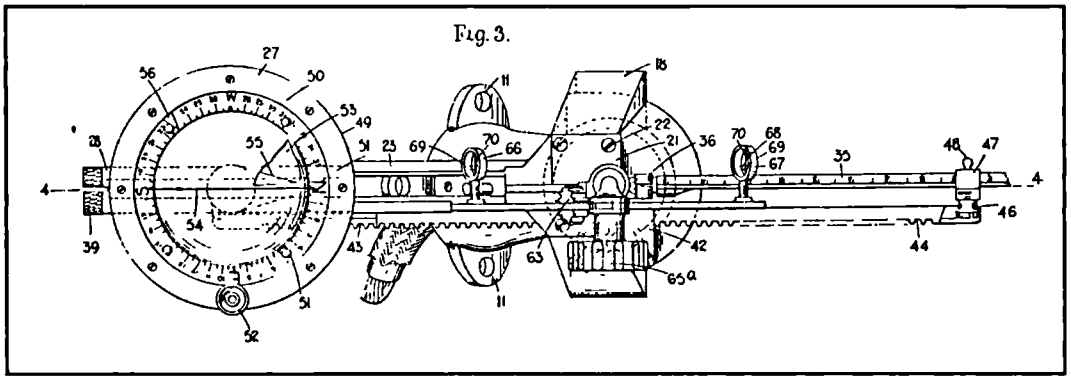


Fig 9.4 Boettcher Sight 1918.

sight was now known as the BOETTCHER. This amounted to infringement under British patent law but not under American patent law.

Therefore the only claim open to Wimperis was to the Royal Commission. Sir Keith Elphinstone of Elliott Brothers, who had known Wimperis and Pollen over many years, was asked to agree the split between them and to estimate the future American use of the course setting sight over the twelve years of the life of the patent.. Wimperis was awarded £1000 for the wartime use of the drift sight and £1100 for the future use of the course setting sight, of which presumably half would go to Argo. He tried unsuccessfully to claim £180 towards abortive legal fees incurred in America. Presumably, the award did contribute to his salary. The real winner was the American Government who acquired a bomb sight which they used for many years at no cost to themselves.

8.6. Post War Research at the Air Ministry Laboratory

After the war ended, Orfordness tested several patented sights, most having some novel feature but handicapped by others.[39] At the Air Ministry Laboratory (AML) at Imperial College, the wartime staff stayed on and development continued on the Gray stabilised sight, first by Horsley and later by Mackower and Bygraves working under Wimperis.[40] In 1921, Wimperis was forced to accept that the Gray sight was bulky, was difficult to

adjust, its zero was disturbed by a slight knock during aircraft maintenance and its settings were temperature sensitive.[41] He transferred development effort to the new AML sight using a Bygraves suspended gyro, but noted that his unstabilised course setting sight had just been used by Mitchell in America to successfully bomb the old battleship Agemennon. He maintained the objectives of a bomb sight should be stabilised 'line of sight' and reduced handling, but that this should not include the complication of automatically setting altitude, air speed and bearing, as the errors from manually setting these parameters was small compared with those from the oscillations of the aeroplane.[42] Optical sights had been tried and abandoned in Britain and Germany as being complicated, heavy, having limited field of view and light, and lacking definition due to vibration, arguments which Wimperis saw had a parallel in rifle sights. During this period, several secret bomb sight patents were taken out by laboratory and college personnel, including the use of pendulum stabilisation, because of continuing problems with gyroscopes.[43]

In the end, no satisfactory stabilised sight was produced. The RAF entered World War 2 with the Wimperis course setting sight, which had been in use for twenty years. It was only when Lindemann, as scientific advisor to the prime minister, found the RAF had no stabilised sight, that Farnborough started research under Blackett, which led to the development of the Stabilised Automatic Sight for precision bombing and the Stabilised Mark 14 Sight for more general work.[44]

Conclusions

Melvill Jones summed up the early bomb aiming research as an example of setting the line of thought too early without experience of active service conditions.[45]

> The factory pilots insisted that the final attack must be in the hands of one man and as Busk was dead we had no one to contradict them or take on the job to resolve the difficulty. Work at the RAF and CFS started with the aim of getting fore and aft accuracy correct by measuring ground speed, while lateral accuracy relied only on flying a straight course to pass over the target. Lucas developed the space damped pendulum, which was useless for the job, while I concentrated on bomb grouping. The camera obscura showed that it was easy to fly any straight course provided you did not have to pass over a particular point and the best way to ensure this was to fly up or down wind. This fact was crucial to our thinking and we did not realise until too late that on active service it was foolhardy to fly up or down wind or to fly straight and level for any length of time over a defended target. It was Wimperis who provide the final solution with his course setting bomb sight. This split the work between pilot and observer and allowed a cross wind approach to a distant point. By the time we realised this, the DH-9 bomber had been designed, which could not use this sight. We would have arrived at the solution earlier, if the experimental people had been pilots and had studied conditions in France.

As with the aircraft compass, Farnborough had pushed ahead without any feed back of active service conditions.

The RFC discontinued their own bomb sight design when they found the Wimperis drift and negative lens sights met their needs. However, Farnborough considered that a stabilised sight was the only way to improve accuracy and Lucas and Lindemann conducted experimental research in this direction using gyrostats salvaged from Sperry stabilisers. Wimperis shared the same conviction and researched gyro stabilisation with the assistance of Professor Gray. In the end, the absence of a small reliable gyroscope defeated both groups.

Wimperis emerges as a more commercial minded scientist than many of the others in this thesis. He was older than most and had worked both in industry and the civil service after graduating and was able to recognise the advantage of laboratory facilities and resources available at Imperial College for his own experimental researches and expand them into the Air Ministry Laboratory. He was very aware of the need for good communications, was a member of the relevant committees, developed good relations with both fellow scientists and more senior ones, and saw his inventions through their trials, commercial production and introduction into service. The war was not a break in his academic work, but was an extension of his working career and eventually led to him remaining in aeronautical research. In this way he was similar to Tizard, as the war provide both men with the opportunity to demonstrate their administrative ability in government research. His commercial attitude was reflected in his attitude to patents and he probably patented more devices than any other commissioned scientist during the war. In the design of the course setting sight there appears to have been an element of plagiarism, or suggestion as the Royal Commission termed it, when Wimperis incorporated a compass, after seeing Pollen's patent drawing. It seems certain that this was done unwittingly as his earlier patent experience made him very conscious of patent infringement, but this was not the first time that the Admiralty had adopted Pollen's ideas without his permission, although the financial implications this time were much less.[37] Wimperis' attitude to patents was to supplement his income and he was therefore similar to Professor J.B.Henderson, but in complete contrast to Lindemann who had a private income. This does not mean that Lindemann was any less dedicated, he had devoted three years to flight testing numerous instruments in the unfriendly conditions of the aeroplane cockpit. The contribution of both men to wartime government research was significant.

By the end of the war, co-operation and co-ordination between military and naval aeronautical research had progressed a long way. The early wartime days of ad hoc experimentation by inexperienced scientists to meet urgent service needs they little understood, had settled down to more logical and coordinated research. Communication initially relied on pre-war university friendships, then became more organised as

individuals from one group were posted or took charge of another group, and finally became institutionalised after the two air services were amalgamated. This established the framework for a mature government aeronautical research organisation when the war ended. This organisation, and how the scientists in this thesis dispersed immediately after the war, are discussed inthe next short but final chapter.

Chapter 9.

The Scientists Demobilise

Summary : Tizard and post-war aeronautical research and education - Wimperis and Air Ministry Laboratory - Lindemann and Southwell to Oxford University - Technical Optics and Aeronautics at Imperial College - Melvill Jones, Thompson, Farren, and Taylor to Cambridge University - Ogilvie and Partners - the Trade.

The final chapter of this thesis is a short account of the post-war organisation of aeronautical research and education to show what happened to the wartime development of aircraft instruments and to the people involved. The cut-off date of 1919 was chosen, because most scientists were demobilised within six months of the end of hostilities in November 1918, most returned to their pre-war careers, some accepted opportunities in the new academic field of aeronautics, the intensive wartime development and production had ceased and the performance of new aeroplanes would soon make most current instruments obsolete.

9.1. Organisation of Post-war Aeronautical Research and Education

The formation of the independent Royal Air Force (RAF) from the RFC and RNAS in April 1918, had placed the aeronautical research at Farnborough, Martlesham Heath, Orfordness, Buckley, Biggin Hill, Isle of Grain and Imperial College under Hopkinson's control at the new Air Ministry. The size of the Technical Department warranted three Assistant Directors and Hopkinson had offered Research and Experimentation to Tizard.[1] However, before the new organisation could settle down, Hopkinson was killed on 25 August when flying from Martlesham Heath to Fairlop. Mayo, a former student of Hopkinson, flying a slower and stable BE 2c wrote in his Log Book,

> Started just before Col. Hopkinson who followed in a Bristol Fighter. His machine dived into ground near North Weald and he was killed instantly - weather very bad.[2]

Hopkinson had become a victim of cloud flying that his own department, and Lindemann in particular, had worked so hard and long to make safer. Tizard's view was that Hopkinson had got into a spin and the low cloud base gave no time to recover. He was buried with full military and university honours at Cambridge on 31 August 1918.[3] Tizard succeeded Hopkinson as Controller, appointing Melvill Jones as the new assistant director.

Tizard's last six months in uniform were busy. As a member of the Advisory Committee for Aeronautical Research and Education, he was involved also in education. This

committee had been set up in 1918, chaired by Sir Richard Glazebrook (NPL) and including,

Sir Frank Heath (DSIR) Dr. F.G.Ogilvie (Science Museum)
Professor Petavel (Manchester University) Lt. Col. Tizard (Air Ministry)
and aircraft makers Holt Thomas and Frederick Handley Page.[4]

It had already been decided to centre aeronautical education at Imperial College and the continuance of the Air Ministry Laboratory at the College was seen to be essential. The Governors had agreed to provide accommodation for it when the Air Ministry took control from the RNAS, their only stipulation being that it should be under the control of one officer and he should be Wimperis.[5] However, it still needed to be financed, which Tizard did by examining the work and salaries of the scientists at Farnborough to see what research could economically be carried out at Imperial College, using the instrument experience that had been developed there.[6] In 1920, the Air Ministry Laboratory was considered a 'good bargain, with salaries of £6000 and free advice from academic staff like Callendar and Conrady'.[7]

Tizard intended to publish the research methods that had been developed at Martlesham Heath and Orfordness to test aeroplanes and equipment. He had covered performance testing at Martlesham Heath in his 1917 paper and this was updated by the staff there, while Melvill Jones, McKerrow and Fairburn prepared chapters on armament testing and bomb aiming research at Orfordness.[8] However, the work was never completed and its contents became obsolete with the passage of time, although much of the Martlesham Heath contribution on instrumentation and test methods appeared later in Barlow's paper.[10] After being demobilised, Tizard returned to Oriel College, Oxford,to become Lee's Reader in Thermodynamics, and was instrumental in proposing Lindemann for the Chair of Experimental Philosophy at the Clarendon Laboratory, with Rutherford and Rayleigh as supporters. Then for the next two years he researched high octane fuels, work he had started during the war. and which was now being carried out at the Shoreham Laboratory of Harry Ricardo (later Sir), a former student of Hopkinson. In this work, Tizard co-opted the assistance of David Pye (later Sir), a Cambridge graduate who had been an Experimental Officer with him at Martlesham Heath. In 1920, Tizard was appointed Assistant Secretary at the Department of Scientific and Industrial Research (DSIR) and became Permanent Secretary in 1927. During all this period he remained a member of the Aeronautical research Committee, and in 1924 was offered the position of Director of Scientific Research at the Air ministry. However, the salary was less then he was getting at the DSIR and eventually Wimperis, who had been appointed Deputy Director, became Director in 1925. Tizard remained at the DSIR until becoming Rector of Imperial College in 1929.[9]

Both Lindemann and Wimperis owed the start of their future careers to Tizard. Of the wartime scientists, Wimperis was the only one to actively continue work on aeronautical instruments and Chapter 5 examined his work at the Air Ministry Laboratory with A.P.Rowe to systematically examine aircraft compasses and air navigation. Papers on aircraft instrumentation were given by Wimperis, Rowe, Tymms and Barlow over the following years.[10] However, after 1925 instrument research had moved to Farnborough under C.J.Stewart from Orfordness. Stewart gave a paper on current instrument developments in 1927, which formed the basis of his 1930 book, which acknowledged the work of Hopkinson, Lindemann, Lucas, Dobson and Melvill Jones in firmly laying down the foundations of scientific instrument design practised at Farnborough.[11]

9.2. Oxford University

Lindemann's priority at Oxford was to modernise the Clarendon laboratory and workshops, which had become run down under Clifton and its use for wartime pilot training - the 'only electrical supply was a Wimshurst machine'. He corresponded with former colleagues to locate surplus machine tools and other equipment.[12] Dobson located a thermo-element and galvanometer, and in the same letter asked Lindemann to get the Oxford member in the House to ask whether Captain Creagh-Osborne drew a royalty from the Government for his aircraft compass, showing that feeling at Farnborough was still strong about the plagiarism of the Lucas compass. I.O.Griffith at the Air Ministry located a German submarine air compressor in an Admiralty store at Battersea, which he earmarked for the Clarendon when he found NPL were also after it. He drafted a proposed letter which Lindemann should write to the Air Ministry regarding the allotment of RAF apparatus to the Clarendon, setting out the lack of machine tools and apparatus for liquifying air and hydrogen, the wartime use made of the Clarendon for student pilot training, and the wartime research that Lindemann, Mackie and himself had carried out without asking for acknowledgement. He provided Lindemann with a list of surplus machine tools, including a lathe used by Griffith Brewer to make Ogilvie air speed indicators, which Stewart had located and was going cheap. Later, he also located a Gaede vacuum pump in Cologne. Negotiations were also made for the Clarendon to supply liquid air to Stewart at Farnborough and Rutherford at Cambridge. Even after Dobson and Griffith joined Lindemann at the Clarendon, Farnborough supplied details of a blower suitable for a centrifuge, that Lindemann should write for.

A history of the Clarendon and the scientists involved after this date is provided by Morrell.[13] Two other Farnborough people later went to Oxford. R.V.Southwell was

appointed Professor of Applied Mechanics in 1929, after first replacing Farren as Head of Flight Testing at Farnborough and then moving to NPL in 1920 as Head of Aeronautical Department. About the same time, Roderic Hill became officer in charge of Oxford University Air Squadron.[14] This association continued after the Second World War, when Southwell and Hill, both knighted by this time, became successive rectors at Imperial College.

9.3. Imperial College

The first year of war had dramatically affected the College. Seventy six staff had joined the armed forces by September 1915, including the Rector Sir Alfred Keogh, who was absent for the whole war as Director General of Army Medical Services with the rank of Surgeon General, an absence that Tizard as Rector would repeat in the second war. The college continued to pay staff throughout the war on the basis of their college salary less their armed service pay. Professor W.Watson (Physics) was in charge of the Testing Laboratory at the Front, Professor J.Strutt (Physics) had been in France on X-ray work and Professor T.Mather (Electrical) had produced devices for locating aircraft and Submarines and had tested them at Farnborough and Upavon. Most of the science and engineering professors were on Advisory or Inventions Committees and chemistry Professors Baker and Thorpe were retained by the Trench Warfare Research Department of the Ministry of Munitions.[15] The British Science Guild listed university departments involved in Government work, suggesting that those historians who quote Professor J.A.Flem .ing's letter to the Times, complaining that no one had sought his services, are presenting the exception rather than the rule.[16]

In addition to instrumentation development in the Air Ministry Laboratory, Imperial College had a Department of Technical Optics. Since 1911, discussions had taken place on advanced instrument and optical design between the College, Northampton Polytechnic, London County Council and leading instrument makers. In 1915, the national emergency for optical instruments convinced the Governing Board that such a department should be established as soon as possible.[17] The Technical Optics Committee was formed in April 1917, comprising,

> Acting Rector the Rt. Hon. A.H.D.Acland (Chairman)
> R.T. Glazebrook (NPL) and A.Schuster (Royal Society)
> Lt. Col. A.C.Williams (Inspector of Optical Munitions - Army Council)
> E.D.Esslemont (Optical Department - Ministry of Munitions)
> Capt. F.Creagh-Osborne (Admiralty Compass Department)[18]

Their initial responsibilities were to select a professor for the proposed department and determine the split in teaching responsibilities between technical optics at Imperial College

and Northampton Polytechnic. A list of eight candidates was reduced to two and F.W.Cheshire was left unopposed after Capt. Hill withdrew before leaving for France - the minutes give no initials to show who Capt. Hill was. Cheshire was 56 and was Scientific and Technical Director of the Optical Department under Esslemont. He had held a studentship at Somerset House, had studied chemistry at the Royal School of Mines, had joined the Patents Office in 1884, specialising in optics, before joining the Ministry of Munitions at its foundation. He lectured to undergraduates at Birkbeck College and was President of the Optical Society, but he was appointed to Imperial College for five years at £1000 a year for his administrative ability. One of his first duties was to detail the courses both in his own department and at Northampton Polytechnic, which would provide systematic instruction for workmen and apprentices in both glass and metal trades on visual optics and the scientific principles underlying their workshop practice.[19] To support Cheshire technically, A.E.Conrady, from the instrument maker W.Watson & Sons then aged 50, was appointed Professor of Optical Design with a five year contract at £650 a year. Lecturing staff at £250 were B.K.Johnson from the instrument maker Adam Hilgar and L.C.Martin (later Professor) a year following his return from the Dardenelles campaign. Two years later in 1919, A.F.C.Pollard, who as Capt. Pollard had been Sub Section Director of Aircraft Instrument Development under Hopkinson at the Air Ministry, was appointed Professor of Mechanical Design with a two year contract.

With the war over, the way appeared open for Britain to train the future instrument designers that its expanded instrument industry would need. Government funding was provided to translate German optical textbooks into English.[20] However, circumstances quickly changed and the importance which the Governors anticipated for a department of instrument design did not materialise. The fault was not theirs. The war had produced a surplus of all type of instruments and the industry was having a difficult period, but more importantly the idea of a specialist degree in instrument design did not appeal to students. Initially, the presence of the Air Ministry Laboratory helped, but student numbers decreased and it became increasingly difficult to fund the chairs.[21] Eventually, the department became solely post graduate and was later absorbed into the Physics Department following staff retirements. The Optical Society had earlier merged with Physical Society, reflecting the problem of identity faced by the post-war instrument industry. Many precision instruments were not optical and words like Optical Society, Optical Munitions and Technical Optics were confusing. The Society of Optical Instrument Makers (SOIM) became the Scientific Instrument Makers Association (SIMA), a name which would later face similar generic difficulties itself. On the design side, the principle of geometrical design, proposed by Maxwell and practised by Darwin and Lucas, was renamed kinematical design and Pollard produced a popular treatise on it.[22] All these changes added to the confusion of students deciding on a career.

The Department of Aeronautics took longer to establish but was more successful than the Department of Technical Optics.[23] When the industrialist Sir Basil Zaharoff offered to provide chairs of aviation in London and Paris, the Government had already decided that the post-war centre for aeronautical education and research should be Imperial College. The Board of Governors had wanted the title of Professor of Aeronautics, but as Zaharoff attached importance to it being a Chair of Aviation, it was agreed to have a Chair of Aviation within a Department of Aeronautics. To retain academic control of the new department, the College funded a departmental directorship at £200 a year, stating that he and the professor should be the same person and that the College should have the final word as to the Director. The Government had seen Hopkinson as the obvious professor, but wrote to the Governors in November 1919 asking that the Board of Advisors select a successor to Hopkinson, suggesting the appointment might be made on terms which would allow the definition of the duties and the salary of the Professor to be worked out. Within two weeks, the Board of Advisors unanimously recommended that Sir Richard Glazebrook, who was about to retire as Director of NPL aged 65, should be offered a three year appointment, based on his high distinction as a man of science, his experience in education and the part he had played in the development of aeronautics. The unanimous recommendation is interesting as the Board of Advisors included Glazebrook himself - the others were Hon. R.C.Parsons, F.G.Ogilvie, Prof W.E.Dalby, with Rayleigh, Petavel and Holt Thomas as external advisors. Glazebrook accepted, but pointed out his acquaintance with aeronautics did not come from personal work as an investigator and he could not undertake to give courses of lectures on a wide range of subjects although he hoped from time to time to address students on special matters. The Governors agreed as they considered his experience in organisation was more important and were able to secure Bairstow from NPL as Professor of Aeronautics at £1000 a year in February 1920. At first, he said he could not come for less than £1500, but agreed to the lower figure provided he would still be retained and remunerated by the Air Ministry as an advisor, which was not materially different from any other professor undertaking consultancy work. Bairstow was selected on Glazebrook's recommendation that he was 'head and shoulders above anyone else in the world'. This may not have been the view outside NPL, as Bairstow was accused of persistently ignoring Lanchester's vortex theories throughout the war, only to find after it that they had formed the basis of Prantdl's work at Göttingen.[24]

Bairstow completed a textbook on aerodynamics for the course and lecturing staff were appointed in June 1920, most like A.J.Sutton Pippard (Structures), A.T.Evans (Engines), and Cave-Brown-Cave (Airships - later Professor of Aeronautics at Southampton University) were former Air Ministry staff and had served on various Advisory Sub Committees with Glazebrook. Sir W.N.Shaw, who was retiring from the Air Ministry

Meteorology Office, South Kensington, was appointed Professor of Meteorology and Air Navigation within the Department. Navigational lectures were given by Wimperis and instrument lectures by Dobson and McKinnon Wood from Farnborough. Where Air Ministry staff lectured, the Government grant of £8500 to the department was reduced by the difference between civil service and academic lecturing pay scales. The Air Ministry presented their engine test bed to the governors in recognition of their assistance during the war. It was relocated from alongside the Science Museum to the new Watson Motor Laboratory, dedicated to the memory of Professor Watson who was gassed at his laboratory on the Western Front.

9.4. Cambridge University

Although the Government's plan was to make Imperial College the centre of aeronautical education and research with Hopkinson as professor, this was not Hopkinson's own view. Just before he was killed, he proposed to the Vice Chancellor that Cambridge should consider a Department of Aeronautics linked with experimental work at adjacent RAF Stations. His proposal was formally submitted to the Air Ministry when the University was offered the Mond Chair in Aeronautics, in memory of Mond's son Francis who had been killed in the RFC, conditional that the Government provided the research flying facilities. The Air Ministry agreed and provided an aeroplane and pilot at Duxford. The potential candidates for the chair were reduced to R.V.Southwell at Farnborough and B.Melvill Jones at the Air Ministry.[25] Jones (Emmanuel) was successful and fortunately survived a plane crash prior to returning to Cambridge.[26] Hilken describes how Jones established his Department with the help of the Engineering Department and of W.S.Farren and G.P.Thomson, funded only by his personal book allowance, after the University had used Mond's endowment for other purposes.[27] Farren designed and helped a carpenter build the wind tunnel, not as demanding as being in charge of flight testing at Farnborough, but in the Second World War, he returned to Farnborough in charge of the whole establishment and was knighted for his work. Thomson had spent a year with the Aircraft manufacturing Company, where he wrote a textbook on aeronautics. G.I.Taylor and F.W.Aston were back at Cambridge, but in the Cavendish. Melvill Jones retained an interest in instrumentation - part of his research program was air navigation, including cloud flying, as post-war commercial aviation was concerned to maintain schedules in poor weather. His paper on the subject, concluding that although cloud flying was practised by military aviation, the risk involved for commercial purposes was too great, was discussed in Chapter 6.[28] In 1966, many of those involved in early aeronautics wrote their reminiscences to mark the centenary of the Royal Aeronautical Society. Jones' contribution was not about himself, but about the work of Keith Lucas to develop a compass for cloud

flying.[29] This was not the first time he had taken an opportunity to set the record straight. In 1935, he was influential in gaining recognition for the work of F.W.Lanchester.[30] Jones' own contribution to aerodynamics would be on streamline theory, which was used by R.J.Mitchell and S.Camm to design the Spitfire and Hurricane.

9.5. The Trade

Demobilisation provided opportunities for private venture. Alec Ogilvie who had run his own aeronautical business at Eastchurch before the war, formed the consultancy firm of Ogilvie and Partners Ltd, at Gwydir Chambers, 104 High Holborn, WC1. His partners were colleagues from the Air Ministry Technical Department - R.H.Mayo (aeroplane design), A.J.Sutton Pippard (structure design), H.C.Watts (propeller design) and W.A.Bristow, and their work and clients can be traced through the technical reports of the company.[31] A report on *Aircraft Instruments* is unsigned, but a hand written note,

I am a shareholder of the British Wright Company, but nothing to do with the management of it.

shows the report was by Ogilvie and was presumably added to avoid any conflict of interest in recommending their instruments. As the report provides a clear statement of what he considered the *best* aircraft instruments and their makers in 1919, it is summarised in the following table (all addresses are London unless otherwise shown).

Flying Instruments

a) Air Speed Indicators to RAF Specification Mk IVa
Ogilvie by British Wright Co., 33 Chancery Lane, WC1 and made by
Aeronautical Instrument Co., Galen Place, WC1.
Hollocombe Clift by Smiths & Co, 179-185 Gt. Portland St., W1.
Standard pitot-static heads by Elliott Brothers, Central Buildings, Westmount ?
b) Altimeter
Short and Mason, 46A Holborn Viaduct, EC1.
c) Climbometer
RAF Mk Va by Davenport & Co., 101 Clerkenwell Rd., EC1.
d) Compasses
RAF Mk II long period by Casella & Co., 73 Gurney St., EC17.
5/17 and Mk II short period (with turn indicator) by Kelvin, Bottemley & Baird, Lewisham, SE13,
e) 8 Day Watch
Zenith Watch Co., 119 High Holborn, WC1.
f) Gyroscopic Turn Indicator
Henderson type by S.G.Brown, Willesden Lane, North Acton, W3.
g) Lighting Sets
Joseph Lucas, Birmingham.

Engine Instruments

a) Revolution Indicator
Centrifugal type - Mk IVa 800-2000 rpm and Mk V 600- 2600 rpm by North & Sons, Whippendell Rd., Watford; London Office - 14 Soho St., W1.
Electrical Type and all gear boxes and drives by Elliott Brothers.
b) Petrol Tank Gauges
Electrical by Elliott Brothers.
Air Pressure by J.W.Benson, 62 Ludgate Hill, EC4 and French design by Nonox, 186 Piccadilly, W1.
Float by Sims Motor Units, Gresse St., W1.
c) Petrol Flow Indicators
Prismatic by Dewrance & Co., 165 Gt. Dover St., SE1.
d) Oil Pressure Gauges
Dewrance & Co., and Schaffer & Budenburg, 77 Queen Victoria St., EC4.
e) Thermometers
Transmitting type RAF Mk I by Foxboro, Mass, USA, and Cambridge Scientific Instrument Co.

Flight Test Instruments

a) Recording Barograph
Jules Richard of Paris and camera barograph of Martlesham Heath.
b) Recording Air Speed Indicator
Trussaint type by Leperc of Paris, but this will be superseded by RAE type.
Also British Wright Co. make one for balloon work.
c) Strut Thermometer
J Hicks, 8 Hatton Gardens, EC1.
d) Statoscope
British Wright Co.
e) Petrol Flow Meter
RAE circular type by Troughton & Simms, 340 Woolwich Rd., Charlton, EC7.

