VII—British Radio Observations During the Second International Polar Year 1932–33

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1—INTRODUCTION

The present communication deals with radio observations made by British workers as part of the general geophysical investigation of polar regions carried out during the Second International Polar Year, 1 August, 1932, to 31 August, 1933.

In the long period which has elapsed since the first International Polar Year of 1882–83, the field of geophysical inquiry has been greatly extended by the use of improved methods and instruments. Such advances have been especially notable in atmospheric physics. Among the new methods which have been developed we may count the use of radio waves for the exploration of upper-atmospheric electrification. The prosecution of such methods in recent years has supplemented in many ways the information obtainable from a study of terrestrial magnetism and the aurora.

The development of radio methods of ionospheric exploration has proceeded in England during the last ten years under the auspices of the Radio Research Board of the Department of Scientific and Industrial Research. On the scientific side the work has been directed to the elucidation of the structure of the ionosphere, its variation with time, and the correlation of such variations with other geophysical phenomena. Quite independently of any participation in the work of the International Polar Year, the results of work in England had, for reasons which will be stated later, suggested the need for carrying out similar observations in high latitudes, and Sir GEORGE SIMPSON, F.R.S., a member of the Board, had pointed out the special suitability of Northern Norway for such work. The proposals for an expedition were, however, held in abeyance because of the great advantages which were seen likely to accrue from merging such work in the international effort of the Second

Polar Year. The radio research part of this effort was organized by the Union Radio Scientifique Internationale at its Copenhagen meeting in 1931, where a sub-commission was appointed, with Professor E. V. APPLETON, F.R.S., as President, and Mr. R. A. WATSON WATT as Secretary, to coordinate the ionospheric work to be carried out by workers in different countries. An international programme of radio observations was drawn up by the President and Secretary of this sub-commission for coordinated work on the International Days chosen by the International Polar Year Commission. This international programme was kept strictly limited in extent in order to permit the prosecution of further special investigations according to the facilities available in different countries.

2—ORGANIZATION OF BRITISH RADIO WORK DURING THE SECOND INTERNATIONAL POLAR YEAR

The plans for British participation in the work of the Second Polar Year were worked out by a National Committee under the chairmanship of Sir HENRY LYONS, F.R.S. In addition to the main expedition to Fort Rae in Canada (under the leadership of Mr. J. M. STAGG) for meteorological, magnetic, and auroral observations, it was decided that there should also be, if possible, a radio expedition for the exploration of the upper atmosphere in high latitudes. The Department of Scientific and Industrial Research, on the advice of its Radio Research Board, took over the responsibility for the whole of this work, offering to transfer to northern latitudes both the apparatus and personnel which would have been employed during the Polar Year on similar work in England, provided the additional costs of transportation and maintenance were met by other authorities. The greater part of the latter cost was defrayed by a grant made by the National Polar Year Committee, while later in the year, when it was clear that this sum would not suffice, the Council of the Institution of Electrical Engineers generously defrayed the remaining expenses by a most timely benefaction.

Following the suggestion of Sir GEORGE SIMPSON, it was decided to choose a site in Northern Norway for the radio work in high latitudes, and the Norwegian Committee for Cosmic Physics (under the Presidency of Professor L. VEGARD) invited the expedition to make its principal station at Nordlysobservatoriet, Tromsö (Fig. 1), where they were good enough to provide laboratory facilities and living accommodation. Special facilities and privileges in connexion with the transit of apparatus into and out of the country were accorded by the Norwegian Government, while the Bergenske Steamship Company granted generous concessions in the fares of personnel and in carriage charges.

In March, 1932, Mr. R. A. WATSON WATT (Superintendent, Radio Research Station, Slough) visited Tromsö to select sites for the work and make more detailed arrangements. There he found that the town had an alternating-current electric supply served by a hydro-electric station at Simavik on the island of Ringvassøy, about 10 miles away (*see* fig. 2). It was therefore arranged that the sending station should be erected at Simavik, accommodation for the apparatus and living quarters for one member of the expedition being rented from the maintenance engineer of the hydro-electric station (Herr A. Børge). Advantage was also taken of the offer of the Norwegian Committee for Cosmic Physics to install the receiving station at Nordlysobservatoriet, Tromsö. The notable convenience of the arrangement chosen by Mr. Watson Watt was that the sending and receiving stations worked on a common electric supply, thereby facilitating the necessary synchronization for the work. There was, moreover, telephonic communication between Simavik and Tromsö.

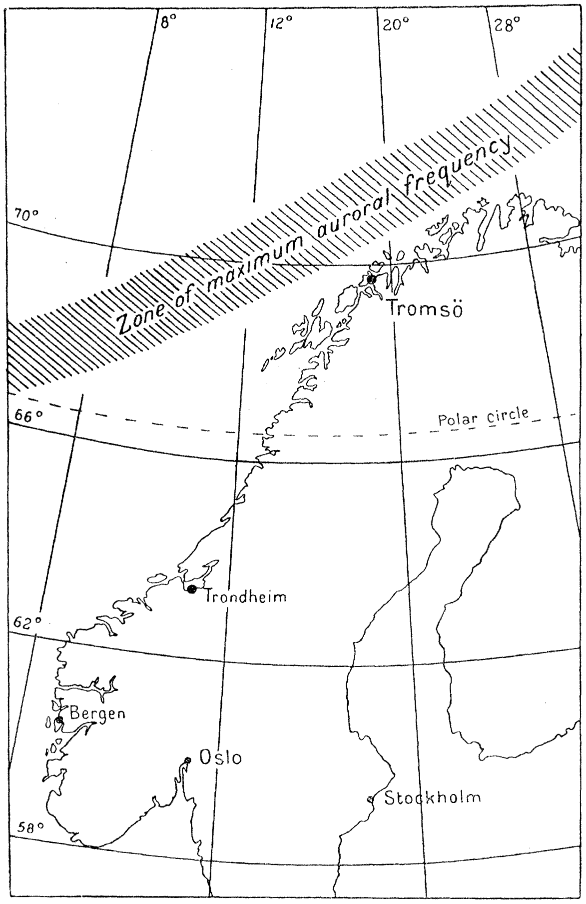

Fig. 1—Map illustrating the situation of Tromsö, Norway, relative to the zone of maximum auroral frequency.

On 9 July, 1932, a party consisting of Professor E. V. Appleton and Mr. G. Builder, of King's College, London, and Mr. R. Naismith and Mr. W. C. Brown, of the Radio Research Station, Slough, proceeded to Tromsö via Newcastle and Bergen to erect the necessary stations. The party arrived at Tromsö on 15 July. On 22 July the stations at both Tromsö and Simavik were completed and the first measurements of equivalent height of reflexion were made. A number of preliminary observations were therefore made before the beginning of the International Polar Year, and from these it was possible to decide on the scope of the national programme to be pursued in addition to the programme of work on International Days.

Professor APPLETON and Mr. NAISMITH left Tromsö on 20 August, 1932, leaving Mr. G. BUILDER in charge of the receiving station at Tromsö, and Mr. W. C. BROWN in charge of the sending station at Simavik. In March, 1933, Mr. NAISMITH proceeded to Tromsö and relieved Mr. BUILDER, who had been appointed to a post under the Australian Department of Scientific and Industrial Research. Mr. W. C. BROWN remained in charge of the sending station at Simavik during the whole of the Polar Year. Professor APPLETON went out to Tromsö again in July, 1933, to arrange for the conclusion of the work and the return of the expedition to England.

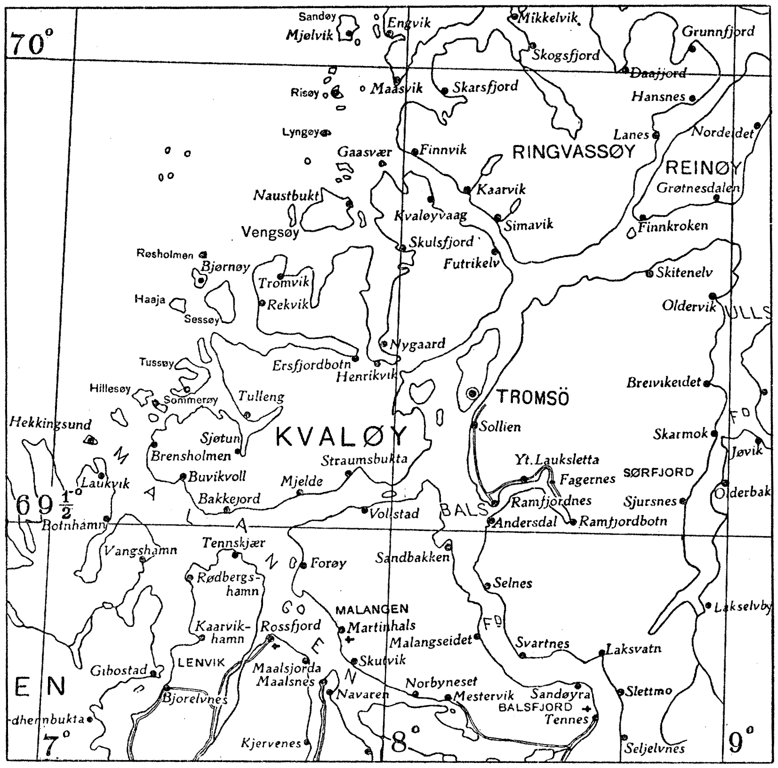

FIG. 2—Local map of Tromsö district.

The debt of members of the expedition to other workers and to other institutions cannot be over-estimated. Particular mention should be made of members of the staff of the Slough Radio Research Station. To Mr. WATSON WATT (formerly Superintendent of the Radio Research Station and now Superintendent of the Radio Department, National Physical Laboratory) the expedition was especially indebted for the admirable arrangements made in Norway in the first instance and for helpful discussion throughout the year. The late Mr. J. F. HERD and also

Mr. L. H. Bainbridge-Bell, of Radio Research Station, Slough, gave unstinted help in the many technical problems involved in these experiments. The apparatus was all designed and constructed at Slough, and the quality of the work done by Mr. J. E. Airey and his staff in the Slough workshops, in the building and packing of the three tons of delicate equipment used by the expedition, is illustrated by the fact that the equipment completed its 1500-mile voyage without the breakage of so much as a single receiving valve. Miss A. C. Stickland and Miss E. Rogers have also given valuable help in the reduction of the data.

The work at Tromsö was assisted in every possible way by Director L. Harang and his staff (Herr. E. Tönsberg and Herr. M. Jacobsen) and also by Herr. P. Thrane (Director of the Meteorological Institute for North Norway), all of whom gave generous help on many occasions.

Thanks are due to the Norwegian Government for permitting the scientific apparatus to be taken into Norway free of customs charges, and also to the Norwegian Post Office for permission to transmit wireless signals over a wide band of frequencies, and for generous concessions in telephonic charges.

The British Consul at Bergen and the British Vice-Consul at Tromsö gave valuable assistance in connexion with the arrangements made for the transit of personnel and apparatus.

Thanks are also due to the Astronomer Royal, Dr. H. Spencer-Jones, for the magnetic data from Abinger.

3—The Programme of Observations

As mentioned above, the programme of observations drawn up by the President and Secretary of the Union Radio Scientifique Internationale Polar Year Sub-Commission allowed for the possibility of great variations from one national organization to another in respect of available personnel, apparatus, means, and methods. The international, as opposed to the national, programme was therefore restricted to include only such measurements as could readily be undertaken by every participating country.

The type of observations suggested was based on the following considerations. In measurements of the equivalent height of reflexion from the ionosphere we may proceed in two ways. Using a single-mean frequency f we can observe how the equivalent height h' varies with time t; from the data obtained we can plot an equivalent height/time graph. Another and more productive method is to make as quickly as possible a number of measurements of the equivalent height h' for a range of frequencies from which an equivalent height/frequency curve can be drawn. The discontinuities in such a curve which indicate critical penetration frequencies may be used, as previously shown,* for the measurement of maximum ionization content. Since the essential quantity measured in observations of this

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* Appleton, ' Proc. Phys. Soc. Lond.,' vol. 45, p. 673 (1933).

kind is the group-time for a signal to travel to the upper atmosphere and back, and since we obtain the equivalent path P′ of the atmospheric waves directly by multiplying the group-time by the velocity of light *in vacuo*, it will be seen that we can either measure P′ as a function of t or measure P′ as a function of f. Our ionospheric information is therefore embodied either in (P′, t) curves or in (P′, f) curves. If, as in the present series of experiments, the waves are reflected at substantially normal incidence, the equivalent path P′ is evidently equal to twice the equivalent height h'.

a—International Programme—This may be given, in an abbreviated form, as quotations from the original document circulated to National Committees :—

" The International Day is taken as beginning at 16.00 G.M.T. Wednesday and ending at 16.00 G.M.T. Thursday ".

" All times of observations are to be read as local mean times for the observing station concerned ".

" On International Days of the First Order, *i.e.*, on one day per month, the following measurements will be made within the quarter-hour periods ending at midnight and noon, local mean time, viz. :—

" Using central frequencies of 4 Mc./sec. and 2 Mc./sec. (wave-lengths of 75 m. and 150 m.), determination of the equivalent height of the ionized regions effective in returning these emissions to earth at substantially vertical incidence (*i.e.*, over base lines not exceeding 25 km.). These determinations will be indicated by ' MN ' (Midnight–Noon) in the calendar attached. The observations on 4 Mc./sec. are most important, those on 2 Mc./sec. next in importance ".

" On International Days of the Second Order, *i.e.*, on one day per month displaced by fourteen days from the day of the First Order, the following measurements will be made throughout the 24 hours :—

" Using the one central frequency of 4 Mc./sec. (wave-length 75 m.), determination at each hour local mean time, throughout the 24 hours, of the equivalent height of the region returning emissions of this frequency to earth at substantially vertical incidence (base lines not exceeding 25 km.). This series of determinations will be indicated by ' 24 ' (24-hour runs) in the calendar ".

" On International Days of the Third Order, *i.e.*, on the Wednesdays to Thursdays of the weeks intervening between weeks containing First and Second Order days, determinations of the following general type will be made, viz., measurement of the approximate ionization density, near noon local mean time, in the ionized regions by the method described by APPLETON* which involves essentially the determination of the critical frequencies for the lower (E) and upper (F) ionized regions. Attention will be concentrated on the upper and on the lower regions respectively on alternate days of the Third Order, in accordance with the attached

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* ' Nature, Lond.,' 7 February, 1931 ; *see also* further details, APPLETON and NAISMITH, ' Proc. Roy. Soc.,' A, vol. 137, p. 36 (1932), and A, vol. 150, p. 685 (1935).

calendar, in which days devoted to the lower (E) region are denoted by ' E ', those devoted to the upper (F) region by ' F ' ".

Dates for Observations " MN "

1932 :—10–11 August, 14–15 September, 12–13 October, 9–10 November, 14–15 December.
1933 :—11–12 January, 8–9 February, 8–9 March, 12–13 April, 10–11 May, 7–8 June, 12–13 July, 9–10 August.

Dates for Observations " 24 "

1932 :—24–25 August, 28–29 September, 26–27 October, 23–24 November, 28–29 December.
1933 :—25–26 January, 22–23 February, 22–23 March, 26–27 April, 24–25 May, 21–22 June, 26–27 July, 23–24 August.

Dates for Observations " E "

1932 :—4 August, 1, 22 September, 20 October, 17 November, 8 December.
1933 :—5 January, 2 February, 2, 30 March, 20 April, 18 May, 15 June, 6 July, 3, 31 August.

Dates for Observations " F "

1932 :—18 August, 8 September, 6 October, 3 November, 1, 22 December.
1933 :—19 January, 16 February, 16 March, 6 April, 4 May, 1, 29 June, 20 July, 17 August.

b—National Programme—An attempt was made to supplement the international programme by a national one which was directed to specific problems. In view of the correlations which had been previously found between magnetic activity and wireless transmission, it was considered very desirable to keep as close a watch on ionospheric conditions as possible. For this purpose a method of automatic recording was devised and (P′, *t*) records, as nearly continuous as possible, were made on the international frequencies of 2 and 4 Mc./sec. For the days on which the International Programme was scheduled observation " E " or observation " F ", the national programme was extended so as to include determinations of critical frequencies for both Regions E and F. In addition, (P′, *f*) runs were made on certain other days at noon for the determination of the structure and ionization maxima of the ionized regions.

After the work at Tromsö had been in operation for five months, the German Polar Year Party arrived, and from 1 January, 1933, a close collaboration between both groups of workers was possible. A second sender was built at the British station at Simavik so that it was possible to send out, simultaneously, pulses on the two international frequencies. Continuous recording was carried out by the two receiving stations, British and German, one recording on 2 Mc./sec. and the other on 4 Mc./sec. In order to obviate any possible influence of the instrumental characteristics of the two sets of receiving and recording apparatus, a change-over of the two frequencies was made each week. By the interchange of records it will be seen that it was possible for both parties to obtain complete sets of data for both frequencies, whereas with a single station complete data on one frequency (or incomplete data on two) could only have been obtained. Our collaboration with the German workers, Dr. K. Kreielsheimer and Herr W. Stoffregen, was a very happy one, and we wish to express our gratitude to them for their helpful assistance in many ways.

In order to provide for an adequate comparison of the results obtained in high and in temperate latitudes, it was decided to carry out a programme of ionospheric observations, as nearly as possible identical in character with that pursued at Tromsö, at the Radio Research Station, Slough, with co-operation at King's College, London, and the Cavendish Laboratory, Cambridge. The great advantages of such a comparison were recognized at the outset and, as will be seen later, have been realized.

In connexion with the programme of observations, a further word is necessary. The beginning of the Polar Year coincided with a time when the subject at which we were working was advancing. Our own technique, moreover, was being improved as we made use of it. For example, our own method of continuous registration of echoes was developed after arrival in Tromsö. The question of interpretation of the normal (P′, *f*) curves was also progressing and, during the year, evidence was put forward by Appleton* which illustrated the more detailed information which could be derived from such curves when obtained from observations spaced very closely in frequency. This detailed information was concerned with (*a*) the occasional existence of an intermediate region of ionization between the E and F regions and (*b*) the gradual development of a composite character in Region F during the daytime under the direct influence of ultra-violet light from the sun. For these reasons it will be found that the observations became more complete and the information derived from them more detailed and reliable as the year progressed.

4—DESCRIPTION OF APPARATUS USED AT SIMAVIK AND AT TROMSÖ

From what has been said above, it will be seen that the types of observation made at Tromsö fall into two classes :—

(i) Measurements of the equivalent path P′ (which is equal to $2h'$ where h' is the equivalent height of reflexion assuming deviation at vertical incidence) as a function of the time t for a single mean wave frequency. We shall refer to a curve illustrating this relation as a (P′, t) curve.

(ii) Measurements of the equivalent path P′ as a function of the mean wave frequency f. We shall refer to a curve illustrating this relation as a (P′, f) curve.

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* ‘Proc. Phys. Soc. Lond.,’ vol. 45, Pt. 5, No. 250, p. 673 (1933).

In order to facilitate the work of reduction of the data, it was decided to attempt photographic registration of the measurements wherever possible. The apparatus used is therefore described under the three headings, (*a*) sender, (*b*) receiver, and (*c*) photographic recorder. The description of these is given in detail only in connexion with the later developments, since a technical description of the original apparatus has already been given by Dr. G. BUILDER.*

a—Sender—It was decided to use the group retardation method of measuring the equivalent height of reflexion, using the type of pulse-generator described by APPLETON and BUILDER.† This was installed at the hydro-electric station at Simavik where ample power was available. The fundamental circuit is shown in fig. 3, which is seen to be a self-excited oscillator, the modulation of which was effected by the use of particular values of grid condenser and grid leak resistance. By suitable adjustment of the grid circuit constants, brief trains of oscillations of radio frequency were produced with suitable time spacing. The resistance R was actually a saturated diode as this was found to be a conveniently variable high resistance which would also withstand the necessarily high voltages involved. The values of the condenser C_1 and the resistance R were adjusted so that the circuit produced short pulses of radio-frequency energy lasting only 10^{-4} second, and recurring at the rate of 50 per second. This permitted the complete resolution at the receiver of wave groups which had travelled with differences of equivalent path greater than 30 km. The temporal spacing of the pulses also eliminated any ambiguity in reading the sequence of echoes, the delay time of which did not exceed 20 milliseconds. It was found that these limiting conditions were generally not of great importance.

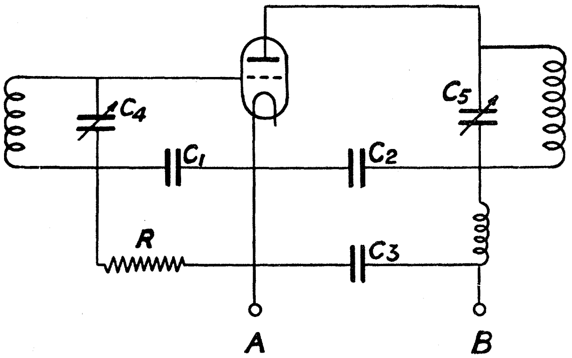

FIG. 3—Circuit diagram of oscillator-section of Simavik sender.

In order to permit synchronism between the pulse recurrence at the sender and the time-base recurrence at the receiver, the supply voltage to the sender was provided from the alternating-current mains in a manner described by J. F. HERD.‡

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* 'J. Inst. Elect. Engrs.,' vol. 73, p. 419 (1933).

† 'Proc. Phys. Soc. Lond.,' vol. 44, p. 76 (1932).

‡ 'Proc. Phys. Soc. Lond.,' vol. 45, p. 221 (1933).

One of the main difficulties encountered at Simavik was, however, due to the poor voltage regulation and the non-sinusoidal character of the supply. In order to provide a rigid control of the pulse recurrence frequency, therefore, the circuit of fig. 4 was adopted, in which a thyratron was used in a series modulator control of the time of emission of the pulse.

The points A and B in fig. 4 are respectively connected to A and B in fig. 3.

A simple form of visual monitor consisting of a low voltage cathode-ray tube and circular time scale was employed to indicate phase stability, recurrence frequency, and pulse duration.

The emitted mean radio frequency was readily altered by the tuning condensers C_4 and C_5. A slight readjustment of the grid tuning condenser while watching the monitor enabled the operator to obtain the shortest pulse duration and the correct recurrence frequency.

The range of radio frequencies covered by the sender was 0·6–10 megacycles per second. This was covered by four sets of tuning coils.

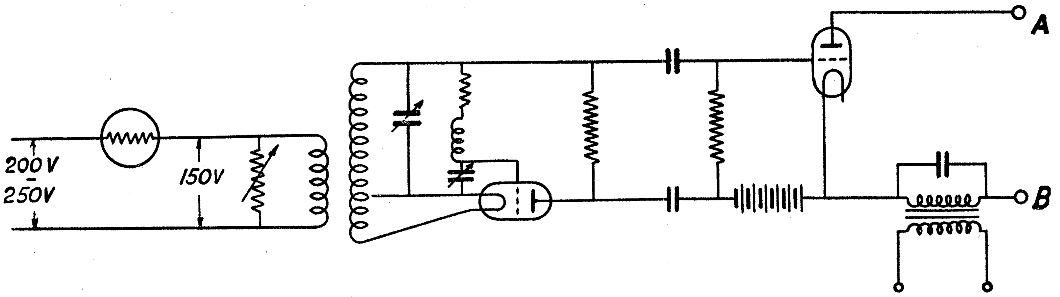

FIG. 4—Circuit diagram of modulator-section of Simavik sender.

At first a power of 3 kw. was used, but after one month this was reduced to 100 watts, at which value it was maintained for the rest of the Polar Year.

b—Receiver—The receiver, which was primarily designed for pulse reception, was constructed on the superheterodyne principle.* The signals, which were received on a horizontal dipole, were applied to the input side of a single stage of a high-frequency amplifier followed by anode-bend detection. The push-pull principle was employed in both these stages and the symmetry thereby attained had many advantages. The heterodyne voltage was applied in the common grid lead to the two detectors and arranged to produce the condition of optimum-heterodyne.†

The relation between the signal voltage amplitude received on the dipole and that obtained at the output of this first detector was approximately linear. This

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* " Applications of the Cathode Ray Oscillograph in Radio Research," by WATSON WATT, HERD, and BAINBRIDGE-BELL, p. 114.

† APPLETON and TAYLOR, ' Proc. Inst. Radio Engrs.,' vol. 12, p. 277 (1924), and HERD, ' Wireless Engr.,' vol. 7, p. 493 (1930).

output was then applied to an amplifier which consisted of three screened-grid valve stages and a diode rectifier. This amplifier had a uniform response from 100 to 120 kc. per sec. and delivered 40 volts rectified output without serious distortion. The limited band-width of this amplifier was essentially a compromise between loss of the higher modulation frequencies present in the pulse and freedom from interference. The linear relation between the input and output voltages of the receiver as a whole was obtained over a range of intensities of 100–1.

In the operation of the receiver there were actually three circuits to be tuned, but it was found that observations spaced 250 kc./sec. apart could be made at the rate of two or three a minute. During such observations telephonic communication was maintained between sending and receiving stations. It was arranged for convenience that the frequency range covered by one set of coils at the receiver was identical with that at the sender. This permitted coil changing to be done simultaneously at both stations and resulted in reducing the overall time taken in the observations. Later in the year the three tuning circuits of the receiver were ganged and permitted observations over a continuous range of frequency.*

Alternating current was supplied to the heaters of the receiver valves while accumulators supplied the anode and screened-grid voltages. The accumulator bank was trickle-charged.

c—Recorder—The output voltage from the diode rectifier was applied across one pair of plates of the cathode-ray oscillograph, and a time-base potential across the other pair. It was essential that the time base should be approximately linear in the sense that the spot travelled at a uniform velocity over the screen during the application of the voltages from the receiver. This linear sweep of the time scale was obtained by charging a condenser through a resistance and allowing a control voltage, obtained from the 50 cycles/sec. alternating-current mains, to discharge it once during every cycle. Synchronism between this time base and the emission of the pulses at the sender was effected by using the same supply mains at both stations. In this way a stationary pulse picture was obtained on the oscillograph screen and at the same time the system permitted a valuable discrimination against random noise, because, although the instantaneous level of such noise was much greater than the amplitude of many of the weaker echoes, lack of synchronization between this noise and the time scale often permitted the echoes to be clearly visible at such times. The effective length of the time scale was restricted to about 10 milliseconds.

For recording purposes, a simple box camera was employed in conjunction with specially fast bromide paper. This paper was 10 cm. wide and was supplied in rolls 30 metres long. After each record was taken, the paper was moved on either by hand or by automatic signals obtained from an electric clock. In this way snap pictures of the echo groups observed on different frequencies were taken and after development a permanent record of the observations was available. Fig. 5 (Plate 3)

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* NAISMITH, ' Nature, Lond.,' vol. 133, p. 66 (1934).

shows a series of observations made in this way. Later, when it became necessary to observe continuously on one frequency, a drum camera was employed. The drum, which was of 1 metre circumference, was rotated by clockwork once in 24 hours. In this way a strip of photographic paper was passed slowly in front of a mask (*see* fig. 6, Plate 3) placed in front of the cathode-ray tube, so that the breaks in the time scale due to the ground pulse and the echoes formed traces on the paper.

Each hour the output from the set was switched off and a calibration signal from a 2500 cycles/sec. oscillator was recorded. This oscillator frequency was also synchronized with the supply mains so that it produced a stationary picture on the oscillograph screen. This signal therefore placed on the record both a time scale and a scale of equivalent heights. The cathode-ray tube was mounted in a box from which the screen of the tube was visible. An observation door was cut in the side of this box through which it was possible to look through the glass of the tube to the back of the fluorescent screen and observe the echo group while adjustments to the receiver were being made. Flexible leads were taken to this box which was pivoted so that it could be turned to record either in the box camera or the drum camera. Stops were fixed to permit the correct setting of the tube in relation to the camera to be quickly obtained.

5—Description of Apparatus Used in England

It has been mentioned previously that a parallel series of observations were made in England and, while parts of the apparatus used at the three observing sites—

a—Radio Research Station, Slough,
b—King's College, London, and
c—Cavendish Laboratory, Cambridge,

were similar in character to those used at Tromsö and already described, there were several important differences.

a—Slough—The Slough sender consisted of a self-excited Hartley-type of oscillator modulated by direct voltage pulses in an associated thyratron circuit as shown in fig. 7. The method of generating such short pulses has already been described. The grid of V_2 was normally so negative that no anode current could flow through the tube, and consequently the circuit of tube V_3 was non-oscillating. Fifty times per second this negative bias was removed by the switching action of the thyratron T for an interval of about 10^{-4} sec. during which the sender radiated.

