

## Horizontal Motion in Ionospheric Regions—A Review

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A historical account of the discovery of a radio method of investigating horizontal drift in the ionosphere is presented. The discovery was made by the author around 1947, while he was working at the Cavendish Laboratory, Cambridge. The spaced-receiver technique, or A-1 method, involves three receivers spaced at the corners of a right-angled triangle spaced about one wavelength apart. The fading of a down-coming pulse transmitted from a nearby transmitter, as received by the three receivers, is simultaneously recorded on a 35-mm film and displacement between any two of the records gives the magnitude and direction of the velocity of the horizontal drift. The method has been followed throughout the world and specially during IGY and IGC. Subsequently, a few other methods for similar measurements have been developed. These have been compared for their relative merits. The spaced-receiver technique has stood the test of time and is still the best method for investigating horizontal drift in the ionosphere at all times during day and night.

### 1 Introduction

I am grateful to the Organising Committee for S K Mitra Commemoration Seminar for inviting me to speak on *horizontal drift in the ionosphere*. I have chosen the subject with which I started my research career more than four decades ago. The outline of this research has been published in the *Upper Atmosphere* (2nd Edition) by Prof. S K Mitra. The spaced-receiver technique<sup>1</sup> for measuring horizontal drift in the ionosphere was developed while I was a research student at the Cavendish Laboratory, University of Cambridge, during 1946-48. The method is currently known as D<sub>1</sub> technique, for in subsequent years a few other techniques D<sub>2</sub>, D<sub>3</sub> etc. have been developed to obtain similar results. In this talk, I would like to describe briefly: (a) the historical account of measuring horizontal drift in the ionosphere, (b) summary of the results obtained so far in other laboratories of the world, where the same method was followed, (c) other techniques subsequently developed and results obtained therefrom and (d) unsolved problems and future work.

Although horizontal drift in the ionosphere has been investigated in the beginning rather sporadically through noctilucent clouds and meteor trails and subsequently quite extensively by the spaced-receiver technique in many parts of the world for many years, a clear picture of the drift system has not yet emerged.

The spaced-receiver technique has, however, stood the test of time and has been accepted as, perhaps, the best method of investigating the horizontal drift system. During the IGY, more than 70 organizations at different parts of the world carried out extensive measurements of drift system following this technique. The investigation was continued through IQSY and IGC. In India, extensive measurements were made at AIR stations at Delhi and Trivandrum; Physical Research Laboratory, Ahmedabad; Thumba Equatorial Rocket Launching Station (TERLS), Trivandrum; Banaras Hindu University, Varanasi; Calcutta University, Calcutta; Andhra University, Waltair; Defence Electronic Research Laboratories, Hyderabad; Udaipur University, Udaipur and a few other places. It will not be possible to discuss all the results obtained. Only salient features of the observations made will be briefly reviewed.

### 2 Historical Background

The possibility that there might be a steady wind in the ionosphere analogous to that existing in the lower atmosphere attracted the attention of many earlier investigators. There was great difficulty in a thorough experimental study of the subject as there was no direct means of approaching ionospheric heights. The appearance of noctilucent clouds at a height of about 80 km above the surface of the earth provided an indirect approach to the subject to many astronomers.

The first systematic observations of the noctilucent clouds were reported by Otto Jesse<sup>2</sup>, the Berlin

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astronomer in 1884. The clouds were visible some 20 min after sunset and appeared to have a silver or bluishwhite colour which changed to golden yellow on the horizon as darkness approached<sup>3</sup>. Jesse photographed these clouds from two observing stations situated at the ends of a line 35 km long. In later years, these clouds were systematically observed, wherever they appeared, by workers both in the northern and southern hemispheres. Information, although of a very limited nature, was available of the various characteristics of these clouds from 1883 to 1934. There was a high degree of consistency in the determination of their heights made in different years and from different locations. The most probable height of appearance of these clouds was found to be 80 km and the velocity ranged from 44 to 83 m/s with the mean near 60 m/s. The direction of the movement was predominantly towards NNE. The origin of these clouds is still a mystery. In subsequent years, some more information has been added from similar investigations. But the appearance of these clouds was so unpredictable and bad weather being an inhibitive factor, a systematic investigation of the horizontal drift system from the motion of noctilucent clouds was not possible. Nevertheless, it is of great historical importance to note that the first ever observation of a horizontal drift in the ionosphere was provided by the motion of noctilucent clouds.

The long enduring meteor trail also supplied information about the drift system at a height of about 80 km. Oliver's<sup>4</sup> observations on the Leonid meteors of 1932 gave the near-end height of the meteors to be 88 km and the velocity varied between 37.2 and 65.5 m/s. In subsequent years, specially after the second world war, radar detection of meteor trails was taken up by many investigators. A new branch of science, viz. Meteor Astronomy has been developed from these investigations. We shall have occasion to refer to these results later in this paper.

It is important to note that around 1930s, there was a fair amount of information about a horizontal drift system at a height of about 80 km blowing the noctilucent clouds and distorting the meteor trails. But there was no method to investigate the problem at all times of the day and night and at different heights above the earth's surface. Pawsey<sup>5</sup>, while working on the lateral deviation suffered by a downcoming radio wave, once detected wind of the order of 100 m/s. Mimno<sup>6</sup> found effects of movement of the E-layer using two receivers about 60 km apart. There was a difference of 1 min between the fading at the two receivers pointing to velocities of about 1 km/s. Until about 1945, no systematic attempt was made to study the horizontal drift system by means of a radio technique.

In 1946, the spaced-receiver technique for measuring horizontal drift in the ionosphere was first developed at the Cavendish Laboratory, Cambridge. The principles involved were quite simple and were as follows:

For radio waves reflected from the ionosphere, the received amplitude at any point has been found to vary with time. This is commonly known as fading. If one uses pulsed transmissions in which interference between ground wave and skywave and between skywaves is eliminated, even then fading occurs. A plausible explanation of this phenomenon is that there are irregularities in the ionosphere and an incident wave gets scattered from them. The scattered waves combine at the receiving point and if the irregularities are moved by a steady drift or by a random motion, there will be fading of the resultant wave. In other words, one may consider the ionosphere as a diffracting screen (Fig. 1), the irregularities comprising the diffracting centres. When this screen is moved, one would expect a fading of the received signal.

Let us now place three receivers at the corners of a right-angled triangle and record the fading patterns simultaneously at the three receiving points employing pulsed transmissions. If the irregularities are blown by a steady horizontal drift unchanged in form and without any other displacement amongst themselves, one would expect the patterns to be similar but displaced with respect to one another. The measured time shift can then be converted into velocity of the irregularities. This was the basic principle of the spaced-receiver technique employed by the author in 1946.

### 3 Experimental Arrangement (Ref. 1)

The first ever experiment to investigate horizontal drift was made with frequencies in the range 2-6 MHz

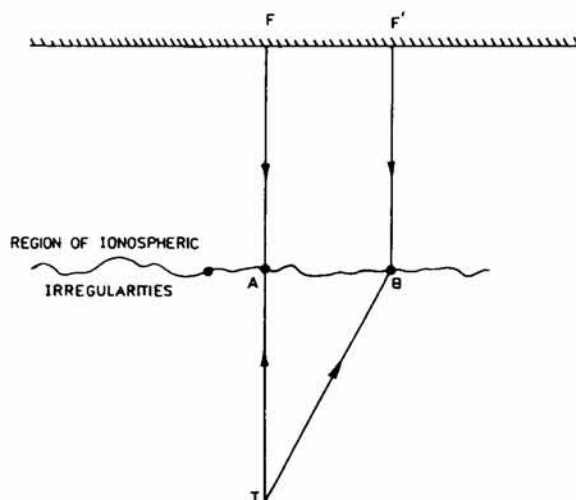


Fig. 1—To illustrate diffractive transmission through an irregular region

and with pulses of duration about  $200\ \mu\text{s}$ . Most of the observations were made with a transmitter situated 100-150 m from the receiver. The transmitting antenna was either a vertical rhombic or a horizontal half-wave dipole. The pulses were received at three receivers placed at the corners of a right-angled triangle as shown in Fig. 2.

