WINDS IN THE UPPER ATMOSPHERE

by

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SUMMARY

In this thesis is described work carried out in the Department of Physics, U. of A., and extending over the years 1955-1959 inclusive.

In the introduction the ideas underlying this study are developed in an historical manner. There is the evidence that currents of electricity existed in the upper atmosphere. The attempts made to explain this led to suggestions that there were charged layers in the upper levels of the atmosphere. Confirmation of this came in the course of time and the properties of the layers were then investigated with more flexible methods as radio techniques improved. Finally, before the second World War, elementary observations had been made on the motion of the ionospheric layers.

After the War, much more versatile apparatus made possible the elaboration of the experimental work leading to the estimation of the ionospheric winds. Such work was stimulated both by theoretical work on the tidal patterns of the atmosphere, and by other experimental work wherein the linear ion clouds created by meteors were used to measure winds at sub-ionospheric levels. It became desirable to see if the circulation pattern deducible by this means extended to higher levels, where, it was assumed, the

methods used in this study were applicable.

The meteor trail method of studying winds in the upper atmosphere had been in use at Adelaide for several years before the experiment using the methods outlined in this thesis was initiated. Reliable results were available, from meteor studies, up to altitudes of about 105 Km. though results for altitudes above 100 Km. were less reliable than the rest. The methods of the present thesis were used to extend the range of measurement and also to test the validity of the method, since some of the assumptions basic to the method were subject to doubt.

The two methods were run simultaneously at Adelaide for May and June, 1959, but no direct comparison was possible. Indirect comparison was resorted to, while at the same time a comparison with similar results obtained elsewhere by the same method proved encouraging. The results seem to indicate that the methods of this study are sound and yield information of the true drift of the atmosphere at the height of the E-region. This is confirmed by similar comparisons carried out abroad. As a matter of interest, three other methods of analysis of the same results (out of several recently proposed) were also used.

This is to certify that this thesis contains no material which has been accepted for the award of any other degree or diploma in any University and that, to the best of my knowledge and belief, the thesis contains no material previously published or written by another person, <u>except</u> where due reference has been made in the text of this thesis.

Signed ....

(C. R. McGEE).

HISTORICAL
INTRODUCTION

HISTORICAL INTRODUCTION:

The presence of electric currents in the upper atmosphere had been postulated in 1882 by BALFOUR STEWART[1] in order to explain the small regular oscillations of the compass needle occurring daily at the earth's surface. According to STEWART'S "dynamo theory" (referred to by BAKER and MARTIN[2] as the atmospheric dynamo theory), "convection currents (of air) established by the sun's heating influence in the upper region of the atmosphere are to be regarded as conductors moving across lines of magnetic force, and are thus the vehicle of electric currents which act upon the magnet". So, the semi-diurnal oscillations of a free-swinging magnet located near the north magnetic pole (viz., 72°N, 94°W), observed by SABINE[3] in 1863, could be explained by assuming the presence, in the upper atmosphere, of electrical currents, of which the horizontal components form a set of positive currents flowing, at one time towards the pole and later, similar currents flowing away from the pole; these current systems to alternate continually. Difficulty was experienced in explaining how the conductivity of the upper atmospheric regions concerned could be so high as was required by the theory.

The next step towards definite knowledge of ionized regions in the upper atmosphere was made when MARCONI[4] in December, 1901, at Cornwall, England, produced electromagnetic signals (Hertzian waves) which were received at St. John's, Newfoundland, after they had crossed the Atlantic Ocean, a distance of 1800 miles. Subsequently, in experiments carried out aboard S.S. Philadelphia, MARCONI noticed that the signals received were stronger by night than by day, and, also, that signals were readable at a greater distance by night (1500 miles) than by day (700 miles). The convexity of the Earth's surface in a distance of 1,800 miles amounts to about 110 miles, and HEAVISIDE[5], arguing by analogy from the way in which an electric conductor guides electric waves around bends and curves, suggested, with reference to a possible mode of propagation of the Hertzian waves, that "there may possibly be a sufficiently conducting layer in the upper air" so that "then the guidance will be by the sea on one hand and the upper layer on the other", and it would then follow that "the waves might spread with two dimensional divergence".

Opposed to this sort of argument were the attempts that were made to explain the propagation of Hertzian waves in terms of diffraction effects acting around the curved earth; but these attempts were shown to be unable to stand mathematical proof and so, by the 1920's, the existence of the so-called "Heaviside layer" was generally accepted on the strength of indirect evidence.

Prior to this time, in 1912, the theory governing the propagation of electromagnetic waves through an ionized atmosphere containing electrons and positive ions had been developed by ECCLES[6], in an incomplete form. This theory was modified and improved upon by LARMOR[7], in 1924. In the ray treatment of this theory, an electromagnetic wave moving upwards meets a horizontal, ionized region of the atmosphere, and due to the decrease in refractive index at higher levels caused by the increase in ion and electron concentration, the ray moves along a curved path until ultimately it passes downward through the lower face of the region and then goes along a straight line back towards the earth. The deficiency of this theory was that no account was taken of the effect of the earth's magnetic field upon the propagation of the waves in the ionized region. This, however, was remedied by a development due to APPLETON and BARNETT[8], published as the magneto-ionic theory. There was little doubt that the necessary ionization was produced by the absorption, in the upper atmosphere, of ultra-violet light from the Sun, yet, what was required at that time was "adequate experimental evidence on the existence of the Heaviside layer"[9]. This experimental evidence was provided in three separate instances; in England, by APPLETON and BARNETT[10] in 1924-25, by SMITH ROSE and BARFIELD[11] in 1925, and, also in 1925 by BREIT and TUVE[12] in America.

In the early literature on the subject there is clearly drawn the distinction between the relatively steady strength of wireless signals received during the day and the remarkably variable nature of the wireless signals received by night; these variations were observed to commence about sunset and to continue till sunrise. According to APPLETON and BARNETT[13], this "may be explained in a general way if it is assumed that there is a variable ray returned by ionic deviation from the upper atmosphere which interferes with the direct ray which travels along the ground. During the daytime the indirect ray returned from the atmosphere is practically negligible, due to its being deviated in the lower layers of the atmosphere where the absorption is considerable. As the sun is setting the ionization in the lower layers of the atmosphere begins to disappear, due to recombination, and the result is an increase in the height....

of the stratum which deviates the direct ray. Deviation without undue absorption is thus possible, and the increase in the intensity of the indirect ray is accounted for". APPLETON and BARNETT thought that it would be "of interest to investigate during ....(the) solar eclipse (of 24th January, 1925) the effect of the partial withdrawal of solar radiation on the strength of the ray returned from the upper atmosphere". As it happened, the effect of the eclipse upon the signals was just that to be expected of an abnormally early sunset, namely, that when the eclipse started so, too, did the variations in received signal strength.

It was from studies carried out soon after the above experiment upon this variable ray, supposed to be returned from the upper atmosphere, that proof was obtained confirming the existence of the Heaviside layer.

The first study was that of APPLETON and BARNETT[10] (mentioned above), who used two receivers, one fed from a vertical straight wire aerial, the other from a loop aerial whose plane was in the plane of propagation, and the outputs from the two receivers by day were adjusted to be equal. Assuming the presence of the layer and that an atmospheric wave did come down from above after reflection, APPLETON and BARNETT concluded that, taking account of the polarized nature of the aerial, there should be by night a greater variation of the signal in the vertical loop aerial than in the vertical straight wire aerial. This they showed conclusively to be the case. They noticed also that there was very pronounced similarity in phase of the signals at the two receivers when their aerials were close together, for instance when separated by 90 feet when the wavelength used was 390 m., but, that "it was found that the maxima and minima of equal intensity on the two sets did not appear to be simply correlated". Besides this, APPLETON and BARNETT were also able to show that the atmospheric waves were, in general, elliptically polarized. They had been led to expect this from their magneto-ionic theory, which suggested the possibility of differential absorption of the two circularly polarized waves into which a linearly polarized wave may be split when incident upon the deflecting layer; the recombination of these circularly polarized beams of unequal amplitude upon re-emergence from the layer yields the observed elliptically polarized wave. No mechanism was suggested, though, to account for such changes of intensity and polarization as were observed to occur in the down-coming wave.

The experiment of BREIT and TUVE[12] was of a quite different nature from those of APPLETON and BARNETT, and of SMITH ROSE and BARFIELD, the experiments of these latter two groups of workers being essentially of the same type. For, whereas APPLETON and BARNETT had used a galvanometer for displaying the receiver output, and their transmitter gave mainly unmodulated signals, BREIT and TUVE made use of an oscillographic display together with photographic recording; this was an essential part of their equipment since they used pulse techniques and desired to view the atmospheric pulse, or "echo" returned from the Heaviside layer, independently of the direct ground-wave pulse. The pulsing of their crystal-controlled transmitter, working on a wavelength of 70 m., was achieved by supplying alternating current to the amplifier tubes while supplying the master oscillator with direct current. The pulse repetition frequency was 500 cycle/second and the pulse width variable (by means of varying the grid bias of the amplifier tubes) from 0.4 milli-seconds to 0.7 milli-seconds. Most of BREIT'S and TUVE'S recording was done by day, with a separation between transmitter and receiver of some 8 miles, so that they studied pulses that had been subject to virtually vertical incidence upon the reflecting layer. On the other hand, the English workers had used transmitter-receiver separations of the order of 50-100 miles, and this meant that the angle of incidence between the atmospheric rays and the reflecting layer was relatively large. It is also interesting to note that BREIT and TUVE used straight wire aerials connected to superheterodyne receivers of intermediate frequency 50 kilocycle/second.

BREIT and TUVE obtained photographs that showed large pulses of constant amplitude in between which appeared other pulses of variable, but usually smaller amplitude. In order to provide unambigous identification of the pulses, i.e. to identify positively ground waves and sky waves, BREIT and TUVE transmitted a series of dots and dashes. They argued that "the first hump must always be received along the shortest path and the last along the longest". Therefore, the first pulse of any dot or dash must be a ground wave and the last pulse of any dot or dash must be a sky wave. The reflected pulses or "echoes" showed marked amplitude variations, the period of these variations having wide limits. This experiment had therefore shown that the "fading can exist quite apart from interference between ground and reflected waves", "and that a considerable part of it is due to the different effectiveness of reflection"..."caused by sudden changes in the layer more or less as a flickering of the light on the wavy surface of water".

They suggested also that multiple reflections, such as occurred at various times, could be more easily explained on the hypothesis of a "wavy surface in the layer". ECCLES[6], in 1912, had referred to inhomegeneities in the layer when he mentioned that waves could be "plentifully scattered downward.... by the irregularities in the reflecting surface"; but BREIT and TUVE went further and attributed dynamic properties to the irregularities.

The researches of APPLETON and BARNETT, of SMITH-ROSE and BARFIELD, and of BREIT and TUVE led them to state that the Heaviside layer was located at about 80-90 kilometre, and also, that its equivalent height varied both diurnally and seasonally, being, on the average, lower in summer than in winter, and at its lowest at noon and at its highest by night in any season. These estimates have since been reviewed and corrected.

Subsequent to 1926, experiments were carried out to determine the relative part played in fading by the following four factors; angle of incidence, intensity, phase, and polarization. Each of these was known to be variable but it was thought possible that one or two might be dominant. The results of experiments by APPLETON and RATCLIFFE[14], interpreted in the light of a mathematical analysis of their system, yielded a great deal of information, among which was an indication of a second deflecting layer more than twice as high as the Heaviside layer (250 km. compared with 100 km.). In these experiments, use was made of a vertical straight wire aerial and a loop aerial, whose plane was vertical also. These two aerials were coupled in such a way as to eliminate ground waves, received from their transmitter, so leaving the atmospheric wave to be studied separately. Their results showed that "the signal variations are due chiefly to variations in the intensity of the downcoming wave, and to a lesser degree to the variation in phase difference between the ground and atmospheric waves. The changes in the downcoming wave are real intensity changes, as measured at the ground, and are not due to the rotation of a plane polarized wave. Changes in angle of incidence of the downcoming waves, although present, are not responsible in any marked degree for the signal variations, any effect which they may produce being masked by simultaneously occuring intensity changes". APPLETON and RATCLIFFE were unwilling to attribute "these fluctuations ...... to the alterations in reflection power of a fixed flat surface". They suggested that interference mechanisms were at work, for "the intensity fluctuations themselves exhibit a kind of periodicity which seems to vary with wavelength and distance of transmission". For instance, if "T is the period of the fluctuations and λ the wavelength, $^{T}/\lambda$ is found to be single valued function of the distance of transmission, d". And also, a possible cause is "the simultaneous 'reflection' of waves from two or more portions of a layer of non-uniform horizontal stratification", the mean height of the layer remaining sensibly constant.

Later, in 1932-33, RATCLIFFE and PAWSEY[15] conducted more experiments to investigate further the intensity fluctuations of the downcoming waves. Use was made again of the suppressed ground wave system and, from the fact that there was lack of correlation between the variations of the intensities recorded in two receivers whose aerials were separated by a distance of the order of one wavelength, in a direction perpendicular to the plane of propagation, they concluded that an appreciable part of the atmospheric wave is not incident in the plane of propagation" (this being the plane of the great circle between transmitter and receiver); the waves were said to be laterally deviated. Of importance also was the fact "that the frequency of fading was roughly proportional to wave frequency".

From a theoretical discussion, RATCLIFFE and PAWSEY concluded that the intensity variations are due to interference effects occasioned by reflections from a "series of diffracting centres, the disturbances from which give rise to the resultant observed intensity at the ground". By assuming a particular value for the height of the Heaviside layer, they were able to deduce, from the magnitude of the aerial spacings beyond which there is lack of correlation in fading records, that the diffracting centres "lie within a region of radius not less than 20 km". (for a wavelength of approximately 356 m.), and, from polarization measurements, that the magnitudes of the two magneto-ionic components of the downcoming wave are very unequal, the fading being due mostly to variations "in the left-handed circularly polarized component".

PAWSEY[16], in 1934, continued the study of the amplitude variation of downcoming waves using pulse techniques with photographic recording, while paying great attention to the effect of aerial spacing upon correlation of the fading pattern. He decided that "the wave which is usually called a single reflected wave does not consist of a single ray but is built up of elementary contributions from a series of diffracting centres distributed more or less at random in the ionosphere ...... The random variations of these elementary contributions might well account for the fading which is experienced when only a single reflected pulse is observed. The resultant electric field would then be produced by compounding a set of components of random amplitudes and phases, and the probability of occurrence of any resultant amplitude could be calculated". His results show such a degree of agreement between theoretical and experimental curves that he felt justified in believing that fading was due to some type of diffraction in the ionosphere. From a theoretical discussion he concludes that, as a horizontal displacement of one receiver relative to another gives an entirely different fading pattern, there must be important horizontal irregularities in the ionosphere, and that as the variations at these two receiving points seem then to be independent, the irregularities must be constantly changing.

From this point PAWSEY, arguing from the observations of other workers (viz. STØRMER[17] and TROWBRIDGE) of movements of horizontal winds in the neighbourhood of the E region (noctilucent clouds and meteor trails), deduced what would be some consequences of similar winds in the E layer of the ionosphere. For instance, suppose that there was a uniform horizontal drift carrying along irregularities in the ionosphere, which did not change in form. A signal reflected from such a layer would result in a diffraction pattern moving over the ground with a velocity twice that of the diffracting layer, and in the same direction. This would give rise at two points, displaced along the line of drift, to fading patterns that were similar except for a relative time lag between them. Some records did show this and the winds deduced from these records showed good agreement with the winds of STØRMER and TROWBRIDGE.

PAWSEY goes on to calculate fading periods for horizontal winds of velocity 100m./sec. (this being the average for all types of observations) and compares these with the observed mean periods of fading. "The good agreement which exists between the observed and calculated fading periods for the E - region is strong evidence that horizontal movements in the E - region are very important causes of fading".

Between 1935 and 1949 a few attempts were made to study the motion of irregularities in the ionosphere. For example, in the winter of 1942-1943 BEYNON[18], working at Slough in England, made some observations on transmissions from Zeesen in Germany, 990 km. East, and also on transmissions from Slough, at the same time. Reflections were obtained from the F_2 layer, by oblique incidence from Zeesen and by vertical incidence at Slough.

BEYNON noticed that "small irregularities in the F_2 layer occurring near the midpoint of the oblique trajectory, ... were repeated overhead at Slough some 60-75 minutes later". To BEYNON the explanation lay in assuming "a rapid east-west motion of or within region F_2 ionization". Later, in 1947-1948, MUNRO,[19] in Sydney, using widely spaced transmitters and receivers obtained records which appeared to show the presence of progressive phenomena in the F region: "either a horizontal drift in the atmosphere, with superimposed local variations in ionization gradient, or ... progression of a wave motion of such a nature as to cause changes in ion concentration".

Then in 1949, and subsequently, the method of closely spaced receivers was developed specifically for the observation of movements in the ionosphere. This method of observation was developed by MITRA[20] from a suggestion by RATCLIFFE, who thought that it would be of interest to see whether, by extending PAWSEY'S[16] method of observation it might be possible to find conditions under which winds could be measured more frequently. The method of closely spaced receivers has been widely used since its introduction and is the method used in the study described herein. A discussion of the theory underlying the method is given later, but a brief outline at this stage will serve to introduce the present study. Whereas PAWSEY used two receivers MITRA used three, which were located at the apices of a right-angled triangle, with separations of the order of one wavelength. Pulses transmitted vertically are diffracted by an irregular ionospheric layer. As a result of the movement of the diffracting layer, there is produced, on the ground, an amplitude pattern that drifts with a velocity twice that of the layer. The receiving aerials intercept the amplitude pattern and enable the amplitudes to be recorded. If the same pattern passes in turn through the three receiving aerials, the records obtained should appear similar in shape but should be displaced, relative to one another, in time. Then a knowledge of aerial separations, of their orientations, and of the observed time shifts would enable the velocity of drift of the pattern over the ground, and hence the velocity of the ionospheric wind, to be obtained. There are several complicating factors however, that introduce uncertainties of various types into the interpretation of the recorded amplitude patterns. These difficulties will be discussed in the section dealing with the analysis of the records. It will suffice to say here that any record may, in general, be liable to more than one type of interpretation.

The closely - spaced receiver method has been used by a number of workers[21] in many countries since its introduction, since it is useful, with choice of suitable frequency, for collecting information on the E- and F- layers.

One of the difficulties referred to, but not mentioned, in the penultimate paragraph, is that the motion of the diffraction pattern on the ground could be due to random motion of the ionospheric irregularities in the absence of wind. The ionosphere contains equal numbers of negative and positive ions embedded in a neutral gas. What is observed at the ground, in the closely - spaced receiver method is movement of a diffraction pattern. This is a result of the motion, presumably horizontal , of the irregularities in the ionosphere. This motion could be caused by the neutral gas moving horizontally and carrying with it the embedded ions, in which case the motion of the diffraction pattern is related ultimately to the motion of the neutral gas. Of course, it does not necessarily follow that, if this is the actual state of affairs, the velocity with which the irregularities move is equal to the velocity of the neutral gas; possibly the two velocities may only be proportional. On the other hand, motion of the irregularities may be brought about by random horizontal changes in ionization density, which could occur within a motionless neutral gas. The motion, also, could be due to a combination of these two processes. Some means of differentiating the processes is necessary, some indication is required whether or not horizontal motion of the neutral gas does occur at or near to the levels being considered. The word "wind" could then be understood to have either the usual meteorological meaning (motion of a mass of neutral gas) or a special meaning, used to describe random horizontal changes in ionization density in the ionospheric layers.

There is a means available of deciding whether or not neutral air does in fact move at ionospheric level, a method that derives from the study of meteors and which makes use of radar techniques.

Meteors had been studied visually for a considerable number of years before the second World War. The quantities of major importance in the theory of meteors are the heights of appearance and disappearance of the meteors and the relation of these heights to the mass and velocity of the meteor. For obvious reasons the visual observations were confined to night-time periods and then only to the brightest incident meteors, but it has been found that the numbers of meteors increases rapidly with diminishing brightness.

By using purely visual methods, the amount of data collected was comparatively small and in some measure unreliable. In 1936, WHIPPLE,[22] in America, began work on what has developed into the precision photographic methods now in use. In these studies two cameras at the ends of a base line of some 40 km. simultaneously photograph the trail of a meteor, so that its trajectory may be determined. Rapid and periodic occultation of the lens by rotating shutters allows for the determination of velocity and deceleration. However, even with the use of the specially-developed Super Schmidt meteor camera, the yield of photographed meteors amounts only to about one per hour. Also, of course, such studies are limited to meteors of +4 magnitude under best conditions and then only at night.

The far more powerful radio echo technique for studying meteors has been used since 1945,[23] which enables meteors to be observed equally easily by night, in full daylight and even through overcast sky. The method is made possible by the intense ionization produced along meteor trails, for, provided that the intensity in the trail is high enough it will reflect a radio wave, giving echoes that may be picked up by suitably designed receivers and so recorded. The method is an extension of the pulse techniques long used in ionospheric researches, but with a degree of refinement made possible by the development of radar during the second World War. In essence a radar technique involves the transmitting of pulses of radio waves that are of only a few microseconds duration and of constant p.r.f. From a knowledge of the time between transmission and reception of the echo, and also of the direction from which the echo is returned the range, altitude and azimuth of the reflecting object or body can be determined.

The radio method was quickly adapted to the measurement of meteor velocities, though how this was done is irrelevant here. What is important for the purposes of the present study is the fact that the accumulation of evidence showed that meteors form columns of ionization within a narrow limit of heights, in particular, between 80 km. and 120 km. These figures correspond to altitudes just below and partly overlapping the E - layer of the ionosphere.[24] Very soon after radio echo techniques had been applied to the study of meteors, it was found that some meteor trials persisted long enough to be capable of giving rise to echoes lasting one second or more, and that many of these long-enduring echoes showed a change of range with time. The suggestion was at once made by ELLYETT[25] and others that winds at heights of 80 to 100 km. might be an important factor in explaining this effect, since it was thought possible that these high-altitude winds could carry along with them any ionized columns, once these had been formed due to meteor impact. Experiments were designed to measure these supposed upper atmospheric winds. These experiments used a variety of techniques, including C.W. and pulse methods, and also a combination of these two. The theory behind these experiments may be briefly outlined as follows. If the ionized column drifts after it is formed, its range from the observing station will change with time and the radial component of its velocity can be measured. For instance, the radio system used at Adelaide[26] for measuring the velocity of drift and position of meteor trails uses continuous wave radiation on a frequency of 27 Mc/s. This is emitted vertically within a cone of semi-angle 40°, and a meteor trail suitably oriented within this cone reflects radiation back to an aerial array on the ground by means of which the direction of the reflection point can be determined. The component of the velocity of drift in the direction of observation is derived from the doppler frequency change of the reflected wave, while the range of the reflection point is found by the radar technique using pulses superimposed on the C.W. If it be supposed that the drift is due to a uniform horizontal motion of the atmosphere, then two columns at different azimuths relative to the observing station will have different radial components of velocity. The measurement of these two positions and radial velocities will be sufficient to determine the magnitude and direction of the horizontal movement. A more complete verification of the assumption of a uniform horizontal movement can be obtained if a large number of meteor trails can be observed in a small interval of time, covering all values of azimuth angle at the observing station. If this were possible, a plot of the observed horizontal components of radical velocity against azimuth angle should yield a sine curve, as in fact it does.

The radio method used at Adelaide, which was referred to above, was devised by ROBERTSON, LIDDY and ELFORD[27] and has been in use since 1952. It yields information on the motion of the upper atmospheric winds between altitudes of 75 km. and 104 km. The topmost few kilometres within this height range includes the lower part of the E- region, and nowhere in the remainder of this range, even though it includes the lower ionized regions (e.g. the D- layer), does the density of ionization approach that of the E- layer. Indeed, the ionization falls off rapidly below the E region. This is due to the high value of the recombination co-efficient α, which limits the intensity of ionization that solar radiation normally produces. The high value of α has another effect. When regions of higher-than-normal ionization occur below the E region, as, for instance, in a newly-formed meteor trail, these regions have a life time of seconds only, before ambipolar diffusion and recombination dissipate them and restore the intensity of ionization to normal. Consequently, it is not to be expected that the meteor trail will exhibit an increase of range due to a unilateral diffusion process occurring at the same time as an inhibited recombination process. Therefore, the only way in which a meteor trail could show an increase of range would be that the neutral gas in which it is embedded should move and carry the trail with it, until the density of ionization in the trail returns to the density of ionization in the surrounding atmosphere.

This is, therefore, the evidence that there is, quite definitely, movement of the neutral air at or near ionospheric levels. The MITRA method of closely-spaced receivers purports to give information of the motion of irregularities in the ionosphere, and, in particular, by an appropriate choice of the frequency of the radio waves used, to give information of the motion of irregularities in the E- region. If this motion is due to neutral air moving (i.e. a normal wind) and carrying with it the irregularities referred to, then it is reasonable to suppose that the magnitude, direction and phase of the winds in the E- layer deducible from the MITRA method, should bear a distinct relationship to the magnitude, direction and phase of the winds known to occur in a slightly lower stratum of the upper atmosphere, namely the 95-104 km. region.

It was thought desirable to investigate the validity of the MITRA method of closely-spaced aerials by comparing the results of the meteor observations and of the closely-spaced aerials study, taking the results of the meteor observations as a standard of reference, and making due allowance for changes of magnitude and phase of the calculated wind velocities as a function of altitude, assuming the validity of extrapolating such changes (measurable in the meteor zone) to slightly higher altitudes.

The author commenced work on this project, on a full-time basis, in 1955, using apparatus constructed by his predecessor. This apparatus was incomplete and basically unworkable so that extensive rebuilding was necessary. After a great many delays, a workable system was devised that could obtain continuous recordings of the amplitude pattern in all three aerials, as suggested by the Cambridge workers for observations made by stations co-operating in the I.G.Y. It was anticipated that results obtained at Adelaide (if any) during the I.G.Y. would be made available for analysis by the full correlation method at Cambridge, and this fact fixed the criteria according to which records taken were judged suitable for analysis. (See Chapter III).

Since several other "simple" methods of analysis had been discussed in the literature between the time of commencing this study and the time of obtaining the records finally, it seemed desirable to see how some of these later methods of analysis compared with the MITRA method, in terms of the winds deduced from the same set of records; though it must be emphasized, that this comparison is secondary to the original intention of testing the validity of the MITRA method against the meteor-based method.

MATERIALS AND METHOD.

II.A. TRANSMITTING EQUIPMENT.

II.A.1. Block Diagram of Complete Equipment.

Fig. 1. shows a block diagram of the complete equipment. All systems, transmitter, receiver suppression, and delayed recorder gate, etc., were keyed by pulses originating in a blocking oscillator (B.O.). Any small variations in the pulse-repetition-frequency of this oscillator would therefore affect all systems in the same way.

II.A.2. Blocking Oscillator and Pulse-Forming Circuits.

A blocking oscillator, (Fig.III.) which incorporated a variable pulse-repetition-frequency (p.r.f.) control, was used to provide pulses that, with suitable modification, triggered the transmitter, besides providing other systems with pulses.

The pulse-repetition-frequency of the oscillator was made variable for the following reason. The signals from the receivers were monitored visually on a Cathode-Ray Oscilloscope (not shown in Fig.I), whose time base was triggered by a pulse from one of the pulse-forming circuits. Therefore, since it was desirable to be quite certain from which layer of the ionosphere the echoes were being received, it was necessary to have available a means of making the interval of time between successive transmitted pulses greater than the interval of time between any transmitted pulse and the longest-delayed echo pulse to which this gave rise. This arrangement enabled echoes from the E-region to be distinguished easily from echoes returned from the F-regions.

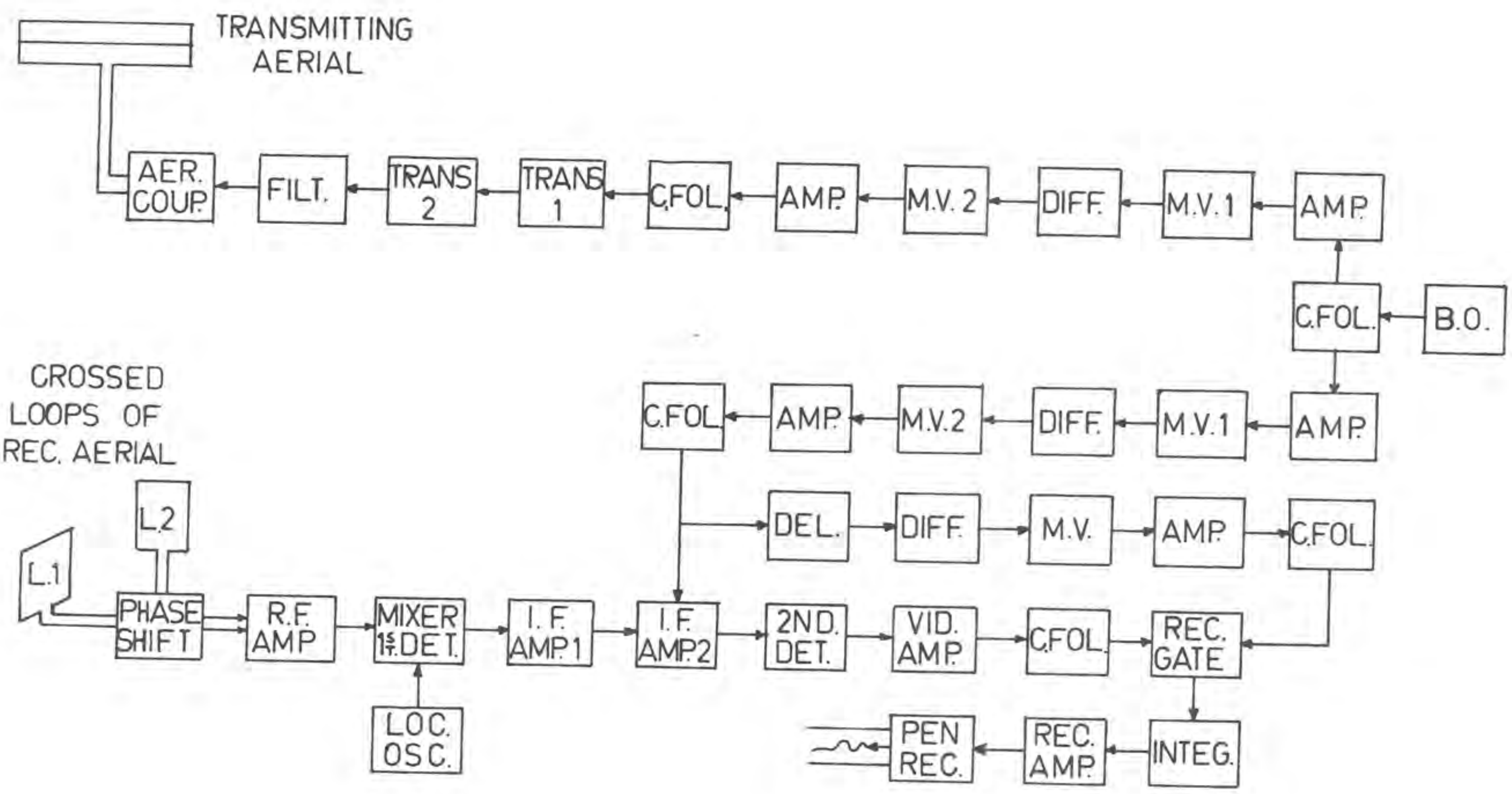

TRANSMITTING AERIAL
AER. COUP.
FILT.
TRANS 2
TRANS 1
C.FOL.
AMP.
M.V. 2
DIFF.
M.V. 1
AMP.
C.FOL.
B.O.
CROSSED LOOPS OF REC. AERIAL
L.1
L.2
PHASE SHIFT
R.F. AMP
MIXER 1st DET.
LOC. OSC.
I. F. AMP 1
I. F. AMP 2
2ND. DET.
VID. AMP.
C.FOL.
REC. GATE
C.FOL.
AMP.
M.V. 2
DIFF.
M.V. 1
AMP.
DEL.
DIFF.
M.V.
AMP.
C.FOL.
INTEG.
REC. AMP.
PEN REC.

