

THE APPLICATION OF THE SUSPENDED GYRO-THEODOLITE ^{IN} ~~TO~~ MINING

by

R. C. H. Smith, B.Sc. F.R.G.S.

March, 1980

A Thesis submitted for the Degree of Doctor of Philosophy
of the University of London and for the Diploma of
Membership of the Imperial College.

Department of Mineral Resources Engineering,
Royal School of Mines,
Imperial College,
London, S.W.7.

ABSTRACT

This thesis contains the results of five years of research into accurate orientation using Gyroscopic methods with a bias towards use within the Mining Industry. Several standard models of gyro-theodolite are examined plus one important modification to the Wild G.A.K.-1.

The three basic methods of reduction technique, namely Amplitude, Timing and Transit are evaluated comprehensively for repeatability and for ease of working. Reduction formulae used are those developed at the Royal School of Mines during the research period and results obtained are from the clamped observing mode. With the advent of the micrometer modification to the Wild G.A.K.-1 the simple Amplitude method has been shown to be as accurate as other reduction techniques, and for the first time in this country a method of obtaining bearings using times alone, has been evaluated.

Accuracy obtained from the three methods using the Royal School of Mines procedure, the modified Wild G.A.K.-1 mounted on a T-2 with a standard wooden tripod have ranged between $\pm 4''$ to $\pm 7''$ of arc for one observation. The ranking of the methods as indicated by several series of trials being Amplitude, Timing and finally Transit; although statistically it is difficult to separate them.

Investigations into various internal and external factors which may effect accurate gyro observation are discussed and suggestions are made as to the cause of such factors and their possible eradication. In this respect important discoveries have been made

linking the behaviour of the gyro in the Non Spin and Power Spin Modes.

The concept of applying a correction for tape zero in suspended gyro systems is carefully analysed and is shown in the majority of field observations to improve results.

Finally application of gyro orientation to offshore oil and gas instalations are discussed.

ACKNOWLEDGEMENTS

The author would like to acknowledge the help and assistance received from the personnel of Wild (UK), especially Messrs. Simpson, Snelling, Davis and Schindale. Without their individual support the development of this project would have been difficult.

Thanks are also due to the manufacturers M.O.M. of Hungary for the loan of various models of Gyro-theodolite for evaluation purposes and to Clarksons, agents for Sokkisha, for their interest.

Within the mining industry thanks are given to many areas of the National Coal Board, Geevor Mining Co., Wheal Pendarves, Chartered Consolidated, Panasqueira and the Lonhro organisation for allowing access to underground workings at home or overseas, and for use of their own gyroscopic equipment for trials and for the time spent with their surveying staff.

Appreciation is also acknowledged for the assistance given by The British Army (Survey Regiment), The Norwegian Geodetic Survey, Gardline Surveys and U.D.I. Operations Limited in arranging offshore work.

In the Department of Mineral Resources Engineering the constant encouragement and help received from Dr. T.L. Thomas has been of particular value. As overall supervisor not only has he devoted many hours discussing the project as it developed but also has spent much time in proof reading this thesis.

With sadness the author would like to record his regret that the recent death of Professor R. Pryor of the Mining Section prevented him seeing the conclusion of a project to which he gave his full support and backing.

Finally, thanks are made to the authors' wife and children for their patience, understanding and encouragement during these past years.

INDEX

	<u>Pages</u>
Abstract	i - ii
Acknowledgements	iii - iv
Index	v - x
List of Figures	xi - xiv
List of Plates	xv
1. Introduction	1
2. Reason for Research	2
3. History of the Gyroscope	7
4. Equipment Examined	16
4.1 Introduction	16
4.2 Wild G.A.K.-1	17
4.2.1 Gyro Unit	17
4.2.2 Theodolite	19
4.2.2a Bridging Link	21
4.2.3 Converter Unit	22
4.2.4 Power Pack	23
4.2.5 Tripod	23
4.2.6 Accessories	23
4.2.7 Accuracy	23
4.3 M.O.M. GiB1	24
4.3.1 Gyro Unit	26
4.3.2 Theodolite	27
4.3.3 Generator/Converter Box	29
4.3.4 Power Pack	30
4.3.5 Tripod	30
4.3.6 Accessories	31
4.3.7 Accuracy	31
4.4 M.O.M. GiC11	32
4.4.1 Gyro Unit	33
4.4.2 Theodolite	34
4.4.3 Converter Unit	35
4.4.4 Power Pack	35
4.4.5 Tripod	36
4.4.6 Accessories	36
4.4.7 Accuracy	36

	<u>Pages</u>
5. Basic Principles relating to the Suspended Gyroscope	37
5.1 Introduction	37
5.2 Precession	37
5.3 Tape Torque	40
5.4 Damped Simple Harmonic Oscillation	41
5.5 Modes of Oscillation	42
5.5.1 Non Spin Mode	42
5.5.2 Tracking Mode	43
5.5.3 Clamped Mode	43
5.6 Finding the Centre of a Damped Simple Harmonic Oscillation	45
5.6.1 Schwendener's Transit	45
5.6.2 Thomas Amended Transit	46
5.6.3 Thomas New Transit	46
5.6.4 Amplitude	47
5.6.5 Thomas Timing	47
5.7 Variations of Instrument Constants with Latitude	48
6. Practical Use of a Gyro-Theodolite	50
6.1 Grid Systems	50
6.2 Convergence of Meridians	51
6.3 Underground Correlation	52
6.4 Taking Measurements from the Suspended Gyro-Theodolite	54
6.5 Determining the Centre of Oscillation	56
6.5.1 The Gyro Scale	56
6.5.2 Modes of Observation	57
6.5.3 Methods of Observation	58
6.5.3i a) Amplitude or b) Reversal Method	58
6.5.3ii Transit Method	63
6.5.3iii Timing Method	67
6.6 Tape Zero Position	69
7. Improvement to the Wild G.A.K.-1 Gyro Attachment	71
7.1 The Modification	71
7.2 Numbering of the Micrometer	74
7.3 Use of the Micrometer	76

	<u>Pages</u>
8 - 9 Factors which influence Accurate Gyroscopic Observations	78
8. External Factors	79
8.1 Magnetic Influences	79
8.2 Stability	80
8.3 Atmospheric Factors	81
8.4 Centring	84
8.5 Levelling	87
8.5.1 Dislevelment in the Direction of the Meridian	89
8.5.2 Dislevelment to the East and West of the Meridian	92
8.6 Technique of Observation	95
9. Internal Factors	96
9.1 Drift	96
9.1.1 Short Term Drift in the Spinning Mode	97
9.1.1a Primary Drift	97
9.1.1b Secondary Drift	101
9.1.1c Tertiary Drift	107
9.1.2 Long Term Drift in the Spinning Mode	111
9.1.2a Drift occurring over a period of weeks	111
9.1.2b Long Term Drift occurring over a period of Years	112
9.1.3 Short Term Drift in the Non Spinning Mode	115
9.1.3a Short Term Drift Before and After Extended Spin	119
9.1.4 Long Term Drift in the Non Spinning Mode	121
9.1.5 Stability of the Observed Drift Pattern	122
9.1.5a Stability during Power Spin	123
9.1.5b Stability during Non Spin	125
9.1.6 Cause of Such Drift	128
9.1.6.1 Short Term Drift	128
9.1.6.1a Primary Drift	128
9.1.6.1b Secondary Drift	129
9.1.6.1c Third and Fourth Phase Drift	136

	<u>Pages</u>
9.1.6.1d Non Spin Drift observed before and after Power Spin	138
9.1.6.2 Long Term Drift	139
9.1.7 The Practical Use of Detectable Drift	140
9.2 Voltage Stability	144
9.3 Internal Magnetism	148
9.4 Damping	151
9.4.1 Damping over 17 hours at 12 volt Stabilised Supply	152
9.4.2 Damping over 15 hours at 10 volt Stabilised Supply	154
9.4.3 Conclusion on Damping	156
9.5 General Remarks on Section 9	156
10. Experimental Trials	157
10.1 Amplitude and Modified Schwendener Transit 1974/75	158
10.1.1 Headings around True North	163
10.1.2 General Accuracy	166
10.1.3 Conclusion	167
10.2 Amplitude 1976/77	170
10.2.1 Results	172
10.2.2 Conclusions	172
10.3 Amplitude, New Transit and Timing 1978	174
10.3.1 Recording Information	177
10.3.2 Testing of the Hewlett Packard Timing System	177
10.3.3 Results of Comparison Trials	181
10.3.4 Analysis of Results	186
10.4 Special Trials - Amplitude, Transit and Timing - November 1978	187
10.4.1 Observational Techniques	188
10.4.2 Analysis of Results	189
10.4.2a Amplitude	190
10.4.2b Timing	190
10.4.2c Transit	194
10.4.3 Conclusion	194
10.4.4 Tape Zero Values	198
10.5 Stability Trials	200
10.5.1 Introduction	200
10.5.2 Results of Trials	201
10.5.3 Assessment of the Method	202

	<u>Pages</u>
10.6 Hungarian Equipment	203
10.6.1 Introduction	203
10.6.2 M.O.M. GiBl	204
10.6.2a Results and Analysis	206
10.6.2b Summary	207
10.6.3 M.O.M. GiBl1	211
11. Investigation into Accuracies of Times measured within the Timing Formulae	213
11.1 Accuracy Lose due to Variations in the Position of Timing Centre	213
11.2 Accuracy of Timing through a Constant Centre	216
11.3 Accuracy of Timing through the Selected Third Point	218
11.4 Autocorrelation of Times in Balanced Pairs within One Oscillation	220
11.4.1 Extended Spin	224
11.5 Influence of the Selected Third Timing Position	229
12. Tape Zero	232
12.1 Introduction	232
12.2 Application of a Tape Zero Correction to the R.S.M. Modified G.A.K.-1	233
12.3 Application to Other Modified G.A.K.-1 Machines	234
12.4 Tape Zero Correction as applied in Mining Conditions	237
12.5 Independant Tape Zero Evidence supplied by the N.C.B.	239
12.6 Conclusions	241
13. Experiments conducted on Offshore Structures	243
13.1 Steel Structures	244
13.2 Concrete Structures	246
13.2.1 Frigg Field Survey	246
13.2.2 Observations on C.D.P.1.	248
13.2.3 Results	251
13.2.4 Conclusion	253
14. Instrumental Aids	254
14.1 Introduction	254
14.2 Special Carrying Box	254
14.3 Base Plate Adaptor	255

	<u>Pages</u>
14.4 Bridge/Link Cover	256
14.5 Transportation Base	258
14.6 Booking Sheets	261
14.7 Electronic Stopwatch	261
15. Conclusions	264
15.1 Introduction	264
15.2 The Modified Wild G.A.K.-1	264
15.3 Damping	265
15.4 Comparison of Reduction Methods	266
15.5 Drift	267
15.6 Tape Zero	269
15.7 Original Aims of Research	270
Appendix I - Further Research	272
Appendix II- Suspended Gyro-Theodolites Today	273
References	275
Bibliography	278

LIST OF FIGURES

	<u>Page</u>
1. M.O.M. GiBl Gyro Scale Readings	28
2. M.O.M. GiBl Gyro Scale Readings	28
3. Precession of the Spin Axis around the Vertical Axis of the Suspended Gyro System	38
4. Convergence of Meridians	52
5. Example of Convergence of Meridians applied to a Gyro Bearing using Simplified Formulae	53
6. Precession of a Suspended Gyroscope - Plan View	55
7. Reversal Points of a Spinning Gyro	59
8. Example of a Reversal Point Booking : Ashanti Mine, Ghana	62
9. Timing and Reversal Points for the Transit Method	64
10. Timing Points for the Timing Method	68
11. Modified Wild G.A.K.-1	73
12. Reversal Points as shown of the Wild G.A.K.-1	75
13. Details of Weisbach Triangle	87
14. Diagram to illustrate the effect of Dislevelment on Pendulous Gyroscope	88
15. Example of Plate Bubble Calibration : Wild T-2	90
16. Typical Examples of Dislevelment in Meridian	91
17. The Effect of East/West Dislevelment on Non Spin Values	93
18. The Effect of East/West Dislevelment on Power Spin Values	94
19. Illustration of Primary Drift under Power Spin	98
20. Examples of Quasi-Secondary Harmonics from Observational Data (SPAR effect) - Williams and Belling 1967	102
21. Primary and Secondary Drift Patterns (Extended Spin)	104
22. Primary and Secondary Drift (Power Spin Heavy Damping of Oscillation Required)	106
23. Extended Spin GiBl (Halmos 1971)	109
24. Extended Spin - Wild G.A.K.-1 Power Supplied at 12 Volts	110
25. N.C.B. South Midlands G.A.K.-1 Attachment T-16 Theodolite Amplitude Results	113
26. K Factor Drift for Four Wild G.A.K.-1 Gyros - Hodges and Brown 1976/77	114

	<u>Page</u>
27. Extended Spin (Non Spin Mode) Wild G.A.K.-1	117
28. Non Spin - Tape Zero - Drift Extended Oscillation - Wild G.A.K.-1	118
29. Drift of Non Spin Tape Zero Values from Extended Spin Experiments	120
30. Individual Tape Zero Values N.C.B. South Midlands Gyro Attachment - T-16 Theodolite	122
31. Illustration of Change of Heading during Extended Power Spin	124
32. Power Spin Drift Patterns including Change of Heading	125
33. Composite Figure showing Non Spin (Tape Zero) and Power Spin Drift	127
34. Diagram to Illustrate the Result of any regular Rotational Movement of the Suspension Tape	131
35. Variation in Spin Axis Position	133
36. Position of Spin Axis during Extended Spin assuming Spin Axis Deviation	134
37. Plot of Battery Voltage Decay - Nickel Cadmium	135
38. Battery Decay during Extended Power Spin - Wild G.A.K.-1	137
39. The Effect of Voltage Changes during Extended Power Spin	146
40. Oscillation Times during "Changes in Voltage" Trials	147
41. Extended Power Spin - Wild G.A.K.-1 Power supplied at 10 volts	149
42. Tape Zero Values Recorded Around Full Circle	151
43. Oscillation Times during Extended Power Spin - Wild G.A.K.-1, Power Supplied at 12 volts	153
44. Oscillation Times during Power Spin - Wild G.A.K.-1 Power Supplied at 10 volts	155
45. Data Obtained from each Heading during Comparison Trials 1974-75	160
46. An Example of the Amplitude Method	162
47. An Example of the Transit Method	164
48. Cornish Observations - April 1975 (T-16 Theodolite)	165
49. Results from Standard G.A.K.-1 (Thomas 1974)	166
50. Amplitude Results - 1975 (T-16 Theodolite)	168
51. Transit Results - 1975 (T-16 Theodolite)	169
52. Cornish Observations - April 1976 (T-2 Theodolite)	172
53. Amplitude Results - 1976 (T-2 Theodolite)	173

	<u>Page</u>
54. Data Obtained from Each Heading during Composite Comparison Trials - 1978	176
55. Amplitude Results - 1978 (T-2 Theodolite)	182
56. Timing Results - 1978 (T-2 Theodolite)	183
57. New Transit Results - 1978 (T-2 Theodolite)	184
58. Summary of 1978 Comparison Trials	185
59. Amplitude Results (Special Trials 1978) - T-2 Theodolite	191
60a Timing Results (Special Trials 1978) - T-2 Theodolite	192
60b Timing Results (Special Trials 1978) - T-2 Theodolite	193
61a New Transit Results (Special Trials 1978) - T-2 Theodolite	195
61b New Transit Results (Special Trials 1978) - T-2 Theodolite	196
62. Comparison of the Three Reduction Methods (Special Trials 1978) T-2 Theodolite	197
63. Stability Trials - Cornwall 1977	202
64. Summary of Short Trials on M.O.M. G1B1 - 1977	208
65. Example of Amplitude Method - M.O.M. G1B1	209
66. Example of Transit Method - M.O.M. G1B1	210
67. Repeatability Results using M.O.M. G1C11	212
68. Layout of Experiments investigating Timing through Unstable Centres	214
69. Plotted Values from 'Unstable Centre' Experiment (Data in Figure 68)	215
70. Illustration of Error in Azimuth due to Error in Central Time	218
71. Error in Azimuth due to Error in Third Time	219
72. Data Obtained from each Heading during Non-Auto-correlation Trials	221
73. Diagrammatic Representation of Data used in Obtaining Results using Different Timing Centres	223
74. Data Obtained during Autocorrelation Trials	225
75. Extended Spin Autocorrelation Trials (First Series)	227
76. Extended Spin Autocorrelation Trials (Second Series)	228
77. Influence of the Position of the Third Timing Point - Timing Method	230
78. June 1976 N.C.B. Amplitude Results	236

	<u>Page</u>
79. The Effect of Tape Zero Values on Cornish Results	238
80. Layout of the Frigg Gas Field	248
81. Diagramatic Cross-Section at Working Level C.D.P.1.	251
82. Royal School of Mines Base Plate Adaptor	257
83. Cover for Wild G.A.K.-1 Bridge Unit	259
84. Royal School of Mines Transportation Support	260
85. Pocket Sizes Booking Sheets (Amplitude Method)	262
86. Block Schematic for Stopwatch	263
87. Summary of Accuracies Obtained in the Minimum Time Period	268
88. Approximate Rankings of Gyro Theodolites as Known Today	274

PLATES

	<u>Page</u>
1. The Complete Wild G.A.K.-1 Gyro Equipment	18
2. Three Pin Locating System in the "Bridge" of the Wild G.A.K.-1	21
3. The M.O.M. GiBl Gyro-Theodolite	24
4. Split Diagram showing Construction of the M.O.M. GiBl Gyro-Theodolite	25
5. The M.O.M. GiCl1 Gyro-Theodolite	32
6. An Underground Observation with the Royal School of Mines/Wild Modified G.A.K.-1	72
7. Hewlett Packard 55 Calculator - showing Timing Values in Register	178
8. Steel and Concrete Structures - Frigg Field	244
9. Concrete Structure CDPl - Frigg Field	247
10. Frigg Gas Field	249
11. Observing on the C.D.P.1 Platform	250
12. View of Survey Station on outer concrete wall of C.D.P.1.	252

1 - INTRODUCTION

This thesis has been prepared with the aim of setting out as clearly as possible a research programme which has spanned the period between 1974 and 1979.

In common with most proposed plans of study many ideas have become altered as work progressed and it was found that several subsidiary and extended areas of study were gradually revealed which merited time being spent on their investigation. The most obvious example of this concerns the deviation from the main link with mining problems to those in other fields.

In addition to laboratory work undertaken in the Department of Mineral Resources Engineering, Royal School of Mines, Imperial College, much time has been spent conducting field trials at various sites in the United Kingdom and Overseas.

The layout of this work has attempted to put all these pieces into a logical order which follows the development of ideas throughout the period.

2 - REASON FOR RESEARCH

This research project was conceived originally to investigate the methods and accuracies of transferring bearings between survey stations underground using gyroscopic equipment. In underground surveying one of the major causes of anxiety is the provision of accurate headings at the various working places. Unlike surface situations it is often difficult and sometimes impossible to check the accuracy of work by closing on other established control. In many cases the only check which can be made is to repeat correlation and traverse observations many times and even then there are still examples in the world where tunnelling from two opposite directions on the "same" heading and elevation have failed to meet or "hole through".

Conventional techniques for many years entailed:-

- a) Carrying bearings underground via a traverse along a drift directly from surface;
- b) Traversing underground between two previously connected shafts. Co-ordinates in both shafts having been plumbed from the surface.
- c) Transferring the bearing from surface using two or more weighted plumb wires. In this method it is assumed that the wires remain perpendicular throughout their length and therefore any bearing taken between them on the surface would be identical at depth.

These techniques have provided first class control for many years and are still being used with success in many areas. However, the various systems have their weaknesses. Method a) can only be

used in situations where there is a direct connection to the surface via a level or sloping drift and can only be checked by repeated observations until the development closes or holes through to another known point. Any advancement is therefore totally dependent on the accuracy obtained in preceding observations. In this situation the surveyor takes on the added responsibility for large amounts of capital expenditure in tunnelling on directions cantilevering out considerable distances from any known control.

Method b) is probably the easiest and initially should be the most accurate. However, this type of situation cannot arise during extension or development work as the system depends on the accurate knowledge of positions at two points between which normal traverse adjustments are made.

Method c) is the more usual system encountered in underground situations linked to the surface by shaft. There are, however, several disadvantages:-

- i) The wires which are manufactured usually of stressed steel rarely adopt a stationary position at depth. The normal situation being one where the weights on the lower end of the wires, although being heavily damped in buckets of water or light oil, rarely settle and the wires adopt a slow pendulum swinging motion. When observing at depth one must often spend a considerable time following the swing of each wire in order to determine the mean swing position. This swing rarely remains in one place and often gyrates gradually.
- ii) A considerable amount of time must be allowed for lowering the wires down a shaft in preparation for the survey and further time to allow the pendulous swinging of the weights to dampen sufficiently for normal observational purposes.

- iii) To ensure that the wires maintain their position in the shaft with minimum movement it is sometimes necessary to reduce the effect of any ventilation systems within the shaft and observing areas.
- iv) Even taking precautions as mentioned in iii), it is a known fact that in many cases the plane between the wires on surface and at underground locations differ.

As can be appreciated, mining is a business like most others where the prime motive is to produce a profit as reimbursement for investment and for providing further working capital. Lowering wires in a shaft and possibly cutting ventilation for many hours effectively closes the shaft as a normal access route and indirectly shuts down other working areas through lack of moving air. When shaft survey work is being carried out neither men, materials or broken rock can be raised or lowered. Wires within a shaft therefore have a direct economic effect on the normal working life of the mine. Consequently shaft survey work is generally planned well in advance and programmed for weekends or holiday periods to avoid such interruptions.

Accurate position and bearings are required for three main types of underground work:-

- a) Driving development tunnels from the base of a shaft into a given area.
- b) Driving a connection between two working areas or between two separate shafts or mines.
- c) Developing sub-surface shafts into a new area or as raises or winzes between different levels already in existence.

In b) and c) it is often advantageous to work from several ends at the same time and have the various faces advancing towards each other. Accurate determination of direction at these drilling positions is therefore of prime importance.

From 1960 there has been a steady introduction and at first cautious acceptance of gyro-theodolite derived bearings in mining situations. Initial work was carried out with the bulky machines described in Section 3 but the difficulty of movement and the high cost delayed their wide use. The Precision Indicator of the Meridian was successfully used in many mining areas throughout the world and was capable of giving accuracies of around $\pm 20''$ standard deviation for one result.

With the advance of gyro technology the size of equipment has been reduced considerably and accuracies improved. There are several alternative machines on the market today and many mining organisations have their own equipment.

Deriving a bearing underground by using a gyro-theodolite removes the problems of shaft accessibility as the equipment can be used to link any two points required. For example in several cases bearings have been established within crosscuts well away from the normal activity of the shaft and levels. Two or more survey stations are used and these become permanent bases from which conventional traverses can be linked.

Unfortunately for many years the repeatability of gyro bearings

were doubted and their main use in British Mines was to check bearings brought down by the methods outlined above.

Recently this decision has been changed and the gyro-theodolite is now widely used as a prime source of direction. Gyro-theodolite bearings are also being used extensively to strengthen normal traverse work. For example in situations described in method a) of the conventional techniques, the problem of cantilevering out from one known base can be alleviated by inserting check gyro bearings at regular intervals.

In 1974 the majority of gyro-theodolites available for mining organisations had quoted accuracies of around $\pm 20''$ of arc as a standard deviation for one observation. It was at this stage that an investigation into the various gyro designs led to the initiation of this research programme.

3 - HISTORY OF THE GYROSCOPE

It is widely assumed⁽¹⁾ that the basic gyroscopic principles were observed during very early Chinese culture periods, probably associated with the development of studies relating to the spinning top. The Chinese led the world in astronomical knowledge and application long before the birth of Christ and precise observations were made to determine the regular precession of the equinoxes. Although there are many early references to the spinning top the full development of mathematical theory did not occur until the nineteenth century. Earlier, work by Euler (1707 - 1783) had already established the basic dynamic equations of a rotating solid mass and this was supplemented by the works of Clairaut (1713 - 1765); later, Poisson (1781 - 1840), Jacobi (1804 - 1851) and Poincot, provided the final development of mathematical theory relating to the Rotating Elipsoid.

Bohnenberger is reputed to have produced between 1810 and 1813 his "Maschinchen", later known as the "Precession Machine", which demonstrated how a spinning mass could become stable in its axis direction and how the axis could be made to precess. This "Maschinchen" was later improved by Johnson, an American from Philadelphia, when in 1832 he produced his "Rotascope". There has been no recorded evidence of either the Maschinchen or Rotascope being used for actual field studies and the impression given is that the instruments were used merely to demonstrate the basic principles of a spinning mass in the laboratory. .

Unfortunately for many years there had been a lack of detailed information about Bohnenberger's original work and consequently little evidence to support the reputed existence of such equipment in the early 1800s. Eventually Lauf⁽²⁾ of South Africa made some exhaustive researches and discovered an article published in Annalen der Physik by Von Bohnenberger in 1819 - "Beschreibung einer Maschin welche die Gesetze der Undrehung der Erde um ihre Axe, und der Veranderum der Lage der Erdoxe zee erlautern dienst". (Description of a Machine which serves to Expound the Laws of the Spin of the Earth around its Axis and the change in the position of the Earth's Axis.)

Contained within this article was a reference to another article written by Poisson in 1813 "Memoire Sur un Cas particulier du Mouvement de rotation des Corps pesans". (A paper on a specific case of rotational movement of heavy bodies.) In this article Poisson refers to an instrument used by Bohnenberger in the Physics Department of the Polytechnic at Tubinger to illustrate the phenomenon of the precession of the equinoxes. This information therefore confirmed that such a machine was in existence prior to 1813. Bohnenberger's own article included a detailed description of his machine " it consists of a flattened round body rotating about an axis and mounted in three metal rings. By winding a silk thread around the axis of the round body and pulling it tightly, a rotary motion can be imparted." Bohnenberger also mentioned that when the rotating wheel reached a certain speed it was possible to move the frame of the machine in any direction "without altering the direction of the axis of rotation". He also

experimented with weights applied to the axis of spin in order to induce precession, and finally calculated that "the sun and moon supplied a gravitational couple which caused the spinning earth to precess with a period of more than 25,800 years."

The credit given for the first gyroscope is again not a clear cut issue. Historically, several scientists were either working on, or writing about, their own projects in this same field at roughly this same period of time. Two major candidates were Leon Foucault (1819 - 1868) and Edward Sang. Sang apparently suggested in a paper given in 1836 to the Royal Scottish Society of Arts that principles set out by Troughton in 1819 relating to a spinning top might well be used to demonstrate the rotation of the earth "While using Troughton's top an idea occurred to me that a similar principle might be applied to the exhibition of the rotation of the earth. Conceive a large flat wheel, poised on several axes all passing directly through its centre of gravity, and whose axis of motion is coincident with its principal axis of permanent rotation, to be put in a very rapid motion. The direction of its axis would then remain unchanged. But the directions of all surrounding objects varying, on account of the motion of the earth, it would result that the axis of the rotating wheel would appear to move more slowly". (Encyclopedia Britannica).

Unfortunately for Sang this paper, although delivered as stated in 1836, was not published by the Royal Scottish Society of Arts until 1856. The full implication of this delay was that between 1850 and 1852 Foucault carried out two significant experiments in

Paris. Initially he demonstrated most successfully, the rotation of the earth by using a long wire pendulum. The bob was constructed of a lead filled brass case which weighed 28 kg and swung at the end of a wire approximately 67 metres in length. Each swing of this giant pendulum was designed to score a ridge of soft sand, and successive swings over a long period of time showed by regular changes in the position of the score lines that the earth rotated with a period of about 24 hours. His second experiment in 1852 involved the construction of a gyroscope which comprised a wheel which rotated rapidly, mounted in gimbals and suspended on a vertical tape or thread. The experiment was designed to show that the spin axis would slowly precess around the vertical axis until the spin axis would become held in the plane of the meridian. This experiment however, was not a complete success mainly due to the inability of the equipment to maintain an adequate rotation of the spin axis for a period of sufficient length. The angular momentum being too small.

At the time there was considerable friction in various quarters with claim and counterclaim for developing the first gyroscope. Today it is generally acclaimed that the first gyroscopic machine had been produced by Bohnenberger with his "Maschinchen". Sang was the first to think of using such equipment to demonstrate the rotation of the earth, and Foucault was the first to modify, build and demonstrate practically such effects. Foucault is also credited with being the first to use the word 'Gyroscope' to describe a spinning wheel or rotor mounted in gimbal rings. The word Gyroscope was derived from the Greek: - Gyros meaning rotation and Skopein meaning to view. It is also accepted that Foucault built his gyroscope without any prior knowledge of Sang's earlier

predictions and suggestions. The major difference between Foucault's gyroscope and the instrument of Bohnenberger was that whereas Bohnenberger's equipment had three degrees of freedom, Foucault's had two degrees of freedom and a tape suspension.

Foucault's demonstration in 1852 marked the beginning of the application age of the gyroscope. Initially the ability to have an instrument capable of giving a constant meridian heading was of great interest to naval departments of various world powers. In 1856 a gyro compass was patented by Smythies but apart from a brief description of the instrument very little is known. A major problem of the time was to maintain a constant and sufficient speed of the spin axis and for this reason several scientists concentrated on the development of electrically driven instruments. Trouve is reputed to have been the first to develop such a machine and in 1865 produced an instrument in which the rotor of a direct current electric motor became the actual spinning mass of the gyro. This was followed in 1878 by Hopkin's version, also driven by an electric motor, with the gyro system based entirely on the Foucault design.

During 1884 the French Navy began to use a form of gyroscope to check their magnetic compass systems whilst their ships were being refitted in port. Today such equipment is known as a Gyro Direction Indicator.

Gyro compasses were of particular interest and between 1908 and 1922 several designs were produced. Gyro compass systems at sea were subjected to continual sea movement and much research was associated with minimising the effects of pitch and roll. In 1908

Herman Anschütz-Kamfe, working in Kiel, produced the first gyro compass which was acceptable for sea use. His design being based on the original ideas of Max Schuler. The first of these gyro compasses was used on a German warship in 1910 and the first Automatic Pilot for ships, also designed by Anschütz, was installed in a Danish passenger ship in 1916. The United States of America were represented by the Sperry instrument in 1911 and Great Britain by the Sperry-Brown partnership in 1916. Sperry had designed previously the first gyroscopic Automatic Pilot for aircraft in 1909. In 1922 Anschütz-Kamfe patented a twin gyro instrument, the gyros being placed one above the other. This machine was more stable than previous attempts based on a system incorporating three gyros.

The use of gyros in land situations began to appear much later and the first to be designed for determining underground directions was a product of the partnership of Anschütz and Breithaupt in 1924/25. This was a modification of the 1922 machine and in fact was far too heavy and bulky for mining work, and gave results of insufficient accuracy. A second machine was constructed in 1936-37 but again no records of this type of equipment being used in practical situations have been discovered. Although historically the Anschütz machines were the first to be designed specifically for underground orientation the credit for the first thoughts on the subject belong to Haussmann⁽³⁾ who in 1919 delivered a paper to the German Institute of Mine Surveyors describing a mining gyro compass.

The most significant advances in the design and application of

gyro systems for the mining environment were made at the Clausthal Mining Academy in Germany. Initially Jungwirth, an assistant of Professor Rellensmann, modified the basic 1922 Anschütz gyro compass. Power was supplied by compressed air and the suspension for the gyro system was a conducting liquid. The gyro compass was attached to the base of a Fennel theodolite and tested at Rammelsberg Mine. This "gyro-theodolite" was capable of giving accuracies of approximately 1 minute of arc but required many hours of patient observation for one result and had a major disadvantage in that the equipment was still very heavy and bulky. Other defects were susceptibility to magnetic fields and to fluctuations in the voltage of the power system.

Further research at Clausthal led to the development of the Fennel Ktl gyro-theodolite in 1959. This instrument differed from previous attempts in that the suspension was by means of a thin tape. The total weight had been reduced to 50 kg and the power supply came via a DC/AC power converter.

Later designs saw the gyro unit as a separate attachment which could be mounted on the standards of the theodolite above the telescope. Economically this made the product more attractive and versatile in that the theodolite could be used for routine work when not required as the base for the gyro system. Extreme accuracy during manufacture to guarantee constant alignment of theodolite and gyro when assembling for use as a gyro-theodolite is a prime requirement.

The Clausthal tape suspension method known as the "Rellensmann

system", was soon adopted by other manufacturers such as Wild (Switzerland), MOM (Hungary) and more recently Sokkisha (Japan) and today forms the basis of most gyro-theodolite designs.

Although the Rellensmann system with its tape suspension has been at the fore of gyro designs over the past twenty years there have been other systems available.

In 1958 Mueller of the Astro-space laboratories at Huntsville, Alabama, designed a gyro which used a solid quartz spherical rotor having a hydrostatic gas support. The rotation of the rotor was comparatively low, being only 6,000 revolutions per minute as opposed to the 20 - 24,000 revolutions per minute of the tape suspension systems. Little development has yet been made on this version for normal survey requirements.

British Aircraft Corporation designed and produced a floating suspension type of gyro-theodolite in 1960 which was mounted beneath a Hilger and Watts single second theodolite. This was known as the Precision Indicator of the Meridian and supported the spinning gyro, which was rigidly attached to the vertical axis of the theodolite under which it was mounted, by floating the mass in a suspension of light oil. One of the major differences between this system and the pendulous tape suspension system is that the gyro cannot oscillate and is restrained from doing so by a torque motor. This equipment was used extensively by military organisations but again was quite heavy and bulky. It has also been used in mining both in Canada and in Sweden - the mining application (i.e. $\pm 20''$) was developed at the Royal School of Mines.

Other designs of gyro under investigation today are those using gas bearings, as originally conceived by the Astronics Division of Lear Siegler in 1967 and now, 1979, this method is being developed by the British Aircraft Corporation with its Automatic Meridian Indicator; and those based on Laser techniques such as the Honeywell system of America.

4 - EQUIPMENT EXAMINED

4.1 INTRODUCTION

Although the bulk of this study has revolved around instruments marketed by Wild (U.K.) it was felt that every opportunity should be taken to gain familiarity with other gyroscopic equipment. However, there are relatively few manufacturers of gyroscopic equipment in the world because of the expense of purchasing and the obvious limitation on use (relatively speaking compared to other surveying equipment) different types of gyro-theodolites are rarely in active commercial competition. The more usual position is that once a manufacturer has made an inroad into the gyroscopic requirements of an area, other manufacturers find it difficult to enter the market and generally attempt to concentrate on their own separate regions. Prospective purchasers of sophisticated equipment, such as the gyro-theodolite, are often reluctant to deal with an unfamiliar organisation as invariably service and maintenance could involve lengthy delays, often requiring the return of the equipment to the country of manufacture.

Because of these commercial behaviour patterns although it is easy to obtain technical information and literature from manufacturers it is extremely difficult to obtain various designs of gyro-theodolite for examination and evaluation. Of the limited number of manufacturers it was possible to obtain assistance from two others apart from Wild (U.K.) who are the major suppliers of the U.K. market - these being M.O.M. (Hungarian Optical Works) of

Budapest, Hungary and Sokkisha Limited of Tokyo, Japan. Both of these companies offered equipment. M.O.M. agreeing to supply the GiC11 and the large GiB1, the latter being the first time this instrument had been released for evaluation in the U.K., and Sokkisha offered their new G.P.-1 of ± 20 second accuracy, comparable with the G.A.K.-1. Although excellent experience was gained from the Hungarian equipment, due to an unfortunate incident, when the Japanese machine was inadvertently badly damaged before it arrived at the R.S.M., use of the Sokkisha machine was withdrawn. It is hoped that access to this machine will be possible in the near future.

This section, therefore, describes the three models of gyro-theodolite used during the research period and forms a technical introduction to the results analysed in later sections.

4.2 WILD G.A.K.-1

The Wild G.A.K.-1 is an attachment type of gyro-theodolite and in the course of this study is compatible in design with the M.O.M. GiC machines. The equipment is formed of five separate units, namely: Gyro Unit, Theodolite, Converter Box, Power Pack and Tripod. Weight of the equipment above is 24.1 kg (53.1 lb), and when transported in protective cases 42 kg (92.6 lb) - see Plate 1. (If T-16 theodolite is used, deduct 0.9 kg (2 lb); if T-1A is used, deduct 0.6 kg (1.3 lb).)

4.2.1 Gyro Unit

The gyro unit is mounted above the theodolite on a specially

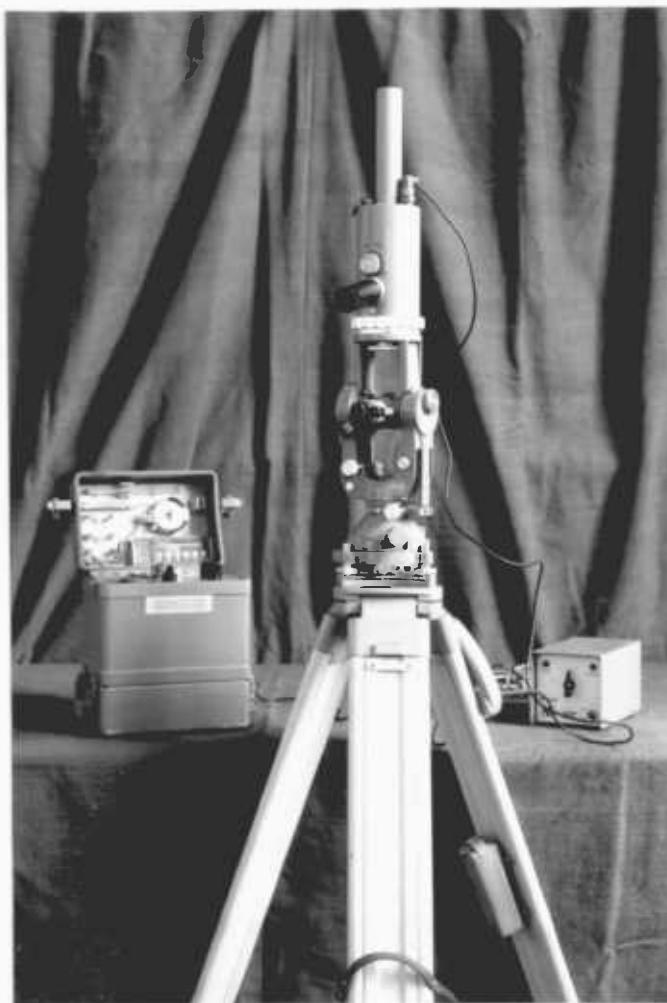


Plate 1 - The Complete Wild G.A.K.-1 Gyro Equipment

designed bridge linkage system. Within the housing is located an American Perkin-Elmer gyro suspended on a fine rectangular section metallic tape. This tape is anchored at the top of the chimney-like structure by a clamping system which cannot be reached during observations. Unlike the M.O.M. equipment described later, the position of the tape cannot be altered relative to the outer housing before undertaking an observation. Any adjustment of the tape is carried out in the laboratory after removing the protective metal housing.

Power is supplied through a socket mounted in the top of the unit and feeds the contained gyro rotor. This rotor spins at approximately 22,000 revolutions per minute under power spin and has the axis of spin aligned close to the direction indicated by the collimation axis of the theodolite below.

The gyro rotor system is protected from external magnetic forces by the introduction of a metal shield between the outer metallic housing and the rotor. In 1969 it was stated that this protective shield was composed, as would be expected, of Mu metal, however, in the standard G.A.K.-1 handbook this is referred to as mild steel. If the latter is correct it would appear to be of limited value in situations having variable magnetic fields - see Section 9.

The oscillation of the gyro spin axis is read on an illuminated glass scale using a magnified eyepiece. This scale has divisions at intervals of approximately 10 minutes of arc. Movements of the spin axis are shown by projecting an image from a collimator via a system of prisms towards the illuminated scale. A narrow light gap between a pair of grey shadows represents the position of the spin axis and will move slowly across the scale in sympathy with the oscillating axis of the gyro system. The extent of the scale is 5° of arc.

4.2.2 Theodolite

Wild recommended originally that the gyro attachment should be

mounted on their T-16 theodolite which is an instrument reading directly to one minute of arc and by estimation to one tenth of a minute or 6 seconds. With the accuracies quoted for the gyro attachment this combination was compatible; the theodolite being able to be read more accurately than the illuminated scale of the attachment. However, over the years prior to this period of research several gyro attachments were linked with T-1A and T-2 theodolites - 20 second and one second reading accuracies respectively. This was due either to using existing equipment held by the purchaser, or to the fact that an accurate theodolite was required for routine survey work at those times when the attachment was not being used.

Extensive trials conducted over the past few years, the results of which are discussed in detail within this thesis, would point to the more accurate T-2 theodolite being the more acceptable link today.

Each theodolite carries its own design of bridge to link the gyro unit and the theodolite. Unlike the comparable M.O.M. systems all Wild linkages allow the theodolite telescope to transit beneath the gyro unit. A useful aide in the case of the T-16 and T-1A where the angle shown is from one side of the plate and could suffer from errors due to circle eccentricity. This obviously does not happen in the T-2 model which displays a mean of angles 180° apart in the optical reader.

The T-16 and T-1A carry modifications to the horizontal plate tangent screw which has been extended to enable continuous tracking

of the oscillation to be made. This is of value for the Tracking or Reversal Point method of observation. Such a modification is unsuited to the T-2 theodolite and therefore the tracking method can rarely be used.

4.2.2a Bridging Link

As stated above each model of theodolite requires its own bridge design. Differences being confined to variations of the lengths of the two supporting legs which fit to the theodolite standards. The actual system of locating and locking the gyro unit and theodolite remains identical. Accurate location between the two sections is basically a simple three pin forced centring system - see Plate 2. At one time doubts were expressed as to the consistent accuracy of relocation but extensive trials have discovered no measurable discrepancies. The manufacturers claim relocation accuracy is within 2 seconds of arc.



Plate 2
Three Pin Locating System in the "Bridge" of the Wild G.A.K.-1

Once the three pins and sockets are located the gyro unit is lightly clamped into position using a threaded locking ring. Pressure is not required and could possibly distort the union.

4.2.3 Converter Unit

The Wild G.K.K.3 converter unit requires an input of 12 volts D.C. and transforms this into an output of three phase 115 volt A.C. with a frequency of 400 Hz. A general guide to the level of voltage is indicated on a crude dial which is sufficient to show if the power will maintain the speed of the gyro unit.

A separate input socket is provided for linking to an external power supply whilst a nickel cadmium power pack can be attached beneath the unit to provide an internal source. The connecting cable between converter and gyro unit is housed in a compartment adjacent to the main control panel. An individual switch controls both the internal and external power supply and a rheostat governs the brightness of illumination of the gyro scale.

The gyro is spun up by activating the off/run and brake switch. This switch is set at run and once the required speed has been achieved the dial immediately above the switch which showed red on commencing the spin will revert to white. Once the observation has been concluded the gyro may be stopped by switching off power or by setting this switch to 'brake' position.

The lid of the unit contains storage space for the various accessories.

4.2.4 Power Pack

The converter unit can be run from a fully charged 12 volt vehicle battery or from a nickel cadmium battery pack which clips conveniently beneath the converter box. A fully charged nickel cadmium pack gives an operating time of approximately 8 hours. Investigation into power supplies for the Wild G.A.K.-1 are contained in Section 9.

4.2.5 Tripod

Wild manufacture several designs of tripod and their equipment is fully interchangeable. However, to give the maximum possible stability using a standard wooden tripod, a heavy design is generally supplied, or requested. The tripod normally used is the GST 20, which is of conventional design with sliding wooden legs.

4.2.6 Accessories

All accessories required are contained in the lid of the converter box. These include spare bulbs and fuses, magnified gyro eyepiece, trailing hand stop watch and spare suspension tapes.

4.2.7 Accuracy

The accuracy quoted for the standard Wild G.A.K.-1 for many years has been ± 20 seconds of arc.

N.B. Description of the Modified Wild G.A.K.-1 appears in Section 7.

4.3 M.O.M. GiBl

The M.O.M. GiBl is a complete gyro-theodolite and therefore differs from the attachment types in that the theodolite is positioned above the gyro unit and is not detachable - see Plates 3 and 4. Weight of the equipment alone is approximately 42 kg (93 lb) and the necessary accessories add a further 16 kg (55 lb), making a total of 58 kg (128 lb). Wooden cases to house the various sections are supplied to ensure safety during transportation. It is impossible to move the GiBl without these protective cases and, therefore, to position the equipment on site requires the movement of four bulky units weighing in total 78 kg (172 lb) or approximately 1.5 cwt. This is significantly higher than the attachment types

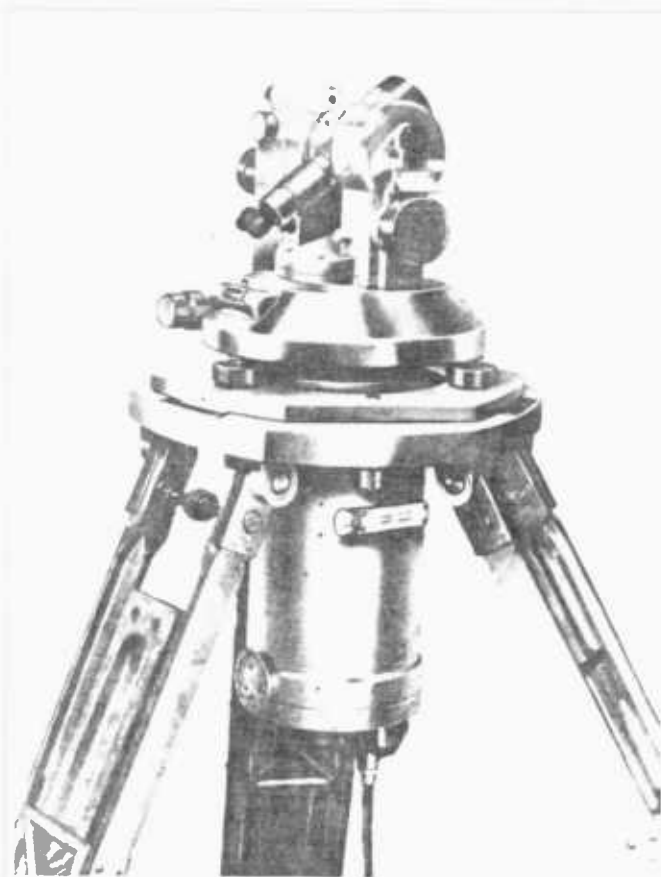


Plate 3 - The M.O.M. GiBl Gyro-Theodolite

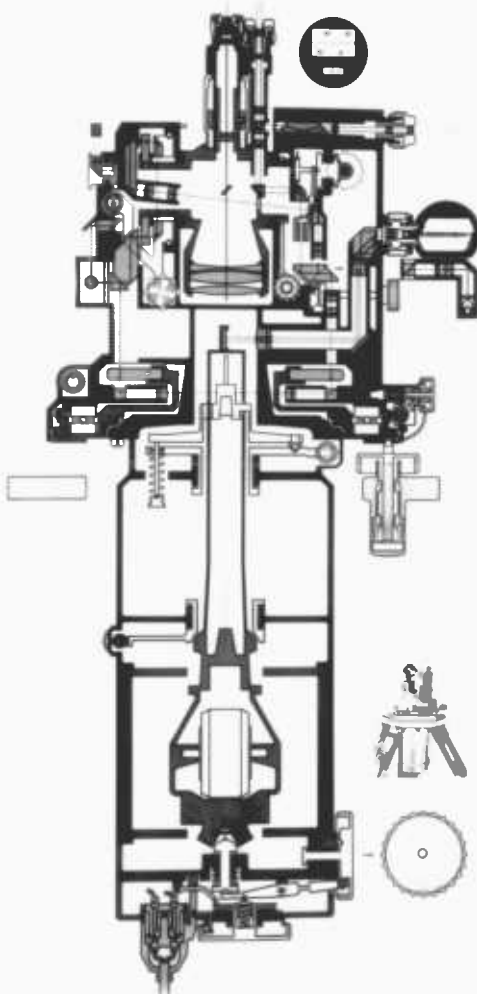


Plate 4 - Split Diagram Showing Construction of the
M.O.M. GiBl Gyro-Theodolite

and obviously limits general portability - especially in many mining situations. However, it is recognised that this additional weight assists in the overall stability of the equipment during operation.

The various sections of the GiBl are best described in the following order: Gyro Unit, Theodolite, Generator/Converter Unit, Power Pack, Tripod and finally, Accessories.

4.3.1 Gyro Unit

This unit contains a gyroscopic rotor of Russian design which spins in a sealed vacuum. The axis of the gyro is aligned approximately 90° to the collimation axis of the theodolite and the spinning mass is suspended by a conventional tape. This tape differs from that of other manufacturers in that it is of concave section and it also forms one of the power input leads to the rotor. A separate knob is placed near the top of the gyro outer casing to enable the operator to adjust the position of the tape relative to a zero mark before each individual observation. Tape zero correction is essential for all M.O.M. suspended gyroscopic equipment due presumably to the expected alteration in the molecular structure of the tape brought about by the effect of heat generated by the passage of electrical current through the suspension band. In the case of M.O.M. equipment the manufacturers recommend that the tape position is zeroed before an observation and then read immediately after completion of power spin observations and a correction applied.

The theodolite and gyro section are supplied as one unit and the potential problem of obtaining correct alignment of separate units as occurs in the attachment types does not exist. However, the GiBl contains a control to adjust the position of the outer case of the gyro section prior to each observation. This control brings the projected image of the collimator scale, on the gyro unit, into the field of view of the auto-collimator eyepiece contained in one of the standards of the theodolite. The position of the gyro axis varies between each set of observations. The

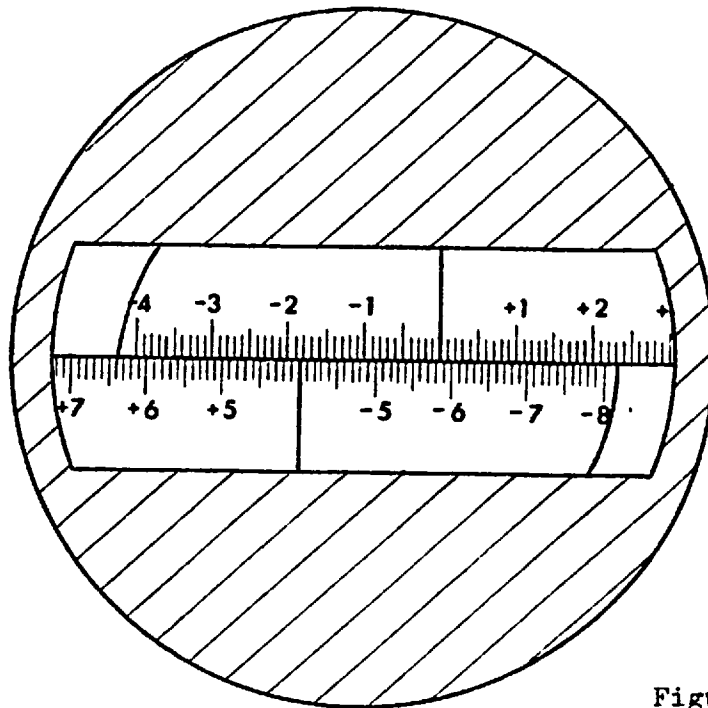
adjustment is made with the spin axis directed close to the north/south direction.

A vertically mounted hand wheel found at the base of the gyro unit is used to uncage the spinning mass once the required speed of rotation is reached.

4.3.2 Theodolite

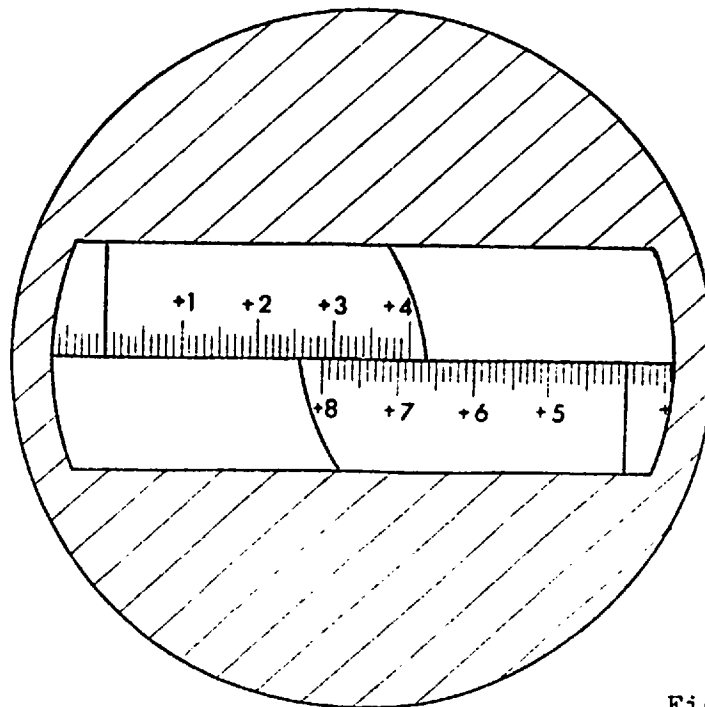
The theodolite used in the GiBl is the M.O.M. TeBl having an optical micrometer capable of reading horizontal and vertical angles to one second of arc. A link to the gyro unit below is arranged via an extension of the vertical axis.

To enable this theodolite to be used within the gyro-theodolite a small modification has been incorporated in one of standards to introduce an autocollimation system as mentioned above. This system of prisms allows the swing of the gyro spin axis to be measured by watching the progress of two parts of an optically separated scale moving in apparently opposite directions. This scale, graduated from +80 to -80 is separated at +40/-40 - see Figures 1 and 2 - and is read at the reversal points when the moving sections come to a halt. If an oscillation has an amplitude of less than ± 40 divisions the line separating positive and negative values on the lower section of the scale is used as a point of reference to read values from the upper section. Figure 1 gives an example of this type where the whole units are read from the upper section and partial units estimated. Each whole unit on the scale is equivalent to 30 seconds of arc.



Scale Reading
-18.5

Figure 1



Scale Reading
+68.6

Figure 2

M.O.M. GiBl Gyro Scale Readings

In the case of amplitudes greater than ± 40 the extremities of the upper scale, either +40 or -40, are used as points of reference according to the position of the spin axis being either east or west of True North. Figure 2 shows a result of this nature.

The above reading system allows the Amplitude method to be used with more accuracy than could be achieved with a standard Wild G.A.K.-1 or other models of M.O.M. manufacture apart from the GiBs simply because of the smaller scale unit value.

If the Transit system is used with the GiB1, times are recorded when the split scales reach a position where the 0 point of the upper scale section coincides with the line separating positive and negative values above 40 divisions on the lower section. Reversal points are observed as described previously by estimation within a scale division.

The autocollimator is read by placing the telescope of the theodolite in a vertical downward looking position. Angular values from theodolite scales are read using a conventional optical reader mounted adjacent to the telescope.

4.3.3 Generator/Converter Box

The converter box requires an input of 12 volts (± 1 volt) D.C. and will supply the gyro unit with three phase current at 3 x 50.5 volts (± 0.5 volt). A heating element, fitted within the control box is governed by a thermostat. This heating system can be switched

on manually when outside temperatures fall below 0° centigrade.

Spinning of the gyro takes between two and four minutes according to outside temperature conditions and the state of the power pack. After reaching the required speed the gyro unit can then be uncaged for observation purposes.

In addition to heating controls the converter box carries gauges for monitoring input and output currents during operation, and switches for starting and braking the gyro motor, and for governing illumination within the reading system of the theodolite and within the control box.

4.3.4 Power Pack

It is stated that a normal 12 volt car battery is sufficient to supply power to the generator and converter unit but if temperatures fall below 0° centigrade it is recommended that a battery with a minimum capacity of 40 ampere hours should be used.

Nickel cadmium power packs are also suggested for use in temperatures higher than 0° centigrade but in the model loaned for evaluation purposes these were not supplied.

4.3.5 Tripod

The tripod weighs around 8 kg (17.6 lb) and has been designed specially for use with heavy equipment, being most robust and stable. Stability is assisted further by the inclusion of separate steel

pegs which can be driven beneath the tripod legs if setting up in weak ground.

4.3.6 Accessories

Included within the accessory case is a combined optical plummet and magnetic compass. When mounted on the tripod head the optical plummet can be used to centre the base plate either under or over a selected point. The magnetic compass serves to give an approximate heading for the first observations. Once the base plate has been centred and levelled and an approximate heading obtained the plummet/compass is detached carefully. The composite gyro unit and theodolite can then be placed in position on the base plate and should require a minimum of precise levelling, using the theodolite levelling screws, before observations can begin.

Other accessories include a comprehensive set of tools and instruments to assist in the routine maintenance of the equipment during normal use and the usual spare bulbs, fuses and connection cables.

The only difference between the GiB1 and GiB2 is that the latter has an automatic following device to eliminate the need for tracking. There is also an instrument fitted for timing.

4.3.7 Accuracy

The manufactures claim that the M.O.M. GiB1 machine is capable

of obtaining an accuracy of $\pm 3''$ of arc. However, for one determination the internal precision is quoted as $\pm 10''$ of arc.

4.4 M.O.M. GiC11

This instrument is the Hungarian equivalent to the Wild G.A.K.-1. It is an attachment type and the gyro unit is mounted above the observing theodolite - see Plate 5. Weight of the equipment including gyro unit, theodolite, converter box and tripod totals approximately 19 kg (42 lb) and when cased for transportation this is increased to approximately 35 kg (77 lb).

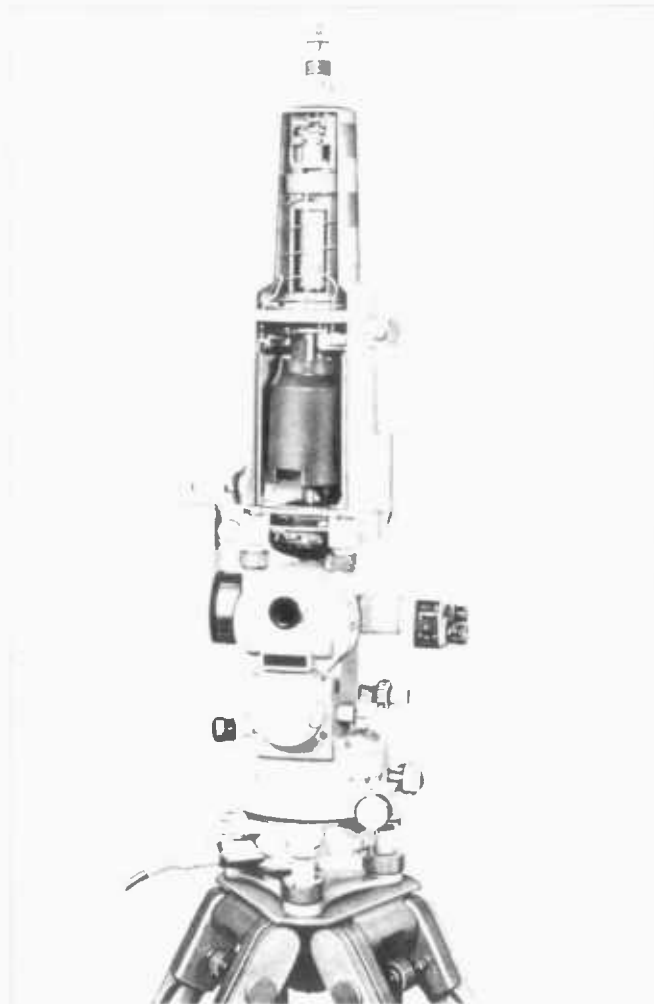


Plate 5 - The M.O.M. GiC11 Gyro-Theodolite

4.4.1 Gyro Unit

The gyro unit contains the gyroscope motor which rotates around its axis at 24,000 revolutions per minute when under power spin. This axis being aligned with the collimation axis of the theodolite. The unit is suspended by a tape or band as expected but in the unit examined this consisted of a rectangular section and not a concave section as described previously in the GiBl. As in the M.O.M. GiB machines it is imperative that a correction is made for any movement in the positions of the tape observed during each spin-up set. The position of the tape can again be zeroed by the operator prior to power spin by turning an adjusting knob placed near the top of the unit.

The gyro unit is attached to the theodolite by three rigid steel screws and can be mounted and secured with ease. These three screwed joints are sufficient to guarantee repeatability of the linkage over lengthy periods within the quoted accuracies of the equipment. M.O.M. have again provided an optical collimation link to the theodolite in order to ensure that correct alignment is achieved. A system of prisms projects an image of the crosshairs of a collimator mounted in the gyro unit into the telescope of the theodolite below. The operator checks to see if these collimator crosshairs coincide with the normal vertical crosshairs contained in the telescope of the theodolite. If adjustment is required a horizontal screw, mounted just below the gyro unit enables the operator to carefully rotate the unit until coincidence is obtained. This procedure should always be carried out before each observation.

As in the larger machines a vertically mounted hand wheel close to the base of the gyro unit is used to uncage the spinning gyro once it has reached the required number of revolutions per minute.

4.4.2 Theodolite

The single second optical micrometer TeBl theodolite again forms the basis for the M.O.M. gyro unit. However, in the attachment types the theodolite is placed below rather than above the spinning mass. Again slight modifications have been made to the basic theodolite design. The provision of an extended length slow motion horizontal plate tangent screw, for tracking purposes, is similar to that found in the GiBl but the mounting of the three attachment linkage screws to the upper part of the theodolite is different. These GiCl1 models have a similar scale reading system to that used by the Wild G.A.K.-1. The only difference being that the scale divisions are in units of 4 minutes of arc as against the 10 minutes of the G.A.K.-1.

A major difference between the GiCl and the later GiCl1 is the change in design of the telescope which incorporates a split coincidence sighting system. When in use an observed object appears with a lateral split approximately midway down the field of view; fine adjustment of the slow motion horizontal plate tangent screw will cause these two images to move either towards or away from each other. Careful manipulation of the tangent screw will ensure accurate coincidence and accuracy of sight. The reading system of the GiCl1 is similar to the GiBl in that the collimation

link from the gyro unit also carries an image of an optically split scale, similar to the GiBl system. This scale is divided into a total of 200 units, 100 on each section of the scale, and each unit represents approximately 2 minutes of arc. Use of the scales for reading reversal points and for timing has been described in 4.3.2.

4.4.3 Converter Unit

The converter unit supplied with the model under evaluation was type GiCl/E. This unit gives more accuracy to the complete system than an alternative unit coded as GiDl/l/E. The difference appears to be linked with operating frequency; the former operating at 410 c/s and the latter at 300 c/s. Apart from this the technical specifications are identical.

The unit is not as sophisticated as that supplied with the GiBl but contains the usual controls to check input and output voltages, to start and brake the gyro rotor, and to govern internal illumination of the converter unit and gyro-theodolite. Input for both units of this class is 24 volts D.C. and converts this into a three phase output of 34 volts. The gyro unit requires an operating current to be supplied by the converter unit. The supply voltage can have a maximum deviation of 1 volt in order to maintain accurate operations. During operations this output has a minimum value of 8 volts and during initial power spin of 17 volts.

4.4.4 Power Pack

Normal operations are carried out either with a heavy duty

vehicle battery or nickel cadmium cells.

4.4.5 Tripod

The tripod for the GiC models of gyro-theodolite is less robust than that manufactured specifically for the more accurate GiB instruments. There is a choice between the conventional sliding leg wooden tripod - type K-001 - as normally supplied with the single second TeBl theodolite, or a rigid leg wooden tripod - type K-019 - the latter weighing 4 kg and K-001 4.5 kg. For mining work it is assumed the sliding leg form would be used. In sympathy with other manufacturers M.O.M. have not marketed a special tripod for this class of equipment and have not introduced any modification to increase stability.

4.4.6 Accessories

The only significant accessory supplied with the GiC models is a magnetic compass which can be fitted to the theodolite to obtain an approximate heading for the first observation.

4.4.7 Accuracy

Manufacturers state that using three reversal points the GiC1 machine is capable of an accuracy of $\pm 30''$ if used with converter unit GiC1/E and $\pm 35''$ if used with converter unit GiD1/E. In similar circumstances the GiC11 models can obtain $\pm 25''$ and $\pm 30''$ respectively. If four reversal points are observed all these figures are improved by 5".