The outputs from the three receivers were brought to a central recording point and applied to three recording oscilloscopes without any time base so that there appeared on the screens bright lines proportional to the output of the receivers. Examination of the echo pattern on a monitor oscilloscope enabled the desired echo to be selected by an electronic gate of variable width and delay (Fig. 3). The gated output modulated the brightness of the oscilloscope. Right-angled reflecting prisms were used in conjunction with a camera lens to focus the three traces side by side on a moving 35 mm film and the time variations of the

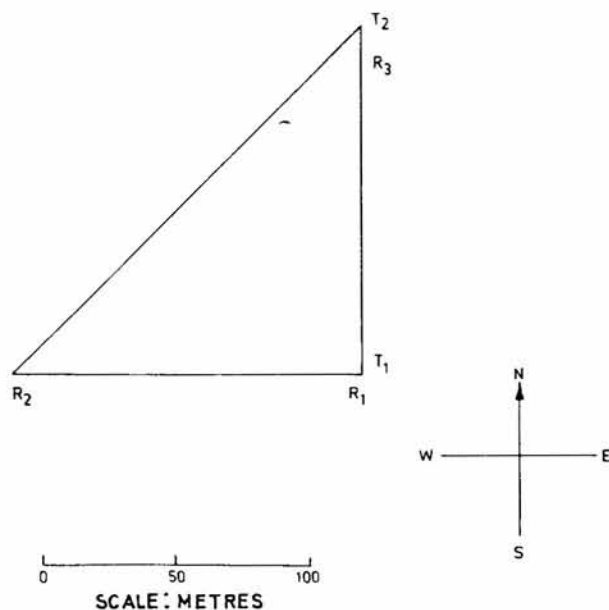


Fig. 2—Plan of the receiving system with position of the local transmitter

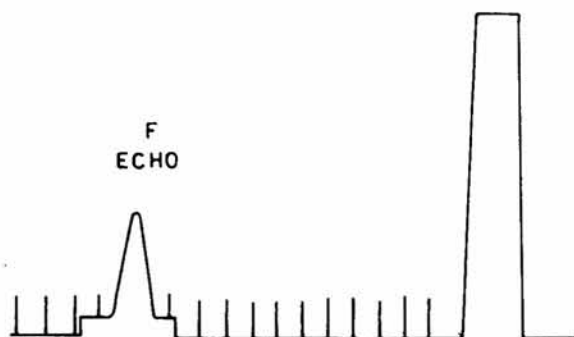


Fig. 3—Gated echo

amplitudes of the three echoes were thus photographically recorded. The plan of the system is shown in Fig. 4.

Time marks were produced on the moving film every 15 s by momentarily closing the camera lens so as to produce narrow gaps in the continuous fading curves. The film was moved at a rate of 10-15 cm/min. A typical fading record indicating the presence of a horizontal drift is shown in Fig. 5.

I have spoken of the historical background of the first experimental set-up for investigating horizontal drift system. Subsequently, there have been many improvements in the techniques but the basic principles have remained unchanged. Electronic Sequence Switching Systems have replaced the receivers by aerials and only one receiver is enough for the purpose. Similarly, the optical system has been replaced by splitting the cathode ray beam and beam switching.

In actual practice, the three patterns do not remain absolutely identical. Sometimes, there are considerable variations in the patterns themselves. Thus, in addition to a steady horizontal drift, there are random motions of irregularities amongst themselves although usually of less magnitude than the steady drift. When random motion predominates, the identical nature of the fading patterns disappears and it becomes difficult to deduce drift velocities. But such instances are rare and in this experiment, on most of the occasions, one obtains similar but displaced fading patterns. The velocity of

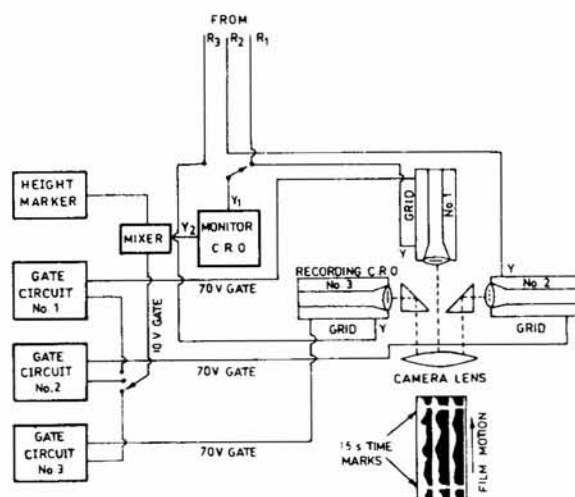


Fig. 4—The recording arrangement

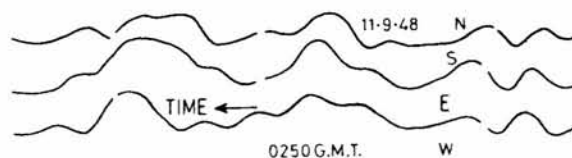


Fig. 5—Fading indicating horizontal drift

the horizontal drift can be determined in the following manner.

Let A and B (Fig. 6) represent a pair of receiving stations a distance  $x$  apart on an east-west line and let the drift velocity  $V$  be in the direction AP, BQ making an angle  $\phi$  with the north. Then the time shift  $t_x$  giving maximum correlation between the two fading curves recorded simultaneously at A and B is given by

$$t_x = x \sin \phi / V \quad \dots (1)$$

Similarly, the time shift  $t_y$  between the north-south pair of receivers (distance  $y$  apart) is given by

$$t_y = y \cos \phi / V \quad \dots (2)$$

The components of the drift velocity  $V_x, V_y$  along east-west and north-south directions, respectively, are given by

$$\begin{aligned} V_x &= V \sin \phi \\ V_y &= V \cos \phi \end{aligned} \quad \dots (3)$$

From the time shifts in the actual records, we can measure the "apparent" components  $V'_x$  and  $V'_y$  defined as

$$\begin{aligned} V'_x &= \frac{x}{t_x} = \frac{V}{\sin \phi} \\ V'_y &= \frac{y}{t_y} = \frac{V}{\cos \phi} \end{aligned} \quad \dots (4)$$

Therefore

$$\frac{1}{V^2} = \frac{1}{V'^2_x} + \frac{1}{V'^2_y} \quad \dots (5)$$

Thus Eq. (5) enables us to calculate the magnitude of the true drift velocity from a knowledge of the "apparent" components. The measured value of  $V$  has to be divided by a factor 2, since the diffraction pattern sweeps past the receiver with twice the velocity of the drift. The direction of the drift is given by

$$\tan \phi = \frac{V'_y}{V'_x} \quad \dots (6)$$

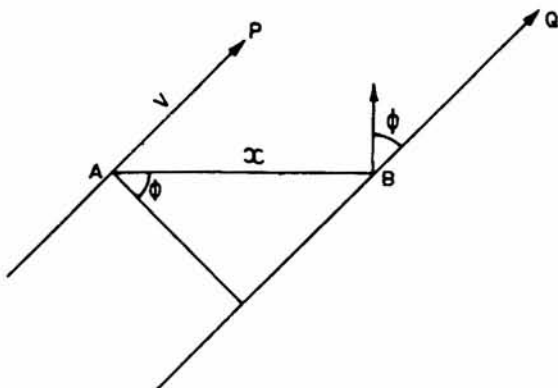


Fig. 6—Diagram to illustrate the calculation of drift velocity

Thus, from the apparent components in the E-W and N-S directions directly obtained from the time shift in the fading curves, we can obtain the true velocity and the direction of the drift.

