

IONOSPHERIC MAGNETIC FIELDS
ASSOCIATED WITH MID-LATITUDE SPORADIC-E

THESIS
submitted by

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A B S T R A C T

The thesis describes, in two parts, an investigation at Woomera, South Australia during November and December, 1965 into the relationship between sporadic-E (E_s) ionization and the total intensity of the geomagnetic field, by means of rocket-borne and ground-based equipment.

Part I describes two similar experiments launched in Skylark rockets from Woomera Rocket Range on 19th November and 13th December, 1965. The experiments included contributions from several British Universities to measure electron densities, positive ion densities, wind velocities and magnetic total intensities (with which the author was concerned) in the E-region of the ionosphere, with particular reference to E_s . The magnetic experiment using a proton precession magnetometer is described in detail. The results obtained are considered in conjunction with those of the other contributions and with ionosonde readings made available from the Woomera ionosonde installation. On 19th November two, or possibly three, layers of E_s , indicated by the ionograms, were detected between 110 and 120 km. as maxima of electron and ion density. The magnetic profile showed no pertinent feature and no wind measurements were obtained. On 13th December a layer of E_s , indicated by the ionograms, was detected at 108 km. as a maximum of electron and ion density and a minimum of magnetic intensity. The wind measurements indicated a region of negative east-to-west wind shear at that altitude. These results are discussed in the light of the commonly accepted wind-shear theory of E_s formation, which requires that the wind shear be positive east-to-west, and in the light of previous work, which has found E_s layers in regions of positive and of negative east-to-west wind shear. It is concluded that, when possible errors of measurement are considered, no acceptable evidence contrary to the wind-shear theory has previously been obtained and that the present wind profile can be validly adjusted to give agreement with the wind-shear theory.

The observed minimum of magnetic intensity at the altitude of the E_s layer is also in agreement with the wind-shear theory.

Part 2 describes the ground-based experiment to measure total magnetic intensity, with a rubidium vapour magnetometer, which was conducted by the author at Woomera during the period November and December, 1965. The magnetograms obtained are compared with the author's interpretation of concurrent ionograms provided from the Woomera ionosonde, with particular attention to the daily variation in height and critical frequency of E_s layers. It is concluded that daily variations in the height of E_s are related to the daily Sq variations in magnetic intensity, in that increasing magnetic intensity is associated with descending E_s layers and vice versa. For these E_s layers, the height and critical frequency have been found to vary inversely. Two known mechanisms for vertical transport of ionization, involving internal atmospheric gravity waves and Sq currents, are invoked.

CONTENTS

	Page
CHAPTER 1 INTRODUCTION	5
1.1 Previous work	5
1.2 Description of the sporadic-E phenomenon	11
1.3 The wind-shear and other theories of temperate-zone sporadic-E	18
P A R T I	
CHAPTER 2 THE ROCKET FLIGHTS	54
2.1 Conditions at launch	54
2.2 Rocket performance	63
2.3 Rocket payload	70
2.4 Description of the Imperial College magnetometer	74
2.5 Data analysis - Imperial College magnetometer	81
2.6 Results - the integrated rocket experiment	87
CHAPTER 3 DISCUSSION OF THE ROCKET FLIGHTS	96
Conclusions	104
P A R T 2	
CHAPTER 4 THE GROUND EXPERIMENT	105
4.1 Description of the magnetometer	105
4.2 Field work	111
4.3 Ionospheric sounding	117
CHAPTER 5 DATA REDUCTION AND ANALYSIS	124
5.1 Digitization	124
5.2 CalComp plotting	127
5.3 Inspection of ionograms	128
CHAPTER 6 DISCUSSION OF THE MAGNETOGRAMS AND PARAMETER-PLOTS FOR NOVEMBER AND DECEMBER, 1965	139
6.1 The magnetograms	139
6.2 The parameter-plots	149
6.3 Correlation of the magnetograms and the parameter-plots	154
6.4 Explanation	156
Conclusions	167
ACKNOWLEDGEMENTS	169
BIBLIOGRAPHY	170

LIST OF FIGURES

Figure	Page	Figure	Page
1.1	52	2.9	79
2.1	57 & 130	2.10	85
2.2	60	2.11	88
2.3	62 & 131	2.12	89
2.4	64	3.1	101
2.5	66	4.1	106
Plate 2.1	69	4.2	108
2.6	71	6.1	145
2.7	78	6.2	146
2.8	79	6.3	151 & 152
		6.4	158

Magnetograms and Parameter-plots,

(inside back cover)

C H A P T E R I

INTRODUCTION

1.1 Previous Work

The earliest experimental work on the relationship of sporadic-E (E_s) to the geomagnetic elements in ^{temperate} temperature latitudes (Yonezawa, 1950) was conducted in the Japanese Islands, using ionogram and magnetogram data gathered during 20th Co-operative Observation for the period June 10th to July 10th, 1949. The data comprised ionograms from Kakubunic Ionospheric Station and magnetograms (H, Z, D) from Kakirks, which are separated by about 90 km. Although statistical errors in the analysis made definite conclusions impossible, it was estimated that from approximately one day before to one day after a period of intense E_s ionisation the magnetic declination tended to increase westward, enhancing its diurnal variation, and the horizontal component of the magnetic field tended to decrease.

Yonezawa (1951) showed that the same tendencies occurred at the same stations, in results from the Co-operative Observation for the period June 10th to July 10th, 1950. By applying a superposed epochs technique, he concluded that the declination tended to be eastward, of its average diurnal value, before a time of intense E_s , and westward after. He substantiated this from results covering 1947 to 1950 which, when average curves were drawn, showed the declination eastward for 20 hours before and westward 18 hours after a time of intense E_s . Subsequently Hojo and Yonezawa (1953) argued that if E_s is produced by the incidence of particles (including meteors) producing an increased ionization of the E-region, there should be some concurrent change in geomagnetism which in the case of declination would be apparent as a deflection in the deviation enhancing its diurnal variation.

From a consideration of world-wide data, covering a period from 1948 to the I.G.Y., a number of authors have discussed the

geographic distribution in the temperate latitudes, of the occurrence frequency of E_s with a critical frequency greater than 5 Mc/s ($pE_s > 5 \text{ Mc/s}$), and the relationship of this distribution to the strength of the horizontal component of the magnetic field. Smith (1957 and 1962), in describing the total annual geographic distribution of $E_s > 5 \text{ Mc/s}$, noted an anomalous peak of occurrence in the Far East and a minimum over South Africa. Further, he noted a minimum in horizontal magnetic intensity, H , over South Africa and pointed out that the world-wide distribution of horizontal intensity bears a resemblance to the distribution of temperate-zone E_s . Smith's work is presented in more detail in the section 'Description of the E_s Phenomenon'. I.G.Y. data (Leighton, Shapley and Smith, 1962) have since confirmed the anomalously high occurrence of E_s in the Far East, for the June solstice, and shown that the peak extends into the Northern Hemisphere, towards the Mediterranean Sea, also that it has a counterpart in the Southern Hemisphere over the Eastern Pacific, during the December solstice.

These features would seem to confirm a suggestion by Smith and Finney (1960) that such peaks would occur in local summer in those areas where the geographic latitude is higher than the magnetic latitude; thus, in the Northern Hemisphere, to the north of where the magnetic equator is farthest north of the geographic equator (i.e. the Far East and Europe) and in the Southern Hemisphere, to the south of the most southerly excursion of the magnetic equator (i.e. South America). The correlation of high horizontal magnetic intensity with peak occurrences of E_s is positive for the Far East anomaly but negative for the South American anomaly. However, Heisler and Whitehead (1960) obtained a statistically positive correlation between the percentage of time (for all times of day and year) for which the critical frequency of E_s is greater than 5 Mc/s ($\%E_s$) and the horizontal intensity (B_H), in temperate latitude, using the same data (1968 I.G.Y.) as Smith and Leighton et al. Whitehead (1960,

1961) has developed a theory for the formation of E_s in temperate latitude based on this statistical result, (ref. section on theory of formation of E_s). Subsequently Matsushita (1962) argued that Heisler and Whitehead's correlation of % E_s with B_H is not statistically better than a correlation between % E_s and geomagnetic latitude and, moreover, that an even better correlation existed between % E_s and the parameter $(0.65 - |B_Z|)B_H$, where B_Z is the vertical component of magnetic intensity and 0.65 (in c.g.s. units) is an approximate value of B_Z at the magnetic north pole, which is introduced to overcome the cancelling effect of the inverse dependence on latitude of B_Z and of B_H . Matsushita considered that such statistical evidence is not strong enough to form the basis of a theory for the formation of E_s .

These objections were rejected by Heisler and Whitehead (1964) in a presentation of further evidence that % E_s is correlated principally with B_H and that correlations of % E_s with B_Z or the angle of dip, θ , arise because of the inherent relationship of these three geomagnetic elements. Their evidence, however, consists of a statistical re-examination of the data previously used by them and Matsushita, and does not really refute Matsushita's point that B_Z is also involved in the relationship with % E_s . Ovezgel'dyyev and Vasil'yeva (1964) have demonstrated the relationship of % $E_s > 5$ Mc/s to B_H between 0900 and 1600 hours local time for 23 mid.-latitude stations in the Northern Hemisphere, but failed to find it for the rest of the day. The relationship for % E_s (for all frequencies) and % $E_s > 7$ Mc/s was not so pronounced.

An experimental investigation of the relationship between E_s and the horizontal component of magnetic field was conducted at Brisbane, (36° S. magnetic), using an ionosonde and a horizontal component magnetometer at the same site, by Wilkie. His results were reported by Thomas (1962). The magnetograms showed on occasions, a small reduction in

H during the time when the ionograms showed an E_s cloud passing overhead. The effect was confirmed by a careful analysis which showed, in average monthly curves for a period of 15 months, a depression in the field at or near the central time of passage of an E_s cloud in almost every month. An average of all monthly graphs showed a depression of 7 gammas over a period of 3 to 4 hours, which conforms to the average duration of an E_s cloud over the 15 month period. A further analysis, for a period of 9 months, showed an average depression of 3 gammas over a one hour period centred on the time of initial occurrence of an E_s cloud, and a similar rise associated with its disappearance. Thomas does not fail to point out that the correlation in individual magnetograms was not high. Wilkie even questioned that the effect is genuinely associated with E_s in noting that central times of passage of E_s clouds have occurrence maxima at 1700 hours and 0100 hours, while readings of H taken at 13, 17, 21, 01 and 05 hours, irrespective of E_s occurrence, give an average curve with a depression of about 7 gammas at 1700 hours and a smaller depression at 0100 hours. Thereby, he suggested, there might be some other common cause for the concurrent production of E_s and the reduction of H. However, it would seem that by averaging H for days when E_s occurred at 1700 and 0100 hours, as well as for days when E_s did not occur at those times, Wilkie was bound to find a depression in the average curve of H due to the influence of the days when E_s did occur at 1700 and 0100 hours. The magnitude of that influence would depend on the percentage occurrence of days with E_s at 1700 and 0100 hours. A more significant test of Wilkie's doubts would have been an average curve of H for only those days when E_s did not occur at 1700 or 0100 hours. In any case, Wilkie produced a further test to show that the reduction in H was genuinely associated with the passage of an E_s cloud overhead. He took an equal number of E_s occurrences for each hour of the day, so eliminating the

FOOTNOTE: % E_s is equivalent to pE_s

predominance of occurrences at 1700 and 0100 hours, and, as before, constructed superposed epoch curves of H. The average curve showed a depression of 3 - 4 gammas about the central time of passage of an E_s cloud. A resulting theoretical paper by Wilkie and McNicol (1962) admitted that lack of contemporaneous information about the E-W and vertical components of the magnetic field, precluded a detailed explanation of the coincidence of a decrease in H with an E_s cloud, but suggested, on the basis of a close relationship between travelling ripples in F_2 -region ionization contours and isolated E_s clouds (Bowman, 1960) that the magnetic effect may result from changes in the height of the highly conducting F_2 -layer, in the manner suggested by Parker (1956).

In contrast to the results of Wilkie, Goodwin (1965) found a positive correlation between variations in H at Brisbane, sampled for 15 minutes at intervals of a few hours, and in the amplitude of direct backscatter echoes ($E_{s\phi}$) from the constant height sporadic-E (E_{sc}) region above Cassino, 150 km. away. $E_{s\phi}$ echo amplitudes and the occurrences of E_{sc} echoes at vertical incidence, i.e. at Cassino, were found to be positively correlated. Thus, Goodwin suggested, there is a positive correlation between changes in H and in the occurrence of vertical incidence E_{sc} echoes and that this result can be compared directly with Wilkie's work. He pointed out the consistency of such a positive correlation with Whitehead's (1962) theory for the formation of E_s in temperate latitudes; whereas a negative correlation such as Wilkie's was consistent with Cole's (1963) mechanism of E_s -layer formation. Goodwin considers it possible that both Whitehead's and Cole's mechanisms operate over Brisbane, either simultaneously or not, and that perhaps his time scale (15 minutes) conforms to that of Whitehead's process while Wilkie's (several hours) conforms more closely to that of Cole.

On the other hand, Ovezgel'dyyev and Korsunova (1964) and Ovezgel'dyyev (1965), from the results of an investigation at Ashkhabad carried out from May to August, 1962, concluded that the appearance of an intensive E_s -layer does not exert a significant influence on the daily variations of the horizontal or vertical components of the magnetic field, nor on the declination. They did, however, note a departure from the mean in some of the daily variation curves for the horizontal component, at approximately 0600 hours, which occurred just before a marked increase in the curve showing the probability of occurrence of E_s at different hours of the day. On that ground, they did not exclude the possibility of an indirect connection between the appearance of intensive E_s ionization and variations in the horizontal component.

Rocket-borne magnetometers have been used in several investigations of the mid-latitude Sq current system (Burrows and Hall, 1965; Davis, et al., 1965; etc.) and the equatorial electrojet (Maynard, 1967; Davis, et al., 1967; etc.). The detection of E_s layers with a rocket-borne magnetometer was first reported by Cloutier and Haymes (1968), although their launchings from Wallops Island, Virginia (on 24th November, 1965 and 17th February, 1966) were approximately concurrent with similarly successful launchings from Woomera, South Australia (on 19th November and 13th December, 1965). The magnetometer experiments on these latter flights were carried out by a group from the Geophysics Department, Imperial College and are reported as part of this thesis. Cloutier and Haymes flew a cesium vapour magnetometer with bias coils, designed for vector measurement of the Sq current system. Although resolution was poor due to instrument failures, the data indicated that thin, intense current sheets near 105 km. altitude were traversed on both flights. E_s layers at about that altitude were indicated on ionograms taken at the flight times, therefore the current structures were attributed to the enhanced electron concentration within

the E_s layers. Electron concentration profiles obtained from the ionograms tended to confirm this. The current vector in the E_s layer, obtained on the second flight, was mainly westward but fluctuated in direction, indicating a disordered current layer with regions of strong field.

Seddon (1962) reviewed six rocket flights, spread over several years from 1946, which successfully detected E_s from electron densities measured by a radio propagation technique (Seddon, 1953). Three of these were flown over New Mexico and three over Manitoba, Canada. A discussion of the technique and information about E_s layers obtained from these flights is included in the section 'Description of the E_s Phenomenon'. In addition, Seddon mentions some unpublished measurements with a rocket-borne proton precession magnetometer over Manitoba, made by Meredith et al. in 1958, which showed minima in the magnetic field at the altitudes of E_s layers.

1.2 Description of the E_s Phenomenon

Sporadic-E is abnormal, or sporadic, ionization masking the E-region of the ionosphere. The sections following will attempt to set the phenomenon in its ionospheric context, illustrating its abnormality and sporadicity, and summarise the more recent theories for the formation of E_s at mid.-latitudes.

The Ionosphere and the E-region

The ionosphere comprises the partially ionized region of the earth's atmosphere between 50 km. altitude and about 1,000 km. altitude. If it is considered as that region where ions and electrons are present in sufficient numbers to affect the propagation of radio waves, then the lower boundary may lie below 50 km. while the upper boundary is indeterminate.

The ionosphere is conventionally subdivided into the D-region (below 20 km.), the E-region (90 - 160 km.) and the F-region (above 160 km.). Occasionally reference is made to a C-region below the D-region. Use of this term 'region' has supplanted that of 'layer' because rocket sounding experiments have shown, contrary to deductions made from early ionospheric sounding experiments, that the electron density profile is continuous and without the distinct peaks which supposedly corresponded with the so-called layers. The layers are now seen to be merely 'ledges' in the curve where the gradient of electron density is large. However the nomenclature D, E and F, based on Appleton's original E-layer and F-layer is now applied to the ionospheric regions.

The trend of the electron density-altitude curve is indicated by the following average values for the three regions, as given by MacDonald (in DeWitt et al., 1962, p. 281). The D-region has a low level of ionization, daytime concentrations ranging from 10 electrons/cm³ at 60 km. altitude to about $10^3 - 10^4$ at 90 km. At night the concentration drops markedly but the mean ionization level is unknown. D-region ionization is enhanced, for periods of 30 - 90 minutes, by sudden ionospheric disturbances (S.I.D.) associated with solar flares. The E-region shows a strong diurnal fluctuation in ionization, plus seasonal, annual and geographic variations. Near noon the electron density may vary between about $8 - 9 \times 10^4$ at 100 km. and about $1 - 2 \times 10^5$ at 150 km. Little is known about the night-time ionization and it is thought to vary from hour to hour but estimates of $1 - 3 \times 10^3$ electrons/cm³ have been made. E_s occurs as an irregular thin layer, with electron densities which may be twice as high as those of the regular E-region, at about 100 km. in the E-region. (E_s layers can occur at various heights in the region 95 - 115 km.).

The F-region comprises two separate regions in the day-

time. The F_1 region extends to about 200 km. while F_2 has a true electron density peak at 300 - 400 km. During the night this subdivision disappears. The electron density curve for F_1 shows a slight inflection at about 180 km. with an electron density of $1 - 4 \times 10^5$ electrons/cm³. In summer and at the minimum of the solar cycle this 'ledge' is most pronounced, while it disappears in winter during maximum solar activity. The F_2 region exhibits considerable temporal and spatial variations of electron density with a broad maximum of $2 \times 10^5 - 2 \times 10^6$ extending over a height range of 100 - 200 km. At night the electron density drops sharply. Electron density falls off slowly above the F_2 maximum; at a distance of several thousand kilometers the density is of the order of $10^3 - 10^4$ electrons/cm³.

Structure of E_s at temperate latitudes

Two types of structure have been suggested; a thin horizontal layer of high electron density embedded in the regular E-region, and discontinuous blobs of ionization with higher electron density than the surrounding E-region. The appearance of E_s on ionograms indicates that it can sometimes behave as a reflecting layer and sometimes as a semi-transparent layer, over a large frequency range.

The thin horizontal layer is better thought of, in view of the results of rocket investigations (Seddon, in Smith and Matsushita, 1962, p. 78), as a steep-gradient section of the electron concentration-altitude curve within the E-region, where the gradients can be as large as $10^5 - 10^6$ electrons/cm³/km. A thin homogeneous layer would explain the cases where no transparency occurs, which constitute in temperate latitudes about $1/3$ of all cases. The thickness of these layers has been deduced, from rocket observations and ionogram interpretation, to be something less than 5 km. probably about 1 km. Rocket observations (Seddon, 1962, *ibid.*) have found five or more superposed E_s layers occurring at the same time and

at specific altitudes (eg. 100, 105, 111, 117, 129 km.), with a constant separation of 5 - 6 km. In addition, E_s layers at 142, 153, 184 km. were found during these flights.

The cases where E_s appears to be a semi-transparent layer can be explained by adopting either a model thin layer with 'holes' i.e. patches of smaller electron density, or a model thin layer containing more strongly ionized 'clouds'. The first model is really a simplification of the second in that it assumes only two distinct values of electron density within the layer, whereas the second assumes continuous gradations between the ambient electron density of the thin layer and the peak values which constitute the 'clouds'. The horizontal dimension envisaged for the 'holes' is about 5 km., which is small enough to preclude total transparency and large enough to minimise lateral diffraction of the radiation. Lateral diffraction would be expected to produce oblique echoes whereas it has been shown (Rawer, in Smith and Matsushita, 1962, p. 326) that E_s echoes are practically always vertical ($\pm 10\%$ from the vertical) in temperate latitudes. In the 'holes' model the reflection coefficient can have only three distinct values corresponding to the reflected frequency being below the minimum plasma frequency, above the maximum plasma frequency (when the reflection coefficient is zero), or at some intermediate value. However observations at Freiburg (Rawer, 1962) has shown that the reflection coefficient is a continuous function of frequency. The second model accords with this fact, there being a continuously decreasing reflection coefficient between the lowest frequency at which the layer begins to become transparent (corresponding to the basic ionization of the thin layer) and the highest frequency at which a reflection is obtained (corresponding to the ionization level at the nuclei of the 'clouds').

Temporal and Geographic variations of E_s

There are three geographic zones between which the temporal behaviour of E_s differs. The differences are so marked that distinct phenomena, all termed E_s , are thought to operate in the different zones. The zones are illustrated by Smith (in Smith and Matsushita, 1962, p. 4). The north and south auroral zones extend from the polar caps to between 70° and 50° geomagnetic latitude, the boundary being the 5% auroral isochasm (line of equal observed frequency of aurora). The auroral isochasms are not concentric at the geomagnetic axis and exhibit, towards the equator, excursions of about 10° geomagnetic latitude, over Canada in the Northern Hemisphere and towards Australia in the Southern Hemisphere. The equatorial zone follows the magnetic equator, defined as the line along which the magnetic dip is zero at an altitude of 100 km., extending by 10° of dip on either side of it. Thus the equatorial zone follows the excursions of the magnetic equator from the geomagnetic equator, notably an excursion of about 30° (geomagnetic latitude) towards the south over South America. The north and south temperate zones are taken as extending continuously between the north and south auroral zones, being unaffected by the intrusion of the equatorial zone. The crucial difference is that the temporal variations of E_s are chiefly diurnal in the auroral and equatorial zones, whereas they are chiefly seasonal in the temperate zones. In the auroral zones E_s is a night-time phenomenon with its diurnal maximum around local midnight and shows little seasonal variation. In the equatorial zone E_s occurs almost exclusively in the daytime, with a maximum at local noon, and again exhibits little seasonal variation. In the temperate zones there is a well defined seasonal maximum in the summer solstice and a smaller less defined maximum in the winter solstice, with minima at the equinoxes. These variations become less pronounced in the vicinity of the equatorial zone. In these zones E_s is chiefly a day-time phenomenon with a maximum around

1000 hr. Local Time, frequently a secondary maximum around 1800 hr., and a minimum around 0400 hr. The longitudinal variations of E_s within the temperate zones have already been discussed in the section "Previous Work".

The three zones are further differentiated with respect to the relationship of E_s to the sunspot cycle, the relationship of E_s to geomagnetic activity, and by the dissimilarity between the types of E_s occurring in the different zones. Although the correlation of E_s with the 11-year sunspot cycle is difficult to confirm, because of the considerable year-to-year variability in the occurrence of E_s at any one place and the relatively small number of years for which records have been kept, a tentative picture has emerged. The correlation is positive in the auroral zones, slightly negative in the temperate zones and indeterminate in the equatorial zone. In the case of magnetic activity the picture is very similar, which is to be expected as magnetic activity is positively correlated with the sunspot cycle, and again rather tentative. A relationship between E_s and sunspot activity has been predicted on the ground that the intensity of solar radiation affects the ionization of the E-region.

Eight types of E_s were standardised in 1957 from the appearance of the echo trace on ionograms and it is found that certain types are exclusive to certain zones. The auroral zones are characterised by a-type (auroral) and r-type (retardation) with s-type (slant) occurring in association with the other two. The equatorial zone displays q-type (equatorial) and associated s-type. In the temperate zones four types are found, as follows: h-type (high) which is largely confined to the lower latitudes, c-type (cusp) which is the most common and widespread, l-type (low) which occurs in morning and evening hours near the equatorial zone and around midday at higher latitudes, and f-type (flat) which occurs at night only.

The hypothesis that the zonal variation in E_s constitutes distinct phenomena is reinforced when the possible energy sources are considered. Solar corpuscular radiation is thought to cause magnetic activity and aurora and, therefore, could account for auroral-zone E_s . There is thought to be a strong connection between equatorial zone E_s and the electrojet, the assumption being that the overhead current supplies energy for the production and maintenance of ionization inhomogeneities. Theories for the formation of E_s in temperate latitudes will be considered in a later section but it can be said here that several energy sources are considered possible. These are overhead currents at E-region heights, winds and turbulence producing blobs with a different dielectric constant from the mean, and the pre-discharge field of thunderstorms. The possibility that meteor showers could alter the ionization in the ionosphere so as to produce E_s has been considered inconclusively.

1.3 The Wind-Shear and Other Theories of Temperate-Zone Sporadic-E

The normal E-region is constituted by an essentially neutral gas which is, however, weakly ionized to give electrons and various species of ion by a quasi-equilibrium process of photoionization and recombination. Sporadic-E occurs within the E-region, at temperate latitudes as thin layers of enhanced ionization density which may persist for up to several hours. The wind-shear theory states that these layers consist of ion species with suitably low recombination rates, plus electrons, which converge at certain levels under the action of forces due to the geomagnetic field and to vertical shears in horizontal winds in the neutral gas.

The theory has been evolved by several authors. Dungey (1956 and 1959) first suggested that thin, dense layers of ionization could be produced as a result of shearing motions of the neutral gas, but Whitehead (1961 and 1962) and Storey and Hersé (1963) first proposed the now accepted form of the theory, involving one species of positive ion. Axford (1963) lent support to the wind-shear mechanism and, further, suggested that E_s layers could be vertically transported by the type of atmospheric gravity wave which Hines (1960) proposed. There was an exchange between Layzer (1964, a and b) and Axford (1964) on the former's objections to certain aspects of the wind shear theory. MacLeod (1966) contributed what he described as, "a simplified equilibrium theory of sporadic-E", which is outstanding for its clarity. Whitehead (1966) extended his own theory to take account of two species of positive ion, and Axford and Cunnold (1966) discussed a mixed-ion theory which included negative ions. Layzer (1967, a) proposed a mechanism for mid-latitude E_s akin to the wind-shear theory but based on fluctuations in the neutral wind speed. Whitehead (1967) objected to this and Layzer (1967,b) replied.

Wright, Murphy and Bull (1967) described the daytime evolution of an E_s layer and its subsequent nighttime association with the wind structure. Chimonas and Axford (1968) extended the wind-shear theory to take account of effects associated with a neutral wind profile having a descending phase-velocity. The ionospheric setting in which the wind-shear mechanism operates is conceived to be as follows:

As mentioned above, the composition of the E-region is that of a slightly ionized gas with three components; heavy neutral particles, heavy positive ions and electrons. This state is maintained in quasi-equilibrium by the processes of ion and electron formation, recombination and ambipolar diffusion. Winds of neutral gas blow throughout the region which is, in addition, permeated by the geomagnetic field. Some approximate values of recombination and diffusion coefficients, and diffusion times, are given below, from Wright, Murphy & Bull (1967).

The recombination coefficient, α = $3 \times 10^{-7} \text{ cm}^3 \text{ sec.}^{-1}$ for ions of
the normal E-region; as given
by Cole and Norton.
OR = $10^{-12} \text{ cm}^3 \text{ sec.}^{-1}$ for monatomic
ions; as given by Nicolet.
OR = $3 \times 10^{-8} \text{ cm}^3 \text{ sec.}^{-1}$; as given
by MacLeod (1964), based on
simultaneous wind-shear and ion-
osonde observations.

Considering a wind-shear mechanism involving more than one species of ion, Axford and Cunnold (1966) state that "it seems reasonable to assume, at present", that one of the major ionic constituents, (possibly No^+ , as suggested by Danilov), has a recombination coefficient of the order of $3 \times 10^{-8} \text{ cm}^3 \text{ sec.}^{-1}$, while certain minor constituents, (such as the meteoric

ions Mg^+ , Fe^+ , Si^+), have recombination coefficients of the order of $10^{-12} \text{ cm}^3 \text{ sec.}^{-1}$.

The ambipolar diffusion coefficient, $D = 10^5 \text{ cm}^2 \text{ sec.}^{-1}$ at 100 km.

The electron number density, $N = 10^5 \text{ cm}^{-3}$ at an E_s peak.

Thus, the characteristic times of recombination (T_α), diffusion (T_D) and transport (T_T) are:-

$$T_\alpha = \frac{1}{2\alpha N} = 17 \text{ sec. for normal E-region ions}$$

$$= 58 \text{ days for monatomic ions}$$

$$T_D = \lambda_z^2 / 4D \text{ or } \Delta^2 / 4D, \text{ (where } \lambda_z = \text{ the vertical wavelength of a quasi-oscillatory wind profile, and } \Delta = \text{ the characteristic } E_s \text{ layer thickness of } 0.5 \text{ km.)}$$

$$= 30 \text{ days for diffusion across the interval } \frac{1}{2}\lambda_z$$

$$= 100 \text{ minutes for diffusion across the } E_s \text{ half-thickness}$$

$$T_T = \lambda_z / 2V_o, \text{ (where } V_o = \text{ the amplitude of the wind profile } = 20 \text{ m/sec.)}$$

$$= 8.3 \text{ minutes for transport of ions within the interval } \lambda_z \text{ to a level where the wind profile passes through zero.}$$

In addition, the rate of formation of electrons and ions does not vary with height (Whitehead, 1961). A fact which will later emerge as basic to the wind-shear theory is worth noting here.

The ratio, $\frac{\text{ion/neutral collision frequency}}{\text{ion gyrofrequency}} \left(\frac{\nu_i}{\omega_i} \right)$ is of the order 1 - 10 within the altitude range where the wind-shears are high (80 - 120 km.), whereas the same ratio for electrons is less than 1, in the same altitude range.

According to Whitehead (1961).

Electron collision frequency $\nu_e \approx 2 \times 10^4 \text{ sec.}^{-1}$ at 120 km. The electrons have a mean free path about $4\sqrt{2}$ times that of the ions and the electron velocity is about $\sqrt{3} \times 10^4$ times the ions velocity, therefore the collision frequency of ions ν_i is about 1/30 that of electrons, i.e. about $7 \times 10^2 \text{ sec.}^{-1}$ at 120 km. Positive ions present are principally those

of atomic oxygen with a mass about 3×10^4 that of electrons, therefore their gyrofrequency ω_i is about $3 \times 10^2 \text{ sec.}^{-1}$. Thus, as E_s usually occurs in the vicinity of 120 km., it appears that $\frac{\text{ionic collision frequency}}{\text{ionic gyrofrequency}}$ is of the order of 7/3 for E_s -layers.

The ion composition of sporadic-E layers is not known exactly but the following information is available (Whitehead, 1970). In the vicinity of 120 km. the neutral atmosphere consists mainly of

N_2 ($2.36 \times 10^{11} \text{ cm}^{-3}$), O_2 ($3.94 \times 10^{10} \text{ cm}^{-3}$), O ($1.30 \times 10^{10} \text{ cm}^{-3}$), Ag ($7.84 \times 10^8 \text{ cm}^{-3}$) and He ($2.18 \times 10^7 \text{ cm}^{-3}$),

but the ion composition is quite different. During daytime NO^+ and O_2^+ exist in almost equal amounts in the E-region, while at night NO^+ dominates, by an order of magnitude, over O_2^+ . Various species of metallic ion have been detected in the E-region, below 130 km. The total E-region content of Mg^+ , Fe^+ and Ca^+ has been estimated as $7 \times 10^9 \text{ cm}^{-2}$, 10^{10} cm^{-2} and $3 \times 10^8 \text{ cm}^{-2}$ respectively. There is a strong tendency for metallic ions, Mg^+ , Fe^+ , Ca^+ , Na^+ , and Si^+ , to form thin layers at various heights in the region 95 - 115 km. A most interesting example is of a layer approximately 1 km. thick, at 106 km., consisting chiefly of Mg^+ ions, which had an ion density (10^5 cm^{-3}) consistent with sporadic-E observed at the same time. The NO^+ ions, dominant outside this layer, had a density less than 10^2 cm^{-3} inside the layer. Other examples include a layer of Mg^+ & Fe^+ (10^4 cm^{-3}) plus Ca^+ at 104 km., Mg^+ and Na^+ ($\sim 6 \times 10^3 \text{ cm}^{-3}$) at 95 and 112 km., Mg^+ at 93 km. and Si^+ at 113 km. Little is known about neutral metallic atom densities. Neutral Na and Li have contents of $\sim 10^{10} \text{ cm}^{-2}$ and $10^6 - 10^7 \text{ cm}^{-2}$, respectively.

The origin of these metallic ions is thought either to be meteoric, whereupon they are carried down to 120 km. by diffusion and turbulence, or to result from charge transfer between N_2^+ , O_2^+ , N^+ and O^+

and metallic atoms liberated from dust by collisions with excited atomic and molecular species.

The problem of a multiple-ion mechanism is more complicated but, according to Axford and Cunnold (1966), can be subjected to the same assumptions as the single-ion theory provided that,

- (a) diffusion is neglected,
- (b) the wind is assumed to be east-west,
- (c) the vertical electric polarization field is assumed to be small.

Whitehead (1966) specifies some assumptions relating the two positive ion species which he considers, namely,

(a) both have identical vertical motions: he points out that, as vertical motion depends on $\frac{\text{collision frequency}}{\text{gyrofrequency}}$ for each ion, this will not in general be the case but that, as one species tends to predominate at the electron density maximum while the other species tends to predominate at the electron density minimum, the inequality of the vertical motions is unlikely to have a marked effect on the formation of E_s ;

(b) both have rates of ionization which do not vary with height, and the ambient electron density is independent of height.

The nomenclature used throughout is as follows:

a right-handed set of Cartesian coordinates with Z-axis vertically upwards and X-axis in the direction of magnetic north (Y-axis is directed towards west)

velocity of the neutral gas $\bar{U} = (u_x, u_y, u_z)$

(i.e. the neutral wind velocity)

velocity of ionization $\bar{V} = (V_x, V_y, V_z)$

polarization electric field $\vec{E} = (E_x, E_y, E_z)$
 geomagnetic field $\vec{B} = B_0 (X, Y, Z)$

Mathematical expressions and terms which follow have been converted, where necessary, to this nomenclature and are in M.K.S. units.

The equations of motion for singly charged ions and electrons are, respectively

$$\begin{aligned} n_i m_i \left\{ \frac{\partial}{\partial t} + \vec{V}_i \cdot \nabla \right\} \vec{V}_i &= n_i e (\vec{E} + \vec{V}_i \times \vec{B}) \\ &+ \frac{1}{2} n_i m_i \nu_{in} (\vec{U} - \vec{V}_i) \\ &- \nabla p_i + n_i m_i \vec{g} \end{aligned} \quad \dots (1)$$

and

$$\begin{aligned} n_e m_e \left\{ \frac{\partial}{\partial t} + \vec{V}_e \cdot \nabla \right\} \vec{V}_e &= -n_e e (\vec{E} + \vec{V}_e \times \vec{B}) \\ &+ n_e m_e \nu_{en} (\vec{U} - \vec{V}_e) \\ &- \nabla p_e + n_e m_e \vec{g} \end{aligned} \quad \dots (2)$$

where n_r is the number density, of particles of the r-species, m_r is the particle mass, $\vec{V}_r$ is the velocity of charged particles, e is the magnitude of the electronic charge, $\vec{E}$ is the electric field intensity, $\vec{B}$ is the magnetic induction, ν_{rn} is the collision frequency between the charged particles and the neutral particles, $\vec{U}$ is the neutral wind velocity, P_r is the particle pressure and $\vec{g}$ is the acceleration due to gravity.

The continuity equations for ions and electrons are, respectively

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \bar{V}_i) = q_i - \alpha_i n_i n_e \quad \dots (3)$$

and

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \bar{V}_e) = \sum_i q_i - (\sum_i \alpha_i n_i) n_e \quad \dots (4)$$

where q_i is the ion production rate and α_i the ion-electron recombination coefficient. Adopting a Cartesian coordinate system (X, Y, Z), since the ionosphere can be taken as plane because the horizontal dimensions of sporadic-E layers are small compared with the radius of the earth. With Z vertically upward, X directed magnetically northward and Y westward, the components of vector quantities are taken as follows:

$$\bar{U} = (U_x, U_y, 0)$$

$$\bar{V} = (V_x, V_y, V_z)$$

$$\bar{E} = (E_x, E_y, E_z)$$

$$\bar{B} = B_0 (X, Y, Z), \text{ with } X^2 + Y^2 + Z^2 = 1$$

The following assumptions and simplifications are usually made in the single ion wind-shear theory. The list is compiled from Axford and Cunnold (1966), Axford (1963) and Whitehead (1961), between whom there are no fundamental points of disagreement.

(1) The neutral wind is taken to be non-divergent ($\text{div } \bar{U} = 0$), and the vertical component is considered irrelevant to E_s formation ($U_z = 0$).

(2) The undisturbed geomagnetic field is taken as uniform throughout the sporadic-E region and changes in magnetic

field due to ionospheric currents are small and can be neglected. It is also assumed that there is no vertical current flow and that the net horizontal current flow is zero (i.e. although currents may be flowing in different horizontal directions at different heights). Thus to a first approx. $Y = 0$ and $X^2 + Z^2 = 1$.

(3) Sporadic-E layers can be taken as quasi-one-dimensional (i.e. $\partial/\partial x = \partial/\partial y = 0$, $\partial/\partial z = \frac{d}{dz}$) since their characteristic horizontal dimensions greatly exceed their vertical dimension.

(4) The E_s layers are sufficiently long-lasting to be treated as steady-state equilibrium layers (i.e. $\partial/\partial t = 0$).

(5) Inertial effects on the charged particles can be neglected because the time scales involved in the wind-shear mechanism are much greater than the gyroperiods and mean collision intervals of the particles. For example, as given above,

$$T_T \approx 8.3 \text{ minutes}$$

$$v_e \approx 2 \times 10^4 \text{ sec.}^{-1} \text{ (collision interval } \approx 10^{-5} \text{ sec.)}$$

$$v_i \approx 7 \times 10^2 \text{ sec.}^{-1} \text{ (collision interval } \approx 10^{-3} \text{ sec.)}$$

$$\omega_i \approx 3 \times 10^2 \text{ sec.}^{-1} \text{ (gyroperiod } \approx 10^{-3} \text{ sec.)}$$

(6) Charge equality is assumed throughout the E_s region, so that, considering only one species of positive ion,

$$n_i = n_e = n$$

$$\sum_r n_r V_{zr} = 0$$

$$V_{zi} \approx V_{ze} = V_z$$

(7) The motion of the neutral gas is unaffected by the presence of the charged particles. This is a reasonable assumption since the neutral-ion collision interval in the E-region is comparatively long (≈ 3 hours).

(8) The ionospheric 'background' is uniform, so that anomalous concentrations of ionization are due entirely to non-uniformities in the neutral wind. Although this is not a realistic assumption it must be tolerated in order to elucidate the wind-shear mechanism.

Maxwell's equations

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t}$$

and

$$\nabla \cdot \bar{B} = 0,$$

under assumptions (2), (3) and (4) give

$$E_x = E_y = \text{constant}$$

and

$$B_z = B_0 Z = \text{constant}$$

Similarly, Maxwell's equation

$$\nabla \times \bar{H} = \bar{j} + \frac{\partial}{\partial t} (\epsilon_0 \bar{E}),$$

where $\bar{H}$ is the magnetic field intensity, $\bar{j}$ the current density and ϵ_0 the permittivity of free space, can be written as

$$-\frac{dH_y}{dz} = j_x = e \left\{ \sum_i n_i V_{xi} - n_e V_{xe} \right\} \quad \dots (5)$$

$$\frac{dH_x}{dz} = j_y = e \left\{ \sum_i n_i V_{yi} - n_e V_{ye} \right\} \quad \dots (6)$$

$$0 = j_z = e \left\{ \sum_i n_i V_{zi} - n_e V_{ze} \right\} \quad \dots (7)$$

And from Maxwell's equation

$$\nabla \cdot (\xi_0 \bar{E}) = \rho = (\sum_i n_i - n_e) e ,$$

$$\frac{dE}{dz} = \frac{e}{\xi_0} (\sum_i n_i - n_e) \quad \dots (8)$$

By adopting assumption (5), the inertial terms on the left hand side of the equations of motion (1,2) can be set equal to zero, such that

$$\begin{aligned} \frac{\bar{E}}{B_0} + \frac{\bar{V}_i \times \bar{B}}{B_0} + R_i (\bar{U} - \bar{V}_i) - \frac{k}{eB_0 n_i} \frac{d(n_i T_i)}{dz} \bar{K} \\ + \frac{m_i}{eB_0} \bar{g} = 0 \end{aligned} \quad \dots (9)$$

and

$$\begin{aligned} -\frac{\bar{E}}{B_0} - \frac{\bar{V}_e \times \bar{B}}{B_0} + R_e (\bar{U} - \bar{V}_e) - \frac{k}{eB_0 n_e} \frac{d(n_e T_e)}{dz} \bar{K} \\ - \frac{m_e}{eB_0} \bar{g} = 0 \end{aligned} \quad \dots (10)$$

where $\bar{K}$ is a unit vector parallel to the Z-axis and

$$R_i = \frac{m_i v_{in}}{2eB_0} , \quad R_e = \frac{m_e v_{en}}{eB_0}$$

The six component equations of (9) and (10) are linear in

$$V_{xr}, V_{yr}, V_{zr} \text{ and } E_z$$

which can be solved for V_{xr} , V_{yr} and E_z in terms of V_{zr} . In particular

$$\begin{aligned} \frac{E_z}{B_0} = \frac{-\Delta_i}{R_i^2 + Z^2} V_{zi} + \frac{k}{n_i B_0 e} \frac{d(n_i T_i)}{dz} - \frac{XZ}{R_i^2 + Z^2} \frac{E_x}{B_0} \\ + \frac{XR_i}{R_i^2 + Z^2} \frac{E_y}{B_0} + \frac{R_i \Gamma_i}{R_i^2 + Z^2} \dots (11) \end{aligned}$$

where

$$\Delta_i = -R_i(R_i^2 + 1) \text{ and } \Gamma_i = -ZXU_x + R_i XU_y - (R_i^2 + Z^2)U_z$$

and

$$\begin{aligned} \frac{E_z}{B_0} = \frac{-\Delta_e}{R_e^2 + Z^2} V_{ze} - \frac{k}{n_e B_0 e} \frac{d(n_e T_e)}{dz} - \frac{m_e g}{eB_0} \\ - \frac{XZ}{R_e^2 + Z^2} \frac{E_x}{B_0} - \frac{XR_e}{R_e^2 + Z^2} \frac{E_y}{B_0} - \frac{R_e \Gamma_e}{R_e^2 + Z^2} \dots (12) \end{aligned}$$

where

$$\Delta_e = R_e(R_e^2 + 1) \text{ and } \Gamma_e = -ZXU_x - (R_e^2 + Z^2)U_z - (R_e XU_y)$$

By eliminating E_z between equations (11) and (12) we obtain for $i = 1 \dots N$

$$\begin{aligned} \frac{\Delta_i}{R_i^2 + Z^2} V_{zi} - \frac{\Delta_e}{R_e^2 + Z^2} V_{ze} = \\ - \left(\frac{R_i XZ}{R_i^2 + Z^2} - \frac{R_e XZ}{R_e^2 + Z^2} \right) U_x + \left(\frac{R_i^2 X}{R_i^2 + Z^2} - \frac{R_e^2 X}{R_e^2 + Z^2} \right) U_y \\ - (R_e + R_i) U_z - \left(\frac{XZ}{R_i^2 + Z^2} - \frac{XZ}{R_e^2 + Z^2} \right) \frac{E_x}{B_0} \\ + \left(\frac{XR_i}{R_i^2 + Z^2} - \frac{XR_e}{R_e^2 + Z^2} \right) \frac{E_y}{B_0} - \frac{k}{B_0 e} \left(\frac{1}{n_i} \frac{d(n_i T_i)}{dz} + \frac{1}{n_e} \frac{d(n_e T_e)}{dz} \right) \\ - \frac{g}{eB_0} (m_i - m_e) \dots (13) \end{aligned}$$

The N continuity equations

$$\frac{d(n_i V_{zi})}{dz} = q_i - \alpha_i n_i n_e$$

together with equations (13), (7), (8) and either (11) or (12) form a set of $(2N + 3)$ equations which determine the $(2N + 3)$ unknowns V_{zi} , V_{ze} , n_e and E_z , provided $\bar{U}$, E_x , E_y , α_i , q_i , T_i , T_e and $\bar{B}$ are given. In this form the equations are difficult to handle, but by assuming charge equality, assumption (6) and neglecting the second term on the left hand side of equation (13) on the grounds that $R_e \ll R_i$ in the sporadic-E region and $V_{zi} = V_{ze}$, we simplify the mathematics to the following set of $(2N + 1)$ equations for n_i , V_{zi} and n_e

$$\frac{d(n_i V_{zi})}{dz} = q_i - \alpha_i n_i n_e \quad \dots (14)$$

$$V_{zi} = \phi_i - \frac{(R_i^2 + Z^2)}{R_i(R_i^2 + 1)} \cdot \frac{k}{B_0 e} \left\{ \frac{1}{n_i} \frac{d(n_i T_i)}{dz} + \frac{1}{n_e} \frac{d(n_e T_e)}{dz} \right\} \quad \dots (15)$$

$$n_e = \sum_i n_i \quad \dots (16)$$

where

$$\phi_i = \frac{R_i^2 + Z^2}{\Delta_i} \left\{ - \left(\frac{R_i X Z}{R_i^2 + Z^2} + \frac{R_e X Z}{R_e^2 + Z^2} \right) U_x + \left(\frac{R_i^2 X}{R_i^2 + Z^2} - \frac{R_e^2 X}{R_i^2 + Z^2} \right) U_y - (R_e + R_i) U_z \right\}$$

$$\left\{ - \left(\frac{XZ}{R_i^2 + Z^2} - \frac{XZ}{R_e^2 + Z^2} \right) \frac{E_x}{B_0} + \left(\frac{XR_i}{R_i^2 + Z^2} + \frac{XR_e}{R_e^2 + Z^2} \right) \frac{E_y}{B_0} \right\}$$

In particular, when only one species of ion is present $n_e = n_i = n$ and, by assuming T_i and T_e to be constant, n satisfies the equation

$$D \frac{d^2 n}{dz^2} + \frac{d}{dz} \{ n \phi(z) \} = \alpha n^2 - q \quad \dots (17)$$

where D is the ambipolar diffusion coefficient, α the recombination coefficient and $q = \alpha n_0^2$ the photoionization rate, $\phi(z)$ is given by

$$\phi(z) = A + Bu_x + Cu_y \quad \dots (18)$$

where A is constant involving E_x , E_y and U_z . Under the approximation that $R_i \gg R_e$ which applies to the lower ionosphere. (In the region 80 - 120 km. altitude $R_i \approx 10$ and $R_e \approx 0.003$).

$$B \approx + XZ/R_i^2 \text{ and } C \approx XR_i$$

If diffusion is neglected the equation becomes

$$\frac{d}{dz} \{ n \phi(z) \} = \alpha (n^2 - n_0^2) \quad \dots (19)$$

which must, in general be solved by numerical methods. However, the extreme of n can be found without solving the differential equation by putting $dn/dz = 0$. Thus

$$N_{\max} = \frac{1}{2} \left[\frac{d\phi/dz}{dn_0} + \left\{ \left(\frac{d\phi/dz}{dn_0} \right)^2 + 4 \right\}^{\frac{1}{2}} \right] \approx n$$

where $\eta = \frac{|d\phi/dz|}{dn_0}$ and $N = n/n_0$

the derivative being evaluated at the point of maximum density. A similar expression holds at points of minimum density, except that $N_{\min} \approx 1/\eta$. The parameter η represents the ratio of the rate of accumulation of ionization by vertical transport to the rate of loss due to recombination. Because equation (19) is not simple, singularities can occur in the higher derivatives of n . For example n need not have a maximum at a zero of $\phi(z)$ unless $\phi''(z)$ also vanishes at this point. Further, where the maximum does coincide with $\phi(z) = 0$, then $\frac{d^2n}{dz^2}$ becomes infinite and the density profile has a cusp. In this case the effects of diffusion cannot be neglected since $D \frac{d^2n}{dz^2}$ does not tend to zero with D at the point of maximum density.

From equation (18) it can be seen that since $|B/C| \ll 1$ the east-west component of the neutral wind (U_y) predominates in the wind-shear mechanism within the E-region. The north-south wind component becomes important in the F-region, where $1 \gg R_i \gg R_e$ ($R_i \approx 1$ at about 120 km). It is apparent from equation (18) that shears ($\frac{d}{dz} U_y$) in the east-west wind component, combined with the north-south horizontal component of the geomagnetic field (because C depends on X) provide the driving force for the accumulation of E_s layers in temperate latitudes. The physical picture is one of positive ions in the E-region moving vertically in the presence of vertical induced electric fields which result from the east-west wind component and the north-south geomagnetic component. The ions are free to move vertically because $R_i \gg 1$, but electrons are largely constrained to move along the geomagnetic field lines since $R_e \ll 1$. Provided the geomagnetic field is oblique, as in temperate latitudes, the electrons are able to move vertically following the ions, to form a sporadic-E layer with charge neutrality. However, near the dip equator this becomes

difficult, and instead a vertical polarization electric field builds up, tending to cancel the effects of the induced field.

The physical picture of sporadic-E formation can be better understood by examining the simplified equations set up by MacLeod (1966). Assuming an equilibrium in motion to be attained under the influences of collision and geomagnetic forces only, thereby neglecting forces due to ion pressure gradients, plasma polarization, etc., the equation of motion (1) can be written as

$$\frac{d\bar{V}_i}{dt} = \frac{v_{in}}{2} (\bar{U} - \bar{V}_i) + \frac{e}{m_i} (\bar{V}_i \times \bar{B})$$

And hence if the accelerations are small

$$\rho_i (\bar{U} - \bar{V}_i) + v_i \bar{V}_i \times \bar{F} = 0 \quad \dots (20)$$

where

$$\bar{B} = B_0 \bar{F}, (\bar{F} \cdot \bar{F} = 1)$$

and

$$\rho_i = \frac{m_i v_{in}}{e B_0} = 2 R_i$$

If equilibrium is to be maintained under the action of the collision and geomagnetic forces, then $\bar{V}_i$ must satisfy equation (20), which can be solved to give

$$\bar{V}_i = \frac{1}{1 + \rho_i^2} \{ \rho_i^2 \bar{U} + \rho_i \bar{U} \times \bar{F} + (\bar{U} \cdot \bar{F}) \bar{F} \} \quad \dots (21)$$

From this equation it can be seen that, in general, the ion velocity has components parallel to the neutral wind, perpendicular to both the neutral wind and the geomagnetic field and parallel to the geomagnetic field.

The component of ion velocity given by

$$\frac{\rho_i^2}{1 + \rho_i^2} \bar{U} = \bar{V}_{ic}$$

predominates low in the E-region, where $\rho_i \gg 1$, such that the ions are carried along with the neutral particles. $\bar{V}_{ic}$ thus represents primarily the effect of the collision force on the ion motion. The component

$$\frac{1}{1 + \rho_i^2} (\bar{U} \cdot \bar{r}) \bar{r} = \bar{V}_{ig}$$

predominates high in the E-region where $\rho_i \ll 1$, that is the geomagnetic force predominates over the collision force and the ions are driven along the geomagnetic field lines by the neutral wind. At intermediate altitudes ρ_i is of order unity hence all three components contribute to the ion velocity. The component

$$\frac{\rho_i}{1 + \rho_i^2} \bar{U} \times \bar{r} = \bar{V}_{im}$$

contributes appreciably in the altitude region 100 - 140 km., where temperate latitude sporadic-E forms, and depends upon a balance between the collision and geomagnetic forces. (It vanishes where either of these forces predominates over the other). The magnitude of the 'mixed' component is

$$V_{im} = \frac{\rho_i}{1 + \rho_i^2} \{u^2 - (\bar{U} \cdot \bar{r})^2\}^{\frac{1}{2}} = \frac{\rho_i}{1 + \rho_i^2} u |\sin k|$$

where k is the angle between the neutral wind and the geomagnetic field. Because ρ_i and $\bar{U}$ vary with altitude, although $\bar{r}$ can be taken as constant in

direction, $\bar{V}_i$ varies in magnitude and direction with altitude. If this variation is such that there is a net flow into some altitude region, then a sporadic-E layer can form. This net flow is measured by the convergence (or negative divergence) of the equilibrium ion drift velocity. The divergence is given by

$$\begin{aligned} \nabla \cdot \bar{V}_i = & \frac{1}{1 + \rho_i^2} \{ \rho_i^2 \nabla \cdot \bar{U} + \rho_i \bar{F} \cdot \nabla \times \bar{U} + \bar{F} \cdot [(\bar{F} \cdot \nabla) \bar{U}] \} \\ & + \frac{1}{(1 + \rho_i^2)} \{ 2\rho_i [\bar{U} - (\bar{U} \cdot \bar{F}) \bar{F}] \\ & + (1 - \rho_i^2) \bar{U} \times \bar{F} \} \cdot \nabla \rho_i \quad \dots (22) \end{aligned}$$

and is negative if one or more of the following conditions dominates the transport process:

- (1) the neutral wind divergence is negative;
- (2) the neutral wind vorticity has a substantial component antiparallel to the geomagnetic field;
- (3) the projection on the geomagnetic field of the derivative of neutral wind vector along the geomagnetic field is negative;
- (4) the projection of the neutral wind component perpendicular to the geomagnetic field on the gradient of ρ_i is negative;
- (5) the projection of $\bar{V}_{im}$ on the gradient of ρ_i is positive (negative) when $\rho_i > 1$ ($\rho_i < 1$)

The first three terms may be called the wind-shear terms. The last two may be called the wind terms. The second and third terms as discussed in a

different form by Whitehead (1961), Axford (1963) etc., represent the contributions generally associated with the wind-shear theory.

Generally speaking, the drift velocity divergence is affected by (a) the altitude variation of the coefficients and (b) the geometry of the neutral wind field. The effect of (a) is that the three wind-shear terms are weighted with altitude. Low in the E-region the collision convergence mechanism (1) is weighted most strongly, while high in the E-region the geomagnetic convergence mechanism (3) is weighted most strongly. The combined collision-geomagnetic convergence mechanism (2) is weighted most strongly in the lower middle E-region, where sporadic-E is observed most frequently. The altitude weighting factors applicable to the two wind terms are such that the combined collision-geomagnetic convergence mechanism dominates in the lower middle E-region ($\rho_i < 1$) and upper middle E-region ($\rho_i > 1$). In the lower middle E-region the projection of $\bar{V}_{im}$ on $\nabla\rho_i$ must be positive to give convergence, while in the upper middle E region it must be negative to give convergence. The contribution of the other, perpendicular wind term is weighted most strongly in the central middle E-region ($\rho_i = 0(1)$) where its projection on $\nabla\rho_i$ must be negative to give convergence.

The effect of the geometry of the neutral wind field on divergence is complex. For example, it can happen that the $\bar{V}_{im}$ flow is divergent while the $\bar{V}_{ig}$ flow is convergent, and vice versa., in which case the $\bar{V}_{im}$ flow will generally dominate when $\rho_i > 1$ and the $\bar{V}_{ig}$ flow will dominate when $\rho_i < 1$. Also, the neutral vorticity could be perpendicular to the geomagnetic field but a lesser convergent flow could still be established in the lower E-region by the geomagnetic term.

The comparative effectiveness of the several convergence mechanisms can be clarified by adopting the assumptions, that the vertical wind component can be neglected, that $\frac{d\bar{U}}{dx}$, $\frac{d\bar{U}}{dy}$ can be neglected, and that

the east-west component of the geomagnetic field can be neglected, which were introduced previously. Then

$$\bar{U} = U_x \bar{i} + U_y \bar{j}$$

$$\nabla \approx \bar{K} \frac{\partial}{\partial z}$$

$$\bar{r} = r_x \bar{i} + r_z \bar{k}$$

where r_x is positive and r_z is negative (positive) in the northern (southern) geomagnetic hemisphere. Equation (21) can be written

$$\begin{aligned} \bar{V}_i = & \frac{1}{1 + \rho_i^2} \{ (\rho_i^2 u_x + \rho_i u_y r_z + u_x r_x^2) \bar{i} \\ & + (\rho_i^2 u_y - \rho_i u_x r_z) \bar{j} \\ & + (u_x r_x r_z - \rho_i u_y r_x) \bar{k} \} \end{aligned}$$

and its divergence, equation (22), becomes

$$\begin{aligned} \nabla \cdot \bar{V}_i = & \frac{r_x}{1 + \rho^2} \left\{ -\rho_i \frac{\partial u_y}{\partial z} + r_z \frac{\partial u_x}{\partial z} \right. \\ & \left. + \frac{1}{1 + \rho_i} \frac{d\rho_i}{dz} \left[-2\rho_i r_z u_x - (1 - \rho^2) u_y \right] \right\} \approx \frac{\partial v_{iz}}{\partial z} \\ & \dots (23) \end{aligned}$$

FOOTNOTE MacLeod's right-handed coordinate system, with Z vertical and Y north, has been translated to the present system, with X north and Y west.

The first two terms of expression (23) are identical with the corrected expressions of Whitehead (1962) (see Hines, 1964) and consistent with that of Axford (1963). Convergence obtains when $\frac{\partial v_{iz}}{\partial z}$ is negative, i.e. if v_{iz} goes through zero at some altitude and the ions above that level are moving downward while the ions below are moving upward. Equation (23) demonstrates that convergence may be obtained in four ways: (1) if the first term dominates and the geomagnetic east to west shear is positive (the westward wind increases with altitude); (2) if the second term dominates and the geomagnetic south to north shear is positive (negative) {the northward wind increases (decreases) with altitude} in the northern (southern) geomagnetic hemisphere; (3) if the third term dominates and a northward (southward) wind is found in the northern (southern) hemisphere; or (4) if the fourth term dominates and a westward (eastward) wind is found for $\rho_i^2 > 1$ ($\rho_i^2 < 1$). The first, third and fourth terms tend to contribute strongly in the middle E-region, while the second term dominates at higher altitudes. Further, MacLeod has shown that the maximum electron density of sporadic-E layers produced by his collision-geomagnetic equilibrium mechanism occurs within a region of high convergence close to a zero of the vertical ionization drift velocity profile.