5 - BASIC PRINCIPLES RELATING TO THE SUSPENDED GYROSCOPE

5.1 INTRODUCTION

This brief section is included as a statement of existing fact as opposed to later work concerned with advances in known techniques and behaviour patterns. There are many text book references, often written from the theoretical point of view by physicists, which describe at length highly involved gyroscopic principles - see bibliography. These are ably supported by several eminent authors in the survey field, Bennet, Graferend, Gregerson/Katinas, Halmos, Lauf, Rellensmann, Thomas, Williams, etc., who have extracted those points pertinent to suspended gyro systems as used in gyroscopic equipment relating to survey tasks. This section, therefore, reiterates these points as an explanation of terminology and formulae used in subsequent sections.

5.2 PRECESSION

The rapidly spinning gyro unit in instruments of this type is the rotor of an induction motor. This unit is suspended on a thin tape which allows the axis of spin, around which the unit rotates, to be kept in an approximately horizontal plane by the force of gravity. The spinning motion of the earth attempts to attract the spin axis of the gyro into such a position where the axes of earth and gyro will be in the same plane.

The horizontal movement of the gyro spin axis towards the axis of earth rotation is known as precession and results in an

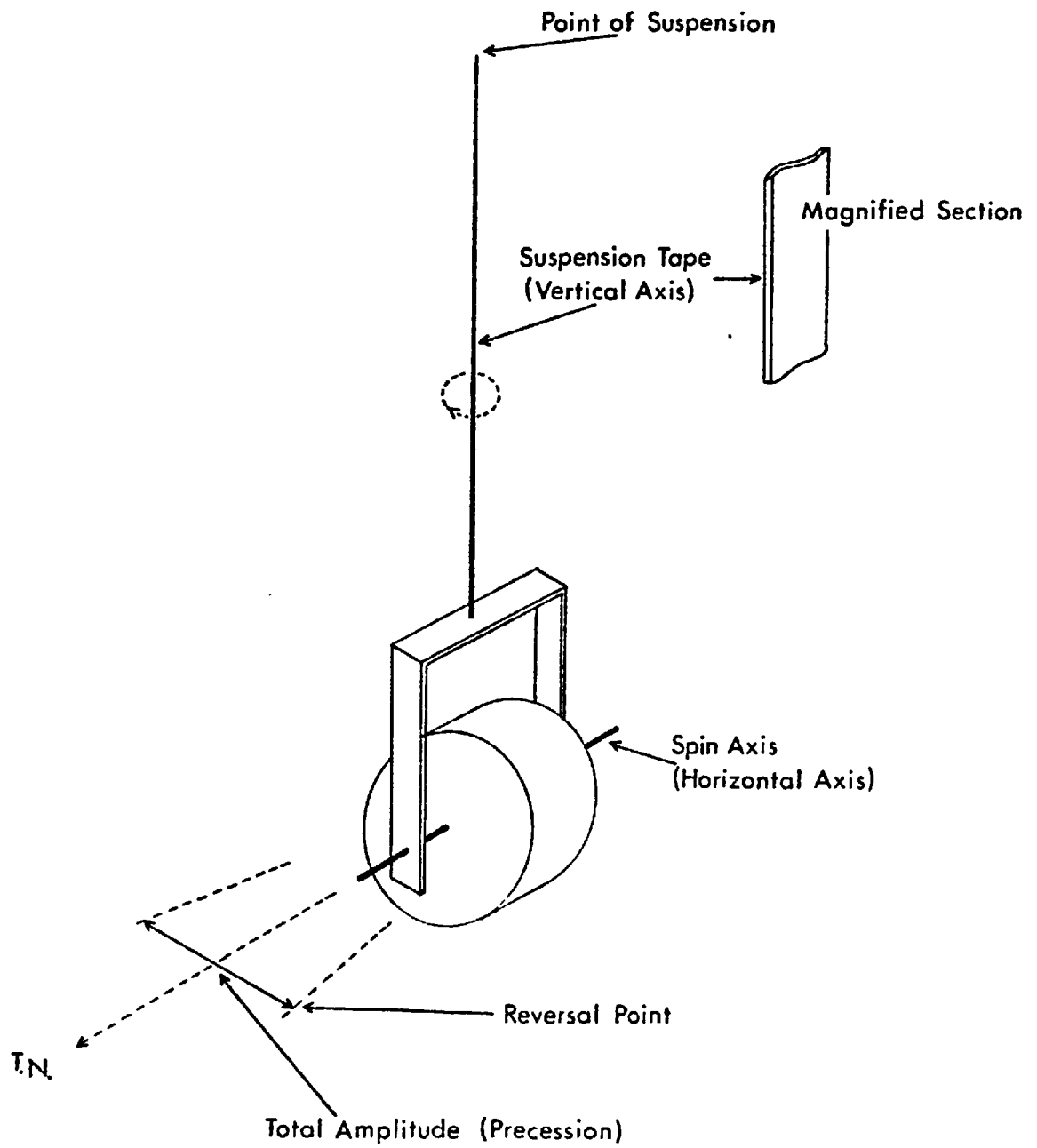


Figure 3 - Showing Precession of Spin Axis around the Vertical or Plumblne Axis of the Suspended Gyro System

oscillation around the vertical axis or plumbline of the gyro system - see Figure 3. The oscillation develops as the movement of the gyro spin axis over runs the meridian and is attracted from the opposite direction. Repetition of this movement leads to an oscillation or precession around the N/S meridian. The amplitude of such oscillations are slowly reduced through damping and if the spinning system were left undisturbed for a considerable length of time should eventually disappear leaving the spin axis aligned to True North.

The torque due to precession (P_A) is given by:

$$P_A = m H \Omega \cos \phi \sin \epsilon \quad (\text{Thomas}^{(4)})$$

where

m = Constant

H = Angular momentum of spinner

ϕ = Latitude

Ω = Rate of Earth Spin

$\Omega \cos \phi$ = Horizontal Component of Earth Spin

ϵ = Horizontal Angle between Spin Axis and North

Constants m , H , and Ω can be written as one constant k_0

Therefore, $P_A = k_0 \cos \phi \sin \epsilon$

or $P_A = k \epsilon$ if $k = k_0 \cos \phi$ and if ϵ remains within 5° of True North and is measured in radians.

5.3 TAPE TORQUE

Precession of the suspended gyro-theodolite, by definition in 5.2 necessitates a movement around the vertical axis of suspension. This axis is generally formed by a thin tape, of metallic structure often rectangular in section, clamped to the outer housing at the point of suspension. During the natural precession of the gyro unit it is obvious that if the theodolite is clamped the suspension tape will twist and untwist during the oscillation. Even in the unclamped mode it is doubtful whether twisting is completely avoided. Thomas ⁽⁴⁾ gives the formula

$$P_B = k_1 \epsilon_1 \quad \text{to describe suspension torque, where}$$

P_B = Torque due to tape

ϵ_1 = Horizontal angle of twist of the suspension system from its zero torque direction

k_1 = Constant

From the above it can be seen that although the oscillation of a suspended gyro unit around the vertical axis is induced by earth rotation, the fact that the suspension tape itself can be a source of additional torque must not be overlooked. Any formulae developed for the spinning gyro should therefore allow for the effect of the two torques.

It is now possible to define the torque ratio constant C :-

$$C = \frac{k_1}{k} = \frac{k_1}{k_0 \cos \phi}$$

5.4 DAMPED SIMPLE HARMONIC OSCILLATION

The oscillatory movement of the spin axis of the gyro unit around True North has always been regarded by all writers as a damped simple harmonic motion. Mathematical models based on this assumption have been developed from standard text book solutions of the differential equation of motion. This solution is as follows:-

$$\mathcal{E} = A e^{-\frac{1}{2}\mu t} \sin \frac{2\pi}{T} t$$

where $\mathcal{E} = 0$ when $t = 0$ and $\left(\frac{2\pi}{T}\right)t$ is in radians

$\mathcal{E}$ = Angular distance from centre of oscillation

μ = A damping factor

t = Time

T = Period of oscillation

A = Constant

In addition:

$$T = \frac{2\pi}{\sqrt{ak}} \quad (\text{Thomas}^{(4)})$$

where a = constant, ak = the torque causing the oscillation.

Experimental work on the damping of the Wild G.A.K.-1 is included in Section 9 and although the centre of the model tends to drift over a period of extended spin the fit between the theoretical and practical results have been excellent.

5.5 MODES OF OSCILLATION

There are three modes of oscillation of the suspended gyro-theodolite which will be referred to below. The object in all modes is to find the central point of the oscillation, however in the following it is assumed that the centre is known.

5.5.1 Non-Spin Mode

If the gyro unit is suspended without spinning the rotor the oscillation of the spin axis can be observed with the effect of precession removed. By preventing power spin the only torque affecting the oscillation should be tape torque, or P_B . Great care is taken by the manufacturers to align the centre of the non-spin oscillation close to the centre, or zero point of the gyro scale. However by observing non-spin oscillations it will be found that the centre of oscillations will vary - see Sections 10 and 12 - and will not coincide with the central scale marker. The scale value of the centre of a non-spin oscillation is known as the tape zero reading, and at the Royal School of Mines has been used as a correction to individual True North observations. This correction can be found as follows:

if δ = Centre of non-spin oscillation in gyro scale units
 C = Torque ratio constant
 S = Value of one scale division in angular measure
 y = Tape zero correction

as $y = -sc\delta$ (Thomas⁽⁴⁾)

and will affect the central position of oscillations in both of the other modes.

5.2.2 Tracking Mode

The tracking mode involves the gyro operator following the oscillation throughout by moving the theodolite around its vertical axis and taking readings from the horizontal circle of the theodolite of the extremities or reversal points of the oscillation. A more detailed description of this mode is contained in Section 6 and for the purposes of this introduction it is sufficient to state that

if θ_m = Theodolite circle reading of the centre of oscillation

W = Theodolite circle reading of True North

then $W = (\theta_m - sC\delta)$

(Note $\gamma = -sC\delta$ has been dealt with in 5.5.1)

5.5.3 Clamped Mode

In this mode the theodolite remains clamped throughout the observation and the oscillation of the gyro spin axis is projected as a slow movement of a light gap across the fixed gyro scale. Extremities of each oscillation can therefore be measured in terms of gyro scale values - see Section 6

if θ = The horizontal circle reading of the clamped theodolite

β = Gyro scale reading of centre of oscillation

W = Theodolite circle reading of True North

$$\text{then } W = \theta + s\beta(1+c) - sC\delta$$

(Note $y = -sC\delta$ - see 5.5.1)

The value of C may be determined experimentally by taking symmetrical observations around north during the same spin up. Circle readings (θ) and (θ_1) of the two clamped positions of the theodolite during such work should differ by at least 40 minutes of arc.

$$\text{if } W = [\theta + s\beta(1+c) - sC\delta]$$

$$\text{and } W = [\theta_1 + s\beta_1(1+c) - sC\delta]$$

$$\text{then by subtraction } (1+c) = \frac{\theta_1 - \theta}{s(\beta - \beta_1)}$$

At this point it should be stated that any value of W derived by either the tracking or clamped mode should be adjusted by the additive constant. This constant represents in arc value the misalignment between the gyro spin axis and the theodolite collimation axis. To all intents and purposes the above constants have remained constant over lengthy periods - see Section 10 - but naturally are unique for each machine. Wild and some authors regard this additive constant as the K factor which at times has shown large variation but at The Royal School of Mines it has been shown that these variations have been due largely to variations of tape zero. Once these variations have been removed K factor can

be regarded as a constant - see Section 12.

5.6 FINDING THE CENTRE OF A DAMPED SIMPLE HARMONIC OSCILLATION

Five separate formulae will be referred to within this thesis. Three are variations of the Transit method, one concerns the Amplitude method and one the Timing method. Apart from Schwendener's original Transit formulae⁽⁵⁾ the remainder have been developed or amended at The Royal School of Mines by my colleague Dr. T.L. Thomas. The five formulae are stated below with a brief explanation of terminology. A more thorough explanation of each method is contained in Section 6 together with references to other formulae developed by other authors.

5.6.1 Schwendener's Transit

$$W = \theta + s \frac{\pi}{2} \cdot \frac{(1+c)}{T} \cdot \alpha (\Delta T)$$

N.B. The notation is the notation of this thesis rather than that adopted originally by Schwendener⁽⁵⁾.

where S = Arc value of one gyro scale division in angular measure

T = Period of oscillation in the clamped mode

$$\alpha = \left(\frac{\alpha_1 - \alpha_2}{2} \right)$$

α_1, α_2 = Observed gyro scale readings of two successive Reversal Points

$$\Delta T = (S_1 - S_0) - (S_2 - S_1) = (2S_1 - S_0 - S_2)$$

S_0, S_1, S_2 = Three consecutive stopwatch times through centre of the gyro scale.

$S_0 \rightarrow \alpha_1 \rightarrow S_1 \rightarrow \alpha_2 \rightarrow S_2$ is the correct sequence.

if β = Centre of oscillation

and $W = [\theta + s\beta(1+c) - sC\delta]$ - see 5.5.3

then $\beta = \frac{\pi}{2} \cdot \alpha \frac{\Delta T}{T}$

N.B. At the time of Schwendener's formula the importance of tape zero was not realised and the term $sC\delta$ has an assumed value of 0.

5.6.2 Thomas Amended Transit⁽⁴⁾

Using definitions as shown in 5.6.1

$$\beta = \frac{\pi}{2} \cdot \alpha \frac{\Delta T}{T} \left(1 - \frac{\pi^2}{24} \cdot \frac{\Delta T^2}{T^2} \right)$$

and is used in the basic formula $W = [\theta + s\beta(1+c) - sC\delta]$. It was at this stage that the term $-sC\delta$ (tape zero) was introduced into the Transit method with the Wild G.A.K.-1.

5.6.3 Thomas New Transit⁽⁶⁾

If α_0 = Any selected scale graduation - preferably close to the centre of the oscillation

S_0, S_1 = Two consecutive stopwatch times through α_0

α_R = Reversal reading of oscillation in scale units between times S_0 and S_1

T = Period of oscillation in the clamped mode

($T = S_2 - S_0$ if α_0 is close to the centre of oscillation)

$$\rho = 2 \sin^2 \mu$$

$$\mu = \frac{20}{T} (S_1 - S_0)$$

then $\beta = \left(\frac{d_0 + d_n (p-1)}{p} \right)$ and must now be substituted in the basic formula

$$W = [\theta + s\beta(1+c) - sc\delta]$$

5.6.4 Amplitude

If $d_1, d_2, d_3, d_4 =$ four consecutive reversal readings in scale units

$$\beta = \left(\frac{d_1 + 2d_2 + d_3}{4} \right) \quad (\text{Schuler Mean})$$

$$\text{or } \beta = \left(\frac{d_1 d_2 - d_2^2}{d_1 + d_3 - 2d_2} \right) \quad (\text{Exact solution - Thomas}^{(4)})$$

$$\text{or } \beta = \left(\frac{d_1 + 3d_2 + 3d_3 + d_4}{8} \right) \quad (\text{Double Schuler Mean or Thomas Four Point Mean})$$

N.B. All the formulae in this section and other sections can be used in all three modes of operation. The preceding examples all refer to the clamped mode giving values for β , but if in the non-spin mode, $\delta_1, \delta_2, \delta_3$, and δ_4 are four consecutive scale readings of reversal points, then

$$\delta = \left(\frac{\delta_1 + 3\delta_2 + 3\delta_3 + \delta_4}{8} \right) \quad \text{etc}$$

Similarly if in the tracking mode, $\theta_1, \theta_2, \theta_3$, and θ_4 are four consecutive theodolite circle readings of reversal points, then

$$\theta_m = \left(\frac{\theta_1 + 3\theta_2 + 3\theta_3 + \theta_4}{8} \right)$$

5.6.5 Thomas Timing⁽⁶⁾

If $d_0 =$ Selected scale graduation corresponding to approximate centre of oscillation

α_a = Selected scale graduation for additional time S_a

$$A = \cos \frac{180}{T} (S_1 - S_0)$$

T = Time of one oscillation (constant or $S_2 - S_0$)

S_0, S_1, S_2 = Consecutive stopwatch times through α_0

$$B = \sin \frac{180}{T} (S_1 - S_a)$$

$$D = 2 \sin \frac{180}{T} (S_a - S_0)$$

then $\beta = \alpha_0 + (\alpha_0 - \alpha_a) \frac{A}{BD}$ and can be substituted in the basic formula $W = \{ \theta + s\beta(1+c) - sc\delta \}$

5.7 VARIATIONS OF INSTRUMENT CONSTANTS WITH LATITUDE⁽⁶⁾

If the values of C and T are known for a particular latitude (experimental methods of finding them have been given above in 5.5.3) it is a simple matter to calculate the expected values at other locations prior to making observations on site.

Two new constants independent of latitude are calculated as follows:

$$C_0 = C \cos \phi$$

$$F = \frac{2\pi}{T \sqrt{C_0 + \cos \phi}}$$

C and T being evaluated at latitude ϕ

then if C_1 = Value of C)

$$\begin{array}{ll}
 T_i = \text{Period of oscillation in the} &) \\
 \text{clamped mode} &) \\
 &) \text{ at latitude } \phi_i \\
 T_o = \text{Period of oscillation in the} &) \\
 \text{tracking mode} &)
 \end{array}$$

$$C_i = \frac{C_o}{\cos \phi_i}$$

$$T_i = \frac{2\pi}{F\sqrt{C_o + \cos \phi_i}}$$

$$T_o = \frac{2\pi}{F\sqrt{\cos \phi_i}}$$

These formulae are explained with examples in reference⁽⁴⁾.

6 - PRACTICAL USE OF A GYRO-THEODOLITE

As explained in Section 2 the major difficulty confronting a surveyor concerned with controlling underground development is obtaining precise information on direction at depth. The gyro-theodolite is an extremely versatile and convenient tool which has led to a gradual reduction in the use of conventional shaft plumbing techniques.

6.1 GRID SYSTEMS

A working mine has often developed historically, or through necessity, its own individual Mine Grid. In many mines the East-West axis of such a grid would follow the underlying direction of the strike of the mineral lode. Coordinates based on these independent schemes are often then linked by transformation to an overall National System. In Great Britain this is now compulsory, in other areas of the world where National Surveys exist the choice is left to the individual mine. A few National schemes have decayed over the years or have been proved to be weak in certain areas, and in some countries a National Survey has yet to be implemented. In either of these situations the mine has either elected to or been forced to develop its own grid system.

However, the basic fact remains that each mine will be working on some form of grid scheme and it is imperative that all underground operations must be correlated to the surface workings above. Coordinates used in an underground mining operation must therefore have three values:- the normal x and y and z directions. By

plotting these values it should therefore be possible to form a three dimensional image of the whole mine.

6.2 CONVERGENCE OF MERIDIANS

A gyro-theodolite will give accurate bearings in both surface and underground situations but these bearings will be related directly to True North or Astronomic North, not to Magnetic North or to any particular Grid North being used by a mine. To convert gyro bearings to Grid North it is necessary to apply a correction for grid convergence together, possibly, with a constant correction for non alignment of the grid. If the centre of the particular grid projection being used is known, then either by simple formulae - if the distance from the centre line is comparatively small (say < 30 km) - or by reference to National formulae it is possible to calculate the value of convergence at any required point. Figure 4 shows how convergence values increase with distance from the centre line of a projection and change sign east and west of the centre line. It is therefore imperative that an approximate idea of the co-ordinates of points being used for gyro bearings are known. Only coordinates in the x and y directions are required - to the nearest 10 metres. From these coordinates convergence values can be calculated and applied to the observed gyro bearing thus obtaining the required mine or national grid bearing. An example of the calculation, based on the simple formulae mentioned above is shown in Figure 5. A more general solution together with additional corrections such as the $t - T$ correction can be found in reference (4).

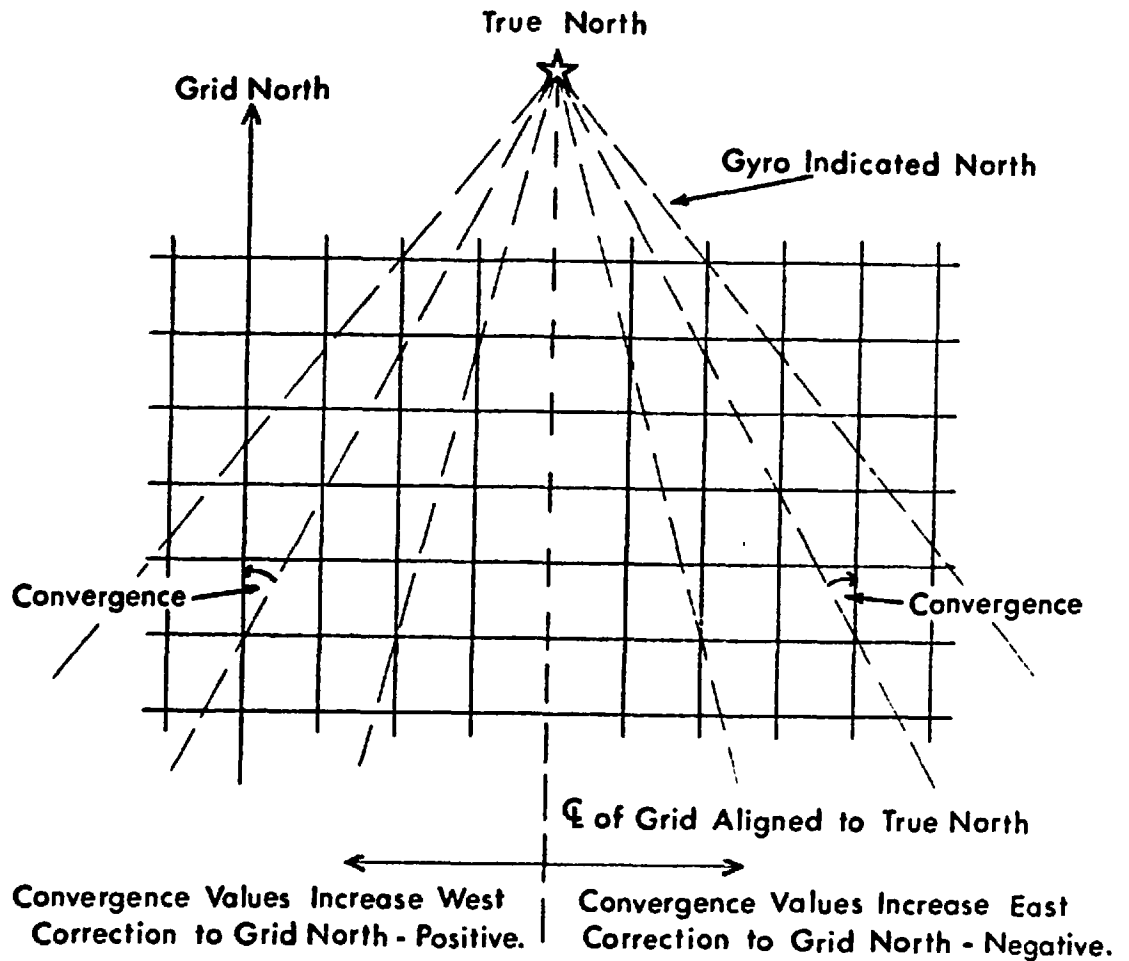


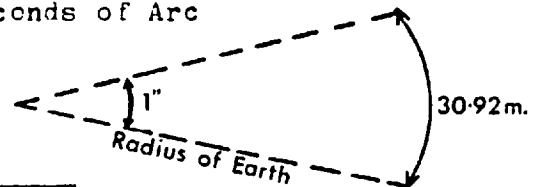
Figure 4 - Convergence of Meridians

6.3 UNDERGROUND CORRELATION

Every underground correlation attempted with a gyro-theodolite should include a direct comparison with a known surface line on the day of observation. Any survey equipment which is used in a mining environment must be regularly checked for any inadvertent knock which may have occurred during transportation in mine cages or underground vehicles. The normal observation pattern adhered to in many mines is one where the gyro-theodolite is first set up and observed at one end of a known surface line, then taken underground and observations made at both ends of the required line, and then

- Let i) $E_0 N_0$ = Coordinates of Point of Zero Convergence
- ii) $E_1 N_1$ = Coordinates of any other point on Grid Scheme
- iii) G = Gyro Bearing of Grid North at $E_0 N_0$
- iv) A = Observed Gyro Bearing from any other point on scheme
- v) ϕ = Approximate Latitude of $E_0 N_0$
- vi) P = Perpendicular distance of point $E_1 N_1$ from $E_0 N_0$
- vii) Δc = Convergence in seconds of Arc

$$= \frac{P \tan \phi}{30.92 \text{ m}}$$



If $E_0 N_0$ = 100,000.000E, 99,703.114N

$E_1 N_1$ = 99,036.349E, 99,672.440N

G = $336^{\circ}06'20''$

A = $214^{\circ}23'22''$

ϕ = $40^{\circ}09'$ North

Then using formulae in vi) above P = - 868.635 metres

$$\Delta c = - 23.698''$$

and Grid Bearing from Point $E_1 N_1$ = $A - G - \Delta c$

$$= 214^{\circ}23'22'' - 336^{\circ}06'20'' - (-24'')$$

$$= \underline{\underline{238^{\circ}17'26''}}$$

Figure 5 - Example of Convergence of Meridians applied to a Gyro Bearing using Simplified Formulae

returned to surface for a final set up at the other end of the known line. This procedure therefore includes a check on the behaviour of the gyro system both before and after being taken underground. If there are any large discrepancies between the two surface readings there may be a strong possibility of the equipment having been damaged between observations. Similarly a check on the general stability of the gyro can be made.

This procedure may appear to some observers as being unnecessary, especially in the light of evidence contained in this thesis regarding gyro stability over long periods, but directions given underground must be correct for economic and safety reasons. If a gyro was accidentally knocked on the way underground the calibration could possibly shift and although both readings taken underground would agree they could both be in error regarding surface comparison.

6.4 TAKING MEASUREMENTS FROM THE SUSPENDED GYRO-THEODOLITE

The suspended gyroscope is mounted either directly under or directly above the telescope of a theodolite. If the mounting is above the telescope a slight modification in the form of a connecting unit to take the gyro is fitted to both theodolite standards. In the G.A.K.-1 this allows the telescope to be transitted beneath the gyro attachment.

In both types of instrument the manufacturers have made every attempt to maintain a constant relationship between the collimation axis of the theodolite and the spin axis of the gyro rotor. The Hungarian instruments use a separate collimation device to measure

and correct any misalignment before observations begin. Wild have developed a three pin forced mounting device which under rigorous tests by the author has been shown to be repeatable within 2" of arc.

When a gyro-theodolite has been set up and pointed towards True North its rotor is spun up to the required number of revolutions per minute and then unclamped thus allowing the spinning mass to become suspended on the fine suspension tape. In accordance with gyroscopic principles the spin axis will seek True North and the gyro will slowly precess about the vertical axis of the spinning mass. Figure 6 shows how the spin axis precesses from one side to the other

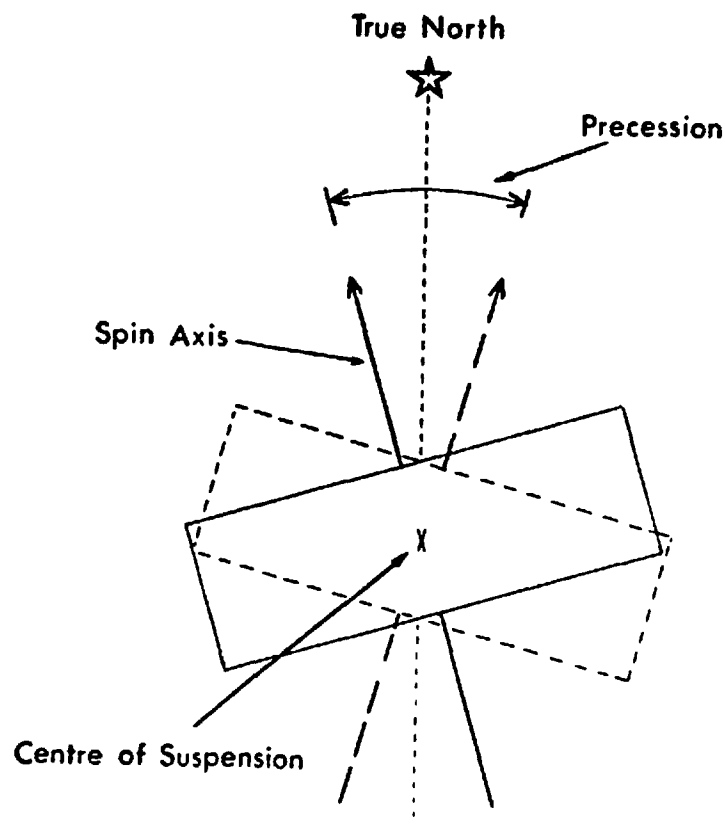


Figure 6 - Precession of a Suspended Gyroscope - Plan View

of the True North position.

The time taken for the spin axis to oscillate around the north direction is determined by the size of the spinning mass and length of suspension but will remain constant at the same latitude. For example in the clamped mode the Royal School of Mines Wild G.A.K.-1 at latitude $51^{\circ}30'$ north takes 7 minutes 13 seconds to complete a full oscillation, and at latitude 60° north the time increases to 7 minutes 51 seconds and at latitude 4° north takes only 5 minutes 59 seconds, whilst at latitude $51^{\circ}30'$ north the M.O.M. GiB1 equipment takes 8 minutes 58 seconds and the M.O.M. GiC11 equipment takes 6 minutes 56 seconds. This constant time factor is independent of the amplitude of the oscillation of the spin axis. The amplitude of this oscillation during precession will vary from observation to observation according to the care taken in releasing the clamped gyro unit after spin-up, but the time taken to complete a single oscillation will remain constant. Speed during precession is however variable and related to the size of "swing" or oscillation.

The basic requirement behind all gyro observations is to determine accurately the central position of this precession and to relate this position to the horizontal circle of a theodolite. Angles taken to stationary survey points from this circle position will therefore become bearings from True North.

6.5 DETERMINING THE CENTRE OF OSCILLATION

6.5.1 The Gyro Scale

When the gyro unit begins to oscillate the position of the spin

axis relative to the outer casing will change gradually. A collimator is built into the unit in order to transmit the image of such movement via an optical train to a fixed illuminated scale. Total movement of the spin axis should be contained within the range of the scale, and this can be achieved by damping the swinging mass by raising and lowering the gyro clamping mechanism very gently.

The scale divisions on the gyro scale differ between manufacturers and between models: M.O.M. GiBl has scale units of 30 seconds of arc; the M.O.M. GiCl1 has divisions of 2 minutes of arc and the Wild G.A.K.-1 and Sokkisha have divisions of 10 minutes of arc. It has become apparent that the accuracy of reading such scales has great influence on the final accuracy of the indicated bearings.

6.5.2 Modes of Observation

The term mode of observation refers to the theodolite. One mode requires the theodolite and its attached gyro system to follow the movement of the spin axis of the gyro as it precesses around the True North direction. This is known as the Tracking Mode. The other mode has the theodolite and gyro outer case clamped in an arbitrary position close to True North whilst the spin axis of the gyro unit precesses relative to the fixed outer case. This is known as the Clamped Mode.

In addition to the basic difference in the movement of

equipment during observations the two modes also produce differing values for oscillation time. The reason for this is linked to the tape suspension system. In the clamped mode the spinning mass is under the influence of two torques one due to precession and the other due to the slow twisting of the suspension tape which is secured at the top of the machine by a clamp. Whereas in the Tracking Mode this torque due to the tape is removed as the instrument and tape clamp are turned in sympathy with the precessing spin axis. Time values stated in 6.4 are for the Clamped Mode and will be increased in the Tracking Mode. For example at $51^{\circ}30'$ North the value for one oscillation of the Wild G.A.K.-1 increases from 7 minutes 13 seconds to 8 minutes 17 seconds and the M.O.M. GIB1 value increases from 8 minutes 58 seconds to 9 minutes 47 seconds. A full description of the Tracking Mode will be found in 6.5.3i b).

6.5.3 Methods of Observation

There are three methods of determining the centre of oscillation each of which could be applied to both modes. These methods are known as:

- i) The Amplitude Method and the Reversal Method, the first in the clamped mode and the second in the tracking mode.
- ii) The Transit Method; and
- iii) The Timing Method.

6.5.3i a) Amplitude or b) Reversal Method

- a) The Amplitude Method is associated with the clamped mode and is

undoubtedly the simplest method to use in the field. Observations are taken at four consecutive reversal points during one oscillation. The point of reversal being the instant when the gyro spin axis begins to precess in the opposite direction. In Figure 7 reversal points of the oscillation are shown as $\alpha 1$, $\alpha 2$, $\alpha 3$ $\alpha 4$.

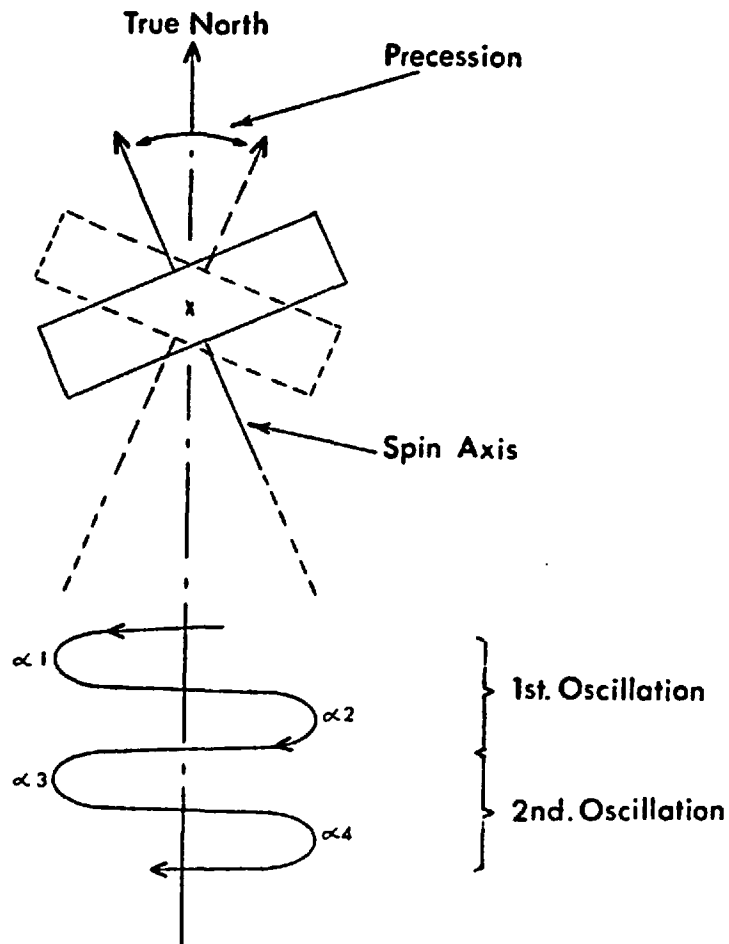


Figure 7 - Reversal Points of a Spinning Gyro

The illuminated scale of the gyro unit is divided into equal segments which are generally numbered on either side of the centre line of the scale - positive in one direction and negative in the

other. As the oscillation proceeds the internal collimator projects an image of the movement towards the gyro scale. Since movement virtually ceases for a few seconds at a reversal point it becomes possible to read from the scale the position of such points in scale units. The centre line of the scale is assumed to represent the collimation axis of the theodolite and if the gyro-theodolite were pointed exactly towards True North, the centre position of the oscillation should be zero - centre position being determined by the simple formula

$$\beta = \left(\frac{\alpha_1 + 3\alpha_2 + 3\alpha_3 + \alpha_4}{8} \right)$$

a double Schuler mean. In the majority of cases the observed centre line or β does not coincide with the scale zero line. These values of β can be used, using the formulae given in 5.6 to calculate the circle reading of north.

This method was regarded generally as being of low accuracy owing to the impossibility of reading precise reversal point values from the gyro scale. Wild equipment having scale divisions approximately 10 minutes of arc apart meant that the points of reversal could only be estimated at best to 1 minute of arc or 1/10th of a scale unit. M.O.M. instruments were able to obtain higher accuracy in measuring reversal point values by using smaller scale divisions. However, the Amplitude method as originally available gave less accurate results when compared with other methods.

Contained in a later section are details of a simple

modification developed in collaboration with Wild U.K. which has made it possible to measure such reversal points on the scale with a high degree of accuracy. Subsequent trials have now made the Amplitude Method more than competitive with other techniques.

b) The Reversal Method is the equivalent of the Amplitude technique but used in the Tracking Mode. This was the original method used for determining True North with gyroscopic surveying equipment and utilised merely a central index mark on an illuminated glass plate in place of the gyro scale. After spinning and suspending the gyro unit the oscillation of the spin axis is tracked by moving the theodolite using specially designed double tangent screws attached to the horizontal plate of the theodolite. Tracking entails keeping the projected image of the spin axis in coincidence with the central index mark on the gyro scale. The suspension tape, by being attached to the outer case of the gyro unit, remains in the same vertical plane relative to the outer case and therefore does not become twisted during tracking of the spin axis. As explained in 6.4 the time taken for one oscillation of the suspended gyro in the tracking mode is slightly longer than in the clamped mode due to the fact that the tape does not twist.

Tracking is continued throughout the oscillation until precession ceases in one direction. At this point, which is the normal reversal point of an oscillation, a reading is taken quickly of the position reached on the horizontal plate of the theodolite. Movement of the oscillation is now reversed and the projected image is again tracked using the extended horizontal plate tangent screws until it gradually slows and stops at the opposite point of swing.

A second reading of the horizontal plate of the theodolite is taken and tracking is then renewed in the direction of the first plate reading. Some observers continue this tracking procedure for four reversals (two oscillations), others for six and others for more.

Reduction of a typical set of data is shown in Figure 8 where it can be seen that the object of the method is to obtain a direct theodolite horizontal circle reading of the mid point of oscillation or True North (θ_m). In this method the same formula is used as in the Amplitude technique except the θ values refer to horizontal circle readings of the theodolite.

Wild GAK-I Gyro Attachment. (Reversal Point Method)

Theodolite No. *T/6 - 160313*
GAK I No. *11310*
Station. *A5334 (U.G.)*

Converter No. *9905* Observer. *Ogo Ayrakwa*
Battery. *Internal* Date. *14-7-76.*
R.O. *A5470*

Rev. Points Left		Rev. Points Right		Schuler's Mean	
o	'	o	'	o	'
		<u>358</u>	<u>17.4</u>		
<u>00</u>	<u>19.2</u>	<u>358</u>	<u>17.4</u>	<u>359</u>	<u>18.30</u>
<u>00</u>	<u>19.1</u>	<u>358</u>	<u>17.4</u>	<u>359</u>	<u>18.25</u>
<u>00</u>	<u>19.0</u>	<u>358</u>	<u>17.45</u>	<u>359</u>	<u>18.23</u>
<u>00</u>	<u>19.0</u>	<u>358</u>	<u>17.5</u>	<u>359</u>	<u>18.25</u>
<u>00</u>	<u>19.0</u>				
			θ_m	<u>359</u>	<u>18.26</u>

nb. Observed Values Underlined.

	o	'
RO Face Left	196	00.0
RO Face Right	16	00.1
Mean RO	196	00.05
Gyro Orientation	359	18.26
	196	41.79
Calibration Value +		0.60
Geog. Azimuth	196	42.39
Convergence +		0.00
Grid Bearing	196	42.39

Final Grid Bearing: 196°42' 23"

Figure 8 - Example of Reversal Point Booking : Ashanti Mine, Ghana

This method has given excellent results in the past but requires a first class observer. The technique is simple but the continuous strain of keeping a moving mark constantly in coincidence with a centre line on an illuminated scale for periods of twenty minutes is undoubtedly a disadvantage. An observer employing this method must not impart any involuntary vibration into the movement of the gyro and must adopt a smooth tracking procedure throughout, which is very difficult.

6.5.3ii Transit Method

This method is more generally applied in the Clamped Mode although as explained later it can also be used in the Tracking Mode.

The Transit Method makes use of an important fact of gyro theory - constant swing time during each complete oscillation, coupled with an extremely small damping factor. In the clamped mode the image of the moving spin axis is projected towards an illuminated glass scale containing numbered divisions at regular intervals - as described in the Amplitude Method. Schwendener of Wild Heerbrugg developed the original transit system in 1964 and used a combination of four amplitude readings, or reversal points, and five timing values to obtain the centre of the oscillation. One proviso of Schwendener's transit formula was the necessity to align the initial heading of the gyro-theodolite within 10 minutes of True North before beginning the precise observation. This meant that the oscillation of the spin axis was depicted on the scale as almost symmetrical around the central mark of the scale - see Figure 9.

After allowing two or three swings for the suspended gyro system to settle a stopwatch with lap timing facilities is started as the moving mark crosses the central scale marker. The observer waits until the moving image reaches the end of its swing and then estimates the point of reversal from the numbered scale divisions. A further wait for the moving mark to reach the centre

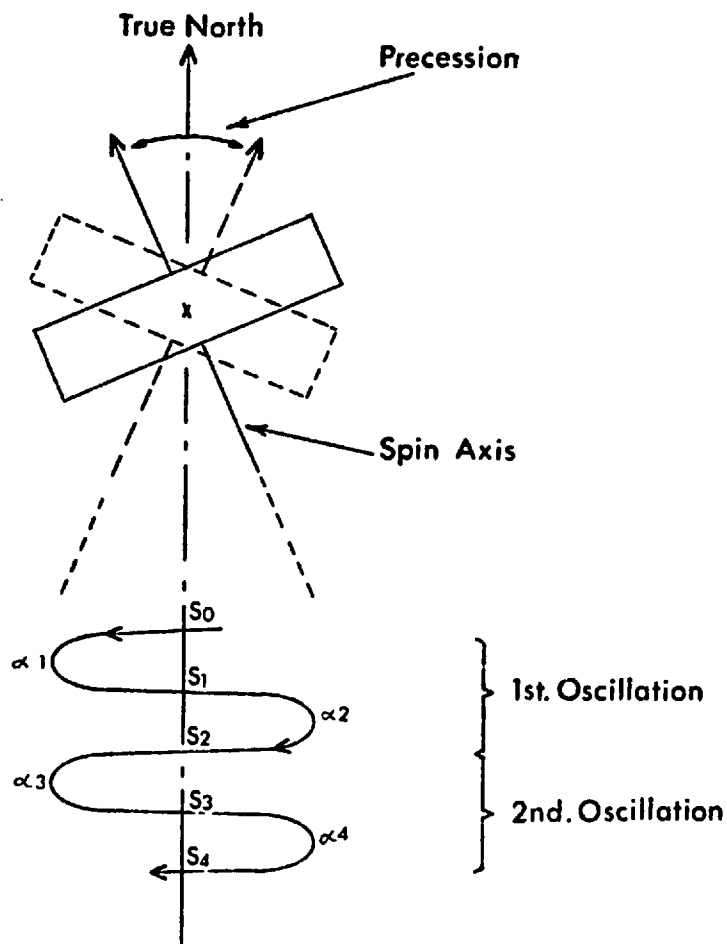


Figure 9 - Timing and Reversal Points for the Transit Method

scale line on its return passage and a time is recorded at the instant of crossing. This process is repeated until the required number of reversal points and times have been recorded. A typical sequence of events would be:

- a) Start the stopwatch at the centre line (S_0).
- b) Estimate reversal point (α_1).
- c) Record time at second crossing of centre line (S_1).
(Recorded times would give time interval $S_1 - S_0$).
- d) Estimate reversal point (α_2).
- e) Record time at third crossing of centre line (S_2).
(Recorded times would give time interval $S_2 - S_0$ and $S_1 - S_0$).
- f) Estimate reversal point (α_3).
- g) Record time of fourth crossing of centre line (S_3).
(Recorded times giving time interval $S_3 - S_0$ and $S_3 - S_2$).
- h) Estimate reversal point (α_4).
- i) Record time at fifth crossing of centre line (S_4).
(Recorded times giving time interval $S_4 - S_0$ and $S_4 - S_3$).

The advantage of this method as opposed to the only other method available at the time - the Reversal Method in the Tracking Mode - was less operator contact with the equipment due to adopting the clamped mode. The operator by simply watching the illuminated scale at intervals found the method less tiring and it gave him less opportunity of inducing accidental vibration into the system.

Disadvantages were the need to be within 10 minutes of True North before being able to use the method and the necessity of recording accurate timed positions of a constantly moving mark. Results were a little difficult to reduce because the formula contained a combination of time values from the stopwatch and arc values converted from the gyro scale. The recent introduction of

small electronic calculators has simplified such work.

Schwendener developed his original formula in 1964 and published an extensive description of the method in 1966⁽⁵⁾. The simplified formula was:

$$\Delta N = C_T a \Delta T$$

where ΔN = arc correction required to correct the theodolite circle reading .

C_T = constant of proportionality to convert readings from the gyro scale to true arc values.

a = mean amplitude of the oscillation calculated from the observation - see 5.6.1.

and if S_0 , S_1 and S_2 are three consecutive stopwatch times through the zero mark then $\Delta T = (S_1 - S_0) - (S_2 - S_1) = (2S_1 - S_0 - S_2)$

Several attempts have been made to improve this basic approach:

- i) Halmos in 1969⁽⁷⁾ using similar formula to Schwendener extended the method to include transit times at scale markings placed symmetrically around the central zero mark.
- ii) Bennett in 1969⁽⁸⁾ also extended the method by taking transit times of scale divisions either side of the scale centre but in addition introduced a further term into the basic formulae which improved the accuracy of the method.
- iii) Thomas in 1975⁽⁹⁾ also amended Schwendener's formula by introducing an additional term which enabled the transit method to be used far from the original limit of 10 minutes of arc from True North. He also introduced the tape zero correction which was ignored by Schwendener and showed that Schwendener's assumption of no damping was not required.

- iv) Thomas in 1978⁽⁶⁾ produced a further refinement of the Transit method which has effectively removed the constant of proportionality from the formula and enables an answer for ΔN to be obtained, with all systematic errors including damping eliminated, from a quarter oscillation requiring only two precise measurements. This formulae has been evaluated in a later section.

The Transit Method can be used in the Tracking mode but in this case readings on the horizontal circle of the theodolite replace the reading of marks on the gyro scale at which timings are taken. These points are selected from information on the total swing in amplitude observed during an initial oscillation. It is a simple matter to calculate, approximately, the centre point and other positions, symmetrical or otherwise about the centre of oscillation, but the method requires two observers. One observer should concentrate on keeping the gyro mark stationary about the centre of the gyro scale by slow and steady movement of the extended horizontal plate tangent screw; the other watches the progress of the theodolite as it moves around the horizontal circle by using the optical reader attached to the telescope of the theodolite. At predetermined points on the theodolite scale, times are taken by the second observer. Some gyro-theodolites do not allow the use of two observers, e.g. M.O.M. GiC instruments.

6.5.3iii Timing Method

This method has been investigated by several authors over the past years but has not been accepted widely, and is relatively unknown in this country. To obtain a determination of the centre of the oscillation it is necessary to take accurate timings of the oscillation as it transits, or crosses various graduations on the

gyro scale and these times together with the known oscillation time produces the centre of oscillation - see Figure 10.

The major contributors to this form of measurement have been Graferend, Halmos, Williams and Thomas.

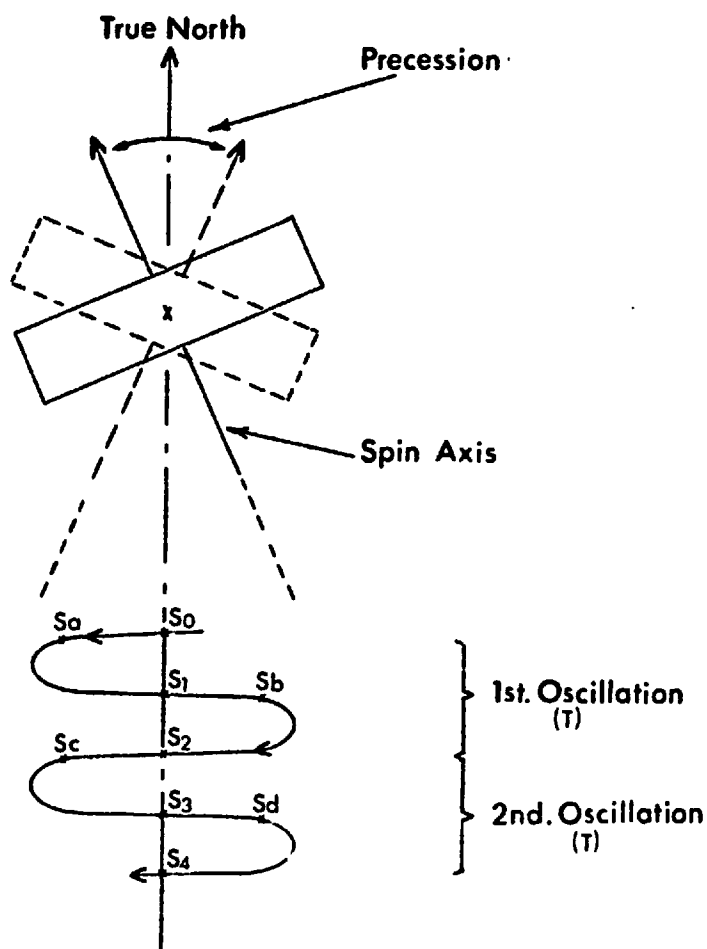


Figure 10 - Timing Points for the Timing Method

Graferend in 1967⁽¹⁰⁾ and 1969⁽¹¹⁾ published formulae which utilised a system of automatic timing of the passage of the oscillation over predetermined positions on the gyro scale.

In 1971⁽¹²⁾ Graferend in conjunction with Rymarezyk published a further series of equations for determining the centre of the oscillation for various situations which used combinations of either three or four timings taken during a single swing. Halmos analysed the timing method in 1975 and came to the conclusion that solutions obtained by timings alone were of medium accuracy and could only be bettered by an increase in the accuracy of timing. He proceeded to offer his own formulae for pure timing solutions using timing information taken at three positions during an oscillation.

Thomas in 1979⁽⁶⁾ published a further simplified formula for the timing method which has been evaluated in a following section.

In a similar fashion as described under the Transit Method 5.3.2 it is possible to use the Timing Method in the Tracking mode. Again positions on the horizontal circle of the theodolite are selected as timing points, these points being determined from observations taken on the total swing of a preliminary oscillation. This requires similarly two observers; one tracking the gyro oscillation using the collimator attached to the gyro housing, the other using the optical scale reader of the theodolite.

In view of the disadvantages of the tracking mode described within this section it was decided to concentrate the analysis of methods on results obtained from observations using the gyro-theodolite in the Clamped mode.

6.6 TAPE ZERO POSITION

In addition to the two modes of operation described in this

chapter there is a third mode of oscillation. This is the Non Spin mode, previously ignored by all users of the G.A.K.-1 but of particular importance to the measurement of tape zero values which have shown by continual work at the Royal School of Mines to be a major source of error. Tape zero will be dealt with extensively later in this thesis.

7 - IMPROVEMENT TO THE WILD G.A.K.-1 GYRO ATTACHMENT

A simple modification to the Wild G.A.K.-1 attachment has been designed and developed with the close co-operation of Wild (U.K.) The need for this particular type of modification, which was designed with the aim of improving the reading accuracy of the illuminated gyro scale, has been referred to in Section 6. Technical data pertaining to the standard Wild G.A.K.-1 is contained in Section 4.2.

7.1 THE MODIFICATION

Originally several proposals put forward by the Royal School of Mines and Wild (U.K.) of how to obtain such an increase in scale reading accuracy were discussed, but eventually it was decided to adopt the idea of Mr. Schindele - Service Manager of Wild (U.K.) - to insert a parallel plate micrometer system within the optical train of the instrument.

The modification⁽¹³⁾ is small and unobtrusive, and does not in any way give the impression of being "just an added refinement". To all intents and purposes the micrometer, placed immediately above the eye piece of the gyro attachment appears part of the original machine - an important factor in any change of instrument design.

Although the modification was primarily produced as a research project it was important to bear in mind that if successful, the manufacturers would wish to market the modified equipment. It was therefore essential to ensure that the modification was simple in design, would be easy to use and adapt to the basic machine, and would

not impair the aesthetic appearance of the original equipment - see Plate 6.



Plate 6 - An Underground Observation with the
R.S.M./Wild Modified G.A.K.-1

Figure 11 shows the basic mechanics of the micrometer drum and parallel plate. The micrometer drum is graduated over approximately three quarters of its circumference into 10 main units, each unit is then sub-divided into a further five divisions. Rotation of the micrometer drum over these 10 main units covers one whole division on the gyro scale. Additional graduations have been engraved at

either end of the micrometer to facilitate over-run when measuring. Divisions on the drum allow direct readings to be taken to 0.02 of a gyro scale division or 12 seconds of arc. Estimations can be

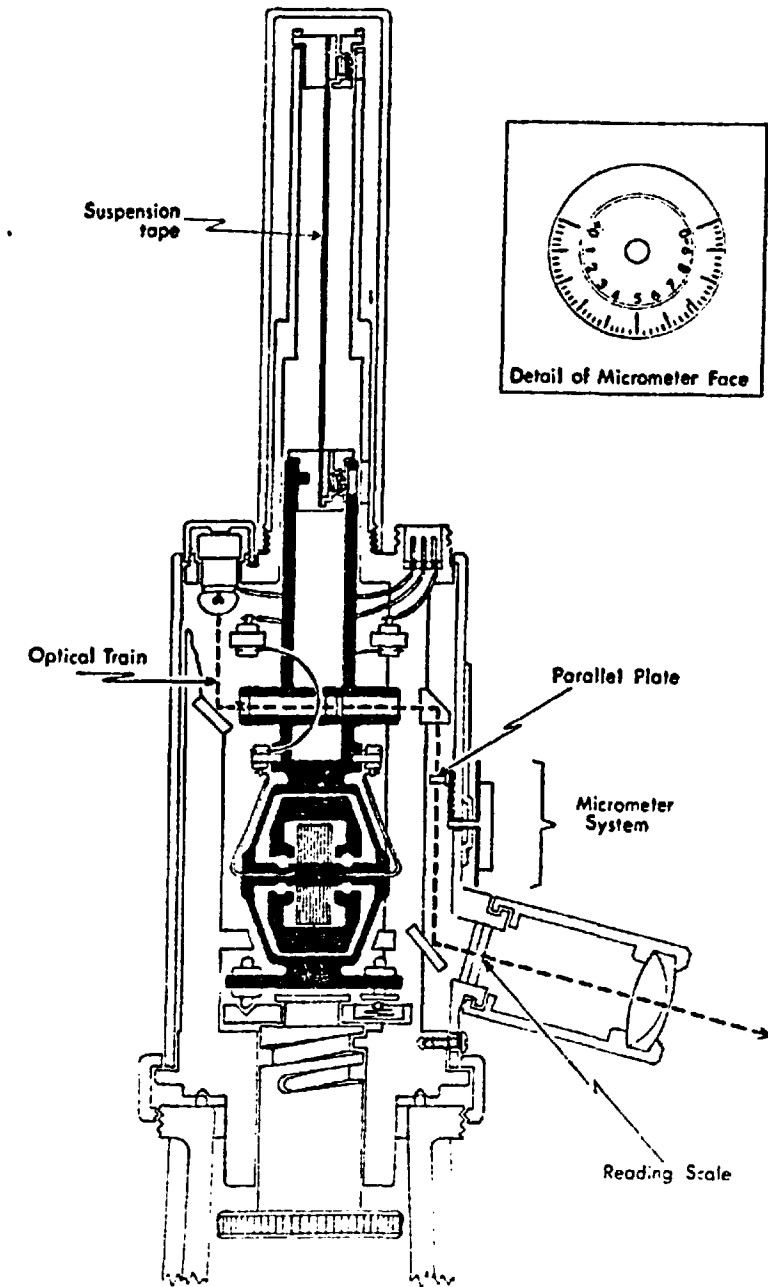


Figure 11 - Modified Wild G.A.K.-1

made comfortably to 0.01 of a gyro scale division, 6 seconds of arc, and after some experience with setting the modification it is possible to estimate smaller quantities with ease.

By turning the micrometer drum the optical train from the gyro collimator is therefore displaced from its original projected position on the illuminated gyro scale by a maximum of 1.2 divisions or approximately 12 minutes. It is essential to check that the run of the micrometer is correct and that turning the drum over 10 major divisions moves the gyro mark one division on the scale. This can be carried out quite easily with the gyro unit remaining clamped, power is only required for illuminating the scale.

7.2 NUMBERING OF THE MICROMETER

One minor problem was encountered during the initial measurements made with the modified G.A.K.-1. This was the fact that the micrometer was to be used to accurately measure small quantities at either end of the gyro oscillation. Figure 12 indicates typical quantities. In this example the gyro oscillation has been shown to have moved from one side of the scale to the other and by estimation would have a total amplitude of from + 11.7 to - 11.3 scale units. The function of the micrometer is therefore to measure accurately the quantities 0.7 and 0.3. On the positive side of the scale the quantity would be positively in excess of the + 11 scale division - or towards the left (west), whilst on the negative side of the scale the quantity required would be negatively in excess of the - 11 scale division - or towards the right (east).

It therefore became apparent that a decision should be made on the numbering sequence of the micrometer divisions. Because of the necessity to measure quantities in opposite directions it was essential that a fool proof system should be developed. One idea,

which is common to some vertical circles on vernier theodolites, was to have a numbering system progressing from 0 to 10 from the left hand division on the drum and a second numbering sequence progressing from 0 - 10 in the opposite direction, with the second 0 engraved immediately above the original 10 value. Basically a double reading micrometer. It was felt that this could lead to difficulties and possible confusion by the operator especially when one considers observing conditions and hazards prevailing in typical underground survey situations.

The idea finally selected was to have one numbering sequence running from + 0 at the left hand extremity of the drum through 9 to - 0 in place of 10, as shown in Plate 6 and Figure 11.

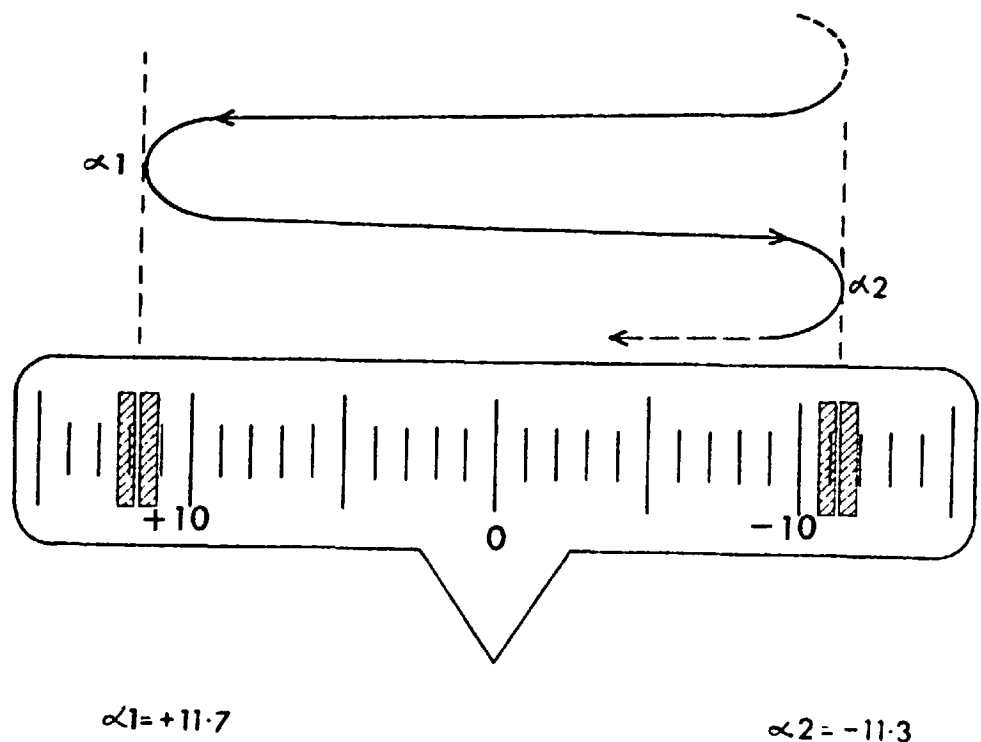


Figure 12 - Reversal Points as shown on the Wild G.A.K.-1

A reading mark to which the micrometer drum could be zeroed or read was engraved on the metal eye piece housing adjacent to the lower edge of the drum.

7.3 USE OF THE MICROMETER

With the system shown, the method of reading is as follows. After initially setting up and orientating the gyro the micrometer is set at + 0, zeroed to the mark on the collimator housing. The gyro is spun to the required rate, uncaged, and the oscillation observed. Two complete swings are left for settling down, and for observations of the approximate scale values at reversal points, in order to give some idea where to use the micrometer measuring system. As an example, assume reversal points were recorded as greater than 9 on the positive side and greater than 5 on the negative side. Taking the positive side first; as the oscillation travels through the + 9 graduation on the gyro scale, the micrometer drum is turned slowly clockwise to keep the light gap central about the + 9 scale mark. When the oscillation stops, prior to the beginning of its return swing, the micrometer scale is read from the + 0 end. In this example the micrometer could read + 0.76 plus an estimated fraction, giving a reading of say + 0.765. For the positive side of the swing an amplitude of + 9.765 would therefore be recorded.

The method of reading the negative side of the swing is a little different. The micrometer is reset on - 0 which means that the estimated negative reversal point has been shifted by one whole division to that observed from the + 0 position, prior to the measuring sequence. In this case the oscillation is watched until it reaches the $- 5 + (- 1) = - 6$ graduation of the gyro scale.

The micrometer is used in the same way as on the positive side to keep the light gap central around the - 6 scale marker but this time the drum is rotated slowly in an anticlockwise direction. At the end of the swing the micrometer is read again from the + 0 marker, for example say + 0.930. The correct reading on the negative side would be $- 6 + 0.930 = - 4.070$.

This reading system is straightforward and easy to use, the only additional work involved being an extra column in the basic booking sheet design - see later examples. It was proved to be comparatively easy to obtain precise measurements with the micrometer system and that no difficulty was experienced with balancing even rapidly vibrating moving gyro marks around the selected main scale graduation. The human eye appears to be capable of such balancing to a high degree of accuracy. Prior to the modification some difficulty had been experienced in estimating reversal points from the scale when the reference gyro mark contained vibration movements.

8-9 - FACTORS WHICH INFLUENCE ACCURATE GYROSCOPIC OBSERVATIONS

The gyro-theodolite like many pieces of modern advanced surveying equipment, is an instrument capable of giving highly accurate results. Progress over the past few years has increased steadily the accuracy obtained from gyro-theodolite observations to a level where results are approaching first order accuracies.

It is becoming increasingly obvious that a knowledge of minor influences which at one time could for the greater part be ignored, or in some cases were impossible to measure, are of extreme importance in accurate gyroscopic observation. In some cases such disturbances can be avoided easily, in others which are unavoidable, corrections can be applied to minimise their influence.

The various factors fall into two main divisions; External and Internal.

- | | | |
|-----------------------------|---|--------------|
| 1. Magnetic |) | |
| |) | |
| 2. Stability |) | |
| |) | |
| 3. Atmospheric |) | 8 - External |
| |) | |
| 4. Centring |) | |
| |) | |
| 5. Levelling |) | |
| |) | |
| 6. Technique of Observation |) | |
| | | |
| 1. Gyroscopic Drift |) | |
| |) | |
| 2. Voltage Stability |) | |
| |) | 9 - Internal |
| 3. Internal Magnetism |) | |
| |) | |
| 4. Damping |) | |

8 - EXTERNAL FACTORS

8.1 MAGNETIC INFLUENCES

The major contributors who have dealt with magnetic disturbances are Halmos,⁽¹⁴⁾ Stier⁽¹⁵⁾ and Tichomirova⁽¹⁶⁾ with more recent work by Dzierzega⁽¹⁷⁾. In mining environments it is highly probable that observations taken with a gyroscopic device may be influenced by differing magnetic forces. These forces may be in the form of natural anomalies which vary in intensity throughout the world or be caused by man made electrical equipment and machinery. Electricity is a major power source for mining machinery and transport systems, and the precise location and force field generated by such equipment should be known prior to work being carried out with a gyro-theodolite.

