VERTICAL CHARACTERISTICS OF TRAVELLING IONOSPHERIC DISTURBANCES

By L. H. Heisler*

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Summary

The vertical dimensions of travelling disturbance phenomena have been investigated by derivation of the associated true height distributions of ion density. The height at which they appear often has an upper limit which may fluctuate in height from day to day.

It appears that direction of travel is related mainly to season, with the possibility of some additional form of solar control only evident at times of sunspot maximum.

During a particular season, there is no obvious change of direction of travel with height in the height range under observation.

No definite variation of speed with height is evident in the ionospheric region considered, which extends from 160 to 230 km.

I. Introduction

Munro (1950, 1953) has described disturbances on 5·8 Mc/s fixed-frequency records, using a three-station triangulation to determine speed and direction, and has recently published (Munro 1958) comprehensive statistical data of eight years' results. Munro and Heisler (1956*a*, 1956*b*) have described large disturbances which occur in variable-frequency ionosonde records, and Heisler (1958), comparing records from Australian ionosonde stations, has shown that these disturbances travel distances of at least 3000 km, with fronts possibly broader than 1000 km. The existence of similar disturbances in the northern hemisphere, first mentioned by Munro (1957), has recently been confirmed by Valverde (1958), using backscatter techniques.

Recently there has been an increasing appreciation by many workers of the importance of $N(h)$ electron density profiles in ionospheric research. The usual ionosonde presentation, which relates virtual height to frequency, has many shortcomings when used for investigating ionospheric phenomena and, in fact, can give rise to entirely misleading results. For the purpose of many investigations, it is the knowledge of the true height at which a certain ionospheric event occurs, and of the change in electron density N at this point, which is of importance. In particular, recent probings of the ionosphere by rockets and artificial satellites have necessitated a knowledge of true heights of ionospheric layers for comparison with experimental measurements. Furthermore, the derived $N(h)$ curve may be used to estimate n, the total ion content of the layer up to maximum ion density, and variations in this quantity give valuable information on ionization and recombination processes, as shown in applications by Ratcliffe (1951).

Many methods have been developed to obtain the necessary $N(h)$ curves from the available $h'f$ presentation, and as early as 1938 Booker and Seaton

* Radio Research Board Laboratory, Electrical Engineering Department, University of Sydney.

suggested a simple technique based on a parabolic distribution of electron density with height, neglecting the effect of the Earth's magnetic field (Booker and Seaton 1938). This has been superseded by the more accurate integral methods of Manning (1947) and of Kelso (1954), the latter method including the magnetic field correction. These analyses and others are discussed in an excellent survey by King (1957).

The complicated and tedious calculations necessary, particularly in accounting for the magnetic field, have always been a deterrent in employing these methods for ionospheric research. However, Jackson (1956), King (1957), and more recently Duncan (1958), have developed techniques which are especially suitable for programming automatic electronic computers, and a program prepared by Duncan has been used by this laboratory in SILLIAC, the electronic computer situated at the Physics Department of Sydney University. The data consisting of virtual heights and corresponding frequencies from the ionosonde record, enough readings to sufficiently describe the curve, are supplied to the machine on punched paper tape. The results are given in true heights and electron density, which are then plotted to give the requisite $N(h)$ curve. The complete analysis of one $h'f$ curve is performed by the machine in approximately 20 seconds.

Approximately 200 of these calculations have been made during an investigation of travelling ionospheric disturbances.

Published data refer mainly to horizontal dimension of movements. The present investigation considers vertical dimensions and variation of characteristics with height using improved methods for the deduction of true heights. It is to be understood that the term height as used in this paper always refers to true height in the ionosphere, not virtual height.

II. Observational Data

In any study of heights of F-region travelling ionospheric disturbance phenomena it is important that the observational data do in fact pertain to that ionospheric layer, and that the effects observed are not due to disturbances in lower parts of the medium through which the probing radio ray has to pass. Briggs and Spencer (1954) have indicated that this uncertainty about precise height of measured movement is an inherent disadvantage of the fading method due to Mitra (1949), as applied to F-region measurements. There is a similar ambiguity in observations using radio star scintillations, and the height at which contributing irregularities occur does not seem to be known with certainty.