The single tuning control of the Hartley circuit facilitated rapid observation of the echo pattern on different frequencies. For ordinary working, no monitor was required at the transmitter, since neither the duration nor the recurrence frequency of the pulse altered as C_1 was altered.

A form of remote control, whereby the tuning condenser was rotated in small steps, was used during the early part of the year. This was later replaced by the

" Selsyn " system which permitted the observer to effect the smooth rotation of the sender condenser C_1 from the receiving site.

During the first part of the Polar Year, the receiver used was essentially of the type employed at Tromsö, but later this was modified by the replacement of all accumulators by mains supply. The sender and receiver were only 200 metres apart but, by using horizontal aerials at both stations, the ratio of the direct signal to the echo was sufficiently reduced to prevent undue overloading of the amplifier by the signal coming direct from the sender to the receiver.

The same receiving installation was used for both (P′, *t*) and (P′, *f*) observations. Change-over from one method to the other was facilitated by having two cathode-ray tubes in parallel, each facing its appropriate camera. In this way it was possible by simply throwing a switch to change from one type of recording to the other.

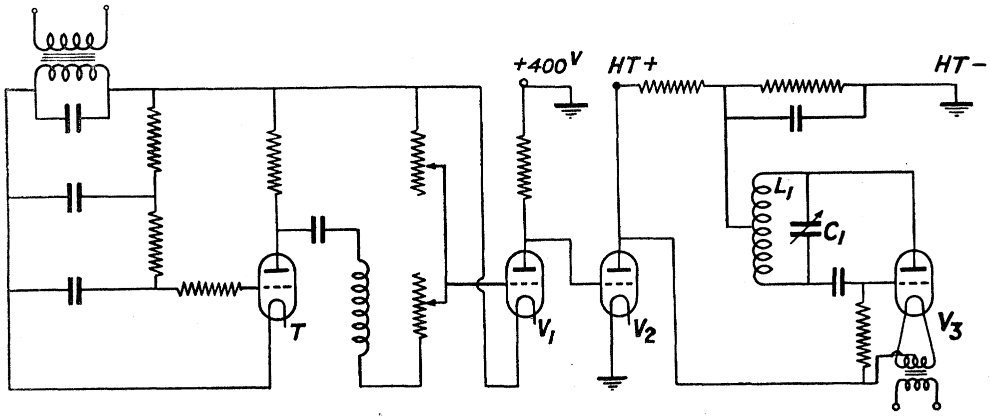

FIG. 7—Circuit diagram of both oscillator and modulator sections of Slough sender.

b—London—The sender was located at East London College and the receiver 5 km. away at King's College. The sender was a series-fed valve oscillator of the type shown in fig. 3. It was not required for long-period automatic recording, so that the rather elaborate synchronization arrangements used in conjunction with the other senders were not necessary. Moreover, the sender and receiver were not on the same alternating-current supply mains which rendered synchronization more difficult. (These difficulties have now, however, been overcome.*) With this circuit, the duration of the pulse is dependent on the time taken for the grid condenser to charge up negatively and the rate of production of pulses depends upon the time constant of the grid circuit. This was adjusted to give about 80 pulses/sec. each of duration 10^{-4} second.

The " electrical noise-level " at the receiving site was a serious factor and it was necessary to use a small frame as the antenna system because of its directional advantages.

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* PULLEY, ' Proc. Phys. Soc. Lond.,' vol. 46, p. 853 (1934).

The time scale on the oscillograph screen at the receiver and the pulse recurrence frequency at the sender were separately controlled by battery-driven dynatron oscillators giving 80 cycles/sec. A vernier adjustment of the dynatron oscillator at the receiver permitted accurate synchronism and therefore a stationary pattern on the cathode-ray oscillograph screen for photographic purposes.

c—Cambridge—At the beginning of the Polar Year, the apparatus already in use at Cambridge* was particularly suitable for recording automatically on a single frequency the values of equivalent height of echo reflexion, and therefore (P′, *t*) observations were made there throughout the Polar Year. In addition to recording heights of reflexion, the polarization of the echoes was also indicated.

The essential difference between the (P′, *t*) type of record obtained at Cambridge and that obtained at Slough was that in the former case the receiver was arranged to saturate for large signals, so that for all values of signal greater than a certain limiting value, the tips of the ground pulse and the echoes all appeared on the same horizontal line. By masking the tube so that only this line showed, it was possible to photograph the light marks which appeared there. In the Slough recording the breaks in the time base caused by the ground pulse and echoes were recorded as described above.

6—INTRODUCTORY REMARKS ON THE EXPERIMENTAL RESULTS

Before proceeding to discuss the experimental results it may, perhaps, be useful to mention the kind of problem which it was hoped would be solved by a comparison of ionospheric measurements in high and temperate latitudes. At the time the work was planned it was known that the ionosphere could be broadly divided into two regions, the lower Region E (equivalent height approximately 100 km.) and the upper Region F (equivalent height 230 km. and upwards). The diurnal and seasonal variations of the ionization maxima for Regions E and F were also known to some extent for the single case of South-East England.†

On the other hand, there were conflicting theories as to the nature of the solar radiation responsible for the ionization in the upper atmosphere. ELIAS‡ had put forward the theory that there was an upper ionized region maintained throughout the day and night by a stream of α-particles from the sun (80 km.), and a lower region (50 to 60 km. in height) existing only in the day-time and produced by ultra-violet light. If we make the necessary changes consequent on our increase of knowledge concerning ionospheric structure, this would lead us to re-formulate

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* RATCLIFFE and WHITE, 'Proc. Phys. Soc. Lond.,' vol. 45, p. 399 (1933); 'Phil. Mag.,' Ser. 7, vol. 16, p. 125 (1933).

† APPLETON and NAISMITH, 'Proc. Phys. Soc. Lond.,' vol. 45, p. 389 (1933).

‡ 'Jb. drahtl. Telegr.,' vol. 27, p. 66 (1926).

ELIAS's theory as assuming charged particles for the ionizing agency of the upper Region F and ultra-violet light for the lower Region E. In 1931 CHAPMAN* put forward a different suggestion, namely, that Region E was ionized by a neutral stream of solar corpuscles and that Region F was ionized by ultra-violet light; while, in the following year, APPLETON and NAISMITH† concluded that the radio observations made on the occasion of the eclipse in 1927 supported the ultra-violet light theory of Region E origin. They also pointed out, however, the need for further experiments to decide the point definitely and mentioned that the solar eclipse which occurred during the Polar Year (31 August, 1932) provided an opportunity for such work.

It was felt that the comparison of radio measurements in high and in temperate latitudes would assist substantially in the assessment of the relative importance of ultra-violet light and charged particles as ionospheric ionizing agents. For example, if ultra-violet light is the ionizing agency for either of the two main reflecting regions in the upper atmosphere, it is clear that we should expect that region to be more strongly ionized by day than by night and also (for the six months of winter and for day-time conditions in summer) to be of lower electrical content at Tromsö than over South-East England. On the other hand, if charged particles, entering the earth's atmosphere from outside, constitute the ionizing agency, the influence of the earth's magnetic field is such (as demonstrated by BIRKELAND and STØRMER)‡ as to cause these particles to converge to the polar regions and also to affect the dark side, as well as the light side, of the earth. It will readily be seen that the effects of charged solar corpuscles should be radically different from those produced by ultra-violet light and should be more pronounced in high than in temperate latitudes.

On the immediately practical side it was hoped that observations in high latitudes would perhaps also elucidate the special difficulties which had been found to occur in maintaining communication in circumstances in which the wireless ray traverses the polar cap.

In presenting the experimental results, it has been found convenient to divide the description and discussion into three parts, I, II, and III, which form §§ 7, 8, and 9 respectively. In Part I there are grouped all matters relating to normal variations of the ionosphere such as find a satisfactory explanation in terms of the ultra-violet light theory of ionization origin. In Part II are collected all matters referring to the connexion between magnetic activity and abnormal ionospheric effects. Part III is devoted to a further description and discussion of abnormal Region E phenomena, including especially matters which could not appropriately be dealt with in Part II. Part IV is an additional section dealing with ionospheric phenomena and the sunspot cycle.

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[*] 'Proc. Roy. Soc.,' A, vol. 132, p. 365 (1931).

[†] 'Proc. Phys. Soc. Lond.,' vol. 45, p. 389.

[‡] BIRKELAND, "The Norwegian Aurora Polar Expedition, 1902–03," Christiania (1913); STØRMER, 'Terr. Magn. atmos. Elect.,' vol. 22, p. 22, and p. 97 (1917).

7—Experimental Results and Discussion—Part I

a—The Ionospheric Structure—During the Polar Year further elucidation of the ionospheric structure was possible from the observations made at Slough as well as from those made at Tromsö. In particular, a comparison of ionospheric conditions at the two places has been helpful, a similar programme having been carried out at both. A partial account of the Slough part of this work has already been published* and only the chief conclusions need be summarized here. These are as follows :—

(1) For nocturnal conditions the ionosphere can be divided into two main Regions E and F.

(2) For day-time conditions the influence of solar radiation is such as to produce (α) a protuberance or " step " on Region F, and (β) considerable ionization between Regions E and F with occasionally a maximum of ionization there (Intermediate Region).

The nomenclature proposed (which has since been adopted officially by the International Scientific Radio Union) is illustrated in fig. 8, which is drawn for day-time conditions. In this figure the relative values of the ordinates are approximately correct but not those of the abscissae.

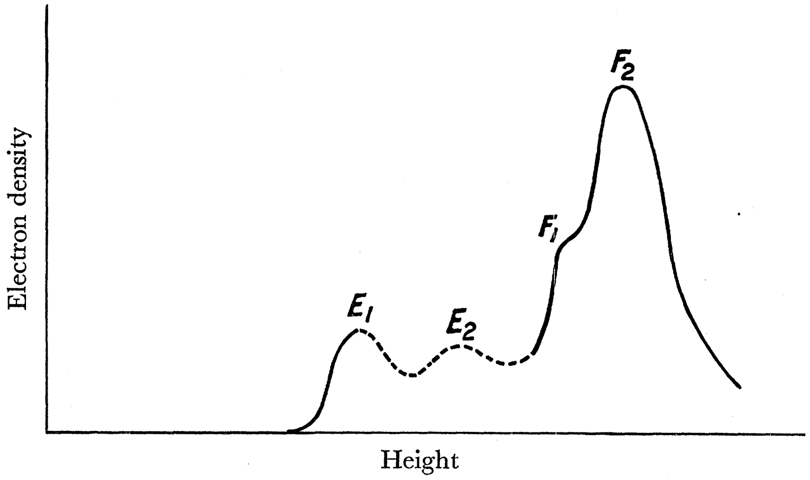

Fig. 8—Diagram showing nomenclature of ionospheric regions.

In Tromsö, as will be seen from the data given below, the ionospheric structure is very similar to that in South-East England, yet certain differences may be noted. There are two main regions which may be clearly differentiated under conditions of magnetic calm. Also, on such days, the formation of Region F_1, which from observations at Slough we know to be well defined only under conditions of relatively high solar altitude, could be detected. At Tromsö, echo-reflexions from equivalent

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* Appleton, ' Proc. Phys. Soc. Lond.,' vol. 45, p. 673 (1933) ; *see also* Schafer and Goodall, ' Nature, Lond.,' vol. 131, p. 804 (3 June, 1933).

heights between Regions E and F were, however, very frequent. Another marked feature was the relative complexity of all types of echoes compared with the simpler types obtained at Slough. Such complex echoes were rarely constant in structure, there being ceaseless changes in the components. The general impression is that the ionospheric structure at Tromsö is less definite and certainly more variable with respect to time than is the case in South-East England.

It is highly probable that the marked variability in the intensity and structure of the echoes at Tromsö is to be associated with the magnetic activity which is rarely absent in such latitudes. Support for this view is found in the fact that during magnetic activity, when echoes were obtained, they were found to be of marked variability and often did not fall into the usual category of Region E or Region F echoes. In other words, magnetic activity was associated with an ionospheric structure different from the normal configuration.

Our ionospheric observations preceding and during the Polar Year led us to recognize an outstanding difficulty in connexion with the interpretation of the results obtained for Region F. This difficulty was also appreciated by workers in other countries and we were of opinion that until it could be solved the elucidation of the actual observations made during the Polar Year was bound to be incomplete. A continuation of the work was therefore arranged at Slough during the remaining months of 1933 and during 1934, special attention being paid to the difficulty in question, and the publication of this memoir has been delayed in order that advantage might be taken of our appreciation of the points which have emerged from the more recent work.

The difficulty mentioned above arises in connexion with the interpretation of the diurnal and seasonal trend of the observed critical frequencies of Region F_2, the highest of the regularly occurring ionospheric regions. In its simplest form the matter may be referred to the case of ordinary ray critical penetration frequencies observed at noon. For the case of Region E this critical frequency, which is an index of the maximum noon ionization, is greater in summer than in winter, and the observed ratio of summer to winter ionization in South-East England (namely 1·8) lies very close to the theoretical value (namely 1·84) predicted from a theory of photo-electric ionization by solar radiation with the recombination of electrons and ions as the predominant process of electron dissipation. Exactly similar results are obtained for the case of Region F_1 (the "step" region). But in the case of Region F_2 such an agreement with theory is not obtained. Here it is found that the ratio of summer noon to winter noon ionization, as indicated by the observed critical frequencies, is not 1·8 but is less than unity.

Our examination of the relevant data has led us to conclude,* contrary to the views of American workers, that the Region F_2 anomaly is a real effect and not

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* APPLETON, 'Phys. Rev.,' vol. 47, pp. 89, 704 (1935); APPLETON and NAISMITH, 'Proc. Roy. Soc.,' A, vol. 150, p. 685 (1935); APPLETON, 'Nature,' vol. 136, p. 52, 13 July (1935). *See also in this connexion,* HULBURT, 'Phys. Rev.,' vol. 47, p. 422 (1935), *and references there cited.*

a spurious one consequent on the failure of the critical frequency method due to the influence of absorption. The two most striking aspects of this anomaly, together with possible explanations, may be summarized as follows :—

(1) The maximum content of Region F_2 is not always found to reach its highest value at noon. For example, on a summer day, there is a rather ill-defined pre-noon maximum and a higher well-defined evening maximum with a minimum in the afternoon. The occurrence of low values in the middle of the day may possibly be due to the expansion of the atmosphere, such expansion causing a dilution of ionization content and also causing a reduction of ion production, by way of a reduced molecular density, at the level of maximum ionization.

(2) The abnormally low maximum ionization on a summer noon as compared, for example, with that observed on an equinoctial noon may partly be due to the same cause, though evidence has recently been put forward[*] that an annual (as opposed to a seasonal) variation in the solar ionizing agency is responsible.

b—Disturbed and Undisturbed Magnetic Conditions—The results obtained at Tromsö demonstrate in no uncertain fashion that it is essential to distinguish between observations made on days of magnetic disturbance and those made on days of magnetic quietude. Further, the work carried out by Henderson and others[†] on the occasion of the eclipse in Canada on 31 August, 1932, demonstrated the primary importance of ultra-violet light as an ionospheric ionizing agent. We are therefore led to examine the data obtained on magnetically quiet days with reference to the hypothesis that the whole of the ionospheric ionization is due to ultra-violet light. The advantage of doing this is that we are able, to some extent, to make quantitative comparisons with theoretical predictions.

c—The Expected Influence of Ultra-Violet Light—In discussing the results for days of magnetic calm it is convenient to preface them by a short account of the effects to be expected in the ideal case of ionization produced by an agency which travels rectilinearly and which suffers absorption according to the simple mass-absorption law. Various writers[‡] have discussed this problem so far as ion-production is concerned, but Chapman[§] has further extended the investigation to include the effects of the diurnal and seasonal variations of the angle of incidence of the solar

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[*] BERKNER, WELLS, and SEATON, 'Terr. Magn. atmos. Elect.,' vol. 41, p. 173 (1936).

[†] "Canad. J. Res.,' vol. 8, p. 1 (1933) ; *see also* APPLETON and CHAPMAN, 'Proc. Inst. Radio Engrs.,' vol. 23, No. 6, p. 658 (1935).

[‡] LENARD, 'S.B. heidelberg. Akad. Wiss.,' 12, abh. (1911) ; ELIAS, 'Tijdschr. ned. Radiogenoot.,' vol. 3, No. 1, p. 1 (1926) ; HULBERT, 'Phys. Rev.,' vol. 31, p. 1018 (1928) ; PEDERSEN, "The Propagation of Radio Waves," Copenhagen, 1927, p. 59.

[§] CHAPMAN, 'Proc. Phys. Soc. Lond.,' vol. 43, p. 26 (1931), and vol. 43, p. 484 (1931). *See also* MILLINGTON, 'Proc. Phys. Soc. Lond.,' vol. 44, p. 580 (1932), and vol. 47, p. 263 (1935).

radiation, as well as the influence of recombination. In a recent paper,* dealing with work in England only, we have shown that the diurnal and seasonal trends of the ionization for Regions E and F_1 are remarkably similar to those predicted by CHAPMAN but that, for the main upper ionized Region (Region F_2) they are in flagrant disagreement with the theoretical variations according to our interpretation of the records.

For our present purpose it is only necessary to cite one or two of the results concerning ion production. We assume that the air density ρ in the atmosphere falls off exponentially with height h, so that

$$\rho = \rho_0 e^{-h/\mathrm{H}}, \qquad (1)$$

where ρ_0 is the density at ground level and H is the height of the homogeneous atmosphere.

It may then be shown that the maximum rate of ion production in the atmosphere ($q_{\max}$) is given by

$$q_{\max} = \gamma \mathrm{S}_\infty \frac{\cos \chi}{\mathrm{H} \exp 1}, \qquad (2)$$

and the air density at that level of maximum ion production is given by

$$\rho = \frac{\cos \chi}{\mathrm{AH}}. \qquad (3)$$

Here, following CHAPMAN, S_∞ is the intensity of the solar radiation outside the atmosphere, γ is the number of ions produced by the absorption of unit quantity of the radiation, χ is the sun's zenith distance, and A is a constant.

We assume that recombination is the principal electron-dissipative influence in the ionosphere and that the attachment of electrons to neutral molecules or atoms is quite a subsidiary effect. We thus have, generally

$$\frac{d\mathrm{N}}{dt} = q - \alpha \mathrm{N}^2, \qquad (4)$$

where N is the number of electrons (or positive ions) per cc., α is the coefficient of recombination, and t is the time.

If we assume, as is known to be the case at Slough for Regions E and F_1, that the ionization is a maximum at noon, we have $d\mathrm{N}/dt$ equal to zero, and thus

$$q = \alpha \mathrm{N}^2. \qquad (5)$$

If now, for a particular season, we wish to make a comparison between the noon ionization maximum at Tromsö and that at Slough we have from (2) and (5)

$$\frac{\mathrm{N_T}}{\mathrm{N_S}} = \sqrt{\frac{\cos \chi_\mathrm{T}}{\cos \chi_\mathrm{S}}} = \sqrt{\frac{\sin (\theta_\mathrm{T} + \delta)}{\sin (\theta_\mathrm{S} + \delta)}}, \qquad (6)$$

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* APPLETON and NAISMITH, 'Proc. Roy. Soc.,' A, vol. 149, p. 685 (1935).

where the subscripts T and S refer to Tromsö and Slough respectively and θ is the co-latitude of the place of observation and δ is the sun's declination. We may note here that in deducing (6) we have assumed that α and H (which is proportional to the absolute molecular temperature) are the same at both Tromsö and Slough.

It may further be added that MARTYN and PULLEY have recently shown that a relation similar to (6) may be derived from a theory in which attachment of electrons to oxygen atoms is considered the main electron-dissipative process, the supply of oxygen atoms resulting from the dissociation of molecules by ultra-violet light.

The measurements of maximum ionization have all been made using values of critical penetration frequency. The relations used have been those deduced from the magneto-ionic theory, namely :—

$$
\begin{aligned}
N_{\text{max.}} &= \frac{\pi m}{e^2} f^2 \quad \text{(ordinary ray)} \\
&= 1 \cdot 24 \times 10^{-8} f^2 \quad \ldots\ldots\ldots\ldots \quad (7)
\end{aligned}
$$

and

$$
\begin{aligned}
N_{\text{max.}} &= \frac{\pi m}{e^2} (f^2 - f f_H) \quad \text{(extraordinary ray)} \\
&= 1 \cdot 24 \times 10^{-8} (f^2 - f f_H), \quad \ldots\ldots\ldots\ldots \quad (8)
\end{aligned}
$$

where e and m are the charge (e.s.u.) and mass of the electron and f is the critical frequency (cycles per second) in question, and f_H is the gyro-frequency of the electronic motion caused by the influence of the earth's magnetic field. At Tromsö and Slough f_H is approximately 1·47 and 1·32 Mc./sec. respectively.

We may further note that if ordinary wave critical frequencies (f°) are in question, we have in any comparison between Tromsö and Slough,

$$\frac{N_T}{N_S} = \left(\frac{f_T{}^\circ}{f_S{}^\circ}\right)^2 . \quad \ldots\ldots\ldots\ldots \quad (9)$$

Also for any particular site at noon, we have from (2), (5), and (7)

$$f^\circ = \text{const} \sqrt[4]{\sin(\theta + \delta)} . \quad \ldots\ldots\ldots \quad (10)$$

A particularly simple approximate result can be obtained from (4). It is found that, for Regions E and F_1, during full day-light the value of dN/dt is numerically small compared with estimated values of q and αN^2. We can thus write, to a first approximation,

$$q = \alpha N^2,$$

so that, substituting for q from (2) and f° from (7),

$$f^\circ = \text{const} (\cos \chi)^{\frac{1}{4}} . \quad \ldots\ldots\ldots\ldots \quad (11)$$

It should be noted that (10) is a special case of (11) and is rigorously true, if dN/dt at noon is zero.

Thus for ionization by ultra-violet light we are able to make the three following tests :—

(1) A comparison of noon ionization at Tromsö and Slough should satisfy the relation

$$\frac{N_T}{N_S} = \sqrt{\frac{\sin(\theta_T + \delta)}{\sin(\theta_S + \delta)}} . \quad \ldots\ldots\ldots\ldots \quad (6)$$

(2) The ionization at either site should vary during the hours of full day-light proportionally to $(\cos\chi)^{\frac{1}{2}}$.

(3) *A fortiori* the same relation should hold for the seasonal variation of noon ionization.

d—Critical Frequency Measurements at Tromsö and Slough. i—*Seasonal Variations*—The critical frequency measurements made during the Polar Year are most conveniently recorded in the form of graphs. In fig. 9 are exhibited the values of $f_E{}^{\circ}$ (ordinary ray critical frequency for Region E) and of $f_{F_1}{}^{\circ}$ (ordinary ray critical frequency for Region F_1) for Tromsö at noon. In the same graph are shown the variations to be expected according to the theoretical relation (11). Here the constant in (11) has been adjusted in each case to make the values fit the observations at the equinoxes. In fig. 10 are shown the corresponding curves for Regions E and F_1 at Slough.

It will be seen that in both figs. 9 and 10 there is substantial agreement between the observed seasonal variations of $f_E{}^{\circ}$ and $f_{F_1}{}^{\circ}$ and the theoretical curves strongly supporting the view that the ionization at noon varies with the solar altitude as expected according to an ultra-violet light theory of its origin. It is noteworthy that, at the season when the sun just failed to rise at Tromsö, no Region E or Region F_1 echoes were obtained, but that, at midwinter, echoes from about the height of Region E reappeared, although there was no corresponding reappearance of Region F_1 echoes. It will be noticed that the measurements of $f_{F_1}{}^{\circ}$ at Tromsö are comparatively few, partly owing to the fact that its occurrence there is indicated by a very ill-defined maximum on the (P', f) curve and partly due to the possibility of its being missed altogether in one of the 0·25 Mc./sec. steps in which the frequency range of observations was covered. However, the little evidence we have supports the view that this region behaves at Tromsö as could be predicted from its behaviour at Slough according to the ultra-violet light theory.

The corresponding results for Region F_2, the main upper region, are shown in figs. 11 and 12. Here it will be seen that there is no pronounced seasonal variation, the summer values being, if anything, slightly less than the winter values at Slough. The rapid decrease of critical frequency over the week preceding midwinter and the corresponding increase just after this date at Tromsö appears to be more than fortuitous. It is also significant that the highest sequence of critical frequencies covering a period of weeks was obtained at both places at the same season, namely, early in February.

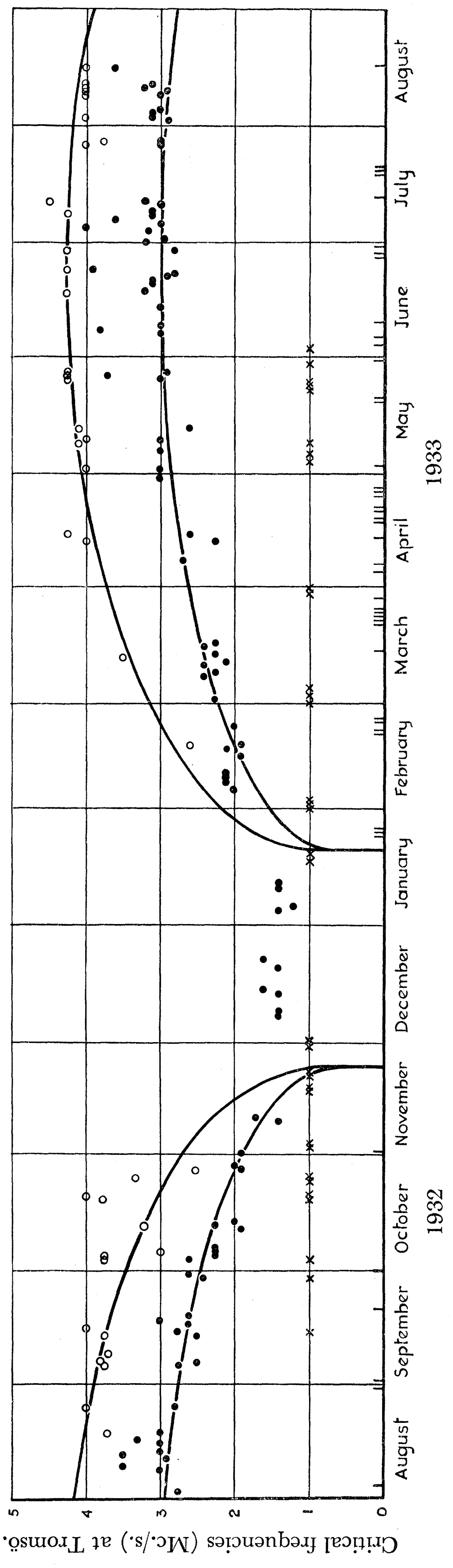


FIG. 9—Noon values of ordinary ray critical frequencies for Regions E and F$_1$ at Tromsö. ○ $f_{F_1}{}^{\circ}$; ● $f_{E_1}{}^{\circ}$; — theoretical curves; × No E; I no echoes.

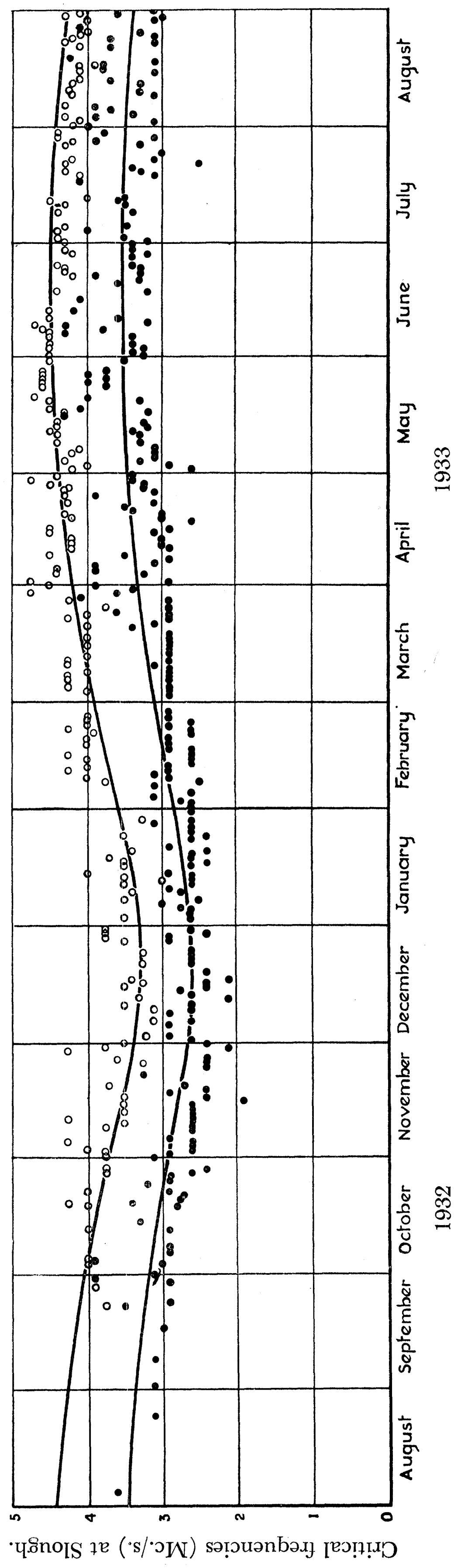


FIG. 10—Noon values of ordinary ray critical frequencies for Regions E and F$_1$ at Slough. ○ $f_{F_1}{}^{\circ}$; ● $f_{E_1}{}^{\circ}$; — theoretical curves.