Multiple ion theories

Layzer (1964) pointed out that, while observed peak electron densities were several times the background, the minimum densities, in contradiction to the single-ion-wind-shear theory, were not noticeably less than the background. To overcome this objection, theories dealing with mixtures of ions having different recombination coefficients have been developed. According to Axford and Cunnold (1966) the ratio η , which determines the ratio $(n/n_0)_{\max}$, is typically observed to lie in the range 1 - 10, while observed E-region wind-shears are of the order of 0.1 sec.^{-1}

giving $|d\phi/dz| \approx 0.01$ in the relation

$$\eta = \frac{|d\phi/dz|}{\alpha u_0}$$

Taking $u_0 = 10^5 \text{ cm}^{-3}$ gives an effective recombination coefficient in the range $10^{-7} > \alpha > 10^{-8}$. MacLeod (1966), from simultaneous wind-shear and ionosonde observations, has estimated $\alpha \approx 3 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$. Although laboratory determinations of α for NO^+ and O_2^+ are an order of magnitude greater than this, they are in effect only an estimate of the upper limiting value. Values of α determined for the E-region during eclipses seem to be at least $10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ but, as Axford and Cunnold (1966) point out, this could be accounted for by assigning a sufficiently large recombination coefficient to only one of the ion species present. Axford and Cunnold conclude it reasonable to assume that one major ionic constituent (possibly NO^+) has a recombination coefficient as small as $3 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$ and that minor constituents (such as the meteoric ions Mg^+ , Fe^+ and Si^+) have recombination coefficients as small as $10^{-12} \text{ cm}^3 \text{ sec}^{-1}$. They treat the multiple-ion problem under the assumptions that (a) diffusion is neglected, (b) the wind is east-west and (c) the vertical electric polarization field is small. For the case in which there are r types of positive ion present it is possible to determine the values of N_{max} and N_{min} by putting $\frac{dn}{dz} = 0$ in equation (19), and assuming that the wind profile is symmetrical. Thus at the maximum

$$\sum_{i=1}^r N_i / (N - \eta_i) = N \quad \dots (24)$$

where N_{i0} is the density of type i ions which would exist if the wind was absent, and $\eta_i = X |d\bar{V}/dz| / \alpha_i N_{i0} R_i$. The $(r+1)$ roots of equation (24) are such that one root is negative, $(r-1)$ roots lie in the intervals (η_1, η_2) , $(\eta_2, \eta_3) \dots$ etc. where $\eta_1 < \eta_2 < \dots < \eta_r$, and one root exceeds η_r . It can

be shown that this last root is the relevant one for $N_{\max}$ and hence the maximum electron density attained is determined by the smallest recombination coefficient among the ions present. Axford and Cunnold also emphasize that meteoric ions, because of their very small recombination coefficients, and because they are easily concentrated into layers by only small wind-shears, must play an important role in the production of sporadic-E.

There is some evidence for the existence of negative ions in the ionosphere (Bowen et al., 1964). Axford and Cunnold consider three possible cases: (a) no electrons present so that the negative and positive ion densities are equal ($n_+ = n_-$), (b) an abundance of electrons ($n_+ \gg n_-$) and (c) comparable numbers of negative ions and electrons. In case (a) the formal analysis is the same as for a single positive ion plus electrons, except that R_+ and R_- both exceed unity in the E-region and hence the north-south component of the neutral wind is more significant than the east-west component, as would be found in the F-region with a single positive ion present. In case (b), if there are enough electrons present, the vertical electric field remains of $O(R_e)$, as in the case with no negative ions. It is interesting that at points where the positive ion motion diverges and

$$dn/dz = 0 = dn_+/dz,$$

$$N\eta = 1 - \epsilon N^2/(1+\epsilon)$$

where $N = n_+/n_0$ and $\epsilon = n_e/n_-$ so that, provided wind shears are small ($\eta \ll 1$), a layer of enhanced ion density can form in the position of positive ion divergence. However the effect of ion-ion recombination is to reduce this tendency if the recombination coefficient is sufficiently large. In case (c) the effect, although not fully examined by Axford and Cunnold, seems to be that layers of enhanced ionization density can be produced simultaneously at both the convergent and divergent positions for

positive ions.

Vertical Transport of Ionization

So far the wind profile has been considered as invariant with time. Observations of neutral winds, however, suggest that the profile of horizontal velocities descends with time (Rosenberg and Justus, 1966; Wright et al., 1967). This can be accounted for by the theory of internal atmospheric gravity waves (Hines, 1960) which predicts that the phase velocity of the waves is directed downwards when the group velocity is upwards. Axford (1961, 1963, 1967) has shown how layers of long-lived ions (sporadic-E layers) can be transported downwards with the descending wind profile by means of the "corkscrew" effect. His theory has been further developed by Chimonas and Axford (1968) to explain the occurrence of low-altitude (85 - 95 km.) sporadic-E layers in regions of ion-divergence, in contradiction to the wind-shear theory. Chimonas and Axford take the east-west component of the neutral wind to be a function of altitude and time ($U_y(z,t)$) which is sinusoidal on a vertical scale normalized to the local scale height. The observation of neutral winds (Rosenberg and Justus, 1966) suggests that vertical wavelengths are of the order of 2 - 4 scale heights and that the profile of $U_y(z,t)$ descends with a phase velocity of about 1 wavelength per 12 hours. Thus Chimonas and Axford assume

$$U_y(z,t) = A \sin \frac{2\pi}{\lambda} (z - U_{yp} t) + B$$

where $-U_{yp}$ is the phase velocity of the profile and A and B are constants. In addition the Z-component of velocity for ions, under the usual assumptions and simplifications, can be written as

$$V_z(z,t) = -XU_y(z,t) R_i(z)/(1 + R_i^2(z))$$

where X is the northward component of magnetic field. The variations in

v_{in} due to temperature variations in the ionosphere are probably much less than those due to the neutral density variations, so that $R_i(z)$ can be taken as

$$R_i(z) = e^{-z/h}$$

where h is the scale height, and the origin of the vertical scale is chosen so that $R_i(0) = 1$. Thus in terms of the non-dimensional variables

$$z' = z/h, \quad t' = U_{yp} t/h$$

the ion velocity equation can be written

$$\frac{dz'}{dt'} = \frac{-X e^{-z'}}{1 + e^{2z'}} \{p \sin 2\pi\mu (z' - t') + Q\}$$

Here $1/\mu$, the wavelength in scale height units, is in the range 2 - 4 and P , the ratio of the maximum of the sinusoidal component of the neutral wind to the phase velocity of the profile, is typically 50 - 200 in the lower E-region. From this equation, Chimonas and Axford have calculated numerically the trajectories of representative points of ionization, equally spaced at $t' = 0$ over a height range of two wavelengths, for particular values of X , P , Q and μ . These computations illustrate the following physical picture.

At medium altitudes (95 - 120 km), where $R_i/(1 + R_i^2)$ is of order unity, ionization is effectively trapped in layers at levels on the wind profile where the vertical velocity of the ionization just equals the downward phase velocity of the wind profile. These layers descend at about the phase velocity over tens of km., giving rise to sequential sporadic-E. However, at higher altitudes, where $R_i^2 \ll 1$, an east-west wind is not very effective in moving the ionization vertically, and the

ionization descends slowly with the passage of several waves in the velocity profile, until it reaches the level where $R_1/(1 + R_1^2)$ becomes of order unity. Again, at altitudes below 95 km. dynamic equilibrium is not maintained in that the layers are not able to follow the motion of the wind profile, because $R_1/(1 + R_1^2)$ is small and decreases exponentially with decreasing altitude. This leads to an accumulation of these meteoric ions in the vicinity of 90 km., as successive traps in the wind profile become ineffective and dump their layers of ionization. The subsequent motion of dumped layers falls into three cases:

- (1) if $Q = 0$, the layers continue to descend in a series of oscillations of diminishing amplitude, with an overall rate of descent much less than the phase velocity of the wind profile;
- (2) in the trivial case of $P = 0$ and $XQ > 0$ the layers would descend continuously with time, so that if $P \neq 0$ and $XQ > 0$ the layers can be expected to descend in an oscillatory fashion but slightly faster than for $Q = 0$;
- (3) if $XQ < 0$ the uniform component of the neutral wind tends to force the layer upward and the overall movement is a descent only if $|P| > |Q|$, such that the layers descend initially but eventually oscillate with constant amplitude about a particular level determined by the ratio $|P/Q|$.

In cases (1) and (2) successively formed layers remain separate, although closely spaced, provided the effects of turbulence, diffusion and changes in the wind structure can be ignored. In case (3) successive layers merge as they reach the equilibrium altitude range. The

wind-shear theory in which the wind profile is stationary predicts that equilibrium layers should form in regions of ionization convergence and in the vicinity of points where $U_y(z) = 0$. When the wind profile is not stationary, equilibrium layers occur in convergent regions only at altitudes greater than about 95 km. Further, such layers will be positioned so that $V_z \approx U_y p$, which does not necessarily coincide with points where $U_y(z) = 0$. Below about 95 km. where the layers are not trapped in the wind profile, they are equally likely to be in regions of positive or negative wind shear; i.e. inconsistent in terms of the wind-shear theory. Above about 120 km. the simple, stationary form of the wind-shear theory can give misleading results if there is an appreciable north-south component of the neutral wind. Diffusion, so far neglected, does not affect the motion of layers of finite thickness, (provided the layer is not too close to a node of the wind profile) although it does tend to broaden the layers.

Axford, Cunnold and Gleeson (1966) have calculated the magnetic field variations within a sporadic-E layer and, in addition, have shown that, according to the wind-shear theory, the maximum of electron density within a sporadic-E layer should coincide with a minimum of the magnetic field intensity, provided $d^2 U_y / dz^2$ is effectively zero. On the basis of the wind-shear theory, as it has been set out here, but assuming several species of positive ion to be present, that diffusion can be neglected and that X and Y are constant to a first approximation, Axford et al., (1966) derive the expression

$$\frac{dH_x}{dz} = en_e \{ U_y + E_x / ZB_0 \} + O(1/R_1) ,$$

with diffusion neglected, and a similar expression for dH_y/dz . They then compute profiles of H_x and H_y for three calculated electron density profiles (two for single species of positive ion with different values of ion production rate and ion-electron recombination coefficient, and a third for

a mixture of the two ion species) under the following conditions:

$E_x = E_y = 0$, $X = 0.45$, $Z = -0.9$, $B_0 = 0.6$ G, $R_1 = R_2 = 10$, $R_e \approx 0.003$,
and $\bar{U} = \{0, U_{y0} \sin(2\pi Z/\lambda), 0\}$ with $\lambda = 6$ km. and $U_{y0} = 100$ m/s. Note
that $(U_y + E_x/ZB_0)$ is taken to be sinusoidal with no constant part. In
the most realistic case of a mixture of ions the magnetic profile shows
that the variation of B_x is of the order of 2.5γ and that of B_y is 0.28γ
which, because these variations are small compared with $B_0 (\approx 0.5$ G),
justifies the assumption of constant X and Y . The variation of the total
field is given by

$$\frac{dH}{dz} = \frac{H_x}{H} \frac{dH_x}{dz} + \frac{H_y}{H} \frac{dH_y}{dz}$$

By assuming the horizontal magnetic field is meridional ($H_y = 0$),

$$\frac{dH}{dz} \approx X \frac{dH_x}{dz}$$

Thus

$$\frac{dH}{dz} \approx en_e X (U_y + E_x/ZB_0)$$

and hence H is stationary at the height $Z = \xi$ where $U_y(\xi) + E_x/ZB_0 = 0$

At these stationary points,

$$\frac{d^2H}{dz^2} = en_e X \frac{dU_y}{dz}$$

so that maxima and minima of H occur where $(U_y(\xi) + E_x/ZB_0) = 0$ and the
east-to-west wind shear is respectively negative or positive.

The correlation of these magnetic maxima and minima with
the electron density profile can be worked out as follows. The expression
for ϕ_i in equation (15) can be simplified to

$$\phi_i = U_z - \frac{X}{R_i} (U_y + \frac{E_x}{ZB_0})$$

by neglecting terms of $O(R_e)$ and $O(1/R_i^2)$. Then, if U_z is neglected,

$$\frac{dH}{dz} = en_e R_i \phi_i$$

so that the functions ϕ_i are all zero at points where H is stationary.

(U_z is typically 1 m/s while E_x/ZB_0 is 100 m/s and since $X/R_i \approx 0.1$ the omission of U_z is not serious). The stationary points of the magnetic field intensity can be related to the electron densities by the approximate equations, with diffusion neglected

$$\frac{d(n_i \phi_i)}{dz} = q_i - \alpha_i n_i n_e$$

$$\sum_i n_i = n_e$$

Hence at the points $z = \xi$ where $\phi_i = dH/dz = 0$,

$$n_i(\xi) = q_i / \{ \phi_i'(\xi) + \alpha_i n_e(\xi) \}$$

where primes denote derivatives w.r.t. Z .

Substituting this result into $\sum_i n_i = n_e$ gives $n_e(\xi)$ as a solution of

$$n_e(\xi) = \sum_i q_i / \{ \phi_i'(\xi) + \alpha_i n_e(\xi) \}$$

If $U_y'(\xi) < 0$ then $\phi_i'(\xi) > 0$ for all i , and it can be shown that $n_e(\xi) < n_0$ where $n_0^2 = \sum (q_i / \alpha_i)$; conversely, if $U_y'(\xi) > 0$, then $n_e(\xi) > n_0$. Thus n_e is enhanced at a minimum of H and reduced at a maximum. The maximum of n_e coincides almost exactly with the minimum of H , the displacement being trivial. Therefore Axford et al. have shown that the maximum of the electron density in a sporadic-E layer should coincide with a minimum of the magnetic field intensity and occur at a position where $(U_y + E_x (ZB_0)) = 0$

and $dU_y/dz > 0$. They point out that a coincidence of the electron density maximum with points on the wind profile where $U_y' = 0$ and $dU_y/dz > 0$, which has been predicted from an oversimplified wind-shear theory neglecting electric fields, should not be expected. Further, they suggest that simultaneous observation of the magnetic field profile and the electron density profile would provide a better test of the wind-shear theory, than observation of wind profiles.

Whitehead (1970) maintains that the corkscrew mechanism probably does not operate all of the time. Because the downward transport mechanism of Axford et al. is so effective for metallic ions, it may well be that each sporadic-E layer formed by a gravity wave and carried down into the D-region sweeps the E-region almost clear of these metallic ions. (To form a layer 1 km. thick with a density of $3 \times 10^5 \text{ cm}^{-3}$, which is equivalent to $f_D E_s = 5 \text{ Mc/s}$, requires a total content of $3 \times 10^{10} \text{ cm}^{-2}$ which exceeds the estimated (Jones, 1966) total content of Mg^+ and Fe^+ in the E-region. The production of new metallic ions has an estimated time constant of hours or days). Whitehead suggests that the corkscrew could be inhibited either by the reflection of gravity waves above the E-region, or by the interaction of two or more gravity waves with an eastward S_q current flow. In the first case, a standing wave pattern would be formed above the E-region so that layers would form and disappear at intermediate heights without any net transport - only partial reflection would be required to inhibit the corkscrew effect. In the second case, the downward ion velocity will be small at a minimum in the interference pattern of the two gravity waves, and will be opposed by the upward force produced by the eastward current so that the ions cannot corkscrew down through the minimum. In fact, because the velocity of the interference pattern is upward, the minimum moves upward and the net ion transport must be upward. By this mechanism, metallic ion content should peak in the evening (morning) on the equatorial

(poleward) side of the S_q current focus, and the effect should be more pronounced during summer. The diurnal and seasonal variations of blanketing sporadic-E deduced by Reddy and Matsushita (1968) bear some resemblance to these predictions.

Associated Theory

Cole (1963) has worked out a theory of sporadic-E formation in terms of ionospheric currents rather than winds, claiming that vertical shears in horizontal winds are sufficient, but not necessary, to explain the accumulation of ionization in a thin layer. Starting with the equation for the rate of change of electron density at some point in the ionosphere

$$\frac{\partial n}{\partial t} = q - L - \nabla \cdot (n\bar{V}) \quad \dots (25)$$

which is similar to equations (3) and (4), where n is the electron density, q is the rate of production of electrons, L is the rate of recombination and $\bar{V}$ is the drift velocity of ionization, Cole then puts

$$n\bar{V} = \phi \bar{j} \times \bar{B} \quad \dots (26)$$

with $\phi = (m_i v_{in} + m_e v_{en})^{-1}$ and $\bar{j}$ the current density ($\bar{j} = \sum_r n_r e \bar{V}_r$).

Equation (26) expresses the analogy between Cole's theory and the wind-shear theory, in the following way.

Horizontal neutral winds blowing through the E-region impart their motion to ions rather than to electrons because the ratio

$$\frac{\text{collision frequency with neutrals}}{\text{gyrofrequency}}$$

is >1 (<1) for ions (electrons). This relative flow constitutes a current $\bar{j}_i$ which interacts with the magnetic field, as $\bar{j}_i \times \bar{B}$, to impart a drift velocity $\bar{V}_i$ to the ions. The electrons then 'follow' the ions along

magnetic field lines. Cole then writes

$$\nabla \cdot (\alpha \bar{V}) = \bar{j} \times \bar{B} \cdot \nabla \phi + \phi \bar{B} \cdot \nabla \times \bar{j} - \phi \bar{j} \cdot \nabla \times \bar{B} \quad \dots (27)$$

Assuming $L = \alpha n^2$

$$\frac{\partial n}{\partial t} \approx q - \alpha n^2 - \bar{j} \times \bar{B} \cdot \nabla \phi - \phi \bar{B} \cdot \nabla \times \bar{j} \quad \dots (28)$$

since the last term of equation (27) is negligible except in the strongest electrojets. It is obvious from (28) that to produce an accumulation of ionization there is required (1) a gradient of ϕ (i.e. a gradient of neutral particle density) in the opposite direction to $\bar{j} \times \bar{B}$, or (2) a component of $\nabla \times \bar{j}$ in the opposite direction to $\bar{B}$. When treating strong, large-scale irregularities in electron density (i.e. sporadic-E layers) for which $\partial n / \partial t \approx n$ each of the electromagnetic terms in equation (28) must be comparable with αn^2

$$|\bar{j} \times \bar{B} \cdot \nabla \phi| > \alpha n^2 \quad \text{requires}$$

$$|\phi \bar{j} \times \bar{B} / \alpha n^2| > |\phi / \nabla \phi|$$

Assuming no irregularities in neutral particle density except the height variation, $\nabla \phi$ is vertically upwards and therefore

$$-\bar{j} \times \bar{B} \cdot \nabla \phi = H \cdot (\nabla \phi) j_w$$

where j_w is the westward component of $\bar{j}$ and H is the horizontal component of $\bar{B}$. Thus concentration of ionization into a layer occurs when

$$\phi j_w H / \alpha n^2 > \phi / \nabla \phi \quad \dots (29)$$

Cole then compares calculated values of $\phi j_w H / \alpha n^2$, (assuming $\alpha = 10^{-8}$, $n = 10^5$, $H = 0.3$ gauss and $j = 7 \times 10^{-12}$ e.m.u.) with values of the scale height of ϕ ($= \phi / \nabla \phi$) for a chosen model atmosphere over the height range 80 - 150 km.

(ARDC 1959). ($\phi/\nabla\phi$ is the same as the scale height of neutral particle number density, since $\phi \approx (m_i v_i)^{-1}$ and v_i is proportional to neutral particle density). The comparison confirms equation (29) in the height range 120 - 150 km. It is therefore suggested that, in the real atmosphere, westwards ionospheric current can cause concentration of ionization in the E-region into a thin layer. At heights above 150 km. the value of j falls off so that $|\phi j H / \alpha n^2|$ becomes less than the scale height and the term $\bar{j} \times \bar{B} \cdot \nabla \phi$ becomes ineffective.

The second electromagnetic term in equation (28) can be written

$$\equiv \phi \bar{B} \cdot \nabla \times \bar{j} = \phi H \partial j_w / \partial z$$

if the ionospheric current is assumed to be everywhere horizontal and with only vertical gradients. Thus

$$\phi \bar{B} \cdot \nabla \times \bar{j} > \alpha n^2 \quad \text{requires}$$

$$\phi j_w H / \alpha n^2 > |j_w \frac{\partial j_w}{\partial z}| \quad \dots (30)$$

The scale height of $j_w (= j_w / \partial j_w / \partial z)$ is usually less than 10 km. From the same comparison as before it is seen that equation (30) may be satisfied at times in the E-region. Thus equation (28) can be written

$$\frac{\partial n}{\partial t} = q - \alpha n^2 + j_w H \nabla \phi + H \phi \partial j_w / \partial z \quad \dots (31)$$

Clearly from equation (31) the formation of strong large-scale sporadic-E should be correlated with the horizontal component of the geomagnetic field, as has been observed by Heisler and Whitehead (1960). A westward current decreases the horizontal component. Cole points out that wind-shears, as invoked by Whitehead (1961) to explain this kind of sporadic-E, may create significant $\partial j_w / \partial z$ but are not necessary to explain the accumulation of

ionization. Westwards currents become effective in causing such accumulation whenever

$$j_w > |\alpha n^2 / H \nabla \phi|$$

The larger j_w is, the lower in the E-region is it able to accumulate ionization. Once the formation of large scale sporadic-E has commenced through the action of the term $\bar{j} \times \bar{B} \cdot \nabla \phi$, the term $\phi \bar{B} \cdot \nabla \times \bar{j}$ increases in importance due to the creation of significant $\partial j_w / \partial z$. In general, in the quasi-steady state ($\partial n / \partial t \approx 0$) equation (31) yields

$$n \approx \left\{ \frac{1}{\alpha} (q + j_w H \nabla \phi + H \phi \partial j_w / \partial z) \right\}^{1/2}$$

which demonstrates how n can be augmented or diminished by the action of westward current. Cole also considers the case of weak small-scale irregularities with $\delta u \ll u$ and shows that these can be generated by small-scale perturbations in neutral particle density and in current density. Finally, Cole applies his arguments to the E-region at night, when the ionization is generally expected to vanish because of the high recombination rate. Supposing, as is usual, that $q = 0$ at night, then equation (28) becomes

$$n = \left\{ \frac{H}{\alpha} (j_w \nabla \phi + \phi \partial j_w / \partial z) \right\}^{1/2}$$

if the last term is neglected and only large-scale processes are considered. This suggests that electromotive forces driving current may force ionization down to the lower E-region and so maintain detectable ionization there. What is required is that

$$j_w \nabla \phi + \phi \partial j_w / \partial z > 0$$

which can be written

$$j_w / (\partial j_w / \partial z) + \phi / \nabla \phi > 0$$

Then, since it is to be expected that $\partial j_w / \partial z$ be negative, the requirement becomes that the scale height of ϕ (i.e. of air density) be greater than the scale height for current.

OTHER THEORIES

The instability theory

Partially ionized plasmas that contain a magnetic field and gradients in ionization density are subject to a unique type of instability under the influence of an externally applied electric field. This instability can give rise to growing irregularities in ionization density that are aligned along the direction of the magnetic field. The ionosphere is a plasma with the appropriate properties in which electric fields are always present, and which frequently displays the presence of field-aligned irregularities with scale-sizes in the range of a few tens of meters to a few kilometers. The theory, developed chiefly by Tsuda et al. (1966) and Reid (1967), demonstrates how the dynamo region of the ionosphere (100-120 km.) is likely to be unstable against the growth of such irregularities, in the presence of the steady electric fields produced by dynamo action. Tsuda et al. applied a form of the theory originally developed for laboratory plasmas to the case of sporadic-E ionization. Reid has developed a different treatment, which he claims is more realistic to the ionosphere. This physical picture of the instability mechanism, with two possible modes of operation, is as follows - see Figure 1.1.

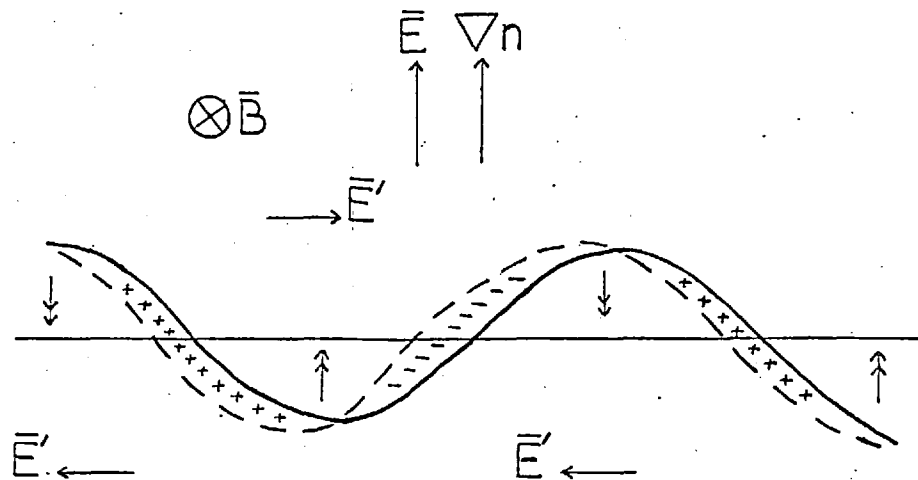


FIGURE 1.1

The horizontal line represents an unperturbed contour of constant electron density: E is the steady electric field: ∇n is the steady density gradient: B is the magnetic field vector, directed into the paper. The density is then perturbed by a small-amplitude sinusoidal variation.

In the first mode of operation, the $\bar{E} \times \bar{B}$ drifts of the ions and electrons, resulting from the density perturbation, will carry them both to the left. Since the Hall mobility of ions is always less than that of electrons, space charges will appear, giving rise to small-scale electric fields $\bar{E}'$ directed alternately to left and right. The corresponding $\bar{E}' \times \bar{B}$ drifts will then carry the enhanced regions downward and the depleted regions upward, so that they will both appear to grow in amplitude against the background density. If either the electric field or the steady density gradient were reversed the perturbations would tend to disappear and stability would be attained. A second mode of operation arises if the steady electric field is directed towards the right, instead of upward, in Figure 1.1. Then the driving force of the mechanism is provided by the Pedersen mobilities of the ions and electrons which, being in opposite directions, tend to produce a similar periodic space-charge potential, with

similar results. This latter mode produces larger-scale irregularities at greater altitudes than the former mode, because the Pedersen mobility, although smaller than the Hall, persists to greater altitudes. Reid further suggests that the space-charge potentials associated with the growth of these larger scale-size irregularities can be conducted up the magnetic field lines into the F-region, to give rise to similar irregularities there. Reid points out that it is difficult to devise any conclusive experimental test of the theory. Whitehead (1967 and 1968) has shown that horizontal thin layers cannot be the result of any gradient instability in the E-region.

The turbulence theory

One other theory remains to be discussed; the production of irregularities by turbulence in the neutral air. Gallet (1951, 1955) suggested that turbulent mixing in a gradient of ionization would give sporadic-E. The scale-size was estimated to be 100 - 200 meters. Sporadic-E should occur at the steepest parts of the N:h profile. According to Whitehead (1970) the theory is weak in the following points: it does not produce a thin layer; it does not account for sporadic-E occurring sometimes at the E-region maximum and sometimes above this (turbulence is confined below about 95 km.); and third, air turbulence would produce much more intensive irregularities by the mechanism of wind-shear than by mixing of the background gradient.

CHAPTER 2

THE ROCKET FLIGHTS

Two British Skylark rockets were launched from Woomera range, South Australia carrying similar integrated experiments, by four separate university groups, designed to investigate sporadic-E ionization. The Imperial College experiment was to detect any anomalous changes in the total intensity of the geomagnetic field on passing a rocket-borne magnetometer through a sporadic-E layer. The experiments from the other university groups were directed at elucidating the mode of formation of such sporadic-E layers. To that end, observations were made of ion density (University College, London), electron density (Birmingham University) and wind velocities by means of vapour trails (Queen's University, Belfast).

The Imperial College experiment was conceived from the following suggestions made by K. Weekes of the Department of Physics, University of Wales, Aberystwyth E_s layers may produce a local magnetic disturbance field in excess of the S_q field. The E_s disturbance field should be opposed to the horizontal component of the geomagnetic field and should amount to about 30% of the horizontal component when the critical frequency of E_s is 10 Mc/s. The disturbance field should be inappreciable outside the E_s layer and should reach a maximum at the centre of the layer. Sporadic-E of the strong blanketing type is most likely to produce such a disturbance field.

2.1 Conditions at launch

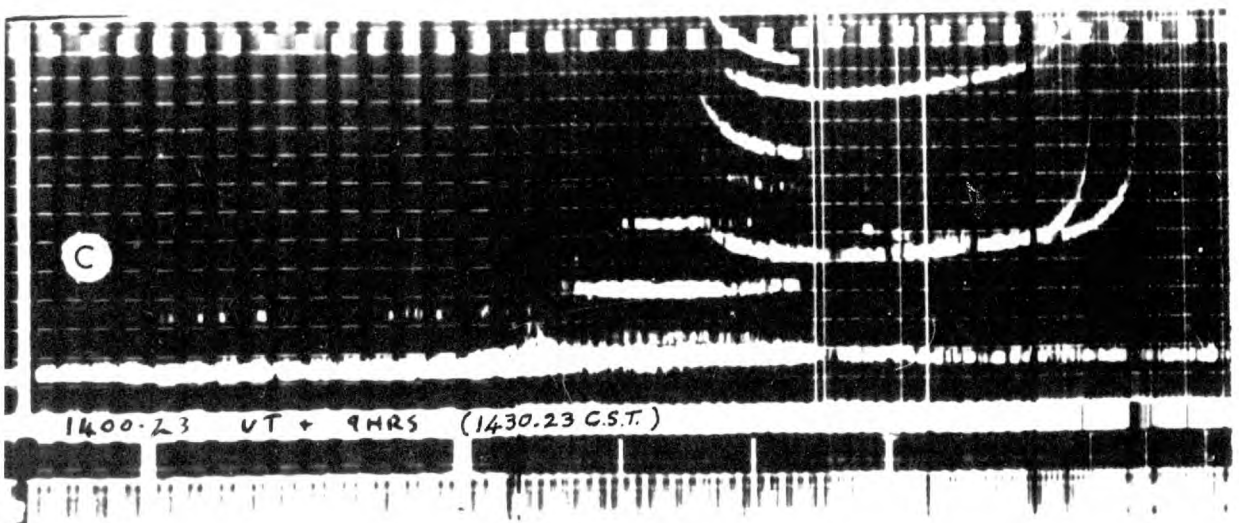
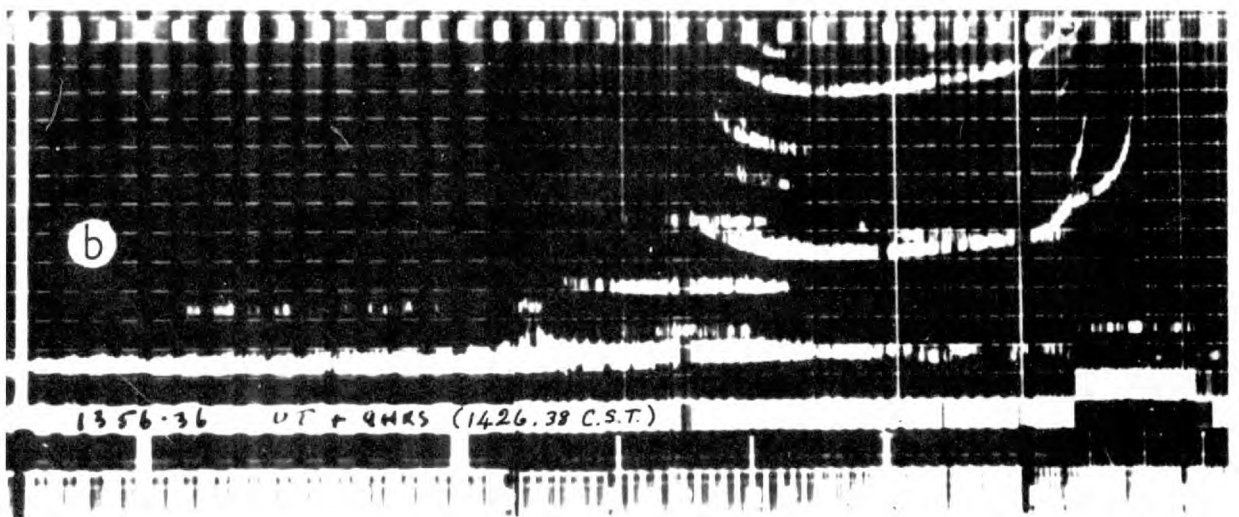
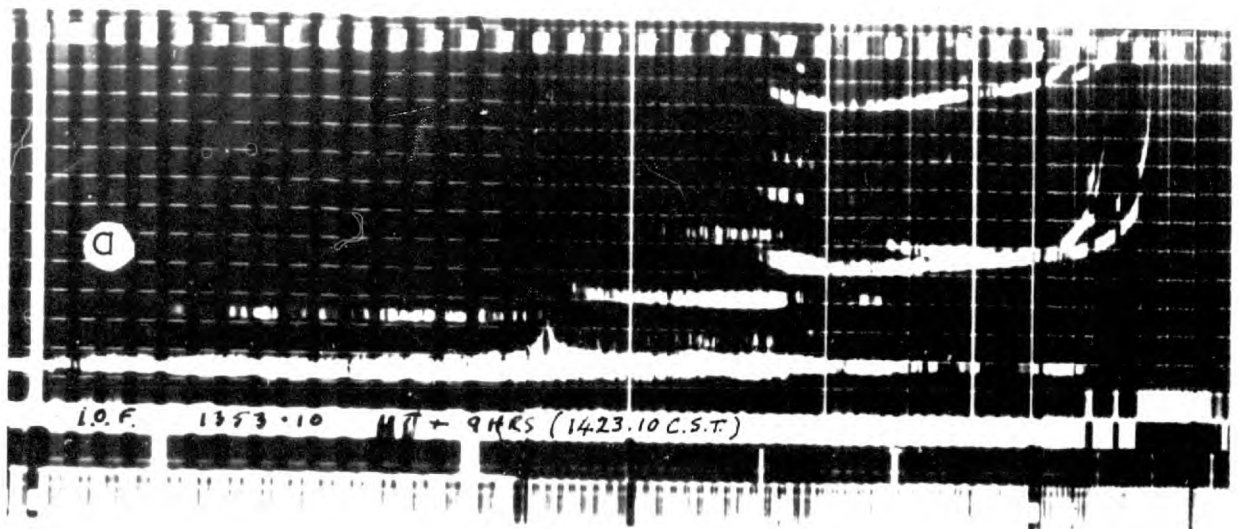
The requisite meteorological and ionospheric conditions for a launching to take place were laid down as being (a) good visibility

with minimal cloud cover for successful optical tracking of the rocket vehicle and photographing of the vapour trails, (b) a surface wind of less than 40 ft./sec. to ensure a correct trajectory and (c) a E_s blanketing frequency greater than 4.0 Mc/s. The selection of times most favourable to the possibility of launching into a strongly-blanketing type of E_s layer was based on the observed seasonal and diurnal patterns of E_s occurrence in S. Australia. High values of blanketing frequency occur most often during November and December while the typical diurnal variation of blanketing frequency has a main peak around 0900, 1000 and 1100 hr. L.T. and a second peak around 1800, 1900 and 2000 hr. L.T. However, the blanketing frequency usually exceeds 4.0 Mc/s in the period 0900 and 2000 hr. L.T. An unsuccessful attempt to launch the present experiments was made during November and December of 1964, at twilight (around 1930 hr. L.T.). On several occasions failure was due to insufficiently high values of blanketing frequency. Consequently, in 1965, it was decided to use lithium vapour, in place of sodium vapour, for the first launching in an attempt to obtain a visible vapour trail during daytime, when blanketing frequencies are likely to be higher. The attempt was unsuccessful because the lithium vapour could not be satisfactorily photographed against the bright daytime sky background and, therefore, the second rocket was launched at twilight carrying both sodium and lithium.

On 19th November, 1965 Skylark 130 (SL 130) was fired at 1424.13 hr. Central Standard Time (0454.13 hr. G.M.T.) The weather was fine with a trace of cloud; visibility was 30 miles and surface wind velocity was 12 ft./sec. Ionograms (Figure 2.1) were recorded at (a) 1423.10hr. C.S.T., i.e. 63 sec. before firing time, (b) 1426.36 hr. C.S.T., i.e. 145 sec. after firing (+ 143 sec.) during ascent, and (c) 1430.23 hr. C.S.T. (+ 370 sec.), i.e. after impact. The rocket was traversing the E_s region, between about 100 km. and apogee at 138.5 km., from about + 100 sec.

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FIGURE 2.1 Ionograms recorded during the flight of S.L.130, 19th November, 1965.



to about + 285 sec., therefore only ionogram (b) is strictly pertinent.

The ionograms were interpreted to yield the following parameters

fbE_s in Mc/s	No. of layers of E_s	Approx. height in km. ± 2	E_s type	foE_s (of higher layer) in Mc/s
(a) 4.9	<u>2</u> or 3	110 - 120	high	7.0
(b) 4.6	<u>2</u> or 3	110 - 120	high	>9.5
(c) 4.8	<u>2</u> or 3	110 - 120	high	13.8

The difference between the critical frequencies (foE_s) and the blanketing frequencies (fbE_s) is due to the E_s layer being non-uniform in electron density, i.e. of a patchy nature. The explanation is as follows.

Reflection of the incident frequency, f , occurs at a level where f equals the plasma frequency, f_N ; f_N expresses the electron density (N) in terms of frequency, viz.

$$f_N = \sqrt{\frac{Ne^2}{\pi m}}$$

where e and m are, respectively, the charge and mass of the electron.

When $f = f_o$, f_N is equivalent to the maximum electron density in the layer, whereas when $f = f_b$, f_N is equivalent to the mean electron density of the layer. The blanketing frequency is therefore considered the better parameter from which to calculate an equivalent electron density representative of the layer. Applying the formula

$$N = 0.124 \times f_b^2 \times 10^5$$

to case (b) gives $N = 2.63 \times 10^5$ electrons/cm³ at + 145 sec. of the rocket flight. At the same time the critical frequency for the E-region as a whole (f_oE) can be estimated as 3.4 Mc/s, from ionogram (b), giving an ambient E-region electron density of about 1.42×10^5 electrons/cm³. Thus a concentration of ionization in excess of the average in the E-region, by about 1.2×10^5 electrons/cm³, constitutes the E_s layer. Magnetically, the 19th November was an International Disturbed Day but the planetary index for the 3-hour period in which the flight occurred, $K_p = 2+$, indicated fairly quiet conditions. The diurnal variation of the magnetic field total intensity at ground level near the launching site is shown by Figure 2.2, which is a compressed version of the record obtained from the rubidium magnetometer.

On 13th December, 1965 Skylark 131 (S.L. 131) was fired at 1938.00 hr. C.S.T. (1008.00 hr. G.M.T.). The weather was fine with $\frac{1}{8}$ cloud cover at an altitude of about 2 km.; visibility was 30 miles; and surface wind velocity was 27 ft./sec. Ionograms (Figure 2.3) were recorded at (a) 1938.04 hr. C.S.T., i.e. 4 sec. after firing time (+ 4 sec.) but before the magnetometer was deployed for operation, (b) 1941.36 hr. C.S.T. (+ 216 sec.) during descent and (c) 1945.00 hr. C.S.T., i.e. about 1 minute after the rocket impacted. Only ionogram (b) was recorded while the rocket was within the E-region. The ionograms yielded the following parameters

f_bE_s in Mc/s	No. of layers of E_s	Approx. height in km. ± 1	E_s type	f_oE_s in Mc/s
(a) 4.2	1	108	flat	4.2
(b) 4.1	1	108	flat	9.5 (approx.)
(c) 3.8	1	108	flat	12.5 (approx.)

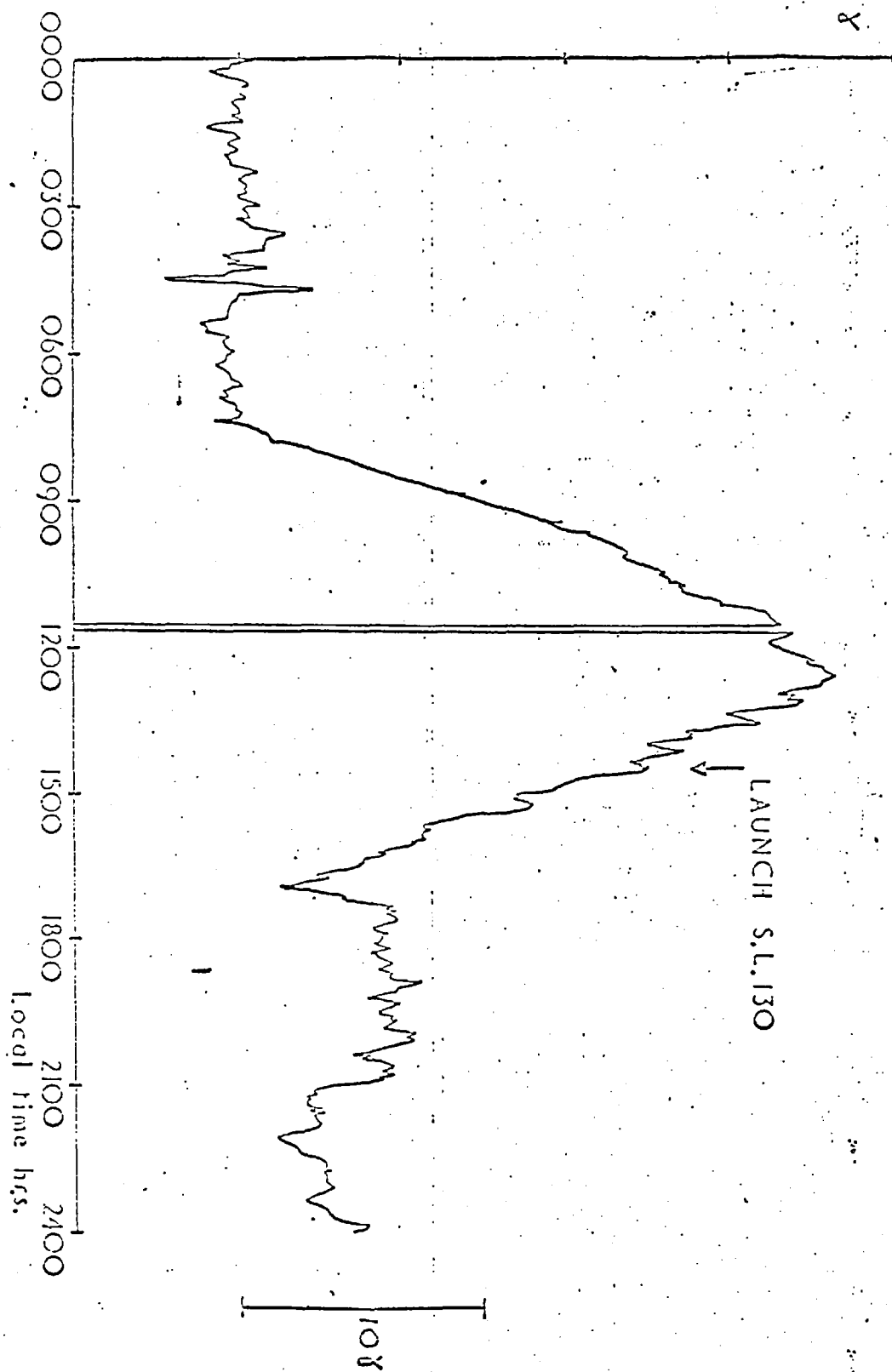
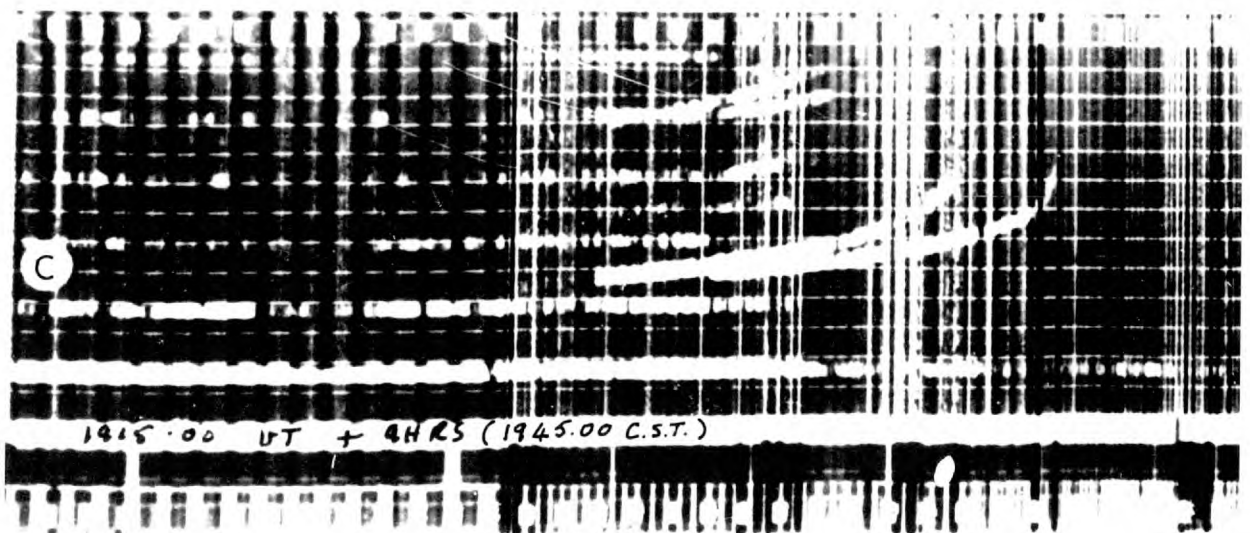


FIGURE 2.2 Compressed magnetogram (total force) for 19 November, 1965. S.L.130 launched at 1424 hr.

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FIGURE 2.3 Ionograms recorded during the flight of S.L.131, 13th December, 1965.



From (b), the equivalent electron density of the E_s layer at + 216 sec. of the rocket flight is given by $N = 2.08 \times 10^5$ electrons/cm³. The ambient E-region electron density cannot be estimated in this case since foE cannot be read from ionogram (b). The planetary magnetic index for the 3-hour period in which the rocket flight occurred on 13th December was $K_p = 1.0$, which is a quiet condition. Figure 2.4 shows the diurnal variation of magnetic field total intensity at ground level.

2.2. Rocket Performance

The specification of SL 130 - 131 were as follows

Length:	SL 130 - 34 ft.; SL 131 - 35 ft.
Diameter:	17 $\frac{1}{4}$ inches
Boost motor:	Cuckoo-type using solid feed, giving a 6 sec. thrust
Sustained motor:	Raven 7A-type using solid fuel (Information on the type of fuel, the impulse of thrust and the duration of thrust supplied by the Raven 7A is not available.)
Separation systems:	Head separation - electro-mechanical; Nose cone jettison - electro-pneumatic; Lithium bay separation (SL 131 only) - explosive. SL 130 - 131 were not spin-stabilized.

A full description of the Skylark sounding rocket has been given by Hazell & Dorling (1959).

The Skylark launcher at 30.945° S, 136.522° E (Range Origin) was trained as follows

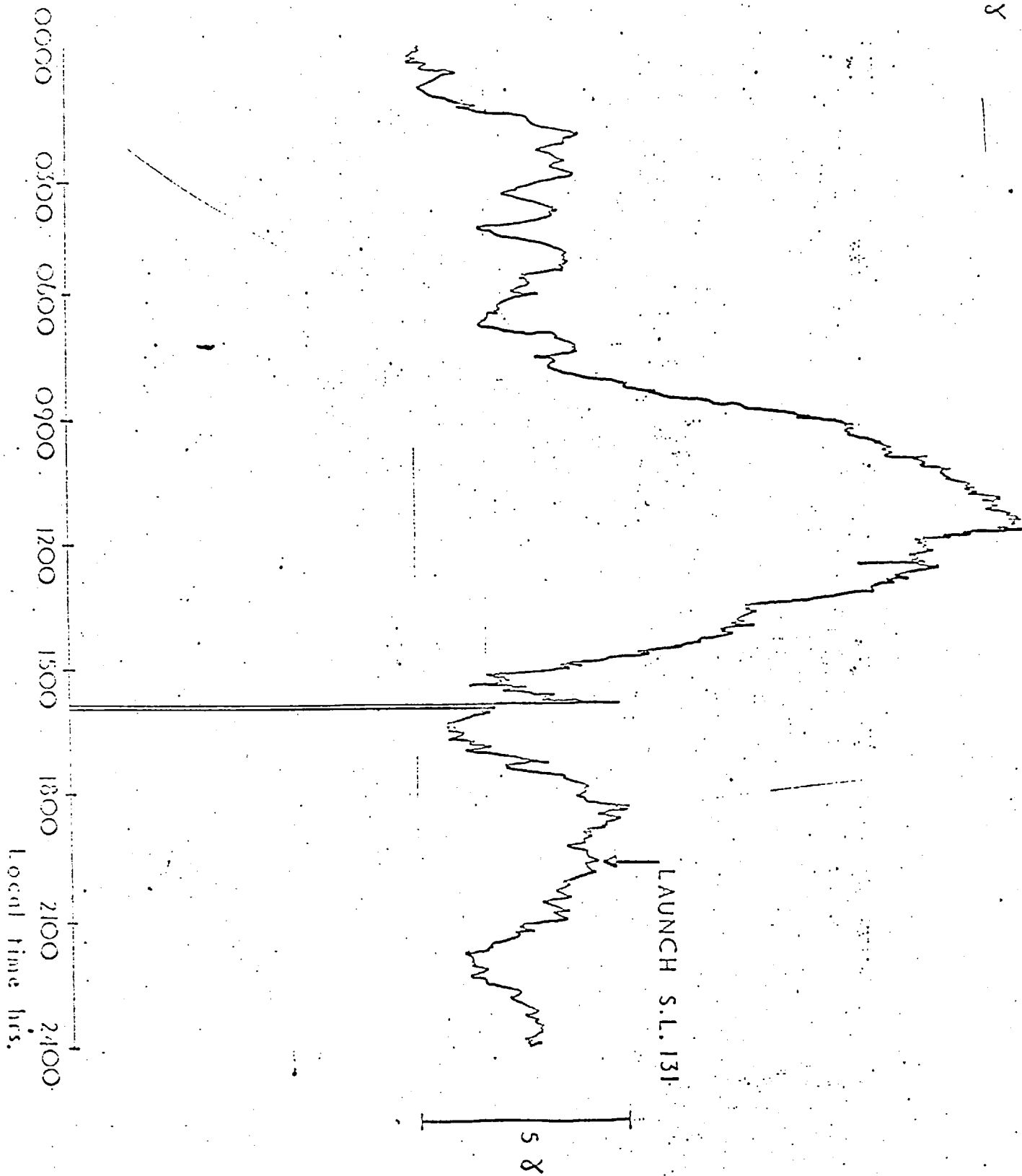


FIGURE 2.4

Compressed magnetogram (total force) for 13 December, 1965.
S.L.131 launched at 1938 hr.

	<u>SL 130</u>	<u>SL 131</u>
Nominal line of fire:	320°	320°
Predicted impact bearing:	320°	320°
Effective QE	85°	85°
True elevation	86.8°	81.0°
True azimuth	313°	358°

The estimated trajectory of SL 130 - 131 is shown in Figure 2.5. The rockets were optically tracked by kine-theodolites and cine cameras (Tracking lamps were fitted to SL 131, as it was launched at twilight). In addition the rockets were electronically tracked by radar (type FPS16), M.T.S. and trans-doppler. The necessary tracking equipment is provided as part of the standard facilities at Woomera. Best-fit ballistic trajectories were computed from the radar trajectories, obtained for the flight interval + 80 to + 300 sec., of both rockets. These actual trajectories differed from the estimated trajectory as follows

		<u>Best-fit</u>		<u>Estimated</u>
		<u>SL 130</u>	<u>SL 131</u>	<u>(SL 130 & 131)</u>
Apogee	- height (Kft)	454	426	429
	- range (Kft)	183	119	179
	- deviation (Kft)	26	-47	53
	- time (sec.)	+191	184	+191
Impact point of head				
	- range (Kft)	353	224	353
	- deviation (Kft)	41	-89	102
	- bearing (deg.)	311	283	320
Impact point of motor				
	- range (Kft)	352	237	353
	- deviation (Kft)	45	-98	102
	- bearing (deg.)	312	282	320

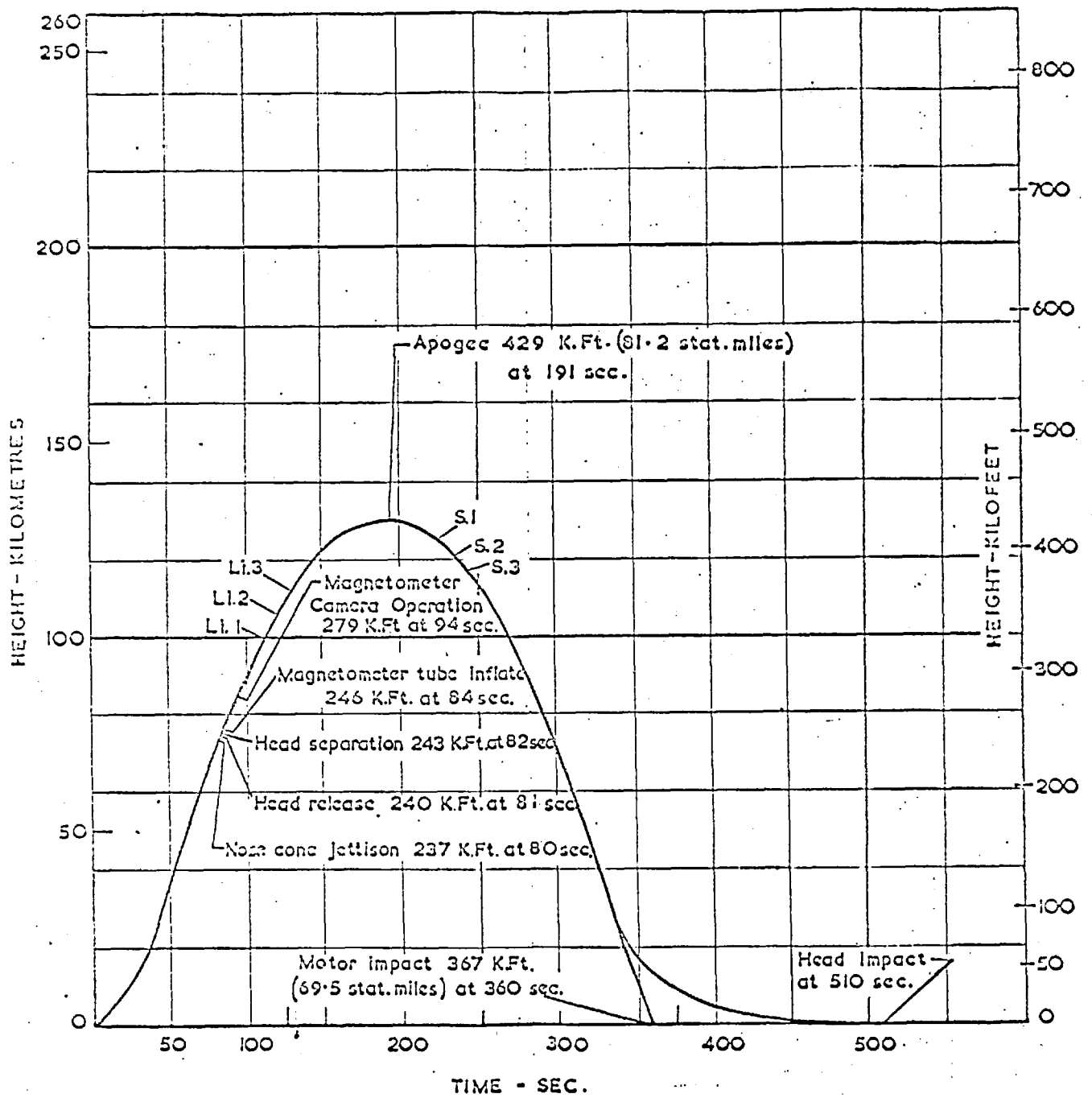


FIGURE 2.5 Estimated trajectory for S.L. 130 and S.L. 131
Line of fire - 3200 (nominal)

Note:

SL 131 deviated sharply to the left of the nominal line of fire immediately it left the launcher.

Maximum velocities in flight, obtained from the doppler equipment, were 4,800 ft./sec. after 37 sec. for SL 130 (estimated - 4490 ft./sec. after 52 sec.) and 4,710 ft./sec. after 36 sec. for SL 131 (estimated - 4490 ft./sec. after 52 sec.)

The motion of the rockets in flight, deduced from data telemetered from the linear accelerometers and rate gyros, was as follows

SL 130: The roll rate increased slowly to about 110 deg./sec. by + 37 sec., then decreased slightly to 85 deg./sec. by + 52 sec. and was constant until inflation of the Imperial College pneumatic probe began, at about 82 sec. The roll rate varied frequently during inflation and deployment of the tube. (150 deg./sec. at + 82 sec.; - 50 deg./sec. at + 92 sec.; 15 deg./sec. at + 110 sec.) The WRECISS camera photograph, Plate 2.1/a, shows that the pneumatic tube may have become entangled with one of the head-separation plungers during deployment, becoming, perhaps, the tail which wagged the dog. The roll rate remained 15 deg./sec. from +110 sec. to re-entry at about + 315 sec. The pitch rate was small up to + 77 sec. and then increased to about ± 7 deg./sec. From about + 90 sec. the pitch rate increased rapidly and oscillated between 0 and + 20 deg./sec. to re-entry, i.e. the motion of the head was complex after + 90 sec.

SL 131: The rocket oscillated in the pitch plane from launch (up to ± 16 deg./sec.) but this motion was damped out by about + 7 sec. The roll rate increased steadily from launch to 200 deg./sec. by + 32 sec. The pitch rate increased from + 28 sec., when the motor thrust reached a peak, and exceeded 20 deg./sec. by + 38 sec. This suggests that resonance occurred at + 28 sec. between the pitch natural frequency and the roll rate. By + 76 sec. the roll rate was 10 deg./sec. and the pitch rate 15 deg./sec.

