A PRELIMINARY DISCUSSION OF D-REGION HEIGHT FLUCTUATIONS DETECTED BY REFLECTING 100KHz RADIO WAVES

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ABSTRACT

Much work has been done concerning height fluctuations in the D-region of the ionosphere. The most widespread method of determining these changes is by reflecting radio waves from a D-region layer and watching phase shifts of the sky wave signal with respect to the ground wave. The work done so far has concentrated on the VLF frequency spectrum and most of the results now at hand are from the extensive research in this range. The research for this paper was carried on in a similar manner but at the lower end of the neighboring LF frequency range, and the data shows effects similar to those of the previous research.

The fluctuations in height of the D-region are linked to other observable indicators such as the K-Indices, magnetotelluric activity, etc. Day to day height changes are linked to the energy flux changes from the sun, with the Lyman Alpha component being the important one in the D-region.

Interesting correlations can be seen between Jet Stream activity and D-region activity. Atmospheric gravity waves have been detected on the ground and related to the Jet Stream from which they are generated. These waves are also thought to propagate upward through the D-region and into the higher regions of the ionosphere where they are eventually dissipated by electromagnetic processes. Their effect upon the D-region may explain many of the 3-60 minute period fluctuations.

A continuing mystery is the great activity evident in the data at night compared with daytime fluctuations which are always much smaller. Two approaches to the explanation of this phenomenon are offered but neither gives the correct answer. The guided-wave mode interference theory offered as a probable

explanation in the following text is also in error. The guided-wave modes are not a factor at the close range between transmitter and receiver used for this research. It also seems unlikely that the radio waves could interfere through other means such as interference between one-hop and multi-hop skywaves (which are not detected). Attention in future will have to be directed at this very basic problem before proceeding to other things.

DESCRIPTION OF EXPERIMENT AND ELECTRICAL EQUIPMENT

On Nantucket Island, Massachusetts is installed a LORAN-C navigational beacon at 100 KHz carrier frequency. This radio wave is pulsed in groups of eight pulses 1 msec apart with a new pulse group occurring every 0.1 sec. Each pulse lasts only about 200 microseconds. Figure 1 shows the propagation of this radio signal from the transmitter on the island to Boston, Massachusetts via two paths: one along the ground and one by reflection off the ionosphere. The excess path length in the reflected route causes a delay in time for this so-called sky-wave as compared to the arrival time at the receiver of the ground wave. By comparing the sky-wave and ground wave arrival times on a continuous basis, one can observe fluctuations in the height of the ionosphere as changes in the delay time between the two signals assuming that the travel time of the ground wave is constant.

This process is carried out electrically by locking a servo-loop using a voltage-controlled oscillator to each signal and observing the consequent changes in phase between the signals. In this method the ground wave is used as a reference. A local oscillator may also be used as was actually done in this experiment as the reference, but the drift of the local oscillator with respect to the master oscillator controlling the beacon (represented by the ground wave faithfully since this wave is unvarying) must then be known. The actual units employed in this research were an Aerospace Research, Inc. LFT-502 Lorchron and a General Radio Corp. reference oscillator working in conjunction. The Lorchron can be phase locked to any 30 microseconds of the LORAN C pulses, and produces an output which records directly any relative variation in phase of the locked signal with respect to the local oscillator. Taking into account the drift of the local oscillator with respect to the master oscillator at the National Bureau of Standards, the output of the Lorchron can record variations in the excess path length when locked on to the sky wave signal, and these variations are easily linked to fluctuations in the apparent height of the ionosphere.

Figure 2 is a photograph of an oscilloscope trace showing one complete LORAN pulse on the left and the beginning of the next pulse 1 msec later on the right. The horizontal oscilloscope divisions stand for 100 microseconds each, and are faintly visible. The first hump is ground wave and the third hump is sky wave. The hump in between is probably mostly ground wave also since no variations in phase were observed when the equipment was locked on to a portion of the signal less than 300 microseconds delayed from the beginning of the ground wave. Since the first cycle of the sky wave is very difficult or impossible to identify, this method does not lend itself to the determination of absolute apparent heights. Rather it excells in the determination of relative changes in the apparent height with a height starting point taken arbitrarily equal to zero. Roughly speaking, however, we can take the sky wave in Figure 2 as commencing about 300 microseconds after the start of the ground wave which would mean an apparent height of the ionosphere for 100 KHz of 90 km. The sky wave under discussion is a single hop sky wave reflecting in the D region of the ionosphere. More than one reflection is, of course, also possible, but no two hop signal has yet been found. If it were visible it would appear in the photo delayed by at least 600 microseconds, and nothing is seen in this region except noise. The ground wave received in Boston has an amplitude much greater than that of the sky wave. Therefore, to separate these two waves and display them to the same scale it was necessary to artificially and selectively attenuate the ground wave. This was done by simply rotating the vertical loop antenna of the Lorchron receiver system until the ground wave amplitude was at a minimum. Since the sky wave signal arrives at the antenna at a high angle with Faraday rotation, it was not disturbed by the new antenna orientation. Thus in Figure 2 the ground wave and sky wave humps have about the same size.

GENERAL NOTES ON THE DATA

The data is presented in Figure 3. It is the output of the Lorchron system recorded by a standard RUSTRAK recorder whose pin taps the pressure-sensitive paper about once a second. The scale is in microseconds of sky wave phase delay with a full scale of 100 microseconds. Each large division is then 10 microseconds and each small division 2 microseconds. When the ionospheric height changes sufficiently to move the recording pin off one side of the paper, the Lorchron automatically resets the pin to the extreme opposite side of the paper from which the pin may proceed to move further in the same direction. If the height varies too rapidly, however, the Lorchron can conceivably lose its lock since there is a maximum allowable slewing speed of the system logic elements. This would show up in the output as a continuous drift across the paper over and over with no fine structure in the trace. This did not occur at any time during data acquisition so that the traces shown are considered reliable. With a servo loop time constant of 2 minutes, the unit was able to stay locked all the time, although any fluctuations occurring with a period of only a few minutes or less would not be seen.