Since random motion of the irregularities amongst themselves produces some dissimilarity between the fading patterns, it is always desirable to carry out the full correlation analysis in order to arrive at the correct value of the time shift. For this purpose, a cross-correlogram between the two fading curves is obtained in the following manner.

Let  $x(t)$  represent the departure from the mean of the signal amplitudes on one record at time  $t$ , and  $y(t)$  the corresponding quantity on the other record. We define the cross-correlation coefficient,  $\rho(\tau)$ , between  $x$  and  $y$  by the expression

$$\rho(\tau) = \frac{\Sigma [x(t)y(t-\tau)]}{\{\Sigma x(t)^2 \Sigma y(t-\tau)^2\}^{1/2}} \quad \dots (7)$$

If the quantity  $\rho(\tau)$  is evaluated for different values of  $\tau$ , it will have a maximum at a value corresponding to the time displacement between the two fading curves. An example of an analysis made in this manner for the middle and bottom (E-W pair) fading curves of Fig. 5 is shown in Fig. 7. The time displacement is seen to be 1.5 s.

#### 4 Early Experimental Results

In the experiment at Cambridge, the author could not carry out extensive measurements lasting for several years. But very consistent results were obtained and some of the early results are described below.

Fig. 8 shows the distribution of the magnitude of the drift velocities. The most probable value is seen to be about 50 m/s. Fig. 9 shows the polar histogram of the direction of the drift. The most probable value is found to be towards NNW.

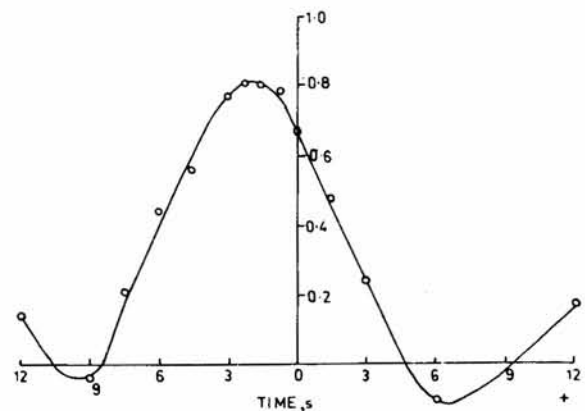


Fig. 7—"Cross Correlogram" of fading curves at two receivers. The function  $\rho(\tau)$  of Eq. (7) is plotted vertically, and the time ( $\tau$ ) horizontally

The author carried out the same experiment at Delhi during the IGY (1958-1964). Fig. 10 shows the distribution of the magnitude of the drift velocity observed at Delhi. The most probable value is around 90 m/s somewhat higher than that observed at Cambridge. Fig. 11 shows the polar histogram of the direction of the drift velocity, and it is towards south.

Observations of drift by the spaced-receiver technique have been made in many parts of the world

numbering, perhaps, more than 100. Great variability in direction has been observed. But the magnitude of the drift velocity is found to be between approximately 50 and 100 m/s. Fig. 12 shows the observations made at three stations of USSR. Fig. 13 shows similar measurements made at six stations in USSR. Table I gives the values of  $V$  (in m/s) and  $\phi$  (in deg. east of north) at some of these stations. The magnitude of the velocity is found to be within a range of 40-120 m/s and the direction between 220 and 290 deg. i.e. toward SSW.

Location of the drift system has also been subjected to many investigations. If the frequency is low and the echo is from the E-layer, the drift velocity measured is

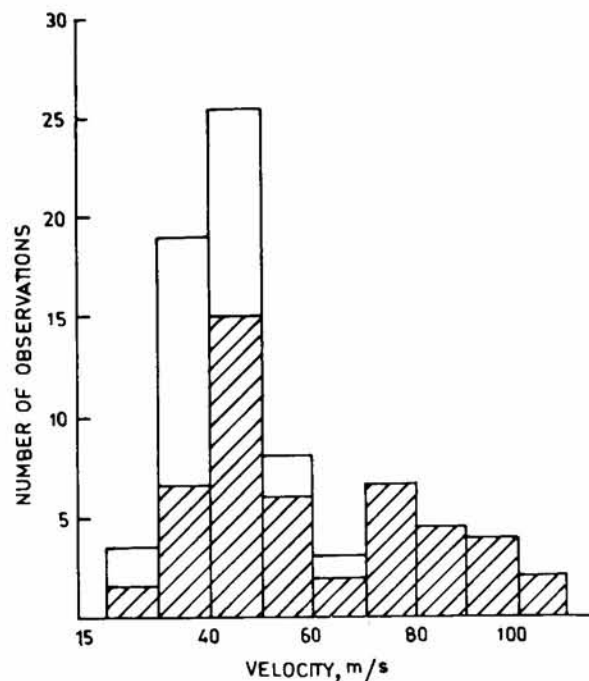


Fig. 8—Histogram showing the distribution of the observed wind velocities; the shaded areas refer to observations taken throughout a 24-hr period

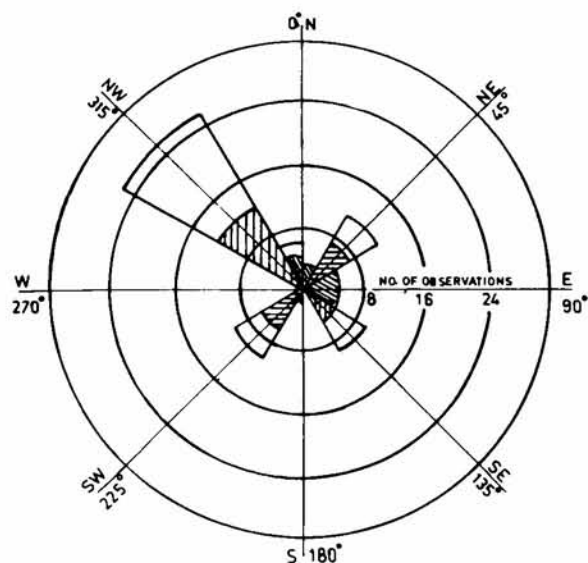


Fig. 9—Polar histogram of the direction of wind motion; the shaded areas refer to observation taken throughout a 24-hr period