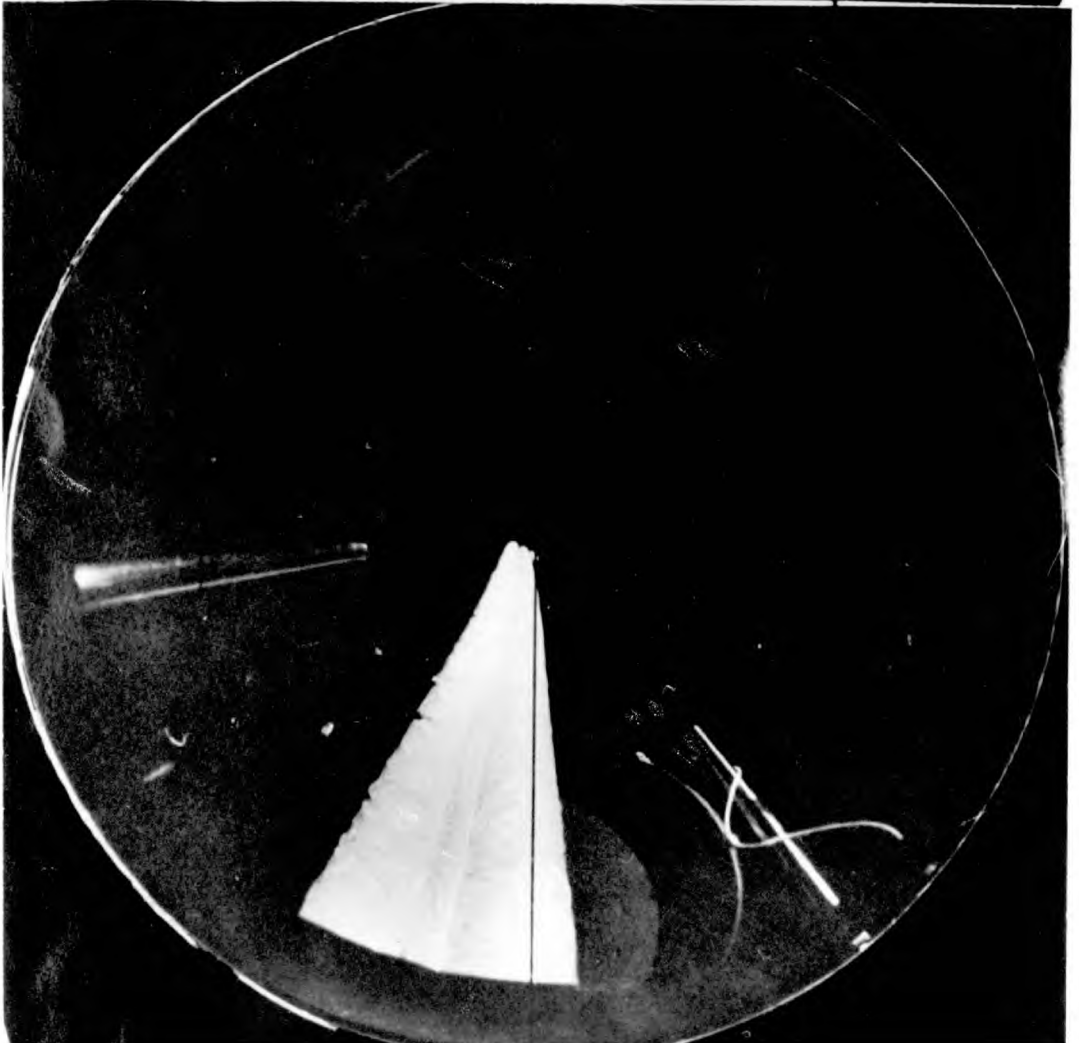
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PLATE 2.1 Wreciss camera photographs of deployed magnetometer probe:
(a) on S.L.130, (b) on S.L.131.

a



b



The pitch and roll rates varied from about + 80 sec. to about + 93 sec. while the pneumatic tube was deploying. From + 93 sec. to re-entry about + 290 sec. the pitch rate varied between $\pm$ 20 deg./sec. while the roll rate was 24 deg./sec. The precession rate was about 19 deg./sec.

Faulty performance occurred on SL 130 in that head separation occurred at about + 85 sec., 4 sec. later than its programmed time. This meant that the pneumatic probe was being inflated while the motor section was still attached to the head. The pneumatic bottle pressure suddenly decreased at about 81 sec., as programmed, and the tube pressure increased between 81.1 sec. and 81.2 sec. However the tube pressure had dropped to zero by 81.3 sec., suggesting that the tube may have ruptured and that it never became fully inflated.

2.3 Rocket Payload

The rocket configuration is shown in Figure 2.6. In addition to the Imperial College experiment, the payload consisted of experiments from Birmingham University, University College, London and Queen's University, Belfast. The rockets also carried standard flight equipment, tracking beacons telemetry senders and battery power supplies.

The Birmingham University experiment (E.C. Mackenzie) was designed to measure the change of electron density with altitude. The apparatus (Mackenzie and Sayers, 1966), called an R.F. Electron Probe, is essentially a capacitor formed by two grids, which were mounted on a boom under the nose cone (which was jettisoned before observations commenced). One grid was charged with 3 volt. r.m.s. at 39 Mc/s and the current flowing to the other grid was recorded. The current flowing is proportional to the number of free electrons present between the grids, because at radio frequencies the dielectric constant of the ionospheric gas depends on the

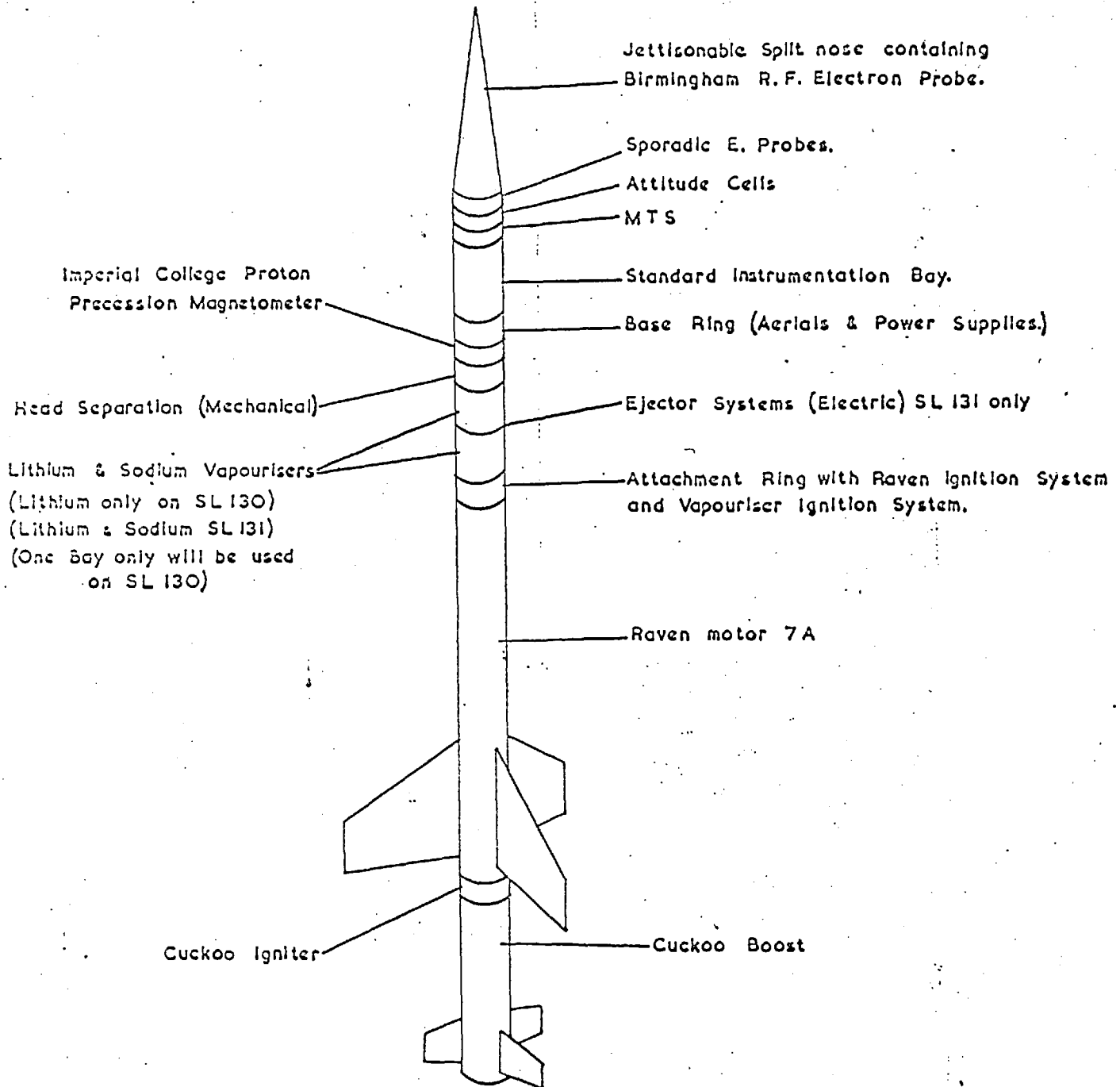


FIGURE 2.6 Arrangement of payload on Skylark rockets 130 and 131

number of free electrons present. The detection system was designed to respond to small changes of current and ignore large steady signals. From the results, true ambient electron density was obtained.

The University College experiment (E. B. Dorling) was designed to obtain a positive ion density profile. The apparatus (Dorling et al., 1969) consisted of four plane probes, of the Langmuir type, mounted at 90° intervals round the skin of the rocket head. (These are the Sporadic-E Probes shown in Figure 2.6). Each probe was at negative potential relative to space potential during the flight, and at negative potential relative to the rocket head. As a result of this potential difference a current of positive ions from the ionospheric gas flows to each probe. Each probe was connected to its own amplifier but the amplifiers were arranged in pairs, one with a high gain setting and the other with a low gain setting, in order to cover as wide a range of ion densities as possible. In both flights the high gain setting proved to be too high so that only the two low-gain amplifiers provided results.

The Queen's University experiment (G. J. MacGratten) was designed to determine wind-shear in the region 100 to 130 km. SL 130 carried three lithium vapourisers and SL 131 carried three lithium and three sodium vapourisers (Figure 2.6). The first lithium vapouriser was lit at about 105 km., and the other two at about 5 km. intervals, during ascent, to produce a vapour trail. On SL 131, the first sodium vapouriser was lit at about 120 km., and the other two at about 5 km. intervals, during descent. The vapour trails were photographed by tracking cameras on the ground. The lithium vapour released from SL 130 in daylight did not contrast with the sky-background sufficiently well to be photographed. N. - S. and E.-W.

component velocities were determined from the reduction of the camera plates by an analog projection method. Wind-shears were calculated as gradients of the component velocities.

Standard flight equipment carried by SL 130 - 131 consisted of sun slits (attitude cells) to obtain the attitude of the head relative to the sun, flux gate magnetometers to obtain the attitude of the head relative to the geomagnetic field, rate gyros to obtain the angular rates of motion of the head and accelerometers to obtain the linear accelerations of the head. The magnetometers, rate gyros and accelerometers were housed in the Standard Instrumentation Bay (Figure 2.6).

The tracking beacons carried were an M.T.S. (Missile Tracking System) transmitter which was a 6 cm. oscillator, and a Doppler transponder, Type RR5 sending at a frequency of 208 Mc/s. Figure 2.6 shows the housing of the M.T.S.; the Doppler transponder was housed in the Standard Instrumentation Bay.

The standard Skylark 465 Telemetry System was used. Two telemetry senders were carried. Sender 1 was a 24 channel, sub-switched type with a carrier frequency of 455 Mc/s. Sender 2 was a single channel type with a carrier frequency of 443 Mc/s. The senders were housed in the Standard Instrumentation Bay with the 4 spike-type aerials fixed to the skin of the rocket just below the Instrumentation Bay (Figure 2.6). The purpose of a multi-channel telemetry sender is to monitor a large number of low frequency signals from the circuitry in the missile, during flight. In the present case the 24 channels were allocated amongst the various experiments in the rocket payload, e.g. channel 5 monitored the polarizing volts of the Imperial College magnetometer and channel 8 monitored, at discrete voltage levels, (a) the air pressure in the pneumatic probe, (b) the pressure in the air bottles, (c) the operation of the head release mechanism and (d) the magnetometer amplifier volts. The single channel sender was used to relay the precession signal from the Imperial College magnetometer.

2.4 Description of the Imperial College Magnetometer

On SL 130 and SL 131 the magnetometer was housed in the last bay of the head section of the rocket (Figure 2.6), so that when the head and motor sections were separated in flight (Figure 2.5) the pneumatic probe of the magnetometer was free to deploy at the rear of the head section. The magnetometer bay (12 inches deep) was subdivided by an intermediate bulkhead; the forward compartment contained the magnetometer electronics and the rear compartment contained the pneumatic system. The magnetometer has been described in detail by Burrows (1965).

Physical principles of the proton precession magnetometer

A proton, which constitutes the nucleus of a hydrogen atom, possesses spin angular momentum and, hence, a magnetic moment, in addition to its orbital angular momentum. These momenta combine to give the total angular momentum. The absolute value of the total angular momentum of a given nucleus must be measured experimentally. In addition, the nuclear magnetic moment of a given atom is constant, but cannot be deduced from the angular momentum except that it is zero when the angular momentum is zero.

The ratio of $\frac{\text{nuclear magnetic moment}}{\text{nuclear angular momentum}}$, called the gyromagnetic ratio, has been measured for the proton and is given by

$$\alpha = 2.67513 \times 10^4 \text{ gauss}^{-1} \text{ sec}^{-1}$$

The spinning proton is acted upon by the torque produced by the interaction of its magnetic moment and the ambient magnetic field. As a result the spin axis of the proton is deflected and will precess, wherein the angular momentum vector moves on the surface of a cone with axis parallel to the magnetic field. The angular rate of this precession is inversely proportional to the angular momentum and directly proportional to the

deflecting torque, which depends on the strength of the ambient magnetic field. In order to detect the precession rate and hence measure the magnetic field intensity, some of the protons in a liquid sample must first have their magnetic moments aligned by being placed in a strong magnetic field (the polarizing field) directed at an angle to the ambient field. If the polarizing field is suddenly interrupted, the remaining ambient field will cause the protons to precess about it in phase coherence. Each precessing proton sets up an external, rotating magnetic field which can be resolved into true orthogonal sinusoidal components of the same frequency but 90° different in phase. A properly orientated sensing coil will therefore have an induced voltage at the frequency of precession, called the Larmor frequency, given by

$$f_p = \alpha/2\pi F \text{ gauss}$$

where α is the gyromagnetic ratio and F is the magnetic field intensity. The value of F at Woomera is typically 0.5820 gauss, giving precession frequencies of the order of 2478 c/s. In practice the same coil is used for polarization and sensing. The precession is damped-out after a few seconds, but the rate of precession remains constant. This relaxation is an exponential decay in a time characteristic of the proton sample. In the present case, a proton-rich paraffin sample in the sensing head is polarized for 0.5 sec. and then the precession frequency is detected for a period of time which varies in proportion to the duration of the precession signal; a timer unit re-initiates polarization when triggered at a pre-determined level of the decaying signal.

The pneumatic system

The sensor consists of a coil, (1500 turns of 20 S.W.G., Sungold 'M', high-temperature enamelled copper wire), encapsulated by a 3-inch-diameter tufnol cylinder. The coil has an inductance of 34.4 mH and a resistance of 6.5 ohm. A polarizing voltage of 24 volt is applied to the coil for 0.5 sec. and the signal voltage induced is of the order of 1 - 2 μ volt. The signal voltage, which is monitored for 0.25 - 2.0 sec., has an amplitude proportional to $\sin^2 \theta$, where θ is the angle between the coil axis and the geomagnetic field. It is necessary to remove the sensor from the magnetic field due to the material and instrumentation of the rocket vehicle while the magnetometer is operating in flight. This is achieved with a pneumatically-operated system which ejects the sensor from the rocket body on a 20 foot-long inflated probe, once the rocket motor has been separated from the body in flight. The probe is made by doubling over a 40 ft. length of 2 inch-diameter rubber tube (reinforced with nylon fabric) and the sensor is secured, within a leather jacket, to the terminal loop so formed. The cable from the sensor to the magnetometer electronics runs the length of the probe in a pocket which is stitched into an outer probe-cover.

Before ejection, the sensor and probe are packed in a canister with a lid which is laced down with nylon cord. The twin tubes of the probe are connected through the base of the canister, via an air ring-manifold and twin solenoid valves, to 6 duralumin air cylinders which are charged to 2,000 p.s.i. Inflation is initiated by an electrical pulse from the rocket's programme motor to the solenoid valves. The probe is inflated to 65 - 75 p.s.i. during the 10 sec. pulse, Manifold and probe pressures are monitored by transducers. The inflating probe breaks the nylon cord (100 lb. breaking strength) holding the lid on the canister and then extends to its full length behind the rocket body. The extended

probe is photographed by a WREICISS camera which can be recovered after the rocket body impacts with the ground, thus permitting a post-flight check on tube deployment. The relevant photographs for SL 130 - 131 are Plates 2.1/a & b, respectively.

The Magnetometer Electronics

The main function of the electronics package is to switch the sensor coil between its polarizing and sensing modes and to amplify the signal output from the sensor. This is performed by the various units shown in the circuit diagram, Figure 2.7, which are a relay unit (RLA, RLB, L2, L3 and C1), a timer unit (VT7 to VT13 and associated components), an emitter-follower (VT1 and VT2) and an amplifier unit consisting of amplifier I (VT3 and VT4) plus amplifier II (VT5 and VT6, and including L4). These are arranged as plug-in units in a screened aluminium box fixed to a dummy base on the intermediate bulkhead. These units have been fully described by Burrows (1965).

A Filter Unit (Figure 2.8) regulates the 28 volt nominal supply from the rocket power supplies to provide a steady 24 volt polarizing supply to the sensor. The overall response of the amplifier/filter was designed to be 100c/s centred at 2350 c/s to ensure maximum S/N at E region altitudes.

A Monitor Unit (Figure 2.8) feeds a stepped-down analogue of the polarizing voltage and of the amplifier 12 volt negative supply to two channels of the rocket telemetry sender, so that these voltages can be monitored during the flight as a check that the magnetometer is operating correctly. The voltage reduction is achieved with bias packs which consist of a 60 μ F Tantalum capacitor plus several Mallory TR 115 cells in series. The value of the reduced voltages to be monitored (the monitor levels) is pre-selected, as indicated in Figure 2.10, to be in the range 0 to + 6 volts.

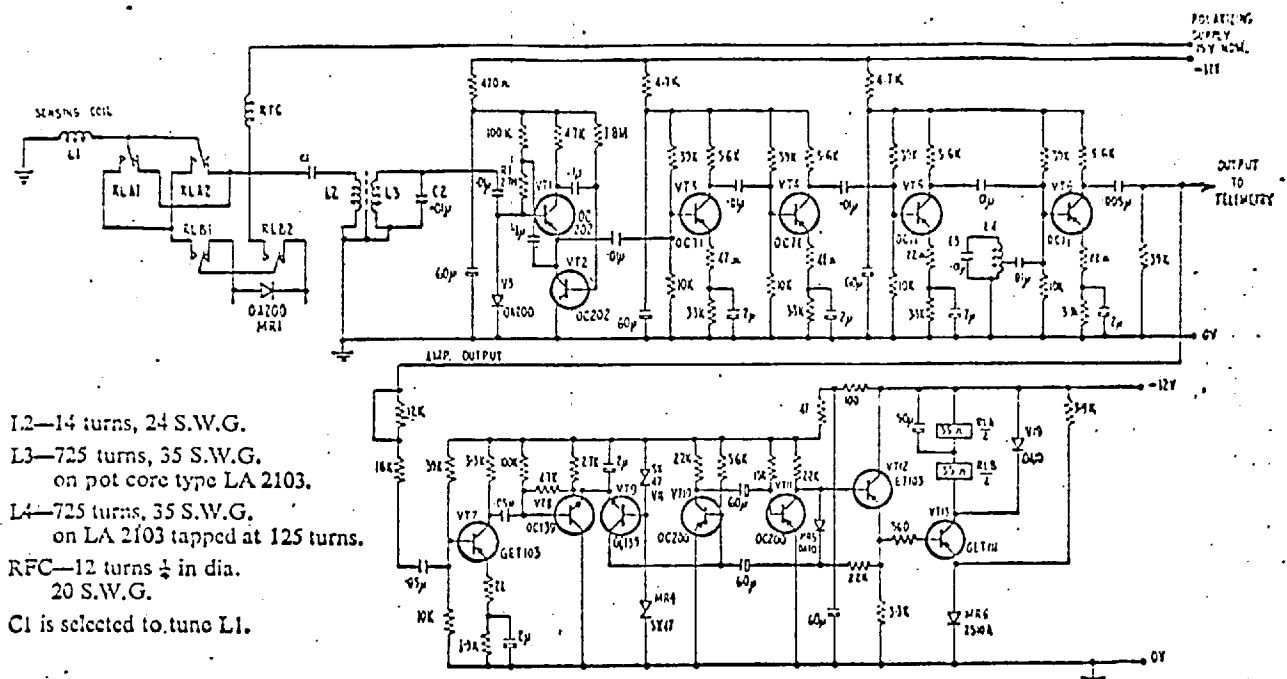
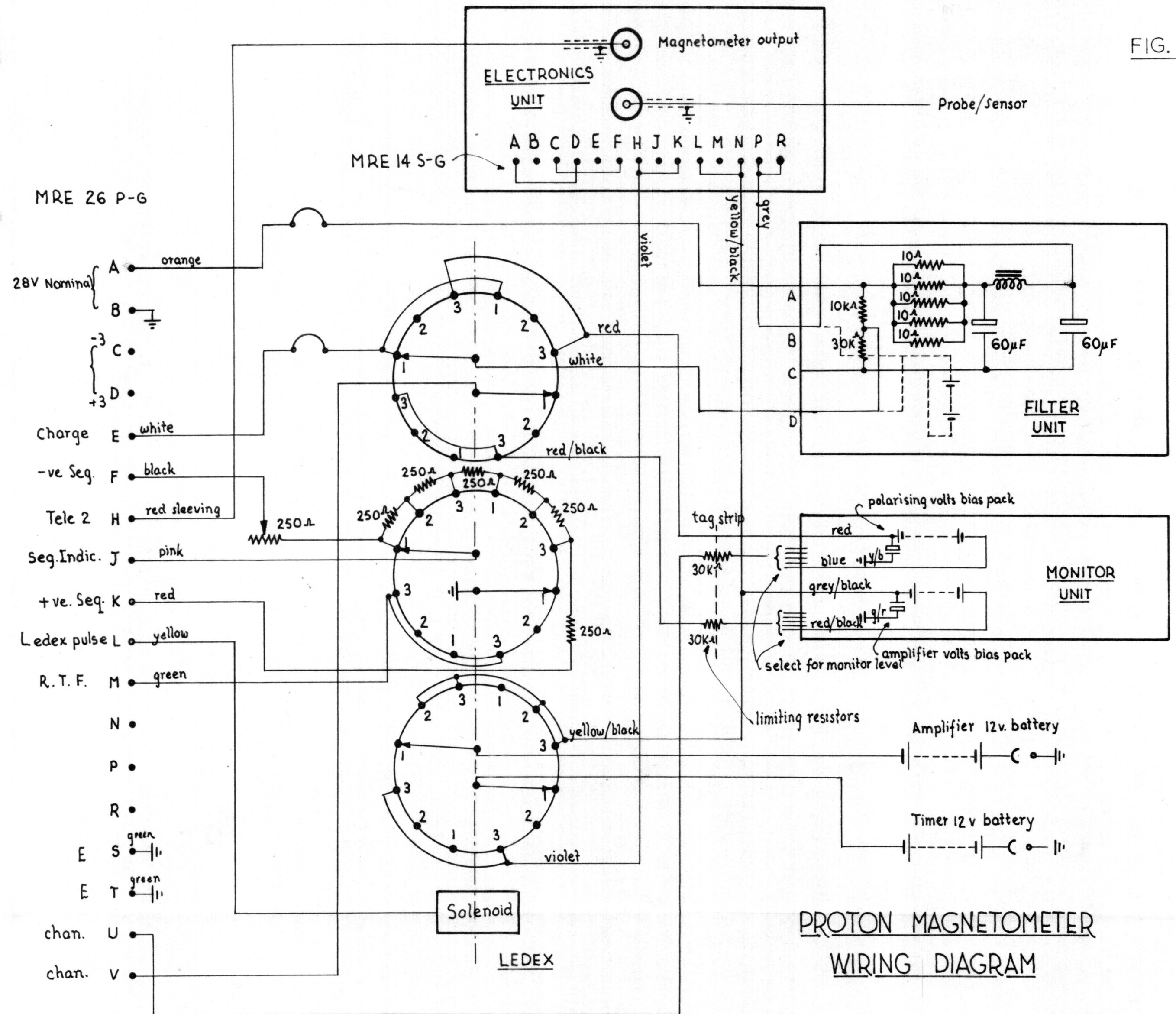


FIGURE 2.7 Proton magnetometer circuit diagram

FIG. 2.8



PROTON MAGNETOMETER
WIRING DIAGRAM

A Ledex Rotary Stopping Switch (Figure 2.8) essentially performs the function of switching on the magnetometer. This is done prior to launching (at a certain juncture of the 'count-down') and is initiated by an electrical pulse (from the external equipment used to prime the rocket for launching) to the solenoid of the Ledex. Switching occurs through 3 steps, namely

- (1) everything OFF
- (2) amplifier On
- (3) timer ON and polarizing supply ON
i.e. everything ON

The wafers, shown schematically in Figure 2.8, are synchronously rotated on a spindle, either automatically or manually (for test purposes). Contact is made through twin wipers on each wafer, which occupy positions 1, 2 or 3, as illustrated in Figure 2.8. Thus, the amplifier supply battery is OFF in position 1 and ON in position 2, when the connection is made via the bottom wafer and the yellow/black lead to pin N of the MRE 14 S-G socket on the electronics unit. In position 3, on the bottom wafer, the amplifier supply connection is maintained and the timer supply battery is connected via the violet lead to pin H on the electronics unit. When the timer is thus energised the 28 volt polarizing supply from the rocket batteries (pin A of MRE 26 P-G), which is connected directly to the filter unit where it is stepped-down to 24 volts and then to the electronics unit (pin P), is switched to the sensing head. Also in position 3, the polarizing and amplifier supplies are connected, via the top wafer, to the monitor unit and thence to channels U and V of the telemetry sender.

In position 3 on the middle wafer the lower, earthed wiper is connected to pin M of MRE 26 P-G and thence to the external rocket-priming unit. The earthed condition is used to indicate that position 3 has been reached in the switching sequence and that, therefore, the magnetometer experiment is ready to fire (R.T.F.). The complete switching

sequence is indicated in the priming unit by tapping the circuit formed between pins F and K of MRE 26 P-G, via the middle wafer. Tapping is done by the wiper which is directly connected to pin J of MRE 26 P-G. The variable 250 Ω potentiometer between pin F of MRE 26 P-G and the wafer is used to adjust the levels indicating positions 1, 2 and 3 on the priming unit.

2.5 Data analysis - Imperial College magnetometer

Good telemetry records were obtained up to + 456 sec. on SL 130 and up to + 530 sec. on SL 131. The telemetry signals were recorded on a 24 channel tape-recorder, at a tape speed of 60 inches/sec., from - 80 sec. to loss of signal. The Range Timing Code and a 50 Kc/s reference frequency were co-recorded with the signals. The tape was subsequently replayed at Weapons Research Establishment, Salisbury, South Australia, for recording on film, at various speeds, as follows. The Imperial College magnetometer signals (from Sender 2) were replayed at 8 inches and 64 inches per second. The signals from Sender 1 were replayed at $\frac{1}{4}$ inch, 2 inches and 4 inches per second.

The following analytical technique is due to Burrows (1965). The frequency of the magnetometer precession signals is measured from the data recorded on magnetic tape, as follows. Figure 2.9 is a block diagram of the equipment used in the analysis. The principle is to 'beat' the precession frequency against a known frequency close to the precession frequency; a manual count of the beat frequency gives the difference between the precession and the known frequency. The 50 Kc/s reference signal is doubled before being divided down, in order to provide five different known frequencies. To accommodate the range of precession frequencies encountered during the flight the division was such as to give

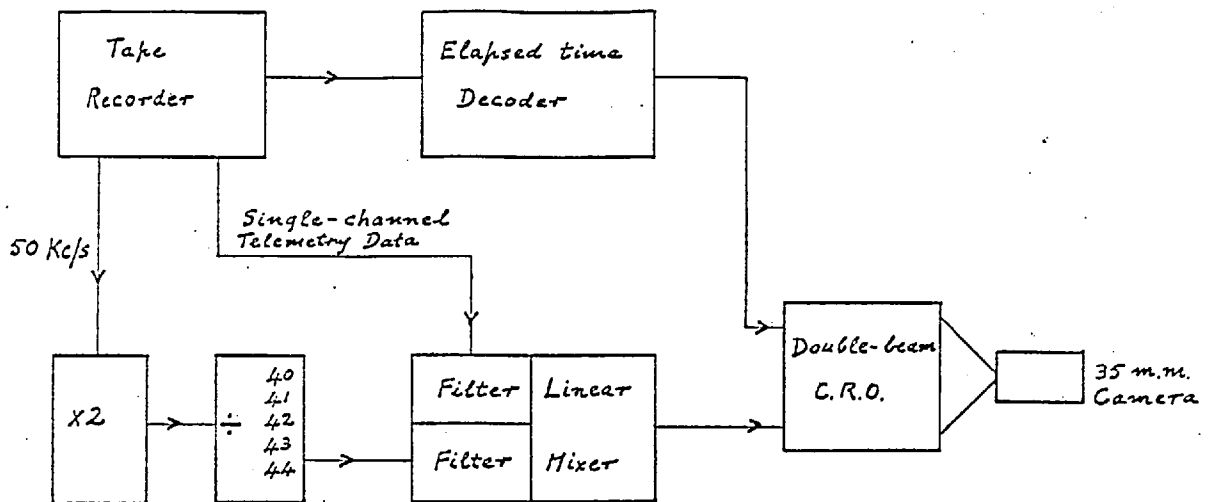


FIGURE 2.9 Block diagram of equipment used in analysing the magnetometer data

known frequencies of 2500.00, 2439.02, 2380.95, 2325.58 and 2272.73 c/s. As the interval between known frequencies is less than about 60 c/s, beat frequencies are always less than about 30 c/s. The output from the divider unit is in the form of pulses, with a mark/space ratio which varies with the dividing factor. A filter unit is used to standardise the mark/space ratio of this output before it is fed to the linear mixer. The magnetometer signal is filtered during play-back to improve the signal/noise by reducing the bandwidth, viz. the signal/noise can be improved by an approximate factor of $(\frac{100}{B})^{\frac{1}{2}}$ where 100 c/s is the bandwidth of the rocket magnetometer and B is the 3 d.B. bandwidth of the filter. The filter bandwidth is continuously adjusted, manually, (in the range 30 - 15 cycles) to 'track' the optimum signal/noise. The two filtered signals are then linearly mixed by means of a resistance network. Because the 50 Kc/s reference was recorded on the same tape as the precession signal, there is first-order compensation for any variations in precession frequency due to variations in tape speed. The 35 mm. film displays the 'beats' along with the timing code, in divisions of 10^{-2} sec., so that beat frequencies can be computed by measuring the duration of a fixed number of cycles.

A preliminary analysis of the data was made by inspecting the 8 inch/sec. replay-film of the magnetometer signals. The purpose was to reject (a) those portions which showed frequency modulations due to rotational motions of the sensor (Hall, 1962) as the rockets precessed in flight, and (b) precession signals of very short duration or very poor quality. Signals of a quality suitable for further analysis were obtained from + 88.5 sec. to + 328.5 sec. in the case of SL 130 and from + 87.0 sec. to + 312.5 sec. in the case of SL 131.

The value of geomagnetic total field intensity (F), corresponding to each value of precession frequency (fp) recorded during

the two flights, was computed from the equation

$$f_p \text{ in c/s} = 4257.8 F \text{ in gauss}$$

An upward continuation of the earth's main magnetic field was computed, by the Royal Greenwich Observatory, Hurstmonceux, from the coordinates of the range origin and the flight coordinates of the ballistic trajectory. The spherical harmonic coefficients used in the computation were those for the epoch 1965.0 due to Leaton, et al. (1965). Values interpolated from this theoretical field were subtracted from corresponding (in altitude and time) values of F to obtain values of the anomalous geomagnetic field (ΔF) encountered during the flights. Figure 2.10(a) shows values of ΔF for SL 131, plotted against time from launch, up to the time of re-entry (about + 290 sec.).

The initial amplitude of the precession signal and the ensuing period of free precession depend on the orientation of the sensor in the geomagnetic field, therefore signals from the rocket magnetometer vary in signal/noise ratio, duration T and, consequently, in accuracy. Although the signal/noise ratio is improved during the data-handling process to a degree dependent on maintaining an optimum filter bandwidth, the varying quality of beat patterns leads to errors δT in measuring the duration T of n cycles. The resulting error in the computed beat frequency would be

$$\frac{n}{T} - \frac{n}{T + \delta T} = \frac{n\delta T}{T^2 + T\delta T}, \text{ giving an error in } \Delta F \text{ of}$$

$$\frac{2\pi}{\gamma_p} \cdot \frac{n\delta T}{T^2 + T\delta T} \approx 23.5 \frac{n\delta T}{T^2}$$

$$(T\delta T \ll T^2)$$

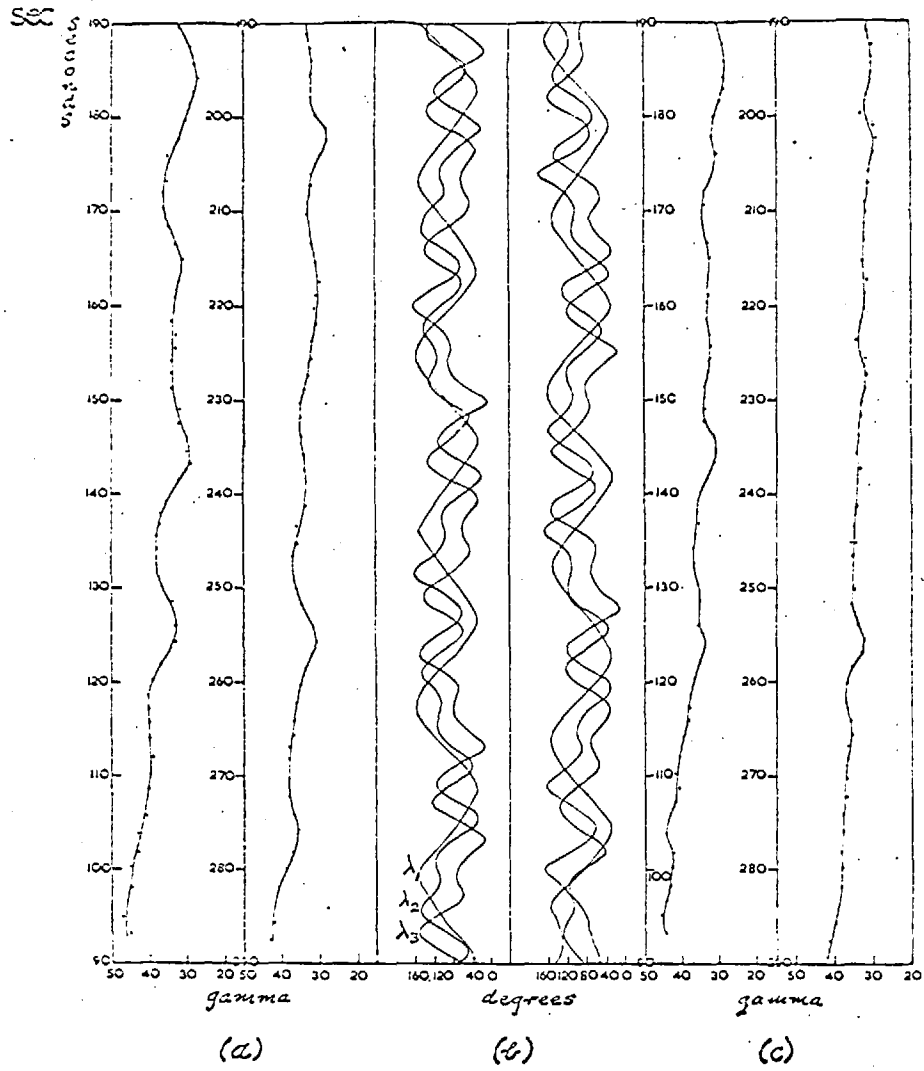


FIGURE 2.10 S.L.131: (a) ΔF , (b) angles ($\lambda_1 \lambda_2 \lambda_3$) between orthogonal rocket axes and ΔF , (c) ΔF , corrected for heading effect.

The duration of a good quality beat pattern can be measured to the nearest m. sec. on the timing code, i.e. δT can be estimated as ± 1 m. sec. In this case the errors in ΔF range from ± 2.6 gamma for $n = 10$ and $T = 0.3$ sec., sec., to ± 0.5 gamma for $n = 20$ and $T = 1$ sec. Precession signals of duration less than 0.3 sec. were rejected, during the preliminary analysis. The standard error of the mean in ΔF , calculated from several analyses of all the data, ranged from ± 2.9 gamma at $T = 0.3$ sec. to ± 1.0 gamma at $T = 1.2$ sec. In view of these errors in computed values of ΔF , the full line profile in Figure 2.10(a) has been drawn as the running mean of groups of 3 values.

It is apparent in Figure 2.10(a) that a heading effect of approximately 10 γ amplitude existed during the flight of SL 131. This consistent heading effect ΔF_R is attributed to magnetic fields localised in the rocket head section and, assuming the cause to be permanent magnetisation in the head section, can be expressed approximately as

$$\Delta F_R = A \cos \lambda_1 + B \cos \lambda_2 + C \cos \lambda_3$$

where λ denotes the angles between the orthogonal rocket axes and the geomagnetic total force vector; λ_1 is the angle made with the longitudinal rocket axis while λ_2 and λ_3 are the angles made with the transverse rocket axes. The three curves of Figure 2.10(b) were computed from the data of the rocket fluxgate magnetometers. The coefficients A, B and C were determined by a least squares selection of 10 equations from points on curve (a) in the interval + 193 to + 243 sec. Figure 2.10(c) shows the corrected running mean profile, using $A = -2$, $B = -1$ and $C = 1$.

Footnote Consistent values of the coefficients A, B and C were achieved for the results of SL 131 (by repeated applications of the least squares method) but not for the results of SL 130.

The inconsistency is explicable because the sensor was incorrectly deployed and probably swung into the magnetic field due to the head section many times during the flight of SL 130. For this reason, the heading error of about 10° seen in the results from SL 130 was not removed. The results from SL 130 are presented in the following section.

2.6 Results - the integrated rocket experiment

Figures 2.11 and 2.12 show all the results from the flights of SL 130 and SL 131, respectively, plotted on a common height scale. The significant features of the various curves are emphasised in the following, while a discussion of the qualitative correlation between these results and concurrent ionosonde observations of sporadic E is undertaken in the next section.

Ion density (Figure 2.11(a) and Figure 2.12(a))

The results of the positive ion probe experiment, conducted by University College, London, are presented as profiles of mean probe current. This current, the mean of the currents recorded at 2 probes spaced at 180° around the skin of the rocket, flows as a result of the attraction of ionospheric ions to the probe surfaces, therefore the current profiles are tantamount to profiles of ion density.

Footnote The results from the 4 experiments which made up the integrated payloads were freely exchanged between all experimenters from the 4 university groups involved in the launching of SL 130 and SL 131. The reduction and interpretation of data from experiments other than that of Imperial College was, of course, performed by members of the other groups concerned. The results of the positive ion density experiment have been presented by Dorling et al. (1969).

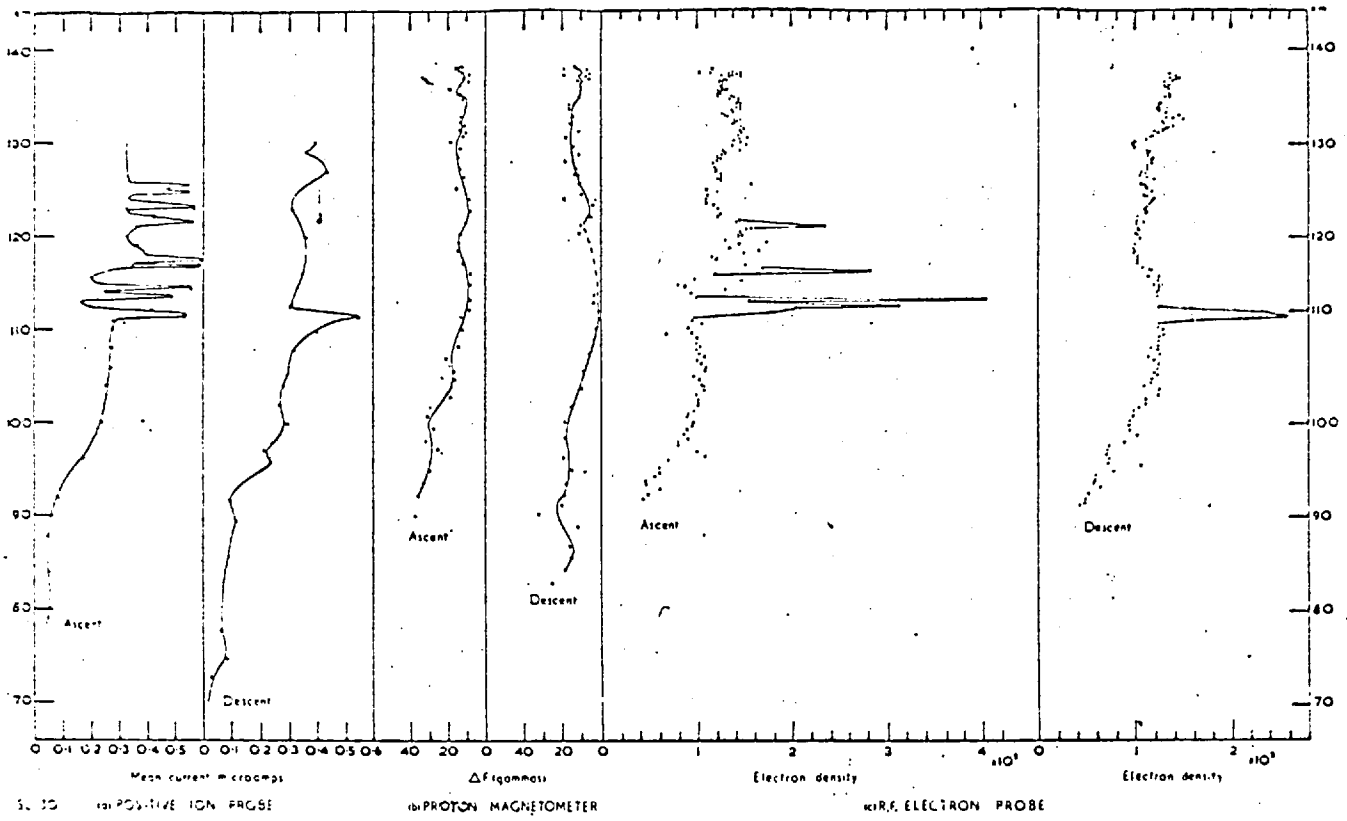


FIGURE 2.11 Results obtained from S.L.130

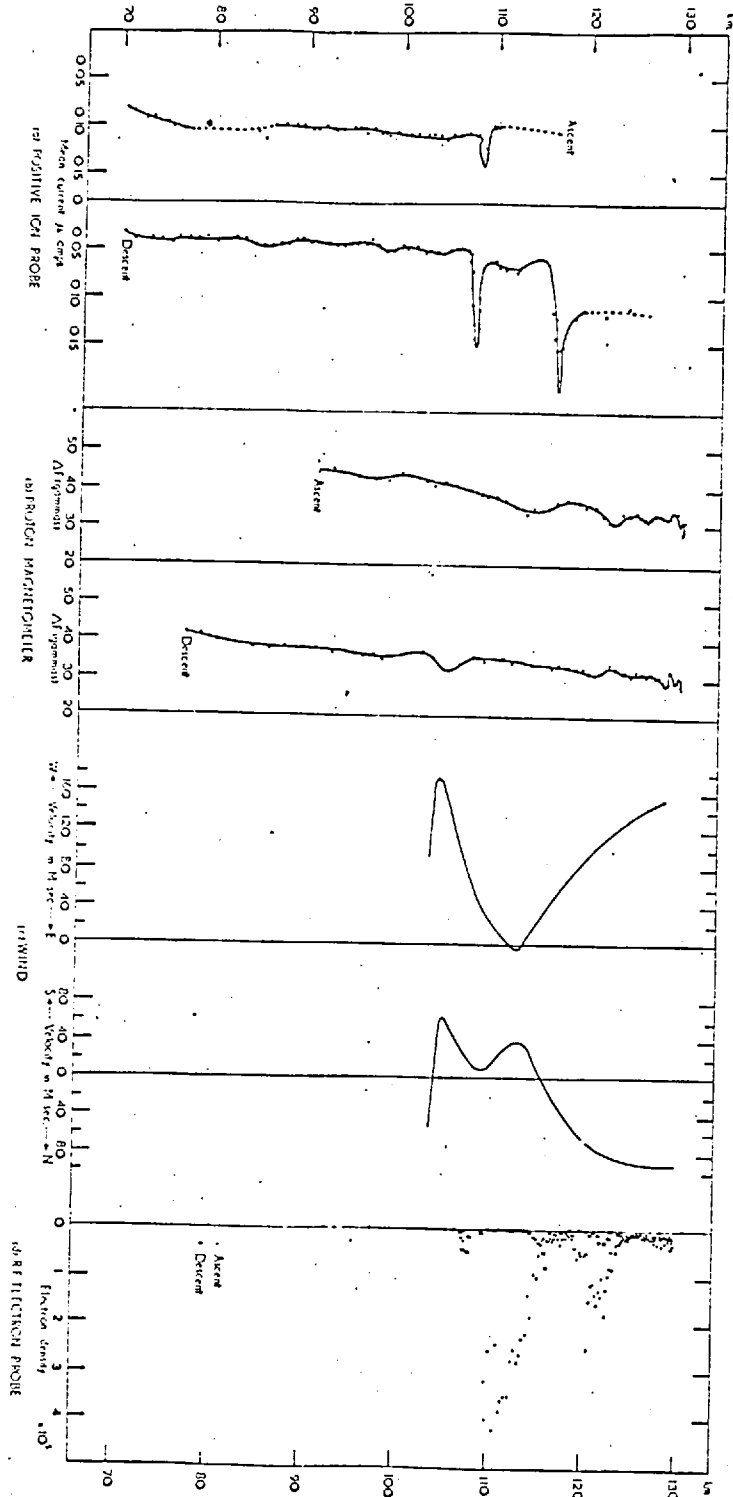


FIGURE 2.12 Results obtained from S.L.131

It was not possible to make absolute measurements of positive ion concentration on either flight because of the lack of detailed knowledge of the aspect of the rockets in flight. (An explanation of this emerges in what follows).

A probe current is modulated by in-flight rocket motions because the relative velocity of ions in the direction normal to the probe surface changes as the rocket aspect changes. It was impossible to make a detailed correction for this effect because the motions of SL 130 and SL 131 were too complex to allow a solution of the aspect data which was telemetered to ground. However, it has been found in previous rocket-borne ion probe experiments (Dorling et al., 1969) that, to a reasonable approximation, a probe at 90° to the direction of rocket motion collects half the current of a probe facing directly forwards, while a probe at 180° collects no current at all. Thus an approximate correction is made by taking the mean of two currents which are drawn from probes at 180° to each other on the skin of the rocket. The data points on the plotted profiles are the average values of groups of 4 measurements. Solar ultra-violet light causes emission of a secondary electron current, from the ion probe surfaces, comparable in magnitude to the positive ion currents. Thus the ionization profile of Figure 2.11(a) is modulated by this secondary current. Because a solution of the SL 130 aspect data has not been found, it has not been possible to correct for this modulation. It was possible, however, to make a rough correction, because of the comparatively simple rocket motion, for this effect in the results from SL 131. Therefore the profile in Figure 2.12(a) has been de-modulated.

During the ascent of SL 130 signals from the probes were swamped between 111 km. (+ 115 sec.) and 125 km. (+ 140 sec.) Figure 2.11(a). This is thought to be a result of the presence of lithium vapour, which was released into the ionosphere at + 110 sec., + 120 sec. and + 130 sec.

Above 125/km, and on the descent, good signals were received from the probes. The descent profile indicates a well defined layer of enhanced ionization at approximately 111 km.

During the ascent of SL 131 a layer of enhanced ionization was detected at about 108 km (+ 115 sec.), (Figure 2.12 (a)). Immediately after this the probe signals were again swamped by the release of lithium (it is thought). The profile from 108 km. to apogee has not been plotted. The signals received during descent were clean, apart from a noisy event at $117\frac{1}{2}$ km. (+ 236 sec.) which Dorling et al. (1965) have ascribed to interference caused by the sodium burners. (Sodium was released during descent at + 225, + 235 and + 245 sec. from burners attached to the separated motor section). A very clean event occurred at 108 km. (+ 252 sec.) which clearly corresponds with the layer of enhanced ionization detected at the same height during ascent. As Dorling et al. (1965) point out, the difference of approximately 0.05μ amp between the ambient ion current during ascent and that during descent is a reflection of the drop in background ionization due to the twilight fading of the E-layer (twilight occurred in the $2\frac{1}{2}$ minutes between ascent and descent). (Also, it can be seen in Figure 2.11(a) that the level of background ionization increases above about 90 km., which level can be regarded as the base of the E-region during daylight).

Magnetic field (Figure 2.11(b) and Figure 2.12(b))

The results from SL 130 are presented as a height profile, in Figure 2.11(b). Between 120 km. and 115 km., approximately, during descent (the dotted portion of the curve) the signals were of poor quality because the sensor was in unfavourable attitudes as a result of faulty probe deployment. Weekes' prediction of a magnetic field minimum coincident with a layer of E_s is not substantiated by the profile; which

has no outstanding minimum. The concurrent ionograms (Figure 2.1) indicate E_s layers of the blanketing type at 120 km. and 125 km. approximately and a small minimum can be detected on the profile at about 122 km., on both ascent and descent. However, because of the unsatisfactory deployment of the magnetometer sensor on this flight and because a heading error has not been removed from the data, the profile must be regarded as being of dubious accuracy. Any more detailed interpretation would be speculative and it cannot be said that these results provide a reliable test of Weekes' suggestion.

The results from SL 131 (Figure 2.12(b)) give a profile having a distinct minimum on the descent leg at about 105 km. An E_s layer was recorded at 108 km. on ionograms taken at the time of the flight (Figure 2.3). It is therefore possible that this magnetic field minimum constitutes a confirmation of the suggestion made by Weekes. There is no corresponding minimum at 105 km. on the ascent leg of the profile. The ascent leg does, however, have a minimum at about 122 km., which may correspond to an ill-defined minimum at about 121 km. on the descent leg, and a perturbation at about 115 km. which may be regarded as a minimum. The relevant ionograms indicate only one layer of E_s , at 108 km., so that these minima are probably not associated with E_s but may be due to ionospheric currents.

Electron densities (Figure 2.11(c) and Figure 2.12(d))

The results obtained from the electron probe on SL 130 (Figure 2.11(c)) indicate 3 or 4 peaks of electron density at about 111 km., 113 km., 116 km. and 121 km. during ascent and at about 111 km. during descent. It is thought that the 3 peaks occurring above 111 km., on ascent only, may be due to interference from the lithium burners; the same interference which swamped the positive ion probe results between 111 km. and 125 km. The burners were mounted on top of the separated motor section,

therefore the distance by which they were separated from the electron probe during the rest of the flight is not known. On the other hand, as the relevant ionograms (Figure 2.1) indicate that 2 or 3 layers of E_s were present both 63 sec. before and 145 sec. after firing time (which is during ascent) but that only 1 layer of E_s was present 347 sec. after firing time (during descent), it is possible that the three higher peaks on the ascent leg may represent E_s electron-concentrations. This second possibility is supported to a certain extent by Plate 2.1(a) which shows the separated motor section at some apparent distance from the rear of the head section; the photograph being taken approximately 16 sec. before the first lithium burner was ignited. There is little doubt that the peak at about 111 km., on both ascent and descent, represents a layer of E_s . Quantitatively, the peak electron densities which can be read from Figure 2.11(c) agree quite closely with those deduced from the relevant ionogram, viz.

3.0×10^5 at 111 km. on ascent

2.6×10^5 at 111 km. on descent

c.f. 2.63×10^5 from the ionogram

Similarly, the ambient electron density from Figure 2.11(c) is between 1×10^5 and 2×10^5 which compares with the E-region electron density of 1.42×10^5 deduced from the ionogram.

The results from SL 131 (Figure 2.12 (d)) show a small peak at about 108 km. on both ascent and descent, which correlates with the ion density peak and the recorded sporadic-E layer at that height.. The precessional motion of the rocket head periodically carried the probe into an electron-depleted region, in the wake of the head, at about 21 sec. intervals. This produced a cyclic pattern of maxima and minima in the probe results, up to apogee and throughout the descent. Thus, a minimum appears at about 117 km., a maximum at about 121 km. and a further minimum at about 125 km. The higher part of the broad peak around 110 km., may be

one such maximum. Electron densities read from Figure 2.12 (d) do not agree exactly with that deduced from the relevant ionogram, viz.

0.8×10^5 at 108 km.

c.f. 2.08×10^5 from the ionogram

4.0×10^5 at 110 km.

They are however of the same order of magnitude.

The above interpretation of these results is essentially the same as that originally made by E. C. MacKenzie then of Birmingham University, (Present address: Physics Department, University of Adelaide).

Winds (Figure 2.12(c)).

As previously stated, wind information was obtained from SL 131 only. The results presented were obtained from the lithium vapour trail which, due to the twilight conditions prevailing and the camera filters used, gave better results than the sodium release. The results were interpreted by G. J. MacGratten of Queen's University, Belfast.

The measured wind velocities were resolved into east-west and north-south components, to give the two curves of Figure 2.12(c) which are smoothed profiles of measurements taken at 2 km. intervals with an accuracy of ± 5 m/sec. Indicated directions are those towards which the wind was blowing.

Summary

In the case of SL 130 the presence of an E_s layer at approximately 111 km. is pretty well established by the ion probe results, the electron probe results and the ionograms. The co-existence of at least two higher layers of E_s (between 110 km. and 120 km.) is suggested by the electron probe results and the ionograms. The magnetic results contribute nothing to the evidence.

In the case of SL 131 the existence of an E_s layer at 108 km. is well established by the ion probe results and the ionograms. In view of this, the peak of electron density at 108 km., although small compared with the major peak at 110 km., may truly represent the E_s layer. The larger peak at 110 km. could be due to the wake effect already mentioned. The magnetic results indicate the E_s layer at 105 km. A possible explanation of such a height discrepancy will be discussed later, as will the role which the ionospheric winds play in the formation of such E_s layers.

C H A P T E R 3

DISCUSSION OF THE ROCKET FLIGHTS

The wind-shear theory of sporadic-E formation (Whitehead, 1961 - as corrected by Hines, 1964) requires a +ve. E. - W. shear, interacting with the geomagnetic force, to compress ionization into a sporadic-E layer. Therefore the evidence from SL 131 of a sporadic-E layer existing at 108 ± 1 km. in a region of -ve. E. - W. shear appears to contradict the theory. The rest of the discussion is concerned with the validity of this apparent contradiction. Similar evidence of sporadic-E layers existing in regions of -ve. E. - W. wind-shear was reported by Bowen et al. (1964), who consequently suggested that the formation of sporadic-E is not dependent on the sense of the wind-shear. The doubt which that work cast on the wind-shear theory has become established in the literature, (*Aubry et al., 1966; *Dorling et al., 1969; Matsushita, 1966; Tsuda et al., 1966; Kato, 1966), even to the extent that Whitehead (1970), in a review article on Sporadic-E, emphasizes the need to clarify the relationship between sporadic-E and wind-shear in order to test the wind-shear theory.

Bowen et al., from two evening firings at 1836 hr. L.T. and at 31° N. latitude, found positive ion density peaks associated with a +ve. E. - W. wind-shear at approximately 95 km. and with -ve. E. - W. shears in two instances at approximately 115 km. The ion density and wind velocity measurements were made during ascent and descent respectively, so that they were separated horizontally by 20 - 30 km. The results of a third firing, at 1939 hr. L.T., for which the horizontal separation of measurements was 90 km., showed no correlation between ion densities and wind-shear. Whitehead (1970) has emphasised the importance of such space and time discrepancies in the interpretation of rocket results. Two very patchy

sporadic-E layers, at 98 ± 2 km. ($f_c E_s = 2.0$ Mc/s) and at 127 ± 2 km. ($f_c E_s = 1.8$ Mc/s), were recorded on the single ionogram available for the first 1836 hr. L.T. firing. Bowen et al. identified the lower sporadic-E layer with the ion layer at 95 km., where the sense of the wind-shear is theoretically correct, but suggested that the upper sporadic-E layer is associated with a third ion layer at approximately 130 km. rather than with the ion layer at 115 km. It is noteworthy that the wind profile showed a +ve. E. - W. shear in the region of 127 km. In view of the space and time discrepancies inherent in the experiment, the association of ion layers with -ve. E. - W. wind shears at 115 km. might have been fortuitous. Alternatively these ion layers may belong to a class of ionization phenomena, detectable by probes but not by ionosondes, whose exact nature and cause is not known although they are akin to sporadic-E. (Hines, 1966). In either case Bowen et al. have not in fact demonstrated the existence of an identified sporadic E layer in a region of -ve. E. W. wind-shear. On the contrary, no sporadic-E layer appeared at 115 km. on the ionogram but two were identified, at 98 and 127 km., in regions of +ve. E. - W. wind-shear. Therefore it seems that Bowen et al. were not justified in concluding that the formation of sporadic-E is independent of the sense of the wind-shear.

Bowen et al. cited the results of Rosenberg et al. (1964) as interpreted by Hines, 1964 as further evidence of the independence between sporadic-E and the sense of the wind-shear. Rosenberg et al. compared wind velocities measured from vapour trails with nearly simultaneous ionograms in four flights (1720 hr., 1801 hr., 2145 hr. and 2245 hr. L.T.) on 3 December, 1962 at 29.6° N. latitude. The results showed sporadic-E layers were correlated with +ve. E. - W. shears at 109, 108, 103 and 100 km. during the 1720 hr., 1801 hr., 2145 hr. and 2245 hr. L.T. and that no corresponding sporadic-E layer was recorded. These results therefore support the wind-shear theory except for the case of sporadic-E

occurring at 96 km. Chimonas and Axford (1968) have shown that a sporadic-E layer, formed according to the wind-shear theory at altitudes above 145 km. and carried downwards on a neutral wind-profile having a descending phase velocity, can be dumped in the 85 - 95 km. region. Because the wind profile then continues its descent, the sporadic-E layer can co-exist with either a +ve. or a -ve. E. - W. wind-shear in the vicinity of 95 km. An examination of the E. - W. component wind profiles given by Rosenberg et al. indicates strong support for the Chimonas and Axford theory - the profiles maintain a wavelength of approximately 12 km. while descending at speeds of 1.5 - 3.0 km./hr. Thus, the correlation of sporadic-E layers with -ve. E. - W. shears at 96 km. can be explained by the Chimonas and Axford theory, so that the results of Rosenberg et al. thoroughly support the wind-shear theory.