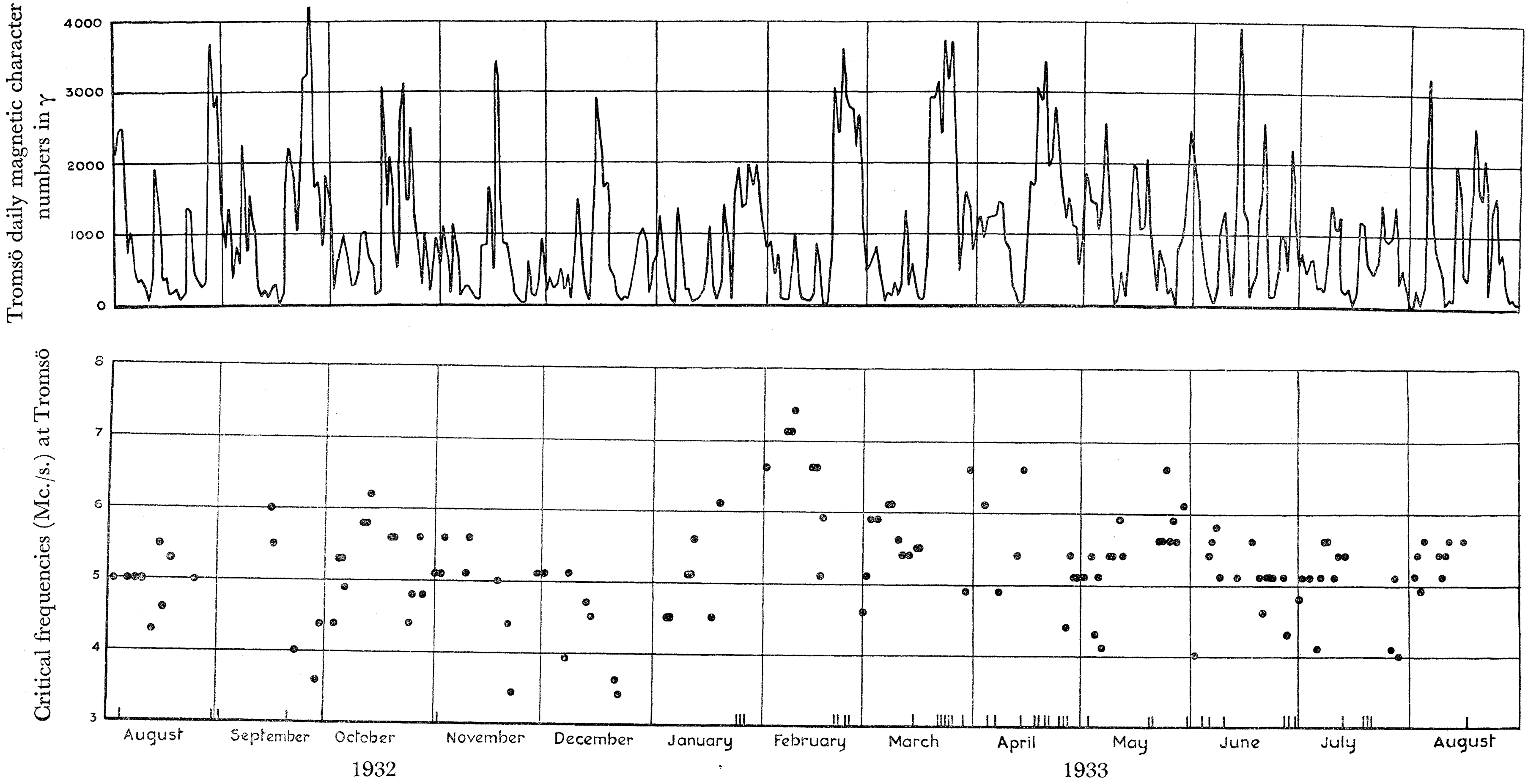


FIG. 11—Noon values of extraordinary ray critical frequencies for Region F_2 at Tromsö (lower diagram). Daily magnetic character number for Tromsö (upper diagram). ● $f_{F_2}{}^X$; I no echoes.

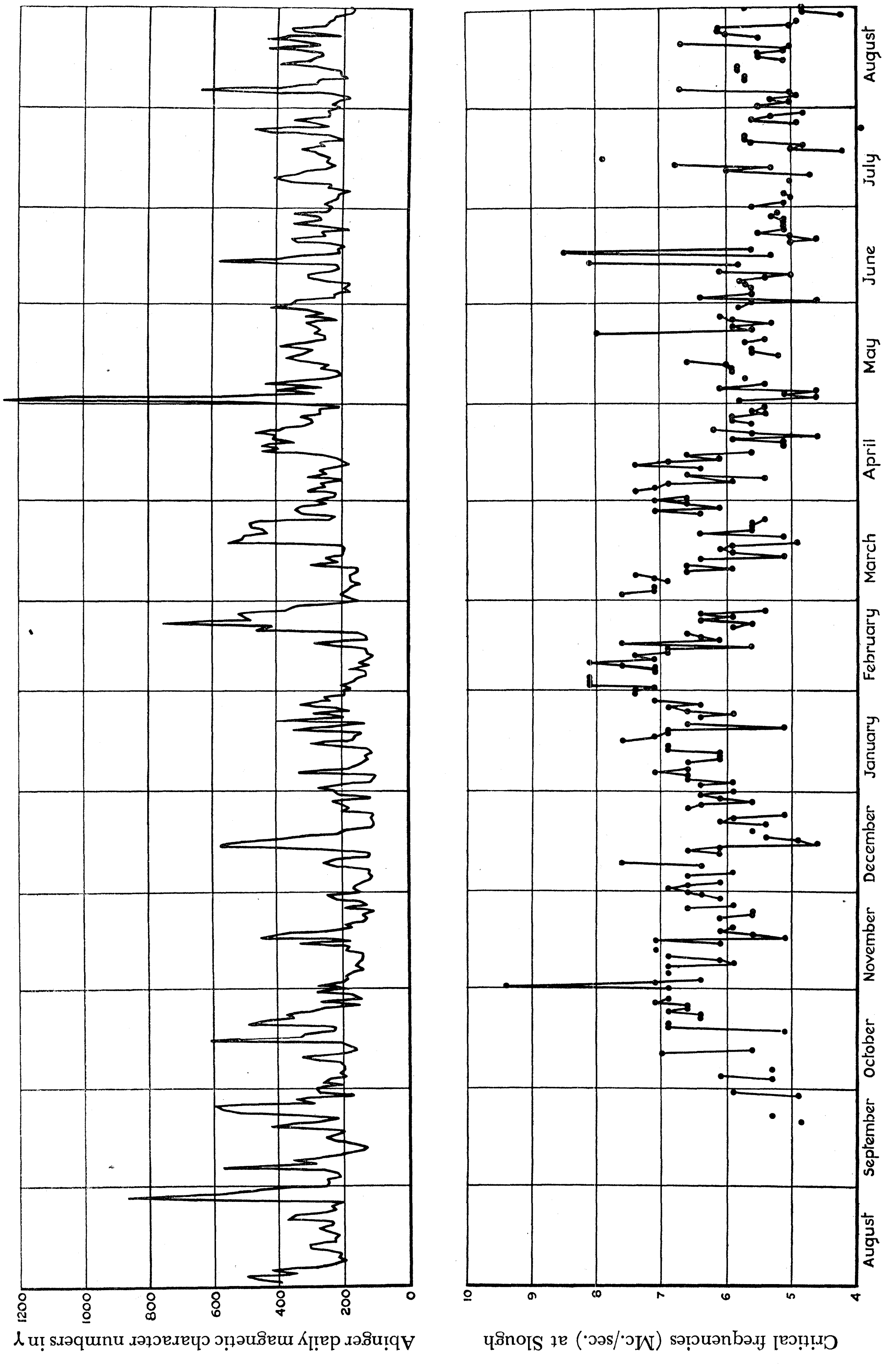


FIG. 12—Noon values of extraordinary ray critical frequencies for Region F_2 at Slough (lower diagram). Daily magnetic character number for Abinger (upper diagram). ● $f_{F_2}X$.

Another striking feature of the day-to-day results is the extreme variability. Further inspection shows this variability to be connected with magnetic activity at both Tromsö and Slough. This will be discussed in greater detail below, but the daily magnetic character numbers are plotted on the diagrams for comparison. A 27-day recurrence tendency is, however, suggested by visual inspection of the curves for the months of January–April, 1933, when, as the magnetic records show, this recurrence tendency was especially marked.

ii—*Diurnal Variations*—As has already been found in South-East England, from critical frequency measurements, the ionization on a magnetically quiet day follows approximately the trend expected according to the ultra-violet light theory for Regions E and F_1.

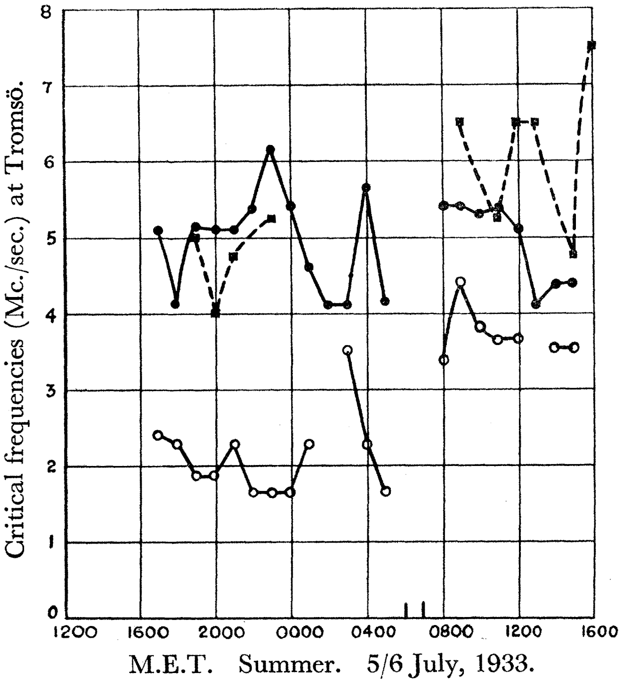


FIG. 13—Diurnal variation of critical frequencies for summer day at Tromsö. ● $f_{F_2}^{X}$; ○ $f_{E_1}^{o}$; ■ E persists.

In accordance with the programme, a number of simultaneous 24-hour runs were made at Tromsö and Slough which permit us to compare the diurnal trend of ionization at the two places at different seasons. The results of these observations are exhibited in figs. 13 to 17.

The most striking feature about the midsummer curves is the lack of diurnal variation at Tromsö as compared with Slough. The tendency for echoes to be observed from Region E on high frequencies, especially at Slough, is also apparent. It was decided to use the curves of 5/6 July, 1933, instead of the June ones, as on both the June days of observation Region E was not penetrated at Slough during

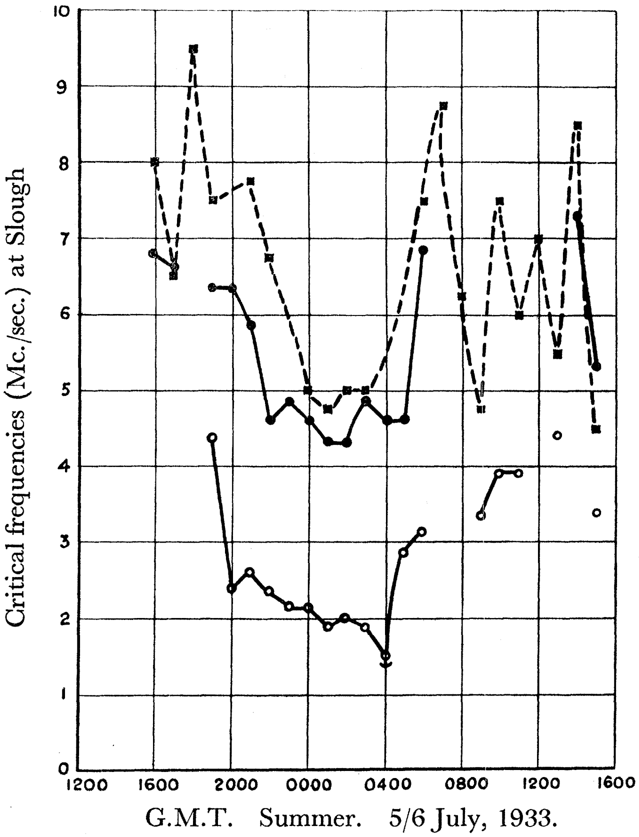


FIG. 14—Diurnal variation of critical frequencies for summer day at Slough. ● $f_{F_2}^{X}$; ○ $f_{E_1}^{o}$; ■ E persists.

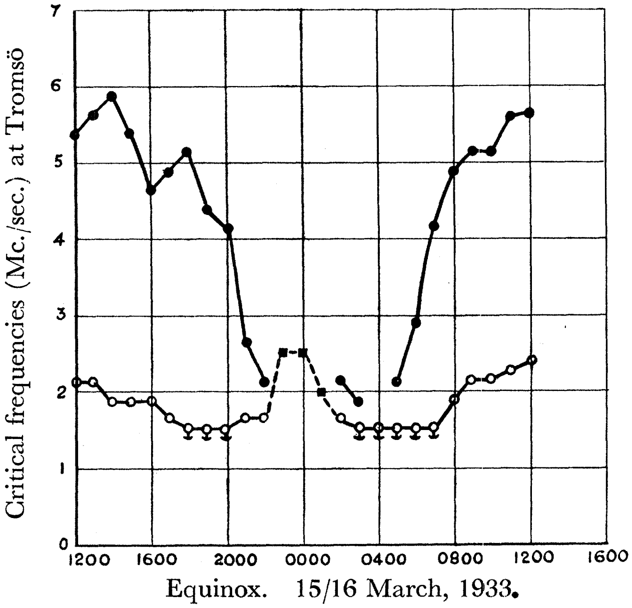
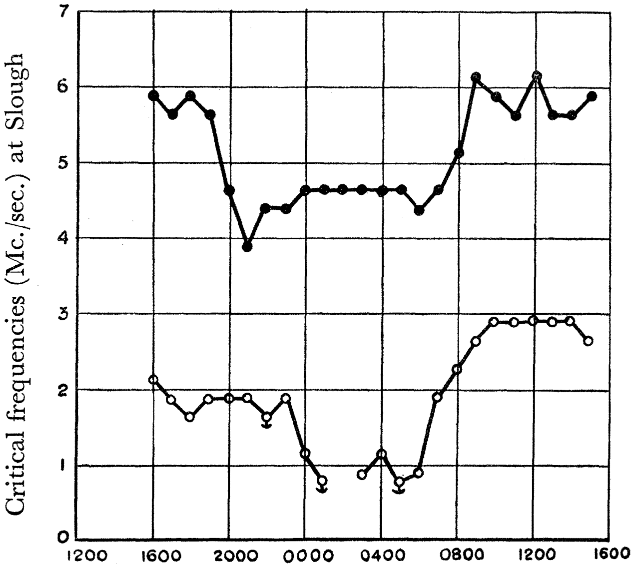


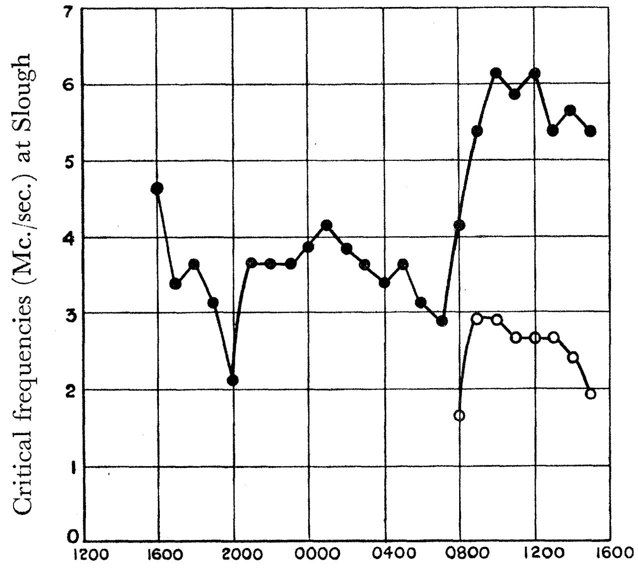
FIG. 15—Diurnal variation of critical frequencies at Tromsö (Equinox). ● $f_{F_2}^{X}$; ○ $f_{E_1}^{o}$; ■ E persists.

the day and so even less idea of the behaviour of Region F could have been inferred from them. Although Region E critical frequency at Tromsö is much greater by day than by night, supporting the ultra-violet hypothesis, Region F_2 critical frequency is actually greater at midnight than at midday. This effect is further illustrated in fig. 18, in which the critical frequencies of Region F_2 at midnight and noon are plotted over the season of the midnight sun. We believe that this



G.M.T. Equinox. 15/16 March, 1933.

FIG. 16—Diurnal variation of critical frequencies at Slough (Equinox). ● $f_{F_2}^{X}$; ○ $f_{E_1}^{o}$.



G.M.T. Winter. 21/22 December, 1932.

FIG. 17—Diurnal variation of critical frequencies at Slough for winter day. ● $f_{F_2}^{X}$; ○ $f_{E_1}^{o}$.

remarkable result can be explained along lines previously indicated. In a recent account* of the diurnal and seasonal variation of Region F_2 ionization it has been shown that in South-East England on a summer day there are two maxima of ionization, a minor one in the forenoon and a major one in the late evening. Other evidence, which need not be set down here, shows that this afternoon maximum occurs latest at midsummer (*e.g.*, 20.00 to 22.00 G.M.T.). It is therefore fairly certain that the notably high values of Region F_2 maximum ionization at midnight are to be associated with this late evening maximum experienced in lower latitudes. A possible reason for the existence of high values of maximum ionization when the sun is low is that at this period of the day the higher atmosphere is cooling and maintaining a relatively high electronic density by shrinkage.

At the equinox, both curves (figs. 15 and 16) show the variation due to ultraviolet light very markedly. Region F_2 critical frequency during the night hours is very much higher at Slough than at Tromsö. This seems to have been a peculiarity of the night rather than the normal condition. Magnetic disturbances were so frequent about this time that it has been impossible to find a 24-hour record on a quiet day. The Tromsö curve illustrates rather strikingly the Region E which grows up during the dark hours and persists to the highest frequency at midnight.

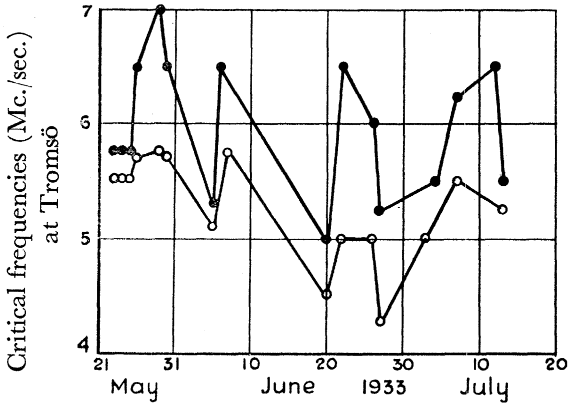


FIG. 18—Extraordinary ray critical frequencies for Region F_2 under midnight sun conditions at Tromsö. (Dots indicate midnight values and circles noon values.)

At midwinter only the Slough curve has been drawn. The critical frequencies for both Regions E and F_2 vary with the angle of the sun, having a maximum about noon, as theory predicts. There is no tendency at this season for the noon value of Region F_2 critical frequency to be lowered in an anomalous way. Region F_2 critical frequency increases markedly during the dark hours after its rapid fall around sunset. This nocturnal increase of ionization in Region F_2 is frequently associated with scattering, there being then no well-defined critical frequency. There is also a marked increase in equivalent height. No curve has been drawn

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* APPLETON and NAISMITH, ' Proc. Roy. Soc.,' A, vol. 149, p. 685 (1935).

for Tromsö, because scarcely any echoes were obtained, although the day was exceptionally quiet magnetically. The echoes which did appear were mostly from the height of Region E, except for about four hours around noon, when echoes were definitely obtained from Region F. We feel bound to conclude, bearing in mind the evidence of the (P′, *t*) records over this period, that this is a case of genuine electron limitation during most of the day. The occasional appearance of echoes from Region E may have been due to the arrival in our atmosphere of charged solar particles, but the unmistakable Region F echoes around noon were almost certainly due to ultra-violet radiation from the sun. Evidently this is due to the fact that although the sun does not rise at ground level at Tromsö at midwinter, its rays penetrate to Region F and are capable of ionizing there although they have traversed a large part of the atmosphere.

Although shortage of personnel did not permit more than relatively few 24-hour runs for the hourly determinations of critical frequency, we have been able to supplement this information at certain times of the day from the (P′, *t*) records obtained on the international frequencies. For example, on such records obtained, using a frequency of 2 Mc./sec., it is found that there is a " jump " from reflexion at Region F to reflexion at Region E in the morning with the advent of sunrise, and a " jump " in the opposite direction just before sunset. At these particular times the critical frequency for Region E is the frequency used (*i.e.*, 2 Mc./sec.). These times at which Region E critical frequency was 2 Mc./sec. have been extracted from the records and are plotted for Tromsö (fig. 19) and Slough (fig. 20). In both cases the curves showing the times of ground sunrise and sunset are added for comparison. These curves illustrate the point already mentioned concerning the regular variation of Region E ionization with the altitude of the sun. The times when the frequency of 2 Mc./sec. is critical for Region E vary with the times of ground sunrise and sunset as shown. The symmetry about noon shows that the rate of recombination must be very great, as the ionization only depends on the altitude of the sun and not on the previous history. During the summer the times indicated are those when the echoes ceased to be returned from Region E in the evening and penetrated to a level only slightly higher and when reflexion from the normal Region E was resumed in the morning.

Other data of similar character for Region F_2 can be extracted from the same records. For example, on the advent of sunrise the ionization builds up steadily until it is sufficient to reflect waves which have previously penetrated it. Thus when Region F_2 echoes are first obtained for any particular frequency we can count that frequency as the critical value for Region F_2 at the time.

In figs. 21 and 22 are plotted the times of disappearance of Region F_2 echoes and their early morning reappearance (extraordinary ray) for the international frequency of 4 Mc./sec. together with curves of ground sunrise and sunset. Fig. 21 is for Tromsö and fig. 22 for Slough.

As compared with the curves when 2 Mc./sec. is critical for Region E, these show much more variation, though the influence of sunrise and sunset is very marked.

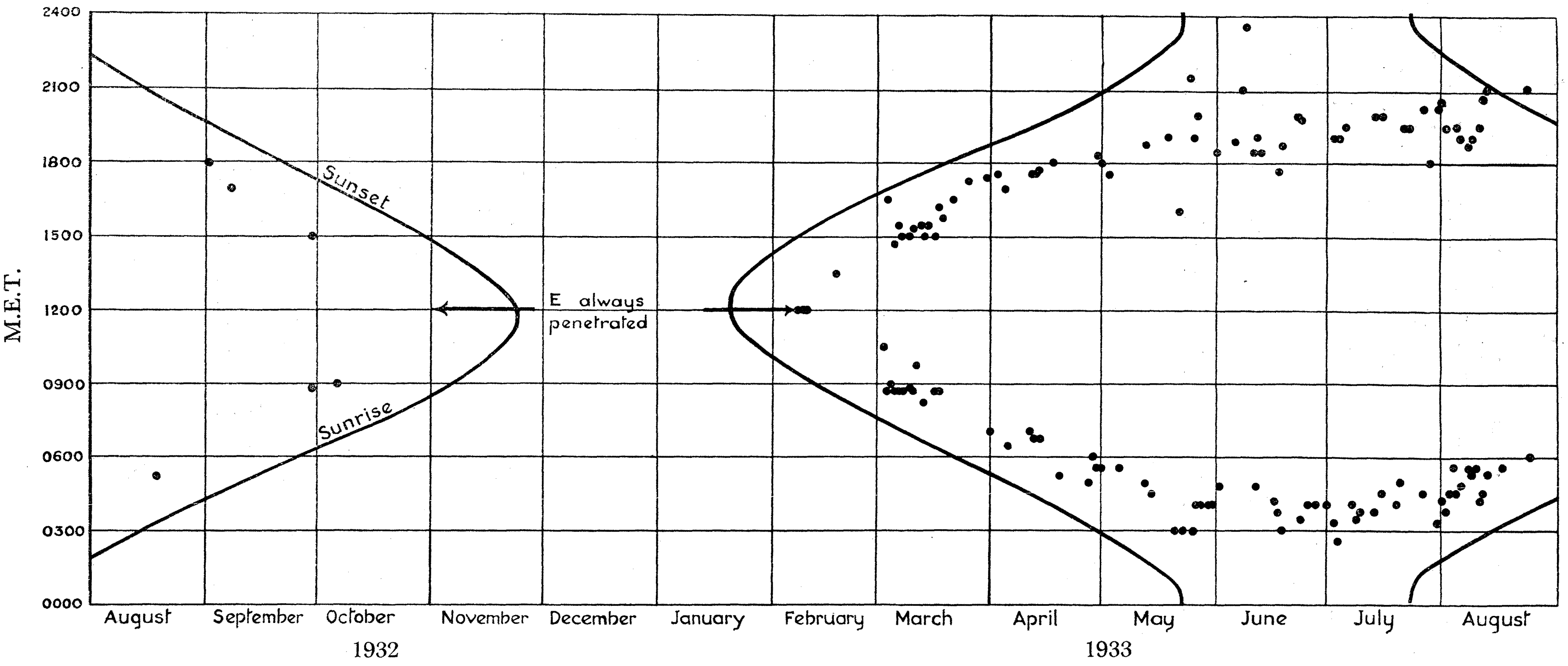

FIG. 19—Diagram showing times at which Region E ionization at Tromsö is just sufficient to return echoes on a frequency of 2 Mc./sec. at vertical incidence. Full curves show times of ground sunrise and sunset.

In particular, on magnetically disturbed days we do not get echoes from Region F on 4 Mc./sec. This is the reason for the few observations shown at the end of March and in April. On days following those of " no echoes " the time of commencement of reflexion from Region F_2 in the morning seems to be delayed. This accounts for the points which lie above the curve in March. There was usually a break in the (P′, *t*) recording from about 20.00–24.00 hours, the result of which is apparent in the graph. In summer, Region F_2 echoes were generally observed throughout the night at Tromsö. On other nights nocturnal Region E appeared to prevent radio signals reaching Region F_2. These curves are not symmetrical about noon, which illustrates the fact that Region F_2 critical frequency does not vary according to the simple theory. In fig. 23 are shown the times at which Region F_2 ionization is just sufficiently intense at Tromsö to return waves of 2 Mc./sec. at vertical incidence. The full curves in the same diagram show times of ground sunrise and sunset. The curve is drawn omitting the midnight sun period, for at that time the critical frequency for Region F_2 never reaches such a low value as 2 Mc./sec. throughout the whole day. For a similar reason no such corresponding curve can be given for Slough since $f_{F_2}{}^{\circ}$ is greater than 2 Mc./sec. in South-East England throughout the whole year.