Calibration Instruments

a) Altitude Pressure Chamber
Casella, 73 Gurney St., SE17 and Baird & Tatlock, 14 Cross St, Hatton Gardens, EC1.
b) Air Speed Indicator Calibration
Alexander Wright & Co., Westminster Palace Rd., SW1.
c) Revolution Indicator Tester
Tinsly & Co., Stranger Rd., South Norwood, EC28, and BTH , 83 Cannon St., EC4.
d) Carburettor Jet Calibration
Brown & Barlow, Coventry.

Several point are worth noting. Munro and Negretti & Zambra are not mentioned as having any good instruments at this time, but both would produce aircraft instruments until after the Second World War. Negretti and Zambra were asked to produce a mercury in steel distance thermometer for oil and water in 1920, and made the decision that year to give up optical instruments and concentrate on aircraft and industrial instruments.[32] Smiths are only included because they had taken over production of the Clift air speed indicator from Munro, as the accuracy of Smiths revolution indicator varied considerably if mounted out of vertical, which was often the case on an aircraft panel. The Cambridge Scientific Instrument Company is mentioned for the radiator thermometer which they mass

produced. In spite of the opportunity to make several prototype instruments they never developed an aircraft instrument division. Perhaps Darwin was conscious that he was the only 'trade' member on his various committees and did not want to make commercial capital from his position, or perhaps he was more interested in the underlying scientific problems. He remained on the Advisory Committee for Aeronautics and his Air Inventions Committee continued through 1919, members included L.Bairstow, H.L.Callendar, R.T.Glazebrook, A.V.Hill, B.Melvill Jones, G.I.Taylor and H.E.Wimperis.

The aircraft instrument trade that emerged from the war faced a difficult time when the government cancelled wartime orders and sold its large surplus stocks at bargain prices. Only a handful of firms continued to make aircraft instruments, because of the specialist requirements and the amount of expensive research and testing needed for a relatively small instrument market.

Chapter 10

Conclusions

The history and development of early aircraft instruments have been examined in the previous nine chapters. It remains briefly to examine how far the objectives mentioned in the Introduction have been met, to reflect on the historical significance of what has been discovered and consider lines for further research.

The Thesis - objectives and originality.

This thesis provides a building block in the history of Twentieth Century instrumentation and for aviation in particular. It presents the early history of aircraft instruments in a logical sequence of events, sometimes retracing a sequence from another perspective to substantiate the initial account. Both the history and the sequence in which it is presented are entirely my own as there is no previous history or secondary source material to follow. When my research started, I had no idea how the history would evolve, or who was involved, or where it was enacted. My starting point was Farnborough, which has a very substantial aeronautical library, which contains all published reports since 1909, but no internal reports and records prior to 1920, the cut off date of this thesis. Subsequent research progressed by systematically examining all instrument related material in other locations, noting everything that might be relevant to this thesis, even though what that exact relevance might be was not always immediately clear. Gradually the jig-saw of information formed a picture of the development of each instrument, but the continual difficulty was that there was no indication whether missing information existed or where it would be found, nor was there anyone to consult. The final account in this thesis is the result of extensive research through hundreds of files and documents, of which only a small proportion contained material relevant to aircraft instruments. If the history is researched by another writer, emphasis, details and the conclusions drawn may differ, but the basic development would be that in this thesis.

This thesis is written about a period when the technology itself was evolving and the word *aeroplane* had not fallen into disuse. I have not intentionally emphasised any one development more than another, each instrument had its own importance and its own history, but together they contributed to the rapid advance in aeronautics during the First World War period. I have given equal emphasis to the instrument technology and to the

people involved in it, so that this thesis is also an historical account of wartime scientists in this field. This account is based on the published and unpublished reports of their aeronautical instrument work and supplemented by their personal papers, their diaries, their comments in discussions on papers by their colleagues, their patent specifications and their claims for government utilisation of their inventions. I have used the word *scientist* through out the thesis as most of those involved were either natural or mechanical science graduates. However, some were mathematicians but Fowler found that,

> all were anxious to get on with the war in their own way, and although one could sometimes feel a natural irritation between the different trained classes, it did not show openly.[1]

He added that Farnborough was the biggest laboratory in the country; this thesis only covers a small fraction of their work.

Thesis conclusions.

Each instrument had its own distinct history and the conclusions on specific developments have been drawn at the end of each chapter and will not be repeated. The application of simple physical principles and the dedication of those involved were a common feature of each development; individual problems were not new, but the combination of them was. The development had three distinctive features, (i) the aeroplane and the environment in which it operated was new, (ii) there were severe constraints imposed on the instruments fitted to it, and (iii) a scientific based approach to solve problems was adopted early.

1. The aeroplane and its environment.

a) The aeroplane was different from previous forms of transport because it did not come safely to rest when its engine or part of its structure failed. Instruments were introduced to reduce the likelihood of this occurring by indicating the condition of the engine and the narrow speed limits between stall and disintegration. Suitable engine revolution indicators, air speed indicators and altimeters were available when the war began, but war brought new requirements and a determination to meet them quickly. Instruments like the compass and turn indicator were developed to assist the pilot fly in poor visibility, but the main requirement was for scientists to accurately compare the performance of one machine against another or against its wind tunnel prediction. Early aircraft instruments were essentially instruments of discovery in a new science rather than instruments of necessity for the pilot.

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1. PRO/AIR 1/732/176/6/146, 'Reminiscences of Sir Henry Fowler', SRAF, undated.

b) Early aircraft instruments were mechanical, self-contained, self-powered devices, made and assembled by skilled instrument makers. Other than basic instrument skills, there was no prior technology to adopt. Air velocity and pressure measurement had been established in meteorology, mountaineering and ballooning and the compass was well understood in marine navigation, but the transfer of this technology to the aeroplane proved difficult and involved considerable resource and experimentation. Direct association with aeronautics was more important than established instrument making practice in the design of new aircraft instruments during the first 10 years and some technology, like the gyroscope, was not successfully transferred during this period.

c) All research involving aerial measurement proved difficult. The laboratory was the cramped, cold and generally hostile open cockpit aeroplane, which operated in an experimental environment over which those conducting the experiments had no control. Height and air speed were inferred from differential air pressure instruments. These did not provide an absolute measurement as the density of the atmosphere varied continually and meant that all height and air speed measurements had to be laboriously reduced to a standard atmospheric density. The accuracy of air speed measurement was also affected by the passage of the aeroplane through the air and optical methods had to be devised to accurately calibrate air speed instruments from the ground. This reduction of measurements and air calibration of instruments involved considerable time and effort in wartime aeronautical research. Fortunately, the problem of monitoring the movement of an aeroplane from a fixed location on the ground was the converse of bombing a target, and aeroplane performance measurement and bomb aiming research were both able to take advantage of the same camera obscura and mirror devices.

d) The movement of the aeroplane also affected measurement accuracy by subjecting instruments to forces or combination of forces which were not present on the ground. These forces were difficult enough for the scientist to understand, but to the service pilot they were incomprehensible and led to the distrust of aircraft instruments in general and the compass in particular. Gravity controlled, spring controlled and magnetic controlled mechanisms took on new importance, and became generalised into elastic attachment to the earth or elastic attachment to the aeroplane.

e) The military pilot and scientist had conflicting priorities for instruments. Convenience and serviceability were more important than accuracy to the pilot, while the scientist was willing to sacrifice convenience to obtain accurate measurements. The same attitude was also true for bomb-sights, where the less accurate negative lens sight was preferable to leaning out over the side of the fuselage with a stop watch.

f) The development of early aircraft instruments showed that a wide range of scientific knowledge, innovative prototype design and intensive experimentation was involved for a relatively small number of instruments. What appeared scientifically easy in theory, proved technologically difficult to achieve in its early stages. Aircraft instrumentation was not an isolated example; sound ranging and submarine detection needed the same kind of applied scientific effort by wartime scientists. Even simple devices like the military gun sight, the trench periscope, and day light signalling lamp, took much more effort than would be imagined.[2]

2. The constraints the aeroplane imposed on instruments fitted to it.

a) The cramped cockpit and small instrument panel severely limited the size of instruments and the freedom to locate them for the convenience of the pilot, while low engine power made weight reduction the priority for all airborne equipment.

b) Any instrument fitted to the airframe was subject to severe vibration and acceleration forces. The early designer was faced with the difficulty of designing sensitive mechanisms that could tolerate these forces. On instruments like the aircraft compass, anti-vibration features became essential for the instrument to work. No automatic recording mechanism was able to cope successfully with these forces and the trained conscientious observer was preferable to any recording instrument.[3] Photographic recordings based on manometers or pin-hole kymographs were used in research flying, but were never very reliable.

c) The manometer proved the most adaptable early instrument in the absence of better technology. It was used for indicating height, air speed, rate of climb, height

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2. Transactions of the Optical Society; B.K.Johnson, 'The No. 7 Dial Sight Mk II', **XXI**, 1919-20, p 176-186. W.A.Dixey, 'Design, Details of Construction and Use of Trench Periscopes', **XV**, 1914-15, p 78-98, and A.C.W.Aldis, 'The Optical Theory of Portable Daylight Signalling Lamps', **XXI**, 1919-20, p 113-126. G.M.B.Dobson was actively involved with Aldis, see Tizard Papers, Ref HTT 5/152, 'CFS-Aldis Daylight Signalling Lamp', draft of Orfordness report addressed to Major Wimperis, undated.

3. The trained conscientious observer is not unique. J.Hughes, *The Radioactivists*, PhD Thesis, Cambridge University 1993, examines the importance of the trained observer in scintillation measurement.

holding, angle of turn, angle of incidence and distribution of pressures and had the advantage that it could be mounted remotely from its sensing heads and its shadow could be photographically recorded.

d) In the period examined, there was little in the way of equipment like environmental chambers to observe the behaviour of aircraft instruments in the laboratory. The aeroplane itself remained the only place to test instruments that were needed for it.

3. The speed of development.

a) Rapid wartime development was due to the foresight of J.B.Haldane, who believed that aeronautical research should be on a scientific basis. The establishment of the Advisory Committee for Aeronautics in 1909 fortunately ensured that there was sufficient lead time for research thinking to mature and effectively use the wartime scientists five years later. The main wartime aircraft instrument development was conducted by scientists within the services with the active assistance of university staff, but little from the DSIR or Inventions Committees. During these first ten years, the development had no sociological drives.

b) New instruments were based on simplicity and functionality, using proven technology. Prototypes were fabricated for expediency in local workshops and often remained 'wooden boxed', reminiscent of university research laboratory practice.

c) Scientists were able to quickly interpret apparent inexplicable instrument behaviour, like that of the magnetic compass in an aeroplane, with little previous experience of the subject or the environment. Melvill Jones' views were that,

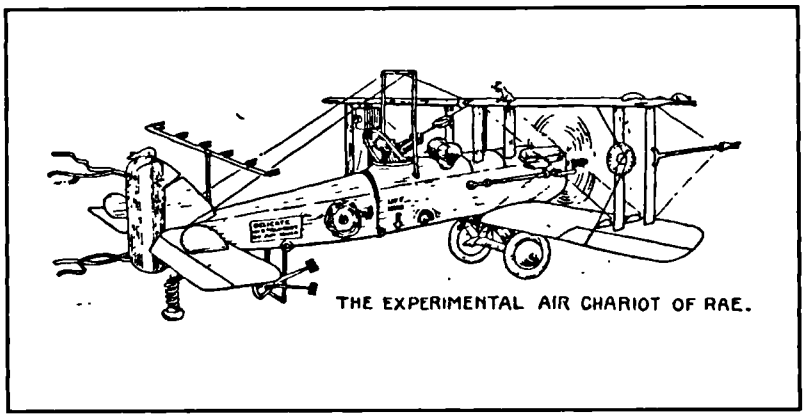
> Experience of research lies in the decisions that have to be made fairly early in the work, with inadequate data for a rigid logical conclusion to be drawn - otherwise it would not be called research. A good researcher is one who knows he has sufficient data to make a decision although he may not be able to back the decision by logical argument. If I had to choose a man for some particular research, I would prefer a man with previous research experience but little knowledge of the subject, than a man well up in the subject but with little or no experience of research. Detailed knowledge is comparatively easy to require by comparison with the power to make decisions in research work.[4]

The wartime scientist had merely changed his lab coat for a flying suit .

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4. Imperial War Museum, Ref AC 76/6/62, 'Some Wartime Experiments', undated but about 1919, Lecture given by B.Melvill Jones to Royal Aeronautical Society but not published.

d) The following cartoon, which depicts aircraft research instrumentation mentioned in this thesis, shows that the RAE scientists at Farnborough were well aware of the improvisatory nature of their work.[5]



The Experimental Chariot of RAE.

The significance of this thesis.

The principal significance of this thesis is that it documents the history of early aircraft instruments to provide the foundation for any subsequent history of aircraft instruments or bomb-sights after 1919. It identifies many developments, techniques, limitations and arguments that are invisible in subsequent developments, such as the liquid manometer, geometric design principles, gravity and spring controlled instruments, short and long period compasses, etc.

However, because it also examines the people involved in the development from a range of record sources,

a) It documents the activities of groups of scientists in the First World War, that has not been seriously addressed before. They were new to aeronautics, but quickly became effective and many found an earlier opportunity to demonstrate their administrative ability than would have been possible in their pre-war universities. Their technical knowledge, skill and administrative abilitywere not lost afterwards

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5. Illustration by W.D.Douglas in *The Book of Aeron*, issued as an Internal Report in 1918 and attributed to R.V.Southwell, H.Glauert, H.L.Stevens and W.D.Douglas. Original copies in Tizard papers and at Royal Aeronautical Society, but published in part in *Journal of Royal Aeronautical Society*, **70**, January 1966, 85-88.

as several remained in aeronautics, either in new university departments or directly in Air Ministry work, while many who returned to previous careers remained on aeronautical advisory and research committees. They had been part of a pre-war academic network, a wartime government network and were now a post-war network that realised scientists could make a substantial contribution to war effort. The First World War provided an apprenticeship for the second, the young scientists of the first were the senior scientists of the second, while in turn a new generation of young scientists had 'all the fun'.

b) It shows the academic network that existed in government aeronautical research and development at the time. The Advisory Committee for Aeronautics had a strong FRS and Cambridge representation, the wartime Farnborough and Admiralty Air Department instrument groups were predominantly Cambridge, while the Upavon group was mainly from Oxford. The groups were self recruiting, adopted senior common room style behaviour ι, received high military rank without military training, and eventually administered themselves under the direction of a Cambridge professor. Post-war advisory committees were based on academic and wartime associations.

This does not mean they were sheltered from danger. When they found that recording instruments could not he transferred to the aeroplane, they either had to accept data from a trained observer or fly themselves. Many learned to fly to be more directly involved and some were killed like many front line pilots, because it was not official policy or standard practice to carry parachutes.[6]

c) It follows the change from ad hoc empirical research, with theoretical support from older scientists who had been trained to ask,

> what fundamental principle is involved and how can it be applied, rather than ask what is the proper way to do it or how have other people done it.[7]

to the practical research methods of more recent graduates.

d) It supplements the biographies of Lindemann and Tizard during the First World War period. It shows that Lindemann's contribution to the development of new aircraft instruments was significant. Some of the instruments had been designed by others, but he flew relentlessly day after day to perfect their performance. This was a

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6. T.Orde-Lees, 'Saving Life in Air Wrecks', *Aeronautical Journal,* **XXV**, July 1921. Parachutes were heavy and inconvenient until G.I.Taylor mathematically established the best design.

7. C.V.Boys, 'H.R.A.Mallock 1851-1933', Obituary Notices of Fellows of the Royal Society, **1**, 1932-35, 95-100.

period in his life when his work was largely directed by others. Tizard had a more open task of determining how to compare the performance of different aeroplanes, which eventually led to a more administrative role.

e) It provides the first substantial account of the work of H.E.Wimperis, who later became Director of Scientific Research in the Air Ministry and for whom no biography exists.

f) It adds more detail to instrument histories, like those involving Darwin, Pollen and Creagh-Osborne and introduces the wartime contribution of several professors to aircraft instrumentation.

g) It provides a more technical history of work at Farnborough, Upavon, Martlesham Heath and Orfordness during the First World War than has appeared before, and describes the work of the Air Ministry Laboratory at Imperial College for the first time.

h) It examines the government strategy to marginalise the value of wartime invention after hostilities had ceased through the transcripts of hearings of the Royal Commission for Awards to Inventors and shows the importance of these records in the history of wartime technology.

So why has this history not been examined before? There is no obvious answer. The history of instrumentation in the Twentieth Century has received little attention, so aircraft instruments are not alone in this respect. Possibly the subject of Twentieth Century instrumentation is too recent and too vast, or the results are more important than the measurements, or the preserved machine is more interesting than the lifeless instruments within it. Certainly, the modern mass produced instrument has little interest to collectors, its life span is often so transitory that it leaves little impression behind it, and most are highly specialised and used for surveillance rather than discovery.

However, this thesis has shown that the history of early aircraft instruments is about discovery and famous people, the application of scientific principles and the use of simple mechanical instruments, during a very adventurous period of aviation. I suggest the more likely reason for the neglect to date is that little has been written to publicise its interest.

Suggestions for Further Research

This thesis has opened up several avenues for further research into wartime laboratories and instrumentation. The most obvious is the parallel development of aircraft instruments in France and Germany. The French air services provided no instrument specifications, but relied on the maker developing devices acceptable to pilots. This may account for no French aircraft instruments being adopted in Britain during the war, but gives no insight into the instruments used to assist French aeronautical research or assess the performance of their aircraft. The same is true for Germany. The development of aircraft instruments in the inter-war and Second World War years in Britain would be a logical progression. It has been suggested that the problems thrown up by the First World War were effectively solved by the start of the Second, but by then the design and requirements for aircraft had so changed that research started all over again.[8] This research would also need to examine the parallel developments on the Continent and in America. Although America made no contribution to aircraft instruments in the First World War, their research and development rapidly advanced after it and they quickly became a world leader in the field. Durand at NACA pointed the way in 1920,

> Regarding instruments, the field bristles with problems of the highest interest to scientists. The modern aeroplane has become a flying meteorological and physical laboratory.[9]

A useful precursor to further research on aircraft instruments would be to catalogue those in museum collections, both in aeroplanes and display cabinets.

The instrument trade and the supply of military, naval and aircraft instruments in the First World War are poorly researched at present. Any new research should include the records of the Royal Commission for Awards to Inventors, which assess the novelty and utility of the invention against the priority and status of the inventor.

Callendar's laboratory at Imperial College was not the only laboratory working on wartime instruments. Dalby's mechanical laboratory was involved in instruments to predict the location of aircraft for anti-aircraft gun aiming and for setting shell fuses. Although similar in principle to measuring the performance of an aeroplane from the ground, enemy aircraft did not co-operative by flying straight and level and the reduction of measurements had to be several orders of magnitude faster. Mathematical support for the research was provided by the Galton Laboratory at Kings College, under Karl Pearson. A.V.Hill was overall in

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8. Discussion with Brian Kervall, RAE Archivist, Farnborough.

9. W.F.Durand, 'Some Outstanding problems in Aeronautics', *Aeronautical Journal*, **XXII**, June 1918, 178-201, 6th Wilbur Wright Lecture.

charge of this work as Head of the Ack-Ack Experimental Station, and his unpublished papers at Churchill College, Cambridge, would supplement public records. The chemistry, biology and physiology laboratories at Imperial College were also active in wartime research, while Professors Watson and Baker set up laboratories on the Western Front. The history of Imperial College at War would undoubtedly make a very interesting study.

Similarly, the work of H.E.Wimperis at the Air Ministry Laboratory, Imperial College, until 1925 should be researched to complete its ten year history. Following this by researching his work as Director of Scientific Research at the Air Ministry up to 1937 would provide the substantial part of a biography of Wimperis. As part of my thesis, his family was traced to give permission for a copy of his diary to be made available in this country. This covers the 20 years after this thesis. He was involved with aircraft instrumentation for much of this time, summarising the problems with a masterly understatement when he said,

Any aircraft instrument is beset with difficulties.[10]

One is tempted to add that so is its history, but the subject is full of interest and much remains to be done and the results would shed valuable light on the history of Twentieth Century instrument technology.

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10. H E Wimperis, 'Scientific Instruments and Aeronautics', *Jnl Scientific Instruments*, Vol 9, Nov 1932, p 337-41.

Appendix 1

F.A.Lindemann at Farnborough 1915-1919

Lindemann's work at Farnborough has figured prominently in this thesis. This appendix adds (1) his pre-war training and how he came to be at Farnborough, (2) his early work there before learning to fly, (3) the design of his accelerometer, which was not strictly an aircraft instrument as it was not fixed to the airframe, and (4) his involvement with patents, to provide a fuller account of his work in the First World War and of his relationship with colleagues.

1. Lindemann before the war.

Frederick Alexander Lindemann was born in Baden-Baden on 5 April 1886. His father was Alsatian, financially well off, who had settled in Devon and become naturalised; his mother was American. Lindemann later received his university education at Berlin University under Nernst, and continued post-graduate research there. This combination of his name, birth place and university career later prevented him from being commissioned in the RFC with his fellow scientists at Farnborough.

Other students with him under Nernst included A.C.G. Egerton, A.S.Russell, A.H.Gibson, H.E.Watson and H.T.Tizard.[1] Egerton and Gibson would also work at Farnborough, while Tizard would command the Testing Squadron at Upavon and then at Martlesham Heath. Comments by Russell and Watson about Lindemann at this time have some bearing on his work at Farnborough. Russell remembered Lindemann,

> as a good mathematician and experimenter, who had a flair for designing instruments,

while Watson,

> was struck by the craftsmanship which accompanied Lindemann's originality in the development of instruments, particularly his skill as a glass blower. His favourite demonstration was making very small vacuum vessels a comparatively simple but delicate operation.

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1 - Earl of Birkenhead, 'The Prof in Two Worlds', (London : Collins), 1961. Later, A.C.G.Edgerton would join Lindemann at Oxford, A.H.Gibson would work at Farnborough during the war and become Professor of Engineering at Manchester University, and H.E.Watson would become Professor of Chemistry at London University.

With the outbreak of hostilities, Lindemann returned to Sidmouth, where he appeared to devote the next few months suggesting to the three services how various scientific ideas could be applied to their war needs.[2] He proposed to the war Office the use of sound ranging to locate concealed guns and offered to conduct experiments on Salisbury Plain.[3] This was followed by a suggestion to cause havoc behind enemy lines by dropping large quantities of incendiary paper.[4] This consisted of phosphorus paper, impregnated with nitrogen-iodide solution ($N_2H_3I_5$) with a backing of celluloid, which would be stored under water in a tin box until required. Though perfectly harmless when wet, the nitrogen iodide would explode at the slightest touch when dry and Lindemann felt the sound of gunfire would probably suffice, while printing a message to the German troops on the paper would disguise its real purpose. He gave no thought to the military difficulty of storing and dropping the paper. Even after he joined Farnborough, he was officially writing from H Department to the Admiralty, suggesting the detection of submarines by measuring the change in electrical resistance of sea water between stationary metal plates on the sea bed, due to a large metal object and offering to assist development.[5] This would seem an impractical suggestion if the plates had to be lowered from stationary ships at sea, though it might have had some application in a harbour entrance, but no reply is filed.

His application to Farnborough in March 1915 was accompanied by an impractical suggestion for a turn indicator as O'Gorman bluntly replied,

> Kindly let me have the names of one or two references. I received your letter of 2nd instant, but have not forwarded the notes as they do not appear helpful. The banking indicator would be quite useless, as it would be disturbed by vertical acceleration without banking, and apart from this, the flyer has no time to make calculation to correct his compass readings. What is wanted is a correct reading compass, if it can be produced.[6]

The references were acceptable, and O'Gorman replied,

> I am pleased to be able to ask you to come and work at the Royal Aircraft Factory as a temporary assistant at a salary of £3 per week, to which you agreed. Will you kindly let me know if you can start on Monday March 29th or say Easter Tuesday.[7]

Lindemann's wartime career at Farnborough had started and we have seen that he became deeply involved in correct reading compasses and turn indicators.

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2. This may have been in response to letter from Royal Society asking all scientists to suggest inventions, *Trail and Error : The Autobiography of Chaim Weizmann*, (London), 1950, 218.

3. Cherwell papers, Ref C9 and C10, Correspondence Lindemann to War Office on Sound Ranging, undated.

4. Cherwell papers, Ref C 11, Draft of Report on Incendiary Packages, undated.

5. Cherwell papers, Ref C11, Copy of letter on Submarine Detection by change in resistance of sea water due to large metal object, 29 April 1915, headed H Department, Farnborough, no addressee but presumably Admiralty.

6. Cherwell Papers, Ref A10/f1, O'Gorman to Lindemann, Referenced 131&4/L-H Compasses, 12 March 1915.

7. Cherwell Papers, Ref A10/f2, O'Gorman to Lindemann at 27 Queen Anne St, Cavendish Sq, London, Ref Employment at RAF, 23 March 1915.

2. Early work in H Department.

Lindemann worked initially in H Department,

> Like all scientists without knowledge of aeronautics, I was put in H Dept., a branch to which all sorts of odd questions were referred which did not seem to fit into any special field.[8]

but he was not happy with the early work and would have preferred to work elsewhere, as after two months he wrote to his father,

> I shall try and get my thing sent to Mr Balfour through Strutt or Rayleigh, but I do not think that there is any prospect of my getting a good job from the Admiralty. My job here is about all I am fit for and I think I had better stick to it.[9]

His work involved measurement and instrumentation, but was not initially associated with aeroplanes. In the first week, O'Gorman arranged for him to visit Professor Callendar at Imperial Institute, to discuss the detection of aircraft at a distance using long wave radiation, on which Callendar had done some work in connection with solar corona.[10] Lindemann discussed the use of this method of detection with Admiralty and also with T.R.Merton at Oxford, who felt it would not work.[11] Nicol prisms and secret signalling feature in three draft reports. The first concerned signalling with polarised light using Nicol prisms rotated horizontally and vertically.[12] The second described the use of a charcoal brazier as an infra red transmitter with an ebonite sheet to cut out the visible light and a metal sheet to transmit the dots and dashes.[13] The receiver employed more modern technology, using a parabolic mirror with a thermopile at the focus, connected to an Einhoven string galvanometer, but the range of the transmitter or the time for it to reach transmitting frequency is not mentioned! The third report described Lindemann's trip on Royal Navy Airship SS-12, piloted by Midshipman Goddard, to test a nicol prism

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8. Cherwell Papers, Ref E19-20, Draft of Lindemann's contribution to mark RAE 50th Anniversary, 1956.

9. Cherwell Papers, Ref A92/f6, Lindemann at Queens Hotel, Farnborough to his Father, 30 May 1915.

10. Cherwell Papers, Ref C13/2, O'Gorman to Professor Callender, Imperial Institute, South Kensington, 8 April 1915.

11. Cherwell Papers, Ref C13/4, Admiralty to Lindemann, 16 July 1915, and Ref C13/3, Thomas Merton to Lindemann, 13 September 1915.