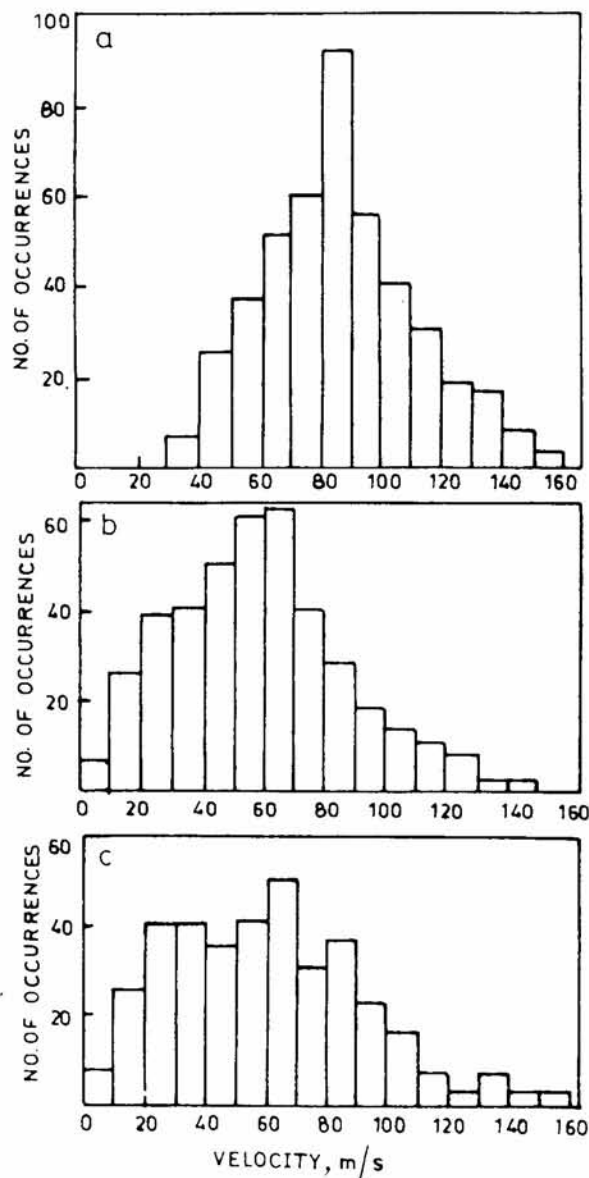


Fig. 10—Histogram showing the distribution of: (a) the magnitude of the drift velocity; (b) histogram of the E-W component of the drift velocity; and (c) histogram of the N-S component of the drift velocity

called as E drift,  $V_E$ . Similarly, if the echo is from the F-layer, the measured drift is called  $V_F$ . The drifts whose values are measured by this technique could occur either in the reflecting region for the wave used or in an irregular absorbing or refracting region below the level of reflection or at both the places. While for echoes from E, we could be reasonably sure about the location of the drift system, for F-layer echoes we could not say with conviction that the measured drift occurs in the F,

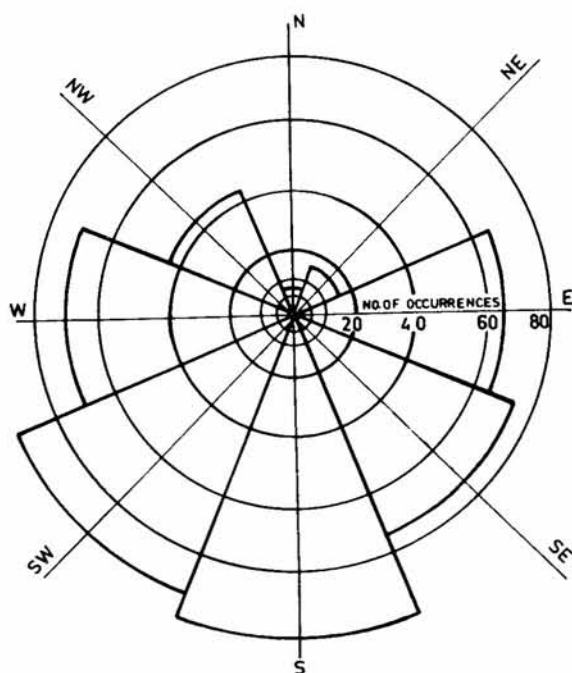


Fig. 11—Polar histogram of direction of the drift velocity

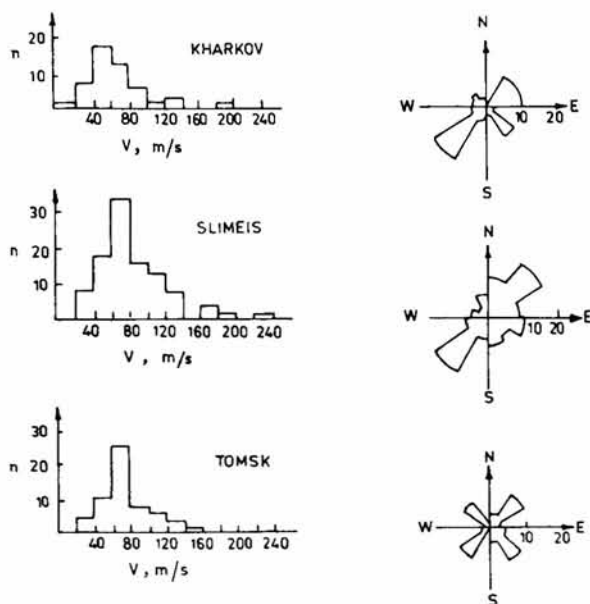


Fig. 12—Distribution of speeds and of directions of the drifts in region-E for observation from July 1957 to April 1958

for the diffracting screen known to exist in E would profoundly influence the final result. This point has yet to be resolved.

Some of the drift measuring stations have been in operation for a full solar cycle. At Ibadan (Nigeria), measurements of E-region drift were carried out from 1958 to 1974. It is interesting to find that the sunspot

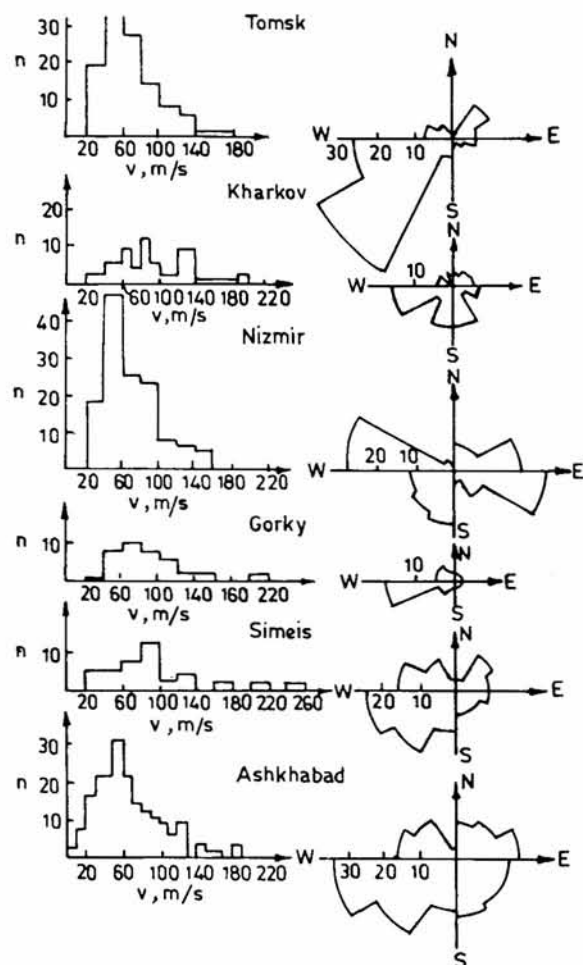


Fig. 13—Distribution of speeds and of directions of the drifts in the region-F2 for observations from March to May 1958

Table 1—Values of  $V$  and  $\phi$  at Different Stations

| Place of observation | Period of observation | $\phi$ deg   | $V$ (m/s) |
|----------------------|-----------------------|--------------|-----------|
| Ashkhabad            | Jan. 1958-Feb. 1958   | $240 \pm 20$ | 60-80     |
| Gorky                | June 1957-Apr. 1958   | $260 \pm 20$ | 60-80     |
| Moscow (NIZMIR)      | 1956                  | $280 \pm 20$ | 80        |
|                      | 1957                  | $280 \pm 10$ | 80-100    |
|                      | Jan. 1958-May 1958    | $270 \pm 10$ | 50-80     |
| Simeis               | Dec. 1957-July 1958   | $220 \pm 40$ | 60-100    |
| Tomsk                | Sept. 1957-Apr. 1958  | $240 \pm 10$ | 100-120   |
| Kharkov              | Oct. 1955-Apr. 1956   | 270          | 80-100    |
|                      | Sept. 1957-May 1958   | 240          | 40-60     |