The data covers a period of about six days from 1600 July 25 to 1200 July 31, 1968. This is not long enough to get any statistically accurate picture of many ionospheric processes or of long period variations such as those relating to the seasons or to the sunspot cycle. As time on the Lorchron was at a premium, it is lucky that I was able to get these six days without interruption. Currently under design and nearing completion here in Professor Theodore R. Madden's laboratory is a two servo loop system which will shortly be put into operation on this problem. I was unfortunately not able to have this system completed in time for this paper and in time to get a longer sample. However, though the discussion may be preliminary only, there are already several striking features in the data to be seen. The discussion to follow will center on diurnal variations and other aspects readily inferred from the sample.

Two last notes need to be mentioned. First, on July 26 there is a break in the trace around 1600 EST (all times are given in EST unless otherwise noted). It is an artificial break associated with renewing the paper roll in the recorder and making some tests. As heights are all relative to some arbitrary starting point, this poses no serious problem in the interpretation of the data. Second, the direction of increasing phase delay (or increasing apparent height) is downward.

DIURNAL VIRTUAL HEIGHT FLUCTUATIONS

Measurements of oscillator drift were made on three separate days during or near the data acquisition period. The measurements were made by locking a second Lorchron (when available) onto the ground wave instead of onto the sky wave of a Loran-C signal, and comparing the reference oscillator (local) in this way to the master oscillator controlling the East Coast Loran chain. With this method the drift of our General Radio Corporation unit was displayed graphically on Rustrak paper, and values of 17.7, 17.3, and 11.6 microseconds per day were recorded on the three occasions. An average drift of about 15 microseconds per day can therefore be expected as error introduced by the local oscillator. This corresponds to one and one-half divisions per day, yet differences much greater than this are observed in the levels at noon from one day to the next. With reference to the level at 1700 E.S.T. on 7/26/68, the differences in height levels of the next five successive days at 1700 (except for 7/31/68 where the noon value is assumed to prevail until 1700) are +5, -35, -45, -75, and -45 microseconds respectively. These differences in delay time correspond to height differences as great as 5 km from one day to the next even after the oscillator drift is taken into account.

This may be due to changes in the energy flux from the sun from day to day since, as Moler[1] reports, in the daytime, photoionization of nitric oxide by Lyman alpha

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[1] William F. Moler, "VLF Propagation Effects of a D-Region Layer Produced by Cosmic Rays," Journal of Geophysical Research, Volume 65, No. 5, pp. 1459-1467, May, 1960.

radiation and cosmic-ray ionization of other constituents are the important electron-producing processes in the D-Region. He also reports that at night ionization is caused principally by the cosmic-rays alone which produce a layer near 95 km capable of reflecting VLF waves. Figure 4b shows the diurnal behavior of the reflecting layers from Moler.

A very great deal of work on the D-region has been done in the VLF frequency range by Moler, Mitra, Crombie, Bracewell, Bain, Bates, Wait, and many others, but very little so far in the closely neighboring LF frequency range in which our 100 kc/s carrier wave falls at the lower end. In the VLF range and possibly in lower portions of the LF range waves are reflected at levels of maximum-electron-density gradient rather than at levels for which the electron density itself is merely that required for a wave of 100 kc/s plasma frequency. If, however, Moler is correct in referring to distinct layers of ionization in the D-region, the height of maximum-electron-density gradient cannot, for our purposes, differ too greatly from the proper plasma frequency height.

Using the familiar plasma frequency formula $w_p{}^2 = \frac{ne^2}{m_e \epsilon_o}$, solving for $n = \frac{w_p{}^2 m_e \epsilon_o}{e^2}$, and plugging in $w = 2PI \times 10^5$ with the proper values of m_e, ϵ_o, and e, n is found to be about 1.2×10^2 electrons per cm^3. A line is drawn down the electron density graph of Figure 4a corresponding to this density at which the Loran signals are reflected. Thus we see that from rocket measurements we might expect the Loran signal to be reflected from nearly 90 km at night and from 55 to 70 km during the day. The rocket density measurements, assuming only small variation in the values over the period of a day, show a daytime convolution at the levels of interest which might also help to explain the day to day height change mentioned above. Taking the value of daytime density above the convolution (at 67 km), the graph predicts maximum diurnal height changes of about 20 km. This is in rough agreement with the collected data which shows diurnal differences in phase delay of up to 70 microseconds. A 10 microsecond change in phase delay at a mean height of 75 km corresponds to a height change of 2 km. So 70 microseconds corresponds to 14 km. The 20 km height change from rocket measurements compared to our 14 km change can be explained by seasonal variations. Our data was collected during the summer with nights so short that the ionosphere has only little time relative to long winter nights, during which the rocket values were observed,to rise before it must again fall with the approach of dawn. And, therefore, we would expect greater maximum diurnal height changes in the winter.

Earlier in this paper, the beginning of the sky wave was reported delayed by about 300 microseconds from the start of the ground wave, corresponding to a (daytime) apparent or virtual height of about 90 km. The actual height as we can see from the rocket measurements is more in the neighborhood of 70 km. The discrepancy is not explained solely by the fact that it is difficult or impossible to identify the first cycle or starting point of the sky wave (even the first cycle of the ground wave is tricky to identify, and often ambiguous). Rather it can be explained by the fact that the sky wave must travel through regions of considerable electron density before and after reflection. As a consequence, the wave will be slowed down to a speed less than the speed of light in a vacuum in these regions, and an extra phase delay will be introduced yielding a seemingly higher reflection height. It is also in passing through these regions of plasma that the polarization of the wave undergoes Faraday rotation, accounting, as mentioned earlier, for the persistence of the sky wave signal when the ground wave is nulled.