12. Cherwell Papers, Ref C12/f1-8, Draft reports stamped H Dept, unsigned and undated. 'Methods of Signalling', Report H-498, 16 June 1915

13. Cherwell Papers, Ref C14/1, 'Secret Signalling by Infra Red Rays', F.A.Lindemann, 19 January 1916. He had earlier borrowed a quartz lens when he started this work from Professor Herbert Jackson, who suggested an ebonite lens and infra red might be better, Ref C13/1, Jackson to Lindemann, 17 September 1915.

monocular polariser of 3.5 magnification to observe submerged objects, but the sea was too turbid to obtain any results.[14]

Not all the reports of Lindemann's early work survive. Report H-500, *Methods for determining the true vertical in aircraft* of 18 June 1915, was one of twelve of his Farnborough reports destroyed in the May 1965 review of his papers because copies existed at the RAE![15] Farnborough have no copy now and the report could have been valuable to this thesis.

The Farnborough Flight Log and Lindemann's Pilots Log Book provide the only record of some of his early work. His first flight as observer was with Mayo in a BE 2c on 28 May 1915, a 20 minute flight given as Experimental Test. There were no more flights until two in October, again with the same machine and pilot, and logged as 'bomb sights'. and made following several for the same purpose by Professor Hopkinson. In December and January, Lindemann made three bomb sight tests and one speed indicator test with Strutt, and one horizon sighting test with Goodden. Throughout May 1916, he made ten flights testing the Climbmeter, followed by a long gap until 7th September 1916, when he made his final flight as a passenger on the same test. Lindemann conducted these teststo improve his version of the 'thermos flask' instrument developed by Upavon, which he had reduced in size with his glass blowing skill.

During this period he made attempts to get commissioned in the Hampshire Aircraft Park, or 'starred' as he referred to it. He felt that failure meant that his services were not indispensable to Farnborough and rather than wait until he was attested he proposed to apply for a commission in another unit, but

> wanted to be sure that there will be no hitch in leaving the Royal Aircraft Factory before getting the general, who is good enough to tell me I would be of use to him, to apply for me.[16]

O'Gorman replied that he did not want to spare him, and that he was looking into the question of his application for commission and could probably arrange it, but that he must get himself proficient.[17] What *attested* or *proficient* meant, or who the general was and

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14. Cherwell Papers, Ref C14/1, 'Experiments with Polariser for observing Submerged Objects', F.A.Lindemann, 11 February 1916. Sea Scout (SS) airships were small non rigid ships with the fuselage of a BE 2 aeroplane slung below for the two man crew.

15. Cherwell Papers, note in index to papers.

16. Cherwell Papers, Ref A10/f3, Lindemann to O'Gorman, 10 February 1916.

17. Cherwell Papers, Ref A10/f4, O'Gorman to Lindemann, 10 February 1916.

what use he intended for Lindemann is not made clear, but Lindemann was never commissioned and remained at Farnborough throughout the war.

It was therefore as a civilian that he learned to fly at the Central Flying School (CFS), Upavon, 'with a complete disregard for wearing civilian dress and with no need to drill and parade'.[18] Farren said that after O'Gorman left Farnborough, Lindemann drafted a request for scientists to learn to fly and persuaded the assistant superintendent Major Heckstall-Smith to send it to the War Office. Permission for five or six was granted, of whom Lindemann, Farren and Lucas were the first three. Lindemann said later that he wanted to experience flying and be in full control of his experiments, because he was frustrated with the Factory pilots, who decided how, when and for how long they flew. An earlier request had been refused by O'Gorman who did not wish to weaken the position of the professional pilots. His graduation certificate is dated 25 October 1916.[19]

Lindemann had one problem with flying which was well known to his colleagues - he was very short sighted in one eye, which made his distance judgement poor and his landings heavy and which was not detected at his medical because he memorised the eye chart. As G.I.Taylor wrote from Chudleigh to Lindemann at Upavon,

> When Farren did not return on the appointed day and when no news of you came to hand, I began to get anxious, so I set up a seismograph to register the number and magnitude of your landings. Unfortunately, Thomson started mending his bike with a hammer and since then the poor seismograph has been in the hands of a skilled mechanic.[20]

Farren recalls that later at Farnborough, Lindemann had the undercarriage of his machines strengthened to deal with this difficulty of impaired stereoscopic vision.

A letter from his instructor indicated Lindemann's activities at Upavon were not only confined to flying lessons,

> The chart will prove useful and your remarks confirm my opinion that a lot of time is wasted here trying to tune up engines, owing to the fact that the markings on the jets is quite unreliable and it is necessary to test and correctly number all the old jets we are now using. The matter is well in hand at the moment. I'm glad to hear that your time here was not to bad and that you had no complaints to make regards instruction on the gentle art of flying. I wish all so called 'Huns' were as satisfactory and pleasant to teach.[21]

Trainee pilots were termed *Huns*, as they were responsible for wrecking more aeroplanes than were shot down by the Germans. Lindemann would also have spent time with Tizard, but there is no record of this.

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18. W.S.Farren, '4000 words on Lindemann', 28 May 1958, in G.I.Taylor papers at Trinity College Library, Cambridge.

19. Cherwell Papers, Ref A13/f2, Graduation Certificate - Central Flying School Upavon, 25 October 1916.

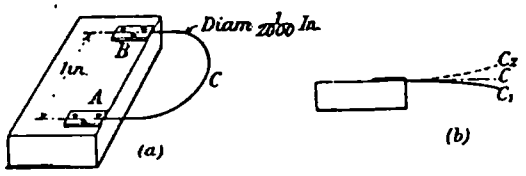
20. Cherwell Papers, Ref D239.1, Taylor at Chudleigh Mess to Lindemann, undated.

21. Cherwell Papers, Ref A13/f1, Capt Cooper at CFS Upavon to Lindemann, 16 November 1916.

3. Lindemann-Searle Accelerometer

In mid February 1917, Lindemann was measuring the stress on aeroplanes during taxiing, getting off, normal flight, turns, loops and spirals with an accelerometer. The instrument was far more sensitive than the Wimperis accelerometer used by Busk four years earlier, and so the experiments represent the first time it was really practical to record stresses imposed on an aeroplane. Lindemann reported the experiments jointly with G.F.C.Searle, who before being recruited as an assistant at Farnborough, was formerly a demonstrator in the Cavendish Laboratory at Cambridge.[22] The purpose of the instrument was to obtain reliable information on the factor of safety to apply to structural members taking the 'lift' forces in aeroplanes, measured in terms of the weight of the aeroplane - for example, if an aeroplane had a mass M tons, the force exerted by the wings in horizontal straight and level flight would be M tons, but this value would increase considerably when the machine was being pulled out of a dive. (Today we talk of *g* forces.)

From Newton's Second Law of Motion, the forces acting on a body in any direction are proportional to the acceleration on the body in that direction. Therefore acceleration can be measured by attaching a mass to a spring balance, providing the periodic time is small enough and the movement sufficiently damped to measure an abrupt change of acceleration without the mass oscillating afterwards. However, a practical limit is soon approached as the reduction in periodic time also reduces the extension of the spring, and some form of optical magnification is then required. In Lindemann's accelerometer, the spring balance was a semi-circular arc of glass fibre, about 1.3 centimetres diameter and 1/100 millimetre thick. The arc of glass fibre was held by its ends in a horizontal plane, and had a period of 1/20 second with its motion highly damped by the viscosity of the air. It was housed for protection in a small cell provided with windows. The fibre arc was illuminated by an electric lamp and its image focused onto a vertical plate as a horizontal line. The plate had a vertical slit in it of width 1/2 millimetre, behind which a kinematograph film recorded the movement of the image. A base line for measurement was provided by the image of a second fibre, which was more



22. Cherwell Papers, Ref C19/1, *Note on Recording Accelerometer for Measuring Stress on Aeroplanes*, RAF Report No. 621, 15 June 1917. F.A.Lindemann and G.F.C.Searle, *Preliminary Report on Measurement of Acceleration of Aeroplanes in Flight*, R&M 376, (HMSO), September 1917. L.Bairstow, 'Progress in Aviation in the War Period', *Aeronautical Journal*. **XXII**, 1918,1-24. R.T.Glazebrook, 'Some Requirements of Modern Aircraft', British Association meeting at Cardiff August 1920, *Engineering*, 19 November 1920, 683-4. See also P.Hill, *To Know the Sky : Life of AVM Sir Roderic Hill*, (London : William Kimber), 1962, who conducted the dog fight test.

accurate than using the edge of the film. This was a short straight vertical fibre, the tip of which was level with the edge of the first fibre. The instrument was calibrated on a whirling arm and checked before each flight by running the film with the box horizontal and then with the box upside down - this reversal gave twice gravity ($2g$). To avoid vibration the accelerometer was either carried by the observer or strapped to the body of the pilot.[23]

The Mark 1 version of the accelerometer simultaneously recorded acceleration and air speed, by using a second microscope to project the image of a fibre attached to the diaphragm of an air speed indicator. Later, Searle and Cullimore modified the instrument to simultaneously record three directions of acceleration and air speed.[24] The development, which took a year, is explained in the draft account of Lindemann's contribution to the RAE Jubilee booklet and the ensuing correspondence with Sir Arnold Hall.[25] It appeared that the original accelerometer was designed by Lindemann and Keeley, certainly the first internal report at Farnborough was by Lindemann.[26] In one draft after the words,

> the recording glass fibre accelerometer with which he had obtained records of all known stunts,

Lindemann had added somewhat tongue in cheek,

> fortunately before it was handed to Dr. Searle for over lengthy development.

This was naturally questioned by the RAE, but Lindemann explained that,

> this was one of the jokes we all enjoyed, otherwise there would have been no point in mentioning it specially

and suggested, that if they would rather not mention Searle by name, they could rephrase the sentence to read,

> with which I fortunately obtained records of all known stunts, before it was handed over to somebody else, whose zeal for perfectionism kept it out of use until the end of the war.

Farnborough also felt that the Jubilee publication was not the place for Lindemann to praise the freedom of research which O'Gorman encouraged to get the best out of people,

> a lesson which is still useful to keep in mind in these days of ~~highly organised researeh~~ (deleted and rephrased by Lindemann) hyper-conscientious self styled watchdogs.

After his accelerometer, Lindemann's main work was on turn indicators, stabilised bomb-sights, aerial rangefinders and rudder gyros and is covered in Chapters 6 and 8.

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23. If the deflection of the image was z centimetres and that due to gravity g was h centimetres, then the acceleration was gz / h.

24. G.F.C.Searle and W.Cullimore, *Report on Measurement of Accelerations on Aeroplanes in Flight*, R&M 469, (HMSO), June 1918.

25. Cherwell Papers, Ref E19-20, 'Contribution to RAE Jubilee 1956', and correspondence with Sir Arnold Hall, Director, RAE, Ref E20/12-18, 1955.

26. Cherwell Papers, Ref C19/1, F.A.Lindemann, 'Note on Recording Accelerometer for Measuring Stress on aeroplanes', 15 June 1917.

4. Lindemann's Gyroscopic Turn Indicator and Aerial Rangefinder Patents.

Although Lindemann did not pursue any further aircraft instrument work after moving to Oxford, the shadow of his aerial rangefinder and gyroscopic turn indicator followed him there. A brief account of this is worthwhile as, unlike many other scientists, he had no wish or need to claim recognition of his wartime inventions, and the correspondence involved displays the networking of the scientific community with some humour.[27]

Government policy on new ideas by those in their employ was for the inventors to take out the patent in their own names and assign it to the Government when the application was successful.[28] The gyro turn indicator had been provisionally patented in the names of W.S.Smith and F.A.Lindemann. The letters of assignment, which the Treasury Solicitor (Air) sent to Lindemann at Oxford, contained a clause that required him to provide any future technical assistance that may be required to secure the patent. Unhappy with the clause, he returned the document and was not reassured when the Treasury Solicitor wrote on 15 March 1920 that 'he would be put to no trouble and presumably to no expense'. Since leaving Farnborough, Lindemann had corresponded with H.Grinstead, his former departmental head. Grinstead wrote to Lindemann on 30th April that turn indicators were now going from strength to strength, and joked that he expected Lindemann to be sent to the Tower, because of his defiance of the Lords of the Treasury. He told Lindemann that the Lords of the Treasury thought they had him because of an earlier agreement he had signed, but said all the fuss could be avoided if they waited until the complete patent specification was accepted, after which the assignment was a much less terrible one. He assured Lindemann that the agreement would not let him in for anything and that the RAE would bear any expense, but agreed the principle involved was not a very good one.

The Air Inventions Committee wrote to Lindemann on 5 July 1920, asking whether in pursuance of his agreement dated 17 March 1919, he would assign to the Secretary of State his benefits in the invention, and also whether he proposed to apply for a United States patent as a turn indicator was being sent to the USA Government. Lindemann replied on 8th July, that he would naturally carry out his earlier agreement, but wished to make his position clear;

> At the request of the RAE, I consented to sign the application for leave to apply for patent as a matter of form to prevent it being exploited by a private individual or firm. I then received a letter from the Treasury Solicitor enclosing a document for signature. By this agreement, I was expected to transfer all my rights and benefits in the invention to the Air Council without receiving anything in return, and at the same time making

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27. Cherwell Papers, Ref C 31/1 to 10, Correspondence regarding patents for Lindemann's invention of turn indicator and aerial rangefinder.

28. PRO/AVIA 8/9, Minutes of conference on 'Patents and their Disclosure', April 1918.

> myself liable for an indefinite amount of work and expenditure. I wrote to the Treasury Solicitor and pointed out that I was prepared to assign any rights I may have to the Air Council, but I could accept no future liabilities and that I would only sign the assignment if this was made perfectly clear. He replied that my liabilities would be reduced to a minimum, and in any case the draft was a standard form of assignment and could not be altered.
> I replied refusing to sign and have been pestered by a succession of letters threatening to compel me to do so. I consider I am treating the Air Council fairly, not to say generously in not claiming compensation and am of the opinion that I cannot be compelled, either in law or in equity, to undertake future liabilities.
> I do not know anything about Mr Sidney Smith's plans about an American patent. Am I to conclude that all foreign rights are invested in me, and that I am at liberty to deal with them as I think fit, without any reference to the RAE or Air Council, or is it suggested that I should have the trouble and expense to take out foreign patents and that all benefits should accrue to the Secretary of State for Air.

The Air Inventions Committee replied by return post informing Lindemann to his surprise,

> that he was at liberty to deal with the foreign rights as he thought fit, without reference to the RAE or Air Council, but subject to the 'Crown Right of Use' of the invention for government purposes abroad.

There is no more correspondence to indicate whether the Treasury Solicitor changed his document, or the full patent specification was approved first to make the assignment more simple. However, Lindemann had sufficient information on patent procedure to avoid the same problem re-occurring with his aerial rangefinder, and to exact a small revenge.

He wrote to Smith at the RAE about the position of patents on this device, who replied on 2 February 1921 that he was aware Lindemann was *fluttering the official dovecotes*. However, there appeared to be no patent covering the rangefinder system, and since there was no patent there was nothing to assign to the Admiralty. Lindemann then wrote to the Secretary of the Admiralty in March;

> Sometime ago I invented and worked out a new method for determining the range and bearing of a ship or target from another ship or battery by aerial observation. The system, known in official correspondence as 'The Lindemann Rangefinder' is capable of considerable accuracy and should in my opinion be of great use in naval operations, since it is used when the proposed target is out of sight. It was put before the Admiralty and demonstrated at Dover, but the system does not appear to have been taken up.
> I have reason to believe that foreign governments are likely to be more interested in the .invention. Since our Navy appears to have no need of it, I imagine that there is no objection to my entering into negotiations with them. Before doing so, however, I would like to have official assurance that this is the case. Though no doubt legally at liberty to make what use I like of my own ideas in peace time, I should be sorry to do anything which could in anyway be construed as opposed to the interest of our fighting services.
> I shall conclude that you have no objection to my taking any steps I please in the matter, unless I hear from you in seven days.

The Admiralty immediately acknowledged on 11 March that his letter was receiving attention and again on 1 April that it was still under consideration. On 12 April, Smith wrote briefly to Lindemann,

> Just a line to tell you that I have got orders to patent the rangefinder.

and with this note, Lindemann's wartime association with Farnborough ended.

Appendix 2

Hucks on Cloud Flying

Chapter 6 opened with reference to Captain B.C.Hucks' recent experience in cloud flying. This account of loss of orientation resulting from the confusion in trying to interpret the readings of his compass and air speed indicator, and the technical explanation of what in fact was actually happening, follows in full.[1]

Hucks said that although like many other experienced pilots he seldom used instruments in normal flying,

> I am going to suggest one more instrument be fitted as standard, an instrument to reduce the risk of flying in clouds. There have been a large number of fatal accidents during the last three years entirely due to flying through clouds. The accidents have not been questions of want of height, but that the machines have become hopelessly out of control. I will give you an instance of what happened to myself a few weeks ago, and you will realise why I consider this a serious matter requiring particular attention.
>
> I set out on a very cloudy, windy day to do a test climb to 10,000 feet on a late two seater. I had so often on previous occasions succeeded quite comfortably in reaching this height in spite of cloudy, overcast days by pushing up through the clouds, usually only a matter of a few minutes, into bright sunshine and the bluest of skies, and after reaching the desired height, coming down again through the clouds, having flown by compass and time. On this particular day however, the wind was very gusty, and on reaching 1,200 feet we got into a dense rain cloud, but carried on to beyond 5,000 feet, still in cloud, when the compass apparently began to swing (really its the machine that begins to swing, not he compass), and efforts to check the compass had the effect of causing it to swing more violently in the other direction. The air speed then rushed up far beyond normal flying speed; all efforts to pull her up checked her only slightly; then the rudder was tried, back went the air speed to zero; there was an uncanny feeling of being detached from the machine, and I knew her to be literally tumbling out of the clouds. All efforts to settle down again to a straight flight seemed to be unavailing, until we emerged from the cloud very nearly upside down. Assuming control again was then a easy matter.
>
> This sort of thing has happened to me more than once, and in the Flying Corps vernacular 'puts the wind up you'.[2] It has also happened many times to other pilots. In some cases they emerge from the clouds in a spin, in other cases the planes have collapsed under the strain of a sudden pull-up

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1 • B.C.Hucks, 'A Further Three Years of Flying Experience', *Aeronautical Journal*, **XXI**, October 1917, 426-29, read on 6 June 1917.

2 D.Young, *Rutland of Jutland*, (London : Cassell), 1963, incorporates an edited autobiography of Sqdn. Cmdr. F.J.Rutland, RN. Rutland explains (p 18) that the origin of this now common expression came from flying in open framework aeroplanes. If you stalled, instead of the air rushing past you, it came rushing upwards, literally 'putting the wind up you'.

from a vertical nose dive. A few days ago, a squadron commander told me that on one occasion everything loose in his machine fell out whilst in the cloud.

Flying in clouds is a very unpleasant state of affairs. First of all in cloud you see nothing whatever but your machine around you. There is no fixed point visible. The only means by which you can tell if you are flying in a straight course is by your compass and your air speed. The compass should give you your direction horizontally, your air speed your direction vertically. The first thing that happens, and very readily too if its windy and bumpy, is that your compass card will begin to move slightly. It really appears to you that your compass has been effected by the cloud, and that you are still flying straight ahead. How often you hear a pilot say that when he got into cloud his compass started spinning. The moment the compass starts moving, it requires extremely delicate ruddering to get it back to a steady position; in fact one invariably over-corrects the compass movement and so the trouble begins. Once the compass starts on a good swing, I have found it nearly impossible to get it steady again until out of the cloud. Before your compass starts to move, the machine has already started to turn. You rudder the opposite way to check it, over correct it, and turn sharper the other way on a bank turn; then the nose drops and the speed goes up. Pulling back on your elevator lever has little or no effect, for if you are banked above an angle of 45 degrees the elevator has become a rudder. All this occurs without the pilot being in the least bit aware of the position that his machine is taking relative to the ground.

The instruments available are of little use once he loses his control. Of what use is 150 mph on his air speed indicator, if the machine is on a spinning spiral, but he imagines that he is merely descending too fast on a steep, straight glide. He naturally tries to pull-up, but to no effect. The bubble does not help him as centrifugal force will send that anywhere. It may be argued that if a stable machine is left alone, it will right itself eventually and assume a normal glide. It very likely would if the pilot could steel himself to let it entirely alone, but before he did so it would have to be left to do a sheer vertical nose-dive for a few moments,and in these days of big weights and little head resistance one is liable to attempt to pull-out too suddenly from the dangerously high speed attained in this dive.

What I want to see fitted is an instrument that will show a constant vertical or horizontal line and be independent of centrifugal force. I have no ideas on the subject or suggestions as to how this is to be brought about, unless something in the nature of a small gyroscope driven by the air-screw could be employed in some way, but until something is provided I think we shall continue to have accidents from this cause.

Appendix 3

Biographical Notes

This appendix provides brief biographical notes for scientists mentioned in this thesis. The information has been mainly taken from *Who was Who* and *Obituaries of Fellows of the Royal Society*. More comprehensive notes for **Keith Lucas** are provided on page 246.

Bairstow, Sir Leonard, 1880-1963,

Royal College of Science,
NPL, 1912-1920,
Professor of Aerodynamics, Imperial College, 1920

Baker, Herbert Brereton, 1862-1932,

Balliol College Oxford,
Chief Professor of Chemistry, Imperial College, 1912-1932,
Set up Chemical Laboratory at St. Omer in 1915 and consulted on numerous wartime problems 1915-1918.

Blackett, Patrick Maynard Stuart, 1897-1974.

Royal Naval College Osborne and Dartmouth, R.N. 1914-18,
Magdalene College Cambridge, 1920-23,
Fellow Kings College Cambridge, 1923-1933,
Professor of Physics, Birkbeck College, 1933-1937,
Professor of Physics, Manchester University, 1937-1953,
Professor of Physics, Imperial College, 1953-1965.
Dean of Imperial College, 1955-1965,
Pro Rector of Imperial College, 1961-1964.

Bourdillon, Robert, 1889-1971.

Balliol College Oxford, BA Nat Sc, 1912,
Lecturer in Chemistry, Balliol College, 1912-1914,
Fellow and Praelector, University College Oxford, 1913-1921,
Intelligence Corps in France, then Lt Col RFC and RAF,
Dean University College Oxford, 1920-1921,
Physician, St Mary's Hospital, London, 1925-1928,
National Institute for Medical Research, Hampstead, 1928-1946,
Director Electro-medical Research Unit, Stoke Mandeville Hospital, 1946-1954.

Callendar, Hugh Longebourne, 1868-1930.

Trinity College Cambridge, Classics 1883, Wrangler 1885,
Professor of Physics, Royal Holloway College, 1888-1893,
Professor of Physics, McGill University, 1893-1898,
Professor of Physics, University College London, 1898-1902,
Professor of Physics, Royal College of Science and Imperial College, 1902-1930.

Cheshire, John Frederick, 1860-1939.

Birkbeck College, Royal School of Mines and others,
Excise 1880-1882, Government Laboratory 1882-1885,
Patents Office, 1885-1915,
Scientific and Technical Director, Ministry of Munitions, 1915-1916,
Deputy Director General, Ministry of Munitions, 1916-1917,
Professor and Director of Technical Optics Department, Imperial College, 1917-

Clerk, Sir Dugeld, 1854-1932,

Trained as mechanic, 1868,
Various colleges in Glasgow and York,
Invented 2 stroke engine,
Consulting and Patent Engineer, Partner with Lord Marks, 1882-1932.
Director of Messrs Kynock, 1892-1899,
Specific heat of gases and gaseous explosions - FRS, 1908,
Member of Board of Invention and research, 1915-1919,
Member of Air Inventions Committee, 1916-1919.
Director of Engineering Research, Admiralty, 1916-1918,

Dalby, William Scott, 1862-1936,

Great Eastern Works, aged 14, then North Western Railway, Crewe,
Scholarship Royal School of Science, 1883
Teaching staff of Professor Ewing at Cambridge, 1893 1896,
Professor of Mech Eng and Applied Maths, Finsbury Technical College,
Worked on balancing engines,
Professor of Civil and Mech Eng, City & Guilds and Imperial College, 1904-1931,
Member of Board of Invention and Research, 1914-1917.

Darwin, Sir Horace, 1851-1928.

Trinity College Cambridge, Natural Sciences,
Founder and Chairman of Cambridge Scientific Instrument Company,
Member of Advisory Committee for Aeronautics
Chairman of Air Inventions Committee.

Dobson, Gordon Miller Bourne, 1889-1976,

Gonville and Caius Cambridge, Natural Sciences,
Meteorological Office, Kew, then Met/ Advisor to CFS, Upavon,
Head of Experimental Dept., RAE, 1916-1920,
Reader in Meteorology Oxford, 1927.

Egerton, Sir Alfred Charles Glyn, 1886-1959.

University College London,
Reader in Thermodynamics, Oxford, 1921-1936,
Professor of Chemical Technology, Imperial College, 1936-1952.

Elphinstone, Sir George Keith Bullar, 1965-1941,

Charterhouse followed by apprenticeship,
Joined Elliott Brothers as partner, 1893,
Chairman Elliott Brothers.

Fage, Arthur, 1890-1978,

Royal College of Science,
NPL, from 1912

Farren, Sir William Scott, 1892-1970,

Trinity College Cambridge, Maths and Mechanical Sciences,
British Thomson Houston, Rugby, 1914-1915,
Aeronautical Experiment and Design, RAE, 1915-1918,
Armstrong Whitworth, 1918-1920,
Lecturer Aeronautics and Engineering, Trinity College Cambridge, 1920-1937,
Lecturer in Aircraft Structures, Imperial College, 1922-1931,
Deputy Director of Scientific Research Air Ministry, 1937-1939,
Director of Technical Development, Min. of Aircraft Production, 1940-1941,
Director of RAE, Farnborough, 1939-1946,
Technical Director at Blackburn, Avro and Hawker Sidderley, 1946-1961.

Filon, Louis Napoleon George, 1975-1937,

University College London, BA Greek 1896,
where Mathematics was part of BA curriculum under Karl Pearson,
Demonstrator in Applied Maths, 1896-1898,
1851 studentship, Kings College Cambridge, 1898-1902, D.Sc.,
Lecturer in Applied Maths, University College London, 1903-1912,
Succeeded Pearson as Goldsmid Professor of Applied Mathematics, 1912-1937,
Active service France and 2nd Battalion London (Reserve) Regiment, 1914-1916,
then Admiralty Air Service and Air Board, 1916-1917,
Dean of Science Faculty, University College, 1926-1934.

Frazer, Robert Alexander, 1891-1959,

Pembroke College Cambridge, Wrangler and Rayleigh Prizeman,
NPL,
Chief Scientific Officer, NPL.

Garner, Sir Harry Mason, 1891-1971.