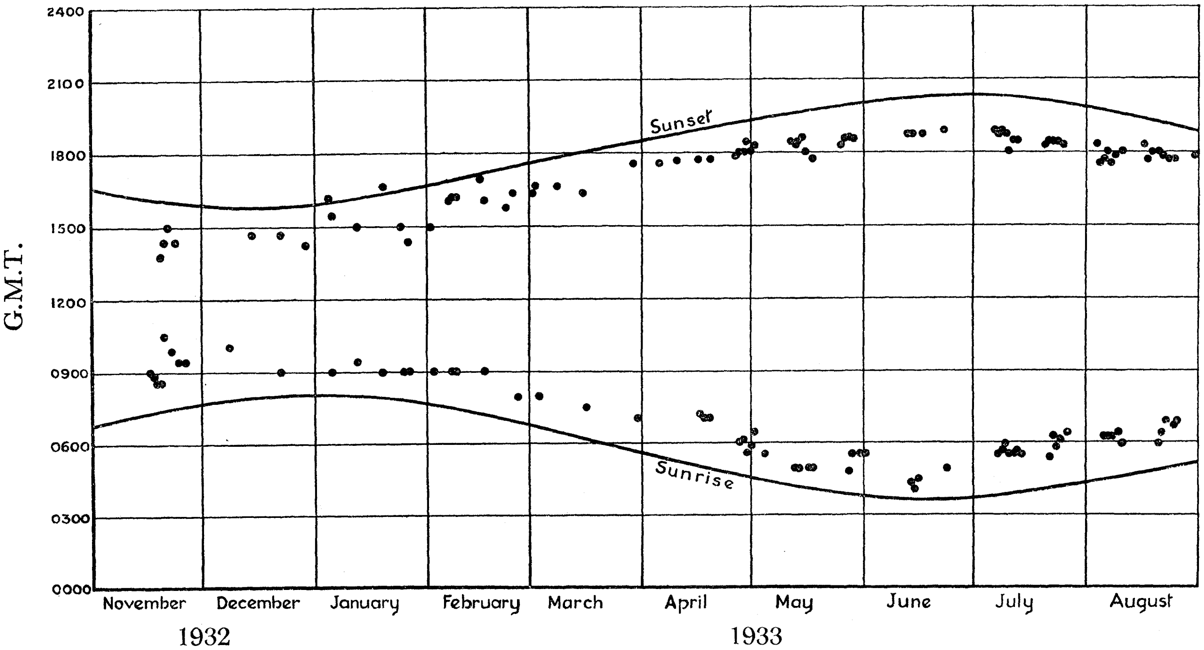

FIG. 20—Diagram showing times at which Region E ionization at Slough is just sufficient to return echoes on a frequency of 2 Mc./sec. at vertical incidence. Full curves show times of ground sunrise and sunset.

e—Quantitative Tests of Ultra-Violet Light Theory—We have seen that the seasonal trend of noon ionization for Regions E and F_1 at both Tromsö and Slough is such

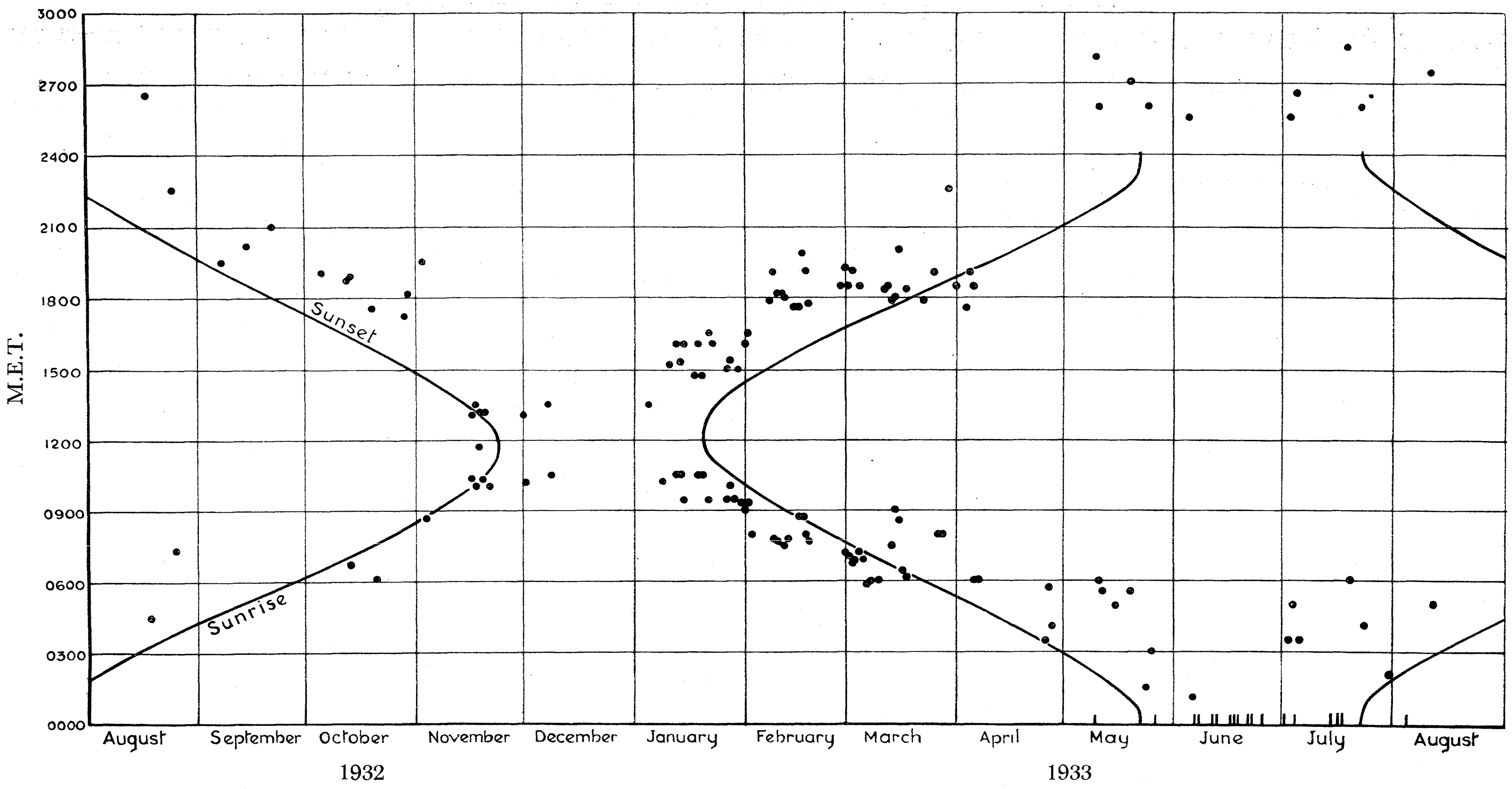

FIG. 21—Diagram showing times at which Region F_2 ionization at Tromsö is just sufficient to return extraordinary ray echoes on a frequency of 4 Mc./sec. at vertical incidence. Full curves show times of ground sunrise and sunset.

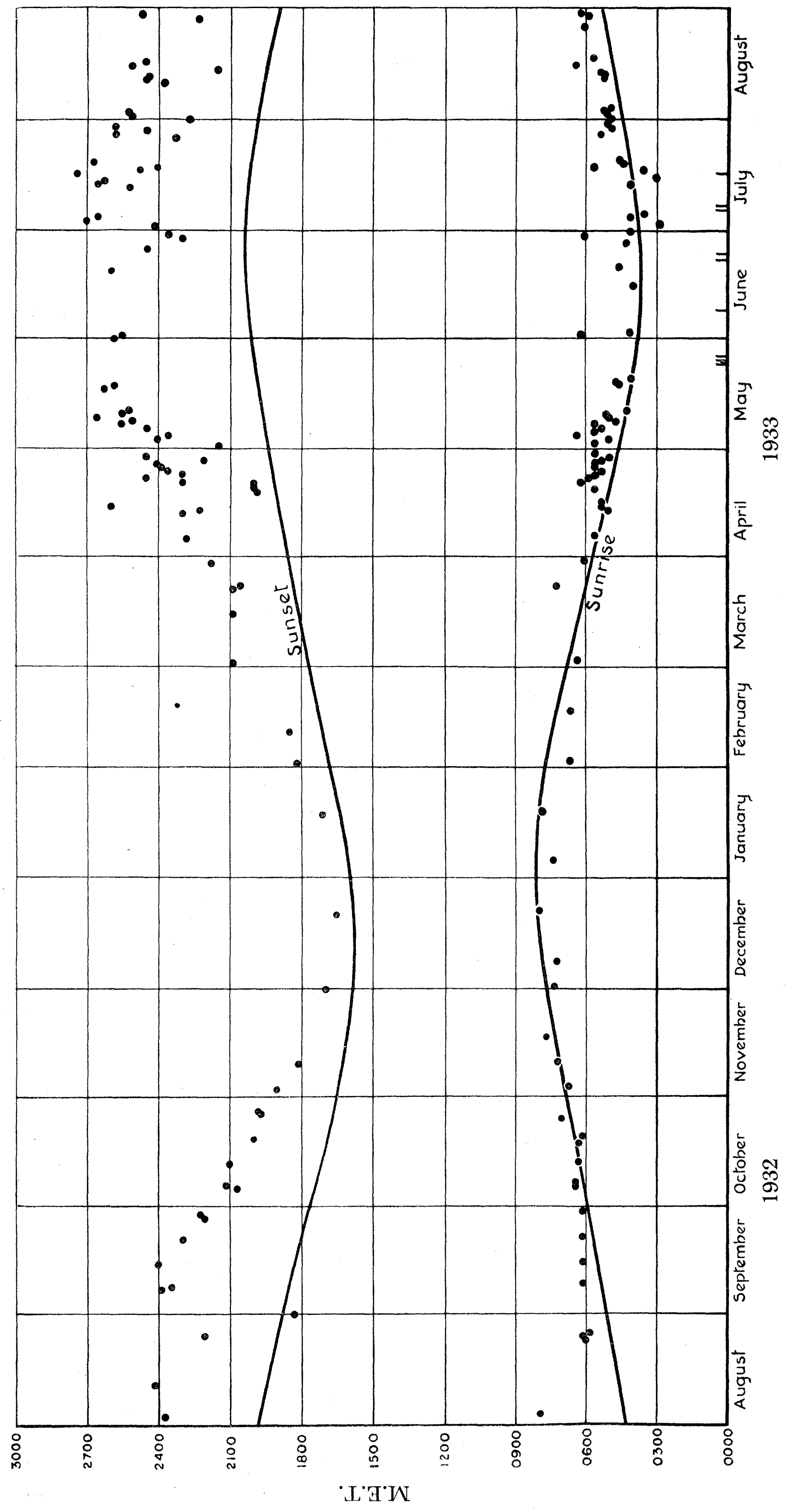

FIG. 22—Diagram showing times at which Region F_2 ionization at Slough is just sufficient to return extraordinary ray echoes on a frequency of 4 Mc./sec. at vertical incidence. Full curves show times of ground sunrise and sunset.

as to be adequately explained in terms of the varying solar altitude. It is, however, possible to make a further check by considering the ratio of noon ionization for the same season at the two places.

We have

$$\frac{N_T}{N_S} = \sqrt{\frac{\sin(\theta_T + \delta)}{\sin(\theta_S + \delta)}}. \qquad (6)$$

On substituting the appropriate values for θ_T and θ_S and for varying δ we get the expected variation of N_T/N_S at noon throughout the year, which can be compared with the experimentally observed values of the same quantity for any particular region. In figs. 24, 25, and 26 are shown the experimental values of N_T/N_S for Regions E, F_1, and F_2 respectively. In each case the theoretical values calculated from relation (6) are shown by the continuous line.

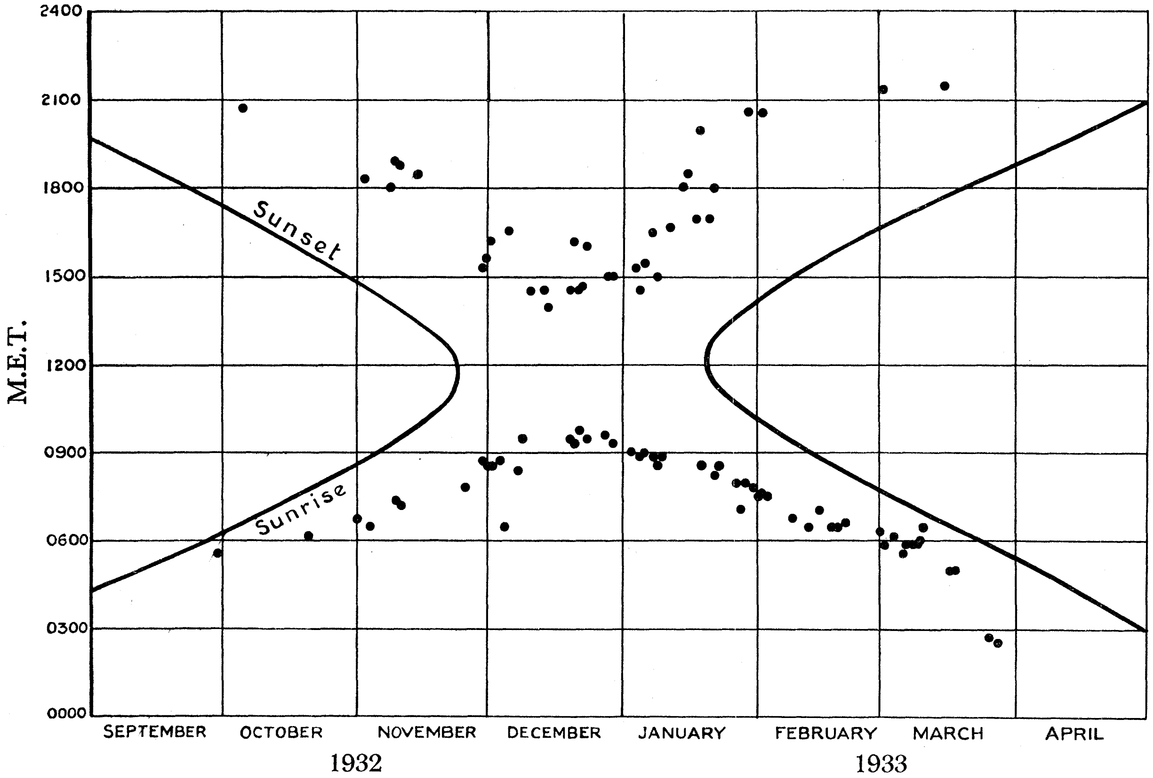

FIG. 23—Diagram showing times at which Region F_2 ionization at Tromsö is just sufficient to return extraordinary ray echoes on a frequency of 2 Mc./sec. at vertical incidence. Full curves show times of ground sunrise and sunset.

It will be seen that good agreement is obtained for Regions E and F_1 but that for Region F_2 the agreement is less marked. In fig. 26 the Tromsö magnetic character figures are plotted for comparison with the ratio of the observed ionization of Region F_2 at the two places.

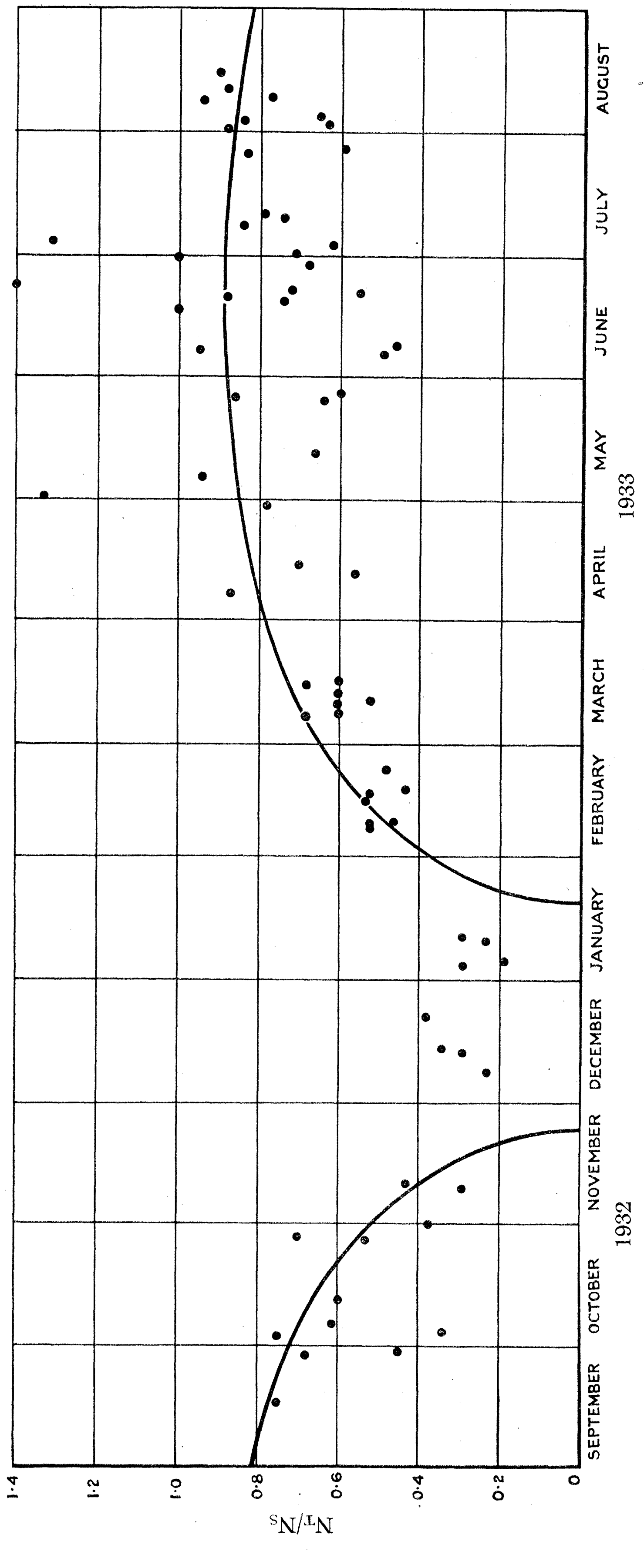

FIG. 24—Values of N_T/N_S for Region E at noon. The full curve shows the theoretical values as plotted from relation (6).

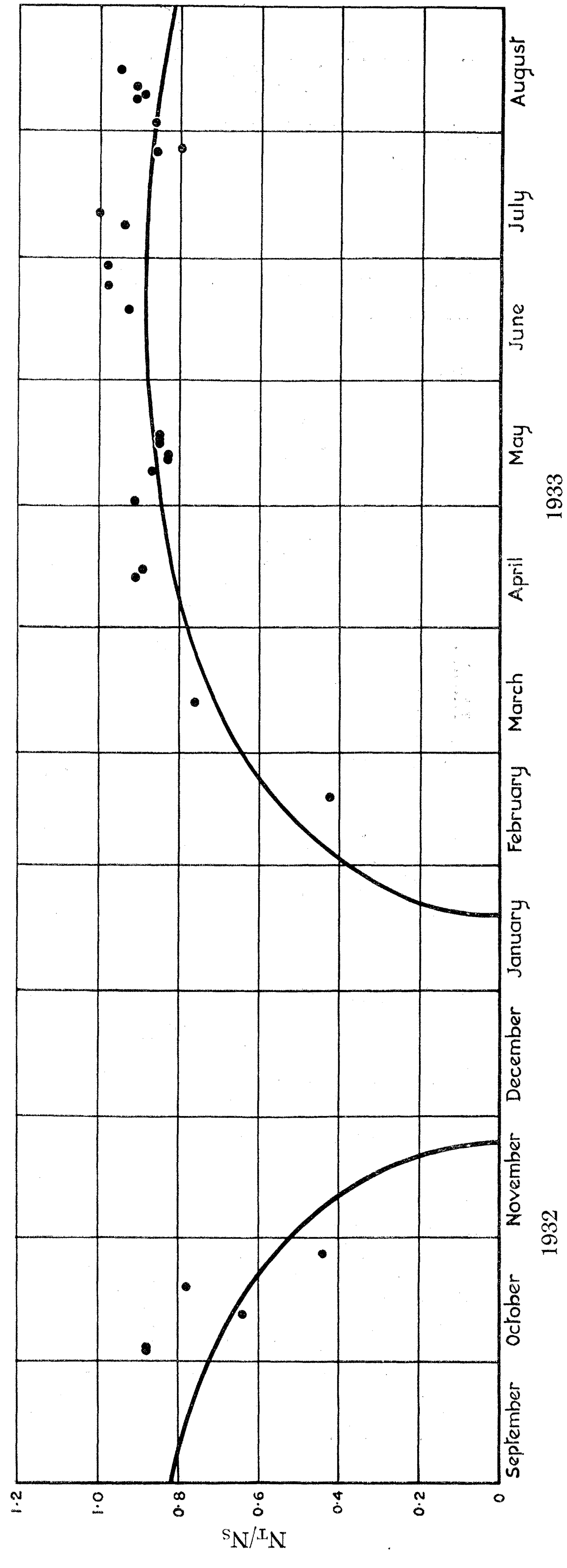

FIG. 25—Values of N_T/N_S for Region F_1 at noon. The full curve shows the theoretical values as plotted from relation (6).

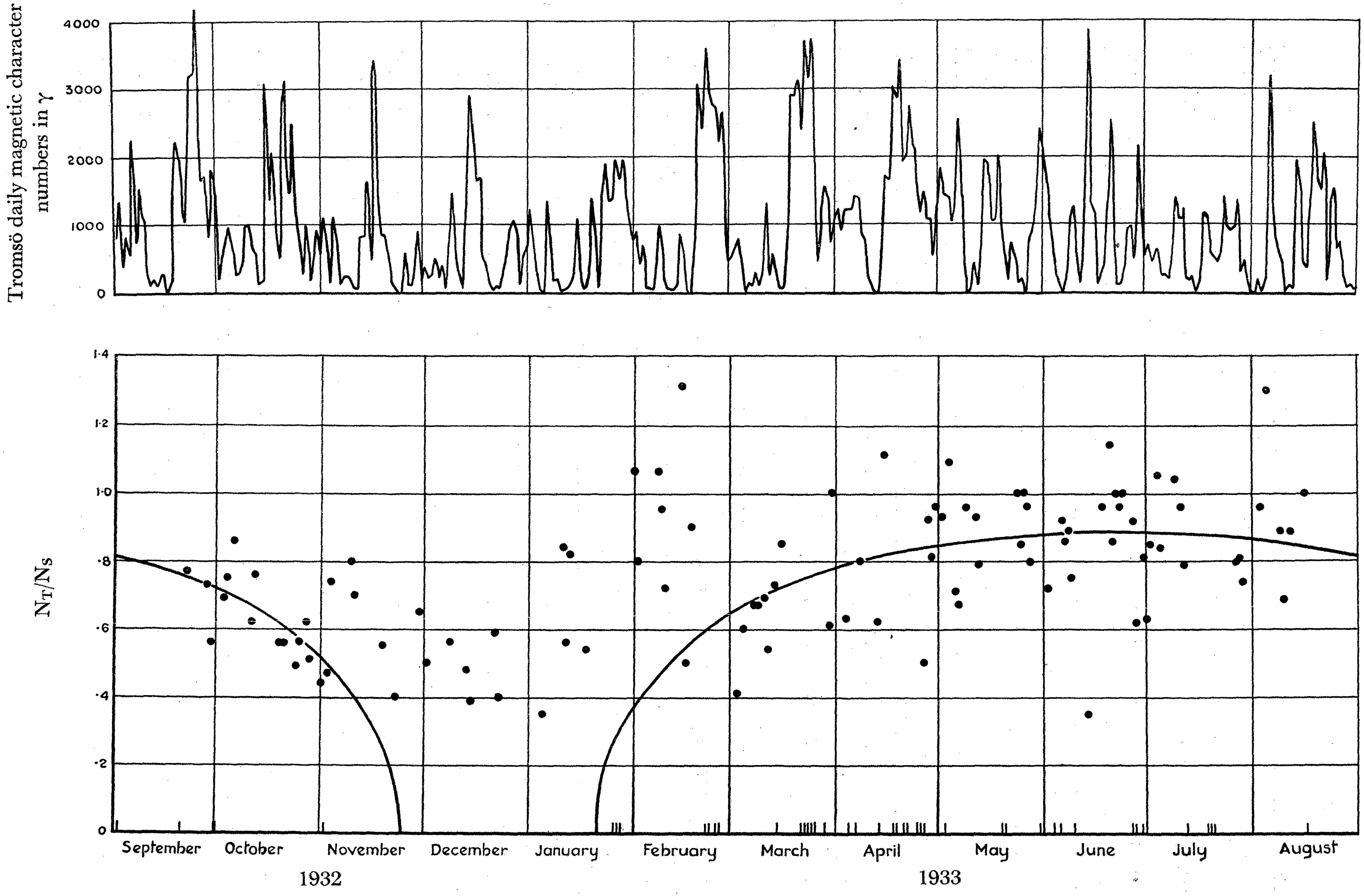

FIG. 26—Values of N_T/N_S for Region F_2 at noon together with Tromsö daily magnetic character numbers. The full curve shows the theoretical values as plotted from relation (6). The small vertical lines at the bottom of the lower diagram indicate days on which no echoes were observed at Tromsö at noon, although observations were made.

8—Experimental Results and Discussion—Part II

We now turn to consider the observations made at Tromsö and Slough during times of magnetic activity, when the results obtained are such as cannot be explained in terms of the ultra-violet light theory discussed above. We preface our account of the experimental results with a description of the magnetic conditions at Tromsö.

a—The Quiet-day Diurnal Variation of Magnetic Force at Tromsö—The quiet-day diurnal magnetic variation at Tromsö exhibits the usual features for a station in high latitudes, there being a marked seasonal correlation. This is shown in two ways : (*a*) the times of maximum increase in H (the horizontal component of the earth's magnetic field) alter seasonally following sunrise and sunet, (*b*) the amplitude of the changes in H is greater in summer than in winter, the summer to winter ratio being of the order 11 : 1. (The corresponding ratio for South-East England is about 2 : 1.) From this we may deduce that the quiet diurnal variation is produced in a region which exhibits a marked seasonal trend of conductivity and, therefore, ionization. As a working hypothesis we therefore assume that the quiet diurnal variation is associated with the flow of currents in the lower part of the ionosphere where we have found the required seasonal variation of ionization to take place.

b—Magnetic Activity—Some General Considerations—If the influence on the ionosphere of the agency causing magnetic storms were merely an increase of conductivity, we should expect the result to be merely an enhanced amplitude of the quiet diurnal variation. But an examination of the analysis of the Tromsö records made by Harang and Tönsberg shows that the perturbing vector (which expresses the additional effects of activity) exhibits a diurnal and a seasonal variation which are quite different from those associated with the ordinary quiet-day variations. We can conclude, generally, that during a magnetic storm not only is the local conductivity of the ionosphere increased but additional electromotive forces are developed since the ionospheric current systems during the magnetic storm are of a different disposition from those responsible for the quiet-day variations.

Such electromotive forces can only result from large-scale motion of the conducting air and it is therefore necessary to look for some cause of such motions in the effect of the storm itself. This large-scale motion may possibly arise from the local heating and thermal expansion of the atmosphere.

c—Auroral and Disturbed Magnetic Manifestations at Tromsö—Tromsö is situated near the auroral zone, and auroral and magnetic phenomena are relatively marked there compared with those experienced in temperate latitudes.

Auroral displays there are usually introduced by a quiet auroral arc with occasionally parallel components. After about 20 minutes the arc begins to have ray structure, fluctuations in the light intensity ensue, and draperies gradually develop. Such a simple arc is usually situated at right angles to the magnetic meridian but other forms lying north and south occur occasionally. The height of the lower border of the normal yellowish aurora lies between 80 and 150 km., while the upper limit of luminosity is 250–300 km. as measured by Størmer's photographic method. The quiet arc produces only a small magnetic disturbance without pulsations, the magnitude of the effect depending, of course, on the proximity of the arc. Draperies and coronae give a much more pronounced and irregular magnetic effect.

Although auroral displays and magnetic activity are correlated, there is by no means a direct correspondence between their intensities at Tromsö. Auroral displays usually begin in the late evening and die down about midnight or just after, very often, however, recurring at about 4 a.m. usually with renewed intensity. Under corresponding conditions the magnetic disturbance, as will be shown later, occurs about local midnight. All auroral forms tend to move parallel to themselves.

An examination of the Tromsö magnetic records, and particularly their analysis by HARANG and TÖNSBERG,[*] shows that the perturbing magnetic vectors associated with magnetic activity must be due to currents flowing along the auroral zone. Such currents presumably flow in the ionosphere, and the magnetic records suggest that their height above the ground is of the order 150 to 400 km. It should, however, be mentioned that while at Tromsö the perturbation is greatest in the horizontal magnetic force, the corresponding disturbance at Abisko (lat. 68° 21′ N., long. 18° 49′ E.) is mainly in the vertical magnetic force. This would indicate a current element lying north of Abisko. The Tromsö records further show that the perturbing vector in the horizontal magnetic force associated with storminess is to the north during the day (06.00 to 18.00 h. approximately) and to the south during the night (18.00 to 06.00 h. approximately). This would require that the current in the auroral zone was flowing from west to east during the day and from east to west during the night. It may be remarked that this is not in agreement with the idealized current system associated with polar magnetic storminess suggested by S. CHAPMAN,[†] in which the currents flow west to east from 00.00 to 12.00 and east to west from 12.00 to 24.00.