Speeds and directions of disturbances used in this paper are based on time differences of anomalies in F traces recorded at three spaced stations, a technique described by Munro (1950). A feature of these records is that the manifestations at a particular station usually occur at different times on the o- and x-ray traces (Munro and Heisler 1956*a*, 1956*b*). Moreover, the time differences so obtained are consistent with expected separations of o- and x-reflection points in the F region. The observed effects, therefore, are almost certainly due to phenomena occurring in this region at a height corresponding to the reflection height of the probing frequency.

Consideration must also be given to the validity of analysis as applied to the observational data. If θ is the angle which the probing ray makes to the vertical and t is the sweep time occupied by an ionosonde record, then in the integral method of actual height analysis $d\theta/dt$ must be zero or a very small quantity. This ensures that, for each frequency, the integration process is always along the same path through the ionized medium.

A travelling disturbance manifests itself on an ionosonde record as a complexity due in part to non-vertical reflection during portion of the frequency sweep. According to the above hypothesis, analysis of such a record would not be valid. However, in the results which follow below, ionosonde examples for analysis have been carefully chosen, either immediately before the advent of a disturbance or during that phase of the disturbance where non-vertical complexity is absent.

III. Height of Occurrence of Travelling Disturbances

(a) *Fixed-frequency Observations*

Most of these observations at this laboratory have been made on a fixed frequency of 5·8 Mc/s. This immediately predetermines the height of observation as that height in the ionosphere at which an electron density of $4\cdot17\times10^5$ electrons/cm^3 occurs, and will consequently vary with season, sunspot number, and time of day. The observations considered in this paper were made during the years 1952 to 1954 inclusive and a determination of heights from carefully selected disturbance-free ionosonde records shows that the median seasonal midday values are as follows: winter, 189 km; equinox, 197 km; and summer, 205 km. In each case there is a scatter of heights 10 km each side of these values.

Disturbances are identified on the film record as complexities in the F_2 trace, and are due to off-vertical reflections from curved isoionic surfaces which possess an apparent velocity relative to the observing station. Munro (1953) and Price (1959) have shown that the appearance of the disturbance as a complexity depends on the relationship between the radius of curvature r of the distorted isoionic surface and its height h above the observing point. If $r \geqslant h$ the disturbance passage will cause height and intensity changes in the record only, and these are not normally recorded as disturbance effects. Also, for a given value of r, the number of complexities and therefore recorded disturbances should increase with h. Absence of complexities therefore does not imply absence of disturbances and the film records must be carefully studied for height changes. Unless otherwise stated the statistics considered here concern only those disturbances which have produced complexities on film records.

Munro (1958) has shown that the number of disturbances observed varies considerably from day to day and indicates that, while ease of observation depends to some extent on the ionization gradient at the time, this does not account entirely for the fluctuations. A variation in occurrence of disturbances is found to be often associated with change in height of observation. This is illustrated in Figures 1 (*a*) and 1 (*b*). These are $N(h)$ curves for approximately the same time on consecutive days. On March 24, 1954 there were a large number of 5·8 Mc/s disturbances, whereas on March 25, 1954 there were no 5·8 Mc/s disturbances and very few height rises. It will be noticed that on the disturbed day the 5·8 Mc/s reflection height was approximately 23 km lower than on the quiet day. Munro (1953) has indicated that travelling disturbances are more readily recognized on ionosonde records in a region where electron density changes slowly with height. The resultant manifestations on the film record are then more likely to be complex and hence more easily recognizable. It is possible therefore that differences in electron density gradient may influence the number of observed disturbances. On this basis, since the gradient is steeper on March 25, it would be expected that more disturbances would be observed on