St. John's College Cambridge, Mechanical Sciences,
Army, 1914-1915, transferred to Admiralty Air Dept, 1915,
Farnborough, 1916,
Marine Aircraft Experimental Establishment, Felixstowe, 1927-1929
Senior Scientific Officer, RAE, 1929
Deputy Director of Scientific Research, Min.of Aircraft Production, 1923-1946,
Principle Director of Scientific Research, (Air) Min. of Supply, 1946-1949.
Senior Scientist, Ministry of Supply, 1949-1953.

Gibson, Arnold Hartley, 1878-1959,

Manchester and Berlin University,
Head of Maths Dept., Salford, 1903-1904,
Lecturer in Engineering and Hydraulics, Manchester University, 1904-1909,
Professor of Engineering, St Andrew's, 1909-1920,
Member of Aeronautical Research Committee.

Glauert, Hermann, 1892-1937.

Trinity College Cambridge, Wrangler 1913,
Issac Newton Scholarship 1914, Rayleigh Prizeman 1915,
Royal Aircraft Factory and Establishment, 1916-1937.
Went for 'duration', but stayed until his accidental death.
Fellow of Trinity, 1920-1926,
Head of Aerodynamics Department RAE after KcKinnon Wood.

Glazebrook, Sir Richard Tetley, 1854-1935.

Trinity College Cambridge, 5th Wrangler 1876,
College Lecturer in Maths and Physics, 1881-1895,
University Lecturer in Maths, 1884-1897,
Worked in Cavendish under Maxwell,
Appointed demonstrators with Shaw under Rayleigh in Cavendish, 1879,
Did not get Rayleigh's job in 1884,
Assistant Director of Cavendish, 1884,
Principle of University College, Liverpool, 1896-1899,
where Oliver Lodge was Professor of Physics,
Director of NPL, 1899-1919,
Zaroff Professor of Aviation and
Director of Dept. of Aeronautics, Imperial College, 1920-1923,
Chairman of Advisory Committee for Aeronautics and then Aeronautical Research Committee, 1909-1923,
President of Institution of Electrical Engineers, 1906-1907.

Gold, Ernest, 1881-1976,

St. John's College Cambridge, 3rd Wrangler 1903,
Schuster Reader in Dynamical Meteorology and fellow of John's,
Superintendent of Instruments, Meteorological office, 1910,
Commissioned captain with no regiment and sent to France as meteorologist, 1915,
Lt. Col. with establishment of 28 officers and 187 other ranks, 1919.
Meteorological Office, 1910-1947.

Greenhill, Sir Alfred George, 1847-1927.

Trinity College, Cambridge, 2nd Wrangler 1870,
Professor of Mathematics, Royal School of Artillery, Woolwich, from 1876.

Grinstead, Harold, 1889-1955,

City and Guilds, South Kensington, B.Sc.,
Farnborough, 1912-1931,
Air Ministry, Min. of Aircraft Prod., Min of Supply, 1931-1950.

Griffith,Idwal Owen, 1880-1941,

Oxford University,
RFC/RAF, 1915-1919,
Senior Demonstrator,Clarendon Laboratoy,
Fellow of Brasenose, Oxford, 1920-1941.

Griffiths, Alan Arnold, 1893-1963,

Liverpool University, BA 1914, D.Eng 1921,
Royal Aircraft Factory, with G.I.Taylor on soap bubble work, 1915
Aeronautical Engineer and Research Consultant Rolls Royce.

Henderson, Sir James Blacklock, 1871-1950,

Universities of Glasgow and Berlin,
Lecturer in Physics, Yorkshire College Leeds, 1894-1898,
Head of Scientific Department, Barr & Stroud, Glasgow, 1898-1901,
Lecturer in Elect. Eng. and University Assistant in Eng, 1901-1905
Professor in Applied mechanics, Royal Naval College, Greenwich, 1905-1920,
Advisor On Gyroscopic Equipment to Admiralty, 1920-1925.

Hill, Archibold Vivian, 1886-1977,

Trinity College Cambridge, 3rd Wrangler 1907, Natural Sciences 1909,
Captain Cambridge Regiment, 1914-1916,
Ack-Ack Experimental Station, 1916-1918,
Fellow of Kings College Cambridge, 1916-1925,
Professor of Physiology, Manchester University, 1920-1923,
professor of Physiology, University College London, 1923-1925,
Fowler research Professor, Royal Society, 1926-1957.

Hopkinson, Bertram, 1874-1918,

Trinity College Cambridge,
Called to bar 1897 but on death of his father the electrical engineer John Hopkinson, went in partnership with uncle Charles Hopkinson on electrical tramway equipment for Crewe, Leeds and Newcastle,
Professor of Mechanisms and Applied Mechanics, Cambridge, 1903-1918.
Promoted Officer Training Corps of Electrical Engineers at Cambridge and was immediately called up as Major in Royal Engineers in 1914.
Initially teaching duty at Chatham to release others for active service, then explosive experiments. Department of Military Aeronautics, 1915-1918.
Member of Board of Invention and Research, 1915-1917 and original member of Advisory Committee of Dept of Scientific and Industrial Research.

Jones, Sir Bennett Melvill, 1887-1975,

Emmanuel College Cambridge, Mechanical Sciences,
Workshop student Woolwich Arsenal,
Research Scholarship, Imperial College (tenable at NPL), 1911-1913,
Armstrong Whitworth (airships), 1913-1914,
Lt. Royal Engineers, but transferred to Royal Aircraft Factory, 1914-1915,
RFC Orfordness, 1916-1918, Lt. Col at Air Ministry, 1918-1919,
Professor of Aeronautical Engineering, Cambridge, 1919-1952.
Ministry of Aircraft Production, 1939-1945.

Keeley, Thomas Clews, 1894-1988.

Cambridge, Natural Sciences,
Farnborough 1915-1919,
Clarendon Laboratory, Oxford, 1919-

Lanchester, Frederick William, 1868-1946,

Royal College of Science,
Designed first British automobile, 1895-1896,
Founded Lanchester Company, 1899,
Designer and Advisor to Damlier and BSA, 1910-1930,
Member of Advisory Committee for Aeronautics, 1909-1918.

Lattey, Robert Tabor,

Oxford, Chemistry 1903,
Upavon, 1915-1916, Orfordness, 1916-
Electrical Laboratory, Oxford, 1919,
University Demonstrator, 1927.

Levy, Hyman, 1889-1975,

Edinburgh, Maths and Physics, Oxford and Göttingen,
NPL, 1916-1920
Assistant Professor of Mathematics, Imperial College, 1920-1923
Professor of Mathematics, 1923-1954,
Dean, 1946-52.

Lindemann, Frederick Alexander, Lord Cherwell, 1881-1956. See also Appendix 1.

Berlin University,
Royal Aircraft Factory and Establishment 1915-1919,
Professor of Experimental Philosophy, Oxford, 1919-1939 and 1953-1956.
Scientific Advisor to Winston Churchhill, 1939-1945,
Paymaster General 1942-1945 and 1951-1953.

Lucas, Keith, 1879-1916. See also page 246.

Trinity College Cambridge, Classics and Nat Sc Tripos Pt 1, 1898-1901,
New Zealand, 1901-1903,
Nat Sc Tripos Pt 2, 1904, D.Sc. 1911, FRS 1912,
Fellow of Trinity College, 1904-1914,
Lecturer in Natural Sciences, 1911, Physiology Research Laboratory
where his students included A.V.Hill and E.D.Adrian.
Royal Aircraft Factory, 1914-1916.

Macgregor-Morris, John Turner, 1872-1959,

University College London,
Assistant to Professor Flemming,
Worked on submarine detection 1915-1918.
Professor of Electrical Engineering, Queen Mary College.

Mallock, Henry Reginal Arnuph, 1851-1933,

St. Edmund's Hall Oxford,
Assistant to his uncle William Froude, Naval Architect,
Assistant to Lord Rayleigh, 1876
Designed numerous instruments for measuring small movement, tremors, bending or stretching.
Consulted by railway companies, War Office, Admiralty and Air Force.
Member of Ordnance Committee and Advisory Committee for Aeronautics.

Mason, C.C.,

Trinity Hall Cambridge, Wrangler,
Director of Cambridge Scientific Instrument Company,

Mayo, Robert Hobart, 1890-1975,

Trinity College Cambridge, Mechanical Sciences,
Head of Experimental Dept. Royal Aircraft Factory, 1914-1915,
RFC in France, 1915-1916,
Testing Squadron, Martlesham Heath, 1916-1919,
Director Ogilvie and Partners, 1919-1924,
Consulting Engineer to Imperial Airways, 1925-1936
Technical General manager Imperial Airways, 1936-1939.

Ogilvie, Alec, 1882-1968,

Trinity College Cambridge,
Eastchurch 1909-1915, developed Ogilvie air speed indicator, 1912-1914,
RNAS, 1915-1919,
Repair Department, RNAS Dunkirk, 1916-1917,
Lt Col Technical Department, Air Ministry, 1917-1919,
Aeronautical Consultant, Ogilvie and Partners, 1919-1925.

O'Gorman, Mervyn, 1871-1958,

University College Dublin and City and Guilds Institute,
Consulting engineer, Swinburne, O'Gorman and bailee
Superintendent Royal Aircraft factory, 1909-1916,
Consulting Engineer to Director general of military Aeronautics, 1916-1919.

Pearson, Karl, 1857-1936,

Kings College, Cambridge, 3rd Wrangler 1879, and Heidelberg,
Goldsmid Professor of Applied Mathematics, UCL, 1884-1912,
Succeeded by Filon,
Galton Professor of Eugenics and Statistics, UCL, 1911-1933,
Galton Laboratory staff worked on Government statistics and then stress in aeroplane propellers before being taken over by the Munitions Inventions Department and put at the disposal of the Ack-Ack Experimental Station under A.V.Hill, 1914-1918.

Petavel, Sir Joseph Ernest, 1873-1936,

University College London,
Royal Institution Davy Faraday Laboratory, 1896-1898,
Lecturer, Manchester University, 1900-1903,
Professor of Engineering, Manchester University, 1908-1919,
Director of NPL, 1919-1936.

Pollard, Alan Faraday Campbell, 1877-1948,

University and Kings College London,
Captain RFC 1914,
Sub Section Director of Development of Aircraft Instruments, Air Ministry,
Professor of Instrument Design, Imperial College, 1921.

Pollen, Arthur Joseph Hungerford, 1866-1937,

Trinity College Oxford,
Called to Bar, 1898,
Director of Lynotype Company,
Director of BSA and Daimler.

Pye, Sir David Randall, 1886-1960.

Trinity College Cambridge, Mechanical Sciences,
Lecturer Engineering Science, Oxford, 1909-1914,
Experimental Officer RFC and RAF, 1914-18,
Lecturer Engineering Science, Cambridge, 1919-25,
Deputy Director of Scientific Research Air Ministry, 1925-1937,
Director of Scientific Research Air Ministry, 1937-1943,
President Institution of Mechanical Engineers, 1952-1953.

Raikes, Humphrey Rivas, 1891-1955

Balliol College Oxford,
1st Battalion The Buffs, then RFC, 1914-1919,
Fellow of Exeter College Oxford, 1919-1927,
Demonstrator Balliol and trinity College Laboratory Oxford, 1920-1927,
Chief Instructor Oxford University Air Squadron, 1925-1927,
Principal and Vice Chancellor, Witwaterstrand University, 1928.

Ricardo, Sir Harry Ralph, 1885-1974,

Trinity College Cambridge, Mech Sc,
Consulting Engineer with Rendal, Parmer and Tritton, 1906-1915,
on locomotives, steam plant, hydraulic and pneumatic equipment,
Consulting Engineer to Mechanical Warfare Dept, Ministry of Munitions, 1916,
on tank engines,
Consulting Engineer to Air ministry, 1917-1918,
on high speed internal combustion engines,
Chairman and Director, Ricardo and Company, 1919,
President of Inst of Mech Eng, 1944-1945.

Rowe, Albert Percival, ?-1976,

Ack-Ack Experimental Station,
Air Ministry Laboratory,
Superintendent Telecommunications Research Establishment, Malvern, 1938-1945,
Deputy Controller Research and development Admiralty, 1946-1947,
Scientific Advisor to Australian Government, 1947-1948,
Vice Chancellor of Adelaide University, 1948-1958,
Emeritus fellow of Imperial College, 1958.

Russell, Alexander Smith, 1888-1972,

Glasgow, Berlin and Glasgow University, (Worked with Soddy in
Glasgow 1909-10, Nernst 1910-11 and Rutherford 1911-13).
Army in France, 1915-1918,
Tutor, Christ College Oxford, 1920-1955.

Searle, George Frederick Charles, 1864-1954,

Peterhouse College Cambridge, 28th Wrangler 1887, Natural Sciences 1888,
Assistant Demonstrator, 1888-1890,
University Demonstrator Experimental Physics, 1890-1935 and 1940-1945,
Technical Assistant, RAE, 1917-1919.

Shaw, Sir William Napier, 1855-1945,

Emmanuel College Cambridge, and Berlin under Helmholtz,
Lecturer in Experimental Physics, Cambridge, 1887-1899,
Senior Tutor Emmanuel College, 1890-1899,
Meteorological Office, 1900
Director of Meteorological Office, 1905-1920.

Southwell, Sir Richard Vynne, 1888-1975.

Trinity College Cambridge, Maths and Mechanical Sciences,
Fellow and Lecturer Mechanical Sciences, Trinity Hall, 1912-1920,
RASC 1914-1915, RNVR on rigid airships 1915-1918, RAF 1918-1920,
Superintendent of Aerodynamics Dept. NPL, 1920-1925,
Fellow of Trinity and University Lecturer in Mathematics, 1925-1929,
Professor of Engineering Science and fellow of Brasenose, Oxford, 1929-1942,
Rector of Imperial College, 1942-1948.
Member of Aeronautical research Committee, 1927-1930.

Strutt, John William, Lord Rayleigh, 1842-1919.

Trinity College Cambridge, Senior Wrangler 1865,
Professor of Experimental Physics, 1879-1884.

Taylor, Sir Geoffrey Ingram, 18861975,

Trinity College Cambridge, Maths and Natural Sciences,
RFC Experimental Aeronautics 1914-1918,
Schuster Reader in Meteorology (Second one, first was Gold)
Fellow of Trinity and Lecturer in Mathematics, Cambridge, 1919-1923,
Royal Society Yarrow Research Professor, Cambridge, 1923-1952,

Thomson, Sir George Paget, 1892-1975,

Trinity College Cambridge, Maths and Natural Sciences,
1st Queen's Regiment 1914-1915, RFC 1915-1919,
Aircraft Manufacturing Company, 1919,
Fellow of Trinity, 1919-1922
Professor of Natural Philosophy, Aberdeen, 1922-1930,
Professor of Physics, Imperial College, 1930-1952.
Master of Corpus Christi , 1952-1962.

Thurston, Albert Peter, 1881-1964,
Queen Mary College London,
Chief assistant to Hiram Maxim, 1903-1910,
Founder and head of Aeronautical Department, Queen Mary College, 1909-1914.
Air Inspection Department 1915
Design Safety and Metal Construction Departments, Air Board, 1915-1918,
President Newcomen Society 1948-49.

Titterington, Morris M.,

Joined Sperry 1914,
Left with Charles Colvin to form the Pioneer Instrument Company.

Tizard, Sir Henry Thomas, 1885-1959.

Magdelene College Oxford, Natural Sciences,
Lecturer in Natural Science, 1911-1920,
Experimental Officer RFC and RAF, 1915-1918,
Lt. Col. and Assistant Controller of Exp. and Research Air Ministry, 1918-1919,
Under Secretary DSIR,
Permanent Secretary DSIR, 1927-1929
Rector Imperial College, 1929-1942,
Chairman Aeronautical Research Committee, 1933-1943,
President Magdalene College, 1942-1946.

Trotter, Alexander Pelham, 1881-1964,

Trinity College Cambridge, Natural Sciences,
Goolden and Trotter, Dynamo Manufacturers, Halifax, 1883-1887,
Editor of Electrician, 1890-1895,
Government Electrician, Cape of Good Hope, 1896-1999,
Electrical Advisor to Board of Trade, 1899-1917,
(Recreation - remembering he was no longer a government official).

Watson, Herbert Edmeston, 1886-1980,

London, Berlin, Geneva and Cambridge University,
Assist. Professor, Indian Institute of Science, Bangalore, 1911-1916,
Professor of Inorganic and Physical Chemistry, Bangalore, 1916-1934,
Professor of Chemistry, University College London, 1934-1951,
Service to Admiralty, 1939-1945.

Watson, William, 1868-1919,

Royal College of Science,
Professor of Physics, Royal College of Science,
Lt. Col. and Director of Central Laboratory of Western Front, 1916-1919.

Whipple, Robert Stewart, 1871-1953,

Kings College, London,
Assistant Kew Observatory, 1888,
Assist manager L.P.Casella, 1896,
Manager and Secretary, Cambridge Scientific Instrument Company, 1898,
Joint Managing Director, 1909-1935,
Chairman, 1939-1949,
Collection of instruments given to University of Cambridge,
formed basis of Whipple Museum collection.

Wimperis, Harrry Egerton, 1876-1960.

Gonville and Caius, Cambridge, Mechanical Sciences,
South Western Railway and Armstrong Whitworth,
Crown Agents for Colonies,
Experimental Officer RNAS and RAF, 1915-1924,
Director of Scientific Research air ministry, 1925-1937,
President of Royal Aeronautical Society, 1936-1938.

Wood, Ronald McKinnon, 1892-1967,

Pembroke College, Cambridge,
Farnborough, 1914-1934, Head of Aerodynamics Department, 1919-1934,
Political work, 1934-1940,
LCC Educ. Com., 1937, Chairman of LCC Educ. Com. 1950-1955,
Min. of Aircraft Production, 1940-1946,
Chairman of LCC, 1957-1958,
Hon. Fellow of Imperial College, 1959-1967,
Hon. Fellow of Queen Mary College, 1967.

Keith Lucas

Keith Lucas was born 8 March 1879. A brief review of his earlier life provides some insight to his later aeronautical instrument work.[1] His father, Francis Robert Lucas, was manager of the Telegraph Construction and Maintenance Company, and had sailed on many of the early cable laying voyages, including those of the *Great Eastern*. The Lucas depth sounding machine, patented in 1888, was in marine survey use for nearly one hundred years.[2] Keith Lucas learnt the use of tools in his father's workshop. In 1896 at seventeen, he designed and patented a focusing mechanism for a microscope, based on geometric design principles. At Trinity College, Cambridge , he took First Class Honours in the Natural Science Tripos 1901. Following a three year break in New Zealand, he was elected a Fellow of Trinity in 1904, and appointed Lecturer in Natural Sciences following his D.Sc. in 1911. He gave the Croonian Lectures in 1912 and was elected FRS in 1913. However, his remarkable ability to design the instruments he needed in the Physiology Laboratory had already been realised by Horace Darwin, who made him a Director of the Cambridge Scientific Instrument Company in 1906.

The following instruments were designed for his own experiments on nerve response and then manufactured and sold by the Cambridge Scientific Instrument Company.[3]

The Lucas Pendulum designed to opening in rapid succession (0.16 to 0.00008 seconds) electrical contacts in the primaries of two coreless induction coils, to produce two successive high voltage pulses to nerve or muscle fibre connected to the secondaries.

The Electro-Magnetic Time Signal instrument to signal the time between these two signals, using a microscope and rapidly moving photographic plate to magnify the movement of two Einhoven string galvanometers in the primary of each induction coil.

The instrument for mechanically Correcting the lag in Photographic Records from a Capillary Electrometer when recording nerve responses.

The instrument for Drawing-out Capillary Tubes.

The Co-ordinate Comparator, consisting of a rigid geometric frame with two travelling microscopes fixed on a sliding carriage, to determine the co-ordinates of any selected points upon a photograph and so accurately estimate the time intervals in electro-cardiographic records.

The Lucas Recording Drum, the Lucas Rectilinear Myograph for measuring the contraction of muscles, and the Lucas Muscle Trough.

The important feature of all these instruments was that they followed the geometric design principles favoured by Darwin. As Darwin summarised of Lucas, 'His mastery of the design of new instruments, coupled with his capacity of making what he wanted, gave him great power in the art of experiment in such dissimilar fields as Physiology and Aeronautics'.[4]

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1. H.Darwin in Alys Keith-Lucas (ed), *Keith Lucas*, (Cambridge : Heffer), 1934.

2. A.McConnell, *No Sea too Deep*, (Bristol : Hilgar), 1982.

3. Cambridge Scientific Instrument Company archive, List 124, July 1913, in Folder 'About 1912-1915', University of Cambridge Library. Examples of some of these instruments are kept by Wipple Museum, Cambridge.

4. H Darwin, Obituary of Keith Lucas, Proc. of Royal Society 'A', **90**, 1919, xxxi-xlii.

Chapter 1

A Scientific Footing : Politics, People and Places

1. R.B.Haldane, *An Autobiography*, (London : Constable), 1929, 164-5, H.Penrose, *British Aviation : The Pioneering Years 1903-1914*, (London : Putnam), 1967, A.Gollin, *No Longer an Island : Britain and the Wright Brothers*, (London : Heinemann), 1984. P.B.Walker, *Early Aviation at Farnborough, Vol 2, The First Aeroplane*, (London : Macdonald), 1974.

2. R.T.Glazebrook, 'Some Important Points in the Work of the Advisory Committee for Aeronautics', *Aeronautical Journal*, **XXIV**, September 1920, 479-495.

3. M.J.G.Cattermole and A.F.Wolfe, *Horace Darwin's Shop : A History of the Cambridge Scientific Instrument Company*, (Bristol : Adam Hilgar, 1987.

4. P.W.Kingsford, *F.W.Lanchester*, (London : Arnold), 1960.

5. G.de Havilland, *Sky Fever*, (London : Hamish Hamilton), 1961.

6. C.Babbington-Smith, *Testing Time*, (London : Cassel), 1961.

7. Advisory Committee for Aeronautics, *Report for Year 1911-1912*, (HMSO), 1912.

8. Cambridge Scientific Instrument Company archives, Folder 11, Letter from M.O'Gorman to R.S.Whipple, 8 January 1943.

9. M.J.G.Cattermole and A.F.Wolfe, op cit, 88.

10. H.Darwin, 'Scientific Instruments : Their Design and Use in Aeronautics', *Aeronautical Journal*, **XVII**, July 1913, 170-190.

11. J.C.Maxwell, *Scientific Papers*, **2**, (Cambridge University Press), 1890, 550.

12. M.Busk, *E.T.and H.A.Busk*, (London : John Murray), 1925.

13. M. Busk, ibid, Chapter IX.

14. H.L.Stevens, 'Early Days at RAF - 1914 onwards', *Jnl of Royal Aeronautical Society*, **70**, January 1966.

15. R.McKinnon Wood, 'Recollections 1914-1934', *Jnl of Royal Aeronautical Society*, **70**, January 1966.

16. G.I.Taylor, 'When Aeronautics was Young', *Jnl of Royal Aeronautical Society*, **70**, January 1966.

17. T.J.N.Hilken, *Engineering at Cambridge University*, (Cambridge University Press), 1965.

18. H.Garner, 'Early Research at Farnborough and Felixstowe', *Jnl of Royal Aeronautical Society*, **70**, January 1966.

19. PRO/AIR 2/145/200739/20, 'History of Hampshire Aircraft Park', anon, March 1920.

20. S.B.Gates, 'Then and Now', *Jnl of Royal Aeronautical Society*, **70**, January 1966.

21. Birkenhead, The Earl of, *The Prof in Two Worlds*, (London : Collins), 1961. R.F.Harrod, *The Prof, A Personal Memoir of Lord Cherwell*, (London : Macmillan), 1959. R.V.Jones, 'Lindemann beyond the Laboratory', *Notes and Records of Fellows of the Royal Society*, **41**, 1987, 191-210, provides a better account.

22. Imperial War Museum, R.H.Mayo Papers, Ref 87/49/1, 'Time Table of CFS Training Course, Mar - Apr 1915'.

23. R.W.Clark, *Tizard*, (London : Methuen), 1965, 21-38.

24. Tizard Papers, Ref HTT 5/4, War Office to Tizard, 27 June 1915.

25. Tizard Papers, Ref HTT 5/23 and 5/26 respectively.

26. Tizard Papers, Ref HTT 5/25, Tizard, Bourdillon and Griffith to the Officer Commanding the Experimental Squadron, Upavon, 8 May 1916.

27. Cherwell Papers, Ref D243/13, H.T.Tizard to Lindemann, 24 July 1916.

28.T.Heffernan, 'The Aeroplane and Armament Experimental Establishment', *Jnl.of Royal Aeronautical Society*, **70**, 1966, 98-9, and A&AEE, Boscombe Down, *50 Years of Aeroplane and Armament Testing*, (HMSO), 1971.

29. J.T.Houghton and C.D.Walshaw, 'Obituary ; G.M.B.Dobson', *Biographical Memoirs of Fellows of the Royal Society*, **23**, 1977, 41-57.

30. G.Kinsey, *Orfordness*, (Lavenham, Suffolk : Terence Dalton), 1981, and Martlesham Heath, (ditto), 1983.

31. PRO/AIR 2/39/AIR 143308/1917, 'Annual Survey of RNAS Laboratory at Imperial College', H.E.Wimperis, December 1917.

32. R.M.Macleod and E.K.Andrews, 'Scientific Advice in the War at Sea 1915-1917 : The Board of Invention and Research', *Jnl of Contemporary History*, **6**, 2, 1971, 3-40.

33. M.Pattison, 'Science, Inventors and the Military in Britain 1914-19 : The Munitions Inventions Department',*Social Studies of Science*, **13**, 4, 1983, 521-568. Imperial War Museum, *Minutes Book, Aeronautical Committee of the Munitions Inventions Panel*, Sept 1915 to Sept 1917. Minutes consist of 'items of interest' followed by list of favourable and unfavourable inventions - instrument references are few and unfavourable.

34. PRO/AVIA 8/7, *Air Inventions Committee*, 'Preliminary Statement of Chairman', H.Darwin, June 1917.

35. PRO/AVIA 8/7, *Air Inventions Committee*, note from M.O'Gorman (for Lord Cowdrey) to H.Darwin, 17 June 1917.

36. H.Darwin, 'Aeronautical Inventions', *The Aeronautical Journal*, **XXII**,June 1918, 207-8, is the one summarised.

37. PRO/AVIA 8/7, 'Report on conference called to consider questions in connection with patents and their disclosure to Allied Governments', April 1918. Present were Ministry of Munitions, Air Ministry, Colonial Office, Foreign Office, Admiralty, Patents Office and Treasury.

38. PRO/AIR 1/751/176/6/5, *Instrument Repair and Inspection at RAF from August 1914 to November 1918 -Report 554*, Capt (?), undated. Report provides a history, organisational 'tree' of departments, plans of departments, routes taken by repairs, and repair statistics. PRO/AIR 1/732/176/623, *Monthly Work*

Summaries at RAF- Nov 1916 to Nov 1918, SRAF to large distribution. These summaries provide an account of development work and routine repair and inspection. Hendon RAF Museum, Ref ARD/1977/182 - 59500-59678, *Royal Aircraft Factory Specifications and Drawings*, of aircraft instruments and test equipment.