Consequently, in the present author's opinion no acceptable experimental evidence against the wind-shear theory has yet been presented. There is, however, evidence from rocket experiments (Rosenberg et al., 1964; Wright et al., 1967) and from a recent Mitra drift experiment (Wright and Feddor, 1969) in support of the theory. In view of this, it is worth re-examining the results from SL 131 to see if they are truly at variance with the theory. First, the location of the Woomera ionosonde w.r.t. the rocket trajectory is such that the horizontal separation between the wind measurements and the vertical incidence ionosonde readings was no greater than 10 km.

Dorling et al. (1969) have ascribed the ion density peak observed at 108 km. during both ascent and descent of SL 131 to a sporadic-E layer, but have discounted the ascent profile above 108 km. and the peak at 116 km. during descent as being effects of the release of lithium and sodium. Lithium was released in three stages nominally at + 110, + 120 and + 130 sec., (the probable maximum deviation in time being 3%), thus, from the best-fit ballistic trajectory of SL 131, at altitudes

of 104.5 ± 2 , 111.0 ± 2 and 116.5 ± 2 and 116.5 ± 2 km. Similarly, sodium was released at altitudes of 121.5 ± 3 , 117.2 ± 4 and 111.9 ± 4 km. In the case of SL 130 Dorling et al. have ascribed the several ion density peaks between 111 km. and 125 km. during ascent to effects of the release of lithium, and the peak at 111 km. during descent to a sporadic-E layer. (There was no release of vapour during the descent of SL 130.) The altitudes at which lithium was released were 107.9 ± 2 , 115.0 ± 2 and 121.1 ± 2 km. If the release of lithium and sodium vapour did cause spurious peaks of ion density, one would expect such peaks at 104.5 ± 2 km. during ascent of SL 131 and 107.9 ± 2 km. during ascent of SL 130. Their absence suggests that, contrary to Dorling et al., the release of vapour did not interfere with the ion probe results; in which case layers of enhanced ionization are indicated at 108 km. and 116 km. for SL 131 and between 111 km. and 124 km. for SL 130. This is readily confirmed in the case of SL 130 by the relevant ionograms, which show the presence of at least two sporadic-E layers with virtual heights in the region $110 - 120 \pm 2$ km. This situation persisted throughout the flight so that the presence during descent of only a single, well-defined ion density peak, at 111 km., requires an explanation. The rocket during ascent through the region 111 - 125 km. was 5 - 15 km. from the ionosonde, whereas during its descent through the same region it was 45 - 55 km. from the ionosonde. The horizontal extent of sporadic-E layers, or patches, is known to be very variable, therefore the difference between ascent and descent legs of the ion density profile may be a true reflection of ionospheric conditions at the time. In addition, the observed electron density peaks of 4.0 , 2.8 and 2.6×10^5 electrons/cm.³ at 112, 116 and 121 km. respectively are the same order of magnitude as the electron density calculated from the blanketing frequencies shown on the ionograms, ($2.6 - 2.7 \times 10^5$ electrons/cm.³), which lends support to the suggestion that the observed peaks of both ion and electron density are due to sporadic-E and not to interference effects. In the

case of SL 131 the presence of a sporadic-E layer at 108 km. is clearly established by the ionograms, which indicate only one, strongly-blanketing ($f_oE_s = 4$ Mc/s) layer. The electron density results are confused by the wake-effect, but a peak at approximately 116 km., in addition to one at 108 km., can be discerned. This information is insufficient to establish the presence of a sporadic-E layer at 116 km. However, a revised form of the wind-shear theory (MacLeod, 1966) has shown a strong tendency for sporadic-E to form at levels where ions are converging and their vertical drift velocity is zero. A profile of ion velocity for SL 131 (Figure 3.1), derived from the E. - W. wind profile (Figure 2.12 (c)) and values of the parameter ρ_+ (the ratio of ion-neutral collision frequency to ion cyclotron frequency) given by MacLeod, indicates a convergent node of zero ion velocity W_i between 114 and 115 km. (Positive values of W_i indicate upward velocity). The wind measurements, and consequently the calculated ion velocities, are accurate in height to approximately ± 2 km., therefore it is possible to correlate the convergent node with the ion and electron density peaks at 116 km., thereby supporting the suggestion of a sporadic-E layer at that level.

Thus it seems possible that two sporadic-E layers existed during the flight of SL 131. The higher layer, at 116 km., can be accounted for by the +ve. E. - W. wind-shear at that altitude, in accordance with the wind-shear theory. The position of the lower layer at 108 km. in a region of -ve. E. - W. wind-shear is ostensibly a contradiction of the wind-shear theory. As Dorling et al. (1969) have pointed out, the hypothesis offered by Chimonas and Axford (1968) to account for sporadic-E layers observed in regions of -ve. E. $\rightarrow$ W. shear does not apply in the present case. However, the estimated error in height of ± 2 km. for the wind profile allows the possibility that a region of +ve. E. $\rightarrow$ W. shear, located below 105 km. on Figure 2.12(c), may in fact have existed at about 107 km. so

SL.131, VERTICAL ION VELOCITY PROFILE

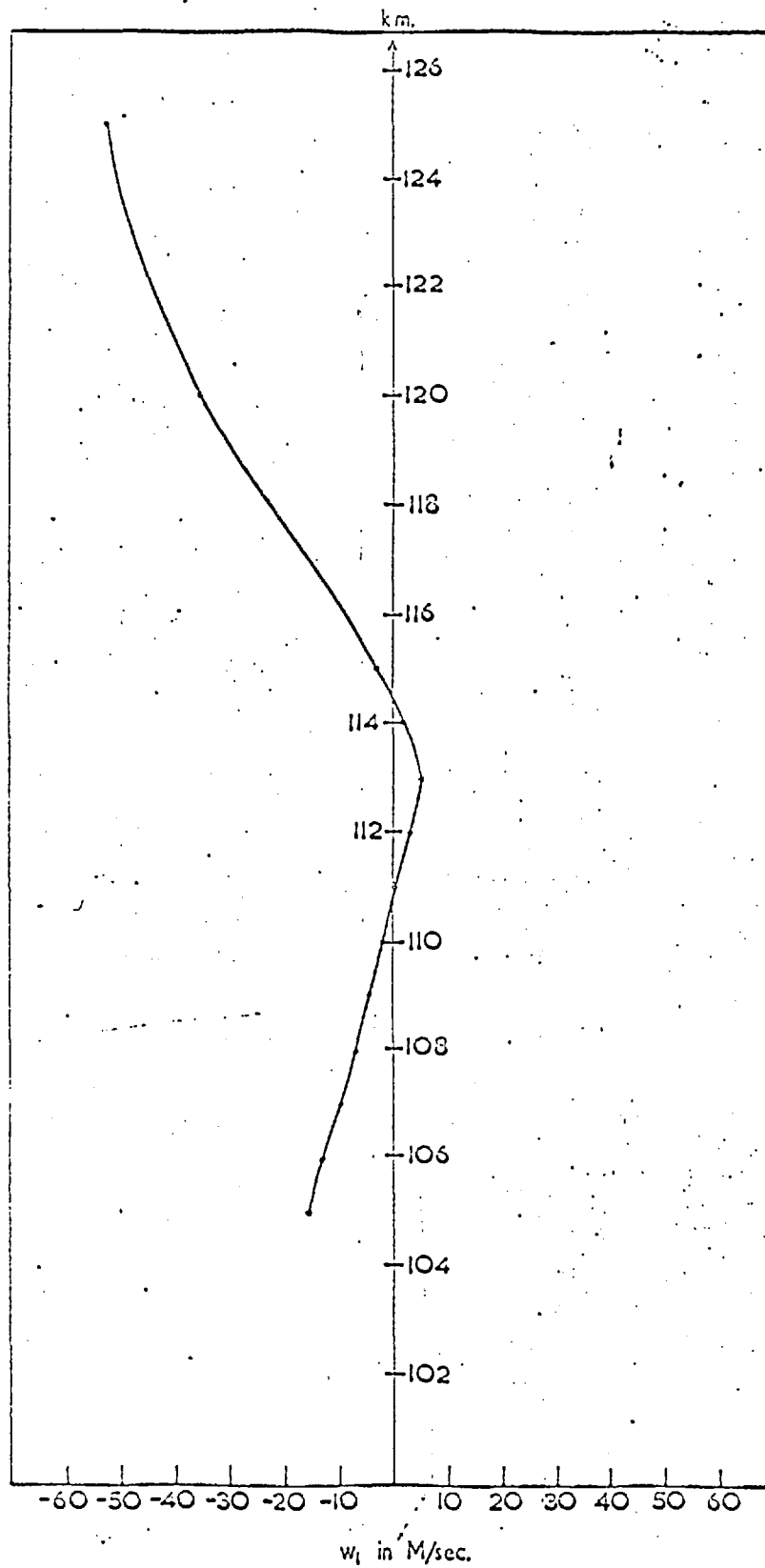


FIGURE 3.1

as to encompass the sporadic-E layer. It should be remembered that the virtual height of the sporadic-E layer, 108 ± 1 km., is greater than the true height and that, according to Chimonas and Axford, the ionization is located slightly above the convergent node on the wind profile. Although this suggestion may seem to stretch the evidence as far as possible, its validity should be judged in the context of previous results which have shown sporadic-E layers at medium altitudes (95 - 120 km.) associated only with +ve. E. - W. wind shears.

The results of the magnetic experiment on SL 131 remain to be discussed. Since Weekes put forward his suggestion, Axford, Cunnold and Gleeson (1966) have shown theoretically, by extending the wind-shear theory to include the effects of electric fields, that a minimum in total magnetic field intensity should roughly coincide with the maximum electron density within a sporadic-E layer which has been formed according to the wind-shear theory. They have calculated that in twilight conditions, (as was the case for SL 131), when the sporadic-E layer consists mainly of slowly-recombining ion species, the magnetic minimum should be of the order of 3.5γ . Thus the 5γ minimum which occurred between 105 and 106 km. during descent of SL 131 may be associated with the sporadic-E layer at 108 km., in the manner suggested by Axford et al. The discrepancy of 2 - 3 km. in height is not serious. The height resolution of the magnetometer was no better than 1 km. and, in addition, Axford et al. have pointed out that the magnetic minimum does not usually coincide exactly with the electron density maximum. If a +ve. E. - W. wind-shear existed in the region up to about 108 km., as has been suggested here, the observed magnetic minimum can be explained by the theory of Axford et al. Its presence also substantiates Weekes' suggestion. Because the magnetic experiment recorded a distinct minimum on only one occasion, out of a possible four on SL 130 and three on SL 131, it cannot, in its present

form be regarded as a reliable means of detecting sporadic-E. Either the measuring rate of the magnetometer requires to be increased, or the Axford, Cunnold and Gleeson theory is not sufficiently general.

CONCLUSIONS

A careful interpretation, taking account of experimental errors, of the results from SL 130 and SL 131 has shown it possible to explain the existence of two sporadic-E layers during the flight of SL 131 by means of the wind-shear theory. A layer at 108 km. appears, from the experimental profiles of ion density, electron density and wind velocity (Figure 2.12), to exist in a region of -ve. E. - W. wind-shear; which is contrary to the prediction of the wind-shear theory. However, the height-errors inherent in the wind velocity measurements allow the possibility of 'raising' a portion of the wind profile having +ve. E. - W. shear to encompass the sporadic-E layer at 108 km. This interpretation in accordance with the wind-shear theory is preferred because previous rocket experiments have provided satisfactory evidence of sporadic-E layers existing in association with +ve. E. - W. wind-shears, but not with -ve. E. - W. shears. Two such previous experiments (Bowen et al., 1964 and Rosenberg et al., 1964) have been examined in detail to show that Bowen et al. are not justified, because of the experimental errors involved, in saying that their results prove the existence of sporadic-E layers in regions of -ve. E. - W. wind-shear. The presence of a second sporadic-E layer, at 116 km., has been deduced from the ion density results and a calculated profile of ion vertical-drift velocity, although the layer was not seen on ionograms taken during the flight of SL 131. A 5 γ minimum in magnetic intensity recorded at 105 - 106 km. during the descent of SL 131 can be taken as confirmation of Weekes' suggestion that a sporadic-E layer has an intrinsic magnetic field. Its presence is explained by the later theory of Axford et al. (1966). In general, the present work emphasises the need for stricter experimental accuracy in future investigations of the sporadic-E phenomenon, which is so variable in time and space.

C H A P T E R 4

THE GROUND EXPERIMENT

The experiment was conducted during November and December, 1965 at the Woomera Rocket Range, South Australia. It involved continuous measurement of the total intensity of the geomagnetic field at ground level. In addition, ionograms provided from the Woomera ionosonde were examined for the occurrence and characteristics of sporadic-E.

4.1 Description of the magnetometer

The instrument used was a self-oscillating rubidium vapour magnetometer, designed and built in the Geophysics Department of Imperial College, (Usher, Stuart and Hall, 1964, and Stuart, 1964). The magnetometer was originally designed for rocket and satellite experiments but can be used as a ground instrument, in which capacity it has proved its high reliability and sensitivity at several magnetic observatories over a number of years.

The Sensing Head (Figure 4.1)

The Rubidium lamp comprises a 1 cm. glass bulb, containing a 0.1 mg of natural rubidium in a buffer gas of krypton at low pressure (1.5 mm Hg), enclosed in an evacuated jacket, and a small power oscillator which produces lamp excitation by applying a radio-frequency field to coils wound round the bulb. The gas cell is a 2 inch diameter, 1.5 inch-long glass cylinder containing 0.3 mg of rubidium in a buffer gas of helium at 20 mm Hg. A radio-frequency coil is wound on a former round the cell and the cell unit is lagged with expanded polystyrene. The cell is heated to its operating temperature of 25 - 45° by passing a current of several amps through the coil. The thermal lagging is sufficient to maintain operational temperature in the cell for the several minutes of a short duration rocket

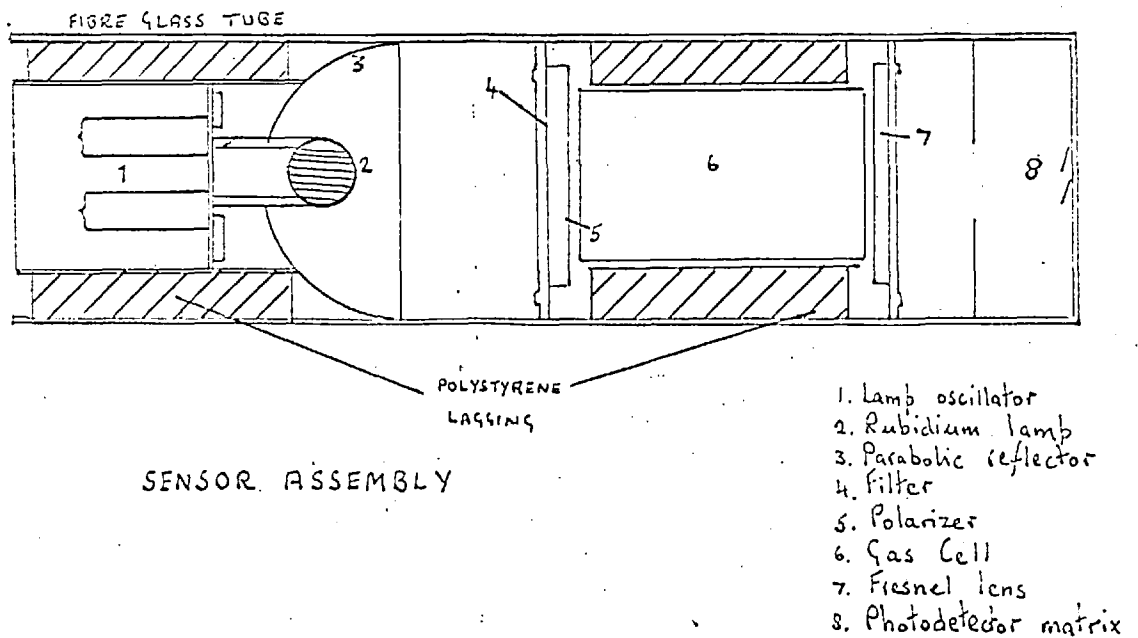
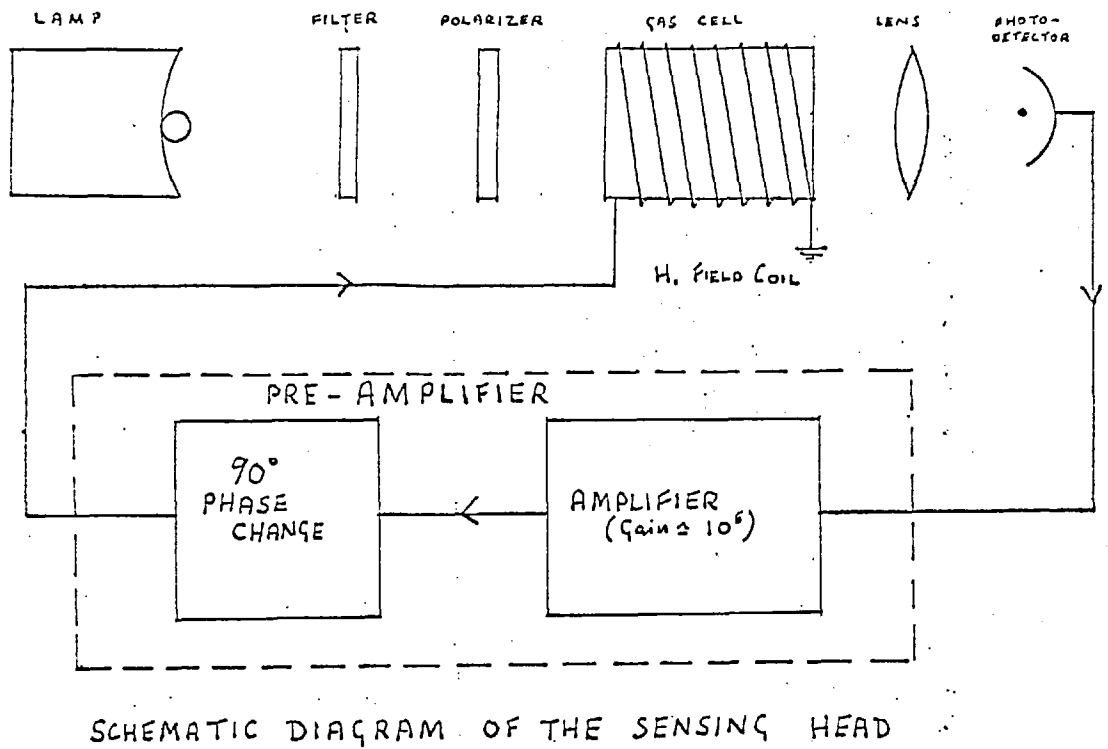


FIGURE 4.1 Rubidium vapour magnetometer after Usher, Stuart and Hall (1964)

flight but protracted ground operation requires an active thermal control system, (the thermal enclosure).

Principles of Operation

A technique of optical pumping and monitoring was developed by Dehmelt to produce and detect the separation of Zeeman sub-levels (Figure 4.2) and thereby measure the total intensity of the ambient geomagnetic field.

The light emitted from the rubidium lamp is filtered to pass the D_1 spectral line ($7948 \text{ }^\circ\text{A}$) and reject the D_2 line ($7800 \text{ }^\circ\text{A}$), circularly polarized and passed through the gas cell approximately in the direction of the ambient magnetic field vector. Optical pumping then takes place in the following manner. The light emitted in the direction of the magnetic field vector consists of two groups of σ -components, one right-hand circularly polarized and the other left-hand circularly polarized. The polarization is then made uniformly right-handed by the choice of polarizer. Energy transitions in atoms of the rubidium vapour are thereby governed by the selection rule $\Delta m_F = +1$ because the component of the atomic magnetic moment parallel to the light beam is increased one quantum by the energy of the magnetic vibrations of the right-hand circularly polarized e.m. wave. Transitions are also governed by the selection rules $\Delta l = \pm 1$ and $\Delta j = \pm 1, 0$, plus the fact that a photon of D_1 light can excite atoms in the $5^2S_{1/2}$ ground state into the $5^2P_{1/2}$ state only (Figure 4.2). Note that $\Delta f = 0$ because $\Delta j = 0$ and i is constant ($i = 5/2$ for Rb^{85}). Thus a typical transition involving a valence electron is from the level ($l = 0, j = \frac{1}{2}, f = 3, m_F = +2$) to ($l = 1, j = \frac{1}{2}, f = 3, m_F = +3$). The excited electron tends to return to a lower energy with emission of a quantum of light, but this transition is governed by the normal selection rule $\Delta m_F = -1, 0$. In the above example, the electron would return from the $m_F = +3$ sub-level of

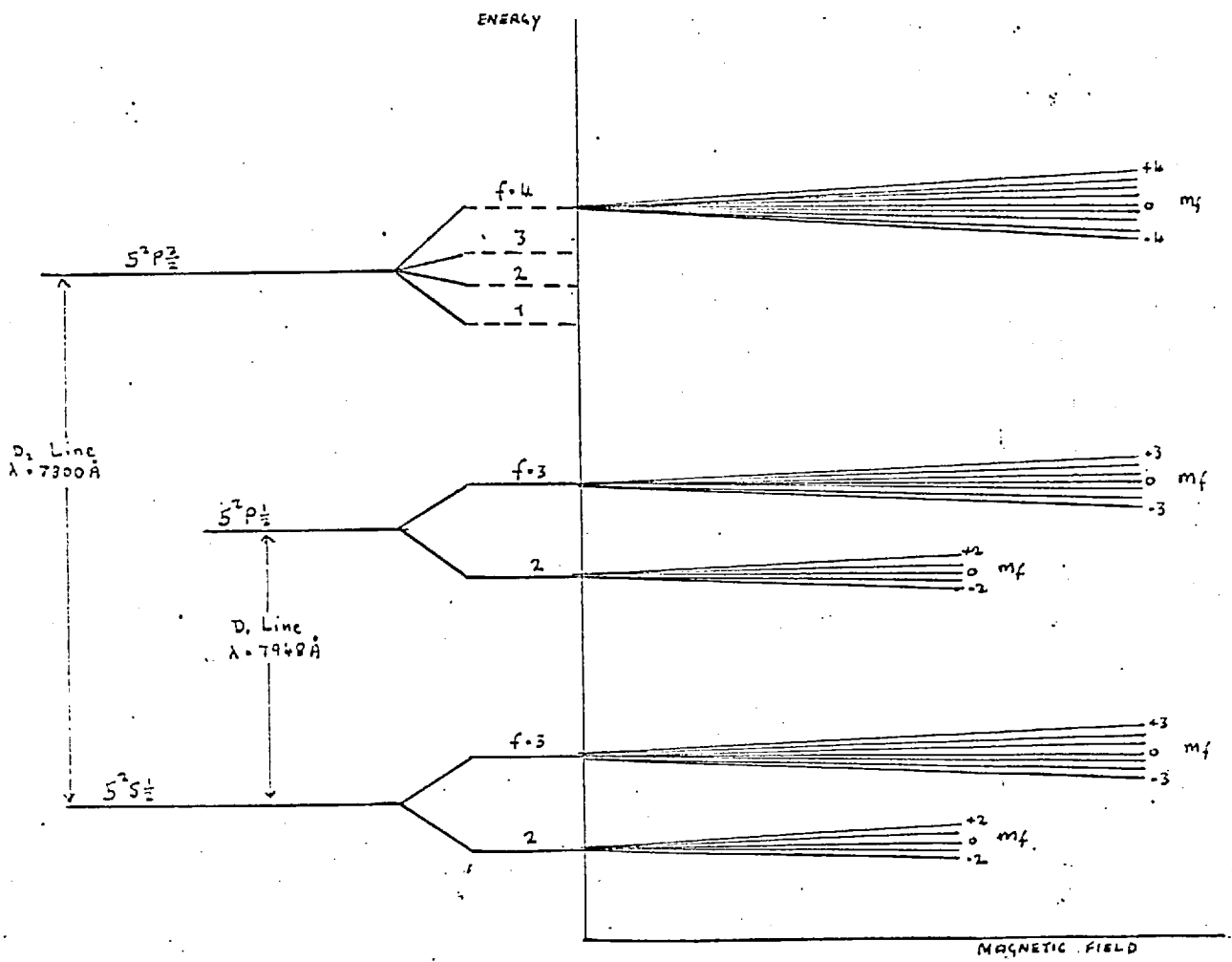


FIGURE 4.2 Energy level diagram pertaining to the valence electron of R⁸⁵

the $^2P_{1/2}$ state to either of the $m_f = +2, +3$ sub-levels of the $^2S_{1/2}$ state. From the $m_f = +3$ sub-level, the electron can make no further absorption transitions because the $^2P_{1/2}$ state has no sub-level $m_f > +3$. Successive absorptions and emissions lead to a concentration of the electron population in the $m_f = +3$ sub-level of the $^2S_{1/2}$ state, which constitutes a momentary alignment of the atomic magnetic moments in the direction of the ambient geomagnetic vector at the Larmor rate, in the same sense but with random phase. If a weak magnetic field is made to rotate about the ambient field in the correct sense, phase coherence is produced. The applied magnetic field results from an alternating current in the coil wound round gas cell. When the frequency of the a.c. field corresponds to the energy difference between two Zeeman sub-levels, i.e. the Larmor frequency for the ambient geomagnetic field, the electron population is re-distributed amongst the various Zeeman sub-levels of the ground state. The vapour is then said to be "de-pumped" and immediately re-absorbs light; thus there is a continuous cycle of pumping and de-pumping. The in-phase precession of the atomic magnetic moments intensity-modulates the light, at the precession rate. The intensity of light is proportional to the square of the amplitude of the electric vibration of the e.m. wave. The optical modulation is detected by a matrix of silicon photovoltaic cells, amplified, changed in phase by 90° and fed back to the coil round the gas cell. The system therefore self-oscillates at a frequency determined by the Larmor precession of the atoms of rubidium in the ambient geomagnetic field. The separate processes of pumping and monitoring utilise, respectively, the magnetic vibrations and the electric vibrations which together constitute the e.m. light wave. These vibrational motions are mutually orthogonal, therefore the instrument is most favourably oriented when the optical axis and the geomagnetic vector are 45° apart. A reliable signal is obtained within $\pm 35^\circ$ of this optimum and, for a fixed orientation, the instrument is free from drift. Rubidium

has an optimum vapour pressure for self oscillation at about 35° C, a good signal can be achieved between 25° and 45° C.

Auxiliary Equipment

The rubidium magnetometer, when used as an observatory or field instrument, consists of the sensing head (sensor and pre-amplifier) and its thermal enclosure, a control unit, a counter and a recorder. The pre-amplifier signal is fed to a tuned amplifier with a bandwidth of 10 Kc/s. The tuned amplifier stage contains a Schmitt trigger circuit which is activated at the crossover point of the sinusoidal amplifier output. It is the output of the Schmitt trigger which is counted by a 1Mc/s Venner frequency counter, Type TSA 3336, thus ensuring that variations in the amplitude of the pre-amplifier signal are eliminated from the frequency counting. The signal may be counted for a precisely-known time determined by the internal reference oscillator (1Mc/s) of the counter, (the frequency mode of operation), or the cycles of the reference oscillator may be counted for the time taken for a precisely determined number of signal cycles to occur, (the period mode of operation). The counter has an indeterminacy of 1 cycle which, taking 200 kc/s of magnetometer signal as equivalent to 50,000 gammas ($f = 4.667$ c/s/gamma), limits the resolution of the instrument when operated in the frequency mode to 0.2 gamma for a one-second counting time. In the period mode the error is ± 1 cycle of oscillator signal of 1 μ second. This corresponds to a resolution of 0.05 gamma for a 1 second counting time. The counter output is in binary coded decimal which requires conversion to a series decimal form for analogue recording. This is done by transistorised switching circuits and a weighting resistor chain within the control unit which decode the last two decimal digits of the counter visual display into a voltage staircase. The system includes a latching arrangement which samples the count during the display time and holds the

reading until the next count is over, so producing a staircase of discrete steps, at a sampling rate of about once per second.

The full scale deflection on the pen recorder is 139 steps which, in the period mode with a 1 second counting time, represents 7 gammas. As only the last two digits of the count are decoded, a count of 99 should give full scale deflection. However, if the count fluctuated between 99 and 100, there would be a succession of full scale traverses by the pen which would obscure the magnetic information. This possibility is eliminated by a 'preventer unit' which expands the scale to 139, taking account of the third-to-last digit, so that a count of 140 is recorded as 040 and subsequent fluctuations less than 40 counts (2 gammas) cause no troublesome scale shifts.

4.2 Field work

Location

The original intention was to run the ground magnetometer as close to the Woomera Ionosonde as possible; the object being to achieve the maximum accuracy of correlation between observations of ionospheric events and measurement of the geomagnetic field at ground level.

Accordingly, the instrument was set up at the site of the ionosonde, which is located at 30.8° S and 136.3° E. However, on test running the magnetometer it was found that there was interference in the magnetometer signal due to switching transients originating in the ionosonde. These took the form of spikes at intervals of about 1 minute appearing on the sine wave displayed by an oscilloscope connected to the output of the pre-amplifier. The linkage could be between the ionosonde antennae and either the sensing head or the control unit.

This site was abandoned in favour of a second one located some 3,000 yd. south and 1,500 yd. east of the ionosonde, which proved to be magnetically quiet and free from R.F. interference effects. The sensor will operate in the presence of fairly high magnetic gradients (up to 50 γ /cm.) although the signal amplitude is reduced if the gradient exceeds about 5 γ /cm. The second site proved suitable in this respect; the instrument was successfully established at this site.

Setting-up

The sensing head was placed in a thermal enclosure set on the ground some 50 yd. from a trailer van in which the auxiliary equipment was housed.

As previously stated, the optimum vapour pressure of rubidium occurs around 35° C so that it is desirable to operate the sensor in a steady temperature environment of 35° $\pm$ 3° C. The mean maximum and minimum air temperatures at Woomera for the months November and December are, respectively, 30° C and 15° C. The maximum can reach 40° C and the minimum 5° C, so that the daily range averages 15° C but may be as large as 35° C. In addition, measurements of soil temperature at Giles Meteorological Station, South Australia, which has the same type of soil as Woomera, show that the daily range at a depth of 1 inch exceeds that of the air (measured at 4 feet above the surface) by about 15° C. An exposed sensing head at ground level might, therefore, be subjected to temperatures between 45° C and 15° C (the daily minima of air and soil temperature should roughly coincide) on the average, and between 55° C and 5° C in extreme cases. Although a useable signal can be obtained between 15° C and 50° C, the optimum sensing temperature of 35° $\pm$ 3° C necessitates a thermal enclosure.

The enclosure is a 3 ft. cube of expanded polystyrene building board, with a lid, containing a heater and thermostat. The sensor is mounted on a tufnol stand which orientates it correctly about 1 ft. off

the ground. The pre-amplifier is mounted on the base of the stand. The heater, a non-inductively wound, mains operated device consuming 120 W., is mounted on asbestos board inside an aluminium box which is bolted in place about 1.5 inches away from an inside wall of the enclosure. The thermostat, which is non-magnetic and variable over 15°C , is mounted in an aluminium box fixed to the wall opposite the heater and at the level of the sensor. The thermostat input to the control unit operates a transistor switching circuit which energises a relay to switch mains power to the heater. The return load from the heater to the control unit is connected through a pilot bulb, shunted by 10Ω , on the control unit front panel to indicate whether the heater is active, or not. The heating circuit can be checked by means of a test switch which shorts out the thermostat, and should cause the pilot bulb to light up. In practice, it was found that this thermal enclosure lost so much heat overnight that the instrument had ceased to function by morning. This was remedied by constructing a 2 ft. cube of hardboard, placing it inside the 3 ft. cube enclosure and packing the space between with fibreglass wool. The sensor heater and thermostat (set for slightly higher temperature) were placed inside the 2 ft. cube.

The trailer van used to house the auxiliary equipment was provided with the necessary 240 - 250 volt mains power outlets. The control unit contains, in addition to the tuned amplifier, decoding system and heating system relay and driver already referred to, two power supplies to modify the mains voltage, as follows:

1. H.T. power supply to the rubidium lamp power oscillator. This provides voltages between +85 volt and +150 volt at 50 mA.
2. L.T. power supply to the valve heaters of the lamp oscillator, the pre-amplifier, the tuned amplifier, the

decoding unit and the heater. This provides a nominal voltage of -12 V., with a range of -5 to -15 V. at 500 mA.

The counter and recorder were, of course, also housed in the van. The total power consumption of the equipment is less than 200 W. The thermal enclosure and the control unit were linked by a five-way cable carrying shielded leads between the following components:

1. H.T. supply to the lamp assembly
2. L.T. supply to the pre-amplifier
3. L.T. supply via the relay to the heater
4. Return from the heater via the thermostat to the control unit
5. The pre-amplifier output to the tuned amplifier.

Running

The routine for switching on the instrument is as follows:

1. Switch ON control unit mains supply. The H.T. supply is monitored by a meter which should read 100 V. The corresponding L.T. meter should read 12 V.
2. Adjust L.T. meter to exactly 12 V. and switch L.T. supply ON. Switch ON heater supply.
3. Adjust H.T. meter to the striking voltage of the lamp and switch on lamp H.T. supply. The behaviour of the lamp depends on its temperature in quite a complicated way. The lamp strikes into a whitish discharge at about 130 V. and reaches its optimum temperature and light output (when the discharge becomes pink at the outside) after about 30 seconds. However, the stable

condition (when the discharge is pink throughout with a darker centre) is reached after a further 30 seconds, the temperature being higher than the optimum while the light output has fallen slightly from the optimum. If the voltage is then reduced, the light output falls initially but subsequently builds up to a slightly larger value than before (though still less than the optimum). This process can be continued until the lamp goes out. The best magnetometer signal is achieved at the lowest possible voltage consistent with a stable temperature and light output. This best running voltage is about 120 v.

4. After 5 minutes reduce the H.T. to the best running voltage. The lamp is ready for use after a further 5 minutes. If the sensor is cool, about 1 hour is required for thermal equilibrium to be established, before continuing the switching-on routine.

5. Switch tuned amplifier supply ON.

6. Monitor the pre-amplifier and tuned amplifier signals with an oscilloscope (plugged into the "scope monitor" socket on the control unit front panel). The readings should be as follows:

Pre-amp.: 10 V. p/p, 10/1 5/N, 200 kc/s approximately.

Tuned amp.: 6 V. p/p, 200 kc/s square wave.

7. Switch ON decoder supply.

8. Set the Venner counter to operate in the period made with a counting time of 1 second. Switch ON and set sensitivity control to maximum. The display time is

set at minimum.

9. Check recorder, paper chart and clock. Switch on the recorder and the chart drive motor.

The recorder which was used combined a "Record" moving-coil type electrical movement and pen with either a "Record" "single-wind" spring-driven chart motor, or a "Mervyn" electrically-driven synchronous motor, these two units being completely interchangeable. The electrical movement possesses quick response (0.42 sec.), extreme sensitivity, low consumption (1.5 mW.) and adequate damping. The pen is fed by capillary action from a trough containing a special "Aclimatic" ink which is impervious to extremes of temperature and will give a clear trace under any climatic condition. The accuracy of the recorder is about 2% of full-scale deflection, which amounts to 0.14 gamma. The "Record" "single-wind" spring drive runs through a complete chart at any speed in a single wind, the speed being regulated by a jewelled escapement. The speed is selected by choosing the appropriate combination of gear wheels which are mounted on the driving shafts of the chart-drive mechanism. In the present case, a speed of 6 inches per hour was used. The accuracy is within $\pm 2\frac{1}{2}$ minutes per day. The "Mervyn" synchronous motor, powered by the mains voltage, drives the chart through the train of gears. This type of drive has excellent time-keeping properties since the speed of the motor depends entirely on the frequency of the mains supply. The speed used was 15 inches per hour.

It was originally intended to use the 15 inches per hour chart drive during the rocket flights and the 6 inches per hour drive at other times. However, after only a few days use, the "Record" chart drive became clogged with dust (a constant hazard at Woomera) and was replaced, on the 16th November, with the "Mervyn" chart drive which was used thereafter. "Record" paper roll-charts of 65 ft. total length and 3 in. width (ruled),

comprising 50 divisions were used. At a speed of 6 inches per hour these lasted 5 days, 10 hours and, at a speed of 15 inches per hour they lasted 2 days 4 hours. The "zero" and "full-scale" positions of the pen can be adjusted by setting the counter reading to 000 and 139 respectively. In the present case, 42 divisions on the chart were utilised to represent 7 gamma; thus 1 gamma equalled 6 divisions. Timing marks, at 5 minute intervals, were provided by a standard observatory chronometer which activated a relay to momentarily short out the recorder, such that the pen was deflected towards zero while the relay was active and returned to its previous position on the chart when the relay went off. Thus spikes were produced on the record.

The magnetometer began recording regularly from the 10th November, 1965 and produced records covering the period up to the 13th December, when it was shut down. As only the last 2 decimal digits of the count are recorded, the records are of relative changes in total field intensity. The value of the total field at Woomera is approximately 58,200 gamma. The minimum detectable period of magnetic fluctuation is given by

$$\begin{aligned} & 5 \times (\text{counting time} + \text{display time}) \\ &= 5 \times (1 \text{ second} + 0.5 \text{ seconds}) \\ &= 7.5 \text{ seconds.} \end{aligned}$$

4.3 Ionospheric sounding

Radio propagation in the ionosphere

The group velocity of a radio pulse travelling vertically upwards through the ionosphere is gradually reduced. The group velocity in a hypothetical ionosphere without magnetic field and collisions can be taken as

$$u = c\mu$$

where c is the velocity of the electromagnetic waves in free space and μ , the refractive index of the ionosphere, is less than unity. When μ becomes zero, at a certain height, the group velocity becomes zero and the pulse is reflected. Also,

$$U = c\mu = \sqrt{1 - \frac{Ne^2}{\pi mf^2}} \cdot c$$

where N is the electron or ion density, e and m are the particle charge and mass respectively, and f is the carrier frequency of the pulse. Thus the condition for reflection at vertical incidence is that

$$N = \frac{\pi mf^2}{e^2} = (1.24 \times 10^4) f^2 \text{ electrons/cm.}^3$$

so that for different pulse frequencies the density at the point of reflection (and therefore the height of reflection) will be different. The refractive index can also be written as

$$\mu = \sqrt{1 - \frac{f_N^2}{f^2}}$$

where f_N , having the dimensions of a frequency, is called the plasma frequency corresponding to the ion density N . The condition for reflection may now be expressed:

$$f = f_N$$

The peak local value of plasma frequency within an ionized layer is called the critical or penetration frequency of the layer. Pulse frequencies greater than the critical frequency pass through the ionized layer, undergoing only attenuation.

In the real ionosphere, the geomagnetic field exerts a force on electrons set in motion by the electromagnetic wave of the radio

pulse. The force is at right angles to both the magnetic field and the direction of movement of the electrons, so that the electrons rotate about the field. The rate of rotation, called the gyro-frequency, depends only upon the total strength of the field H . At medium latitudes, a plane-polarized wave sent vertically upwards will in general be resolved into two elliptical components of opposite sense of rotation. This, in effect, gives rise to two waves travelling independently which, for a given rapid-pulse frequency, require two different ion densities to reflect them. Neglecting the effect of collisions, one of the reflection levels for a given frequency satisfies the reflection condition derived for the case of no magnetic field. The corresponding polarized component is called the ordinary wave, while the other polarized component is called the extraordinary wave. If the pulse frequency f is greater than the gyro-frequency f_H , there are found to be three values of f_N for which the frequency f may be reflected in the presence of a magnetic field. These values are:

$$f_{N1}^2 = f^2 - ff_H$$

$$f_{N2}^2 = f^2$$

$$f_{N3}^2 = f^2 + ff_H$$

If f is less than the gyro-frequency, reflection may occur only for f_N and f_H . At medium latitudes it is found in practice that when $f > f_H$ only the reflection levels f_{N1} and f_{N2} are observed. The third reflection level (f_{N3}) becomes important only at high geomagnetic latitudes. When $f < f_H$, f_{N3} is observed, as the extraordinary reflection level; in addition to f_{N2} . Also, in practice, the time of transit of the pulse, Δt , from the transmitter to the reflection level and back is taken to be

$$\Delta t = \frac{2h'}{c}$$

where h' is the apparent or virtual height of reflection and c is the velocity of light. Because the electromagnetic wave actually travels through the ionosphere at less than the velocity C , the apparent height exceeds the true height of reflection. In a sweep-frequency ionosonde the transmitted pulse carrier frequency is continuously varied through a frequency band of about 1 Mc/s - 20 Mc/s, and the received signals are displayed on a cathode-ray screen, as virtual height versus frequency ($h'f$) plots. Photographic records of the cathode tube display, called ionograms, are normally taken.

The Ionosonde

The standard ionosonde is described in I.G.Y. Instruction Manual for the Ionosphere (Beynon and Brown, 1957). An ionosonde consists essentially of a wide-frequency-band pulse transmitter and a wide band pulse receiver, together with auxiliary display equipment, timing equipment, frequency markers, etc.

The transmitter and receiver may be kept in tune either manually or automatically, but the latter method is now almost universal. Automatic tracking is achieved either by mechanically linking the control movements of the transmitting and receiving tuning condensers, or by means of a servo-mechanism which keeps the receiver in tune with the transmitter. The entire frequency range of the ionosonde, usually 0.5 to 25 Mc/s, cannot be covered by one coil-condenser unit and is therefore swept in 4 to 5 contiguous bands. The receiver output is displayed on a cathode-ray oscilloscope together with suitable height and frequency markers

There are two types of display, the A-scan display and the B-scan display. A-scan is commonly used for visual observation of

ionospheric echoes. The time base of the oscilloscope is synchronized to the transmitted pulse-repetition frequency so that a stationary pattern of echoes, appearing as vertical 'pips' on the horizontal time-base trace, is displayed. Virtual heights are measured from the beginning of the ground pulse (the first 'pip') to the leading edge of the first E-region echo (the second 'pip'). For photographic purposes B-scan is frequently used. In this display, the ground pulse and echo pulses are used to blank out the time-base trace. By moving the photographic film at right angles to the time-base, variations of height with time can be recorded. If the frequency of the radio wave is altered with time, i.e. 'swept', then the record obtained is a height/frequency record, i.e. an ionogram.

Height marks are usually applied in the form of narrow blanking pulses which interrupt the sweep trace every $1/3$, $2/3$ or $3^{1/3}$ m.sec., corresponding to virtual heights of 50, 100 or 500 km. respectively. Frequency marks are achieved by blanking the entire sweep trace for a short interval as the transmitter frequency passes through each whole number of Megacycles (or $1/10$ Megacycle in some cases). Thus a grid of reference lines is produced to identify the frequency and height of reflections.

A recording camera is mounted in front of the oscilloscope which both photographs the screen and automatically records the date and time, to the nearest minute, during each sounding. The nominal time of a sounding is defined as the time when the ionosonde records the standard frequency 3 Mc/s.

Accurate timing of observations is often very important in the analysis of ionospheric data, and it is essential that the starting time of a sounding (called the schedule time) and the nominal time should be equal to within half a minute. The accuracy of the height scale should allow measurement of E-region heights (around 100 km.) to ± 1 km. F-region

heights (150 to 500 km.) should be measureable to an accuracy of ± 5 km. The frequency scale is accurate to about 0.5% and is checked at least once a month.

The ionosonde at Woomera is a Union Radio Recorder, Mark II, 1958 built in the U.K. and supplied by the Royal Society, London. The ionosonde is located at 30.8° S and 136.3° E and has been operating on a routine basis since May, 1961.

The pulse transmitter consisting of a master oscillator and power amplifier is tuned through the frequency range in 5 bands. The receiver output is presented on two oscilloscopes, one for monitoring and one for photographic recording, each displaying a linear frequency sweep. The height and frequency calibrations are derived from a crystal source, and a crystal-controlled time-switch is incorporated for automatic operation of the equipment.

Both the transmitting and receiving antennae are vertical rhombic systems terminated in 600 ohms. The antenna must have wideband, i.e. non-resonant, characteristics. This is achieved by treating the antenna as a transmission line and terminating it in its characteristic impedance of 600 ohms. A vertical rhombic system is sufficiently directional to be able to confine radiation and reception to the vertical. The dimensions are of the order of 35 meters per rhomb side. No single antenna is optimum over the entire frequency range 1 to 20 Mc/s but, as there is usually insufficient time to switch to a second antenna during a sounding, the largest antennal dimensions are optimum as they are more efficient at the low frequencies where ionospheric absorption is highest.

The Union Radio Recorder, Mark II has the following characteristics:

Frequency range:	0.7 to 25.0 Mc/s
Number of sub-ranges:	5
Sub-range frequencies:	0.7 to 1.4, 1.4 to 3.2, 3.2 to 7.0, 7.0 to 15, 15 to 25 Mc/s
Sweep time:	50 sec. per band; 10 sec. interval between bands
Pulse-repetition frequency:	50 c/s
Pulse length:	100 to 300 microsec. (normally 150)
Pulse shape:	Square
Peak pulse power:	1 KW.
Height range:	100 to 2,000 km.
Frequency marks at:	0.1 and 1 Mc intervals
Height marks at:	50 km. intervals
Display:	B-scan

C H A P T E R 5

DATA REDUCTION AND ANALYSIS

The magnetograms obtained from the rubidium magnetometer were digitized on a semi-automatic analyser (the OSCAR-J machine) giving punched-card and electrotypewriter outputs. The punched-card output was then written into a (Calcomp) programme for the Imperial College I.B.M. 7090 computer, which produced time-condensed plots of the original magnetograms. The concurrent ionograms were 'scaled' according to standard techniques, and the various parameters were plotted against Local Time.

5.1 Digitization

The available magnetograms were first inspected for continuity and noise. It was decided to digitize only for those days with largely continuous magnetograms without excessive random noise. Such noise does not, of course, include periods of high magnetic activity. Inspection of the 3-hour Range Indices, Kp, for November and December, 1965 (Lincoln, 1966(a) and (b)) showed no figure higher than 4+ during that period; which means that magnetic activity was always moderate. The magnetograms for 19 November and 13 December (the dates of the rocket flights) were digitized at 1 minute intervals. The magnetograms for all other days were digitized at 5 minute intervals.

The OSCAR Model 'J' System (Oscillograph analyser and reader)

The OSCAR 'J' system is a semi-automatic machine designed for reading and analysing continuous oscillograph traces recorded on paper or film. In the present application, the paper record magnetograms obtained from the pen recorder constitute the continuous trace to be

analysed. The instrument is manufactured by Benson-Lehner, Southampton. The system provides outputs to an I.B.M. electrotyper and an I.B.M. 24 card-punch.

The equipment has two major components - a reader console and a programme control console.

The reader console consists of the reading-head mechanism, trace holding and levelling mechanisms and a fluorescent lighting screen. The paper trace can be rolled between two spindles across the lighted screen so that successive portions can be clamped, levelled and then read. The reading-head which is located on a track below the lighting screen, consists of a binary coded decimal commutator, Readout button, two control knobs and the overlay assembly.

One control knob ('X') translates the reading-head laterally along the length of the trace (the X-axis) while the second knob ('Y') controls the overlay assembly such that the readout point can be translated along an axis transverse to the paper trace (the Y-axis).

The overlay assembly consists of a bar set along the Y-axis, which can be translated along the lateral dimension of the reading head (i.e. along the X-axis) by means of knob 'Y', and a clamp set at right angles to the bar which holds a plastic overlay with lines inscribed at an angle to both X and Y-axes. By adjusting knob 'Y' one of the inscribed lines can be made to intersect the trace at any desired readout-point. Depressing the Readout button then activates the readout-counter circuitry in the central console, via the commutator. The appropriate readout value is displayed in a light-bank on top of the reader console. The readout value is in fact the amplitude of the trace at a particular point, measured from some arbitrary base-line. The reading-sensitivity is given by full scale deflection on the trace divided by the range of the 'Y' control

(+ 000 to + 999). In the present case the sensitivity was fixed, by inclining the inscribed lines suitably, at 60 counts per gamma, i.e. 1/60 gamma. The whole range of amplitude (in gammas) encountered throughout an entire trace can be accommodated by progressively re-positioning the plastic overlay in the clamp so that successive parallel inscribed lines 'take over' from the one before. At the same time, the counting range can be extended by use of negative counts (the overlay must be reversed) and use of a fixed-digit facility (up to 9999).

The control console houses five module drawers, a readout counter and the necessary ancilliary circuitry. The five modules are (a) readout, (b) channel counter, (c) fixed digit, (d) accumulator and (e) power supply, which have the following functions.

The readout module incorporates a plugboard which programmes the readout sequence to the card-punch and electrotyper. The desired format (e.g. (1) Sign; (2) Fixed Digit; (3-5) Readout Value; (6, 7) Space; (8, 9) Channel counter; (10) Space; (11) Tab). is achieved by arranging shorting pins into the appropriate rows and columns in the plugboard.

The channel counter determines the number of times the format is repeated on each punched card or in each row of electrotyper output.

When the count reaches the desired number, which is set by means of a batch-size switch, the channel counter clears back to 1, the punch card or typer is advanced and the accumulator advances by 1. The function of the accumulator is to record, both visually in a light bank on top of the reader console and for output to the card-punch and typer, the number of readouts in a chosen trace-time interval.

5.2 CalComp plotting

This part of the data analysis consisted merely of writing a computer program to feed the OSCAR-J punched-card output into a CalComp Digital Incremental Plotter, in order to obtain time-compressed plots of the original magnetograms.

The program, written in Fortran IV, calls in a package of CalComp subroutines, which form part of the Imperial College Fortran IV Library (I.B.LIB), and thence a magnetic tape is prepared which governs the plotter operation. The written programs are very simple and need not be detailed here. The compressed magnetograms are included (see inside back cover). A second program was written to produce a single CalComp output including all the daily compressed magnetograms plotted on a common magnetic base-line.

5.3 Inspection of ionograms

All available ionograms (see Table 5.1) were interpreted according to the standard routine laid down in I.G.Y. Instruction Manual, The Ionosphere, Part 1 (Beynon and Brown, eds., 1957). In order to illustrate the technique of interpretation and the various E_s parameters to be measured, (scaled) the ionograms for 19th November and 13th December, (Figure 2.1 and Figure 2.3, respectively), are reproduced here, with suitable annotation.

Definition of the parameters to be scaled:

(a) The ordinary critical frequency (f_o) of a layer is the highest frequency, observed for the ordinary magneto-ionic wave, at which the layer reflects and transmits equally; i.e. the high-frequency end of the mainly continuous ordinary trace (weak, discontinuous traces are ignored).

TABLE 5.1

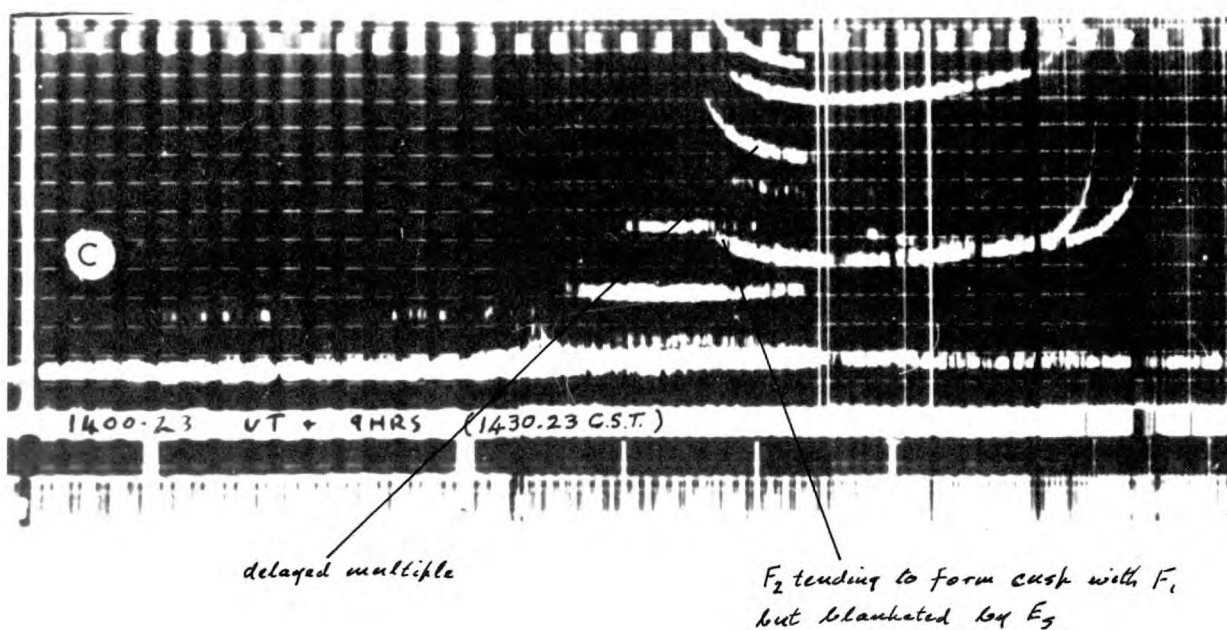
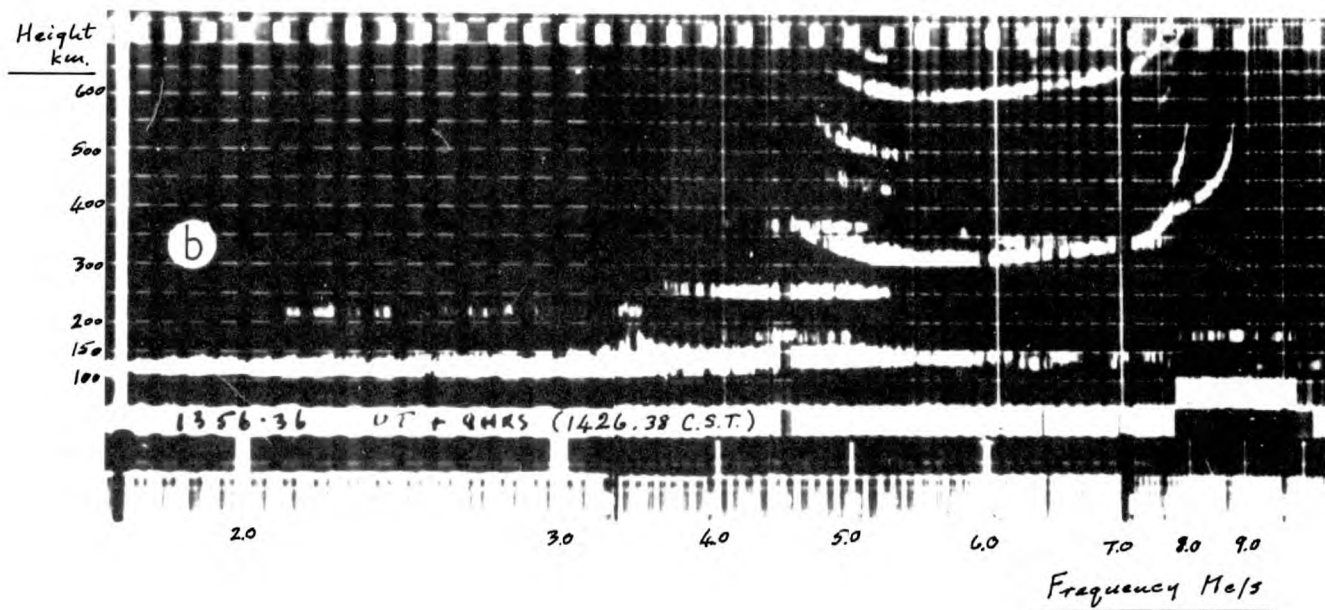
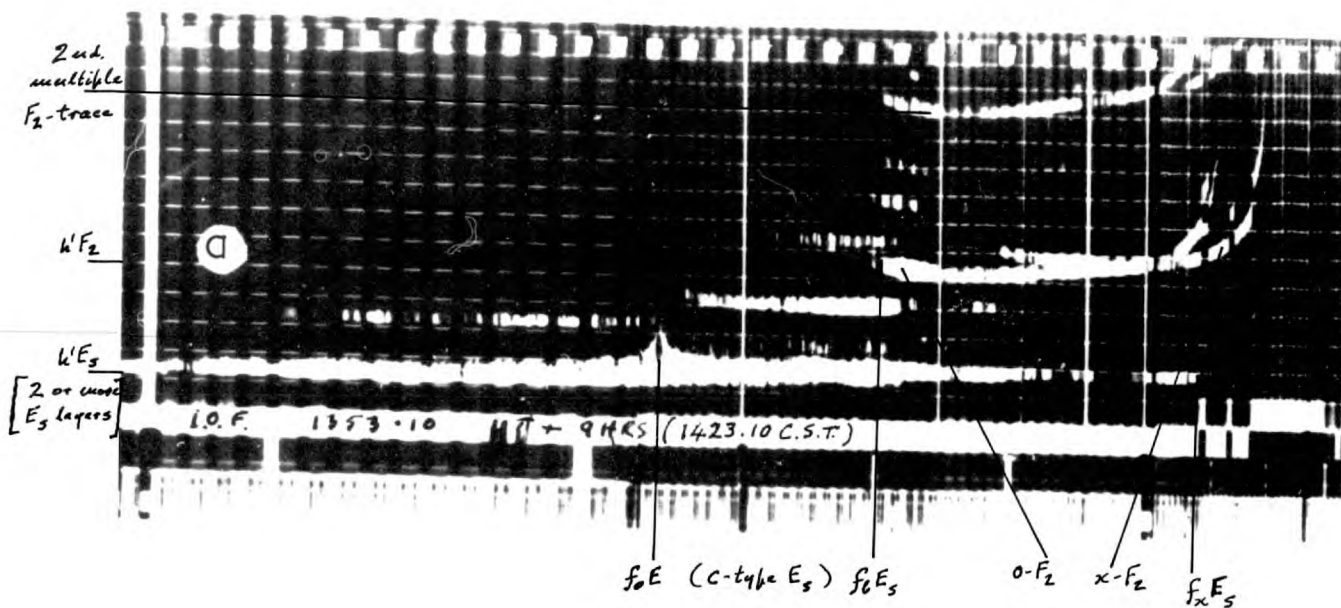
NOVEMBER IONOGRAMS

Date	Total No.	Time (L.T.) at 1 hour intervals, unless otherwise indicated
10	35	0030 $\frac{1}{2}$ hr. 1130 1 hr. 2330
11	26	0030 - 0930 1003 1030 1117 1130 - 2330
12	24	0030 - 2330
13	24	0030 - 2330
14	24	0030 - 2330
15	39	0030 1 hr. 1030 1100 1130 1138 1200 1230 1300 1315 1330 1345 1400 1430 1 hr. 1630 $\frac{1}{2}$ hr. 2330 2400
16	48	0030 $\frac{1}{2}$ hr. 2400
17	39	0030 $\frac{1}{2}$ hr. 1530 1 hr. 2330
18	24	0030 - 2330
19	74	0030 - 0730 0800 0830 0845 0900 0915 0930 0939; 41; 45; 48; 52; 55; 59; 1002; 06; 09; 12; 16; 19; 23; 26; 1030 1033- 37; 40; 44; 47; 51; 54; 57; 1130 1200 1230 1245 1300 1315 1330; 42; 45; 48; 51; 55; 58; 1402 05; 09; 12; 16; 19; 23; 26; 1430 1433; 37; 40; 44; 1500 1530 - 2330
20	24	0030 - 2330
21	24	0030 - 2330
22	24	0030 - 2330
23	24	0030 - 2330
24	24	0030 - 2330
25	25	0030 - 1430 1459 1530 - 2330
26	24	0030 - 2330
27	24	0030 - 2330
28	24	0030 - 2330

TABLE 5.1 (Continued)

NOVEMBER IONOGRAMS

Date	Total No.	Time (L.T.) at 1 hour intervals, unless otherwise indicated.
29	25	0030-1330 1402 1430-2330
30	24	0030-2330
		<u>DECEMBER IONOGRAMS</u>
1	30	0030-1030 1108 1130-1330 1400 1430 1500 1530-1830 1900 1930 1946 2000 2030-2330
2	26	0030-1830 1838 2000 2015 2030-2330
3	14	1030-2330
4	24	0030-2330
5	24	0030-2330
6	27	0030-1830 1900 1930 1945 2000 2030-2330
7	29	0030-1230 1600 1630 1700 1730 1800 1830 1845 1900 1915 1930 1940 2000 2030-2330
8	35	0030-1430 1500 $\frac{1}{2}$ hr 1800 1815 $\frac{1}{4}$ hr 1900 1909 1920 1930 1945 2000 2030-2330
9	33	0030-0830 0902 0930-1830 1845 1900 1910 1915 1919 1930 1940 1947 1954 1958 2130-2330
10	24	0030-2330
11	24	0030-2330
12	24	0030-2330
13	45	0030-1330 1400 $\frac{1}{2}$ hr 1800 1815 $\frac{1}{4}$ hr 1900 1912 1919 1922 1925 1929 1932 1935 1938 1941 1945 1948 1951 1955 2015 2030-2330
14	11	0030-1030



1915.00 UT + 9HRS (1945.00 C.S.T.)

C

1911.31 UT + 9HRS (1941.36 C.S.T.)

B

(f-type E_s)

1908.04 UT + 9HRS (1938.04 C.S.T.)

E_s

D

6 ft.
unstable
 E_s trace

$f_c E_s$
 $f_c E_s$
F-trace

(b) The blanketing frequency (f_b) of a layer is the lowest ordinary wave frequency at which the layer begins to become transparent. This is usually identified by the appearance of echoes from a layer at greater heights.