FIG. I

For example, with the pulse-repetition frequency control set to give lowest frequency, some 300 pulses per second were transmitted; the interval between pulses would then be approximately 3,300 μ sec. A reflection from the E-region would appear as an echo at about one-quarter of the interval between two transmitted pulses, as displaced on the Cathode-Ray Oscilloscope. On the other hand, an echo coming back from the F-regions would show at about three-quarters of the distance between two transmitted pulses, as displayed. The times involved in the return of these echoes are about 700 μ sec. and 2,000 μ sec., respectively, and these time intervals, in turn, represent total vertical distances of about 200 km. and 600 km. respectively. This is taken as showing the presence of two reflecting layers at heights of 100 km. (the E-layer) and 300 km. (the F-layer). An unambiguous location of the source of reflection can, therefore, be quickly and easily effected before recording is commenced.

If the p.r.f. were set too high, for instance at 600 c/sec., and echoes from the F-region only were present, these would show on the screen at about the same position relative to a transmitter pulse as that where one would expect to see an echo from the E-region. A small adjustment of p.r.f. in this case would result in the displayed transmitter pulse and an F-echo pulse moving relative to each other on the screen. A genuine E-region echo would maintain a constant separation from the preceding transmitter pulse at all p.r.f. up to a maximum of about 1200 c/sec.

Also, at those times when multiple echoes occurred, had the p.r.f. been too high, some little confusion could have occurred in identifying the first echo, which at any instant need not have been the biggest. Here also a variable p.r.f. was an advantage, though, at such times no recordings were made, since strongly fluctuating multiple echoes suggest a rather perturbed reflecting layer. It was thought desirable, also, to make some night-time records of F-region echoes and for this a variable p.r.f. that could be reduced to an extent to display unambiguous first F-region echoes was thought to be preferable to a fixed p.r.f. In all, the apparatus benefited in flexibility from the inclusion of a variable p.r.f. control.

A cathode follower enables the blocking oscillator to supply pulses to several pulse-forming circuits, one of which forms the transmitter pulse. In this circuit the pulses are amplified and applied to a multivibrator (Fig.II), which has a potentiometric means of varying the width of the pulse formed by it. Next the output of the multivibrator is differentiated, and the negative spike formedfrom the back edge of the pulse from the multivibrator is selected by an appropriately connected diode. There is, therefore, a delay between the input of the pulse from the blocking oscillator and the output from the diode that is equal to the width of the pulse formed by the multivibrator, and this is variable.

The negative pulses are amplified and applied to a second multivibrator, whose output pulse (which also has a control to

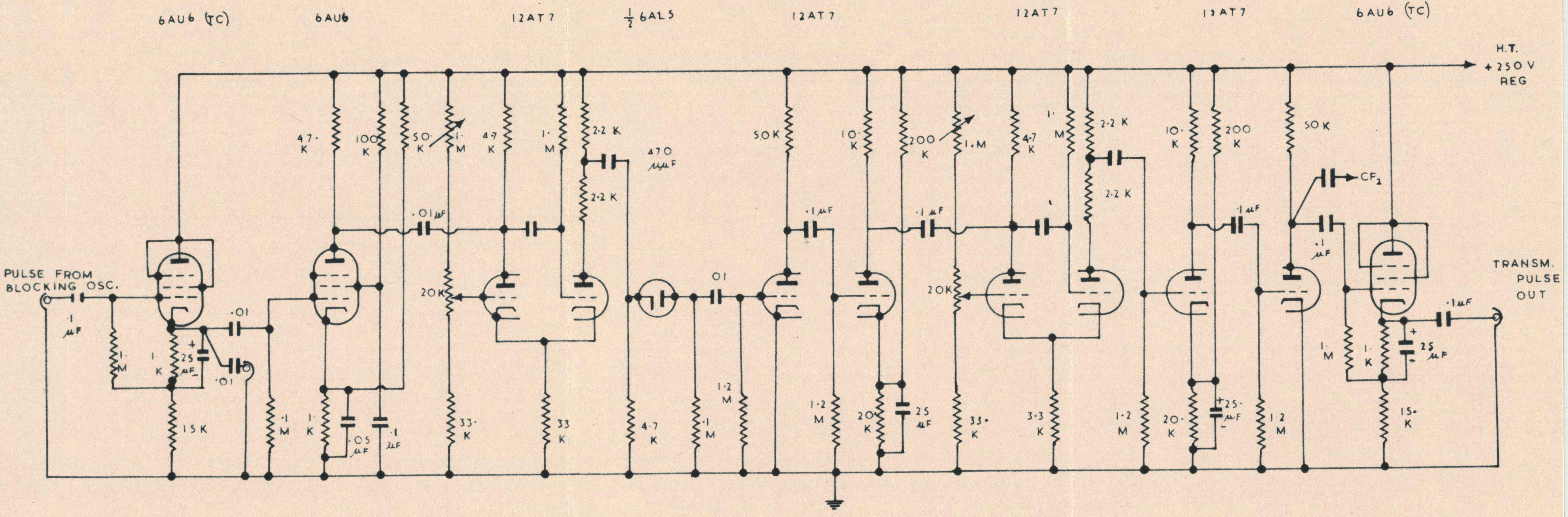


FIG. II

DELAYED TRANSMITTER PULSE NETWORK

vary its width) is further amplified. The final output to the transmitter is by way of a cathode follower.

The circuit, therefore, produces large pulses (approximately 150V) of variable pulse-repetition-frequency. The pulses have variable width and can be delayed by 100 u sec. or more relative to the pulse from the blocking oscillator.

The pulses are applied to a keying valve (6V6G), in the smaller transmitter, that completes the cathode circuit of the master oscillator valve. The output from the smaller transmitter is coupled inductively into the coil in the master oscillator circuit of the larger transmitter, when the crystal of the M.O. circuit is removed.

II.A.3. Transmitters and Aerials.

The original transmitter was a small "portable" Phillips transmitter (Transmitter Installation, Type S.V.C. 100 L/110), with a power output of 100 watts C.W. This was found to be inadequate due to pronounced absorption, particularly from about October to April. More power was obtained by using this transmitter to drive another, larger transmitter that was to hand. The second transmitter was a Phillips 500 watt Broadcast Transmitter (Type 1567, Serial No.51). It was altered somewhat to provide 1000 watts C.W. power. This was achieved by disconnecting the two type -813 valves from the modulator section, and reconnecting them into the power output section, by placing them in parallel with the two type -813 valves already used there. It was also necessary to build another tank coil in this stage, because the transmitter was designed originally to operate up to a maximum frequency of only 1600 kilocycle/sec., whereas the operating frequency used in this study was 2140 kilocycle/sec.

Besides this modification, it was found necessary to have an inductive-capacitive filter connected between the transmitter and the aerial coupling unit. The filter was incorporated in order to eliminate harmonics that resulted from using the transmitter, originally designed for audio-modulation, to generate radar pulses.

The aerial feeder was one that had been used previously and consisted of two wires separated by ebonite spacers.

The aerial was a three-element, centre-fed, folded dipole made from three single strands of copper wire, spaced by oil-impregnated wooden dowelling spacers. The aerial was suspended at a height of about 50 feet, roughly north-south. It behaved as a resistive load of 150Ω, when a capacitor was connected across it at the output terminals of the aerial coupling unit.

A close check was maintained on transmitter frequency by monitoring the frequency with a frequency meter, when C.W. transmission was operating. There was found to be very little drift of frequency after several hours continuous running.

The duty cycle was such that, with the p.r.f. at 300 cycles/sec. and pulse width of 200 u.sec., the peak output power when operating with pulse amounted to about 16 kilowatt.

Tuning of the various stages of both transmitters is effected normally, by grid and anode dip as indicated by the appropriate meters, when the keying valve of the smaller transmitter is short-circuited.

The frequency and pulse shape were also kept under observation by the local G.P.O. Frequency Measuring Station, who first drew attention to the harmonic content of the transmitted signal.

II.B.RECEIVING EQUIPMENT.

II.B.1.a). Construction of Loop Aerials.

Each receiving aerial, of which there were three, consisted of two vertical loops, held at right angles to each other. Each loop consisted of two turns of coaxial cable (75 ohm impedance), which had a gap of one inch or so in the braid shielding at the middle, that is, between the first and second turns. Each loop was stapled to the outside of a wooden frame in such a way as to make the loops 4 foot squares. The frames were constructed to hold the loops perpendicular each to the other at their midpoints and had wooden legs to keep the loops some 2 feet above ground at their lowest sides. The phase-shifting units were supported, by inch-long aluminium ferrules, above the upper surface of the lower side of the frames, in such a way as not to interfere with the coaxial cables. The ends of the loops passed into the metal box housing the phase-shifting unit one from each side through rubber grommets. The leads, connecting the aerials to their receivers, were of 75 ohm impedance, twin-shield cable; these leads were several feet above ground, because of the need to cross roadways and paths, where foot and vehicular traffic could have caused damage.

II.B.1.b).Reason for Inclusion of Phase-Shift Apparatus.

Each of the three receiving aerials is in fact a circularly-polarized loop-aerial. That is, the two vertical and mutually-perpendicular loops, that make up one aerial, are so coupled that, at all times, one of the circularly polarized components of the echo is suppressed, leaving the aerial to provide the receiver with a signal that depends simply on the magnitude of the other circularly polarized component. This precaution is necessary since, under certain conditions, the phenomenon which Mitra terms "polarization fading" might produce fading curves which could be interpreted, though erroneously, as being due to winds.
"Polarization fading" is explained in terms of the magneto-ionic theory of Appleton and Barnett. The plane-polarized beam from the transmitter is magneto-ionically split into two circularly polarized beams (originally of equal amplitude) upon penetrating the ionosphere. There may or may not be greater absorption of one of those components than of the other, and also one component is retarded relative to the other, i.e., their equivalent paths in the region differ. In general, then, the two circularly polarized beams emerge from the ionosphere having different amplitudes and with a phase difference. As a result they recombine to form an elliptically polarized beam that constitutes the echo. If conditions are such that the equivalent paths of the circularly polarized beams alter over a relatively short period of time, the result is that the ellipse formed at the ground will rotate.
In this case a single loop, or horizontal wire aerial, will provide

a signal that varies in amplitude at a rate that depends upon the rate of change of equivalent paths of the beams in the ionosphere, and the records produced under these conditions will show maxima and minima similar to those produced by actual winds. Furthermore, if two receivers are used connected to similar vertical loops, whose planes do not lie parallel, the recordings made from the type of echo being discussed will show displacements in time, leading to the possibility of actually calculating a wind velocity, that would be entirely spurious!

Therefore, with one of the components suppressed the receiver will respond to the amplitude of the remaining component, irrespective of its orientation relative to the planes of the loops.

During testing, all three aerials were placed as close together as was convenient and connected in the same sense. The traces obtained were quite similar. Then with two aerials untouched the third was connected in the other sense; the result was a trace of quite different appearance. This was done to all three, and it was thereafter assumed that with the connections of the phase-shifting circuits made in the same sense, the same component was being recorded at all three.

It was also necessary to be quite sure that there was no pickup of signal in the wires connecting the aerials to the receivers. These leads were 75 ohm impedance twin shielded cable. To test for this the following method was used. A metal box, of the same size and shape as that in which the phase shifting circuits were contained was fitted with a similar socket and a resistive load, equal to the impedance of the phase-shifting circuits, connected across the terminals of the socket. Whenever this dummy load was connected in place of any of the aerial assemblies, in the presence of well-defined echoes, the trace produced in the recorder from the particular receiver concerned fell to zero, to be restored to its normal appearance as the aerial was reconnected.

II.B.1.c). Design of Phase-Shift Apparatus.

The actual design of the phase-shifting circuits follows that outlined by PHILLIPS[28]. Basically, there are two inductance-capacitance lattice networks (Fig.IV), each of which acts as a length of transmission line whose electrical length depends upon the ratio of two frequencies f and f_o; where f is the frequency applied to the input terminals of the lattice, and f_o is a frequency related to the inductance, L, and the capacitance, C, of the lattice by the equation

$$f_o = \frac{1}{2\pi\sqrt{(L C)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The characteristic impedance, Zo of the transmission line to which the lattice is equivalent is given by

$$Z_o = \sqrt{(L/C)}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

and the electrical length, β, of the lattice by

$$\beta = 2.\text{arc tan}\,(f/f_o), \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

provided that the lattice is terminated by a resistance equal to Zo. In practice, the frequency, f_{o1}, of one lattice is 1·5 Mc/sec, and that of the other lattice, f_{o2}, is 9·0 Mc/sec. Then for these values, we have $f_{o2} = 6f_{o1}$. If now, the same e.m.f. is applied to the input terminals of the two lattice networks, each will introduce a different phase shift, β, into the output voltages, but with the values of f_{o1} and f_{o2} such as they are, it will be found that the difference in phase angles will approximate to 90° for quite a range of frequencies, f, of the applied e.m.f. (For the particular frequency used, viz. 2.14 Mc/sec, it will be seen that $\beta_1 - \beta_2 = 82^\circ$). This means, also, that if two e.m.f. that are of the same frequency, but which differ in phase by 90°, are applied one to one lattice network and the other to the other lattice network, they will add in phase at the output terminals, provided that these are connected as shown in Fig.V.

Considering one circularly polarized beam incident vertically upon one of the double loop aerials, it will be seen that this induces an e.m.f. in one loop that is proportional to sin ϕ, where ϕ is the angle between the normal to the plane of the loop and the magnetic vector of the ray. In a second loop perpendicular to the first, the e.m.f. induced at the same time, by the magnetic component of the ray, will be proportional to cos ϕ. Thus, each loop will have an e.m.f. induced in it and these e.m.f. will be 90° out of phase. The phase-shifting network will add these together, so providing an output voltage proportional to the magnitude of the magnetic component of the incident ray. It will be apparent that the other of the two circularly polarized beams will induce e.m.f. in the loops which, when applied to the phase-shifting circuits, result in voltages that are out of phase by 180°.

The phase-shifting circuits, used in conjunction with the loop aerials, therefore offers a means of separating the circularly polarized beams from the ionosphere, and by appropriate setting of the switch either the right-hand or left-hand polarized beam may be selected for recording.

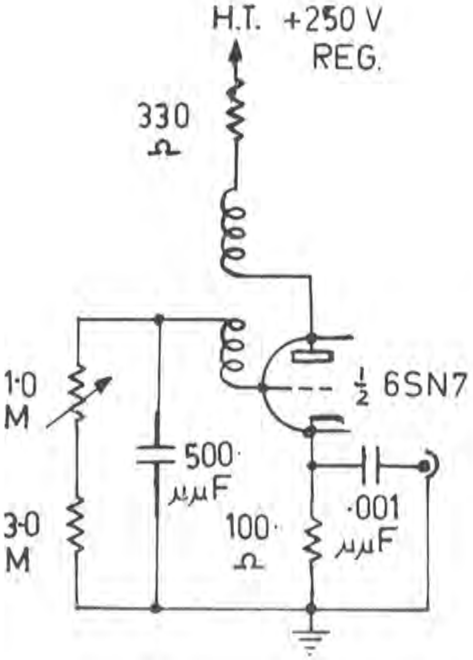
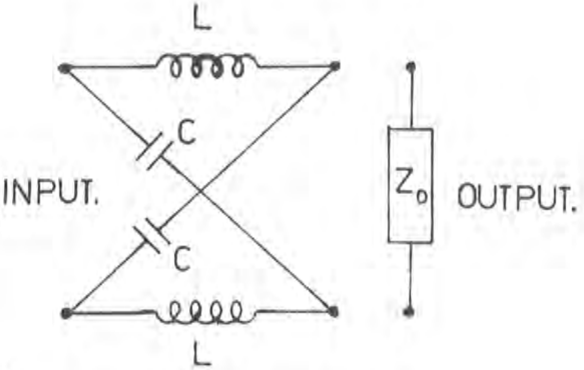


FIG. III

FIG. IV.



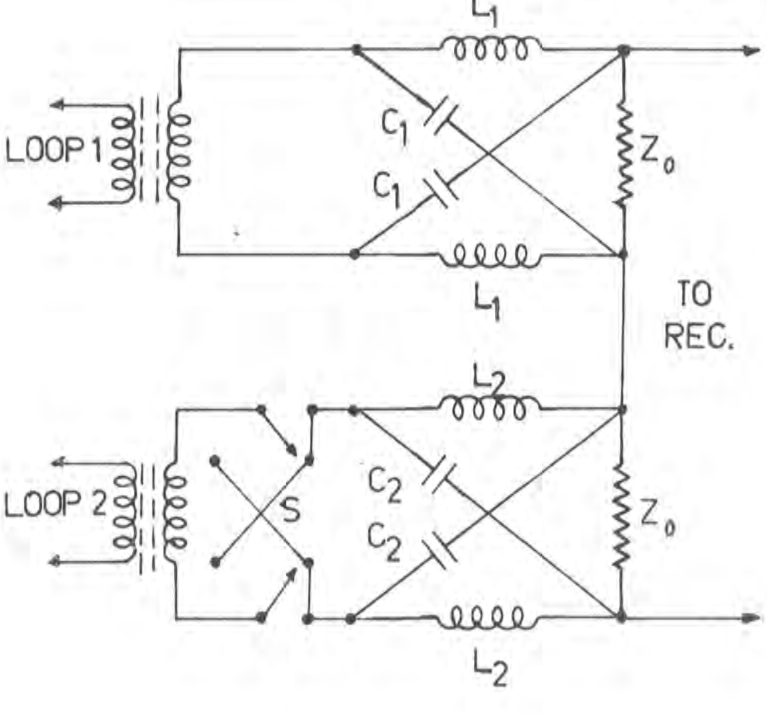


FIG. V.

The transformers were wound on E-cores of Ferrox-cube, there being seven turns on both the primary and secondary, which were wound together to ensure as close a coupling as possible. The lattice networks were tuned individually by varying the values of the capacitors C_1 or C_2 until the response on a vacuum tube voltmeter across the output terminals indicated resonance of the lattice network with the signal applied to the input terminals from a signal generator. Preliminary testing of the phase-shifting properties of the lattice networks was achieved by applying the same e.m.f. from a signal generator to the two lattice networks when their output terminals were not connected together. The voltages appearing at the output terminals were then applied, one to the X-plates of a cathode-ray oscilloscope tube and the other to the Y-plates of the same tube. The sensitivities of the X-plates and Y-plates, in cm./volt, having been determined previously by calibration, it was possible to re-scale the ellipse that resulted on the screen, from the simultaneous X- and Y- deflection of the spot produced by the voltages obtained from the output terminals of the lattice networks and to ascertain that the phase difference between the signals on the X- and Y- plates was approximately 90°. A satisfactory design having been decided upon, three units, as similar as possible, were constructed and tested, as indicated above.

Since Zo = 106 ohms, equations (1) and (2) require that the values of inductances and capacitances be $L_1 = 11.3\ \mu H$, $C_1 = 0.001\ \mu F$,

$L_2' = 1.87\ \mu H$, $C_2 = 167\ \mu\mu F$. The inductances were wound on 3/4" paper formers, L_1 having 22 1/3 turns and L_2 7 1/6 turns of enamelled copper wire.

II.B.1.d). Location of Loop Aerials.

The aerials were located at the position shown in Fig. XXIV. thereby forming a triangle of the following size and orientation. The two arms of the triangle, viz., OW and OS, are perpendicular, or very nearly so, OW having an orientation of 29° North of West and, therefore, OS has an orientation 29° W of S. The length of OW was 117 metre, and of OS 102 metre.

II.B.2a). Radar Receivers.

The 2.14 Mc/sec. radar receivers employed one stage of radio frequency (R.F.) amplification, two stages of intermediate frequency (I.F.) amplication with a gain control, and one stage of video amplification also with gain control. The local oscillator was built on a separate chassis and a cathode follower with three outputs provided the receivers with 2.595 Mc/s oscillation for heterodyning. The I.F. stages worked at a frequency of 455 kc/s and consisted of single-turned units. Suppression was applied to the suppressor grid of the second I.F. amplifier valve and the I.F. gain was controlled by applying a variable D.C. voltage to the grid of the first I.F. amplifier valve. Gain was also kept down by mean of negative feedback in the second I.F. amplifier stage, resulting from the unbypassed cathode resistor.

The receiver output was delivered, from a cathode follower, im the form of pulses of variable height, of width somewhat in excess of 200 u sec., and, of course, having a p.r.f. of 300 c/sec.

Circuit diagrams of the radar receivers and the local oscillator are shown in Figs. VI and VII.

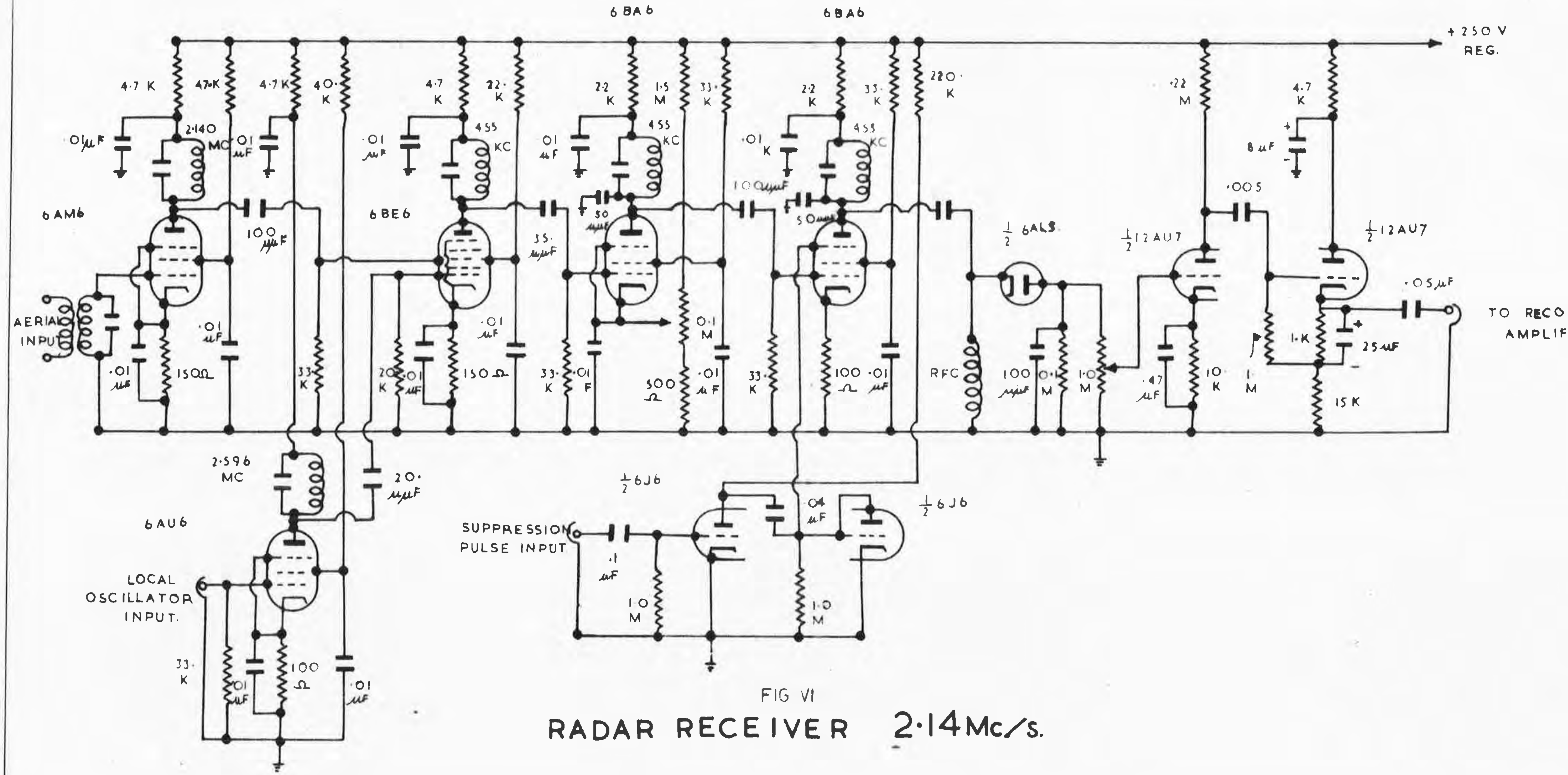
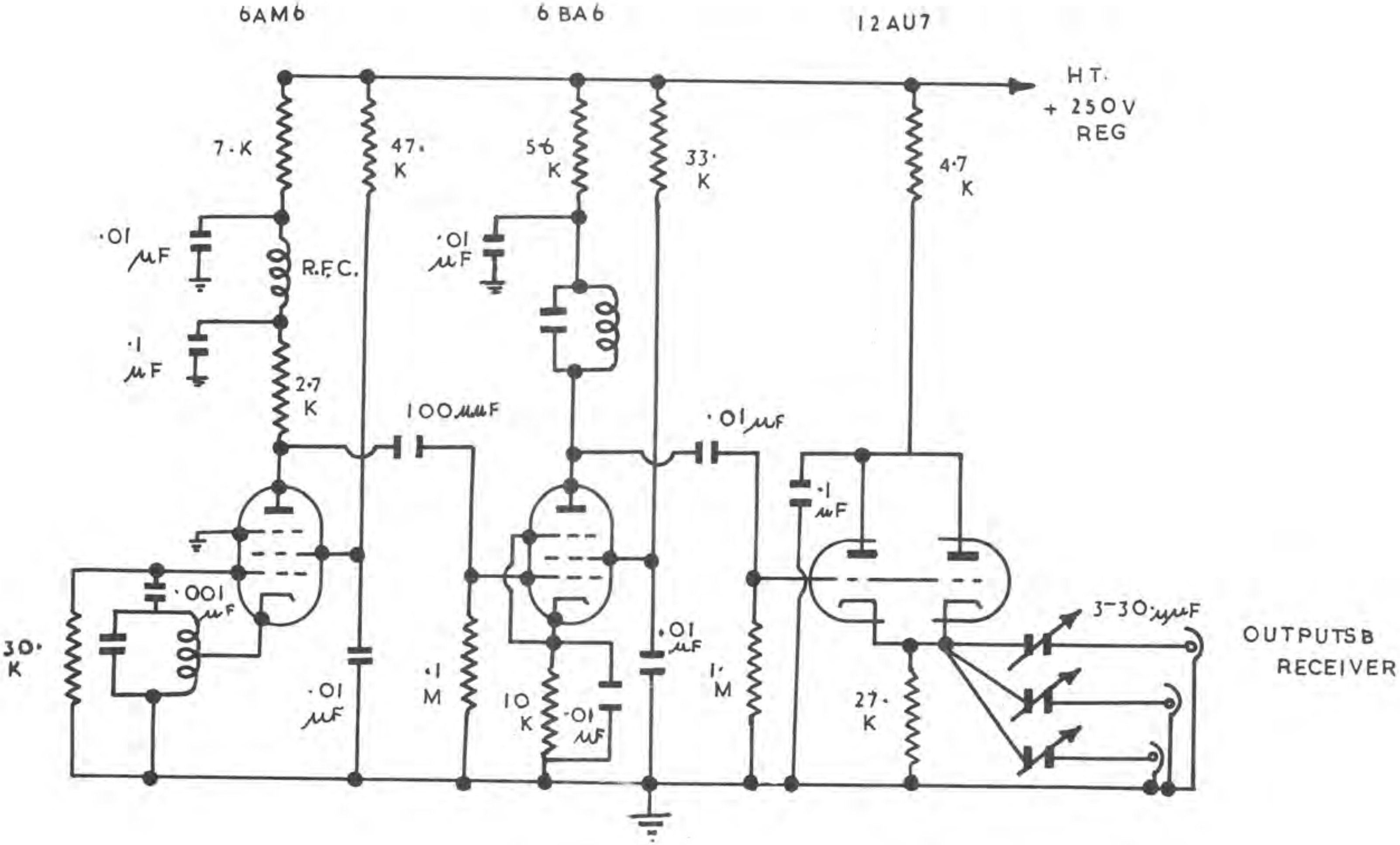


FIG VI

RADAR RECEIVER 2·14Mc/s.



LOCAL OSCILLATOR

2·595 MC/S.

FIG. VII

II.B.2.b). Receiver Suppression.

In order that the receivers be able to operate at maximum gain during the interval of time when the signal reflected from the ionosphere reached the receiving aerials, it was necessary to use some method of receiver suppression so as to mask the effect on the receivers of picking up the transmitter pulse direct from the transmitting aerial. This suppression prevented paralysis of the receivers and removed all signs of the direct pulse from the receiver output signal.

The pulse from the cathode follower after the blocking oscillator was applied to another multivibrator and amplifier network, which was similar to that referred to except that it formed a much longer pulse. The leading edge of this pulse is in advance, in time, of the leading edge of the pulse that is applied to the transmitter. Due to the fact that the output pulse from the transmitter was delayed somewhat relative to the triggering pulse, the receiver suppression pulse, when made long enough, completely overlapped the transmitter output pulse, both in fron and behind, thus ensuring adequate suppression.

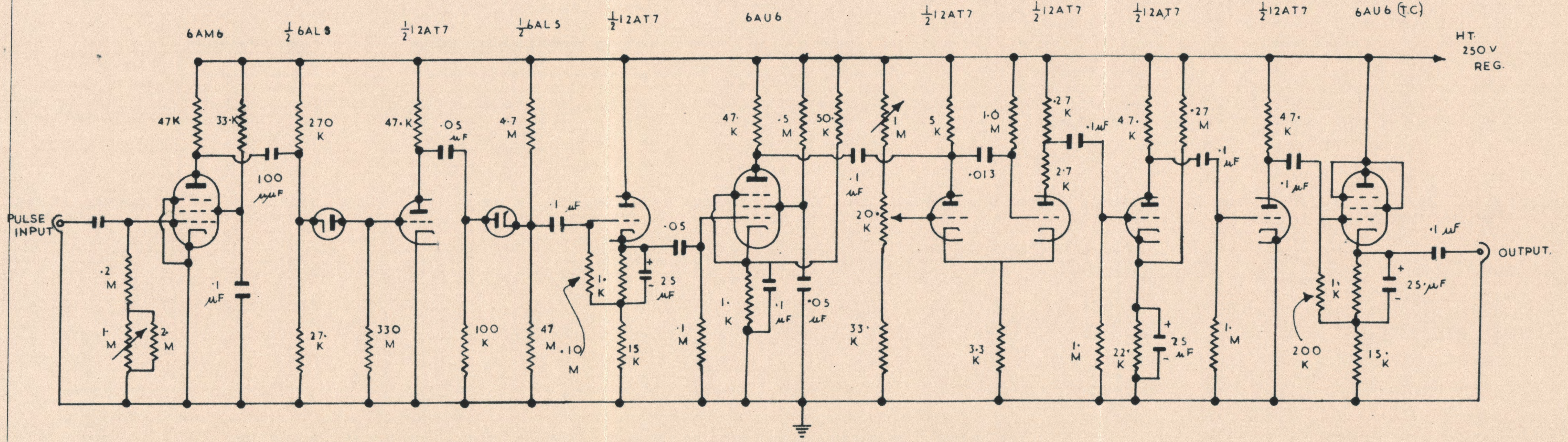
II.C.RECORDING.

II.C.1.a).Gating of Recording Amplifier Input.

The pen-recorders were designed to be fed with the integrated echo pulses from the receivers and so the integrating circuits were not permitted to receive anything except these echo pulses. This was effected by providing a gating pulse whose function was to operate electronic switches, which were to act only for the brief interval of time in each transmit-receive cycle when an echo pulse could be expected to pass through the amplifying circuits.

It was necessary, therefore, in view of the fact that the interval of time between 'transmit and 'receive' was liable to vary for several reasons, to have a variable delay incorporated in the gate-pulse-forming network. This ensured that the gating pulse could be positioned exactly over the echo pulse at all times, and that the gating pulse need therefore be only as wide as was necessary to select the desired echo pulse, with the consequent exclusion of unwanted noise.

The main part of this network (Fig. VIII) is very similar in most respects to the other pulse-forming networks and so need not be described further.