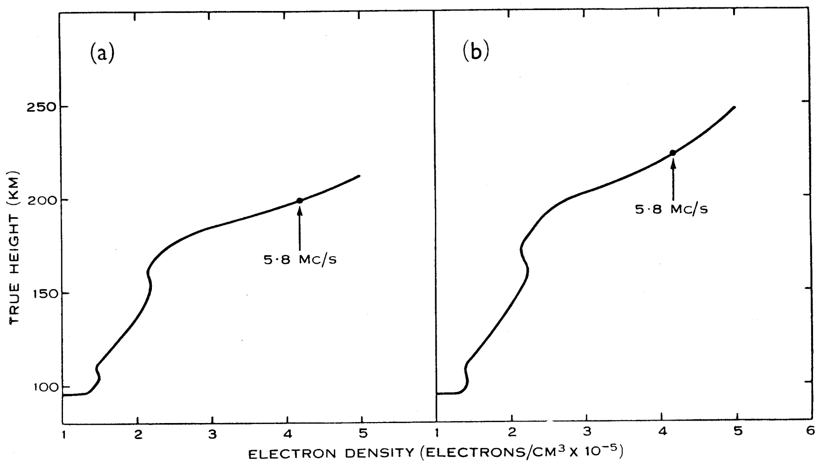

Fig. 1.—Electron density distributions illustrating relationship between height and occurrence of disturbances. (*a*) Camden 1243 hr, March 24, 1954, a day of numerous 5·8 Mc/s disturbances. (*b*) Camden 1230 hr, March 25, 1954, a day of no 5·8 Mc/s disturbances.

this day, whereas the converse is true. In this particular case therefore it would appear that gradient is not a contributory factor and height of observation governs the number of disturbances observed. Several similar cases seem to indicate that disturbances are more prevalent at lower reflection heights.

More definite information on this point was provided by a series of observations taken over a period of several months, using three frequencies simultaneously. A typical record on October 2, 1956 showed disturbed conditions on 4·5 and 5·8 Mc/s, while simultaneous observation on 9·8 Mc/s showed very few disturbances even when height rises as well as complexities were carefully checked on the film record to avoid electron density gradient influence on observational results as discussed above. The $N(h)$ curve of a typical ionosonde record for this period shown in Figure 2 places the 4·5 and 5·8 Mc/s reflection heights at 175 and 202 km respectively, whereas the 9·8 Mc/s reflection point is at the much greater height of 270 km.

The conclusion from these fixed-frequency observations is therefore that in the height range under observation there is a definite tendency for disturbances to be more prevalent at the lower heights, with the probability of an upper boundary to the height at which they are apparent. This has been previously suggested by Heisler (1958).

(*b*) *Variable-frequency Observations*

The fixed-frequency technique described above is particularly valuable for studying small ionospheric disturbances, as it provides a very sensitive means of detection. It is limited, however, to observation of one isoionic contour and therefore cannot record the disturbance effect on a cross section of ionospheric heights. Large disturbances are more readily observed and their nature studied from sequences of ionosonde records made with a panoramic type recorder. Anomalies in such records due to travelling ionosonde disturbances have already been described (Heisler 1958). One particular type described therein as a *C* type

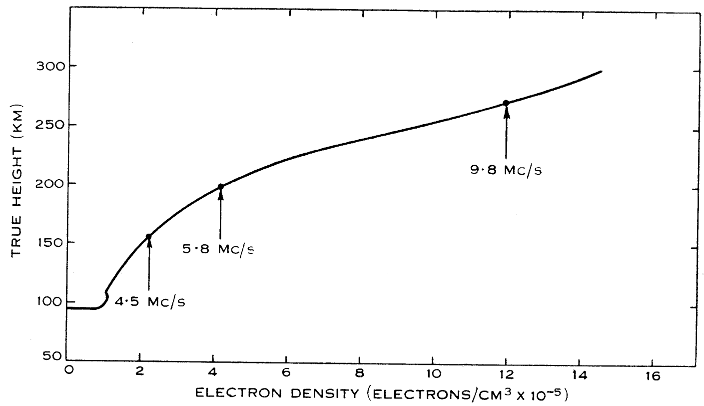

Fig. 2.—Electron density distribution at Camden for 1303 hr, October 2, 1956, showing true height of 4·5, 5·8, and 9·8 Mc/s reflection points.

anomaly occurs as a cusp-shaped trace at the top of F_1 forming a double peak, and gradually travels down the F_1 trace. An $N(h)$ curve of the ion density distribution giving rise to this type of disturbance is shown in Figure 3 (*a*). The F_1 peak in the original virtual height curve corresponds to an electron density of $3\cdot1\times10^5$ electrons/cm^3 and occurs at a height of 160 km. On this day there were no 5·8 Mc/s disturbances or height rises on fixed-frequency records but frequent type *C* anomalies on ionosonde records, so, while disturbances occurred at a height of 160 km and below, there were no disturbances at the 5·8 Mc/s height of 185 km.