(c) The minimum virtual height (h') is the height at which the ordinary wave trace is horizontal. For a thick, reflecting layer the virtual height increases with the radio frequency (because higher frequencies penetrate the layer more deeply before being reflected). However, if the reflecting layer is sufficiently thin no increase of virtual height is observable, (which is the case for E_s layers), the trace being horizontal up to the top frequency (f_o).

Rules for identifying the parameters

(1) The fundamental trace, from which all numerical scaling is done, is the once-reflected echo from a layer. Pulses travelling several times between the sounder and the ionosphere give rise to multiple echo traces, which appear at several times the virtual height of the fundamental trace. Some multiples from a given pulse may be received during the height-sweep associated with the next pulse, in which case they appear with increased slope at curious positions on the ionogram (see Figure 2.1 - delayed multiples).

(2) The ordinary and extraordinary traces are distinguished by the fact that the top frequency of the ordinary trace (f_o) is always less than the top frequency of the extraordinary trace (f_x). This follows from the equations

$$f_{N_1}^2 = f^2 - ff_H \quad (\text{extraordinary})$$

$$f_{N_2} = f \quad (\text{ordinary}),$$

given in Chapter 4, which show that, for a given ion density, the extraordinary wave is reflected at a lower frequency (f_{N_1}) than the ordinary wave (f_{N_2});

so that the extraordinary wave eventually penetrates the layer at a higher critical frequency (f_x) than the critical frequency (f_o) of the ordinary wave.

(a) In the case of thick layers (the normal E layer, F_1 and F_2) the ordinary and extraordinary traces are easily distinguished, as is shown in Figure 2.1. There are, however, certain difficulties of interpretation, as follows:

(i) The F_1 layer may be insufficiently separated from the F_2 layer to allow the determination of $f_o F_1$. This usually occurs near sunrise or sunset, when the day-time F_1 and F_2 layers are developing from, or merging into, the single night-time F layer, (which is taken to be a continuation of the F_2 layer). At these times, instead of a sharp cusp, the junction between the F_1 and F_2 traces is marked only by a very smooth and rounded transition.

(ii) In cases similar to the above, the shape of the F_1/F_2 trace determines if $h'F_1$ and $h'F_2$ can be determined.

(iii) Travelling ionospheric disturbances (TID) may cause oblique echoes, stratifications and spread echoes.

(iv) It may happen that the ion density of the F_2 layer becomes less than that of the F_1 layer, so that no F_2 trace is seen (the F_2 layer is occulted by the F_1 layer). This condition was found in only

one or two isolated ionograms during the present study.

(v) A frequent source of difficulty in scaling the normal E layer is the absorption of radio waves at relatively low frequencies by the D region, such that no E layer trace appears.

(vi) The E layer trace may be confused or blanketed by sporadic-E traces. Total blanketing is shown in Figure 2.3. In Figure 2.1 the E layer trace is partially blanketed by embedded E_s , but $f_o E$ can be determined. However, $h'E$ cannot be accurately scaled in that case.

(vii) The sunrise development of the E-layer may give confusing traces. This difficulty can be resolved by studying a sequence of ionograms.

(viii) Stratification of the E-layer may give rise to a layer (the E_2 layer) between the E and F_1 layers. It is sometimes difficult to distinguish this E_2 trace from stratifications of the F_1 layer.

(b) In the case of the thin sporadic-E layer the ordinary and extraordinary traces are superposed and may be indistinguishable. Certain internationally accepted rules have been formulated to determine $f_o E_s$, as follows:

(i) At night, when absorption is negligible, if the top frequency f_t equals or exceeds the gyrofrequency f_H ,

$$f_{ts} = f_{xs}$$

The ordinary critical frequency is then scaled as $f_t - f_H/2$. (The ordinary and extraordinary critical frequencies are separated by approximately half the gyrofrequency. In the present study $f_H/2 = 0.8$ Mc/s). If the f_t is less than f_H ,

$$f_t E_s = f_o E_s$$

(ii) Compare $f_t E_s$ with the minimum frequency of the x-component trace for the ionogram as a whole, $f_{\min} x$, which is necessarily above the gyrofrequency. If E_s traces occur above $f_{\min} x$, the extraordinary component must be present, hence $f_t E_s = f_x E_s$. Alternatively, if the E_s trace stops at a frequency below $f_{\min} x$ the extraordinary component cannot be present and $f_t E_s = f_o E_s$.

(iii) As an alternative to rule (ii), compare $f_t E_s$ with the low frequency end of the F layer x-trace, $f_{\min}^F x$.
 If $f_t E_s > f_{\min}^F x$, then $f_t E_s = f_x E_s$
 If $f_t E_s = f_{\min}^F x$, then $f_t E_s = f_x E_s$
 If $f_t E_s < f_{\min}^F x$ and no E-region trace appears within half the gyrofrequency below $f_{\min}^F x$, then $f_t E_s = f_o E_s$
 (the x-trace for the ionogram as a whole stops at $f_{\min}^F x$ so that $f_{\min}^F x = f_{\min} x$ and the observed E_s trace cannot be an x-trace.)

Rule (iii) has been applied in Figures 2.1 and 2.3.

(iv) In cases where $f_{\min}^F x$ cannot be determined, either because the F-layer traces are superposed, or because the F-layer is totally blanketed by E_s , assume

that $f_t E_s = f_x E_s$, especially when $f_t E_s$ greatly exceeds $f_o E$. Sequences of ionograms should be examined in such cases.

These parameters have been scaled to an accuracy of 0.1 Mc/s in frequency and 2 km - 5 km in height. The frequency and height calibrations are shown in Figure 2.3. The parameters $f_b E_s$, $f_o E_s$, $h' E_s$, $h' E$ and $h' F$ have been plotted against height in km., for each day. These 'parameter-plots' are included (see inside back cover).

Qualifying and descriptive letters

Certain letters are used either to indicate the reliability of the measurement of a scaled parameter (qualifying letters), or to indicate the main reason for uncertainty in, or absence of, a numerical value (descriptive letters). Qualifying letters cannot be used to replace a numerical value and must always be accompanied by a numerical value and by a descriptive letter. A descriptive letter accompanying a numerical value without a qualifying letter indicates the presence of a phenomenon which may, but need not, affect the accuracy of the measurement. Those letters occurring in the 'parameter plots' presented in this study are as follows:

E - qualifying letter meaning that the actual numerical value is less than the tabulated limiting value.

A - descriptive letter used when a higher layer (such as the F-layer) is 'blanketed' by a lower thin layer (such as E_s). Also, when the E_s layer completely blankets higher layers the letter A replaces a numerical value of $f_b E_s$.

B - descriptive letter used when there is non-deviative absorption in the vicinity of f_{min} . For example, when neither E_s nor E echoes are observed but f_{min} can be scaled, $f_o E_s$ and $f_b E_s$ are tabulated as the numerical

value of f_m , accompanied by the letters EB.

- C - descriptive letter used when measurements are impossible because of equipment or power failure.
- G - descriptive letter used when the ionization density of a layer is too small for measurements of the parameters to be made. This letter is also used when f_oF_2 is less than f_oF_1 .
- H - descriptive letter used to indicate stratification of a regular layer.
- S - descriptive letter used to indicate interference or atmospherics.

Classification of E_s into different types

The type of E_s occurring, which is defined by the appearance of the E_s trace, has been indicated on the 'parameter plots'. The number of multiple echoes present is also indicated. Where two, or more, E_s types occur simultaneously, the type from which f_oE_s was measured is tabulated first. The types encountered in the present study are as follows:

- f type - a trace which shows no appreciable increase of height with frequency.
(flat) (This classification may be used only at night).
- l type - a flat E_s trace at or below the normal E-layer minimum virtual
(low) height.
- c type - an E_s trace showing a relatively symmetrical cusp at or below f_oE .
(cusp) This is usually continuous with the normal E trace.
- h type - an E_s trace showing a discontinuity in height with the normal E-
(high) layer trace at or above f_oE . The cusp is not symmetrical; the low frequency end of the E_s trace lying above the high frequency end of the normal E trace.

NOTE

An attempt was made to apply cross and auto-correlation techniques to the magnetic and E_s data. This was unsuccessful because of the difference in frequency of observation between the two sets of data.

A 'superposed epochs' method was also tried unsuccessfully.

CHAPTER 6

DISCUSSION OF THE MAGNETOGRAMS AND PARAMETER-PLOTS

FOR NOVEMBER AND DECEMBER, 1965.

6.1 The magnetograms

The total intensity magnetograms presented show the effects of the solar quiet day (Sq), lunar daily (L), disturbance (D) and non-cyclic (N) variation fields. The relative importances of these variations in the present study can be gauged, as follows:

(1) The N magnetic variation appears as the difference between the total intensities at 0000 hr. and 2400 hr. on any given day. For example, the difference on 10th November is between +3 γ at 0000hr. and -11 γ at 2400 hr., a decrease of 14 γ . Of the 17 days in November and December for which the N variation can be measured, an average decrease of 4 γ occurred on 10 days, an average increase of 2 γ occurred on 6 days and there was no difference on 1 day. It is noticeable that on all 6 days (18th, 19th, 30th November; 1st, 2nd, 3rd December) which showed an increase the magnetogram was affected by magnetic disturbance (D variations) around 0000 and 2400 hr., whereas all days which were magnetically quiet showed a decrease. (Magnetic disturbance was apparent on only 2, or possibly 3 days showing a decrease). It seems then that the typical N variation for

FOOTNOTE: The magnetograms show relative total intensities in gammas.

The zero base lines are arbitrary, and different on different days. The absolute value of magnetic total intensity at Woomera is approximately 58,200 γ . (Burrows and Hall, 1965).

November and December, 1965 was a decrease of about 4γ ; the variation on 10th November being unusually large.

(2) The intensity of magnetic activity which gives rise to D variations is recorded on a world-wide, routine basis. Table 6.1 gives values of the 3-hour Range Index (K_p) for November and December, 1965. A comparison of the magnetograms with Table 6.1 readily identifies those portions affected by D variations. An exception occurs on 6th December between about 0900 and 1530 hr., when the magnetogram is very disturbed but the K_p values are only 1_0 and 0_+ . The disturbed portion probably represents the warm-up period of the magnetometer, which was switched-off during the 5th and early part of 6th December. Also, the large spike occurring just after 2030 hr. on 9th December is due to a short break in recording.

(3) The L daily variation consists of a regular semi-diurnal oscillation amounting to only about $1/10$ of the amplitude of the Sq variation. The L variation cannot be recognised at sight because of its very small amplitude and can only be removed by averaging over many days. Although Matsushita (1962) has shown there to be an association between lunar tides and variations in E_s occurrence, lunar magnetic variations are not considered in the present study.

(4) The Sq variations

Table 6.2 indicates the typical form which the Sq daily variation in total intensity at Woomera takes. The daily maximum increase in intensity, measured from the value at 0000 hr., ranges from 8 to 24γ , the average being 13.4γ , (for the 21 days on which it can be measured). It is interesting that the increase in intensity as measured from the lowest pre-noon value, (which occurs consistently at 0630 - 7000 hr. on 10 of the days) is more regular; ranging from 11 to 17γ with an average of 15.1γ . 0630 hr.

TABLE 6.1

3-HOUR RANGE INDICES (Kp) FOR NOVEMBER & DECEMBER, 1965.

(LINCOLN, 1966(a) & (b))

DATE	LOCAL TIME AT WOOMERA (= U.T.+9½ hr.)								INTER-NATIONAL DAYS
NOV.	½-3½	3½-6½	6½-9½	9½-12½	12½-15½	15½-18½	18½-21½	21½-24½	
10	0 ₊	0 ₊	0 ₊	0 _o	0 _o	0 _o	0 ₊	0 _o	Q
11	0 _o	0 ₊	0 _o	0 ₊	0 _o	0 _o	0 ₊	0 ₊	q
12	2 ₋	2 _o	1 ₊	0 _o	0 _o	0 _o	0 ₊	2 ₋	q
15	1 ₊	1 ₊	0 ₊	1 ₊	2 ₋	0 _o	0 _o	0 _o	q
16	0 ₊	1 ₊	0 _o	0 _o	1 ₋	0 ₊	0 _o	0 _o	Q
17	0 ₊	0 _o	0 ₊	1 ₋	2 _o	2 ₋	1 _o	1 _o	
18	0 ₊	0 ₊	1 _o	2 ₋	3 _o	0 ₊	1 ₊	2 ₋	
19	1 _o	2 ₊	1 _o	1 _o	2 ₊	4 ₋	3 ₋	3 ₋	D
20	2 ₊	2 ₊	2 ₋	4 ₋	3 _o	4 ₋	3 ₊	3 ₊	D
21	3 _o	3 _o	2 ₊	3 ₊	3 _o	3 _o	2 ₋	2 _o	
27	2 ₋	1 ₋	1 ₋	1 ₊	1 ₋	1 _o	0 ₊	0 ₊	
28	2 ₊	2 _o	1 _o	1 _o	0 _o	0 _o	0 _o	1 ₋	Q
29	1 ₋	1 ₊	0 ₊	0 ₊	1 ₊	0 ₊	0 ₊	0 ₊	q
30	1 ₊	1 _o	1 ₊	0 ₊	0 ₊	1 ₋	2 _o	4 ₋	D

TABLE 6.1 (Continued)

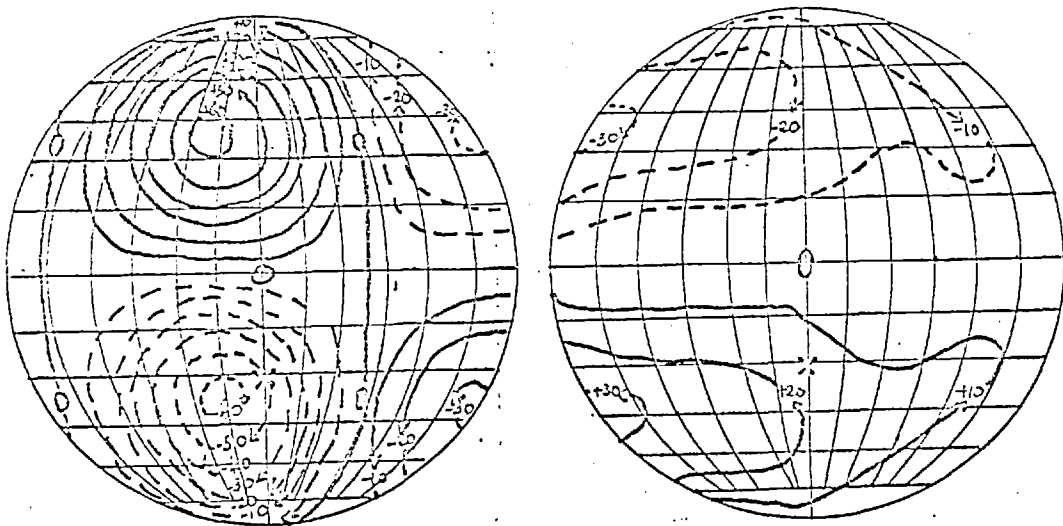
DATE	LOCAL TIME AT WOOMERA (= U.T.+9½ hr.)								INTER- NATIONAL DAYS
DEC.	½-3½	3½-6½	6½-9½	9½-12½	12½-15½	15½-18½	18½-21½	21½-24½	
1	3 ₊	3 ₊	4 _o	3 ₋	1 _o	2 ₊	2 ₊	4 ₊	D
2	4 _o	4 ₊	4 _o	3 _o	3 ₊	2 ₋	2 ₊	1 ₊	
3	2 _o	2 ₊	1 ₊	1 ₊	0 _o	0 _o	0 ₊	0 ₊	q
4	1 ₋	0 ₊	2 ₋	2 _o	1 ₊	2 ₋	2 _o	3 _o	
5	0 ₊	0 _o	1 ₋	1 _o	0 ₊	1 ₋	0 ₊	0 ₊	q
7	1 ₋	1 _o	1 _o	1 ₊	1 _o	2 ₊	1 _o	1 ₋	
8	0 _o	0 _o	0 _o	0 ₊	0 ₊	1 ₋	0 _o	0 ₊	
9	2 _o	2 _o	2 ₋	2 _o	1 _o	1 _o	2 _o	3 ₊	
10	0 ₊	1 _o	1 _o	2 ₋	0 ₊	0 ₊	1 ₋	2 ₋	
11	3 ₋	3 _o	4 ₊	3 ₋	3 ₊	2 ₊	1 ₊	1 _o	
12	3 ₋	2 ₊	3 _o	3 _o	3 ₋	1 ₊	2 ₋	3 ₋	
13	2 _o	3 _o	1 _o	2 ₊	3 ₋	2 ₊	1 _o	2 _o	

TABLE 6.2

Date	Magnetic intensity at 0000 hr. (F ₁) in gammas	Time of peak intensity in hr. L.T.	Peak magnetic intensity (F ₂) in gammas	F ₂ -F ₁	Time of minimum pre-noon intensity hr. L.T.	Minimum magnetic intensity (F ₃) in gammas	F ₂ -F ₃
Nov. 10	+ 3	1130	+12	9	0700	- 5	17
11	+ 1	1230	+19	18			
12	0	1300	+11	11			
17	+ 1	1230	+12	11	0700	- 2	14
18	- 2	1330	+11	13	0630	- 4	15
19	+ 7	1230	+31	24			
20	+11	1030	+27	16			
21	+11	1100	+22	11	0630	+ 7	15
27		1000	+14		0630	- 1	15
28	- 1	0900	+ 7	8	0630	- 4	11
30	0	1130	+15	15	0630	- 1	16
Dec. 1	+ 1	1100	+13	12			
2	+ 2	1100	+25	23			
3	+ 4	1130	+14	10			
4	+ 2	1230	+13	11			
7	0	1030	+11	11	0630	- 4	15
8	- 8	1000	+ 4	12	0630	-12	16
9	-12	1130	+ 4	16	0630	-13	17
10	-12	1200	- 2	10			
11	0	1130	+17	17			
12	- 2	0930	+ 6	8			
13	+ 7	1130	+22	15			

is very close to the time of sunrise at Woomera during November and December, when the Sq current pattern is assuming its daylight form. The time at which the daily peak intensity occurs is quite variable, with unusually early peaks on 28th November and 12th December. Distinguishable double peaks occur on 28th November (0900 and 1100 hr.), 10th December (1030 and 1200 hr.) and 11th December (1130 and 1330 hr.). The presence of D variations could account for the examples on 10th and 11th December ($K_p = 2-$ in the period $9\frac{1}{2} - 11\frac{1}{2}$ hr. on 10th December and $K_p = 3-$ and $3+$ in the period $9\frac{1}{2} - 15\frac{1}{2}$ hr. on 11th December), but presumably not for the double peak on 28th November ($K_p = 1_0$ in the period $6\frac{1}{2} - 12\frac{1}{2}$ hr.). Although comparatively high magnetic activity occurs in the period $9\frac{1}{2} - 15\frac{1}{2}$ hr. ($K_p = 3-$ to $4-$) on several other days (18, 20, 21 November, 1, 2, 12, 13 December), which might affect the time of peak intensity, there remains a noticeable spread in time of peak intensity over all 21 days recorded in Table 6.2. This time-spread (0900 - 1300 hr.), in which 1130 hr. occurs most frequently, is larger than would be expected in the regular daily Sq variation as described by Chapman and Bartels (1940).

From the fact that the Sq current focus probably passes very close to Woomera (assuming a current system as in Figure 6.1), the east (Y) and vertical (Z) magnetic components can be expected to show the greatest diurnal variation. This has been confirmed during the present study by examining component magnetograms, in H and Z, for November and December 1965, obtained from Gnangara observatory in Western Australia ($31^{\circ} 47' \text{ S.}, 115^{\circ} 57' \text{ E.}; -43.2^{\circ}$ magnetic) which is at approximately the same latitude as Woomera. It is also substantiated by examining the example given by Vestine et al., (1959) of the Sq variations in the magnetic components at geographic latitude 30° S. for November and December 1922 - 1933, which are of the form shown in Figure 6.2.



✕ WOOMERA

FIGURE 6.1 The position of Woomera relative to the Sq current system for the equinox (the southern vortex is enhanced during Southern Hemisphere summer) of a sunspot minimum (after Chapman and Bartels, 1940).

Left - at midday as viewed from the sun

Right - at midnight as viewed from the night hemisphere

The flow between adjacent current lines is 10,000 amp.

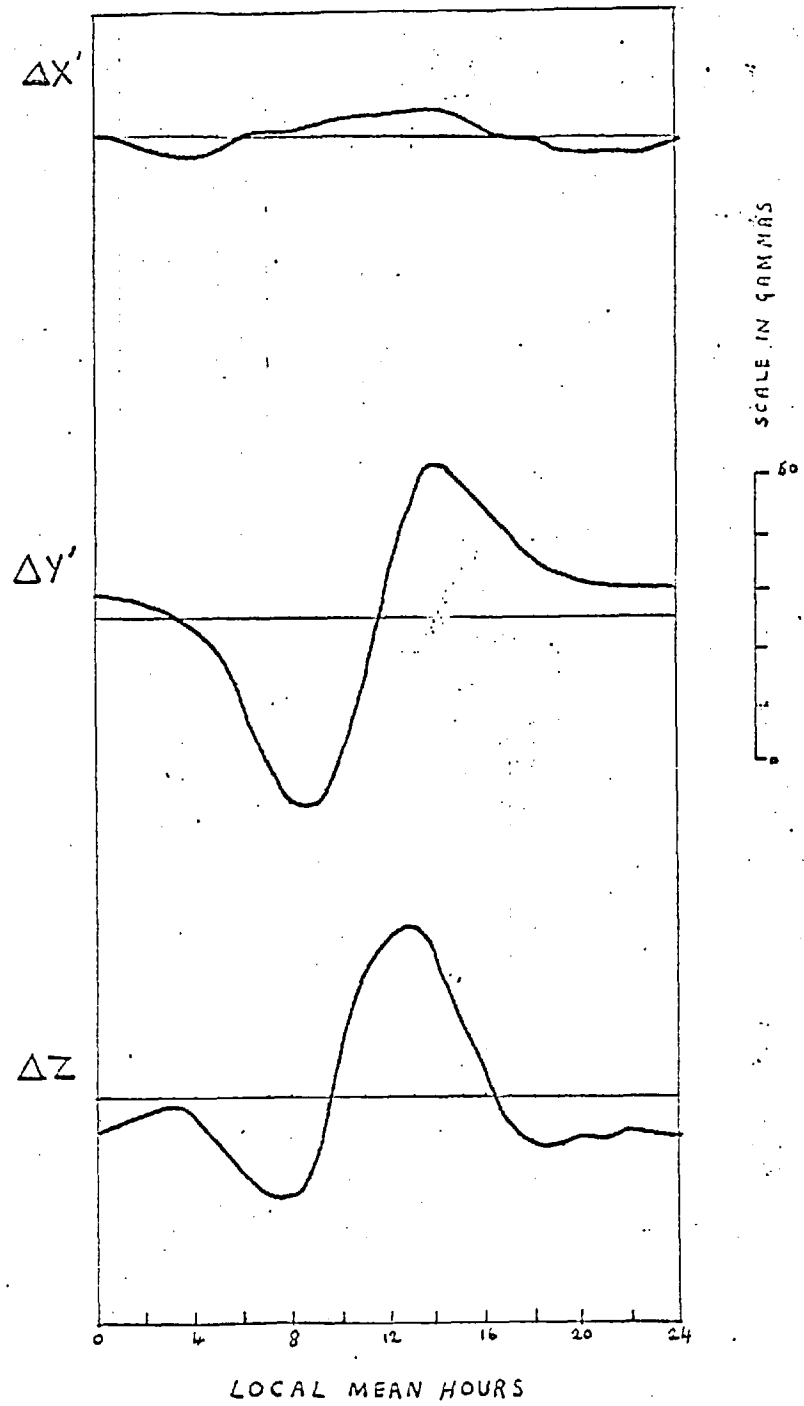


FIGURE 6.2

Sq variations in the magnetic components at latitude 30°S. (after Vestine et al., 1959)

From a consideration of Table 6.2 it can be said that a 'typical' quiet-day total intensity magnetogram from the present study (i.e. one showing the typical Sq variation) would have a minimum at about 0630 hr. and a maximum at about 1130 hr. This is most closely approached by the magnetograms for 10th November (apart from its large N variation), 17th November (apart from the D variations between $9\frac{1}{2}$ and $15\frac{1}{2}$ hr.) and 30th November (apart from the D variations between $18\frac{1}{2}$ and $24\frac{1}{2}$ hr.). A composite of these four would have a form closely resembling that of the vertical component variation in Vestine et al.'s example.

It was originally intended to run a component magnetometer, in conjunction with the total intensity rubidium magnetometer, at the Woomera recording site in order to obtain some indication of the position of the Sq current focus w.r.t. the recording site, by examining the north(X) component variations. To that end, a fluxgate instrument was to be borrowed from The Bureau of Mineral Resources, Melbourne, as was done by Burrows and Hall (1965), but it was learned upon arriving in Australia that no instrument was available. Woomera ($30^{\circ} 56' \text{ S.}$, $136^{\circ} 31' \text{ E.}$; -41.0° magnetic) lies on the locus of the Southern Hemisphere Sq current focus. It is well known (Chapman and Bartels, 1940; Hasegawa, 1960) that the X magnetic component variation can be reversed between consecutive days at stations in these latitudes ($30^{\circ} - 40^{\circ}$). This has been ascribed to corresponding latitudinal variations of the Sq current focus. Hasegawa estimated that these variations usually amount to 1° or 2° of latitude, but has recorded variations as large as 15° . He has shown that the changes in position of the Sq focus are not completely random, in that the focus will pass to the north of a given station for several days and subsequently to the south for several days. More recently Brown and Williams (1969) have observed similar day-to-day reversals in the X component variation at latitudes removed from the

Sq current foci, (i.e. at mid-latitudes, mostly on the poleward side of the foci), which they ascribe to fluctuations in either the atmospheric wind systems, or the solar wind communicated via the magnetosphere. Whereas Hasegawa discounted changes in the distribution of E-region ionization and conductivity as a possible explanation, either of the explanations advanced by Brown and Williams could result in a re-distribution of E-region ionization. In any case, Brown and Williams' results mean that it is no longer possible to assume the position of the Sq focus from an examination of X component variations. Thus, the lack of a component magnetometer in the present study is a somewhat less serious drawback than was at first thought. Although it has not been possible to deduce the direction of Sq current flow at any given time of day, which would have been possible from component magnetograms, nor to investigate the known relationship between the horizontal magnetic component and E_s (Heisler and Whitehead, 1960; Wilkie and McNicol, 1962 - see section 1.1 Previous Work), a relationship between the magnetic total intensity and E_s has been found and is described in the following section (6.3).

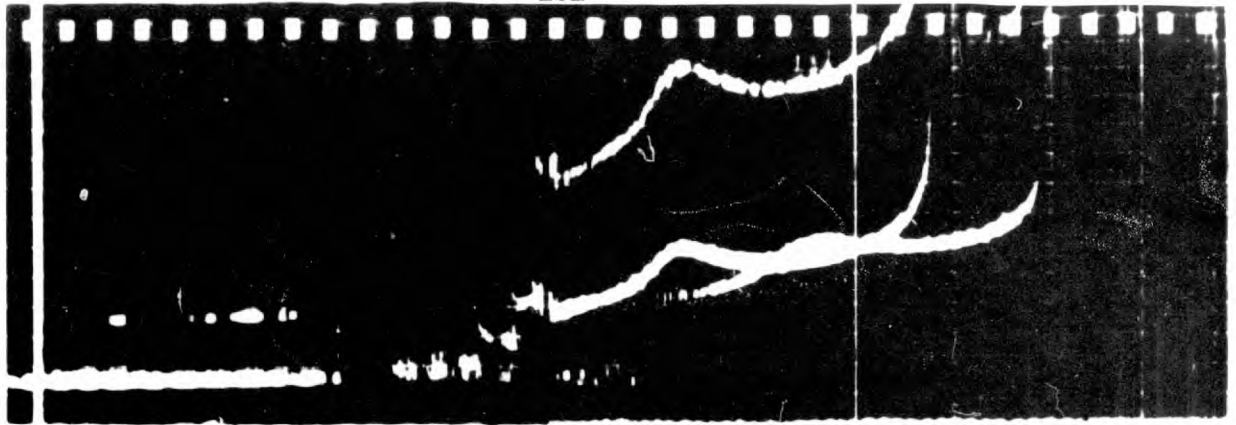
6.2 THE PARAMETER-PLOTS

Thomas (1956) made a detailed study of the occurrence and characteristics of E_s at Brisbane ($27^{\circ} 32' S.$, $152^{\circ} 55' E.$; $- 35.8^{\circ}$ magnetic), with which the present results can be compared. Thomas's data cover a period of 11 years, from 1943 to 1953. The most striking feature of E_s behaviour at Brisbane, to emerge from Thomas's study, is the regular development of sequential E_s (E_{ss}) layers from a stratification (E_2) at about 200 km. between the E and F_1 regions. The descending stratification becomes recognisable on ionograms as E_s at about 150 km., which then continues to descend to the 95 - 100 km. region, with increasing blanketing and critical frequencies. An example of such a sequence of events can be seen on the ionograms for 10th November (Figure 6.3). E_2 is clearly defined at about 175 km. by 0800 hr., although apparent before that, and can be seen developing into E_{ss} at about 125 km. by 0830 hr. This E_{ss} layer has descended to 115 km. by 0930 hr.

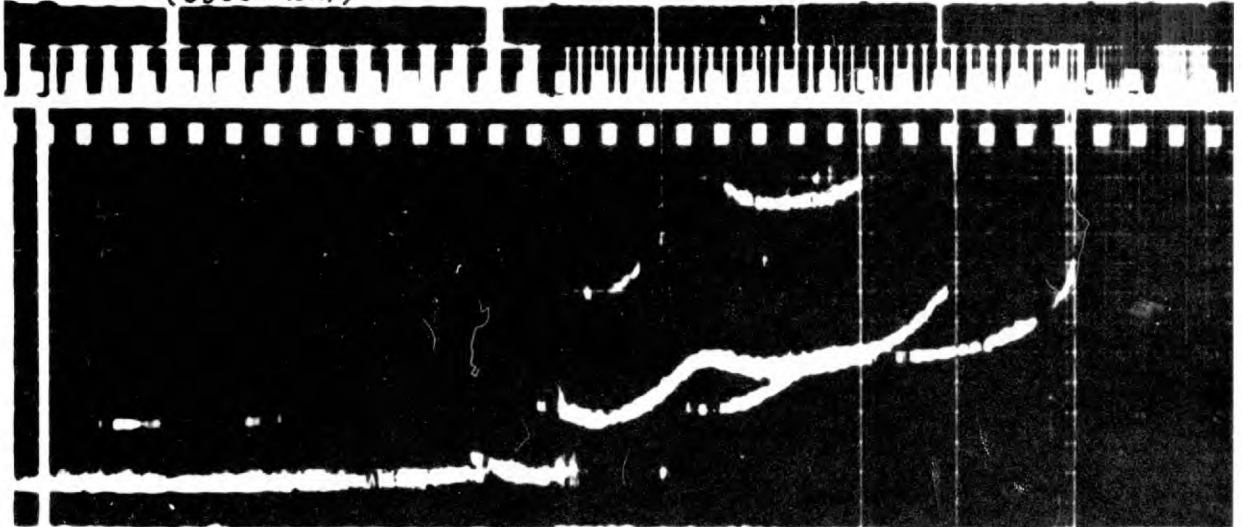
A closely associated phenomenon, not mentioned by Thomas, which appears frequently in the present study is the travelling ionospheric disturbance (TID). Heisler (1959 and 1963) has described the various forms (he classified 4 seasonal types) which these F-trace anomalies take as the TID progresses down through the F-region. Heisler suggests that the disturbance in the F-region results in a downward transport of ionization which leads to E_{ss} formation. Occurrences of F-trace anomalies corresponding to Heisler's 'all-year' and 'summer' (southern hemisphere) types have been found on almost all days in the present study. Although the interval between ionograms (usually 1 hour) makes it difficult to follow the sequences in detail, there is sufficient evidence to show that these TID develop progressively through E_2 to E_{ss} . An example appears in the ionograms for 10th November (Figure 6.3). At 1030 hr. a TID anomaly appears near the F_1/F_2 cusp at about 350 km. By 1102 hr. a lower stratification of the F_1

ON THE FOLLOWING TWO PAGES

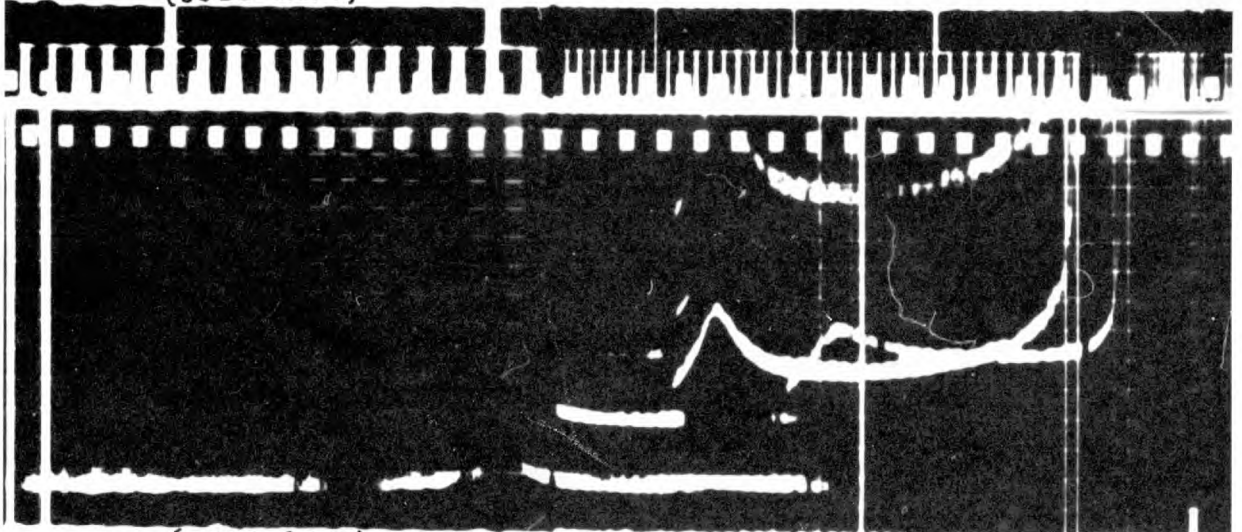
FIGURE 6.3 Ionograms for 10th November, 1965.



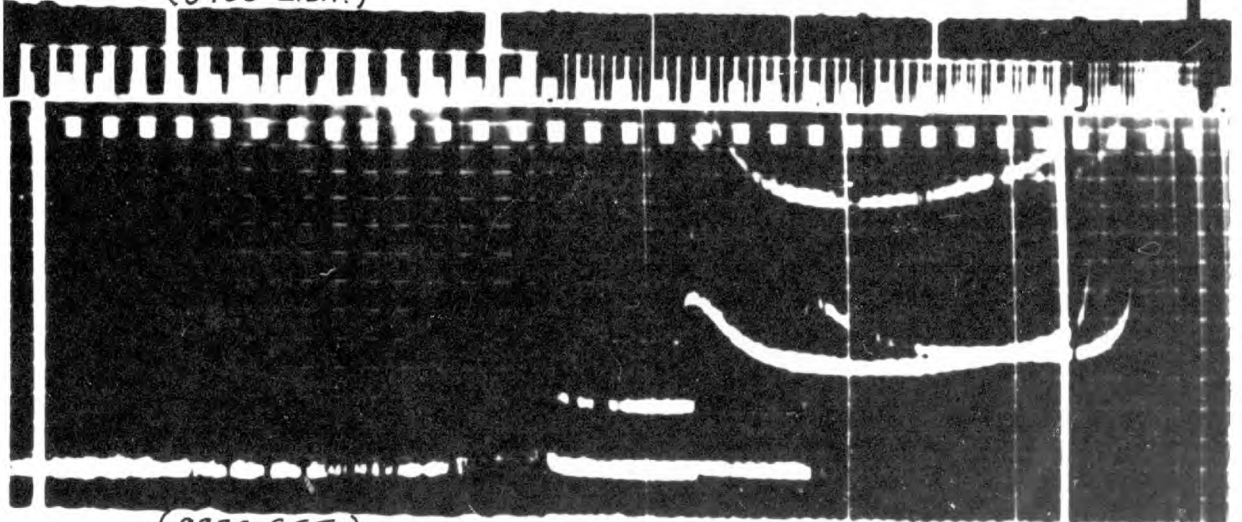
(0800 C.S.T.)



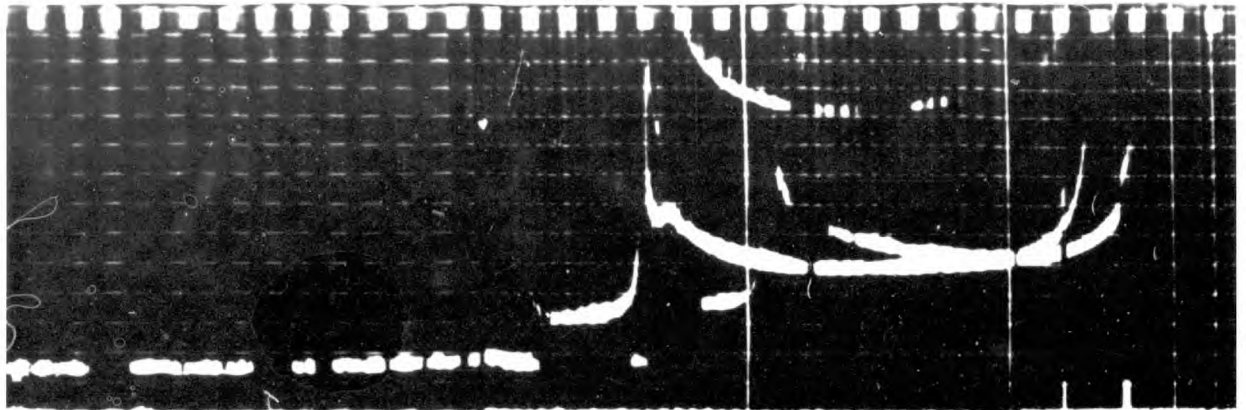
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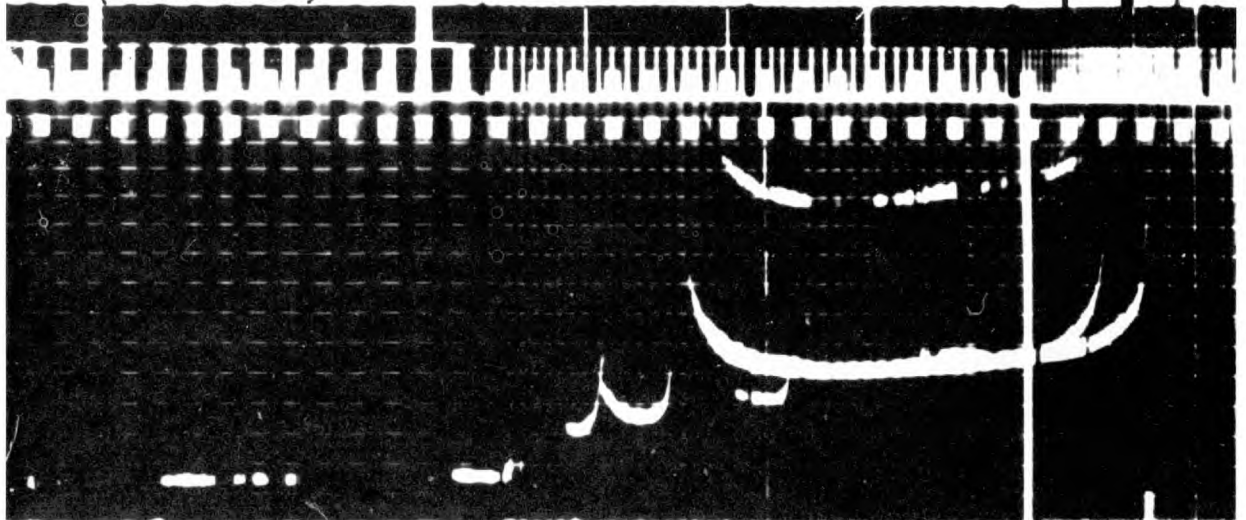
(0900 C.S.T.)



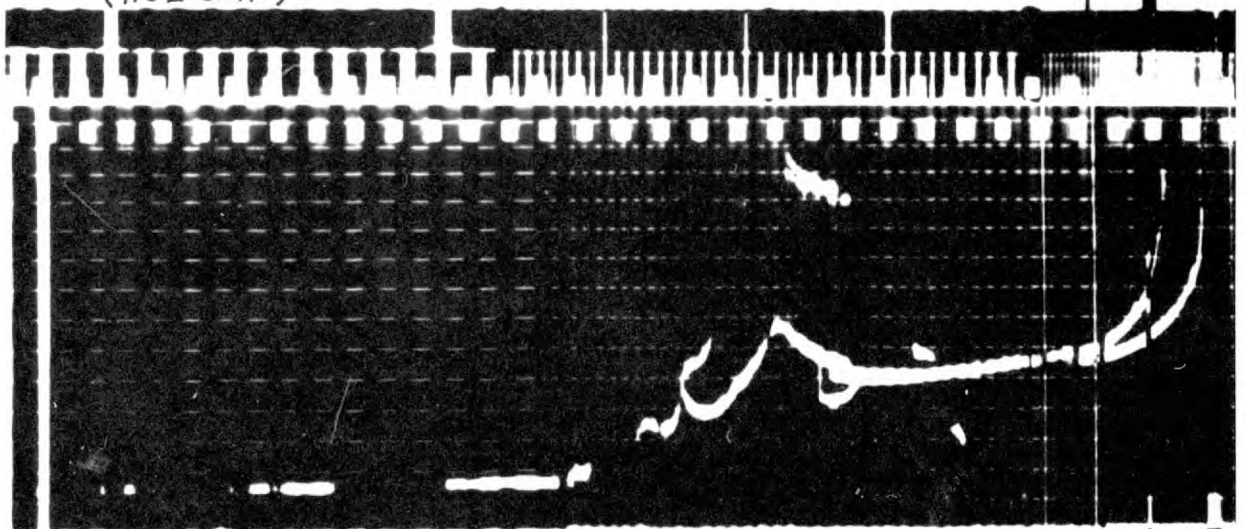
(0930 C.S.T.)



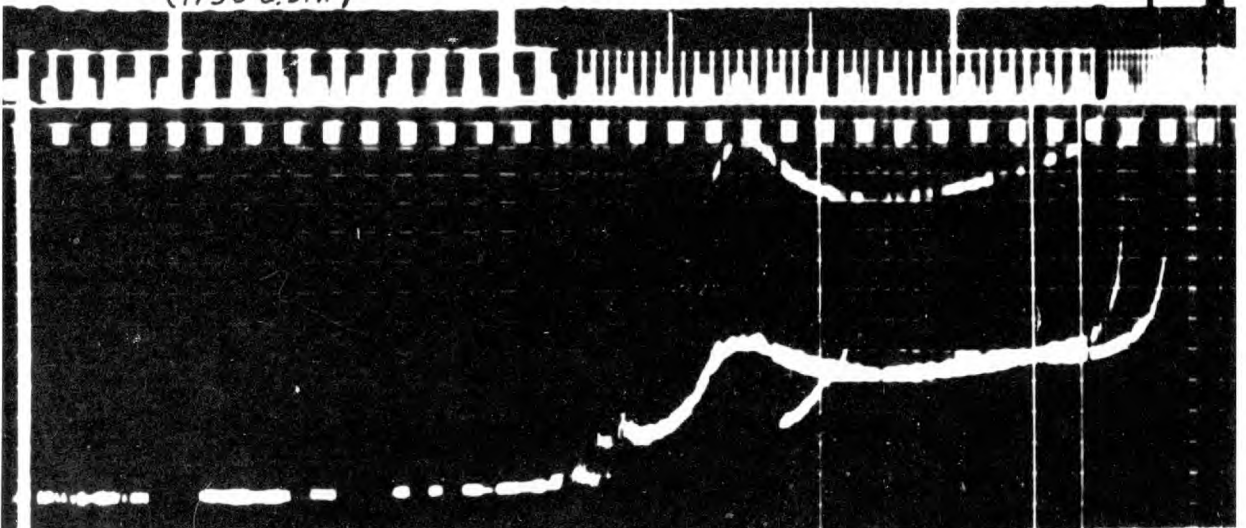
(1030 C.S.T.)



(1102 C.S.T.)



(1130 C.S.T.)



(1230 C.S.T.)

layer appears at about 200 km. An anomaly appears in the F_1 trace where it forms a cusp with this lower stratification, at 1130 hr. By 1230 hr. the lower stratification is distinguishable as an E_2 layer at 200 km.

On the parameter-plots an E_{ss} layer appears initially above the E-layer, as h-type E_s , and then descends to form a cusp with the E-layer, when it appears as c-type E_s . Such sequences can be seen on all the parameter-plots and usually occur 2 or 3 times in a day. Starting times usually fall in the periods 0530 - 0630 hr. and 1430 - 1630 hr., sometimes with a third sequence interposed. Thomas found sequences beginning at about 0530 and 1330 hr.

Thomas also differentiated two types of E_s occurrence at Brisbane. In addition to E_{ss} , he described a constant-height type (E_{sc}) which grows and decays (in critical frequency) at about 100 km., without any progressive change in height. He pointed out that the two types were very difficult to distinguish below 120 km. (In other words, anything above 120 km. is bound to be E_{ss} whereas anything below 120 km. could be of either type). The differentiation is especially difficult, Thomas states, between E_{ss} in its final stages of decay (when the layer has reached the 100 km. level and its blanketing frequency is decreasing rapidly) and E_{sc} (which never attains high blanketing frequencies). Careful examination of the present results has not clearly revealed the E_{sc} type and, therefore, the distinction between the two types has not been drawn.

6.3 Correlation of the magnetograms and the parameter plots

A day-by-day comparison of the magnetograms and parameter-plots has revealed a relationship between the total intensity of the magnetic field and E_s , as follows:

Magnetic intensity and the critical frequency of E_s vary concomitantly. The critical frequency and the height of E_s layers are inversely related.

This relationship can be demonstrated satisfactorily for most days in the present study. By way of illustration, consider 27th November and 8th December, for which the data is complete and magnetic activity is low.

27 November

Magnetic intensity increases after 0630 hr. to a peak at about 0930 hr. and then decreases until about 1200 hr. Concurrently, the blanketing (f_b) and critical (f_o) frequencies of E_s increase to a peak at 0830 hr., while the E_s layer is descending from 160 to 115 km. and developing from an h-type into a c-type.

At this juncture it should be pointed out that significant changes in E_s characteristics may occur in the time intervals (usually 1 hour) between points on the parameter-plot, which therefore gives only a general picture. Thus an exact correlation in time between a parameter-plot and a

FOOTNOTE

h-type E_s is above the regular E-layer; i.e. the virtual height ($h'E_s$) is above the level of maximum E-layer electron density. c-type E_s is at about the same height as the E-layer; i.e. the fact that the E_s trace forms a cusp with the E-layer trace at f_oE is taken to mean that E_s lies between $h'E$ and the level of maximum E-layer electron density.

magnetogram cannot be expected, although mutual trends can be discussed. A case in point arises on 27th November. Although on the parameter-plot f_o and f_b are higher at 0830 and 1030 hr. than at 0930 hr., whereas the magnetic intensity peaks at about 0930 hr., the unknown values of f_o and f_b at times close to 0930 hr. may have constituted a peak to correspond with the magnetic intensity peak. Nevertheless, the trend of f_o values between 0830 and 1130 hr. is a decrease, which is compatible with the decreasing magnetic intensity. At the same time, $h'E_s$ increases from 0830 to 0930 hr. and then levels-off through 1030, 1130 and 1230 hr. The magnetic intensity increases again after about 1200 hr., to a peak at about 1300 hr., and then decreases till about 1530 hr. The trend of f_o and f_b in the same time interval is seen to be similar, while $h'E_s$ decreases from 1230 to 1330 hr. (to correspond with the increasing magnetic intensity) and then increases from 1330 to 1430 hr. (to correspond with the decreasing magnetic intensity). Magnetic intensity increases between 1530 and about 1930 hr., but less steeply than previously, and the increasing trend of f_o is correspondingly less steep. $h'E_s$ decreases steadily from 1530 to 1930 hr.

8 December

The increase in magnetic intensity from 0630 hr. to a sharp peak at about 1000 hr. correlates almost exactly with an increase in f_o to a peak at 0930 hr. and with a decrease in $h'E_s$, from approximately 170 km. at 0630 hr. to 115 km. at 0930 hr. Between 1000 and 1330 hr. magnetic intensity and f_o decrease together. In this time interval $h'E_s$ increases at first, according to the proposed relationship, but then decreases between 1130 and 1330 hr. However, while the E_s layer is descending between 1130 and 1330 hr. it remains of the h-type; which means that it remains above the level of the E-layer. This point may be significant in distinguishing two types of variation in $h'E_s$; one a descent to the level of the E-layer, culminating in c-type E_s , and the other a levelling-off above the E-layer of

h-type E_s . The first type is associated with increasing f_o and magnetic intensity, according to the proposed relationship, whereas the second type appears to be indifferent to that relationship. After 1330 hr. the magnetic intensity curve continues to descend, but less steeply. This correlates with a decreasing trend in f_o , although there are some random variations between 1330 and 1730 hr. The variations in $h'E_s$ are fairly compatible. (The levelling-off and slight descent after 1530 hr. is moderate in scale).

A few comments on the other days in the present study are necessary. On 10th November comparison is difficult because $f_o E_s$ is near to or below $f_o E$, and therefore cannot be measured (the G condition on ionograms), at 1130, 1330, 1430 and 1530 hr. The value of $f_o E$ is 3.8, 3.4, 3.3 and 3.2 Mc/s at those times, respectively. If these values of $f_o E$ are taken as indicating the trend of the $f_o E_s$ curve, then the agreement between it and the magnetogram is fair. Similarly, the parameter-plots for 11th and 30th November, and 7th December are incomplete, but the correspondence between magnetic intensity and f_o is fairly good. The magnetograms for 12th, 15th, 16th, 21st and 28th November are incomplete. Correspondence between magnetic intensity and f_o is good for 15th, 21st and 28th November, fair for 12th November, but rather poor for 16th November. The 6th December has not been considered because of the erratic magnetogram on that day. On 18th November and 4th December there is apparently only one development of sequential E_s , starting at dawn, throughout the day. The correspondence between magnetic intensity and f_o is generally good, but no obvious increase in $h'E_s$ occurs to correlate with decreasing magnetic intensity and decreasing f_o .

6.4 Explanation

Ionospheric ionization under the influence of an electric field and/or atmospheric wind is subject to electromagnetic drift effects. In the E and F-regions the electrodynamic force exceeds the collisional

interaction between the charged and neutral constituents, so that the ionization drifts relative to the neutral gas; whereas in the D-region the neutral gas is sufficiently dense for the collision interactions to dominate, so that ionization is carried along with the motion of the neutral gas. When the mean drift velocities of the positive ions and the electrons are unequal, ionospheric currents, such as the Sq currents, arise. The relationship between particle drift velocities, the electric and magnetic fields, and the resultant current is shown in Figure 6.4 (after Martyn, 1953). It should be noted that if $\vec{E}$ is the 'dynamo field' due to an atmospheric wind, (as is the case when $\vec{E}$ is the Sq variation field) the velocity of this wind, which is $-\vec{E}/B$ directed at right angles to $\vec{E}$ in the opposite sense to OB , must be superposed upon C_{oei} to give the resulting ionization drift.

When the ionosphere is considered as a thin spherical conducting sheet, so that vertical currents are negligible, with the magnetic field inclined to its surface, then the neutral ionization drift $\vec{V}$ ($= C_{oei}$) is perpendicular to both $\vec{j}$ and $\vec{B}$. Martyn (1953) gives the vertical (upward) and horizontal components of $\vec{V}$ as, respectively

$$V_z = G j_y \cos I \quad 6.1$$

and

$$V_{x,y} = G j_x \sin I \quad 6.2$$

where $G = \tan \alpha_e \tan \alpha_i / B \sigma_o$ (see Figure 6.4)

σ_o is the conductivity parallel to $\vec{B}$

I is the magnetic dip angle

z , x and y denote, respectively, vertically upward, magnetic southward and magnetic eastward coordinate axes.

The horizontal current densities are

$$j_x = \sigma_{xx} E_x + \sigma_{xy} E_y$$

$$j_y = -\sigma_{xy} E_x + \sigma_{yy} E_y$$

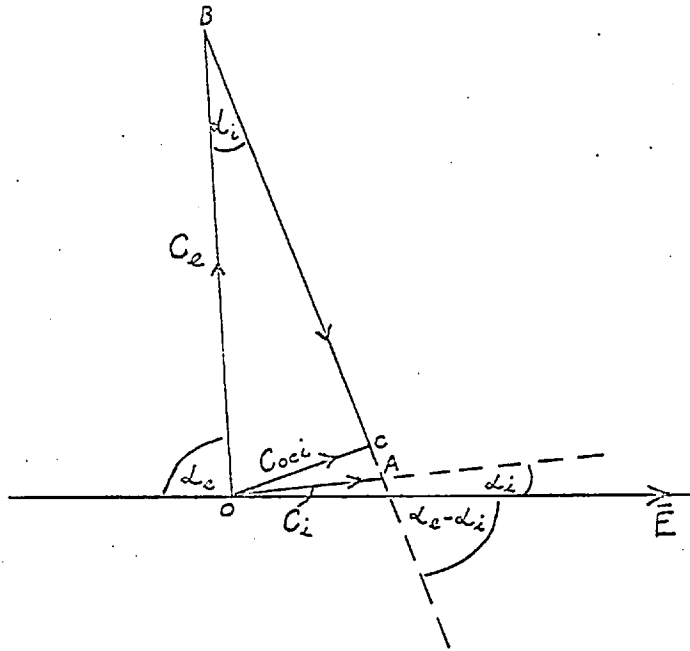


FIGURE 6.4 (after Martyn, 1953)

$\vec{E}$ is the electric field
 The magnetic field $\vec{B}$ is supposed perpendicular to the plane of the paper
 C_e and C_i are the velocities of electrons and ions, respectively.
 C_{oei} is the velocity of 'neutral' ionization drift (i.e. electrons plus ions)
 j is the current density (in the direction in which C_e and C_i are opposed)

$$C_{oei} = \sin \alpha_e \sin \alpha_i E/B$$

$$j = N_e \sin (\alpha_e + \alpha_i) E/B$$

FOOTNOTE

The effective conductivities σ_{xx} , σ_{xy} , σ_{yy} are defined as

$$\sigma_{xx} = \sigma_o \sigma_1 / q$$

$$\sigma_{xy} = -\sigma_{yx} = \sigma_o \sigma_2 \sin I / q$$

$$\sigma_{yy} = (\sigma_o \sigma_1 \sin^2 I + \sigma_1 \sigma_3 \cos^2 I) / q$$

where

$$\sigma_o = \frac{1}{B} \sum_r \frac{n_r \omega_r}{v_r} e_r, \text{ is the direct conductivity}$$

(parallel to the magnetic field)

$$\sigma_1 = \frac{1}{B} \sum_r \frac{n_r v_r \omega_r^2}{v_r^2 + \omega_r^2} e_r, \text{ is the Pedersen conductivity}$$

(perpendicular to the magnetic field)

$$\sigma_2 = \frac{1}{B} \sum_r \frac{n_r \omega_r^2}{v_r^2 + \omega_r^2} e_r, \text{ is the Hall conductivity}$$

(perpendicular to both the magnetic and electric fields).

$$\sigma_3 = \sigma_1 + \sigma_2^2 / \sigma_1, \text{ is the Cowling conductivity}$$

$$q = \sigma_o \sin^2 I + \sigma_1 \cos^2 I$$

n_r , v_r , ω_r , e_r are respectively, the number density, collision frequency, gyrofrequency and charge of particles of the r th species (electrons, positive ions and negative ions).