It seems reasonable to assume that the delay caused by travel through the ionized regions alone will be the same night or day. Regardless of where the reflecting height is, the radio wave will always have to travel through regions of similar ionization character at night or in the daytime. And the radio reflection technique should, therefore, be reliable in showing height changes over absolute height measurements.

MAJOR FEATURES OF THE DATA AND CORRELATIONS WITH OTHER INDICES

The single most striking feature of the Loran data is the calm and quiet daytime trace as compared with the wildly fluctuating nighttime record. From ionospheric sunrise (at about 0700) to sunset (at about 1700) there is hardly a ripple of activity on several of the days, while at night there is great activity on almost all of them. The question therefore arose as to why the daylight hours should be so much more inactive than the rest of the time. Attempts were made to explain this effect based on some sort of damping to the fluctuations of the daytime which did not occur at night. In one attempt it was postulated that the time constant for recombination of electrons was somehow smaller in the daytime than at night such that daytime disturbances were more quickly neutralized. Study of day-night effective recombination coefficients and time constants proved inconclusive, however. It turns out that we were asking the wrong question. We should have supposed the daytime trace to be normal and asked why such large variations occur at night. Height changes of as much as 6 km in only fifteen minutes seem evident from the data (e.g. 7/30/68 at around 0315 to 0330). The answer again lies in work done in the VLF frequency range. Bates and Albee[2], using guided-wave mode propagation theory[5], suggest that "...the correct explanation of the large reported differences in effective reflection heights for 18 to 20 kc/s signals over various paths (cf. Brady et al.) are primarily due to second-mode interferences rather than to large differences in the height of the D-region..."[2]

> "The presence of the second guided-wave mode at night [but not during the day] makes the computation of effective reflection-height changes unreliable from a research standpoint unless care is taken."[3]
>
> "The mere occurrence of large VLF phase and amplitude variations does not, therefore, necessarily signify the existence of a large-scale D-region disturbance or storm in the usual sense. Large signal variations do indeed signify that the D-region is disturbed, but the disturbances may be small and localized. Thus, using long-distance VLF waves as a D-region research tool, we face the very considerable task of sorting out phase and amplitude changes produced by wave interference from similar-appearing changes produced by other means."[4]

The Bates and Albee work was done by receiving VLF waves at long distances. However, wave interference must be dominating our comparatively short range results as well

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[2] H.F. Bates and P.R. Albee, "General VLF Phase Variations Observed at College, Alaska," J.G.R., Vol. 70, No. 9, May, 1965, p. 2203.

[3] *Ibid.*, pp. 2206-7.

[4] *Ibid.*, p. 2206.

[5] K.G. Budden, *The Wave-Guide Mode Theory of Wave Propagation*, 1961.

since movements of speeds like 24 km per hour in the ionosphere strike one as unlikely or unphysical.

Looking at the daytime traces in Figure 3, another feature of the data is the relatively greater activity evident on 7/26 and 7/30/68. Without trying to pin down this activity increase any more accurately in time than to the day on which it occurred, we can, nevertheless, observe certain correlations with other data and indices. As a first step, let us compare our data with the magnetic-activity K-Indices for the period as graphed in Figure 7. The level of activity in general is seen to be low, and it seems to be begging the issue, therefore, to point out that peaks in the K-Indices coincide with the observed days of higher activity from the data (7/26 and 7/30 and 7/28 as well).

Figure 5 shows telluric fluctuations for the period which are also recorded in our laboratory. Again there is an increase in activity evident on 7/26 and 7/30 compared with the other days. This activity is most easily seen in the DC - .002 cps frequency band of channel 4 (arrows).

Figure 6 shows the wind speed at Jet Stream altitude during the data acquisition period. Peak winds are seen to have occurred again on 7/26 and 7/30. This last observation may be promising. It is suspected that internal gravity waves may be generated in the atmosphere by the Jet Stream and propagate up to D-region altitudes before being fully attenuated. The vertically propagating waves might cause real height fluctuations in the D-region which could be detected with the Loran system. Claerbout[6] has detected

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[6] Jon F. Claerbout, Electromagnetic Effects of Atmospheric Gravity Waves, 1967, p. 2, p. 8 ff.

gravity waves on the surface of the earth with instruments which measure small atmospheric pressure differences, and he has been able to correlate the occurrence of the waves with Jet Stream activity. He predicts that gravity waves propagating upward might explain small scale high altitude winds and ionospheric disturbances. The wave periods, 3 - 60 minutes, are in a good range for detection with phase loop equipment, and it is possible that the short-period activity observed in the data on 7/26 and 7/30 is indeed of gravity wave, jet stream origin. Unfortunately, however, gravity waves were not much in evidence at the ground level during the data acquisition period, and a correlation could not be made between the surface pressure differences and Jet Stream activity.

CONCLUSIONS AND ACKNOWLEDGEMENTS

The detection and continuous recording of phase delays in sky waves reflected from the D-region of the ionosphere can be an important tool in upper atmospheric research. The method provides a correlation to other indices of activity such as the K-Indices, S.I.D.'s, magneto-telluric records, or Jet Stream wind speed. Values of absolute heights in the D-region are difficult to determine, but agree qualitatively with values derived from rocket launched tests. Diurnal height variations are also seen to agree with expected variations from the rocket experiments. The level of the reflecting layer is different from day to day, and this information may be useful in determining energy fluxes from the sun. Lyman Alpha radiation and cosmic-rays are the principal sources of ionization in the D-region with the former dominating in the daytime and the latter at night.