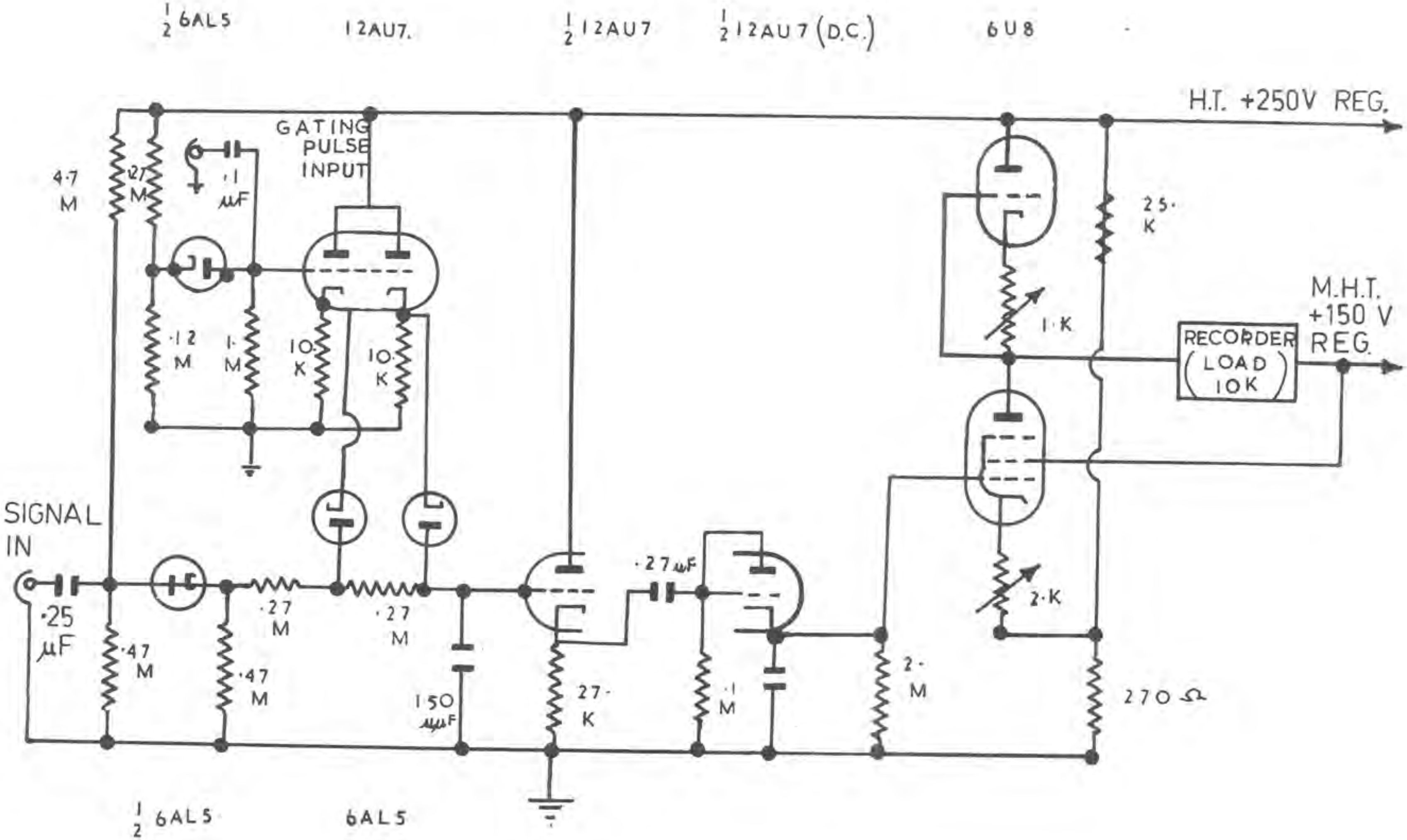
PULSE FORMING MULTI VIBRATOR WITH VARIABLE DELAY

FIG. VIII

II.C.1.b).Recording Amplifier.

The heart of the recording amplifier is the differential amplifier that supplies the pen-recorder with its power (Fig. IX). These amplifiers needed to be provided with two different regulated voltages, one of +250 volts D.C. and the other of +150 volts D.C. All three amplifiers used the same +250 volt supply, but to avoid interaction it was found necessary to have three separate +150 volt supplies. The coil which moves the pen acts as a load having an impedance of approximately 10 kΩ and is connected between the plate of the pentode section of the differential amplifier valve and the +150 volt D.C. supply. There are two controls built into the amplifier each of which, though to a different extent, influences the position of the pen for zero input signal (i.e. the zero position of the pen), and also the maximum deflection of the pen before saturation of the amplifier. Each differential amplifier was adjusted for zero position and maximum deflection of the pen, by adjusting these two controls, while a high voltage pulse was applied simultaneously to the electronic switch and to the terminal normally used to lead in the signal from the receiver. In this latter case, the pulse was reduced by a voltage divider incorporating a variable resistance, so that pulses of known size could be supplied to the input terminal, making calibration easier.

For the duration of the gating pulses the two triode sections of the 12AU7 valve in the electronic switch are made to conduct,



RECORDING AMPLIFIER WITH GATE

FIG. IX

Their cathodes then are lifted to a high positive voltage due to the presence of their cathode resistors (10 k Ω). Connected to each cathode of the 12AU7 is the cathode of a diode, with the plates of these diodes connected to the opposite ends of a 0.27 megohm resistor, that is itself in series with another resistor of the same magnitude. These four resistors, the two 0.27 megohm resistors and the two 10 kilohm cathode resistors, form two successive voltage dividers, which function whenever the diodes conduct. The effect of these two voltage dividers is to reduce the voltage passed on to the integrating circuit to about $\frac{1}{700}$ th of the voltage applied to the voltage dividers from the receiver. The diodes, however, conduct only for so long as the triodes do not conduct, or, to put it another way, whenever the triodes conduct and their cathodes attain a positive voltage the diodes do not conduct and, consequently, at such times the voltage dividers do not operate, so that the signals from the receiver are then applied more or less directly to the integrating circuit. This state of affairs obtains, of course, for the duration of the gating pulse, and this pulse, if it is correctly timed and of suitable duration, provides the means of ensuring that the electronic switch selects only the echo pulses for recording.

The plate of the second diode in this switch needed to be connected to earth, by a small condenser, in order to reduce a certain distortion to the wanted signal that results from the fact that the interelectrode capacitance of the diodes causes the differentiation of the voltage pulse that appears across the cathode resistors of the 12AU7 triodes whenever the gating pulse is applied.

II.C.2 Pen Recorder.

The Pen-Recorder used to record the way in which the amplitudes of the echoes varied with time was a type made locally by Both Equipment Ltd. The machine originally was capable of producing simultaneously four separate traces, each on its own squared paper. However, as there were only three aerials and receivers, the mechanism operating the fourth pen was replaced by a relay that was activated by a synchronous motor, in such a way as to produce time-marker pips along one side of the paper. These time-marker pips were at one second intervals. The paper speed was set at about one centimetre per second by gearing down an electric motor. The drive was communicated to the paper by a milled-edged friction wheel, that pressed the paper onto a smooth, wide, freely-turning wheel whose edge was set flush with the smooth metal plate which acted as the writing table, onto which the pens pressed the paper as it moved. The zero deflection of each of the amplitude-recording pens was to the left of each of the three separate recording strips, as seen by an operator standing so as to face the machine with the paper moving toward him. The time scale, therefore, as read by the person analysing a record, runs from right to left, when the records are spread out with the zero amplitudes of the strips nearer the reader.

The machine inked well if used regularly, but needed to be shielded from dust, which could cause the moving coils, that activate the pens, to stick, since, as the construction is very similar to that of a loud-speaker with field magnet and voice coil, the space between the coil and the magnet is very small and must not be obstructed.

Photographic recording was tried more or less successfully in the earlier stages of the study, but a Phillips-type recording system that had been built up in preparation was never used, due to that fact that the defect peculiar to this method of recording had caused its use to be discontinued elsewhere.

The fourth pen in the machine, as has been mentioned, provided time markers. These took the form of small, more or less rectangular pulses, the leading edges of which were taken as the reference points of the markers. It was necessary to have this means of checking the time scale, or what amount to the same things, the paper speed, since it was found that the paper exhibited considerable expansion and shrinkage, depending on the prevailing weather conditions. As a result of expansion the paper would tend to stick in the exit chute so distorting the record, and, at times, stopping the paper altogether. In damp, cold weather the paper would expand as the result of absorption of moisture due, no doubt, to the hygroscopic nature of the sizing material. In dry weather the paper shrank and gave no trouble. To ensure dryness, therefore, a small 15 watt electric lamp was placed inside the recorder case, where the paper was stored, and left burning. This eliminated most of the trouble.

II.C.3. Pen Recorder Output.

The traces produced by the pens of the recorder take the form of continuous lines, smooth or spiked --- depending on the absence or presence of noise. These lines, as seen from the front of the recorder, show lateral undulations of periods ranging from about 1 second upwards. The amplitudes of the traces was subject to considerable change but by varying the two gain controls in the receivers the full width of the paper could generally be covered. It was not necessary that the amplitudes of swing of the pens (and hence the amplitudes of the traces) should bear a direct proportionality to the amplitudes of the echo pulses as picked up in the receiving aerials, but merely that the traces show well-defined maxima and minima. This enables the time displacements to be measured readily.

Also it was found not to be necessary to reject the less noisy of the traces, since, by carefully drawing a smooth line through this noise, a fairly consistent set of readings was obtainable.

A facsimile of an actual record is shown in Fig.X.

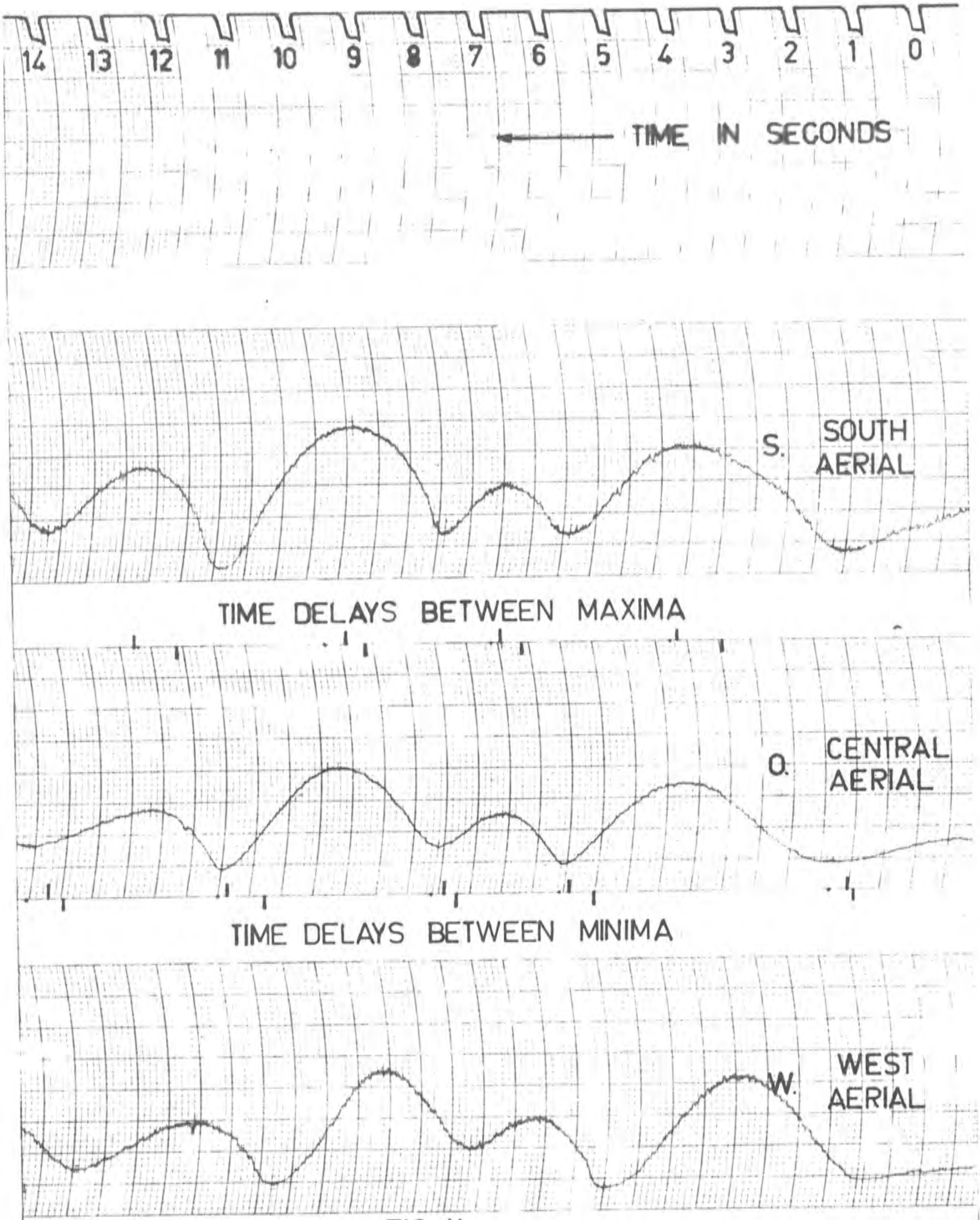


FIG. X

Sample of actual record showing (from top to bottom) time marker pips, trace from South aerial, trace from Central aerial, trace from West aerial.

II.D.MONITORING.

The monitoring of transmitter frequency has been referred to previously. It remains to mention the monitoring of pulse shape and pulse width. This was carried out by picking up the transmitter signal capacitively by looping some insulated wire around one of the aerial leads. The signal was detected by a germanium diode, in a simple R.F. rectifying circuit, and the output from this circuit displayed on a Serviscope, which, incidentally, has an in-built calibration pulse. Pulse shape and pulse width were quickly checked by this means.

Monitoring of receiver outputs was simply effected by placing terminals for this purpose by the normal output terminals of each receiver. The effect of receiver suppression could be quickly checked to ensure that it was adequate.

Monitoring terminals were also located on each of the pulse-forming circuits, in particular the recorder-gate-forming circuit, so as to be able to ensure proper positioning and width of this pulse, in order to limit the amount of noise passed on the recorder.

THE RECORDS
AND
THEIR ANALYSIS

III.A. THE NATURE OF THE DIFFRACTION PATTERN ON THE GROUND.

The diffraction pattern on the ground consists of more or less separate "blobs". These "blobs" are areas where the amplitude of the electric field vector rises more or less regularly from a relatively low value at the periphery of the "blob" to a maximum value near the middle of the "blob". In plan view, therefore, the diffraction pattern that is present at some instant over an area of ground, that is contained by a pair of rectangular axes OX and OY and the straight lines $x=x_4$ and $y=y_4$, may be represented as a projection of contour lines (i.e., lines of constant amplitude) onto the XOY plane, as shown in Fig. XI. A three-dimensional reconstruction of Fig. XI is attempted in Fig.XII, where the amplitude is measured along an axis normal to the XOY plane. This figure (Fig.XII) may be likened to a diagram of a collection of hills and intervening valleys, the hills representing the "blobs" of the diffraction pattern and the intervening valleys the spaces between the "blobs".

Interesting properties of the diffraction pattern are the temporal stability of the pattern, the size of the "blobs" in the pattern, the shape of the "blobs" in the pattern, and the motion of the pattern. These properties of the pattern will now be discussed briefly, in the order in which they appear above.

III.A.1. The Temporal Stability of the Diffraction Pattern.

By temporal stability of the pattern we may understand the persistence of the pattern in terms of the shape, size, the

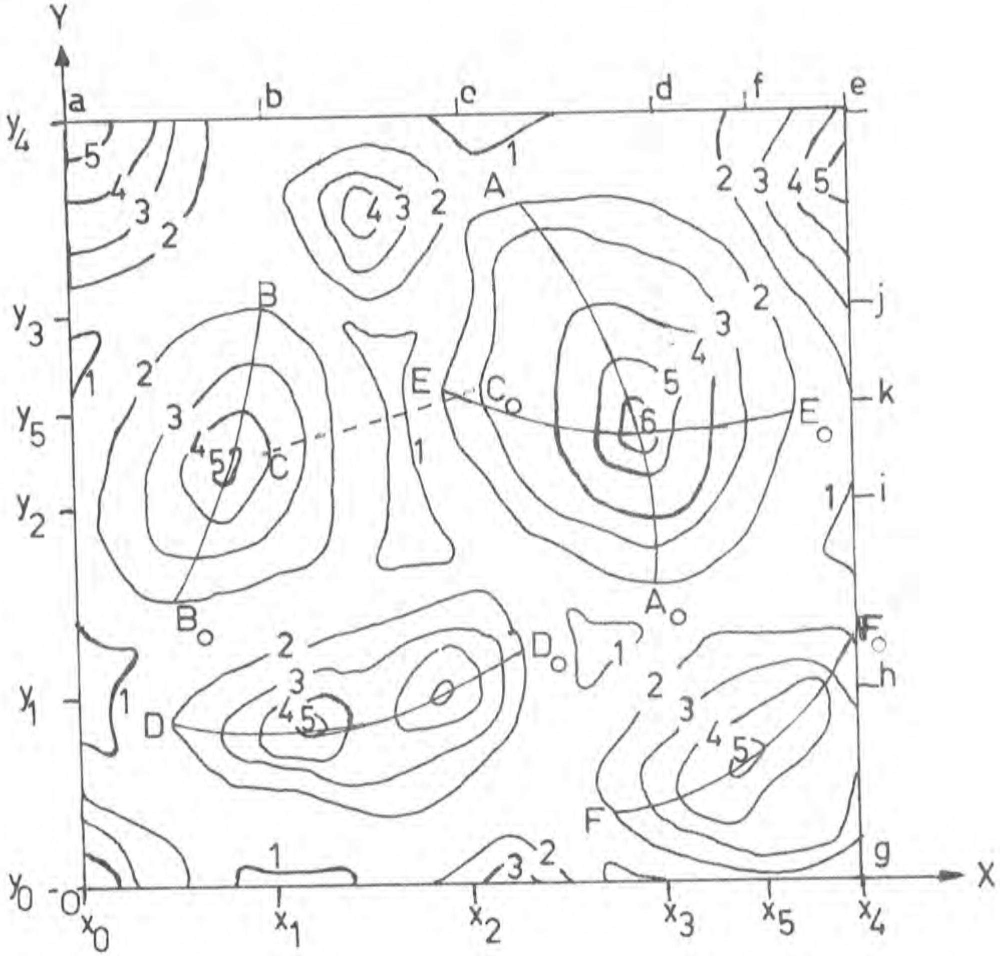


FIG. XI

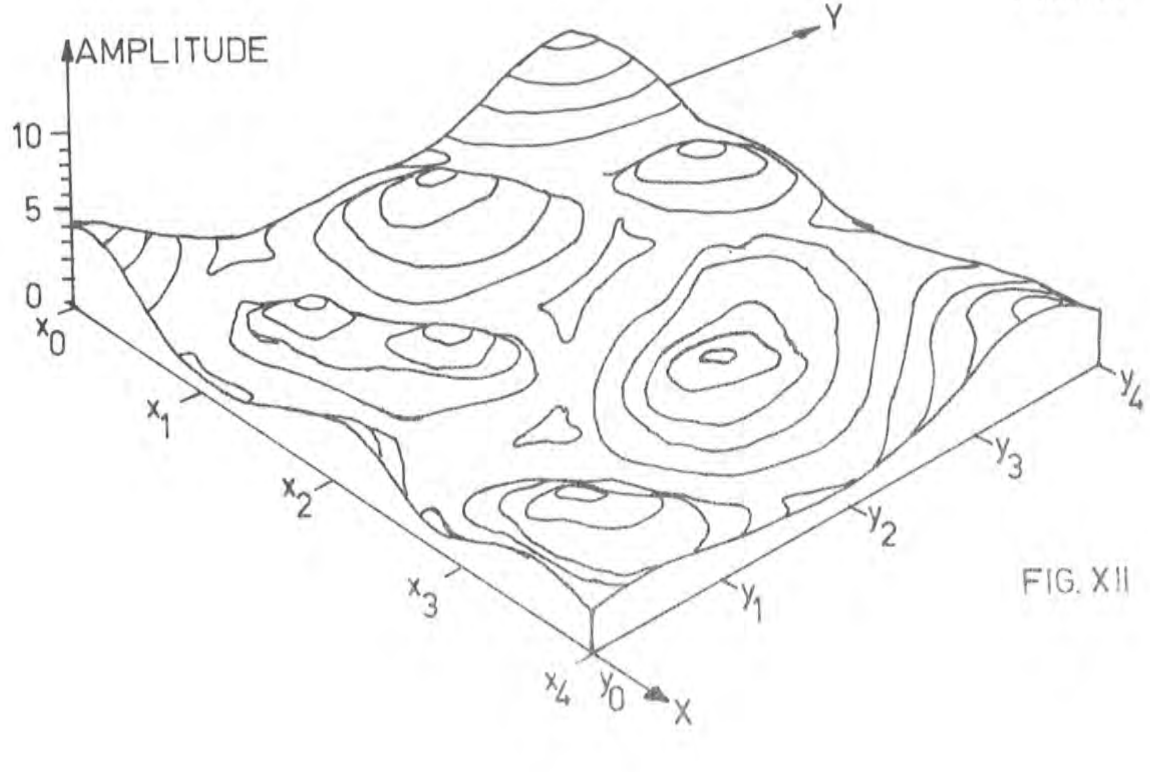


FIG. XII

relative separation and amplitude of its constituent "blobs" as a function of time; although, of these four factors the size of the "blobs" is almost certainly the least variable. In this sense, a temporally stable pattern would be one that remained quite unchanged in shape, etc., for so long as it took any distinct part of the pattern to pass across that region of the ground where there were aerials capable of detecting the amplitude of the electric field. We need not concern ourselves with what happens to the pattern before or after it traverses the detection area. The detection area could be made very large indeed by setting up a sufficiently large number of suitable aerials. In the same sense, a temporally unstable pattern would be one where the shape, etc., of the diffraction pattern altered in the time required for any part of the pattern to pass over the detection area.

In a temporally stable pattern each "blob" maintains its identity at all times while it passes over the detection area. On the other hand, it is conceivable that, in a temporally unstable pattern, the amplitude over the whole of any "blob" in the direction area may fall, finally causing the "blob" to disappear, after which it may then be replaced by a new "blob" that arises as the pattern moves over the detection area in the XOY plane. If all the "blobs" in a pattern had this property we could then talk in terms of the average "life" of the "blobs", this being the average time between the appearance and disappearance of an "blob" in the pattern. The property of temporal stability or instability may be shown in diagrammatic form.

Suppose that the diffraction pattern moves across the ground with uniform velocity and that the contour line projections onto the XOY plane be drawn at equal intervals of time, e.g., $t=\tau$, $t=2\tau$, $t=3\tau$, etc. Suppose, further, that the pattern is temporally stable. The successive positions of the point of maximum amplitude of any particular "blob", when drawn onto the XOY plane, will be points on a straight line, which is the locus along which the "peak" of the "blob" moves. This is shown, <u>for</u> <u>one</u> "<u>blob</u>" <u>only</u>, in Fig.XIII. Now, suppose that, instead of drawing all the contour-projection diagrams onto the XOY plane constructed on one sheet of paper as in Fig.XIII, as many separate diagrams be constructed on separate sheets of paper as there are times at which observations are made, so that there is one diagram for the time $t=0$, which represents the contour-projection for that time, another diagram for the time $t=\tau$, and so on. Let these diagrams then be stacked one above the other vertically and spaced equal distances apart so that there is, in effect, a vertical axis - a time axis - where the scale is such that the interval between the plane of one diagram and the next above or below it equals τ seconds. This has been done, <u>for</u> <u>one</u> "<u>blob</u>" <u>only</u>, in Fig.XIV. The locus of the "peak" of the "blob" is a straight line, inclined at some angle κ to the XOY planes, and this locus together with its projection onto the XOY plane for $t=0$ (the locus of Fig.XIII) defines a plane. It

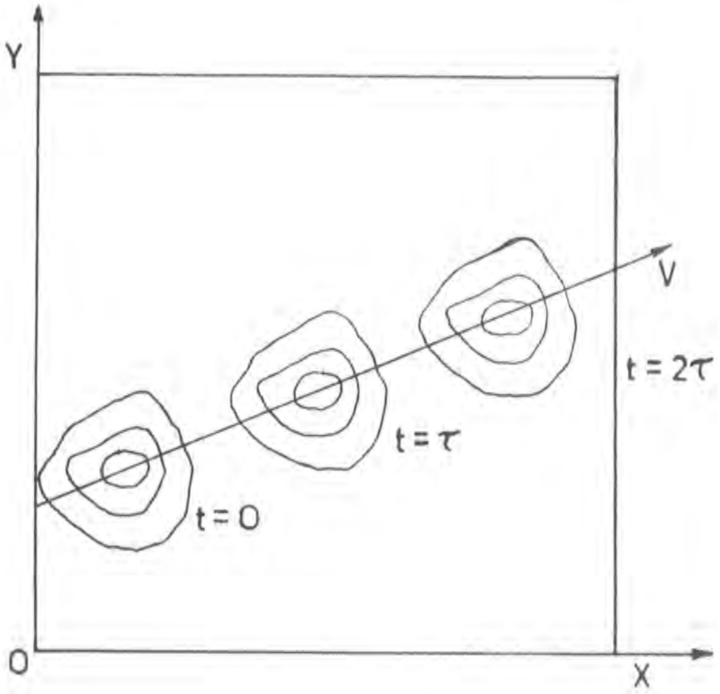


FIG. XIII

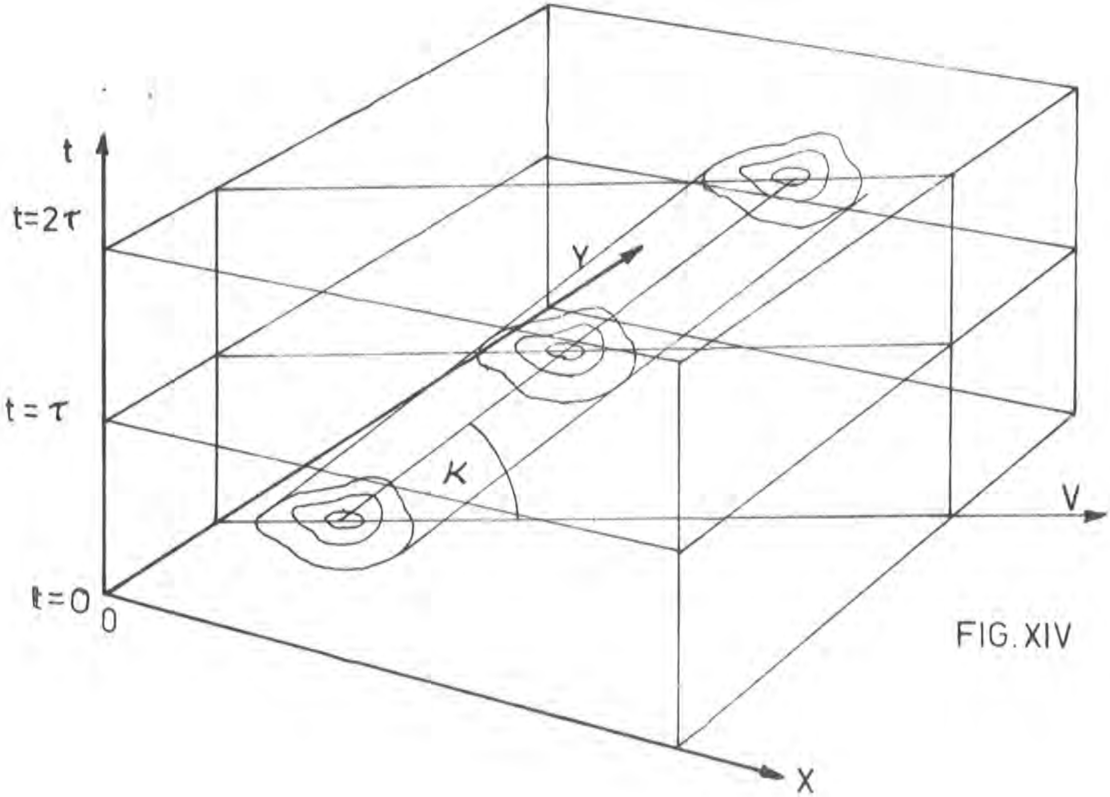


FIG. XIV

will be observed that the peripheral contour-projection of the "blob" traces out an unbroken column, whose axis is the locus of the "peak" of that "blob". The three-dimensional spacetime diagram for a temporally stable diffraction pattern moving with a uniform velocity over the ground is, therefore, a set of inclined columns.

A set of contour-projection diagrams drawn for a temporally unstable diffraction pattern which moves with uniform velocity across the ground will yield a figure such as that shown in Fig.XV, which has been drawn for a single "blob" of duration 3τ seconds (i.e., $4\tau - \tau$). The dotted lines are drawn from contours of a particular low-valued amplitude for each of the times $t=\tau$, $t=2\tau$, $t=3\tau$, and $t=4\tau$. The "blob" wells up and then subsides over its entire area, so that its size is fairly well determined 'ab origine'; the principal changes during its life being changes of amplitude rather than of size. The effect of this is that a contour line of any given amplitude appears to move out from the centre as the "blob" wells up, and appears to move in to the centre as the "blob" subsides. The axis of the short column is inclined at an angle μ to the XOY planes. The angle μ of Fig.XV will equal the angle κ of Fig.XIV when the vertical (time) axes have the same scale and the velocity of drift of the patterns has the same magnitude in both figures. In both figures (Fig.XIV and XV), the direction of the drift velocity of the pattern on the ground is the angle between the XOt plane and the plane containing the locus of the "blob".

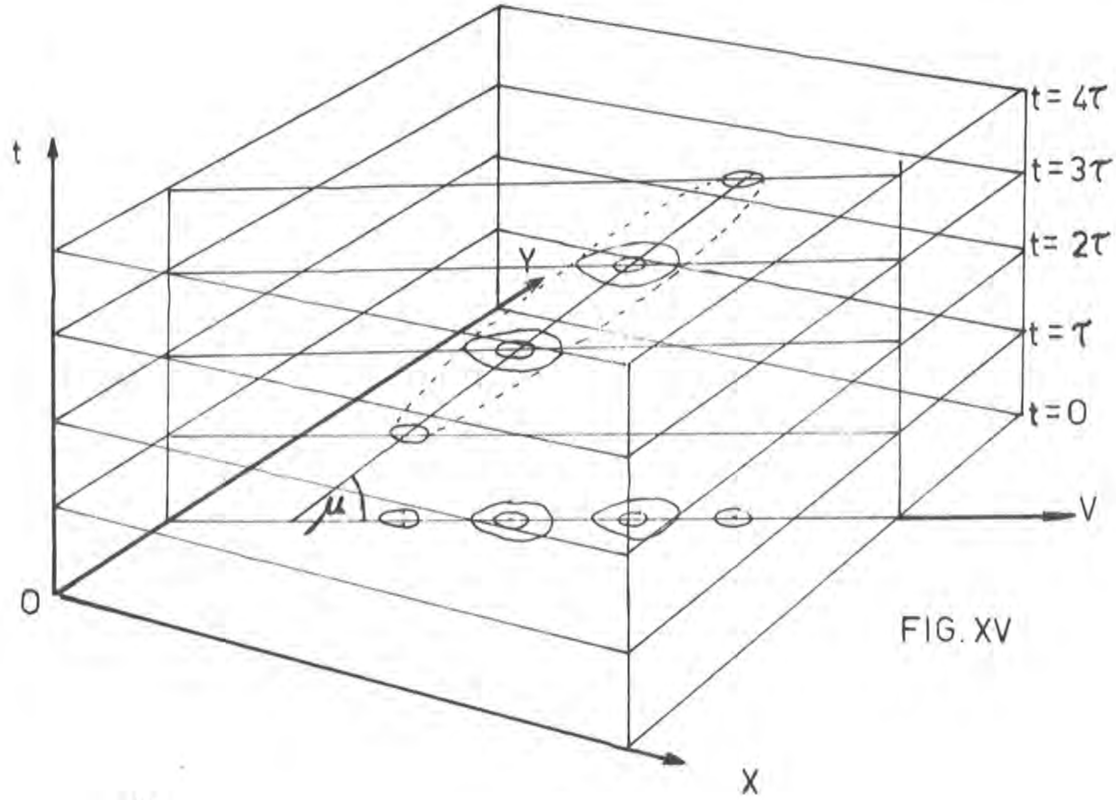


FIG. XV

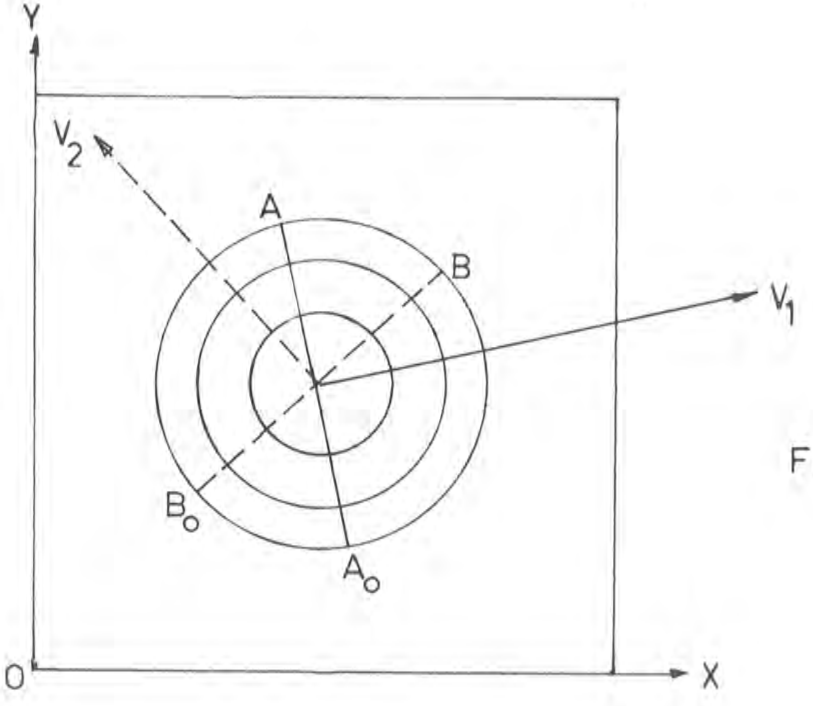


FIG.XVIII

III.A.2. The size of the Diffraction Pattern "Blobs".