A very striking feature of magnetic activity is its dependence on local time, the maximum effect being observed at Tromsö at night. This phenomenon was first observed by BIRKELAND[‡] in polar regions. As a further illustration of it, we quote a comparison we have made of the magnetic records at Tromsö and Fort Rae (Lat. 62·8° N., Long. 116·1° W.) which shows that similar magnetic events are repeated at similar local times.[§]

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[*] HARANG and TÖNSBERG, "Tromsö auroral observatory: Results of magnetic observations for the year 1932 (1933)." 'Publ. fra det Norske Inst. for Kosmik Fysik.,' Nos. 4 and 5, Bergen (1934).

[†] 'Proc. Roy. Soc.,' A, vol. 115, p. 263 (1927).

[‡] BIRKELAND, "The Norwegian Aurora Polaris Expedition" (1902–03), vols. 1 and 2.

[§] This result has been further illustrated with a greater wealth of data by STAGG, 'Proc. Roy. Soc.,' A, vol. 149, p. 298 (1935).

Another aspect of the same phenomenon is to be noted in the diurnal recurrence tendency which is displayed by magnetic storms near the auroral zone. If a storm occurs one evening it is usually succeeded on the following evening by a similar disturbance starting at about the same local time. After a few nights the intensity of the storm has usually diminished and relatively quiet conditions again prevail. There is, however, a tendency for a corresponding series of disturbances to be repeated after 27 days, the solar rotation period.

Concerning the time of maximum magnetic activity, we may note that an analysis of the Tromsö records shows that it occurs there at about 00.00 h. local time. Corresponding disturbance maxima, however, take place at Eskdalemuir (Lat. 55° 19′ N.) at 22.00 h., and at Potsdam (Lat. 52° 23′ N.) at 21.00 h. local time. There thus appears to be evidence that the time of maximum magnetic activity gets later as the auroral zone is approached.

If we adopt, for purposes of illustration, the solar corpuscular theory of magnetic disturbance, we see an immediate explanation of the diurnal tendency mentioned above. The solar stream must be considered as subject to magnetic focussing and as impinging on the dark side of the earth. As the earth revolves, each part of the auroral zone comes under its influence at a period centring approximately on midnight, local time. The solar stream is supposed to be of such a structure that the earth passes through it in a few days. It is unlikely that the emission of particles from the sun endures only for a few days since the corresponding diurnal cycle of magnetic activity often recurs after a solar rotation.

The magnetic activity at Tromsö showed the usual seasonal variation during the Polar Year. This is illustrated by fig. 27 in which are plotted the average magnetic character numbers for each month of the period August, 1932–August, 1933. It will be noted that there are two maxima, in April and September. This seasonal effect in magnetic activity is well known but has not been explained.

d—Magnetic Activity and Ionospheric Conditions at Tromsö as Elucidated by Radio Measurements—As has been previously shown, the ionospheric measurements made on days of magnetic calm are satisfactorily explained in terms of ionization by ultra-violet light from the sun.

We now turn to discuss the abnormal effects which have been found to be associated with magnetic activity. Now abnormality of ionospheric conditions might be expected to show itself in the following ionospheric characteristics :—

(1) Critical frequencies of Regions E, F_1, and F_2.
(2) Reflexion coefficients of the deviating regions.
(3) Alteration of the general ionospheric structure such as would be, for example, indicated by the reflexion of waves from ionospheric levels between Regions E and F.
(4) The occurrence of echoes from the abnormal reflecting stratum about the level of Region E, which, from experiments in South-East England, has been found to occur from time to time.
(5) The temporal rate of fluctuation of echo-intensity.

We have made an examination of all the characteristics which are listed above and have found in almost every respect that magnetic activity brings about some change.

Ionospheric echoes at Tromsö are in general more complex and more variable in intensity than those observed at Slough. The variable complexity is markedly enhanced in periods just preceding the most intense magnetic perturbations. At such times also it is often found that the clear division of echoes from Region E and echoes from Region F completely breaks down, there being a continuous echo pattern indicating reflexions from levels of from 100 km. upwards. This can only mean that the ionosphere is much more variable in structure in high than in temperate latitudes and, possibly, that ionospheric winds are relatively more important there.

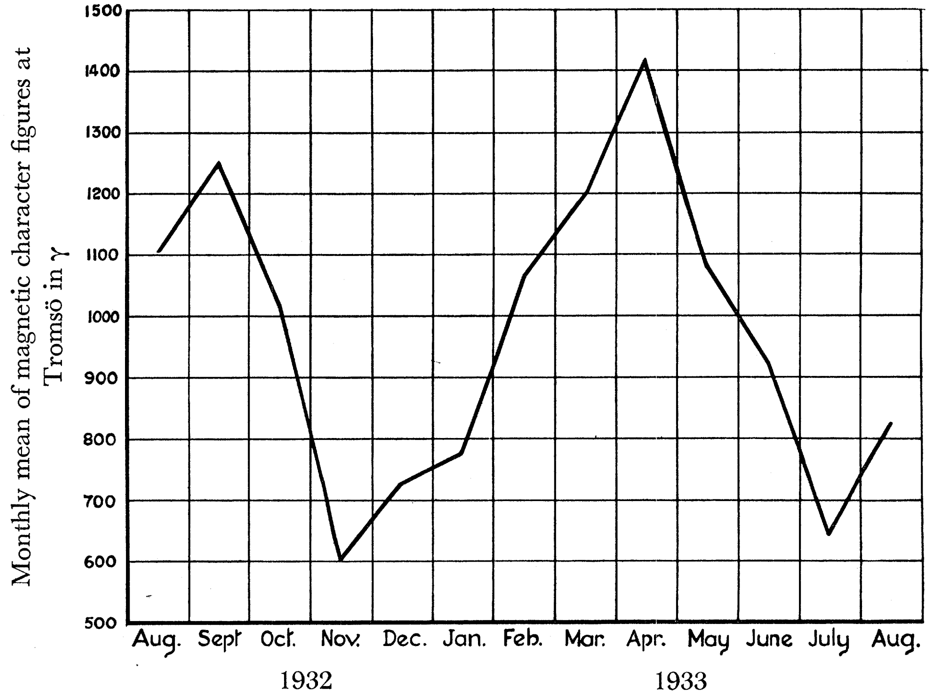

FIG. 27—Seasonal variation of magnetic activity at Tromsö.

Another very striking feature of the Tromsö conditions is the extremely low ionospheric reflexion coefficients which are associated with intense magnetic disturbances. The apparatus used at Tromsö was of comparable sensitivity with that used in South-East England, and yet there was a period of hours' duration associated with every intense magnetic storm when the echo intensity was completely imperceptible. Since much will be said concerning such a state of affairs in what follows, we shall refer to this briefly as the " no-echo " condition.

The remaining further general characteristic of high latitude ionospheric conditions is the occurrence of what are termed abnormal Region E reflexions. This subject is of such special importance that it receives separate treatment in Part III of the Experimental Results and Discussion (*see* p. 241).

The plan adopted for exhibiting the relationship between magnetic activity and abnormal ionospheric characteristics is to consider first the general variation of both over the year and then consider in detail the effects during the progress of selected individual storms. We therefore proceed to the general features.

e—The Relation Between Critical Frequency and Daily Magnetic Character Figures—In fig. 28 are exhibited graphs of 5-day means of f_E° and $f_{F_2}^{X}$ for Slough at noon together with 5-day means of the daily character figures for Abinger. Five-day means have been chosen because it is known that the ionospheric effects of a particular storm last a few days and also because this procedure minimizes the effects of possible fluctuations due to experimental and other influences. A special word of explanation concerning this graph is necessary in connexion with the high values of critical frequency for Region E (Curve III) occasionally shown during the summer period. The values represent the frequency which just permitted the penetration of Region E.

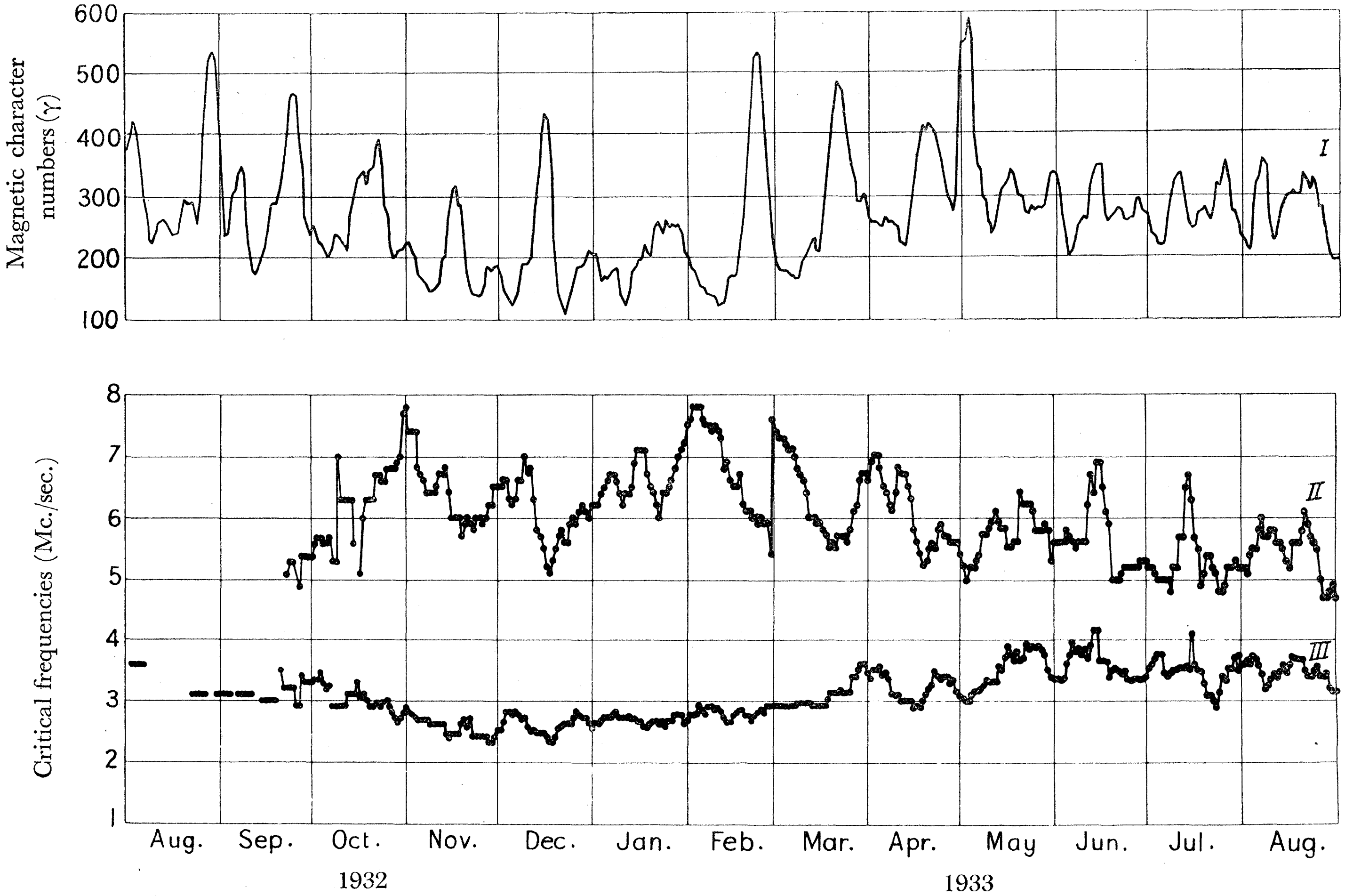

FIG. 28—(I) Five-day means of Abinger daily magnetic character figures. (II) Five-day means of Slough noon extraordinary ray critical frequency for Region F_2. (III) Five-day means of Slough noon ordinary ray critical frequency for Region E.

As will be shown later, the abnormally high values experienced in summer are due to the formation of a region different from the normal one produced each day by ultra-violet light, and which usually had an abnormally high penetration frequency. We refer to this below as abnormal Region E. Days when the penetration frequency of Region E was about 1 Mc./sec. or more greater than the normal value have been omitted. The corresponding graphs for Tromsö are not exhibited because the " no-echo " condition accompanied every big magnetic disturbance and thus it was impossible to obtain on days of intense activity a measure of the ionization present.

Now a remarkable feature of this graph is that the critical frequencies for both Regions E and F_2 exhibit an inverse correlation with the magnetic character figure. When magnetic activity was high the critical frequency was abnormally low. This effect was especially noticeable in Region F_2 during the spring months, as will be seen from the following table of correlation coefficients. A similar effect was present at Tromsö where it was so marked during the spring of 1933 that no measure of the ionization was possible. For this reason the correlation coefficients for Tromsö during the spring months are very misleading, as all days of intense magnetic activity have been removed from the examination. The correlation coefficients at Tromsö and Slough are not exactly comparable, as 5-day mean values of both critical frequency and daily magnetic character figure were employed at Slough, while at Tromsö the noon value of critical frequency was compared with the magnetic character figure for the preceding day. In order to allow for the seasonal variation of ionization, the daily departure of the critical penetration frequency from the appropriate value on a smooth curve drawn through the monthly means has been used as expressing whether a particular daily value was abnormally high or low.

TABLE I—CORRELATION COEFFICIENTS FOR MAGNETIC CHARACTER FIGURES AND REGION F_2 CRITICAL FREQUENCIES AT NOON

Period	Tromsö	Slough and Abinger
Whole of Polar Year	−0·341	−0·397
August, September, October (1932), August (1933)*	−0·496	+0·039
November, December (1932), January (1933)	+0·110	−0·280
February, March, April (1933)	−0·182	−0·713
May, June, July (1933)	−0·552	−0·244

* There were no observations made at Slough during August (1932).

In Table II are given the corresponding figures for Region E.

TABLE II—CORRELATION COEFFICIENTS FOR MAGNETIC CHARACTER FIGURES AND REGION E CRITICAL FREQUENCIES AT NOON

Period	Tromsö	Slough and Abinger
Whole of Polar Year	−0·114	−0·106
August, September, October (1932), August (1933)	−0·559	+0·161
November, December (1932), January (1933)	+0·243	−0·387
February, March, April (1933)	+0·022	−0·197
May, June, July (1933)	−0·167	−0·290

The results summarized in the tables indicate that the inverse correlation between Region F_2 critical frequency and magnetic conditions is more marked at Tromsö than in South-East England except for the winter months. As already stated, the effect was particularly marked at Tromsö as well as at Slough during the spring months of 1933 when a well-defined 27-day recurrence tendency was evident. It will also be noted that magnetic activity is more closely connected with Region F_2 ionization than with that of Region E. This may be due to the greater magnitude of the fluctuations in Region F_2. The positive correlation coefficients at Tromsö during the winter months may be due to the small amount of magnetic activity present. We have noted a tendency for small storms to increase the ionization density while large ones depress it,* although there have been several examples since the Polar Year of increased noon critical frequencies on days of intense magnetic activity. The very high negative correlation coefficient at Tromsö for Region E during the autumn months would be explained on this hypothesis, as the magnetic activity at Tromsö during the Polar Year (*see* fig. 27) has two well-defined maxima at the equinoxes while at Slough there is no corresponding summer minimum.

As already pointed out, very few determinations of the critical frequency for Region F_1 are available for days during the Polar Year. This is due to the rather wide frequency spacing adopted during that period in our measurements which often resulted in our being unable to observe the position of the maximum of equivalent height, which indicates the Region F_1 critical frequency. Now one of the most striking results obtained from the observations on the other two Regions, E and F_2, as set forth above, has been the establishment of a connexion between their ionization contents and the amount of magnetic activity obtaining at the time of observation. An examination of the fluctuations in Region F_1 critical frequency at noon at Slough for the year 1934 has therefore been made. The variations about the values on a smooth curve drawn through the monthly means are very small in comparison with those of the more densely ionized upper region, but when the critical frequency of Region F_2 is lowered by the onset of magnetic activity that of Region F_1 is usually affected to a smaller extent. In the table below correlation coefficients for both Regions F_1 and F_2 critical frequencies at noon are given, the daily values having been compared with the magnetic figure for the preceding day and the seasonal variations of ionization having been removed by the method explained above.

TABLE III—CORRELATION COEFFICIENTS FOR MAGNETIC CHARACTER FIGURES AT ABINGER AND REGIONS F_1 AND F_2 CRITICAL FREQUENCIES AT SLOUGH AT NOON

Period	Region F_1	Region F_2
Year 1934	$-0 \cdot 042$	$-0 \cdot 016$
January, November, December (1934)	$-0 \cdot 015$	$+0 \cdot 207$
February, March, April (1934)	$+0 \cdot 020$	$-0 \cdot 135$
May, June, July (1934)	$-0 \cdot 020$	$-0 \cdot 143$
August, September, October (1934)	$-0 \cdot 288$	$-0 \cdot 127$

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* APPLETON and INGRAM, ‘ Nature,’ vol. 136, pp. 548, 549 (1935).

From Table III it will be seen that the ionization density of Region F_1 is as closely connected with magnetic activity as that of Region F_2. The inverse effect is not so marked for 1934 as for the Polar Year, but this may be due to the smaller amount of activity present especially during the winter when the connexion for Region F_2 is a direct one. (*See* winter value at Tromsö for Polar Year.) The correspondence between the ionization densities of Regions F_1 and F_2 is much greater than the connexion of either with magnetic activity, being represented by a correlation factor of $+0 \cdot 3$. From the above it would appear that magnetic storms during 1934 have not a very great effect upon ionization density, but a detailed examination of the data exhibited in fig. 29 shows that practically all abnormally high or low values of critical frequency are due to magnetic disturbances. The correlation coefficients are merely a measure of the slight preponderating influence of the negative correlation. Fig. 29 suggests the existence of an inverse correlation during the summer months. There were very few big magnetic disturbances, but it is evident that the trends of the magnetic figures and the ionization densities are opposed to one another. Thus from 20–30 June $f_{F_1}{}^\circ$ and $f_{F_2}{}^\circ$ decrease while the magnetic activity increases, and from 6–13 July and 3–10 August $f_{F_1}{}^\circ$ and $f_{F_2}{}^\circ$ increase while the magnetic activity decreases.

As the time of maximum magnetic activity in the latitude of South-East England is in the late evening, we have examined for the year 1934 the midnight values of the critical penetration frequency of Region F_2 at Slough for a correspondence with the magnetic character figure at Abinger for the preceding 24 hours, removing the seasonal variation of ionization as before. The results of this examination show that when there is a small amount of magnetic activity the ionization is above normal, but that when the activity is more severe the critical frequency is much depressed, indicating a reduced value of the maximum electron content. The correlation coefficient, taking all days into account, is $-0 \cdot 247$. The days were then divided into three groups corresponding respectively to magnetic activity less than $180\,\gamma$, between $180\,\gamma$ and $330\,\gamma$, and greater than $330\,\gamma$, and correlation factors found for each group separately.

TABLE IV—CORRELATION COEFFICIENTS FOR MAGNETIC CHARACTER FIGURES AT ABINGER AND REGION F_2 CRITICAL FREQUENCIES AT MIDNIGHT AT SLOUGH

Days of small activity	Days of average activity	Days of intense activity
$+0 \cdot 130$	$+0 \cdot 017$	$-0 \cdot 198$

This result indicates that, up to the value of $180\,\gamma$, there is a tendency for the agency responsible for producing magnetic storms to increase the critical frequency, while, above the value of $330\,\gamma$, the greater the storm the more is the critical frequency depressed. When the magnetic activity lies between $180\,\gamma$ and $330\,\gamma$ the two effects practically balance one another. It should be noted that most of the days when the magnetic activity was less than $180\,\gamma$ occurred in winter, so that the positive correlation with noon ionization for the three winter months agrees very well with the

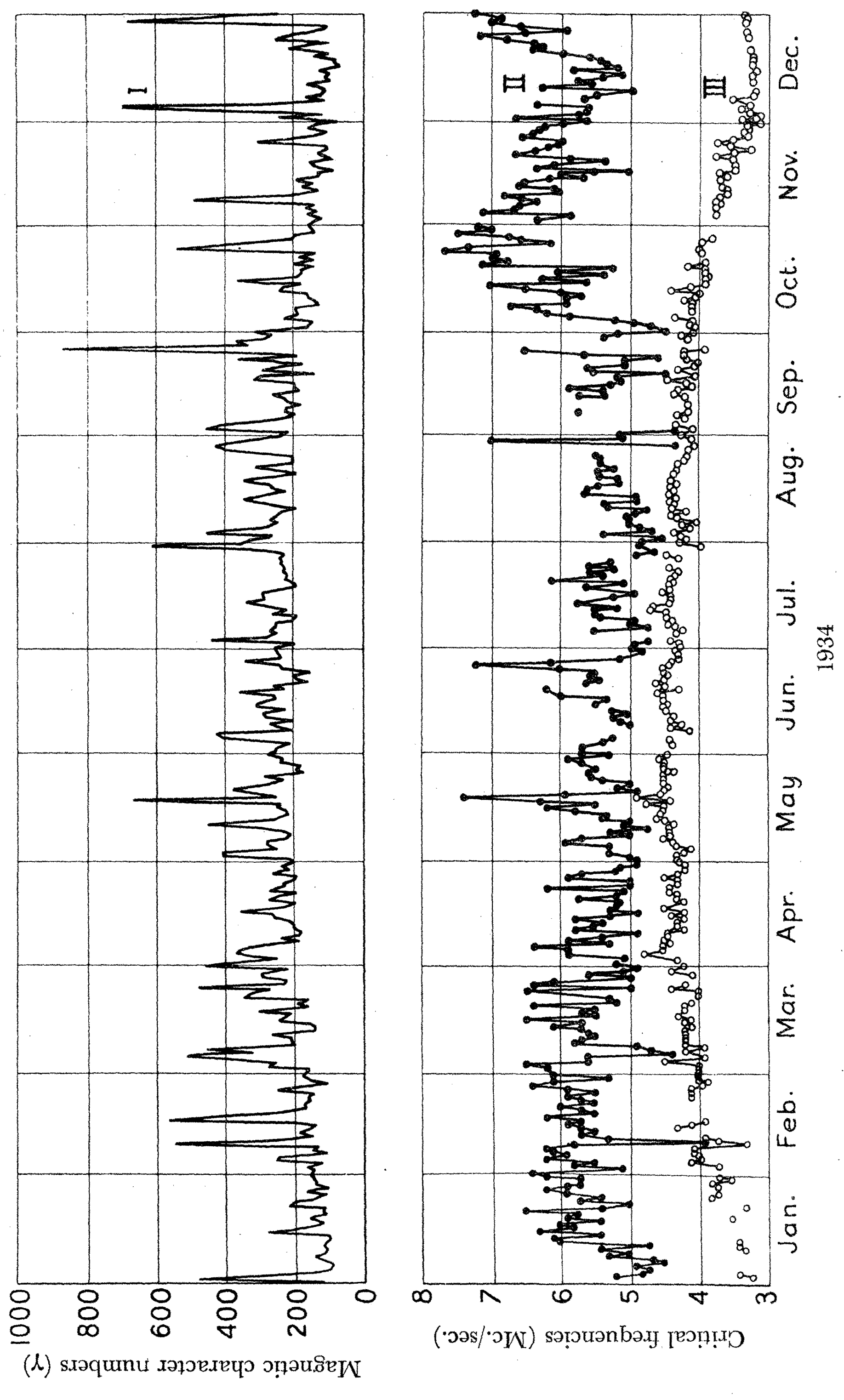

FIG. 29—Curve showing the relation between the noon ordinary ray critical frequencies at Slough for Regions F_1 and F_2 and magnetic activity at Abinger for the year 1934.

result obtained for midnight. Now an increase of ionization density would receive a ready explanation in terms of current theories of the production of magnetic storms by the injection into the upper atmosphere of ionizing particles from the sun, but a decrease of ionization density seems more difficult to explain.

Before attempting to give any explanation of the depression of critical frequency with intense magnetic activity, we must decide whether the abnormally early cessation of Region F_2 echoes with increase of frequency is to be ascribed to electron-limitation or absorption-limitation. We believe in this case that both processes are operative but that the former is the more important. Our reasons for this are as follows. The critical frequencies for both Regions E and F_1 also show evidence of the same effect and there is no reason for associating their abnormally low values with absorption-limitation. Moreover, it is found that after an intense magnetic disturbance the normal morning incidence of Region F_2 echoes, when continuous observations are made on a single frequency, is delayed and the time of their disappearance in the late afternoon hastened.

We suggest, however, that the abnormally low maxima of ionization accompanying big magnetic storms are to be ascribed to the inflation of the atmosphere due to increased temperature. The effect of a magnetic storm is thus to produce, by way of the heating of the atmosphere, effects comparable with summer day-time anomalies in South-East England. Thus, although the integrated amount of ionization may be increased, it is distributed throughout a larger volume and hence the maximum electron density is reduced. As an alternative explanation, we may suppose that the ionizing agent, aetherial or corpuscular, is abnormally low after the first impact of the magnetic storm.

f—The " No-Echo " Condition and Magnetic Activity—One of the really surprising results of the Tromsö observations is the " no-echo " condition associated with magnetic activity. As has been mentioned, we have relied on the (P′, *t*) records on the international frequencies of 2 and 4 Mc./sec. to provide the practically continuous record of ionospheric conditions. It has therefore been possible to estimate each day the number of hours on which echoes would be expected on these frequencies, assuming the ionospheric conditions to be those suggested by the quiet-day observations.

In figs. 30 and 31 are plotted the percentages of hours of observation in which the " no-echo " condition persisted, on frequencies of 2 and 4 Mc./sec. respectively, the hours when they would be expected under normal conditions only having been considered. It will be seen that there is a marked direct correlation between the existence of the " no-echo " condition and the daily magnetic character figure.

As will be illustrated in the later discussion of individual storms, the incidence of the " no-echo " condition is usually as follows. At the onset of an evening storm the echoes become diffuse and scattered in type and with a weak disturbance there is usually the appearance of abnormal E echoes. With a strong disturbance the " no-echo " condition usually coincides with a pronounced increase of the

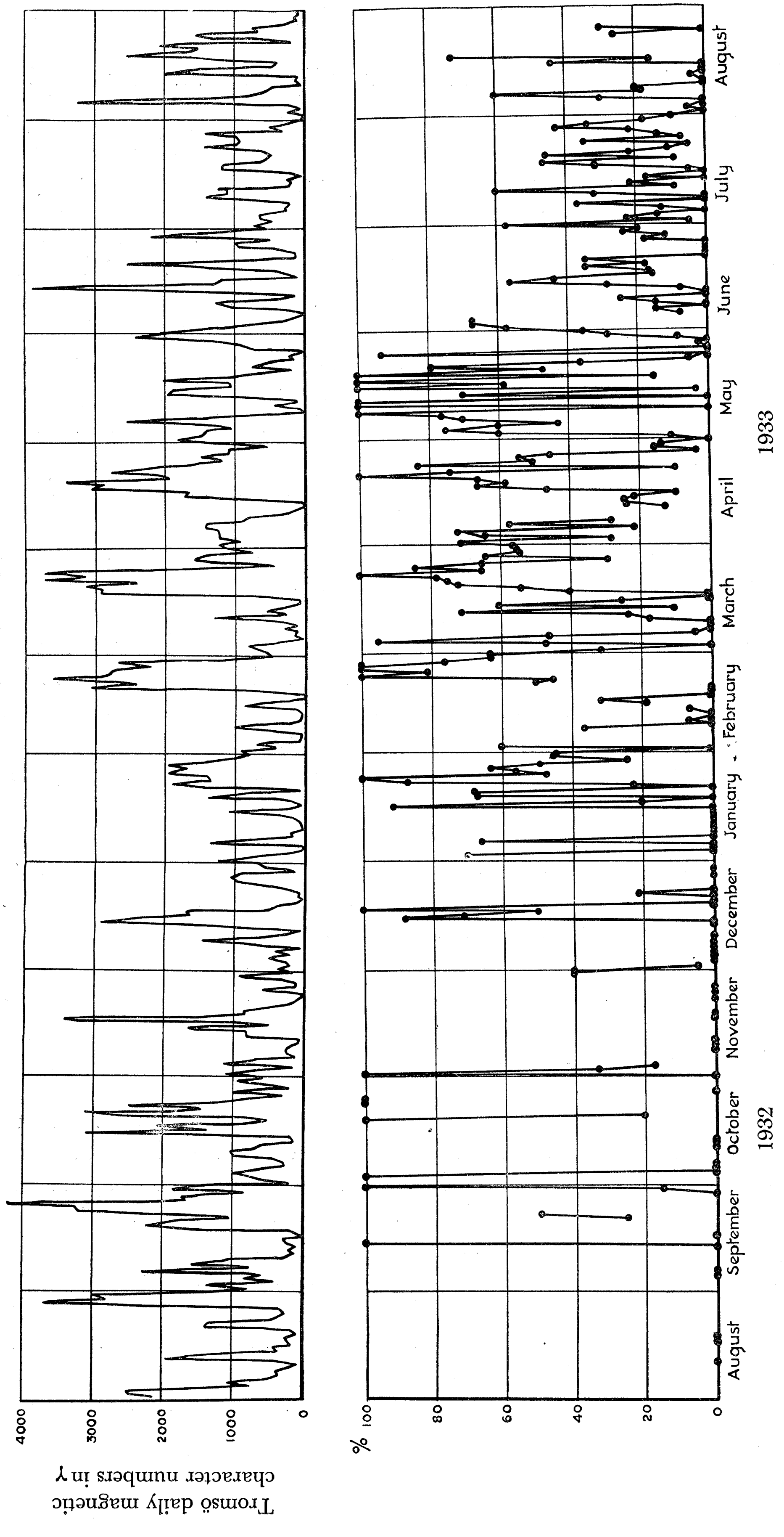

FIG. 30—Graph showing the number of hours of the "no-echo" condition at Tromsö (expressed as a percentage of the hours when echoes are normally expected), together with the magnetic character figure. (Frequency 2 Mc./sec.)