The neutral ionization drift can also be written as

$$\bar{V} = \frac{\bar{j} \times \bar{B}}{\sum_r n_r m_r v_r}$$

with components

$$V_x = -B_z (\sigma_{xy} E_x - \sigma_{yy} E_y) / \sum_r n_r m_r v_r$$

$$V_y = -B_z (\sigma_{xx} E_x + \sigma_{xy} E_y) / \sum_r n_r m_r v_r$$

$$V_z = B_x (\sigma_{xy} E_x - \sigma_{yy} E_y) / \sum_r n_r m_r v_r \quad 6.3$$

(m_r is the mass of particles of the r th species). In the F-region, because v_r becomes much smaller than ω_r , the above equations can be simplified as follows (Matsushita, 1967).

$$V_x = \frac{-E_y}{B} \sin I$$

$$V_y = \frac{E_x}{B} \operatorname{cosec} I$$

$$V_z = \frac{E_y}{B} \cos I \quad 6.4$$

Here E_x and E_y are the same as the electrostatic field in the E-region, since it is commonly assumed that this electrostatic field is communicated to the F-region along the geomagnetic lines of force without attenuation. Support has been lent to this assumption by the recent work of Cocks and Price (1969) on a three-dimensional Sq current system.

Expression 6.1 shows that in a given region of the ionosphere the vertical drift of ionization depends entirely on the east-west current in that region and will be upward when the current is eastward, in both hemispheres. (The horizontal drift, given by expression 6.2,

depends on the total current). In the E-region the vertical drift, as given by expression 6.3, will be due to both north-south and east-west horizontal electric fields. However since $\sigma_{xy} > \sigma_{yy}$ below about 130 km. the north-south electric field will be predominant in causing vertical drift in this region. On the other hand, expression 6.4 shows that in the F-region vertical drift is due to east-west electric fields. ($\sigma_{yy} \gg \sigma_{xy}$ above about 150 km.). Martyn has in fact shown that notable vertical drifts can be produced in the F-region by east-west electric fields and/or by local north-south winds; in the latter case the wind simply blows the ionization along geomagnetic field lines, the vertical component of drift being $\bar{U} \sin I \cos I$ ($\bar{U}$ is the wind velocity).

If the Sq current system shown in Figure 6.1 can be taken as representative of conditions in the E and lower F-regions during the period of the present study an assessment of the daily pattern of vertical drift of neutral ionization above Woomera (30°S) can be made. Thus, if the Sq focus passes to the south of Woomera upward drift will result from the eastward component of current in the middle of the day (approximately 0800-1400 hr.) and downward drift from the westward current at other times (approximately 1600-0600 hr.). Conversely, if the Sq focus passes north of Woomera drift in the middle of the day will be downward. If the Sq focus passes directly over Woomera the drift effects will be small because the currents are predominantly north-south.

Clearly then this essentially diurnal pattern of ionization drifts cannot explain the largely semi-diurnal occurrence and downward transportation of sequential E_s , outlined in Section 6.2. Fortunately an alternative mechanism, embodied in the concept of internal atmospheric gravity waves (Hines, 1960), is ready to hand. As was discussed in Section 1.3, Chimonas and Axford (1968) have shown how E_s layers can be transported downwards by a descending profile of horizontal wind velocities resulting from

gravity waves. The process, known as the 'corkscrew' effect, starts with the formation of a E_s layer at a point on the wind profile where the wind-shear is in the correct sense (i.e. + ve. $E \rightarrow W$ in the altitude range 95-120 km.). This E_s layer is then carried downwards by maintaining a position on the descending wind profile for which the vertical velocity of the ionization just equals the downward phase velocity of the gravity waves, (ionization is trapped in the wind-shear). The vertical velocity of the ionization is given by

$$V_z(z,t) = -XU_y(z,t) R_i(z)/(1 + R_i^2(z)) \quad 6.5$$

where

$X = B_x/|B|$ where B_x is the northward component of magnetic field

U_y is the eastward component of the neutral wind

$R_i = v_i/\omega_i$

(V and U are functions of altitude and time)

According to Chimonas and Axford this mechanism could account for sequential E_s . The gravity wave mechanism is used to account for observed irregular winds which are superimposed upon regular zonal and tidal (atmospheric tides) winds in the E and lower F-regions. The diurnally recurring tidal winds, which often exceed the zonal winds in magnitude, show periodic components of motion. For example, a study at Adelaide, Australia ($35^\circ S$.) has shown solar 24-hr. and 12-hr. components of about equal amplitude. (Elford, 1959). The amplitude of these waves increases with height as in the case of internal atmospheric gravity waves, and in fact Hines regards the latter as a small-scale version of atmospheric tides. The tidal wind vector (as seen from above) rotates clockwise (anti-clockwise) in the northern (southern) hemisphere - hence the term 'corkscrew' effect.

Chimonas and Axford point out that above about 120 km. the east-west wind component is not very effective in moving the ionization,

so that several waves may pass before the ionization is trapped and transported downwards. On this basis it is difficult to estimate the time interval between successive downward transportations of E_s . The difficulty is made more so by the ability of a north-south wind component to move ionization vertically at altitudes above 120 km., by simply blowing it along the geomagnetic lines of force; whereby the ionization could subsequently be trapped in the 'corkscrew' effect below 120 km. Some indication of the occurrence frequency of these downward transportations (i.e. of sequential E_s developments) is to be had from the association of gravity waves with F-region anomalies and travelling ionospheric disturbances (TID). Hines (1960) has accounted for TID by means of the internal atmospheric gravity wave theory and, further, has explained an observed association between TID and E_s (Bowman, 1960; Heisler and Whitehead, 1960, b) on the same basis. One can envisage gravity waves propagating through the E-region into the F-region as being an ascending escalator (the group velocity is upwards) down which ionization descends (in concert with the downwards phase velocity), first in the guise of a TID, then finally as sequential E_s . If this is a valid physical picture the occurrence frequency of sequential E_s should be the same as that of TID. In the present study indications of TID events in the F-region have been found on the ionograms, occurring two or three times in a day (see Section 6.2), from which we can assume that the two or three developments of sequential E_s seen on most of the parameter-plots is entirely accounted for by the internal atmospheric gravity wave theory.

However, the drift effects due to Sq currents, already discussed, can still be expected to affect the vertical movement of these E_s layers. It must be remembered that the prevailing zonal and tidal winds, upon which the irregular winds ascribed to atmospheric gravity waves are superimposed, provide the primary driving force for the Sq dynamo. The

equivalence of winds and currents in causing ionization drifts is obvious (see Section 1.3).

In particular, upward drift of ionization could be achieved if the 'corkscrew' effect were inhibited either because the gravity waves were reflected at some level, or because a sufficiently intense eastward Sq current was flowing. The first possibility, mentioned by Whitehead (1970), is speculative, but the second can be applied in the present study. The assumption is that the upward velocity imparted to the ionization by the eastward current becomes, at certain times, greater than the downward velocity imparted by the 'corkscrew' effect. This situation is most likely to obtain after the ionization has been dumped from the descending wind profile, as Chimonas and Axford suggest happens at the 90-95 km. level, but could conceivably happen at any level where the current drift overcame the 'corkscrew' drift.

Thus instances of upward drift of ionization seen in the present study, as increases in $h'E_s$ on the parameter plots, can perhaps be accounted for. Where these occur in the middle of the day, usually after a downward transportation of sequential E_s , it can be assumed that the Sq focus is passing south of Woomera and that the Sq drift effect takes over from the corkscrew effect after the latter has dumped the E_s layer at around 95 km. Examples occur on 17th and 28th November, 2nd, 8th, 10th and 13th December. If the Sq drift effect overcomes the corkscrew effect before dumping, the usual pattern of sequential E_s development seen on the parameter-plot will be curtailed such that the layer will be 'held-up' as h-type E_s by the upward Sq drift. Examples occur on 12th and 21st November, 1st and 8th December. Alternatively, if the Sq focus passes to the north of Woomera downward Sq drifts in the middle of the day will supplement the downward transportation of E_s caused by the corkscrew effect, so that the general pattern is one of descent throughout most of the day. Examples

occur on 15th, 18th, 19th and 27th November, 4th and 11th December.

The relationship between magnetic intensity, $h'E_s$ and f_oE_s which was proposed previously can now be re-examined. Expression 6.5 for the downward velocity of ionization is derived with the assumption that B, the magnetic total intensity, is constant (Chimonas and Axford, 1968). However, if B is taken to vary diurnally, as is seen in the present study, the terms in 6.5 will vary as follows. An increase in B will decrease X, because the daily changes in B_x are small at Woomera (see Figure 6.3), and will increase the ratio $R_i/(1 + R_i^2)$ where $R_i = \frac{v_i e_i B}{m_i}$, v_i , e_i and m_i being the collision frequency, charge and mass of ions respectively. The effect of reducing X will be a reduction of the downward velocity of the ionization but, perhaps more importantly, the effect of increasing $R_i/(1 + R_i^2)$ will be to prolong the effectiveness of the 'corkscrew' mechanism, while B is increasing. According to Chimonas and Axford, the mechanism loses its effectiveness when $R_i/(1 + R_i^2)$ becomes too small for the dynamic equilibrium of the system to be maintained, with the result that the layer of ionization is no longer able to follow the motion of the wind profile. Thus, while B is increasing the 'corkscrew' mechanism is more likely to be operating to cause the descent of a E_s layer. This could account for the apparent coincidence of increasing B with descending E_s in the present study. The expression, 6.1, for the upward drift velocity of ionization under the influence of ionospheric currents again assumes B to be constant. In this case a decrease in B at Woomera will increase the upward velocity. This in turn could account for the converse situation; when B decreases as the E_s layer rises. It must be remembered that the direction of ionization motion; upward or downward, as given by equations 6.1 and 6.5, is determined by the direction of current flow and of wind, respectively, so that the influence of B is only secondary. However, it is possible, in this way, to justify that aspect of the proposed relationship involving

magnetic intensity and $h'E_s$. The other aspect of the relationship, namely that $f_o E_s$ and $h'E_s$ are inversely related, was previously noted, without explanation, by Thomas (1956) in his study of sequential E_s at Brisbane. The critical frequency f_o is proportional to the maximum electron density N of the E_s layer;

$$N = \frac{\pi m f_o^2}{e^2} \quad (\text{see Section 4.3})$$

where m and e are the electron mass and charge, respectively.

Martyn (1953) has suggested that a descending body of enhanced ionization, viz. a E_s layer, will accumulate ions and electrons from the surrounding ionospheric gas on its leading, i.e. lower, surface. In this way the electron density at the lower surface of a E_s layer, which is the density 'seen' by an ionosonde, would increase as the layer descended. Martyn also suggests that the converse may apply. This may explain the proposed relationship between $f_o E_s$ and $h'E_s$.

C O N C L U S I O N S

1. The present study has shown, for a particular location and season, that observed daily variations in the height of E_s are apparently related to the diurnal Sq variations in magnetic total intensity at ground level. The quality and extent of the data does not permit this conclusion to be stated categorically. It appears that increasing magnetic intensity is associated with descending E_s layers and may have an influence in prolonging the effectiveness of the transport mechanism which causes the layers to descend. Decreasing magnetic intensity is associated with ascending E_s layers and should increase the upward velocity of E_s transport caused by eastward Sq currents.

2. The daily variations in height of E_s can be accounted for by a combination of two known vertical transport mechanisms. A E_s layer, once formed by the wind-shear mechanism, can be carried down by a descending profile of horizontal winds, which is generated by internal atmospheric gravity waves, or can be driven down by a westward Sq current flow. Upward transport of the E_s layer can result from an eastward Sq current flow.

3. It appears from the present study that the wind-shear mechanism, although correct for explaining the formation of E_s at any given height, is only part of a more extensive mechanism, probably generated by internal atmospheric gravity waves, which accumulates and transports ionization throughout the lower ionosphere.

4. As a corollary to the above it can be suggested that E_s should not be regarded as a unique phenomenon but as an integral feature of the lower ionosphere. The present study has demonstrated that E_s occurs so regularly throughout the day, at least for a particular location and season, that the term 'sporadic' is a misnomer. (This view has been

put by others). Conclusions (1) and (2), by implying a connection between spatial variations of E_s and the Sq current system, further suggest that E_s must be studied within its ionospheric context.

5. The feasibility of future work would seem to depend on a greatly increased knowledge of winds in the lower ionosphere.

A C K N O W L E D G E M E N T S

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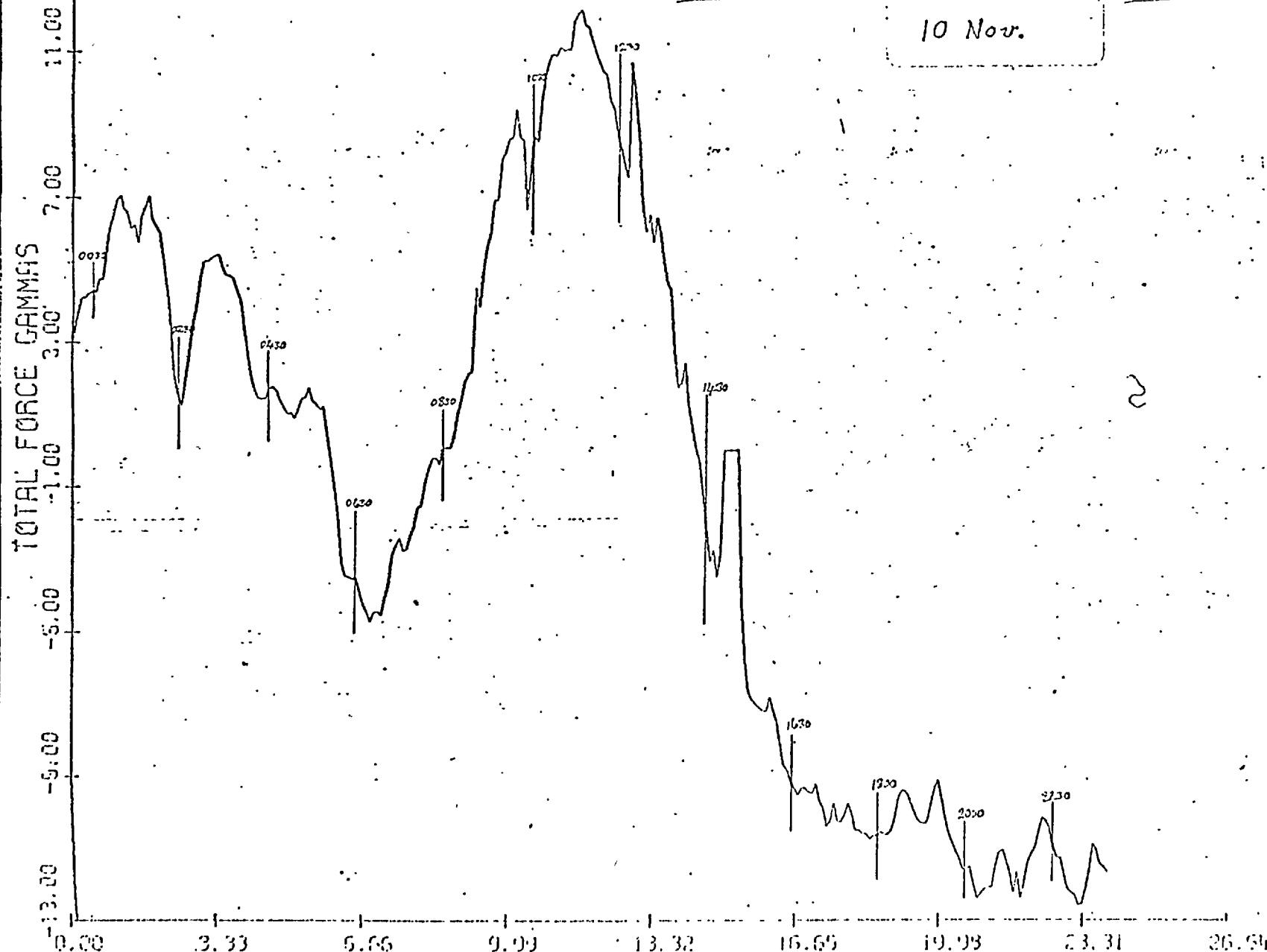
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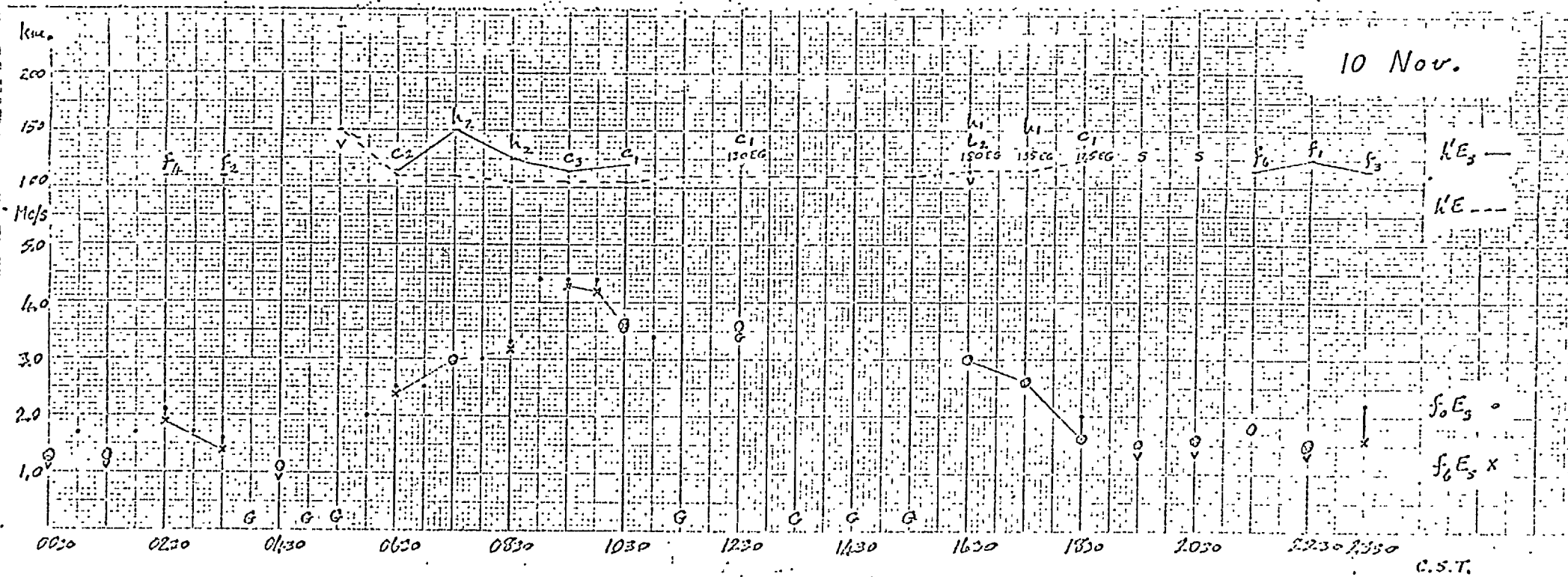
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0.00 3.33 6.66 9.99 13.32 16.65 19.98 23.31 26.64

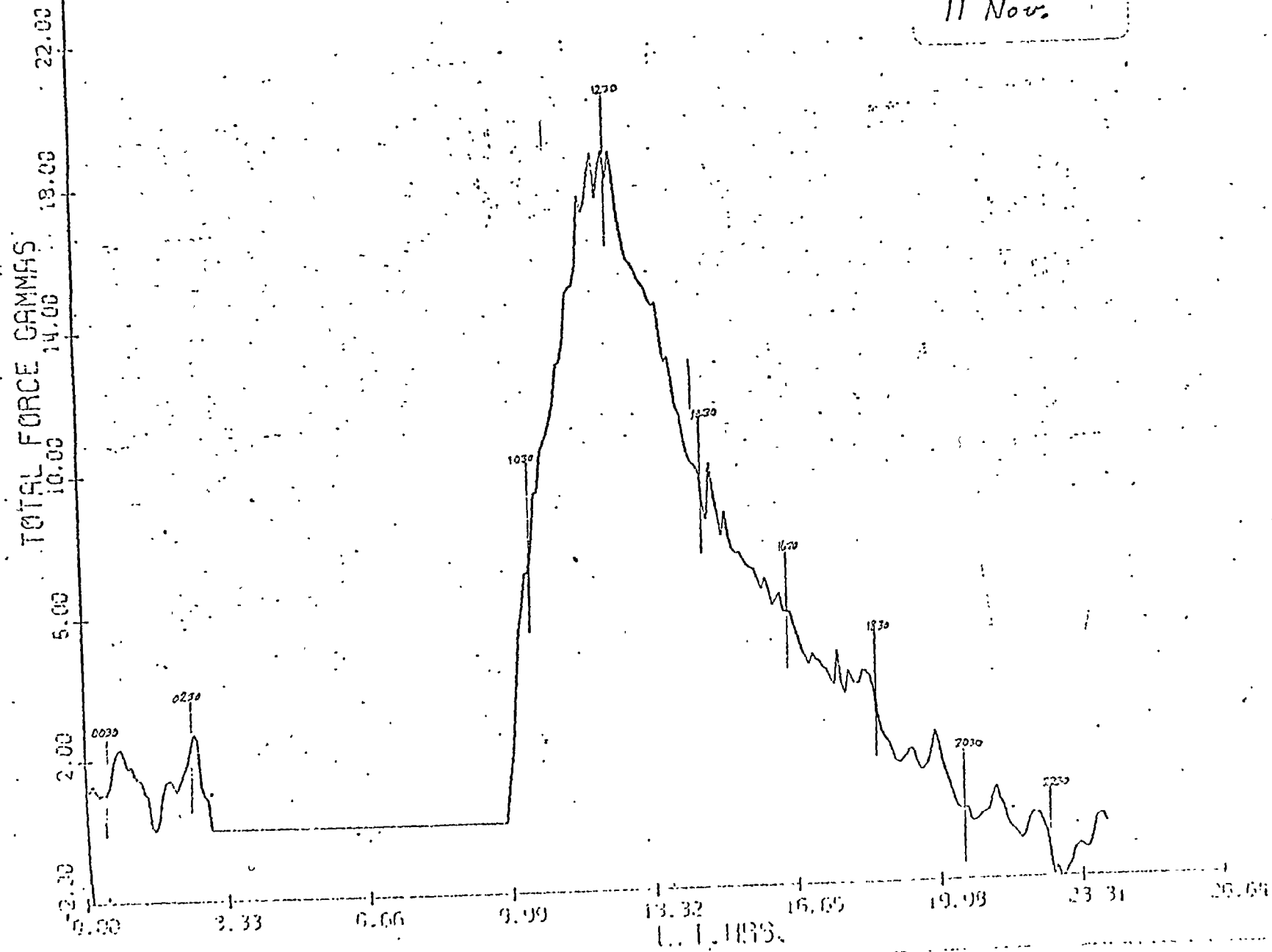
TIME

10 Nov.

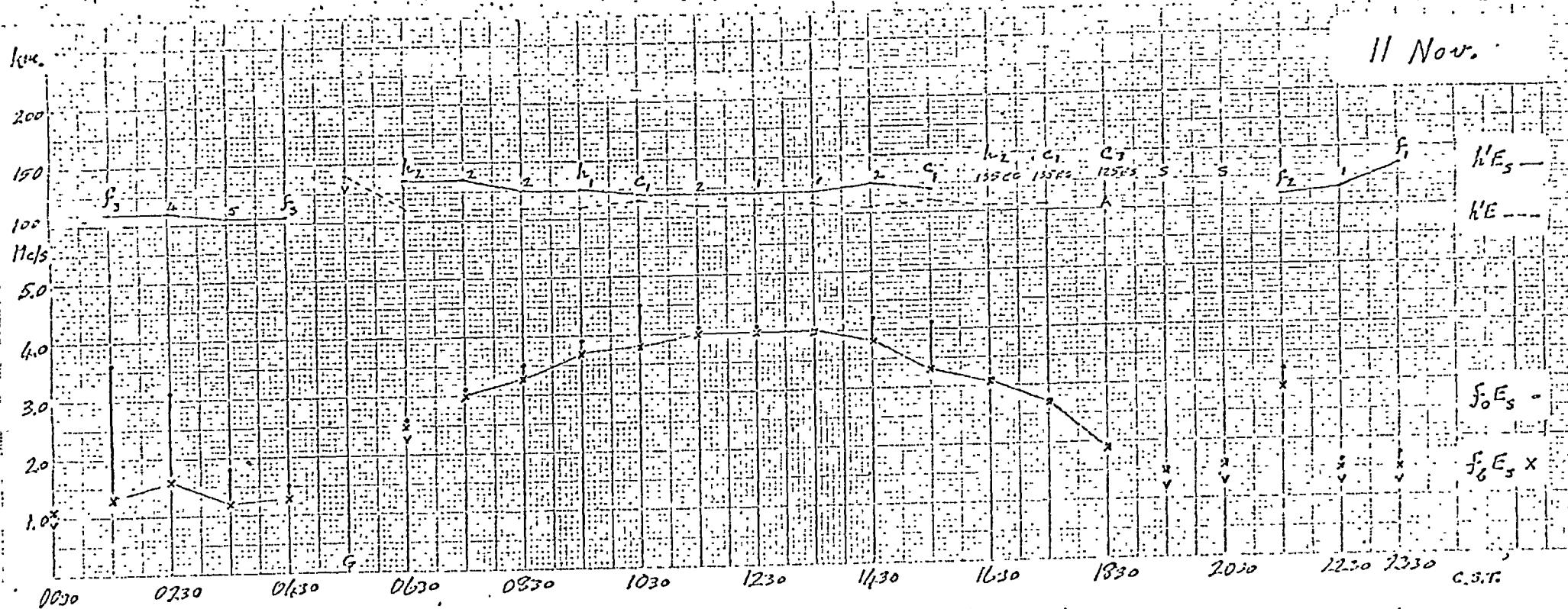


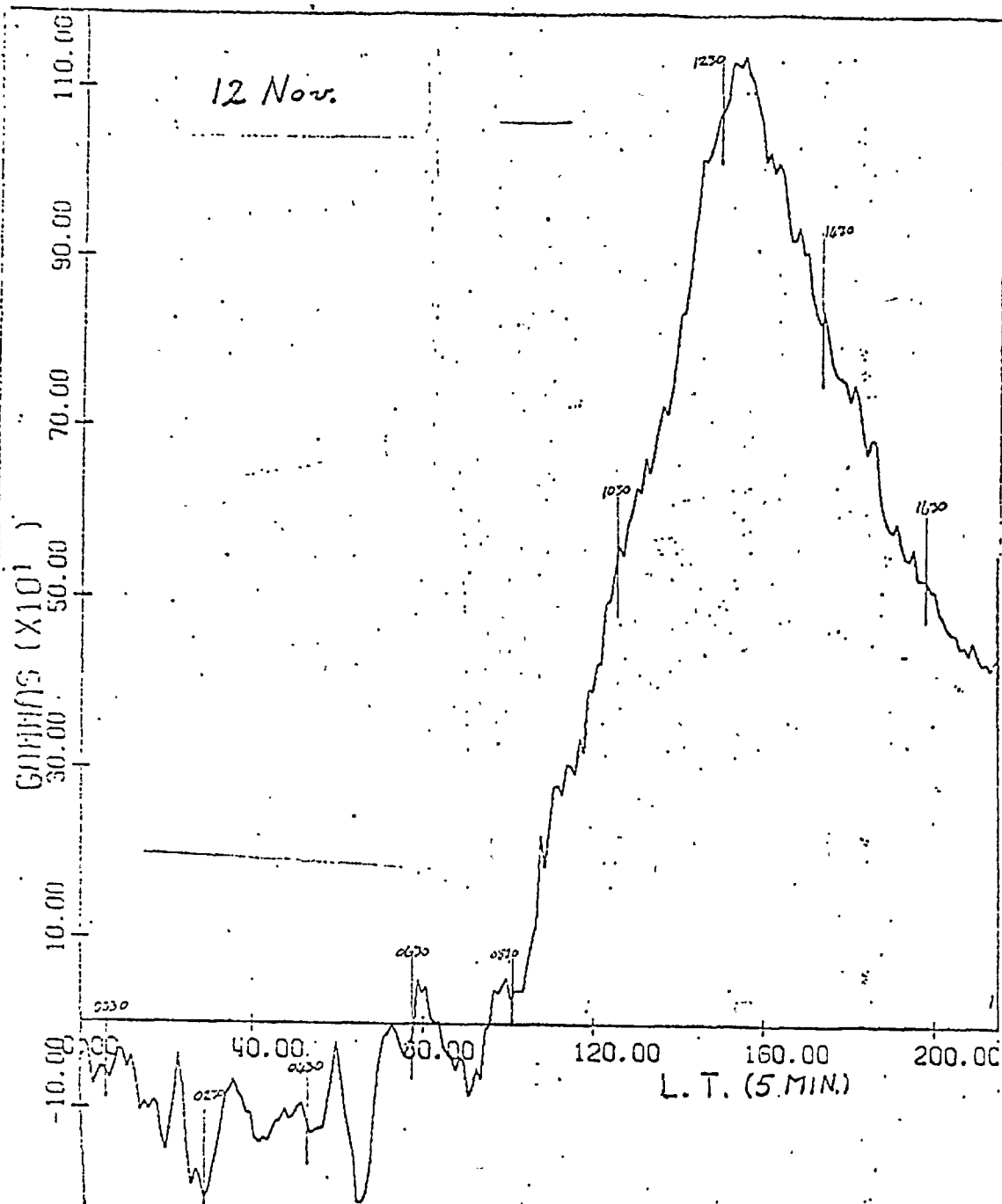


11 Nov.

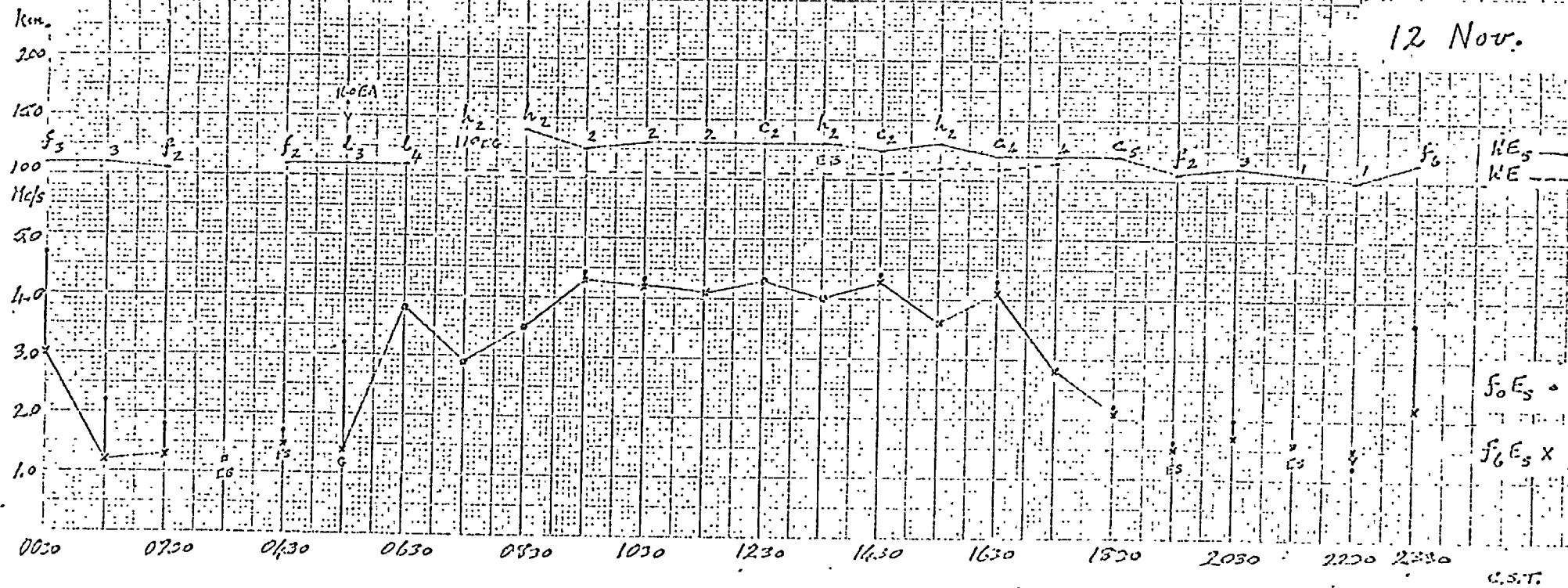


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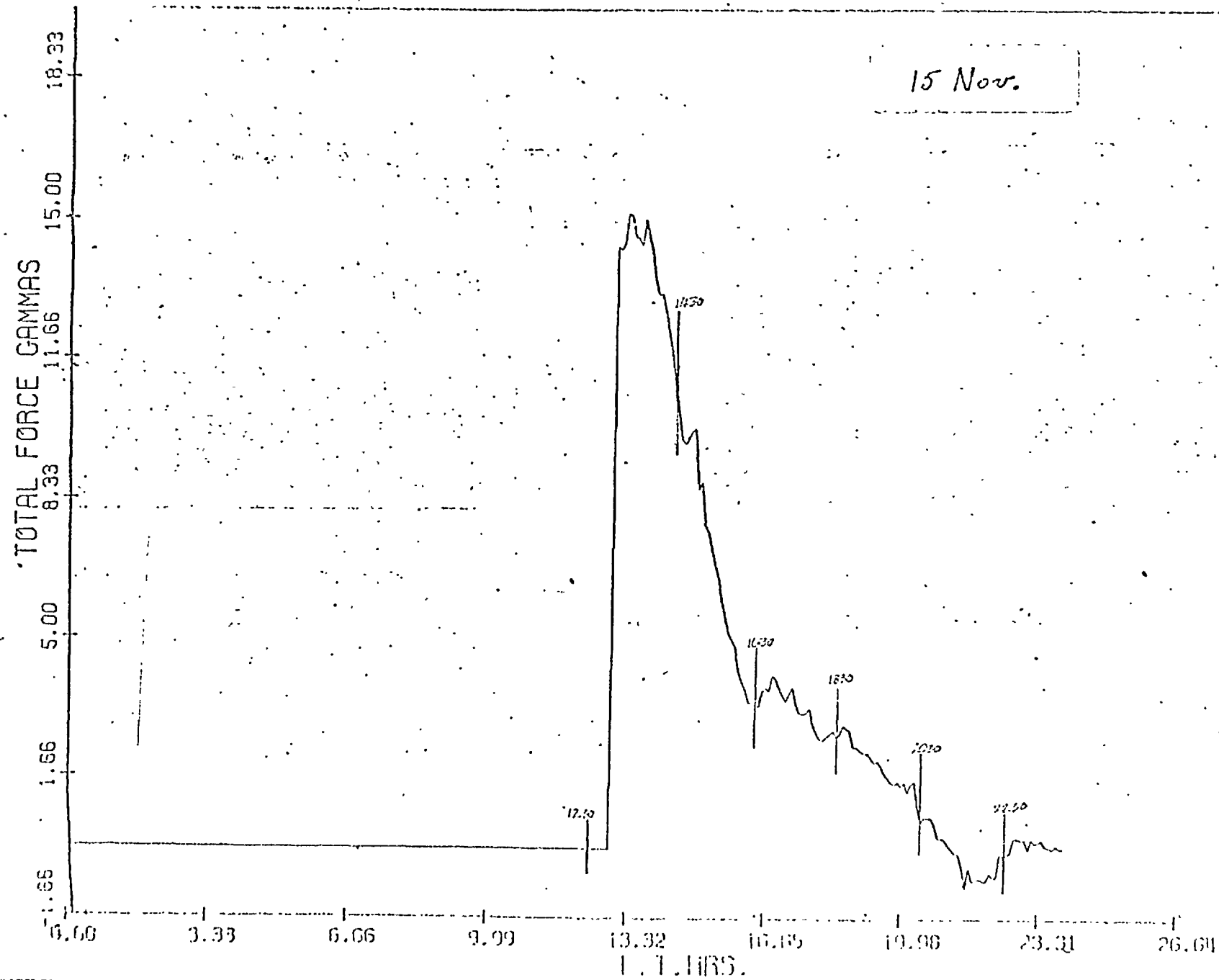




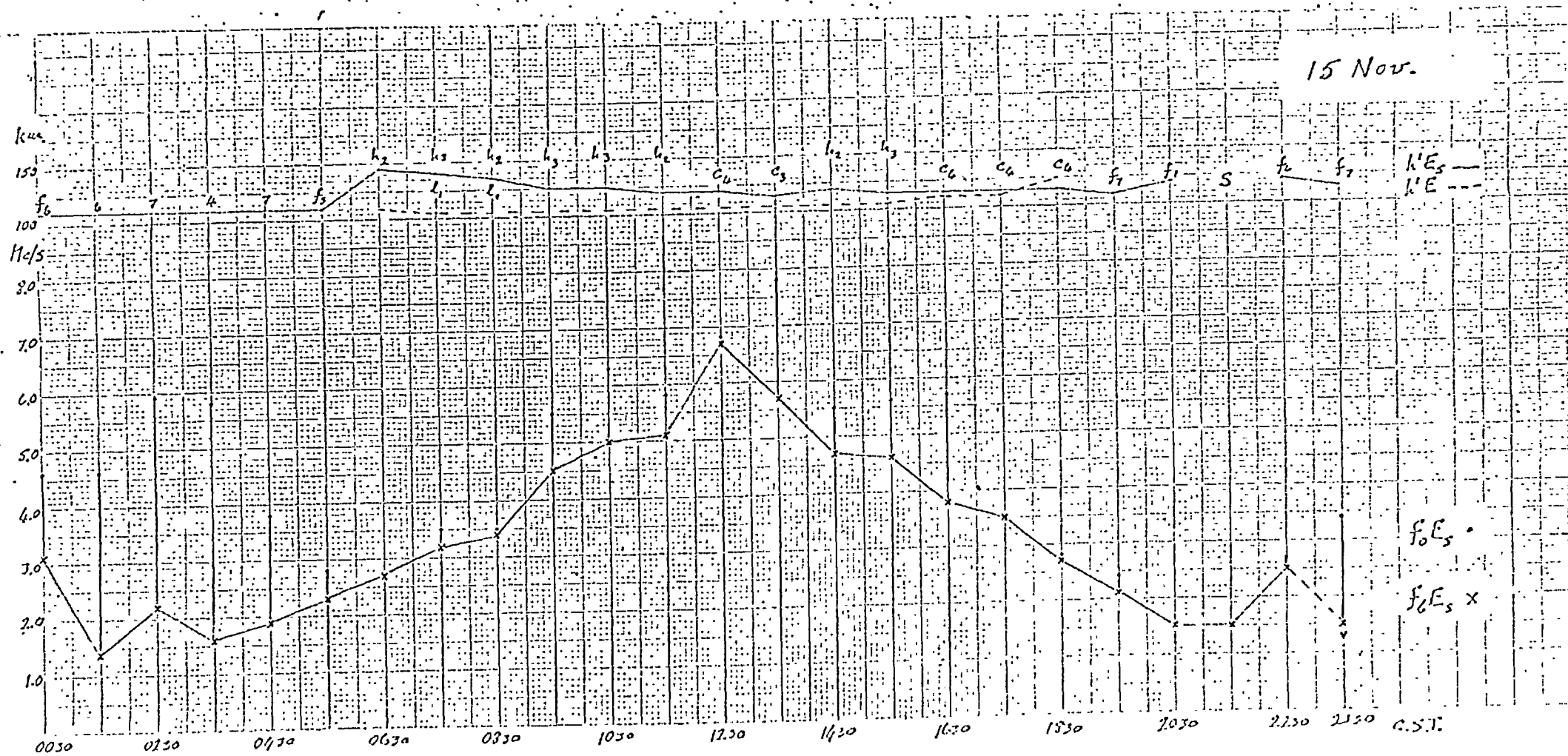
12 Nov.



15 Nov.



15 Nov.



TOTAL FORCE GAMMAS

0.00 3.33 6.66 10.00 13.33 16.66 20.00

16 Nov.

0830

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2230

L.T. HRS.

3.33

6.66

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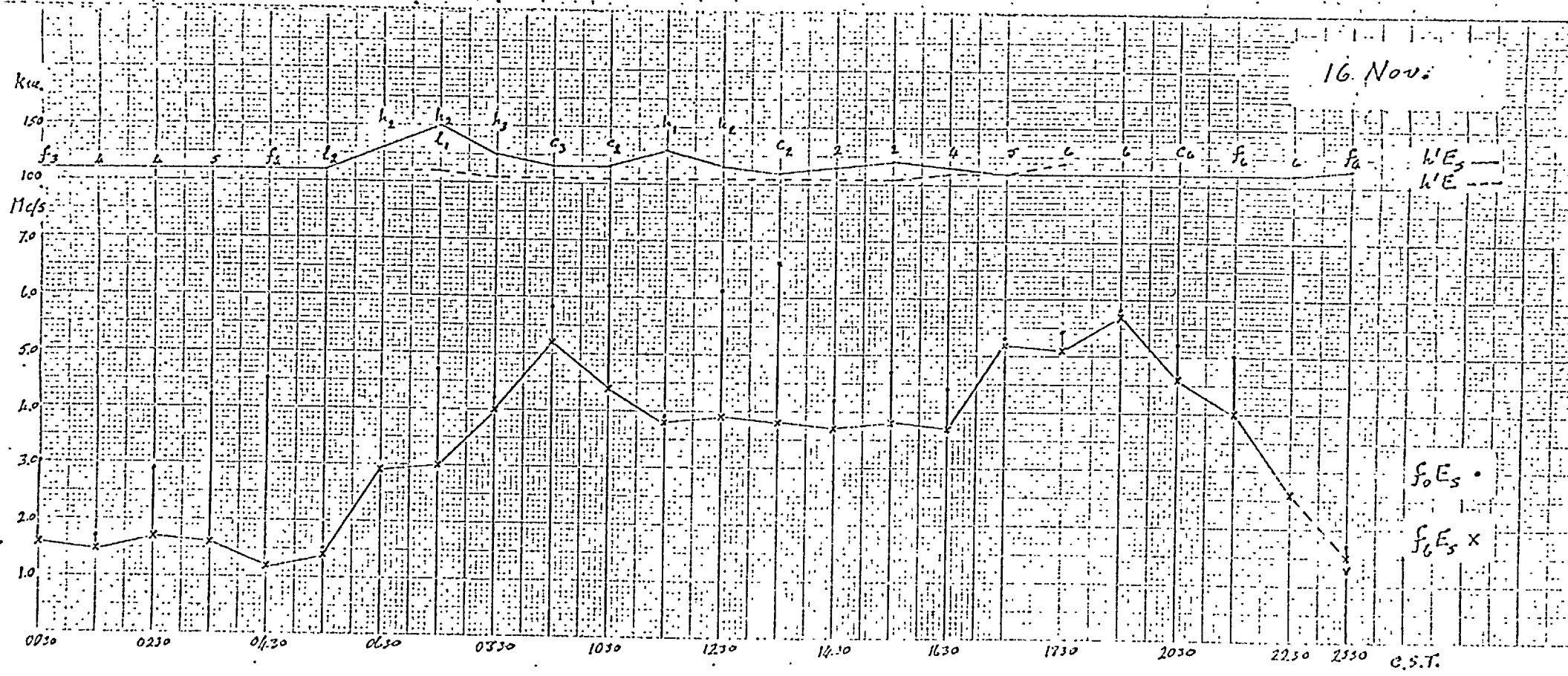
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23.31

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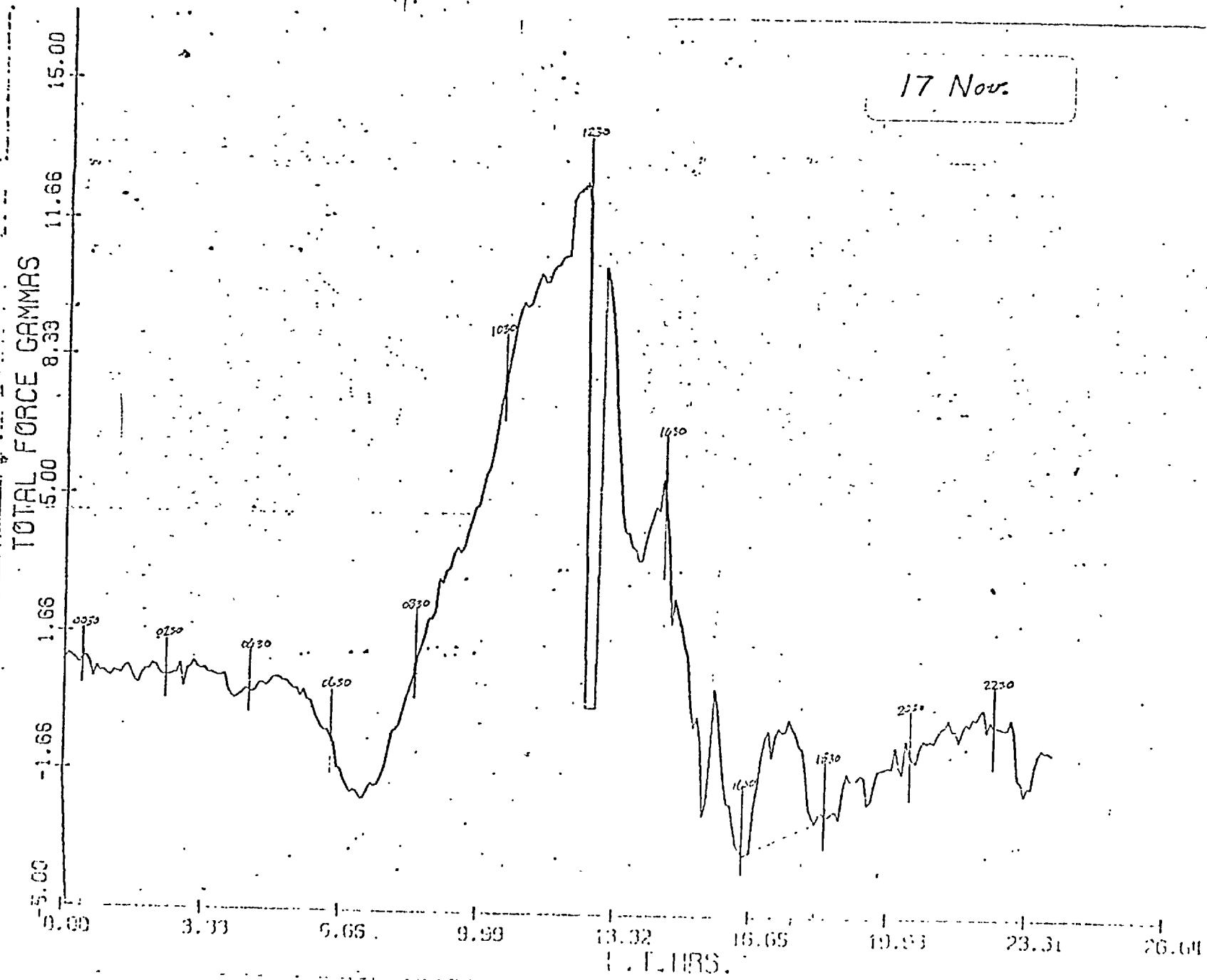
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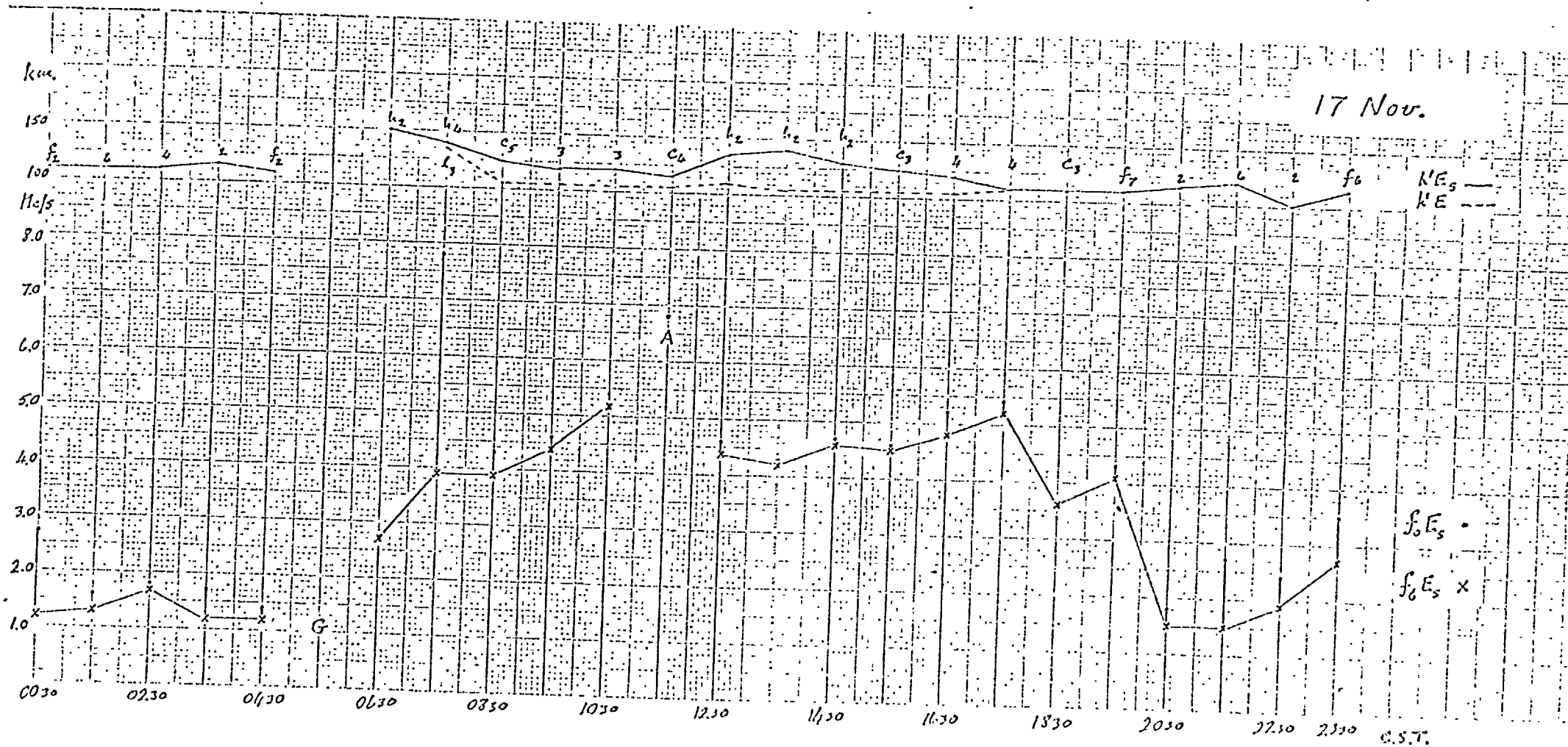


$f_oE_s \cdot$
 $f_oE_s \times$

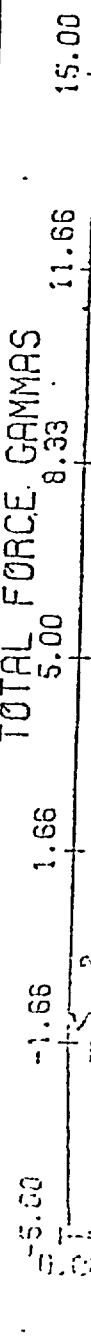
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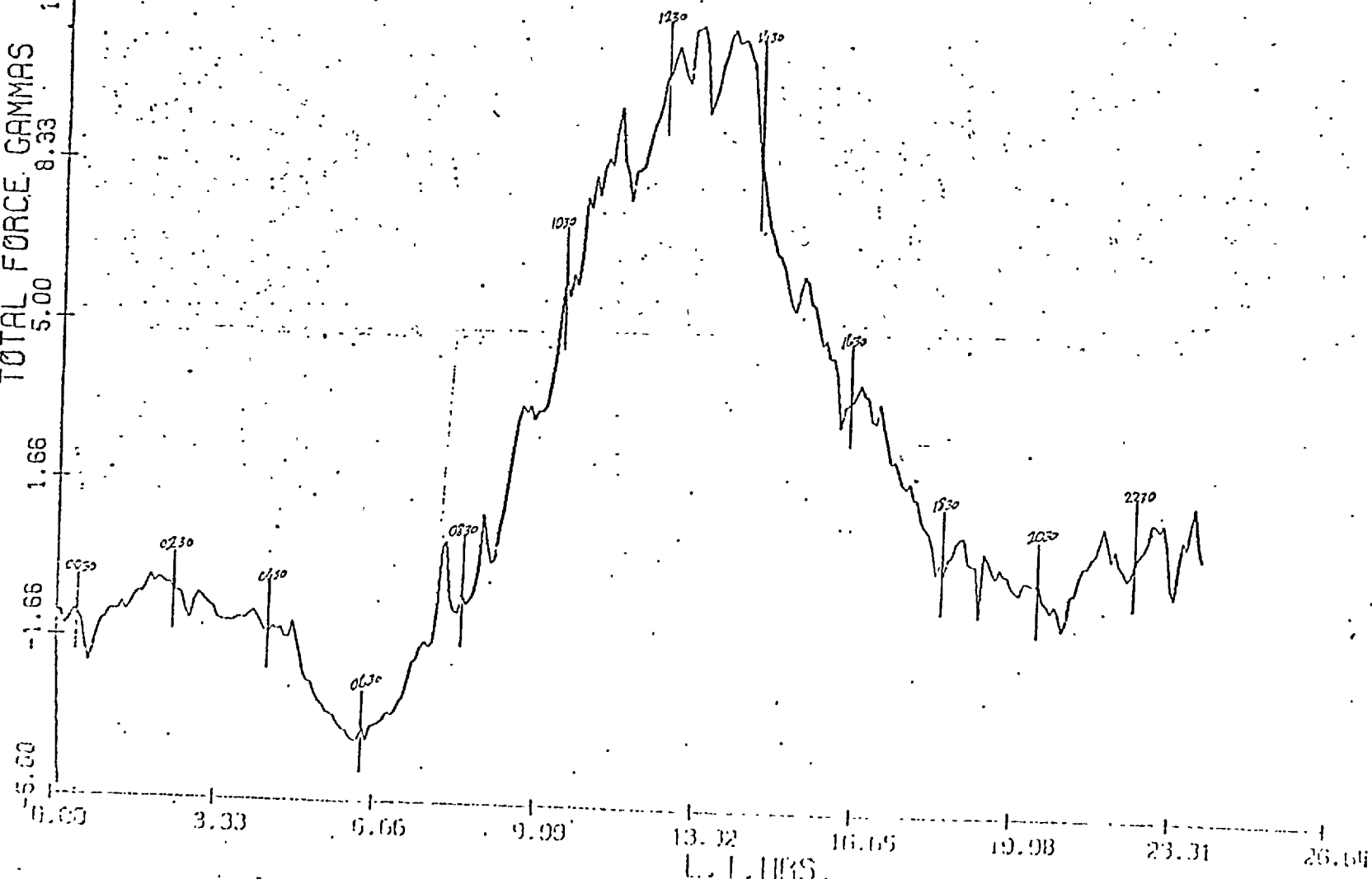


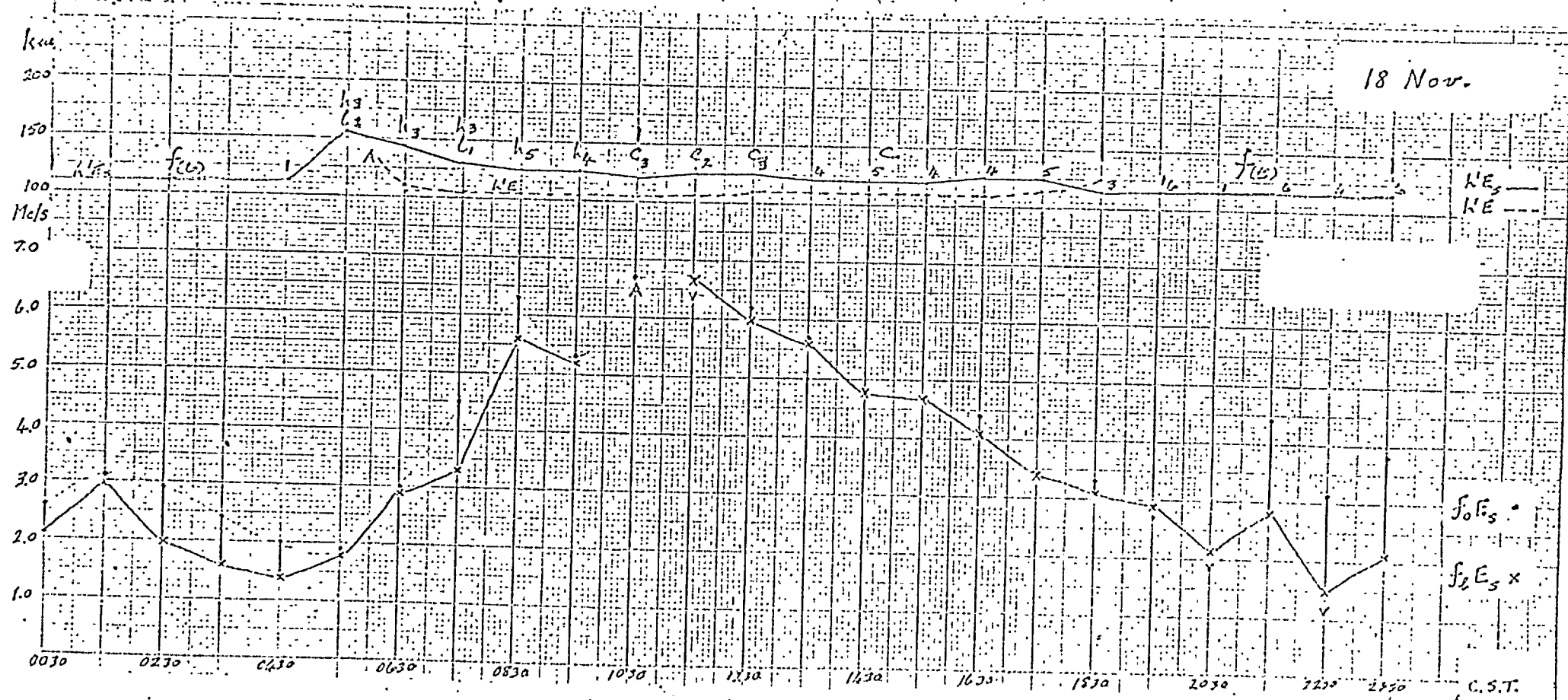


TOTAL FORCE GAMMAS



18 Nov.

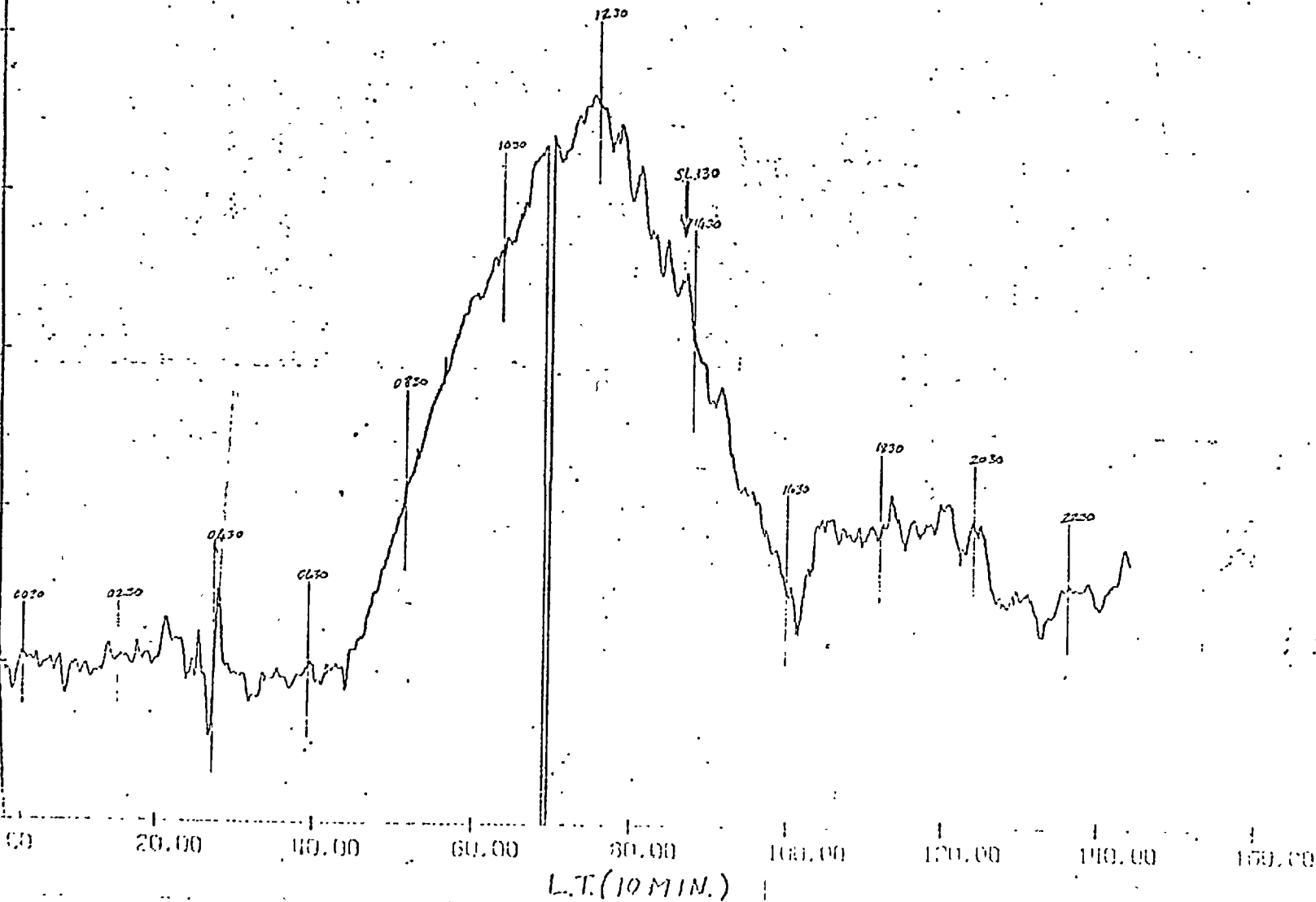




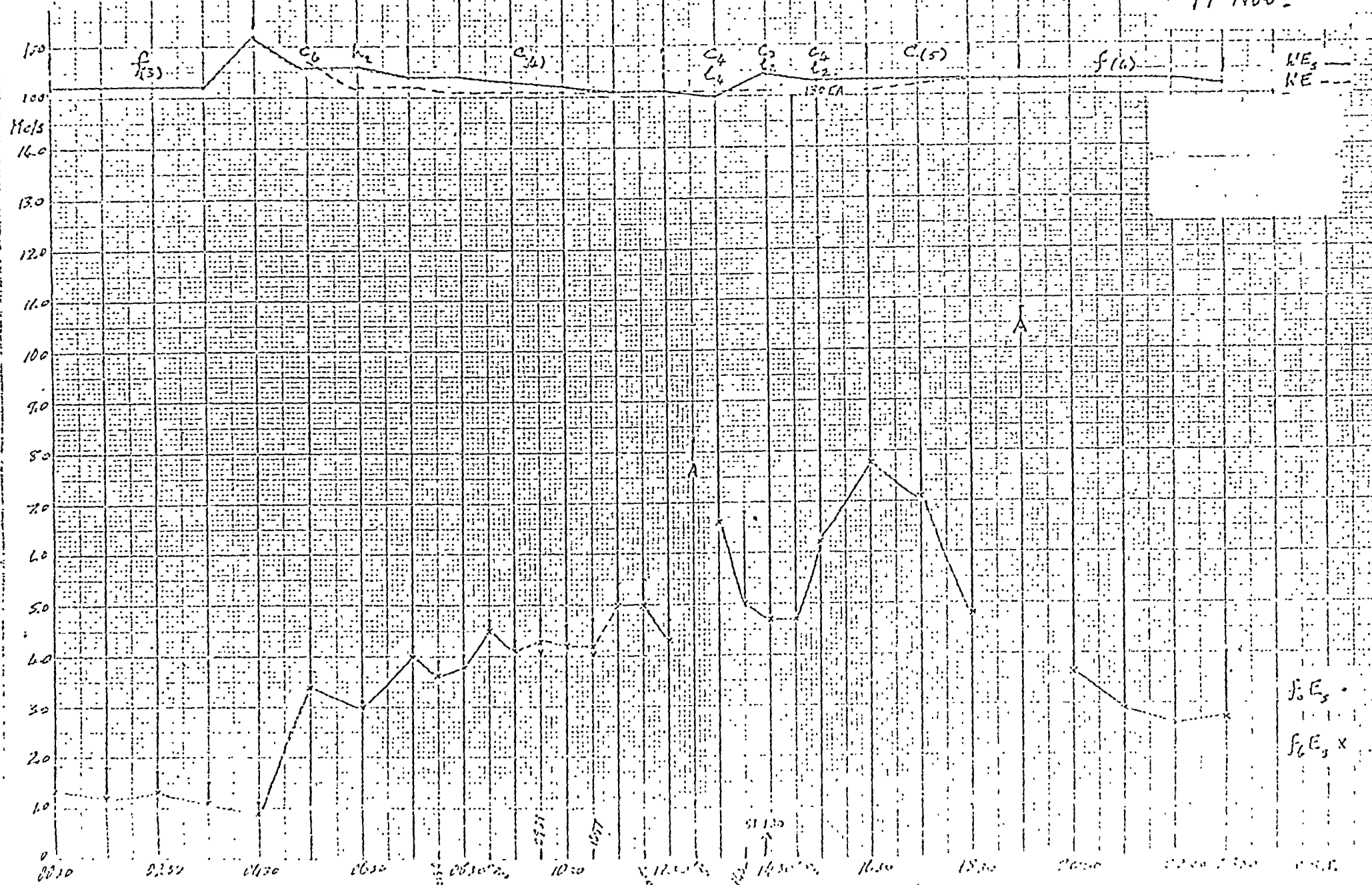
19 Nov.