Aside from the rather general activity correlations, perhaps the most important use of the Loran technique will be in detecting and recording atmospheric gravity waves. At night, legitimate height changes are masked, amplified, or distorted by second guided-wave mode interference of the reflected waves. It is this interference which accounts for the large and rapid apparent fluctuations seen only at night. In the daytime, however, movements in the D-region associated with gravity waves generated by the Jet Stream should be readily recorded. These waves have periods from 3 to 60 minutes in a convenient range for observation with a servo loop system with a 2 minute time constant. Eventually, the detection of gravity waves by pressure sensitive methods on the surface of the earth should correlate with the observance of the waves in the D-region.

I would like to express my gratitude and appreciation to my thesis advisor, Professor Theodore R. Madden, who helped formulate the problem, and gave guidance and direction to the research with many hints and cautions along the way.

Many thanks go to Mr. Alfredo R. Navato with whom I had frequent helpful discussions, and Miss Kathleen Crowley who came late several nights to help type the manuscript.

I am deeply indebted also to Messrs. L. Dennis Shapiro, Val Skov, and Earl Sunderland of Aerospace Research, Inc. for their time, interest, and guidance as well as for the loan of the Lorchron equipment which made the project possible at this time.

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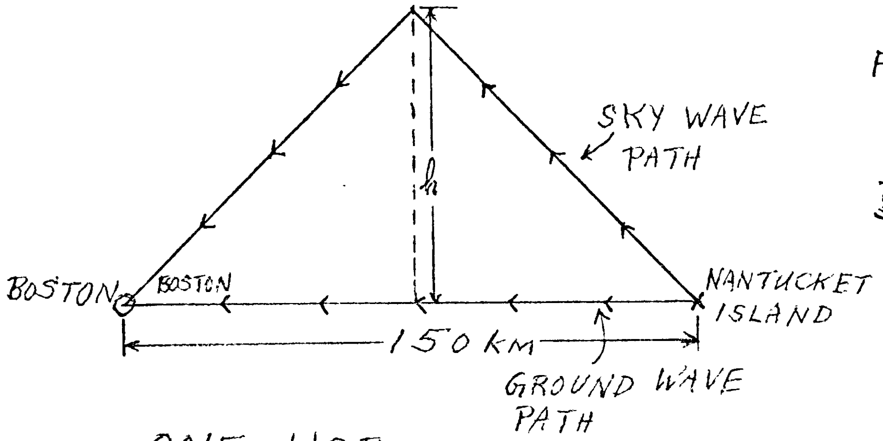
FIGURES

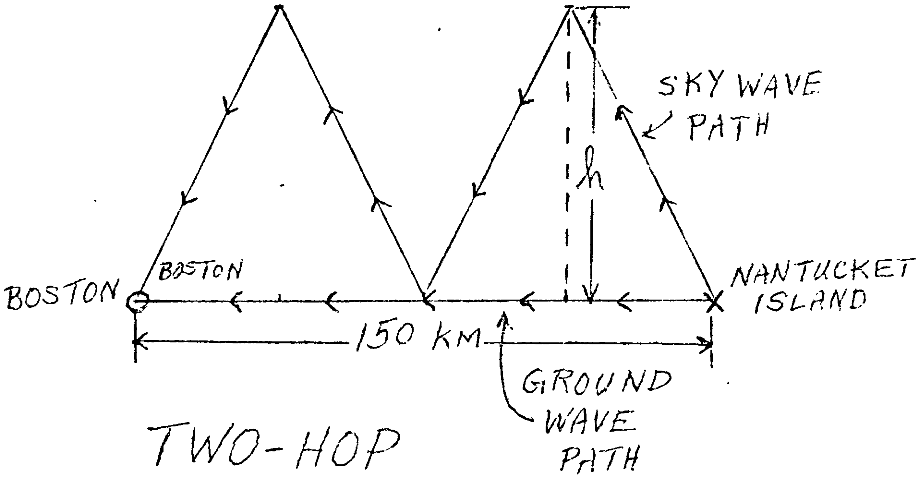


ONE-HOP

For $h = 75$ km

$$\frac{\text{EXCESS PATH LENGTH}}{3\times10^5\ \text{km/sec}} = \frac{62\ \text{km}}{3\times10^5\ \text{km/sec}}$$

$$= 210\ \mu\text{sec}$$



TWO-HOP

For $h = 75$ km

$$\frac{185\ \text{km}}{3\times10^5\ \text{km/sec}} = 618\ \mu\text{sec}$$

Figure 1. Relative Sky Wave Delay For One and Two-Hop Paths

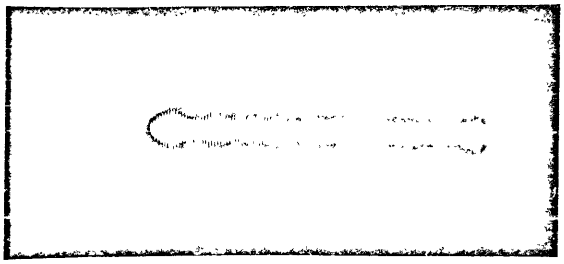


Figure 2. Nantucket Ground and Sky Wave Signals Received at Boston, Mass. on 25 July 1968, 1500 E.S.T. (100 μsec/div.)