To return to Figs.XI and XII. Imagine a set of detecting aerials placed at the points (x_o,y_4),(x_1,y_4),(x_2,y_4),(x_3,y_4),(x_4,y_4), and (x_5,y_4), as well as at (x_4,y_o),(x_4,y_1),(x_4,y_2),(x_4,y_3), (x_4,y_5). Letter these aerials a-k in the order given. Suppose that the diffraction pattern of Fig.XI is temporally stable and that it moves with uniform velocity parallel to the X-axis from left to right; in so doing the amplitude variations across the patterns along the lines $y=y_o$,$y=y_1$,$y=y_2$,$y=y_3$,$y=y_4$, and $y=y_5$ will be detected by the appropriate aerials. Aerials a-f will record the same amplitude variations, displaced in time, but consider the amplitude variations that will affect aerials e,g,h,i,j and k as a function of time. The variations of amplitude to be expected in these aerials with this diffraction pattern are drawn in Fig.XVI; amplitude is measured vertically, time horizontally (parallel to the X-axis), and the recorded traces are spaced along the Y-axis at the same relative distances as the aerials e-k, in this particular three-dimensional representation. (The traces are similar to those actually recorded in the course of this study.) Note that the traces obtained from aerials e,g, and h bear no resemblance to one another (beyond the fact that all contain maxima and minima), nor to the traces obtained in the three aerials i,j, and k. The traces obtained at these last aerials are markedly similar, however. In particular, we note that the first maximum recorded at each of the aerials j,k and i

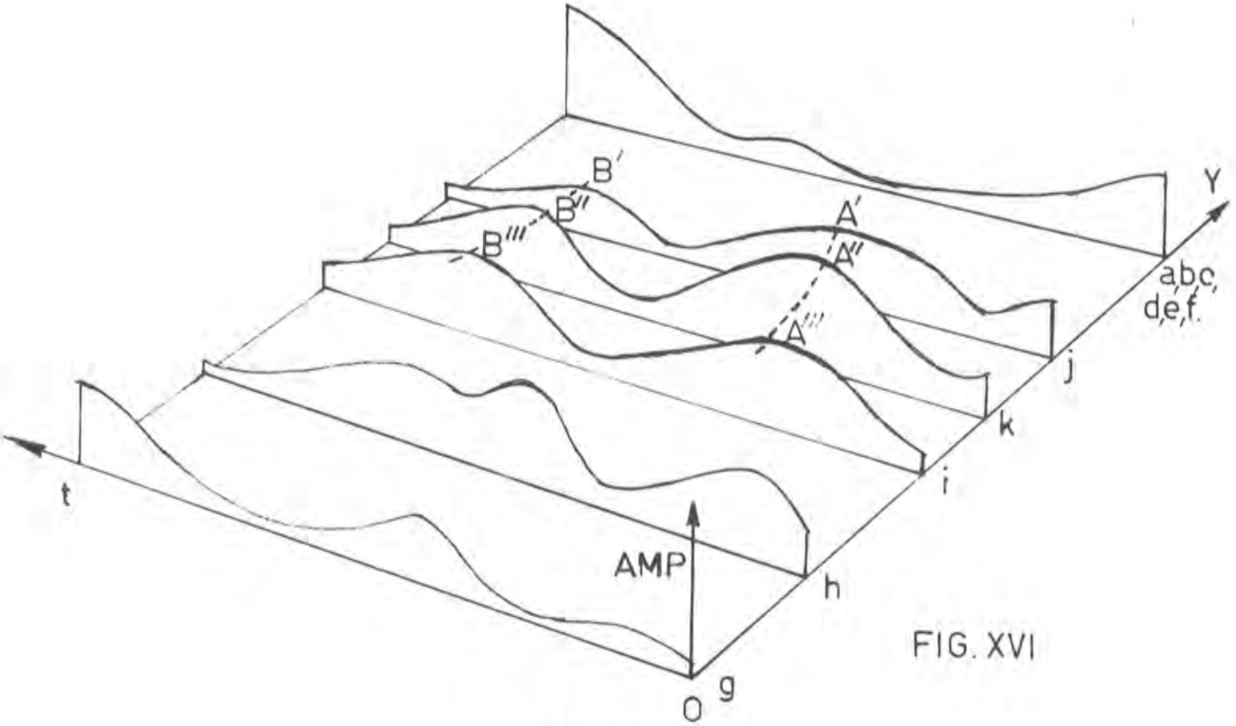


FIG. XVI

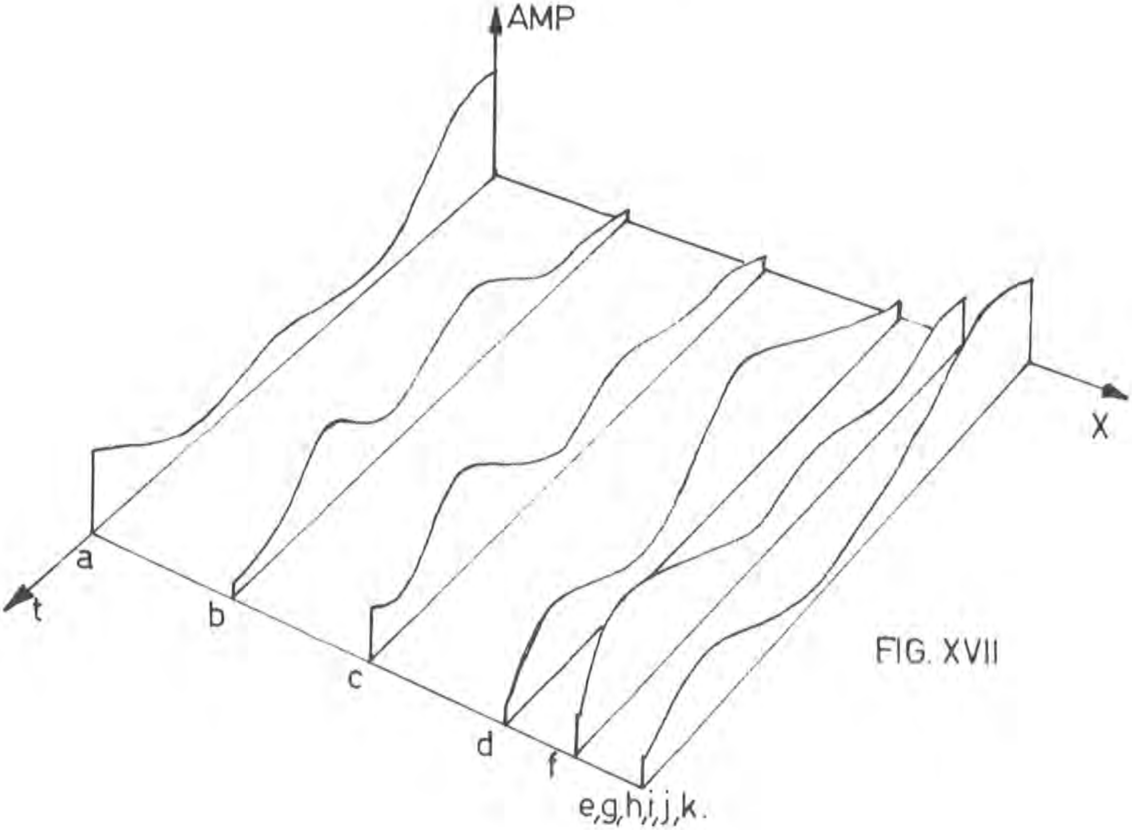


FIG. XVII

(viz.,A',A",and A''' respectively), as shown on the traces correspond to points on the line AA_o drawn on Fig.XI. Similarly, the second points of maximum B',B'', and B''' of Fig.XVI correspond to points on the line BB_o of Fig.XI. It will be seen that, if there are a great many aerials placed close together, between and on either side of the aerials i,j, and k, the points at which maxima are noted on the traces obtained at these aerials will fairly completely define the lines AA_o and BB_o of Fig.XI. We call AA_o and BB_o lines of maximum amplitude or, more simply, lines of maxima. These lines of maxima are seen not to be quite straight, in the case of the two "blobs" considered. Lines of maxima could also be drawn for the other "blobs" on the diagram. It should be apparent that the position of a line of maxima across a "blob" depends upon the shape of the "blob" and also upon the direction of motion of the diffraction pattern across the ground. That this is so is illustrated by considering other motions of the same pattern. In Fig.XVII there are drawn the traces obtained at aerials a,b,c,d,e, and f, due to the motion of the pattern of Fig.XI parallel to the Y-axis from bottom to top with uniform velocity. Traces from aerials d and f are very similar, and traces from aerials b and c are to a certain extent similar, although in this case the similarity in the traces is due in part to the transit of distinctly different "blobs" across aerials b and c. Therefore, lines DD_o, EE_o, and FF_o are true lines of maxima on Fig.XI, while CC_o represents a spurious line of maxima, which would be resolved into its real nature if many more aerials between and on either side of the aerials b and c were used.

The motion of the diffraction pattern in any other direction at some arbitrary angle to the X- or Y-axes will produce traces at the aerials a-k of the same kind as those discussed above, so resulting in the identification of the effective lines of maxima, which are those lines that are operative in producing such maxima as appear on the traces, for the particular motion of the pattern.

From the above discussion, it is clear that it is very important, when using a limited number of aerials (in fact, three is the usual number), to relate the aerial separation to the size of the "blobs" in the pattern. This makes it possible then, to avoid using spurious lines of maxima, such as CC_o in Fig.XI, as a basis of calculation of drift velocity. Hence, the importance of the observations of RATCLIFFE and PAWSEY[15], and of PAWSEY[16] about the separation between aerials and the correlation between the resulting recorded traces. Usually the aerial spacings are less than one wavelength at the frequency used.

When a diffraction pattern which is temporally unstable passes over a set of aerials such as those in Fig.XI and the life of the "blobs" in the pattern is brief while the velocity of drift is comparatively small and uniform, it is conceivable that a "blob" might record a maximum at one or more aerials and have disappeared by the time that the "blob" would have been expected to pass over another aerial of the set. A possible, but faulty, interpretation of such an event is that the motion of the pattern had carried the "blob" to one side or the other of this later aerial, assuming, of course, that the "blob" still existed. This effect would be less liable to occur for large magnitudes of pattern drift velocity, for aerials relatively close together, and for "blobs" of comparatively long life. In practice, when using the closely-spaced aerial system, such an effect as that just discussed cannot easily occur, due primarily to the relative dimensions of the "blobs" and the aerial separation.

The life of the "blobs" in the pattern on the ground, that is, this particular factor of the temporal stability or instability of the "blobs", is a function of the stability of the ionospheric irregularities which give rise to the "blobs" by way of the diffraction process. Also, of course, the average size of the "blobs", or the graininess of the pattern, depends on the size of the ionospheric irregularities.

III.A.3. The Shape of the "Blobs" in the Diffraction Pattern.

So far no explicit assumptions have been made as to the shape of the "blobs" in the diffraction pattern. One ideal type of "blob" shape is the circular one, that is symmetrical about some central point in the XOY plane. Such a shape is also called isometric. Anotherideal type is the elliptical one, of which, of course, the circular type is one extreme case. Of considerable importance in the simple methods of analysis are the assumptions that are made as to the shape of the "blobs" in the pattern. The shape of the "blobs" is important in its own right, since the shape depends upon the shape of the ionospheric irregularities, but, besides this, the shape is important because of its influence on the orientation, in the XOY plane, of the lines of maxima within the "blobs" in the pattern.

For instance, if the "blobs" were strictly circular then, no matter what the direction of motion of the pattern in the XOY plane, the effective line of maxima for any "blob" would always be perpendicular to the drift velocity vector, e.g., AA_0 and BB_0 in Fig. XVIII. Therefore, for strictly circular "blobs" and a uniform drift velocity, all effective lines of maxima in a pattern would be similarly oriented, say at some angle β, measured clockwise from geographic North. For irregularly shaped "blobs" moving also with uniform drift velocity, it may be inferred from diagrams such as Fig. XI (where, for instance, considering the "blob" in the upper right hand quadrant the effective line of maxima when the "blob" moves from left to right parallel to the X-axis is AA_0, and when the "blob" moves from bottom to top parallel to the Y-axis the effective line of maxima is EE_0) that the effective lines of maxima tend to be fairly close to the normal to the drift velocity vector, since the actual line of maxima that is effective in producing maxima in the amplitude traces recorded at the various aerials depends upon the shape of the "blob" as well as upon the direction in which the "blob" moves. A "blob" of a given shape has many potential lines of maxima, that one which is actually effective is determined once the direction in which the "blob" moves has been "chosen", as it were. The lines of maxima may be straight, slightly concave or convex, and may be skewed, at random, either a little to one side or a little to the other of the normal to the drift velocity vector, with the possible result that the average orientation of the effective lines of maxima may be normal to the drift velocity vector. Therefore, a pattern of irregularly shaped "blobs" moving with the same velocity of drift as the pattern of circular "blobs", mentioned above, could have the average orientation of its lines of maxima also at an angle β , measured clockwise from geographic North. Since both these models would yield the same - and correct - velocity of drift, we may say that the irregularly shaped "blobs" are on the average circular, meaning that they have the same properties <u>on the average</u> as the circular "blobs".

In the case of the elliptical "blob", the major and minor axes of the ellipse serve as convenient reference lines to which we may relate the orientation of the lines of maxima, as well as the direction in which the ellipse moves, that is, the azimuth of drift velocity vector. From a series of diagrams (not reproduced, see also PHILLIPS and SPENCER[29]) it is possible to show the following facts. When an elliptical "blob" moves in a direction parallel to its major axis the minor axis coincides with the line of maxima. Similarly, when the motion is parallel to the minor axis the major axis coincides with the line of maxima. In each of these two special cases, the velocity vector is perpendicular to the particular axis concerned and, hence, normal to the effective line of maxima. For any drift velocity vector that makes an angle between 0° and 90° with the major axis, the effective line of maxima makes an angle <u>less than 90°</u> with the velocity vector and, in fact, shows a marked tendency to swing towards the major axis of the ellipse. The approximation of the lines of maxima towards the major axis of the ellipse becomes more pronounced as the eccentricity approaches unity, that is, as the ratio of major to minor axis increases. In consequence, therefore, if the "blobs" of the diffraction pattern were elliptical and also <u>preferentially oriented</u>, it ought to be possible to reconstruct, from the recorded traces, the general orientations of the lines of maxima, which would show concentration about the direction in which the major axes of the ellipses tend to lie. This ought to be possible with diffraction patterns formed by reflection from the irregularities in the F-regions, which, from radio star scintillation studies, are known to be oriented along the earth's magnetic lines of force. A geometrical method to enable the reconstruction of the orientations of the lines of maxima is given in Appendix II.

The ideal circular and ideal elliptical "blob" models involve straight lines of maxima. As seen from Fig.II, non-circular and non-elliptical "blobs" could involve lines of maxima that are not straight over distances comparable to the size of the "blob" itself. However, where the "blob" is of dimensions bigger than aerial separation, short sections of the lines of maxima are fairly straight, and, if this is so for distances along the lines of maxima comparable to the distances between aerials, we may justifiably speak of the lines of maxima as straight. RAO and RAO[30] have shown, using a <u>four</u> - aerial system, that at least more than half the lines of maxima are either straight or only slightly curved, for their latitude (Waltair, India). Highly curved lines of maxima would, if oriented at random even in an otherwise temporally stable diffraction pattern moving with uniform velocity, yield traces showing considerable scatter in the values of the time intervals between the times of transit of corresponding successive lines of maxima, when the trace obtained at one aerial is compared with the traces obtained at the other aerials.

Scatter of this type will not be found in traces produced by <u>strictly circular</u> "blobs" when these move with uniform velocity and pass <u>over all three</u> aerials of the system in turn. The time intervals between the times of transit of any two successive lines of maxima as measured from the traces obtained at one aerial will be exactly the same as the corresponding intervals on the other two traces, regardless of the magnitude and direction of the uniform drift velocity.

For a pattern consisting of irregularly shaped "blobs", scatter of this type must occur as successive "blobs" pass over the aerials, since the successive lines of maxima will, almost certainly, be somewhat differently shaped and/or oriented. If such a pattern moves with a uniform drift velocity, that equals that of the strictly circular "blob" pattern above, the average time intervals measured between the successive maxima on all three traces will again be equal and hence will have little real significance; because, irrespective of the shape and orientation of the various lines of maxima, the average time intervals will depend only on the number of "blobs" passing over the aerials in a particular interval of time. Of more significance than the <u>time intervals</u> are the <u>time delays</u>; a time delay being the interval of time between the time of transit of any particular line of maxima across either of the outer aerials of the set and the time of transit of this line of maxima across the central aerial.

The time delays may have all magnitudes from zero up to an upper limit that is determined by the aerial separation and the magnitude of the drift velocity, assuming that no random motions are present. The delays also may be positive or negative depending on whether or not the line of maxima passes first through the central or an outer aerial. Each single line of maxima, therefore, generates, as it were, a pair of time delays, since there are two pairs of aerials to be considered. The time delays will be equal in <u>magnitude</u> in two separate instances; firstly, when a line of maxima passes through both of the outer aerials simultaneously, and secondly, when a line of maxima takes as long to move from one outer aerial in to the central aerial as it does to move then from the central aerial out to the other outer aerial.

Scatter in the values of the time delays will be present in the traces produced by the transit across the aerial system of irregularly shaped "blobs", even in a pattern moving with uniform drift velocity. Time delays, as defined above, will be present in the traces obtained by the passage of <u>strictly circular</u> "blobs" in a pattern moving with uniform velocity of drift over all three aerials of the system, and, in general, the values of the time delays as measured between the two pairs of aerials will not be equal; but, there will be no scatter in the values of the time delays in this ideal case. As we have seen previously, a pattern of irregularly shaped "blobs" may behave on the average as a pattern of circular "blobs", so that if a pattern of irregularly shaped "blobs" were to move with the same drift velocity as a pattern of circular "blobs", it is possible that the average time delays calculated from the motion of the pattern of irregularly shaped "blobs" might be equal to the value of the corresponding time delays obtainable from the motion of the pattern of circular "blobs" across the aerial system. If this were so then both types of pattern would yield the same and the correct velocity of drift.

Scatter in the values of the time delays may be introduced into the traces obtained at different aerials by changes in the shape of the "blobs" in the pattern as it moves, quite apart from any change in the drift velocity. If a change of "blob" shape occurs the main result will be a slight alteration in the orientation of the effective line of maxima. If such a change occurs progressively as the "blob" moves over the aerial system, then lines of maxima of somewhat different orientation will pass in turn over the three aerials. The points of maximum amplitude on the traces will, therefore, be shifted in time slightly, relative to where one would expect them to be if one were assuming that the "blobs" in question were members of a temporally stable pattern. The actual change in the value of the expected time delays could be positive or negative, or even zero for one aerial pair if the line of maxima were to rotate about that point along its length that passed over the two aerials in turn. It is conceivable, also, that many small random changes of "blob" shape would leave quite unaltered the average orientation of the lines of maxima, so that a pattern of irregularly shaped "blobs", moving with uniform drift velocity and subject to changes of "blob" shape as discussed above, might, nevertheless, still behave on the average as a pattern of circular "blobs".

When the relative separation between otherwise stable "blobs" changes we are then considering what is more generally called random motion of the "blobs", and this will be discussed in the next section.

III.A.4. The Motion of the Diffraction Pattern.

In this section we shall ignore changes in the shape and size of the "blobs" in a diffraction pattern; also, the discussion will be almost entirely confined to a pattern of circular "blobs". In the case of a well-defined unchanging "blob" moving with a uniform drift velocity, the relative positions of points of maximum amplitude of the traces obtained at the three aerials will depend on the type of "blob" (e.g., circular or elliptical), on the magnitude of the drift velocity, and, quite strongly, on the angle between the drift velocity vector and the two aerial axes defined by the lines drawn from the central aerial to the two outer aerials.

Consider a <u>strictly circular</u> "blob"; the effective line of maxima is, for all azimuths of drift velocity, normal to the velocity vector. Hence, if the velocity vector lies parallel to one or other of the aerial axes, points of maximum amplitude should coincide, in time, on the traces obtained at those two aerials lying on the aerial axis normal to the velocity vector, and the corresponding point of maximum amplitude in the trace obtained at the other aerial will precede in time, or lag behind, these coincident maxima by an amount proportional to the aerial separation and inversely proportional to the magnitude of the drift velocity. For any other orientation of the drift velocity vector, the points of maximum amplitude on the traces obtained at the two outlying aerials will be displaced in time from the corresponding points of maximum amplitude on the trace obtained at the central aerial. The time delay will be greater in the case of that aerial lying on the aerial axis with which the drift velocity vector makes the smaller angle; that is, the time delays are greater between those two aerials that define the aerial axis along which the component of the drift velocity vector is greater, and are smaller between the other two aerials on the axis along which the component of the drift velocity vector is less.

Also, if the diffraction pattern is only statistically isometric, and so any "blob" may be irregular in shape, there will be a greater scatter in the time intervals between the times at which corresponding maxima occur in the traces from the three aerials for those two aerials on the aerial axis along which the drift velocity component is less. There will also be a greater scatter in the time delays measured between the maxima in the traces for this particular pair of aerials.

Consider again a pattern of <u>strictly</u> <u>circular</u> "blobs", etc. We now include random velocities in the discussion. The motion of any individual "blob" across the aerial system is due to its resultant velocity at the time of transit. This resultant velocity is the vector addition of the drift velocity and the instantaneous random velocity. Thelatter may have magnitudes from zero up to values possibly very much greater than the magnitude of the drift velocity, so that the resultant velocity of motion of the "blob" may even be, in direction, opposite to the drift velocity, as the random motions may assume all azimuths. Any individual "blob" moving across the aerial system will give rise to a maximum amplitude in the trace obtained at any of the three aerials, but, when the whole traces produced by the transit of many "blobs" in succession across the aerials are considered, and each "blob" has a random velocity that may differ in size and direction from that of the "blobs" that pass across the aerial system before or after it, it will be seen that there may be a pronounced scatter in the time delays in even short sections of the traces.

For strictly circular "blobs", the scatter in the time delays, assuming that each "blob" passes over all three aerials, will depend upon the relative magnitudes of the drift velocity and of the random velocities. If the magnitude of the drift velocity is much greater than the average magnitude of the random velocities, the traces will be very similar in terms of the relative spacing of the points of maximum amplitude, with small scatter in the time delays. When the random velocities' average magnitude approximates to and exceeds the magnitude of the drift velocity, we must expect increased scatter in the time delays. Other things being equal, most pronounced scatter should occur, for any given value of average random velocity, when the drift velocity is zero.

For patterns of irregularly shaped "blobs", that are on the average circular, the resultant scatter in the time delays in the traces may be due to several different causes (e.g., differences in the orientation of lines of maxima, changes in "blob" shape, random motions) which, in any particular instance, may add to one another or may subtract from one another in all possible ways. Random motions in such patterns may, conceivably, not alter the scatter in the time delays to any great extent, or it may modify it considerably.

The weight of evidence[35,39] seems to suggest that very eccentric "blobs" are rare in the diffraction patterns produced by reflection from the E-region, but, in any case, if such "blobs" were present and their major axes were oriented randomly, the overall effect on the traces would differ little from that produced by circular "blobs" subject to the same motions.

The simple methods of analysis, in general, have not been devised to handle traces obtained during periods when random motions were pronounced. For this reason, traces showing large scatter in the time delays were not included in the final analysis, some attempt being made to select those reasonably free from this effect. In the following section some special cases will be treated mathematically in order to see how measures of drift velocity may be obtained from the traces made by the recorder. The discussion given above, and that in the section to follow, is not exhaustive by any means but it serves, at least, to indicate the complexity of the problem.

III.B. ANALYSIS OF RECORDS

III.B.1. General Discussion

The diffraction pattern that moves over the ground contains lines of maximum amplitude; these pass in turn across the receiving aerials and so may be recorded. There are many possible configurations of these lines of maxima and it is necessary to recognize this fact in order to appreciate what effect these various configurations might have upon the recorded time displacements, and hence how they might ultimately affect the values of wind velocities deducible from the time displacements.

Perhaps the best way to introduce the various types of complicating factors is to work through the simple analysis as originally devised by MITRA[20] and then to see what is the effect of modifying his assumptions about the motion of the lines of maximum amplitude, etc.

Consider the three aerials to be placed at the points O, E and N, which make up a right-angled triangle, whose side OE (of length ξ_0) lies along the East-West line, and whose side ON (of length η_0) lies along the North-South line through O (Fig.XIX). Let us suppose that the velocity of drift of the diffraction pattern has a magnitude V and that its direction be inclined at some angle θ, measured anticlockwise from East. Let us suppose further that each of the lines of maximum amplitude makes an angle $\psi = 0$ with the normal to the direction of motion, the diffraction

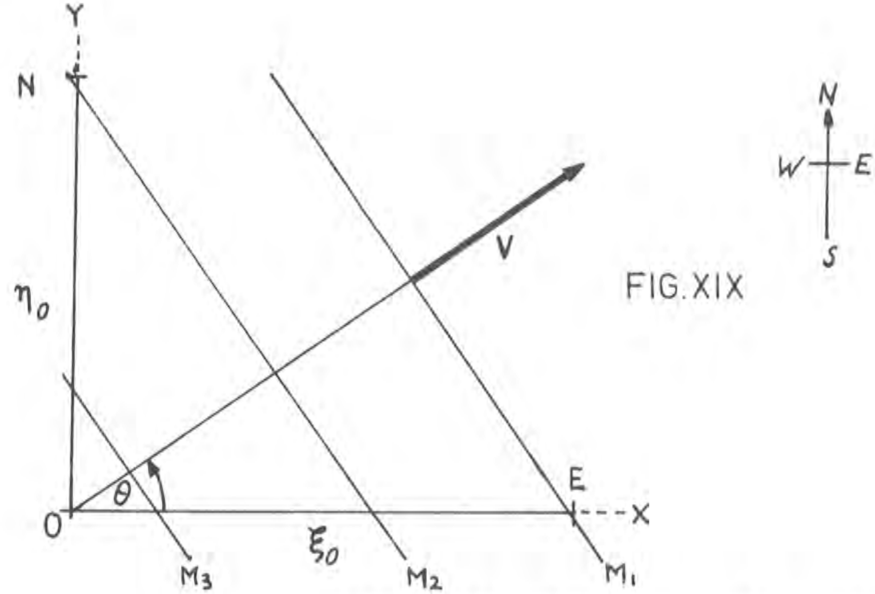


FIG. XIX

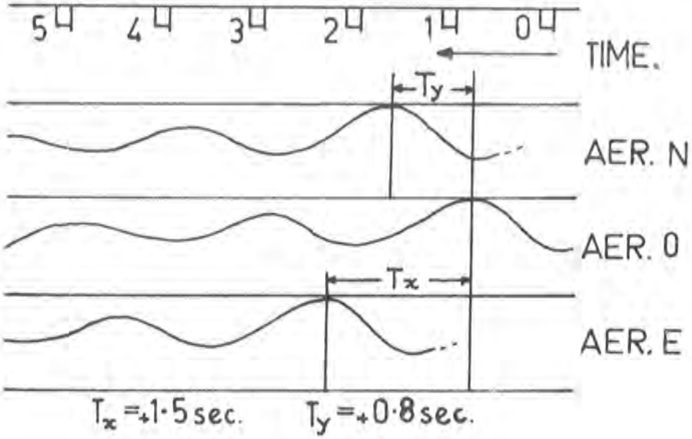


FIG. XX

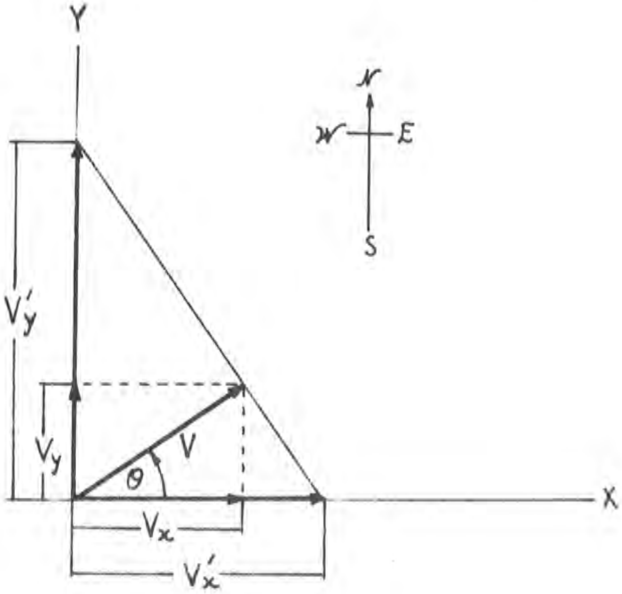


FIG. XXI

pattern may be assumed to be isometric, that is, each "blob" is circular. The lines of maximum amplitude are therefore assumed to be straight over distances comparable to the separation of the aerials, and let us assume that the amplitude pattern is not affected by random motions as it moves. The velocity is assumed constant. Then if three consecutive lines of maxima M_1, M_2 and M_3, pass across the receiving aerials in turn, the records obtained at E, O and N would be as shown (Fig.XX). The convention of sign is that the time-delays, Tx and Ty, of each maximum recorded from aerials E and N, respectively, and measured from the time at which the corresponding maximum is recorded from aerial O, are positive when the maximum is recorded first at O. If all the assumptions noted above hold rigidly, then the time-delays for all three of the lines of maxima, M_1, M_2 and M_3, should be the same. From the diagram (Fig.XIX) we see that this means that, the lines of maxima take a time Tx to move from O to E, and a time Ty to move from O to N. There is, therefore, an apparent component of velocity along the x-axis, call this V_x'. Similarly, there is an apparent component of velocity along the y-axis, call this V_y'. Then

$$V_x' = \xi_o / T_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and,

$$V_y' = \eta_o / T_y \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Now, Tx is also the time taken for the lines of maximum amplitude to travel a distance equal to $\xi_o . \cos \theta$ at a velocity V, where $\xi_o . \cos \theta$ is the projection of OE onto the direction of motion. Similarly, Ty is the time taken for the lines of maximum amplitude to travel a distance equal to $\eta_o . \sin\theta$ at a velocity V. That is

$$Tx = \xi_o . \cos\theta / V \qquad \text{..................}(3)$$

and,

$$Ty = \eta_o . \sin\theta / V \qquad \text{..................}(4)$$

By rearranging (3) and (4) we see that V_x' and V_y' are related to V by the equations,

$$V_x' = \xi_o/_{Tx} = V/\cos\theta \qquad \text{.............}(5)$$

and,

$$V_y' = \eta_o/_{Ty} = V/\sin\theta \qquad \text{.............}(6)$$

Also, if we denote the true components of V along the x-axis (E - W line) and y-axis (N - S line) by Vx and Vy respectively, then

$$Vx = V\cos\theta \qquad \text{..................}(7)$$

and,

$$Vy = V\sin\theta \qquad \text{..................}(8)$$

By solving equations (5) and (6) for cos θ and sin θ respectively, and noting that

$$1 = \sin^2\theta + \cos^2\theta \qquad \text{................}(9)$$

we have that

$$1/_{V^2} = 1/_{V_x'^2} + 1/_{V_y'^2} \qquad \text{...............}(10)$$

Also, from equations (5) and (6) we have that

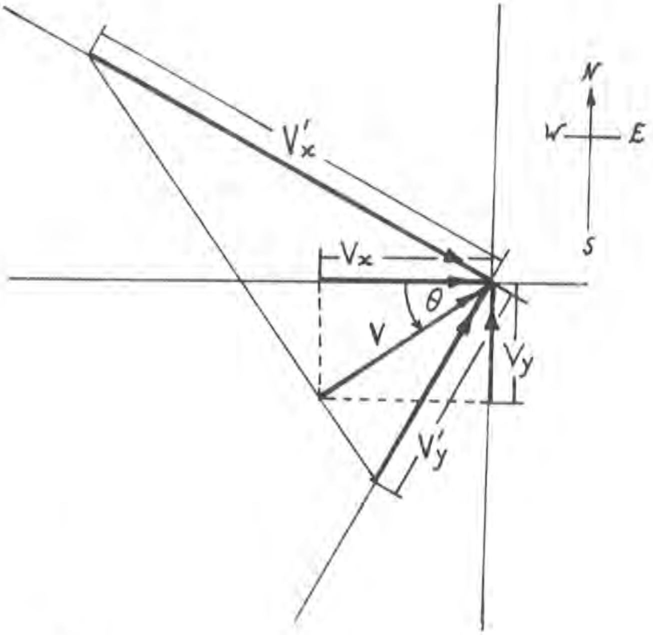
$$\tan\theta = \frac{V_x'}{V_y'} \qquad \text{..................}(11)$$

A simple geometrical construction that enables a rapid determination of V, of θ, and also of Vx and Vy is shown in Fig.XXI. Along the x-axis, to some scale, V_x', as determined (1) above, is marked off to give a point A; similarly, V_y' along the y-axis to the same scale fixes a point B. The join of these two points is seen to give a line having the same slope as a line of maximum and so, by reference to <u>Fig.XXI</u>, we see that the true velocity will be given by a line perpendicular to AB, cutting AB in C, where, as required, OC makes an angle θ with east, and the magnitude of the velocity is given by OC to the same scale as was used to construct V_x' and V_y'. It will be seen that OC, OA and OB (or V, V_x' and V_y') satisfy equations (5), (6), (10) and (11), as required. Then the x- and y- components of V, viz., V_x and V_y are found by dropping perpendiculars from C onto the x- and y- axis, respectively.