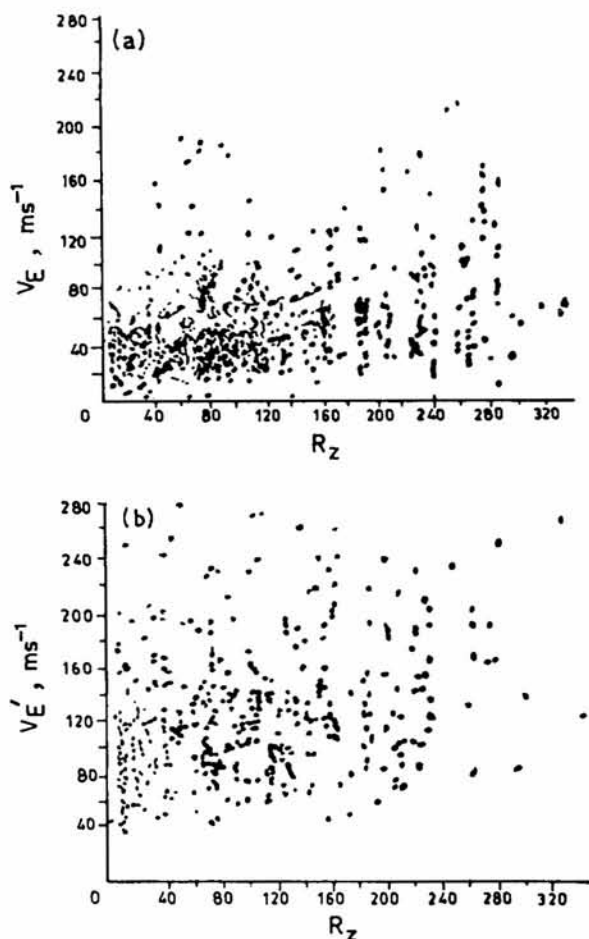


Fig. 14—Scatter plot for Ibadan showing the variation with Zurich sunspot number,  $R_z$ , of the magnitude of (a) the true velocity  $V_E$  and (b) the apparent velocity  $V'_E$  for the ionospheric E-region. The scatter plots are based on the data for 0900, 1200 and 1500 hrs

number has no effect on the magnitude of the drift velocity. Fig. 14 shows a scatter plot giving the variation with Zurich sunspot number  $R_z$  of the magnitude of (a) the true velocity  $V_E$  and (b) the apparent velocity  $V'_E$ . No significant dependence of  $V_E$  on sunspot number is indicated.

It is impossible to describe all the results obtained so far, particularly when the measurements have been in progress since 1947 at many different places on the earth. The same technique has been employed to measure drift in the D-region through partial reflection on high power pulsed transmissions and on long waves, assuming reflection taking place in the D-region.

### 5 Drift Measurements by Other Techniques

Horizontal drift in the ionosphere has also been measured by a few other techniques. Some of the important and commonly used methods are:

(a) Movement of sodium vapour trails from rocket exploration of the E-layer, (b) Doppler shift measurements by coherent radar method and (c) Radio meteor measurements.

In technique (a), sodium or other luminescent vapour is released from a rocket. The vapour trail is kept under observation through radar. Its movement gives an indication of the neutral air drift at ionospheric heights. Many measurements have been made at different parts of the world following this technique including those at Thumba. The order of velocity is found to be the same as observed in the spaced-receiver technique. In view of the short duration of the life of a vapour trail, long-term measurements are not possible.

In the second technique, high-frequency pulsed transmitter is used in conjunction with a directive antenna. The moving irregularities in the layer would give rise to Doppler shift which is measured on the ground. From the Doppler shift, the drift velocity is determined<sup>7</sup>.

In the third technique, VHF radio waves, usually pulses, are transmitted and reflections from meteors obtained. The motion of the echoes, as observed on the ground radar, would enable a determination of the drift system. This is commonly known as D<sub>2</sub> method. It would be interesting to know how the drift velocities observed by different techniques compare. In a recent experiment, a direct comparison has been made of the velocities obtained by using all the three techniques simultaneously at low and midlatitude stations<sup>8</sup>.

The 'apparent' velocity measured by the spaced-receiver method (D<sub>1</sub>) at the dip equator is in good agreement with the phase velocity of the type-2 irregularities observed by coherent radar at 21.3 MHz which is known to be a good approximation of the electron velocity in the E-region during daytime. At midlatitude, the 'real' velocity deduced by the complex correlation analysis from the spaced-receiver technique at 2.1 MHz is equal to the drift velocity measured by the radio-meteor method at the same altitude and can be associated with the neutral gas velocity in the E-region.

Fig. 15 shows a comparison of spaced-receiver technique (D<sub>1</sub>) with 21.3 MHz coherent radar at low latitude in July 1973. It would be noticed that both the velocities are in very good agreement. Fig. 16 shows a comparison of spaced-receiver technique (D<sub>1</sub>) at 2.1 MHz with meteor radar (D<sub>2</sub>). Here too, the correlation between the two is excellent suggesting that the measured drift was the neutral wind at E-region altitude. There are many other measurements on record to show that the drift velocity measured by the spaced-receiver technique is the correct velocity at ionospheric heights.

## 6 Multi-aerial Experiment

If one takes a close look at the fading curves used for measuring drift, one finds a great deal of dissimilarity between the records. We have explained these dissimilarities on the basis of random motion of ionospheric irregularities. It is also evident from the results obtained by following the spaced-receiver technique that they do not repeat at different places of observation. A larger number of aerials than three have

been used to obtain more detailed information about the drift.

Briggs<sup>9</sup> developed a large aerial array in 1968 to study fading patterns. A total of 89 pairs of dipoles were used in the array. The dipole aerials lie on a rectangular matrix with a roughly circular outline. The frequencies employed were 1.98 MHz and 5.99 MHz. The dipoles are resonant at lower frequencies but also operate at the higher frequency, their third harmonic. The dipoles