In this case the upper boundary must be close to the F_1 peak and below the 5·8 Mc/s reflection height, i.e. at about 170 km. By contrast, records several days later, of which Figure 3 (*b*) is an $N(h)$ analysis, showed both F_1 and 5·8 Mc/s disturbances to be present. In this case the F_1 peak reflection point is at 165 km, approximately the same height as before, but the 5·8 Mc/s reflection point is at 210 km; on this day, therefore, the upper boundary is much higher. It will be seen that the gradient is noticeably different on the two days and this may have some connexion with the change in boundary height.

IV. Height and Direction of Disturbances

The variability of direction of travel of fixed-frequency disturbances has been previously described by Munro (1958). During the summer the mean direction is 120° east of north and during winter 30° east of north with an abrupt change from winter to summer conditions during September-October and a more gradual change from summer to winter conditions during March-April.

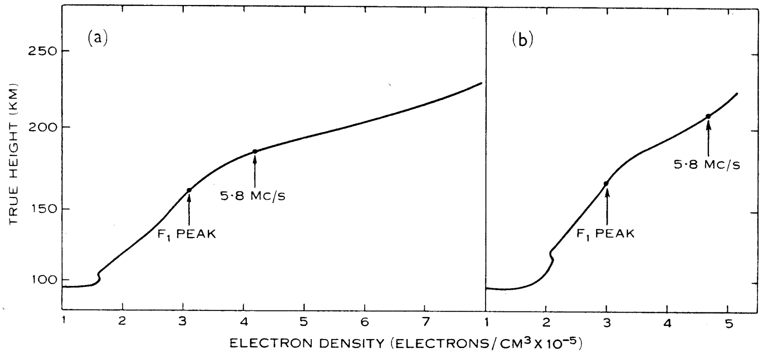

Fig. 3.—Electron density distributions illustrating change in upper bounding conditions for propagation of disturbances during equinoxial months. (*a*) Camden 1040 hr, March 18, 1952. (*b*) Camden 1327 hr, March 22, 1952.

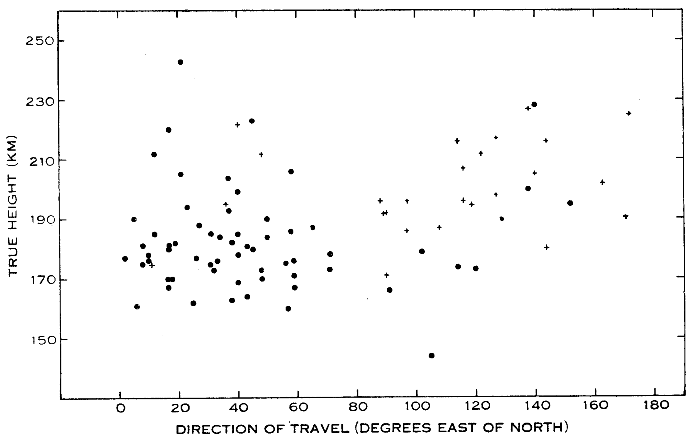

Fig. 4.—Variation of true height with direction of travel (+, summer values ; ●, winter values).

Figure 4 shows a plot of direction against height of observation for disturbance cases in which summer values are plotted with crosses and winter values with dots. There are two obvious groupings ; summer disturbances with heights above 190 km and directions ranging from 100 to 180° ; and winter disturbances with heights below 190 km and directions ranging from 0 to 100°. This is a typical distribution, as summer heights of reflection for a particular frequency in general are higher than winter heights. However, the majority of winter disturbances observed at heights above 190 km also have directions in the range 0–100°, and the few summer disturbances observed at heights below 190 km still have directions in the 100–180° range. It would appear therefore that change in direction is mainly seasonal and it is not valid to associate it directly with change in height of observation.