By extending the axes back through O to allow for negative value of T_x and T_y all possible types of recordings of time-delays may be treated graphically. Also the method is little altered when the lines joining pairs of aerials are not E-W and N-S lines, which is the case at Adelaide. The graphical construction for the case at Adelaide is shown in Fig.XXII for the same velocity as was treated in Figs.XXI. In this case, of course, the values of T_x and T_y would be both negative.

In his original article, MITRA[20] points out that the time delays (T_x and T_y above) obtained from actual records are not constant for successive lines of maxima. He then calculates his velocities using the average time delays ($\overline{T}_x$ and $\overline{T}_y$). This would give the correct velocity if only one of the original assumptions

FIG. XXII



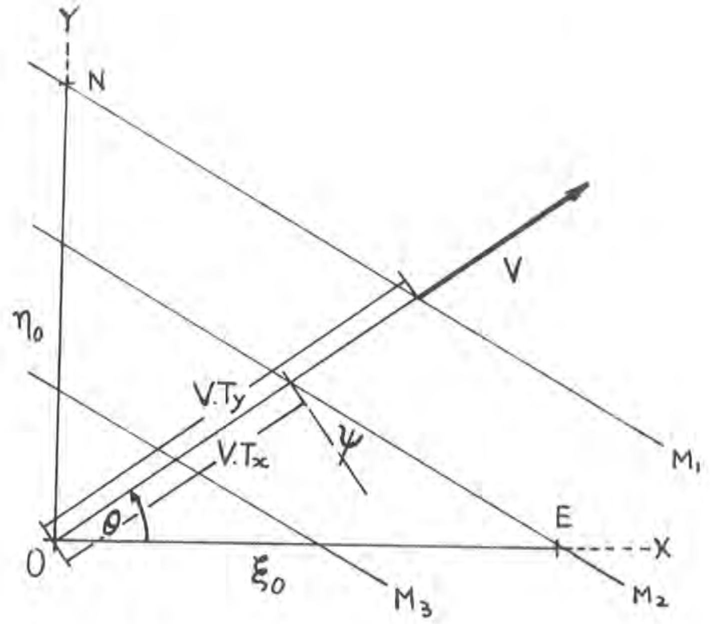
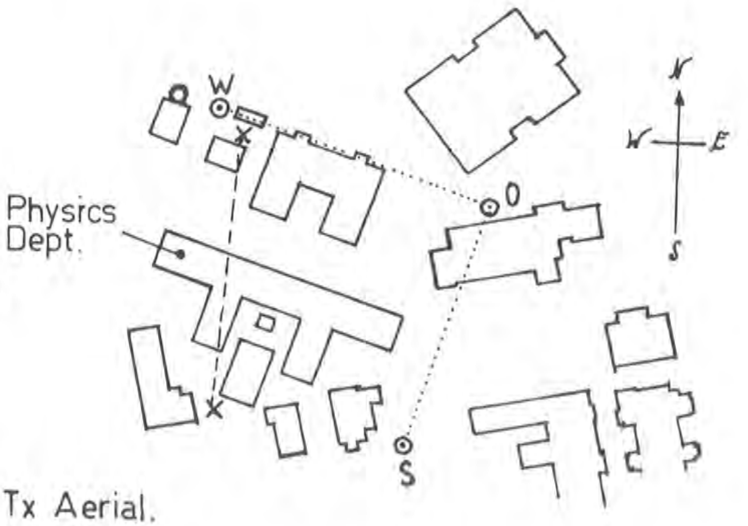


FIG. XXIII

FIG. XXIV



is adjusted. Suppose we alter the assumption about the shape of the pattern. Let us suppose that the individual "blobs" are not isometric or circular but rather that they are so <u>on the average</u>, that is, the "blobs" are statistically isometric, while they may individually be irregularly shaped. The lines of maxima are still essentially straight and may be inclined at angles $\psi \neq 0$ to the normal to the velocity vector. However, although ψ may have small values, either +ve. or -ve., the average value of ψ, viz., $\overline{\psi}$, is zero, that is $\overline{\psi} = 0$, as required by a statistically isometric pattern. The equations (1) - (10) above could then be rewritten, where necessary, by replacing Tx by $\overline{T}$x and Ty by $\overline{T}$y; the geometric constructions would be unaltered.

It is also of interest to mention that, if the pairs of time-delays (Tx, Ty), as they are read from the records, are plotted along axes parallel to the x- and y-axes used in plotting the values of V_x' and V_y', then, in the case being considered, the points so obtained should be along a straight line and, in particular, the line drawn from the origin perpendicular to this straight line will intersect it at a point whose co-ordinates are Tx and Ty. The individual points (Tx, Ty) will be symmetrically distributed along the straight line about the point ($\overline{T}$x, $\overline{T}$y) and, also, the line from the origin to the point ($\overline{T}$x, $\overline{T}$y) will make an angle θ with the positive x- axis (i.e. E-W line). The construction outlined above offers another means of determing θ.

Let us now consider the effect of a preferentially oriented anisometric pattern upon the determination of V and θ. We will assume, as before, that there are no random motions involved. Let V and θ be constant, let the lines of maximum amplitude be straight lines, that each makes an angle ψ with the direction of motion of the wind, ψ may be assumed constant and take any value between $\frac{\pi}{2}$ and $-\frac{\pi}{2}$ (Fig.XXII). Then for the aerial system described before (Fig.XIX), the time-delays, Tx and Ty, that are recorded when a given line of maximum moves through the aerials, are, when one uses the Sine Rule, seem to be related to the constants V, θ, ψ, ξ_o and η_o by the equations

$$Tx = \frac{\xi_o}{V.\cos\psi} \cdot \cos(\psi + \theta) \ldots\ldots\ldots\ldots\ldots(12)$$

and

$$Ty = \frac{\eta_o}{V.\cos\psi} \sin(\psi + \theta) \ldots\ldots\ldots\ldots\ldots(13)$$

This then gives, by dividing (13) by (12),

$$\frac{Ty/\eta_o}{Tx/\xi_o} = \tan(\psi + \theta) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

Also, by solving (12) and (13) for Tx/ξ_o and Ty/η_o, respectively, then squaring and adding, and noting that

$$\sin^2(\psi + \theta) + \cos^2(\psi + \theta) = 1 \ldots\ldots\ldots(15)$$

we have that

$$(Tx/\xi_o)^2 + (Ty/\eta_o)^2 = \frac{1}{V^2.\cos^2\psi} \ldots\ldots(16)$$

By analogy with the analysis due to MITRA we may deduce from Tx and Ty apparent components of the velocity V along the E-W and N-S axes, viz. V''_x and Vy'', where

$$V''_x = \xi_o/T_{x}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

and

$$V''_y = \eta_o/T_y. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

Then, using these substitutions in (16), we get

$$\frac{1}{V''^{2}_{x}} + \frac{1}{V''^{2}_{y}} = \frac{1}{V^2 . \cos^2\psi} \quad \ldots\ldots\ldots\ldots(19)$$

This may be compared with equation (10), from which it will appear obvious that according to the value of the angle ψ, equation (19) will lead to different values of the velocity vector. From (12) and (13) it will be clear that if ξ_o, η_o, θ and V are constant, then for the case where all the lines of maximum amplitude have the same value of ψ (i.e., ψ constant also), T_x and Ty are constant. If, on the other hand, ψ varies over some limited range then, for each value of ψ, there will be a distinct pair of values for Tx and Ty. A plot of these time-delays pairs, ie., the Tx plotted against the appropriate Ty, should result in a straight line, as shown by equation (22), below. This can be seen by expanding the cos $(\psi + \theta)$ and sin $(\psi + \theta)$ factors in equations (12) and (13), rearranging the terms so as to solve each of the resulting equations for tan ψ and then equating the resulting expressions, thus

$$\tan\psi = \frac{\left(Tx/\xi_o - \cos\theta/V\right). V}{-\sin\theta} = \frac{\left(Ty/\eta_o - \sin\theta/V\right)}{\cos\theta} .V..(20)$$

Simplification of these expressions then results in

$$\left(\frac{Tx}{\xi_o}\right).\cos\theta + \left(\frac{Ty}{\eta_o}\right)\sin\theta = \frac{1}{V} \quad \ldots\ldots\ldots\ldots(21)$$

By rearranging this we may solve for Ty and so find the slope of the line through the points of time-delays pairs,

$$Ty = -\frac{\eta_o}{\xi_o} \cdot \cot\theta \cdot Tx + \frac{\eta_o}{V.\sin\theta} \quad \text{........(22)}$$

It follows, therefore, that a line drawn through the origin perpendicular to the line, whose equation is given by (22), will have a slope equal to

$$\tan\lambda = \frac{\xi_o}{\eta_o} \cdot \tan\theta \quad \text{.....................(23)}$$

This implies that the direction of the wind (viz.θ) may be found readily from equation (23), since

$$\tan\theta = \frac{\eta_o}{\xi_o} \cdot \tan\lambda \quad \text{.....................(24)}$$

The method, due to PÜTTER,[21] then is used as follows. Plot the time-delay pairs (Tx, Ty) as read from the records along an x- axis (E-W line) and a y- axis (N-S line). Draw the straight line through them and, from the origin drop a perpendicular to the line so drawn. Measure the slope of the perpendicular (which makes an angle λ with the x-axis, measured anticlockwise from it) and, using equation (24) calculate tan θ and hence θ. The point of intersection of the line through the points and of a line through the origin whose equation is

$$Ty/_{Tx} = \frac{\eta_o}{\xi_o} \tan\theta \quad \text{.....................(25)}$$

has co-ordinates (T_x', T_y') where

$$T_x' = (\xi_0 . \cos\theta)/V \quad \text{.........................(26)}$$

and

$$T_y' = (\eta_0 . \sin\theta)/V \quad \text{.........................(27)}$$

Hence V may be found. Equations (26) and (27) may be compared with equations (5) and (6).

The fact that the points are spaced out along a line means that we have assumed an anisometric pattern that shows a tendency for the lines of maxima to be preferentially oriented on the average, so that although the values of ψ for successive lines of maxima may not be equal they do not differ greatly amongst themselves and, indeed, have a quite definite non-zero average value $\bar{\psi}$, that remains constant for an appreciable period. Implicit in the above discussion is that the points on the line of plot of time-delay pairs are not distributed symmetrically about the point (T_x', T_y'), but will, in general, lie more to one side or the other of this point. If, however, the points are symmetrically arranged on either side of this point, we may interpret this as a case where $\bar{\psi} = 0$; in this instance, the points ($\bar{T}x$, $\bar{T}y$) and ($T'x$, T_y') coincide. Similar changes in the construction apply in this case when the actual aerial system (Fig.XXII) is considered, as applied in the Mitra-type analysis.

It will be seen that the only real difference between the two methods of analysis described above lies in the assumption, in the first case, of diffraction pattern that is actually or on-the-average isometric, and, in the second case, of an anisometric diffraction pattern that is preferentially oriented, either strictly or on-the-average. An anisometric pattern may be considered to be produced by a simple stretching in one direction of a previously isometric pattern. As has been shown, the effect of the preferentially oriented anisometric amplitude pattern is to make the velocity deduced from the simple (MITRA) method of analysis wrong in both magnitude and direction, except in those cases where the major axis of the ellipse lies along or normal to the direction of drift; in these two instances the simple method does give the correct result.

The main objection to the analyses presented above is that rarely, if ever, in practice does the plot of pairs of time-delays yield anything that could be termed, without hesitation, a straight line. This has been the writer's own experience and also the experience of other workers; for instance HARMISCHMACHER and RAWER[21] have this to say on the subject of PÜTTERS method of analysis: "... Berg a examiné quelques expériences, il n'a pu vérifier l'hypothèse de PÜTTER que pour très peu de cas". Also, they conclude: "En effet, parmi un grand nombre d'observations que nous avons ainsi évalué, seulement quelques pour-cent ont donné une répartition de la forme supposée par PÜTTER." We must admit that the case is not so simple as was supposed in laying down the assumptions on which the analyses were based. There may also be random motions in the diffraction pattern as it moves. These, however, greatly complicate the analysis. A veryfull analysis was made, in general terms, by BRIGGS, PHILLIPS, and SHINN[31] for random changes in isometric diffractions patterns, and this was developed later by PHILLIPS and SPENCER[29] to include random changes in anisometric patterns. This method of analysis may be applied to all types of records and certainly yields the true drift velocity, as well as other important information. However, the method has the weighty disadvantage of being quite laborious and time-consuming, and may best be handled by computers. It involves the use of autocorrelations and cross-correlations, and, although a less laborious method has been developed by YERG[32,33] this type of analysis is not possible for a single worker when results are coming in continuously, unless aided in the reading and computing.

BANERJI[34] has developed a method that seems capable of yielding results with a mimimum of work. His method leads to value for V, θ and V_c, the last of these being a measure of the random changes in the pattern; it was termed by BRIGGS, PHILLIPS and SHINN[31] the characteristic velocity. According to BANERJI'S analysis, when random motions are present, the (Tx, Ty) pairs if plotted will form an ellipse, and not a straight line. The major axis of this ellipse, in fact, replaces the straight line of PÜTTER, and the spread of the points about the major axis of the ellipse is an independent indication of the magnitude of V_c. The method proposed by BANERJI may be summarized as follows. First, plot the time-delay pairs (Tx, Ty). The major axis of the ellipse over which they are distributed is, according to BANERJI, inclined to the Tx (i.e., x) axis at an angle ε given by the formula

$$\tan 2\varepsilon = \frac{2 \sum_i (Tx_i - \overline{T}x)(Ty_i - \overline{T}y)}{\sum_i (Tx_i - \overline{T}x)^2 - \sum_i (Ty_i - \overline{T}y)^2}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (28)$$

where (Tx_i, Ty_i) are the individual values of the time-delay pairs. The perpendicular to the major axis through the origin makes an angle λ with the Tx axis where

$$\lambda = \varepsilon + \pi/2. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

And, as before, the perpendicular and the direction of drift are related by

$$\tan \lambda = \frac{\xi_o}{\eta_o} . \tan \theta, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

hence, θ may be found. The line of equation

$$Ty = Tx . \frac{\eta_o}{\xi_o} . \tan \theta, \quad \ldots\ldots\ldots\ldots\ldots\ldots (25.a)$$

intersects the major axis of the ellipse in a point whose co-ordinates are (Tx', Ty'), but these do not lead directly to the velocity V, as in the case of the points lying on a straight line, but, rather, they lead to a "velocity"

$$\frac{V^2 + Vc^2}{V} \left(= \frac{Vc'^2}{V} = V' \text{ of BRIGGS, PHILLIPS and SHINN} \right). \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (30).$$

There is still the possibility of solution since, according to BANERJI, the correlation ρ between Tx and Ty is

$$\rho = - \frac{0.74}{2} . \frac{\overline{T}x . \overline{T}y}{\sigma_{Tx} \sigma_{Ty}}, \quad \ldots\ldots\ldots\ldots\ldots\ldots (31)$$

and, also from the spread of the points about the major axis, ρ is related to V and Vc by the expression

$$\frac{2}{V^2+V_c^2} = \left(\frac{\bar{T}x}{\xi_o}\right)^2 + \left(\frac{\bar{T}y}{\eta_o}\right)^2 + \left\{\left[\left(\frac{\bar{T}x}{\xi_o}\right)^2 - \left(\frac{\bar{T}y}{\eta_o}\right)^2\right]^2 + 4\left(\frac{\bar{T}x}{\xi_o}\right)^2\left(\frac{\bar{T}y}{\eta_o}\right)^2 \cdot \frac{1}{\rho^2}\right\}^{1/2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(32)$$

All the quantities in equations (3) and (31) have been referred to before except σ_{Tx} and σ_{Ty} in equation (30), which are merely the r.m.s. deviations of Tx and Ty respectively. The ellipse as drawn with its major axis enables θ and the point (Tx', Ty') to be found, hence the "velocity" $\frac{V^2 + V_c^2}{V}$ and then from the statistics, of the time delays $\frac{2}{V^2 + V_c^2}$ may be found, leaving it possible to determine V, and then Vc. As pointed out in their complete analysis by BRIGGS, PHILLIPS and SHINN, when V is large compared with Vc, the drift is the predominant cause for fading. On the other hand, if Vc is larger than V, the fading is mainly due to random motions.

As seen from equation (30), following BRIGGS, etc.,

$$V' = \frac{V^2 + Vc^2}{V} = V + \frac{Vc^2}{V} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(30,a)$$

where V' is the "velocity found by using the values Tx' and Ty', mentioned previously, the effect of the random motions, in the case of an approximately isometric diffraction pattern for which $\bar{\psi} = 0$ (i.e. values of distributed isotropically), and where Tx' approximates to $\bar{T}x$, and Ty' to $\bar{T}y$, is that the simple analysis leads to a value of the magnitude of the velocity which, by mistaking V' for V, is too large; although in these cases the direction θ may be quite close to the correct value.

In summary of the methods given above, it will appear desirable, if the simple method of analysis is to be used to obtain reliable results quickly, to select only those records that are obtained on occasion when the random motions are small, and which result from isometric patterns. With this in view, the Cambridge workers[35] suggest, for the selection of records, the following criteria, which, although they do not enable anisometric patterns to be distinguished from isometric patterns, suffice for the majority of records made at Cambridge, since, from comparisons made of results obtained from the simple method of analysis and from the full correlation method, they deduce that there the patterns are usually isometric.

1. A record is acceptable only if the mean time-shift does not change sign during the course of the observing period.
2. When the velocity is estimated to be greater than 100 m./sec, the record should be re-examined carefully, since large velocities result from small average time-shifts, and these may or may not be acceptable. They are acceptable if all the individual time-shifts are small and each component predominately of one sign. However, approximately equal numbers of large positive and negative values will give a small average value that is, of course unacceptable when both components show such time-shifts (20) as it indicates that random changes are producing more effect than any drift that may be present at the same time. When only one component shows this type of variation and the

other is quite steady in magnitude and sign, the small average value is retained and used, as this indicates that the lines of maximum amplitude lie approximately parallel to the line joining one pair of aerials.

In practice, records were read only when they showed obvious similarities in their shape over much of their duration; even so they may contain considerable scatter, as shown by the extracted time-delays. The simple, MITRA-type analysis was carried out mathematically on all readings taken, although the readings were plotted also on a Tx v. Ty diagram. This latter procedure was adopted to try to identify PÜTTER - type diffraction patterns and also because BANERJI'S method of analysis was also carried out and the plot of points is needed for this. Another reason for plotting the time-delay pairs was that a third method of analysis was used. This was a method proposed by CHAPPELL and HENDERSON[36]. The assumptions basic to their analysis are those which RATCLIFFE[37] showed would have to apply if the MITRA-type analysis is to give correct results - with, however, one modification. RATCLIFFE assumed constancy of magnitude and direction of drift during recording, lines of maximum amplitude were straight lines over distances comparable to aerial separations, and lines of maximum amplitude are distributed isotropically about $\psi = 0$, CHAPPELL and HENDERSON modified the last of these three assumptions.

They supposed that, as the straight line drawn through the points of time-delay pairs (on what they called the "dot diagram") was, for their observations, not generally perpendicular to the line drawn from the origin to the mean values point $(\bar{T}x, \bar{T}y)$, they had produced the asymmetrical distribution themselves by virtue of "the short duration (two minutes) of the records". This implies that, given sufficiently long recording periods the asymmetry of the distribution would have been replaced by a symmetrical distribution. In other words, they seem to suggest that over relatively long periods (e.g. 10 minutes) the value of ψ is distributed about zero, but that over short periods (e.g. 2 minutes) the value of ψ is generally concentrated on one side about zero. This further seems to imply the existence of a quasi-periodicity in the way in which the orientation of the lines of maximum amplitude varies. The presence of such an oscillation about the normal to the direction of drift of the lines of maximum amplitude should be detectable from a reconstruction of the orientation of these lines, which should be possible from a knowledge of the time-delays of an uninterrupted succession of maxima on a record (see APP. II); provided one assumes that the lines of maximum amplitude are straight, and that no random motions are present.

CHAPPELL and HENDERSON do not discuss the effect of random changes and presumably they treat only records that show little or no trace of such changes. The possibility of preferentially oriented anisometric patterns appears to have been ignored, though no reason has been given why it should not be considered. By referring to previous diagrams (Figs. XIX, XX), it should be fairly clear that if their assumptions as to the type of record that they are dealing with is correct, the magnitude and direction of velocity calculated by applying the MITRA-type analysis would both be in error. The magnitude of velocity calculated would be greater than the true magnitude, and the calculated direction would be in error by an amount that would be less than $\pi/2$ and usually less than $\pi/4$, either positive or negative. It is of interest, therefore, to use this method of analysis for those cases, in which the random motions are small, as shown by the relative values of V and Vc calculated from BANERJI'S method, and compare the results obtained in these two methods, firstly, with each other, with the results of the simple method of analysis and with the winds obtained from the meteor observations.

The quantities used by CHAPPELL and HENDERSON are the mean time-delays, $\bar{T}x$ and $\bar{T}y$, their respective variances, σ^2_{Tx} and σ^2_{Ty} (i.e. the mean square deviations of Tx and Ty) and also $\sigma^2_{Tx,y}$ (the m.s. deviation of the differences between Tx and Ty, viz. Tx - Ty), and the aerial separations, ξ_o and η_o. They define certain quantities, S_1, S_2, a, K_1 and K_2, in terms of the averages and variances where:

$$S_1 = \text{var}\,(Tx - Ty) - \text{var}\,Tx$$

$$= \sigma^2_{Tx,y} - \sigma^2_{Tx}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(33)$$

$$S_2 = \text{var}(Tx - Ty) - \text{var}\,Ty$$

$$= \sigma^2_{Tx,y} - \sigma^2_{Ty}, \quad \text{.........................(34)}$$

$$a^2 = S_1^2 - S_1 . S_2 + S_2^2, \quad \text{.........................(35)}$$

$$K_1 = \frac{(S_1 - S_2 + a) . \overline{T}x + S_2 . \overline{T}y}{S_1 - S_2 + a} \quad \text{..............(36)}$$

and, $$K_2 = \frac{(S_1 - S_2 + a) . \overline{T}x + S_2 . \overline{T}y.}{S_2} \quad \text{..............(37)}$$

The significance of K_1 and K_2 is that the ratio, K_2/K_1, defines the slope of the line from the origin and normal to the line through the points on the "dot diagram". The slope is expressed as tan α where α is the angle between the normal and north (measured clockwise from north). This normal gives the direction of the wind; a line from the origin to the mean values point ($\overline{T}x$, $\overline{T}y$) makes an angle β with north (also measured clockwise). If the dot diagram is drawn for the case where the aerials form an isosceles right-angled triangle, where the distances between aerials forming the arms subtending the right-angle equal r, the velocity is found directly from the length of the normal on the dot diagram, since its length from the origin to the point of intersection equals r/V.

CHAPPELL and HENDERSON also suggest the following equations for the case when the aerials are not spaced equally about the right-angle: The direction of drift can be found from the equation

$$\tan \alpha = \frac{K_2}{K_1} = \frac{S_1 - S_2 + a}{S_2}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(38)$$

and the velocity may be found from the vector equation

$$V = \frac{1}{\left[(S_1 - S_2 + a).\,\overline{T}x + S_2.\overline{T}y\right]} \cdot \left[(S_1 - S_2 + a).\,\xi_o.i. + S_2.\eta_o.j\right], \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(39)$$

where i and j are unit vectors along the E-W and N-S directions. Equation (39) may be rewritten in terms of magnitudes,

$$V^2 = \frac{\left[(S_1 - S_2 + a).\,\xi_o\right]^2 + \left[S_2.\eta_o\right]^2}{\left[(S_1 - S_2 + a).\ \overline{T}x + S_2.\ \overline{T}y\right]^2}, \quad \ldots\ldots\ldots\ldots\ldots\ldots(40)$$

It will be seen that the only alteration in the interpretation of these equations when applied to the actual aerial system (Fig.XXII) is that α will be understood to be measured clockwise from N 29°E. In all cases the magnitude of velocity found by MITRA'S method (call it V_M) is related to that found by CHAPPELL and HENDERSON'S (call it V) by

$$V = V_M.\sec\ (\alpha - \beta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(41)$$

To simplify the analysis by the methods of BANERJI, and CHAPPELL and HENDERSON, it was decided to take only 26 pairs of time-delays and treat these to determine the values of $\overline{T}x$, $\overline{T}y$, σ^2_{Tx}, σ_{Tx}, σ^2_{Ty}, σ_{Ty}, $\sigma^2_{Tx,y}$, $\Sigma(Txi - \overline{T}x)$, $\Sigma(Tyi - \overline{T}y)$. From these values and, of course, ξ_o and η_o, we can determine:

1. V and θ from MITRA'S method
2. V, V_c and θ from BANERJI'S method.
3. V and θ (from α) from CHAPPELL and HENDERSON'S method.

The plot, as a function of time, of the N-S and E-W components of V is made from the results deduced from each method and the plots compared with the similar plot of components deduced for the same hours from the meteor observations, to see which gives the better fit, though, as has been emphasized, the primary purpose of this study was a comparison of the meteor and MITRA methods.

OBSERVATIONS

AND

RESULTS OF ANALYSIS

IV OBSERVATIONS OF E-REGION

IV.A. RECORDING PROCEDURE

Observations were begun in April following the successful trials of the complete apparatus, which proved its ability to function as a whole at this time. Recordings commenced in early May and by the eleventh of the month the routine procedure had been decided upon; thereafter, at about the hour or half-hour from 0800 to 1800 hours each week-day, and occasionally at the week-end, the transmission of pulses was begun and an echo looked for on the visual display of the monitor C.R.O., while at the same time noting the amount of noise. If the echo appeared strong enough for recording, the recorder was started and the depth of fading, rate of fading and amount of noise, as recorded were noted. If these three factors were seen to be of suitable proportions the recorder was allowed to run for a period of at least 5 minutes. At the commencement of recording the time, date, and equivalent height of the echo were noted in the log book, while the time and date were written on the record itself at the beginning of the record, asa further aid to identification. At the end of recording, the amplifier was switched off and the paper allowed to run on several inches to permit clear separation between successive records.

IV.B. RECORDING TIMES AND NUMBERS OF RECORDS

The echoes were usually apparent some time before 0800 hours but at an equivalent height far in excess of 100 Km. Then, before about 0800 hours, there was a confusion in the appearance of the echo which often spread out into several rapidly varying centres that showed a fast decrease in equivalent height; though quite often, also, the echoes simply disappeared for some time before appearing again at an equivalent height somewhat in excess of 100 Km. and growing quickly into strong, deeply fading echoes. These effects could possibly be attributed to the formation of **the** E-region, or, rather, to the restoration of the ionization density in the E-region up to its usual daylight level as the influence of the Sun's rays was felt in the ionosphere.

Similar effects were observed in the evening from about 1700 hours and later. A succession of changes in the structure of the echoes, from single pulses varying more or less regularly, to more and more widely spread and diffuse echoes showing reflection **from** a number of heights; then a final, fairly rapid shift to equivalent heights well above 100 Km. and often a rapid decline in size of the echo, followed, some little time after the disappearance of E-layer echoes, by strongly-growing and -fading echoes from the F-layer.

There was also a progressive change in the size of the echoes around 1100 to 1300 hours on most days. Quite often the echoes would disappear at about 1100 hours and be quite strong again at 1300 hours. This effect which, according to SHIMAZAKI[38], is most "certainly due to the fact that waves do not return to the ground at these hours owing to the heavy absorption in the lower ionosphere", has quite an effect on the number of results available for use at the hours around noon, making the results of the analysis less reliable at these hours. It might be pertinent to mention that this decrease of the number of observations around the noon hours is particularly pronounced in summer, and, in fact, at Adelaide the effects of absorption are felt strongly all the year round at the frequency used, so that winter is about the only season when the E-region may be studied by the method of closely-spaced aerials. The development and testing of the equipment in this study was profoundly influenced because of absorption effects, since equipment testing was possible only in the winter season. These remarks apply, of course, to the years 1956, 1957, 1958, and 1959, which are centred on the I.G.Y. period, and this was a period of unprecedented sunspot activity. The number of recordings made in May and June, 1959, that were suitable to take time readings from are plotted against local time in Fig.XLI.