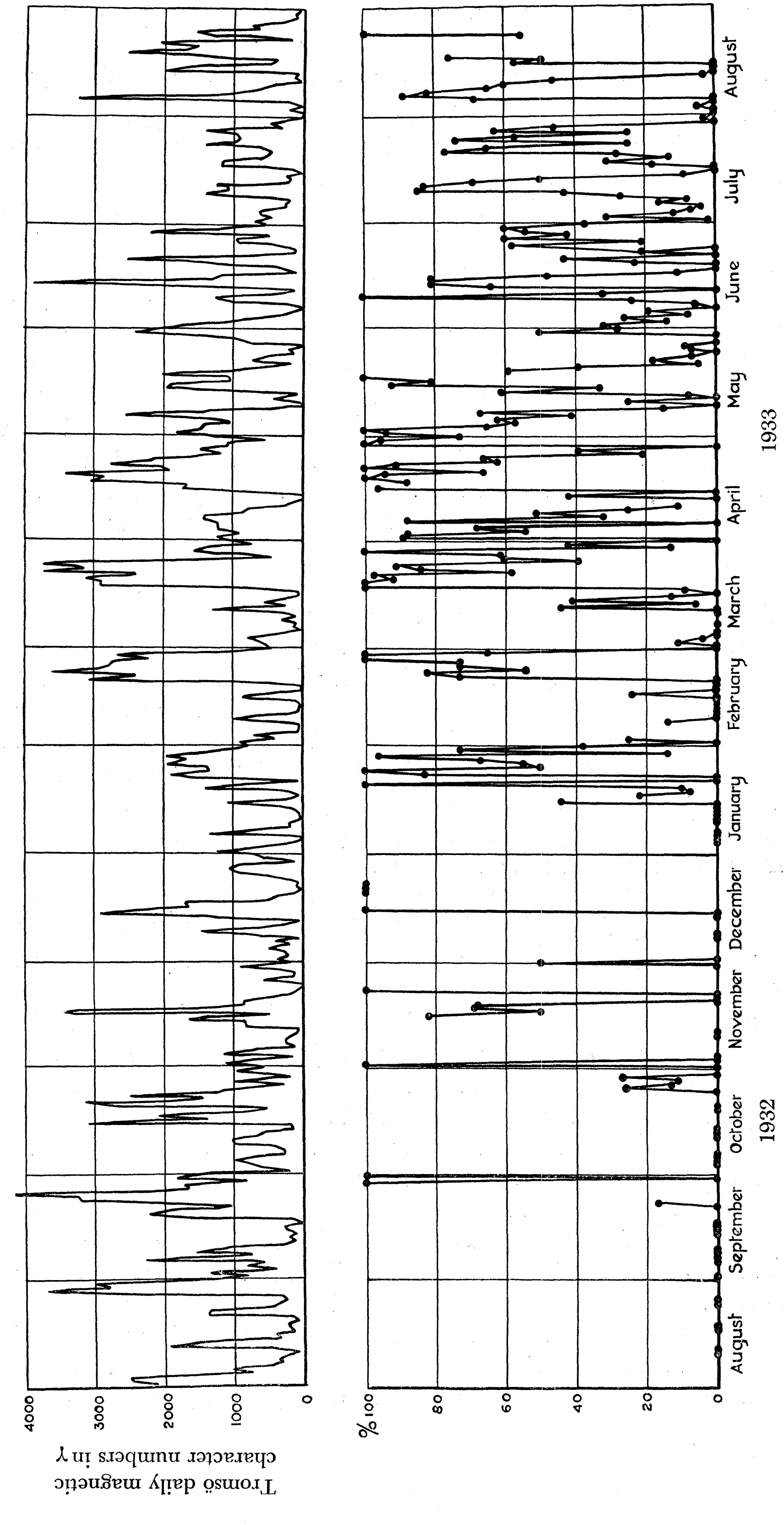

FIG. 31.—Graph showing the number of hours of the "no-echo" condition at Tromsö (expressed as a percentage of the hours when echoes are normally expected), together with the magnetic character figure. (Frequency 4 Mc./sec.)

perturbing magnetic horizontal force. For the rest of the night echoes come back sporadically as the magnetic activity subsides. There is almost invariably, however, a " no-echo " condition on the day following the night storm, even though the perturbing magnetic vector has resumed its normal value.

The " no-echo " conditions during the nocturnal periods when the perturbing magnetic vector is large, and especially during the daylight period on the following day, are of especial interest and are perhaps the most striking result of all those here described. We are again faced with the choice between electron-limitation and absorption-limitation as a cause of the phenomenon. During the night, and particularly during an auroral display, it is difficult to justify a choice of electron-limitation, for the enhanced perturbing magnetic vector clearly indicates large currents and therefore large conductivity. It is therefore most probable that the effect is then one of absorption-limitation, the ionizing agency causing the storm being such as to produce ionization at levels below that at which the normal ionization due to ultra-violet light exists. Such an absorbing fringe to Region E would cause extremely low reflexion coefficients.

The " no-echo " condition in the day-time, however, may not necessarily be due entirely to the same cause, for it occurs at a time when the currents in the upper atmosphere have abated considerably. We may well imagine that the influence of the hypothetical solar stream has subsided, in which case we must consider the " no-echo " condition as an after-effect. Now the only change that would remain effective for a time sufficiently long to be measured in hours would be a change of temperature. Any ionization under Region E would tend to disappear by recombination as soon as its cause was removed. We therefore consider it possible that the day-time " no-echo " condition is partly due to the increased collisional friction consequent on the increased temperature.

g—Detailed Sequence of Events in a Magnetic Storm—To illustrate the effects of a magnetic storm in greater detail, the results on two typical days are illustrated in fig. 32 (Plate 4). First the effect on a magnetically quiet day (24/25 November, 1932) is illustrated, the magnetic trace for the horizontal component being shown as well as the radio observations. During the period 14.30 to 16.25 M.E.T., as illustrated by the echo-pictures, radio conditions were undisturbed. On the other hand, for the corresponding period on the following day, when a small storm occurred, entirely different results were obtained. Here the magnetic trace, which is continuous for the two days, shows a disturbance beginning at 16.15 M.E.T. From the echo-records it is seen that although radio conditions were normal at 14.20 M.E.T., there began at 15.00 M.E.T. a progressive alteration in the nature of the echoes. Region F echoes gradually increased in equivalent height and became more scattered in nature. Eventually Region F echoes practically disappeared. About 16.00 M.E.T. Region E echoes of a distorted character came in strongly and were succeeded by the " no-echo " condition just after 16.30 M.E.T. The operator's log book shows that this condition was maintained for at least an hour afterwards.

It would appear as if the sequence of events in this particular storm was somewhat as follows. The first effect was to reduce the maximum ionization in Region F (probably the result of thermal expansion due to an increase of atmospheric temperature) so that eventually the frequency used became the critical value. It will be noted that this effect took place before the marked change of H associated with the disturbance. The appearance of abnormal Region E echoes and its succession by the " no-echo " condition occurred, however, with the onset of the magnetic disturbance.

(A further example of the detailed succession of events in an individual storm is given below in § 9, p. 251.)

The above example of a moderate storm has been chosen because in such a case it is easier to appreciate the sequence of events. For a large storm, suddenly commencing, the " no-echo " condition sets in very rapidly and the sequence of events similar to that described above occurs in a few seconds, so that although it has been noted visually by an observer it is too rapid to record by our photographic system.

9—EXPERIMENTAL RESULTS AND DISCUSSION—PART III

a—Introduction—We now turn to consider the subject of abnormal reflexions from levels in the upper atmosphere below that of Region F, since many examples of this phenomenon were encountered during the year's observations both at Tromsö and in South-East England. It has been noted by a number of observers that echo-reflexions may occur from a level in the atmosphere, approximating to that of Region E, for wireless frequencies which are higher than the critical value appropriate for the penetration of the normal Region E due to ultra-violet light. A typical example of this effect is the occasional occurrence of echo-reflexion from an equivalent height of about 100 km. during the night when the frequency used is several times as great as the normal critical frequency for the hour in question. We shall term this phenomenon " abnormal Region E reflexion ". It was first reported by APPLETON* in 1930, who concluded that on such occasions " either the recombination of ions is prevented or there is some ionizing agent present which can influence the dark side of the earth ". Similar occurrence of abnormal Region E reflexions at night was noted by SCHAFER and GOODALL† in 1932. In the same year APPLETON and NAISMITH‡, using the critical frequency method, found that in South-East England an abnormally high value of electric-wave penetration frequency for Region E was often associated with magnetic activity. In 1932, RANZI,§ from a series of (P′, *t*) observations on 330 nights, concluded that abnormal night Region E ionization was associated with the presence of barometric depressions either at the point of observation or at a place north of it.

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* ' Proc. Roy. Soc.,' A, vol. 126, p. 567 (1930).

† ' Proc. Inst. Radio Engrs.,' vol. 20, p. 1131 (1932).

‡ ' Proc. Roy. Soc.,' A, vol. 137, p. 36 (1932).

§ ' Nature,' vol. 130, p. 368 (1932).

Abnormal reflexion from the lower levels of the ionosphere is, however, encountered in the day-time as well as during the night. APPLETON and NAISMITH,* for example, found in a series of noon Region E critical frequency measurements that abnormally high values were occasionally noted, especially in summer. This result was considered of special interest in connexion with the suggestion of WILSON,† put forward in 1924, that thunderstorms may contribute ionization to the upper-atmospheric conducting layer, in the form of either intense ionization currents or lightning flashes. To see if there was any connexion between abnormal Region E reflexions and thunderstorm activity, the weekly values of noon penetration frequency were compared by Mr. F. E. LUTKIN with a " thunderstorm index figure " derived as follows. During the period 1 January to 31 July, 1932, observations on the distribution of European sources of atmospherics were made at Slough on a frequency of 10 kc./sec. for half an hour near 13.00 G.M.T. each week-day. On the days on which noon penetration frequencies for Region E were available the peak amplitudes of all atmospherics recorded in this operation as coming from sources within 3000 km. were summed to form the " thunderstorm index figure ". The relation between the penetration frequency and the " thunderstorm index figure " was found to be represented by a correlation coefficient as high as $+0\cdot75$. It has, however, since been found that the occurrence of abnormal Region E reflexion is usually accompanied with improved short-wave communication, so that the question arises whether the value of the " thunderstorm index figure " as defined above would be influenced at all by transmission conditions and whether the high correlation observed is merely the expression of the fact that the intensity of atmospherics is increased, by way of improved transmission, when abnormal Region E reflexion is present. Our knowledge of long-wave transmissions under these abnormal conditions is so slight, however, that we are unable to give a definite answer on this point.

A further contribution to this subject was made by RATCLIFFE and WHITE in 1934‡ who, from a rigorous statistical examination of (P′, *t*) data, confirmed earlier work concerning the connexion between abnormal Region E reflexion and magnetic activity. A similar examination led them to conclude that there was also a definite connexion between such reflexion and British thunderstorms. In connexion with this conclusion and the result of RANZI's mentioned above, it may not be superfluous to recall the well-known connexion between thunderstorms and atmospheric depressions.

b—*The Nature of Abnormal Region E Reflexion*—With the greater number of observations made during, and since, the Polar Year, and particularly because of the greater availability of (P′, *f*) data, we have had the opportunity of considering the abnormal

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* ' Proc. Phys. Soc., Lond.,' vol. 45, p. 248 (1933).

† " Discussion on ionization in the atmosphere " (28 November, 1924) ; *see* ' Proc. Phys. Soc.,' vol. 37, p. 32D (1925).

‡ ' Proc. Phys. Soc.,' vol. 46, p. 107 (1934).

Region E phenomenon afresh. But, although a certain amount of progress has been made in the understanding of its nature, we feel that a completely satisfactory explanation of its occurrence on all occasions is still lacking.

Firstly, it should be noted that evidence of abnormal Region E reflexion may be observed on both (P′, *t*) and (P′, *f*) records. We have already mentioned that it was observed during the night-time by various workers on continuous (P′, *t*) records taken prior to the beginning of the Polar Year. During the Polar Year the (P′, *t*) recording was carried out on the two international frequencies of 2 and 4 Mc./sec. The recording done on a frequency of 2 Mc./sec. gives us evidence relating to nocturnal abnormalities only, since on practically all occasions during the hours of day-light the normal Region E critical frequency exceeds 2 Mc./sec. On the other hand, the occurrence of all echoes at a level of 100–150 km. on the records made on a frequency of 4 Mc./sec. is abnormal, since at neither Tromsö nor Slough does the critical frequency of normal Region E ever attain the value of 4 Mc./sec. Thus it would appear that, provided we choose a frequency just greater than the normal critical penetration value for Region E at all times, we can study, from (P′, *t*) data alone, the variation of the frequency of occurrence of this phenomenon with time of day and with season of year, and examine its connexion with other geophysical data. We must not, however, overlook the limitation of this estimate of abnormal conditions at the lower levels of the ionosphere. During the day-time when the critical frequency for normal Region E is about 3 Mc./sec., only a small change in the amount of ionization or its distribution would be sufficient to return signals on a frequency of 4 Mc./sec., while during the night, when a frequency of approximately 1 Mc./sec. penetrates normal Region E, a sixteenfold increase of ionization would be correspondingly required before similar effects were experienced.

The other, and more satisfactory, method of obtaining evidence concerning abnormal Region E reflexion is from (P′, *f*) data, where its occurrence is shown as a persistence of reflexion from slightly over the 100 km. level as the frequency is increased beyond the normal critical value. This method of observation possesses an advantage over the one just mentioned in that it gives us the frequency range over which abnormal reflexion is experienced, so that some idea of the variation of the extent of the anomaly with time may be gained. The day-time abnormal Region E reflexion, which occurs mostly in summer and is also noted more frequently at Slough than at Tromsö, is first observable on the (P′, *f*) records around sunrise and is usually found to occur at an equivalent height substantially greater than that of Region E. As the day proceeds it is observed over an increasing range of frequency and its equivalent height decreases. This can only mean that the agency producing it becomes more effective as the sun approaches the zenith. Usually the maximum range of frequency over which abnormal Region E reflexion is observed occurs about noon and very often about this time its equivalent height becomes just less than that of the ultra-violet light, Region E. This masking of Region E, however, never lasts very long. While it is correct to say that during the summer months at Slough the appearance of day-time abnormal Region E reflexion each morning is regular, the day-to-day fluctuations are very great, being of a different order of magnitude from the variations of critical frequency observed for the Region E due to ultra-violet light. In the afternoon abnormal Region E reflexion, both as regards frequency range and equivalent height, is much less definite in its behaviour than in the morning, although as a rule the frequency range decreases as the afternoon progresses.

A typical example of this day-time aspect of the phenomenon has been described recently by two of the writers, and is further illustrated by the (P', f) record shown in fig. 33 (Plate 3). Here it will be seen that the equivalent height/frequency curve for the ordinary ray shows the normal trend until the critical frequency for normal Region E is reached. For higher frequencies, however, reflexion persists and the group retardation effect observable for frequencies immediately higher than $f_E{}^\circ$ suggests that such persisting reflexion occurs at a level which is about equal to that of the maximum ionization in Region E. It is important to note that such a phenomenon can be explained if it is assumed that normal Region E is of small thickness measured in vacuum wave-lengths. From the theoretical work of HARTREE on the reflexion of electromagnetic waves from a stratified medium it is possible to show* that appreciable persistence of reflexion after the critical frequency is exceeded does not occur with a thick layer but does occur if the layer is thin. It is therefore possible to account for the persistence of Region E reflexion beyond the critical frequency without assuming that the maximum electronic density is abnormally high. According to such a view, the abnormal reflexions may be regarded as due to the scattering of radiation from the most electrically dense part of Region E so that the equivalent height of reflexion for frequencies substantially in excess of the critical value may be taken as indicating the actual height of the maximum ionization in Region E. The difficulty about accepting an explanation on these lines is, however, that on days on which abnormal Region E reflections are absent the (P', f) data show that Region E is many vacuum wave-lengths thick, and there seems no reason why the thickness should vary markedly from day to day.

The record shown in fig. 33 also illustrates the phenomenon of magneto-ionic splitting, though the extraordinary component of reflexion from normal Region E is absent due to absorption. Both ordinary and extraordinary abnormal Region E reflexions are to be noted, with the usual frequency separation of 0·66 Mc./sec., which may be taken as indicating that the abnormal Region E reflexion is due to electrons, while the marked group retardation effects experienced at frequencies slightly in excess of the normal Region E critical frequencies indicates that the charged particles in the normal Region E responsible for returning wireless waves must be of electronic mass and cannot be heavy ions, as contended by KIRBY and JUDSON.†

It should, however, be added that we have frequently encountered conditions on a summer day under which the above-mentioned group-retardation effects associated

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* HARTREE, 'Proc. Camb. Phil. Soc.,' vol. 25, p. 97 (1929) (*see*, in particular, fig. 33).

† 'Bur. Stand. J. Res., Wash.,' vol. 14, p. 469 (1935).

with the normal Region E critical frequency are entirely absent, the (P′, f) relation indicating constancy of equivalent height over a large range of frequencies. Such conditions are almost always associated with high echo intensities and the occurrence of multiple reflexions. On such occasions it would appear that reflexion from a relatively sharp boundary was taking place.

Fig. 33 also exhibits the phenomenon of partial reflexion, so typical of abnormal Region E reflexion, indicated by the overlap in the frequency scale of echoes returned from abnormal Region E and Region F. Another feature of interest in connexion with abnormal Region E reflexion is also illustrated by this figure, in which there is a faint M-echo showing over the range of frequencies which are simultaneously returned from abnormal Region E and Region F. This echo has been reflected in succession from Region F, Region E, and Region F again, proving that abnormal Region E is partially reflecting for downward as well as upward radiation.

The properties of nocturnal abnormal Region E reflexion are, so far as we know, identical with those of the day-time phenomenon used as an illustration. The occurrence of multiple reflexions from abnormal Region E, of M and (E + F) echoes (the latter being due to successive reflexions from abnormal Region E, the ground and Region F, or alternatively, from Region F, the ground and abnormal Region E), and of overlap of abnormal Region E and Region F echoes, is usually more pronounced for nocturnal than for day-time conditions. This is to be expected, as the absorption of the energy in the lower fringe of the ionosphere must be greater by day than by night, and we need not necessarily invoke the existence of different conditions in the actual reflecting stratum by day and night.

So far as we have been able to test the matter, nocturnal Region E ionization causing abnormal reflexion has a structure similar to that experienced during the day.

c—The Incidence of Abnormal Region E Reflexion—Abnormal Region E reflexions can occur both by day and by night, as mentioned above, and it is obvious that the first question to be answered is whether there is a connexion between their nocturnal and day-time occurrence. We have therefore examined the Slough measurements made during the Polar Year and found that there is a low but definite correlation between the two. We find a correlation factor of $+0 \cdot 341$ between the number of hours of nocturnal Region E reflexion (4 Mc./sec.) and the highest frequency on which abnormal Region E echoes were observed at noon on the previous day ; and a correlation factor of $+0 \cdot 315$ when the noon observations of the following day were used. Since we know that abnormal Region E reflexion is rarely present during the day in winter, we must attribute this low positive correlation to the day and night correspondence in summer.

d—Comparison of Abnormal Region E Reflexion at Slough and Tromsö—Abnormal Region E reflexions at Slough exhibit a reflexion coefficient, as measured by the number of observable multiple reflexions, greater than that found at Tromsö. This is true for both nocturnal and day-time conditions. This may, of course, be one further illustration of the generally low echo intensities observed in high latitudes, but we believe that in the day-time, at any rate, it also means that abnormal Region E effects are much greater over Slough than over Tromsö. In Tromsö during daylight abnormal Region E reflexion rarely prevents an examination of Region F phenomena, but at Slough in summer there are many days when Region F is totally obscured.

e—Seasonal Variation of Abnormal Region E Reflexion at Tromsö—As previously explained, the results of (P′, *t*) recording on a frequency of 4 Mc./sec. show how the incidence of abnormal Region E reflexion varies seasonally and diurnally. The seasonal variation at Tromsö is shown in fig. 34, where we have plotted for each day the percentage of the time of observation during which echoes were obtained from levels appreciably under Region F. It should be observed that such echoes were more frequent during the summer and winter months than at the equinoctial seasons. We have supplemented this information, to ensure that the result is not a function of the frequency used, by plotting in fig. 35 for each day the percentage of the time of observation during which echoes were obtained at similar heights on a frequency of 2 Mc./sec., excluding all times when the normal Region E returned signals on this frequency. There is no difficulty in deciding when reflexion ceases in the evening and starts in the morning from the normal Region E, as on a continuous (P′, *t*) record we can see the group retardation caused by this Region when its ionization increases just beyond the value required to return signals on the frequency in question. Fig. 35 shows the maxima in summer and winter even more markedly than fig. 34. We must bear in mind, however, that the information derived from the (P′, *t*) recording on a frequency of 2 Mc./sec. suffers from the limitation that during the winter months the whole day is under consideration while during the period of the midnight sun only five or six hours of the day is taken into account.

f—Seasonal Variation of Abnormal Region E Reflexion at Slough—In order to determine the seasonal variation of frequency of occurrence of abnormal Region E reflexion at Slough, we have made use of the information derived from the (P′, *f*) records obtained at 30-minute intervals over a frequency band of 2·5–5·0 Mc./sec. during the year 1934, because the (P′, *t*) recording done during the Polar Year was partly on a frequency of 2 Mc./sec. and partly on a frequency of 4 Mc./sec. In fig. 36 are shown what may be termed the daily " abnormal E character figures " for the year 1934. These figures somewhat arbitrarily represent the duration and intensity of abnormal Region E reflexion throughout the 24 hours of each day. Again, the equinoctial months are particularly free from abnormal Region E reflexions, but the winter maximum at Slough is very much smaller than the summer one. There is a sudden and very marked increase in the frequency of appearance of abnormal Region E reflexion in May, due almost entirely to the regular occurrence of day-time reflexion of this type. This effect disappears almost entirely again about August.

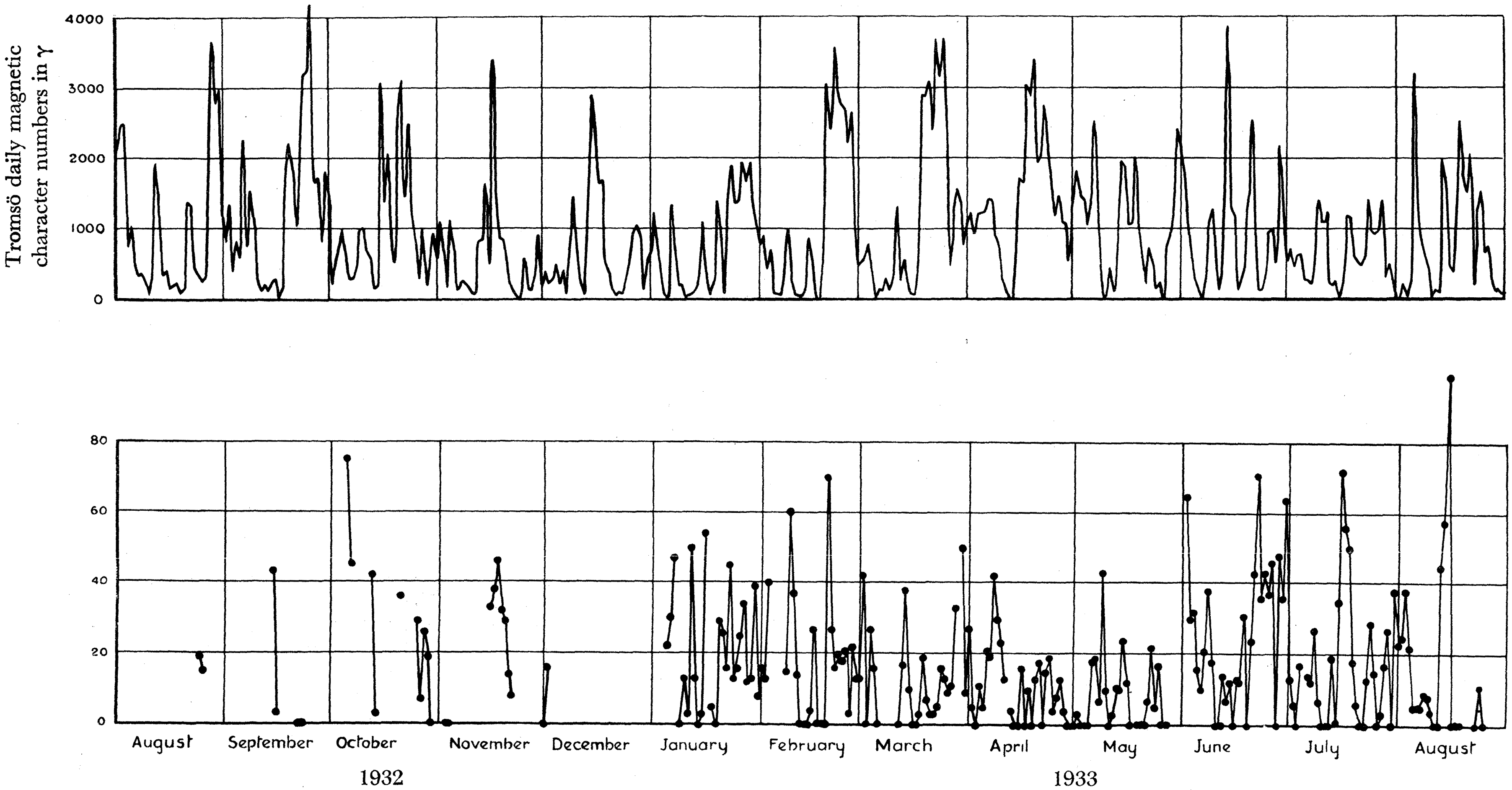


FIG. 34—Graph showing the number of hours in which abnormal Region E echoes were observed at Tromsö (expressed as a percentage), together with the magnetic character figure. (Frequency 4 Mc./sec.)