Investigations at the Royal School of Mines have yet to be initiated into the influence of variations of magnetic force. However, results from the authors above suggest that gyro bearings can be affected; the major factors being field intensity and field direction. Dzierzega⁽¹⁷⁾ indicates that the M.O.M. GiBl is affected most by a field having a bearing of 0° whilst the G.A.K.-1 is most affected from directions at 135° and at 225° to the spin axis of the gyro. He also states that an outside constant magnetic field of 160 amperes per metre has little effect on the Hungarian equipment but a force of 25 amperes per metre causes errors from 0.3" to 1.3" in the directions indicated by the Wild G.A.K.-1 which increases with the intensity of the field.

Both the M.O.M. and Wild equipment are shielded against outside

magnetic influence. The M.O.M. instruments have a total screen of Mu metal whilst the G.A.K.-1 appears to have a Mu metal shield according to Strasser and Schwendener in 1969⁽⁵⁾ but only of mild steel according to their current hand book.

It would appear from the information mentioned above that more work should be carried out on magnetic influence with direct reference to mining and other heavy industry. It may well be necessary to measure the level and direction of magnetic influence at each gyroscopic set-up. Underground mining is possibly the more vulnerable situation where massive electrical equipment may well be installed in a level above, below or to the side of the level in which the gyro-theodolite is assembled. The main danger occurs from Direct Current - the power used by much mining machinery - although thorough investigations should also cover Alternating Currents.

8.2 STABILITY

The suspended gyroscope by virtue of its tape suspension is highly susceptible to movement. This movement may be caused by a variety of factors:

- a) An unstable set-up where the footings may not be well consolidated. A situation which is common in the mining environment.
- b) Vibrations which may originate from passing transport; a common occurrence in mining with heavy equipment being moved regularly, and from the working of locomotives on haulage duties. These vibrations are mainly unpredictable.
- c) Movements which occur due to surface winds or underground ventilation systems.

- d) Vibrations from machinery, such as generators, being transmitted through steel floors and beams throughout installations such as offshore Oil Platforms. In these positions a further vibration pattern, from sea movement, is of an unpredictable nature and damaging to accurate gyro theodolite work using instruments of the tape suspension type.

There is no doubt in anyones mind that vibrations from any of the sources mentioned above are detrimental to suspended gyro-theodolite work. A little work has been conducted by European researchers into this field but the answer at present would seem to be to avoid the influence of vibration if possible by selecting stable set-up positions and shielding the instrument and operator by erecting temporary screens. At present there is no answer to the vibration of passing equipment and steps should be taken accordingly to restrict such movement in the area for the short time required for observation. There have been scientific investigations on vibration carried out recently by Dzierzega⁽¹⁷⁾ and by Cirbus⁽¹⁸⁾.

Offshore work has been treated separately in a later section. Here it will be seen that certain types of offshore installation are more acceptable for gyro work than others.

8.3 ATMOSPHERIC FACTORS

There are three atmospheric factors which could affect the behaviour of the suspended gyro-theodolite. These are temperature, pressure and humidity.

Pressure and humidity would seem to have little effect on the observations carried out over the past four years with the Wild

G.A.K.-1. Changes in pressure have been noted when using the equipment in deep mines but the observations to date have shown little evidence of identifiable correlation. It is hoped to run a series of experiments in the future within a pressurised vessel, but it is not anticipated that results would indicate much change. It is thought that if deviations did occur these would be at pressure conditions well beyond the normal range expected for underground mining use.

The greatest difficulty with humidity has been the reduction in ability to sight clearly underground. Apart from allowing the equipment to adjust to the conditions very little else can be done. Even then constant wiping of the telescope object glass and eyepieces of the theodolite and gyro scale collimator is unavoidable, but visibility is generally poor. A reduction in accuracy in these conditions is therefore due mainly to the inability to sight targets accurately and not to a reduction in the performance of the gyroscopic equipment.

Temperature is possibly the main offender in work of this type. The problems arise when moving from one environment to another between observations. This situation is again common in mining, where a surface observation taken in a temperature of say 30°C may be followed immediately by an observation underground in a temperature near 40°C .

Results from gyro attachments of the suspended type may be affected by temperature due to the different coefficients of expansion of the various metals within the fully assembled instrument.

Assembly of attachment types involves three separate parts; the gyro unit, bridging unit and theodolite. Each section is constructed of metal and each must be subject to minor internal movements due to changes in temperature and possibly to minor movements of a relative nature between sections. Nevertheless the manufacturers have had these possibilities in mind at the design stage and in practice errors from this source are small.

The tape of the suspended gyro is attached by a clamping mechanism to the outer casing of the gyro unit at the top of the "chimney like" extension. Possibly a change in temperature could cause a change in the relative position of the suspension tape axis ?

Several observations have been carried out in differing temperature conditions and although as a precaution time has been allowed for the equipment to adjust to the conditions at the set-up, in several cases quite large differences have been observed in the position of the spin axis in both the spin and non-spin modes.

In one experiment the gyro equipment was kept in a cold store for periods of seven days at a temperature of 0° and then brought into a laboratory environment where temperatures have ranged between 20° and 30°C . In these experiments no time was allowed for the equipment to adjust to the new conditions and the maximum change in the derived heading was + 10" of arc. After a suitable warming up period of approximately one hour, the results were closer to the accented value.

From limited experimental evidence there is a possibility that

changes of temperature could cause differences in the accuracy of the suspended gyro-theodolite. A more thorough investigation is required but the difficulties of controlling operating temperature conditions require an isolated chamber with an optical glass window to an outside target. Any reference marks inside such a chamber would be liable to move with changes in the constructional materials of the chamber itself. (See also notes under causes of Non-Spin Drift - 9.1.6d.)

8.4 CENTRING

Accurate centring is essential for orientation work in underground mining situations as invariably the length of sight is short. On the surface accurate centring can be accomplished by using optical plummets either contained within the theodolite itself or as a separate piece of equipment. In general the equipment is centred over a reference mark.

Although high levels of accuracy are claimed for optical plummets it should be noted that some equipment, for example the Wild T2, have the plummet mounted within the detachable tribrach. In this situation the accuracy of the plummet cannot be evaluated on site by the normal checking procedure of rotation through 180° normal with other equipment.

Underground reference marks are found generally in the roof of the tunnel or excavation. This is to protect the stations from damage caused by passing traffic. Centring must therefore be carried out beneath such markers. The normal way of centring

accurately underground is to use either an upward looking optical plummet or by centring the centring thorn of the theodolite immediately below a suspended precision plumb-bob. This centring thorn is mounted on the telescope of the theodolite and represents a continuation of the theodolite vertical axis. If using the latter technique, it is imperative that the thorn is checked as being central, the theodolite levelled accurately, and that the telescope on which the thorn is mounted is set exactly horizontal. Some observers rely purely on the graduations of the vertical circle after levelling the alidade, or split, bubble. A simpler approach is to use a separate, sensitive, double reading bubble mounted beneath the telescope; if the bubble has been adjusted it is a simple operation to observe this bubble from above the telescope and bring to mid-run.

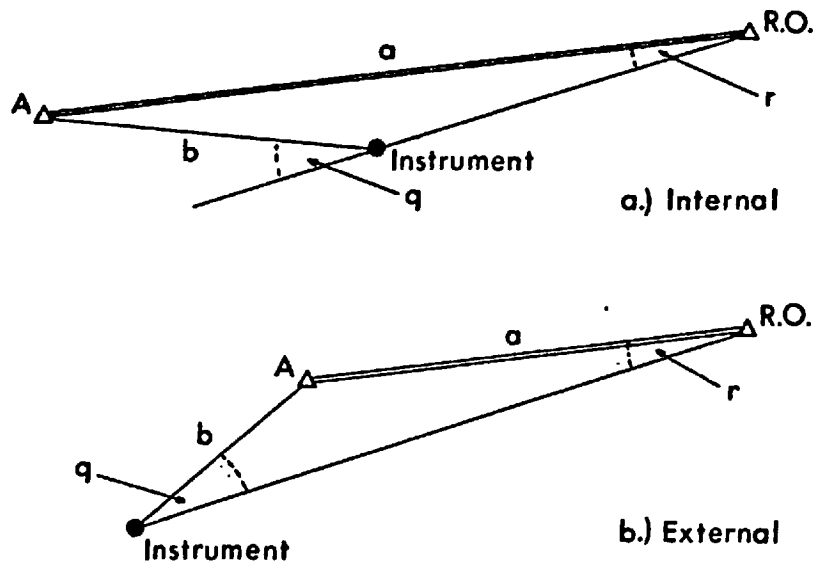
With equipment such as the M.O.M. GiBl and the new Fennell MW77 it is possible to use the centring thorn of the inbuilt theodolite but the more usual equipment in use is of the attachment type where the gyro unit is placed on the standards of the theodolite, thereby covering any centring thorn or other device.

This situation means that any centring must be carried out prior to the gyro unit being attached to the theodolite. The normal difficulties of centring accurately beneath a precision plumb-bob, which itself may be subject to slight movement and deviation caused by environmental conditions, are therefore increased by virtue of the possibility of the theodolite becoming slightly off centre whilst attaching the gyro-unit.

Other authors may reject such suggestions but with the advances made in repeatable accuracies now obtained by gyroscopic equipment of the suspended type, any chance of avoiding error should be examined.

At the Royal School of Mines it has always been the policy to set up close to one end of a line and to use either the internal or external Weisbach triangle system to bring the observation on to the required heading. Weisbach triangles have been used in mining for many years and the accuracy of such systems has been proved theoretically and empirically. The only additional work involved is the measuring of one angle on both faces and taping the distance to the nearby station marker. (The distance between stations being known as a rule prior to the observation.) It should be noted that the distance b (see Figure 13) need only be measured approximately and in some cases even pacing is sufficient. For example if the correction (r) is, say, 56" of arc b need only be measured to 1 part in 56.

The advantage of this technique is not only one of avoiding centring error but also in that the operator is free to select the most stable position to set up the equipment, within the limitations of the method. Time taken for this method and for centring accurately on the point are similar and even in surface situations it is rare for any observations taken at the Royal School of Mines to have used normal centring techniques. It has been found that the Weisbach system is both simple to use and accurate - see Figure 13.



$$r = \frac{b}{a} q \quad (\text{if } q < 40 \text{ minutes of arc.})$$

Figure 13 - Details of Weisbach Triangle

8.5 LEVELLING

Precise levelling is a normal pre-requisite of most surveying equipment if maximum accuracy is to be obtained. The pendulous gyro depends on reading the movement of the suspended spin axis which is projected towards an illuminated horizontal scale. If the equipment was levelled incorrectly the normal vertical position of the suspended gyro would therefore be deflected and erroneous readings observed on the scale - see Figure 14.

It was decided to run a series of experiments on the Wild G.A.K.-1 to evaluate changes in scale readings according to the amount of dislevelment incurred.

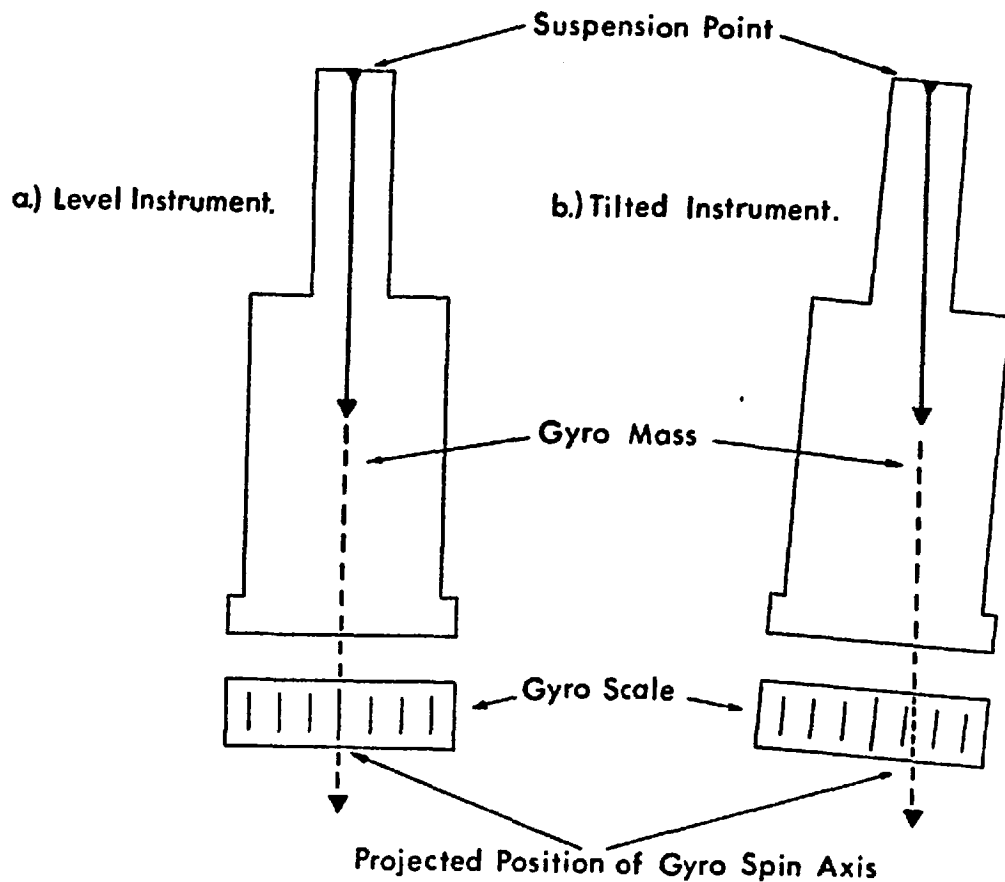


Figure 14 - Diagram to Illustrate the Effect of Dislevelment on the Scale Position of a Pendulous Gyroscope - Tilt Highly Exaggerated

Before setting up the experimental series a system of measuring the dislevelment of the equipment was devised. It was decided that the ideal solution would involve setting the instrument on a heading around True North with the collimation axis of the theodolite telescope passing over one of the three levelling screws in the conventional theodolite tribrach. In this way the vertical circle of the theodolite could be used to measure the amount of induced dislevelment in the collimation axis direction - True North - and the normal theodolite plate bubble could be used to measure induced dislevelment at right angles to the collimation axis - East/West.

For collimation axis dislevelment the equipment was levelled precisely using the theodolite alidade bubble, and the telescope set on a horizontal setting (in the Wild T-2 circle left the vertical heading = $90^{\circ}00'00''$). Dislevelment was induced by setting a value such as $89^{\circ}59'00''$ (i.e. $01'00''$ dislevelment) on the vertical scale using the alidade bubble and then releveilling the alidade bubble by the tribrach foot screw directly beneath the collimation axis.

For dislevelment at right angles to the collimation axis it was necessary to calibrate the plate bubble of the theodolite and then to create dislevelment by turning either of the two foot screws astride the direction of the collimation axis and then measuring the amount of movement of the plate bubble.

Calibration of the bubble was undertaken over a lengthy period using the generally accepted $57'20''$ method⁽¹⁹⁾ and was found to be $27''$ per division as opposed to the given value of $20''$ per division. A typical set of results for this calibration is shown in Figure 15.

To set the collimation axis over one of the foot screws a small mark was made on the top cover of one of the foot screws and this was then observed through the object glass of the theodolite telescope and centred.

8.5.1 Dislevelment in the Direction of the Meridian

The initial experiments were designed to be contained within a movement of + or - one minute of arc from the true horizontal position. The effect of dislevelment in this direction was not

Observer: *B. Stallard.* Place: *R. 146.* Bubble: *Horiz. Plate.*
 Instrument: *Wild T-2 (GAK-1).* Nominal Value: *20" per division.*

Divisions	Circle Readings		Mean	Value
	° ' "	° ' "	° ' "	"
<i>2 Right</i>				
<i>1 Right</i>	<i>232 25</i>	<i>232 23</i>	<i>232 24</i>	} <i>27.5</i>
<i>Centre</i>	<i>231 56</i>	<i>231 57</i>	<i>231 56.5</i>	
<i>1 Left</i>	<i>231 30</i>	<i>231 31</i>	<i>231 30.5</i>	} <i>26.0</i>
<i>2 Left</i>				

Mean Value Per Division: *27."* Date: *4/10/1977.*

Figure 15 - Example of Plate Bubble Calibration : Wild-T2

immediately evident within the original confines mentioned above, and accordingly the experiments were amended to incorporate dislevelments with an increased maximum of 10 minutes of arc. Within these new limits movements in scale values were detected and results showed that the error decreased or increased as a regular trend according to the changes made in level.

If the gyro internal collimation system had been in total agreement with the theodolite collimation axis it is doubtful if any shift in scale position would have been observed. This is because the vertical plane of dislevelment occurs in the same plane as the projected image of the centre of oscillation. The gyroscopic pendulum moving slightly backward or forward as the tilt of the

instrument is increased or decreased.

Therefore if slight dislevelment occurs in the True North direction changes in scale reading would not be apparent from observations on the gyro scale. If, however, dislevelment occurs in directions either side of True North the effect should be more noticeable. Figure 16 illustrates scale movements associated with dislevelment in the direction of the meridian.

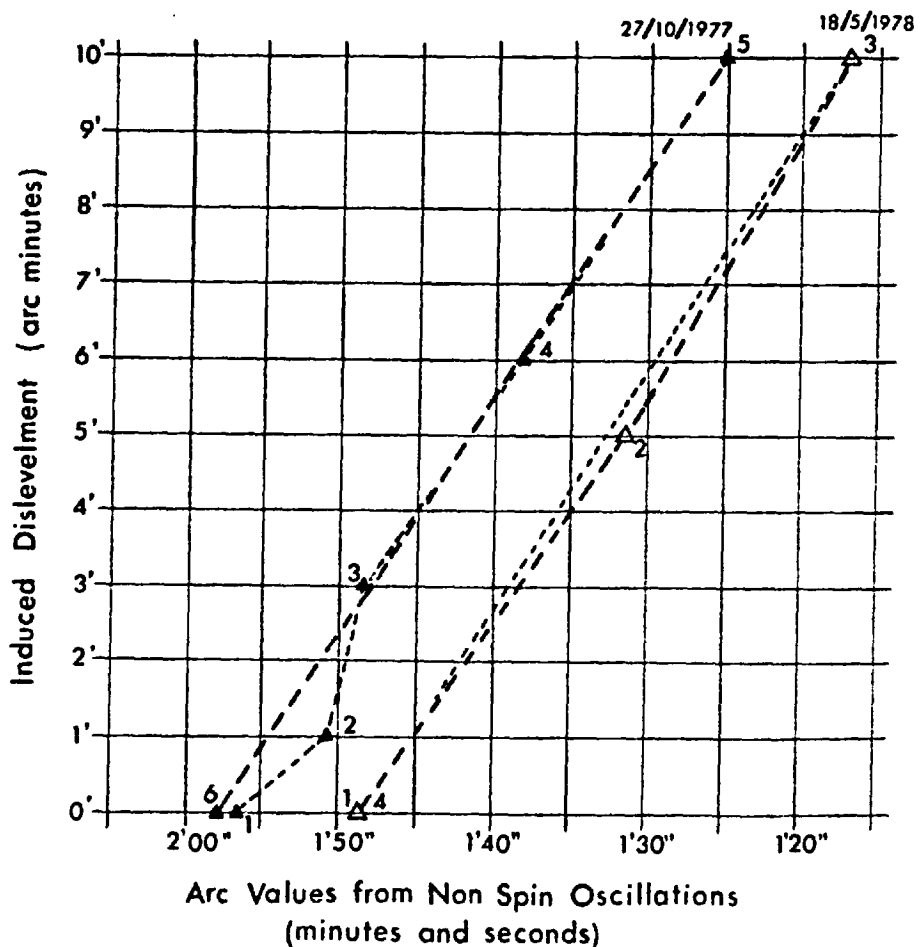


Figure 16 - Typical Examples of Dislevelment in Meridian

8.5.2 Dislevelment to the East and West of the Meridian

Experiments were conducted with the theodolite collimation axis being aligned at various pointings close to True North. Differing amounts of dislevelment were introduced and results taken from both the Non Spin and Power Spin modes. The amount of dislevelment was either increased gradually during the same oscillation or in steps between completed sets of Non Spin and Power Spin observations.

a) Non Spin

It was found that as dislevelment increased either to the east or west of True North within the original confines of 60" of arc, the value for the centre of oscillation showed similar shifts. In Figure 17 the plotted experimental results show this regular trend as recorded from typical observations carried out with the Wild G.A.K.-1. Similar trends were observed in non spin sets taken before and after the normal power spin-up.

b) Power Spin

Figure 18 shows results from observations taken on various headings around True North. Similarly to the non-spin sets, a trend of increasing error commensurate with increasing dislevelment, is clearly visible. However, the power spin trend appears to be less definite as dislevelment increases, with the total spread of error at 1 minute considerably more than seen in the non-spin results. Comparing Figure 17 and Figure 18 the general trends

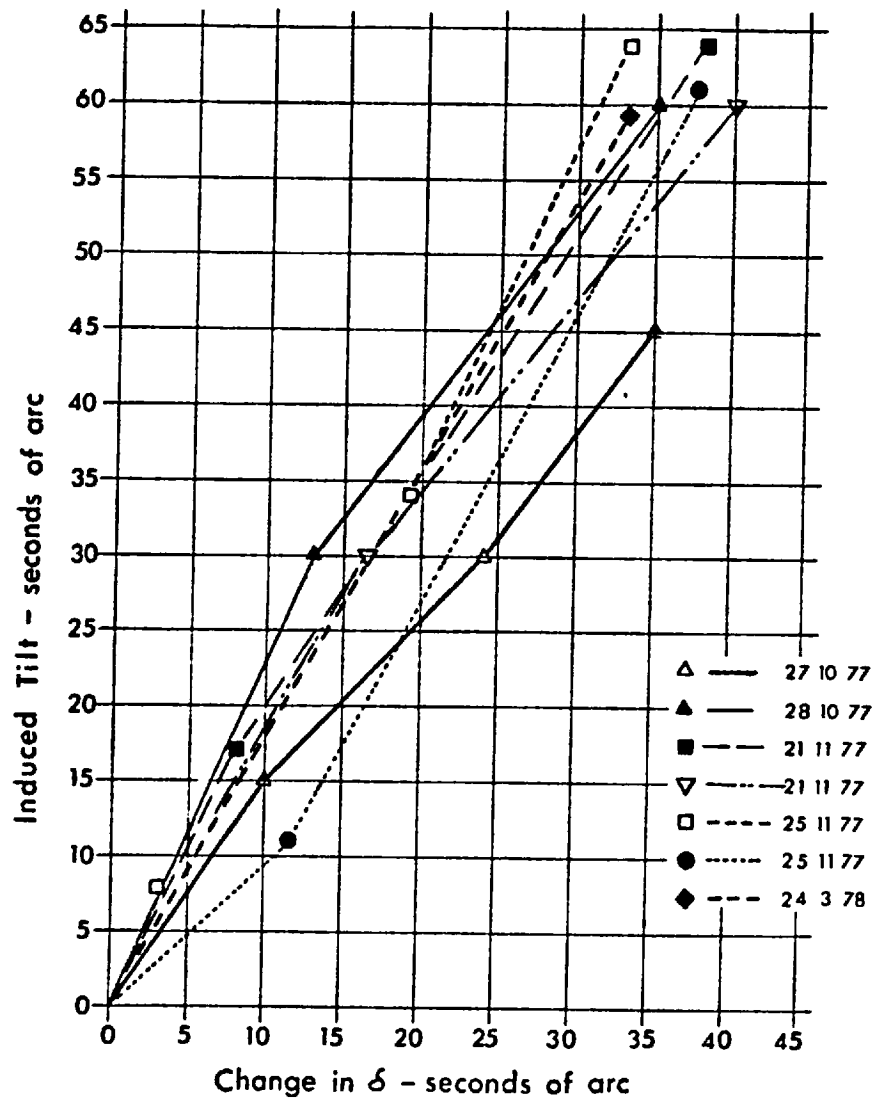


Figure 17 - The Effect of East/West Dislevelment on
Non Spin Values

indicate that under similar conditions of dislevelment non spin values appear to be affected to a greater extent than those involving power spin.

The two series of observations bore out the original assumption that error would increase with dislevelment owing to the pendulous form of the suspended gyro. In both sets of results some of the

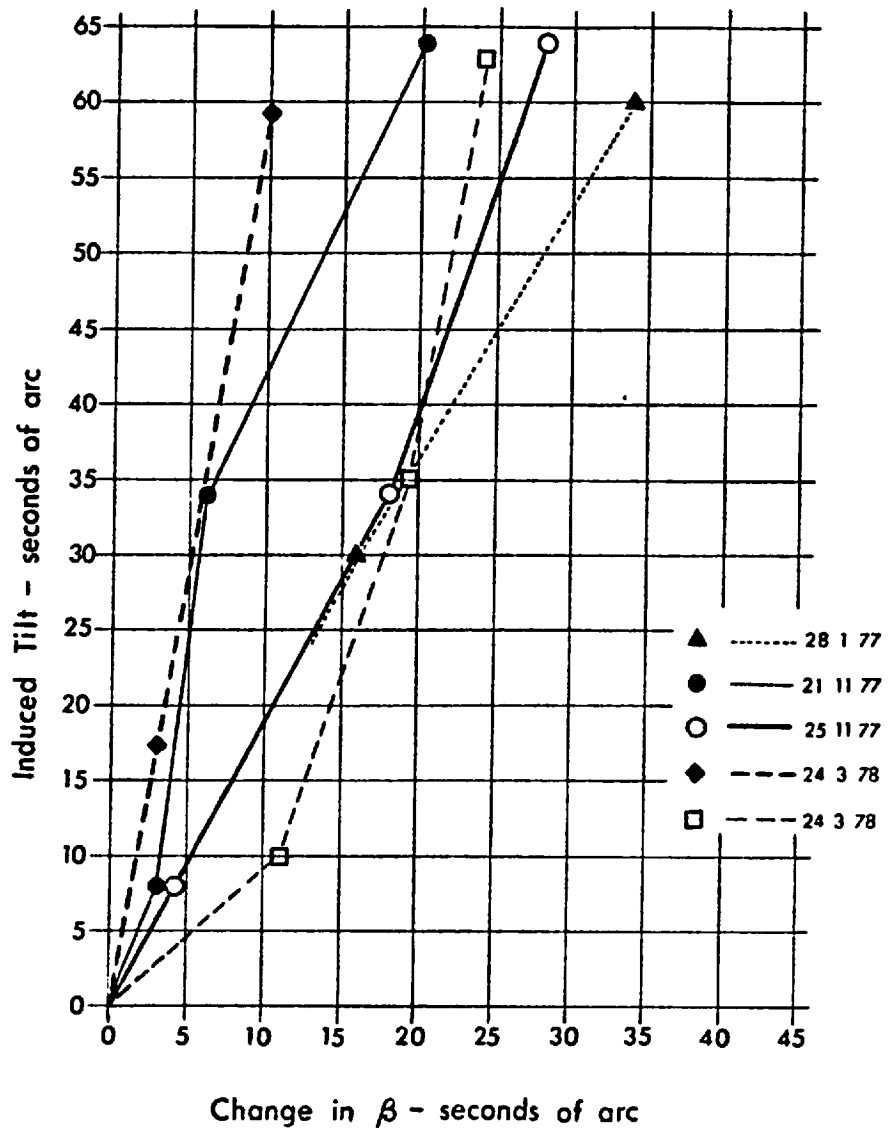


Figure 18 - The Effect of East/West Dislevelment on Power Spin Values

movement may have occurred due to drift - a subject which is discussed more fully in a later section - especially in those trials which spanned longer time periods.

Accurate levelling is therefore seen to be of importance for gyro-theodolite work and careful attention should be paid to keeping a check on the level during observations. In all the work carried out

at the Royal School of Mines it has been normal practice to level the theodolite by using the prism coincidence bubble. This bubble is more precise than the normal plate bubble found on most equipment and is also the bubble nearest to the position of the gyro attachment. During the observation the horizontal plate bubble should be watched as an indicator of East - West levelling and more important, the alidade bubble should be regularly checked for any movement in the direction of the meridian. Dislevelment in the North/South direction cannot be detected on the gyro scale as stated earlier. It would appear to be extremely difficult to adjust any results for dislevelment unless it were possible to measure such movements in all directions. The suspended gyro unit is a pendulum and will precess around True North from a position perpendicularly below its suspension point.

8.6 TECHNIQUE OF OBSERVATION

The technique advocated at the Royal School of Mines comprises taking a "balanced pair" of observations around True North using the same spin-up. As explained in later sections dealing with experimental observations the result obtained from the first circle reading position provides the information for calculating the second circle position. Once calculated the theodolite is gently moved to the second reading using the horizontal plate tangent screw. By adopting such a technique any inaccuracies of the constant C are eliminated through meaning the two results from the same spin-up.

9 - INTERNAL FACTORS

9.1 DRIFT

Introduction

The term drift in the context of this thesis describes movements in the direction of True North as indicated by the gyro over periods of time.

During the research period it became possible to identify several forms of gyroscopic drift and therefore, to clarify the following section a sub-division of the various forms is suggested below:-

9.1.1 Short Term Drift in the Spinning Mode:-

- 1a) Primary Drift
- 1b) Secondary Drift
- 1c) Tertiary Drift

The terms Primary, Secondary and Tertiary refer to the order in which the forms are able to be identified within a spin-up and do not reflect any form of classification of intensity or importance.

9.1.2 Long Term Drift in the Spinning Mode:-

- 2a) Period of Weeks and Months
- 2b) Period of Years

9.1.3 Short Term Drift in the Non-Spinning Mode.

- 3a) Short Term Drift Before and After
Extended Power Spin

9.1.4 Long Term Drift in the Non-Spinning Mode.

The main difference between Short and Long Term Drift is that the Short Term forms are concerned with movements which can be detected within either one, or a number of spin-ups during one day, whereas Long Term Drift describes movements of the indicated positions which take place over a period of days, months or years which incorporate many separate observations.

It is intended to discuss the various forms of drift, to suggest any cause and finally to examine what value, if any, the knowledge of the existence of drift has for practical observational purposes.

9.1.1 Short Term Drift in the Spinning Mode

9.1.1a) Primary Drift

Primary Drift is the initial movement of the mid point of the oscillation which occurs immediately after spin-up has taken place and the gyro unit carefully suspended. This form of drift has been found to last for a period of between 80 and 90 minutes and is seen to be most rapid during its early stages. Graphical plots have been made of successive groups of mid-swing points to avoid the problem of auto-correlation of results; a typical plot is shown in Figure 19.

Gregerson^{(20) (21)} reported a form of Drift in connection with his work with the M.O.M. GiBl1. He noticed that after an early rapid shift in the indicated values the rate of drift steadily decreased until a point was reached when it was concluded that the remaining

minor movements could be regarded as linear. Gregerson was of the opinion that accuracy could be improved by allowing time for the gyro to "warm up" before serious observations were taken. In this way the influence of the period of drift could be minimised. Later work by Gregerson⁽²¹⁾ indicated "the drift is exponential with a time constant of about four hours. Thus in a short interval

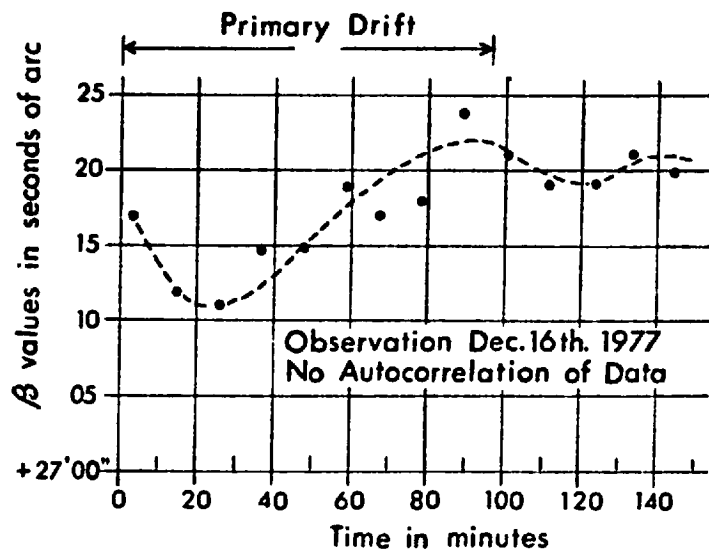


Figure 19 - Illustration of Primary Drift under Power Spin

of half an hour it does not deviate from linearity significantly ...".

Gregerson's published results⁽²⁰⁾ were re-examined by Thomas⁽⁹⁾ who came to the conclusion that the drift pattern resembled a normal decay curve due to the effect of injecting heat during spin-up and suspending the gyro. Drift should, therefore, continue to decrease exponentially with results showing very small random deviations around the increased flattening of the die-away curve.

Similarly standard works on gyroscopic theory and design report early rapid decay.

Investigations over a four year period with both Wild and M.O.M. equipment have verified the existence of this form of drift. Most of the evidence concerns Modified Wild G.A.K.-1 gyro attachments but similar results have been obtained with the M.O.M. GiB1 and GiC11.

With reference to the Wild G.A.K.-1 it has also been possible to identify several phases during this primary period. Although the behaviour of several instruments have displayed certain similarities the direction of drift in respect to the North Meridian during the first twenty minutes of an oscillation cannot be confidently predicted. The amounts of drift detected during this early period have varied between 2 and 12 seconds of arc - see Figure 19. This "random" directional drift is caused possibly by variations in the skill applied by the operator in suspending the gyro unit after spin. Any major vibrations induced during suspension of the unit dictating both speed and direction of drift.

After this initial period the direction of drift becomes constant. In the case of several modified G.A.K.-1 machines the direction of drift causes an increase in scale values when headings are chosen west of North and a decrease in scale values when headings are chosen east of North. During this period of approximately 50 minutes the drift of the gyro has therefore been towards the west. The amount of drift during this phase has varied between 6.5 and 16 seconds and, according to spin-up, has meant either a complete reversal in the direction of drift or in one or two cases a continuation of the direction taken up during the first 20 minutes - see Figure 19.

Only one G.A.K.-1 instrument examined to date has shown the

reverse pattern of the above; this instrument displaying a constant easterly drift.

One fact to emerge from experiments with several G.A.K.-1 attachments is that the amount of drift during this primary period will vary a little according to the heading of the equipment. In instruments which display a westerly drift pattern the amount of drift has always been slightly more when headings are taken East of North than when headings are selected West of North.

Continuing from the two phases mentioned above a further ten or twenty minutes (ten minutes occurring in only one experiment) remain in the primary period during which time the observed values reach the entry point of the Secondary phase. Amounts of drift during this time have been small and have varied between non recorded to 5 seconds. In some cases this has meant a reversal in the direction of drift, which again cannot be predicted during the observation. However, after completing the full experiment the direction can be seen as always towards the point where secondary drift becomes detectable.

In summary it can be stated that after an initial settling down period of approximately twenty minutes the Wild G.A.K.-1 gyro drifts steadily in a predicted direction for a further 60 - 70 minutes along a path which resembles a normal exponential decay curve.

The amount of constant drift indicated cannot be discounted by waiting simply a couple of swings to allow the suspension to settle down. Certainly time should be allowed for vibration to subside and any heat to dissipate but the drift trend continues for at least

twenty two swings before steadying into a more regular pattern - far more time than occupied by the normally accepted observation procedures.

Only limited work has been possible with the Hungarian Gyro instruments but sufficient results have been obtained personally, and by examining raw data published by other authors, to indicate a similar constant movement of the initial drift pattern. However, the trend does not show the secondary drift reported in the following section but moves directly into the tertiary form. This difference in behaviour is most probably due to differing constructional techniques involved in the suspension tape and its mechanism.

9.1.1b) Secondary Drift

This form of drift has been reported previously during 1967 - 1970 by observers in South Africa and Canada. Williams and Belling 1967⁽²²⁾ mention a so called Quasi Harmonic or SHAR effect (Secondary Harmonic) which occurred during protracted oscillations with a standard G.A.K.-1 gyro attachment. The authors observed single oscillations over time periods of between one and a half and two and a half hours. During these observations the mid point of groups of oscillations were constantly recorded and plotted graphically. The final graphs - see Figure 20 - displayed an underlying trend of an harmonic nature having amplitude values varying between 30" and 50". Using the published data it is difficult to obtain a precise value for the period of such drift owing to the series being of short duration and also that in only one case was a full period obtained. The authors plotted the results as variances around a horizontal axis 't'.

however if the evidence contained in the following section of this thesis, on tertiary drift, is accepted then it would be possible to attempt a correlation of these results to give a period of just under two hours. This "suggestion" would be correct for 4 out of the 5 series published - the fifth having a period of one

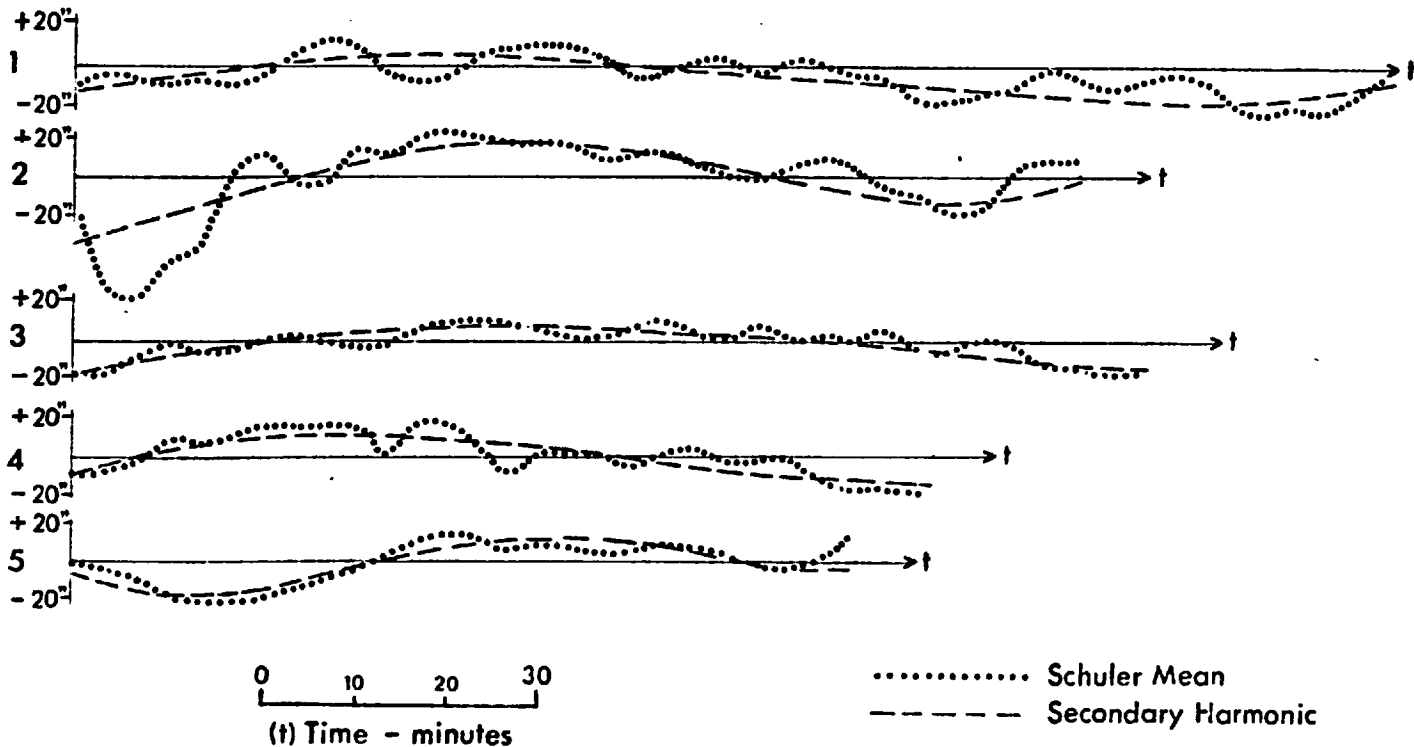


Figure 20 - Examples of Quasi-Secondary Harmonics from
Observational Data (SHAR Effect)
(Williams and Belling, May 1967)

hour. It should be stated that this form of correlation cannot be regarded as completely reliable as the series are not of sufficient length. The authors also stated that similar results were obtained with the Fennel KTL and a second Wild G.A.K.-1.

In 1969 and 1970 Chrzanowski⁽²³⁾ ⁽²⁴⁾ published results of investigations into harmonic drift using a G.A.K.-1 and a TKW gyro attachment. Investigations were carried out at intervals over

periods of 24 hours continuous spin. Results confirmed the work of Williams and Belling and because of the duration of observations, values for the period of the harmonic drift were obtained. Chrzanowski stated that amplitudes with the G.A.K.-1 varied between 20" and 80" within a single spin whilst with the TKW varied between 20" and 40". The harmonic period of the G.A.K.-1 was just short of two hours whereas in only one experiment out of three conducted with the TKW were definite secondary harmonics observed, these having a period of approximately 3.5 hours.

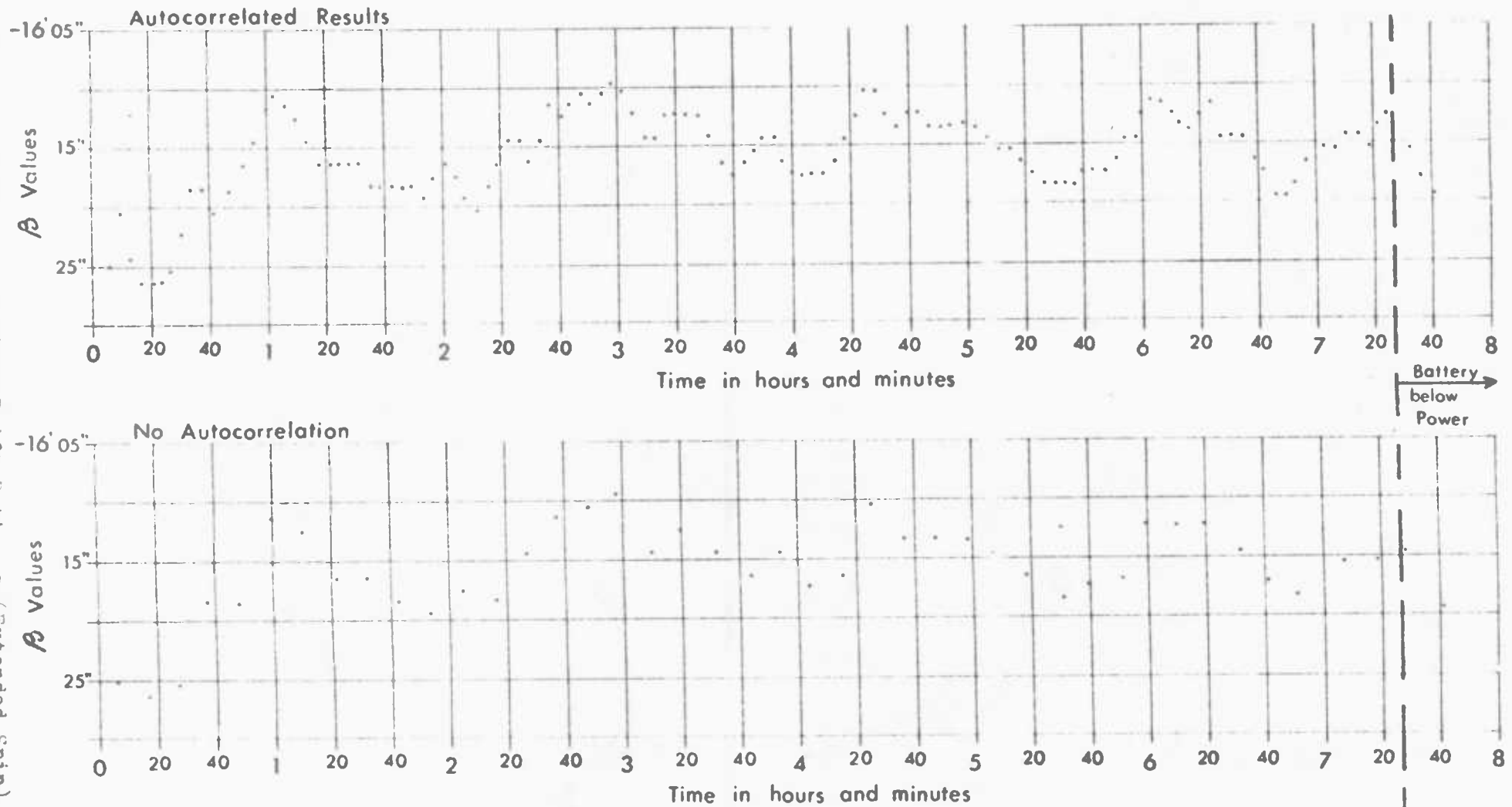
In 1971 Halmos⁽¹⁴⁾ published details of 13 hour and 12½ hour trials conducted with the M.O.M. GiB1 and M.O.M. GiB2 in which he states that "A rapid survey of the figures reveals already that there are scarcely any periodicities". An harmonical analysis was then carried out with a Cellatron SER 2C computer to provide an unbiased machines eye view of the results. Amplitude spectra and autocorrelation functions were examined and the investigations indicated that "long measurement series have no harmonical character".

Present investigations into secondary phase drift have been carried out with modified G.A.K.-1 attachments as it was felt that the micrometer system of the modified instrument would enable the amplitude readings to be taken more accurately and that experiments could be undertaken over a greater arc spread than was possible with standard conventional measuring techniques.

A typical set of results is shown in Figure 21 where the secondary drift pattern can be seen clearly. The various sets of

December 13th 1977 R.1-46

Figure 21 - Primary and Secondary Drift Patterns (Extended Spin)



information, gathered from runs covering observations taken over periods extending to 10 hours were processed through a computer programme to examine the power of rhythmic drift. Computer analysis confirmed that which was graphically obvious and even assuming the results contain random measurement errors it would be difficult to assume that the total pattern itself is of a random nature.

The immediate reaction to these results was to attempt to correlate the feature with the skill in suspending the spinning gyro from its caged position. Several experiments were carried out with deliberate vibration being given to the spinning mass by lowering roughly or by taking the cage halfway up just after suspension and "nudging" the gyro unit. In all cases there were no detectable alterations in either the period and amplitude of Secondary Drift, or in the direction of Primary Drift.

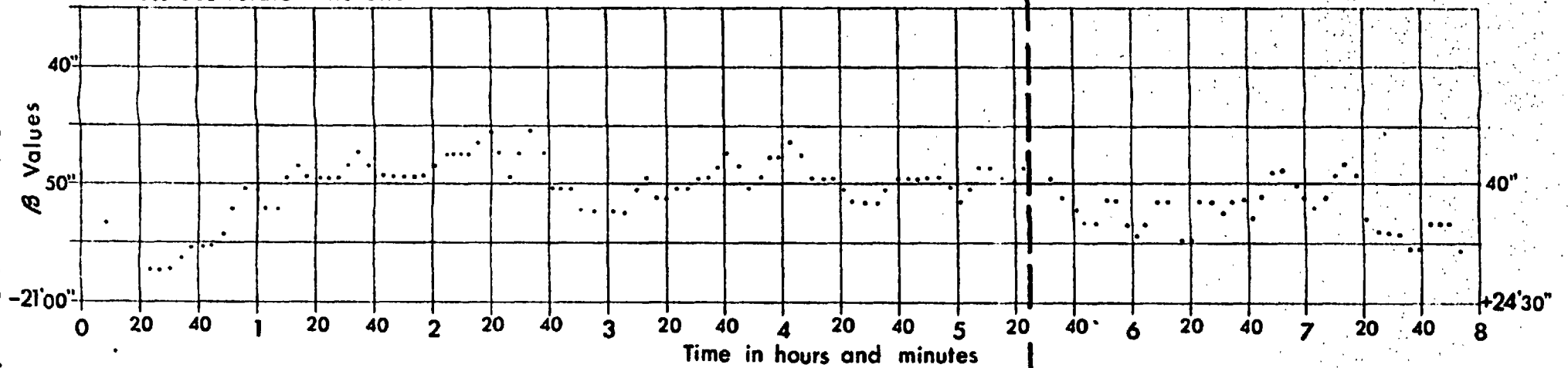
In one experiment - the one indicated in Figure 22 - considerable interference was given to the gyro by raising and lowering the gyro cage which required eventually careful and repeated damping to contain the oscillation on the scale.

With the wild G.A.K.-1 instruments used during the experiments the range of drift has not exceeded 10 seconds which is considerably less than the range reported by Williams or Chrzanowski, possibly this can be explained by the differing observational techniques or by slight changes in the gyro design.

A set of control curves with amplitudes varying between 5 and 10 arc seconds were plotted on stabilised plastic film and used to overlay plots of previous trials carried out when investigating

December 20th 1977 R.1-46

Autocorrelated Results



No Autocorrelation

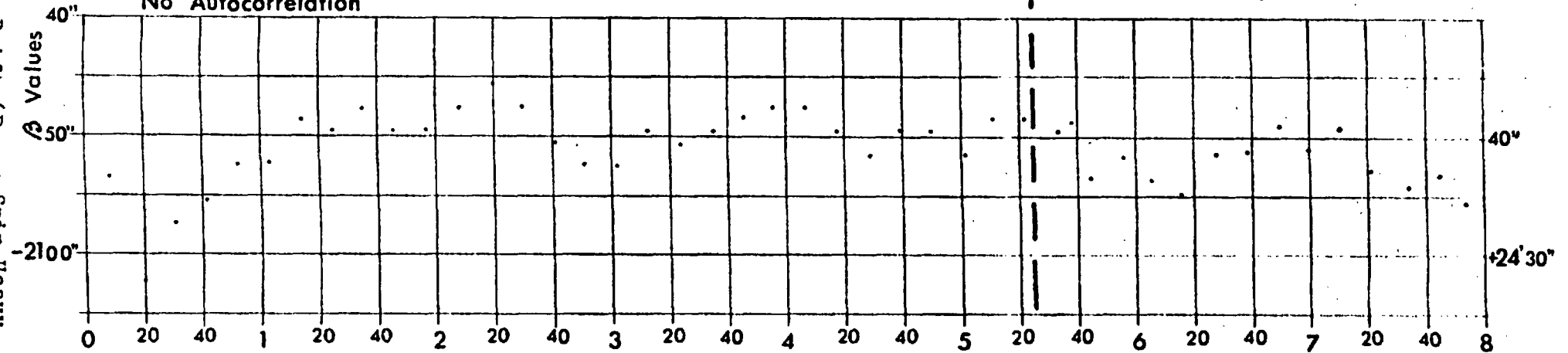


Figure 22 - Primary and Secondary Drift (Power Spin Heavy Damning of Oscillation Required)

damping factors. In these experiments measurements were taken only at 20 minute intervals over total time spans of between 6 and 8 hours. It was possible to fit such curves to these skeleton results and also to those obtained by other operators using similar equipment.

A separate series of experiments were carried out in July 1978 - see Section 10 - using differing voltages and it is significant that the secondary short term drift patterns were absent when voltages below those recommended by the manufacturers were used. Compare Figure 24 with Figure 41.

It can therefore be stated that results obtained from several different Wild G.A.K.-1 gyro attachments indicate that if observations are extended beyond one and a half hours the drift pattern does not stabilise or remain steady and cannot be regarded as a linear movement through random values.

9.1.1c) Tertiary Drift

This form of drift has been reported by Chrzanowski⁽²³⁾ whose results were not really conclusive. Using the standard G.A.K.-1 and TKW gyro attachments he was able to plot a series of results over 24 hour periods using the same spin-up. As mentioned under 9.1.1b he was able to detect secondary drift in several of his observations but then using the same results he was also able to identify a further trend which ran steadily through the original drift pattern.

It is interesting to note that Halmos's⁽¹⁴⁾ computer programme stated correctly that small periodic harmonics (secondary drift)

were not contained in the observation but on the other hand failed to indicate the presence of a considerable sinusoidal trend with a period of some 12 hours. Admittedly the trend is not perfect, as can be seen in Figure 23 and includes two obvious areas where fitting is ambiguous but the overall trend appears to be there and would seem difficult to describe as being random.

The presence of such tertiary drift in observations carried out at The Royal School of Mines became apparent when attempting computer analysis of earlier work on secondary drift. Initial analysis was hampered by an underlying "long low roll" throughout the results which had not originally been detected on a regular scale graphical plot. It was at this stage that the decision was taken to carry out more lengthy trials in an attempt to identify the form of this latest drift pattern.

Owing to the difficulty in persuading other owners of equipment to allow long duration tests, all very lengthy trials have been limited to The Royal School of Mines prototype attachment.

Trials were extended to periods of 16 hours and were designed to collect as much data as possible throughout the runs. Amplitudes, and times at the centre and at selected points throughout each oscillation, were taken, together with continuous monitoring of the d.c. voltage being supplied.

A typical set of reduced results from consecutive groups of amplitudes is shown in Figure 24. Owing to the expected small range of this tertiary pattern the scale of arc values has been increased

Figure 27 - Extended Spin Data (MOMOS 1971)
(1971) MOMOS 1971 (MOMOS 1971)

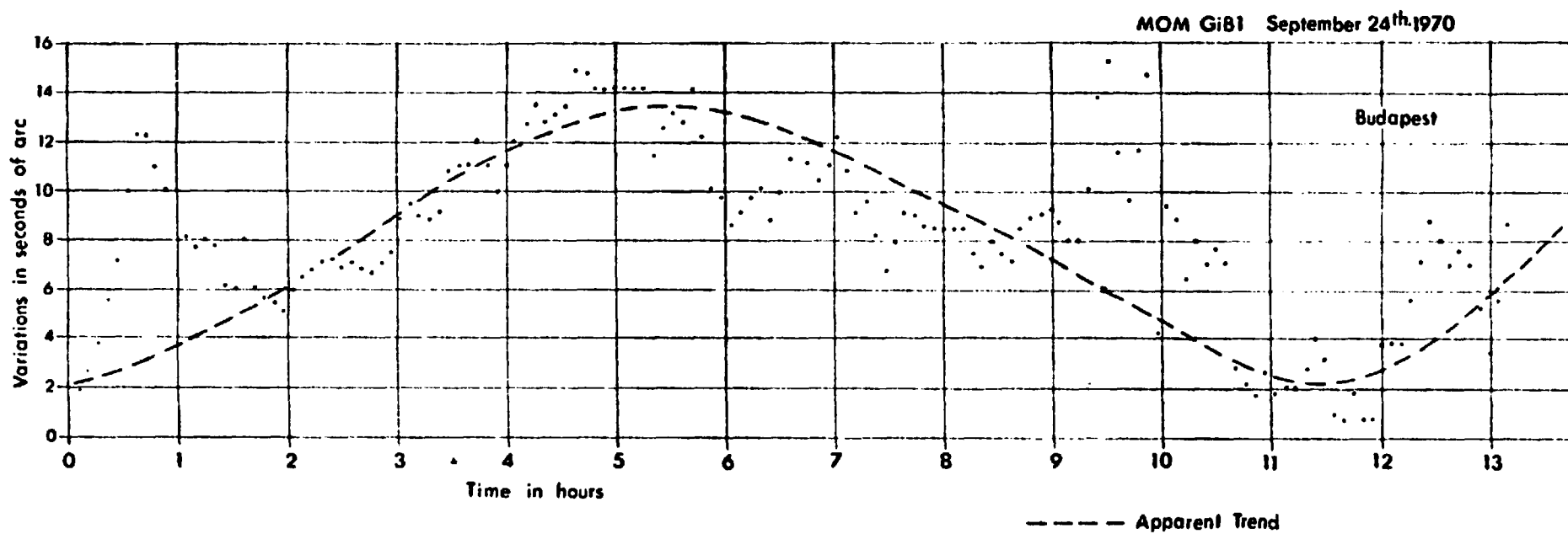
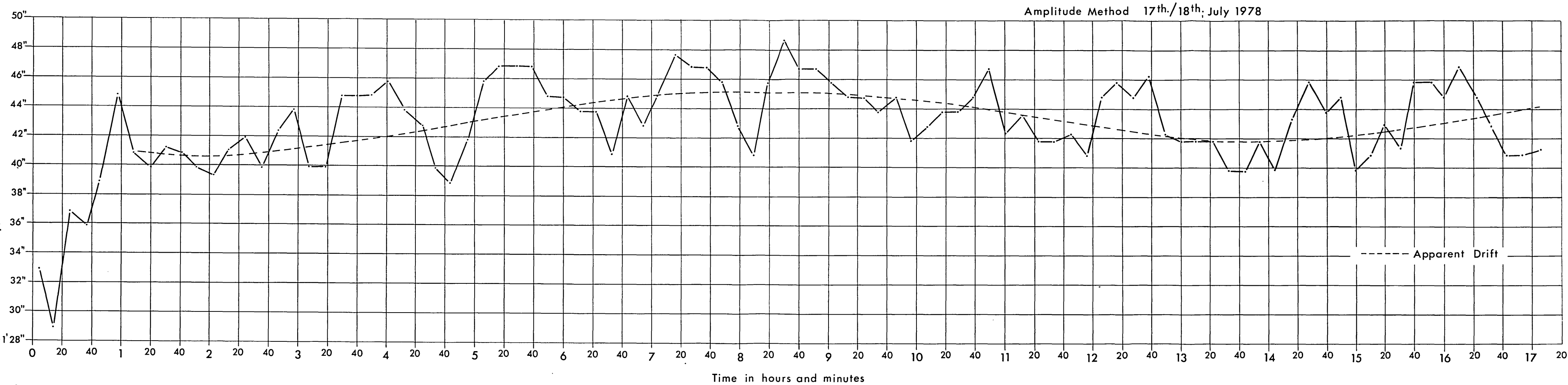


Figure 24 - Extended Spin : Wild G.A.K.-1 - 12 Volts



considerably. However, from the figure, ignoring the primary pattern of the first 80 minutes, the expected secondary drift pattern is seen clearly superimposed over the controlling tertiary trend. In this example the period of tertiary drift is approximately 12 hours and the amplitude around 4 seconds of arc.

This figure should be compared to Figure 23 plotted from results published by Halmos. As can be seen the presence of such a trend is evident in various designs of gyro-theodolite.

In conclusion to this section on tertiary drift mention should be made of yet a further separate drift pattern which emerges beneath the secondary and tertiary trends. In both Figure 24 and Figure 41 it is possible to identify a general increase in values throughout the whole trial period.

Possibly over even longer periods of spin this also would develop sinusoidal qualities but at this stage it is proposed to state merely the existence of such a drift pattern. Investigation of this effect may be thought possible or worthwhile in the future.

9.1.2 Long Term Drift in the Spinning Mode

9.1.2a) Drift Occurring over a Period of Weeks

Long term drift of this nature has been reported by several authors. The Hungarian GiC2 which was investigated in 1974⁽⁹⁾ showed a dramatic drift trend of some 120 seconds over a period of 35 days. In this particular case the drift pattern was so stable

that the amount of change to be expected in future observations could be predicted with some accuracy. A standard Wild G.A.K.-1 attachment also displayed such a drift trend but this particular instrument was reputed to be very old.

Subsequent tests on both Wild and M.O.M. equipment have discovered varying amounts of similar drift but on a much smaller scale than reported above. Possibly the most obvious case to date was seen in the new modified G.A.K.-1 attachment belonging to the National Coal Board, South Midlands area. This instrument was tested on The Royal School of Mines base line for three weeks and during this period the mid oscillation scale values, showed a regular trend amounting to 20 seconds. Results of these trials are shown in Figure 25.

9.1.2b) Long Term Drift Occurring over a Period of Years

At present it has not been possible to identify any regular or rhythmic patterns of drift extending throughout a period of this length. It would seem prudent to suggest that it is highly unlikely that any such form will be identified other than in equipment kept under laboratory conditions throughout its working life. Exposure to the normal working conditions encountered during azimuth determination exercises could induce minor disturbances to the equipment which would outweigh any noticeable rhythmic fluctuations.

The only authors who have presented evidence of this form of drift are Hodges and Brown⁽²⁵⁾. In data examined it was possible to plot the amount of observed drift as a variation in the additive

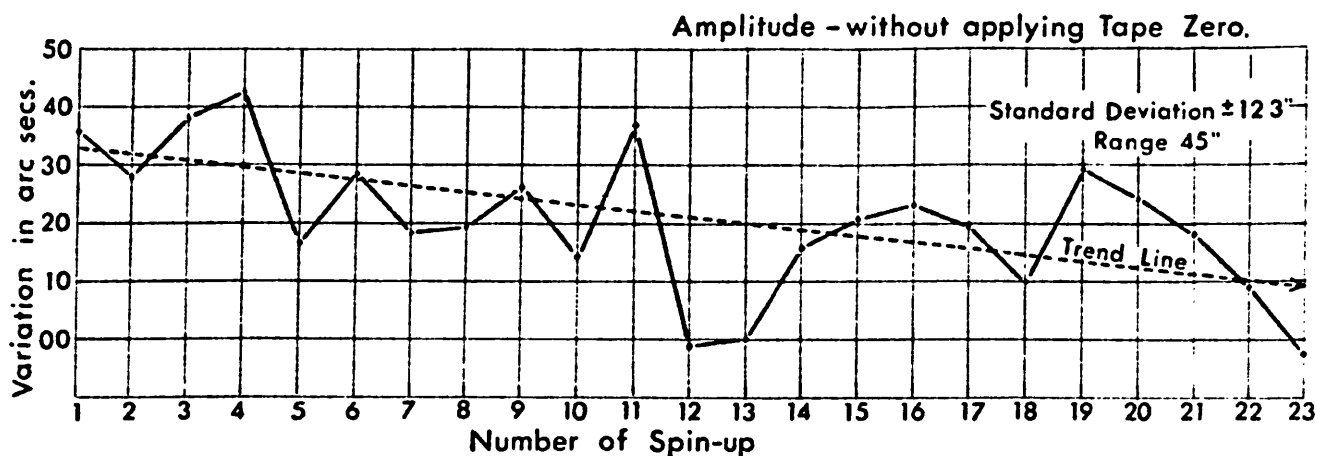


Figure 25 - N.C.B. South Midlands G.A.K.-1 Gyro Attachment
T-16 Theodolite

factor (K-factor) required to adjust the observed to the known azimuth. Results indicated that during early use, drift remained reasonably steady, but eventually the four instruments which were examined began to show more radical changes - see Figure 26. Within the accompanying text is a reference to the number of observations carried out with each machine (Instrument No. 8238 - 444 observations; Instrument No. 6772 = 525 observations; Instrument No. 3160 = 236 observations and Instrument No. 3220 = 277 observations) and it is pertinent to observe that the two instruments having had almost twice the usage as the other two show the greater drift. A graph containing a horizontal axis linked to numbers of observation may possibly have yielded greater overall correlation as it would appear that this form of drift is more likely to be a function of hours used rather than pure time, affecting items as tape, suspension, bearings and motor systems.