39. NACA, *General Classification of Instruments and Problems*, Report 125, 1921.

40. PRO/AIR 1/732/176/6/21, *Complaint against Major Filon*, Private memo from SRAF to Air Board, 17 November 1917.

41. R.H.Mayo Papers, Ref 1/6,'Testing of Aeroplanes', Officers of Technical Staff, Martlesham Heath, February 1919, provides diagrams of the test equipment.

42. H.W.Paul, *From Knowledge to Power : The Rise of the Science Empire in France 1860-1939*, (Cambridge University Press), 1985, 313-7, for brief account of parallel French development.

Chapter 2

Early Commercial and Government Developments

1. A.McConnell, 'The Aneroid Barometer comes to London', *Bulletin of the Scientific Instrument Society,* **38**,September 1993, 20-22, and Chapter 3 of her forthcoming book on J.J.Hicks.

2. C.J.Stewart, *Aircraft Instruments,* (London : Chapman & Halls), 1930, 96-100, and 'Revolution Indicators',*Flight,* 1 March 1913, 260 and 19 October 1912, 943.

3. O.Wright and G.Brewer, 'The Dunne Biplane : Report of Automatic Stability Trials on 20 December 1910', **XIV**, Aeronautical Journal, January 1911, give facsimile of the writing test.

4. Smiths revolution indicator was first fitted to a Blackburn monoplane at Leeds - R.R.Rudall, 'Smiths : An Instrumental Success', *Farnborough 90 International, Society of British Aerospace Companies,* 1990, 64-5. The Elliott Revolution Indicator was described as early as 1909, *Flight,* February 1909, 86, and 7 August 1909, 469.

5. T.O.M.Sopwith, 'Correspondence', *Flight,* 21 January 1911, p 48.

6. Lucien Vidie patented the aneroid in 1844, Patent 10,157, see A.McConnell, note 1. L.B.Hunt, 'The History of Pressure Responsive Elements', *Journal of Scientific Instruments,* Vol 21, March 1944, 37-42. W.E.K.Middleton, *History of the Barometer,* (Baltimore : JohnsHopkins Press), 1966.

7. A.H.Mears, H.B.Henrickson and W.G.Brombacher, *Altitude Instruments,* Report 126, (National Advisory Council Aeronautics),1921, 501-560.

8. RAE, 'Amount and Distribution of Hysteresis and Lag in Standard Pattern Altimeters, Report H-901', 10 January 1923.

9. A.A.Griffiths, *Theory of Pressure Capsules,* R&M 1136, (HMSO), August 1927.

10. T.E.Stanton, 'Resistance of Plane Surfaces in a Uniform Current of Air', Proc Inst of Civil Engineers, **CLVI**, 1903, 78. B.Melvill.Jones and Harris Booth, 'The Measurement of Wind Velocity', *Aeronautical Journal,* **17**, July 1913, 191-198.

11. H.Darwin, 'Scientific Instruments : Their design and use in Aeronautics', *Aeronautical Journal,* **17**, June 1913, 170-190.

12. M.O'Gorman, 'Correspondence', *Flight* , 15 May 1914, 528.

13. PRO/AIR 1/815/204/4/1274, 'Instrument Panels', report from CFS, Upavon to War Office, 11 December 1914.

14. J.R.Pannell and R.Jones, *The Design of a Sensitive Yawmeter,* R&M 445, (HMSO), May 1918, confirmed the best angle between the axes was 120°. Ogilvie used smaller angles.

15. PRO/DSIR 23/1206, 'Yaw Meter - Horace Darwin', Correspondence between M.O'Gorman, Superintendent Farnborough and Horace Darwin, Cambridge Scientific Instrument Company, October 1912.

16. M.O'Gorman and E.T.Busk, *Velocity of the air in the neighbourhood of the tail plane of the Tractor Biplane BE 2,* R&M 132, (HMSO), April 1914.

17. W.S.Farren (SRAF), *Experimental Determination of the Slipstream behind the Airscrew of a Pusher,* R&M 382, (HMSO), October 1916, and *Exploration of the Airspeed on the Airscrew Slipstream of a Tractor Machine,* R&M 438, (HMSO), November 1917.

18. F.Short and J.C.Dines, *Gust Research with the Royal Aircraft Factory's Tetranemograph*, R&M 144, (HMSO), October 1913.

19. Editorial, 'The Ripograph', *Engineering*, **2**, 1913, 845, and 'Instruments used in Experiments on Aeroplanes', *Flight*, 6 November 1914, 1097.

20. M.O'Gorman, *Experiments with Full Scale Flying Machines*, R&M 59, (HMSO), November 1911.

21. Editorial, 'Royal Society Soiree', *Engineering*, **1**, May 1913, 641-2.

22. M.O'Gorman and E.T.Busk, *Lateral Stability*, R&M 133, (HMSO), April 1914.

23. Mary Busk, *E.T. and H.A.Busk*, (Cambridge : Heffer), 1925.

24. M.O'Gorman, *Report on Precautions taken as to the Strength of Details on the BE Aeroplane*, R&M 127, (HMSO, May 1914.

25. H.E.Wimperis, *Application of Power to Road Transport*, (London : Constable), 1913. See also T.N.Whitehead, *The Design and Use of Instruments and Accurate Mechanisms*, (New York : Dover Publications), 1934 (reprinted 1954), who provides a very interesting case study of its design.

26. C.J.Stewart, *Aircraft Instruments*, (London : Chapman & Halls), 1930, 215-6.

27. PRO/AIR 2/51/AB 275/1818, 'Recording Wavemeter for Seaplanes', requested by Wg. Cmdr. l'Strange Malone, April 1917, and made at RNAS, Isle of Grain.

28. A.P.Thurston, 'The Measurement of Air Speed', *Aeronautical Journal*, **18**, July 1914, 246-71.

29. Derivation of *velocity-squared-density*. Consider a column of air of density ρ, having a velocity v, and a cross sectional area equal to that subtended by the obstruction. The mass of air m impinging on the obstruction would be proportional to ρv, and therefore its momentum mv would be proportional to or velocity-squared-density. As force is equal to the rate of change of momentum, and this column of air imparts its momentum to the obstruction, it follows that the force exerted or pressure generated on the obstruction will also be proportional to velocity-squared-density.

30. Negretti and Zambra, 'Advertisement', *Aeronautics*, June 1913, 233.

31. PRO/AIR 1/732/176/6/24, 'Extracts from Farnborough Diary of M.O'Gorman'. This was a personal diary, produced from notes and reports, probably for use in annual reports. Darwin's air speed indicator was tested on 3 May 1911. The details given are taken from a letter from O'Gorman to R.S.Whipple, dated 8 January 1943, after Darwin's death, ref Cambridge Scientific Instrument Company Archives, Folder 11.

32. Both are usually on display at the Science Museum.

33. T.E.Stanton, *Note on Lateral Extent of Maximum Velocity of Wind Gusts*, R&M 56, (HMSO), March 1912.

34. Munro Archives, *J.W.Munro - Centenary Handbook 1864-1964*, 1964, for photograph of test equipment.

35. J.R.Pannell, *Calibration of Tube Anemometers at High Velocity*, R&M 237, (HMSO), February 1916.

36. Tizard Papers, Ref HTT 5/149, *Methods adopted for the Testing of Aeroplanes*, Technical Staff, Martlesham Heath, undated typescript. Another copy of this report can also be found in R.H.Mayo papers, Ref MAYO 1/6, dated February 1919.

37. J.R.Pannell, *The Measurement of Fluid Pressure and Velocity*, (London : Arnold), 1924 and E.A.Griffiths, *Engineering Instruments and Meters*, (London), 1921.

38. Technical Department, Ministry of Production, *Aircraft Instruments*, (HMSO), 2nd Ed., February 1918, shows double capsule. PRO/AIR 1/732/176/6/23, *Summary of Work at RAF - November 1918*, notes that single diaphragm air speed indicator had been made.

39. M.O'Gorman, 'Air Speed Indicators', unsigned and undated draft manuscript of paper on air speed indicators used at Farnborough, but probably 1918, from John Bagley, former Curator of Aeronautics, Science Museum.

40. C.J.Stewart, note 2, 72.

41. Harris Booth, 'A Warning to Pilots', *Flight*, 3 January 1914.

42. E.H.Clift, 'Correspondence', *Flight*, 17 January 1914.

43. L.Bairstow, 'Correspondence', *Flight*, 24 January 1914.

44. E.T.Busk, 'Gravity Controlled Velometers', *Flight*, 24 January 1914, 82-3.

45. Harris Booth, 'Warning to Pilots : A reply to Mr. Busk and Mr. Bairstow', *Flight*, 31 January 1914, and 'The theory of the gravity-controlled air speed indicator as applied to dynamic lift flying machines', *Aeronautical Journal*, **18**, January 1914, 56-58.

46. Advisory Committee for Aeronautics, *Report for the Year 1913-14*, (HMSO).

47. L Bairstow, *Discussion of the action of different types of air speed indicator*, R&M 145, (HMSO), February 1914, and PRO/DSIR 23/358, 'Spring Controlled and Gravity Controlled Air Speed Indicator', 24 February, Report by L.Bairstow following discussion with Harris Booth.

48. Editorial, 'British Association Dundee Meeting', *Engineering*, **2**, 12 December 1909.

49. A.E.Kennelly, C.A.Wright and J.S.Van Bylevelt, 'The convection of heat from small copper wires', *Trans. IEEE*, **XXVIII**, Pt 1, 1909.

50. Munro Archives, Ref 3/15, J Rooker, Sketch and Calculation Book.

51. Munro Archive, *R.W.Munro - Century Handbook 1864-1964*, 1964.

52. Munro Archive, Ref 2/12 to 2/14,Works Order Books 1913-19.

53. PRO/T 173/442, 'Royal Commission for Awards to Inventors, Claim by S.Smith & Sons', 1919, for the Clift Air Speed Indicator.

54. Royal Aeronautical Society, A.Ogilvie, Folder 9, *Summary of Early Work at Sheppey and Eastchurch*, Undated typescript, date of acquisition 24 September 1954.

55. H.Penrose, *British Aviation - The Great War and the Armistice*, (London : Putnam), 1969.

56. Elliott Brothers Archives, Sales Ledger 1914-18.

57. S.T.A.Richards, 'Some Handley Page Recollection', *Aeronautical Journal*, **70**, January 1966.

58. G.Brewer, *Fifty Years of Flying*, (London : Air League of British Empire), 1946, 104-107.

59. Royal Aeronautical Society, Ref - British Wright Company, *Agreement and Indenture between Orville Wright and British Wright Company*, 26 February 1913. Patents involved were 6732/04,24076/08, 24077/08 and 2913/09.

60. Editorial, 'Pioneers of British Aviation XVIII - Griffith Brewer', *Aeronautics*, 27 November 1919.

61. P.B.Walker, *Early Aviation at Farnborough : 1909 1914*, 2 Vols, (London : MacDonald), 1971-4, and A.Gollin, *No Longer an Island*, (London : Heinemann),1984.

62. Royal Aeronautical Society, Ref - British Wright Company, *Memorandum of Association of the British Wright Company*, 19 February 1915. Capital of Company £100 and Subscribers - Griffith Brewer of 33 Chancery Lane, Patent Agent, and George Earnest Ogilvie, 13 Buckingham Gate, SW, Electrical Engineer.

63. H.Darwin, 'Static Turn Indicator', *Aeronautical Journal*, **23**, December 1919, 619-33.

64. J.S.Ames, 'Relation between Aeronautical Research and Design', *Aeronautical Journal*, **27**, May 1923, 381-404.

65. PRO/T-173/442, 'Royal Commission for Awards to Inventors, Claim by S.Smith and Sons', 1919, for award for Clift air speed indicator.

66. PRO/T 173/73. 'Royal Commission for Awards to Inventors, claim by British Wright Company, 1923, for use by American Government of the Ogilvie air speed indicator. The file is not complete.

67. Elliott Brothers Sales Ledger shows this indicator was supplied to the American Embassy in London on 22 May 1916.

68. H.Darwin comments after A.P.Thurston's 1914 paper on 'Air Speed measurement', see note 28.

Chapter 3

Aeroplane Performance Measurement

1. H.T.Tizard, *Methods of Measuring Aircraft Performance*, Aeronautical Journal, **XXI**, April 1917, 108-122.

2. Tizard Papers, Ref HTT 5/20, Scribbling Diary for 1917, each page interleaved with blotting paper, but only used from 1 January to 23 February.

3. Tizard Papers, Ref 5/27, 'Aeroplane Tests at CFS', undated, but end 1916 from content.

4. Tizard Papers, Ref 5/20, *Pilots Log Book*, 1916.

5. W.S.Farren, 'Full Scale Aeroplane Experiments', *Aeronautical Journal*, **XXIII**, February 1919, 14-72, read 18 December 1918.

6. M.O'Gorman, "Experiments with Full Scale Flying Machines', R&M 59, (HMSO), November 1911.

7. H.Levy, 'From Model to Full Scale in Aeronautics', Aeronautical Journal, **XXIII**, 1919.

8. Takehiko Hashimoto, *Theory, Experiment and Design Practice : The Formation of Aeronautical Research, 1909-1930*, unpublished PhD Dissertation, JohnsHopkins University, Baltimore, 1990.

9.F.A.Lindemann, *Note on Recording Accelerometer for Measuring Stress on Aeroplanes*, R&M 376, (HMSO), July 1917, and G.F.C.Searle and W.Cullimore, *Report on Measurement of Acceleration on Aeroplanes in Flight*, R&M 469, (HMSO), June 1918. R.T.Glazebrook, 'Some Requirements of Modern Aircraft', British Association meeting at Cardiff August 1920, *Engineering*, 19 November 1920, 683-4. See also P.Hill, *To Know the Sky : Life of AVM Sir Roderic Hill*, (London : William Kimber), 1962, who conducted the dog fight test.

10. G.L.Smith, RAE, *The Kite Balloon Recorder*, R&M 630, (HMSO), March 1918.

11. PRO/AIR 2/87/Aero/313, Capt. G.M.B.Dobson, Lt. H.T.Tizard and Lt. W.J.Mackie, 'Measurement of air speed of aircraft at height', Report from CFS, Upavon to A.E.1, War Office, Astral House, Victoria Embankment, 4 July 1916, with copy to RAF, Farnborough. This was immediately issued as R&M 266 with the same title.

12. M.Pattison, 'Scientists, Inventors and the Military in Britain 1915-19 : The Munitions Inventions Department', *Social Studies of Science*, **13**, 4, 1983, 521-568. Initially, J.E.Littlewood, R.H.Fowler, E.A.Milne, and then W.Hartree and A.P.Rowe. See also Crowther, *Fifty Years of Science*, for work of Ack-Ack Experimental Station, and PRO/MUN 5/119/700/6, Minutes of Munitions Inventions Department, 9 May 1916.

13. M.J.G.Cattermole and A.F.Wolfe, *Horace Darwin's Shop : A History of the Cambridge Scientific Instrument Company 1878-1968*, (Bristol : Adam Hilgar), 1987, 29.

14. Cherwell Papers, Ref D243/9, Letter from Tizard at Upavon to Lindemann at Farnborough, 9 August 1915.

15. Tizard Papers, Ref HTT 5/5 to 5/16, Bomb Aiming Experiments, August 1915. Data sheets, ground plan and tape record of timing signals are pinned together for each experiment.

16. Air Ministry, *Camera Obscura*, A.P. 242, 1917, A.P. 356, 1918, A.P.961,1924, and J.H.Hammond, *The Camera Obscura*, (Bristol : Adam Hilgar), 1981, 153-4.

17. Aeroplane Testing Squadron, *Notes on a Rate of Climb Indicator for use on Aeroplanes*, R&M 310, (HMSO), January 1917.

18. Aeroplane Testing Squadron, *Baro-Thermograph for use on Aeroplanes*, R&M 295, (HMSO), October 1916.

19. PRO/AIR 1/732/176/6/23, 'Summary of Monthly Work at RAF', SRAF, April 1917.

20. Aeroplane Testing Squadron, *Petrol Flow Meter for use on Aeroplanes*, R&M 295, (HMSO), November 1916.

21. This instability would have been eliminated with a conical shaped displacer. Turbine type flow meters are used in aircraft today.

22. H.T.Tizard, *Electric Timing Apparatus in use on the Speed Course at Aeroplane Experimental Station, Martlesham Heath*, R&M 558, (HMSO), October 1918

23. Tizard Papers, Ref HTT 5/46, 'Calibration of Air Speed Indicators over a Speed Course', Martlesham Heath Repot F-189, Capt. D.R.H.Whiston, 16 April 1919.

24. G.I.Taylor, 'When Aeronautical Science was Young', *Journal of Royal Aeronautical Society*, **70**, January 1966, 108-112.

25. G.I.Taylor, *Accuracy with which the Temperature Error in determining Heights by the Barometer may be corrected*, R&M 239, (HMSO), December 1915.

26. G.M.B.Dobson, *Errors of the reading of altimeters and air speed indicators due to variations of temperature of the air*, R&M 610, (HMSO), May 1919.

27. G.I.Taylor, *Apparatus to measure the pressure distribution over the wing of an aeroplane in flight*, R&M 287, (HMSO), October 1916.

28. W.Ellis Williams, 'Pressure Distribution over an Aeroplane Wing in Flight', *Aeronautical Journal*, **XVIII**, October 1914, 319-323.

29. W.S.Farren (SRAF), *The Exploration of the air speed in the airscrew slipstream of a tractor machine*, R&M 438, (HMSO), November 1917.

30. W.S.Farren (SRAF), *Experiments on the Rotation of a Propeller Slipstream in a Pusher Aeroplane*, R&M 408, (HMSO), November 1917.

31. H.Garner, 'Early Research at Farnborough and Felixstowe', *Jnl of Royal Aeronautical Society*, **70**, January 1966.

32. T.M.Barlow, 'Performance Testing of Aircraft', *Aeronautical Journal*, **XXVI**, May 1922, 152-176.

33. G.I.Taylor, Scientific Methods in Aeronautics', *Aeronautical Journal*, **XXV**, September 1921, 474-491.

Chapter 4

Aircraft Compass Development - Part 1

1. National Maritime Museum, Ref 43-521, Lt. G.H.Alexander, (Chief Compass Examiner 1907-1930),*Compass Catalogue and Explanatory Notes*, with additions by Cmdr W.E.May, (Naval Assistant 1928-1930), 231-239. See also A.E.Fanning, *Steady as she goes : The Official History of the Admiralty Compass Observatory*, (HMSO), 1986.

2.1. M.B.Field and F.A.King, 'The Evolution of the Aero Compass', *Fight*, 5 October 1912, 891-2.

3. PRO/AIR 1/732/176/6/24, 'Extracts from O'Gorman's Diary', 20 March 1911.

4. E.H.Clift, 'Correspondence', *Flight*, 13 May 1911, 429.

5. E.H.Clift, 'The Magnetic Compass - Its Construction and Use, *Flight*, 24 February 1912, 199 and 163-5, and 2 March 1912, 199-201.

6. Editorial, *Flight*, 28 March 1914, 347.

7. E H Clift, "A New Compass", Flight, 20 July 1912, p 661.

8. W.Batty and Sons, 72 Duke Street, Liverpool, Flight, 27 May 1911, 473. Elliott Brothers, Flight, 14 Sept 1912, 840 S.Smith and Sons, Flight, 1 March 1913, 260.

9. R.A.Newton, Cmdr., *Aeronautical Navigation*, (London : Elliott Brothers), 1910.

10. PRO/AIR 1/777/204/4/435, 'Supply and performance of compasses', correspondence between Squadrons and RAF,Farnborough, 1913-14.

11. PRO/DSIR 23/321/f and DSIR 23/366 W.R.Crocker (Lt), Various reports, undated.

12. R.F.Mayo in Alys Keith-Lucas (ed.), Keith Lucas, (Cambridge : Heffer & Sons), 1934.

13. B.Melvill Jones, 'Cloud Flying : The Work of Keith Lucas', *Jnl of the Royal Aeronautical Society*, **70**, January 1966,

14. K.Lucas, *The Error of Compasses on Aeroplanes*, Part 3 of R&M 238, and *On a New Type of Compass for use on Aeroplanes*, Part 4 of R&M 238, (HMSO), April 1915.

15. PRO/DSIR 23/699, 'Compass card support', H.Mallock, April 1916.

16. H.Darwin, 'Scientific Instruments : Their Theory and Use in Aeronautics', Aeronautical Journal, **XVII**, July 1913, 170-190.

17. PRO/DSIR 23/321/g, 'Report on Compass Experiments', Horace Darwin, 24 February 1914.

18. PRO/DSIR 23/530, Professor H B Baker, "Compass deflection due to vibration', undated.

19. G.M.B.Dobson's compass can be seen at the National Maritime Museum, Greenwich, Aircraft Compass Catalogue No. 296. Compass is a Pattern 200 with Dobson's modifications.

20. SRAF, *Report on Compass design*, R&M 352, (HMSO), October 1917.

21. F.A.Lindemann, *The Northerly Turning Error of the Magnetic Compass*, Part 1 of R&M 295, and D.H.Pincent, *Equations of Motion of Magnetic Compass*, Part 2 of R&M 295, (HMSO), February 1917.

22. F.W.Lanchester Paper, Museum of Science and Industry, Birmingham, Carbon copy of letter from Lanchester to Rayleigh, 24 February.

23. A.E.Fanning, Steady as She Goes, (HMSO), 1986, and Wg. Cmdrs. S.C.Bastin and C.M.Dunnicliffe, 'The Development of the Aircraft Compass', Air Ministry Compass Dept R&D Report, 1947-48. Copy at RAF Museum, Hendon, Ref 11350.

24. PRO/DSIR 23/672, 'The Magnetic Compass in Aircraft', Report T-672, Capt. Creagh- Osborne, 1 March 1916.

25. A.E.Fanning, op cit, Appendix A, 'Procedure for installing compasses in aircraft'.

26. S G Starling, "Equilibrium of Aeroplane Compass during a Turn", Phil Mag, Vol XXXII, Nov 1916, p 461.

27. PRO/AIR 1/699/27/3/415. Memo 'Magnetic Compasses in Aircraft' to RNAS from Creagh-Osborne, 4 Aug 1916.

28. Members of Squadron, *Naval Eight : The History of No. 8 Squadron RNAS*, (London : Signal Press), 1931.

Chapter 5

Aircraft Compass Development - Part 2

1. PRO/AIR 1/731/736/6/17, Correspondence on testing the Admiralty Pattern 259 Air Compass.

2. PRO AIR 1/731/176/6/17, 'Comparison of RAF Mk II and CO 259 Compasses', Farnborough Report H-531, 17 January 1917.

3. Cherwell Papers, Ref B2/f2, Letter from G.M.B.Dobson to F. A.Lindemann, 22 May 1919.

4. Cherwell Papers, Ref D239/2 and 3, Letters from G.I.Taylor to F.A.Lindemann, 19 and 22 May 1917. Unfortunately, Lindemann's relies are not in Taylor's Papers.

5. S.G.Starling, 'Aeroplane Compasses', *Transactions of Optical Society*, 1917, 221-36; and *Philosophical Magazine*, **XXXII**, Nov 1916, 461. Starling was Head of Physics at West Ham Technical College and retained by H.Hughes & Sons as a consultant.

6. A.E.Fanning, *Steady as She goes : The Official History of the Admiralty Compass Observatory*, (HMSO), 1986.

7. PRO/T 173/288. File of documents relating the Messrs Hughes and Sons claim to the Royal Commission on Awards to Inventors, 1919-1923; and PRO/T 173/666, transcript of hearing.

8. The same Lt. Alexander who compiled 'Compass Catalogue and Explanatory Notes' for the Admiralty collection of aircraft compasses at Greenwich.

9. Cherwell Papers, Ref C30/5, Letter from H.E.Wimperis to F.A.Lindemann, 11 March 1920, arranging to meet him about a claim by Messrs Hughes for certain improvements, which they state were introduced into various RFC and RAF compasses'

10. These companies included Dent and Johnson, Heath and Kelvin, Bottomley and Baird, as examples of their 5/17 compasses can be found in the Aircraft Compass collection at the National Maritime Museum at Greenwich, Collection Nos. 282,283 and 285 respectively.

11. Creagh-Osborne and Hughes took out American Patent 1,216,953 on 20 February 1917 to cover British Patent 1148/15, and American Patent 1,256,442 of 12 February 1918 to cover 17736/15, although Creagh-Osborne assigned his rights to Hughes on 30 February 1918.

12. Tizard Papers, Ref HTT 5/81, 'Notes on flying through clouds in formation', Report HB-300, Tech. Dept. Aircraft Production, Ministry of Munitions, August 1918.

13. Tizard Papers, Ref HTT 5/150, Copy of G.P.Thomson's compass tests at Orfordness.

14. Tizard Papers, Ref HTT 5 150, "Report on Aperiodic Compasses", Lt. J.H.Mackie, Orfordness, 10 September 1918.

15. H.E.Wimperis, *Forced vibrations in aeroplane instruments*, R&M 685, (HMSO), April 1920.

16. Ft. Lt. R.S.Capon and Dr. Alice Lee, *Preliminary Report on the Forced Oscillations of Aircraft Compasses*, R&M 874, (HMSO), July 1920.

17. H.E.Wimperis and A.P.Rowe, *Some Characteristics of Aircraft Compasses*, R&M 735, (HMSO), March 1921.

1 8. A P.Rowe, *The northerly turning error of compasses in aircraft*, R&M 875, (HMSO), November 1921, and F.A.Lindemann and D.A.Pincent, *The Northerly Turning Error of the Magnetic Compass*, R&M 295, (HMSO), February 1917.

1 9. H.E.Wimperis, *Tests on Improved Models of Aircraft Compass*, R&M 868, (HMSO), December 1922.

2 0. H.E.Wimperis, 'Some recent developments in aircraft instruments', *Aeronautical Journal*, January 1924.

2 1. C.S.Draper, W.MacKay and W.H.Cook, 'Northerly Turning Error of the Magnetic Compass in Aircraft', Jnl of Aeronautical Sciences, **5**, 1938, 345-54. Michael A.Dennis' thesis *Instruments and C.S.Draper at MIT*, John Hopkins University, examines Draper's work, but does not examine where Draper obtained some of his ideas.

2 2. A.J.Hughes, *History of Air Navigation*, (London : George Allen and Unwin), 1946, 36-41.

2 3. PRO/T 173/666, *Royal Commission for Awards to Inventors : Claim by H.Hughes & Sons*, Transcript of hearing, 18 July 1921, 69.

Chapter 6

Static and Gyroscopic Turn Indicators

1. H.R.Brooke-Popham, 'The Air Force', *Jnl. of United Services Institute*, **LXV**, 1920, 43-70.

2. B.C.Hucks, 'A Further Three Years of Flying Experience', *Aeronautical Journal*, **XXI**,October 1917, 426-29, read 6 June 1917.

3. Sir Henry Fowler, 'Flying in Clouds', *Aeronautical Journal*, **XXII**, February 1918, 49-50.

4. F.A.Lindemann, 'Turn Indicators for Aeroplanes', report T 1052 of 18 December 1917, published as R&M 525, (HMSO), December 1917.