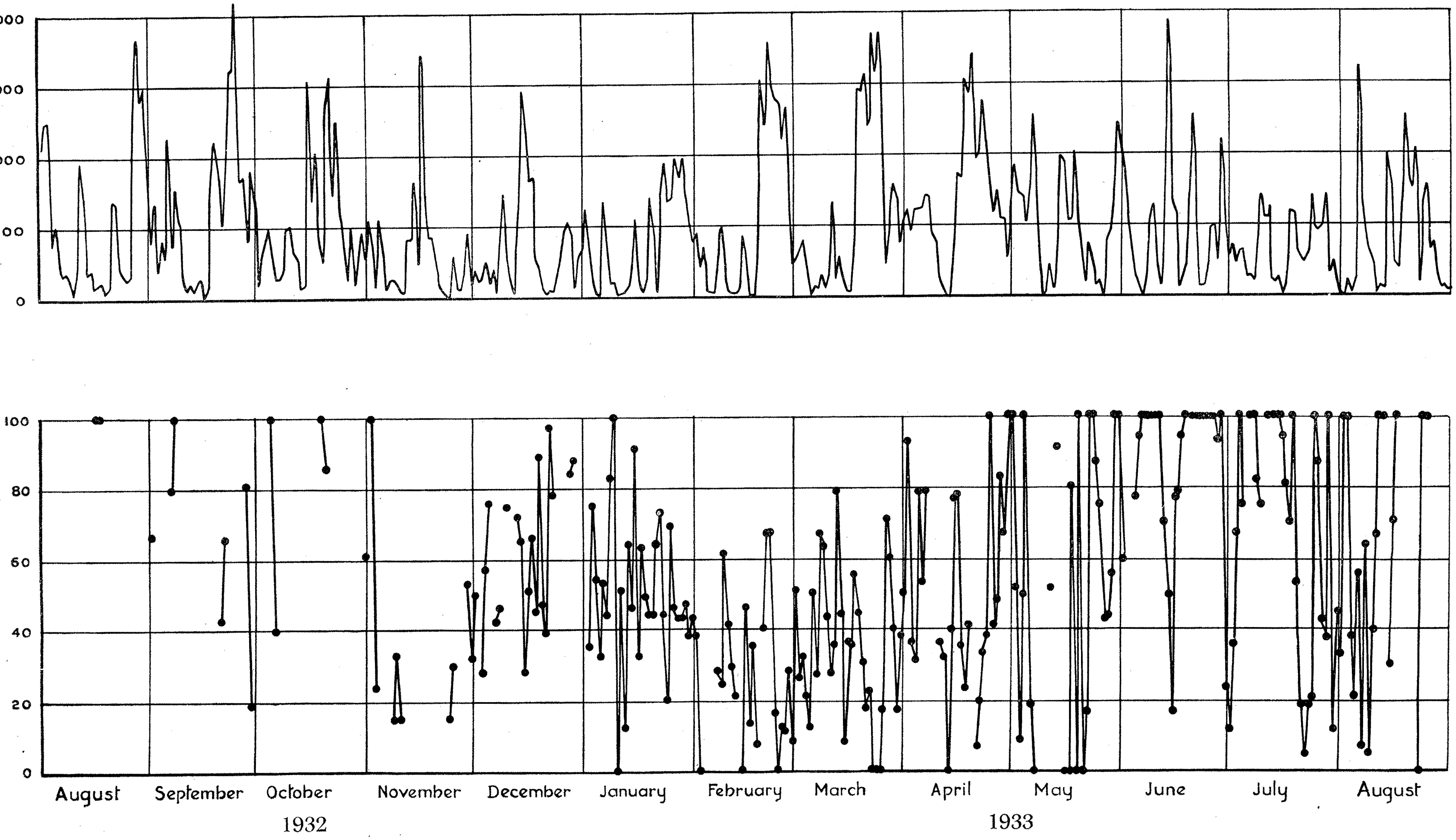
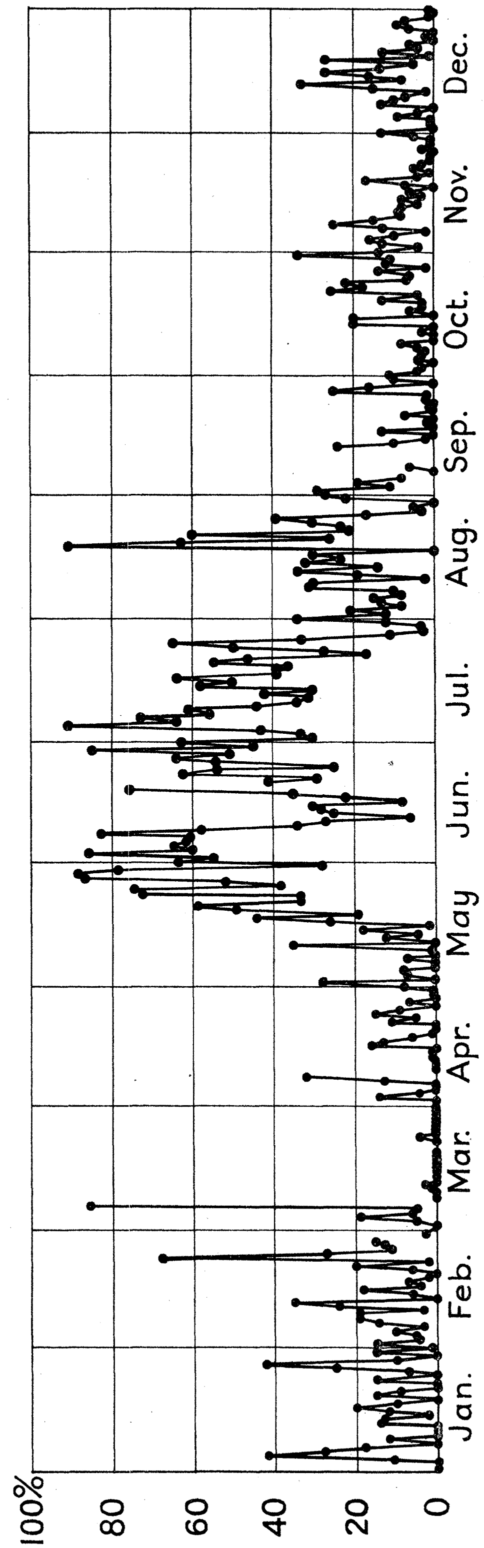


FIG. 35—Graph showing the number of hours in which abnormal Region E echoes were observed at Tromsö (expressed as a percentage). (Frequency 2 Mc./sec.)

g—Diurnal Variation of Abnormal Region E Reflexion at Tromsö—At Tromsö, at all seasons of the year, abnormal Region E reflexion is much more frequently present about local midnight than at any other hour of the day. It is true that there are cases of its day-time occurrence especially in summer, but as a rule the frequency range of abnormal Region E reflexion grows up during the dark hours, reaches its maximum about midnight, and falls gradually as the night advances further. We have summed the number of occasions when abnormal Region E reflexion was observed at each hour on frequencies of both 2 and 4 Mc./sec. during the Polar Year, and there is just one marked maximum on the curves centred at midnight and it is a very flat one. It is interesting also to note that the day-time occurrence of abnormal Region E reflexion in summer, which, as we shall see later, is the predominant effect at Slough, can just be detected on these curves for Tromsö.



1934

Fig. 36—Daily abnormal Region E character figures for Slough.

h—Diurnal Variation of Abnormal Region E Reflexion at Slough—At Slough it is found that the diurnal curve showing the frequency of occurrence of abnormal Region E reflexion has two maxima when the full year's observations are considered. For this lower latitude it is necessary to make a sharp distinction between summer and winter conditions. During the winter the phenomenon occurs chiefly at night while during the summer it occurs largely during the day. There is always a correlation with ground sunrise and sunset, as illustrated by curves showing for each month the hourly values, but this correlation is very slight except during the summer months when it becomes by far the most important factor. Besides this, there is at all seasons a late evening maximum which coincides approximately with the Abinger magnetic maximum. This late evening maximum, which we consider to be analogous to the midnight maximum at Tromsö, is much less definite and more variable, but this may possibly be due to the smaller number of occasions when the magnetic activity in the lower latitude is sufficient to produce this abnormal reflecting condition at the 100 km. level. As has been mentioned previously, the frequency range of abnormal Region E reflexion in summer increases, though not very regularly, to a maximum about noon.

i—Correlation of Abnormal Region Reflexion E with Magnetic Activity at Tromsö—The most frequent occurrence of abnormal Region E reflexion at midnight at Tromsö is interesting, because of the midnight maximum of magnetic activity which is also experienced there. It appears, in fact, that we can say definitely that nocturnal abnormal Region E reflexion is associated in some way with weak magnetic activity. Further evidence for such a conclusion can actually be noted during the course of many magnetic storms which ultimately become intense, for the " no-echo " condition is often preceded for a short time by abnormal Region E reflexions. Also it may be noted that during magnetic activity the " no-echo " condition is often interrupted (for example, during the day-time) by the sudden occurrence of abnormal Region E reflexions, even though the frequency used is such as would normally be penetrating to Region F at that time of the day. In this connexion it is quite possible that the reappearance of abnormal reflexions may be associated with temporary

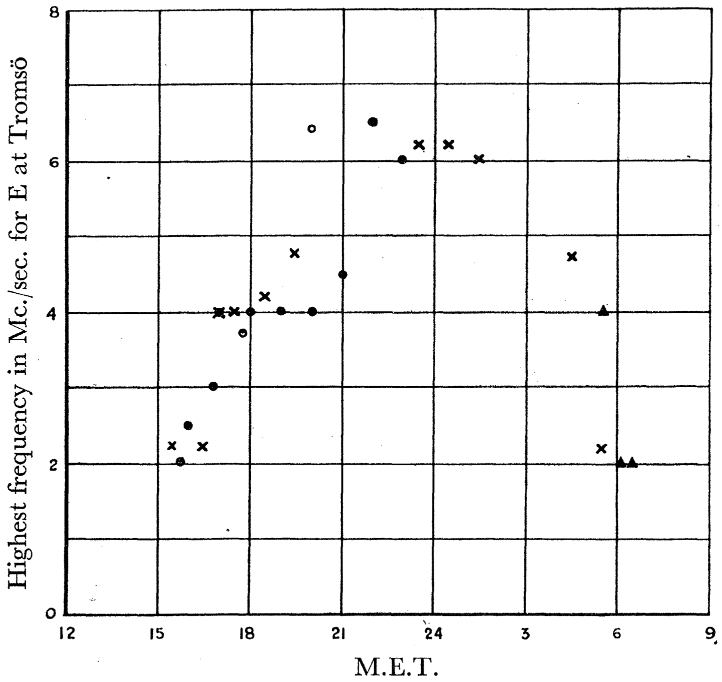
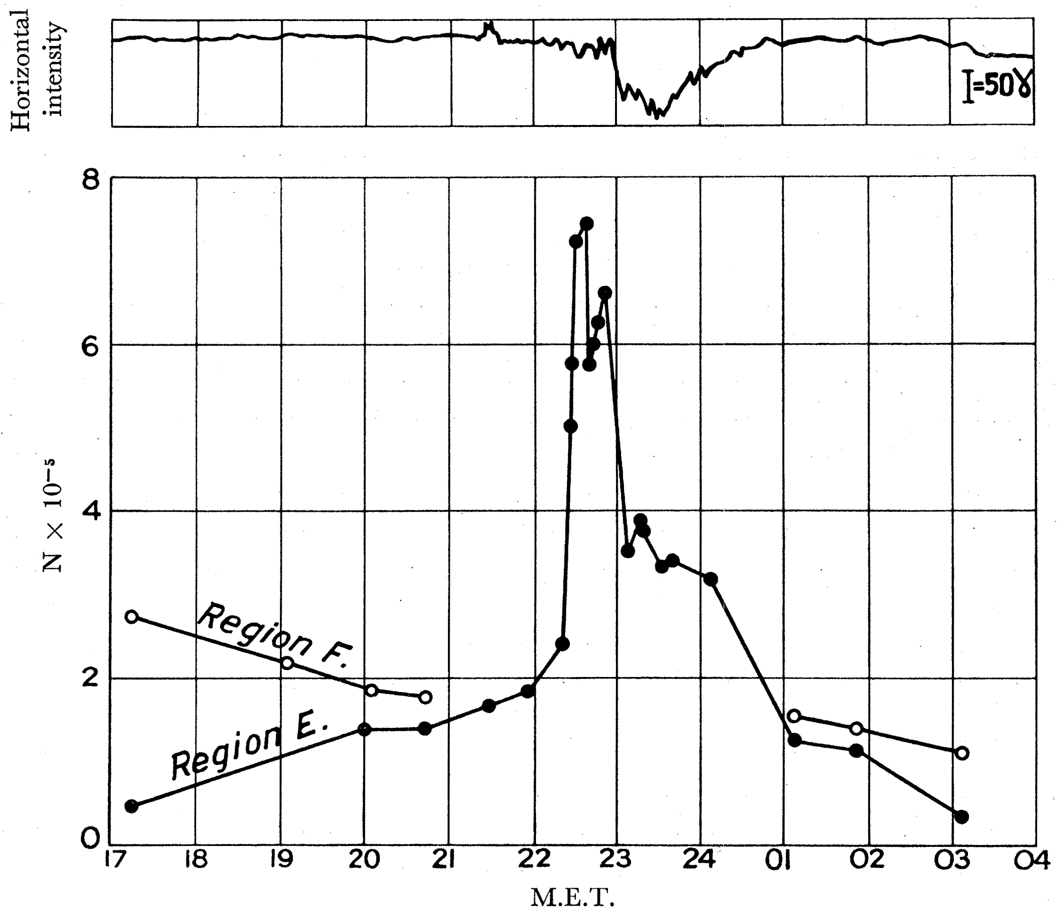


FIG. 37—Graph showing the variation of abnormal Region E at Tromsö during the night-time. ● 29/30 March, 1933 ; × 5/6 April, 1933 ; ○ 19/20 April, 1933 ; ▲ values obtained from (P′, *t*) recording.

abatement of the magnetic activity, for the evidence as a whole appears to suggest the general rule that slight magnetic activity is associated with abnormal reflexions, while intense magnetic activity brings about the " no-echo " condition. The fact that the frequency to which abnormal Region E reflexion persists has its highest value, as distinct from its most frequent occurrence, at midnight, is illustrated in fig. 37 where are plotted the highest frequencies on which nocturnal abnormal Region E reflexions were noted as a function of time. The observations do not all refer to the same day because of difficulties experienced by the interruption of observations by intense magnetic storms, when the condition of " no-echo " usually sets in. They have, however, been adjusted for differences in the time of sunset so that they are properly comparable.



Tromsö, 22/23 March, 1935

FIG. 38—Graph showing the variation of abnormal Region E at Tromsö during a small magnetic disturbance.

We are indebted to Director L. HARANG, of Nordlysobservatoriet, for permission to include here a graph illustrating this point even more satisfactorily and showing its connexion with magnetic activity (fig. 38). It refers to observations made by him, using similar radio methods on 22/23 March, 1935, when a small magnetic storm occurred. There was experienced a marked abnormal Region E reflexion, the most intense effect being observed when there was a faint auroral corona in the zenith.

j—Correlation of Abnormal Region E Reflexion with Magnetic Activity at Slough—Although it is highly probable that the late evening maximum occurrence of abnormal Region E reflexion at Slough is connected in some way with the time of magnetic maximum, we have been unable to show, after observing every night for three years, that the nights of abnormal echoes always correspond to nights of magnetic storms. It is true that on all occasions of large magnetic disturbance abnormal Region E reflexion is present at some time during the night, although as a rule it does not appear until the magnetic activity is abating somewhat about midnight. But abnormal Region E reflexions also occur without the accompaniment of intense magnetic activity. We have tried to get some idea of the connexion between abnormal Region E reflexion and magnetic activity in the latitude of South-East England by finding a correlation coefficient between the daily Abinger magnetic number and a figure formed by summing the amount of abnormal reflexion at each half-hour of the day. We have done this for the three summer months and for the three winter months of 1934 (the equinoxes being particularly free from abnormal Region E reflexion), obtaining values of $-0 \cdot 278$ and $-0 \cdot 274$ respectively. We are altogether at a loss to explain this result, although it may be that weak magnetic activity produces reflecting conditions at the 100 km. level just as at Tromsö, while intense magnetic activity does not do so even if there is now no question of the " no-echo " condition being present.

k—Correlation of Abnormal Region E Reflexion with Thunderstorms at Tromsö and Slough—We have examined the Polar Year observations for a possible connexion between abnormal Region E reflexion and thunderstorms, using data supplied to us by Sir George Simpson (British thunderstorms) and by Dr. J. Bjerknes (Norwegian thunderstorms).

The results are as follows :—

(*a*) Thunderstorms in the British Isles are connected with the highest frequency on which Region E echoes were recorded at noon at Slough by a correlation factor of $+0 \cdot 095$.

(*b*) Thunderstorms in Norway are connected with the highest frequency on which Region E echoes were recorded at noon at Tromsö by a correlation factor of $+0 \cdot 122$.

This result is a little surprising in view of the high correlation already mentioned which was obtained for the first seven months of 1932. We must, however, point out that the thunderstorm index in the two cases in question was obtained in totally different ways. It would have been very interesting to compare the two indices, but unfortunately no daily measurements on atmospherics were made at Slough during the Polar Year. We do not feel justified in concluding that there is very little connexion between thunderstorm activity and abnormal Region E reflexion as the thunderstorm figures used during the Polar Year referred to 13.00–18.00 G.M.T., while the Region E measurements were made at noon. It appears, however, that the connexion is not a simple one, because on several recent occasions at Slough no abnormal Region E reflexion has been obtained while a thunderstorm was passing overhead. We feel bound to interpret the high correlation for the early part of 1932 as being possibly due to the fact that the quantities under comparison have a very marked seasonal correspondence rather than agreement in their day-to-day fluctuations. The latter point could not be tested properly as the observations were made at weekly intervals. The Polar Year results certainly indicate that day-time abnormal Region E reflexion occurs most frequently in the summer months when local thunderstorms are at a maximum, but a marked connexion between the two phenomena on particular days is lacking. It seems as if no decisive answer can be given concerning their inter-dependence until a comparison has been made between atmospherics recorded and abnormal Region E reflexion over the 24 hours of the day. We hope that the data required for this comparison will be available in the near future.

l—The Cause of Abnormal Region E Reflexion—From what has been stated above, it is clear that abnormal Region E reflexions could be caused in a number of ways. It has been explained that the persistence of reflexion for frequencies in excess of the normal Region E critical value can be explained by postulating that Region E is a very thin stratum. But there appear also to be examples of Region E reflexion which can only be attributed to the existence of a layer of abnormally high ionization content and not due to some special form of stratification. This being so, we have to consider possible causes which must be of a variable nature since the phenomenon itself exhibits such marked variability.

The work of the Polar Year has amply confirmed the connexion, announced in 1932, between magnetic activity and abnormal Region E reflexion, and, according to prevailing theories, such reflexion would be due to ionization caused by the incidence of charged solar particles on the upper atmosphere. The maximum of auroral activity at a level of 100 km. is in agreement with such an interpretation. The connexion between such abnormal Region E reflexion and magnetic activity is, however, not a simple one. When the particles arriving are not too numerous or too penetrating, the ionization formed may produce reflexion at a height of about 100 km., but during intense magnetic activity it appears that ionization is produced at still lower levels resulting in the formation of an absorbing fringe. This interpretation explains the Tromsö results satisfactorily and fits in fairly well with the Slough observations, although in the latter case the absorbing fringe is not generally impenetrable. One notable exception occurred on 16 November, 1932, and the two following evenings when a magnetic disturbance was in progress and the

" no-echo " condition prevailed. The recurrence of the phenomenon was at approximately the same local time each evening. The duration of the effect diminished steadily and had practically vanished on the fourth night. This is an interesting example when taken in conjunction with the known tendency for a large magnetic disturbance to recur, somewhat diminished, 24 hours later and with the marked tendency for echoes from the abnormal Region E also to recur after 24 hours.

It is often found at night that abnormal Region E reflexion comes in suddenly, the first reflexion and the multiple reflexions occurring simultaneously. This effect would be satisfactorily explained in terms of the charged particle theory. On the other hand, there have been noted cases where the reflexion coefficient increases fairly slowly, for at first only one reflexion is noted and double and treble reflexions are not of appreciable intensity till later. Using a frequency of 6 Mc./sec., we have also observed a peculiar type of reflexion, at a height of about 100 km., which lasts only a few seconds and which is not registered with the usual type of recording. It is difficult to see how such a phenomenon can be caused, when occurring at night, except by some agency of the nature of ionizing particles.

A possible type of such an agency has been suggested by SKELLET,* who has recently published observations showing that major increases of abnormal Region E ionization occur at night when meteors are observed to pass nearly overhead. This result suggests that Region E reflexions may not necessarily be due to a definite layer but may be caused by scattering from ionic cloudlets of greater density than that of their surroundings.

The evidence as a whole, therefore, suggests that nocturnal abnormal Region E reflexion is caused by the entry of ionizing particles into the ionosphere, either in the form of bursts or in the form of a steady stream, though the relative influences of extra-terrestrial sources (charged solar particles and meteorites) and terrestrial sources (thunderstorms) are not yet clear.

In addition, we must note the possibility of reflexion due to the adjustment of ionization already existing, such adjustment being responsible for the production of an abnormally thin stratum or of an ionization gradient abnormally high.

We now turn to consider the case of the abnormal Region E reflexion which occurs so frequently during the day-time in summer and of which, in South-East England, we have made a special study. In this case the evidence summarized above leaves little doubt that the phenomenon is at least partly connected with some influence of solar origin which travels rectilinearly. We need only mention the marked correlation with sunrise and the maximum noon intensity of reflexion in this connexion. Agencies to be considered in this connexion are neutral solar particles and ultra-violet light. Neutral solar particles would doubtless collect a charge in passing through the earth's atmosphere and thus would acquire the power of ionizing, so that the production of a thin stratum of ionization at a level where the molecular density becomes sufficiently appreciable might be explained.

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* 'Proc. Inst. Radio Engrs.,' vol. 23, p. 132 (1935).

Irregularities in the wave-front of ultra-violet radiation would simulate in the day the localized ionic centres due to meteors at night. Although we must leave the matter unsettled, we can, however, point out that the difficulty of deciding the nature of the responsible agency might possibly be resolved by finding out whether it travelled with the speed of light or not by making observations on the occasion of an eclipse of the sun, using the type of critical test devised by APPLETON and CHAPMAN.*

The influence of thunderstorms in causing abnormal Region E reflexion has been considered, as mentioned above, inconclusively by us but conclusively by RATCLIFFE and WHITE, who found a correlation.

10—EXPERIMENTAL RESULTS AND DISCUSSION—PART IV

Ionospheric Conditions and the Sunspot Cycle—It has been suspected for a considerable time that the ionization density of the upper atmosphere suffers a variation during the sunspot cycle. CHAPMAN,† for example, has estimated that the total conductivity of all the ionized regions is 1·5 times as great at sunspot maximum as at sunspot minimum, while APPLETON‡ has shown that the experimental results of AUSTIN on transatlantic long-wave transmission obtained during the years 1915–26 may be interpreted as indicating that the specific conductivity of the lower region of the ionosphere at sunspot maximum is 1·6 times as great as at sunspot minimum.

With the development of the critical frequency method of measuring the ionization of the different regions, it is possible to examine in greater detail any variation of ionization density from year to year, but such measurements are not yet available for a period as long as the sunspot cycle. It has, however, been reported by APPLETON and NAISMITH§ that for a series of measurements of ionization densities in Region E the general level of ionization was lower in 1932 than in 1931, which change they associated with the general fall in solar activity in the sequence of the solar cycle. They were further inclined to interpret the results as indicating " quite a substantial variation in the sun's ultra-violet light during the solar period ", but pointed out the need for further measurement of the same type.

Vertical incidence measurements of the ionization density of Region F were not reliable until 1931 when the phenomenon of magneto-ionic splitting was discovered. ECKERSLEY|| has, however, shown that for long-distance short-wave observations (in which the distinction between ordinary and extraordinary wave transmission is unimportant) there appeared to be greater nocturnal ionization in Region F in

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* ' Nature,' vol. 129, p. 757 (1932).

† " 2nd Rept. Cttee. on Solar and Terrestrial Relationships, Int. Res. Coun.," p. 37, Paris, 1929.

‡ As above, p. 17.

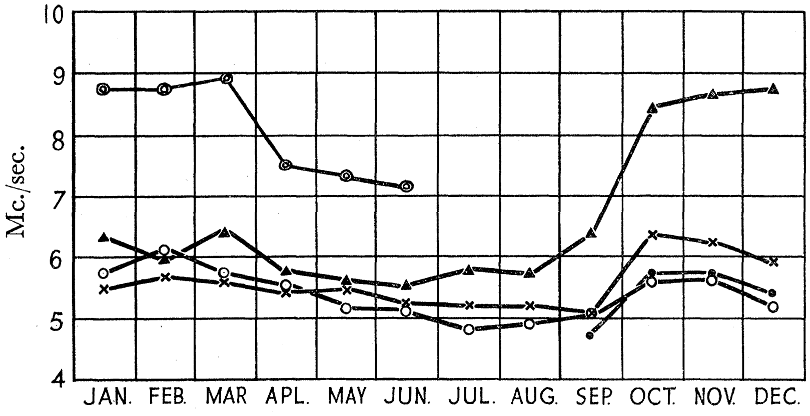
§ ' Proc. Phys. Soc. Lond.,' vol. 45, p. 248 (1933).

|| ' J. Instn. Elect. Engrs.,' vol. 71, p. 405 (1932).

21/22 October, 1928, than in 10/11 May, 1931. He pointed out that this difference was probably due to the influence of the sunspot cycle, 1928 being the last sunspot maximum.

The Second International Polar Year was a year of very low solar activity, for the minimum of the present solar cycle is estimated to have occurred during the second half of 1933. Since the first comprehensive series of ionospheric measurements were made at Slough in connexion with the Polar Year work, and since such measurements have been continued subsequently, it has been considered of interest to indicate briefly here the way in which the ionospheric conditions have varied from 1932–33 to date.

The most pronounced effect has been found for Region F_2 for which the ionization density follows the sunspot cycle directly. This is well shown in fig. 39, where the monthly means of the Region F_2 ordinary wave critical frequency at noon are plotted from September, 1932, to date. It will be seen that, in general, the lowest values were obtained during the latter half of 1933 and that since then, when allowance is made for the usual seasonal change, the ionization density has been increasing.



Monthly mean noon values of $f_{F_2}{}^\circ$ at Slough

FIG. 39—Monthly means of Region F_2 ordinary wave critical frequency at noon from September, 1932, to date. ● 1932 ; ○ 1933 ; × 1934 ; ▲ 1935 ; ◎ 1936.

One of the outstanding characteristics of Region F_2 is the marked day-to-day variations in the ionization densities. It is therefore of interest to see if the range of values experienced varies from year to year. In fig. 40 are shown the minimum and maximum values of $f_{F_2}{}^\circ$ at noon for each year, and it is seen that the range appeared to pass through a minimum about the time of sunspot minimum. In the same curve are shown the average values for the two seasonal maxima (in January–February and in October–November). These are also seen to follow the same general trend.

In deciding whether there is any marked correlation between solar ultra-violet light emission and solar activity we are naturally led to examine the data relating to Regions E and F_1, since for these regions the determination of the critical frequencies is less subject to errors due to absorption than is the case for Region F_2. Our measurements of Region F_1 critical frequency beginning in 1933 round about sunspot minimum do show a variation indicating that, when allowance is made for the seasonal trend, the ionization maximum has increased from 1933 to 1936, but the effect is not so marked as in the case of Region F_2. A similar effect, though slightly more pronounced than for Region F_1, has been noted for Region E where it has also been found that the ionization density varies directly with the sunspot cycle. The effect is found to be more marked at the equinoxes than in summer and winter, a phenomenon which we do not understand.

Since it is now known that the major part of the ionization in the normal ionosphere is caused by ultra-violet light, we believe that the results outlined immediately above confirm the inference made by Appleton and Naismith from the early Region E measurements that there is a variation of the solar ultra-violet light during the sunspot cycle. Since the effect is most marked for the highest ionospheric region, we must conclude that the variation is greatest for the most easily absorbed radiation which is presumably of very short wave-length.

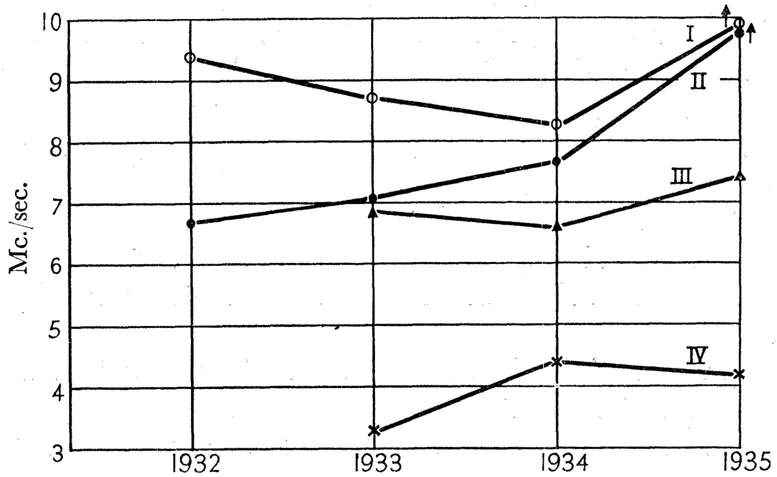


Fig. 40—(I) Maximum values of ordinary wave critical frequency for Region F_2 at noon for each year. (II) Average values of ordinary wave critical frequency for Region F_2 at noon for the October–November maximum. (III) Average values of ordinary wave critical frequency for Region F_2 at noon for the January–February maximum. (IV) Minimum values of ordinary wave critical frequency for Region F_2 at noon for each year. ● October/November peaks. ▲ January/February peaks ; × minimum value recorded for whole year ; ○ maximum value recorded for whole year.