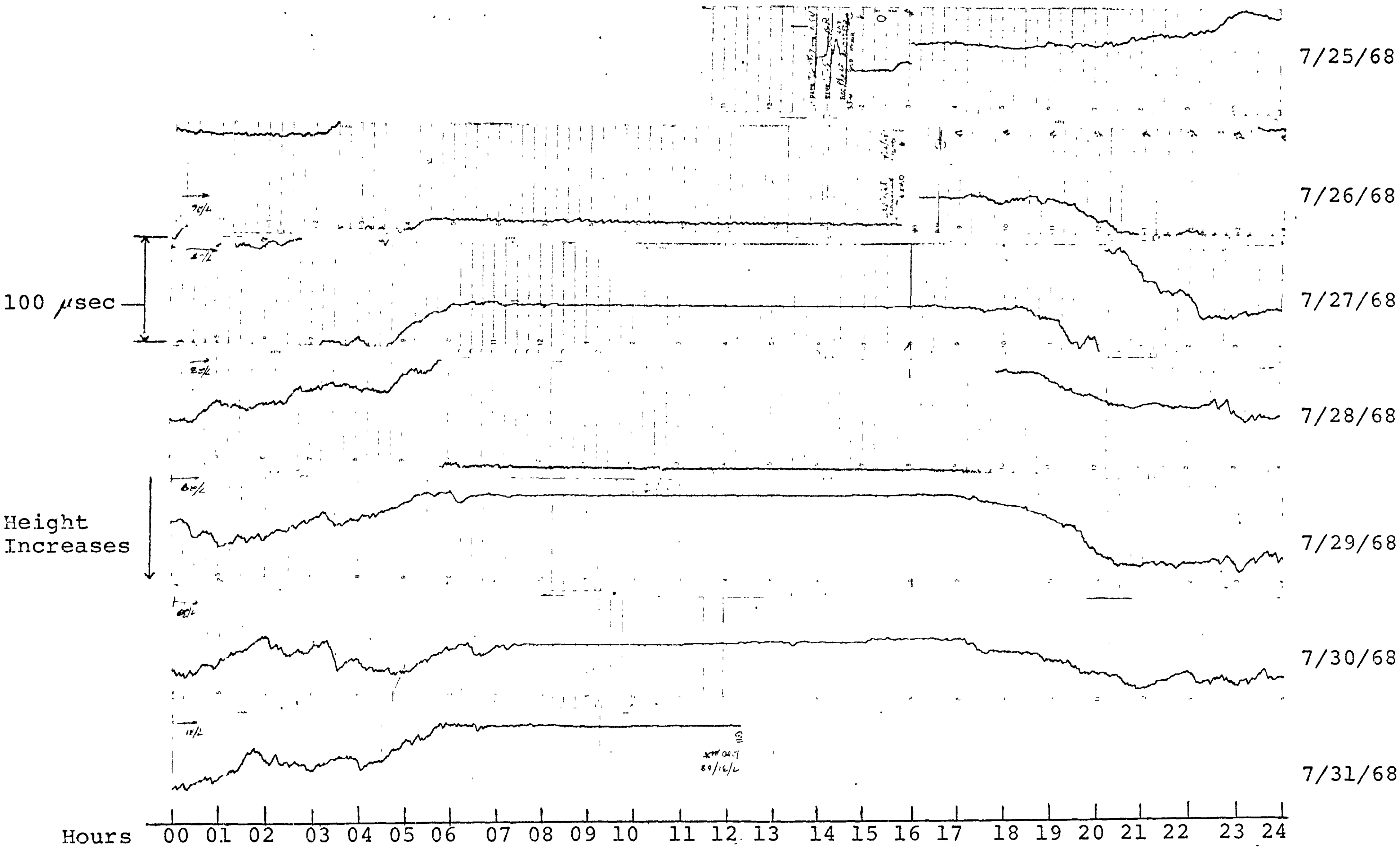


Figure 3. 100 KHz Ionospheric Apparent Height Fluctuations

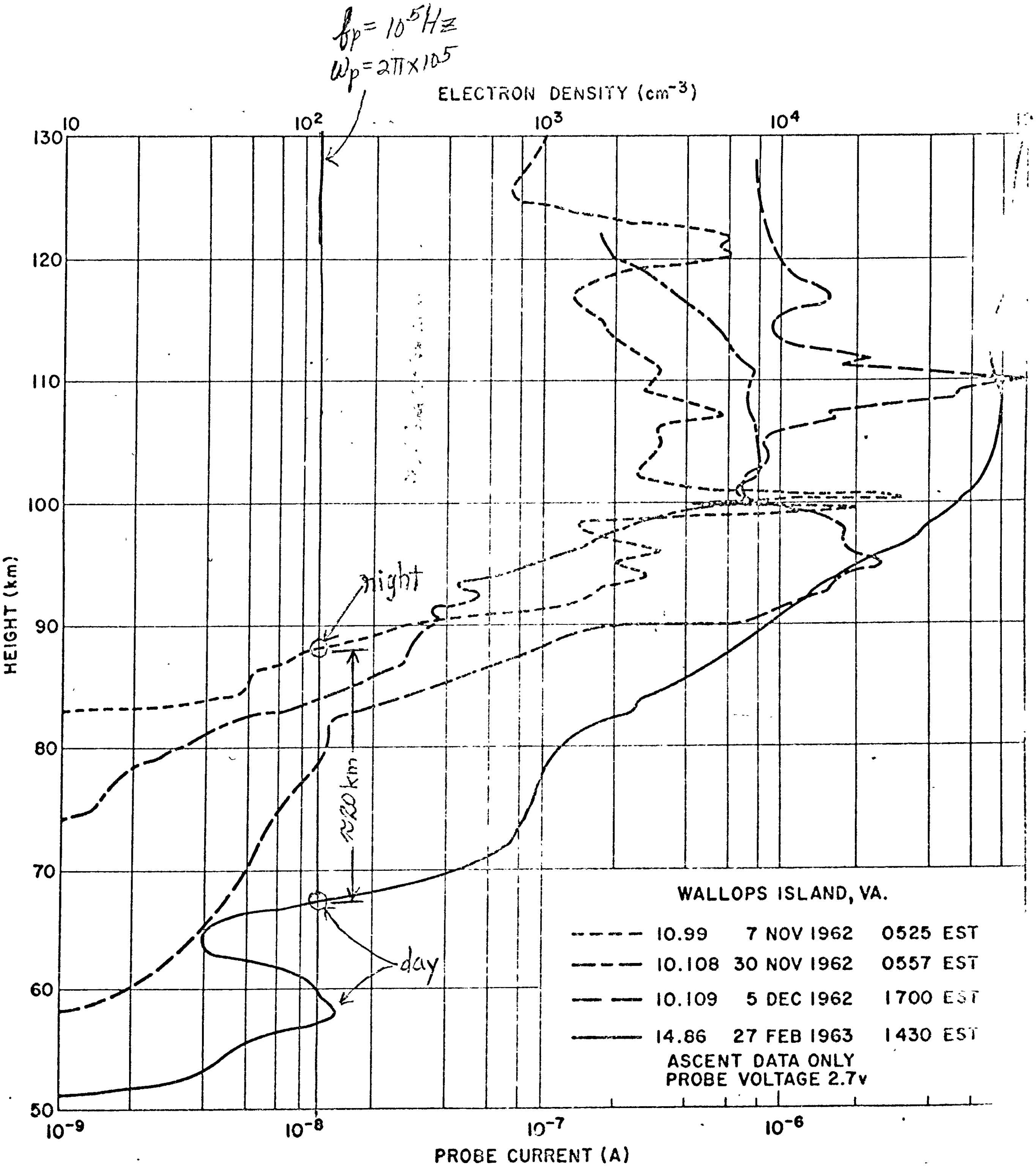


FIG. 4.a [redacted]. Profiles of probe current in the D and lower E region. Measurements by L. G. Smith using Langmuir probes on rockets. (Courtesy of Geophysics Corporation of America.)