It is possible and in fact highly probable that excess vibration or movement encountered in transporting equipment, for example by

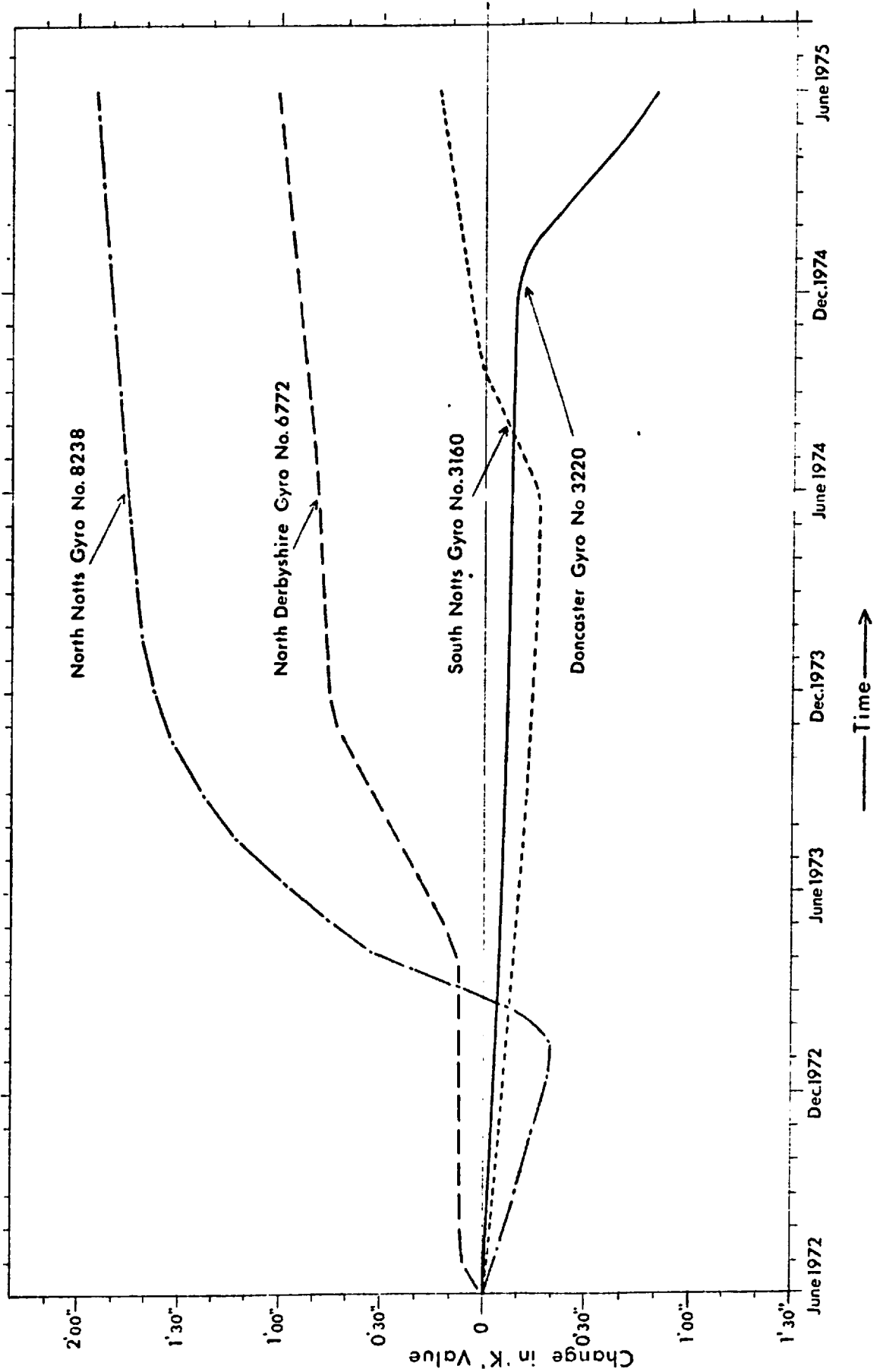


Figure 26 - K-Factor Drift for the Four Wild G.A.K.-1 Gyros
(Hodges and Brown 1976/1977)

helicopter, could cause shifts in the calibration of an instrument and subsequent change or drift in the bearings indicated. This form of change is usually easy to identify but if the equipment was subject to slight accidental knocking whilst under power spin during an observation the change in calibration would be very small and could quite easily be misidentified as drift of the gyro system.

From experience with the Royal School of Mines gyro attachment over a period of five years it is possible to link several separate cases where air transportation has been followed by changes in the additive factor or drift.

Further changes have also occurred immediately following lengthy periods of laboratory trials which have involved extended suspension, dislevelment, or temperature variation. In these cases it has been observed that the drift is more noticeable in the non-spin mode and that after a short period of time the changes slowly become rectified.

9.1.3 Short Term Drift in the Non Spinning Mode

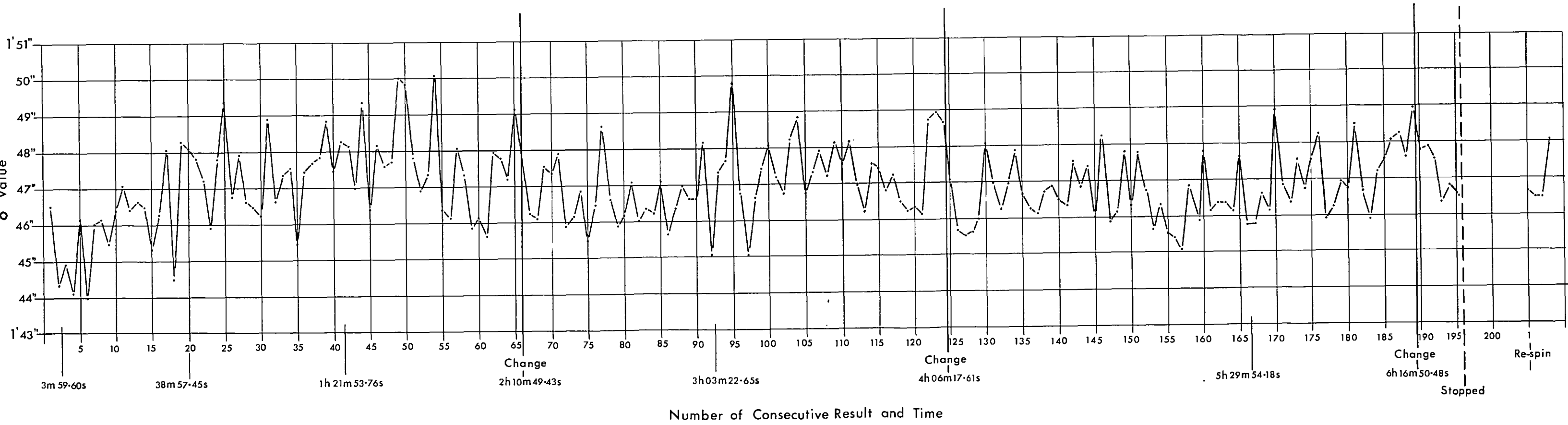
Following the results recorded above, an experiment was devised to investigate the possibility of short term drift occurring within the extended non spinning mode. The gyro attachment mounted on the theodolite was directed towards True North - as if preparing for a normal gyro azimuth determination - and the gyro spun for approximately ten seconds to remove any residual magnetism within the motor. By careful manipulation of the gyro cageing mechanism the gyro unit was suspended and given deliberately a swing covering as much of the scale as possible (i.e. + 14 to - 14 scale units).

Using the amplitude technique of observation successive reversal points or amplitudes were recorded until the non-spin oscillation had decayed by normal damping to barely a division either side of the central scale marker. At this point the gyro unit was gently "nudged" by raising the gyro cageing mechanism in order to induce an increase in swing. Successive reversal points were again recorded until it became necessary to repeat the exercise described above. In this way it was possible to observe the behaviour of the non-spinning mode over a greater range of time using theoretically the same oscillation. Obviously great care was taken not to introduce additional movements or vibrations into the system by rough handling. A typical example of the reduced results from such an experiment which ran for 6 hours 30 minutes is shown in Figure 27.

Shorter series were also conducted without interfering with the decaying oscillations. Figure 28 is a typical example of one these observations.

Analysing these results, using the same computer programme as for drift under spin, it was possible to identify definite wave patterns which, even by cursory examination of Figure 27, can be seen clearly. The wave patterns bore a remarkable similarity to those observed whilst the gyro was under spin - see Figures 3, 5 and 7. In addition, the gyro unit in the non-spin mode drifted in the same direction as the unit when under power - i.e. if the unit under power drifted westward the corresponding drift of the non-spinning unit, immediately after suspension, was also toward the west.

Figure 27 - Extended Spin - Non-Spin Mode - Wild G.A.K.-1



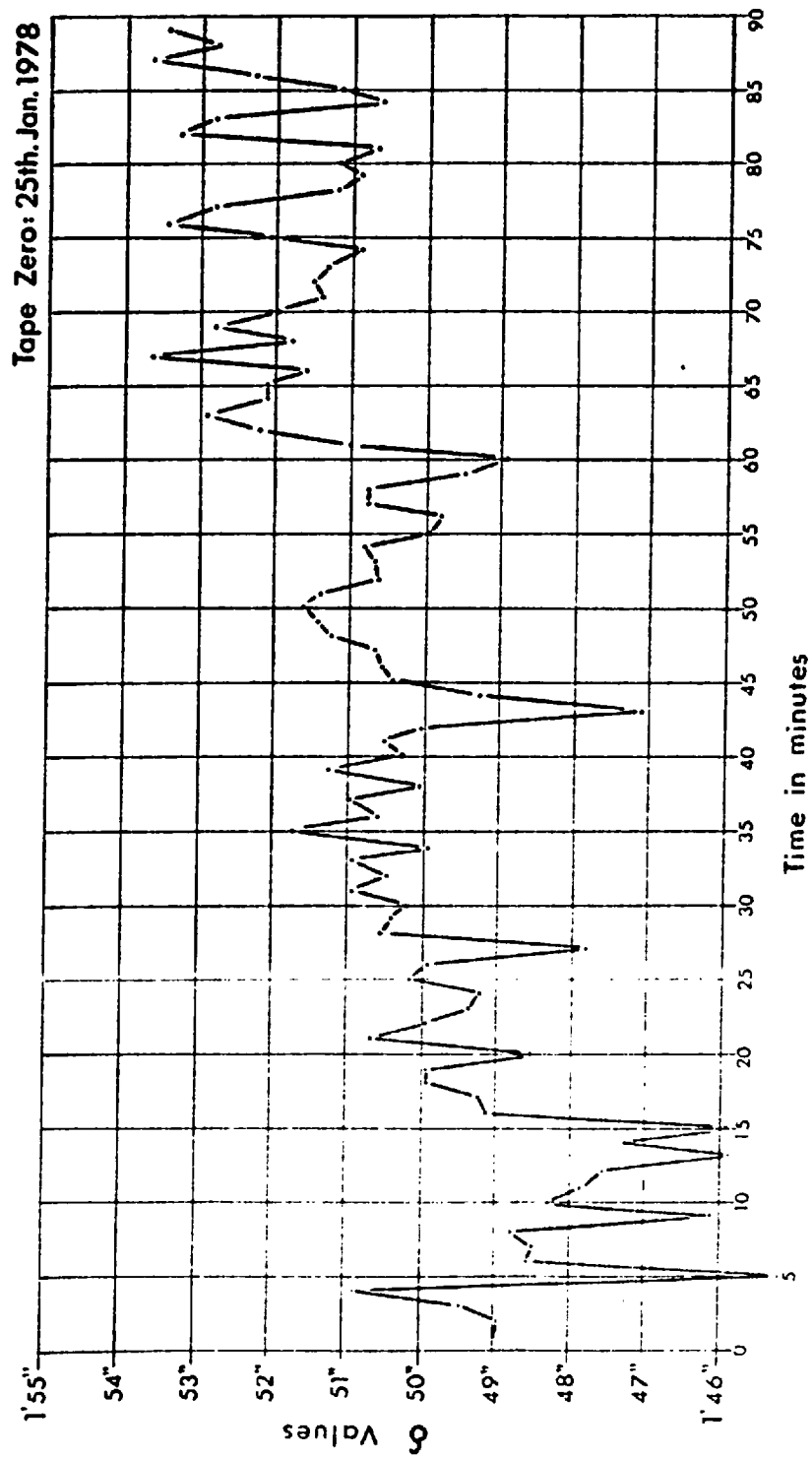


Figure 28 - Non Spin ('Tape Zero') Drift - Extended Oscillation

Wild G.A.K.-1

The total range of all experiments rarely exceeded 8 seconds of arc. Non spin values were obtained by multiplying mid swing positions by C (0.318 in Figure 28); if these mid swing positions had been multiplied by $(1 + C)$, as in the case of β reduction (Power Spin), the total range would become 21 seconds of arc. This is a further pointer to the similarity between drift of the non spin and power spin modes.

9.1.3a) Short Term Drift Before and After Extended Power Spin

This second form of non-spin drift became evident after experiments concerning short term drift during non-spin oscillations were analysed. With the overwhelming evidence of regular movements detected during these extended observations it was assumed that if a short non-spin observation were taken before and after an extended power spin it should be possible to predict the approximate amount and direction of non-spin drift during this period. However, when checking back over the extended power spin experiments it was found that the non-spin position recorded "after" the observations bore little relationship to the expected value based on the "before" non-spin position and time lapse. All experiments recorded a fall in value of the non-spin position, or a movement east, as opposed to the observed west movement mentioned in 9.1.3. This was obviously a second form of non-spin drift within the time of observation. Figure 29 shows the arc value of changes in non-spin position recorded during extended power spin experiments. It can be seen that the decrease in arc value against time lapse taken by power spin is reasonably regular for all results excepting two - result numbers 4 and 7 - an explanation for this is put forward later.

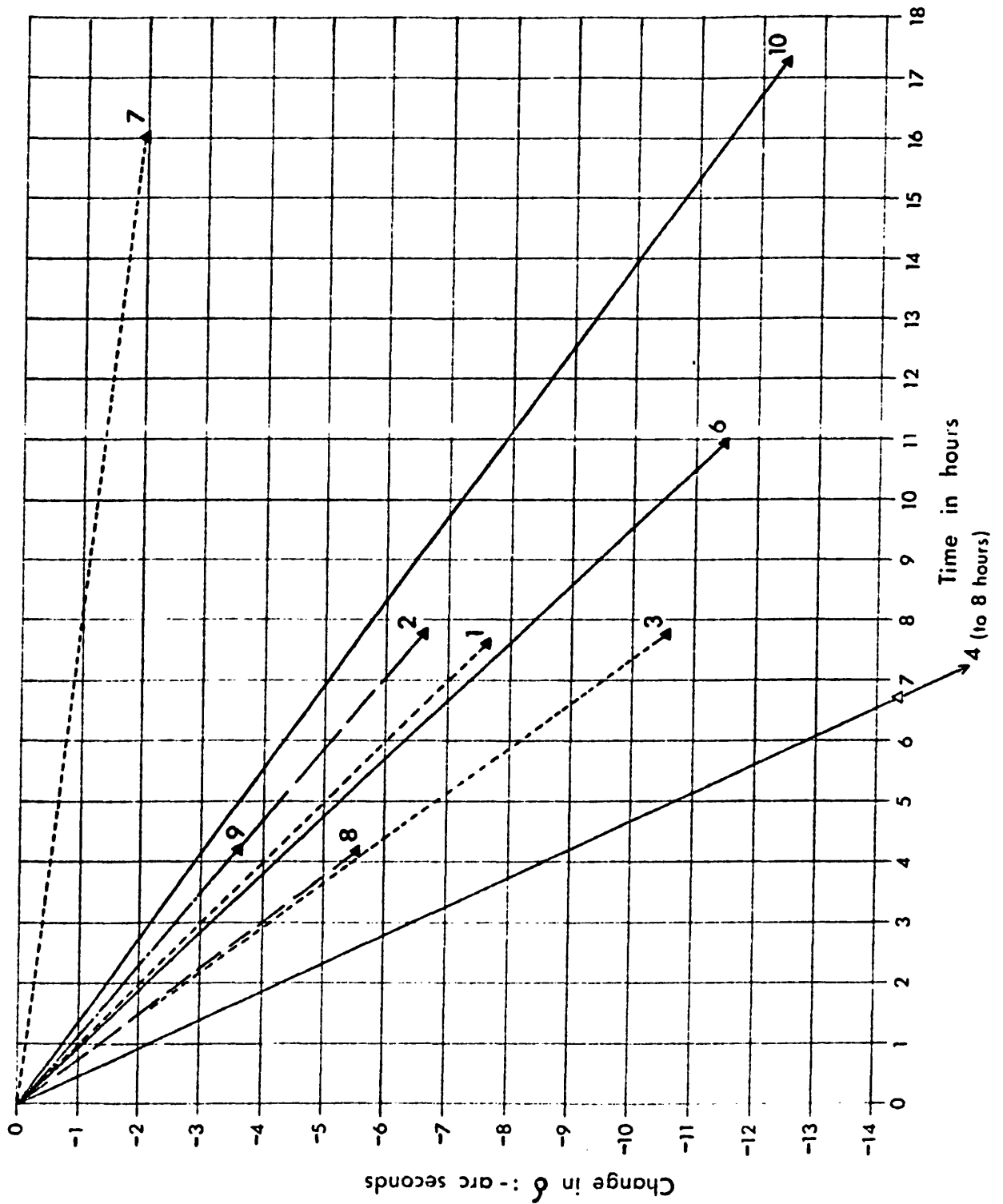


Figure 29 - Drift of Non Spin Tape Zero Values from Extended Spin Experiments (Values were recorded before and after each observation)

Because it is impossible to plot intermediate results during power spin the decrease has been shown as being linear.

Gregerson⁽²⁰⁾ showed that in experiments carried out with the M.O.M. GiB2, drift of the mid swing point in the non-spin mode was always towards the meridian where non-spin values were compared before and after each observation. This meant that when headings were chosen to the East of North drift was to the West and when headings were chosen West of North drift was to the East.

In all experiments conducted with Wild equipment no such corresponding evidence has been detected. All experiments showed consistency of drift direction according to the unit being tested and maintained this direction irrespective of heading.

9.1.4 Long Term Drift in the Non-Spinning Mode

This form of drift is illustrated excellently in Figure 30, where a drift of around 20 seconds was detected in the South Midlands (NCB) gyro over a period of 3 weeks.

In the Royal School of Mines gyro - now being used for its fifth year - changes in non-spin mid point position have been of a general random nature but at times over short periods tendencies towards a definite trend have been observed.

Owing to the controversy surrounding the necessity for recording non-spin information before and after observations there have been no other reports covering such a period of time and until

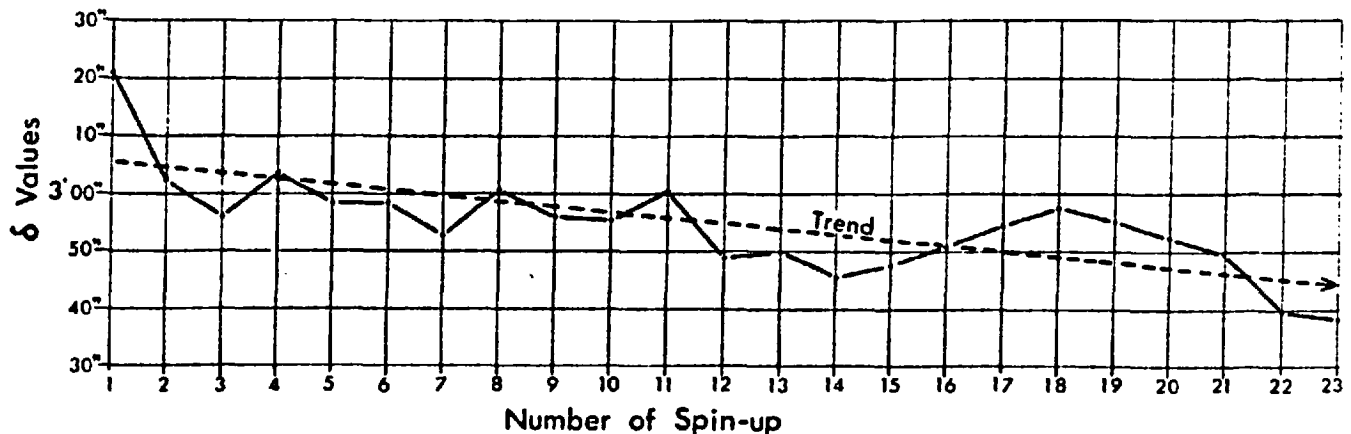


Figure 30 - Individual Tape Zero Values N.C.B. South Midlands
Gyro Attachment T-16 Theodolite

such results are available it would appear that any analysis of other results for the purposes of comparison would not be of value. It is worthy of note, however, that during these studies the two occasions where a sharp fall has been followed by a period of similar low values, have both occurred immediately after laboratory trials involving dislevelment and investigations into the behaviour of the gyro under lengthy spin or suspension. In both cases the non-spin mid point gradually regained its former value.

9.1.5 Stability of the Observed Drift Pattern

The majority of results contained within the sections on short term drift refer to single observations when the theodolite has remained in the clamped mode. Methods of observation at the Royal School of Mines incorporate taking the mean of a pair of balanced results either side of True North using the same spin-up. The possibility that changes in heading would affect the detected drift patterns was therefore of some importance.

9.1.5a) Stability during Power Spin

Experiments were conducted by setting the gyro spinning on a heading one side of True North, monitoring the mid-swing points from Amplitude readings and then moving the theodolite carefully to a new heading the opposite side of North.

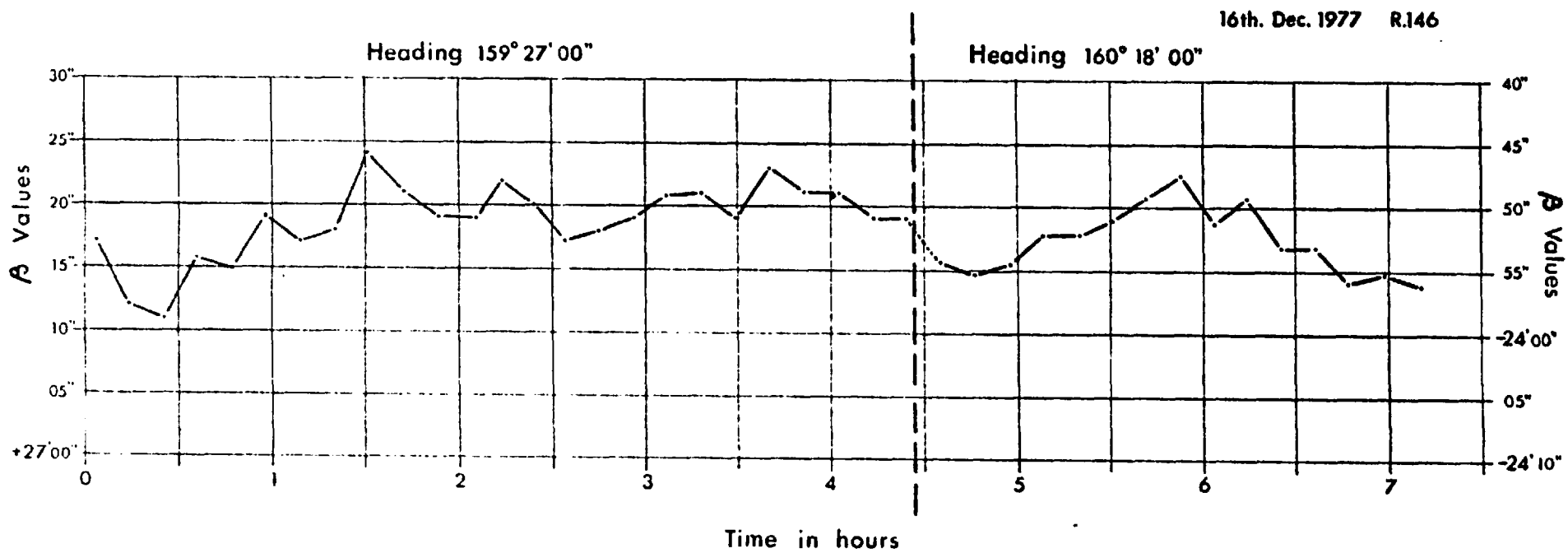
The first experiments were carried out after the oscillation had settled and had entered the secondary drift phase. Figure 31 shows the result of one such experiment where to all intents and purposes the pattern is maintained with a change in heading of 51 minutes. Naturally during normal observations one would not wait this length of time before changing headings and consequently other trials were introduced where changes were made far earlier to coincide with observational techniques. Results still indicated a constant pattern.

A further series of tests were devised with several changes being made during one spin-up. Figure 32 shows such a trial where the heading was changed four times during a two hour period covering an arc spread of over 40 minutes but the composite result is again very similar to the model described in Section 9.1.1b.

Finally a trial was made which incorporated 13 changes of heading within a period of four hours; headings varied within a spread of 1° but this time the expected pattern did not appear although all results were contained in a spread of 19 seconds of arc.

From these trials it was concluded that within the normal

Figure 31 - Illustration of Change of Heading during
Extended Power Spin



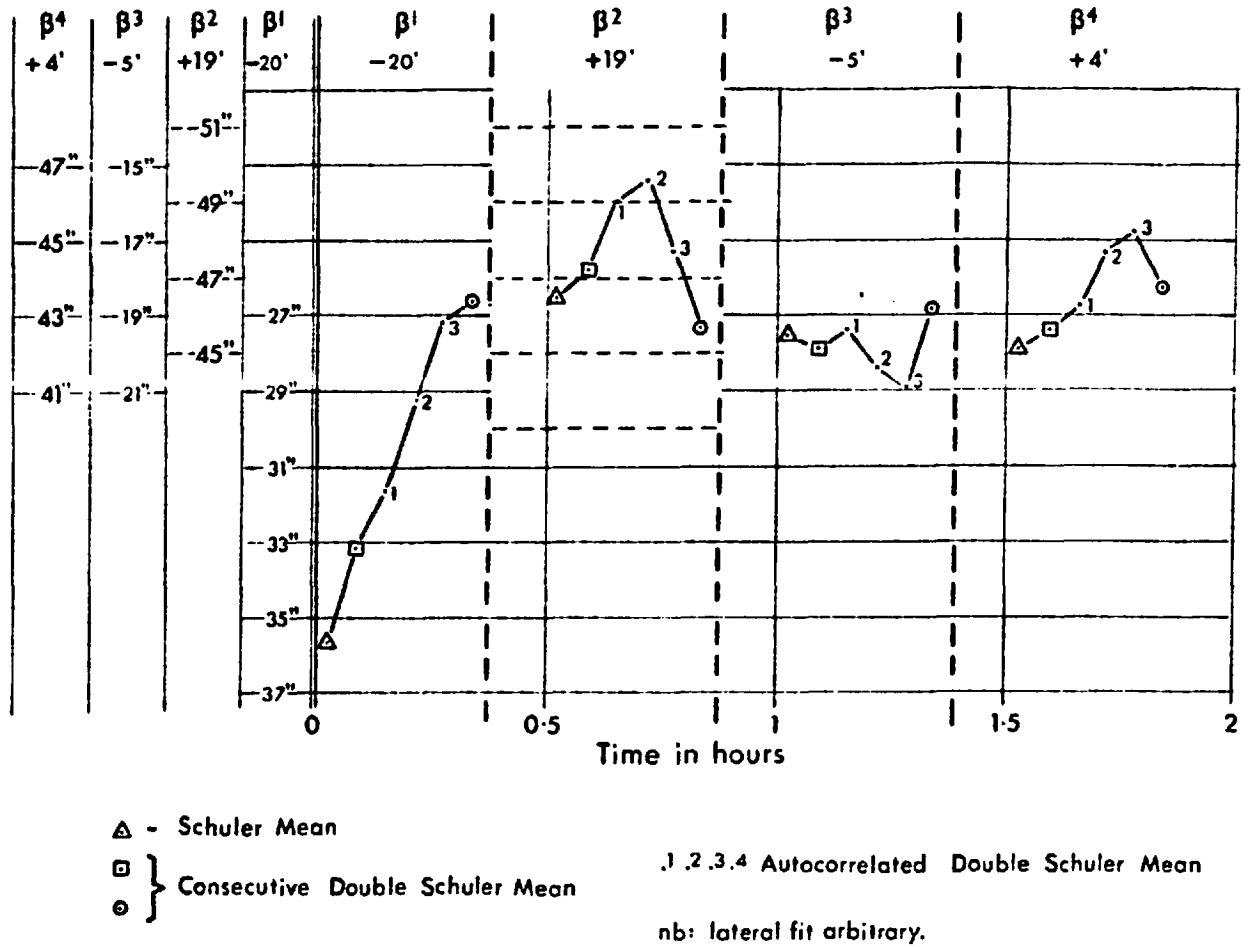


Figure 32 - Power Spin Drift Patterns including Change of Headings

procedures accepted for field observations, drift patterns which have been detected under spin would be maintained irrespective of a careful change in heading.

9.1.5b) Stability during Non Spin

The original question of stability of drift patterns arose

from the fact that the drift of the non-spin mode, observed during normal observations could not be predicted from the model.

Exactly one third of all results did not show the expected direction or amount of drift. It was felt immediately that the change in heading mid way through the normal observational period could have caused a reversal of the pattern indicated from single headings. This was reinforced by the evidence from experiments carried out by Gregerson⁽²⁰⁾ where he found that drift always occurred toward the meridian.

However, experiments at the Royal School of Mines with Wild equipment have not shown this effect and drift has remained constant in direction. Figure 33 shows the drop off in the centre points of oscillations in the non spin mode superimposed over the results depicted in Figure 32. Admittedly intermediate results were not possible but the drift is similar in direction to the expected pattern. Figure 29 in Section 9.1.3a also contains one observation, No. 4, in which a change of heading is accompanied with similar non-spin drift as above. From these trials it would therefore seem that a change in heading rather than cause a reversal of drift in the non-spin mode could actually intensify the original drift rate. However, the amount of change is negligible over the time required for normal observations.

The reason for the random drift which occurs during normal observations in the non-spin mode is still not clear but is bound up presumably with the effect of the intermediate power spin and possibly with environmental factors. However, the unpredictable drift in the non-spin mode reinforces the recording of these values before and after each observation.

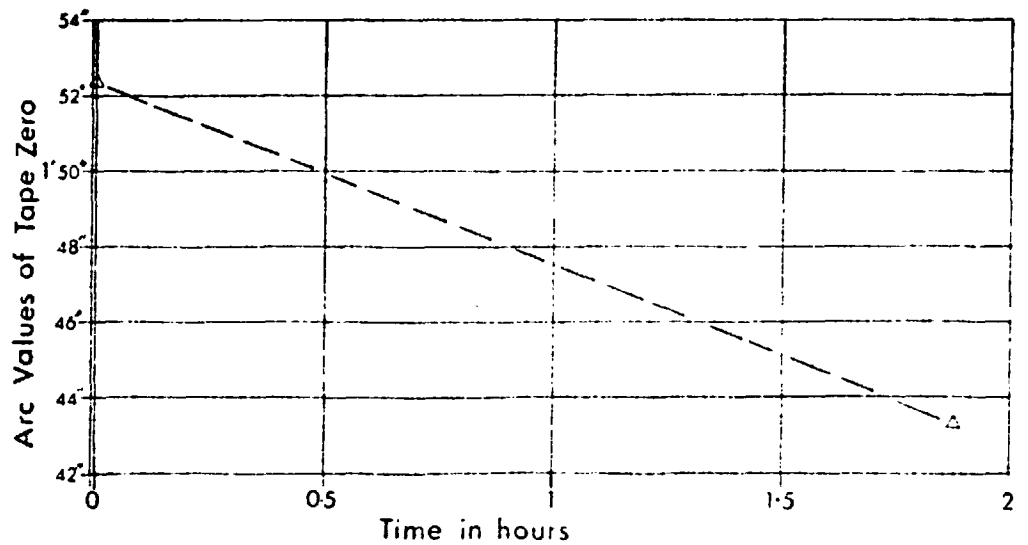
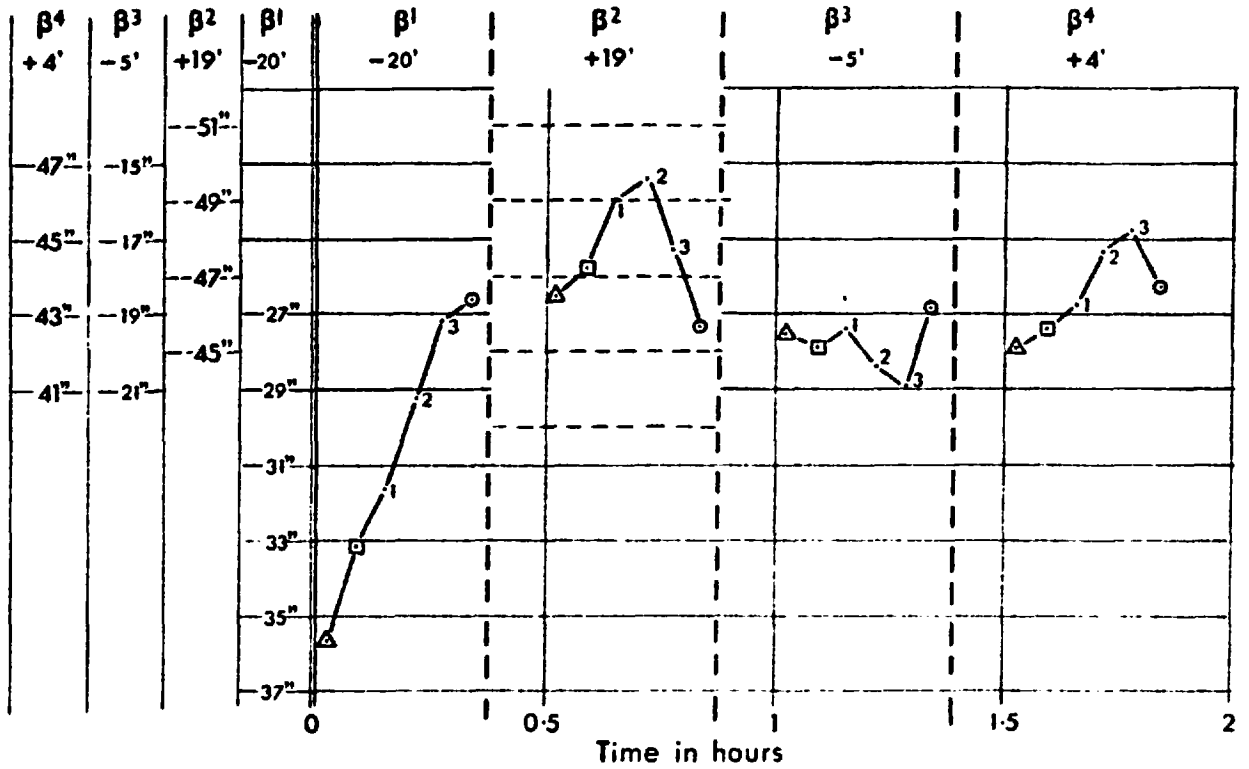


Figure 33 - Composite Figure showing Non Spin (Tape Zero) and Power Spin Drift

A further factor came to light during the most recent work when it was discovered that adopting the observational procedure set out in Section 10.4 it was possible to predict the amount of drift expected between the centre points of "before" and "after" non-spin oscillations with considerable accuracy.

9.1.6 Cause of Such Drift

9.1.6.1 Short Term Drift

9.1.6.1a) Primary Drift

The initial random drift pattern observed in the primary stage under spin is caused undoubtedly by slight vibrations being transmitted to the gyro-unit by the operator's uneven release of the cageing mechanism within the machine, and from the dissipation of heat generated by the motor during spin-up.

There is a strong possibility that the constant direction of Primary Drift is due to the gyro mass seeking its optimum centre of gravity. When it reaches this point any further movements of drift are comparatively small.

There is also strong experimental evidence to support the theory that primary drift patterns in the spinning mode are linked directly with movements in the tape position shown in the non-spin patterns - compare Figures 19, 21, 22, 24 and 41 with Figures 27 and 28.

9.1.6.1b) Secondary Drift

Gregerson commenting on Chrzanowski's early work which incorporated some evidence of the secondary phase, was of the opinion that the cyclic movements could be linked to astronomical causes but this is most unlikely. Williams in 1967⁽²²⁾ and 1977⁽²⁶⁾ states that these secondary phase movements - or his "Shar" effect - were caused by an ageing of the gyro rotor.

Evidence from current research has indicated that similar short term drift patterns are observed readily not only in the spinning mode but also in the non-spin position. Furthermore it is now possible to show that similarity is extended to include the direction of movement and amplitudes of second order drift sequences in both modes over comparable time spans.

The reasons for such drift in the non-spin position when all power has been excluded and the gyro unit is hanging as a mere pendulum on its suspension tape could be attributed possibly to changes occurring within the tape, within the suspension system or within the clamping unit at the top of the tape.

Slight molecular changes in the composition of the tape owing to strain and stress encountered during continual twisting and turning, and to supporting the weight of the gyro unit, cannot be ignored. However it is a little difficult to conclude that such changes would cause regular rhythmic patterns over a lengthy period. Furthermore regular twisting and untwisting cannot be the full explanation, as one would assume that the amount of observed drift could be equated with the amount of twisting involved. As can be

seen from Figure 28, when the oscillation decays less twisting does not lead to less drift and conversely when the oscillation is induced to swing with greater amplitude the rate of drift does not increase.

Minute changes in the tape clamping mechanism are also difficult to isolate and would be extremely difficult to prove. It is, however, an outside thought which may contribute in some small way to the overall changes observed.

From the evidence obtained it would seem that two further suggestions can be made. Firstly all observers to date have ignored the stability of the tape in its truly vertical position. Several authors have conducted trials on dislevelment which has effectively shown the indicated tape position has altered with reference to the "normal" scale marker - see Section 8. The suspended weight of the gyro unit and the force of gravity is regarded generally as being sufficient to keep the tape in a constant vertical plane. However, when a gyro unit is suspended a certain amount of vibration is induced into the tape and increased torque is then applied as the gyro unit begins to oscillate - in both non and power spin modes. There is, therefore, a possibility that the regular movement of the gyro unit would be enough to set up and maintain a separate minute oscillation of the tape around its primary position. If this were the case the mid-swing points of oscillations would slowly change - as is shown in Figure 34.

Evidence taken from Halmos⁽¹⁴⁾ - using GiB1 and GiC1 equipment - shows that the secondary phase is absent. The Hungarian optical works (M.O.M.) have developed a new design of tape which, in

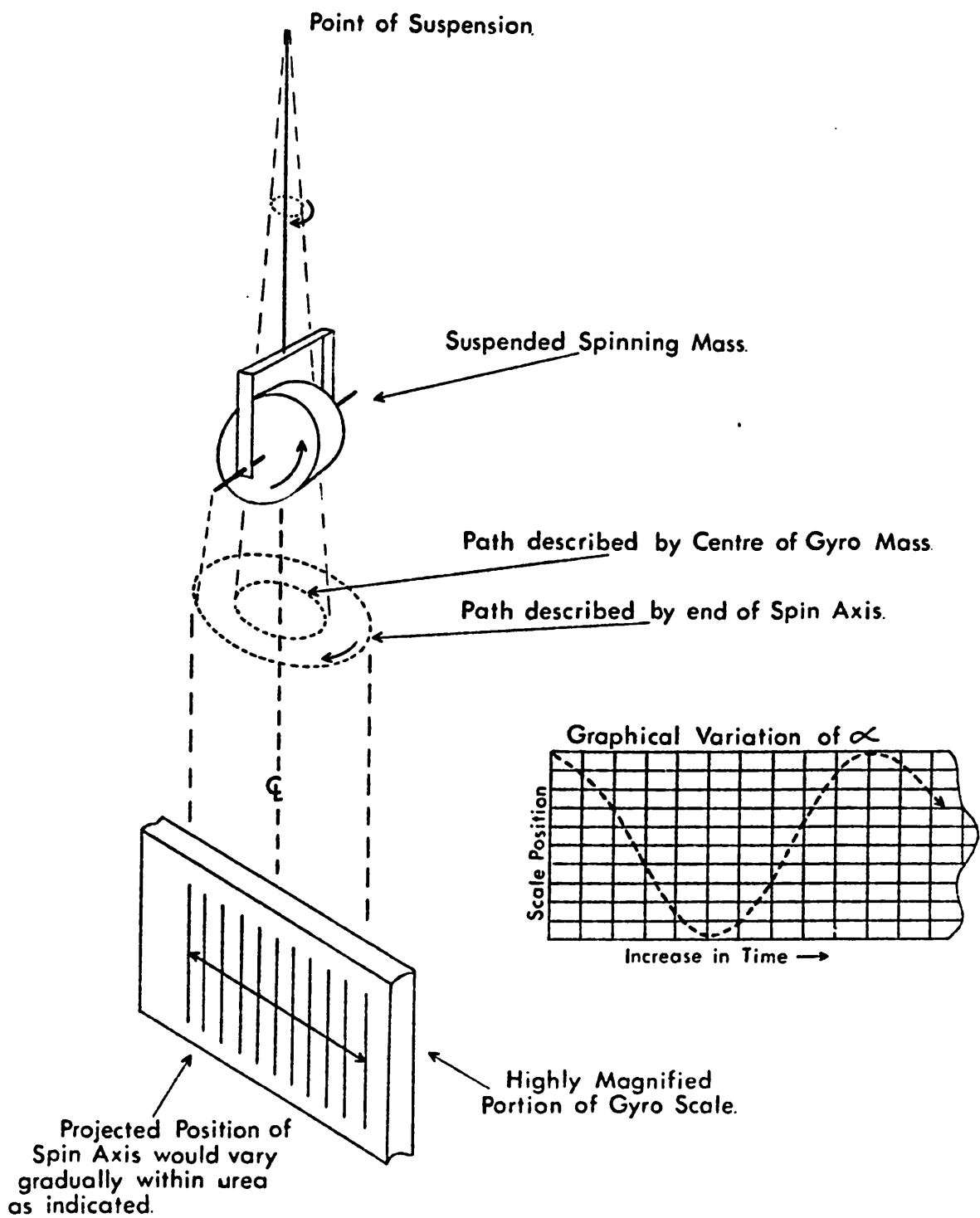


Figure 34 - Diagram to Illustrate the Result of any Regular Rotational Movement of the Suspension Tape

conjunction with the weight mass ratio of the gyro unit and construction of their suspension system, may restrict such movements as stated above. Further research could be carried out on Wild equipment concerned with tape and suspension design in an attempt to isolate this effect.

Secondly, the torque being applied to the suspension tape could be sufficient to induce a small rotation of the axis of spin around its centre of gravity. General gyroscopic theory indicates that this is probable. In this way the ends of the spin-axis would describe small conical figures - see Figure 35. If this were the case and the period of rotation were slow compared to the speed of the main east/west oscillation of the spinning mass, the spin axis would occupy a slightly different position, relative to its "internal" rotation, at each reversal point recorded during an observation. In fact because such a rotation would hold a steady speed the reversal points observed would follow a pattern identical to the secondary phase or shar effect albeit on a miniature scale - see Figure 36. The period of the secondary phase drift pattern would coincide with the complete revolution of the internal spin axis rotation and the amplitude of secondary phase drift would coincide with the diameter of rotation. Differences of amplitude detected by various observers have been small and could be explained by changes in tape torque both during and between observations.

Possibly the two explanations put forward have a combined effect on the observed oscillation; possibly the periods of either rotation are markedly dissimilar and could therefore contain an explanation for the tertiary drift patterns which underlie the shorter

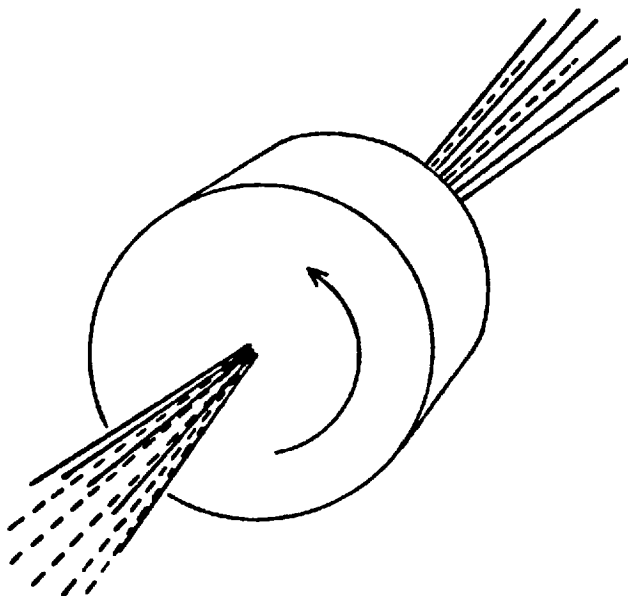


Figure 35 - Variations in Spin Axis Position

periodic secondary phase movements.

At one stage there was a suspicion that secondary phase drift could be influenced by a reduction in the power voltage supply during a lengthy run. A monitoring system was inserted between the nickel cadmium power pack and the G.A.K.-1 converter box which included an automatic tape printout of voltage output taken at every minute throughout the experiments. The system used was a Weir Digital Voltmeter with a paper roll recorder and the final printout was then plotted graphically against time values. Plots for periods of up to seven hours showed that the nickel cadmium power pack decayed as expected along a normal die-away curve. The example in Figure 37 shows this decay from a fully charged 13.2 volts to 11.0 volts during a period of 7 hours 45 minutes. A slight possibility, therefore, existed of linking part of the drift detected in the gyro unit position to this gradual loss of voltage.

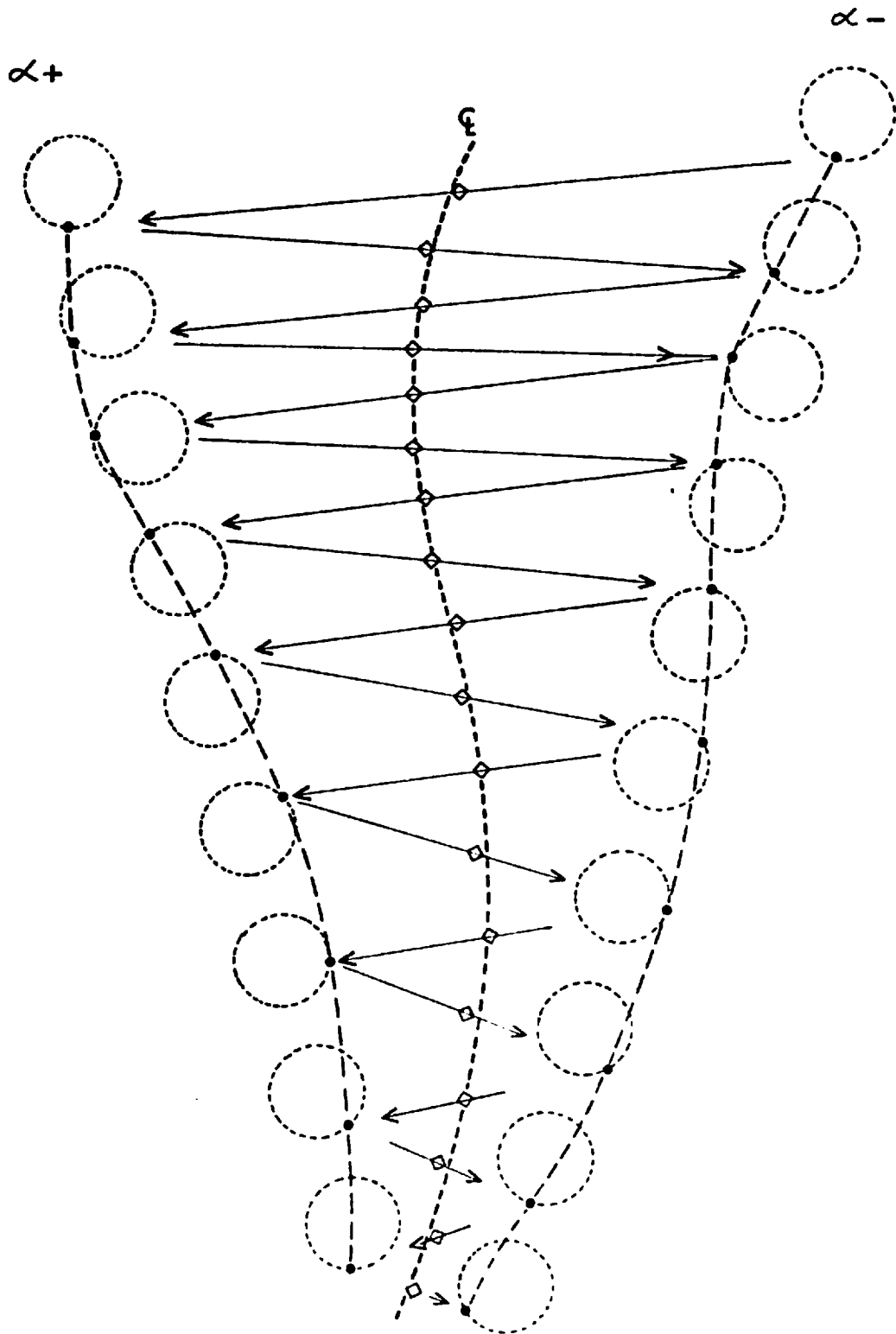


Figure 36 - Position of Spin Axis during Extended Spin
assuming Spin Axis Deviation (Exaggerated Example)

July 20th. 1978

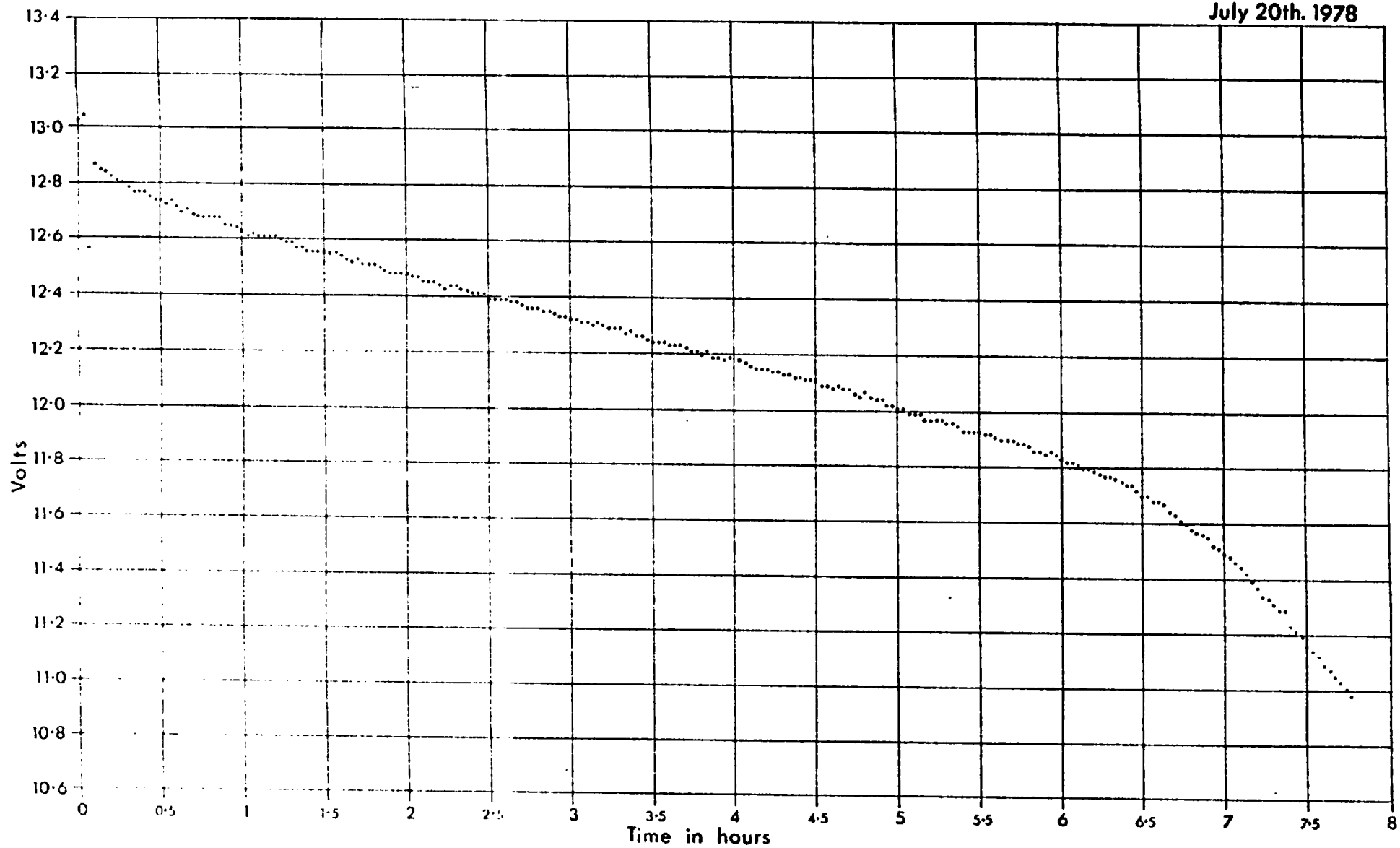


Figure 37 - Plot of Battery Voltage - Nickel Cadmium

It was then decided to extend the running period of the gyro to investigate the existence of further drift patterns. At this point it was realised that the nickel cadmium power pack was not capable of maintaining this length of spin and an external source of power was obtained. This comprised a variable voltage power supply unit run directly from the mains and was programmed to give an output of 12 volts D.C.; an Avo voltmeter being used frequently as an independent check on the output. Results during these long runs have been described in Section 9 and depicted in Figures 24 and 41. Drift patterns were seen to be similar to those produced using the basic power pack but this time were produced using a stabilised power supply. The original ideas of linking power pack decay with the generation of such drift patterns were quickly invalidated. However, the ability to vary a stabilised source of power suggested the separate series of experiments described later under 9.2

9.1.6.1c) Third and Fourth Phase Trends

Sufficient evidence has yet to be gathered to explain successfully all the short term drift patterns recorded and the suggestion that a mechanical cause would solve the third and fourth wave patterns in the spinning mode is a little difficult to justify when similar patterns are exhibited by different machines, produced by different manufacturers. However, the answer may be contained within advanced Gyroscopic Theory.

During the very lengthy trials on the G.A.K.-1 attachment continuous monitoring of oscillation times were also undertaken. These values when plotted graphically - see Figure 38 - indicate

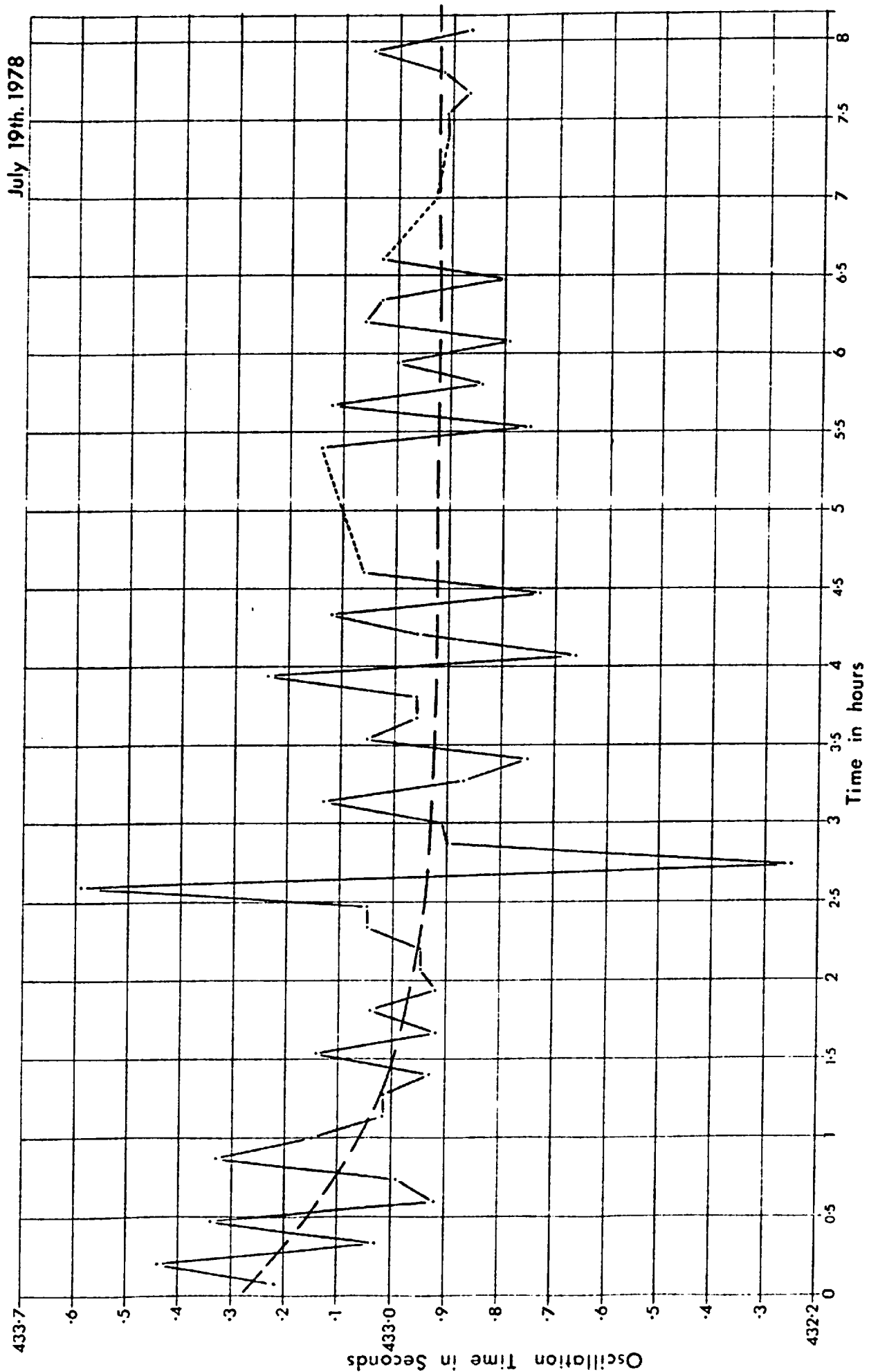


Figure 38 - Battery Decay during Extended Power Spin
(Wild G.A.K.-1)

a similar trend to that of the fourth trend under spin described in 9.1.1c and shown in Figures 7 and 25. It is very tempting to link these two trends and state that one is the cause of the other but again until more evidence is available this must remain merely a suggestion.

9.1.6.1d) Non-Spin Drift observed Before and After Power Spin

This form of drift described under 9.1.3a) may be attributed directly to changes in the molecular composition of the tape. Whereas doubt was expressed as to the tape being the cause of rhythmic secondary drift patterns it would appear that constant strain of twisting, in conjunction with the weight being supported could cause a regular drift effect. Lengthy periods of suspension could cause slight changes to occur within the tape which could effect the centre of swing. A certain amount of elasticity must be combined within such tapes to allow for continual twisting and untwisting during normal observations and it is therefore highly probable that the tape alters a little during oscillations. A further pointer to this being the case is shown in the slow recovery - hysteresis - of the non-spin values after lengthy trials have been completed. It is significant that this type of drift does not become evident in the pure non-spin mode with its rapid damping and is observed as a change only after the introduction of power spin.

When undertaking azimuth observations which include the recording of non-spin values the intervening spinning period between the before and after sets is approximately 30 minutes. Values recorded have not always followed the pattern as would be expected

from above; values have dropped, some risen and some remained the same - see Section 10.

During several successive observations taken within hours of each other but under entirely different environmental conditions large changes in the mid non-spin position have been recorded. If, as evidence presented in this section appears to indicate, a contributory cause of short term drift is linked to changes in the suspension system, any radical change in environmental conditions such as temperature could affect the metallic tape and would affect undoubtedly the outer casing of the machine on which the tape suspension clamp is mounted. Therefore a change in operating conditions could be a partial cause of such drift.

9.1.6.2 Long Term Drift

Some explanation of the more lengthy drift patterns have already been given within Section 9.1.2b. Obviously the more use given to a machine the more wear will take place on the gyro motor and bearings. All manufacturers guarantee their machines for a set number of running hours and it must be deduced that after this time has elapsed various components of the equipment become suspect.

In view of several years work with the Royal School of Mines modified attachment where it was possible to detect similarities of drift in both the non-spin and power spin modes, there is some support for the suggestion that a further contributory cause could be a slow, gradual, change in the elasticity of the tape. At the Royal School of Mines it was found that applying a correction to the spinning mode based on the relative non-spin position observed before

and after each spin-up, more stable sets of results were obtained - see Section 10.

Evidence from the Royal School of Mines machine cannot be used categorically for linking drifts of spin and non-spin modes beyond a three year period because after this time the machine was deliberately used for various experiments which had a noticeable effect on the drift patterns. These experiments placed strain on the equipment well beyond the normal expectations for working conditions.

9.1.7 The Practical Use of Detectable Drift

As has been seen from the various experiments devised, and the wealth of data collected, the presence of several phases of gyroscopic drift has been confirmed. The differences between the various phases are basically ones of period and amplitude but the main fact to emerge is that it takes some time before the majority of drift patterns become established.

From the practical point of view, throughout the world comparatively little time is "wasted" after spinning up the gyro unit before serious observations are taken. Several authors advocate waiting for the equipment to warm up before taking readings, but the definition of "warm up" is rarely explained. From work carried out at the Royal School of Mines a warm up period has always been accepted as the time required for the equipment to adjust to external conditions of temperature, humidity and pressure when moving between completely different environmental areas:- for example an underground observation in a position of considerable depth with temperature

in the 30°C range and high humidity immediately following a set-up on surface with temperatures say around 10°C and little humidity.

In these cases the time taken to set up the equipment and to organise the observation procedure has been thought to be adequate for any major adjustments to have been made. Total time allowed around 45 minutes. However, in the light of results from experiments carried out during this research period and from using other published data it is apparent that the gyro unit requires a period to "warm up" internally - or to reach a position where gyroscopic drift becomes minimal. In the evidence produced earlier this would be after approximately 80 minutes of oscillation.

If one allowed the gyro to settle into this secondary phase drift position before taking observations the total useful life of the gyro, in respect of completed observations, would be severely reduced. Using present methods the normal time that a gyro is under power spin during an observation is approximately 30 minutes (in latitude 51° North). If one allowed 80 - 90 minutes for the unit to reach the area of minimal drift before taking serious readings, the gyro unit would therefore have to be under power spin for 120 minutes per observation.

If the units are guaranteed for 1,000 hours this would mean that only 500 observations could be completed within this period as against 2,000 using the conventional method involving observations taken during the primary drift stage.

In all observations taken for the purpose of defining accuracy

of the various methods used in this thesis no account has been taken of the "warm up period" discussed above yet the accuracies obtained have been good.

Why is this ? There are two contributory factors; firstly all observations are taken with a common routine. As can be seen from the figures illustrating the various forms of drift all observations are made during the initial primary drift stage. During this period drift remains constant and changes rarely by more than a few seconds over the 30 minutes required by the normal Royal School of Mines observation technique. After spin-up and suspending the gyro unit it has been common practice to allow two oscillations for the gyro to "settle" before taking observations which allows time for the oscillation to proceed beyond the initial random drift direction. In rare cases where intense vibration of the moving mark is seen an additional swing has been left. However, in the majority of cases the observations all occur within a similar time from suspending the spinning unit.

When changing heading midway through spin-up it is usually possible to move and set the theodolite within the time interval of half an oscillation, but in rare cases a maximum of one oscillation is missed. This means that it is possible to have a continuous recording of reversal points without any time being lost for settlement of the system after moving.

In this way not only do all observations start within a common time lapse from spin-up but they are all recorded within a minimum time period. It is thought highly probable that this regular

routine has assisted in obtaining consistency of results.

The second factor has been undoubtedly the application of a "tape zero" correction or more correctly a tape torque correction. This correction is based not only on the changes which occur in the mid swing point of the non-spin mode before and after each spin-up but also relative changes which occur between different observations.

Sections 9.1.3a) and 9.6.1d) explain the changes observed during extended spin-ups and the possibility of additional, irregular changes, being induced by differences of environmental conditions.

This correction implies that the torque of the suspension tape changes during spin-up and from spin-up to spin-up, such changes having an effect on the respective power spin oscillation. Several years ago Lauf advised that such a correction should be made when using Fennel equipment but later abandoned the correction as being of minimal importance.

M.O.M. - Hungarian Optical Works - use their suspension tape as a means to carry current to the motor unit. This naturally causes distortion to the tape structure and affects the mid-swing point of the gyro unit. All instruction manuals from M.O.M. regarding gyroscopic equipment state that a "tape correction" must be applied to observed values. This correction is based on readings of the tape taken immediately after braking the gyro unit. As changes only occur after power has passed through the tape there is no need to record pre-spin values of the tape mid-swing position. However, the manufacturers require the tape to be "zeroed" on the central mark

of the scale before spin-up by using an adjusting knob linked to the clamping unit at the top of the tape. Although the correction was designed to rectify changes in the tape brought about by the passage of electric current, inadvertently it may also correct for minor tape movements due to causes explained in 9.1.6.1d.

The application for a "tape correction" at the Royal School of Mines has been investigated for over five years - the results are shown in the following section.