GAMMAS

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26.66
20.00
13.33
6.66
0.00

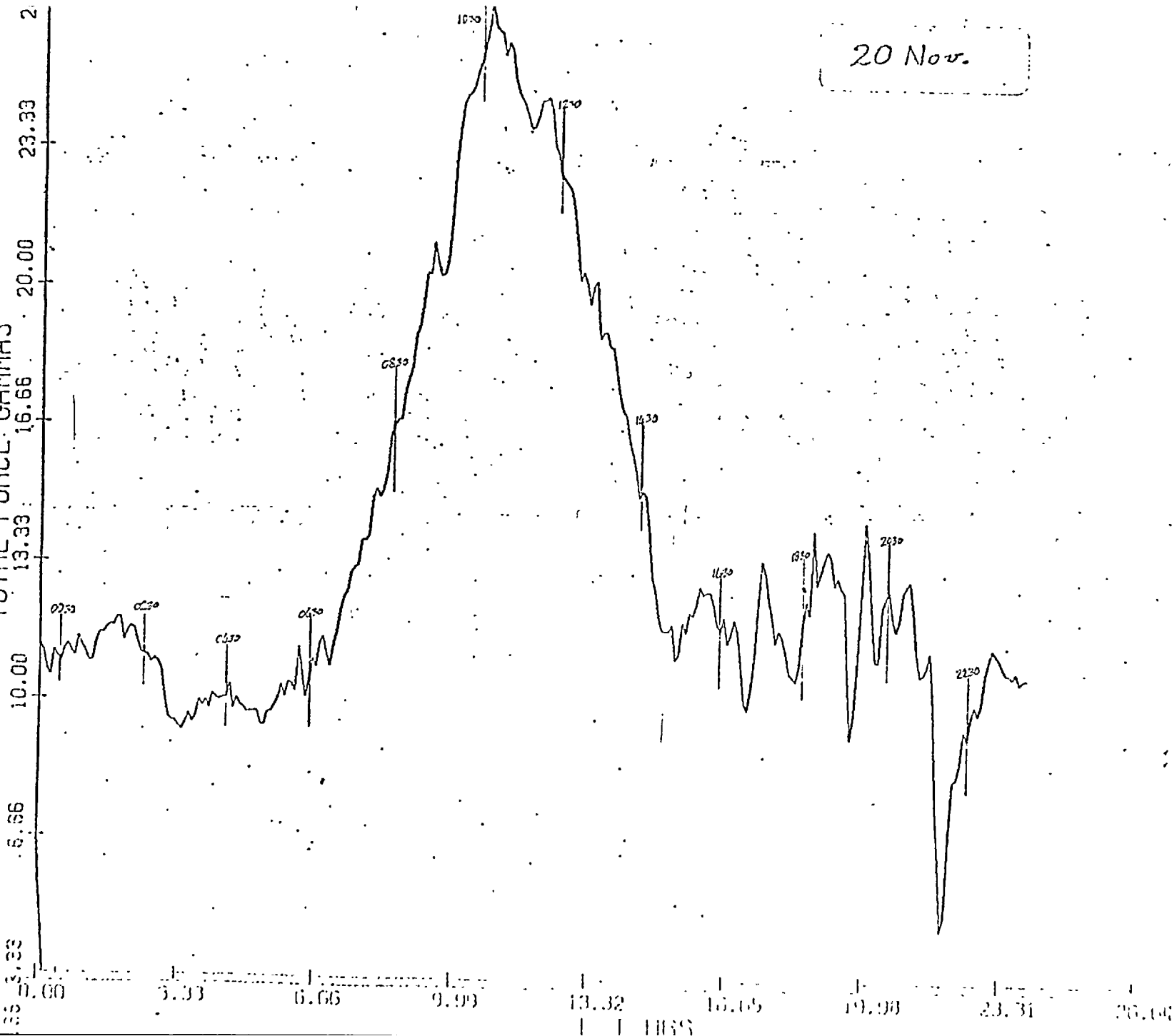


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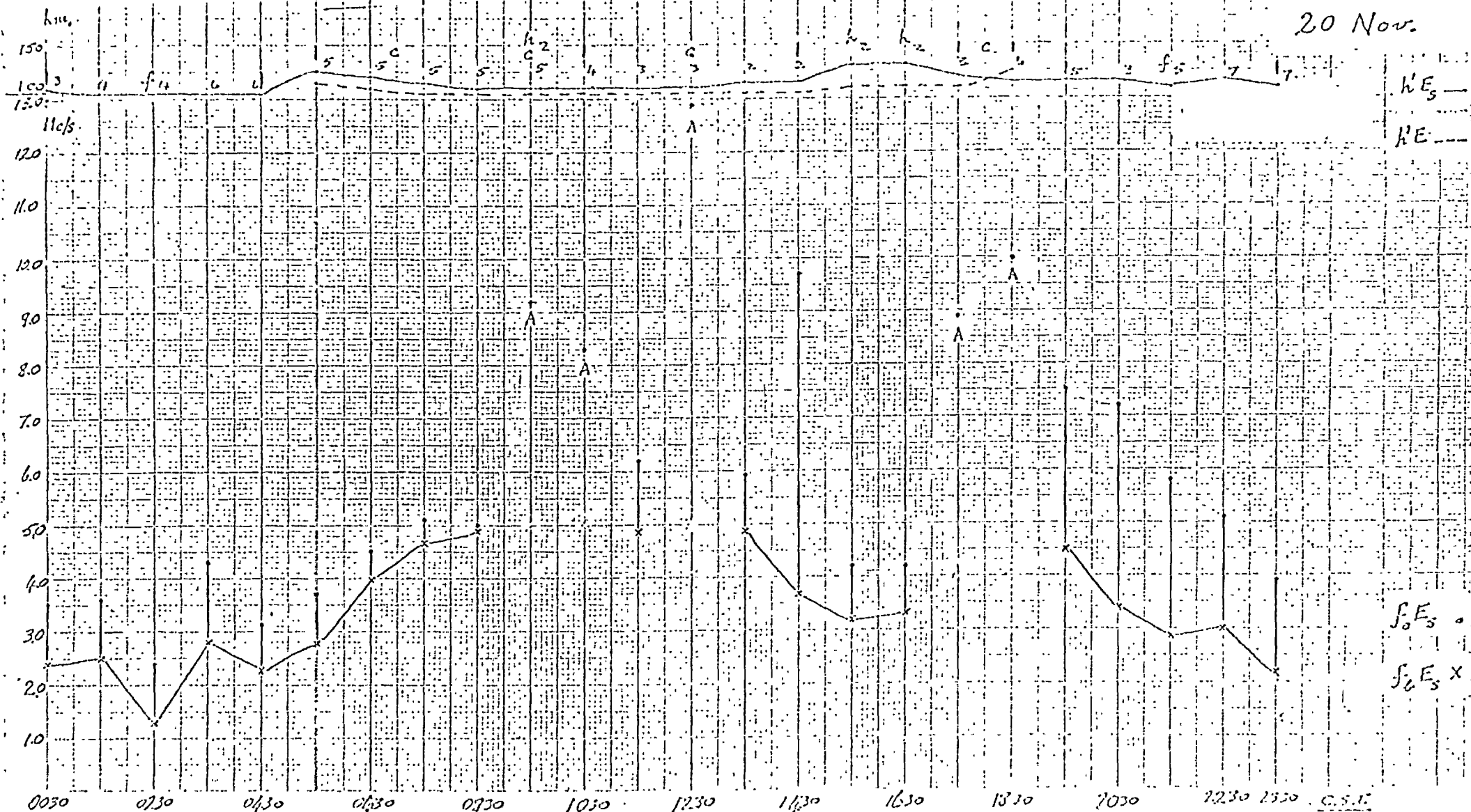


20 Nov.

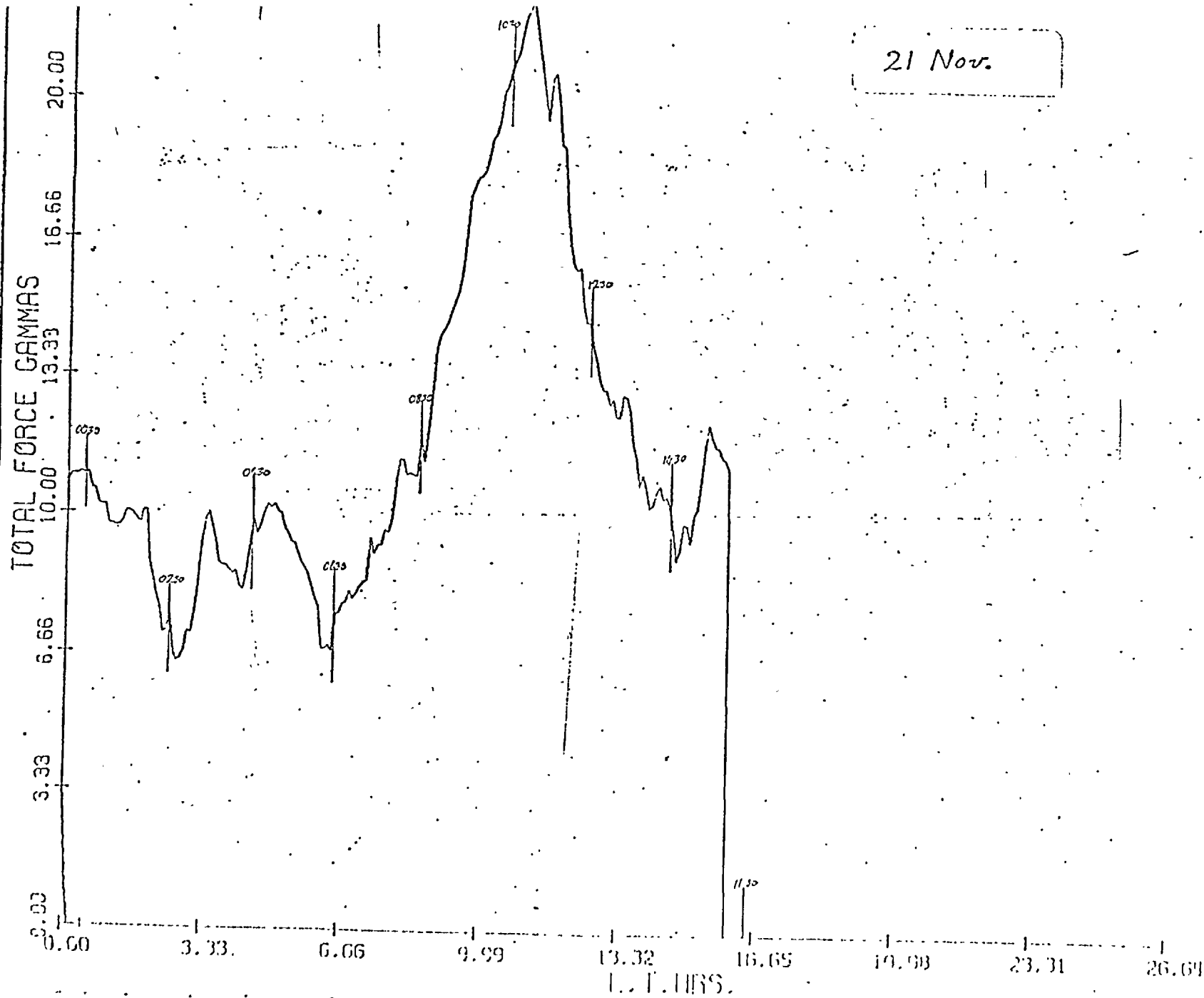
TOTAL FORCE GAMMAS



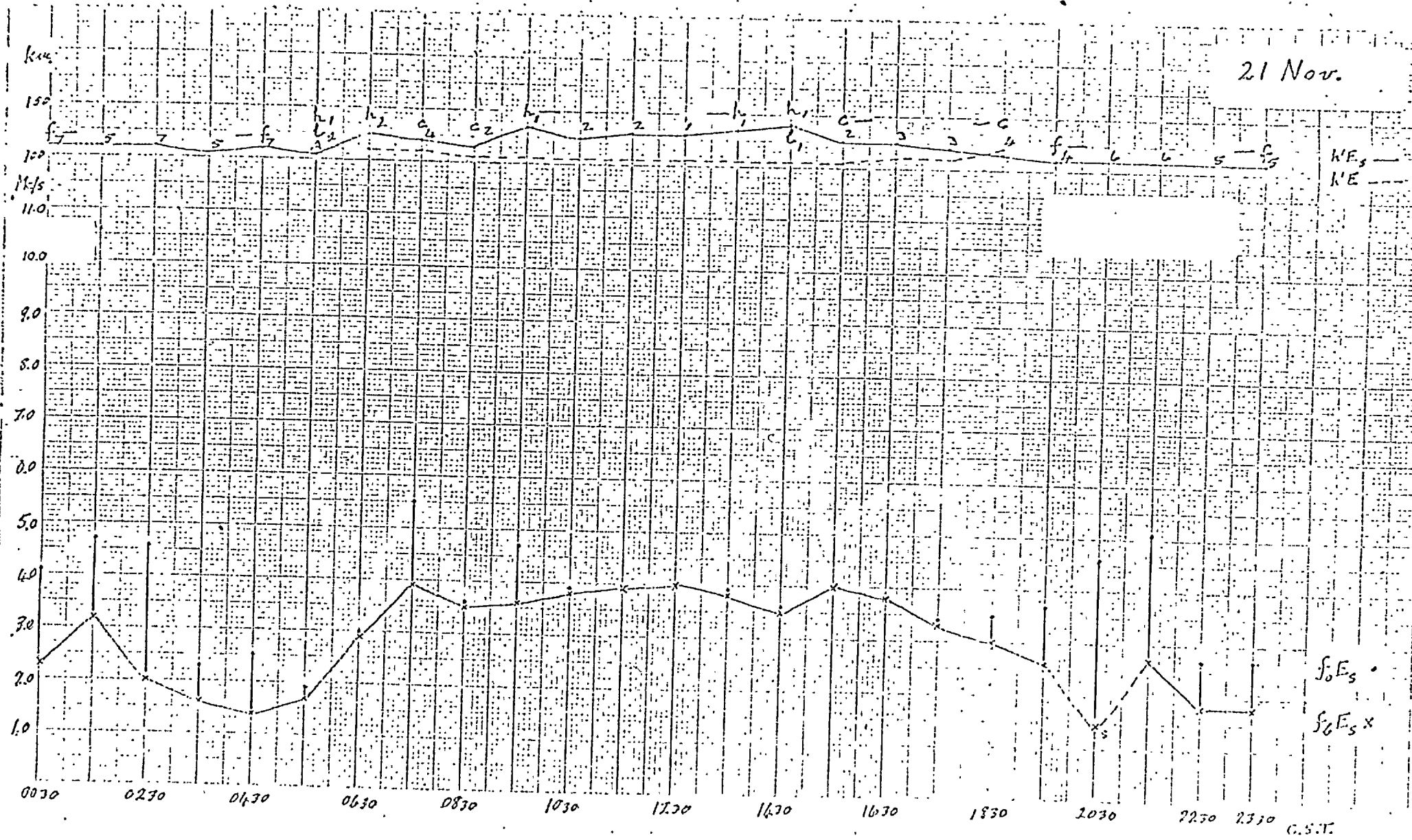
20 Nov.



21 Nov.



21 Nov.



27 Nov.

TOTAL FORCE GAMMAS

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13.33

10.00

6.66

3.33

0.00

-3.33

0.00

3.33

6.66

9.99

13.32

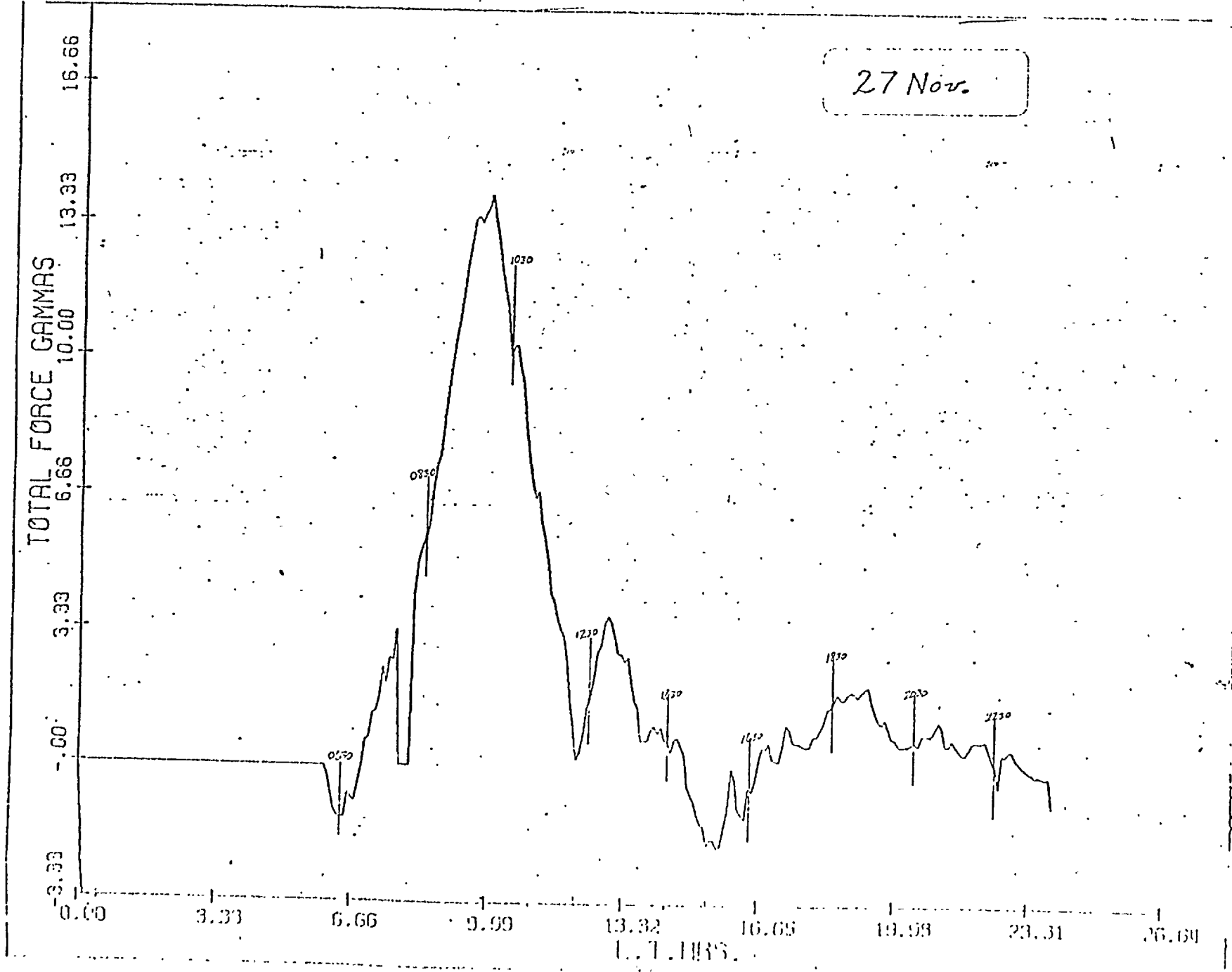
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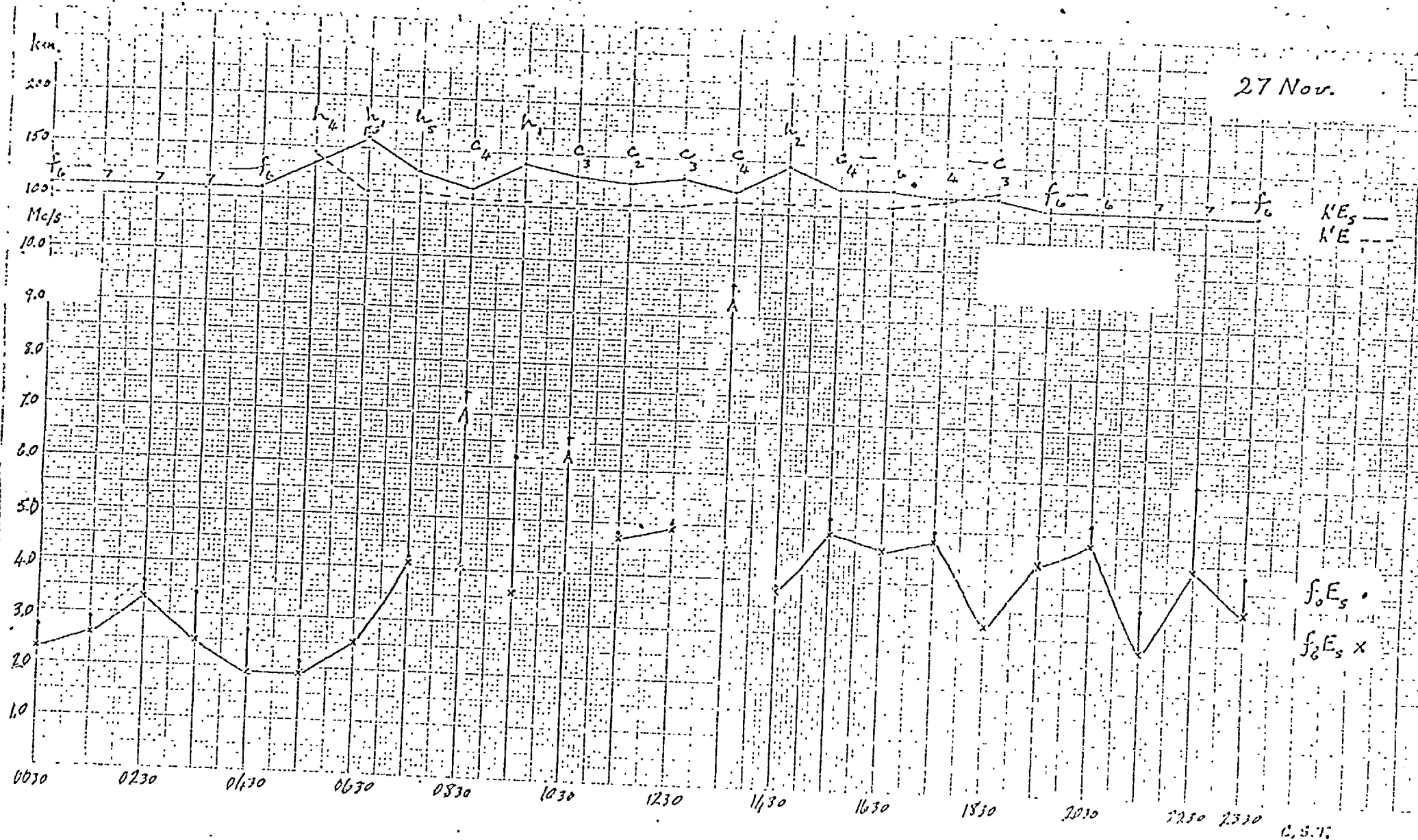
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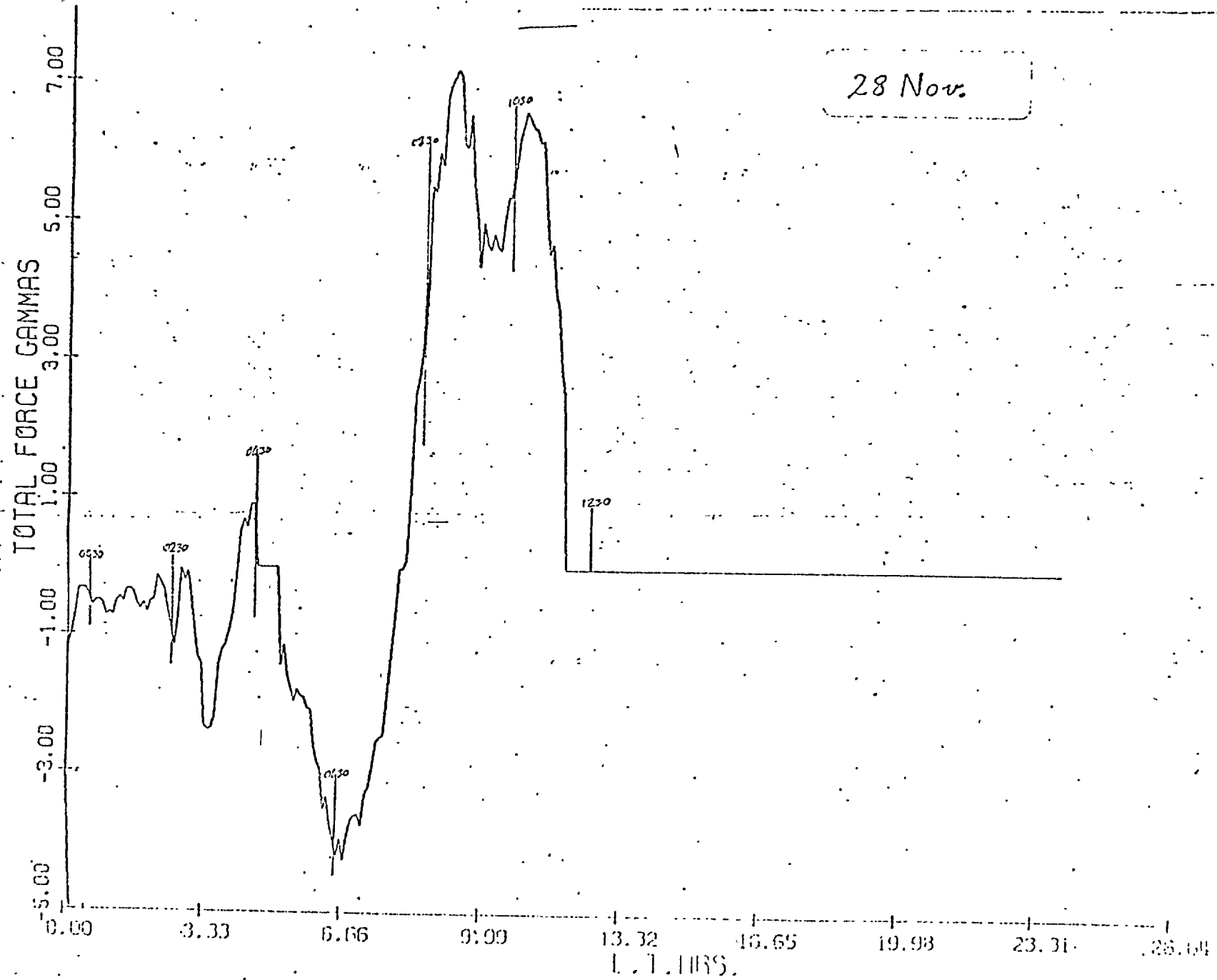
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1.1.1035

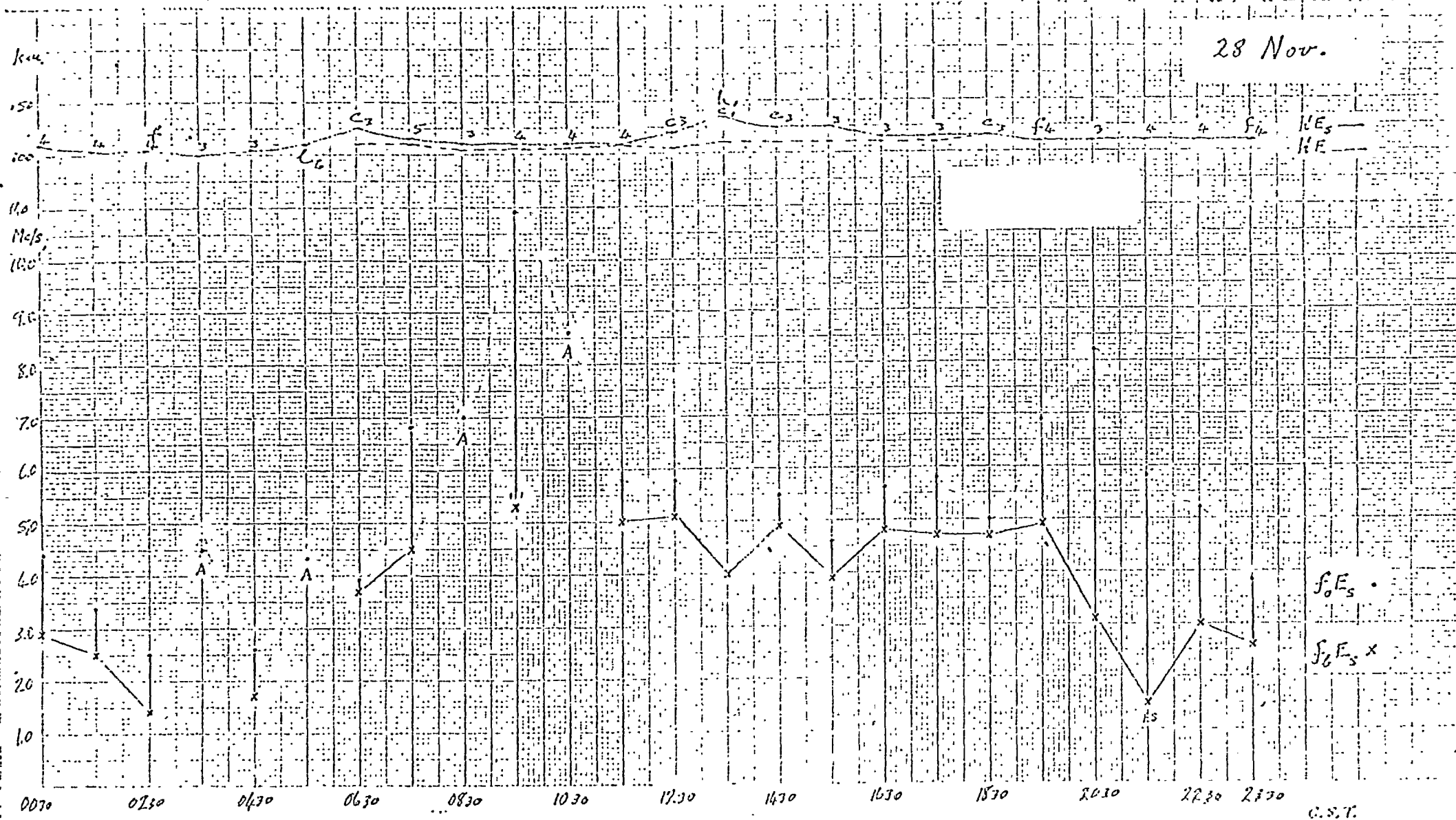


27 Nov.





28 Nov.



30 Nov.

TOTAL FORCE GAMMAS

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11.00
7.00
3.00
-1.00
-5.00

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3.33

6.66

9.99

13.32

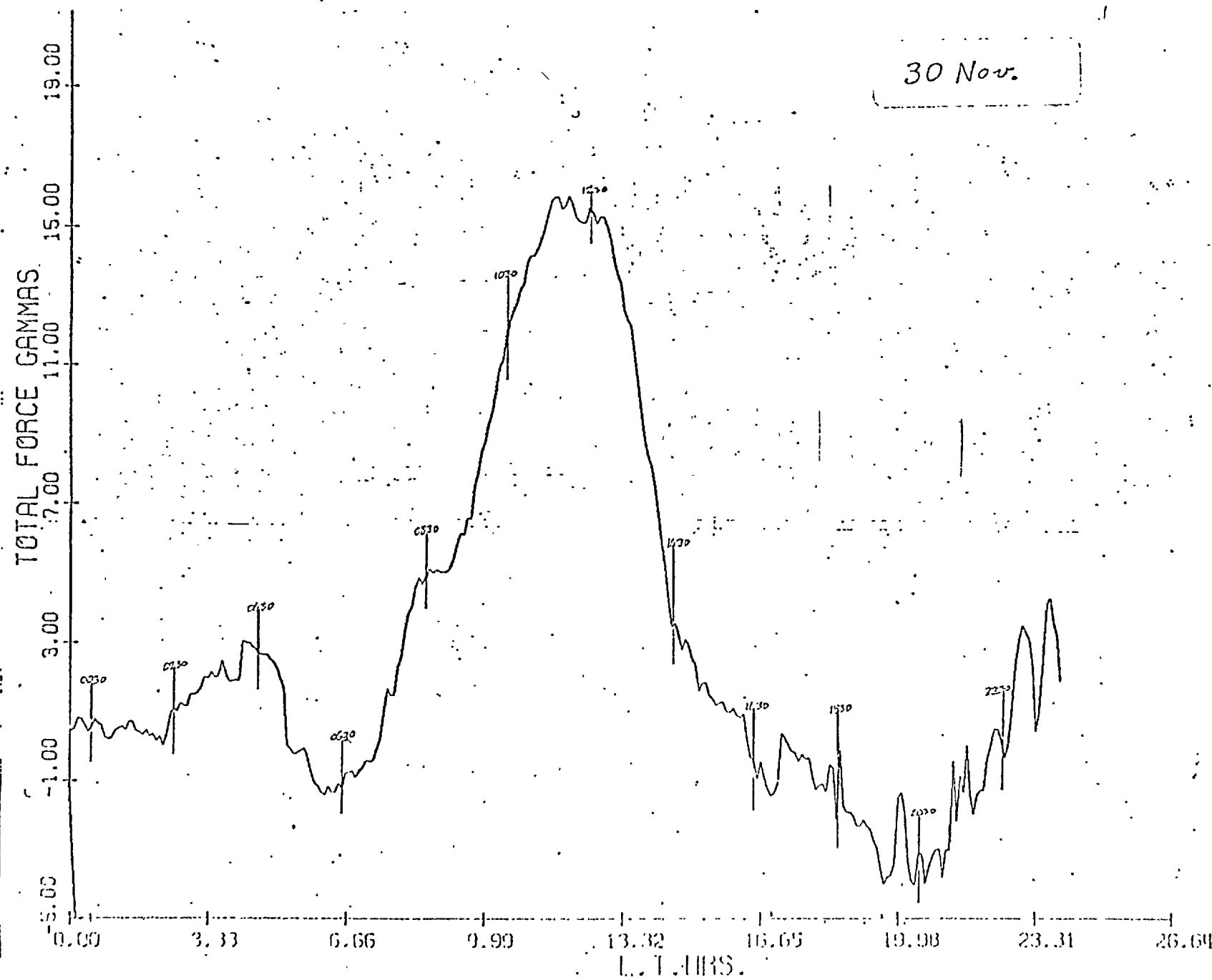
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19.98

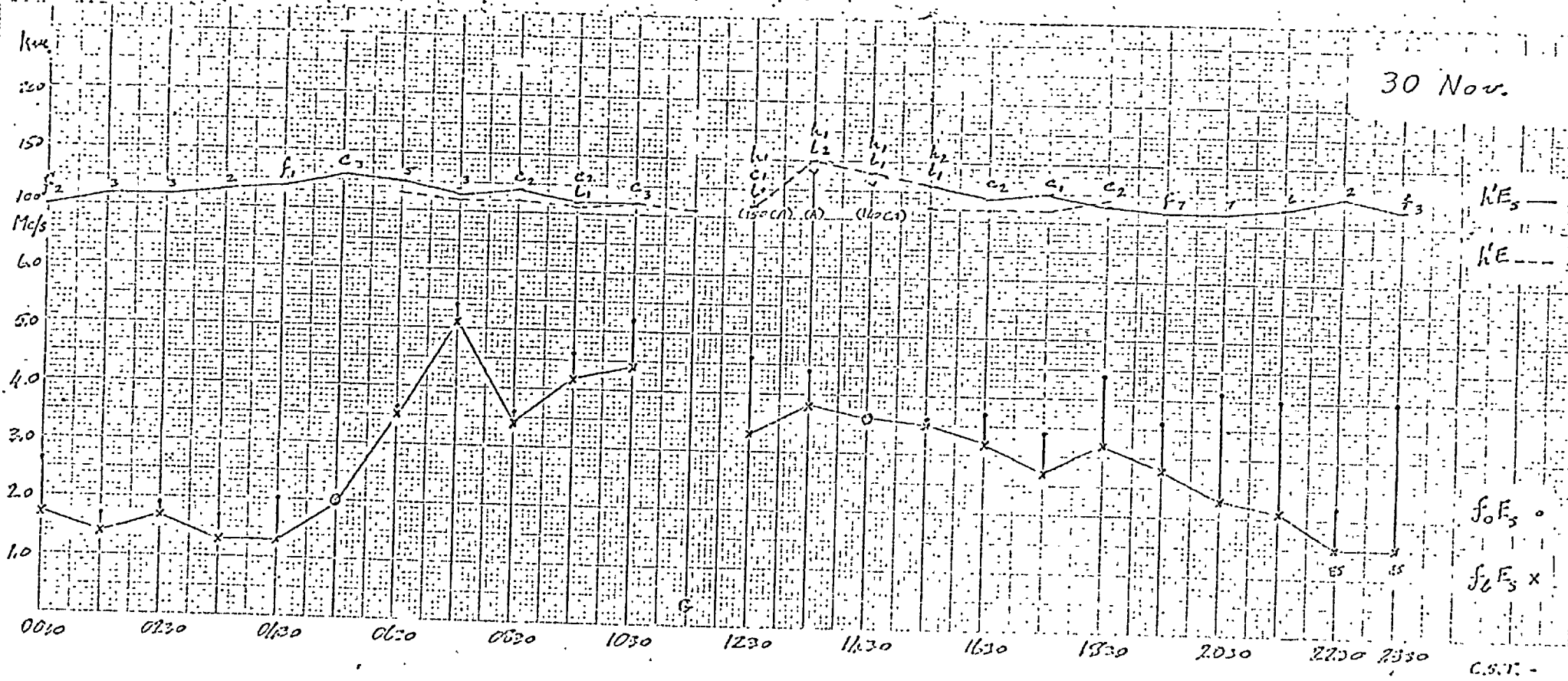
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26.64

L.T.HRS.



30 Nov.



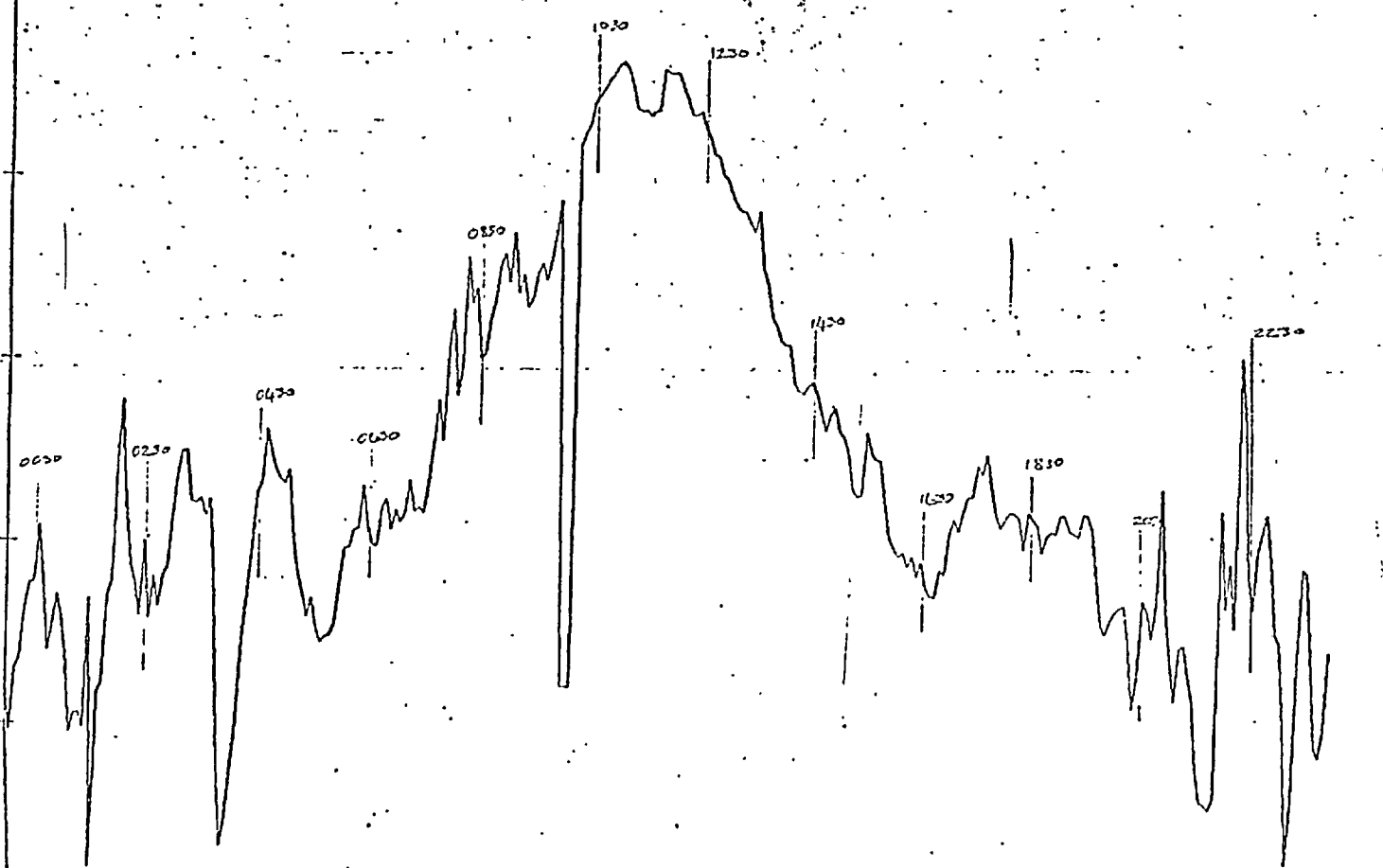
TOTAL FORCE GAMMAS

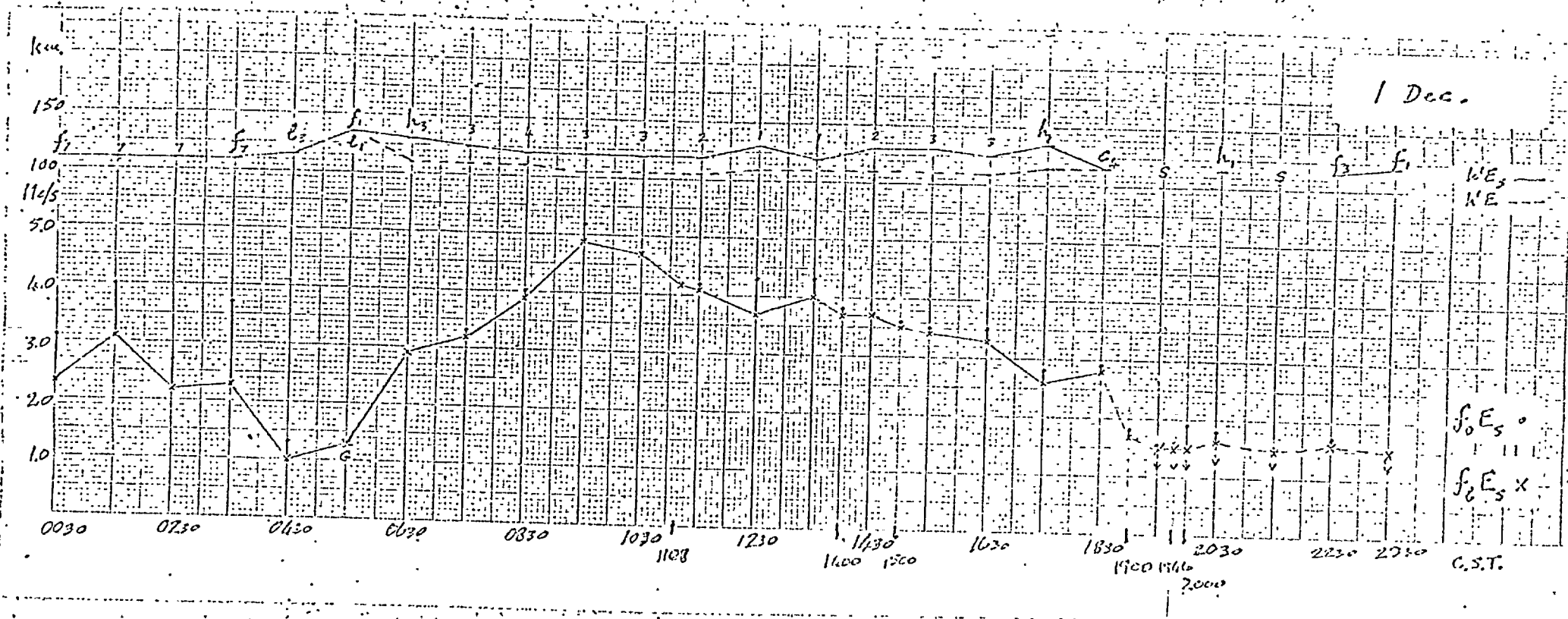
19.00
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0.00 3.33 6.66 9.99 13.32 16.65 19.98 23.31 26.64

UTLINS

1 Dec.





TOTAL FORCE GAMMAS

2 Dec.

25.00
21.00
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5.00
1.00
0.00

0.00

3.33

6.66

9.99

13.32

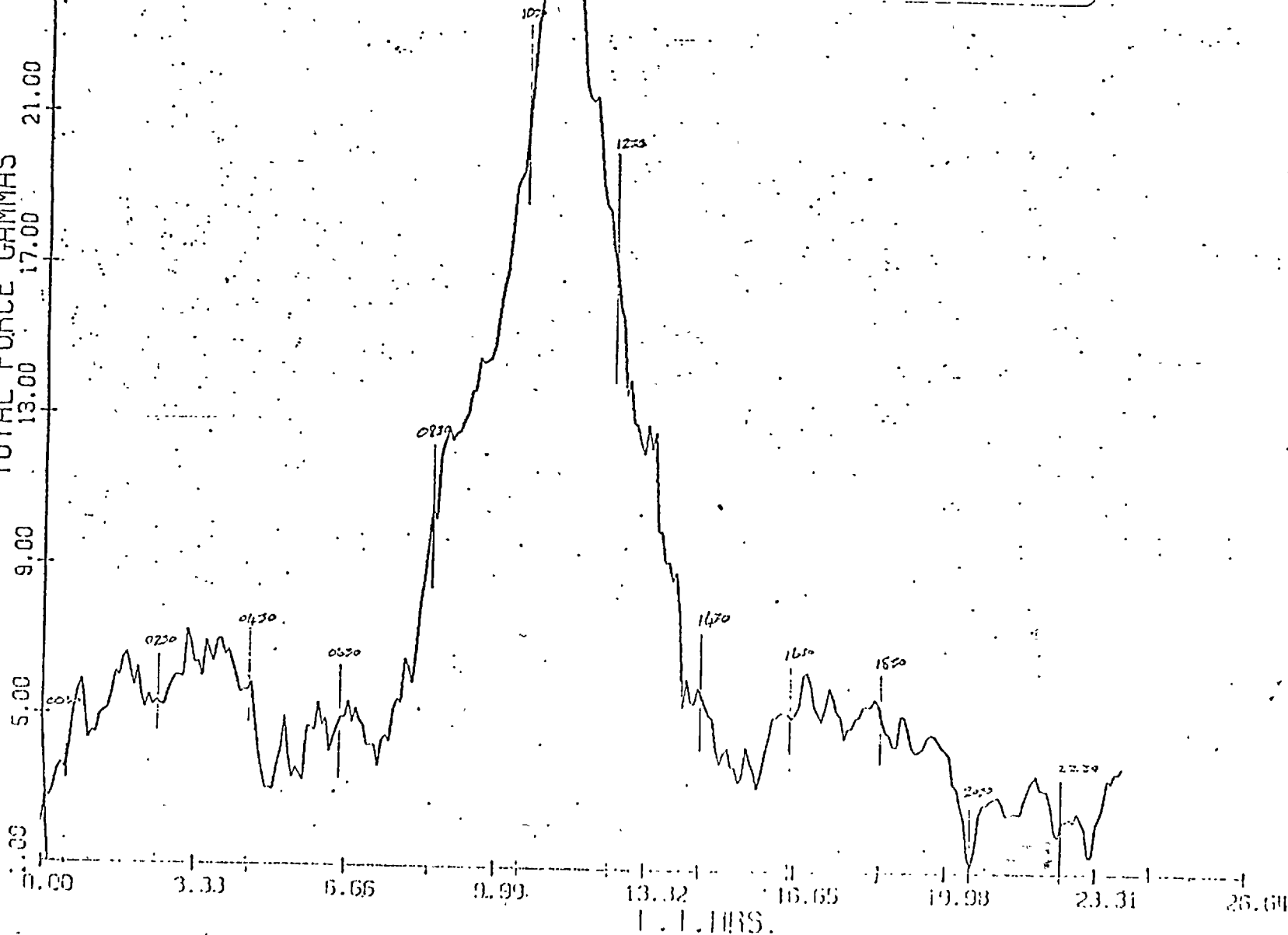
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19.98

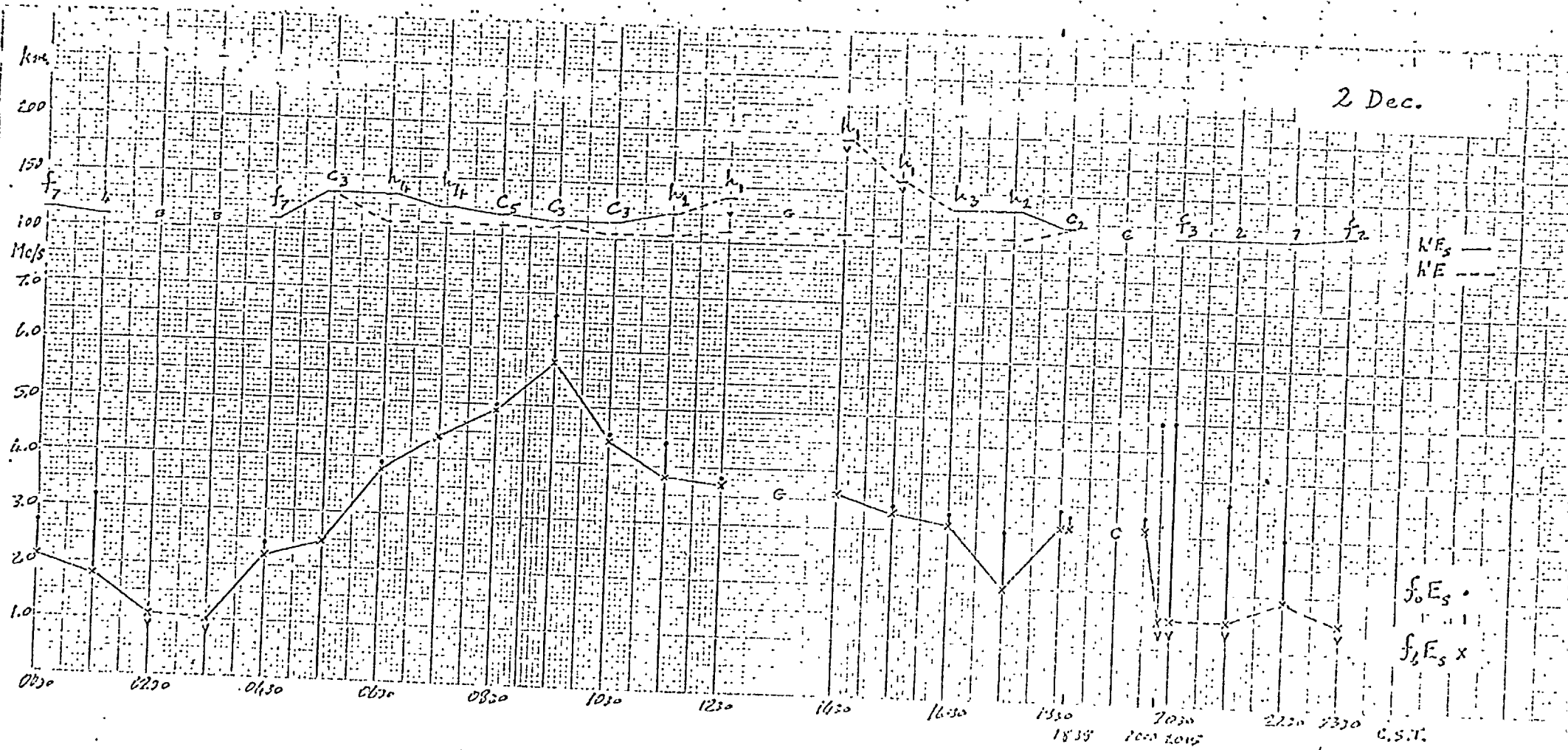
23.31

26.64

TIME



2 Dec.



3 Dec.

TOTAL FORCE GAMMAS

13.00
11.00
9.00
7.00
5.00
3.00
2.00

0.00

3.33

6.66

9.99

13.32

16.65

19.98

23.31

26.64

TIME

00:30

02:30

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06:30

08:30

12:30

12:30

14:30

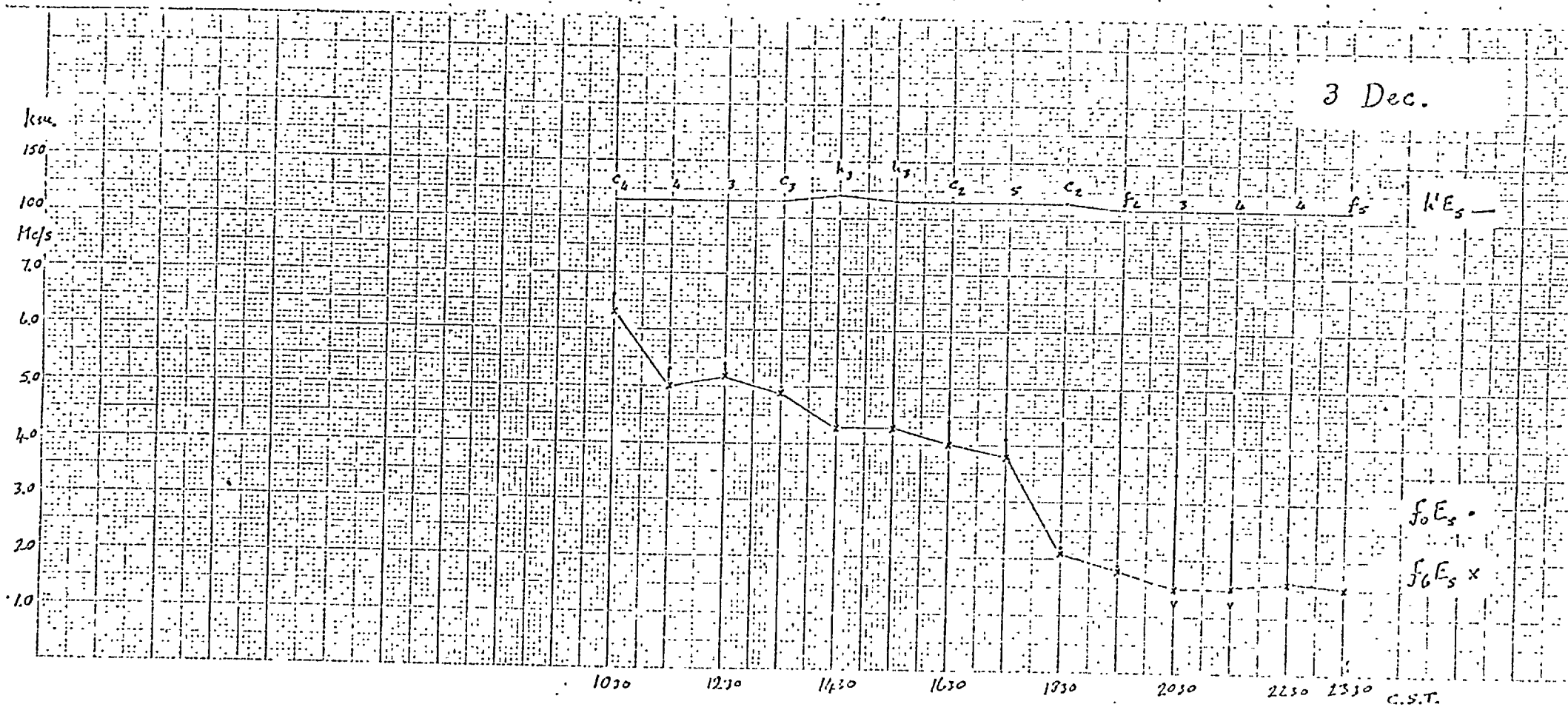
16:30

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3 Dec.