This apparent change of direction with height of observation can be further studied during equinoxial transitional periods when directions are variable. The $N(h)$ curves for such a case are shown in Figure 5. Figure 5 (a) is an $N(h)$ curve for 1151 hr, September 8, 1952, a day of predominant summer directions, and shows that a disturbance travelling 152° east of north at the time of this ionosonde recording was observed at a height of 195 km. However, September 11, 1952 was a day of predominant winter directions and on a similar curve shown in Figure 5 (b) for 1301 hr a disturbance travelling 33° east of north was observed

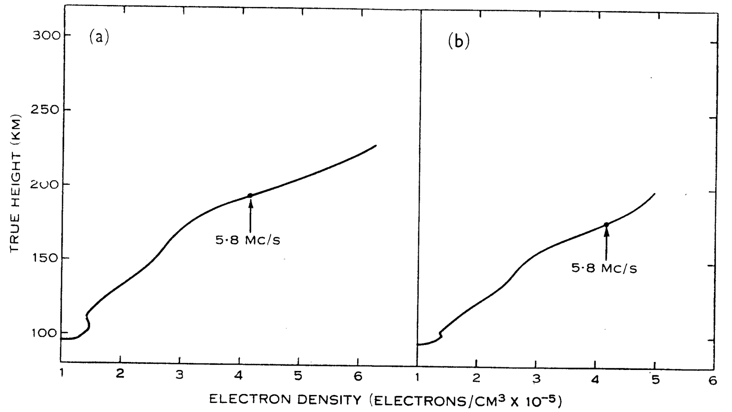

Fig. 5.—Electron density distributions illustrating relationship between height and direction of travel of disturbances. (a) Camden 1151 hr, September 8, 1952, a day of predominant summer directions. (b) Camden 1301 hr, September 11, 1952, a day of predominant winter directions.

at a height of 177 km. It will be noticed that this height is 18 km lower than previously. This difference in observational height for disturbances travelling in different directions has been observed in several equinoxial examples. In all cases low heights of observation are associated with winter directions while high heights of observation correspond to those disturbances with summer directions.

Since Figure 4 would suggest that during any particular season there is no direction gradient with height in the region of the ionosphere considered, it would appear that during the equinoxes there is some form of unstable control which not only causes the ion density distribution to fluctuate between normal summer and normal winter conditions but also governs the direction of movement of disturbances in these distributions.

A similar fluctuation in disturbance directions has been observed during summer, but only during recent sunspot maximum years when on occasional days predominant winter directions occur. A case in particular occurred on January 19, 1957 and Figure 6 (a) shows a typical electron density distribution just prior to a disturbance on this day. Figure 6 (*b*) is an $N(h)$ distribution prior to a summer direction disturbance on the next day. It will be noticed that the 5·8 Mc/s reflection heights are almost identical. Moreover, in contrast to the equinoxial case of Figure 5 there is no very marked change in overall electron density distribution. Several such examples have been analysed and show the same features. It would appear, therefore, that in these cases the factors controlling direction of travel mentioned in connexion with Figure 5 are not significant and, since the particular phenomenon is observed only during sunspot maximum, some form of solar control is indicated.

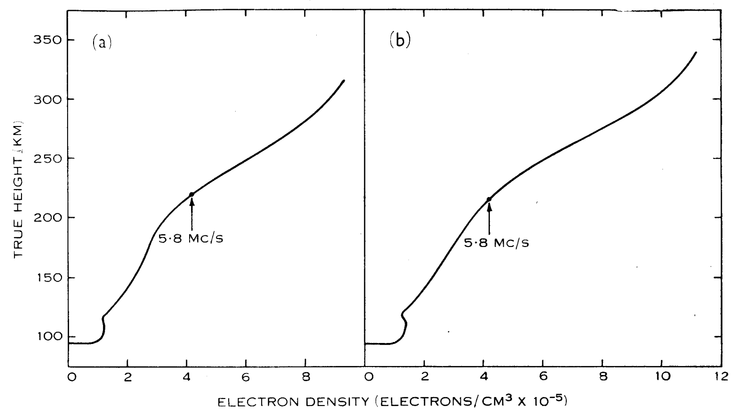

Fig. 6.—Electron density distributions illustrating relationship between height and direction of travel of disturbances during summer at sunspot maximum. (*a*) Camden 1134 hr, January 19, 1957, 5·8 Mc/s disturbance, direction 40° E. of N. (*b*) Camden 1115 hr, January 20, 1957, 5·8 Mc/s disturbance, direction 144° E. of N.