### SIMULTANEOUS IONOSPHERIC DRIFT OBSERVATIONS

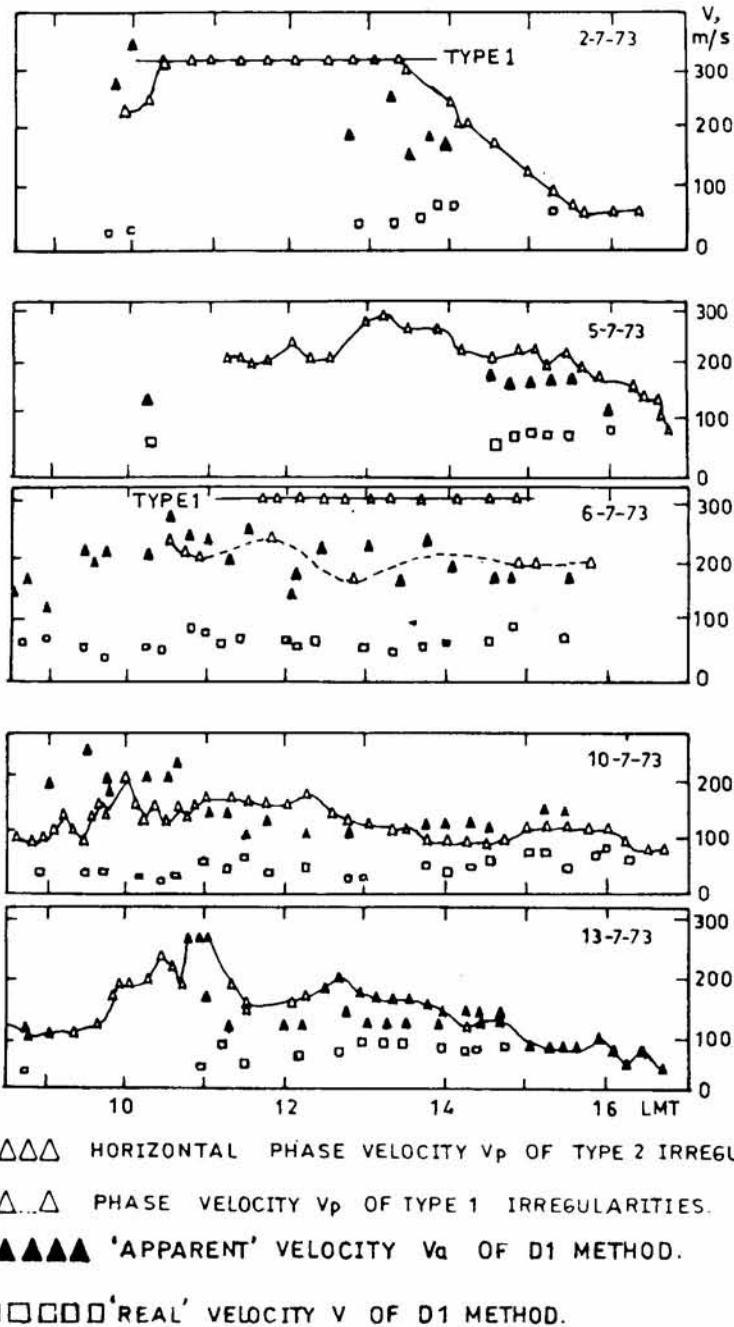


Fig. 15—Comparison of closely-spaced received technique ( $D_1$ ) with 21.3 MHz radar results at low latitude in July 1973

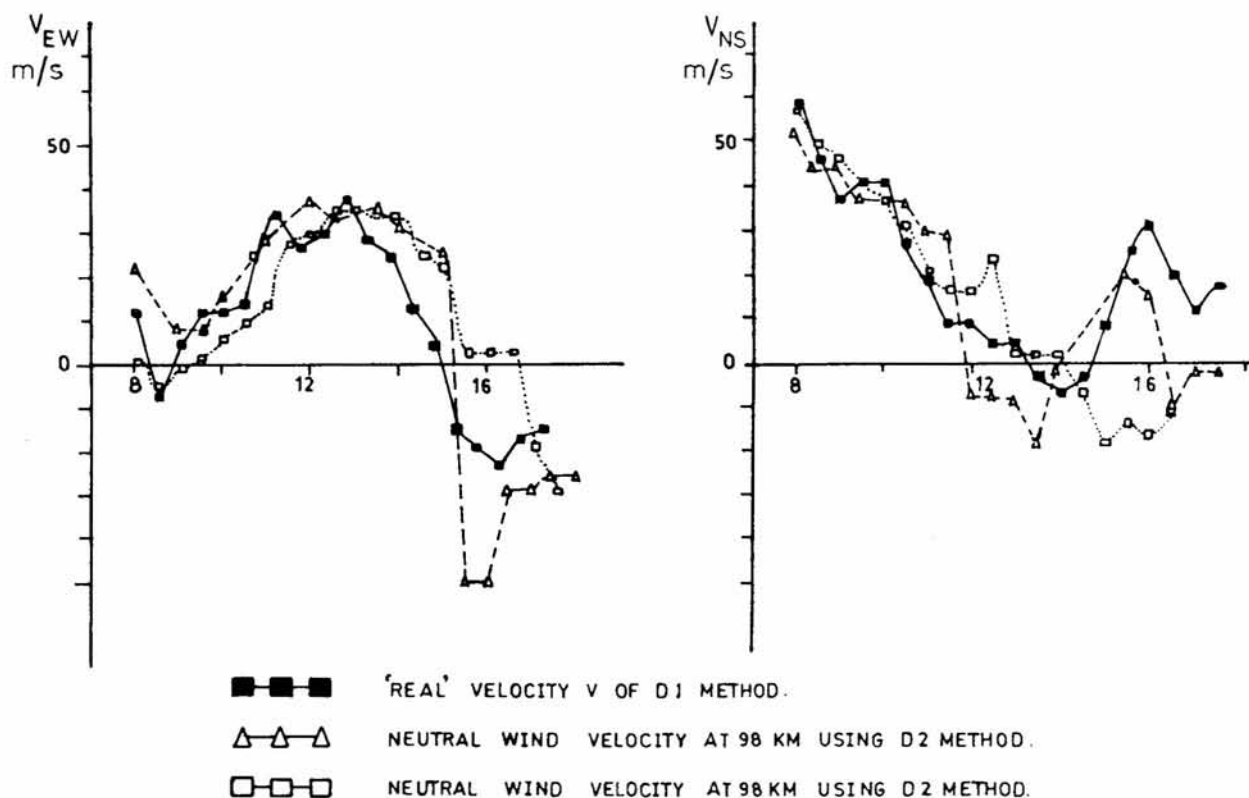


Fig. 16—Comparison of closely-spaced receivers technique ( $D_1$ ) at 2.1 MHz with meteor radar ( $D_2$ ) in France

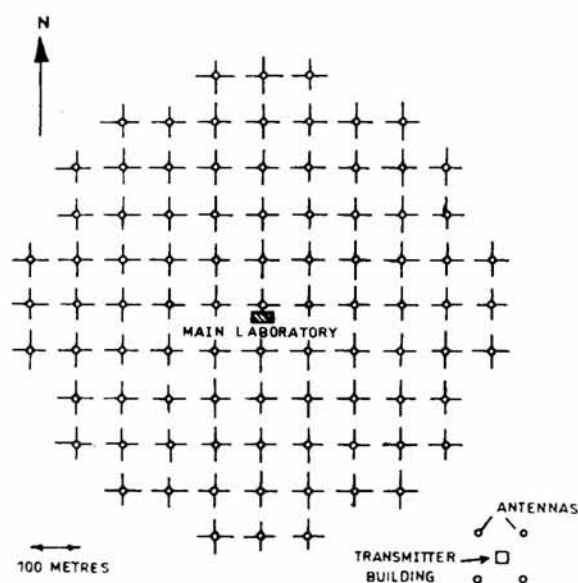


Fig. 17—Buckland Park array

were placed  $\lambda/10$  apart over the ground. A schematic of the Buckland Park Aerial Array is shown in Fig. 17. The main array of 178 dipoles has so far been used only for reception. The pulsed transmission takes place through a separate array of four folded dipoles arranged around a square and situated adjacent to the

receiving array. Left or right circular, or linear polarization can be transmitted.

Using the whole array in conjunction with 89 separate radio receivers, it is possible to record an instantaneous pattern of echo strength over the ground, both photographically and digitally. It is then possible to observe how far the pattern moves in a given time. Using digital methods, the pattern velocity is obtained by computing a two-dimensional cross-correlation function between two patterns recorded with a known time-separation. The correlation shows a peak at the required vectorial displacement. Fig. 18 shows an example<sup>10</sup>.

The method is decidedly an improvement over the spaced-receiver technique employing the three aerials. But Briggs himself has stated, "it is difficult to use it as a routine owing to the problems involved in maintaining 89 separate radio receivers and the large amount of computing involved. The older method seems to be the best suited for the purpose; it is simple and the results are not inaccurate".