9.2 VOLTAGE STABILITY

Experiments were designed to monitor any change in the centre of oscillation arising from different voltage levels. Previous experiments, recorded in 9.1.6.1b) showed that when using a steadily decaying nickel cadmium battery the observed drift pattern showed little difference to the drift pattern from results using a stabilised 12 volt power supply.

However, the nickel cadmium decay was very gradual and it was decided to test the reactions of the gyro unit to a more noticeable change in power by using the variable DC output from the mains converter. The ideal conditions would be satisfied by varying the voltage level at random during extended spins, plotting the results graphically and then comparing with previous patterns obtained from a constant or steadily decaying power supply.

A major advantage of this form of experiment is that the gyro attachment is not touched, the same oscillation remains undisturbed

and any detectable deviation from the "control patterns" should therefore be caused by variation of the voltage. Suitable time was allowed between each shift in voltage level to ensure that any changes recorded were not caused by the sudden change in power. This form of variation should gradually have disappeared.

A typical set of results is shown in Figure 39. Voltage levels were varied within the limits of the converter control box, 11 volts - 15 volts, as set out by the manufacturers, and maintained for periods of approximately one hour. An independent check on the supplied voltages was made by using a separate voltmeter - see 9.1.6.1b). Finally groups of observations were taken at a voltage level below that recommended by Wild (U.K.).

The spread of results, within the recommended voltage band - remained similar to those observed in the control sets but the overall pattern of results is more random. It is possible to identify a form of trend in the results but this is dissimilar to the smooth shape and period of former observations.

Figure 40 shows a plot of oscillation times throughout the experiment indicated in Figure 39.

Referring to these two figures, it can be seen that results taken using a power supply of 10 volts, instead of the recommended 12 volts showed a comparatively large change in the mid-swing position of the oscillation and in the overall oscillation time. The former increased by approximately 10 seconds of arc whilst the latter decreased by approximately 0.5 second of time.

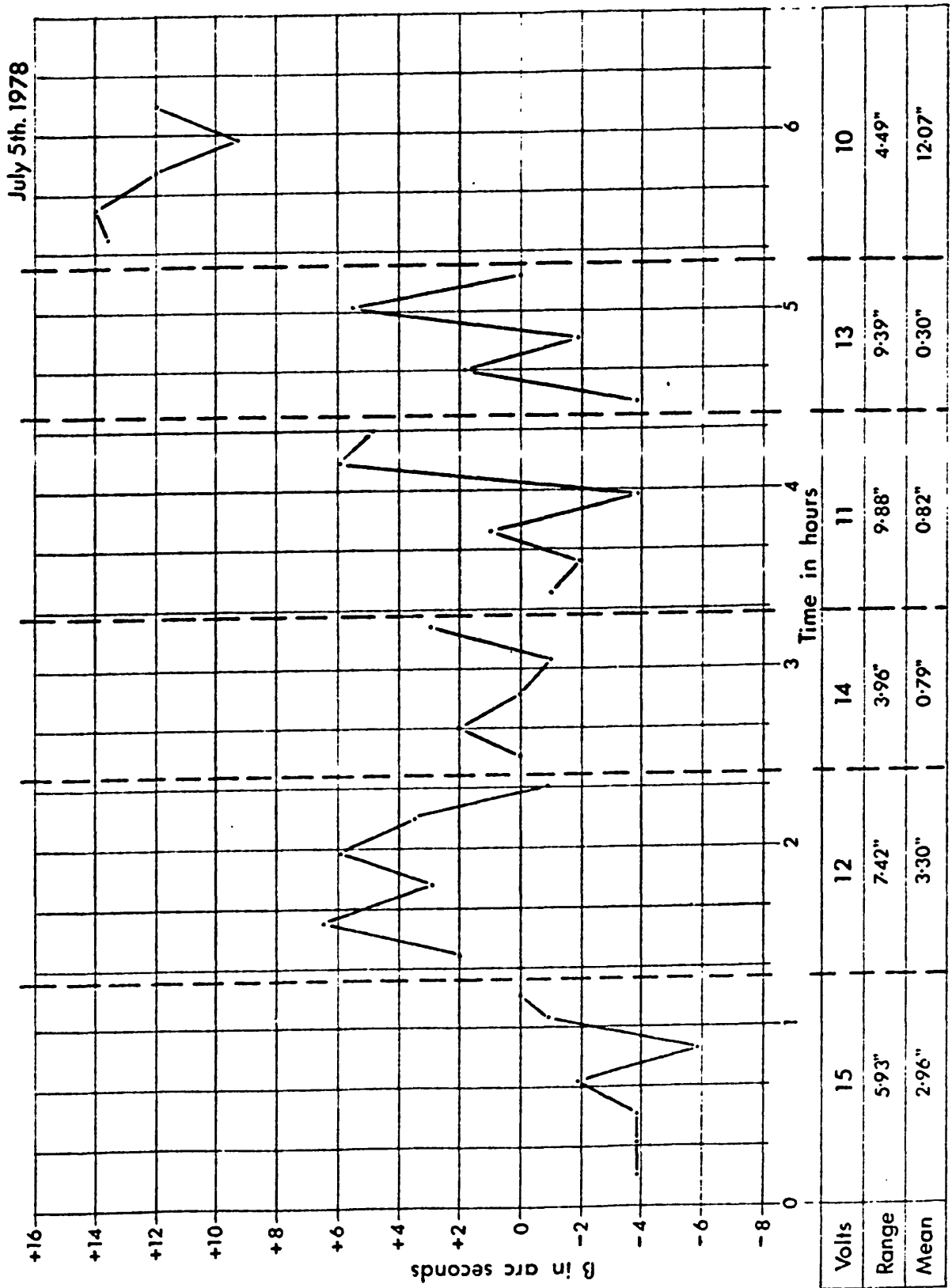


Figure 39 - The Effect of Voltage Changes During
Extended Power Spin

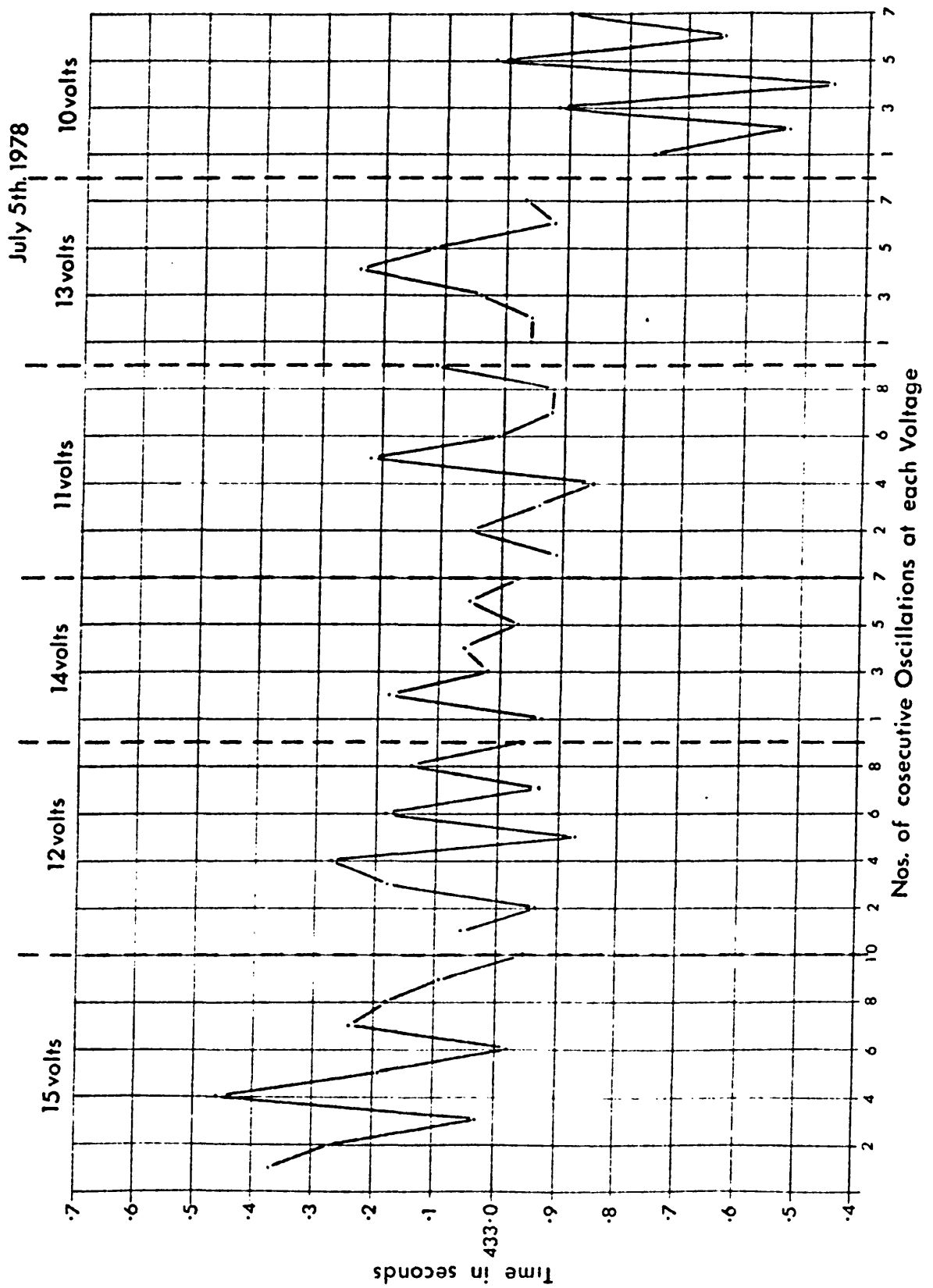


Figure 40 - Oscillation Times During "Changes in Voltage" Trials

These larger deviations caused by a reduction of power initiated thoughts on a further series of trials incorporating lengthy extended spins. The major points at issue were whether the stability of the gyro would be affected by the lower voltage and whether oscillation times remained constant.

Results from one such lengthy trial are shown in Figure 41. The more random pattern of results as reported above during short trials was again evident but there is very little difference in the overall spread of results when compared to previous lengthy trials using recommended voltage values.

However, two important characteristics were identified:-

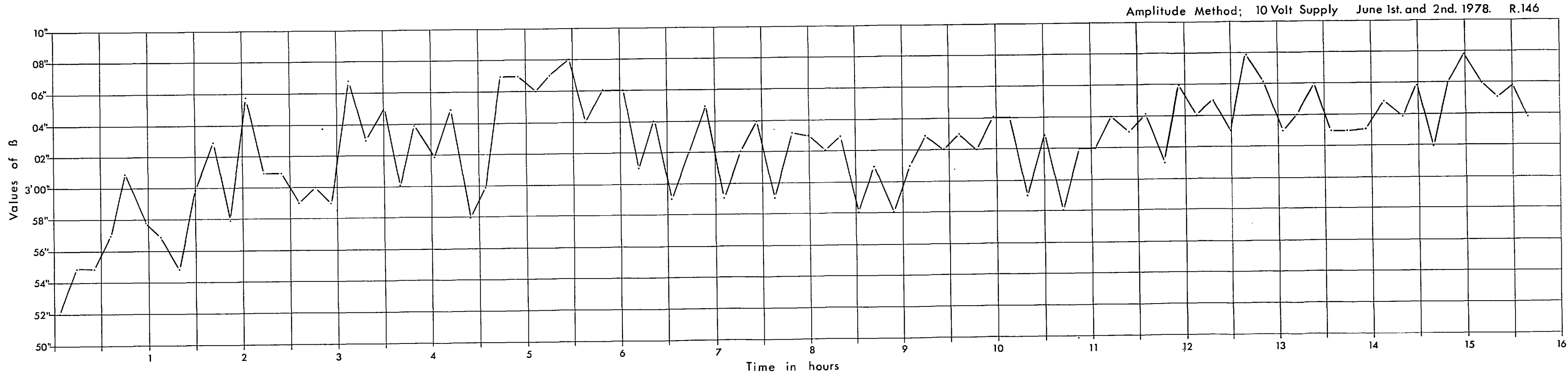
- a) The complete absence of any regular secondary harmonic drift pattern - Williams' SHAR effect; and
- b) The period of the tertiary drift pattern, which can still be seen clearly, is somewhat shorter in length than observed previously - approximately 9 hours, but with an increase of amplitude to approximately 6 seconds.

There can be no doubt that such a severe reduction in power reduces the stability of the spinning mass and therefore produces the more random result pattern which prohibits the gyro settling into the smooth minor oscillatory motions. Again such a reduction does not over-ride the larger drift sequences noted for gyroscopic equipment of several manufacturers.

9.3 INTERNAL MAGNETISM

Several years ago it was reported⁽²⁷⁾ that gyroscopic observations

Figure 41 - Extended Power Spin : Wild G.A.K.-1 -
Power Supplied at 10 Volts



could be affected by the inherent magnetism stored within the motor unit. There was little immediate reaction to this announcement but it was noticeable that subsequently Wild Heerbrugg added an electrical circuit to the gyro unit which, when brought into operation by switching to power spin for a few seconds before observing in the non-spin mode, erased any residual internal magnetic force.

The micrometer attachment made it possible to examine the original statements with more accurate data. . Observations of tape torque values were taken in the non-spin mode with headings set at regular intervals of 20° around the horizontal circle of the theodolite. Two sets of observations were taken at each experiment; one set without the recommended short power spin and the other observed according to the handbook.

Results of these experiments were first published in 1977⁽¹³⁾. One example is repeated in Figure 42 where it can be seen that without the pre spin, total spread of readings was 14 seconds of arc and approximate sinusoidal variation could be detected, as would be expected with the presence of slight magnetism. The second, or control set, has a much reduced spread of only 6 seconds and shows a random pattern of results.

Further, trials gave similar results to those indicated above and therefore substantiated the recommendation made in the manufacturers handbook. However, without the aid of the micrometer it is doubtful whether the patterns shown in Figure 42 could have been depicted with such accuracy. The original remarks⁽²⁷⁾ were

undoubtedly based either on scale estimation or on time differences.

9.4 DAMPING

Original experiments on damping were carried out in 1975 and published in 1977⁽¹³⁾ and were based on amplitude measurements taken over lengthy power spins. These initial examples were compared to a theoretical set of expected values calculated from first and last measured amplitudes and standard damping formula;~

$$E = Ae^{-\frac{1}{2}\mu T} \sin\left(\frac{2\pi}{T}t\right)$$

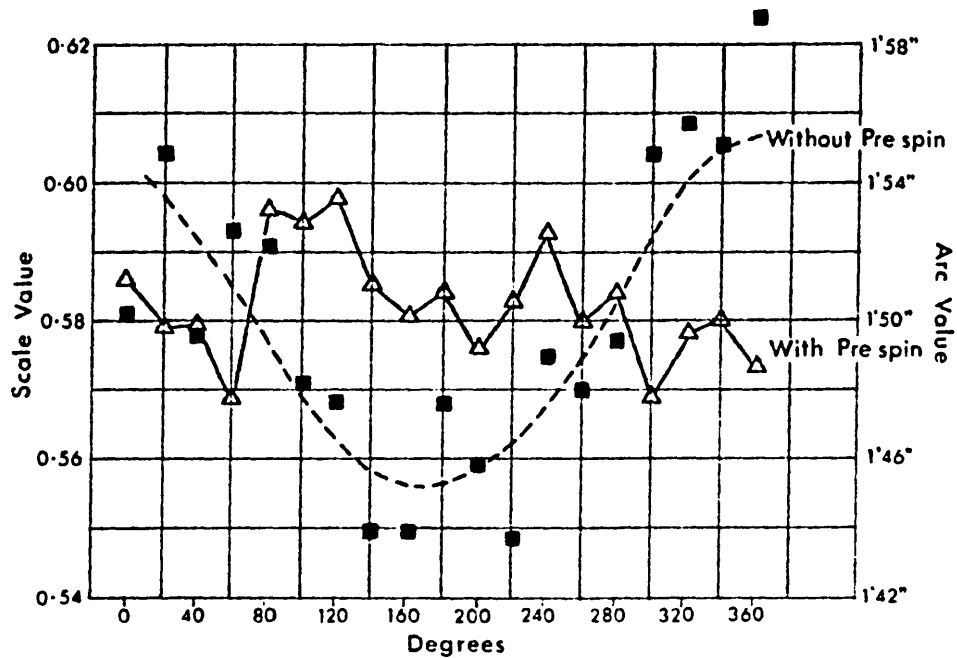


Figure 42 - Tape Zero Values Recorded Around Full Circle

Taking the first and last amplitudes as fixed differences between the recorded and theoretical amplitudes at common times were remarkably small. The greatest differences found did not exceed 0.02 of a scale division, and the general fit was normally within 0.01 of a division. Overall it was discovered that the resulting standard deviation of the residuals were less than 0.005 of a scale

unit, or less than 3 seconds of arc.

These early investigations gave a value for $e^{-\frac{1}{4}\mu T}$ of 0.999609 which represented a reduction in amplitude of approximately 2 seconds of arc per oscillation. The close fit obtained between the observed and theoretically predicted results over time periods as great as seven hours of time were further indications of the general stability of the gyroscopic model and the accuracy of reading amplitudes using the micrometer system.

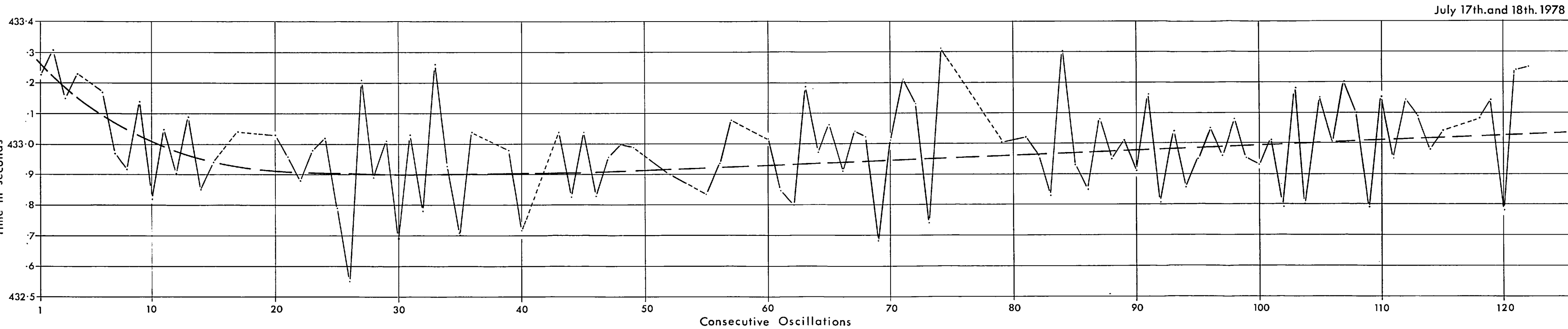
Later work on drift, recorded in Section 9, necessitated further lengthy trials but this time the experiments were far longer, in some cases for periods of seventeen hours, and the amplitude values were recorded continuously as opposed to the thirty minute intervals used in 1975. Results from these trials were then used to re-examine the damping situation.

9.4.1 Damping over 17 Hours at 12 Volt Stabilised Supply

This experiment was designed to record both times and amplitudes over an extended period using the same spin-up. Figure 43 illustrates fluctuations in oscillation time throughout the period and Figure 24 illustrates the drifts recorded in heading.

Using the damping formula noted in 9.4 the value for $e^{-\frac{1}{4}\mu T}$ = 0.99956607 and for $\mu = 4.010 \times 10^{-6}$. Theoretical amplitudes were calculated using these values for time intervals of one oscillation and compared to the actual amplitudes observed during the experiment. The differences between theoretical and actual at 143

Figure 43 - Oscillation Times during Extended Spin : Wild G.A.K.-1
Power Supplied at 12 Volts



check points were calculated to have a standard deviation of ± 0.00831 of a scale division from the mean. This indicated a fit to 4.9 seconds of arc. Attempts at closer curve fitting by freeing the start and finish point failed to increase the accuracy by any significant factor. In all these experiments the fit was so good that it was not worth while to attempt fitting by Least Squares.

9.4.2 Damping over Fifteen Hours at 10 Volt Stabilised Supply

An extended spin experiment capturing similar information as gathered in 9.4.1 was undertaken at a stabilised supply of 10 volts - 2 volts below that recommended by the manufacturer. It was thought that such a reduction of power could lead to a significant change in the damping factor. Figure 44 shows the continuously recorded oscillation times for this experiment. Overall, the values show the same trend as seen in Figure 43 at 12 volts but individually are more erratic throughout.

Calculations for damping in this experiment revealed the value for $e^{-\frac{1}{2}\mu T} = 0.9995533$ and for $\mu = 4.137 \times 10^{-6}$. Theoretical amplitudes were again derived for periods of one oscillation and compared to actual recorded values. Results indicated a standard deviation from the mean throughout the 127 check points of ± 0.00923 of a scale division; a fit to ± 5.1 seconds of arc. Floating the end points of the series caused a minor deterioration of values to a standard deviation of ± 0.00925 and a fit to ± 5.5 seconds of arc.

June 1st. 1978 R.146 (10volts)

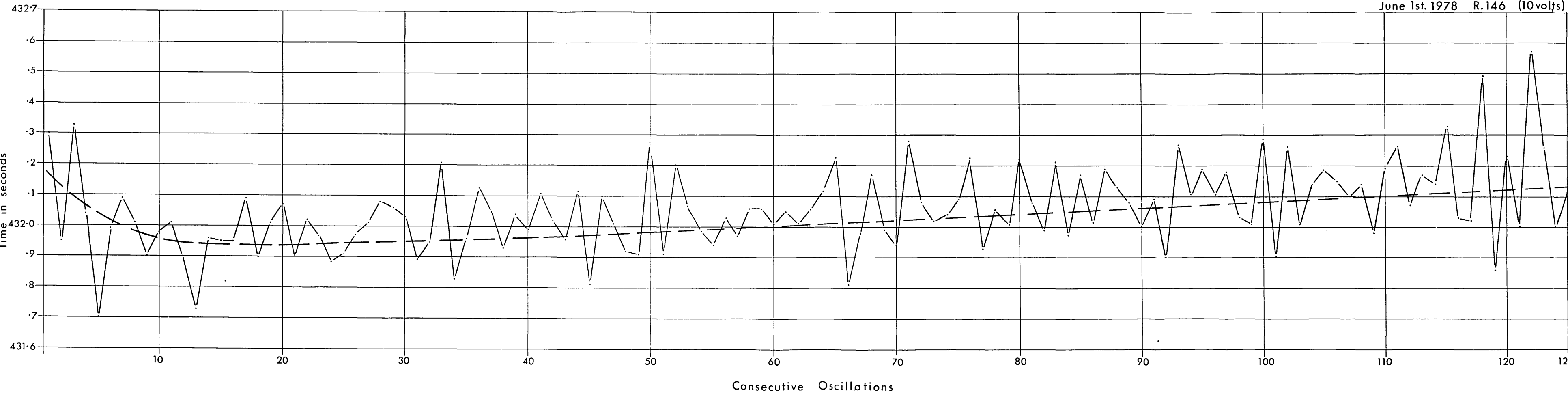


Figure 44 - Oscillation Times during Extended Power Spin : Wild
G.A.K.-1 - Power Supplied at 10 Volts

9.4.3 Conclusion on Damping

The main conclusion to be reached is that over the five years of research the damping factor has remained comparatively constant and even reducing power input has had little effect. The stability of the model has been excellent.

9.5 GENERAL REMARKS ON SECTION 9

The majority of other writers have ignored the possible effect of tape zero on the stability of the gyro axis during extended periods of power spin and to date there has been no other evidence of anyone examining the variations of the gyro axis in the non-spin mode. The experiments described above have shown that there appears to be a distinct correlation between the non-spin correction and drift of the gyro during periods of extended power spin. It has also been shown above, and in subsequent sections, that the correlation is statistically significant over a period of up to eighteen months. By adopting a tape zero correction, as has been advocated at the Royal School of Mines, it is possible to produce improved results.

10 - EXPERIMENTAL TRIALS

The following section describes in detail the various sets of experiments carried out during the research period at The Royal School of Mines in London or at the field station of the school in Cornwall. In the main these trials incorporated various models of the modified Wild G.A.K.-1 gyro attachment although reference is made to important tests on M.O.M. equipment.

Throughout these trials the important points of issue were:

- a) To evaluate the various reduction methods available;
- b) To examine to what extent the development of the modification had affected observational technique and accuracy; and
- c) To investigate the effect of applying a separate correction for the change in position of the centre of oscillation of the tape (tape zero position).

The tape zero correction applied during these and subsequent trials is a weighted mean correction. A value of the tape zero position is obtained directly after braking the power spin mode. This value is multiplied by 3, added to the tape zero value obtained immediately before power spin, and divided by 4.

A long series of experiments were conducted in an attempt to discover the better tape zero correction to apply. Values from a straight mean between before and after; the after value alone; and the weighted mean mentioned above were used to calculate results from similar power spin data. Evidence from these trials pointed against a straight mean but favoured marginally the affect of the

weighted mean as opposed to the final "after" value.

Weighting was at first discovered empirically but later it was found that if an assumption was made that tape zero values altered linearly during the time of an observation, the tape zero value coinciding with the mid time of power spin was almost identical with that calculated by the weighted mean method.

The trials are entered in chronological order to illustrate the various advances in reduction and observational techniques which were evolved during the period. As mentioned in Section 6 there are several variations of formulae for reducing observational data within each of the three techniques: Amplitude (Reversal), Transit and Timing. However, for the purposes of these trials the formulae used are those derived independently at the Royal School of Mines.

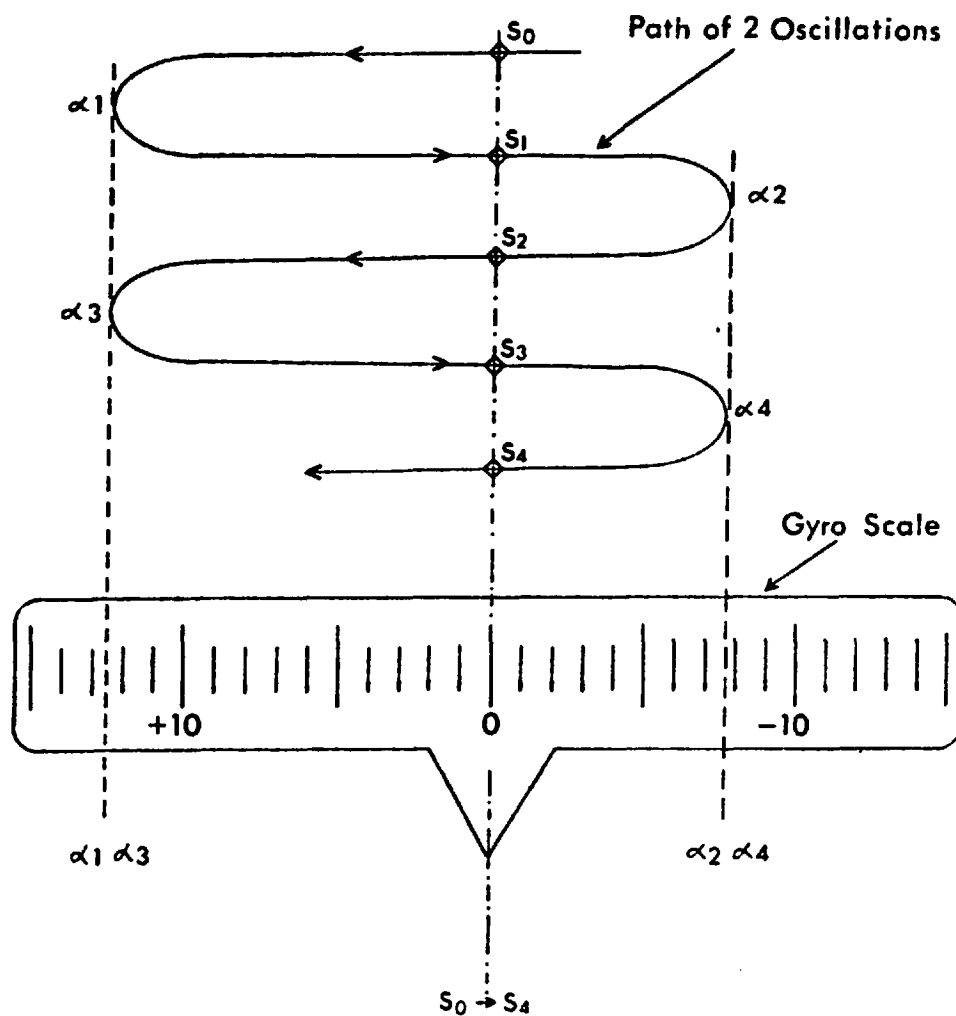
10.1 AMPLITUDE AND MODIFIED SCHWENDENER TRANSIT - 1974/75

The Amplitude Method had been regarded as a technique capable of giving results of low order accuracy. The reason for this being the inability of the operator to obtain accurate readings of oscillation reversal points from the gyro scale of the G.A.K.-1. Estimation from this scale, which is subdivided into intervals of approximately ten minutes of arc only 3 mm (approximately) wide at maximum magnification, could at best be made to 0.1 of a division or one minute of arc. The development of the micrometer attachment however, enabled the same scale to be read directly to six seconds of arc.

The Transit Method using Schwendener's original formulae was recommended by Wild and widely used in Britain and South Africa at the time. A further term was added to the basic formulae in 1974⁽⁴⁾ which enabled theoretically observations to be made at greater arc distances from True North than the Schwendener restriction of 10 minutes.

The first series of trials was designed to evaluate the micrometer system and to compare results obtained by the two methods mentioned above. It was decided to gather sufficient information from each oscillation to calculate independent results using both methods. In this way direct comparisons could be made from the same observation rather than the alternative approach of conducting a separate series of trials for each method. During observations it was necessary to zero the micrometer on + 0 before taking any timing value. Failure to carry out this step would obviously affect the β values obtained. Repeated accurate zeroing of the micrometer could be regarded as a weakness of the system which could lead to inaccuracies in timing, however, sufficient time lapses between readings to enable the operator to set and double check his setting of the zero with comparative ease - see separate experiments in 11.1 and 11.2

The system of observing throughout all trials concerning repeatability of the gyro, was that explained fully in 8.6; basically a balanced pair of headings around True North using the same spin-up. One such heading under spin is illustrated diagrammatically in Figure 45, and shows the total information required to calculate β .



Amplitude Method - - - - $\alpha_1, \alpha_2, \alpha_3, \alpha_4$.

Transit Method - - - - S_0, S_1, S_2, S_3, S_4 .

Figure 45 - Data Obtained From Each Heading During Comparison Trials 1974-75

the mid-swing point, for both methods on one side of True North.

These initial trials were conducted on the London base line and later on the more stable base at the field station in Cornwall. The instrument during this period was mounted on a Wild T-16

theodolite reading direct to 1 minute of arc and by estimation to 6" of arc.

All existing publications dealing with the use of gyro-theodolites before this time were unanimous in their recommendation that for accurate results headings should be relatively close to north. The prime factor behind this recommendation was undoubtedly the limitations set by the existing transit formulae.

During these trials several observations were required to have headings with spreads around True North of around 40 minutes of arc in order to establish an independent calculated value for the constant C. Results from these observations appeared to be little different from those with closer proximity to the meridian. A decision was then taken to put to the test both the observing techniques and the reduction formulae, together with the mechanical behaviour of the suspended gyro-theodolite. At random intervals of time headings for the gyro were deliberately selected at ever increasing arc values from True North. The only difficulty encountered was to generate a suitable oscillation with the limits of the scale when the gyro heading was far from north.

Figure 46 shows one particular observation where the headings contained a spread around True North of 163' or were plus or minus 1°21'30" from north. Transit values could not be reduced due to the fact that swings did not travel through the centre of the scale thereby making timing through centre impossible. Possibly a different scale mark could have been selected as oscillation centre (see later trials) but the normal transit reduction formulae at the

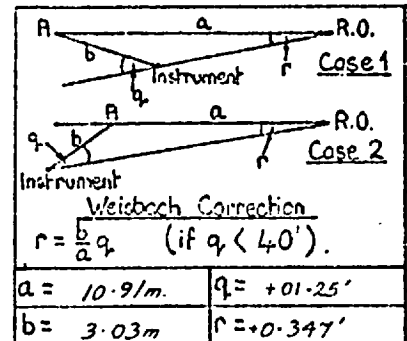
GYRO THEODOLITE BOOKING SHEET (Amplitude Method) Instrument Wild GAK-1 (red)
Observer R. Smith Booked R. Smith Place Power House Date 14th April 1975 (Obs. 10)

Before	C.L.	C.R.	After	C.L.	C.R.	MEAN R.O.
R.O.	124 28.2	304 27.9	R.O.	124 28.2	304 27.9	124 28.05
A	304 29.5	124 29.1	A	304 29.5	124 29.1	
Diff	+01.3	+01.2	Diff	+01.3	+01.2	(+01.25)'
Time	14.45		Time	16.30		

"Before" Tape Zero		
+3.26	-3+0.93	-2.07
+3.22	-3+0.98	-2.02
δ	+0.586	

"After" Tape Zero		
+6.12	-6+0.98	-5.02
+6.06	-5+0.09	-4.91
δ	+0.541	

Weighted Mean δ +0.552



B = Oscillation Centre = $(\alpha_1 + 3\alpha_2 + 3\alpha_3 + \alpha_4)/8$.
 δ = Tape Zero Centre = $(\delta_1 + 3\delta_2 + 3\delta_3 + \delta_4)/8$.
 s = Value of one gyro scale division in angular measure.
 W = Circle Reading of North = $\theta + s\omega$.
 c = Instrument constant.
 θ = Theodolite reading
 $\omega = [\beta(1+c) - c\delta]$
 $(1+c) = (\theta' - \theta)/s(\beta - \beta')$

$\phi = 50^\circ 17' N$ $C = 0.316$ $S = 10'$
 $\theta' - \theta = +163'$ $(1+c) = 1.313$ (calculated).

Reversal Points (1)		
+11.39	+1+0.28	+1.28
+11.41	+1+0.29	+1.29
β	+6.344	

Reversal Points (2)		
-3+0.28	-2.72	-10+0.57 -9.43
-3+0.28	-2.72	-10+0.57 -9.43
β'	-6.075	

Circle Reading (θ)	94 35.00	97 18.00
Correction ($s\omega$)	+01 21.71	-01 21.73
Circle Reading of North (W)	95 56.71	95 56.27
True Bearing of R.O. (R.O.- ω)	28 31.34	28 31.78
Weisbach Correction (r)	+0.35	+0.35
Additive Constant (Δ)	+1.30	+1.30
True Bearing Azimuth (A--R.O.)	28 32.99	28 33.43
MEAN	28° 33' 13"	

Figure 46 - An Example of the Amplitude Method

time could not accept this observation. The amplitude method, however, was used successfully and the reduced result did not differ significantly from those obtained from more "conventional" headings.

Figure 47 shows the maximum spread reached with the Transit method. The difficulty in obtaining such results was the necessity of generating a sufficiently skewed oscillation which also transitted the zero point on the gyro scale. This observation had a spread of 83 minutes or plus or minus 41.5 minutes from True North and ΔT values of + 169 and - 125 seconds. The calculated result from this observation using the modified Schwendener transit formulae was again well within the accuracies obtained from closer headings.

10.1.1 Headings Around True North

Results from the more extensive trials carried out in Cornwall were grouped into representative sets according to the position of their headings relative to True North. The groups selected were as follows:

- i) All results;
- ii) Results from observations with spreads less than 20 minutes around True North;
- iii) Results from observations with spreads between 21 and 40 minutes around True North;
- iv) Results from observations between 41 and 163 minutes around True North; and
- v) All results from observations with spreads greater than 20 minutes around True North.

GYRO THEODOLITE READINGS

Transit Method.

Inst. Wild CAK-1 (Mod)
Date. 15th April 1975
Observation No. 35

Place. Power House
Observer. R. Smith
Booker. R. Smith.

Formulae:-

- S_0, S_1, S_2 = Three consecutive Transits Through Centre.
 α_1, α_2 = Reversal Point Readings ($S_0 \rightarrow \alpha_1 \rightarrow S_1 \rightarrow \alpha_2 \rightarrow S_2$)
 $\Delta T = (T_1 - T_2) = (S_1 - S_0) - (S_2 - S_1) = (2S_1 - S_0 - S_2)$
 $\alpha = (\alpha_1 - \alpha_2)/2$ $\delta = (\delta_1 + 3\delta_2 + 3\delta_3 + \delta_4)/8$ = Tape Zero.
 W = Circle Reading of North.
 S = Value of one gyro scale division in angular measure.
 C_T, C = Instrument Constants $C_T = \pi(1+C)/2T$
 θ = Theodolite Reading. $f = \pi^2/14T^2$
 T = Period of Oscillation.

$$W = \theta + S[C_T \alpha \Delta T (1 - f \Delta T^2) - C \delta] = (\theta + s w)$$

$$C_T = (\theta' - \theta) / S[\alpha \Delta T (1 - f \Delta T^2) - \alpha' \Delta T' (1 - f \Delta T'^2)]$$

$C_0 =$	$\phi = 50^\circ 17' N.$	$C = 0.316$	$C_T = 0.00481$	$S = 10'$	$f = 2.25 \times 10^{-6}$
---------	--------------------------	-------------	-----------------	-----------	---------------------------

	Before	After	Mean	(R.O)
R.O.	208 33.6 (33.2)	208 33.6 (33.2)	208 33.4	
A	28 36.7 (36.1)	28 36.7 (36.1)		
Diff.	+03.0	+03.0	$a = 1091m.$	$b = 3.03m.$
Time	16.05	17.40	$q = +03.0'$	$r = +0.833'$

θ 179 21.00		Time			
	Diff	ΔT	$\Delta T(1 - f \Delta T^2)$		α
S_0 00 00.00		+		α_1 +8.98	+
S_1 04 58.55		169.12		α_2 -2.39	5.685
S_2 07 07.98		+		α_3 +8.99	+
S_3 12 05.99		168.30		α_4 -2.39	5.690
S_4 14 15.70		168.71	(157.91)		(5.688)
θ' 180 44.00		Time			
	Diff	ΔT	$\Delta T(1 - f \Delta T^2)$		α'
S'_0 00 00.00		-		α'_1 +3.79	+
S'_1 02 30.80		125.60		α'_2 -9.81	6.800
S'_2 07 07.20		-		α'_3 +3.78	+
S'_3 09 38.65		124.30		α'_4 -9.81	6.795
S'_4 14 14.40		124.95	(120.58)		(6.798)

$$(\theta' - \theta) = 83.00'$$

$$C_T = 0.004832$$

$$(1+C) = 1.315 \text{ (calc.)}$$

Tape Zero Point.	
Before	
+12.39	-11.22
+12.25	-11.10
(+0.548)	
After	
+8.53	-7.35
+8.45	-7.28
δ	+0.569

$$T = 4.27.6 \text{ (mean)}$$

Circle Reading (θ)	179	21	00	180	44	00
Correction ($s w$)		+ 41	14		-41	19
Circle Reading of North (W)	180	02	44	180	02	81
True Bearing of R.O. (R.O.-W)	28	30	56	28	30	59
Weisbach Correction (r)		+ 0	83		+ 0	83
Instrument Constant (Δ)		+ 1	40		+ 1	40
True Bearing of Lining (A-R.O.)	28	33	19	28	32	82
Mean						
						28° 33' 00"

Figure 47 - An Example of the Transit Method

The results are set out in Figure 48 with their various standard deviations. A more acceptable comparison may have been possible if the numbers of observations within each set were

Amplitude method using weighted mean tape zero	All observations (39 results)	Observations with spreads < 20' (20 results)	Observations with spreads 21' to 40' (9 results)	Observations with spreads > 41' (10 results)	All observations with spreads > 20' (19 results)
Arithmetic mean	28° 32' 02"	28° 32' 01"	28° 32' 05"	28° 32' 04"	28° 32' 04"
Standard deviation of a single set	± 7.27"	± 6.99"	± 7.80"	± 7.04"	± 7.30"
Transit method using weighted mean tape zero	(31 results)	(17 results)	(8 results)	(6 results)	(14 results)
Arithmetic mean	28° 32' 02"	28° 31' 59"	28° 32' 06"	28° 32' 03"	28° 32' 05"
Standard deviation of a single set	± 8.08"	± 7.35"	± 10.20"	± 5.19"	± 8.20"

Figure 48 - Cornish Observations - April 1975
(Using T-16 Theodolite)

more uniform, however, even a cursory glance at the results indicate that although some variation is noticeable the expected major differences are absent from both methods.

Figure 49 shows an earlier series of results using a standard Wild G.A.K.-1 published in 1974⁽⁹⁾. In these observations reversal points, used in both Amplitude and Transit reductions had been estimated from the coarse gyro-scale.

10.1.2 General Accuracy

Comparison of results in Figures 48 and 49 show an increase in accuracy during trials with the modified instrument. Because the amplitude method is based upon an accurate knowledge of reversal point readings of the oscillation, it is this method which has shown

Amplitude Observations			
	All Observations	Observations with spreads < 20'	Observations with spreads > 20'
	17 Results	9 Results	8 Results
Arithmetic Mean	87° 55' 59"	87° 56' 03"	87° 55' 54"
Standard Deviation of a Single Set	±24"	±23"	±27"
Transit Observations			
	17 Results	9 Results	8 Results
Arithmetic Mean	87° 55' 50"	87° 55' 49"	87° 55' 52"
Standard Deviation of a Single Set	±14"	±11"	±18"

Figure 49 - Results from Standard G.A.K.-1 (Thomas 1974)
Mean Tape Zero Correction

the greatest improvement. Results using the transit system have also shown improvement but this is not seen to be evenly spread throughout the different sets; the greatest improvement occurring in the sets of observations farthest from north. These transit results reinforce the application of the micrometer system because it is precisely in the region of larger spreads where the influence of accurate amplitudes becomes greatest within the operating transit formulae.

Figures 50 and 51 show plotted values of each reduced observation. To illustrate the effect of tape zero each result is shown with and without the correction applied, together with each separate arc value of tape zero. A weighted mean correction has been applied in 10.1.

As can be seen from the figures the application of a tape zero correction has produced a lower standard deviation for one set. Reductions without applying the correction indicate trends in calculated values over the trial period. Trends which are mirrored in the plots of individual tape zero values illustrated above; in general as one increases the other decreases. From these initial trials carried out under semi-laboratory conditions the close link between non-spin (tape zero) and power spin can be detected. Without applying such a correction the normal reaction of the day would have been to describe the differing values as further evidence of drift. Drift in E factor. However, as these trials have shown, a large proportion of this drift can be eliminated by applying an individual correction to each observation.

10.1.3 Conclusion

The main conclusion to be drawn from the initial trials was the fact that using the modification led to remarkable improvements in both the range and accuracy previously thought possible with this machine. Both methods were used with ease and final results showed that there was little to choose between the two.

The Amplitude Method, possibly the simpler of the two for field

Figure 50 - Amplitude Results - 1975 (T-16 Theodolite)

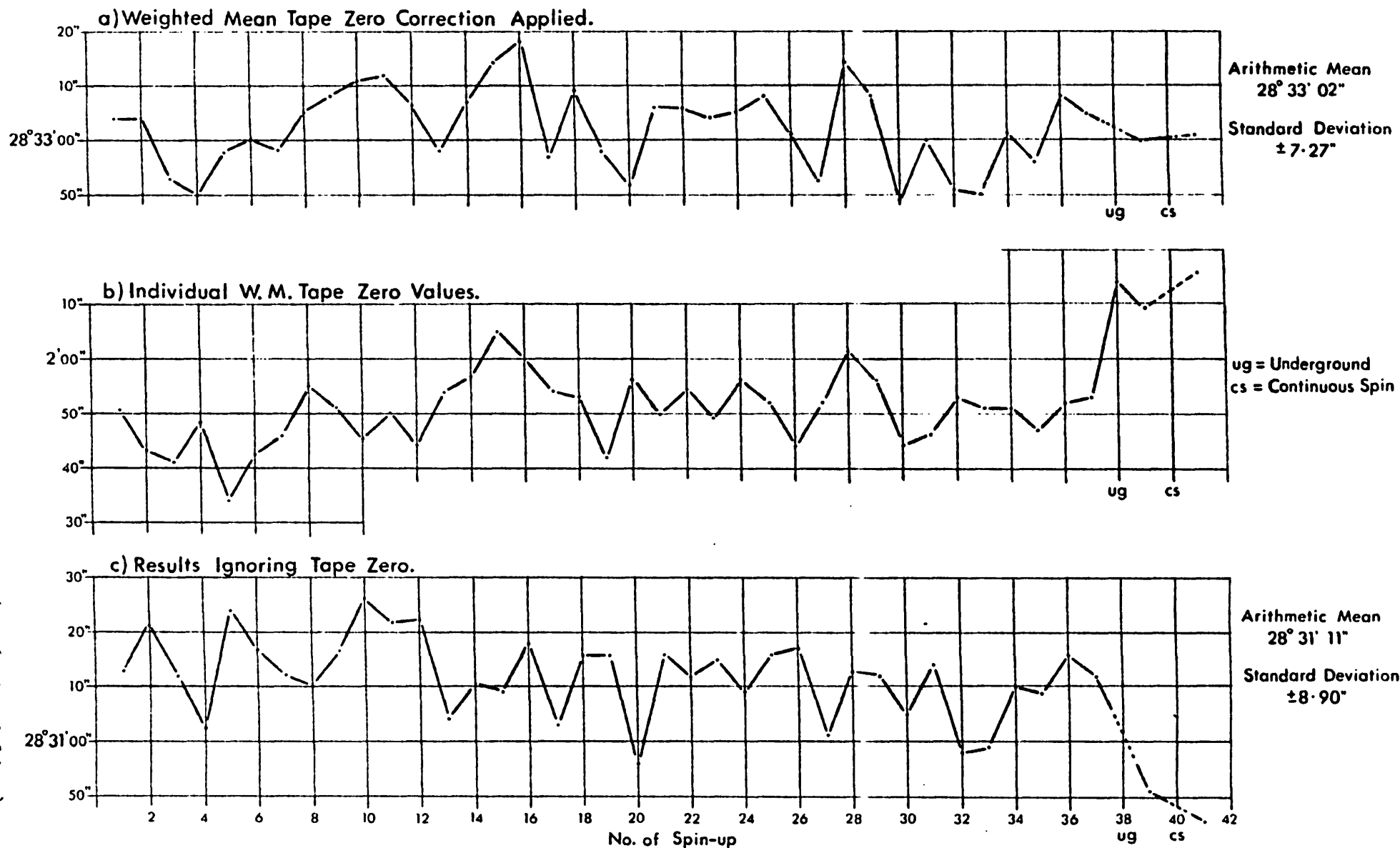
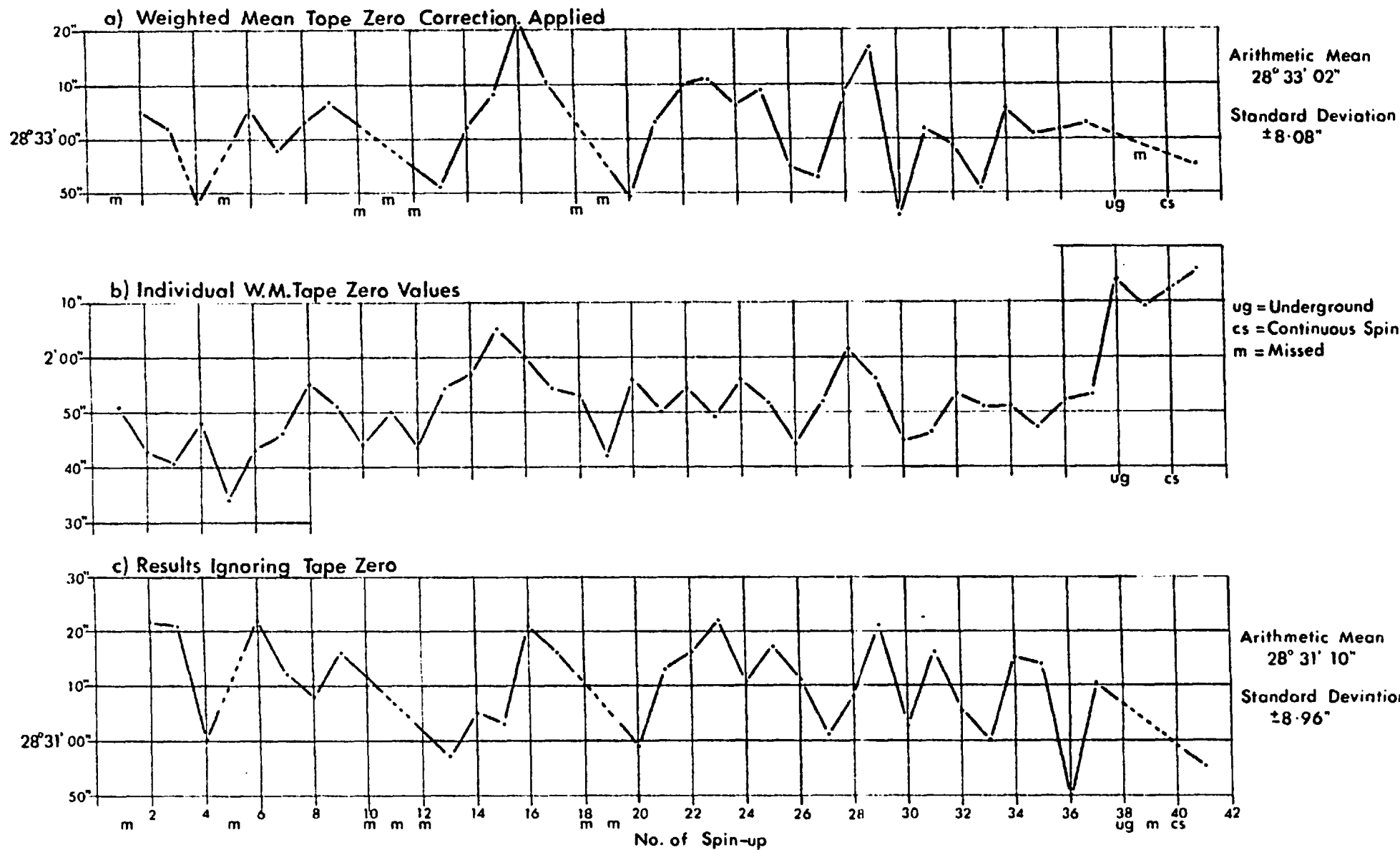


Figure 51 - Transit Results - 1975 (T-16 Theodolite)



use, has been improved by using the micrometer to a state at least equal to the commonly accepted transit method.

Finally further evidence has been found to support the application of a tape zero correction.

10.2 AMPLITUDE 1976/77

The initial trials documented and described in 10.1 led to the decision to exchange the Wild T-16 theodolite on which the gyro attachment was mounted for a Wild T-2 theodolite reading direct to one second of arc. The reason for this step was that by use of the modification it was now possible to read the gyro attachment directly, to a higher degree of accuracy than the theodolite on which it was mounted. The Wild T-2 was selected as a replacement not only for the expected increase in overall accuracy but also for the ability of the instrument to mean both sides of the horizontal circle, thereby cancelling out errors such as circle eccentricity which may have been inherent in the lower order machines.

Whilst exchanging the base theodolite the opportunity was taken to have the modified instrument "flame proofed" by the National Coal Board authorities. This meant that the instrument would be accepted for Coal Board use underground subject to certain conditions. This exercise consisted of supplying a protective bracket over the external input socket on the converter box and separate clamping bars over the normal clips which were used to attach the nickel cadmium power pack to the converter box. In both cases the additional fixtures could be released only by using an allen key.

After clamping, the relevant allen key would be left with the shaft official on the surface, thereby making it impossible to release either external socket or battery clips underground.

After "flame proofing" and remounting on the T-2 theodolite further trials were conducted. It was expected that major changes as above would affect the calibration of the equipment and therefore any comparison between results should bear this fact in mind. For example the additive constant during the initial trials was one minute eighteen seconds whilst during this second period was three minutes twenty four seconds.

Results of the earlier comparison between Amplitude and Transit techniques showed very little significant difference between the two methods. However, the mode of operation and reduction favoured the Amplitude method. It was decided that since one of the factors for research was to discover a simple way of finding True North using a gyro-theodolite, further trials should concentrate on the Amplitude technique. Results shown in this section are therefore confined to this method⁽²⁸⁾.

Again extensive trials were conducted in both London and Cornwall but this time observations were interrupted deliberately with excursions to locations underground and offshore both at home and overseas, in order to test the equipment in working environments. Such excursions were subject to all the dangers of travel with delicate equipment; intensive vibration and shaking from transport varying between jet aircraft to helicopters, private cars to underground mine cars.

10.2.1 Results

Headings were again selected at random along both base lines used for previous trials. Figure 52 illustrates groups of results along the Cornish base line which can be compared with Figure 48. However, results with spreads between 21 and 40 minutes are too few for serious examination.

Figure 53 shows results presented in a similar way to those earlier, along the base line in Cornwall. However, it should be noted that a gap of twelve months separates the last eight results shown. This gap contained many of the excursions mentioned in 10.2.

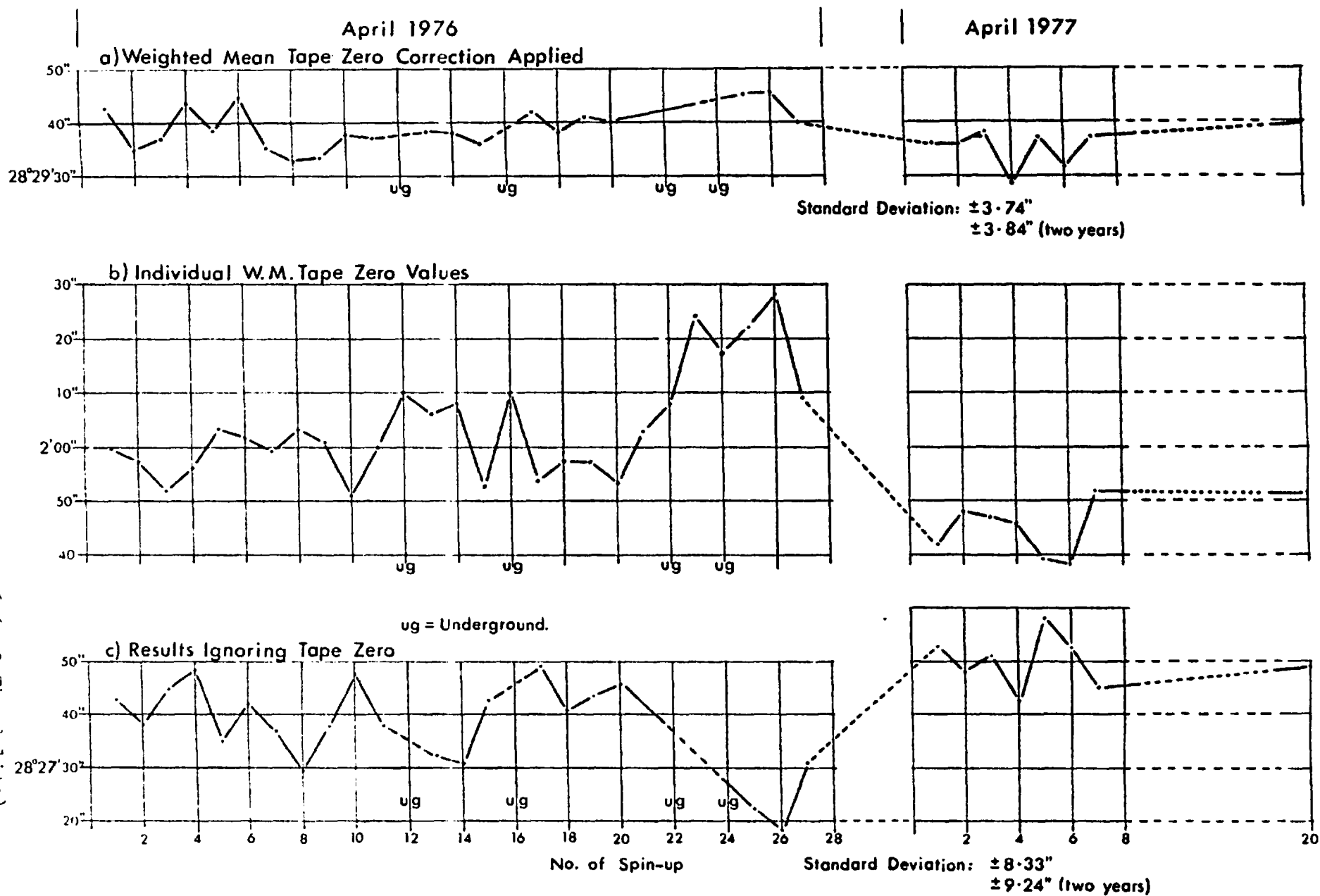
10.2.2 Conclusions

Changing to the more accurate theodolite coincided with an increase in accuracy of the gyro repeatability. This overall increase of accuracy stems from the elimination of inherent systematic theodolite errors combined to a certain extent with increased experience using and reading the micrometer. For example, whereas

Amplitude Method using Weighted Mean Tape Zero	All Observations 21 res.	Observations with spreads <20' 9 res.	Observations with spreads 21-40' 4 res.	Observations with spreads >41' 8 res.	Observations with spreads >20' 12 res.
Arithmetic Mean	28 29' 39"	28 29' 39"	28 29' 40"	28 29' 40"	28 29' 40"
Standard deviation of a single set	±3.74"	±4.11"	±1.71"	±4.38"	±3.60"

Figure 52 - Cornish Observations - April 1976
(Using 1" T-2 Theodolite)

Figure 53 - Amplitude Results - 1976 (T-2 Theodolite)



it was usual to book results to two decimal places of a scale division it was becoming possible in certain circumstances to estimate to three decimal places with comparative ease.

Results in Figure 53 illustrate a continuation of evidence in support of the application of a tape zero correction. Observations applying such a correction during the 1976 trials have a standard deviation for one set of $\pm 3.74''$, by including the eight separate results from 1977 this becomes $\pm 3.84''$. The same observations reduced without applying the correction have accuracies of $\pm 8.33''$ and $\pm 9.24''$ respectively. The general mirror trends of tape zero and uncorrected results are again in evidence and can be seen quite clearly.

10.3 AMPLITUDE, NEW TRANSIT AND TIMING - 1978

Three completely separate series of trials were conducted during the first seven months of 1978; the main purpose of these observations was to compare the repeatability of all three methods. Since the original comparisons of 1974/75 between the Amplitude and Transit methods, new formulae had been developed for the Transit method which removed the requirement for calculating a constant of proportionality and formulae had been introduced for calculating β using Times alone.

These three series, separate because of field course commitments, were observed under the conditions explained in 10.1; basically that sufficient information was extracted from each oscillation to enable computation of β , (the centre of oscillation), using all three

methods. There was a slight complication with the comparison technique this time owing to the two new sets of formulae requiring only one oscillation to obtain a result as opposed to the Amplitude and original Transit which required two. However, in view of the very limited damping measured on power spin it was decided that it would be acceptable to show the comparisons in two forms:

- i) Comparison using the first oscillation only - i.e. from Figure 54 $\alpha_1 + \alpha_2 \div 2$ for the Amplitude, a mean of results from S_0 , α_1 , S_1 and from S_1 , α_2 , S_2 for the new Transit method and a mean of results from S_0 , S_a , S_1 and from S_1 , S_b , S_2 for the Timing method.
- ii) Comparison using two full oscillations which would compare the conventional results from four reversal points using the Amplitude method with the means of four separate results from both the New Transit and Timing methods. In addition, at a later stage, the information obtained was used to compare results from the mean of second oscillation values only.

The advantage of the two new sets of formulae, besides giving additional answers within the normally accepted time for an observation, was that both the new Transit and Timing methods were released from the restriction that the theodolite be set within 10' of north. Both methods require the selection of an approximate centre of oscillation before observations commence. This centre line was selected by meaning the approximate reversal points obtained from each oscillation during its settling down period prior to the taking of actual measurements. The nearest full scale unit to the centre was then used to time S_0 , S_1 , S_2 , S_3 , S_4 as shown in Figure 54.

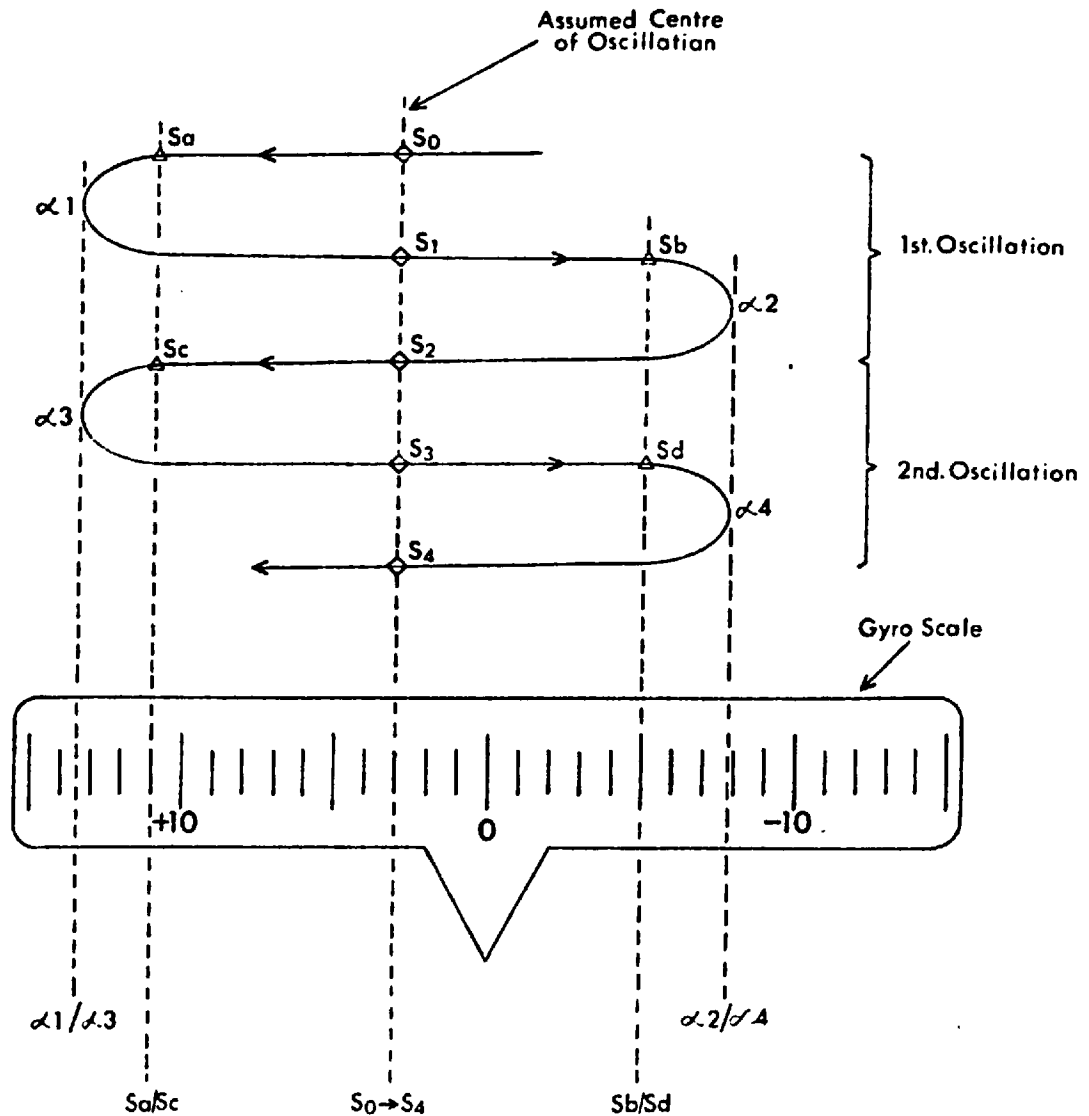


Figure 54 - Data Obtained from Each Heading during Composite Comparison Trials - 1978. Amplitude/Timing/Transit

At this time it was thought that in the timing method the outer times measured within each "loop" of the oscillation should be taken near to the normal reversal point and therefore in the initial trials these are the values being considered. Later work has demonstrated that there is far more flexibility in the selection of these outer timing positions than at first realised. This subject

is evaluated later - see Section 11.