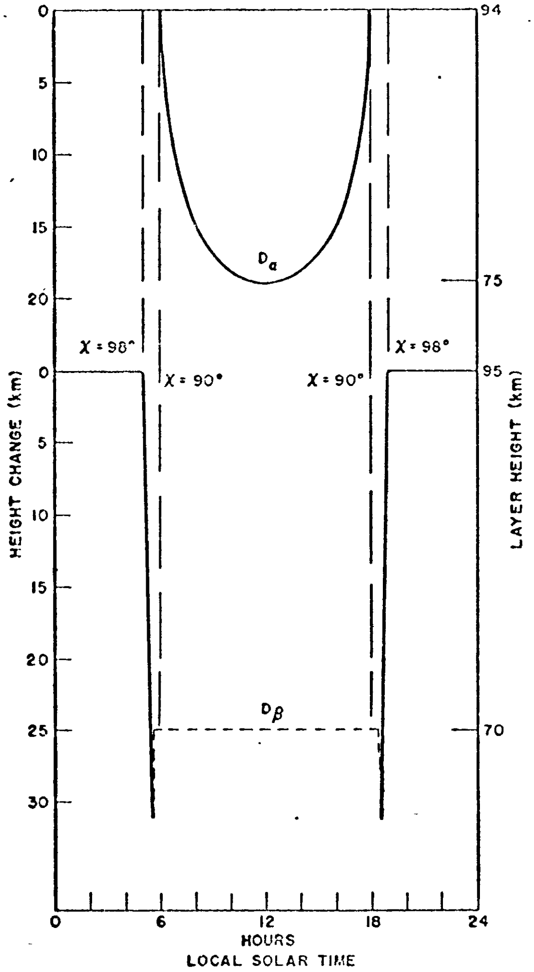


Fig. 4b Diurnal behavior of the height of the maximum-electron-density gradient in the photoionization layer, $D\alpha$, and the cosmic-ray layer, $D\beta$, during the equinoxes over Great Britain.

TELLURIC FLUCTUATIONS
CONCORD-ETNA, N. H.
JULY, 1968

CH. 1 .2-2 cps (rect.)
" 2 .02-.2 " (")