## 7 Nature of the Drift System

There is still some controversy as to the exact location of the drift system. Is it always in the E and lower D? Or could there be a drift in F? The motion of natural air in D and E has been investigated through

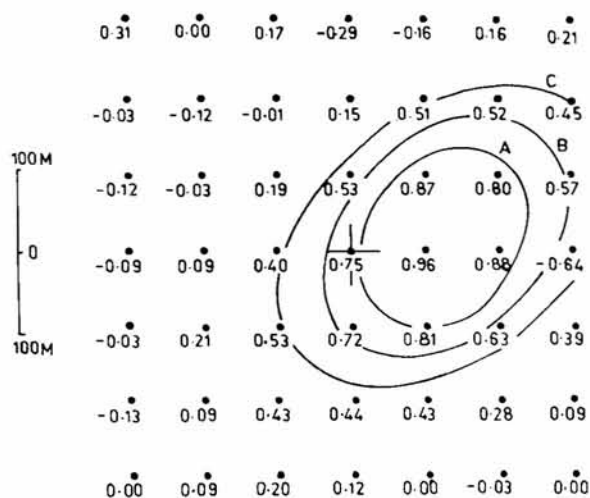


Fig. 18—Two dimensions of cross-correlation

rocket exploration. Let us first consider the E-layer in midlatitude, where equatorial electrojet does not complicate the problem. Because of theoretical uncertainties as to what motion is being measured, comparisons with other methods are particularly important for this region of the atmosphere. Kent and Wright<sup>11</sup> have pointed out that although many such comparisons had been carried out, they all referred to observations widely separated either in time or in space. In general, the agreement was as good as might be reasonably expected and the general conclusion was that the spaced-receiver technique measures the neutral air motion. The measurements compared were with rocket trials, sodium clouds, meteors and with general wind circulation believed to exist in the height range of 0-100 km as derived from a variety of techniques<sup>12</sup>.

For F-region, EW drifts measured by the spaced-receiver technique are in good agreement with the predictions of the electrodynamic theory first proposed by Martyn<sup>13</sup>. According to him,  $\mathbf{E} \times \mathbf{B}$  drifts are produced in the F-region by electric fields arising in the dynamo region and communicated to the F-region along lines of  $\mathbf{B}$ . The N-S component was less well determined, but appeared to be adequately explained by a combination of electromagnetic drifts and neutral air drifts which can produce plasma motions along the lines of force and hence contribute to the NS (but not EW) horizontal drifts.

In an experiment to determine the effect, if any, of earth's magnetic field on F-region drift, it has been concluded<sup>14</sup> that on quiet day, there was no indication of dependence of drift velocity on magnetic field. But on disturbed day, the drift velocity is found to increase and the fading rapid as  $K$  increases. The northward component, which is usually absent at low equatorial latitudes assumes a large value in synchronism with the

magnetic storm and the N-S component increases. Fig. 19 shows the fading patterns observed during a quiet day and disturbed day. Fig. 20 shows the variation of the drift velocity with  $K$  index. The NS component is seen particularly influenced. These results are from Delhi measurements.

## 8 Origin of the Drift System

If we accept the solar and lunar gravitational tides as the main cause of the motion of the earth's neutral atmosphere then we could determine the magnitude and the direction of the neutral wind velocity at the E-region heights. An expression has been worked out<sup>1</sup> following Martyn<sup>15</sup> and others.

Let  $u$  be the southward component and  $v$  the eastward component of the drift velocity. Let  $\sigma$  be the frequency of tidal oscillation of the atmosphere. Then at E-region heights,

$$\begin{aligned} u &= 48.26 \sin \sigma t \quad (\text{in m/s}) \\ v &= 45.6 \cos \sigma t \quad (\text{in m/s}) \end{aligned} \quad \dots (8)$$

(the above values are applicable at Cambridge)

The above result immediately indicates that the wind is semi-diurnal and its direction will go round, approximately, in a circle once every 12 hr and its magnitude is 66 m/s. The observed value is 50 m/s. The semi-diurnal nature of the wind velocity is shown in Fig. 21 where the direction is seen to change once every 12 hr. This suggests that the drift we are measuring at E

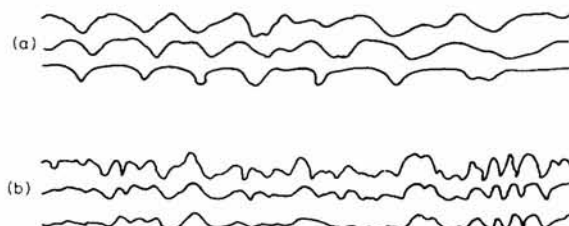
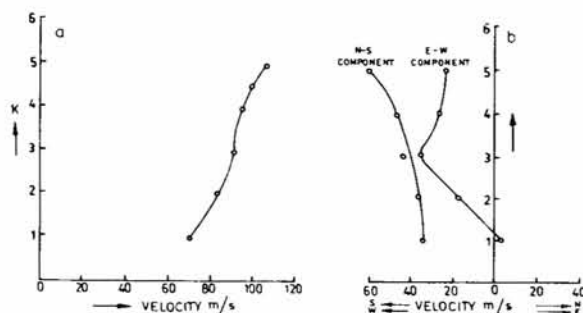

 Fig. 19—Drift records on quiet & disturbed days: (a) Drift record on a 'quiet' day (date: 6 Aug. 1958, time: 0845 hrs IST;  $K = 1.5$ ); (b) Drift record on a 'disturbed' day (date: 4 Dec. 1958, time: 1130 hrs IST;  $K = 4.5$ )


Fig. 20—(a) Correlation between resultant drift velocity and geomagnetic activity; (b) North-south and east-west components of drift velocity and geomagnetic field

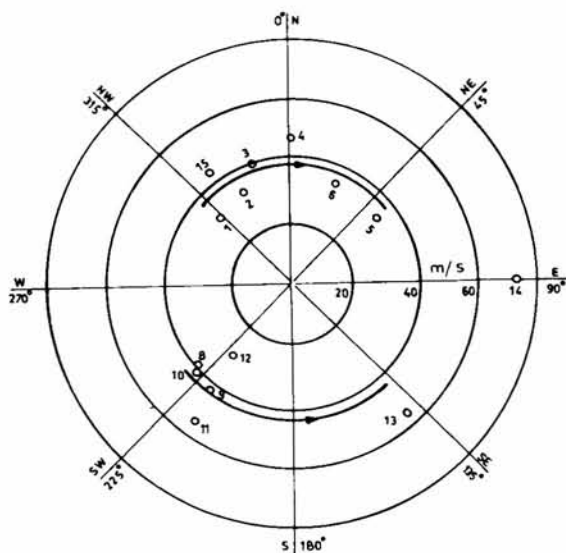


Fig. 21—Semi-diurnal variation of the observed wind velocity. (The numbered points mark the end of the vectors representing the velocity.)

is the motion of neutral air at E-layer heights. But for F-layer drifts, the situation is complicated and no clear picture emerges.

### 9 Ionospheric Irregularities

In order to measure drift in the ionosphere, there should be an irregularity whose motion can be tracked either from fading of a downcoming radio wave or by other methods. The question arises as to what is the origin of the irregularity.

A large number of reasons have been advanced for the origin of the irregularities. These have been tabulated by Kent and Wright<sup>11</sup> and are reproduced in Table 2.