10.3.1 Recording Information

Taking thirteen pieces of information within the two oscillations - in approximately fourteen minutes - posed a problem in the recording and booking of the information rather than in the physical possibility. A minimum of nine times were required and it was felt that the use of the conventional trailing hand stopwatch might be a little difficult and a way of automatically storing accurate times was sought. Various modern wrist and stopwatches incorporating lap time facilities were examined but although giving accurate times were often without storage capacity. Eventually it was discovered that the Hewlett Packard 55 electronic calculator had built-in to the machine a crystal controlled timing system which displayed values to 100th's of a second and had the ability to store and recall ten individual times by pressing the relevant storage button - see Plate 7. This meant that the observer was free to watch the oscillation and had to merely press a calculator key as the moving gyro mark crossed the required scale division. Automatic storage was thus accomplished, which could then be recalled for booking at the end of the observation. Times were also recorded in 100th's of a second as opposed to the 1/10th second on the conventional mechanical stopwatch.

10.3.2 Testing of the Hewlett Packard Timing System

Before using the method outlined above, although the simplicity of the storage facilities of the Hewlett Packard was an advantage in

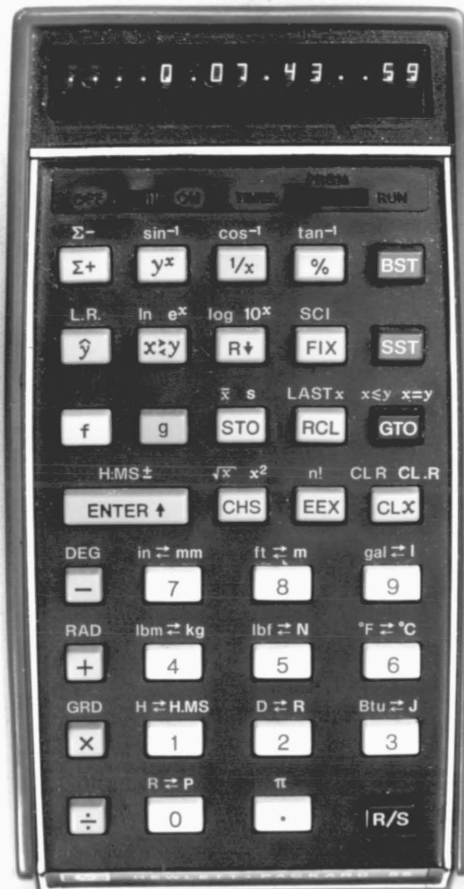


Plate 7 - Hewlett Packard 55 Calculator showing
Timing Values in Register

itself, it was imperative that the accuracy of the timing system was tested. It should be stressed that this method of collecting timing information should not be confused with automatic timing. All times stored are by manually depressing a calculator key at the instant the observer's eye tells him the moving gyro mark and required scale division are in coincidence.

The facility for storing intermediate times within an observation period plus the original start and final stop, twelve

values in all, meant that more times than were actually required could be extracted from the oscillation. Experiments could therefore be extended to cover various combinations of times within the same oscillation. It was then decided to purchase two H.P. 55s and attempt to extend experiments even further to evaluate as many as twenty timing positions within an oscillation. However, a system of linking the two calculators had to be devised.

The two calculators were checked for similarity by running them for lengthy periods, powered from the mains, and checked frequently with the G.P.O. telephone signal. For example, the calculator was set to display a time of say 10 hours 30 minutes and 00.00 seconds. The G.P.O. speaking clock was dialed and the calculator was started by pressing the R/S key at the instant the set time was indicated on the telephone link. At intervals over periods extending to 48 hours the telephone speaking clock was dialed at approximately whole divisions of time, i.e. say 12 hours 30 minutes and 00.00 seconds, listened to until such a time was reached and instantaneously a storage key depressed on the calculator. In this way the G.P.O. time interval could be checked later against the time interval derived from the stored calculator values. In all these experiments the calculator times include operator bias or delay.

Over lengthy periods it was found that both calculators lost around one second in 24 hours of time. As the normal gyro-theodolite observation takes around one hour and timing only for a half of this period it was felt that a loss in accuracy of approximately 0.02 second would have little affect on the methods being evaluated.

A further set of trials were undertaken to obtain some idea as to the accuracy lost in running two machines within one observation. The requirement during observations was that:

- i) Both calculators would be started together and storage keys 0 - 9 on machine one would be pressed as the observation proceeded.
- ii) After filling the stores in machine one storage keys 0 - 9 would then be used on machine two.
- iii) Finally both machines would be stopped together after the conclusion of the observation. In this way it would be possible to store twenty time values.

The weakness of this method was in the linking of the two calculators. Tests were run where both machines were placed side by side on a table and both started and stopped together by using the index finger of each hand. Surprisingly it was found that the machines would be consistently started and stopped with differences in display times of less than 0.02 of a second between them.

Each observation in the comparison of methods being discussed included a check on both calculators, at the end of each oscillation.

This discovery led to the use of timing to supplement reversal point readings during experiments concerned with extended spins, described in Section 9. Continuous timing was achieved by using one calculator initially and starting the second machine by simultaneously depressing store 0 on machine one and R/S (Start) on machine two. This meant that only nine stores could be used for intermediate timing on machine one and all times in machine two required to be adjusted by the time value in store 0 of machine one.

In this way it was possible to extract times from machine one whilst using machine two, clear machine one and then use as machine three by repeating the procedure detailed above. Experiments of over 16 hours duration were successfully carried out using this "leap frog" system. Obviously a final check is made between the overall start and finish times displayed on the calculators and a continuously running chronometer.

10.3.3 Results of Comparison Trials

Figures 55, 56 and 57 show the combined results of two series carried out in London. The results are shown with a weighted mean tape zero correction applied but also include plotted results ignoring tape zero. It can be seen that in these two sets of laboratory trials the value of tape zero changed very little and that the effect of applying such a correction in all cases caused a slight lowering of gyro repeatability. This is only to be expected as firstly in a controlled environment little change should occur in the tape zero position and secondly the measurement of the tape zero is a separate operation which itself could be a source of slight error.

Figure 58 summarises the information contained in Figures 55, 56 and 57. From this table the ranking on repeatability using weighted mean tape zero correction is Amplitude, Timing, Transit; although when looking at the results of the three methods in the final column there is little difference between them. It would appear that both the Transit and Timing methods benefit considerably from the meaning of two oscillations either side of north, whereas

Figure 55 - Amplitude Results - 1978 (T-2 Theodolite)

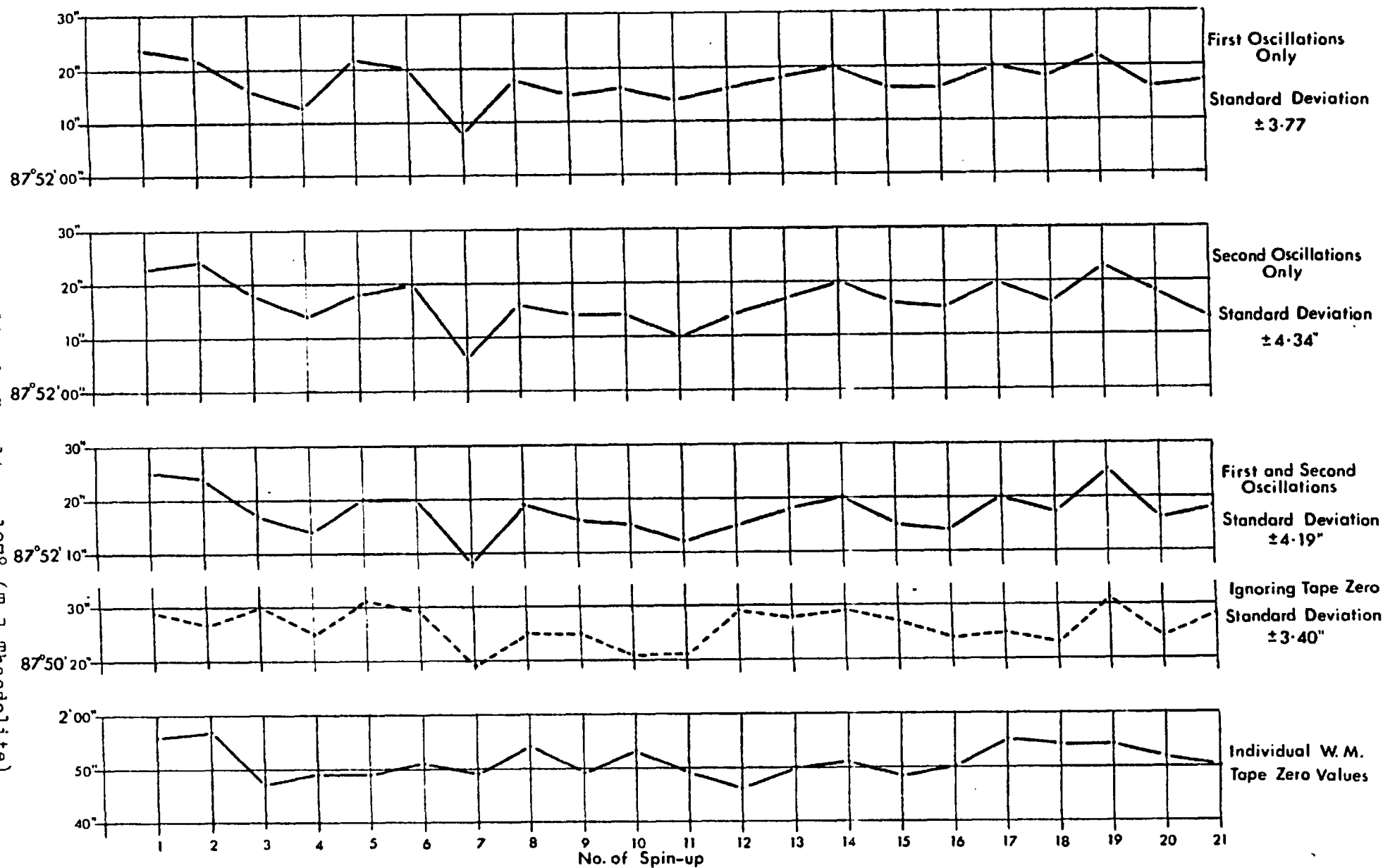


Figure 56 - Timing Results - 1978 (T-2 Theodolite)

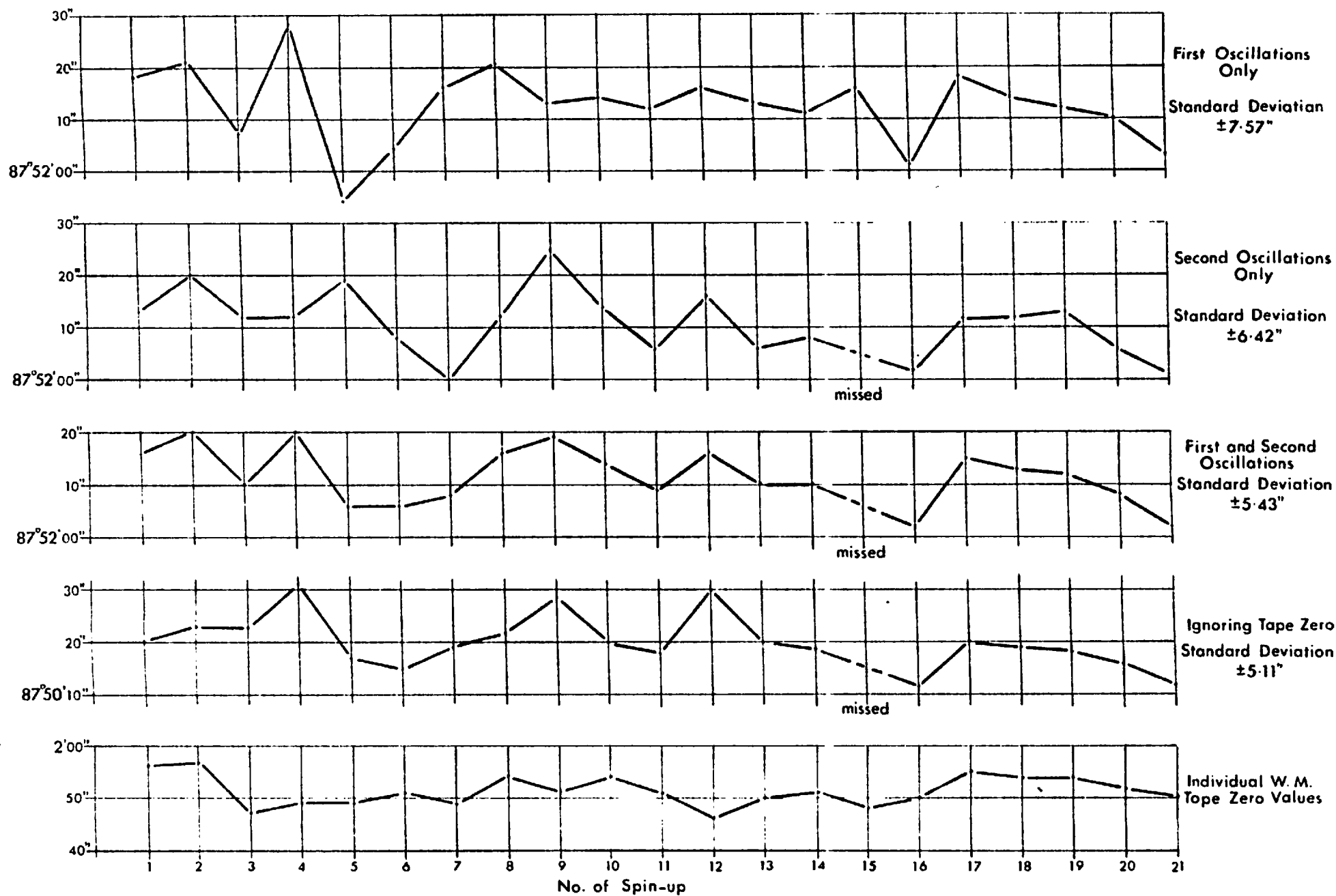


Figure 57 - New Transit Results - 1978 (T-2 Theodolite)

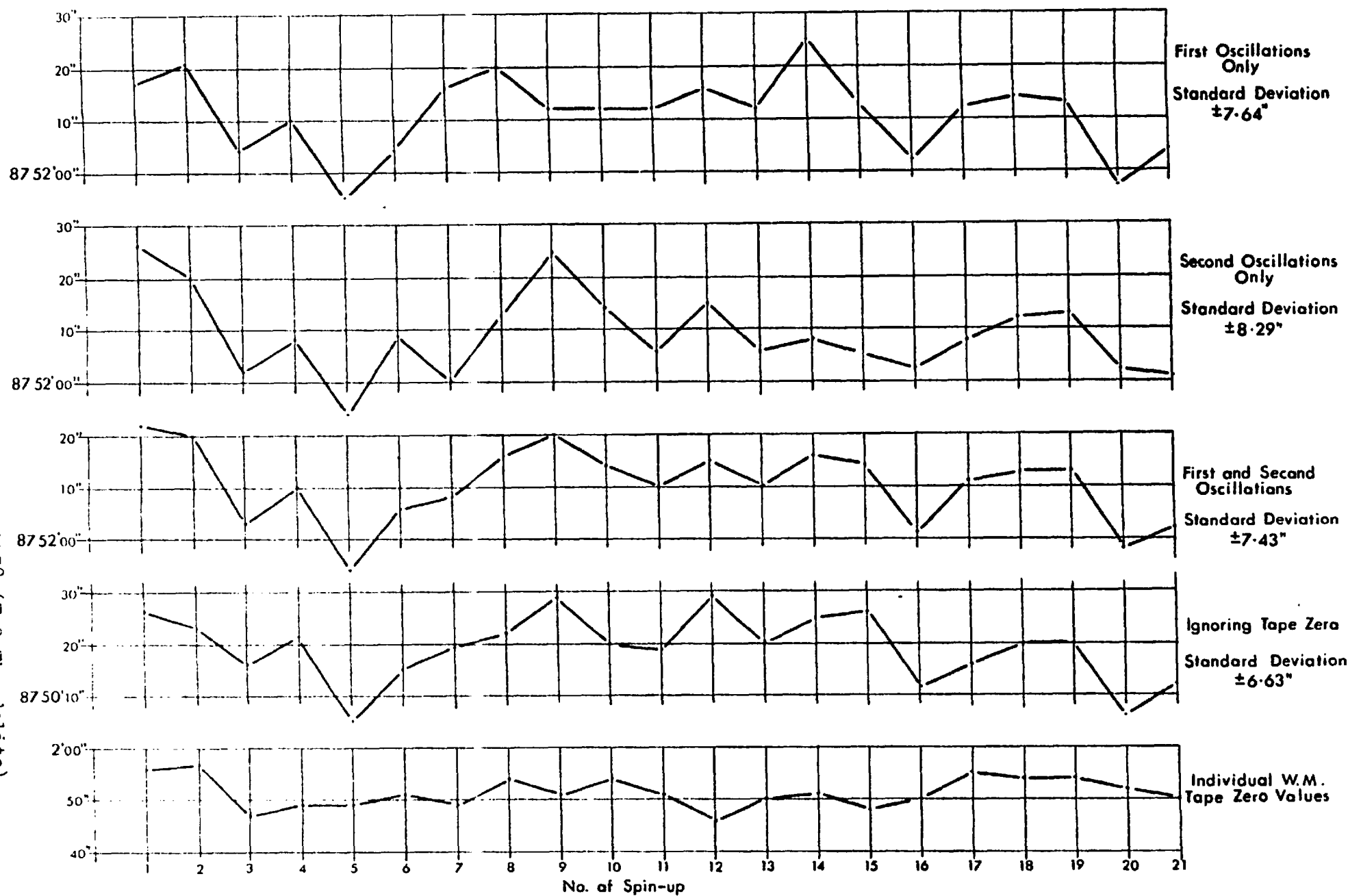
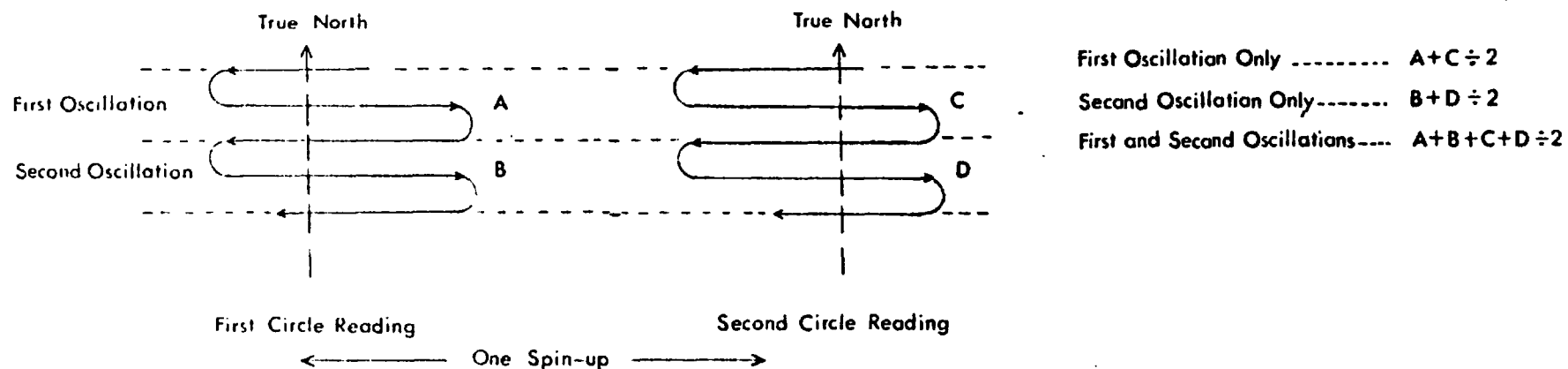


Figure 58 - Summary of 1978 Comparison Trials

	Number of Results	Amplitude (W.M.T.Z.)			Ignoring Tape Zero	Timing (W.M.T.Z.)			Ignoring Tape Zero	New Transit (W.M.T.Z.)			Ignoring Tape Zero
		First Oscillation Only	Second Oscillation Only	First and Second Oscillations		First Oscillation Only	Second Oscillation Only	First and Second Oscillations		First Oscillation Only	Second Oscillation Only	First and Second Oscillations	
Trial 1	11	± 4.70	± 5.34	± 5.04	± 4.01	± 9.22	± 6.90	± 5.49	± 4.72	± 7.74	± 10.21	± 8.40	± 6.30
Trial 2	10	± 2.64	± 3.08	± 3.26	± 2.66	± 5.54	± 5.15 9res.	± 5.07 9res.	± 5.34 9res.	± 7.93	± 5.15	± 6.27	± 7.28
Total	21	± 3.77	± 4.34	± 4.19	± 3.40	± 7.57	± 6.42 20res.	± 5.43 20res.	± 5.11 20res.	± 7.64	± 8.29	± 7.43	± 6.63

Standard Deviations of Single Sets
in Seconds of Arc.



in the Amplitude method the accuracy obtained from direct meaning of the two reversal points contained in one oscillation either side of north is very little different from that obtained from conventional meaning of two swings. It should also be borne in mind that each value given for a single oscillation in the Timing and Transit methods is the mean obtained from two half oscillations whilst the Amplitude system is a pure mean of two reversal points giving only one answer.

10.3.4 Analysis of Results

The immediate question which was posed was why the three separate methods gave differing accuracies, (although not statistically significant), over the same observations. Although impossible as yet, to come to a complete answer, there are nevertheless several factors which could contribute to these differences.

- i) Both the Timing and Transit methods depend on accurate timing through a known and constant centre point of the oscillation. The Amplitude technique, however, requires accurate reversal point readings which as explained earlier uses the rotating micrometer system. It is essential that this micrometer is zeroed on +0 before each timing is made and any mixing of reversal points and times therefore requires frequent re-setting of the drum. The possibility must exist that this re-setting could be slightly in error on a random basis and therefore time differences also be slightly erroneous.
- ii) As explained in the previous comparison work the taking of accurate times at the centre of an oscillation is a little difficult in that times are required when the, often vibrating, gyro mark travelling at its fastest speed, transits a stationary scale marker. This, therefore, must be regarded as a further source for error.

- iii) Each pair of β values obtained for the Timing and Transit methods from each oscillation share a common time value. For example in Figure 54 S_1 is shared in the Transit, S_0 , α_1 , S_1 and S_1 , α_2 , S_2 ; and also in the Timing S_0 , S_a , S_1 and S_1 , S_b , S_2 etc. If the times recorded at S_1 were in error for either of the reasons suggested above, they would affect the results from both halves of the oscillation.
- iv) It was originally thought that in the Timing method that the intermediate time should be near a reversal point.

These four points form the basis of further work which is contained in Section 11.

One final point which came to light was the fact that when methods were confined to one aspect of measurement, i.e. Amplitude with accurate reversal points and the Timing method with accurate timings, the repeatability was always a little better than when times and amplitudes were mixed, as in the Transit method. The reason for this is again not clear at this particular time.

10.4 SPECIAL TRIALS - AMPLITUDE, TRANSIT AND TIMING - NOVEMBER 1978

Introduction

These so called special trials were basically an extension of the previous comparison work carried out in the first half of 1978 but this time incorporating a major change in observation technique. Results obtained from investigations involving lengthy spin-ups suggested the presence of various drift patterns each having its own

period and amplitude - see Section 9. The pattern, which demonstrated the most movement, was the drift recognised initially, which lasted for periods of approximately 80 minutes of time under power spin and termed for the purposes of this thesis Primary Drift. This type of pattern was also shown to exist in the non-spin mode but the life of the movement was generally limited to between 30 and 40 minutes of time.

It was suggested in 9.1.7 that the gyro unit could be left spinning for a suitable time to allow this form of short term drift to disappear before serious observations were undertaken. However, as pointed out, this procedure would be impracticable under normal working conditions for two reasons:

- a) the time involved; and
- b) the reduction in the useable life of the bearings of the gyro unit.

Noting the similarity in reaction of the gyro during this initial stage in both the non-spin and power spin modes it was thought that the movements could have some common cause but the times taken by both modes to reach the limit of this phase were quite different. However, this was thought to be explained by the addition of powered spin introducing torque to prolong the period of drift or simply introducing a separate secondary cause.

10.4.1 Observational Techniques

It was then decided to conduct a series of experiments to test

the theory proposed in 9.1.7. To avoid unnecessary waste of the equipment's working life the gyro unit was suspended in the non-spin mode for varying periods of time before starting the normal power spin observational sequence rather than the original proposal of letting the machine run under power for this preliminary period. If the drift patterns were linked, it was possible that this delay would produce more stable results over a trial period. The length of time of suspension was first set at 80 minutes, in accordance with the initial findings under power spin, and then reduced to 40 minutes and finally 20 minutes of time as the trials continued.

Apart from the varying delays described above the methods of observation were similar to those adopted in 10.3. Two oscillations were observed either side of True North and sufficient information taken to conduct the normal comparisons of method. At this time investigations into the accuracies of timing questioned in 10.3.3 had not been undertaken and therefore the results presented here are subject to the same queries, hopefully answered in Section 11.

10.4.2 Analysis of Results

It is necessary to examine the results from the three methods by studying Figures 59 to 62. The graphical representation of these trials convey a far clearer idea of the repeatability of results than by individual tables. Each method has been used to calculate results from one and two oscillations either side of True North and in the case of the new Transit and Timing methods also from each half oscillation.

Figure 62 gives a graphical comparison of all three methods and also includes the individual tape zero values for each observation and the effect of applying such a correction to each result. It should be noted that the tape zero correction has only been shown applied to the final mean results of both headings around True North. This is because of the impossibility of measuring intermediate tape zero values throughout an observation.

10.4.2a) Amplitude

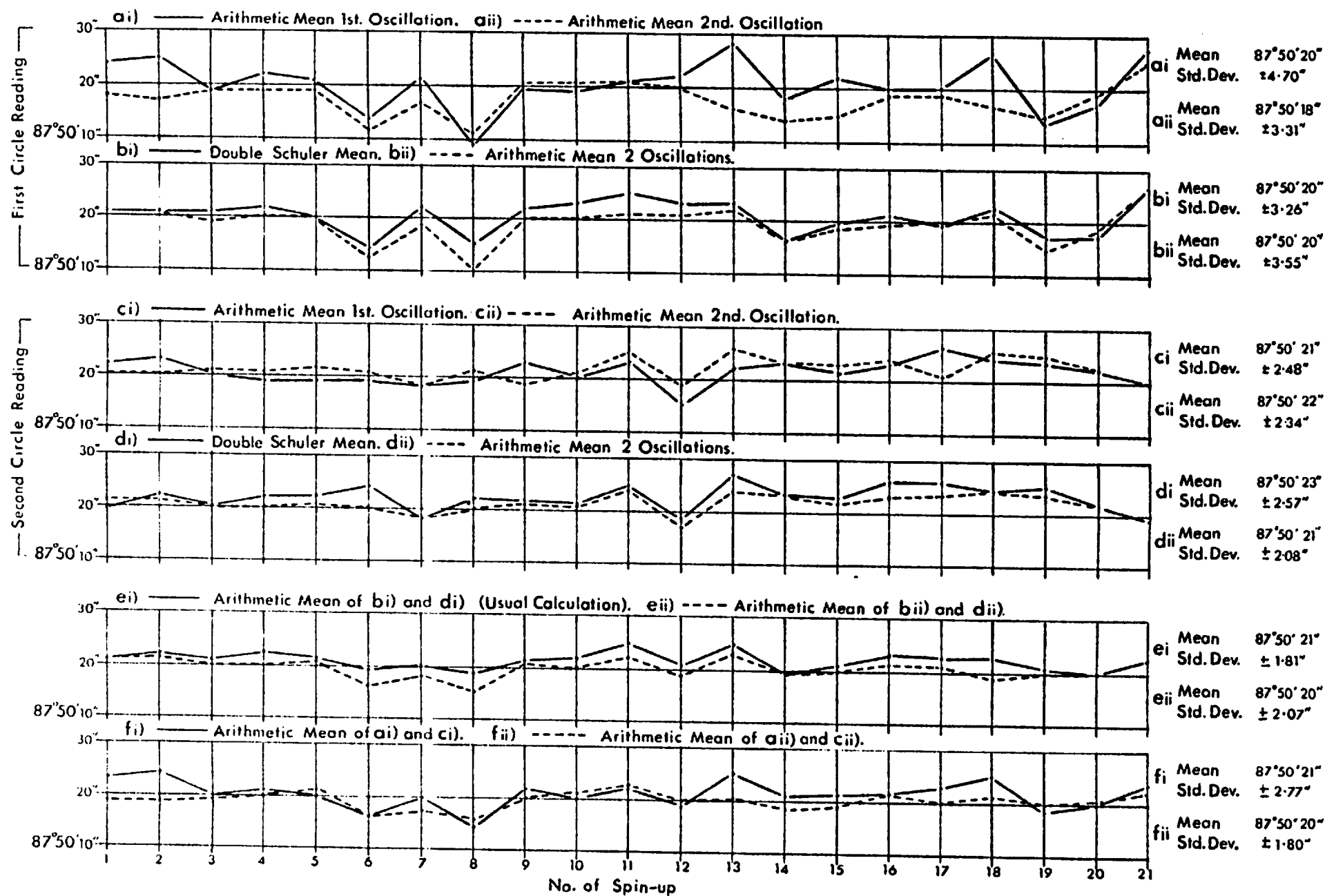
Figure 59 indicates the variety of reduction methods used. Each oscillation has been calculated using a pure arithmetic mean of the reversal points and each pair of oscillations either side of True North by using a double schuler mean and again by a direct arithmetic mean of the four reversal points. Graph e) depicts a final mean of both headings using a total of eight reversal points and again compares the arithmetic mean with results obtained from using the double schuler technique. Graph f) means both sets of 1st and 2nd oscillations from each heading.

The immediate point from Figure 59 is the greater stability of the second heading. Possibly this points towards a combination of delays; time devoted to non-spin plus some time under power. However, differences in the final means of both headings irrespective of meaning technique are extremely small.

10.4.2b) Timing

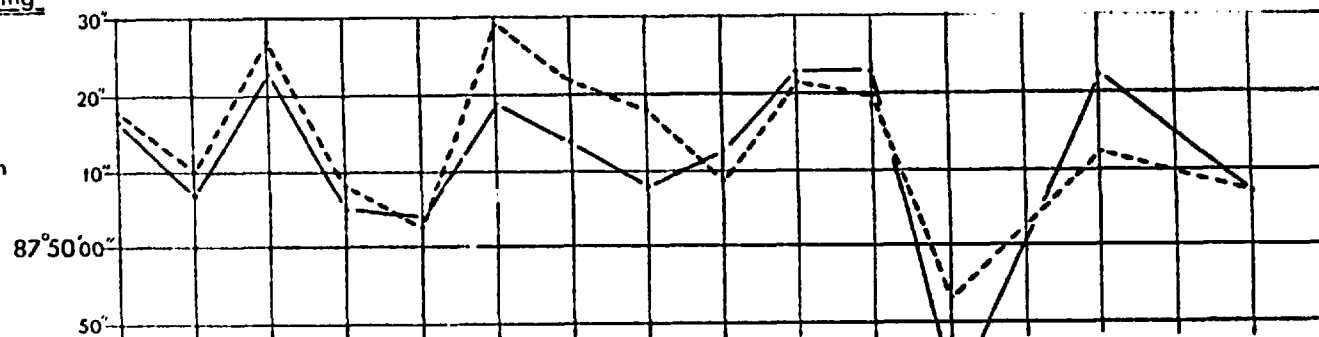
Figures 60a and 60b show the calculated results obtained by the

Figure 59 - Amplitude Results (Special Trials 1978)
T-2 Theodolite

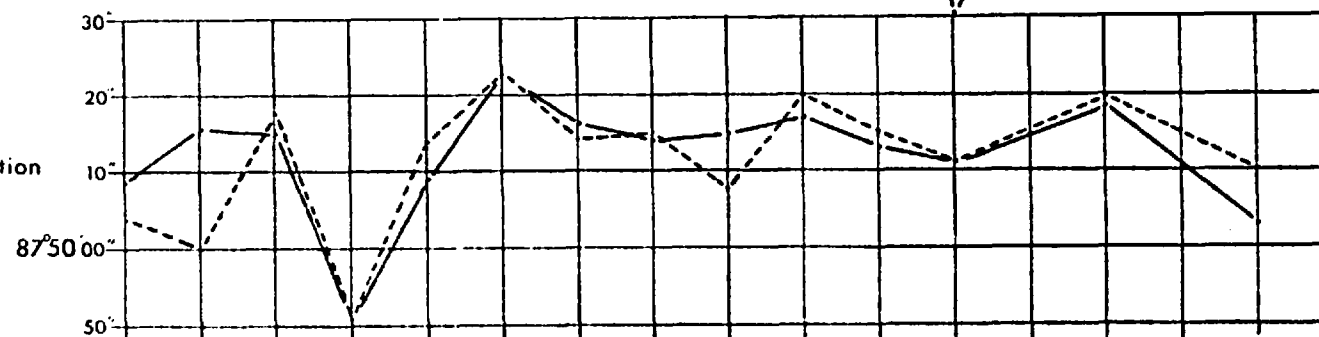


First Circle Reading

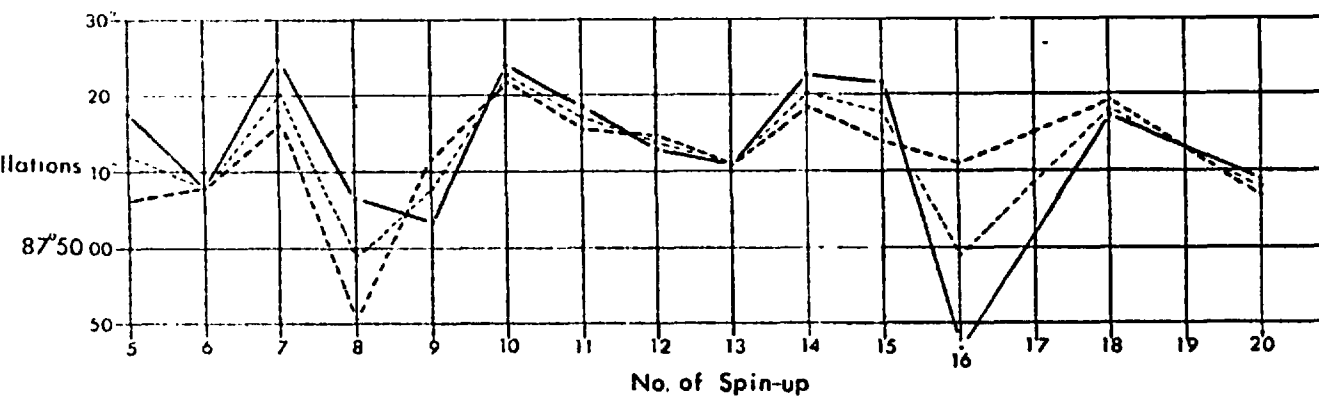
First Oscillation



Second Oscillation



Means of Oscillations



Result from first half of the Oscillation

Result from second half of the Oscillation

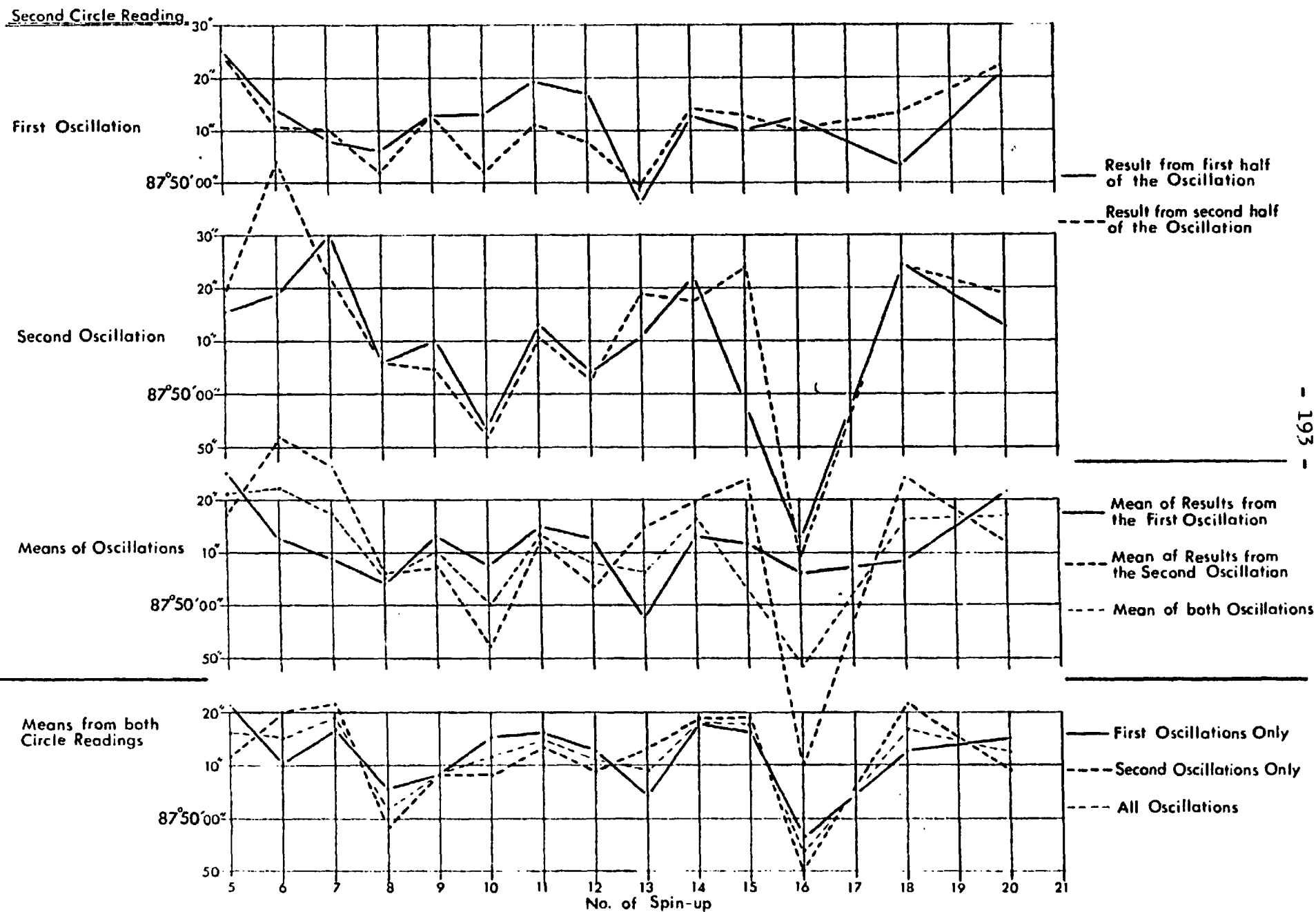
Mean of Results from the First Oscillation

Mean of Results from the Second Oscillation

Mean of both Oscillations

Figure 60a - Timing Results (Special Trials 1978)
T-2 Theodolite

Figure 60b - Timing Results (Special Trials 1978)
T-2 Theodolite



Timing method. The number of observations included in these and the Transit figures are slightly less than the Amplitude. Initially the new observational technique was tested using pure amplitudes to see if the experiment was worth continuing.

The graphs are quite different from those plotted from the Amplitude method and show a more pronounced random nature. The explanation for this could possibly be explained in Section 11 but inaccuracy of timing at the central point is difficult to justify for result 16 when both headings show similar variations. It would have to be a great coincidence for errors to have been made consistently throughout one complete observation.

10.4.2c) Transit

Figures 61a and 61b illustrate the new Transit results and show a marked similarity to the patterns shown for the Timing reductions. This similarity obviously being caused through using identical time values at the centre point of the oscillation.

Comments made under 10.4.2b) are also relevant to these results. The reversal points used during reduction were those used in calculation of the Amplitude method in Figure 59 but these have no effect on the answers.

10.4.3 Conclusion

Figure 62 gives an immediate impression of the three methods as used in these short trials. Undoubtedly the Amplitude method has

Figure 61a - New Transit Results (Special Trials 1978)
T-2 Theodolite

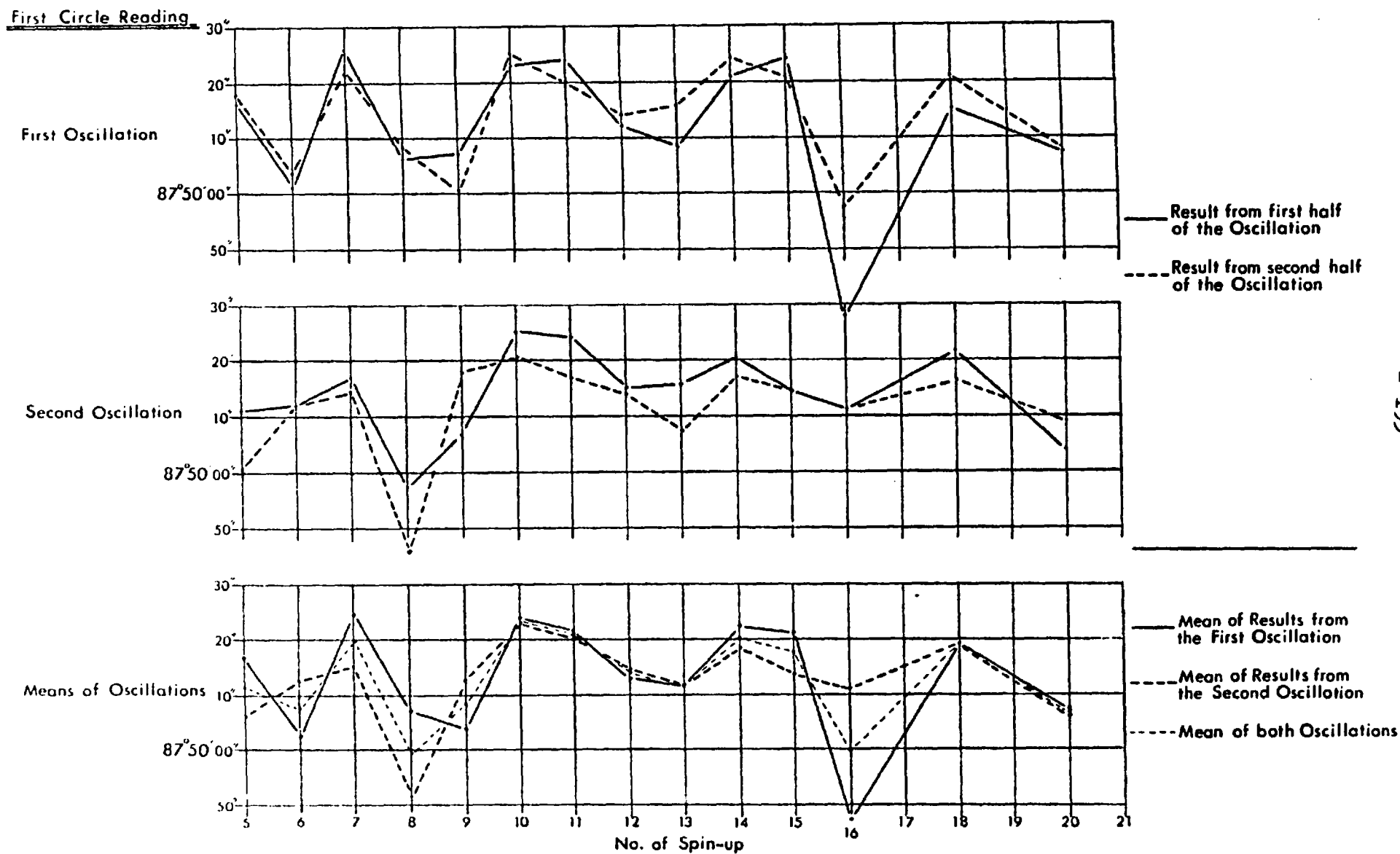


Figure 61b - New Transit Results (Special Trials 1978)
T-2 Theodolite

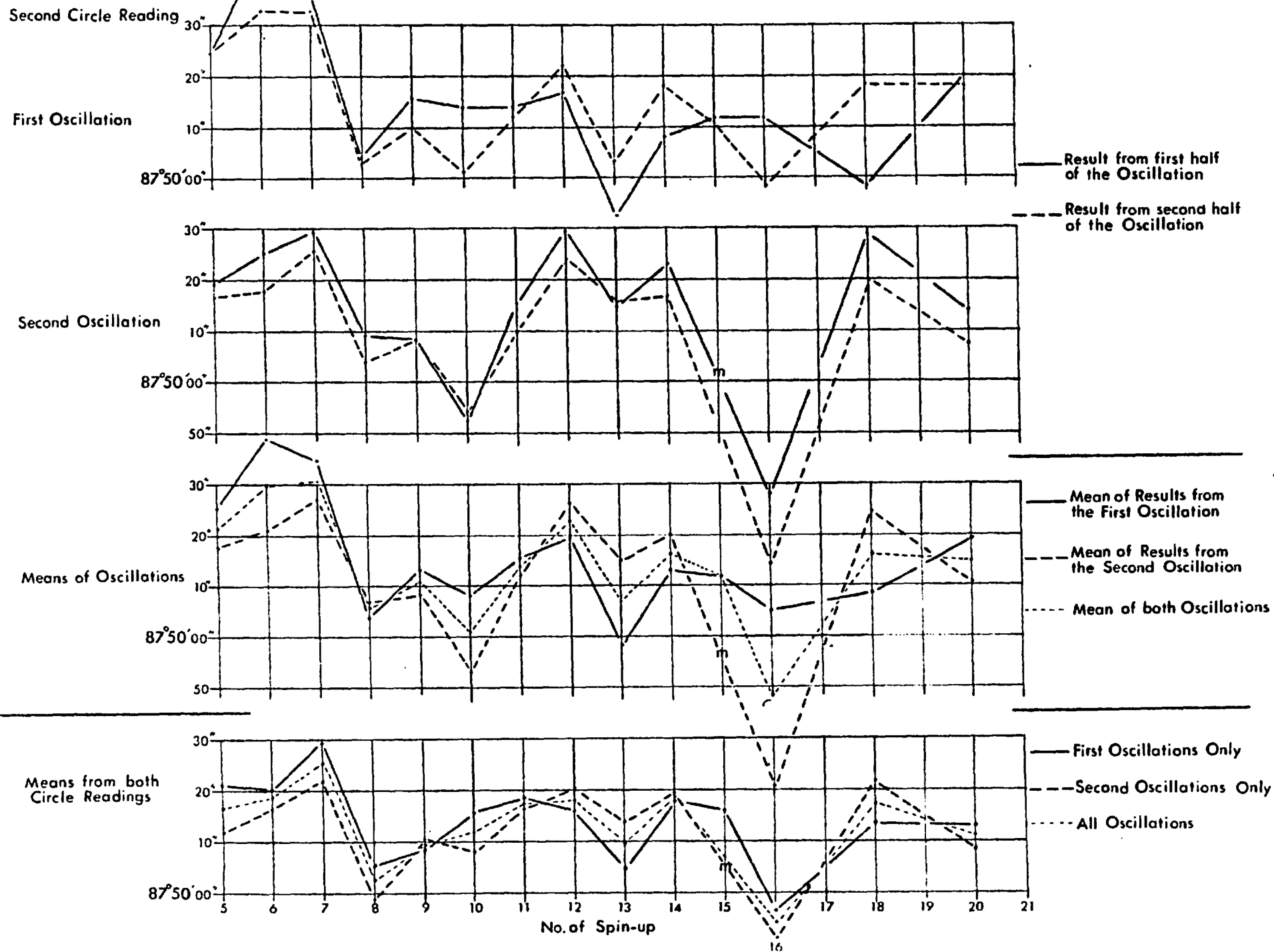
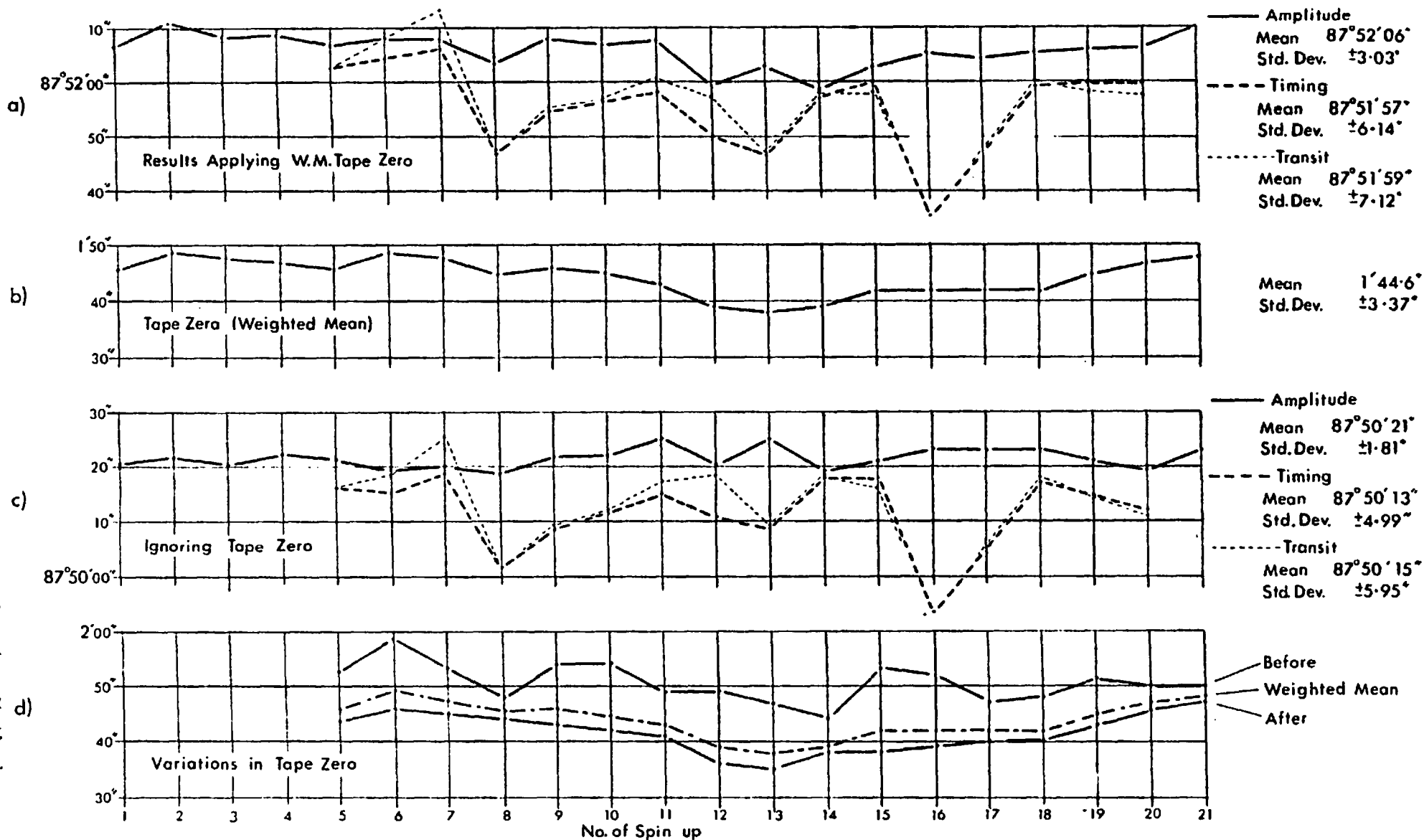


Figure 62 - Comparison of the Three Reduction Methods
(Special Trials 1978) T-2 Theodolite



nb. Means and Standard Deviations for Timing and Transit exclude Result 16.
All Results in a) and c) are from Balanced Observations (4 Oscillations).

again proved to give the more accurate repeatability over similar time periods irrespective of oscillation or heading. The Timing method is the next ranked followed closely by the Transit. This ranking of the methods confirms that found in earlier trials reported in 10.3 but the margin of difference between the methods has shown to be greater.

The experiment of delaying power spin-up certainly improved the accuracy obtained considerably and provided evidence that the initial Primary Drift movements found in Non-Spin and Power Spin modes were linked. Allowing the primary pattern to reach its point of stability in one mode had a noticeable effect on the other even though the time required to reach this position was considerably less in the Non-Spin mode.

The lack of improvement for the new Transit and Timing methods may be answered by the queries on the accuracy of timing values referred to earlier but could also be a pointer to the oscillations in general not being as stable as had been accepted previously. Nutation of the oscillation as it passes through a timing position may also cause errors in accurate timing. This affect has little influence on the taking of reversal points (Amplitude Method) as the human eye balances out such movements as the progress of the oscillation ceases before reversing direction.

10.4.4 Tape Zero Values

Results discussed in this section have been those obtained without the application of a tape zero correction. Figure 11

62 includes information on tape zero and indicates the difference to the repeatability of heading produced by incorporating such a correction to the individual values as previously recommended. It is evident that these results obtained by applying the correction are a little inferior to those without. The cause for this could again be due to the reason given in 10.3.2 of applying additional measured quantities as a correction which themselves could contain slight errors. However, it was noticed that whereas in all previous work there was no definite pattern between "before" and "after" tape zero measurements, in this series of trials tape zero values always decreased throughout the observation, see Graph d) in Figure 62. Remembering how the application of Power Spin prolonged the period of Primary Drift, possibly the earlier tape zero values reflected this effect and produced such random shifts. Having removed, or bypassed, the Primary period possibly the tape zero values obtained during these trials indicate the amount of movement due purely to the stresses encountered throughout an individual observation.

If this were the case there may well be an argument for not applying tape zero if the tape is suspended for a period prior to an observation. Previous improvement of derived headings having been obtained by counteracting the shifts found in the primary period. However, this must be regarded as hypothetical at present until further work is undertaken in positions where large deviations of tape zero have been discovered before. The question must still be posed as to whether the tape zero values obtained using this later technique would still be influenced by other external factors. As there is some similarity in the differences made to the results obtained in the trials described in 10.3 and 10.4, by applying the

tape zero correction it is felt that the reasons given in 10.3.2 are correct and that it will be found later that there will be no change in the original recommendation of applying such a correction as a matter of routine.

An attempt was made to correlate amounts of movement found in tape zero values illustrated graphically in Figure 62, with amplitude of the oscillation, with the distance of headings from True North, with total time of power spin and with the different times allocated for removing primary drift before spin-up. In all cases no correlation could be found.

10.5 STABILITY TRIALS

10.5.1 Introduction

It was discovered that accuracies quoted by Canadian researchers^{(20) (21)} had been derived from observations carried out using specially constructed steel tripods bedded in concrete before commencing operations. The stability given by using such rigid structures was claimed to assist the accuracy of the overall observations.

Results obtained from work carried out at the Royal School of Mines had similar accuracies to that published by the Canadians but these observations had all been taken using the standard wooden tripod as supplied by the manufacturer. Therefore a short series of observations were made with the modified Wild equipment along a new base line established at the out station in Cornwall, to

ascertain whether additional improvement could be made to the Royal School of Mines accuracies by using a rigid steel structure in place of the normal tripod. This structure was built originally as an instrument inspection pillar some years previously and consisted of a 30 cm diameter steel pipe 1 m 20 cm high bolted into the concrete base of a large stone building, surmounted by a 25 mm steel plate carrying the instrument mounting base. To use the Wild equipment on this pillar it was necessary to design a special base plate adaptor to convert the original non compatible steel thread to that used by Wild in the T-2 theodolite - namely a $\frac{1}{2}$ " bolt.

This new base plate was machined out of solid metal and was designed specially to give maximum stability to the theodolite tribrach. It was also possible to incorporate within the design an additional feature which enabled the same base plate to be used on regular ordnance survey pillars. Illustrations and further details of this mounting base are given in 14.3 together with other ancilliary equipment.

10.5.2 Results of Trials

The results obtained during this short series are shown in Figure 63. Each result represents the normal Royal School of Mines observation of a mean from both sides of North within the same spin-up. Between each observation the equipment was stripped down, walked around the laboratory and then reassembled. In this way the possibility of the gyro unit becoming influenced by using the same setting for several observations was avoided.

Using the rigid pillar marginally reduced the spread of results during the trials and after applying a weighted mean tape

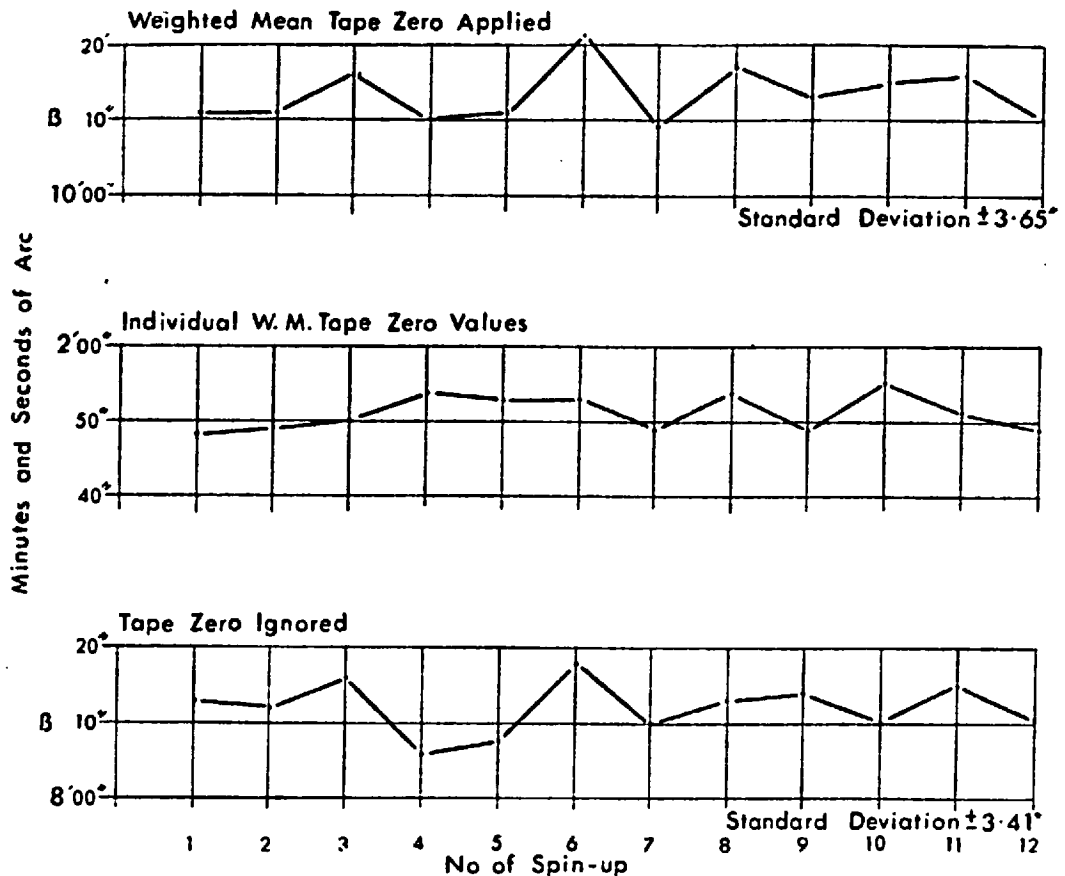


Figure 63 - Stability Trials - Cornwall 1977

zero correction gave a standard deviation of $\pm 3.65''$ seconds per observation. Because of the small number of observations carried out, it is difficult to come to any firm conclusion but it would appear that improved stability of the working platform could lead to slight improvements in repeatability.

10.5.3 Assessment of the Method

Although as stated above the use of rigid steel structures

either in the form of tripod or steel column could lead to minor improvements it was decided to continue with the accepted routine using the standard wooden tripod for several reasons:

- a) The physical difficulty of providing such a stable working surface in a practical situation within the mining industry outweighs the extremely marginal increase in accuracy obtained.
- b) It is highly unlikely that any working mine would allow a survey team the luxury of time to build or erect such a stable structure.
- c) Using such a structure, which by virtue of its description of being rigid, would reduce the general portability of the equipment.

However, it should be noted that improvements can be made by increasing stability and in certain circumstances, either in the research field or in commercial situations where accuracy is required for say the long term monitoring of small movements, there may well be a case for constructing and using such a pillar. The other situation which could arise would be surface positions where either National or local pillars are already in existence. One or two of these could be incorporated within the check baseline used to control other surface or underground gyro work.

10.6 HUNGARIAN EQUIPMENT

10.6.1 Introduction

Interest shown by the Hungarian Optical Works in the research being carried out at the Royal School of Mines led to M.O.M. offering to loan, for a short period, two types of gyroscopic equipment for evaluation purposes. These instruments were the

attachment GiC11 and the purpose built GiB1, both of which are described in Section 4.

Difficulties arose in transporting the equipment from Hungary and due to the equipment being required back at a certain date, reduced the available time for serious evaluation studies. It was therefore decided to concentrate on comparing the performance of these two models with the by now well tested Modified Wild G.A.K.-1 and the Royal School of Mines methods of reduction. Thorough evaluation work on various M.O.M. models had been published previously by authors such as Gregerson of Canada and Halmos of Hungary and there appeared little purpose in repeating much of their work, especially with the limitation of time.

10.6.2 M.O.M. GiB1

This instrument was tested along the known base line in the Royal School of Mines laboratory in London. Results can therefore be compared directly with those derived from previous studies as location and observation conditions were similar. This particular instrument had been given an additive constant of $89^{\circ}42'59''$ based upon work carried out in Budapest and was supplied with a table of values for the constant C which were shown varying with latitude. From this table it was discovered that for the latitude of the base line, $51^{\circ}30'$ North, the value of $C = - 5.67$. This constant differed from that used in the Royal School of Mines techniques in that the quoted values were in fact $C \times \text{scale interval}$. Scale interval on the GiB1 was 30 seconds of arc and to enable standard Royal School of Mines reductions forms to be used C was therefore

converted to 0.189 and $(1 + C)$ to 1.189.

M.O.M. state that tape torque position should be adjusted before each observation and that a final tape zero measurement should be used to adjust the readings from the gyro unit. In the trials conducted at the Royal School of Mines this procedure was followed accordingly but additional results were calculated using the Royal School of Mines weighted mean solution. The reason for this approach came from the inability to completely zero tape torque position before each observation and the feeling that however small the residue was it should be measured and possibly used. If, as was suspected, the tape position was altering gradually during the time of an observation, the weighted mean method would supply a value more commensurate with the time of swing measurement.

During the set of trials described below an opportunity was taken to use the equipment on an offshore drilling platform - the Burmah, Thistle 'A' structure in the Thistle Field. Transporting such bulky equipment, first to Aberdeen, then to the Shetlands and finally to the platform 150 miles offshore meant extensive shaking and vibration. Control over the equipment during transportation was minimal due to the weight and bulk of each piece. The lighter weight attachment types of gyro unit can be protected by being cradled in the arms of the operator during poor transportation conditions, as in the case of the Wild G.A.K.-1. However, with the GiBl, total reliance was placed on the specially designed storage containers. The gyro-theodolite unit for example was bolted onto a heavily sprung platform rigidly mounted within the crate. This equipment was, therefore, manhandled by unskilled labour at all times and on

two occasions winched between platforms in a loading net slung from rig mounted cranes.

10.6.2a) Results and Analysis

Figure 64 shows a short set of 12 results interrupted by the field exercise mentioned above. At this time the two methods under evaluation at the Royal School of Mines were Amplitude and Transit and therefore, as with the Wild equipment, results were obtained from each observation to enable direct comparison. Figure 65 shows a typical Amplitude result and Figure 66 a typical Transit result. Note the value of T for this machine was approximately 537 seconds (8 minutes 57 seconds).

Several facts of interest emerged from these results:

- i) There was virtually no difference between the results calculated using the Transit or Amplitude techniques. With the Wild equipment each modified model showed small differences which had been explained by minute errors in establishing the run of the micrometer drum in each individual machine during manufacture. However, with the GiBl it was possible to read the scale very accurately at reversal points as scale divisions were only 30 seconds apart - as opposed to the 10 minutes of the G.A.K.-1.
- ii) The accuracy obtained from this equipment was very similar to that using the modified G.A.K.-1 attachment. The M.O.M. GiBl had been built originally as the most accurate instrument of its type and it was surprising that under the same controlled conditions results were no better than the smaller modified G.A.K.-1.
- iii) The application of a tape zero correction for this instrument was proved without a shadow of doubt. Non application of such values reduced the accuracy of results by two to three standard deviations. For example a standard deviation for one result fell from $\pm 4''$ to around $\pm 12''$ of arc. Values for tape zero were far from constant but the amount of change discovered between before and after was very similar.