TOTAL FORCE GAMMAS

12.00

10.00

8.00

6.00

4.00

2.00

0.00

1020

0230

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1230

1420

1670

1850

4 Dec.

3.33

6.66

9.99

13.32

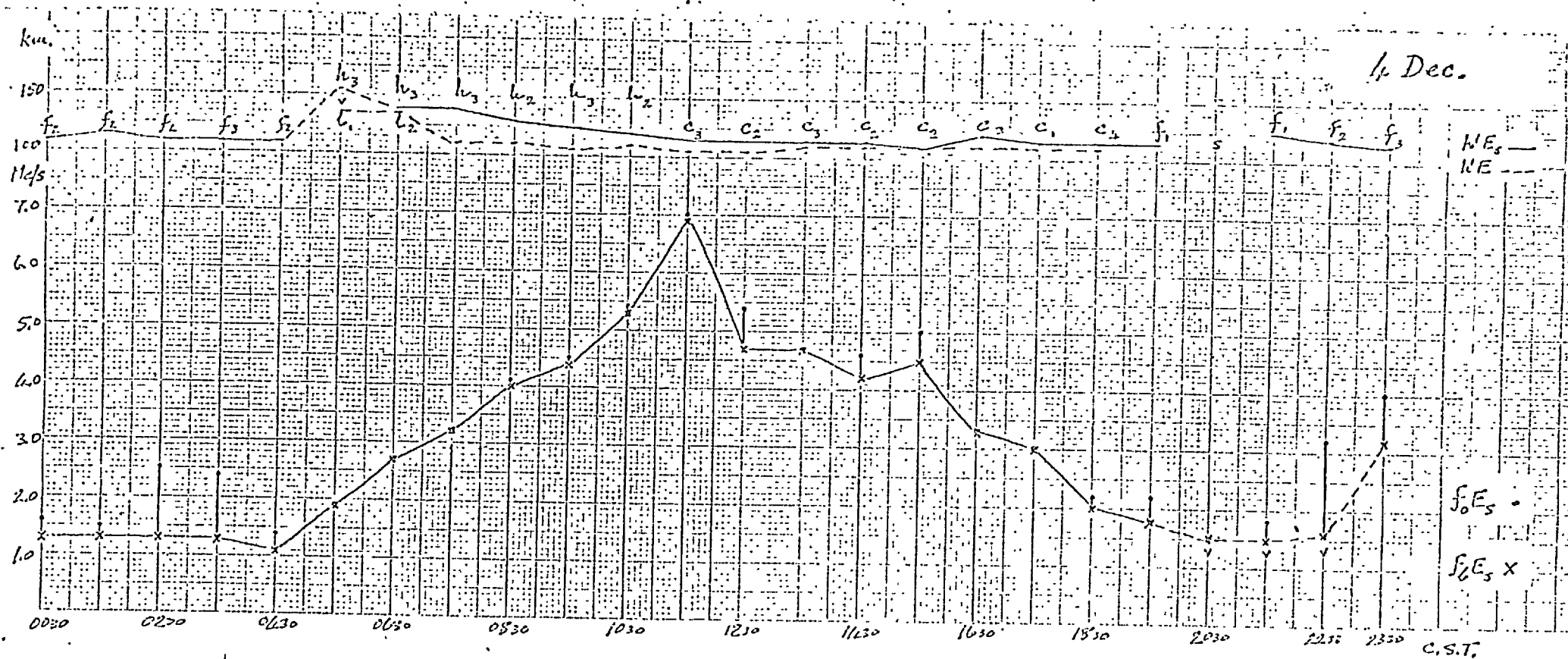
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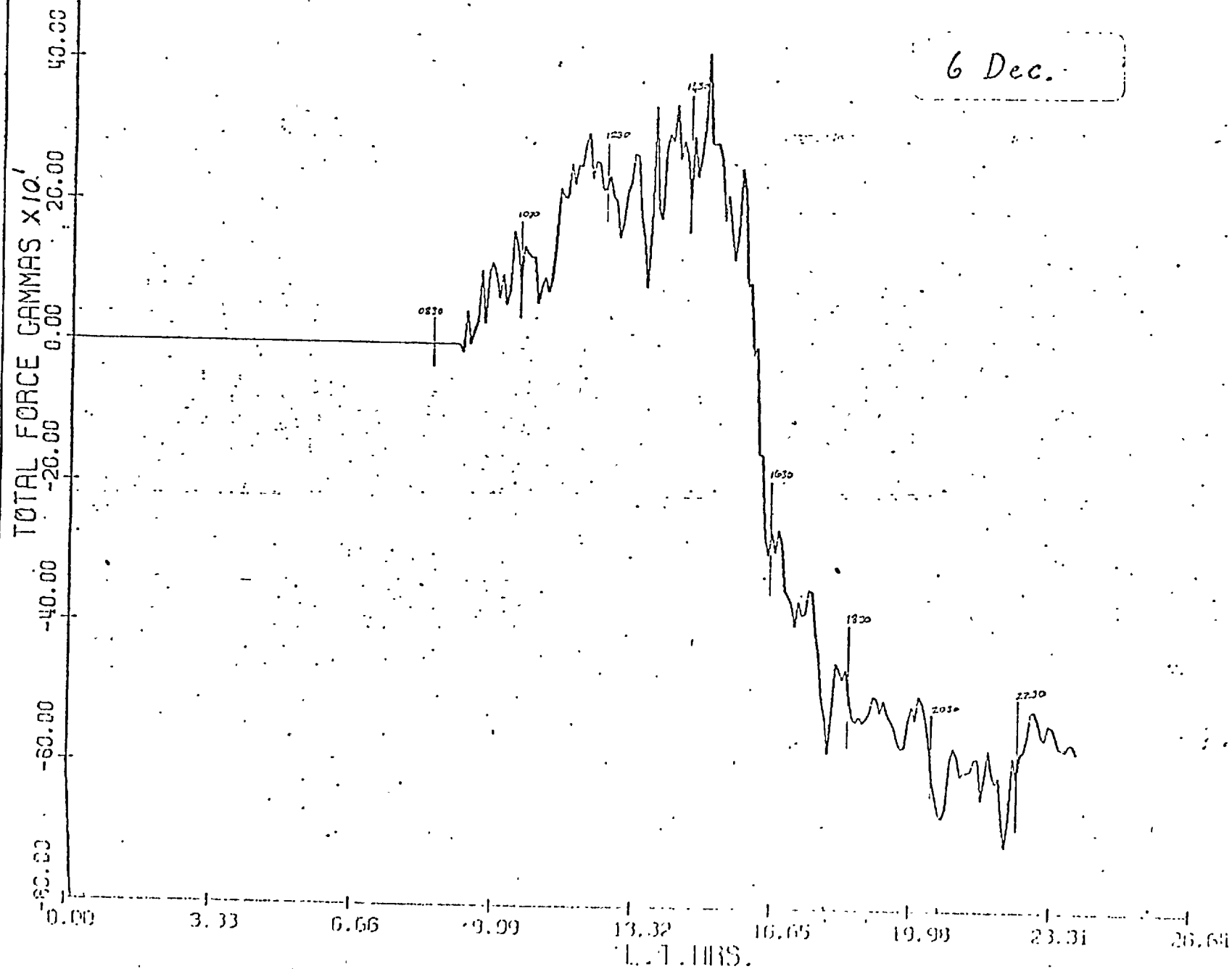
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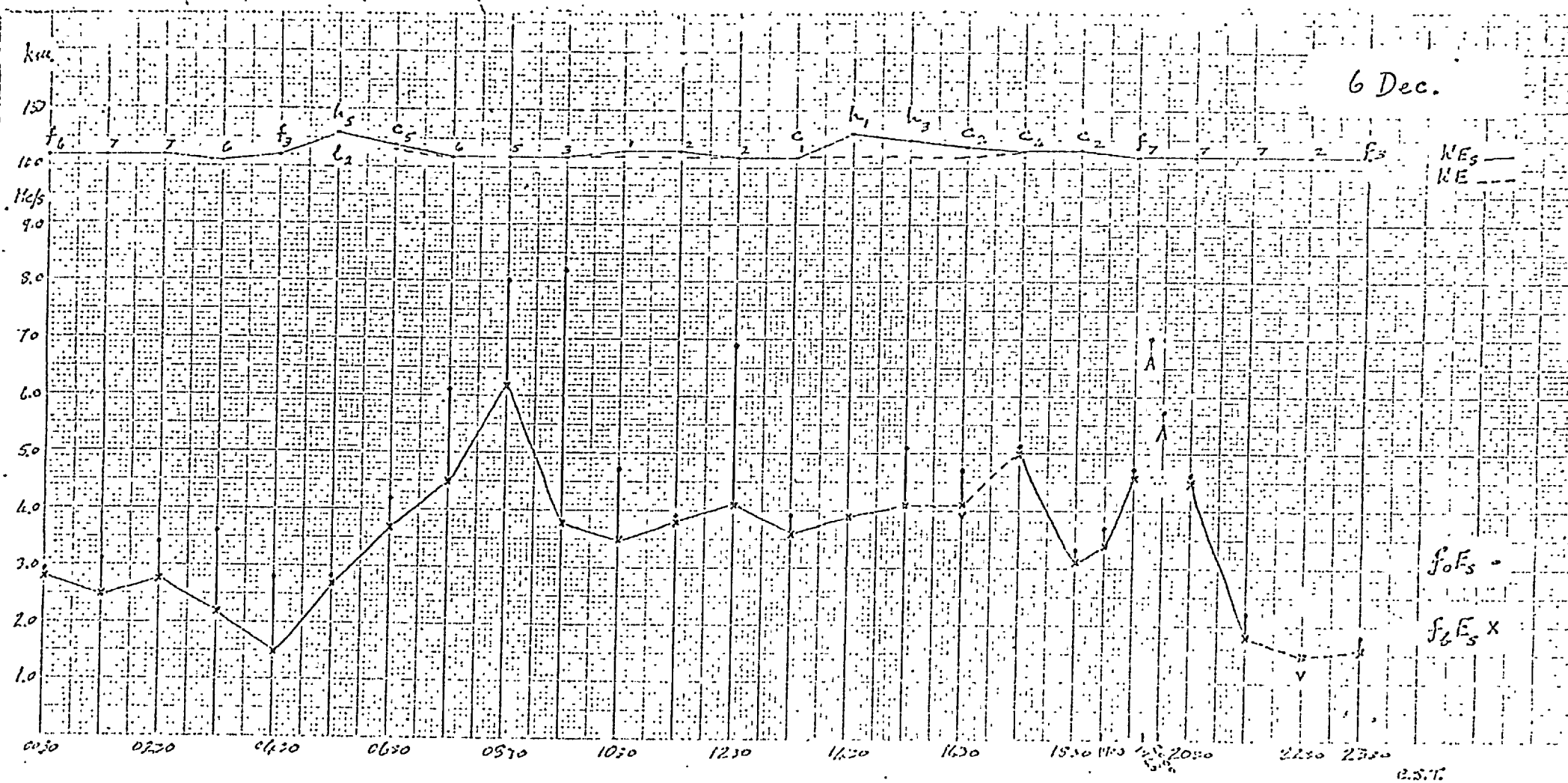
11/11/83



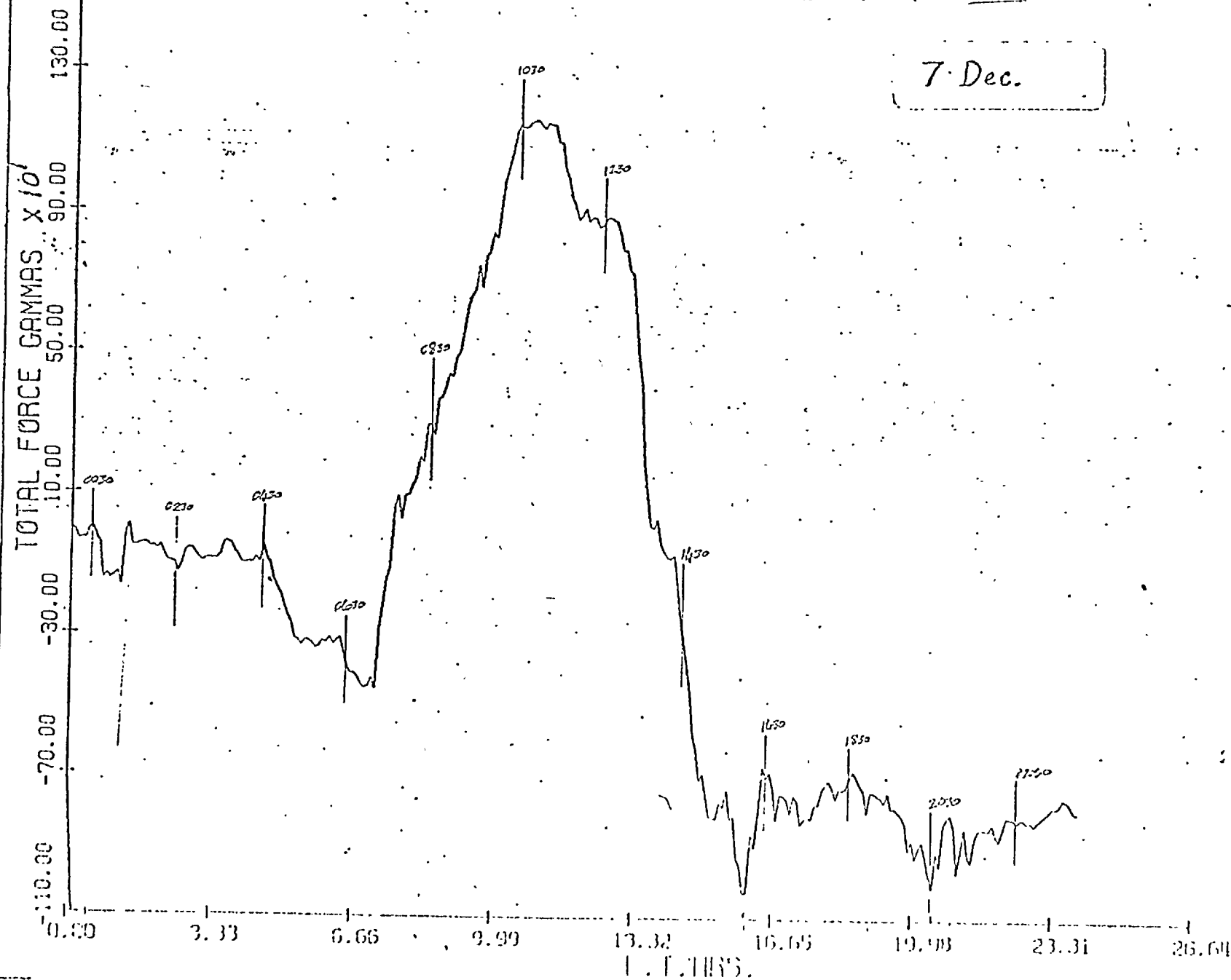
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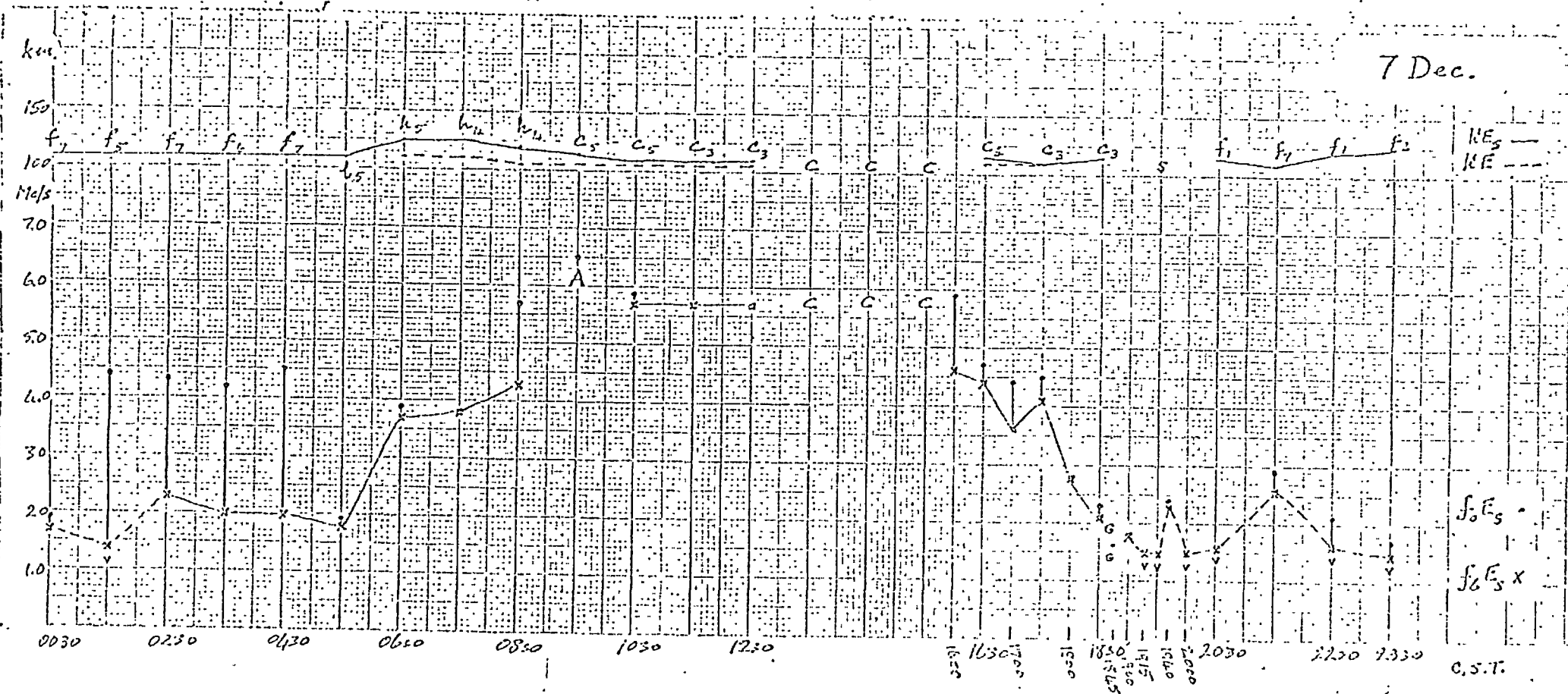
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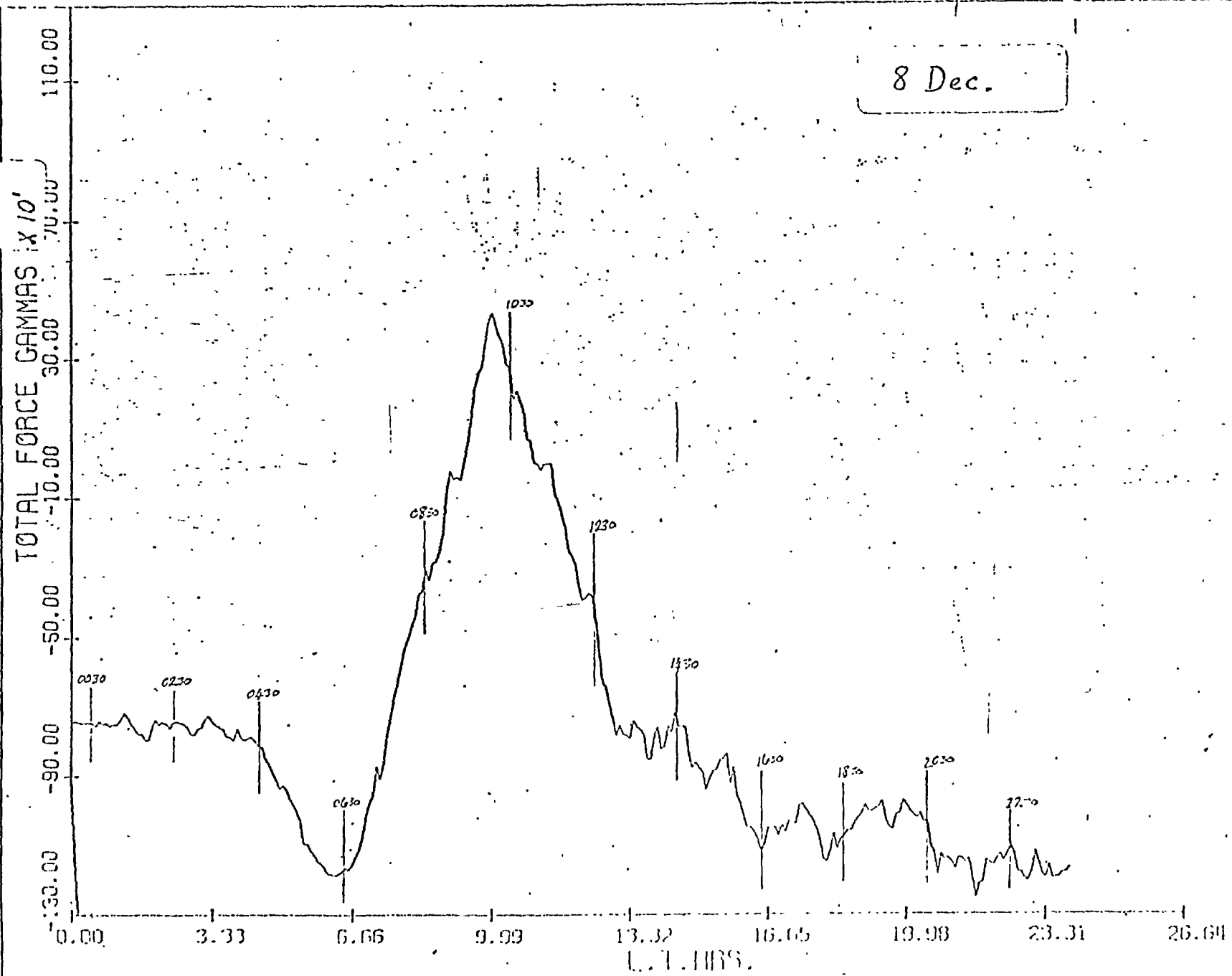
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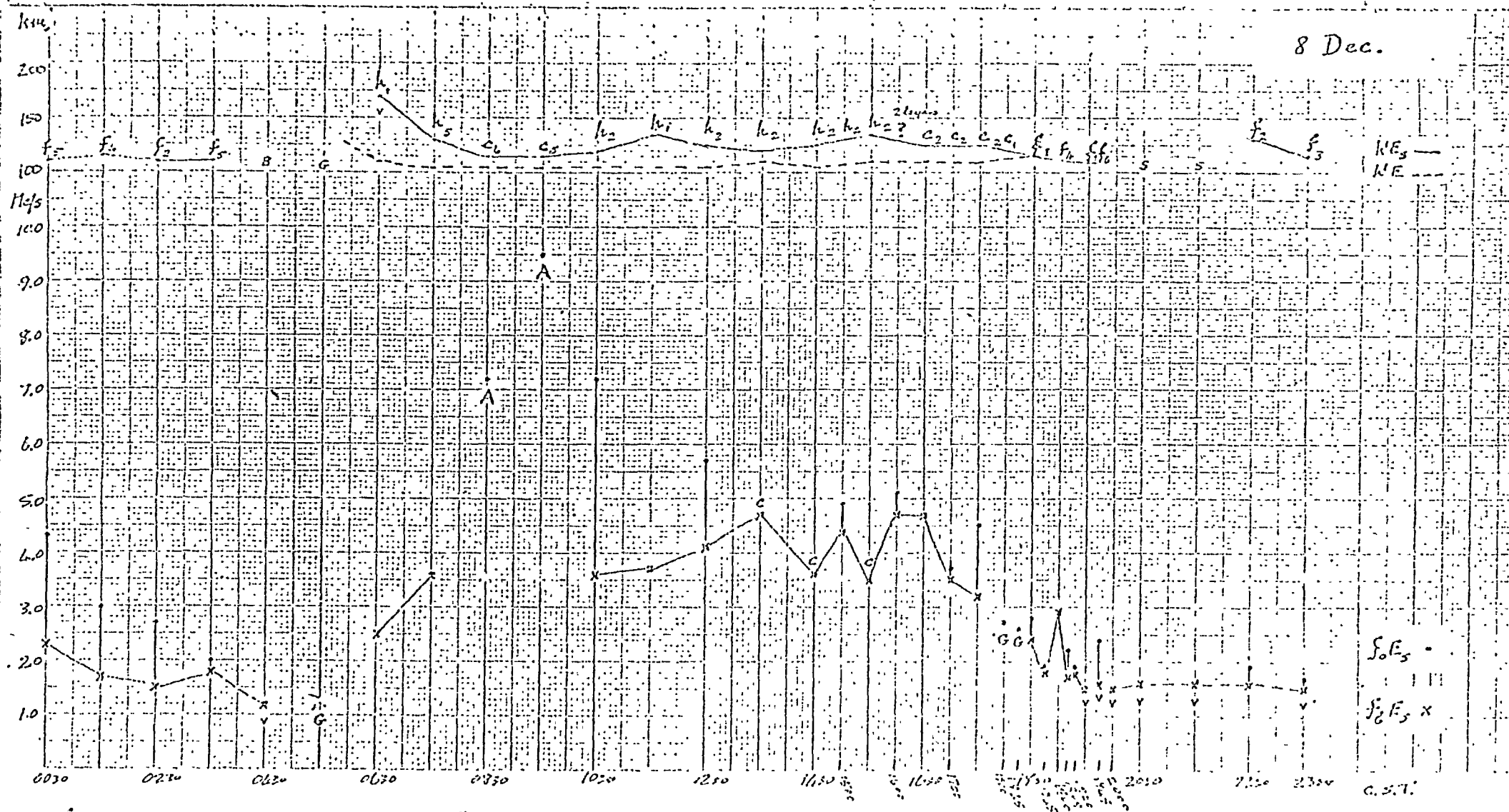
7 Dec.



8 Dec.



8 Dec.



9 Dec.

TOTAL FORCE GAMMAS $\times 10^1$

70.00
30.00
-10.00
-50.00
-90.00
-130.00
-170.00

01.00

3.33

6.66

9.99

13.32

16.65

19.98

23.31

26.64

UTLIRS.

0030

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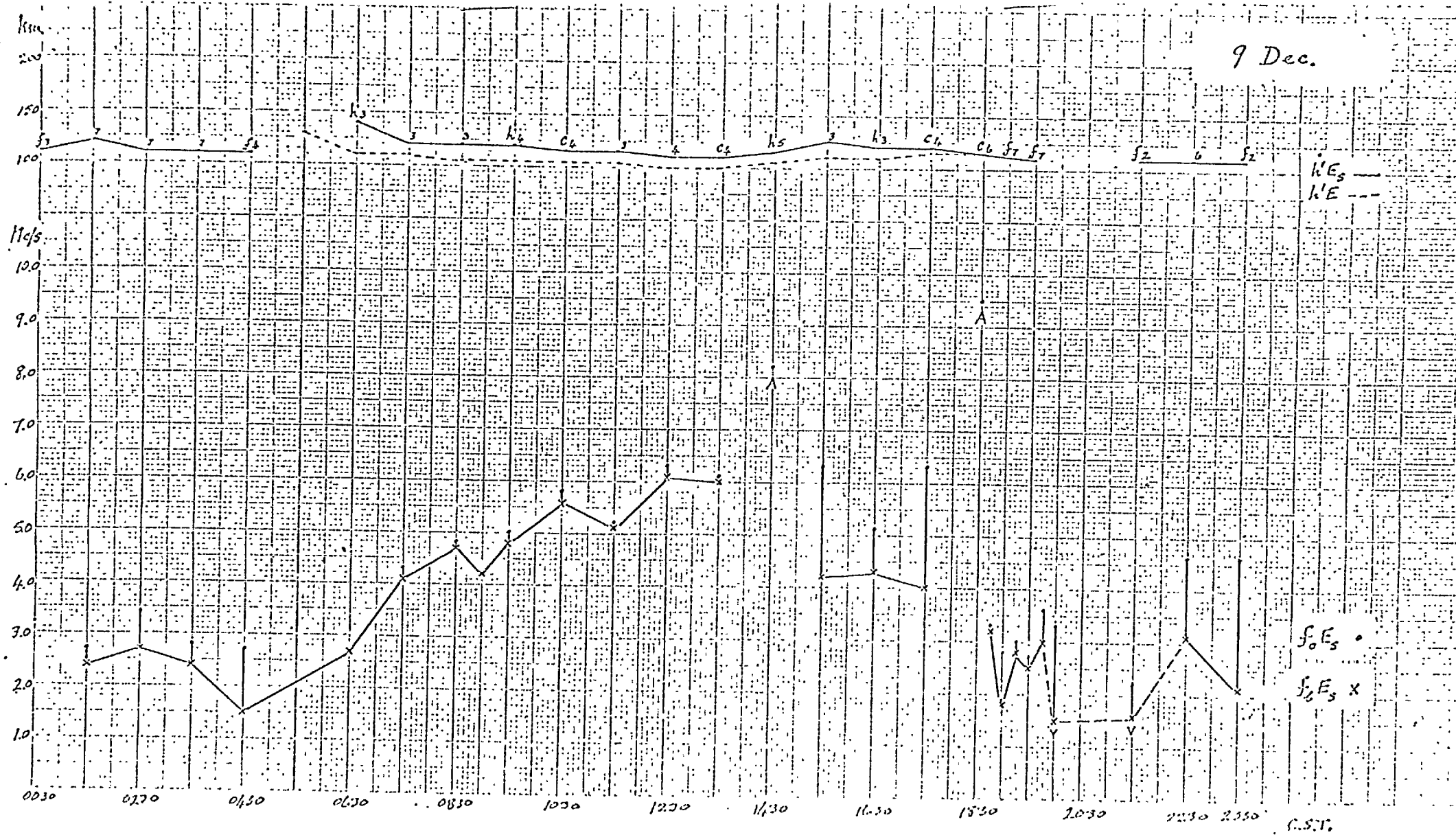
1630

1830

2030

2230

9 Dec.



10 Dec.

TOTAL FORCE GAMMAS

-15.00 -14.00 -12.00 -10.00 -8.00 -6.00 -4.00

0030

0230

0430

0630

0830

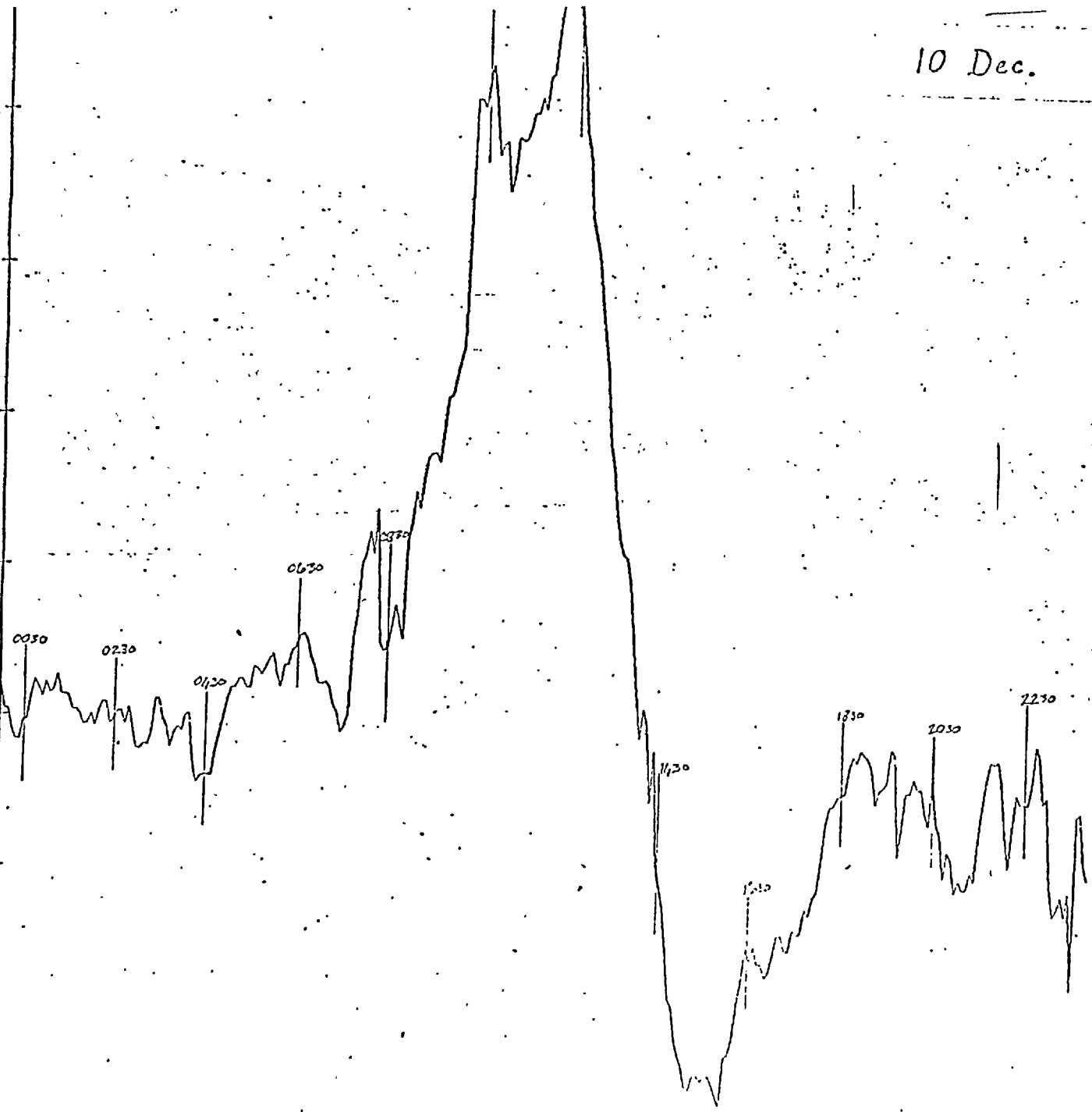
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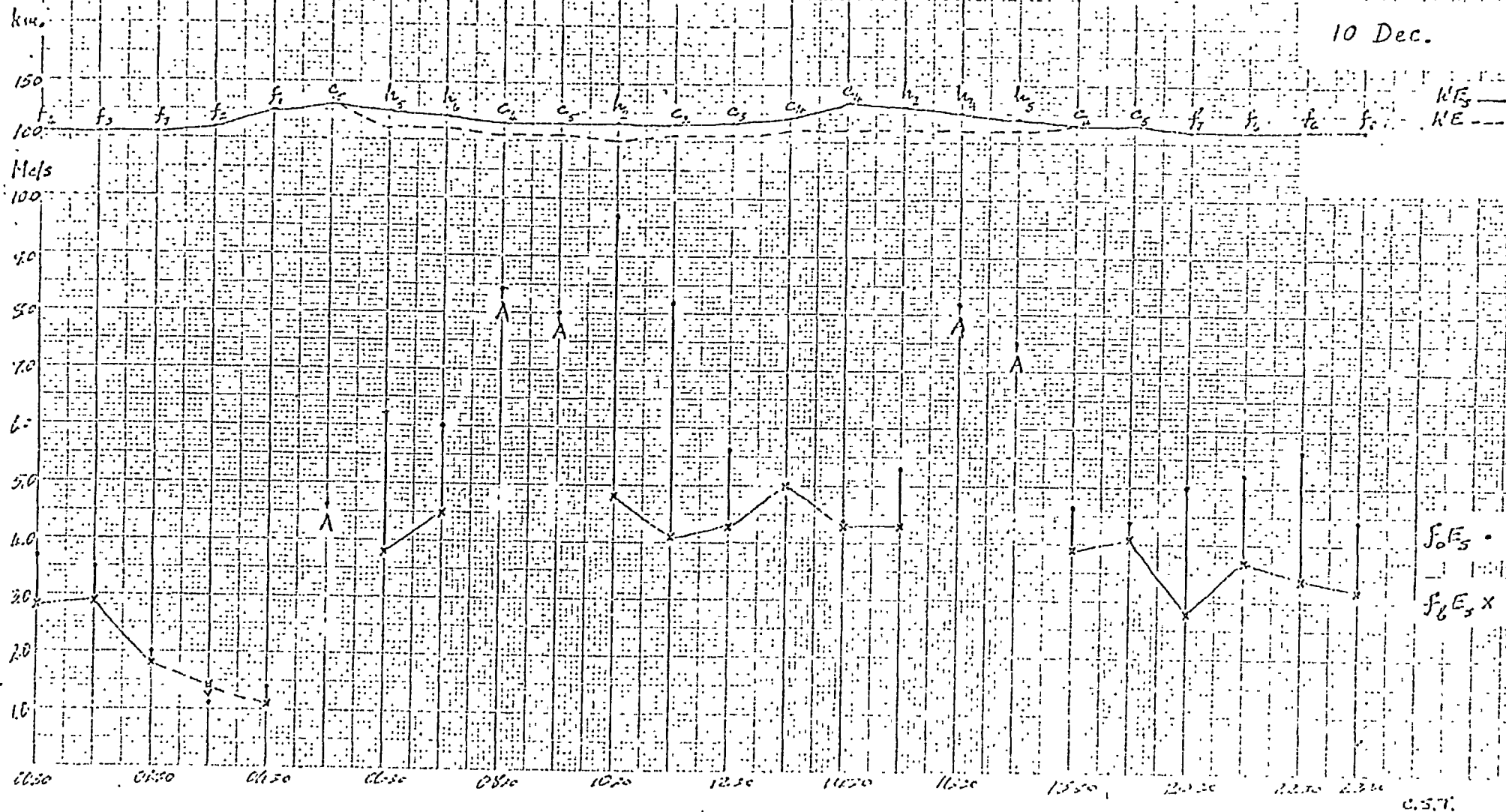
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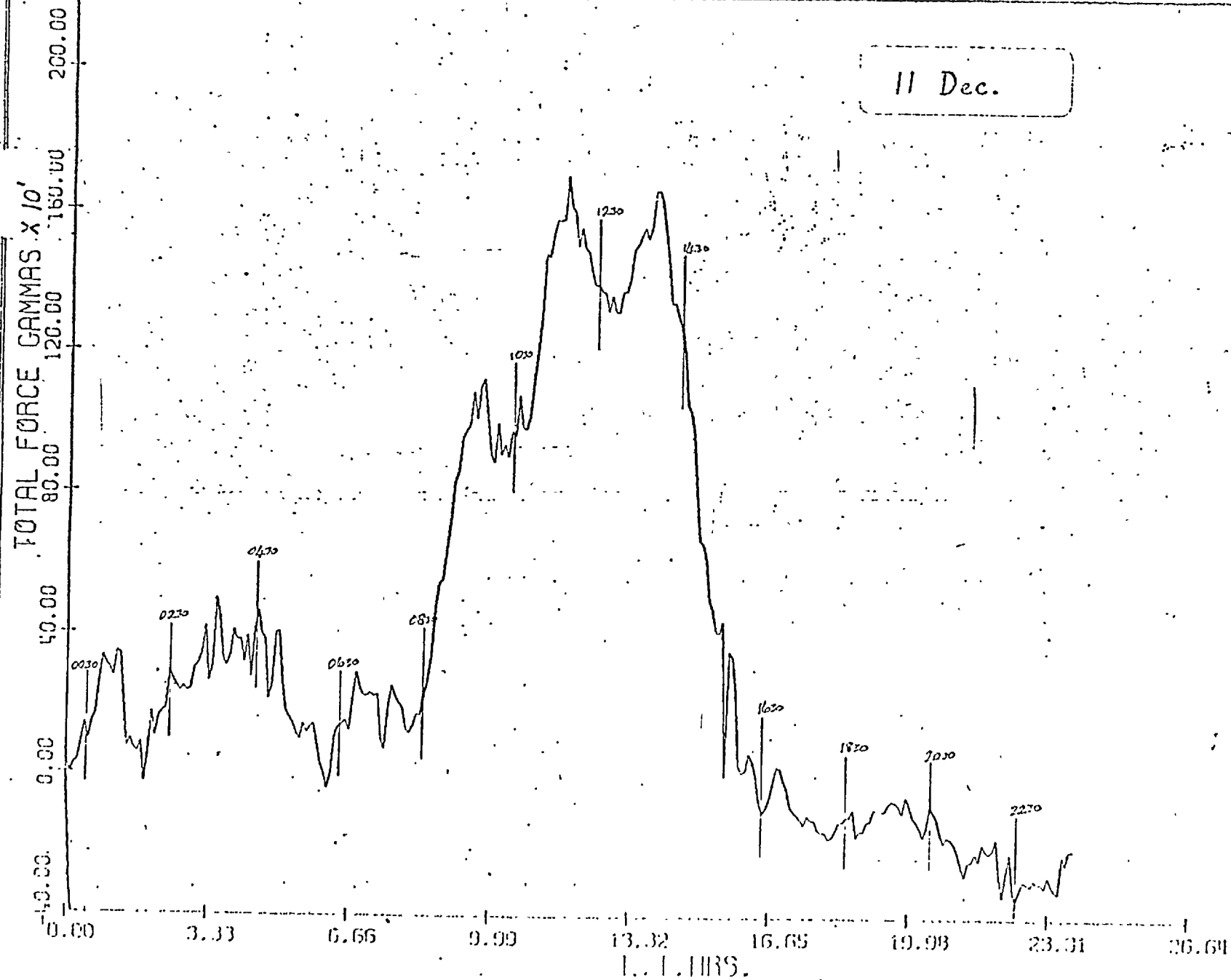
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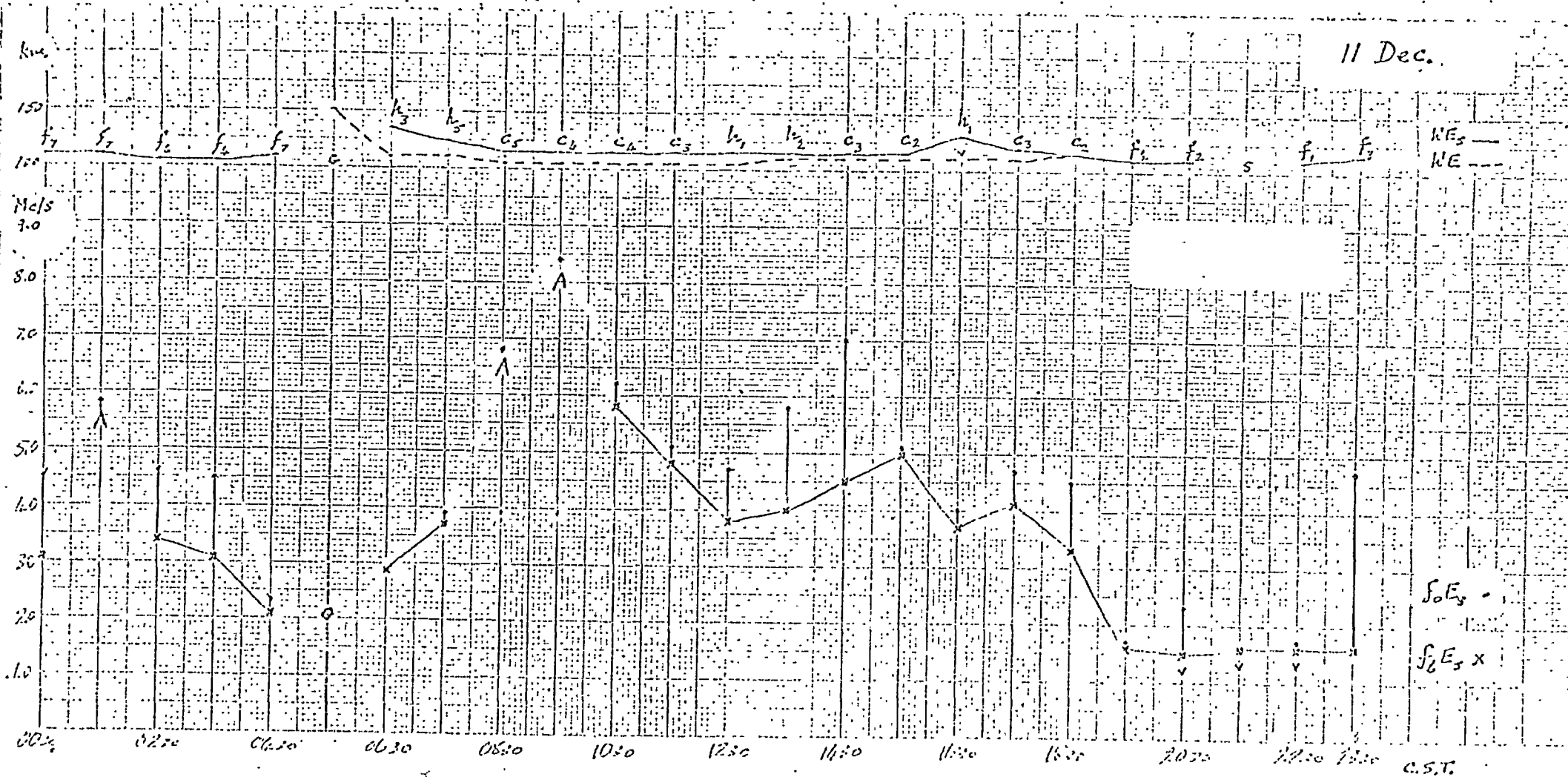
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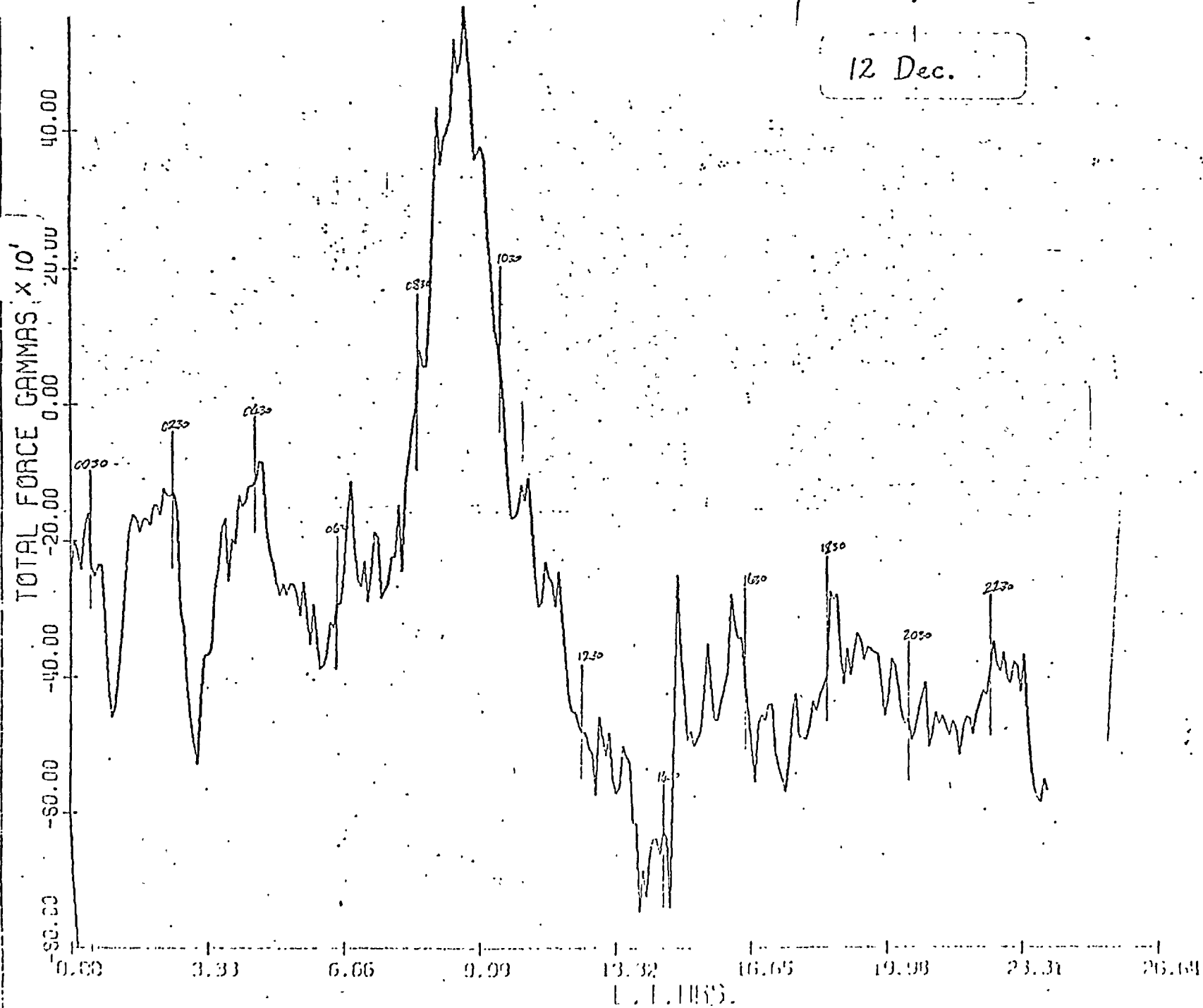
11 Dec.



11 Dec.



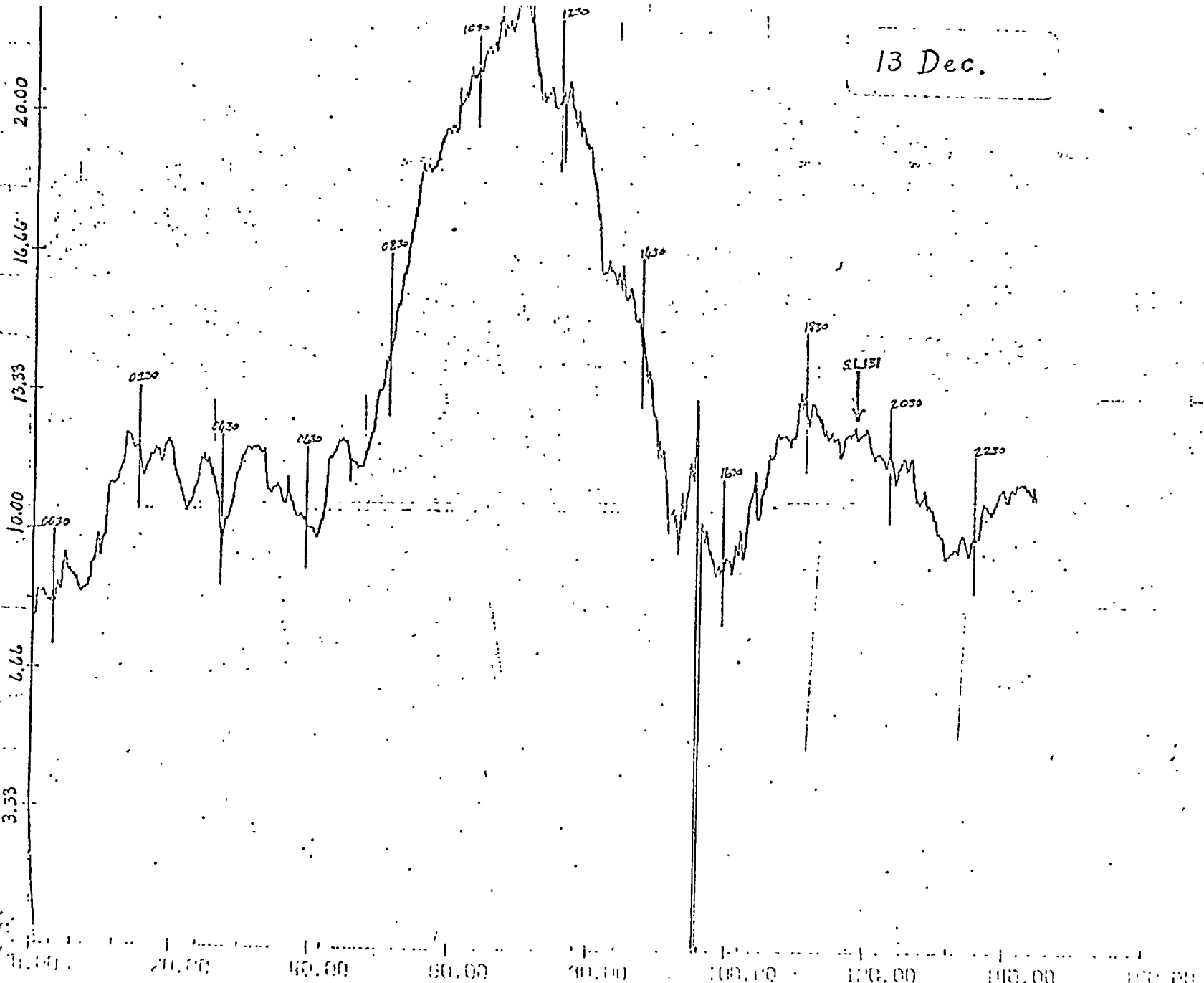
12 Dec.



13 Dec.

GAMMAS

3.33 6.66 10.00 13.33 16.66 20.00



L.T. (10 MIN.)

13 Dec.