In all, some 269 observations and recordings were made in the interval from 1st May to 4th November, 1959. Of these records some 110 were judged suitable for reading for the interval 1st May to 14th September. Then, of these, some 32 in May and 27 in June were selected, from a study of the magnitudes and spread of the values of Tx and Ty as read from the records, for further treatment according to the methods outlined in the General Discussion of the Analysis. These particular ones were selected to give a cover of the hours between 0800 and 1800, and the criteria used in selection were those laid down by the Cambridge workers.[35]

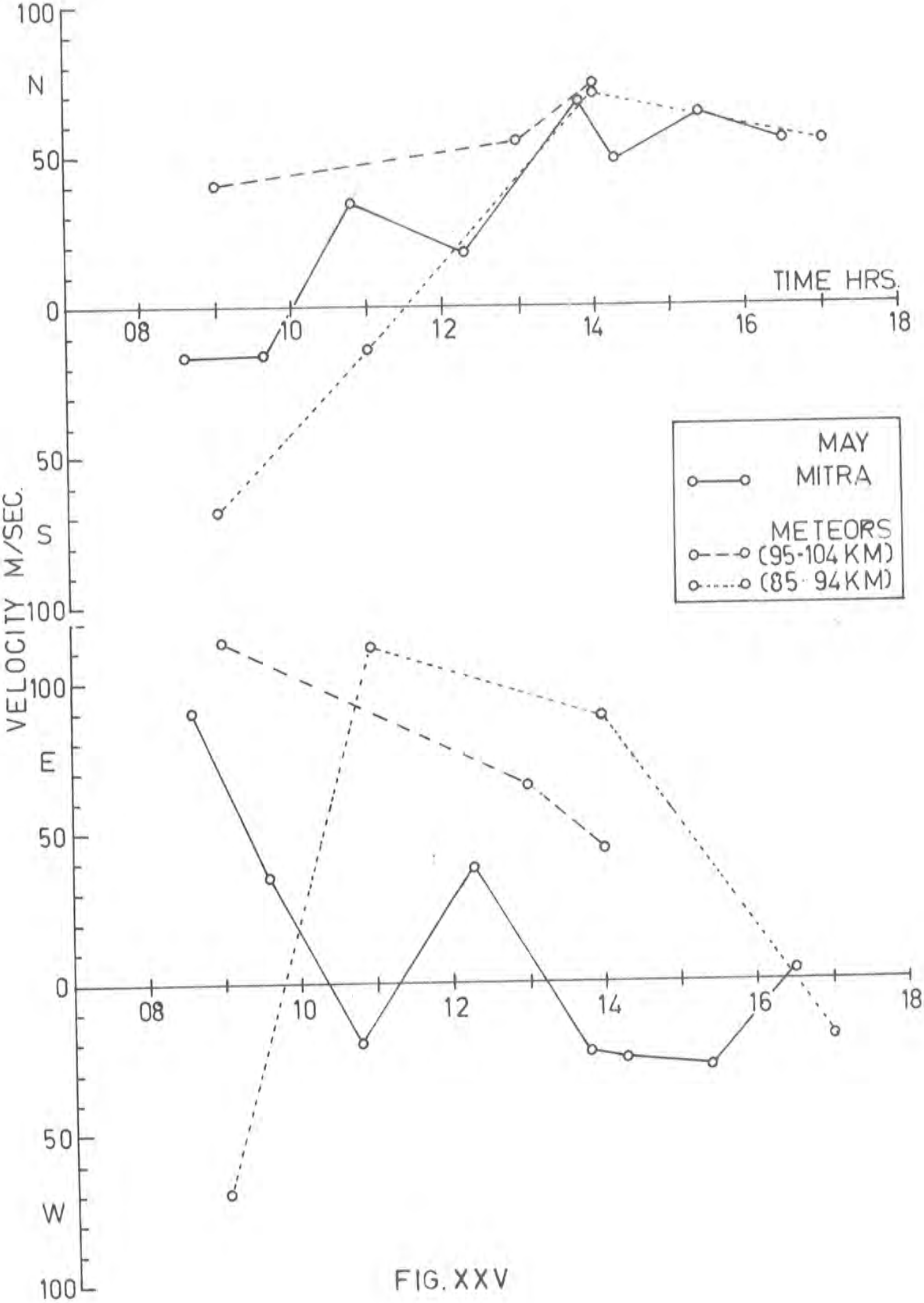
V. RESULTS OF OBSERVATION AND ANALYSIS.

V.A. GENERAL FEATURES OF WIND DEDUCED FROM RECORDS.

The results of the three analyses are tabulated in TABLE II (APPENDIX I) and graphed in FIGS. XXV to XXXII. In these diagrams only the simple hourly means are shown without any attempt to represent the standard deviations, though these have been estimated. These diagrams will now be discussed in order.

The May results (FIGS. XXV and XXVI) by the MITRA or BANERJI type analysis both show the same trend in the N-S and E-W components, viz., a change from south to north at or before midday, and a tendency to swing to the west from east at about midday. The results of the BANERJI - type analysis for May show generally smaller amplitudes, particularly in the E-W component. In FIG.XXVII the results of all three types of analysis for those May records that refer to times when the motion of the pattern on the ground was due mainly to drift (according to the results of the BANERJI - type analysis) are shown. Only for three hours (0900 - 1000, 1500 - 1600, and 1600 - 1700) was there more than one estimate of the drift velocity and so only these hourly means are plotted. The three methods give results indicating the same trend - becoming more northerly and westerly later in the day.

The results for June, given in Figs.XXVIII to XXXII seem to show more regularity when all results of the MITRA- and BANERJI - type analyses are compared with each other, and with the analogous



100
N
50
0
50
S
100
100
E
50
0
50
W
100
VELOCITY M/SEC.
TIME HRS.
08
10
12
14
16
18
MAY
MITRA
METEORS
(95-104 KM)
(85-94 KM)

FIG. XXV

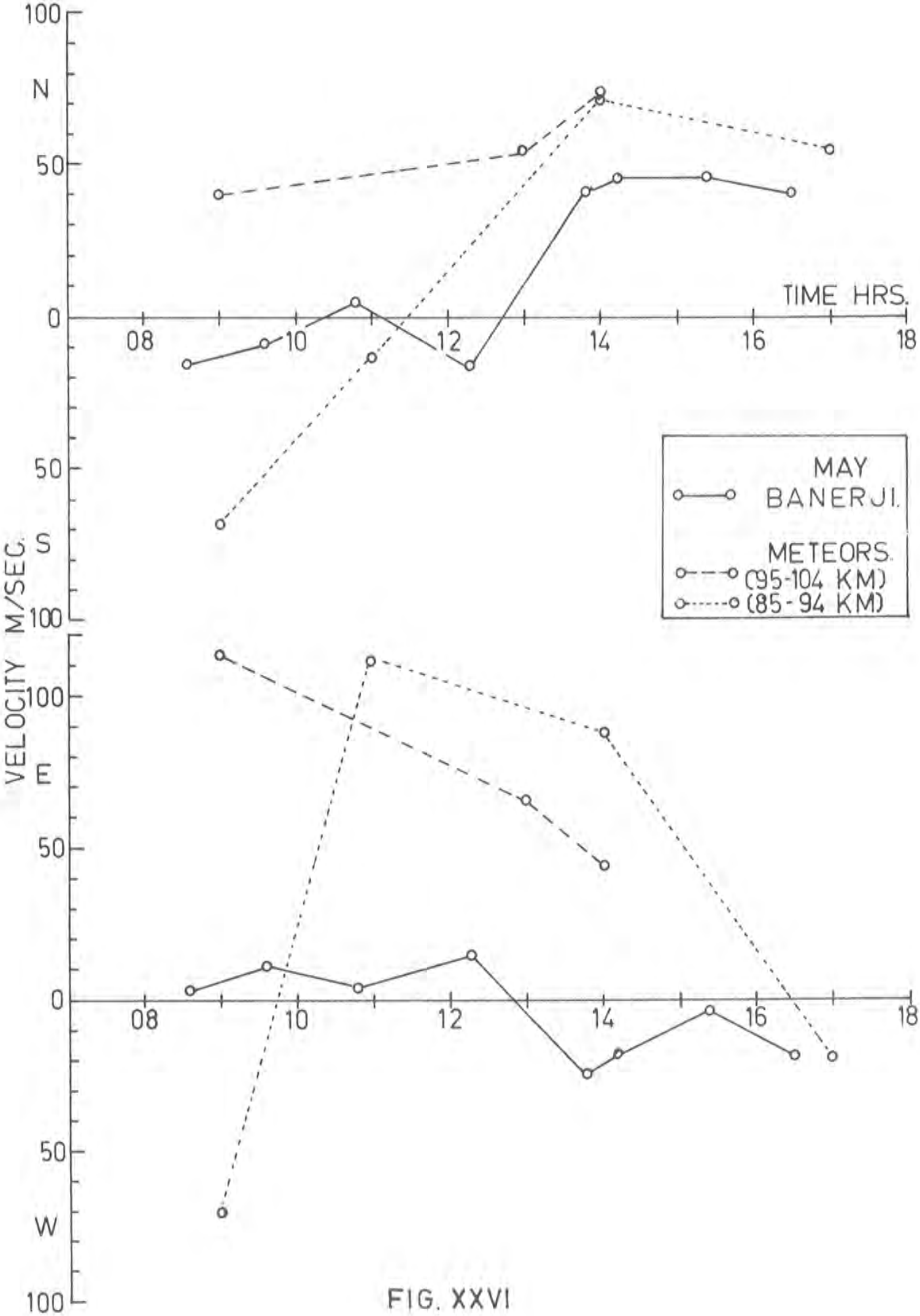
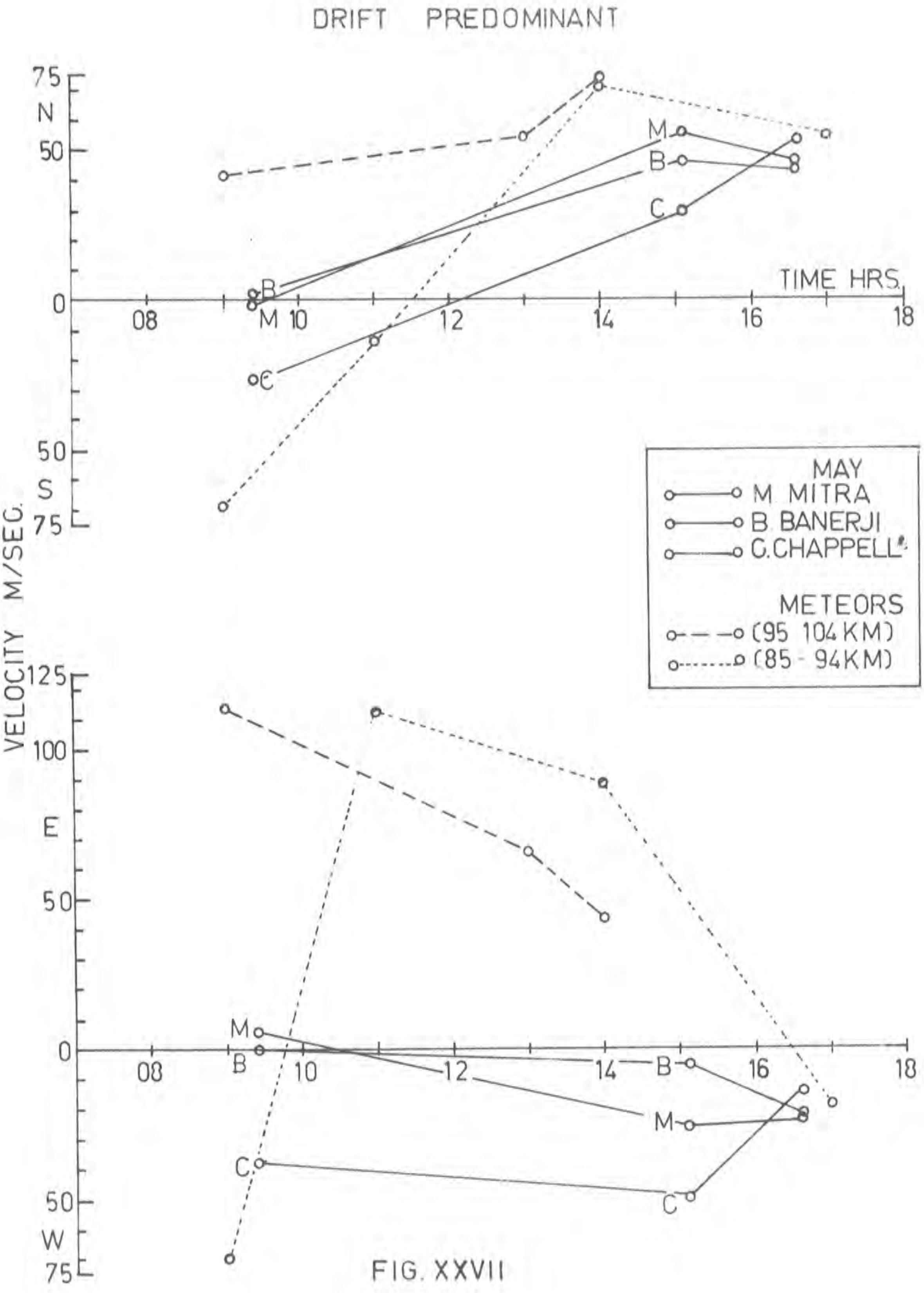

100
N
50
0
50
S
100
100
E
50
0
50
W
100
VELOCITY M/SEC.
TIME HRS.
08
10
12
14
16
18
08
10
12
14
16
18
MAY
BANERJI.
METEORS.
(95-104 KM)
(85-94 KM)

FIG. XXVI



DRIFT PREDOMINANT
VELOCITY M/SEC.
75
N
50
0
50
S
75
125
100
E
50
0
50
W
75
TIME HRS.
08
10
12
14
16
18
M
B
C
MAY
M. MITRA
B. BANERJI
C. CHAPPELL
METEORS
(95 104 KM)
(85 - 94 KM)

FIG. XXVII

results for May. In both results for June, there is a tendency to move south then back strongly north to a maximum after midday, followed by a rapid swing southwards in late afternoon. In the case of the E-W component both show a gradual swing to the west from east, with the changeover about midday. The suggestion, especially in the case of the MITRA - type analysis, is of a strong semi-diurnal content in the E-W component. In this case, also, the BANERJI - derived estimates are smaller than the corresponding MITRA - derived velocities. The graphs of the N-S and E-W components for those cases where drift should be the main cause of fading show very similar trends to each other in the N-S components (FIGS. XXX, XXXI, and XXXII), trends similar to those shown in plots of all the June records (FIGS. XXVIII and XXIX). The E-W components in the graphs of Figs. XXX, XXXI, and XXXII can merely be said to show the same general tendency again, as in May, of a swing from east to west, with the cross-over perhaps occurring before noon.

From a comparison of the May and June results shown in Figs.XXV and XXVI, and Figs. XXVIII and XXIX one can perhaps see a tendency for there to be an advance in phase of the wind system from May to June. This is possibly better defined in the case of the N-S components where in May the maximum may perhaps be around about 1400 hours, while in June it appears around 1300 or 1400 hours. The same general effect may be guessed at in the E-W component, though it is not so marked in this case. What is noticeable also is that the amplitude of the N-S and E-W components appear to

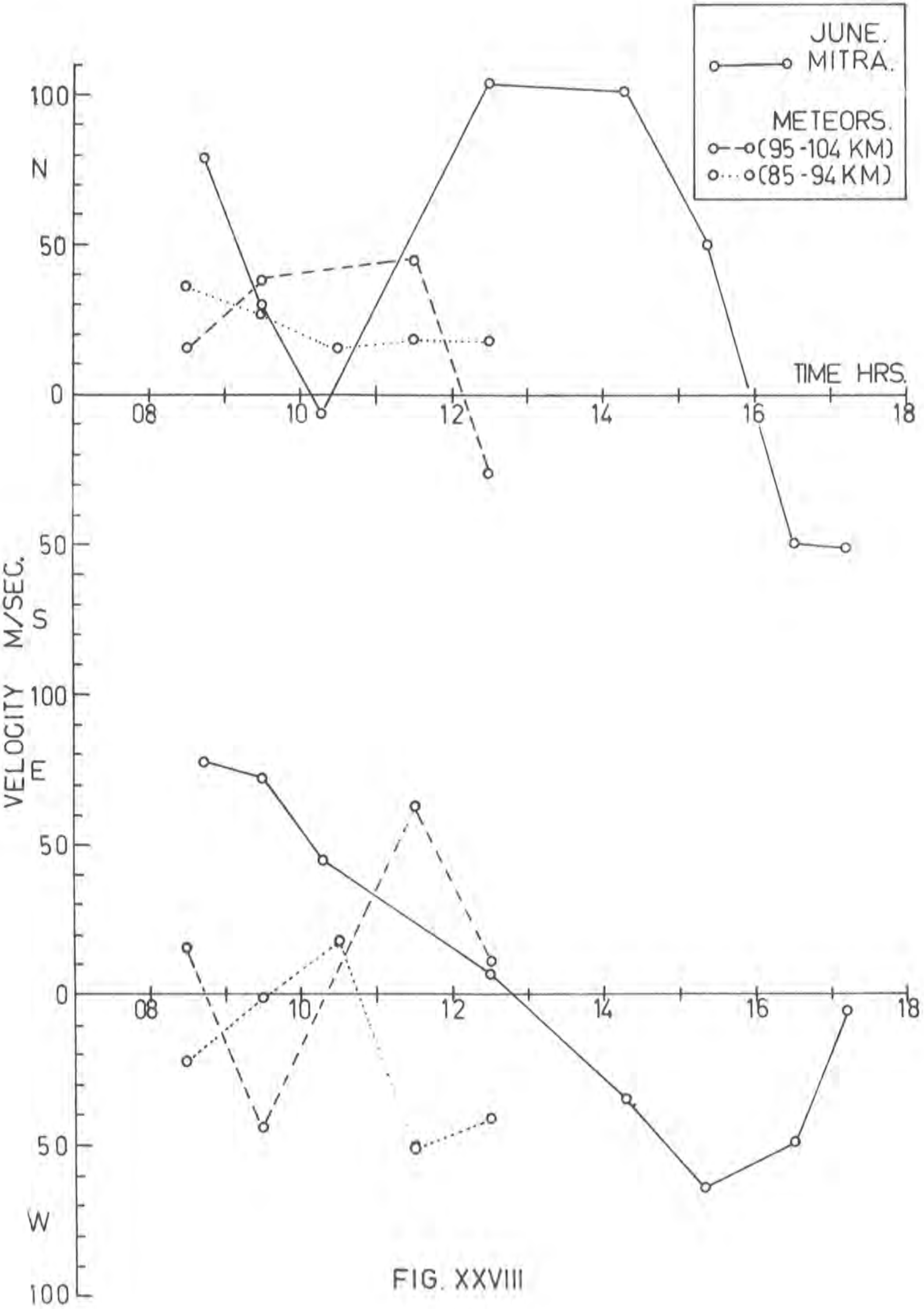

JUNE.
MITRA.
METEORS.
(95-104 KM)
(85-94 KM)
100
N
50
0
TIME HRS.
08
10
12
14
16
18
50
S
VELOCITY M/SEC.
100
E
50
0
08
10
12
14
16
18
50
W
100

FIG. XXVIII

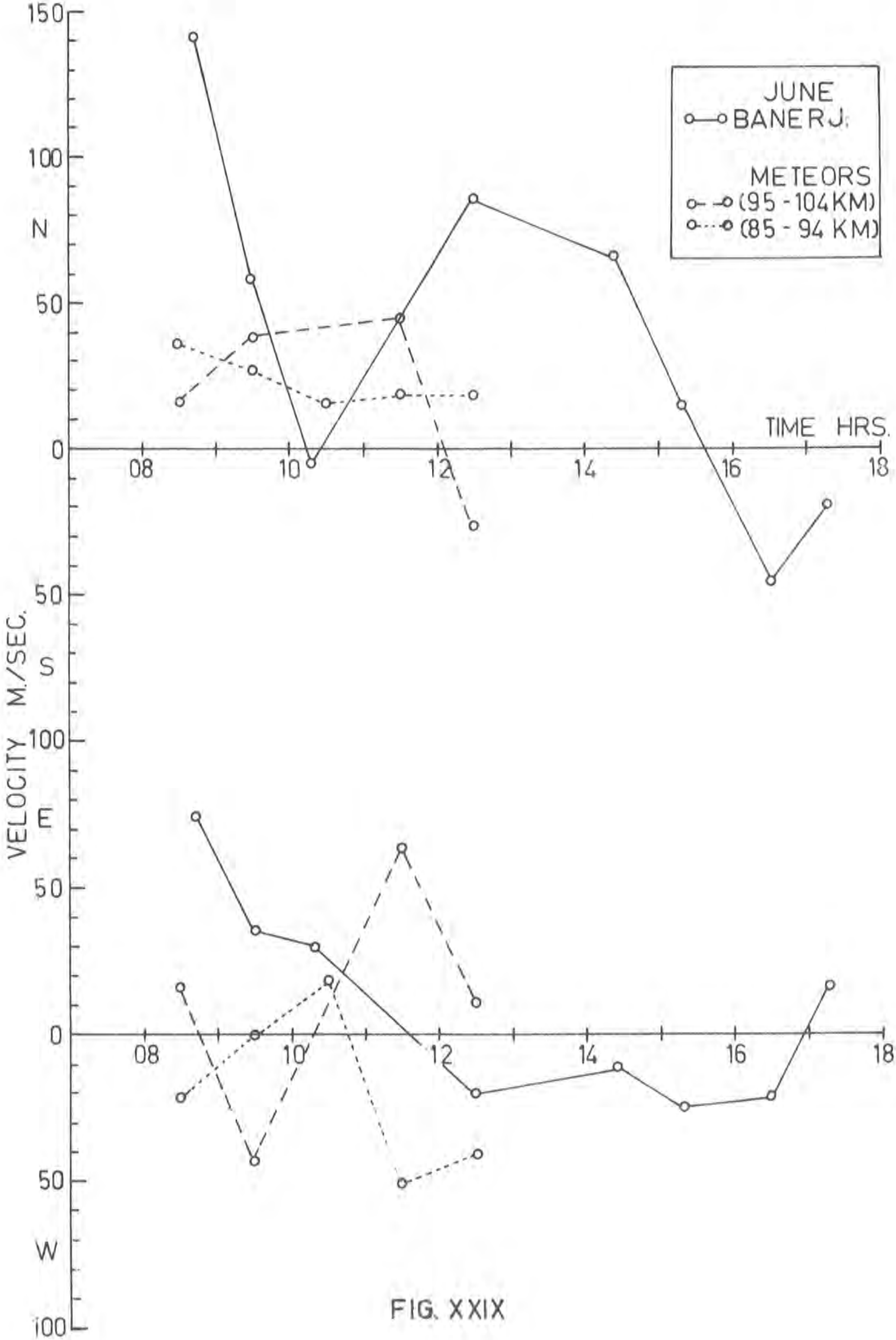

JUNE
BANERJ.
METEORS
(95 - 104 KM)
(85 - 94 KM)
TIME HRS.
VELOCITY M./SEC.
N
S
E
W
150
100
50
0
50
100
50
0
50
100
08
10
12
14
16
18

FIG. XXIX

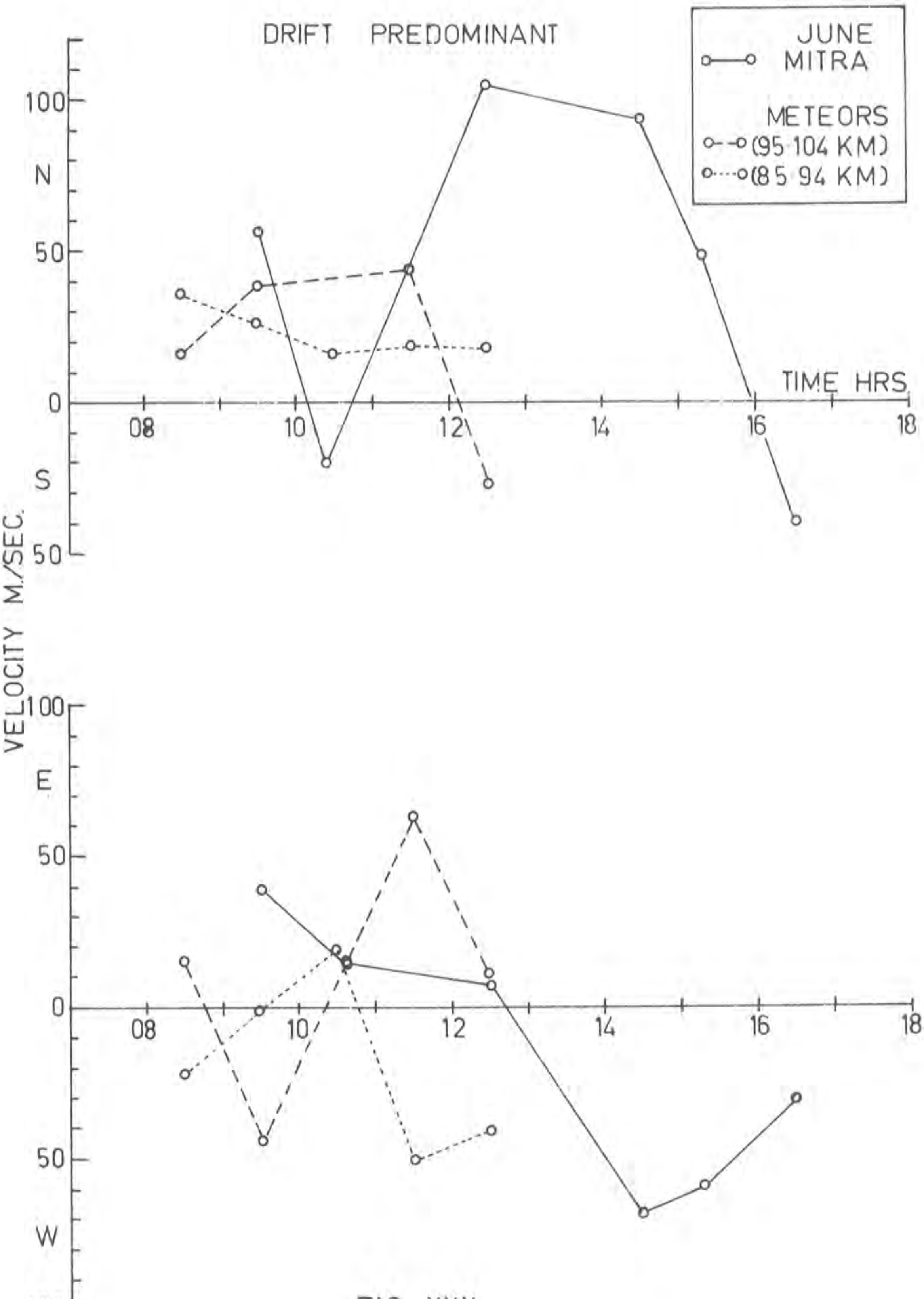

DRIFT PREDOMINANT
JUNE
MITRA
METEORS
(95 104 KM)
(85 94 KM)
100
N
50
0
S
50
TIME HRS
08
10
12
14
16
18
VELOCITY M./SEC.
100
E
50
0
08
10
12
14
16
18
50
W
100

FIG. XXX

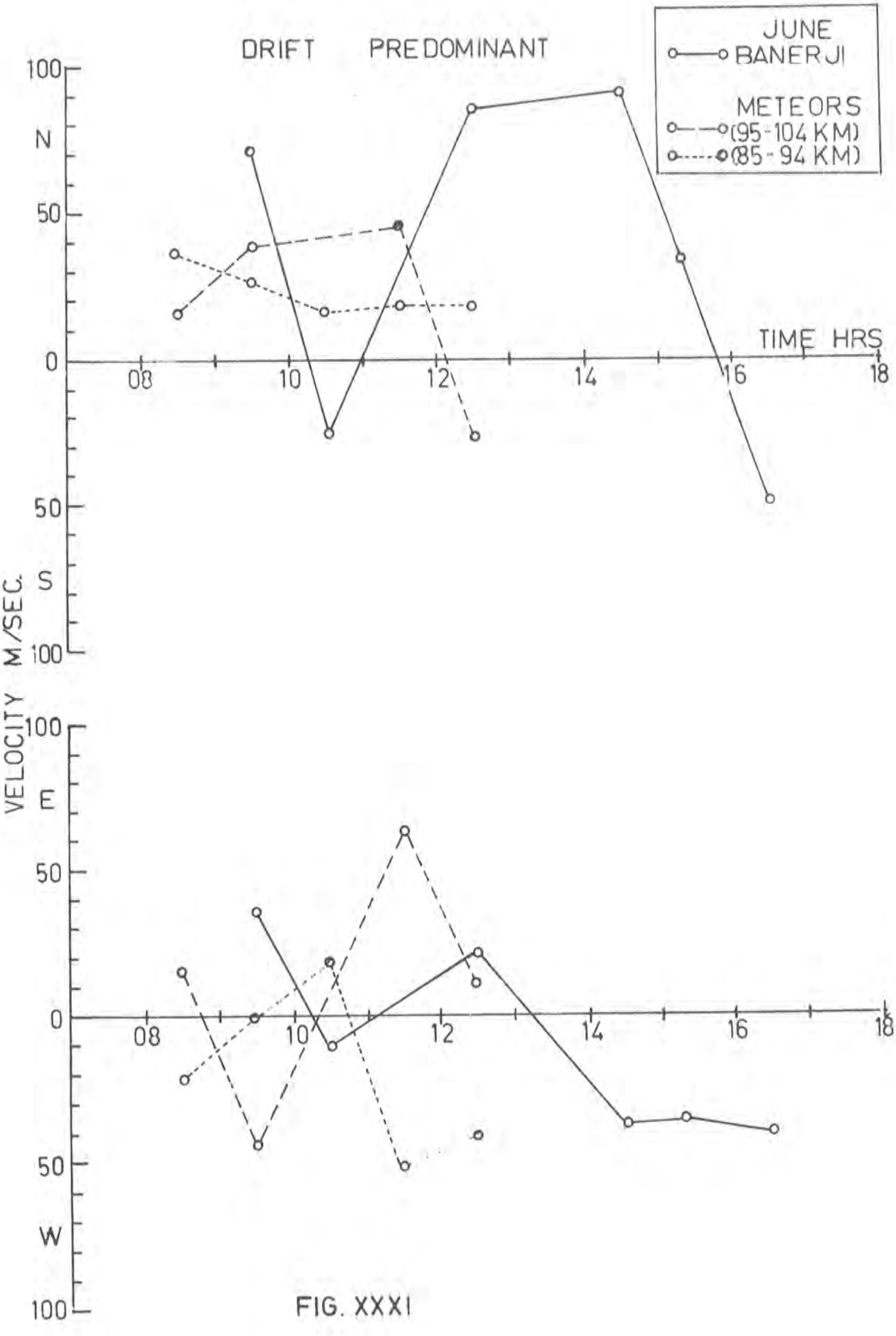

DRIFT PREDOMINANT
JUNE
BANERJI
METEORS
(95-104 KM)
(85-94 KM)
VELOCITY M/SEC.
N
S
E
W
100
50
0
50
100
TIME HRS
08
10
12
14
16
18

FIG. XXXI

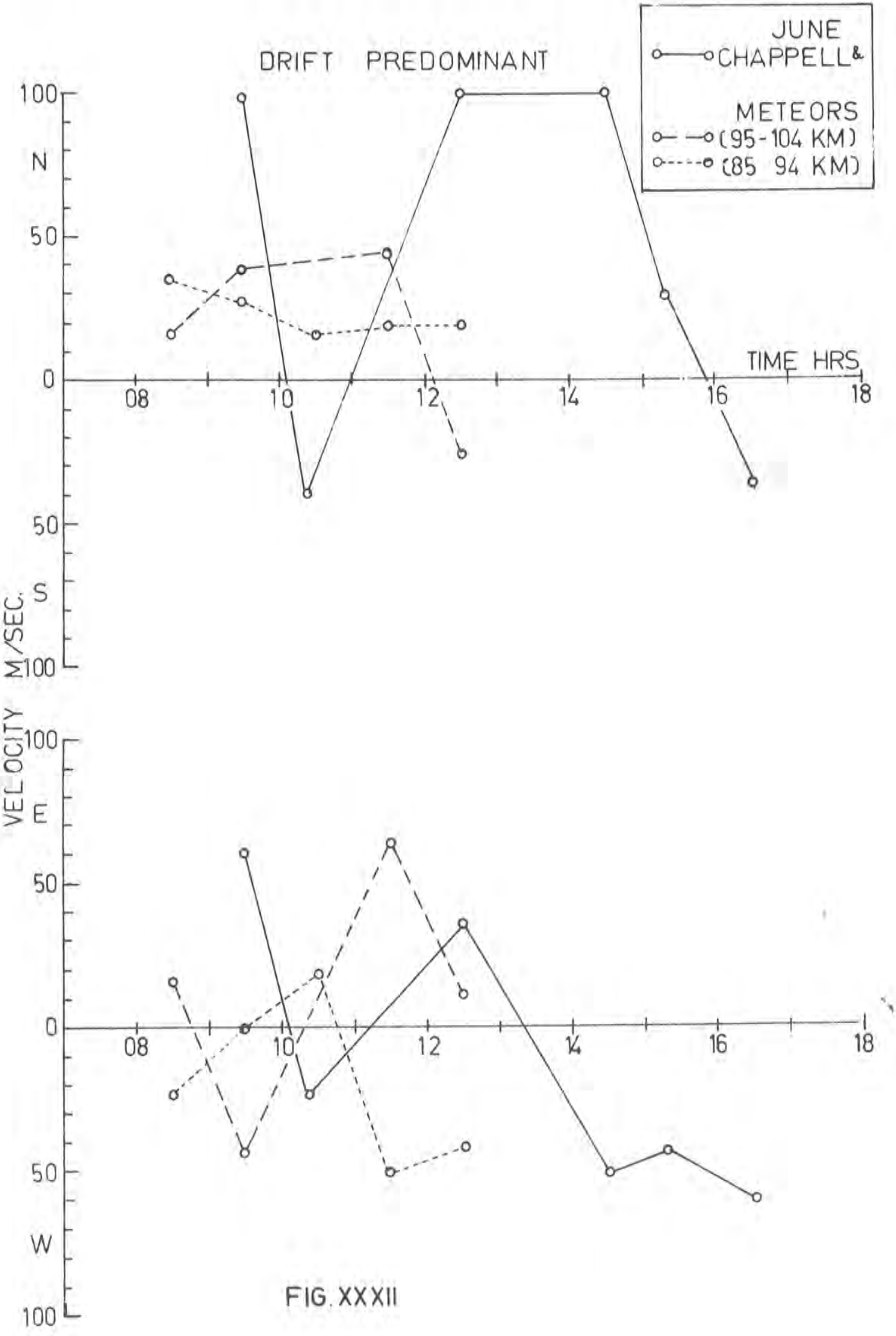

DRIFT PREDOMINANT
JUNE
CHAPPELL &
METEORS
(95-104 KM)
(85 94 KM)
100
N
50
0
50
S
100
TIME HRS
08
10
12
14
16
18
VELOCITY M/SEC.
100
E
50
0
50
W
100
08
10
12
14
16
18

FIG. XXXII

have increased somewhat, from May to June.