CH. 3 .001-.03 cps
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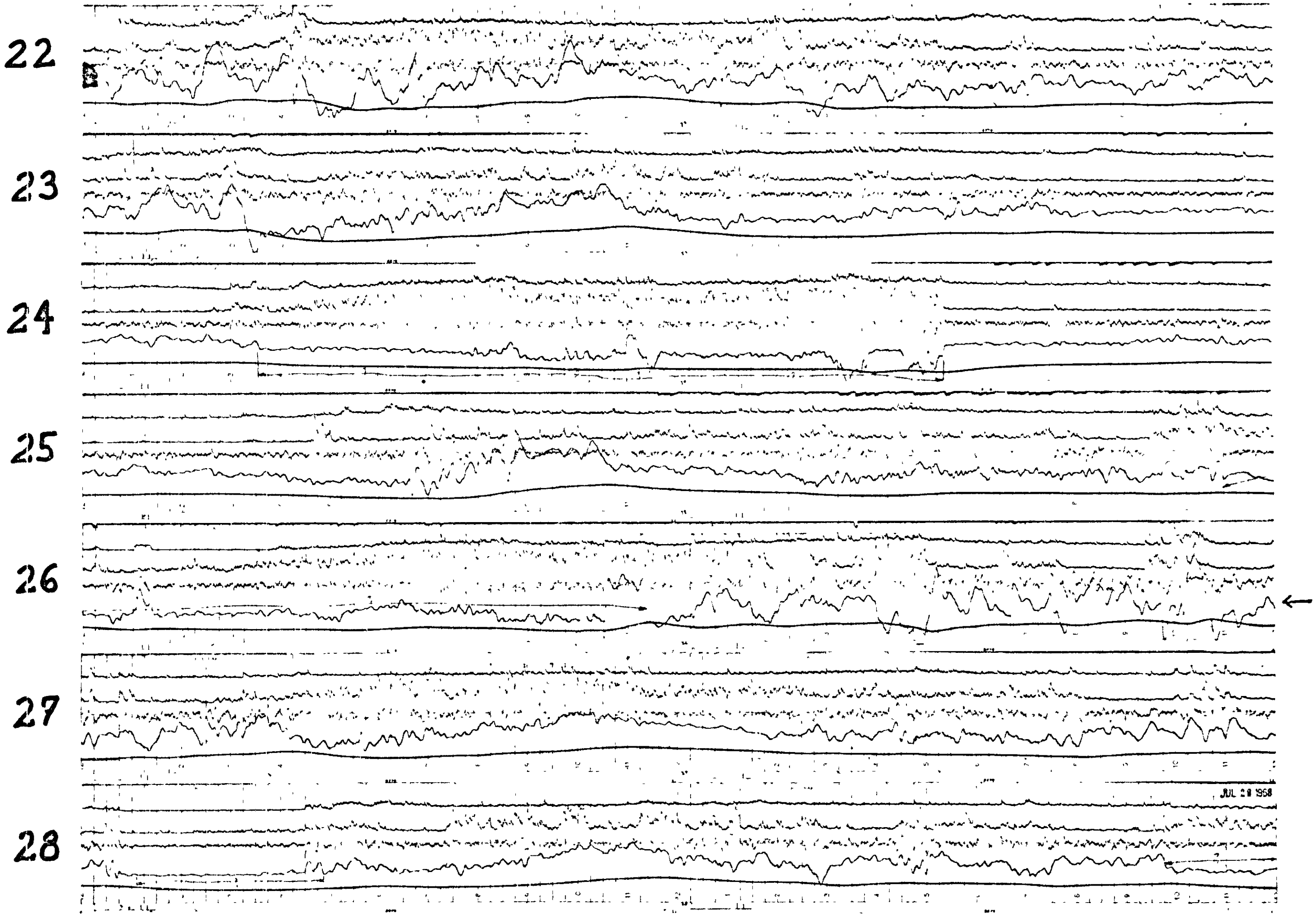
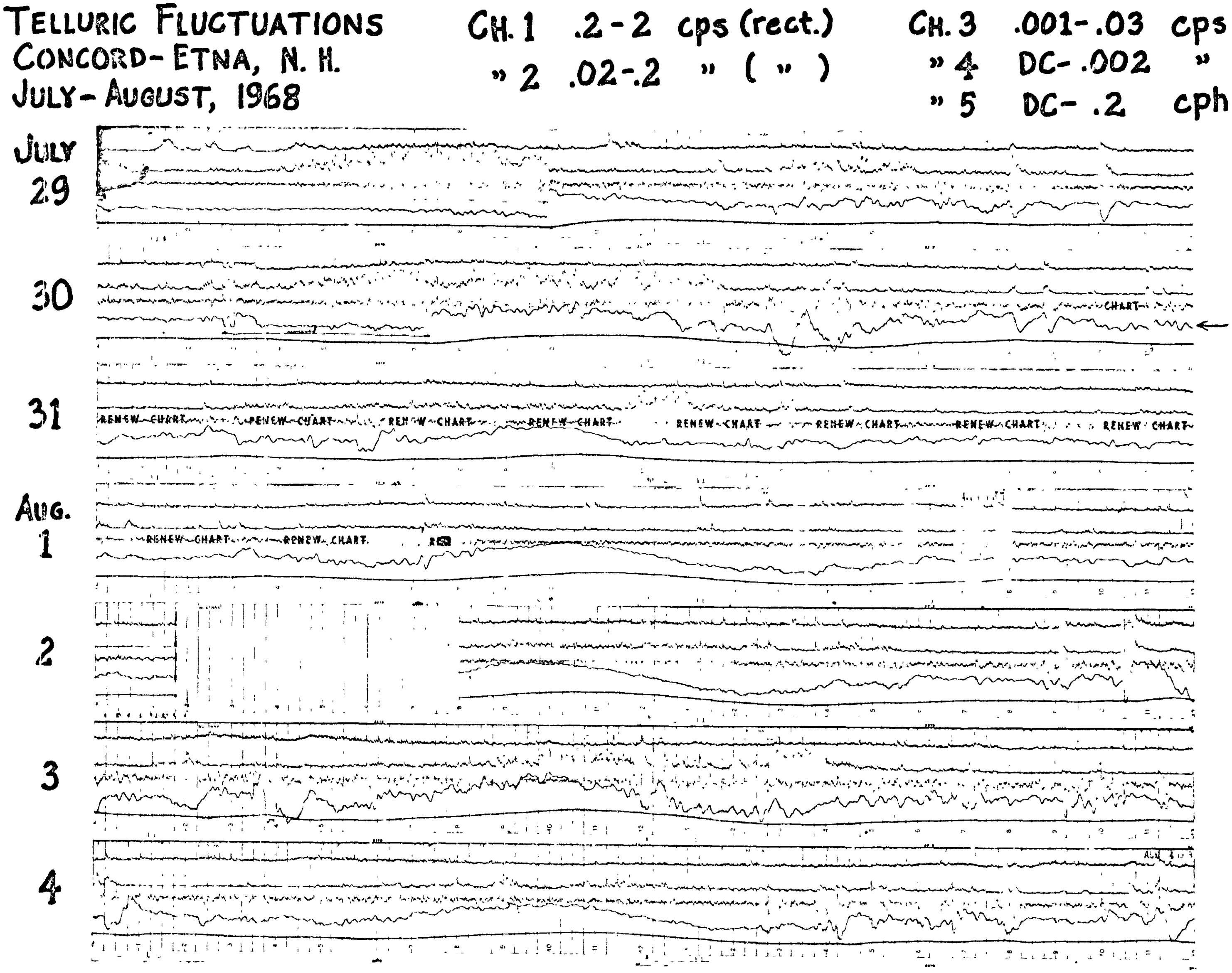


FIG. 5a.


TELLURIC FLUCTUATIONS
CONCORD-ETNA, N. H.
JULY-AUGUST, 1968
CH. 1 .2-2 cps (rect.)
" 2 .02-.2 " (")
CH. 3 .001-.03 cps
" 4 DC-.002 "
" 5 DC-.2 cph
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30
31
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1
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4
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RENEW CHART
AUG 3

FIG. 5b.