Graph a) in Figure 64 shows that excepting one result (No. 9) the value of tape zero fell by between 3 and 9 seconds during the time taken by each observation.

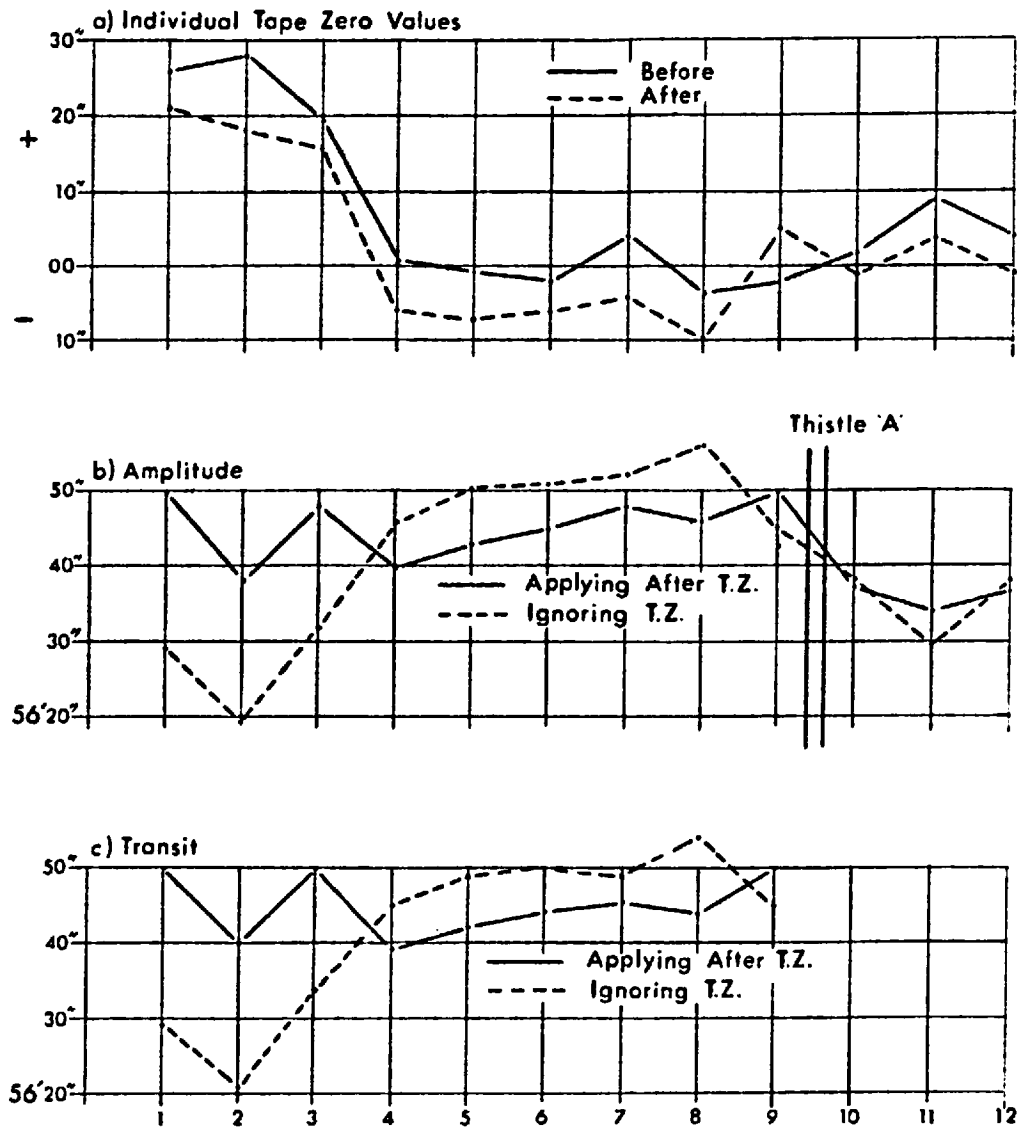
The table included in Figure 64 also shows the same results with a weighted mean tape zero value applied instead of the recommended 'after' value. Weighting was 3 to 1 in favour of the after value and therefore show only minor changes. However, the application of a weighted mean tape zero value tends to increase the accuracy marginally although in the trials carried out these changes are insignificant statistically.

10.6.2b) Summary

In the short period available for trials it was found to be impossible to obtain results from the large, stable M.O.M. GiBl to better those from the more versatile lightweight modified Wild G.A.K.-1 attachment. Conditions for observation were chosen purposely to enable direct comparison although the Hungarian mechanic who accompanied the equipment was a little sceptical of the stability of the set-up for his machine. Possibly greater accuracy could be obtained from concrete pillars, etc.

One other point is that there were slight differences between operating the G.A.K.-1 and the GiBl and lack of familiarity with the equipment could possibly have affected the results obtained. However, it should be pointed out that at this time the author had had several hundred hours of experience with various G.A.K.-1 models.

If the opportunity arises in the future it is recommended that



	Amplitude						Transit		
	After Tape Zero		No Tape Zero		Weighted Mean Tape Zero		A T Z	NTZ	WMTZ
No. of Results	9	12	9	12	9	12	9	9	9
Arith. Mean	56° 45'	56° 43'	56° 42'	56° 41'	56° 47'	56° 45'	56° 45'	56° 42'	56° 46'
Std. Deviation	± 4.27"	± 5.32"	± 12.57"	± 11.33"	± 3.68"	± 5.07"	± 4.28"	± 11.17"	± 3.55"

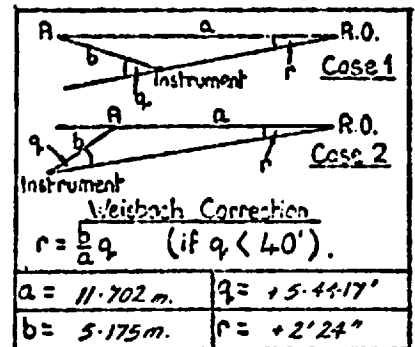
Figure 64 - Summary of Short Trials on M.O.M. GIBI - 1977

GYRO THEODOLITE BOOKING SHEET (Amplitude Method) Instrument M.O.M. G1
 Observer R. Smith Booker R. Smith Place R. 146 Date 3/6/1977

Before	C.L.	C.R.	After	C.L.	C.R.	MEAN R.O.
R.O.	277 33 13	97 33 21	R.O.	277 33 18	97 33 25	97 33 19
A	97 38 46	277 38 43	A	97 38 46	277 38 48	
Diff	+05 33	+05 22	Diff	+05 28	+05 23	(+05.4417)°
Time	14:00		Time	15:30		

"Before" Tape Zero		
+44.1		-43.8
+43.2		-43.2
δ	-0.113	

"After" Tape Zero		
+11.7		-13.9
+11.4		-13.7
δ	-1.1875	



B = Oscillation Centre = $(\alpha_1 + 3\alpha_2 + 3\alpha_3 + \alpha_4)/8$.
 δ = Tape Zero Centre = $(\delta_1 + 3\delta_2 + 3\delta_3 + \delta_4)/8$.
 s = Value of one gyro scale division in angular measure.
 W = Circle Reading of North = $\Theta + s\omega$.
 c = Instrument constant.
 Θ = Theodolite reading
 $\omega = [\beta(1+c) - c\delta]$
 $(1+c) = (\Theta' - \Theta)/6(\beta - \beta')$

$\phi = 51.30'$ $C = 0.189$ $S = 0.5' (30 \text{ seconds})$
 $\Theta' - \Theta = +2.22''$ $(1+c) =$

Reversal Points (1)		
+59.0		-54.9
+58.7		-54.6
β	+1.975	

Reversal Points (2)		
+53.3		-57.1
+53.1		-56.9
β'	-1.950	

Circle Reading (Θ)	279 20 41	279 23 03
Correction ($s\omega$)	+01 17	-01 03
Circle Reading of North (W)	279 21 58	279 22 00
True Bearing of R.O. (R.O.- ω)	358 11 21	358 11 19
Weisbach Correction (r)	+02 24	+02 24
Additive Constant (Δ)	+89 42 59	+89 42 59
True Bearing Backsight (R→R.O.)	87 56 44	87 56 42
MEAN	87 56 43	

Figure 65 - Example of Amplitude Method - M.O.M. G1B1

GYRO THEODOLITE READINGS

Transit Method

Inst. M.O.M. GIBI
Date. 3/6/1977
Observation No. ⑤

Place. R. 146.
Observer. R. Smith.
Booker. R. Smith.

Formulae:-

- S_0, S_1, S_2 = Three consecutive Transits Through Centre.
 α_1, α_2 = Reversal Point Readings ($S_0 \rightarrow \alpha_1 \rightarrow S_1 \rightarrow \alpha_2 \rightarrow S_2$)
 ΔT = $(T_1 - T_2) = (S_1 - S_0) - (S_2 - S_1) = (2S_1 - S_0 - S_2)$
 α = $(\alpha_1 - \alpha_2)/2$ $\delta = (\delta_1 + 3\delta_2 + 3\delta_3 + \delta_4)/8$ = Tape Zero.
 W = Circle Reading of North.
 S = Value of one gyro scale division in angular measure.
 C_T, C = Instrument Constants $C_T = \pi(1+C)/2T$
 θ = Theodolite Reading. $f = \pi^2/24T^2$
 T = Period of Oscillation.

$$W = \theta + S[C_T \cdot \alpha \cdot \Delta T(1 - f\Delta T^2) - C\delta] = (\theta + S\omega)$$

$$C_T = (\theta' - \theta)/S[\alpha \cdot \Delta T(1 - f\Delta T^2) - \alpha' \Delta T'(1 - f\Delta T'^2)]$$

$C_0 =$	$\phi =$	$C =$	$C_T = 0.00347715$	$S = 0.5'$	$f = 1.425 \times 10^{-6}$
---------	----------	-------	--------------------	------------	----------------------------

	Before	ca	After	Mean	
R.O.	277 33 13 (21)		277 33 18 (25)	277 33 19	(R.O)
A	97 38 46 (43)		97 38 46 (48)		
Diff.	+05 33 (22)		+05 28 (23)		$\alpha = 11.702m$ $b = 5.175m$
Time	14:00		15:30		$q = +5.4417'$ $r = +2' 24''$

		θ 279 20 41	Time			
		Diff.	ΔT	$\Delta T(1 - f\Delta T^2)$		α
S_0	00 00 00				α_1	+
S_1	04 34 52	274 52	+12.16		α_2	56.95
S_2	08 56 58	262 36			α_3	+
S_3	13 31 40	274 52	+11.92		α_4	56.65
S_4	17 54 00	262 60	(+12.04)	(+12.04)		(56.60)
		θ' 279 23 03	Time			
S'_0	00 00 00				α'_1	+
S'_1	04 22 52	262 82	-11.68		α'_2	55.20
S'_2	08 57 32	274 50			α'_3	+
S'_3	13 20 10	262 78	-11.82		α'_4	55.00
S'_4	17 54 70	274 60	(-11.75)	(-11.75)		(55.10)

$$(\theta' - \theta) =$$

$$C_T =$$

$$(1+C) =$$

Tape Zero Point.	
Before	
	+44.1 -43.8
	+43.2 -43.2
After	
	+11.7 -13.9
	+11.4 -13.7
δ	-1.1875

$$T = 537.14 \text{ seconds.}$$

Circle Reading (θ)	279 20 41	279 23 03
Correction ($S\omega$)	+01 18	-01 01
Circle Reading of North (W)	279 21 59	279 22 02
True Bearing of N.P. ($R_0 - W$)	358 11 20	358 11 17
Weisbach Correction (r)	+02 24	+02 24
Instrument Constant (A)	+89 42 59	+89 42 59
True Bearing of N.P. ($A - R_0$)	87 56 43	87 56 40
Mean	87° 56' 42"	

Figure 66 - Example of Transit Method - M.O.M. GIBI

further work be conducted on the GiBl and some intensive investigation of the application of a weighted mean tape zero.

The statistical values shown in Figure 64 are shown with and without the results obtained after the work undertaken on the Thistle Field. Possibly the rough handling the equipment received may have caused a slight change in the additive constant. However, the similarity of the results before and after this exercise are a credit to the machine and to the expert design of the travelling cases.

10.6.3 M.O.M. GiCl1

The GiCl1 is the comparable model to the Wild G.A.K.-1 excepting that the gyro scale intervals are four minutes apart.

This instrument was not evaluated on a serious basis for repeatability for several reasons and consequently the results shown below are not regarded as significant. Only a limited number of observations were attempted over a period of approximately 7 weeks. Figure 69 indicates in tabular form the results obtained. From these values, all too few for accurate analysis, the following information was derived:

- i) Amplitude Method - mean bearing = $82^{\circ}18'10.2''$;
standard deviation = ± 21.9 seconds.
These results were obtained from information estimated on the gyro scale which was divided into regular intervals of four minutes of arc. Bearing this fact in mind the results are most creditable.
- ii) New Transit Method - mean bearing = $82^{\circ}18'10.7''$;
standard deviation = ± 4.86 seconds.

- iii) Timing Method - mean bearing = $82^{\circ}18'18.5''$;
 standard deviation = ± 10.42 seconds.
 The Timing Method referred to in these few
 observations should not be confused with the timing
 method given in Section 5 and analysed in Section
 10. At the time of these particular trials the
 timing method was being evolved and several
 variations of the formulae were being evaluated.

With reference to the comments above it is suffice to state
 that no definite conclusions can be reached regarding this instrument
 until it becomes possible to carry out a realistic evaluation study
 incorporating many observations and the finalised formulae.

<u>Obs.No.</u>	<u>Date</u>	<u>Amplitude</u> o ' "	<u>New Transit</u> o ' "	<u>Timing</u> o ' "
1	26/5/77	82 18 15	82 18 18	-
2	29/5/77	-	-	82 18 02
3	30/5/77	82 17 40	82 18 09	-
4	31/5/77	82 17 59	82 18 08	-
5	31/5/77	-	-	82 18 21
6	1/6/77	82 17 38	-	82 17 52
7	14/7/77	82 18 27	-	82 18 06
8	15/7/77	82 18 25	-	82 18 22
9	15/7/77	82 17 59	-	82 18 08
10	18/7/77	82 18 03	82 18 08	-
11	19/7/77	82 18 34	-	82 18 15
12	19/7/77	82 18 42	-	82 18 18
		10 Obs.	4 Obs.	8 Obs.

Figure 67 - Repeatability Results Using M.O.M. GiC11
 (Observer P. Huckle)

11 - INVESTIGATION INTO ACCURACIES OF TIMES MEASURED
WITHIN THE TIMING FORMULAE

From work carried out during the comparison trials reported within Section 10, various factors were discovered which warranted separate investigation into the effect of accuracy of recorded time values on final computed results.

11.1 ACCURACY LOST DUE TO VARIATIONS IN THE POSITION OF TIMING CENTRE

The question of accurate re-setting of the micrometer on + 0 before taking time values instigated a series of experiments where the micrometer was set randomly at known distances from + 0 or the selected timing centre. Comparisons were made to discover the maximum effect this could have on the final results. At an early stage it was discovered that apart from gross errors of mis-setting by one whole division (60 seconds of arc) or by setting -0 instead of + 0 (10 minutes of arc), both of which are due to careless operator technique, the greatest error tolerated by the human eye would be less than 0.1 of a sub division on the micrometer scale, or approximately 1.2 seconds of arc.

A typical experimental series is shown in Figure 6⁸. A continuous spin of approximately one and a half hours monitored throughout; the micrometer being adjusted to give erroneous centre point settings at regular intervals of time. At each micrometer position a complete oscillation was observed and the mid swing point calculated. Amplitude values were also taken at each reversal point throughout the series using the micrometer system to act as a

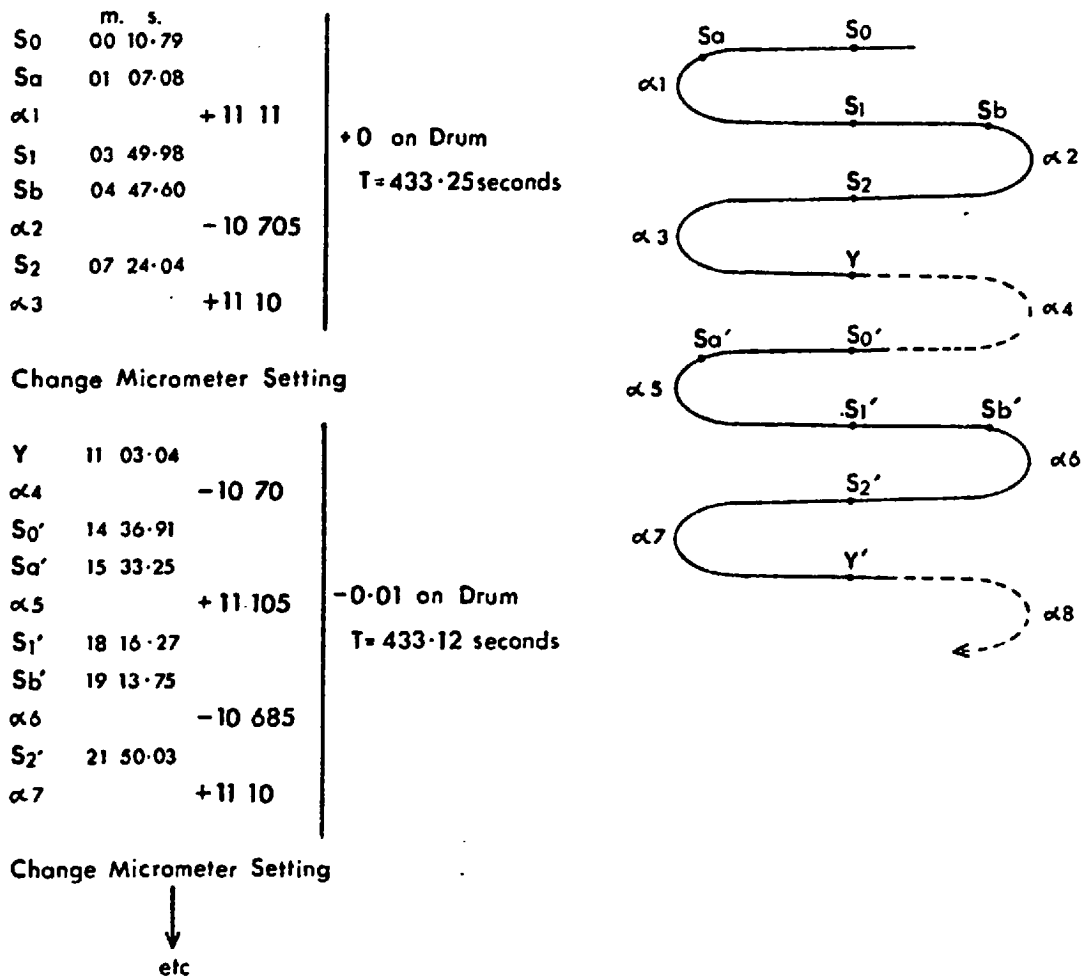


Figure 68 - Layout of Experiments Investigating Timing Through Unstable Centres

form of standard or control. Values indicated above are shown plotted graphically in Figure 69.

As expected an increase in error of setting the micrometer is immediately followed by a movement in the computed mid-swing value. In this particular result the values for β obtained from settings of - 0.01 and - 0.02 of a gyro scale division in error showed differences of 6 seconds of arc; a similar difference was obtained

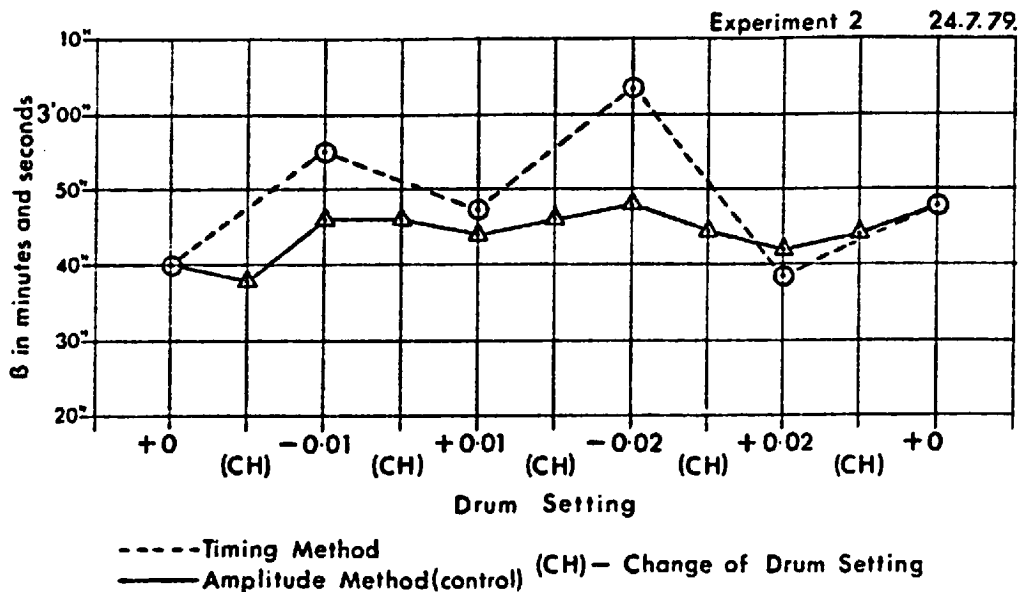


Figure 69 - Plotted Values from 'Unstable Centre' Experiment
 (Data in Figure 68)

from settings increased from + 0.01 to + 0.02 of a scale division. Other comparisons are extremely difficult to justify as any continuous spin series contains a considerable element of drift, as indicated in Section 9, which could abort completely any other small movements. However, in this example, settings with a spread of 0.04 of a gyro scale division gave results with a range not far removed from a normally accepted pattern when using the Timing Method. Possibly the spread is a little more but these results are taken from one oscillation only and the general random nature of values compares favourably with previous timing results using the H.P.55 electronic timing system.

Accurate setting of the micrometer should always be attempted but until further research is undertaken into fully automatic timing

systems any accidental mis-setting of less than 0.1 of a division on the micrometer should not affect the final result by more than ± 5 seconds. Errors in setting the drum are difficult to accept in practice because of the simplicity of lining up the + 0 of the micrometer with the zero measuring mark on the telescope housing. Even errors of 0.05 of a micrometer division should not pass unnoticed by the observer.

Although this source of error has been examined it is thought extremely unlikely within the present system of timing, which is based on the reaction of the human eye, that any slight error through mis-setting would be of sufficient size to affect the required result. This situation may of course change if the method of timing is made fully automatic.

11.2 ACCURACY OF TIMING THROUGH A CONSTANT CENTRE

The capturing of an accurate time when a moving mark crosses a stable scale division has always been a weakness of the Transit Method and now the Timing Method. In addition to the speed of travel at the central point the observer must also take into account any intermittent vibration or nutation of the mark as it precesses around North. Several authors have described automatic timing methods where electronic diodes are inserted on the gyro scale at precise intervals. As the moving mark crosses the diode it triggers a timing system and the precise time is automatically stored. This system has some disadvantage in that the gyro scale is marked and the size of amplitude of the oscillation must somehow be judged to ensure passage over the recording diodes. Vibration or nutation

is still a problem and the majority of observers will not undertake gyroscopic observation until an oscillation is free of such effects.

At the Royal School of Mines all times have been recorded manually either by stop watch or by the electronic timing system described under 10.3.1 and 2. The decision to capture a time has been taken visually by balancing the vibrating mark by eye and results have shown little difference between those obtained by other authors using fully automatic means.

However, the problem exists but should be regarded as being ~~more~~ due to lack of practice. A new observer very quickly gains the experience and confidence to make accurate recordings.

To explain the size of error which could arise from premature or late timing a selection of observations previously examined in 10.4 were adjusted to give slightly false values for the common central timing point and recalculated using the new timing formulae. Figure 70 shows the result of amending the central time value by ± 0.5 of a second and ± 0.2 of a second. Differences detected in the gyro azimuth are plotted against the total range of amplitude of each oscillation as obviously the effect of an error in the central time would be more pronounced on a fast moving mark, typical of larger swings.

The implication of these experiments was that an error in timing of 0.1 of a second could cause an error in gyro azimuth of less than 5 seconds of arc assuming that the total amplitude of the oscillation was less than 18 scale units. As the extent of the oscillation

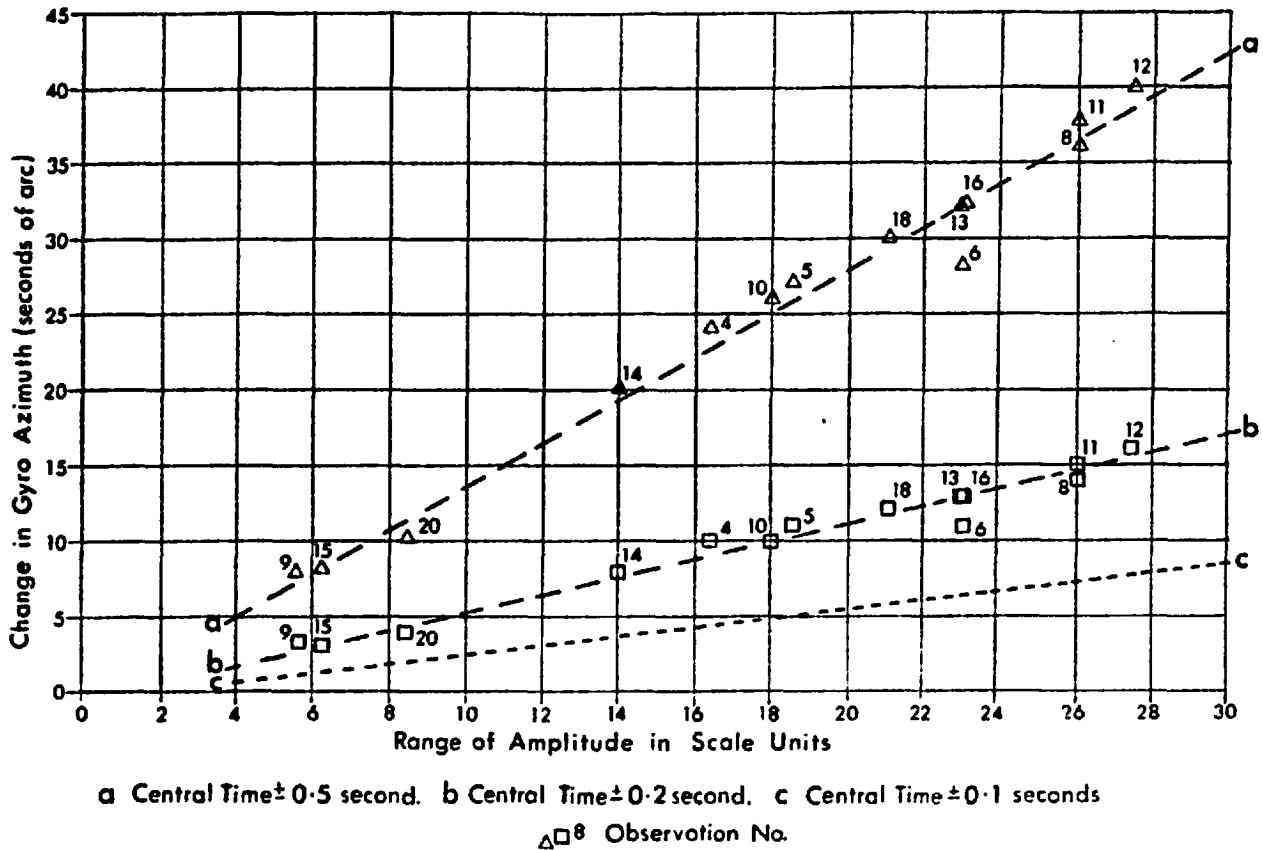
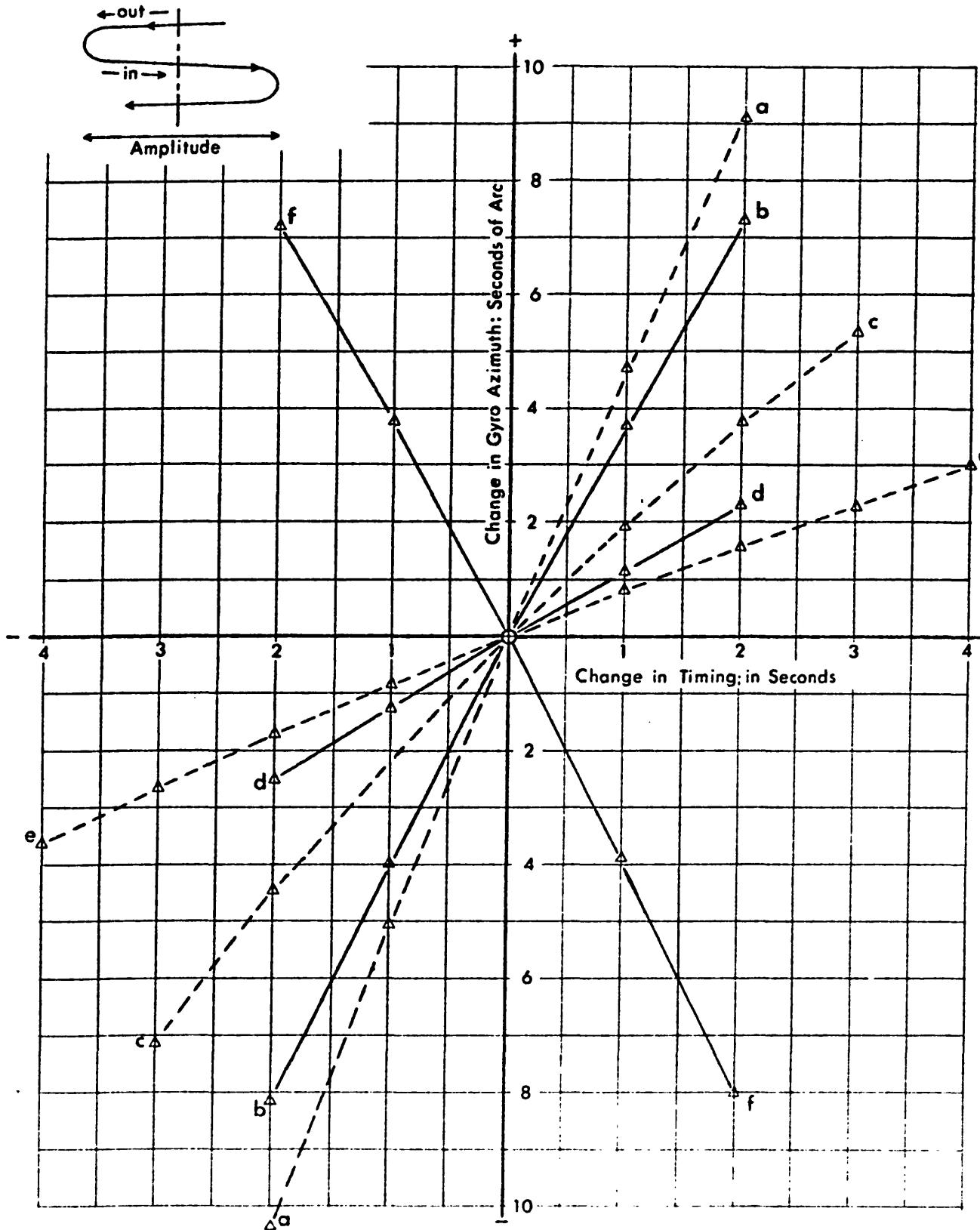


Figure 70 - Illustration of Error in Azimuth due to Error in Central Time

increases the accuracy of central timing becomes more critical.

11.3 ACCURACY OF TIMING THROUGH THE SELECTED THIRD POINT

Original data acquired during the general assessment of the timing method was again carefully adjusted to provide the required time variations at the third timing position within each half oscillation. Results from two typical oscillations are shown in Figure 71. From these investigations three important facts confirmed theoretical investigations:



	Range of Amplitude	Timing Point		Range of Amplitude	Timing Point
a	22.7	6 out	d	22.7	11 out
b	22.7	7 out	e	6.3	3 out
c	6.3	2 out	f	22.7	7 in

Figure 71 - Error in Azimuth due to Error in Third Time

- a) The amount of error in azimuth was again a function of the size of the oscillation;
- b) To obtain a significant error in gyro azimuth the time values required comparatively large adjustments as opposed to the parts of a second in 11.2; and
- c) The nearer the position of the third point to the point of reversal the less accurate were times required.

Providing that the selected third time is near the point of reversal errors of $\pm$ two seconds of time at the third point, irrespective of size of oscillation will generate errors in azimuth of less than three seconds of arc. Errors in azimuth increase rapidly the further the third timing position is selected from the point of reversal. However, in the example shown, using an oscillation of almost 23 scale units, if a time were taken at + 6 (approximately $\frac{1}{3}$ th of an oscillation from centre) with an error of 1 second of time the error in azimuth would still be less than 5 seconds of arc. When undertaking manual timing it is extremely unlikely that timing errors of this magnitude would occur.

11.4 AUTOCORRELATION OF TIMES IN BALANCED PAIRS WITHIN ONE OSCILLATION

As stated in 10.3.3 there could be a disadvantage in using a common timing value within a balanced pair and consequently a series of experiments were devised to avoid this situation. Figure 72 contains a graphical explanation of the system adopted. For example, if the estimated β , or mid swing value, of the oscillation was + 1.55 the normal procedure would be to select +2 as the scale division closest to the centre for timing purposes. (The usual method of selection is to the nearest whole scale division.)

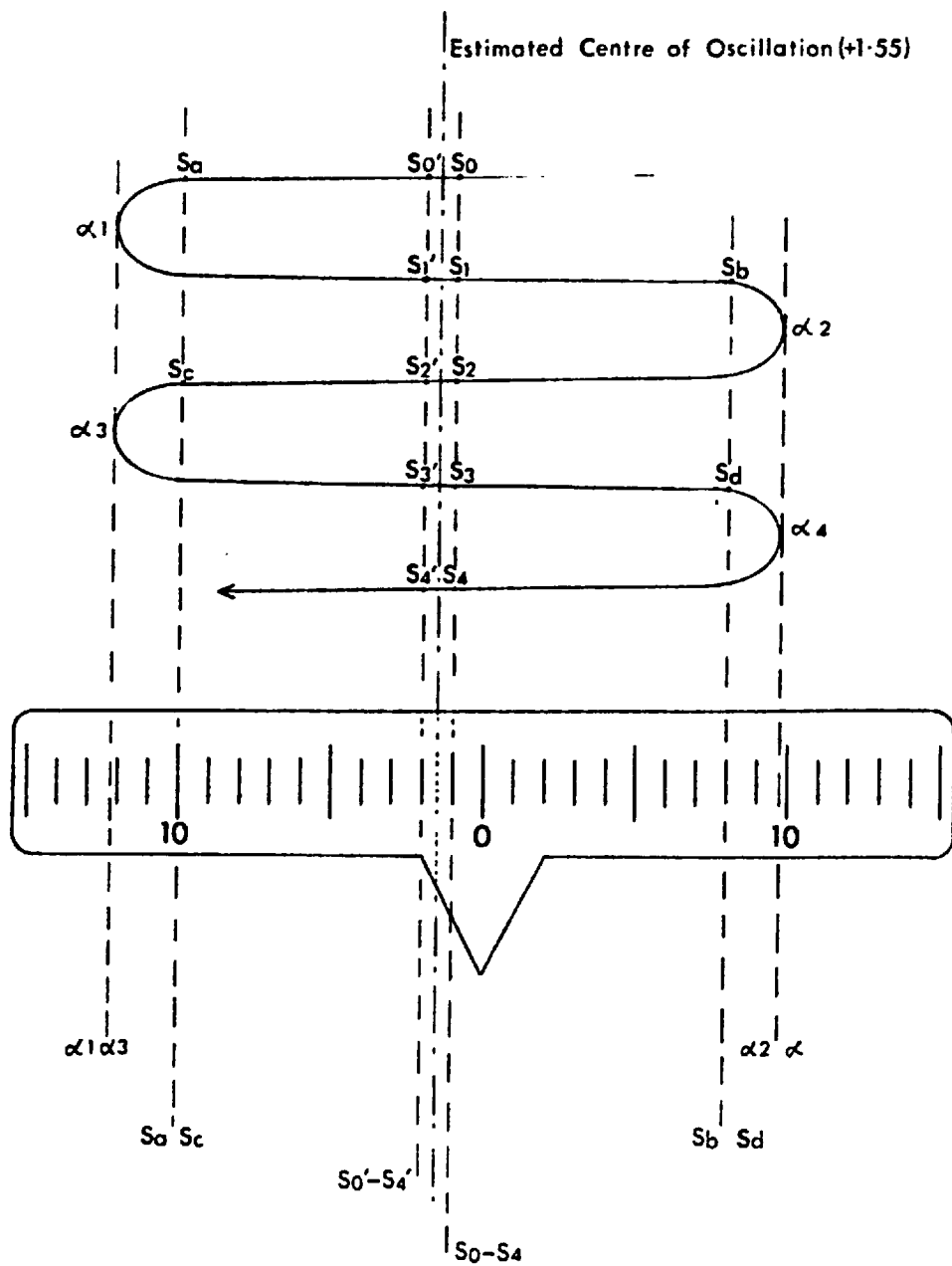


Figure 72 - Data Obtained from each Heading during Non Autocorrelation Trials

However, in this case conventional times taken at + 2 and say + 10 and - 8 would be supplemented by additional times taken at + 1 as indicated. From this information results could be calculated as follows:

1st Oscillation:-

a) So(+1), Sa(+10), S1(+1)	) Mean = result from	)
S1(+1), Sb(- 8), S2(+1)	) timing centre +1	) Autocorrel-
		) ation of
b) So'(+2), Sa(+10), S1'(+2)	) Mean = result from	) central tim
S1'(+2), Sb(- 8), S2'(+2)	) timing centre +2	) values
c) So(+1), Sa(+10), S1(+1)	) Mean = result from	)
S1'(+2), Sb(-8), S2'(+2)	) timing centres +1	) No auto-
	) and +2	) correlation
		) of central
d) So'(+2), Sa(+10), S1'(+2)	) Mean = result from	) time values
S1(+1), Sb(-8), S2(+1)	) timing centres +2	)
	) and +1	)

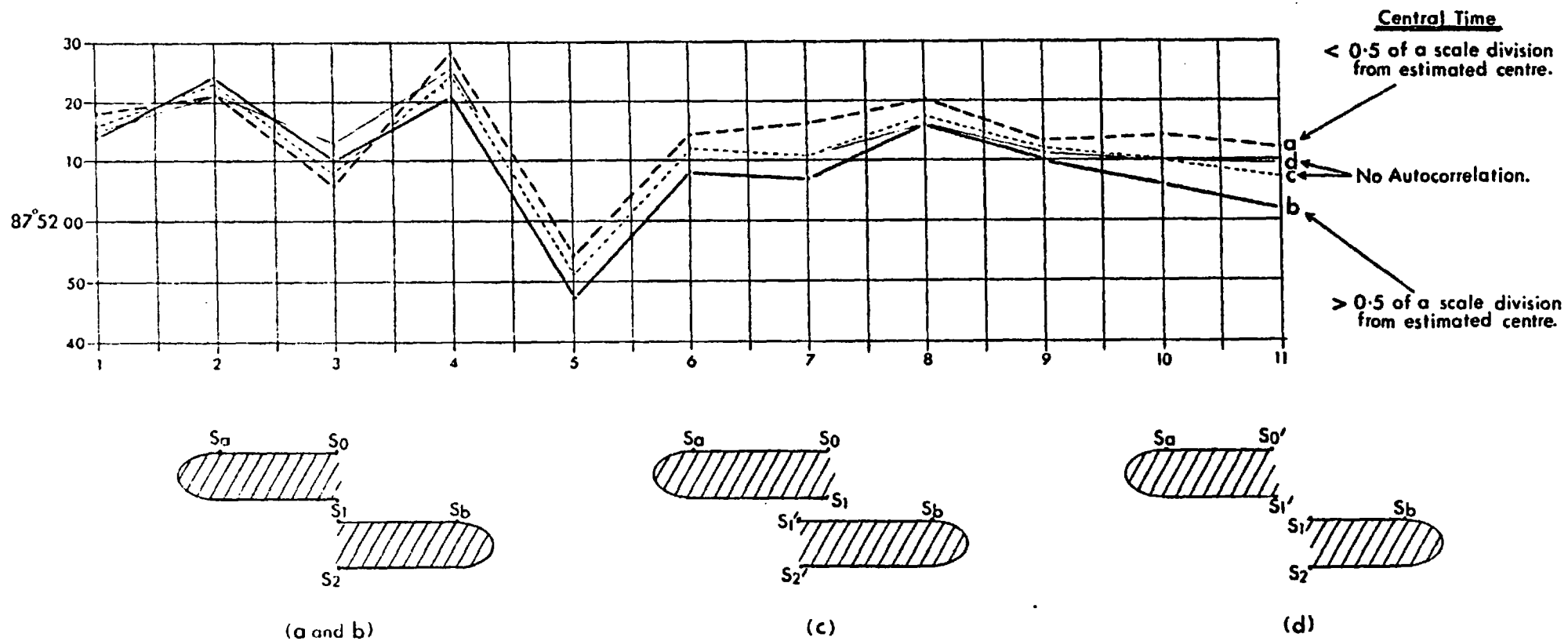
Values from the second oscillation were treated in the same way. The New Transit Method can also be reduced using a similar technique, the third time being replaced by the reversal reading.

Results taken originally during the initial evaluation of the Timing and New Transit formulae also included additional times as illustrated above. These results were therefore re-worked to examine the differences brought about by varying the timing centre and avoiding autocorrelation of common time values.

Figure 73 illustrates the variations of results. Graph a) acts as a control and is a repeat of part of Figure 56; Graph b) illustrates results using the alternative timing point - further than 0.5 of a scale division from the true centre; Graphs c) and d) are the results independent of time sharing.

From these graphs it can be seen that in 9 of the 11 results taking a timing position at more than 0.5 of a scale division from the true oscillation centre caused a lowering of value against the control set. Differences between the two sets involving different

Figure 73 - Diagrammatic Representation of Data Used in Obtaining Results Above using Different Timing Centres



centres varied between 3 and 10 seconds of arc. No accountable reason could be found for this variation and no correlation could be found with mode of observation or size of deviation from the true centre.

The two series of results avoiding autocorrelation gave surprisingly similar values; the maximum difference, apart from result 3, being less than three seconds of arc.

Little evidence could be gathered from these and other similar trials to indicate that autocorrelation was a serious hazard to timing observations.

In Figure 73 for example the low result in observation No. 5 could not be credited to a single autocorrelated poor timing value as similar results were obtained using the alternative centre and non autocorrelated values. In this particular result various third timing positions were also examined but all gave similar values.

11.4.1 Extended Spin

Two series of experiments incorporating prolonged spin-ups were designed to investigate the problem of autocorrelation. The first examined the effect of autocorrelation by using two independent timing centres spaced equally from the true centre whilst the second examined the behaviour of the new timing formulae from wider spaced timing centres incorporating three timing positions.

Figure 74 shows a typical example of the first series where the

centre of oscillation was provisionally calculated as being + 0.56 of a gyro scale division. The oscillation traversed the gyro scale from approximately + 8.3 to - 7.2 and times were recorded, as shown, at 0, + 1, +7 and - 6. Amplitudes were not taken and the micrometer was not moved from its set position at + 0 throughout the experiment. This latter factor also removed any suggestion of irregular re-setting of the micrometer drum between measurements.

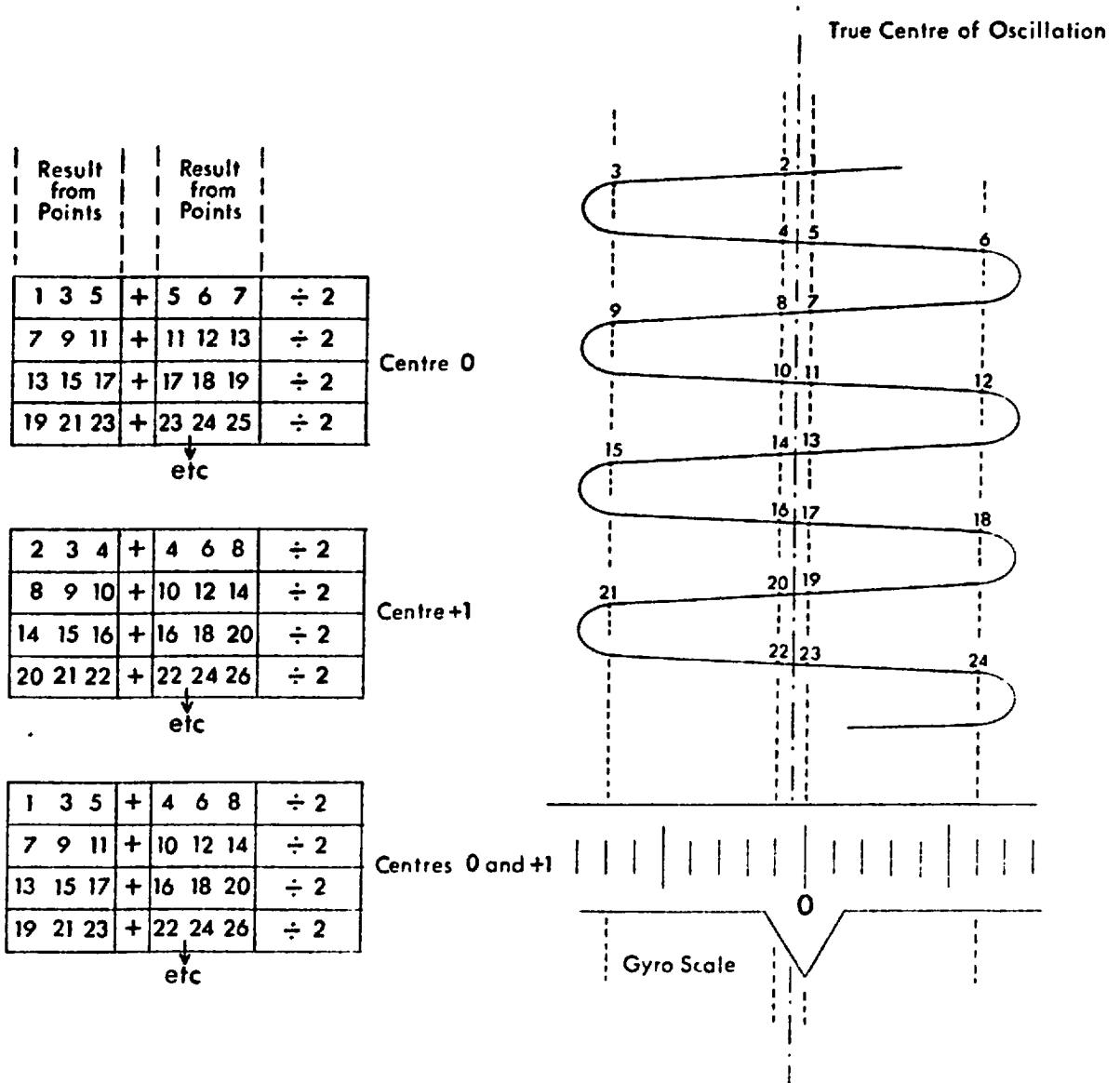


Figure 74 - Data Obtained during Autocorrelation Trials

Owing to the deliberate selection of heading it was possible therefore to calculate values for the centre of oscillation (β) using 0 as timing centre and by using + 1 as timing centre. Results were also calculated using a combination of 0 and + 1 to avoid autocorrelation of the central time value.

Figure 75 shows the variation of result obtained plotted graphically. From these experiments it was discovered that in this particular case where the time centre of oscillation was so placed as to be almost midway between two scale units little difference could be detected from using either for timing centre. A further feature to be discovered was the lack of detrimental evidence regarding autocorrelation of a central time value within a complete oscillation. This highlighted the general accuracy of the timing system being used but does not reduce the over-riding danger of a single bad time affecting both halves of a complete result.

For example the significantly low result 5 in Figure 75 is attributed to a poor time taken at centre 0. (29th Timing Point in scheme shown in Figure 74.) This time is shared in the series dependant on 0 for timing centre and is also evident in the "non correlation" result 5 where time number 29 also appears in half of the overlapping pair.

A second series was also conducted in an attempt to examine the limitation of the timing formulae. Figure 76 shows an extended observation where a heading almost on True North was selected. In this example the immediate reaction would have been to select 0 as timing centre, however, centres were selected at 0, + 1 and - 1.

Figure 75 - Extended Spin Autocorrelation Trials (First Series)

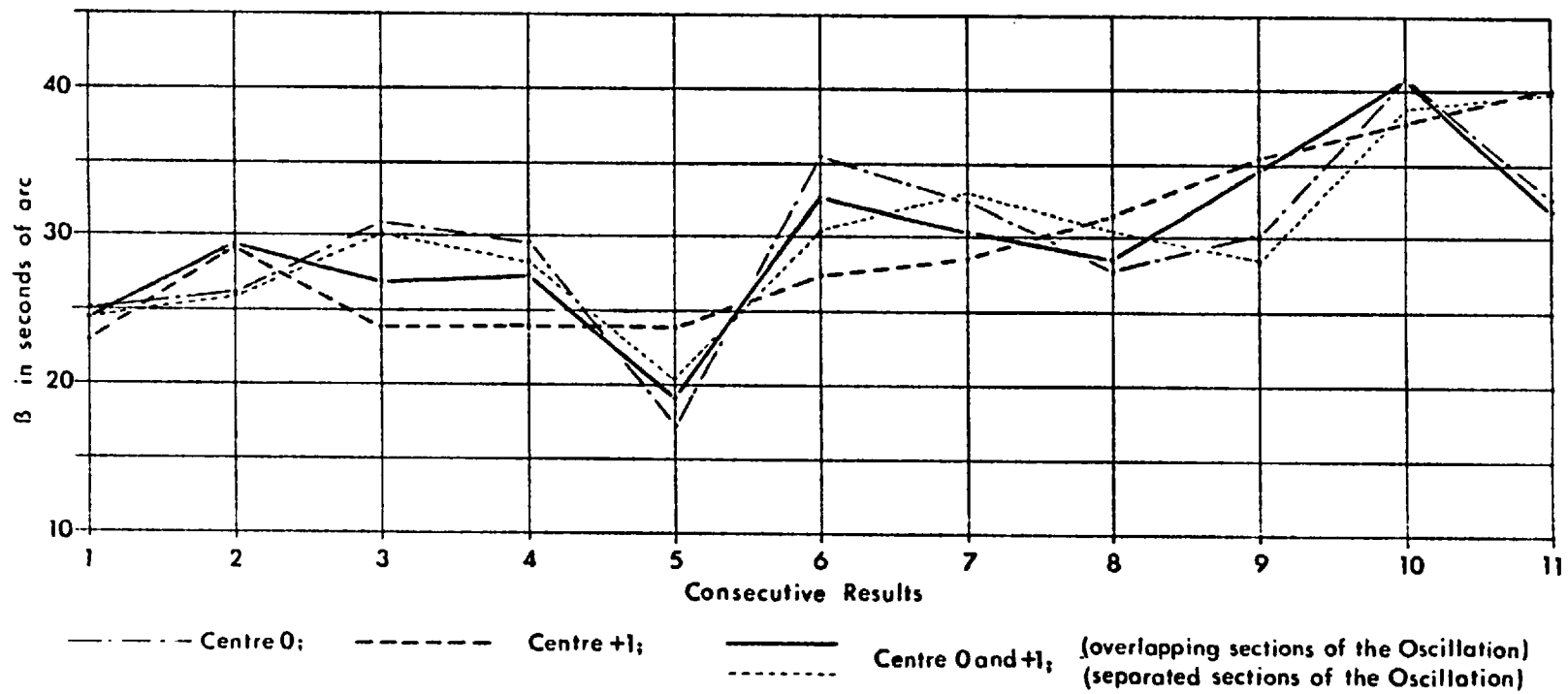
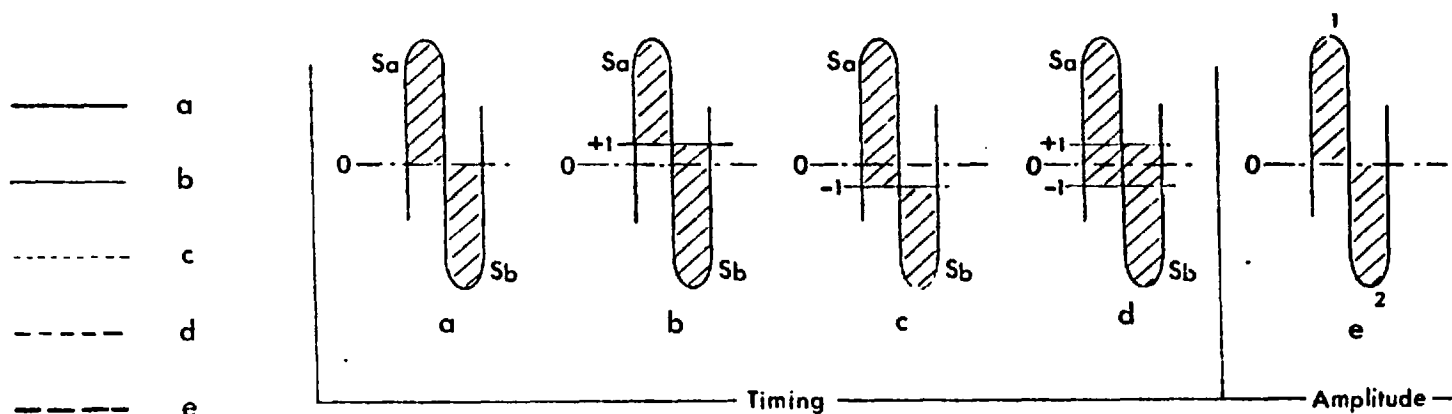
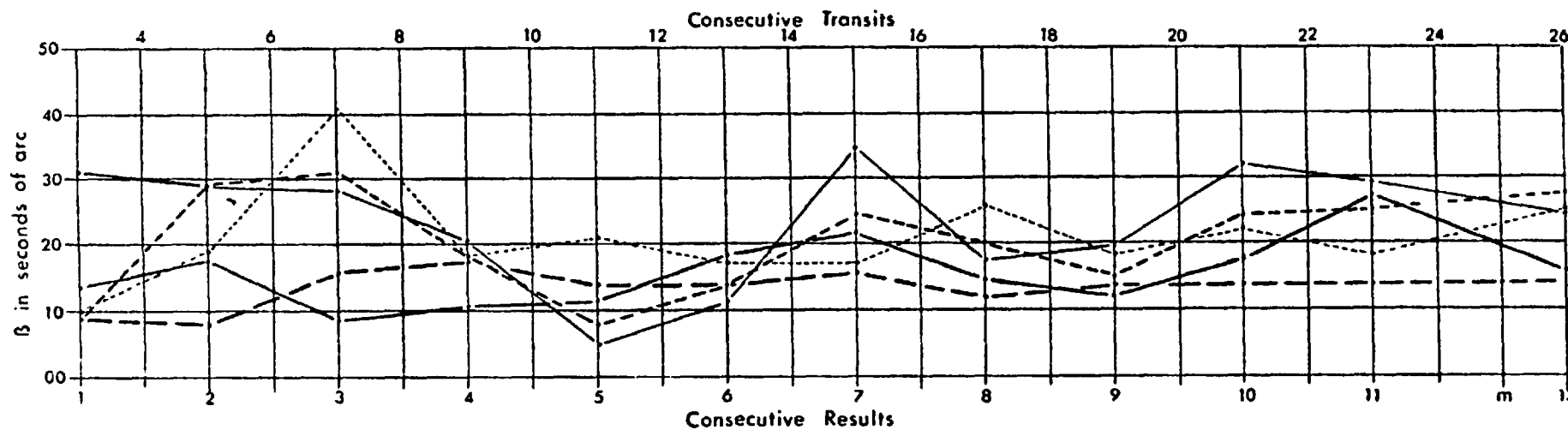


Figure 76 - Extended Spin Autocorrelation Trials
Second Series



	Spread of Results	Mean	Standard Deviation
a	18.72	15.76	± 5.26
b	30.27	23.37	± 9.06
c	31.44	20.96	± 7.53
d	23.35	20.23	± 7.65
e	9.81	13.52	± 2.63

seconds of arc

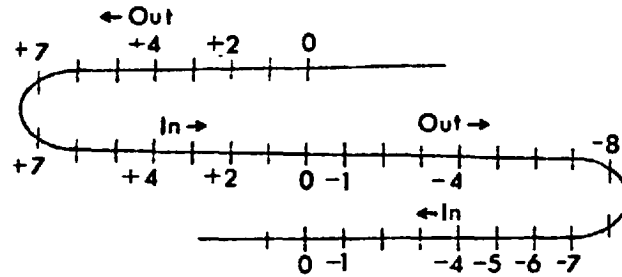
The latter two centres being 0.8 and 1.2 of a scale division from the true centre of oscillation. Three separate series of results were calculated from these three individual timing centres. A fourth series was introduced using an overlapping combination of + 1 and - 1 as centre lines within one oscillation to assess a rather drastic solution of the autocorrelation problem.

11.5 INFLUENCE OF THE SELECTED THIRD TIMING POSITION

As stated earlier, it was thought that the third timing position should be selected near to the normal point of reversal. This assumption arose through a basic similarity to the Transit Method; in that the third piece of information is obtained at the extremity of the swing. One advantage of this is that the oscillation slows down considerably at the ends of swing, making timing a little easier.

However, the information gathered from several years of investigation pointed to the fact that the gyro oscillation was comparatively stable throughout its swing and therefore other intermediate positions for timing could possibly be selected. Accordingly experiments were undertaken to extract times from many positions within an oscillation and to calculate any changes in the value of caused by using various time combinations. Times were selected on both the outward and inward passage of the spin axis as depicted on the gyro scale. Examples of two typical results are shown in Figure 77 where one oscillation centres around the 0 gyro scale marker and the other some distance away at + 2.

Observation No.4. 9/4/1978



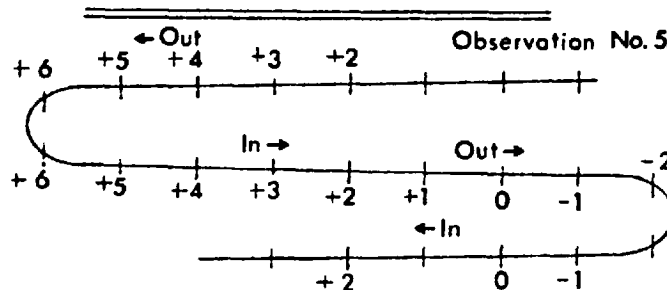
Values Used	β
0 + 7 0	- 01' 30"
0 + 4 0	- 01' 30"
0 + 2 0	- 01' 31"

Values Used	β
0 - 8 0	- 01' 30"
0 - 4 0	- 01' 30"
0 - 1 0	- 01' 30"

Return Towards Centre

0 + 7 0	- 01' 30"
0 + 4 0	- 01' 30"
0 + 2 0	- 01' 30"

0 - 7 0	- 01' 30"
0 - 6 0	- 01' 30"
0 - 5 0	- 01' 30"
0 - 4 0	- 01' 30"
0 - 1 0	- 01' 31"



Observation No.5. 9/4/1978

Values Used	β
+2 + 6 + 2	+ 20' 40"
+2 + 5 + 2	+ 20' 39"
+2 + 4 + 2	+ 20' 37"
+2 + 3 + 2	+ 20' 33"

Values Used	β
+2 - 2 + 2	+ 20' 38"
+2 - 1 + 2	+ 20' 38"
+2 0 + 2	+ 20' 35"
+2 + 1 + 2	+ 20' 33"

Return Towards Centre

+2 + 6 + 2	+ 20' 39"
+2 + 5 + 2	+ 20' 41"
+2 + 4 + 2	+ 20' 39"
+2 + 3 + 2	+ 20' 38"

+2 - 1 + 2	+ 20' 40"
+2 0 + 2	+ 20' 43"

Figure 77 - Influence of the Position of the Third Timing Point - Timing Method

Results showed that a time value from virtually any included scale division within a pair of central times would give similar answers for the value of β or mid swing point. In several cases it was evident that where differences did occur they were greatest when the position of the third time was very close to the central value. It would appear an advantage when using the Timing Method to include additional times within each half oscillation which would then allow several checks to be made on the calculation of β . However, these checks would reflect the accuracy of the times taken throughout the half oscillation and not the accuracy of the final result as all combinations would share the two common central time values.

During the prolonged spin experiment, referred to in Figure 76, timings were also made at every scale division. This meant that many combinations of β could be calculated using differing centres and differing third timing point. In all cases variation of the third timing points had little effect on the final result.

12 - TAPE ZERO

12.1 INTRODUCTION

Tape zero is the term which has been used to define the point on the scale where the tape exerts zero torque measured with reference to a stable marker. In the case of the Wild G.A.K.-1 this marker is taken as the centre of the illuminated gyro scale. With the advent of the modified equipment it became possible to measure the value of this position to a high degree of accuracy. At first measurement was made by using the Amplitude formulae with data derived from non-spin oscillations. However, later work indicated that measurement of tape zero could be made with similar accuracy using the new Transit and Timing methods.

Initial measurements of this tape zero position from non-spin oscillations showed that not only did the position fail to coincide with the central scale marker, but also showed variation in position before and after a power spin and also between separate observations. Wild Heerebrugg, whilst acknowledging that the centre of non-spin did not always coincide with the centre of the gyro scale, made the assumption that if this lack of coincidence did affect the indicated centre of power spin oscillations, the error could be regarded as a constant and could be absorbed within the overall E. factor correction.

Research at the Royal School of Mines showed that this assumption was far from correct and variations of this position could be measured with ease using the new micrometer system. The first discoveries regarding the application of an individual tape zero correction to

the Wild G.A.K.-1 were made long before the full implications of the various drift patterns described in Section 10 were realised. The normal procedure during every observation undertaken during this research period has been to record a tape zero value before and immediately after each power spin set. A correction, based on these two separate readings, was then made to the individual result. Several trials were undertaken to discover the ideal correction to apply; a straight mean of the two separate values, the final value only or a weighted mean of some description. Preference was eventually given to a weighted solution, three times the 'after' value plus the 'before', divided by four. This value, although at first derived empirically, could also be justified because of close agreement with the value expected at the mid time point under power spin, assuming a linear change in tape torque during the total time period.

12.2 APPLICATION OF A TAPE ZERO CORRECTION TO THE ROYAL SCHOOL OF MINES MODIFIED G.A.K.-1

Application of an individual tape zero correction was a new concept as regards the Wild G.A.K.-1 but, because of a difference in design, was an integral part of measurements made with the Hungarian M.O.M machines - see Section 10.6. Trials on the modified Wild G.A.K.-1 during 1975, 1976 and 1977 indicated that application of a weighted mean tape zero correction made a noticeable improvement to results obtained under laboratory conditions. This was of considerable interest as movements detected during the trials were often minor and the results obtained obviously incorporated this additional measured value in the reduction process which itself could be subject to error - see Figures 50, 51 and 53 in Section 10.

Later results in 1977, 1978/79 indicated that at times application of a tape zero correction caused a slight lowering of overall repeatability - see Figures in Sections 10.3 and 10.4. This presumably being due to the reason indicated above.

Observations made, prior to the development of the modification and new methods of reduction, were always corrected to known base lines by using a varying E factor; variations giving a measure of the repeatability obtained. Differences of 60 seconds of arc in E factor were common. With the introduction of the micrometer system and new reduction techniques repeatability was improved and variations in E factor reduced. It then became increasingly apparent that applying a separate correction for tape zero caused further reductions in the variations of the value for E factor. These reductions being of such an extent that E factor could be replaced for lengthy periods by an additive constant - see Figures in Section 10.