However, the plots in this form are not very informative and it was hoped that some correspondence would appear between the results of the winds deduced from the study of E-region reflections and of the winds deduced from a study of radio waves reflected from meteor trails, as mentioned in the Introduction.

VB COMPARISON OF SYNOPTIC RESULTS OF THIS STUDY AND OF THE METEOR TRAIL METHOD.

The two months, May and June, were singled out for special study because these two months were the only ones of those during which results were obtained, in any number, by the methods outlined in this study, and at the same time from the reflection of radio waves from newly-formed meteor trails. The films obtained by the meteor study group for May and June, 1959, were read and subsequently analysed, by the author, in order to see if the winds obtained by the meteor study at heights lower than that of the E-region showed any correspondence with those deducible from the method of closely-spaced aerials. However, the results obtained from the meteors study during the daylight hours were disappointing. In May, only three points could be obtained that yielded only the barest indication of the magnitude and direction of wind, in the height range 95-104 Km., while four points of as little, or less, reliability were obtainable for the other height range of 85-94 Km. These results, for what they indicate, have been inserted on all the graphs of the May results. The merest trends are indicated but no real interpretation can be made or correspondence deduced.

The June results of the meteor method were also lacking in coverage, since only the hours between 0800 and 1300 yielded sufficient data to allow of fairly reliable estimates of wind velocity to be made. These points, especially at the 95-104 Km. level, are fairly widely scattered, and, since normally the wind at these levels is obtained by fitting a smooth curve to such widely scattered points, by the method of least squares, etc., it is not possible in this case, either, to come to any conclusion as to correspondence between the results of the methods of this study and those of the meteor study - from a comparison of results obtained simultaneously.

VC RESULTS OF SIMILAR STUDIES ELSEWHERE IN I.G.Y.

The impasse, reached at this stage in comparing the results of these two methods, suggested that other confirmation of the validity of the method should be sought. The results of similar work done during the I.G.Y. had been published by SHIMAZAKI[38] in 1959. He compared results obtained by the method of closely-spaced aerials at several stations in the Northern Hemisphere. The results were for E-region and F-region drifts deduced from the simple MITRA - type analysis of fading records at Waltair (India), Freiburg (Germany), Yamagawa (Japan), and Cambridge (England), during 1957-1958. The latitude of Yamagawa (see Table I) approximates to that of Adelaide, so that if the wind patterns in the two hemisphere are related, then the results, at these two places, of similar studies should be similar, provided that like seasons are compared. The results obtained by workers at Yamagawa during winter (i.e. Nov., Dec., 1957; Jan., 1958) were compared with those obtained at Adelaide during winter (i.e. May, June, 1959). That is to say, the results for May and June, 1959, at Adelaide of this study were lumped together, treated in the same manner as that in which SHIMAZAKI had treated the results that he had published, and compared with the results mentioned previously. The Japanese results are shown in FIG. XXXIII and the Adelaide results (treated similarly - with standard deviations indicated) shown in FIG. XXXIV. Before discussing their appearance we might mention again that the points around midday and between 0800 - 0900 and 1700 - 1800 are less reliable than the other points due to the fewer records obtained at these hours.

Considering the method of calculation also, we might mention here that SHIMAZAKI calculates the hourly mean for a particular hour by adding all velocity components for three hours, those for the hour preceding the given hour, those during the given hour, and those for hour following, and divides this sum by the total number of readings involved in this estimate.

Now in comparing FIG'S. XXXIII and XXXIV we should observe that as Yamagawa is in the Northern Hemisphere and Adelaide in the Southern, the N-S components of drift velocity may be compared by inverting one or the other; no such inversion is required for a comparison of the E-W components. This is because the wind systems being studied are due to tidal oscillations in the atmosphere, and so, because of the requirements of symmetry, the movements in the

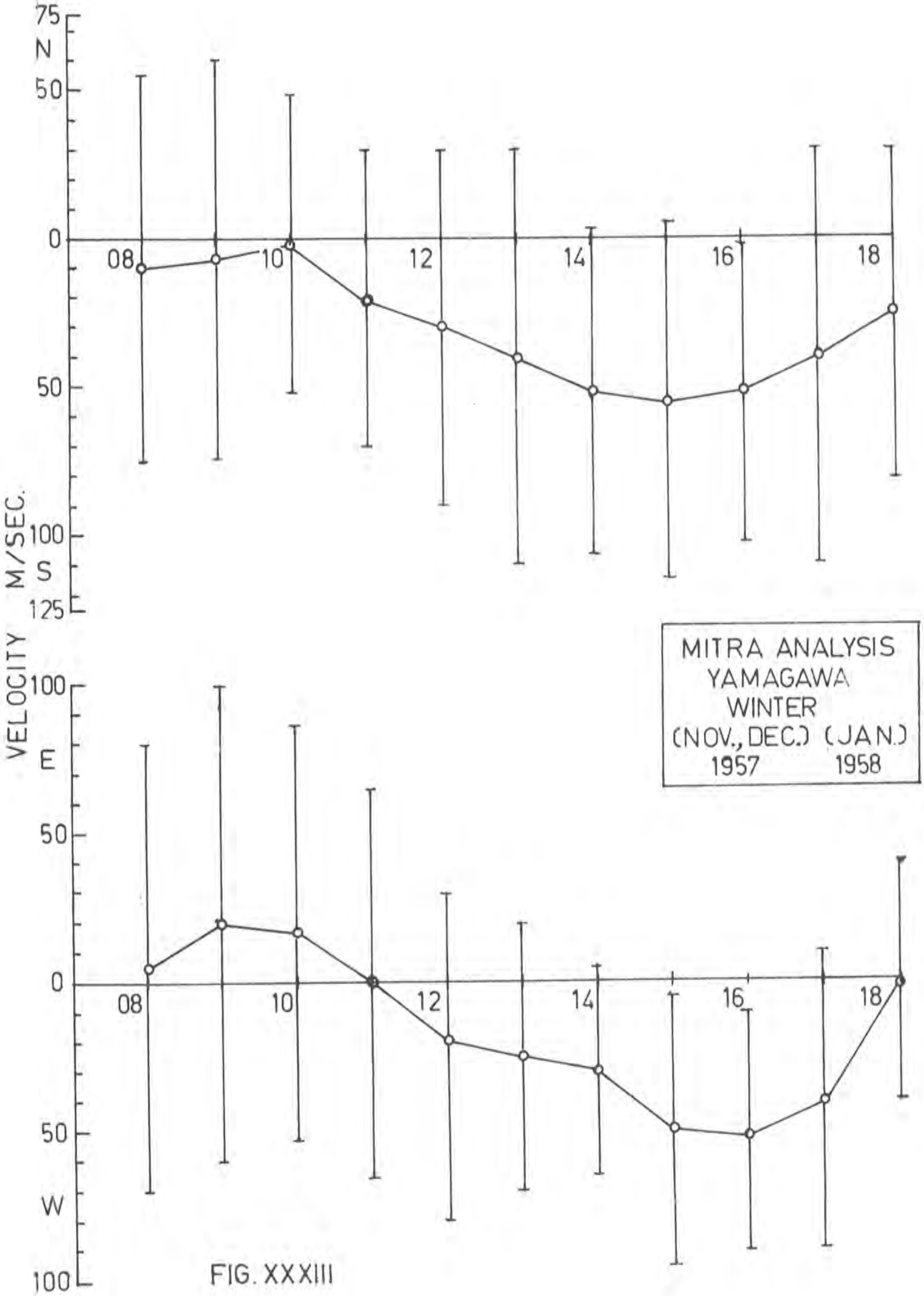

75
N
50
0
50
100
S
125
VELOCITY M/SEC.
100
E
50
0
50
W
100
08
10
12
14
16
18
MITRA ANALYSIS
YAMAGAWA
WINTER
(NOV., DEC.) (JAN.)
1957 1958

FIG. XXXIII

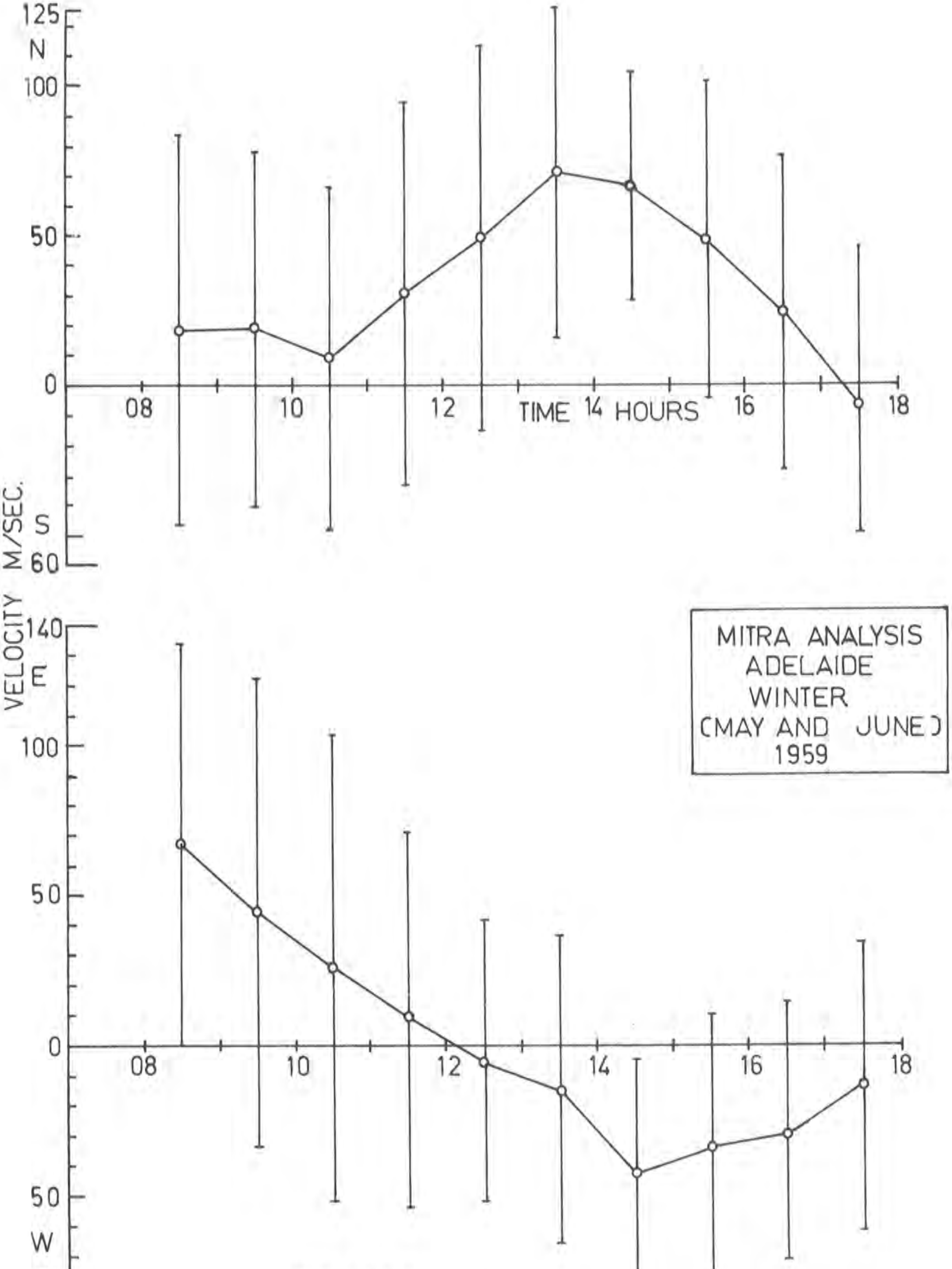

125
N
100
50
0
S
60
VELOCITY M/SEC.
08
10
12
TIME 14 HOURS
16
18
140
E
100
50
0
08
10
12
14
16
18
50
W
80
MITRA ANALYSIS
ADELAIDE
WINTER
(MAY AND JUNE)
1959

FIG. XXXIV

opposite hemispheres should be as indicated; one should, in fact, think in terms of two components in each hemispheres, one parallel to the equator (i.e. zonal, E-W) and the other directed to or from the pole (i.e. meridional, N-S). The results, when compared, show marked similarities. For instance, in the N-S component there is first a slight swing to the South at Adelaide that matches the slight swing North at Yamagawa; each then swings back to a fairly large maximum to the North at Adelaide and to the South in Yamagawa, and so on. The limits of error, as shown by the standard deviations are similar.

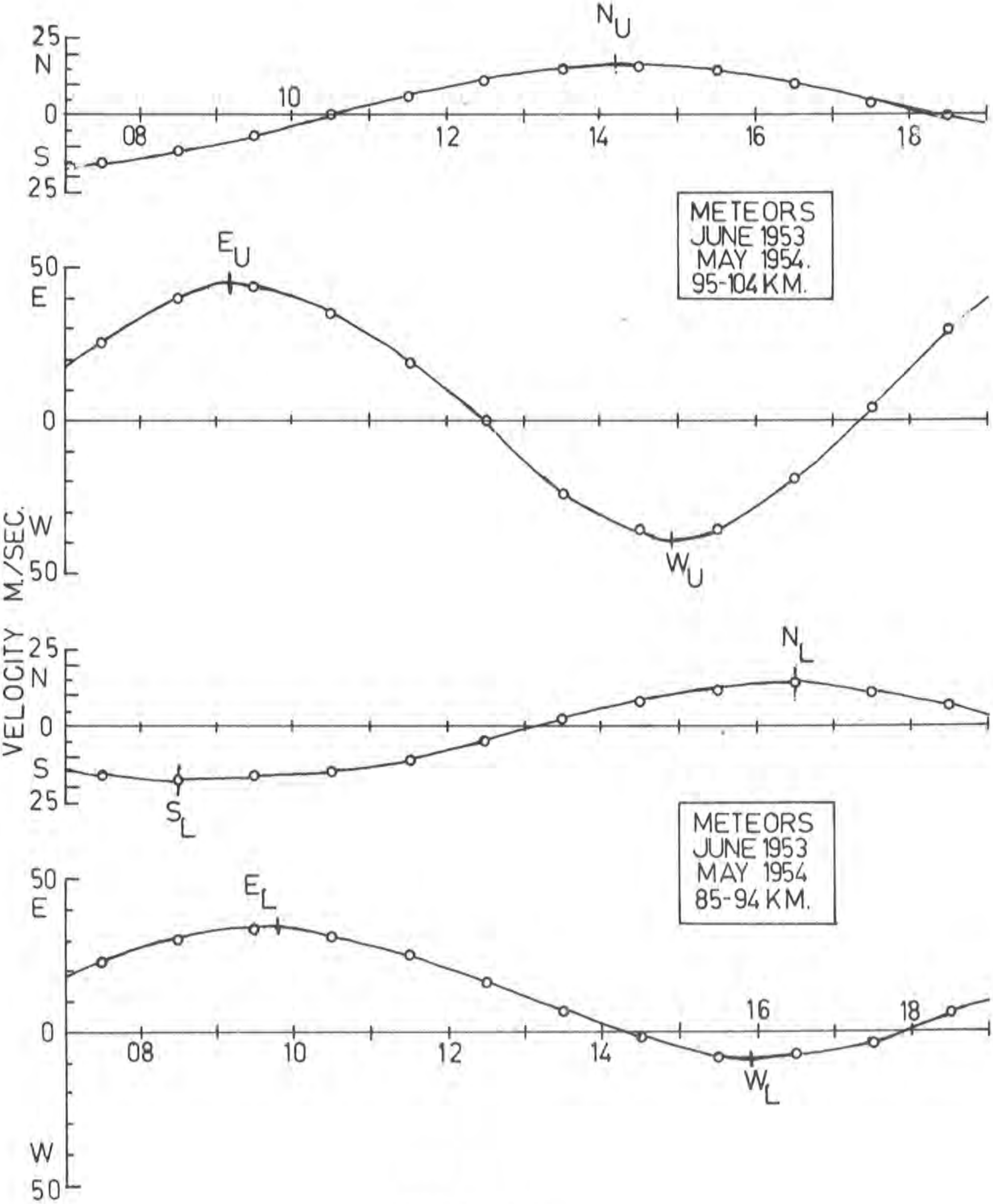
As for the E-W components, we may note that there are general similarities, which, if the effect of the unreliability of the points mentioned above be taken into account, indicate that the wind systems have the same general pattern.

It cannot be expected, of course, that results obtained eighteen months apart in time, at points at approximately the same latitude in opposite hemispheres, should show exactly similar patterns; differences in phase, amplitude and detail can be anticipated, so that what agreement there is between the Adelaide and Yamagawa results can only be described as highly encouraging.

Only the results of the MITRA - type analysis has been treated in the manner described, but if one takes cognizance of the fact that the amplitudes of the components on the BANERJI - type analyses, as plotted on FIGS. XXIV and XXIX, are less than those given by the MITRA - type analyses, as plotted on FIGS. XXV and XXVIII (especially noticeable in the case of the E-W components), one will see that the treatment of the data derived from BANERJI - type analysis, in the manner suggested by SHIMAZAKI, will result in curves similar to those of FIG.XXXIII and XXXIV but with smaller amplitudes, much smaller in the case of the E-W component.

VD. INDIRECT COMPARISON OF THE RESULTS OF THIS STUDY AND OF THE METEOR TRAIL METHOD.

An attempt was made to detect correspondence between the results of the methods of this study and those of the meteor trail method in the following way. The actual records of the N-S and E-W component of drift velocity for May 1954 and June 1953, for the height ranges 85-94 Km. and 95-105 Km., were referred to. The smooth curves drawn through the scattered points for these months were added together in the appropriate height ranges to give a composite N-S and E-W component of drift velocity for the two height groups for Winter (in May and June). The results are shown in FIG. XXXV. The ways in which the N-S component at 85-94 Km. differs from that at 95-104 Km were noted, as also were the points of difference between the E-W component at these two levels. Then, assuming that the trend towards greater or lesser amplitude, advancing or retarding phase, etc., with increasing altitude continued at the same rate the composite components that might be expected at 105 Km and 110 Km. on this model, were estimated and plotted on the same diagram with the smooth curve drawn through the points obtained by the SHIMAZAKI method of averaging the Adelaide results of E-region winds. These curves are shown on FIG.XXXVI.



N_U
25
N
0
S
25
10
08
12
14
16
18
METEORS
JUNE 1953
MAY 1954.
95-104 KM.
E_U
50
E
0
W
50
W_U
VELOCITY M./SEC.
N_L
25
N
0
S
25
S_L
METEORS
JUNE 1953
MAY 1954
85-94 KM.
E_L
50
E
0
16
18
08
10
12
14
W_L
W
50

FIG. XXXV

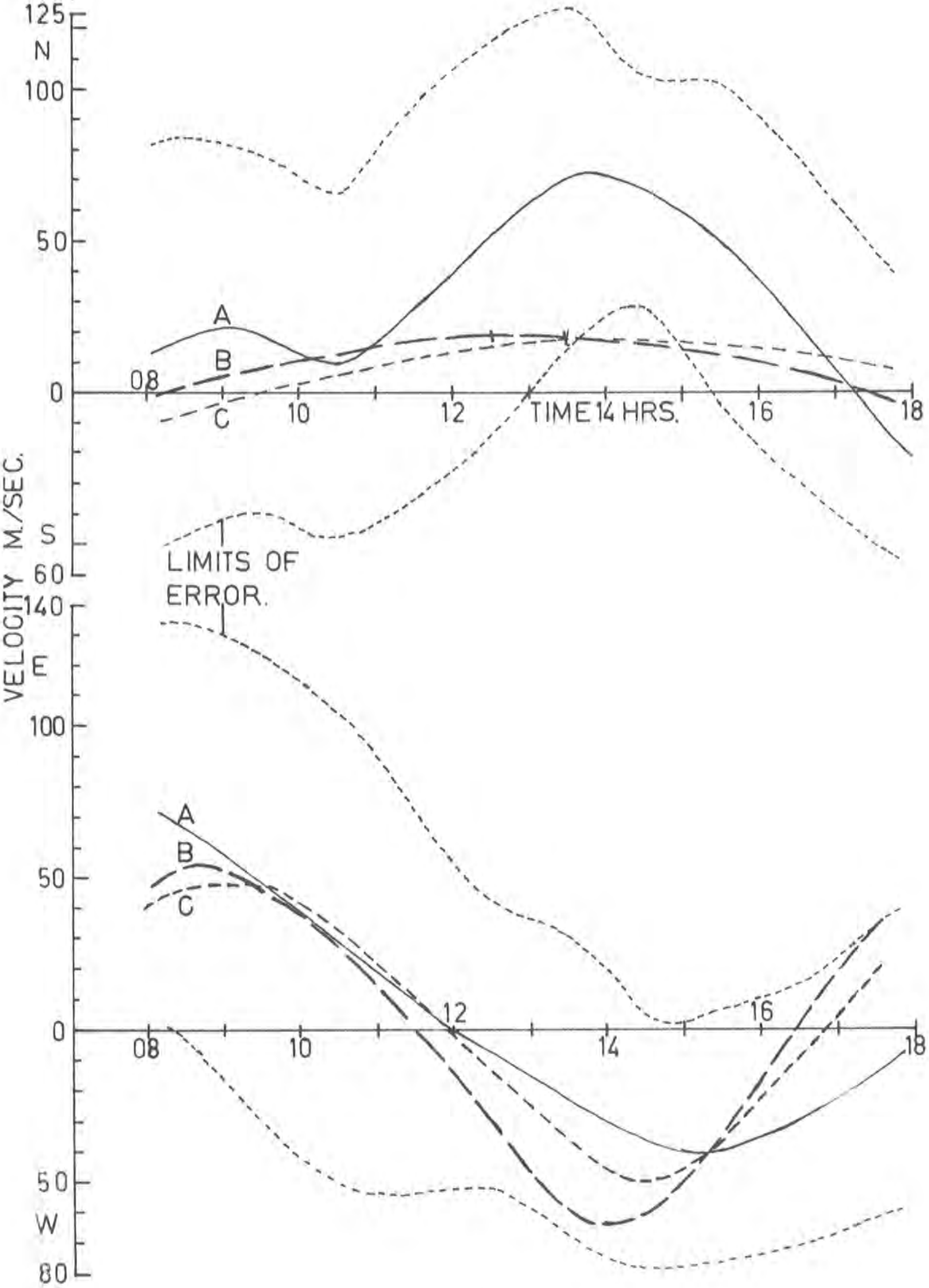

125
N
100
50
0
08
10
12
TIME 14 HRS.
16
18
A
B
C
S
60
LIMITS OF ERROR.
VELOCITY M./SEC.
140
E
100
A
B
50
C
0
12
16
08
10
14
18
50
W
80

FIG. XXXVI

(There is considerable justification for using results obtained several years previously from the meteor trail method as the basis of comparison with the results of this study obtained in 1959. The comparison is possible because, as shown in a published paper [26] where the wind systems of select months in 1952 and 1953 are compared, and as shown more recently in unpublished work - mentioned in private communication where the wind systems of selected months in 1953 and 1961 are compared - the wind systems deduced from the meteor trail method, at Adelaide, are fairly steady for each month, year after year). The continuous lines A represent the result of smoothing the curves through the points of FIG. XXXIV, the broken curves B and C represent the components of drift expected to be found at 110 Km. and 105 km. respectively, as described above. The dotted lines represent the limits of error of the E- region drift velocity components as shown in FIG. XXXIV. First one must take into account the uncertainty in the shape of the curves A for the interval 0800 - 0900 hours as well as for the interval 1700 - 1800 hours, and, more particularly, the intervals 1100 - 1200 and 1300 - 1400 hours, because of the paucity in the number of records analysed in these intervals (see FIG. XLI). Then, too, one must bear in mind that it has been found from the meteor studies that the E-W component of drift velocity is the more stable component of the two over the course of time; the N-S component has been found to be rather more variable from year to year. This means one should look to find similarities between the E-W components rather than between the N-S components. One might then hazard a guess that of the two curves B and C, the curve C is the better approximation to curve A. This implies that the data analysed by the MITRA method refer to echoes reflected from the E-region at a height of about 105 Km

If this be so then, since the correspondence has been arrived at on the basis of the model in which any systematic changes occurring as one progresses upwards from the lower levels, 90 - 100 Km., must continue to occur from 100 - 105 Km. unmodified. Therefore, the phase advances at the rate of 2° $\mathrm{Km.}^{-1}$ and the zonal wind increases in magnitude at the rate of 2m/sec. $\mathrm{Km.}^{-1}$. About the meridional wind no estimate of rate of increase may be made although it appears clear that the wind blows more strongly to the North at higher levels, as may be expected (see ref. 26, page 98).

CONCLUSIONS

VI. CONCLUSIONS.

With the first section in this present chapter the origi planned thesis would have ended, but, with the inclusion of the other methods of analysis in the discussion, it is necessary that something be said, if possible, about the correspondence, or otherwise, between the results obtained by analysing the same set of records by the various methods. Actually, there are too few records for any method of analysis to give a reliable indication of the wind pattern in the ionosphere, so that any conclusions drawn in this chapter must be regarded as tentative only.

VI.A. MITRA'S METHOD OF ANALYSIS.

Synoptic observations of atmospheric drift by the meteor trails method and the method of closely-spaced aerials in England have led JONES[40] to the conclusion that the system of winds present in the E-region is intimately related to the winds known to exist at less high levels of the atmosphere. JONES showed that the rates of variation of wind amplitude and phase with altitude, deduced by using the meteor trails method, for heights up to the E-region were continuous with those deduced for certain levels within the E-region, determined by using the MITRA method of closely-spaced aerials. This may be taken as evidence of the validity of the MITRA method as a reliable means of determining the velocity of winds at these levels.

This study attempted to verify the same fact; however, this proved not to be possible due primarily to three deficiencies in the project. These were, that there were too few results for analysis, no possibility for comparison of synoptic observations of drift made by means of the meteor trails method and the MITRA method, and, no means of determining the actual height of reflection of the pulses used in the MITRA method.

The first of these deficiencies led to the lumping together of all available results in an effort to obtain an indication of the wind system in the E-region, limited in value though this might be. The first-and last-named deficiencies meant that no reliable estimates of the rates of variation with altitude of the velocity amplitude and phase were possible, and such estimates as are given in Section V.D. are based on the assumption that the variations in these quantities are continuous with their respective variations deduced at lower levels from the meteor trails method. In fact, this assumption was used to arrive at an estimate of the height of reflection! As for the third of the deficiencies, the dangers inherent in endeavouring to compare results obtained several years apart must be apparent, especially since, as was mentioned in Section V.D., one of the components of the wind is very variable (i.e., the N-S component), and so the comparison relies entirely on the similarities detectable between the E-W components deduced by the two methods.

However, it is conceivable that a greater number of observations would have removed much of the doubt associated with the results as they stand. Certainly, the general trend of the winds deduced by both methods is very similar, in broad outline; what is needed is more refinement of detail, as well as knowledge of the height.

In effect, therefore, we must conclude that, although the results of this study offer tentative evidence in support of the validity of the MITRA method as a means of determining ionospheric winds with some degree of reliability, the results as they stand are not decisive.

VI.B. PÜTTER'S METHOD OF ANALYSIS.

None of the plots of the pairs of time delays gave a straight line, or anything that approximated to a straight line, so that the PÜTTER method of analysis could not be used on even one of the records. Therefore, as a method of analysis, its utility seems to be rather limited, since, as has been already stated, other workers have endeavoured to use it, but without success. The main criticism that seems to apply to this method is that no allowance is made for the effect of random motions, in the sense that that term has been used in this thesis. This has been pointed out, anyway, by BANERJI in his remarks, and, according to him, the effect of random motions is to result in the displacement of points in the plot of the time delay from the straight line that the PÜTTER method predicts.

VI.C. BANERJI'S METHOD OF ANALYSIS.

The main advantage of the BANERJI method appears to be that it offers a means of determining the statistics of the velocity of drift as well as those of the random velocities. The chief difference in the results of the two methods of analysis applied to the same set of records lies in the magnitude of the E-W components of the drift velocity, which is most apparent in the results for May. Consequently, considering this component only (which is known to be the less variable), it would seem that, applying the averaging process of SHIMAZAKI to the May and June results got from the BANERJI method of analysis, we should be able to fit the curve so obtained tp a curve representing the deduced E-W components of drift velocity estimated from the meteor results and referring to a height rather less than 105 km. This would be so because of the reduced amplitude of the E-W component at the lower level known from the meteor results and because of the smaller amplitude in this component deduced from the BANERJI method as compared with the same component deduced from the MITRA method. Here, however, we are confronted with the same difficulty as appeared in the case of the MITRA-analysed results - we do not know the actual height of reflection, so that we cannot decide whether or not the possible good fit may be taken as evidence for agreement between the meteor and BANERJI methods. Although, what we may be certain of is the fact that, if the MITRA method does give a reliable result then the BANERJI method under-estimates the actual magnitude o f the drift velocity. On the other hand, if the BANERJI method can be shown to give a reliable result then the MITRA method must over-estimate the magnitude of the drift velocity. If only the height of reflection were known then we could make a decision between the two methods, as to which gives the better fit.