The last reason that gravity waves are the main cause of producing ionospheric irregularities has been emphasized by many workers. The point has been critically examined by Kent and Wright<sup>11</sup>. It appears from their analysis that all observed results by the spaced-receiver technique cannot be explained by gravity waves and one has to look for some other better cause. But all evidence points out that the spaced-receiver technique measures the neutral gas motion in both the D- and E-layers.

### 10 Motion of a Single Cloud in the Ionosphere

Sometimes, although very rarely, one could obtain, by the spaced-receiver technique, evidence of motion of a single irregularity in the ionosphere. A single scattering centre behaves as a radiating antenna and will have a characteristic polar diagram. The polar diagram will, however, depend upon the dimension of the cloud in relation to the wavelength. The situation is

Table 2—Mechanisms for Irregularity Production

| Source                                                                                                               | Region                   |
|----------------------------------------------------------------------------------------------------------------------|--------------------------|
| 1 Turbulence                                                                                                         | D and lower E            |
| 2 Solar action in magnetic field <sup>16,17</sup>                                                                    | E, Es spread-F (?)       |
| 3 Meteor ionization trail                                                                                            | D, E                     |
| 4 Particle precipitation                                                                                             | F (high lat.)            |
| 5 Hydromagnetic wave action <sup>18-20</sup>                                                                         | F                        |
| 6 Two stream instability action <sup>21</sup>                                                                        | Equatorial Es            |
| 7 Instability of plasma motion across field lines <sup>13</sup>                                                      | F                        |
| 8 Instability of plasma due to neutral motion across field lines <sup>22</sup>                                       | F                        |
| 9 Irregularities in the E-region transferred to the F-region along the earth's magnetic field lines <sup>23,24</sup> | F                        |
| 10 As in (9) above but from F to E                                                                                   | F                        |
| 11 Gravity waves <sup>25</sup>                                                                                       | D, E, Es, F and spread-F |

simplified if the background reflection is due to the radiation emitted by such an antenna. In that case the polar diagram becomes the same as that of a horizontal antenna radiating some distance above the ground and the ground is regarded as a perfect reflector. In our case, the ionosphere is the 'ground' and the radiating cloud becomes the "horizontal wire antenna". In such a case, the polar diagram will consist of several minor lobes placed symmetrically round a major lobe in the centre. Now, if this pattern is moved bodily, the intensity of radiation at the receiver will go through a series of maxima and minima roughly equally-spaced and the variation of intensity with time will be periodic. When the radiating cloud goes out of the 'contributing zone' for the receiver, the intensity at the receiver will again become steady. Thus, if a periodic fading pattern is observed, preceded and followed by a steady signal, the pattern may be interpreted as due to a cloud moving past in the ionosphere. It should, however, be ensured by using polarized receiving aerial that the periodic fading pattern is not due to an interference between the two magnetoionic components<sup>26</sup>.

An example of such a single cloud moving past in the ionosphere is shown in Fig. 22 (Ref. 27). In this example, the fading had been quite slow for some time and no shift in timing between the fading patterns could be observed. Then the periodic fading started which lasted for about a minute and then the amplitudes became steady again. In the figure, the two sets of fading patterns are, in fact, a continuation of one another. The velocity of the drift was found to be 80 m/s and the direction towards SSE. The dimension of the cloud has been worked out on the basis of

Fresnel zone. The horizontal length of the cloud was found to be 75 m and the first Fresnel zone was of the order of 9 km for a 75 m radio wave. The height of reflection was 250 km. In subsequent years, the dimension of the irregularities contributing to fading has been determined. It is usually between 50 and 200 m.

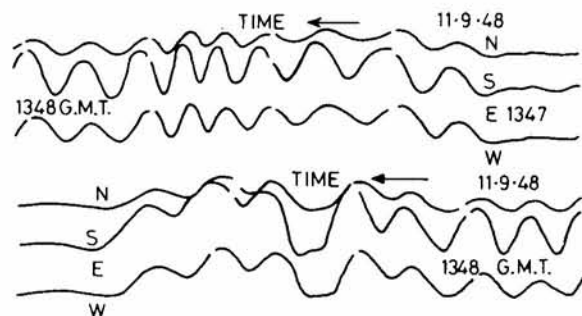


Fig. 22—Motion of a single cloud

Table 3—Principal Advantages and Disadvantages of the Methods of Measuring Ionospheric Motions

| Method                     | Class | Main characteristics                                                          |
|----------------------------|-------|-------------------------------------------------------------------------------|
| Radio meteor               | N     | Relatively simple direct method, restricted height range                      |
| Airglow                    | N     | Little used, interpretation difficult                                         |
| Noctilucent clouds         | N     | Shows horizontal motion, very restricted height range, relatively rare events |
| Aurorae                    | N     | Very dubious interpretation                                                   |
| Chemical trail             | N     | Very direct, trail life-time only a few minutes, nighttime only               |
| Ejected sensors            | N     | Restricted to heights below 80 km                                             |
| Pitot tube                 | N     | Little used                                                                   |
| Acoustic wave              | N     | Restricted to heights below 90 km                                             |
| Thomson scatter            | P     | A new method of considerable promise, needs sophisticated equipment           |
| Plasma injection           | P     | Relatively little used, similar to chemical trail                             |
| Spaced-receiver technique  | I     | Very common, all times and heights interpretation under debate                |
| Doppler shift              | I     | Particularly used to observe waves in plasma                                  |
| Large-scale irregularities | I     | A variety of methods not applicable to small irregularities                   |
| Patches of irregularities  | I     | Restricted to certain classes of ionospheric irregularities                   |

Note: N = Neutral atmosphere; P = Bulk plasma; I = Plasma irregularity

## 11 Discussion and Conclusion

In this review, an account has been given in some detail of the spaced-receiver technique developed by the author in 1947 to study horizontal drift in the ionosphere. In the last four decades, many experiments have been made following the same technique and the technique itself has been advanced although maintaining its basic features. The results obtained at different places in the world appear to agree and give some useful information about motion of ionospheric regions. Many other techniques of investigating the drift have been used in the past. Kent and Wright<sup>11</sup> have made a comparison of the principal advantages and disadvantages of the different methods and this is reproduced in Table 3.

It would be evident from Table 3 that the spaced-receiver technique seems to be the best developed so far for measuring horizontal drift in the ionosphere. The interpretation of various results is still not complete and a global picture has not yet emerged. We have still to explain what is the precise mechanism that causes drift in the ionosphere and what is the role played by magnetic field upon moving plasma specially in the F-region. But we hope that these problems will be solved in the near future. It is, however, gratifying to the author that the little work he did at the Cavendish Laboratory in 1946-48 has stood the test of time and found wide acceptance.

In spite of so many years of observation of horizontal drift in the ionosphere by so many different methods, many fundamental issues are still unresolved. These are as follows.

- Exact location of the drift system
- Vertical gradient of drift velocity
- Has direction of drift any relationship with latitude and longitude of a place, and if so, why?
- The magnitude of the drift velocity and its dependence, if any, on latitude and longitude of a place
- Origin of the drift system

It is gratifying to note that the University Grants Commission has recently funded a project for co-ordinated measurement of drift by the spaced-receiver technique at different locations in India. Measurements will be taken at different places on the same frequency, at the same time, for the same duration employing identical equipment. It is hoped that these measurements, when completed, will lead to the solution of some of the above problems.

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## Note

It is not possible to give an exhaustive list of references. Readers are requested to refer to the bibliography in the papers of Kent and Wright<sup>11</sup> and Briggs<sup>12</sup>. There have been a series of papers from Andhra University, Waltair (Prof. B R Rao), where perhaps most exhaustive work on drift in the ionosphere has been carried out in India.