5. Farnborough Flight Log and Lindemann's Pilots Log Book.

6. PRO/AVIA 8/219, Capt. G.McKerrow, 'Static Turn Indicator', Orfordness Report G-44, 27 February 1918.

7. PRO/AIR 1/1142/204/5/2344, 'Static Turn Indicators', File of reports on the subject, 1918-19.

8. Farnborough Wing Channel Staff, *Some experiments on measurement of static pressure*, R&M 672, (HMSO), February 1920.

9. H.Darwin, 'The Static Turn Indicator for Aeroplanes', *Aeronautical Journal*, **XXIII**, December 1919, 617-25.

10. See Obituary for Bertram Cooper, *Royal Aeronautical Journal*, 1918. Cooper, had been secretary of the Royal Aeronautical Society from 1911-16, then worked for the British Wright Company for a year before joining the Instrument Branch at the Air Board in 1917. He was killed in a flying accident in June 1918.

11. PRO/DSIR 23/514, H.Darwin and C.C.Mason, 'Instrument to Indicate Vertical in an Aeroplane', Report 514, May 1915.

12. H.Glauert and F.A.Lindemann, *The Investigation of the Spin of an Aeroplane*, R&M 618, (HMSO), June 1919. W.S.Farren's account in Sir George Thomson's obituary of F.A.Lindemann, *Biographical Memoirs of Fellows of the Royal Society*, **4**, 1958, 45-71. Lord Birkenhead, *The Prof in Two Worlds*, (London : Collins), 1961.

13. PRO/AVIA 8/219 and 1220 , 'Straight Flying', Air Inventions Committee file of correspondence and reports relating to Static Turn Indicator. Summary taken from correspondence between Darwin, Callendar, Dobson, Taylor and Hill.

14. Royal Aeronautical Society, British Wright Company archive, Agreement between the British Wright Company and Horace Darwin, 20 March 1919.

15. Tizard Papers, Ref HTT 5/50, 'Summary of Orfordness Reports N4, N5 and N6 : Performance Tests on Gyroscopic Indicators, prepared for Tizard by Capt G.McKerrow and countersigned by Major C E Fairburn, 10 March 1919. Summary compared the performance of the Henderson Turn Indicator with tests previously performed on the RAE Gyro Azimuth Indicator, the French Garnier and Hebrard Inclinometers, and the Gray Gyro Inclinometer, concluding that the Henderson Turn Indicator was the only satisfactory instrument. The RAE gyro azimuth indicator was the gyroscope designed by Keith Lucas for bomb aiming. It was the non-continuous type, where the procedure was to fly the required course, switch on the gyro, and then release it.

16. PRO/AVIA 8/219,'Garnier Gyroscopic Level', Orfordness Report G-37, 27 February 1918

17. PRO/T 173/270, Claim by Professor Sir R.B.Henderson for Gyroscopic Turn Indicator to The Royal Commission for Awards to Inventors, and T 173/653 for transcript of the hearing.

18. C J Stewart, *Aircraft Instruments*, (London : Chapman and Hall), 1930, 153-7.

19. Professor J.G.Gray, 'A General Solution to the Problem of Finding the True Vertical for all types of Marine and Aerial Craft, *Proceedings of the Physical Society of London*, **XXXII**, 1923, 266-68, paper delivered 8 June 1923.

20. PRO/AIR 1/732/176/6/23, Farnborough Monthly Work Report, November 1918.

21. Editorial, 'Royal Society Soireés', Engineering, 1919 Vol 1, 709 and 845, and 1920 Vol 1, 864.

22. PRO/DSIR 23/9492, 'Turn Indicators', Report by Sqdn. Ldr. R.H.Hill, i/c Experimental Flying RAE, November 1921.

23. PRO/DSIR 23/9504, 'Turn Indicators', report by C.J.Stewart, 25 February 1922. The file contains reports from January 1919 to February 1922, mostly of trials conducted by Biggin Hill. There is also a report from Mr. Bourdillon at Oxford, 9 July 1919, which implied he was still involved in a civilian capacity, and another from Andover Station, which said they preferred the static turn indicator to the RAE gyro.

24. C.J.Stewart, *Aircraft Instruments*, (London : Chapman & Hall), 1930, 159.

25. PRO/DSIR 23/9524, 'Present Position on Turn Indicators, Report by Sqdn. Ldr. R.M.Hill, 2 May 1924.

26. W.W.Davenport, *Gyro : The Life of Lawrence Sperry*, (N.Y. : Charles Scribner & Sons), 1978 provides copies of some of Lawence Sperry's patents. Other than this the book is trivial and best ignored. R.F.Hallion was polite in his review when he said it was disappointing, *Technology and Culture*, Vol 21, 1981, 132-3.

27. T.P.Hughes, *Elmer Sperry*, (Baltimore : John Hopkins Press), 1971, 235-6.

28. R.H.Mayo Papers, Imperial War Museum, Ref 87/49/1, Curtiss "Canada" Trials .

29. PRO/AIR 1/771/204/4/282, *Sperry Stabiliser*, Report by SRAF of 25 May 1914.
T.P.Hughes, *Elmer Sperry*, Baltimore : John Hopkins, 1971. Hughes is critical of French pilots who rejected the stabiliser after the French government had purchased 40 of them, while assuming it was successful in Britain, who only bought one or two. However, the Testing Flight at Upavon rejected the Sperry stabiliser in 1915 for the same reasons as the French pilots, that it was unnecessary in a stable aeroplane and was too heavy to assist bomb aiming.
Air Ministry file also contains arrangements for Busk to go to France for demonstration flight on Curtiss flying boat, 15 June 1914. Hughes mentions Busk got a ducking in the Seine in Paris when Curtiss made a bad landing.

30. Tizard Papers, Ref HTT 5/29, Diary for January - February 1917, 17 January 1917. Tizard had been involved with the 1915 Sperry trials at the Upavon as he wrote to Lindemann that 'Sperry's representative has been demonstrating his gyroscope, which can do most things', 10 November 1915, Cherwell Papers, Ref D-243/12.

31. Lindemann Papers, Ref E19-20, Lindemann's contribution to publication to mark RAE Jubilee 1956. (In Aircraft Instruments, 1930, Stewart says the design work was by F.W.Meredith, P.A.Cooke and P.S.Kerr. This may have been later as Meredith and Cooke were key figures in the development of autopilots over the next forty years.)

32. Cherwell Papers, Ref E-20/14-17, Draft of Lindemann's contribution to RAE Jubilee 1956.

33. P.S.Kerr, 'RAE Rudder Gyro Control Installed on Imperial Airways H-P Hamilton', Report H-1037, December 1925, filed Farnborough Library.

34. G M B Dobson, 'Design of Instruments for Navigation of Aircraft, *Geographical Journal*, **LVI**, No 5, November 1920, 370-389. Paper read to Royal Geographical Society, 10 May 1920.

35. Sir P.G. Masefield, *To ride the storm : the story of the airship R101*, (London), 1982.

Chapter 7

Bomb Aiming Research - Part 1

Commercial and Government Research to 1917

1. PRO/AIR 1/945/204/5/999, *Conference on Bomb Sighting Policy*, 25 June 1918.

2. N.Jones, *The Origins of Strategic Bombing - A Study of the Development of British Air Strategic Thought and Practice up to 1918*, (London : Kimber), 1973.

3. J.Sweetman, *Bombing and the Origins of the Royal Air Force*, PhD Thesis, Kings College, University of London, 1983. A.R.Kingsford, *Night Raiders of the Air*, (London : Greenhill Books), 1930 (Reprinted 1988). S.E.Wise, *Canadian Airmen and the First World War*, (Toronto University Press), 1991.

4. PRO/AIR 1/756/204/4/91, *Bomb-sights General RFC HQ*, April 1915 - November 1916; and PRO/AIR 1/945/204/5/999, *Bomb-sights General RFC HQ*, December 1916-November 1918.

5. PRO/AIR 1/789/204/4/1018, *Bomb Dropping from Aeroplanes*, Report from No. 3 Squadron RFC, 11 May 1913.

6. PRO/DSIR 22/1, *Minutes of Advisory Committee for Aeronautics*, 9 December 1913. (These Minutes are the original, individually signed by Rayleigh).

7. PRO/DSIR 23/361, *Instrument for indicating the place vertically below the aeroplane*, Advisory Committee for Aeronautics, Report T-361, H. Darwin, 23 February 1914.

8. PRO/AIR 1/810/204/1225, *Bomb Dropping Experiments from HMA Beta - 1913*, Report by Major E M Maitland at South Farnborough to Secretary, War Office, 1 May 1913, and Report of Experiments by Captain Waterlow, 29 May 1913. Jones mentions this incident (page 47), but his explanation is not consistent with the laws of motion.

9. PRO/AIR 1/834/204/5/232, *Reports on Bombs, Bombsights and Grenades - 1909 15.*

10. PRO/AIR 1/776/204/4/389, *Bristol Bombsight* , Correspondence and drawings, 1914-15.

11. Ibid, Letter War Office to Farnborough, 5 march 1915.

12. During the period of this thesis, G.K.B.Elphinstone (1865-1941) was an engineer at Elliott Brothers offices, 36, Leicester Square, London. Later, as Sir Keith Elphinstone, he was Managing Director of the company.

13. H.E.Wimperis, *Application of Power to Road Transport*, Constable, London, 1913.

14. Public Archives of Canada, Ottawa K1A 0N3, Ref MG30-B72, *The Diaries of Harry Egerton Wimperis Diary : 1907-1941*, A brief biography is also provided in Finding Aid 311 by Jane Augler 1975.

15. PRO/AIR 1/175/204/4/368, *Marks Ground Speed Indicator*, File of correspondence on this instrument. Alfred S.Marks address given as 4 Draper Gardens, EC, and telegraphic address as HALCYON.

16. PRO/AIR 1/776/204/5/388, *Cousin Chaurviene Sight*, The Integral Propeller Company Ltd to Farnborough that it had been dispatched, 21 July 1914; and B Hopkinson to Farnborough trying to locate it, 29 July 1916.

17. PRO/AIR 1/756/204/4/91, *Bomb sights General April 1915-November 1916,* War Office to General Officer Commanding RFC in the Field, 20 March 1915; and DAQMG in Field to War Office, 24 August 1915.

18. PRO/AIR 1/674/21/6/77, *Short Notes on the Evolution and Theory of Bomb Sights,* Capt. D.C.Murray, 8 February 1921.

19. PRO/AIR 1/826/204/5/129, *Lever Bomb Sight,* Capt Reynolds in the Field to DAQMG RFC, 2 January 1915.

20. H.L.Stevens, 'Early Days at the Royal Aircraft Factory - 1914 Onwards', *Jnl. of Royal Aeronautical Society,* **70**, January 1966.

21. PRO/DSIR 23/361, *Lucas Space Damped Pendulum,'* Advisory Committee Report T-361, K.Lucas, February 1915. The report contains no diagram of the device.

22. Tizard Papers, Ref 5/115, *Activities of Bertram Hopkinson since beginning of War,* A.H.Chapman, undated but shortly after Hopkinson's death in August 1918.

23. SRAF, *RAF Low Altitude Aimer,* R&M 236, (HMSO). December 1915

24. Tizard Papers HTT 5/113, Pencil comments by R.H.Mayo of flight on 1 and 23 October 1915, in BE 2c No.1688.

25. K.Lucas, *Oscillations of an Aeroplane in Flight and their Effect on the Accuracy of Bomb Dropping,* R&M 213, (HMSO), February 1916.

26. PRO/AIR 1/22/15/1/111, *Award to Lt Col Bourdillon in respect of CFS Bombsights,* Documents and correspondence, 14 Aug 20 - 13 Apr 21.

27. PRO/AIR 1/756/204/4/91, *Bomb Sights General - Apr 15 to Nov 16,* Memos DAQMG to RFC HQ in the Field, 14 July 1916 and ADAE War Office to same, ?.

28. PRO/AIR 1/27/3/444, *CFS 4b Sight with Cowey Course Setter,* RNAS Instruction Manual, 1 July 1916.

29. PRO/AIR 1/756/206/4/91, *Bomb Sights General - Apr 15 to Nov 16,* Answers by RFC HQ in the Field to War Office questionnaire, 8 February 1916.

30. PRO/AIR 1/945/204/5/999, *RFC HQ Bomb sight reports - Dec 16-Nov 18,* various reports.

31. PRO/AIR 1/1200/204/5/2610, *Orfordness 'G' Reports,* Report G/35 Camera Obscura for Bomb Dropping Training, Capt C E Fairburn, 13 October 1917.

32. PRO/AVIA 8/213, *Improvements in angular measuring apparatus - particularly adaptive for timing the release of bombs from aircraft,* H.Darwin and H.Booth, Secret Patent 1735, 3 February 1915, based on application 2647 of 1914.

33. H.Darwin, 'The Static turn Indicator for Aeroplanes', *Aeronautical Journal,* **XXIII**, December 1919, p 617 when discussing his earlier work as an introduction to this paper.

34. PRO/AIR 2/39/AIR 143308/1917, *RNAS Laboratory - Imperial Laboratory,* Annual survey by Lt Cmdr Wimperis,December 1917.

35. Imperial College Archives, *Governing Body Minutes,* Minute 68, 12 November 1915.

36. Presumably A.P.Trotter, formally at the Cavendish Laboratory and now with the Board of Trade.

37. PRO/AVIA 8/214, *Wimperis Patent for Attack Director for use on Aircraft - Secret Patents 16877/15 and 2033/16*, 30 November 1915 and 10 February 1916. The second patent covers the design of a sighting arm.

38. L.Aitchison, 'With Frewen Jenkin at the Ministry', *Jnl.of Royal Aeronautical Society*, **70**, January 1966, 120.

39. PRO/AIR 1/699/27/3/84, *Notes on Aerial Bomb Dropping, Parts II and III*, HMSO, 1917; and PRO/AIR 1/207/31, *Bomb Dropping Mirror*, RNAS Instruction Pamphlet,1916.

40. PRO/AIR 1/699/27/3/84, *Notes on Aerial Bombing Parts II and III*, HMSO, 1917; and PRO/AIR 1/701/27/3/656, *Bomb Sighting with Account of Equipment in use*, Publication H-636, Ministry of Munitions Technical Department, November 1918.

41. PRO/T 173/554, *Bachelor Mirror*, Minutes of Proceeding before the Royal Commission for Awards to Inventors and Commission for Adjustment of Foreign Claims, 20 February 1923; and PRO/T 173/108, File of supporting documentation.

42. PRO/AIR 2/36/AIR 60308/1916, *Method of Finding Speed of Machines*, Letter from Sqdn. Cmdr. A Oglivie, Air Dept., to Commanding Officer, RNAS Eastchurch, 10 January 1916.

43. PRO/AVIA 8/267, Lt. John Kilner Wells, Admiralty Air Department, *Improvement to Sighting Device*, Secret Patent 4906/16, 3 April 1916.

44. PRO/AIR 2/163/MR 7537, *Proposals for Training, Research and Administration of RNAS*, Commodore Murrey E. Seuter, 24 June 1916. PRO/AIR 2/47/AB 203/22, *Imperial College Accommodation*, Gen. Ruck to Lord Sydenham, 4 July 1916, describes his visit to see Wimperis and Dalby following Seuter's proposals. The memo described the accommodation to consist of 2 buildings with 3 storeys and a basement - completed pre-war but practically unoccupied, but thoroughly equipped with physical and chemical laboratories, workshops, water testing tank, wind tunnel and plenty of power - the Air Department Admiralty using a workshop and one or two rooms. Ruck planned for Adm. Lee and Gen. Brancker to visit the facilities.

45. PRO/AVIA 8/264, *Improvement to Bomb Sights, Secret Patent 15319/15*, Frederick William Scarff, RNAS, 30 October 1915.

46. PRO/AIR 1/699/27/3/435, *Drift Bomb Sight*, Manual H-435; and PRO/AIR 1/2103/207/31, *Drift Bomb Sights*, Instruction Manual, 1918. The former shows fore-sight adjusted with vertical height scale and the later with horizontal height scale and bell crank lever to adjust fore sight.

47. PRO/AIR 1/945/204/5/999, RFC Headquarters - Bomb Sights December 1916-November 19181918, Report by Capt McKerrow, 'Wimperis HAD Sight in the Field in France', 17 July 1918.

48. Tizard Papers, Ref HTT 5/114, 'Hopkinson's connections with Orfordness', Unsigned and undated document relating to obituary for Hopkinson.

49. PRO/AIR 1/1200/204/52610, *Orfordness 'G' Reports*, Report G/65 Negative Lens Pendulum Sight, Capt G.McKerrow, 6 November 1918.

Chapter 8

Bomb Aiming Research - Part 2

Course Setting and Stabilised Sight Research

1. PRO/AIR 2/39/AIR 143308/1917, 'RNAS Laboratory - Imperial College - Annual Summary, Lt. Cmdr. H.E.Wimperis, December 1917.

2. National Maritime Museum, Ref 43-521, G.H.Alexander, *Compass Catalogue and Explanatory Notes*, Catalogue No.347. Later versions 371-373.

3. PRO/AIR 2/39/AIR 143308/1917, Submittal Cmdr H.E.Wimperis to Capt A.Stoppard, 17 December 1917, and PRO/AIR 2/39/AIR 143308/1917, Letter Capt A.Stoppard to Sir William Weir, 17 December 1917.

4. PRO/AIR/39/AIR 143308/1917, Professor H.L.Callendar to Capt. the Hon. A.Stoppard, 5 February 1918.

5. PRO/AIR 2/39/AIR 143308/1917, Lt. Col. B.Hopkinson to Capt. A.Stoppard, 14 February 1918, and Capt. A.Stoppard to Lt. Cmdr. H.E.Wimperis, 18 February 1918.

6. PRO/AIR 2/39/AIR 143308/1917 above, Officer i/c Lt. Cmdr. H.E.Wimperis, N3 Section - Lt. E.C.Horsley, Sub Lt. B.S.Cain, W/O J.Meadows, Dr. Gray, N4 Section - Lt. S.R.Mullard, Lt. W.Mackower, Sub Lt. Houghton, A/M S.Franks.

7. P.H.Liddle, *The Airman's War*, (Poole, Dorset : Blandford Press), 1987, p 163, Log of A.V.Price operating out of Calshot in F 2a, No.15Y.

8. R.C.Sutcliffe and A.C.Best, 'Ernest Gold -1881-1976', *Biographical Memoirs of Fellows of the Royal Society*, **23**, 1977, 115-131. His Meteorological Flight was led by Capt. C.K.M.Douglas, another Cambridge mathematician and later well known meteorologist.

9. PRO/AIR 2/53/MA MISC/1098, Major B.Hopkinson, Minutes of Meeting at 13 Albermarle St, 14 April 1916.

10. PRO/DSIR 23/1245, *Double Pendulum Bomb-sight*, and PRO/DSIR 23/691,*Suggested Sight Calculator following analysis of Report T 649*, A Mallock to Advisory Committee for Aeronautics, March 1916.

11. PRO/AIR 2/39/AIR 143981/1917, *Gyrostats for Stabilising Bomb-sights*, Report from Lt. H.E.Wimperis to Wing Cmdr. F.C.Halahan at Admiralty Air Department, 15 April 1916.

12. PRO/ AIR 2/MA MISC/1098, Memo DADAE to CFS, 15 May 1916, and Memo DADAE to Wimperis 6 July 1916.

13. PRO/AIR 2?16/MA AERO/1227, *Trials with Lucas Gyro Sight and CFS 4b Sight*, Orfordness Report B/17, 11 August 1916.

14. PRO/AIR 2/39/AIR 143981/1917, *Report of visit to Orfordness*, Lt. Wimperis to Capt. Davis, 14 September 1916 attaching Lt. Cmdr. Pulford's report of bombing trials.

15. PRO/AIR 2/53/AB 275/3930, Memo from DAE re order, 16 August 1916 and Memo on Fitment to DH 4 Pushers, Maj. Mills at Testing Squadron to DAE, 10 October 1916.

16. PRO/AVIA 1/1, Royal Aircraft Factory Flight Log Book, 1910-20.

17. F.A.Lindemann, Reminiscence published in *Fifty Years at Farnborough*, HMSO, 1955. Drafts in Cherwell Papers, Ref E 19-20.

18. Cherwell Papers, Ref C 19/1, *Experiments with Diving Bomb Sight*, Farnborough Report H-626, 21 June 1917.

19. PRO/AIR 2/53/AB 275/3930, *Bomb dropping with RAF or Lucas Bomb-sight*, Orfordness Report B/38 by Lt. C.E.Fairburn, 17 September 1917.

20. PRO/DSIR 23/1117,*Trial with Gray Sight*, Grain Report, March 1918, including photographs of sight.

21. Cherwell Papers Ref E 19-20, Letter J.K.Wells to Birkenhead, also published in *The Prof of Two Worlds*, p 69.

22. PRO/AIR 2/53/AB 275/3930, Letter B.M.Jones to H.T.Tizard, Assistant Controller Experimental Research Department, Air Ministry, 14 June 1918.

23. Cherwell Papers Ref A-11, Lindemann's Pilots Log Book.

24. PRO/MUN 8/1, *Rangefinder Trails at Orfordness*, Grain Report 1068, 26 May 1918.

25. PRO/AIR 2/58/AB 284/50, *RAE Mk III Rangefinder, Report T 1055*, F.A.Lindemann, December 1917.

26. PRO/MUN 8/1, *Lindemann Rangefinder*, H.T.Tizard, Assistant Controller of Experiments, to DAA, 10 January 1918.

27. PRO/MUN 8/1, *RAE Rangefinder*, Orfordness Report G 1068 - No.1, 26 May 1918.

28. PRO/MUN 8/1, *RAE Rangefinder* , Orfordness Report G 1068 - No. 2, 7 June 1918; and memo Dobson to Tizard 25 June and 29 November 1918.

29. PRO/AIR 2/140/16114/20, *Development of Instruments for Naval Aerial Spotting*, Major H E Wimperis, A.M.L. Imperial College, 11 December 1919. Wimperis suggested that it may be possible to reduce the number of readings if the pilot flew the aeroplane in line with the target and shore battery (though keeping both in view from most aeroplanes at that time would be impractical - my comment). He also mentioned that a similar device was being developed by De Coursey.

30. PRO/AIR 1/1199/204/5/2607, *Aerial Artillery Spotting Device by Lt. Powers*, Orfordness Report D-70, Capt. I.O.Griffith , 13 december 1917.

31. PRO/AIR 2/301/S 25343, *Control of Aircraft by Light*, Prof F.A.Lindemann, Clarendon Laboratory, Oxford, 1925.

32. PRO/T 173/638, *Claim by Professor J G Gray for Stabilising Gear*, Transcript of Hearing before Royal Commission for Awards to Inventors, 30 April 1923, and PRO/T 173/239 for documents and correspondence associated with the claim. Gray claim was for infringement of master patents 13280/15 and 14032/15. Subsidiary patents 14653/16, 1488/17, 4708/18, 1938/19, 4735/19, 13093/19,16345/19 and 22033/19 were not involved.

33. The Argo Company had been founded by A J H Pollen to exploit his patents for naval fire control equipment, called Aim Control or A.C. Reference T Sumida, *The Pollen Papers*, (London : Allen & Unwin), 1984, and *In Defence of Naval Supremacy - Finance, Technology and British Naval Policy 1889 to 1914*, (Boston : Unwin Hyman), 1989.

34. PRO/T 173/711, Transcript of Claims of Gregory, Mathews, Wimperis and Argo to the Royal Commission for Awards to Inventors, 1920, and PRO/T 173/534 for the related correspondence. The files are substantial, the transcript runs to some 70,000 words for the two day hearing, so that the account in this thesis is a drastic reduction of the evidence. The Treasury Solicitor, Moritz, has to be admired throughout the hearing for his appreciation of the principles of navigation, bomb aiming and bombsights that allows him to question expert witnesses and make concise summaries of technical evidence to the chair.

35. Drift Sight - Secret Patent 3129/16 - 4175 ordered @ £11. Negative Lens Sight - Open Patent 13042/17 - 19,750 ordered (6600 cancelled) @ £3, jointly with Lt J Kilner Wells on the basis $^2/_3$ Wimperis - $^1/_3$ Wells. Course Setting Sight - Secret Patent 16871/15 & 2033/16 - 450 ordered @ £50.

36. Faccioli, *L'Aerophile* and *Trattato d'Aviazione*, February 1911.

37. T.Sumida, *The Pollen Papers*, (London : Allen & Unwin), 1984, and *In Defence of Naval Supremacy : Finance, Technology and British naval Policy 1889-1914*, (Boston : Unwin Hyman), 1989. Sumida assumes that Pollen became a war correspondent, disillusioned that the Navy failed to adopt his gun control system. After the war he proved infringement of his Argo clock patent by the Government, a somewhat similar situation to his course setteing sight in this thesis. See also A.McConnell, *Instrument Makers to the World : A History of Cooke, Troughton and Simms*, (York : William Sessions), 1992, regarding manufacture of Pollen's equipment by Cooke and the rival Dreyer's equipment by Elliott Brothers.

38. PRO/T 173/823, Transcript of Wimperis Claim for American Use of his Drift sight and Course Setting Sight, 20 February 1923, and related correspondence PRO/T 173/536.

39. PRO/AIR !/1200/204/5/2610, *Hobbs Electrical Sight*, Orfordness Report G/59, 23 September 1918; *Grubb Sight*, Orfordness Report G/60, 6 September 1918; *Double Bubble Level Sight*, Orfordness Report G/66, 30 November 1918.

40. PRO/DSIR 23/1457, W.Mackower MA, D.Sc., and L.C.Bygraves, AMIEE, *Rate of Recovery of Gyro in Gray's Gyrostatic Stabiliser*, Report T-1443, February 1920, including comments back from Professor J.G.Gray as T-1443a, August 1920, and extracts from Gray's patent as T-1443b, September 1920.

41. PRO/AIR 2/S 16812, Minutes of Meeting at Air Ministry Laboratory, H E Wimperis - Director of Research, 15 September 1921.

42. PRO/AIR 2/S 16812, Wimperis comments to *Proposals by Sdn.Ldr. Sparling*, 16 May 1923.

43. PRO/AVIA 8/ 482, Secret Patent 28949/22, *Improvements to Optical Sights* (using pendulum stabilised mirror), A.E.Conrady, H.E.Wimperis, L.C.Bygraves, E.C.Horsley, Air Ministry Laboratory, 22 October 1922. PRO/AVIA 8/237, Secret Patent 15777/24, *Sighting Device*, L.C.Bygraves, AML, 1 July 1924. PRO/AVIA 8/238, Secret Patent 15776/24, *Sighting Device - Clockwork Driven*, H.E.Wimperis, Air Ministry Laboratory, 1 July 1924.

44. As note 17.

45. RAF Museum Hendon, B M Jones Papers, Ref AC 76/6/63, Typescript of "Some Wartime Experiments", Paper prepared for 'Goodden Memorial Lecture' but given to normal meeting of Royal Aeronautical Society, unpublished, undated.

Chapter 9

The Scientists Demobilise

1. Tizard Papers, Ref 5/90, *Organisation of Air Ministry Technical Department,* Letter Col. R.H.Moore to Brig. Gen. Weir, 25 July 1918. Hopkinson was to be promoted to Brigadier General at £1000/year and Tizard to temporary rank of Colonel at £950/year.