V. Height and Speed of Disturbances

As previously described (Heisler 1958), large ionospheric disturbances extend over a range of ionospheric heights and travel long distances with no apparent change in form or amplitude. Moreover, observations (Munro and Heisler 1956*a*, 1956*b*) indicate that a travelling disturbance always has an apparent vertical component of progression which is assumed to be the result of a forward tilt in the wavefront of the disturbance. If this were due to a height-speed gradient it would be difficult to understand how the disturbance could propagate without considerable change in form, particularly over large distances where tilt of the wavefront would become almost horizontal and hence vertical progression of the anomaly on the ionosonde record would be extremely slow. This is supported by the evidence of Figure 7, which shows the relationship between speeds of disturbances and height of observation. The random scatter of points suggests that in the region 160–220 km no correlation exists.

Distance of travel and duration of small fixed-frequency disturbances have not been fully investigated, but initial examination of several cases indicates that they are much less than those of the large ionospheric disturbances. It is possible, therefore, that an individual fixed-frequency disturbance could possess a speed gradient with height. This would not be obvious on the statistic plot of Figure 7 and would restrict the scale of propagation of the disturbance.

Briggs and Spencer (1954) suggest that a height-speed gradient may exist at times of high magnetic activity, but, to arrive at this opinion, use Mitra method E and F region and radio star scintillation speed data.

As emphasized previously, there is uncertainty about precise heights of measured F-region movements using the Mitra method and a similar ambiguity exists in radio star scintillation measurements. Moreover, there is doubt as to whether the same phenomena are being observed in each case and whether indeed these phenomena are the same as those measured at this laboratory by different experimental techniques. In our observations no evidence of such an effect has been found.

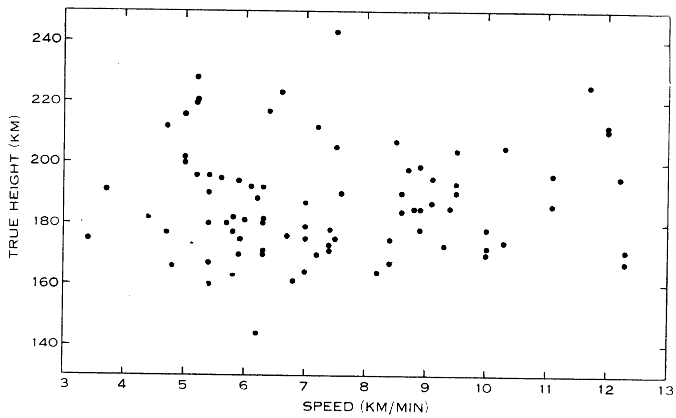

Fig. 7.—Variation of true height of occurrence with speed of disturbances.

Ratcliffe (1954) refers to a height-speed gradient in the ionosphere of 1 m $\mathrm{sec}^{-1}\,\mathrm{km}^{-1}$. This apparently originates in a private communication from Beynon and Thomas, quoted by Briggs and Spencer (1954). There is no indication whether this refers to all disturbance phenomena or to a particular case.

It is of little value to postulate a general gradient of speed with height in the ionosphere when there is a high variability of observed speeds in the region 160–220 km. It is probable that the inconsistency exists because of different phenomena being measured by different experimental techniques or is due to different geomagnetic observational locations. The use of virtual heights, in particular, can give very misleading results.

VI. Conclusions

The heights of observation of travelling disturbances and the mechanics of the phenomenon have been investigated by the study of associated $N(h)$ electron density profiles. Results apply particularly to the sunspot minimum years 1952–1954 and are as follows:

(1) Travelling disturbance phenomena are often contained by an upper boundary when anomalies are observed below this height only. The boundary is not always evident and may fluctuate in height from day to day.

(2) During a particular season there is no definite correlation between direction of travel of disturbances and height. Direction of travel seems to be mainly related to season, change in season being accompanied by a change in ion density distribution and a change in direction of travel of disturbances. Further, variability in direction of travel occurs during summer, but only in sunspot maximum years. There is little accompanying change in ion density distribution or height and the effect may be related to solar-geomagnetic phenomena.

(3) There is no significant correlation between speeds of disturbances and height of observation in the ionospheric region considered, which includes heights between 160 and 230 km. The observed long-distance propagation of large travelling disturbances also suggests that a height-speed gradient is improbable.

VII. Acknowledgments

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