12.3 APPLICATION TO OTHER MODIFIED WILD G.A.K.-1 MACHINES

After the early proving trials of the micrometer Wild U.K. decided to offer the modified equipment as part of their commercial range. Close ties with the manufacturer and often prospective purchasers of the modification, enabled further assessment of the equipment to be made on a variety of machines. Although some indication of the importance of applying a tape correction could be gathered from early results using scale estimation techniques on standard equipment, the strength of the argument had come from accurate measurement using the prototype modified G.A.K.-1. It was

therefore extremely important to evaluate similar machines as and when they became available, to consolidate the original findings.

Several instruments were used on the known base lines and in all cases similar results to the prototype were obtained. When leaving the factory every attempt was made to zero the tape position as regards the gyro scale but each machine when tested was found to have an individual position for tape zero. These positions, irrespective of whether they occurred either on the positive or on the negative side of the central scale marker, always showed measurable variations both within the time period of a gyroscopic measurement and also over a period of days or weeks.

One machine - G.A.K. Attachment No. 192222 mounted on a T-16 theodolite No. G.A.K.-1 14166 - purchased by the South Midlands area of the National Coal Board generated the first thoughts of conducting lengthy investigations into drift patterns. This machine showed a definite drift during trials within the laboratory which could be correlated within a 95% confidence limit to similar drift in the measured tape zero values. Application of tape zero correction to the original results made a significant improvement to the repeatability of the observations and reduced the drifting effect considerably. Figure 78 shows these observed values and clearly illustrates the benefit of applying the tape zero correction. This machine was unusual in that evidence of drift of this order is rarely detected within a controlled laboratory atmosphere and also within such a short period of time.

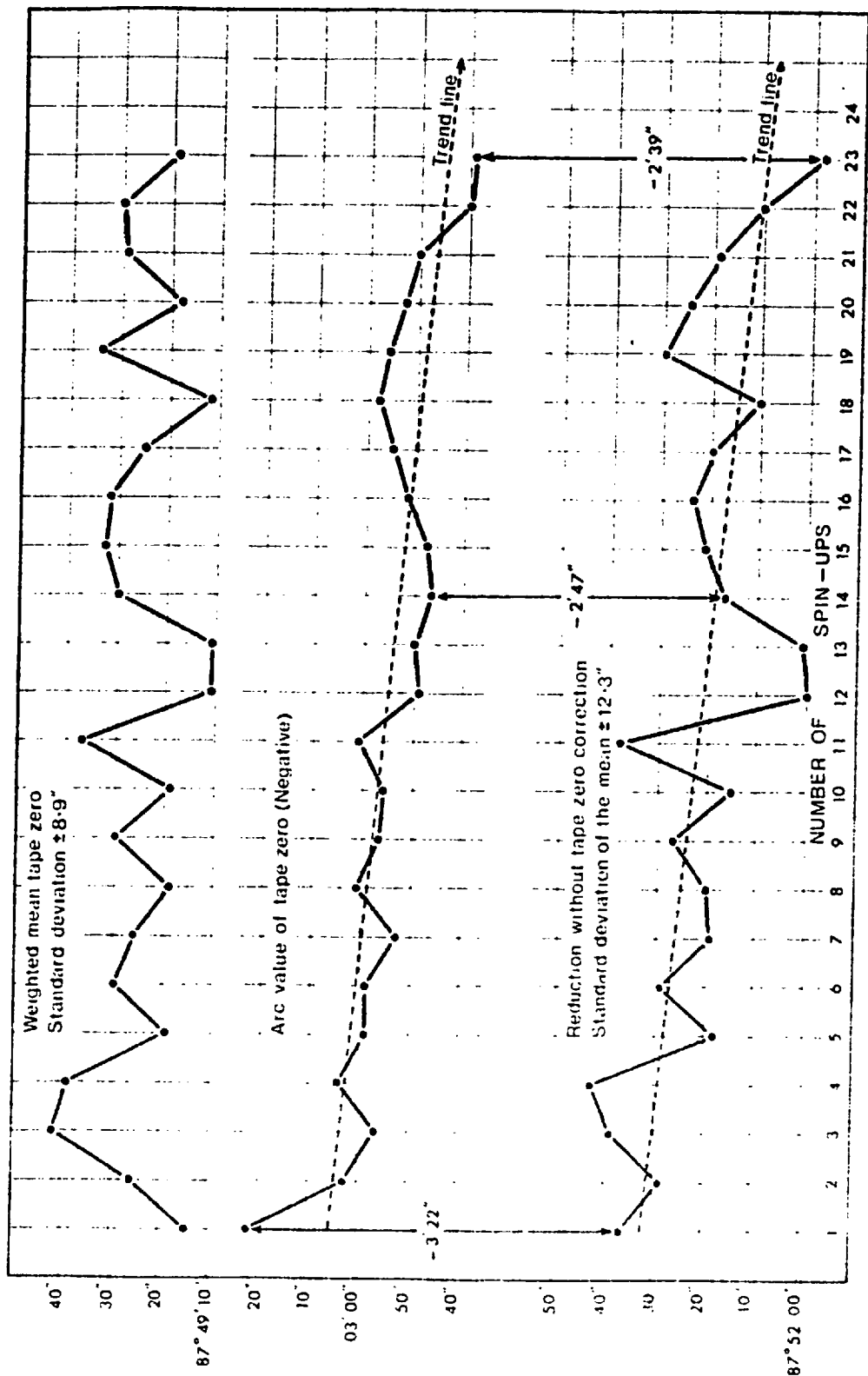


Figure 78 - June 1976 N.C.B. Amplitude Measurement Results
 (Using modified Wild G.A.K.-1 Gyro-Attachment
 mounted on T-16 Theodolite)

12.4 TAPE ZERO CORRECTION AS APPLIED IN MINING CONDITIONS

The preceding evidence indicated clearly that the value of the tape zero position was not a constant and application of a correction based on tape zero readings could assist in obtaining a more accurate result within a laboratory. However, when undertaking field trials consisting of working in actual mining conditions it was noticed that variations in tape zero values were often greater, not so much within an individual observation but within the full spread of the working set. This working set consisting of a minimum of three observations; the first on a known surface line to check the additive constant; the second on the unknown underground line; and the third on the original surface line to re-check the additive constant and the behaviour of the instrument.

Large variations of tape zero values were recorded when the equipment was taken from the surface set up to the underground line and also between the underground line and the final check on surface. These variations were not always apparent, sometimes differences were small, similar to those experienced under laboratory conditions, but sometimes as large as 35 seconds of arc. Often tape zero values taken from observations along the same sets of lines also showed large differences.

Application of tape zero corrections, along these same surface/underground/surface sets, taken on several occasions often separated by days of time, gave a greater measure of repeatability than the same results computed without applying the correction - see Figure 79.

The reasons for these random variations were thought to be due to differences in environmental conditions pertaining at each observing position. However, later work - see Sections 9 and 10 - has suggested that the total variation is more likely to consist of a combination of many factors although changes in environmental conditions are still thought to be the major cause.

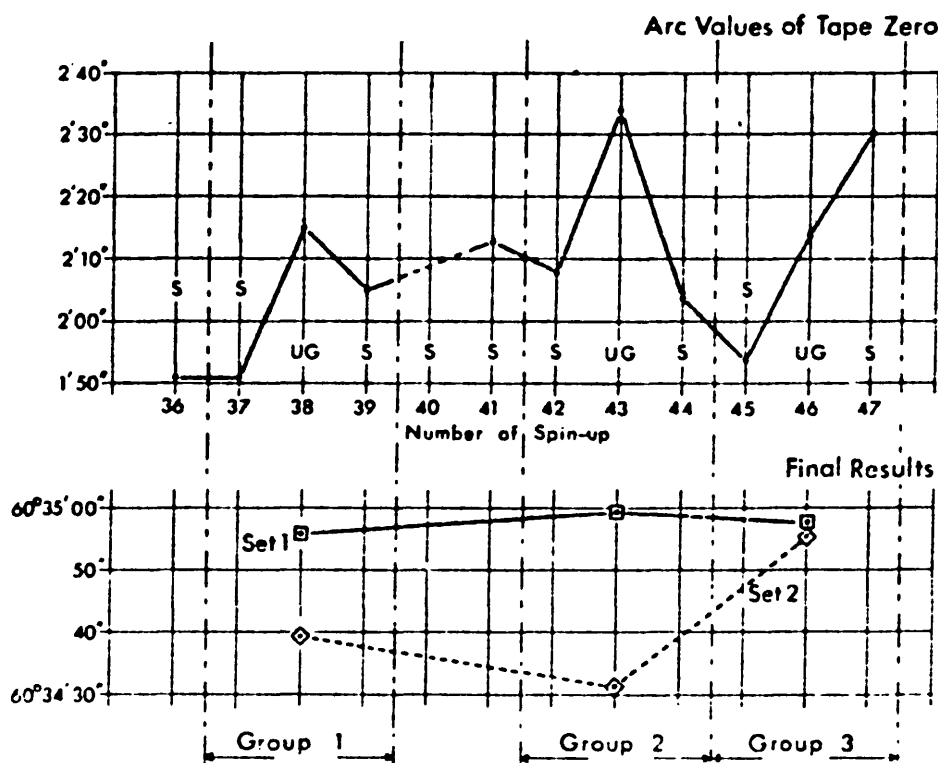


Figure 79 - The Effect of Tape Zero Values on Cornish Results

It was found in all work carried out with the Royal School of Mines modified prototype that results were improved after applying tape zero even in those conditions where variations were small. The conclusion reached was that the time taken to observe data required to calculate tape zero values was minimal in comparison with the total observation period and that even in conditions where variations were not expected it was safer to apply the correction as routine.

Laboratory evidence showed that in some cases when conditions were almost constant, application of the correction could slightly impair the result but movements found in actual working conditions could not be predicted and non application of such a correction could cause greater differences than those found in ideal conditions.

12.5 INDEPENDANT TAPE ZERO EVIDENCE SUPPLIED BY THE N.C.B.

In 1978/79 the Western Area of the National Coal Board were faced with the problem of linking surface and underground workings via extensive drift mining. Both headings involved the development of underground curves within the drifts to reach the required point at depth. The surveyors were therefore working to a high order of accuracy in three dimensions to guarantee final closure.

The area surveyors decided to base the orientation of both drifts from gyro derived azimuths taken at spaced intervals as the tunnelling progressed. The gyro - a modified G.A.K.-1 borrowed from the Stoke Area main office - was checked rigorously on a surface base at Hem Heath and this line was then used as the master to transfer various bases underground.

Long consultations were held at regular intervals between the author and the area surveyor on the various techniques and reduction formulae to adopt. The decision to use the Amplitude method was taken and to apply a weighted mean tape zero correction throughout.

It was found that the value of tape zero showed large variations between the selected sites. This variation amounted to 36 seconds

of arc between the surface base and the furthest base underground, and to 15 seconds at the pit bottom. It was noticed that the variation in tape zero values correlated with the difference experienced in temperature at the various sites. As temperature increased so did the measured value of tape zero. This was not an isolated occurrence. In all N.C.B. survey work the final results were the means of many separate sets of observations and the pattern of correlation indicated above was common throughout.

In any survey work underground, total reliance is placed on accurate azimuths and it is a credit to the N.C.B. surveyors that eventually the two drifts holed through, with a difference in x and y co-ordinates of 0.067 m E and 0.035 m N, an error in co-ordinates of 1 in 81,000. A check survey was run using traditional techniques between the surface base line, in both directions and after adjustments, the value determined for the inbye base (furthest base from pit bottom) was found to differ by only 4 seconds of arc from the previous Gyro Determination.

If tape zero corrections had not been applied in this instance although a holing of a fashion would have been made a loss in accuracy of around 30 seconds of arc would have been found during the closed check surveys.

This evidence has been supplied by the N.C.B. and all observations were undertaken by their own teams of surveyors. It is the opinion of these teams that changes in environment, namely that of temperature, could be the major cause of changes in measured tape zero values.

12.6 CONCLUSIONS

From the data supplied by other users of the modified G.A.K.-1 and from numerous Royal School of Mines observations there is no doubt of the importance of applying tape zero corrections to every observation as part of the general routine. However, there is one cautionary piece of evidence which has arisen from the latest trials described under 10.4. During these special trials an attempt was made to minimise the random effect of the so-called Primary Drift pattern discussed in Section 9. The tape was left suspended for varying periods of time before beginning normal observations. Results obtained from these trials not only showed the closest repeatability experienced during the five years of research but indicated that applying a tape zero correction reduced this repeatability considerably, see Figure 62 in Section 10.4.2. Possibly if this procedure were to be used in underground situations the tape would become adjusted to the differing environmental conditions before spin-up? Evidence to date has been limited to the laboratory where, as already stated, because conditions are generally stable over lengthy periods, application of a further measured value is always liable to introduce further error. However, the improvement in accuracy is significant but further work especially in working situations is required. One factor against implementation of this procedure is of course the additional time involved and whether in fact accuracy of the type described in 10.4 is required in practice for the majority of engineering projects. However, there is also the thought that the standard tape zero correction could consist of separate parts, including Primary Drift, property of the suspension tape, and environmental conditions. If this is true then large

changes in environmental conditions may still require to be corrected by applying individual tape zero observations.

At the present time measurement of tape zero is to be recommended in all instances especially in those underground situations where conditions of operation can be extreme. Before the introduction of this form of correction, although the surface/underground/surface procedure was adopted there was no check on the behaviour of the tape and possibly the measured surface E factor could have given erroneous results when applied to the underground observations.

13 - EXPERIMENTS CONDUCTED ON OFFSHORE STRUCTURES

During recent years the rapid growth of North Sea oil and gas exploration has led to the development of several new survey techniques and to the employment of large numbers of survey staff on offshore installations.

A major problem confronting operators has been the accurate location of their drilling equipment with respect to legally defined areas. To begin with various conventional offshore navigation systems were used but eventually more sophisticated methods involving satellite signals were employed. As exploration continued it was realised that accurate bearings were also required for several reasons, ranging from locating the direction of the side of the huge drilling or production platforms, to pipeline laying, to complete field surveys often consisting of several individual platforms.

The Royal School of Mines were approached several times with a view to assisting such offshore work using the modified gyro-theodolite. There were several reasons why it was thought that gyro-theodolite observations would be preferred to conventional astro sightings; initially it was discovered that several of the platforms were positioned in relatively high latitudes and during the summer although sun shots were possible accurate star sights were obviously difficult, and a further problem was the unpredictability of the weather in the North Sea which often caused considerable delays to the waiting survey crews. Such periods of waiting are inconvenient for the platform operator as continual demand for accommodation requires rigorous time-tabling. On the majority of platforms the

luxury of spare accommodation is non-existent. Another factor is the additional cost of accommodation and food for any inactive period; in an extreme case this may well involve having to organise a second trip at a later date.

There are basically two types of structure used in the design of fixed platforms found in the North Sea - Steel Structures and Concrete Structures - see Plate 8. Each of these can be sub-divided into a variety of shapes and forms. The semi-submersibles were never considered for this type of work due to the continual slight pitch and roll common with any floating vessel.



Plate 8 - Steel and Concrete Structures - Frigg Field

13.1 STEEL STRUCTURES

These structures are the more common and usually comprise

several steel legs either in the form of columns or steel girders which support the platform. These legs are bedded in the sea floor possibly 500 feet below and provide a relatively stable platform on which accommodation modules and working equipment are mounted - see Plate 8 right foreground.

The disadvantage of this type of structure was found to be one of vibration. Vibration took two distinct forms:

- a) The rapid high frequency vibration patterns, originating from the many generators and other heavy electrical equipment installed on the various levels, which were transmitted via the steel structure throughout the platform. These patterns were virtually continuous and it was found impossible to discover any position where such vibrations could not be felt.
- b) A slow low frequency vibration effect which appeared to be unpredictable and was thought to be due to deep sea movements causing the whole structure to twist or shake.

Possibly some form of anti-vibration device could be built to neutralise the more regular high frequency movement but it was felt that little could be done to eliminate the more violent unpredictable movements.

Two periods were spent on Montrose Aloha and Thistle 'A' platforms in attempts to solve these problems. Both the modified Wild G.A.K.-1 and the M.O.M. GIBL were used but it was found that accuracies anything like those obtainable on land were impossible.

Vibration caused the oscillation of the gyro to become unstable and consecutive reversal points and timing values were often very

different. It was thought that if one could observe between the unpredictable low frequency movements an accuracy of ± 2 minutes could be achieved.

On Thistle 'A' an attempt was made to design a make shift anti-vibration mount for each of the tripod legs using polystyrene and heavy duty rubber. Some minor improvements were noted which would appear to give some credence to the possibility of being able to isolate some if not all of this effect.

13.2 CONCRETE STRUCTURES

Concrete structures have been of more recent introduction to offshore work and again can be found in various forms and designs. The most distinctive division is between those platforms which have several concrete columns - see Plate 8, left - in lieu of the conventional steel legs, which support the superstructure and those built with one huge concrete pedestal which sits on the sea bed and supports the platform superstructure on smaller concrete columns rising from its upper level - see Plate 9.

Experimental work has been carried out on the latter type of platform at the request of the British and Norwegian Governments.

13.2.1 Frigg Field Survey

In 1977 The Royal School of Mines were invited to join a team of British Army surveyors and members of the Norwegian Geodetic Survey.



Plate 9 - Concrete Structure - C.D.P.1 - Frigg Field

This team were requested to produce a full survey of the whole field, which was composed of five active platforms, one sunken steel jacket and a flare stack. The relative position of each structure, the elevations both relative and within each platform, and the true position of each structure were required. The last request was extremely pertinent as the field straddles the median line between Norway and the United Kingdom.

To assist the survey it was suggested that both astro and gyro derived bearings would be taken.

The initial reaction to the invitation to join the survey team was to state that in the past it had been found impossible to obtain bearings from offshore structures to the accuracy required for

orientation of such a project. However, it was pointed out that this field contained concrete platforms from where it might be possible to obtain more acceptable results.

13.2.2 Observations on C.D.P.1.

The layout of the Frigg gasfield is shown in Figure 80 and in Plate 10. Of the five platforms, two were conventional steel legged structures - DP-2 (drilling platform - 2) and QP (quarters platform); two were concrete structures incorporating either two concrete supports - T.P.1 (Treatment Platform 1) or three concrete supports - T.C.P.2 (Treatment and Compression Platform 2); and one was of the large pedestal type - C.D.P.1 (Concrete Drilling Platform 1).

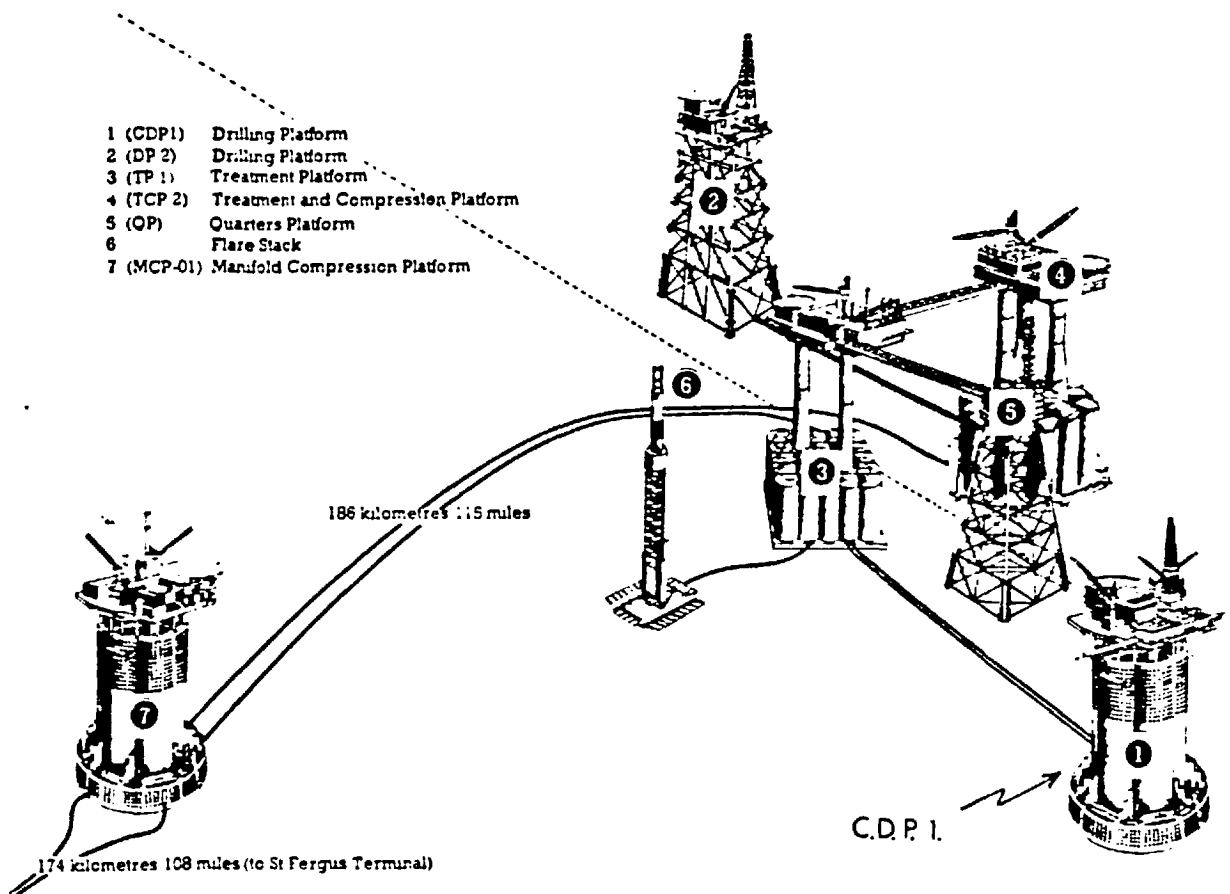


Figure 80 - Lay-Out of the Frigg Field

(29)



Plate 10 - Frigg Gas Field

There was also evidence of a third steel legged platform, the intended D.P.1 which unfortunately sank before being installed in its final position. Part of this platform projected above the waves and being a fixed structure was included in the survey.

Assessing these five working platforms it became obvious that the single legged platform C.D.P.1 showed less vibration movements than the other four, but only at the lowest levels. This meant that any grosscopic observations would be made on the top rim of the main pedestal, near the water level and far below the rig superstructure.



Plate 11 - Observing on the C.D.P.l. Platform

Figure 81 shows an approximate layout of the top of this structure at the recommended level - see also Plates 9, 11 and 12.

Working at this particular position posed several difficulties:

- i) The instrument set-up would be exposed to all of the elements;
- ii) To obtain access to such a position was extremely difficult with bulky equipment which had to be carried by hand whilst walking, without safety guides, along the narrow concrete beams spanning the gap between the outside curtain wall and the central concrete tube;

- iii) The effect of working for several hours on a concrete wall, approximately one metre wide with a 60 ft drop either side to 500 feet of sea water also had to be considered.

Although point one could be alleviated when required by a carefully tied tarpaulin; and point three overcome by installing safety wires and wearing a safety belt; there was no remedy for point two other than extreme care, especially when negotiating the base of the superstructure pillar at the far end of the relevant beam as it met the curtain wall - see Plate 12.

13.2.3 Results

Results obtained from this curtain wall position were excellent when compared with previous experiments involving steel legged structures. Although not approaching the accuracy obtained on land

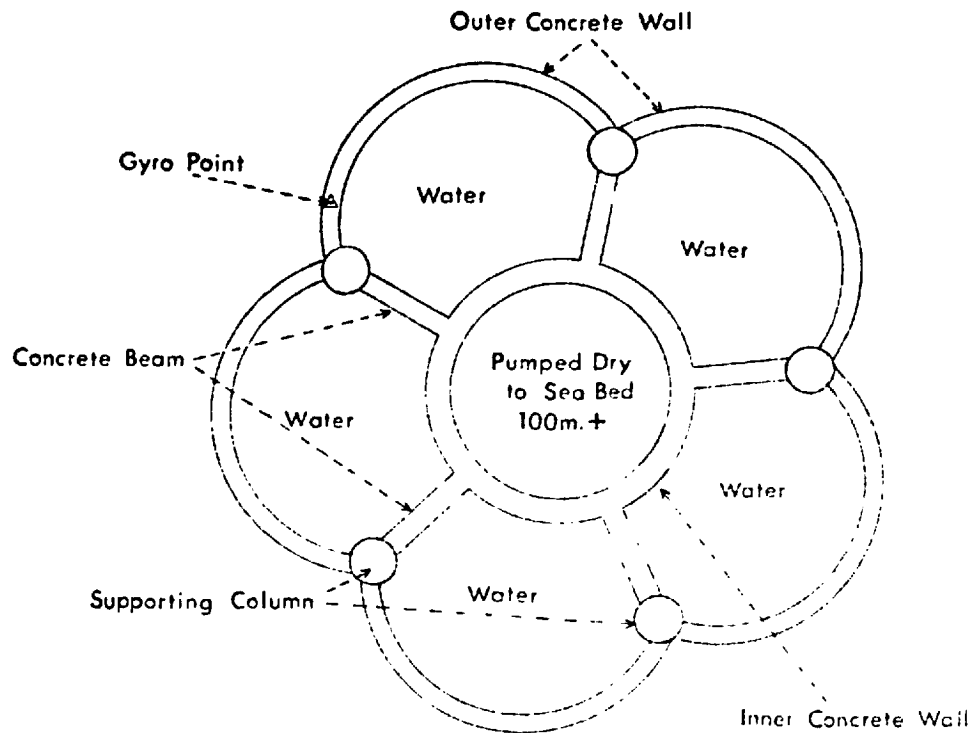


Figure 81 - Diagrammatic Cross-Section at Working Level - C.D.P.-1



Plate 12 - View of Survey Station on Outer Concrete Wall of C.D.P.1.

bases, results taken over several days gave a range of only 32 seconds.

Vibration was minimal although still could be felt slightly within the massive concrete structure but the unpredictable heavy vibration or twisting of the entire structure did not occur.

Unfortunately the results obtained by the Norwegian Geodetic Survey using star sightings were found to be unsuitable for orientation purposes possibly due to the difficulty of obtaining sufficient elevation of sight through overhanging superstructure, and a direct comparison of methods could not be made. However, the decision of the team was to accept the gyro derived base line for the survey and to recheck this azimuth by star shots at a later date. No further information has been supplied by the Norwegian team.

13.2.4 Conclusion

The reason for presenting this information is to draw attention to the type of situation totally divorced from mining, where the use of the gyro-theodolite is becoming desirable for a number of reasons. The limited investigations made to date have already isolated the disadvantages of various types of platform and have shown that certain structures are capable of giving the required stability for suspended gyroscopic observations. Possibly the future will see a development of the less susceptible A.M.I. (BAC) machine which avoids the disadvantages of a tape suspension in conditions of vibration. However, this would only occur if the quoted accuracies of equipment like A.M.I. were increased to the order of the modified Wild G.A.K.-1.

One final point which should be mentioned is that on all occasions when transporting gyroscopic equipment the gyro attachment has been kept by the operator in the cabin of the aircraft or helicopter. In the case of helicopters with intense and often violent vibration the equipment has generally been cradled on the carrier's lap to help cushion any adverse shaking which might possibly upset calibration of the instrument. In this type of project it is imperative that a calibration check is made on the equipment both before and after the offshore work along a known land base line.

14 - INSTRUMENTAL AIDS

14.1 INTRODUCTION

Throughout the research period there have been occasions where the design of special aids have assisted the project. Sometimes these simple aids have had continual use and sometimes have been discarded at a later date. This section contains a brief description of a few of these aids together with the reasons for their development.

14.2 SPECIAL CARRYING BOX

The special carrying box was constructed from scrap timber whilst involved on the first field trials with the modified G.A.K.-1 in Cornwall. Results using the modification had been very encouraging and had been obtained from individual observations; dismantling the equipment completely between spin-ups. It was thought that repeated dismantling and re-location of the gyro unit onto the bridge system mounted on the theodolite could be a source of small errors which, if eradicated, could give further improvements. The location system adopted by Wild is described in Section 4.

A decision was made to keep the gyro unit and theodolite clamped for a period to investigate any changes in accuracy. A strong wooden box was subsequently built containing precise supports for the gyro unit and theodolite and by closing a hinged door an additional system of padded supports effectively clamped the instruments in place. By using this box to transport the equipment between each observation the likelihood of error due to faulty

relocation was avoided.

This temporary box or crate was also fitted with carrying handles which allowed the whole unit to be lowered carefully down small shafts for underground work.

After considerable trials the results obtained from this composite system showed no significant difference to those gained previously. It was concluded that errors contained in repeated relocation of the gyro unit and theodolite were less than 2 seconds of arc.

This carrying clamp system was discarded and all results since have been obtained by conventional techniques. Discussions with Wild (U.K.) at a later date confirmed our assessment of the accuracy of location and tests were carried out using specialised equipment designed by Wild for checking repeatability. The chief instrument engineer also expressed some doubt as to the wisdom of continual clamping and was of the opinion that this could cause unnecessary stress to the equipment.

14.3 BASE PLATE ADAPTOR

The requirement for a special base plate occurred initially prior to the stability trials discussed in 10.6. It was necessary to design an adaptor to link the Wild equipment with a steel pillar already equipped with a threaded union for Vickers equipment. An additional refinement was included in the design to convert this

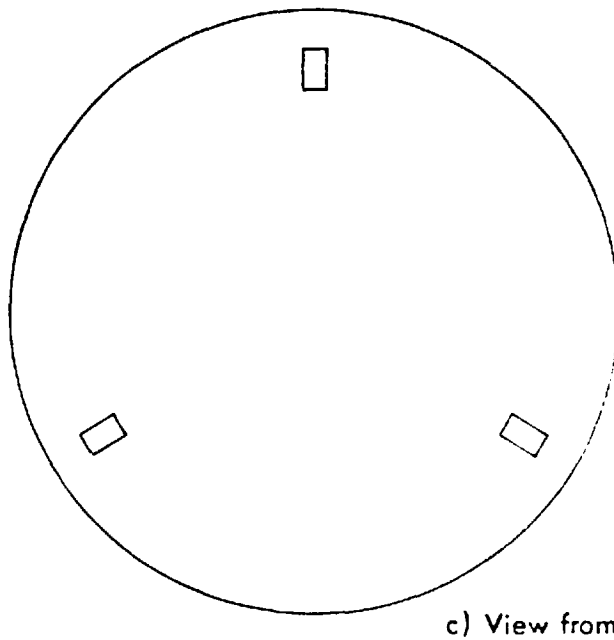
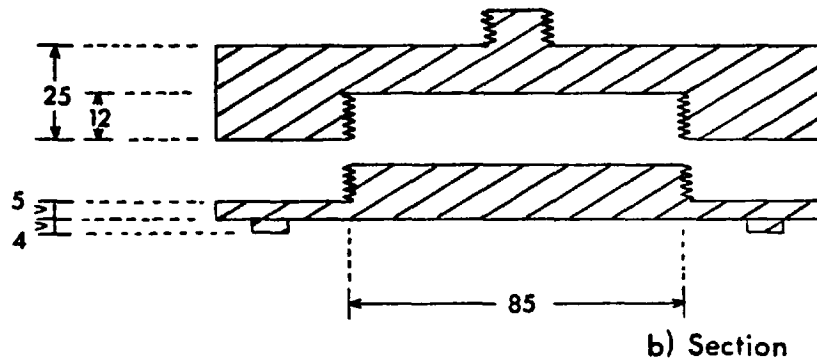
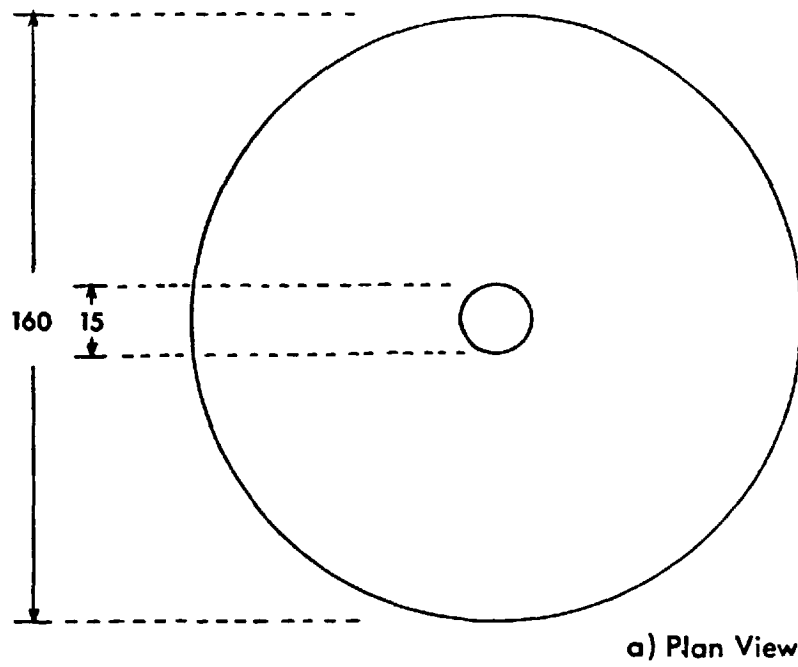
special adaptor to a conventional ordnance survey pillar fitting for other specialised work.

The newly designed base plate was eventually machined from solid mild steel to avoid any twist in the metal and had a diameter and depth to give maximum stability to the instrument. Figure 82 shows the essentials of this simple piece of equipment which has given excellent service. In retrospect possibly more time should have been devoted to selection of a lighter metal; the mild steel composition gives a total weight of 4.5 kg.

14.4 BRIDGE/LINK COVER

All attachment type gyro-theodolites are marketed with the attractive feature that the theodolite can be released for general survey work when not required for carrying the gyro unit. From early use of the Royal School of Mines instrument it was discovered that accuracy can be lost due to errors in centring and levelling. Each time a Wild gyro attachment is mounted on the bridge/linkage system of the theodolite it is essential to ensure that both the three location pins and the surrounding metal work are clean and that the pins are not damaged.

Underground use of the theodolite often entails working in conditions of poor visibility within a dust laden atmosphere. If a theodolite in these conditions has been fitted with the special gyro bridge link there could be a risk of damage being caused to the location system. It, therefore, appeared logical to design some simple form of protection.



nb.) all dimensions in millimetres

Figure 82 - Royal School of Mines Base Plate Adaptor

After some thought the locking ring of the bridge system was removed, and a temporary cover cut from thin tin sheet. Thick, but soft, plastic sheeting was then heat formed over the greased cover and locking ring. When cool the metal ring and cover were removed and the plastic form trimmed to a smooth edge. This soft plastic cover can easily be pushed over the locking ring to protect the location system when the theodolite is being used normally or even when storing away for periods of time - see Figure 83.

14.5 TRANSPORTATION BASE

This particular aid has yet to be produced although the design has been conceived. The reason for this aid has come from practical problems arising in the transportation of the Wild G.A.K.-1. Transportation by road or rail presents few problems and the travelling containers supplied by Wild are excellently designed. However, when travelling by commercial air liner one is faced with the problem of carrying the gyro unit in the passenger cabin. It is recommended that this section is carried personally whilst travelling to avoid any unnecessary jolts to the mechanism and to cushion the equipment if necessary against adverse vibration effects.

In an aircraft such as the Trident the conventional plastic containers will fit beneath ones feet and between the seat and the seat in front. However, if one travels in certain aircraft the space between seats is insufficient for the box. In cases such as these the gyro unit must be carried in its normal metal container without the protective carrying box. The problem then arises of keeping the metal container upright - a further condition of gyro-

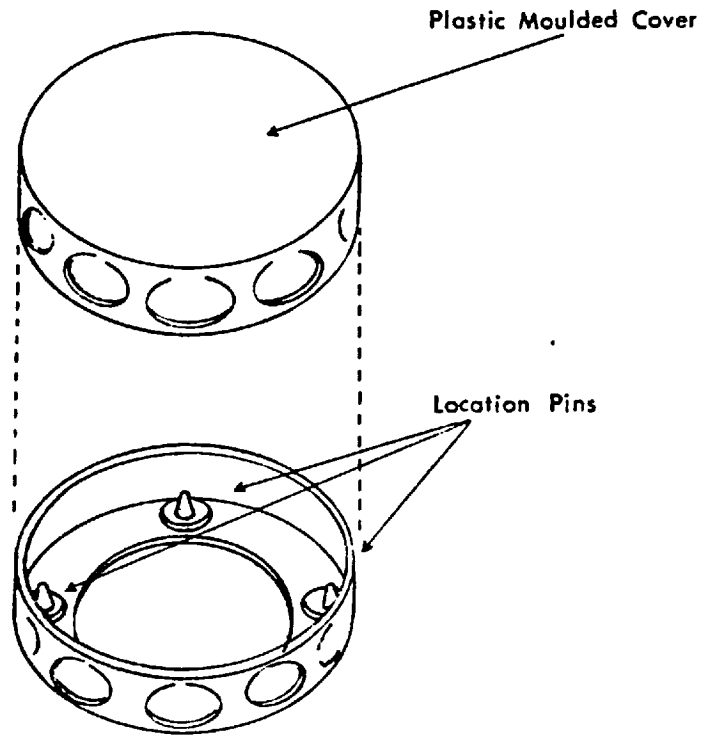


Figure 83 - Cover for Wild G.A.K.-1 Bridge Unit

scopic equipment. Constantly supporting such a container between ones feet can be extremely tiring and uncomfortable.

The aid to this problem is again simple and can be produced from thin aluminium or heavy plastic. Possibly the latter would be more acceptable. Figure 84 shows the design of such a base plate.

Closed the aid can be carried in a brief case. The protective gyro box is sent with normal baggage and the metal gyro cannister is then force fitted into the 'plastic base plate', when setting the

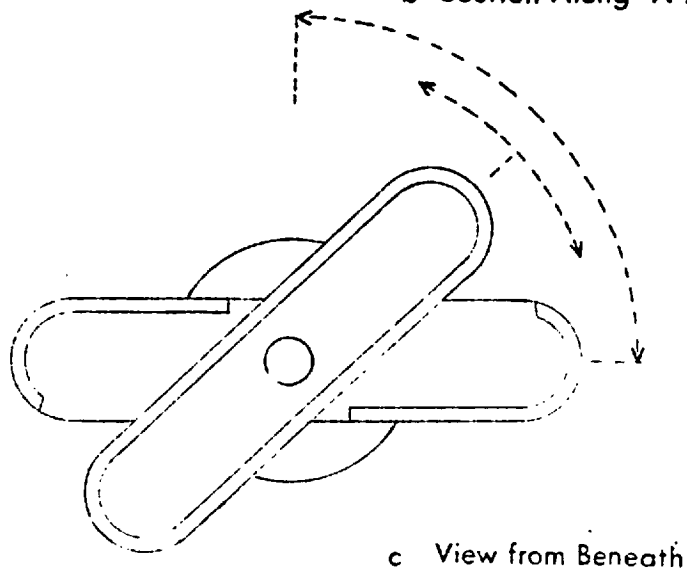
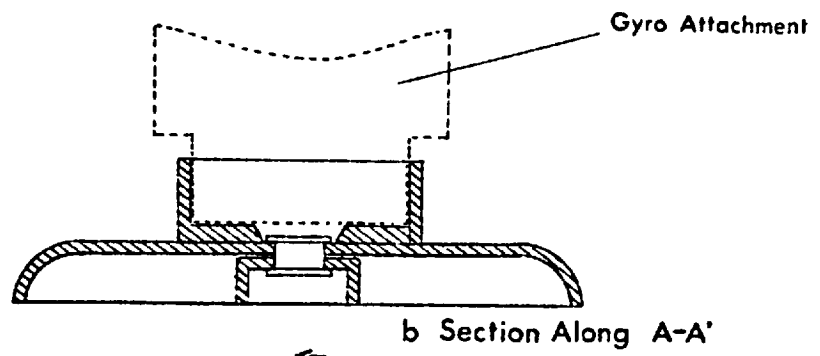
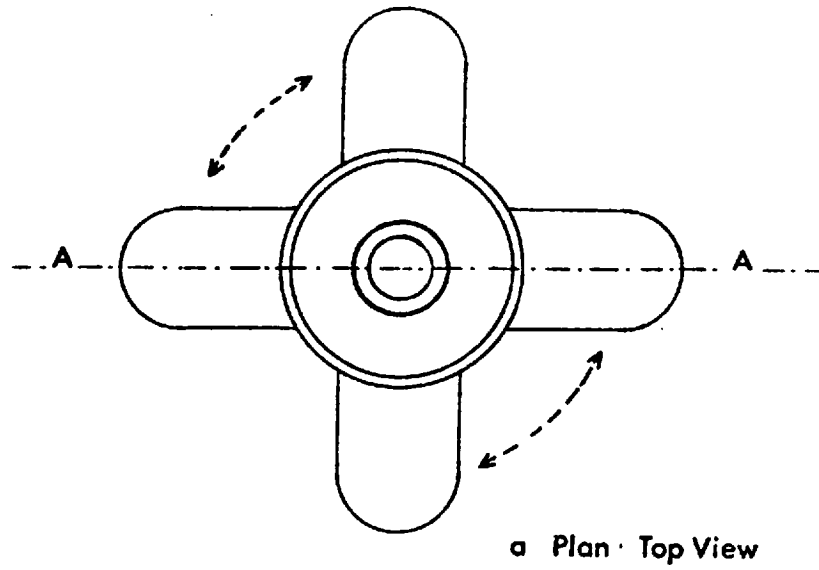


Figure 84 - Royal School of Mines Transportation Support

case down the additional feet are swung into position. It is then comparatively simple to keep one foot on one or other of the supports whilst travelling.

14.6 BOOKING SHEETS

Various booking sheets have been evolved over the past few years, mainly to keep pace with the different systems of measuring and reducing information. Reference here is mainly to the special design of booking sheet by way of reducing the original A4 format to fit a normal survey note book.

Although an A4 booking sheet on a clip board is ideal for laboratory work it is often inconvenient in working conditions either underground or surface. Consequently the conventional form has been contained on four sides of a small pocket book as shown, full size in Figure 85. Booking is certainly easier and can be protected in an overall pocket between readings.

14.7 ELECTRONIC STOP WATCH

As discussed in the section dealing with the timing method, the accuracy of times obtained using the quartz crystal controlled system built into the now obsolete Hewlett Packard 55 calculator were far superior to those obtained using the conventional stop watch at best good to one tenth of a second. If the timing method becomes more established there could be a commercial need for a small electronic stop watch with the capacity for storing the required times to one hundredth of a second accuracy especially in view of the H.P.55

[illegible]

Figure 85 - Pocket Sized Booking Sheets (Amplitude Method)

being taken off the market.

A prototype has been designed at the Royal School of Mines and is in the process of being constructed. In this particular model the proposed storage capacity is far in excess of that required for normal use but the opportunity was taken to use this equipment for future extended spin trials requiring many hundreds of individual time values.

The basis of the construction and components is shown in Figure 86. A smaller version able to store enough time values for general observation work using the timing method is also under consideration.

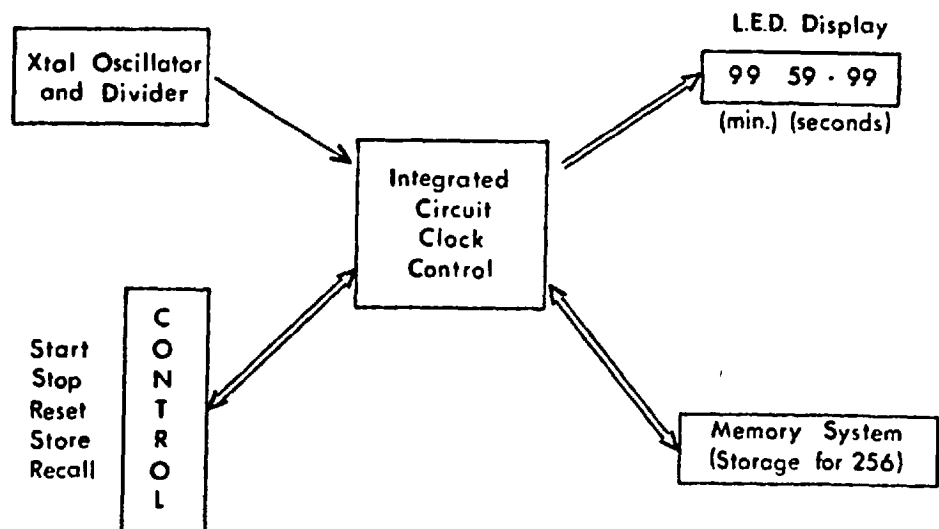


Figure 86 - Block Schematic for Stopwatch

15 - CONCLUSIONS

15.1 INTRODUCTION

This research project began as a practical investigation into the use of the gyro-theodolite in mining conditions. However, at an early stage it became clear that a major area of study would revolve around a modified version of the Wild G.A.K.-1 gyro attachment and also in the comparison of the methods of reduction being evolved at the Royal School of Mines. As the work progressed several other projects requiring investigation were discovered, some of a practical and empirical nature and others bordering on the theoretical. The following section explains the progress made during the course of study.

15.2 THE MODIFIED WILD G.A.K.-1

The modification to the scale reading system carried out in conjunction with Wild (U.K.) was undoubtedly a success. Early trials carried out in 1974 demonstrated quickly how scale readings of reversal points could be measured to one hundredth of a scale division as opposed to the previous approximate estimation to one tenth. Section 7 explains in detail the simple modification and its revolutionary effect on scale reading accuracy.

Possibly the best indication of the success of this part of the project is that Wild (U.K.) are marketing currently the modified version of the standard G.A.K.-1 attachment and that every machine sold for the accurate determination of azimuths subsequent to the

investigations summarised in Section 10 has been fitted with the new micrometer system. The majority of areas within the National Coal Board have either purchased new modified machines or have had the modification made to their existing equipment. Considerable interest has also been shown in South Africa, the Far East and more recently in United States.

15.3 DAMPING

One of the major advantages to arise from being able to read accurate reversal points of the oscillating gyro system was in the discovery of an accurate damping factor for the Wild G.A.K.-1. Section 9.4 explains the lengthy power spins involved and shows the consistency of values obtained over the research period. Acknowledgement of this advance was made by Williams of South Africa at a Seminar in 1977 and in a subsequent publication⁽²⁶⁾.

For many years leading researchers were only able to estimate a value for the damping factor but once an accurately measured value was available it was of considerable importance in developing further methods of reduction. For example, the constant damping factor established for the first time a measure of the stability of the damped simple harmonic motion of the gyro oscillation; this helped to check the mathematical model from which it became possible to derive the Transit and Timing formulae, as explained in Sections 5.6. and 5.6.5.

A further advantage of establishing a stable system was being able to accept a gyroscopic result from just two reversal points.

Observations using this bare minimum of data are contained in the comparison trials of Section 10.4, figures 59 to 61 inclusive.

15.4 COMPARISON OF REDUCTION METHODS

When these investigations began, of the three original methods available for reduction, namely Tracking, Transit and Amplitude, only the latter two were suitable for comparison work involving the modified reading system. Later work involved a further development to the Transit method and new formulae for a method using Timing alone. All these methods have been compared rigorously with each other throughout this thesis; the results of these trials being discussed at length in their chronological order in Section 10.

The system of comparison used is unique to current gyro work in that sufficient data is extracted from each oscillation to enable separate reductions of each method, thereby obtaining a true comparison. This system has distinct advantages over the more usual one of comparing separate sets of each different technique. Results from these comparison trials show for the first time the strength of the three basic reduction methods. It is only in the Special Trials contained in Section 10.4, where the evidence of short term drift of the spinning system has been taken into account, again for the first time, that any differences between methods became noticeable.

Accuracies using the modified G.A.K.-1 mounted on a T-2 single second theodolite, for all three methods vary between ± 4 and ± 7 seconds of arc as a standard deviation for one result, including R.O. readings completed within one hour.

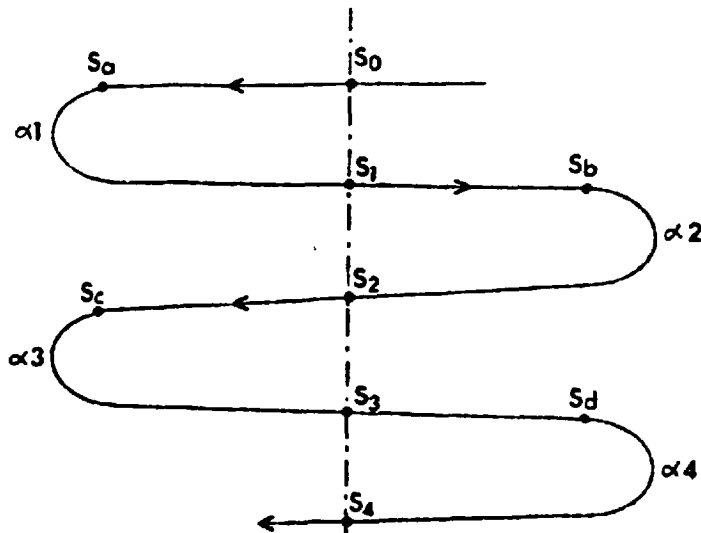
Taking additional information within the same oscillation is not difficult and obviously takes no more time than that set aside for one method. For field use it would therefore be an advantage to take such additional data and calculate a result from two separate and independent methods as a simple checking procedure. Similarly every survey technique used today attempts to incorporate a checking system of some description during the taking or reduction of field data. At least one area of the N.C.B. - South Midlands - have used this technique in their more recent work.

An overall summary of the three methods with reference to total information required and accuracies achieved from one pointing is shown in Figure 87. Note that times shown are for obtaining the required information and do not represent total observation time. The accuracies shown in this figure are those obtained in the minimum time using oscillations taken on one side of True North only. In normal circumstances a "balanced observation" is recommended as described in Sections 8 and 10.

15.5 DRIFT

Section 9.1 discusses the problem of drift and contains for the first time some positive evidence linking short term drift in the Power Spin mode to that identified in the Non Spin mode. Several other authors, referred to within the relevant section, have examined drift of various descriptions but have concentrated their work on the Power Spin mode alone.

Accepting that there is a link between the two modes it was



Method	Data Span	Oscillation	Time	Pieces of Information	Number of Answers	Accuracy
Amplitude	$\alpha 1 \rightarrow \alpha 2$	0.5	3m. 36s	2	1	$\pm 6''$
	$\alpha 3 \rightarrow \alpha 4$	0.5	3m. 36s	2	1	$\pm 4''$
	$\alpha 1 \rightarrow \alpha 4$	1.5	10m. 48s	4	3	$\pm 4''$
Old Transit	$S_0 \rightarrow S_4$	2	14m 24s	9	1	$\pm 7''$
New Transit	$S_0 \rightarrow S_1$	0.5	3m. 36s	3	1	$\pm 7''$
	$S_0 \rightarrow S_2$	1	7m. 12s	5	2	$\pm 7''$
	$S_0 \rightarrow S_4$	2	14m 24s	9	4	$\pm 6''/\pm 7''$
Timing	$S_0 \rightarrow S_1$	0.5	3m. 36s	3	1	$\pm 8'' \pm 9''$
	$S_0 \rightarrow S_2$	1	7m. 12s	5	2	$\pm 8''$
	$S_0 \rightarrow S_4$	2	14m 24s	9	4	$\pm 6''/\pm 7''$

nb. These results are for One heading Only.
See also Special Trials in 10-4.

N.B.

- i) Theoretically, observations using the New Transit and Timing methods require only two accurate pieces of information per 1/2 oscillation - i.e. the central times, the accuracy of the 3rd piece of information having little effect on the final reduction (see Section 11).
- ii) Amplitude results from 2 pieces of information ignores damping.

Figure 87 - Summary of Accuracies Obtained in the Minimum Time Period (Not Recommended for Field Use)

possible to develop the series of experiments known as Special Trials in Section 10.4, where the effect of the more unpredictable 'primary drift' has been reduced significantly. Isolating this effect using the system evolved takes a relatively short time before observations are made. Without identifying such a link similar isolation would take approximately five times longer and would involve a serious reduction in the working life of the gyro system - Section 9.1.7.

The general conclusion reached after investigating the various drift patterns was that for practical use the "Primary Drift" pattern was the more important. Certainly, in common with other authors, it is believed that some of the effect of drift in general must be due to overall gyro design. However, from the experiments carried out in Section 9 and implementing conclusions from these observations in the Special Trials in Section 10.4, it is clear that most of the effect of drift is due to movement of the suspension tape.

15.6 TAPE ZERO

Tape zero corrections were applied throughout the majority of comparison trials contained in this thesis. From the initial work in 1974 it was clear that applying such a correction as a routine during observations reduced the variations in additive constant - or E factor, reported by other writers. At first by empirical means a weighted mean correction, incorporating "before" and "after" values for the tape zero position, was devised. Later it was found that a similar weighting system could be justified mathematically.

Application of a tape zero correction was a new introduction for

Wild equipment but correlation between these values and variations in results obtained by ignoring such values were quite clear - see Figures 50, 51 and 53 in Section 10 and Figure 78 in Section 12. Later work on drift contained in Section 9 and Section 10.4, mentioned in 15.5 shows that errors due to movement of tape zero may possibly be reduced by adopting a different technique of observation.

However, the major problem in mining is the widely differing environmental conditions experienced within one location; it has been shown that such differences can affect the value of tape zero - Section 12.4 and 12.5. In these situations it is imperative that a constant and routine check is made on the tape zero position.

Section 12 deals with tape zero as a separate topic and contains its own conclusion in 12.6.

15.7 ORIGINAL AIMS OF RESEARCH

These investigations were originally conceived to establish the use of gyroscopic bearings as a primary method of orientation within the mining environment as opposed to their existing role at that time of checking bearings which had been derived from more conventional techniques.

Introduction of the modification to the G.A.K.-1, the determination of the damping factor and the importance of the various internal factors such as drift and magnetism, and a thorough comparison of the new reduction techniques has made the Wild gyro-theodolite attachment as accurate as any gyro-theodolite system currently available. High order accuracies can today be obtained in a much shorter period

of time and observations can be deliberately planned to include fully independant checks.

Several important projects recently investigated by the N.C.B. have been based entirely on gyroscopic directions - see Section 12.5 - overseas excavations such as the new Hong Kong Transit system and a lengthy inclined shaft connecting various levels at Panasqueira Mine in Portugal are also being driven on gyro bases alone.

Although some credit is due to the work carried out at the Royal School of Mines many professional surveyors have also contributed in the steady acceptance of the gyro-theodolite today as a primary survey tool.

APPENDIX I - FURTHER RESEARCH

As with all research projects one investigation often leads to another but eventually there comes a time when these topics must be set aside for future study.

- 1) Further work is required on the problem of external magnetism. Preparations have already been made at The Royal School of Mines laboratory to establish a framework of magnetic coils to investigate the effect of differing magnetic fields on the accuracy of gyro determination. Possibly this work will establish a table of magnetic values with their effect on accuracy; possibly this might lead to the introduction of a small magnetic field sensor to be carried as a piece of auxiliary equipment for normal gyroscopic observations.
- 2) More work is also required on general stability of set up and to evolve some form of anti vibration device to minimise the effect of such movements on offshore structures.
- 3) The work on drift patterns should be extended. Comparisons should also be made with other gyroscopic equipment by collaboration with overseas research workers or with manufacturers. This topic has little relation to the use of gyro-theodolites in practice but investigations could widen the knowledge of general gyroscopic theory.
- 4) The small electronic stop watch, referred to in Section 14, and being built within the Royal School of Mines should be evaluated with reference to its use with the new Timing formulae.
- 5) Finally, some thoughts should be given to a fully automated timing modification to the Wild G.A.K.-1. Some work has already been published by the Canadians but a new approach in conjunction with the Royal School of Mines methods of reduction would be of some benefit.

APPENDIX II - SUSPENDED GYRO-THEODOLITES TODAY

Figure 88 contains a breakdown of the more common gyro-theodolites available today, and includes manufacturers quoted accuracies and accuracies published by professional investigators using modified models. This information, originally published in 1977⁽¹³⁾ has been amended to include additional models and latest results.

<u>Model</u>	<u>Accuracy</u>	<u>Number of Reversal Points</u>	<u>Time (minutes)</u>	<u>Remarks</u>
Fennel K.T.1.	$\pm 5''$	5-7	45-60	a) Result reproducible within $\pm 30''$. b) Accuracy obtained as mean of 3 results.
Fennel T.K.3.	$\pm 20''$	3-5	20-30	
Fennel T.K.4.	$\pm 30''$	5 ?	30	
Fennel F.H.K.5	-	-	-	
Bochum H.W.77	6"	2	10	
MOM G1B1	$\pm 10''$ $\pm 16''$ $\pm 15''$	? 3 4	? 32 35	Internal accuracy. Result reproducible within $\pm 20''$.
MOM G1C1	$\pm 15''$ $\pm 40''$ $\pm 30''$ or $\pm 35''$ $\pm 25''$ or $\pm 30''$	? 2 3 4	? 18 22 or 18 25 or 20	Internal accuracy. Accuracy varies accord- ing to additional use of G1-C1 & transverter.
MOM G1C2	$\pm 12''$ $\pm 40''$ $\pm 25''$ or $\pm 30''$ $\pm 20''$ or $\pm 25''$	? 2 3 4	? 18 22 or 18 25 or 20	as G1C1.
MOM G1D1	$\pm 25''$ $\pm 60''$ $\pm 50''$ $\pm 40''$	? 2 3 4	? 15 18 20	Internal accuracy.
Sokkisha G.P.1.	$\pm 20''$	?	?	
Wild G.A.K.1	$\pm 20''$	3	20	

With Modifications

Canadian Modified MOM G1B2 used as G1B1	$\pm 2.5''$			Mean of 2 to 10 determinations.
Canadian Modified Wild G.A.K.1.	± 2.2 to $3.7''$			Mean of 4 to 6 determinations.
R.S.M. Wild(UK)				
Modified Wild G.A.K.1	$\pm 7''$	8	50-60	T-16 theodolite (direct to 1 minute) 1 determ- ination measured both sides of North.
	$\pm 4''$	8	50-60	As above mounted on T-2 theodolite (direct to 1 second).
	$\pm 2''$	8	50-60	*

* + Tape suspension prior to observations. See Section 10.4.

Also note data in Figure 87

Figure 88 - Approximate Rankings of Gyro-Theodolites as Known Today

REFERENCES

1. BENNETT, G.G. (1970) An Historical Review of the Development of the Gyroscope. The Australian Surveyor Vol. 23 No. 4.
2. LAUF, G.B. (1970) The Early History of the Gyroscope and the Gyro Compass. The Canadian Surveyor Vol. 24 No. 1.
3. LAUF, G.B. (1970) Gyroscopic Surveying. Quarterly of the Colorado School of Mines Vol. 65 No. 2.
4. THOMAS, T.L. (1976) The Suspended Gyroscope (Part 2). Chartered Surveyor, Land, Hydrographic and Minerals Quarterly Vol. 3 No. 3.
5. STRASSER, G.J. and SCHWENDENER, H.R. (1966) A North Seeking Gyro Attachment for the Theodolite as a New Aid to the Surveyor. Bulletin Geodesique 70, 23 - 38.
6. THOMAS, T.L. (1979) Precise Methods of Finding North using the Modified Wild G.A.K.-1 and the M.O.M. Gic11. IV I.S.M. Aachen
7. HALMOS, F. (1969) Neue Ungarische Kreiseltheodolite, Zeitschrift fuf Vermessungswesen 6a.).
Methodische Fragen der Analyse von Kreiseltheodolite
messungen 6b) Technical University for Heavy Industry, Miskole,
Hungary.
8. BENNETT, G.G. (1970) The Modified Transit Method of Observation with the Wild G.A.K.-1 Gyro-Theodolite. The Canadian Surveyor Vol. 24 No. 1.
9. THOMAS, T.L. and ASLUTH, D. (1975) The Suspended Gyroscope (Part 1). Chartered Surveyor, Land, Hydrographic and Minerals Quarterly Vol. 2 No. 3.
10. GRAFEREND, E. (1967) Fehler theoretische Untersuchungen und Chronometrische Messverfahren beim Einsatz von Aufsatzkreisel in Kombination mit dem Elektrooptischen Entfernungsmessgerät AGA - Geodimeter 43. Deutsche Geodetische Kommission, Reihe C: Dissertationen, Heft Nr. 112.
11. GRAFEREND, E. (1969) Chronometrische Nordbestimmung mit Vermessungskreisen Zeitschrift fur Vermessungswesen 3.
12. GRAFEREND, E. and KUMAREZYN, H. (1971) Neuartige Chronometrische Messverfahren zur Nordbestimmung mit Vermessungskreisen. Alty. Vermessungs-Nachrichten.
13. SMITH, R.C.H. (1977) A Modified G.A.K.-1 Gyro Attachment. Survey Review XXIV 187.

14. HALMOS, F. (1971) Systematic and Random Errors of Direction Measurements with Gyros. F.I.G. XIII International Congress Weisbaden.
15. STIER, K.H. Meridienweiser im Magnetfeld. Gluckauf 91. 1955.
16. TICHOMIROVA, N.P. Der Einfluss eines Magnetfeldes auf die Weisungeines Markscheider Kreiselkompasses. Ugbetechtizat, Leningrad 1958.
17. DZIERZEGA, A. (1974) Influence of Outside Conditions on the Accuracy of Gyro Bearings Determination by means of Gyro Compasses GiB1 and G.A.K.-1. F.I.G. XIV Congress, Washington.
18. CIRBUS, J. (1977) Einfluss von Erschutterungen auf die Stabilitat der Additionkonstante bei Kreisel Theodoliten. F.I.G. XV Congress, Stockholm.
19. SHEPPARD, J.S. (1952) Precise Azimuths from Steep Sights. Transactions of the Institution of Mining and Metallurgy. Vol. 62 Part 4.
20. GREGERSON, L.F. (1970) An Investigation of the M.O.M. GiB2 Gyroscopic Theodolite. The Canadian Surveyor Vol. 124 No. 1.
21. GREGERSON, L.F. (1974) Using Gyro-theodolites for Precise Determinations of Azimuth. F.I.G. XIV Congress, Washington.
22. WILLIAMS, H.S. and BELLING, G.E. (1967) Quasi Harmonic Patterns of Pendulous Gyroscopes during Protracted Oscillations. Tijdschrift Voor Kadaster en Landmeetkund.
23. CHRZANOWSKI, A.J. (1970) New Techniques in Mine Orientation Surveys. The Canadian Surveyor Vol. 24 No. 1.
24. CHRZANOWSKI, A.J. (1969) The Application of New Instruments and Techniques to Mine Surveying. The Australian Surveyor Vol. 22 No. 5.
25. HODGES, D.J. and BROWN, J. (1977) K Factor Drift Rates in Suspended Gyroscopes. XV International Congress of Surveyors, Stockholm.
26. WILLIAMS, H.S. (1978) A Critical Review of the Practical Use of the Gyro-theodolite. Survey Review XXIV 180
27. BENNETT, G.C. (1969) New Methods of Observation with the Wild G.A.K.-1 Gyro-theodolite. Unisurv Report No. 15. The University of New South Wales, Australia.
28. THOMAS, T.L. and SMITH, R.C.H. (1977) A New Gyro-theodolite and a Modified Gyro-theodolite. XV International Congress of Surveyors, Stockholm.

29. DUFOND, R. and LAFFONT, M. (1978) The First Giant Gas Field on the Northern North Sea. European Offshore Petroleum Conference and Exhibition - EUR 110.

BIBLIOGRAPHY

1. DEIMEL, R.F. (1950) Mechanics of the Gyroscope - Dover Publications Incorporated - New York.
2. GRAY, A. (1959) Treatise on Gyrostatics and Rotational Motion : Theory and Applications - Dover Publications Incorporated - New York.
3. LAUF, G.B. (1970) Gyroscopic Surveying. Quarterly of the Colorado School of Mines. Vol. 65 No. 2.
4. MCCLURE, C.L. (1960) Theory of Inertial Guidance - Prentice-Hall International Incorporated, London.
5. M.O.M. Hungarian Optical Works - Gyroscopic Theodolite - Type GiB1 - Operating Instructions.
6. Wild Heerbrugg Handbook Wild G.A.K.-1 Gyro Attachment.
316 261 e^{-1.71}