2. R.H.Mayo Papers, NRA Ref 30912, Mayo, File 1/4, Pilot Log Book, Science Museum Library, (Ref ARCH : MAYO 1/4).

3. Tizard Papers, Ref 5/108-114, File on Bertram Hopkinson containing obituaries, funeral service and a summary of his wartime achievements. One from Orfordness mentions Hopkinson's disregard for bad weather when the sea was too rough for the ferry, he and Collett took a Bristol Fighter to try to catch the London train from Ipswitch, but crashed on landing at Martlesham.

4. Tizard Papers, Ref 5/152, File containing minutes and memoranda of Advisory Committee of Aeronautical Research and Education. Committee was formed in October 1918 by Lord Weir on Hopkinson's suggestion, Ref PRO/AIR 2/165/MR 14215, Reports on Aeronautical Research and Education. See also R.W.Clark, *Tizard,* (London : Methuen), 1965, 65-66.

5. PRO/AIR 2/AIR 143308/1917, *RNAS Laboratory at Imperial College,* Prof H.L.Callender to Capt. the Hon. A.Stoppard, 5 February 1918.

6. Tizard Papers, Ref 5/152, File containing minutes and memoranda of Advisory Committee of Aeronautical Research and Education. Salaries listed included Capt. H.Grinstead (£1,000 flat), Capt. G.M.B.Dobson (£750 flat), Dr. F.A.Lindemann (£460 + 20% war bonus), Dr. G.F.C.Searle (£420 + 20% war bonus) and Dr. F.W.Aston (£350 + 20% war bonus).

7. PRO/AIR 2/153/316726/20, *Committee to consider the future of certain Experimental Stations,* Minutes for 22 Dec 1920.

8. Tizard papers, Ref HTT 5/149, *Testing of Aeroplanes,* Officers of Technical Staff, RAF Aeroplane Experimental Station Martlesham Heath, February 1919, 87 page typescript of Chapters 1-5 with original photographs, drawings and graphs. Chapter 2 is devoted to Test Instruments. A copy of the same document can be found in Mayo Papers, Ref ARCH:MAYO 1/6, Science Museum. Tizard Papers, Ref 5/150, *Reports relating to Orfordness,* 1916-18, which includes the manuscript on double foolscap of 'Experimental Work at Orfordness Armament Experimental Station on Sights and Tactics in Aerial Gunnery', Chapters 1 - 7, B.M.Jones, undated; and 'Bomb Sights and Methods of Bombing', Capt. G.McKerrow and Maj. L.E.Fairburn, Chapters 1-12, 19 February 1919.

9. R W Clark,*Tizard,* (London : Methuen), 1965, Chapter Three 'Scientific and Industrial Research', 49-81.

10. *Journal of Royal Aeronautical Society,* H.E.Wimperis, 'Some Recent Developments in Aircraft Instruments', **XXVIII**, January 1924, 5-34. A.P.Rowe, 'Aerial Navigation', **XXVII**, September 1923, 450-458. F.Tymms, 'Practical Navigation for Aircraft', **XXIX**, May 1925, 202-239. T.M.Barlow, 'Performance Testing of Aeroplanes', **XXVI**, May 1922, 152-176.

11. C.J.Stewart, 'Modern Developments in Aircraft Instruments', *Journal Royal Aeronautical Society,* **XXXII**, January 1928, and as Aeronautical Reprint 29, 'Aircraft Instruments', (London : Chapman & Hall), 1930.

12. Cherwell Papers, Refs B2 f1-8 and B3 f1-f11, Letters from H.Grinstead, G.M.B.Dobson and I.O.Griffith to Lindemann, 1919.

13. J.Morrell, 'Research in Physics at the Clarendon Laboratory, Oxford, 1919-1939', *Historical Studies in the Physical and Biological Sciences*, Berkley, **22**, Part 2, 1992.

14. Prudence Hill, *To Know the Sky - Life of AVM Sir Roderic Hill*, (London : William Kimber, 1962.

15. Imperial College, Board of Governors, Annual Report for year ending August 1918.

16. British Science Products Exhibition at Central Hall, Westminster, Part 1, 'War Work at the Universities', (London : British Science Guild), 1919. J.A.Flemming's letter to Times, 15 June 1915. J.A.Flem ing and J.G.Pearce, 'Organisation of Scientific Research', *Nature*, **96**, 1916, 692-696. J.B.Poole and K.Andrews, *The Government of Science in Britain*, (London : Weidenfelt & Nicolson), 1972. M.Pattison, "Scientists, Inventors and the Military in Britain 1915 to 1919 - The Munitions Inventions Department', *Social Studies of Science*, **13**, 4, 1983, 521-568.

17. Imperial College, Board of Governors, Annual Report for year ending August 1915.

18. Imperial College, Governing Body, Minutes of Technical Optics Committee, 1917.

19. Imperial College, Executive Committee of Governing Body, Minute 201, 23 March 1917, details the courses at Imperial and Northampton over 7 pages.

20. M. von Rohr (ed), *The Formation of Images in Optical Instruments*, HMSO, 1920, originally written by specialists at the Jena Works and published 1903. A.Gleichen, *The Theory of Modern Optical Instruments*, HMSO, 1921; translated by H.H.Emsley and W.Swaine of Barr & Stroud and interestingly with many references to Maxwell and Schuster.

21. Imperial College, Executive Committee of Governing Body, Minutes 189 (January 1921), 133 and 140 (May 1921) and 145 (May 1922).

22. A.F.C.Pollard, *The Kinematical Design of Couplings in Instrument Mechanisms*, (London ; Adam Hilgar), 1929.

23. Imperial College, Minutes of Executive Committee of Governing Body, Advisory Committee for Zaharoff Chair and Advisory Committee on Aeronautical Education, 1915-1920.

24. Discussion following Prof. L.Bairstow's paper on 'Skin Friction', *Jnl. of Royal Aeronautical Society*, **XXIX**, January 1925, 3-23. A.Fage, *Early Days at NPL, Jnl. of Royal Aeronautical Society*, **70**, January 1966.

25. PRO/AIR 2/A 12449, *Foundation of Aeronautical Chair at Cambridge*, 1919. Other candidates were H.A.Webb (Trinity) who worked under Southwell at Farnborough and R.West at the Aircraft Manufacturing Company and who had previously work at the Hendon Wind Tunnel.

26. Cherwell Papers, Ref B6 f2, Letter Lindemann to G.P.Thomson, 27 Sept 1920.

27. T.J.N.Hilken, *Engineering at Cambridge University*, Cambridge University Press, 1965.

28. B.M.Jones,' Flying over Clouds in relation to Commercial Aeronautics', *Aeronautical Journal*, **XXIV**, May 1920.

29. Sir B.Melvill Jones, 'Cloud Flying in the First World War', *Jnl. of Royal Aeronautical Society*, **70**, January 1966.

30. RAF Museum Hendon, B.Melvill Jones File, Ref AC 76/6/73, *Citation to F.W.Lanchester*, and Ref AC 76/6/72, *General Correspondence*, Letters from F.W.Lanchester, 29 Aug 1935 and 11 September 1935. Lanchester wrote to thank BMJ for his kind words in the Proceedingsof Royal Institution, 1935, page 635, and recalled,

> that Bairstow was almost vindictively hostile to his theory, jeered at it at meetings of the old Advisory Committee, in time impairing the judgement of the other members and NPL. Had he used his undoubted gifts in the right direction, he might have achieved what Prantdl did - when he had to give in and acknowledge the Theory, to save face he always referred to it as Prantdl's Theory.

When Jones tried to excuse Bairstow and suggest the problem was due to the mathematics that Lanchester used to express his theory, Lanchester replied,

> What I don't understand is why, that when my book came into the hands of Prof Runge at Göttingen for review, he wrote straight off to me asking for permission to translate it and arrange for publication in Germany. Why then, if a German can read an English work and understand it so clearly, is it my own countrymen, reading in their own language, could not.

31. Royal Aeronautical Society, Technical Reports of Ogilvie and Partners Ltd., Vol.1, Report 102, *Aircraft Instruments*, A.Ogilvie, 1919 -1925, 7 March 1919.

32. Negretti and Zambra, *Centenary 1950-1950*, (London : N&Z), 1950.

Bibliography

This bibliography consists of 2 sections:

1. Unpublished archival material and manuscript sources.
2. Published reports, memoranda, papers and books referenced.

1. Unpublished Archival Material and Manuscript Sources

Bruce Castle Museum, Haringay
R.W.Munro Company Archive (NRA 2259)

Cambridge University Library
Cambridge Scientific Instrument Company archives

Churchill College Archives Centre, Cambridge
W.S.Farren Papers
A.V.Hill Papers

Elliott Brothers Ltd., Rochester Airport.

Imperial College, London
Governing Board Minutes
Executive Committee of Governing Body Minutes
Technical Optics Committee Minutes

Imperial War Museum, London
R.H.Mayo (Ref 87/49/1)
H.T.Tizard Papers

Nuffield College, Oxford
F.A.Lindemann (Lord Cherwell) Papers

Public Archives of Canada, Ottawa K1A 0N3, Ref MG30-B72.
Diaries of Harry Egerton Wimperis Diary : 1907-1941.
A brief biography is also provided in Finding Aid 311 by Jane Augler 1975.

Public Records Office, Kew
AIR - Air Ministry, AVIA - Ministry of Aviation , MUN - Ministry of Munitions
DSIR - Department of Scientific and Industrial Research, T - Treasury Files

Rose Lipman Library, Hackney
Casella Archive

Royal Aeronautical Society Library, London
G.Brewer Papers
A.Ogilvie Papers and Ogilvie and Partners Ltd. Reports

Royal Airforce Museum, Hendon
B.Melvill Jones Papers

Science Museum Library, London
R.H.Mayo Papers

Trinity College Library, Cambridge.
G.P.Thomson Papers

2. Published reports, memoranda, papers and books referenced.

A&AEE, Boscombe Down, *50 Years of Aeroplane and Armament Testing*, (HMSO), 1971.

P.Abbot : *The British Airship at War 1914-1918* (Levenham, Suffolk : Terence Dalton), 1989.

R.J.Q.Adams, *Arms and the Wizard : Lloyd George and the Ministry of Munitions*, (London : Cassell), 1978.

Advisory Committee for Aeronautics, *Report for Year*, (HMSO), 1909-1920.

Advisory Committee for Aeronautics, Minutes of Meetings, signed by Rayleigh, PRO/DSIR 22/1.

Air Ministry, *Camera Obscura*, A.P. 242, 1917; A.P. 356, 1918 and A.P.961,1924.

L.Aitchison, 'With Frewen Jenkin at the Ministry', *Jnl.of Royal Aeronautical Society*, **70**, January 1966, 120.

A.C.W.Aldis, 'The Optical Theory of Portable Daylight Signalling Lamps',*Trans. Optical Society*, **XXI**, 1919-20, p 113-126.

G.H.Alexander Lt., *Compass Catalogue and Explanatory Notes*, with additions by Cmdr. W.E.May, 231-239, National Maritime Museum, Ref 43-521.

P.Alter, *The Reluctant Patron. Science and the State in Britain 1850-1920*, (Oxford : Berg), 1987.

J.S.Ames, 'Relation between Aeronautical Research and Design', *Aeronautical Journal*, **27**, May 1923, 381-404.

F.W.Aston. 'Neon Lamps for Stroboscopic Work', Proceedings of the Cambridge Philosophical Society, **19**, 1920, 317-323.

C.Babbington-Smith, *Testing Time*, (London : Cassell), 1961.

L.Bairstow, *Discussion of the action of different types of air speed indicator*, R&M 145, (HMSO), February 1914.

L.Bairstow, 'Skin Friction', *Jnl. of Royal Aeronautical Society*, **XXIX**, January 1925, 3-23.

H.B.Baker 1862-1932, *Obituary Notices of Fellows of the Royal Society*, Vol 1932-1935, 523-526.

T.M.Barlow, 'Performance Testing of Aircraft', *Aeronautical Journal*, **XXVI**, May 1922, 152-176.

S.C.Baston and C.M.Dunnicliffe, *The Development of the Aircraft Compass*, Air Ministry Compass Dept R&D Report, 1947-48. Copy at RAF Museum, Hendon, Ref 11350.

B.Beaney, A.H.Cooke, N.Kurti and K.W.H.Stevens, 'F.A.Lindemann, Viscount Cherwell 1886-1957', *Physics Bulletin*, **37**, 1986, 261-263.

D.C.T.Bennett, *The Complete Air Navigator*,(London) : 1936.

R.Berman, 'Lindemann in Physics', *Notes and Records of the Royal Society*, **41**, 1987, 181-189.

J.D.Bernal, 'Lessons of the War for Science', *Proc. of Royal Society, A*, **342**, 1975, 555-574.

W.E.Bijker, T.P.Hughes and T.J.Pinch (eds.), *The Social Construction of Technological Systems. New Directions in the Sociology and History of Technology*, (Cambridge Mass.: M.I.T. Press), 1987.

Birkenhead, Earl of, *The Prof in Two Words: The Official History of Professor F.A.Lindemann, Viscount Cherwell*, (London: Collins), 1961.

P.M.S.Blackett, 'Tizard and the Science of War', *Nature*, 5 March 1960, 647-653.

S.Blume, 'Whatever happened to string and sealing wax?' in R.Bud and S.Cozzens (eds.), *Invisible Connections*, 1992, 87-101.

S.Bok, *Secrets: On the Ethics of Concealment and Revelation*, (Oxford University Press), 1982.

Harris Booth and B.Melvill Jones, 'The Measurement of Wind Velocity', *Aeronautical Journal*, **17**, July 1913, 191-198.

Harris Booth, 'A Warning to Pilots', *Flight*, 3 January 1914.

Harris Booth, 'Warning to Pilots : A reply to Mr. Busk and Mr. Bairstow', *Flight*, 31 January 1914.

Harris Booth, 'The theory of the gravity-controlled air speed indicator as applied to dynamic lift flying machines', *Aeronautical Journal*, **18**, January 1914, 56-58.

J.M.Bourne, *Britain and the Great War, 1914-1918*, (London: Edward Arnold), 1989.

R.J.Bray, *Pivots and Caps in Compasses*, (HMSO), 1917.

G.Brewer and O.Wright, 'The Dunne Biplane : Report of Automatic Stability Trials on 20 December 1910', **XIV**, Aeronautical Journal, January 1911,

G.Brewer, 'Pioneers of British Aviation XVIII - Griffith Brewer', *Aeronautics*, **27**, November 1919.

G.Brewer, *Fifty Years of Flying*, (London : Air League of British Empire), 1946.

British Science Guild, 'War Work at the Universities', in *British Science Products Exhibition Catalogue 1919, Part 1*, (London : British Science Guild), 1919.

H.R.Brooke-Popham, 'The Air Force', *Jnl. of United Services Institute*, **LXV**, 1920, 43-70.

V.Brown, 'Gunsight Trials at Orfordness', *Aeronautical Journal*, **70**, 1966, 247.

R.Bud and S.Cozzens (eds.), *Invisible Connections. Instruments, Institutions and Science*, (Bellingham, Washington: SPIE Optical Engineering Press), 1992.

E.T.Busk, 'Gravity Controlled Velometers', *Flight*, 24 January 1914, 82-3.

E.T.Busk and M.O'Gorman, *Velocity of the air in the neighbourhood of the tail plane of the Tractor Biplane BE 2, R&M 132*, (HMSO), April 1914.

E.T.Busk and M.O'Gorman, *Lateral Stability, R&M 133*, (HMSO), April 1914.

M.Busk, *E.T.and H.A.Busk*, (London : John Murray), 1925.

H.L.Callendar 1863-1930, *Proceedings of the Royal Society 'A'*, **CXXXIV**, 1931-2, xviii-xxvi.

Cambridge Scientific Instrument Company, '50 Years of Scientific Instrument Manufacture', *Engineering*, 11 and 25 May, 15 and 29 June, 1945.

S.Child & C.F.Caunter, *Summary of the Royal Aircraft Factory and its Antecedents - 1887 to 1918*, RAE Report Aero 1280, March 1947.

R.A.Chorley, 'Seventy Years of Flight Instruments and Displays', *Aeronautical Journal*, **70**, August 1976, 323-42.

R.S.Capon and Dr. Alice Lee, *Preliminary Report on the Forced Oscillations of Aircraft Compasses*, R&M 874, (HMSO), July 1920.

M.J.G.Cattermole and A.F.Wolfe, *Horace Darwin's Shop : A History of the Cambridge Scientific Instrument Company, 1878 1968*, (Bristol : Adam Hilgar, 1987.

L.Chitty, 'Miss L.Chitty' (Admiralty Air Department), *Jnl. of Aeronautical Society*, **70**, January 1966, 67-68.

Dugeld Clerk 1854-1932, *Obituary Notices of Fellows of the Royal Society*, Vol 1932-1935,101-102.

R.W.Clark, *Tizard*, (London: Methuen), 1965.

E.H.Clift, 'The Magnetic Compass - Its Construction and Use, *Flight*, 24 February 1912, 199 and 163-5, and 2 March 1912, 199-201.

E.H.Clift, 'A New Compass', Flight, 20 July 1912, p 661.

J.Cockroft, Sir (ed.), *The Organisation of Research Establishments*, Cambridge University Press, 1965.

A.R.Collar, 'Tizard and the Aeronautical Research Council', *Jnl. of Royal Aeronautical Society*, **71**, August 1967.

H.M.Collins, 'The Role of the Core Set in Modern Science: Social Contingency with the methodological Propriety of Discovery', *History of Science*, **19**, 1981, 6-19.

H.M.Collins, *Changing Order. Replication and Induction in Scientific Practice*, (London: Sage), 1985.

H.M.Collins and T.J.Pinch, *Frames of Meaning : The social construction of extraordinary science*, (London: Routledge & Kegal Paul), 1982.

L.F.C.Coombs, *The Aircraft Cockpit*, (Wellingborough : Patrick Stevens), 1990.

B.Cooper, 'Obituary in *Royal Aeronautical Journal*, 1918.

C.F.Cotter, *The History of the Navigators Sextant*, (Glasgow : Brown, Son and Ferguson), 1983.

D.Crane, *Invisible Colleges. Diffusion of Knowledge in Scientific Communities*, (Chicago University Press), 1972.

J.G.Crowther, *Fifty Years with Science*, (London: Barrie and Jenkins), 1970.

J.G.Crowther, *The Cavendish Laboratory 1874 1974*, (London : Macmillan), 1976.

W.S.Dalby 1863-1936, *Obituary Notices of Fellows of the Royal Society*, Vol 1936-1939, by C.E.Inglis.

H.Darwin, 'Scientific Instruments : Their Design and Use in Aeronautics', *Aeronautical Journal*, **XVII**, July 1913, 170-190.

H.Darwin, *Instrument for indicating the place vertical below an aeroplane,* Advisory Committee Report T-361, 23 February 1914, PRO/DSIR 23/361.

H.Darwin, 'Aeronautical Inventions', *Aeronautical Journal,* **XXII**, June 1918, 207-8.

H.Darwin, 'Static Turn Indicator', *Aeronautical Journal,* **23**, December 1919, 619-33.

H.Darwin 1851-1928, *Proceedings of the Royal Society 'A'*, **CXII**, 1929, xv-xviii, by R.T.Glazebrook.

W.W.Davenport, *Gyro : The Life of Lawrence Sperry*, (N.Y. : Charles Scribner & Sons), 1978.

M.A.Dennis, *Instruments and C.S.Draper at MIT*, Ph.D Thesis, John Hopkins University, 1990.

D.Devine, *The Broken Wing : A Study in the British Exercise of Air Power*, (London : Huchinson), 1966.

J.C.Dines and F.Short, *Gust Research with the Royal Aircraft Factory's Tetranemograph,* R&M 144, (HMSO), October 1913.

W.A.Dixey, 'Design, Details of Construction and Use of Trench Periscopes', *Trans. Optical Society,* **XV**, 1914-15, 78-98.

G.M.B.Dobson, *Errors of the reading of altimeters and air speed indicators due to variations of temperature of the air,* R&M 610, (HMSO), May 1919.

G.M.B.Dobson, 'Design of Instruments for Navigation of Aircraft, *Geographical Journal,* **LVI**, No 5, November 1920, 370-389.

G.M.B.Dobson, 'Instruments used on Aircraft', in R.T.Glazebrook (ed), *Dictionary of Applied Physics,* **5**, Aeronautics, 1923, 61-71.

G.M.B.Dobson 1889-1976', *Biographical Memoirs of Fellows of the Royal Society,* **23**, 1977, 41-57, by J.T.Houghton and C.D.Walshaw.

C.S.Draper, W.MacKay and W.H.Cook, 'Northerly Turning Error of the Magnetic Compass in Aircraft', *Jnl. of Aeronautical Sciences,* **5**, 1938, 345-54.

W.F.Durand, 'Some Outstanding problems in Aeronautics', *Aeronautical Journal,* **XXII**, June 1918, 178-201.

H.N.Eaton et al, *Aircraft Instruments,* (New York : Roland Press), 1926.

A.C.G.Egerton 1886-1959, *Biographical Memoirs of Fellows of the Royal Society,* **6**, 1960, 39-64, by D.M.Newitt.

D.Edgerton, 'Science and Technology in British Business History', *Business History,* **29**, 84-103, 1987.

D.Edgerton, *England and the Aeroplane. An Essay on a Militant and Technological Nation,* (London: Macmillan), 1991.

D.Edgerton, 'British scientists and engineers and the relations of science, technology and war: Towards a history of ignorance.', to be published 1994.

D.Edgerton and D.Gummett, 'Science, Technology and Economics in the Twentieth Century', Chapter XXI in G.Jordan (ed), *British Military History - A Guide to Sources*, (N.Y. : Garland Press), 1988.

A.Fage, 'Early Days. Memories of People and Places, *Jnl. of Royal Aeronautical Society*, **70**, January 1966, 91-92.

A.E.Fanning, *Steady as she goes : The Official History of the Admiralty Compass Observatory*, (HMSO), 1986.

W.S.Farren, 'Full Scale Aeroplane Experiments', *Aeronautical Journal*, **XXIII**, February 1919, 14-72.

W.S.Farren 1892-1970, *Biographical Memoirs of Fellows of the Royal Society*, **17**, 1971, 215-241, by A.Hall (Sir) and G.P.Thomson (Sir).

M.B.Field and F.A.King, 'The Evolution of the Aero Compass', *Fight*, 5 October 1912, 891-2.

L.G.N.Filon, 'Measurement of True Altitude by Aneroid', *Journal of Scientific Instruments*, **1**, 1923, 1-

L.N.G.Filon 1875-1937, *Obituary Notices of Fellows of the Royal Society*, Vol 1936-1939,

J.A.Fleming, 'Organisation of Government Research', *Nature*, **96**, 1916, 692-696.

J.A.Fleming and J.G.Pearce, 'Organisation of Government Research', (London), 1921.

R.A.Frazer, "The Rigid Airship in relation to Full Scale Experiment', *Jnl. of Royal Aeronautical Society*, **XXIX**, September 1925, 404-458.

H.Fowler, 'Flying in Clouds', *Aeronautical Journal*, **XXII**, February 1918, 49-50.

R.Fox and G.Weisz (eds), *The Organisation of Science and Technology in France 1808-1914*, (Cambridge University Press), 1980.

H.Garner, 'Early Research at Farnborough and Felixstowe', *Jnl. of Royal Aeronautical Society*, **70**, January 1966.

S.B.Gates, 'Then and Now', *Jnl. of Royal Aeronautical Society*, **70**, January 1966, 295-296.

G.N.Gilbert and M.Mulkray, 'Experiments are the Key : Participants' 'Histories and Historians' Histories of Science', *Isis*, **75**, 1984, 105-125.

H.Glauert and F.A.Lindemann, *The Investigation of the Spin of an Aeroplane*, R&M 618, (HMSO), June 1919.

H.Glauert 1892-1934, *Obituary Notices of Fellows of the Royal Society*, Vol 1932-1935, 607-610, by H.T.Tizard and W.S.Farren

R.T.Glazebrook, *Science and Industry : The Place of Cambridge in any scheme for their combination*, Cambridge University Press, 1917.

R.T.Glazebrook, 'Some Important Points in the Work of the Advisory Committee for Aeronautics', *Aeronautical Journal*, **XXIV**, September 1920, 479-495.

R.T.Glazebrook, 'Some Requirements of Modern Aircraft', *Engineering*, **II**, 19 November 1920, 683-684.

R.T.Glazebrook (ed.), *Dictionary of Applied Physics*, Vols 1-5, (London : Macmillan), 1922-1923.

R.T.Glazebrook 1854-1933, *Obituary Notices of Fellows of the Royal Society*, Vol 1932-1935, by Rayleigh and F.J.Selby.

A.Gleichen, *The Theory of Modern Optical Instruments*, (HMSO), 1921, translated by H.H.Emsley and W.Swaine of Barr & Stroud.

J.Golinski, 'The Theory of Practice and the Practice of Theory : Social Approaches in the History of Science', *Isis*, **81**, 1990, 492-505.

A.Gollin, *No Longer an Island : Britain and the Wright Brothers*, (London : Heinemann), 1984.

G.Gooday. 'Precision Measurement and the genesis of physics teaching laboratories in Victorian Britain', *British Journal for the History of Science*, **23**, 1991, 25-51.

D.Gooding, T.Pinch and S.Schaffer (eds.), *The Uses of Experiment. Studies in the natural Sciences*, (Cambridge: Cambridge University Press), 1989.

A.Gray, *Gyrostats and Rotational Motion*, (London : Macmillan), 1918.

J.G.Gray, 'A General Solution to the Problem of Finding the True Vertical for all types of Marine and Aerial Craft, *Proceedings of the Physical Society of London*, **XXXII**, 1923, 266-8.

G.Greenhill 1847-1927, Obituary, *Proceedings of the Royal Society 'A'*, **CXIX**, 1928, i-iv.

A.A.Griffiths, *Theory of Pressure Capsules*, R&M 1136, (HMSO), August 1927.

E.A.Griffiths, *Engineering Instruments and Meters*, (London : Routledge), 1921.

I.O.Griffith 1880-1941, *Nature*, **148**, 1941, 589.

W.D.Hackmann, 'Underwater Acoustics and the Royal Navy,1893-1930', *Annals of Science*, **36**, 1979.

W.D.Hackmann,*Seek and Strike : Sonar Anti-Submarine Warfare and the Royal Navy, 1914-1954*, (HMSO), 1984.

R.B.Haldane, *An Autobiography*, (London : Constable), 1929.

J.H.Hammond, *The Camera Obscura*, (Bristol : Adam Hilgar), 1981.

N.B.Harbold, *The Log of the Air Navigator*, (USA : Naylor Company), 1970.

R.F.Harrod, *The Prof. A Personal Memoir of Lord Cherwell*, (London: Macmillan), 1959.

G.Hartcup, *The Challenge of War*, (Newton Abbot : David and Charles), 1970.

G.Hartcup, *The War of Invention : Scientific Developments 1914-1918* , (London : Brassey's Defence Publications), 1988.

P.R.Hare, *The Royal Aircraft Factory*, (London :Putman), 1990.