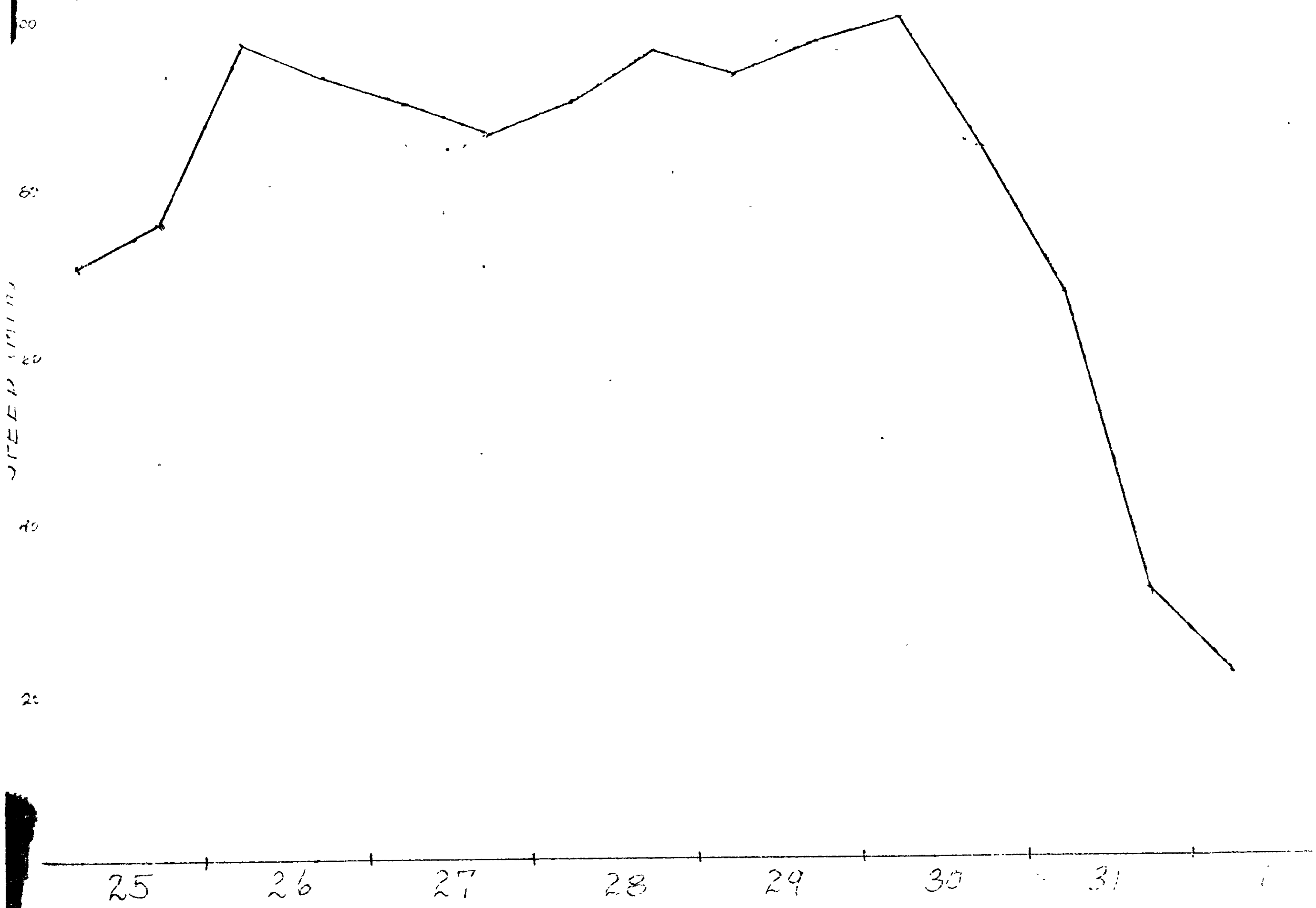

Fig 6 200 milibar Wind Speed Over Nantucket, Mass (every 6 hours of E.S.T.) U.S Weather Bureau

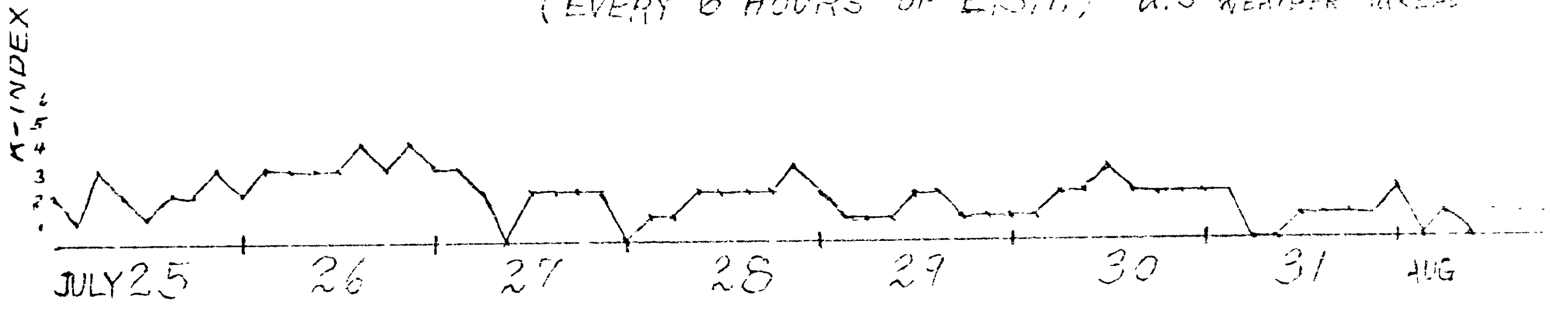

Fig. 7 Fredericksburg K-Indices For Data Period (every 3 hours of E.S.T.)