11—Summary

1—The communication describes the results of radio observations made by British workers during the Second International Polar Year, 1 August, 1932, to 31 August, 1933. Such observations were made chiefly at Tromsö in North Norway and at Slough in South-East England. The international programme of observations organized by the Union Radio Scientifique Internationale was followed, together with a special British programme. The measurements consisted mainly of continuous determinations of the equivalent height of reflexion for waves of frequencies of 2 and 4 Mc./sec. together with systematic determinations of maximum ionic density of the various ionospheric regions by the critical frequency method.

2—The ionospheric structure at Tromsö was found to be very similar to that in South-East England, yet certain differences are to be noted. On days of magnetic calm the ordinary Regions E and F were clearly differentiated but reflexions from equivalent heights between those of Regions E and F were, however, very frequent. Another marked feature was the relative complexity of all types of echoes compared with the simpler types observed at Slough.

3—For days of magnetic calm at Tromsö there was substantial agreement between the observed seasonal variations of noon ionization for Regions E and F_1 and the theoretical curves based on the assumption of ionization by ultra-violet light from the sun. Similar results were obtained at Slough. For the case of Region F_2, there was found no simple seasonal variation either at Tromsö or Slough. A striking feature of the day-to-day results for this region was their extreme variability. The lack of a seasonal trend may be due to the expansion of the upper atmosphere due to heating in summer and/or an annual variation of the intensity or quality of solar radiation.

4—In the comparison of the diurnal variation of ionospheric density at the two places, the most striking feature of the results obtained is that at Tromsö at the time of the midnight sun in summer the maximum ionization of Region F_2 is greater at midnight than at noon. It is suggested that this maximum is due to the cooling of the upper atmosphere at midnight causing a concentration of electrons.

5—Abnormal radio effects were found to be associated with periods of magnetic activity especially at Tromsö. At such times it was found there that the clear division of echoes from Regions E and F completely broke down, there being a continuous echo pattern indicating reflexion from levels of 100 km. and upwards. Another striking feature of the Tromsö condition was the extremely low ionospheric reflexion coefficients which were associated with intense magnetic disturbance, there being periods when the echo intensity was completely imperceptible.

6—The determination of correlation factors between daily values of ionization density and magnetic character figures both at Tromsö and Slough show in general an inverse relation which is specially marked for Region F_2. It is suggested that this reduced maximum of ionization accompanying intense magnetic activity may be due to the inflation of the atmosphere due to increased temperature produced by the agency which causes the magnetic storm.

7—The " no-echo " condition was found to accompany severe magnetic storms and auroral displays at Tromsö. It is considered that in such cases the ionizing agency causing the storm produces ionization below the normal level and so introduces an absorbing fringe below Region E. A detailed account of a storm of moderate severity, in which it was possible to follow the sequence of ionospheric events, is given.

8—A special study has been made of abnormal Region E reflexions at both Slough and Tromsö. It is found that when these are in evidence the stratum in question does not show true critical frequency but exhibits the phenomenon of partial reflexion. Various possible causes of abnormal Region E reflexion are suggested, but no general conclusions relating to its origin are reached.

9—A study has been made of the variation of ionospheric density during the present sunspot cycle, continuing the observations since 1932–33. The most pronounced effect has been found for Region F_2, for which the ionization density is found to follow the sunspot cycle directly. Similar, though smaller, effects are found for Regions F_1 and E. Since it is now known that the major portion of the ionization in the normal ionosphere is caused by ultra-violet light, it is considered that these results show that there is a variation of the solar ultra-violet light during the sunspot cycle and that the effect is most marked for the most easily absorbed radiation which is presumably of the shortest wave-length.

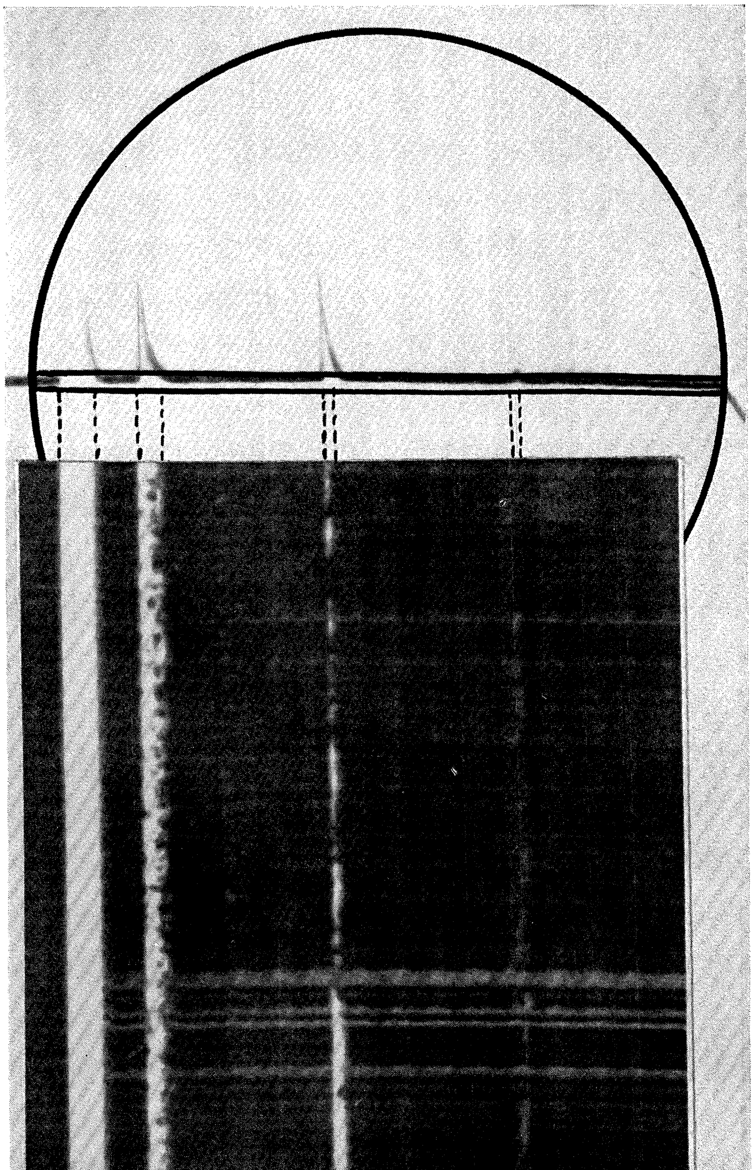


Fig. 6—Diagram illustrating method used for the continuous registration of equivalent heights, together with sample (P′, *t*) record.

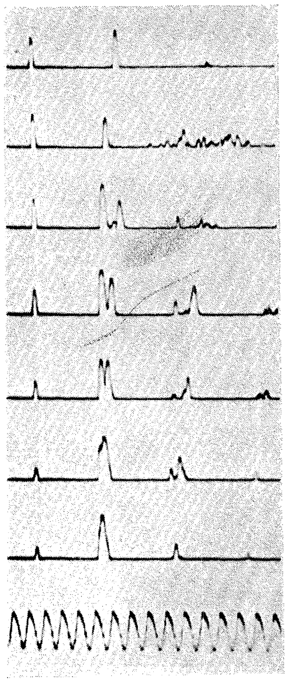


Fig. 5—Series of echo records made during five minutes on frequencies of 7·00, 6·75, 6·50, 6·25, 6·00, 5·75 and 5·50 Mc./sec. (The calibration marking was produced by means of a 2·5 kc./sec. oscillator.)

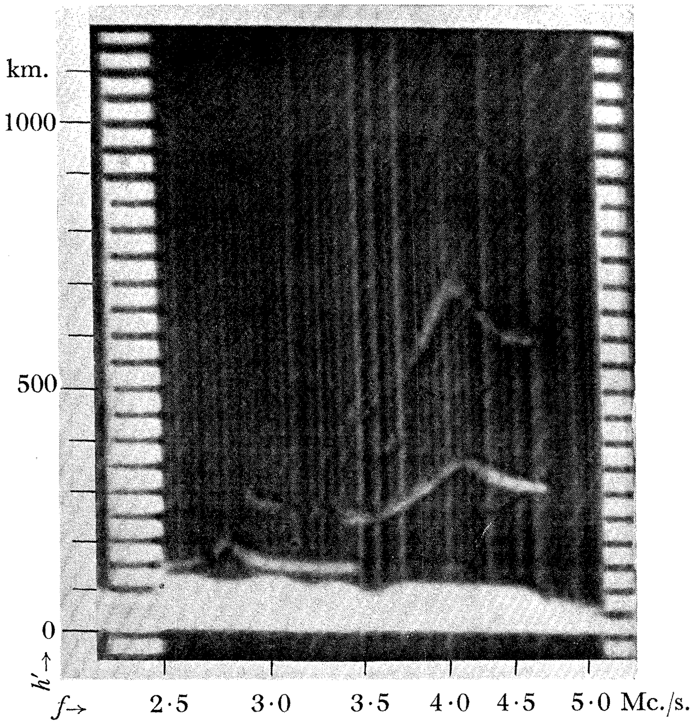


Fig. 33—Photograph showing echoes from the abnormal Region E at Slough at 07·30 G.M.T. on 24 June, 1934.

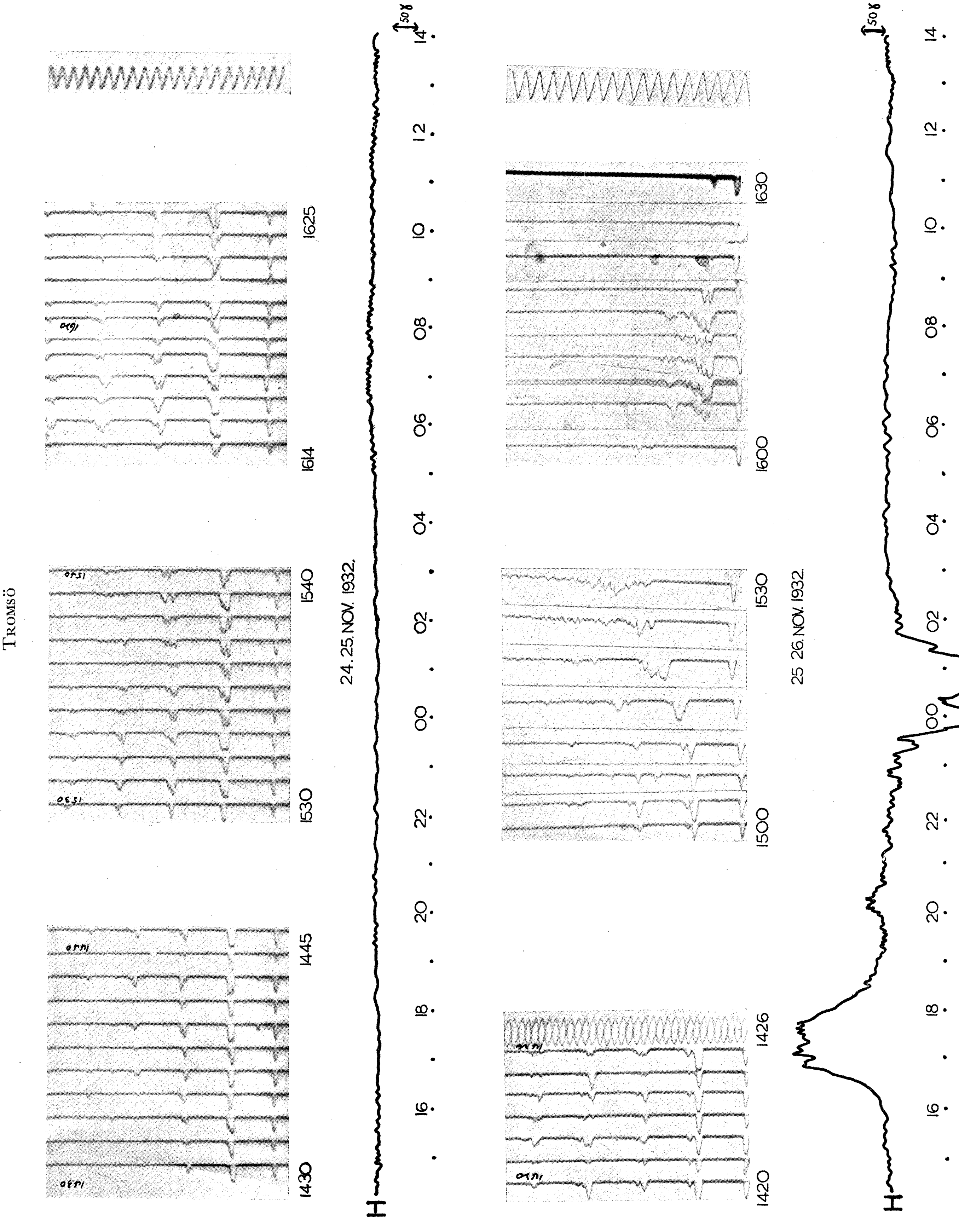


Fig. 32—Detailed sequence of events in a magnetic storm.

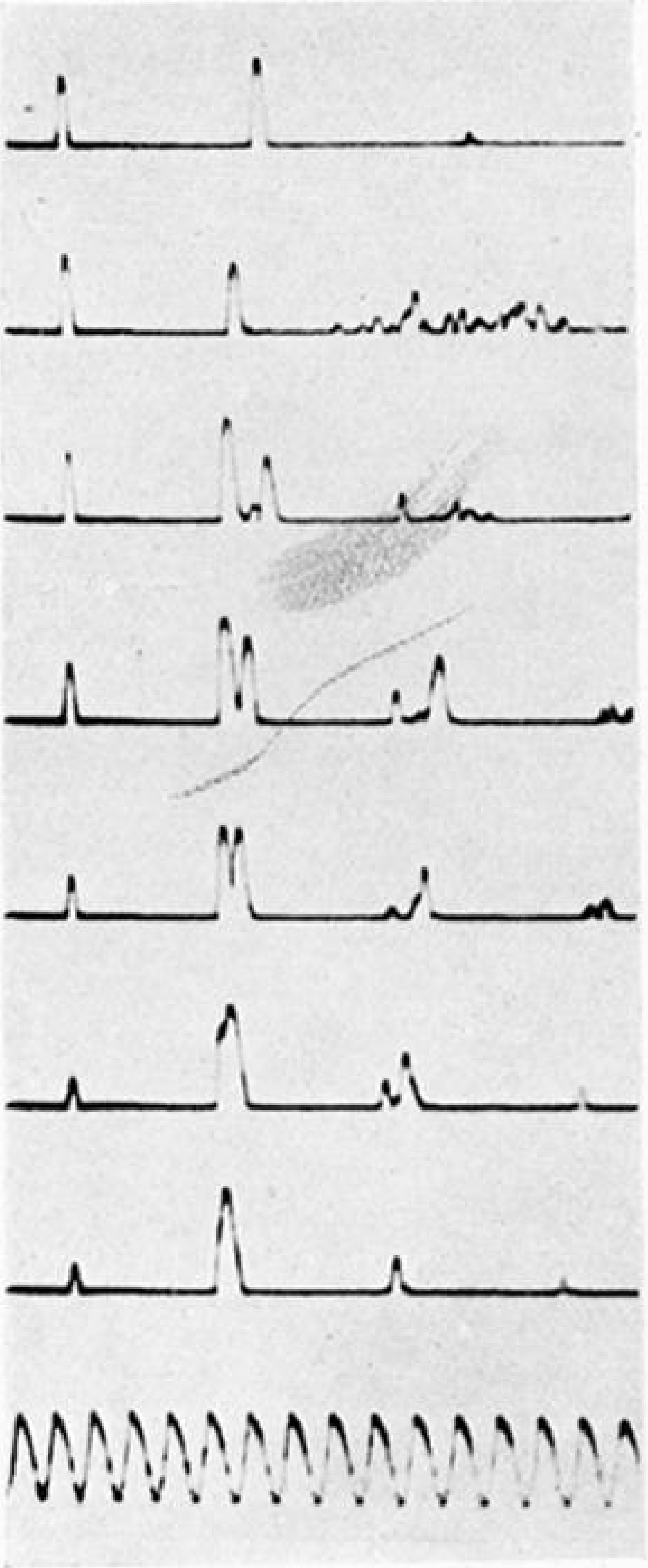


FIG. 5—Series of echo records made during five minutes on frequencies of 7·00, 6·75, 6·50, 6·25, 6·00, 5·75 and 5·50 Mc./sec. (The calibration marking was produced by means of a 2·5 kc./sec. oscillator.)

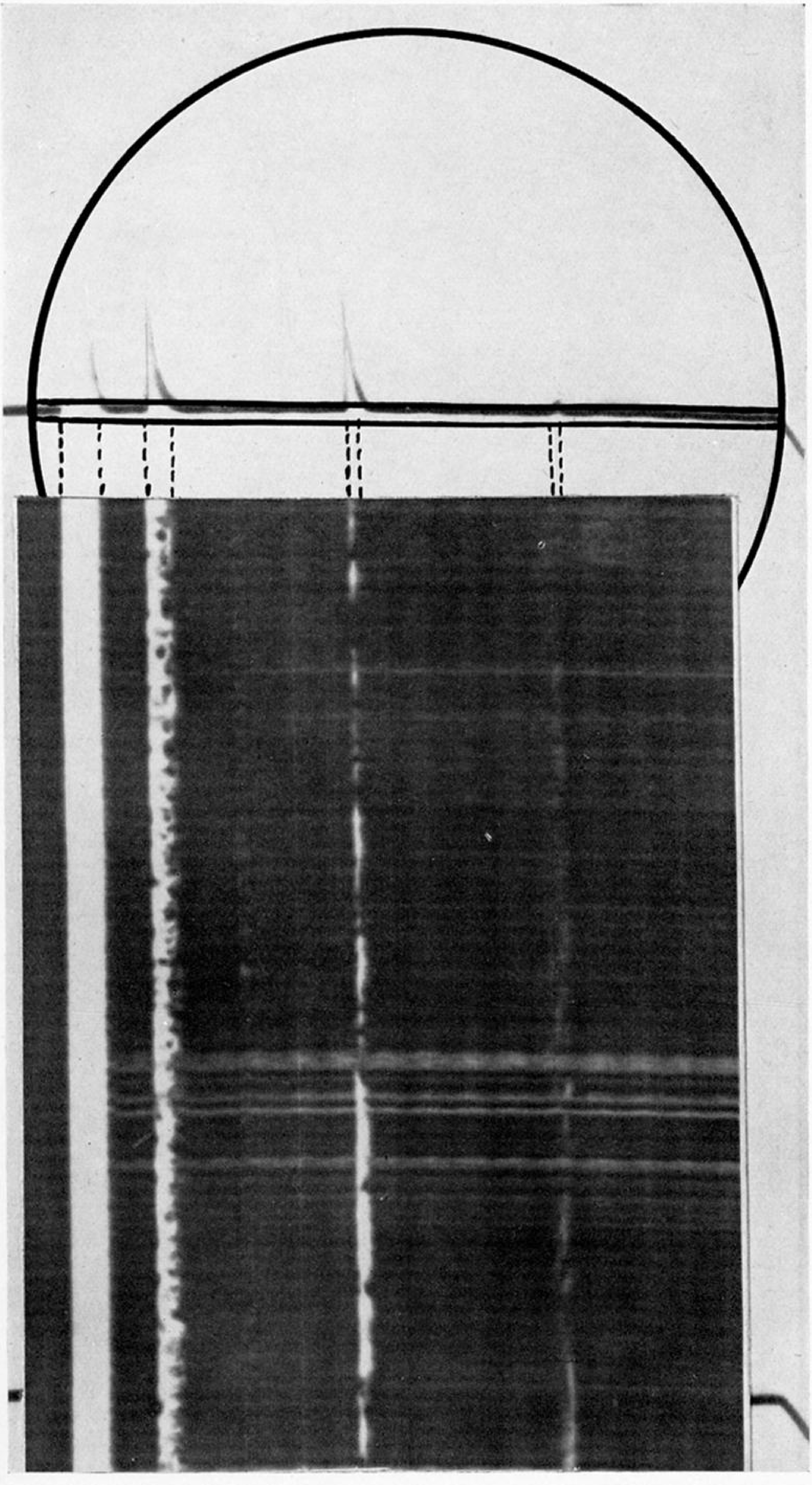


FIG. 6—Diagram illustrating method used for the continuous registration of equivalent heights, together with sample (P′, t) record.

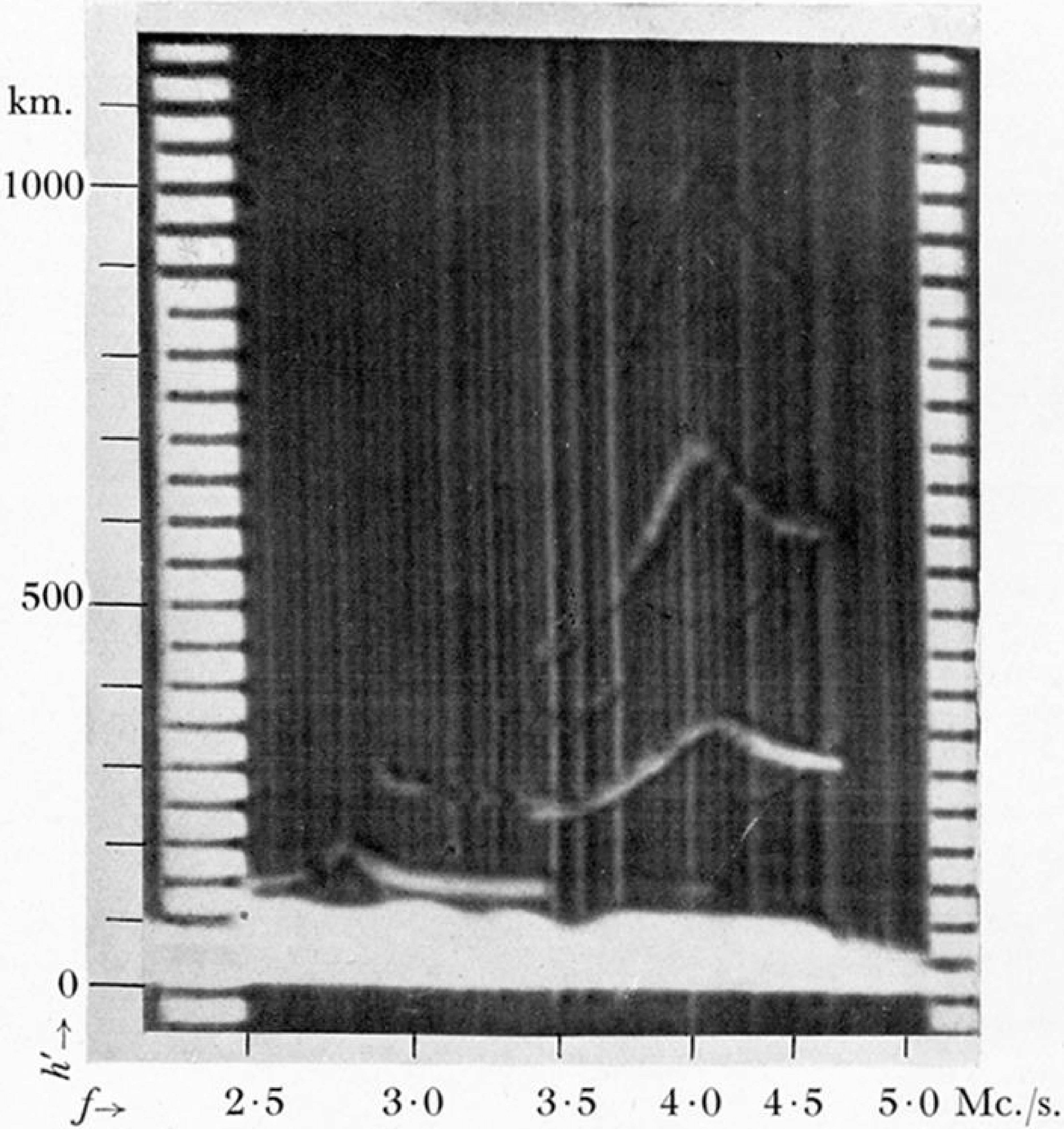


FIG. 33—Photograph showing echoes from the abnormal Region E at Slough at 07·30 G.M.T. on 24 June, 1934.

TROMSÖ

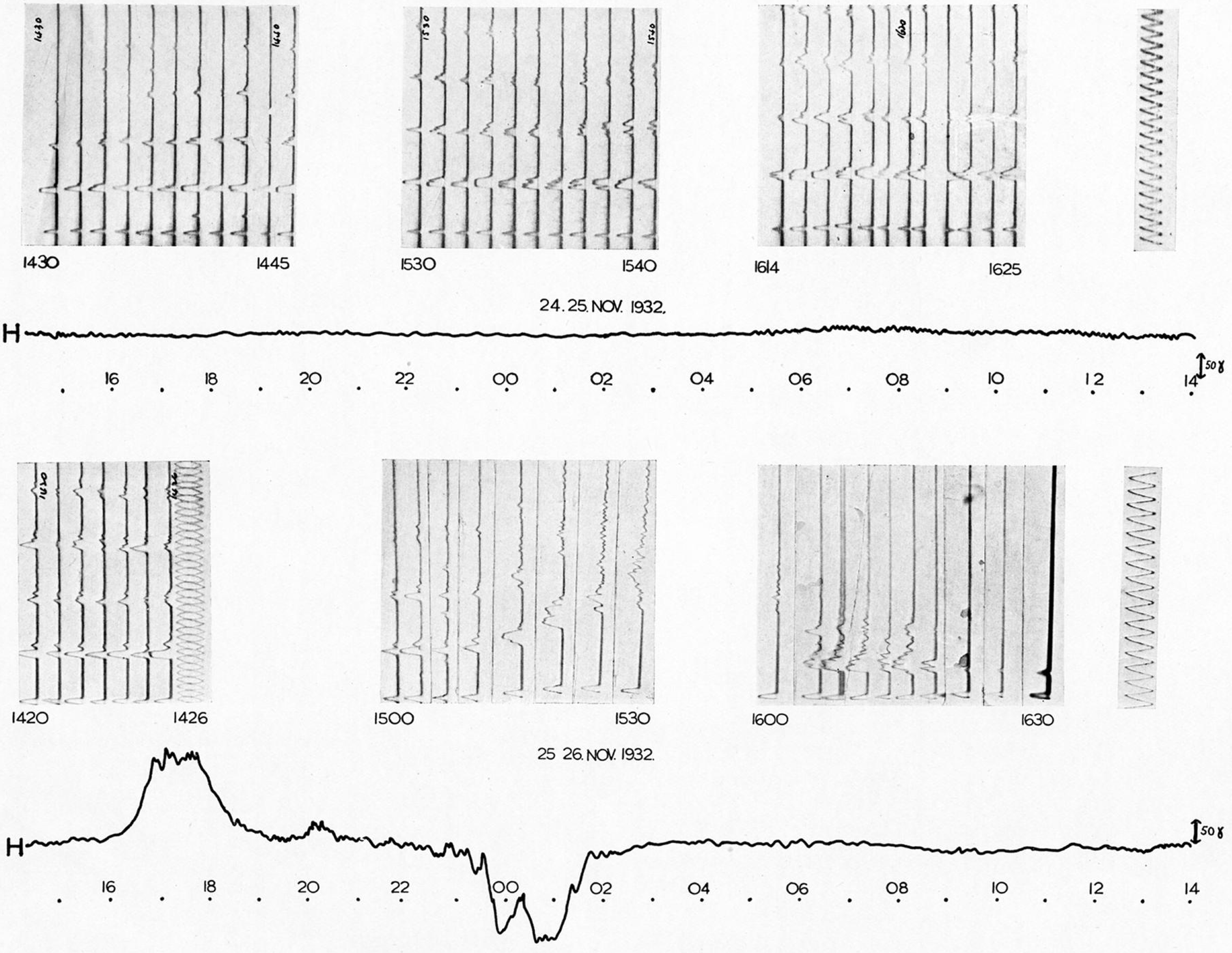


FIG. 32—Detailed sequence of events in a magnetic storm.