Takehiko Hashimoto, *Theory, Experiment and Design Practice : The Formation of Aeronautical Research, 1909 1930*, unpublished PhD Dissertation, John Hopkins University, Baltimore, 1990.

G.de Havilland, *Sky Fever*, (London : Hamish Hamilton), 1961.

T.Heffernan, 'The Aeroplane and Armament Experimental Establishment', *Jnl. of Royal Aeronautical Society*, **70**, 1966, 98-9.

M.D.Hersey, 'Aeronautical Instruments', *Trans. of American Society of Mechanical Engineers*, 1920, 88-120.

M.D.Hersey, 'Diaphragms for Aeronautical Instruments', NACA Report 165, 1923.

T.J.N.Hilken, *Engineering at Cambridge, 1883-1965*, Cambridge University Press, 1965.

A.V.Hill 1886-1977, *Biographical Memoirs of Fellows of the Royal Society*, **24**, 1978, 71-151, by B.Katz (Sir).

Prudence Hill, *To Know the Sky : Life of AVM Sir Roderic Hill*, (London : William Kimber), 1962.

B.Hopkinson 1874-1818, Obituary by J.A.Ewing, Proceedings of the Royal Society 'A', **XCV**, 1918-1919, xxvi-xxxvi.

H.B.Howard, 'Aircraft Structures' (at Admiralty Air Department), *Jnl. of Royal Aeronautical Society*, **70**, January 1966.

B.C.Hucks, 'A Further Three Years of Flying Experience', *Aeronautical Journal*, **XXI**, October 1917, 426-29.

A.J.Hughes, *The Book of the Sextant*, (Glasgow : Brown, Son and Ferguson), 1938.

A.J.Hughes, *History of Air Navigation*, (London : George Allen and Unwin), 1946.

T.P.Hughes, *Elmer Sperry*, (Baltimore : John Hopkins Press), 1971.

T.P.Hughes. 'Model Builders and Instrument Makers', *Science in Context*, **2**, 1988, 59-75.

L.B.Hunt, 'The History of Pressure Responsive Elements', *Journal of Scientific Instruments*, **21**, March 1944, 37-42.

B.K.Johnson, 'The No. 7 Dial Sight Mk II', *Trans. Optical Society*, **XXI**, 1919-20, 176-186.

B.Melvill Jones and Harris Booth, 'The Measurement of Wind Velocity', *Aeronautical Journal*, **17**, July 1913, 191-198.

B.Melvill Jones, 'Experimental Work at Orfordness Armament Experimental Station on Sights and Tactics in Aerial Gunnery', Chapters 1 - 7, undated (1919), Tizard Papers, Ref HTT 5/50.

B.Melvill Jones,' Flying over Clouds in relation to Commercial Aeronautics', *Aeronautical Journal*, **XXIV**, May 1920.

B.Melvill Jones Papers, 'Some Wartime Experiments', paper given to Royal Aeronautical Society, unpublished, undated, RAF Museum Hendon, B.M.Jones Papers, Ref AC 76/6/63.

B.Melvill Jones, 'Cloud Flying in the First World War', *Jnl. of Royal Aeronautical Society*, **70**, January 1966.

N.Jones, *The Origins of Strategic Bombing : British Air Strategic Thought and Practice up to 1918*, (London : Kimber), 1973.

R.V.Jones, 'Lindemann', *Nature*, **180**, 1957, 279-281.

R.V.Jones, 'Sir Henry Tizard 1885-1959', *Jnl. of Royal Aeronautical Society*, **68**, December 1964, 789-798.

R.V.Jones, 'Scientist and Statesman : The Example of Henry Tizard', *Minerva*, **IV**, 2, Winter 1966, 202-213.

R.V.Jones, "Research Establishments', *Proc. of Royal Society, A*, **342**, April 1975, 481-491.

R.V.Jones, 'Lindemann beyond the laboratory', *Notes and records of the Royal Society*, **41**, 1987, 54-61.

R.V.Jones, 'Oxford Physics in Transition', in R.Williamson (ed), *The Making of Physicists*, (Bristol), 1987.

T.C.Keeley, 'Rt. Hon. Viscount Cherwell', Yearbook of Physical Society, 1958, 79-82.

T.C.Keeley 1894-1988, Obituary in *Times*, 27 December 1988.

L Kennett, *The First Air war 1914-1918*, (New York : Free Press [Macmillan]), 1992.

P S Kerr, 'RAE Rudder Gyro Control Installed on Imperial Airways H-P Hamilton', RAE Report H-1037, December 1925, filed Farnborough Library.

G.McKerrow and L.E.Fairburn, 'Bomb Sights and Methods of Bombing', Chapters 1-12, 19 February 1919, Tizard Papers, Ref HTT 5/150.

G.McKerrow, 'Summary of Orfordness Reports N4, N5 and N6 : Performance Tests on Gyroscopic Indicators, 10 March 1919, Tizard Papers, Ref HTT 5/150.

G.Kinsey, *Orfordness*, (Lavenham, Suffolk : Terence Dalton), 1981.

G.Kinsey, *Martlesham Heath*, (Lavenham, Suffolk : Terence Dalton), 1983.

A.R.Kingsford, *Night Raiders of the Air*, (London : Greenhill Books), 1930 (Reprinted 1988).

P.W.Kingsford, *F.W.Lanchester*, (London : Arnold), 1960.

B.Latour and S.Woolgar, *Laboratory Life. The Construction of Scientific Facts*, (London : SAGE), 1979 and 1988.

B.Latour *Science in Action. How to follow scientists and engineers through society*, (Milton Keynes : Open University Press), 1987.

Alice Lee and R.S.Capon, *Preliminary Report on the Forced Oscillations of Aircraft Compasses*, R&M 874, (HMSO), July 1920.

H.Levy, 'From Model to Full Scale in Aeronautics', Aeronautical Journal, **XXIII**, 1919, 326-345.

P.H.Liddle, *The Airman's War*, (Poole, Dorset : Blandford Press), 1987.

F.A.Lindemann, *The Northerly Turning Error of the Magnetic Compass*, Part 1 of R&M 295, (HMSO), February 1917.

F.A.Lindemann, *Experiments with Diving Bomb Sight*, Farnborough Report H-626, 21 June 1917, Cherwell Papers, Ref C 19/1.

F.A.Lindemann, *Note on Recording Accelerometer for Measuring Stress on Aeroplanes*, R&M 376, (HMSO), July 1917.

F.A.Lindemann, *Turn Indicators for Aeroplanes*, R&M 525, (HMSO), December 1917.

F.A.Lindemann, *RAE Mk III Rangefinder*, Report T-1055, December 1917, PRO/AIR 2/58/AB 284/50.

F.A.Lindemann and H.Glauert, *The Investigation of the Spin of an Aeroplane*, R&M 618, (HMSO), June 1919.

F.A.Lindemann,*Control of Aircraft by Light*, 1925, PRO/AIR 2/301/S 25343,

F.A.Lindemann, Reminiscence published in *Fifty Years at Farnborough*, HMSO, 1955.

F.A.Lindemann 1881-1956, *Biographical Memoirs of Fellows of the Royal Society*, **4**, 1958, 45-71, by G.P.Thomson (Sir) and W.S.Farren (Sir).

Alys Keith-Lucas (ed, and wife of), *Keith Lucas* (Cambridge : Heffer), 1932.

K.Lucas, *Space Damped Pendulum*,' Advisory Committee Report T-361, February 1915, PRO/DSIR 23/361.

K.Lucas, *The Error of Compasses on Aeroplanes*, Part 3 of R&M 238, and *On a New Type of Compass for use on Aeroplanes*, Part 4 of R&M 238, (HMSO), April 1915.

K.Lucas, *Oscillations of an Aeroplane in Flight and their Effect on the Accuracy of Bomb Dropping*, R&M 213, (HMSO), February 1916.

K.Lucas 1879-1916', Obituary, *Proceedings of the Royal Society* 'A', **XCV**, 1918-1919, i-xi, by H.Darwin and W.M.Bayliss.

A.McConnell, *No Sea too Deep*, (Bristol : Hilgar), 1982.

A.McConnell, *Instrument Makers to the World : The History of Cooke, Troughton and Simms*, (York : William Sessions),1992.

A.McConnell, 'The Aneroid Barometer comes to London', *Bulletin of the Scientific Instrument Society*, **38**,September 1993, 20-22, and Chapter 3 of her forthcoming book on J.J.Hicks.

D.MacKenzie, *Inventing Accuracy. A Historical Sociology of Nuclear Missile Guidance*, (Cambridge Mass. and London: M.I.T. Press), 1990.

J.H.Mackie, 'Report on Aperiodic Compasses', Orfordness Report, 10 September 1918, Tizard Papers, Ref HTT 5/150.

R.MacLeod (ed.), *Government and Expertise. Specialist, administrators and professionals, 1860-1919*, (Cambridge University Press), 1988.

R.MacLeod and K.Andrews, 'The Origins of the D.S.I.R.: Reflections on Ideas and Men', *Public Administration*, **48**, 1970, 23-48.

R.MacLeod and K.Andrews, Scientific Advice in the War at Sea, 1915-1917: The Board of Invention and Research', *Journal of Contemporary history*, **6**, 1971, 3-40.

R.MacLeod and K.MacLeod, 'The Contradictions of Professionalism: Scientists, Trade Unionism and the First World War', *Social Studies of Science*, **9**, 1979, 1-32.

H.R.A.Mallock 1851-1933, *Obituary Notices of Fellows of the Royal Society*, Vol 1932-1935, 95-100, by C.V.Boys.

Martlesham Heath Technical Staff, *Methods adopted for the Testing of Aeroplanes*, undated typescript, Tizard Papers, Ref HTT 5/149 and another copy dated February 1919 in R.H.Mayo papers, Ref MAYO 1/6, Science Museum Library.

P.Masefield, *To Ride the Storm*, (London : William Kimber), 1982.

J.C.Maxwell, *Scientific Papers*, **2**, (Cambridge University Press), 1890, 550.

H.Melville, *The Department of Scientific and Industrial Research*, (London : George Allen and Unwin), 1962.

K.Mendelssohn, *The World of Walther Nernst. The Rise and fall of German Science*, (London : Macmillan), 1973.

W.E.K.Middleton, *History of the Thermometer and its use in Meteorology*, (Baltimore : John Hopkins University Press), 1965.

W.E.K.Middleton, *History of the Barometer*, (Baltimore : John Hopkins University Press), 1966.

Ministry of Munitions, Tech. Dept. Aircraft Production, *Notes on flying through clouds in formation*, Report HB-300, August 1918, Tizard Papers, Ref HTT 5/81.

Ministry of Munitions, Tech. Dept. AircrAft production, *Bomb Sighting with Account of Equipment in use*, Publication H-636, November 1918, PRO/AIR 1/701/27/3/656.

Ministry of Munitions, 'Supply of Munitions, Part 1, Aircraft', *History of Ministry of Munitions*, **XII**, (HMSO), 1921.

Moon P.B. (1974): 'George Paget Thomson, 1892-1975', *Biographical Memoirs of Fellows of the Royal Society*, **23**, 1977, 529-556.

J.Morrell, 'Research in Physics at the Clarendon Laboratory, Oxford, 1919-1939', *Historical Studies in the Physical and Biological Sciences*, Berkley, **22**, Part 2, 1992.

R.Moseley, 'The Origins and Early Years of the National Physical Laboratory: A Chapter in the Pre-History of British Science Policy', *Minerva*, **16**, 1978, 222-250.

National Advisory Council for Aeronautics - Reports 1921.
Report 125, M.D.Hersey, 'General Classification of Instruments and Problems, Problems and Bibliography', 471-498.
Report 126, A.H.Mears, H.B.Henrickson and W.G.Brombacher, 'Altitude Instruments', Parts 1-4, 1921, 499-560.
Report 127, F.L.Hunt and H.O.Stears, 'Airspeed Indicators', 1921, 561-594.
Report 128, W.S.Franklin, H.H.Stillman, R.L.Sanford, J.A.C.Warner, R.C.Sylvander and W.Pounds, 'Directional Instruments', Parts 1-4, 1921.
Report 129, G.E.Washington, E.P.Muller, R.M.Wilheim, H.N.Eaton and J.A.C.Warner, 'Power Plant Instruments', Parts 1- 5, 1921.

Negretti and Zambra, *Centenary 1950-1950*, (London : N&Z), 1950.

R.A.Newton, Cmdr., *Aeronautical Navigation*, (London : Elliott Brothers), 1910.

No.8 Squadron (Members of), *Naval Eight : The History of No. 8 Squadron RNAS*, (London : Signal Press), 1931.

A.Ogilvie, Report 102, *Aircraft Instruments*, Report 102, Technical Reports of Ogilvie and Partners Ltd., Vol.1, 1919 -1925, 7 March 1919, copy at Royal Aeronautical Society.

M.O'Gorman, *Experiments with Full Scale Flying Machines*, R&M 59, (HMSO), November 1911.

M.O'Gorman, 'Stability Devices for Aeroplanes', *Engineering*, 31 January 1913, 166-168.

M.O'Gorman and E.T.Busk, *Velocity of the air in the neighbourhood of the tail plane of the Tractor Biplane BE 2*, R&M 132, (HMSO), April 1914.

M.O'Gorman and E.T.Busk, *Lateral Stability*, R&M 133, (HMSO), April 1914.

M.O'Gorman, *Report on Precautions taken as to the Strength of Details on the BE Aeroplane*, R&M 127, (HMSO), May 1914.

T.Orde-Lees, 'Saving Life in Air Wrecks', *Aeronautical Journal*, **XXV**, July 1921, 317-332.

E.H.J.Pallett, *Aircraft Instruments*, (London : Pitman), editions 1972-1993.

J.R.Pannell, *Calibration of Tube Anemometers at High Velocity*, R&M 237, (HMSO), February 1916.

J.R.Pannell and R.Jones, *The Design of a Sensitive Yawmeter*, R&M 445, (HMSO), May 1918.

J.R.Pannell, ed. R.A.Frazer, *The Measurement of Fluid Pressure and Velocity*, (London : Arnold), 1924.

M.Paris, *Winged Warfare - The Literature and Theory of Aerial Warfare in Britain 1958-1917*, (Manchester University Press), 1992.

M.Pattison, 'Science, Inventors and the Military in Britain 1914-19 : The Munitions Inventions Department', *Social Studies of Science*, **13**, 4, 1983.

M.Pattison, 'Scientists, Government and Invention : The Experience of the Inventions Boards, 1915-1918', Chapter 7 in P.H.Liddle (ed.), *Home Fires and Foreign Fields, British Social and Military Experience in the First World War*, (London : Brassey's Defence Publications), 1985.

H.W.Paul, *From Knowledge to Power : The Rise of the Science Empire in France 1860-1939*, (Cambridge University Press), 1985.

H.Penrose, *British Aviation : The Pioneering Years 1903-1914*, (London : Putnam), 1967.

H.Penrose, *British Aviation - The Great War and the Armistice*, (London : Putnam), 1969.

J.E.Petavel, 'Engineering and Science during the War', *Engineering*, **II**, 2 September 1919, 350-351.

V.Phillips, *Waveforms : A History of Early Oscillography*, (Bristol : Hilgar), 1987.

D.H.Pincent, *Equations of Motion of Magnetic Compass*, Part 2 of R&M 295, (HMSO), February 1917.

A.F.C.Pollard, *The Kinematical Design of Couplings in Instrument Mechanisms*, (London : Adam Hilgar), 1929.

J.B.Poole and K.Andrews, *The Government of Science in Britain*, (London : Weidenfelt & Nicolson), 1972.

B.D.Powers, *Strategy without Slide Rule : British Air Strategy, 1914 1918*, (London : Croom Helm), 1976.

D.J. de S.Price, 'Of Sealing Wax and String', *Natural History*, **93**, 1 January 1984, 49-56.

N.A.Price & C.Robson, *Bibliography - Flight Instruments and Displays 1903 1976*, RID 1551, Smiths Aircraft Instruments, September 1976.

W.Rayleigh (Sir) & H.A.Jones, *The War In the Air : Being the Part played in the War by the Royal Air Force*, Six vols, (Oxford University Press), 1922-3.

W.J.Reader, *Architect of Air Power : Viscount Weir of Eastwood*, (London : Collins), 1968.

S.T.A.Richards, 'Some Handley Page Recollections', *Aeronautical Journal*, **70**, January 1966.

M. von Rohr (ed), *The Formation of Images in Optical Instruments*, (HMSO), 1920.

A.P.Rowe and H.E.Wimperis, *Some Characteristics of Aircraft Compasses*, R&M 735, (HMSO), March 1921.

A.P.Rowe,*The Northerly Turning Error of Compasses in Aircraft*, R&M 875, (HMSO), November 1921.

A.P.Rowe, 'Aerial Navigation', *Jnl. of Aeronautical Society*, **XXVII**, September 1923, 450-458.

Royal Aircraft Establishment, Farnborough,
Wing Channel Staff, *Some experiments on measurement of static pressure*, R&M 672, (HMSO), February 1920.
Laboratory of the Air : RAE Farnborough, (HMSO), 1948.
Fifty Years at Farnborough, (HMSO), 1955.

'Royal Aircraft Factory and the Industry', Editorial, *Flight*, 31 January 1914, 112-113.

Royal Aircraft Factory Staff, Farnborough,
SRAF, RAF Low Altitude Aimer, R&M 236, (HMSO). December 1915
Experimental Determination of the Slipstream behind the Airscrew of a Pusher, R&M 382, (HMSO), October 1916.
Report on Compass design, R&M 352, (HMSO), October 1917.
Experiments on the Rotation of a Propeller Slipstream in a Pusher Aeroplane, R&M 408, (HMSO), November 1917.
Exploration of the Airspeed on the Airscrew Slipstream of a Tractor Machine, R&M 438, (HMSO), November 1917.

Royal Commission for Awards to Inventors.
Claim by S.Smith and Sons for Clift Air Speed Indicator, PRO/T-173/File 442, 1919.
Claim by Gregory, Mathews, Wimperis and Argo for Drift and Course Setting Sight, PRO/T-173/File 534 and 711, 1920.
Claim by R.Bourdillon for CFS Bomb-sight, PRO/AIR 1/22/15/1/111, 1920-21.
Claim by R.Appleyard for Appleyard Ring, Height Dial, Height Indicator and Air Speed Indicator, PRO/AVIA 289, 1921.
Claim by British Wright Company for American use of Ogilvie Air Speed Indicator, PRO/T-173/File 73, 1923.
Claim by Professor J.G.Gray for Stabilising Gear, PRO/T-173/File 239 and 638, 1923.
Claim by H.E.Wimperis for American use of Drift and Course Setting Sight, PRO/T-173/File 536 and 823, 1923.
Claim by Batchelor for American use of Bomb Practice Mirror, PRO/T-173/File 108, 1923.
Claim by Professor Sir J.B.Henderson for Gyroscopic Turn Indicator, PRO/T-173/File 270 and 653, 1931.

A.L.Rawling, *The Theory of the Gyroscopic Compass and its Deviations*, (London : Macmillan), 1929

R.R.Rudall, 'Smiths : An Instrumental Success', *Farnborough 90 International, Society of British Aerospace Companies*, 1990, 64-5.

G.F.C.Searle and W.Cullimore, *Report on Measurement of Acceleration on Aeroplanes in Flight*, R&M 469, (HMSO), June 1918.

S.Shapin, 'History of Science and its Social Reconstructions', *History of Science*, 20, 1982, 157-211.

S.Shapin 'The Invisible Technician', *American Scientist*, **77**,1989, 554-563.

W.N.Shaw, *Manual of Meteorology*, Cambridge University Press, 1919.

F.Short and J.C.Dines, *Gust Research with the Royal Aircraft Factory's Tetranemograph*, R&M 144, (HMSO), October 1913.

M.Siberry, *Instruments of Flight*, (Newton Abbot : David and Charles), 1974.

R.W.Sloley, *Aircraft Instruments*, (London : Pitman), 1934. W.H.Coulthard, *Aircraft Instrument Design*, (London : Pitman), 1952.

G.L.Smith (RAE), *The Kite Balloon Recorder*, R&M 630, (HMSO), March 1918.

R.V.Southwell, H.Glauert, H.L.Stevens and W.D.Douglas (attributed to),*The Book of Aeron*, issued as an Internal Report in 1918 and reprinted in part, *Journal of Royal Aeronautical Society*, **70**, January 1966, 85-88.

R.V.Southwell 1888-1970', *Biographical Memoirs of Fellows of the Royal Society*, **18**, 1972, 549-565, by D.Christopherson (Sir).

T.E.Stanton, *Note on Lateral Extent of Maximum Velocity of Wind Gusts*, R&M56, (HMSO), March 1912.

T.E.Stanton, 'Resistance of Plane Surfaces in a Uniform Current of Air', Proc. Inst. of Civil Engineers, **CLVI**, 1903, 78.

S.G.Starling, 'Equilibrium of Aeroplane Compass during a Turn', *Philosophical Magazine*, **XXXII**, Nov 1916, p 461.

S.G.Starling, 'Aeroplane Compasses', *Transactions of Optical Society*, 1917, 221-236.

H.L.Stevens, 'Early Days at the Royal Aircraft Factory - 1914 Onwards', *Jnl. of Royal Aeronautical Society*, **70**, January 1966, 92-94.

C.J.Stewart, 'Modern Developments in aircraft Instruments', *Aeronautical Journal*, **XXXII**, June 1928, 425-481.

C.J.Stewart, *Aircraft Instruments*, (London : Chapman & Halls), 1930.

J.W.Strutt 1842-1919, *Proceedings of the Royal Society 'A'*, **CXIII**, 1920, i-l, by A Schuster.

J.Sweetman, *Strategic Bombing and the Origins of the Royal Air Force*, PhD Thesis, Kings College, University of London,1983.

T.Sumida, *The Pollen Papers*, (London : Allen and Unwin), 1984.

T.Sumida, *In Defence of Naval Supremacy - Finance, Technology and British Naval Policy 1889 1914*, (Boston : Unwin Hyman), 1989.

R.C.Sutcliffe and A.C.Best, 'Ernest Gold -1881-1976', *Biographical Memoirs of Fellows of the Royal Society*, **23**, 1977, 115-131.

J.Terraine, *White Heat : The New Warfare 1914-18*, (London : Sidgewick and Jackson), 1982.

G.I.Taylor, *Accuracy with which the Temperature Error in determining Heights by the Barometer may be corrected*, R&M 239, (HMSO), December 1915.

G.I.Taylor, *Apparatus to measure the pressure distribution over the wing of an aeroplane in flight*, R&M 287, (HMSO), October 1916.

G.I.Taylor, 'Scientific Methods in Aeronautics', *Aeronautical Journal*, **XXV**, September 1921, 474-491.

G.I.Taylor, 'When Aeronautical Science was Young', *Journal of Royal Aeronautical Society*, **70**, January 1966, 108-112.

G.I.Taylor 1886-1975, *Biographical Memoirs of Fellows of the Royal Society*, **22**, 1976, 565-633, by G.K.Batchelor.

G.P.Thomson 1892-1975, *Biographical Memoirs of Fellows of the Royal Society*, **22**, 1976

A.P.Thurston, 'The Measurement of Air Speed', *Aeronautical Journal*, **18**, July 1914, 246-71.

H.T.Tizard (Aeroplane Testing Squadron), *Baro-Thermograph for use on Aeroplanes*, R&M 295, (HMSO), October 1916.

H.T.Tizard (Aeroplane Testing Squadron), *Petrol Flow Meter for use on Aeroplanes*, R&M 295, (HMSO), November 1916.

H.T.Tizard (Aeroplane Testing Squadron), *Notes on a Rate of Climb Indicator for use on Aeroplanes*, R&M 310, (HMSO), January 1917.

H.T.Tizard, *Electric Timing Apparatus in use on the Speed Course at Aeroplane Experimental Station, Martlesham Heath*, R&M 558, (HMSO), October 1918

H.T.Tizard, *Methods of Measuring Aircraft Performance*, Aeronautical Journal, **XXI**, April 1917, 108-122.

T.E.Thorpe 1845-1925, *Proceedings of the Royal Society 'A'*, **CIX**, 1925, xviii-xxiv.

F.Tymms, 'Practical Navigation for Aircraft',*Jnl. of Aeronautical Society*, **XXIX**, May 1925, 202-239.

I.Varcoe, 'Scientists and organised research in Great Britain, 1914-1916; The Early History of the D.S.I.R.', *Minerva*, **8**, 1970, 192-217.

P.B.Walker, *Early Aviation at Farnborough, Vol 2, The First Aeroplane*, (London : Macdonald), 1974.

H.C.Watts, 'H.C.Watts' (Admiralty Air Department, *Jnl. of Royal Aeronautical Society*, **70**, January 1966, 68.

P.V.H.Weems, *Air Navigation*, (London : McGraw Hill), 1931 and revised and edited by H.A.Hughes and P.F.Everitt in The British Empire Edition, 1936.

C.Weizmann, *Trial and Error : Autobiography of Chaim Weizmann*, (London), 1950.

G.Werskey *The Invisible College: The Collective Biography of British Scientists and Socialists of the 1930's*, (London: Free Association Books), 1978.

R.S.Whipple, 'The Design and Construction of Scientific Instruments', *Trans.Optical Society*, **XXII**, 1920-21, 35-52..

T.N.Whitehead, *The Design and Use of Instruments and Accurate Mechanisms*, (New York : Dover Publications), 1934 (reprinted 1954).

E.B.Williams & W.J.V.Branch, *A Short History of Navigation*, (School of Navigation, Southampton University, Weems System of Navigation, Maryland), 1942.

W.Ellis Williams, 'Pressure Distribution over an Aeroplane Wing in Flight', *Aeronautical Journal*, **XVIII**, October 1914, 319-323.

H.E.Wimperis, *Application of Power to Road Transport*, (London : Constable), 1913.

H.E.Wimperis, 'Air Navigation', *Aeronautical Journal*, **XXIII**, August 1919, 445-468.

H.E.Wimperis, *Primer on Air Navigation*, (London : Constable), 1920.

H.E.Wimperis, *Forced Vibrations in Aeroplane Instruments*, R&M 685, (HMSO), April 1920.

H.E.Wimperis and A.P.Rowe, *Some Characteristics of Aircraft Compasses*, R&M 735, (HMSO), March 1921.

H.E.Wimperis, *Tests on Improved Models of Aircraft Compass*, R&M 868, (HMSO), December 1922.

H.E.Wimperis, 'Some Recent Developments in Aircraft Instruments', *Aeronautical Journal*, **XXVIII**, January 1924, 5-34.

H E Wimperis, "Scientific Instruments and Aeronautics", *Jnl. of Scientific Instruments*, **9**, November 1932, 337-41.

S.F.Wise, *Canadian Airmen and the First World War*,(Toronto University Press), 1980.

R.McKinnon Wood, 'Aerodynamic Research', in R.T.Glazebrook, *Dictionary of Applied Physics*, **5**, Aeronautics, 1923, 1-19.

R.McKinnon Wood, 'Recollections 1914-1934' (Farnborough), *Jnl. of Royal Aeronautical Society*, **70**, January 1966, 89-90.

M.D.Wright, *Most Probable Position*, (Kansas University Press), 1972.

BIBL
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