There is always the possibility that there are too few results for the comparison to be valid, and that there would be less diffence between the results derived from the two methods of analysis if more records had been compared. That there ought to be some difference between the results of the two methods is to be expected, since, after all, random motions are certainly present, in varying amounts at different times, and concerning these the MITRA method can yield no definite information.

VI.D. CHAPPELL AND HENDERSON'S METHOD OF ANALYSIS.

This method is based on the assumption that the selection of short-duration records introduces an asymmetrical distribution of points on a "dot" diagram". This seems to imply, as was mentioned previously, that there is a quasi-periodic oscillation of the lines of maxima about the normal to the velocity vector, so that the period of two minutes is only a fraction, possibly a large fraction, of the quasi-period, if we may use the expression, which could be of the order of from 3-10 minutes. Since the smallest duration of any recording made in this study was at least 5 minutes, then it ought to be possible to see, if the orientation of a whole series of lines of maxima are drawn using the methods of APPENDIX II, the way in which the lines of maxima swing first to one side and then to the other side, as the record advances, from beginning to end. The gradual trend that seems to be implied in the assumption should then be obvious. If this is done for the records made at Adelaide, it will be seen that the lines of maxima do show a considerable variation in their orientations, yet there is no tendency to regular oscillation. We can conclude, therefore, that at Adelaide the method has no application. Also counting against the method is the fadt that it seems to contain a latent violation of one of the criteria laid down by the Cambridge team[35] for the selection of reliable records, namely, that the mean time delay does not change sign during the course of the recording. That this may possibly happen in the case of an amplitude pattern in which the lines of maxima oscillate in the manner described above may be seen from considering the following.

Suppose that the velocity vector lies fairly close to or along either of the aerial axes. Scatter in the values of the time delays pairs will occur due to irregularities of "blob" shape etc. But, if the lines of maxima are preferentially oriented to one side or other of the aerial axis for so long a time as two minutes, then the time delays measured between the aerials on the other aerial axis will be predominately of one sign and, hence the mean time delay for these aerials will also be of that sign. Then a little later, as the lines of maxima swing to the other side of the aerial axis for another minute or so, the mean time delay will change sign for this next interval, and so on for the successive oscillations. This would mean that the mean time delay has changed several times during the course of the recording and so, according to the criteria listed above, the record would normally be discarded.

As it stands, there is a fairly systematic difference between the results obtained by the MITRA and the CHAPPELL & HENDERSON methods of analysis, with the latter method giving the generally higher velocities, as well as giving a usually smaller angle Ω. This is only to be expected from the equations given, but, for the reasons given above (and earlier) this method does not seem to be better than either of other methods and seems to be based on assumptions that do not apply to the type of pattern at Adelaide.

VI.E SUMMARY.

This study cannot be said to have achieved its aim of validating the MITRA method as a reliable method for deducing the system of winds at ionospheric levels. At best this study has brought forward evidence that offers tentative support for the hypothesis, but, due to a deficiency of planning on the one hand (no provision for knowledge about the height of reflection), and to the unforeseen difficulty associated with the recording (which led to a paucity of records for analysis) on the other hand, no definite assessment is possible. Also, for these self-same reasons, the other method of analysis (BANERJI'S) must be regarded at least as favorably as the MITRA method, so far as this study is able to resolve.

MISCELLANEOUS

APPENDICES

BIBLIOGRAPHY

VII. MISCELLANEOUS.

VIIA. MEAN VELOCITY OF DRIFT.

Fig.XXXVII shows histograms setting out the distribution of velocity of drift according to the month and the method of analysis. In all cases the average drift velocity is higher in June than in May, a result certainly in keeping with results of other MITRA-type analyses elsewhere, and of about the same magnitude. Also as expected the BANERJI-type analysis, by attributing some of the motion of the pattern on the ground to the effect of random motions in the reflecting layer, yields velocities markedly lower than those of MITRA-type analysis, and the method of CHAPPELL and HENDERSON, as could only be the case, yields velocities higher than those deducible from the MITRA method.

VIIB. VELOCITY AND MAGNETIC INDEX (Kp).

Fig.XL shows a plot of averaged velocities against the value of magnetic index, Kp, prevailing when the velocities were recorded. No obvious influence of Kp upon the magnitude of the velocity is apparent. This agrees with results published by TSUKAMOTO and OGATA[41], and as with the statement by RATCLIFFE[42] that "only the greatest magnetic disturbances are accompanied by a measurable increase of the velocities of the E-region".

VIIC. VELOCITY OF DRIFT AND FADING PERIOD, $\overline{T}$.

RAO and RAO[30], from a study of results obtained from the observation of E-region drift by the method of closely-spaced

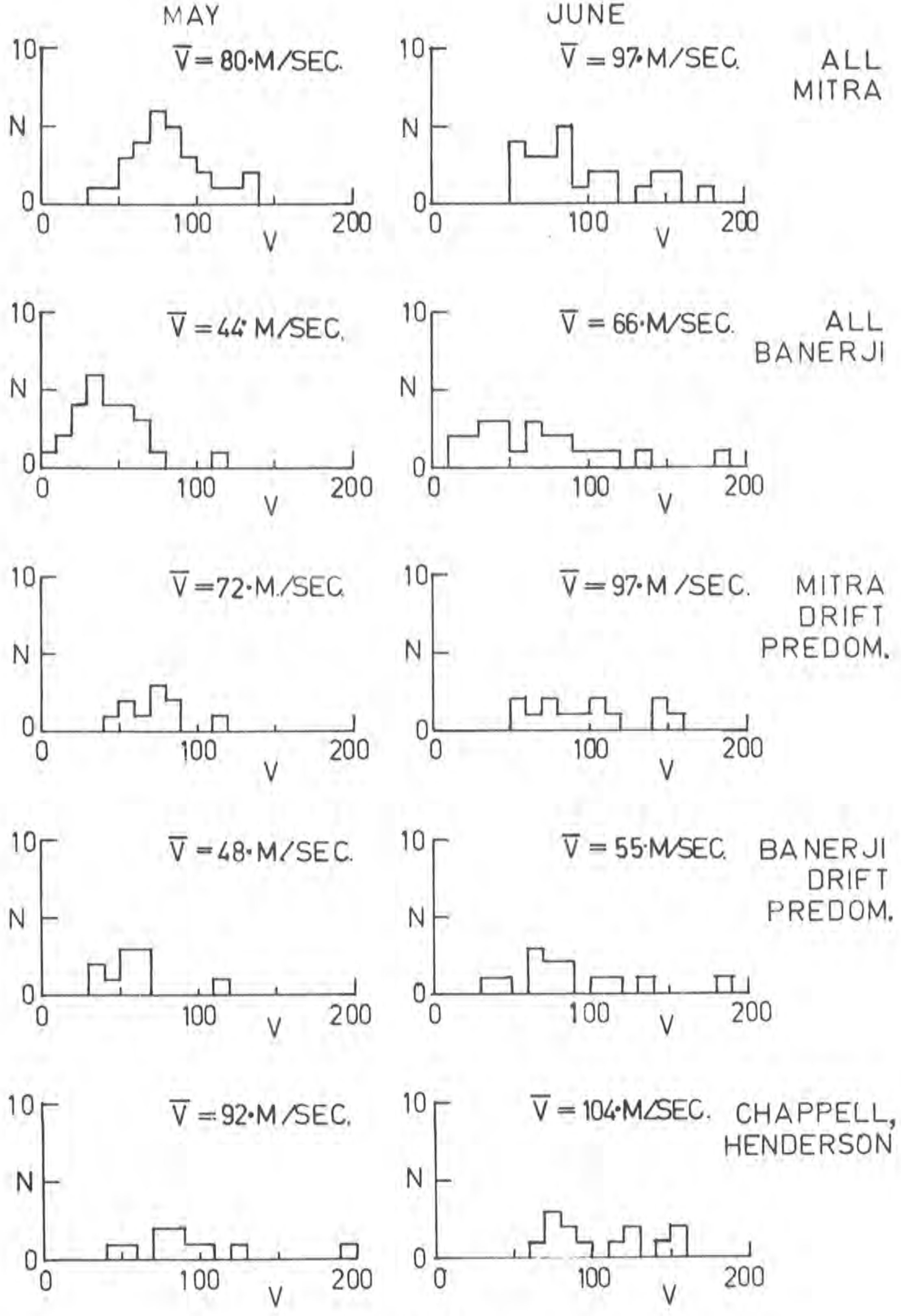

MAY
JUNE
V̄ = 80·M/SEC.
V̄ = 97·M/SEC.
ALL MITRA
V̄ = 44· M/SEC.
V̄ = 66·M/SEC.
ALL BANERJI
V̄ = 72·M./SEC.
V̄ = 97·M /SEC.
MITRA DRIFT PREDOM.
V̄ = 48·M/SEC.
V̄ = 55·M/SEC.
BANERJI DRIFT PREDOM.
V̄ = 92·M /SEC.
V̄ = 104·M/SEC.
CHAPPELL, HENDERSON
N
V
0
10
100
200

FIG. XXXVII

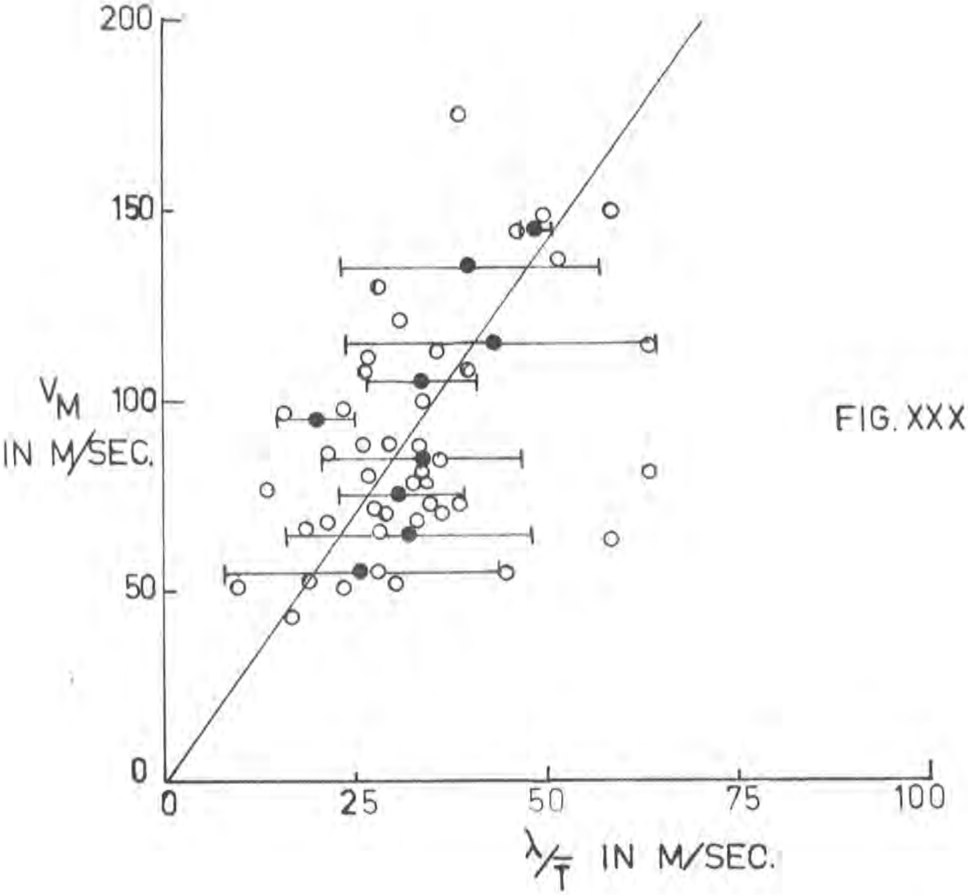
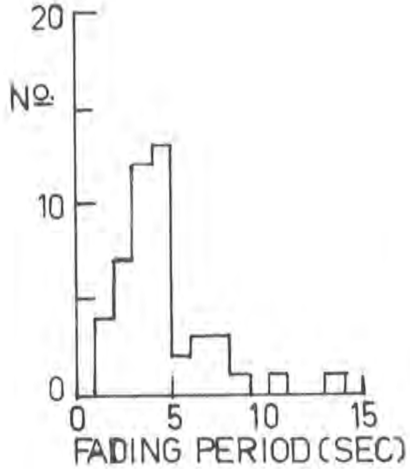


FIG. XXXVIII.



T = 4·5 SEC.

FIG. XXXIX.

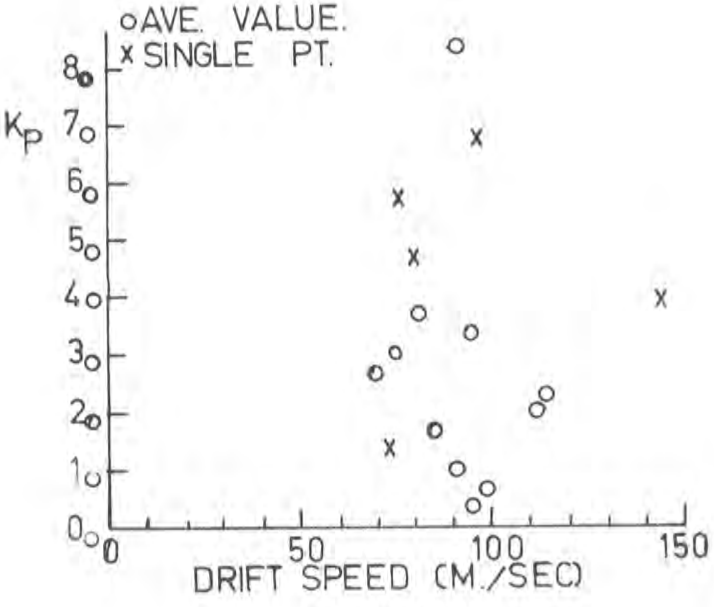


FIG. XL.

aerials, have noted the empirical relation

$$V\overline{T} = 1{\cdot}86\lambda, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (42)$$

which relates the E-region drift velocity V (observed at Waltair) to the wavelength λ employed in their study, and to the fading period $\overline{T}$ (average time between successive maxima or minima) of their records. They assume a general relationship

$$V.\overline{T} = k.\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (42a)$$

and, referring back to work done by PAWSEY[16], in 1935 at Cambridge, they suggest that his relationship between D (the maximum distance of aerial separation for which the signal variations are sensibly the same), the velocity of drift V and fading period $\overline{T}$, viz.,

$$\overline{T} = 2D/V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (43)$$

can be expressed in terms of λ from equation (42a), thus

$$\overline{T} = 2D/V = 2k\lambda/V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (43a)$$

Also one may find D from

$$D = \frac{V\overline{T}}{2} = \frac{k\lambda}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (44a)$$

RAO and RAO have found that, at Waltair, the value of $k = 1{\cdot}86$, thus giving D the value $0{\cdot}9\lambda$, which since the frequency used is 2·5 Mc/sec., gives the value of D as 108 m.

The records obtained at Adelaide were used to obtain $\overline{T}$, the average fading period, for the various velocities V and the results plotted in the form V versus $\lambda/\overline{T}$, since, as may be seen from (42a), this should yield a straight line through the origin, of slope k. The plot of such points $(V, \lambda/\overline{T})$ is shown in Fig. XXXVIII and suggests a line of slope = k = 2·8,

$$\text{i.e., } V\overline{T} = 2.8\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (42b)$$

This differs from the result obtained by RAO and RAO as also does the value of D, at Adelaide, deduced from this relationship, where

$$D = k\lambda/_2 = \frac{2.8}{2}\lambda \ = \ 1.4\lambda = 196\text{m.} \ \ldots\ldots\ldots\ldots\ldots (44b)$$

The appropriate value of D obtained by PAWSEY[16] was 300 m.

If results of fading period and E-region drift velocity at Yamagawa, Japan[41] are also taken we get another value of D = 180 m.

These values refer to different latitudes and the results are tabulated below.

TABLE I.

Station	Latitude	D	λ	k	R
Waltair	17.7°N	108 m.	120 m.	1.86	24 km.
Yamagawa	31.2°N	180 m.	120 m.	3.0	16 km.
Adelaide	35°S	196 m.	140 m.	2.8	17 km.
Cambridge	52.2°N	300 m.	170 m.	4.7	10 km.

These results are plotted (D v. latitude) in Fig. XLII. They seem to suggest that the value of D depends on latitude to a marked degree, so that it would be as well to determine the safe value of D at any latitude before recordings are commenced, in any closely-spaced aerials study.

PAWSEY, by considering the reflecting region of the ionosphere to be divided into half-wave regions, arrives at a relationship between D, λ , d (approximately equal to the height of the reflecting layer) and R (the radius of the region that contributes most strongly to the diffraction pattern on the ground), viz.,

$$R = \frac{1}{4}\lambda . d/D \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (45)$$

Now, is D can be expressed in terms of λ and the constant k we have,

$$R = \frac{1}{4} \lambda . d/(k \lambda /2) = \frac{d}{2k} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(46)$$

Supposing that d be substantially constant, equation (46) shows that the size of the region contributing most to the pattern on the ground is inversely proportional to the factor k. The factor k seems to increase with the wavelength used (though not proportionately) and increases with latitude, the implication being that the size of region that contributes most to the pattern on the ground decreases with increasing latitude. Possibly the relationship deduced by PAWSEY (viz., equation (45)) is derived from too simple a model, but if not, this effect might with profit be further investigated.

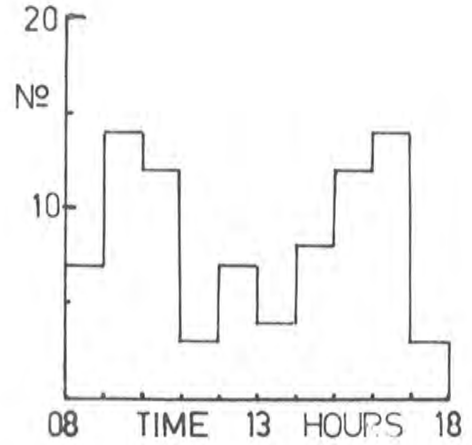


FIG. XL I

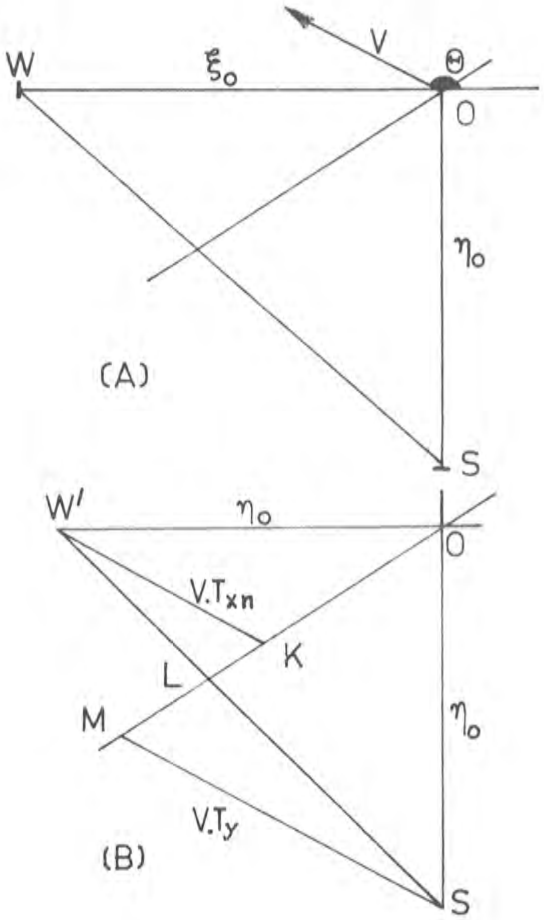


FIG. XLII

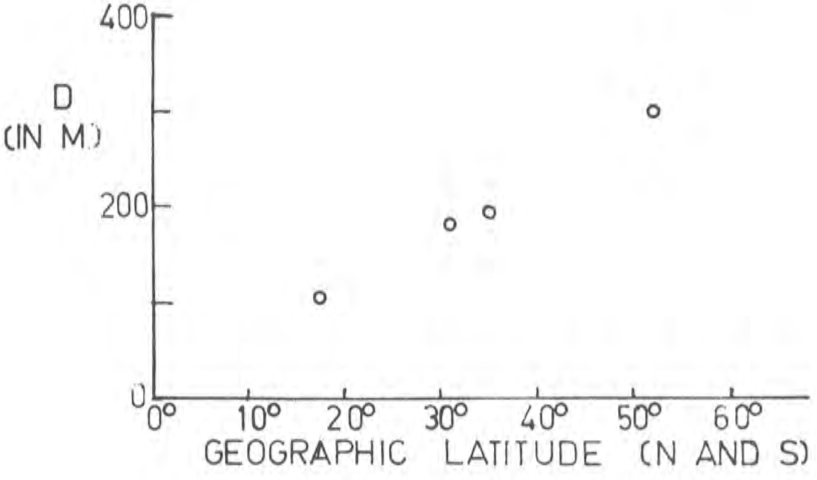


FIG. XLIII

VII.A. APPENDIX I.

TABLE II.

		MITRA				BANERJI					CHAPPELL, HENDERSON						
DATE	TIME	V	θ	V N-S	V E-W	V	V_c	θ	V N-S	V E-W	V	θ	V N-S	V E-W	AV. FAD. PER.	λ/T	K_p
11/5	1345	66	129°	+ 52	- 41	160	299*	71°	+151	+ 52							4-
12/5	1345	97	97°	+ 95	- 13	103	57*	92°	+103	- 3							7-
12/5	1505	77	98°	+ 77	- 13	55	69	90°	+ 55	0	83	75°	+ 80	+ 21	11.0	13	8+
12/5	1612	43	113°	+ 39	- 17	38	25	121°	+ 33	- 20	43	121°	+ 37	- 22	8.1	17	8+
12/5	1650	52	154°	+ 24	- 48	40	55	126°	+ 32	- 24	52	150°	+ 26	- 45	5.3	30	8+
13/5	0857	121	10°	+ 21	+117	39	143	58°	+ 33	+ 21					4.5	31	4-
13/5	1345	68	93°	+ 67	- 4	28	120	150°	+ 24	- 14					6.6	21	3-
13/5	1355	62	116°	+ 56	- 27	69	51*	119°	+ 60	- 33							3-
13/5	1540	85	97°	+ 84	- 11	103	67*	75°	+ 99	+ 27							30
13/5	1615	74	96°	+ 74	- 7	69	43	106°	+ 65	- 19	97	73°	+ 93	+ 28			30
15/5	0907	80	95°	+ 80	- 8	64	96	71°	+ 60	+ 21	103	46°	+ 74	+ 71	5.2	27	5-
16/5	0735	260	297°	-230	+118	73	250	288°	- 69	+ 22							6-
16/5	0822	425	241°	+372	-206	31	219	248°	- 29	- 12							6-
16/5	0842	77	318°	- 52	+ 63	50	104	275°	- 50	+ 1					4.2	33	6-
18/5	1215	99	19°	+ 32	+ 94	46	126	336°	- 19	+ 42							2+
19/5	1425	266	249°	-250	- 98	18	135	243°	- 16	- 8							30

* Unreal values of V_c

APPENDIX I.

TABLE II.

DATE	TIME	MITRA				BANERJI					CHAPPELL, HENDERSON				AV. FAD. PER.	λ/T	K_p
		V	θ	V N-S	V E-W	V	V_c	θ	V N-S	V E-W	V	θ	V N-S	V E-W			
19/5	1540	52	148°	+ 21	- 46	29	62	183°	- 2	- 29					7.4	19	3-
20/5	1200	65	261°	- 64	- 11	53	52	266°	- 53	- 4	81	226°	- 58	- 56	5.0	28	2-
25/5	0942	85	283°	- 83	+ 19	62	98	250°	- 58	- 21	194	221°	-127	-146	3.8	37	3+
25/5	1042	130	145°	+ 75	-106	9	124	216°	- 5	- 7					5.0	28	3+
26/5	1055	98	187°	- 13	- 97	37	126	233°	- 30	- 22					6.2	23	20
27/5	1055	73	61°	+ 64	+ 36	52	70	79°	+ 51	+ 10	73	58°	+ 62	+ 39	4.0	35	1+
27/5	1505	51	132°	+ 38	- 39	38	52	106°	+ 36	- 10	121	191°	- 23	-119	13.4	10	0+
27/5	1655	72	16°	+ 20	+ 68	45	116	70°	+ 44	+ 8					5.1	27	0+
28/5	1230	86	70°	+ 85	+ 30	27	79	77°	+ 26	+ 6					6.8	21	10
28/5	1420	34	207°	- 16	- 30	175	277*	266°	-175	- 12							10
28/5	1630	72	77°	+ 70	+ 16	23	75	110°	+ 22	- 8					4.8	29	0+
29/5	0943	108	336°	- 45	+ 97	45	110	321°	- 28	+ 35					3.5	40	1-
29/5	1040	88	8°	+ 13	+ 87	36	88	10°	+ 6	+ 35					4.1	34	1-
29/5	1400	115	99°	+113	- 19	111	31	104°	+108	- 27	73	97°	+ 72	- 9	2.2	64	0+
29/5	1500	105	106°	+101	- 30	150	157*	99°	+148	- 23							0+

* Unreal values of V_c

APPENDIX I.

TABLE II.

		MITRA				BANERJI					CHAPPELL, HENDERSON						
DATE	TIME	V	θ	V N-S	V E-W	V	V_c	θ	V N-S	V E-W	V	θ	V N-S	V E-W	AV. FAD. PER	$\lambda/\bar{T}$	K_p
1/6	1425	71	119°	+62	-35	65	44	112°	+60	-24	73	106°	+70	-16	3.4	41	10
1/6	1522	109	155°	+45	-98	82	95	163°	+24	-78	123	187°	-15	-122	5.2	27	2-
2/6	0935	51	352°	-7	+50	22	293	62°	+19	+14					6.2	23	3+
3/6	0945	96	110°	+91	-33	60	102	88°	+60	+2	112	77°	+109	+25	8.9	16	3+
3/6	1235	100	101°	+97	-18	86	93	71°	+81	+28	93	67°	+86	+36	4.1	34	4-
3/6	1520	64	150°	+56	-60	38	98	199°	-12	-36					2.4	58	30
4/6	1020	55	284°	-54	+14	39	65	251°	-37	-13	77	241°	-67	-37	5.0	28	4-
4/6	1625	110	219°	-70	-86	45	196	285°	-43	+12					5.2	27	3-
4/6	1650	66	187°	-8	-65	71	13	205°	-30	-64	68	200°	-23	-64	7.9	18	3-
4/6	1700	79	211°	-40	-69	17	162	131°	+13	-11					4.1	34	3-
4/6	1725	69	295°	-63	+33	24	113	358°	-1	+24					4.3	33	3-
5/6	1515	55	111°	+51	-20	42	20	77°	+41	+9	81	63°	+72	+37	3.1	45	3-
8/6	1615	73	271°	-72	+4	70	37	258°	-68	-15	74	223°	-50	-54	3.7	38	3+
8/6	1700	55	298°	-52	+18	76	81*	300°	-66	+38							3+
9/6	1230	145	90°	+145	0	117	115	91°	+117	-2	147	78°	+144	+31	2.6	47	40
10/6	1400	81	138°	+54	-60	57	118	101°	+56	-11					2.2	64	20

* Unreal values of V_c

APPENDIX I.

TABLE II.

DATE	TIME	MITRA				BANERJI					CHAPPELL,HENDERSON						
		V	θ	V_{N-S}	V_{E-W}	V	V_c	θ	V_{N-S}	V_{E-W}	V	θ	V_{N-S}	V_{E-W}	AV. FAD. PER.	λ/T	K_p
10/6	1435	156	129°	+122	-100	130	128	112°	+121	- 49	153	123°	+128	- 83			20
15/6	0840	138	86°	+136	+ 10	161	129*	83°	+160	+ 20							3+
15/6	0847	149	8°	+ 22	+146	183	69	46°	+132	+127	152	30°	+ 76	+132	2.8	50	3+
15/6	0915	113	6°	+ 20	+111	107	124	50°	+ 82	+ 59	128	42°	+ 86	+ 95	3.9	36	2+
16/6	1520	89	146°	+ 49	- 72	34	115	99°	+ 34	- 5					4.9	29	10
17/6	0925	150	5°	+ 14	+150	93	205	51°	+ 72	+ 58					2.4	58	0+
17/6	1010	84	28°	+ 40	+ 75	85	3*	33°	+ 46	+ 71							0+
17/6	1405	175	71°	+167	+ 57	48	169	42°	+ 32	+ 36					3.7	38	10
18/6	1223	81	61°	+ 71	+ 40	68	58	61°	+ 59	+ 37	81	60°	+ 70	+ 40	4.1	34	3+
19/6	1525	89	145°	+ 50	- 73	17	170	224°	- 12	- 13					5.3	26	10

* Unreal values of V_c

VIIIB. APPENDIX II.

The Orientation of lines of Maxima.

Consider, in Fig. XLII A, a straight line of maximum amplitude moving with velocity V in the direction θ, measured anticlockwise from +ve x direction, i.e. WO produced. The line of maximum will pass through aerial S a time Ty before passing through aerial O, and a further time Tx will elapse before it passes through aerial W. From the convention of sign referred to previously Ty is negative, Tx is positive in this particular case. It will be clear from the figure that, if the base line OS were reduced by η_0 times, i.e. the base line OS reduced to unity, the time, Ty, would be reduced also by a factor η_0 times. Similarly, the effect of reducing OW by a factor ξ_0 is to reduce Tx by a factor of ξ_0 also. Let us refer to this supposed reduction of scale as the unit normalizing process. Another possible normalizing process could be carried out by leaving OS unchanged and altering OW by a factor η_0/ξ_0. This would leave the time interval Ty unaltered and reduce Tx by a factor η_0/ξ_0, which would be the time taken for the line of maximum to pass from O to W' when OW' = OS = η_0(and not ξ_0). That is, the normalizing process reduces the aerial system to a right-angled isosceles triangular set. (It will be obvious that this, in fact, is the effect of the factor η_0/ξ_0 that appears in some of the equations given in the general discussion of the analysis). Let W' then represent the position of aerial W which results from the normalizing process and let Tx_n represent the normalized value of Tx. Construct SW'. It will be seen that there are formed two similar triangles W'LK and SLM, where, in particular, the ratio of sides W'L:SL equals the ratio W'K:SM,

$$\text{i.e.} \quad \frac{W'L}{SL} = \frac{W'K}{SM} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(47)$$

But W'K = VTx_n and SM = VTy, hence we may substitute in (47) to obtain

$$\frac{W'L}{SL} = \frac{Txn}{Ty} = \frac{Tx.(\eta_0/\xi_0)}{Ty} \quad \ldots\ldots\ldots\ldots\ldots\ldots(48)$$

If, instead of the individual times Tx and Ty of a time-delay pair to set up particular line of maximum, we use $\overline{T}x$ and $\overline{T}y$, we will be setting up what will be near enough to the average line of maxima taken over the period of time for which the average $\overline{T}x$ and $\overline{T}y$ have been calculated. If this is done we can write

$$\frac{W'L}{SL} = \frac{\overline{T}x\,(\eta_0/\xi_0)}{Ty} = \left(\frac{\eta_0}{Tx}\right)/\left(\frac{\xi_0}{Tx}\right) = \frac{V'y}{V'x} \ldots\ldots(49)$$

where V'X and V'y are the apparent velocity components along OW and OS (vide discussion of MITRA-type analysis). Therefore, we arrive at a construction to reconstitute an average line of maxima. Set up two axes at right angles, viz. XOX', and YOY' along OX' mark off OW' = 1 unit of any scale preferred, along OY' mark off OS = 1 unit of the same scale used to locate W'. (We do not need to mark off OW' = η_0 = OS, since equation (48) shows that in normalizing OW from ξ_0 to η_0, we have produced the same effect as normalizing both sides to unity, for

$$\frac{W'L}{SL} = \frac{\overline{T}x\,(\eta_0/\xi_0)}{\overline{T}y} = \frac{(\overline{T}x/\xi_0)}{(\overline{T}y/\eta_0)} = \tan\theta \ldots\ldots\ldots(50)$$

as required for unit mormalization). Then join W'S and divide W'S in the ratio given by equation (49). The line LO then represents the required position of the line of maximum.

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