Drift Motions of Auroral Ionization

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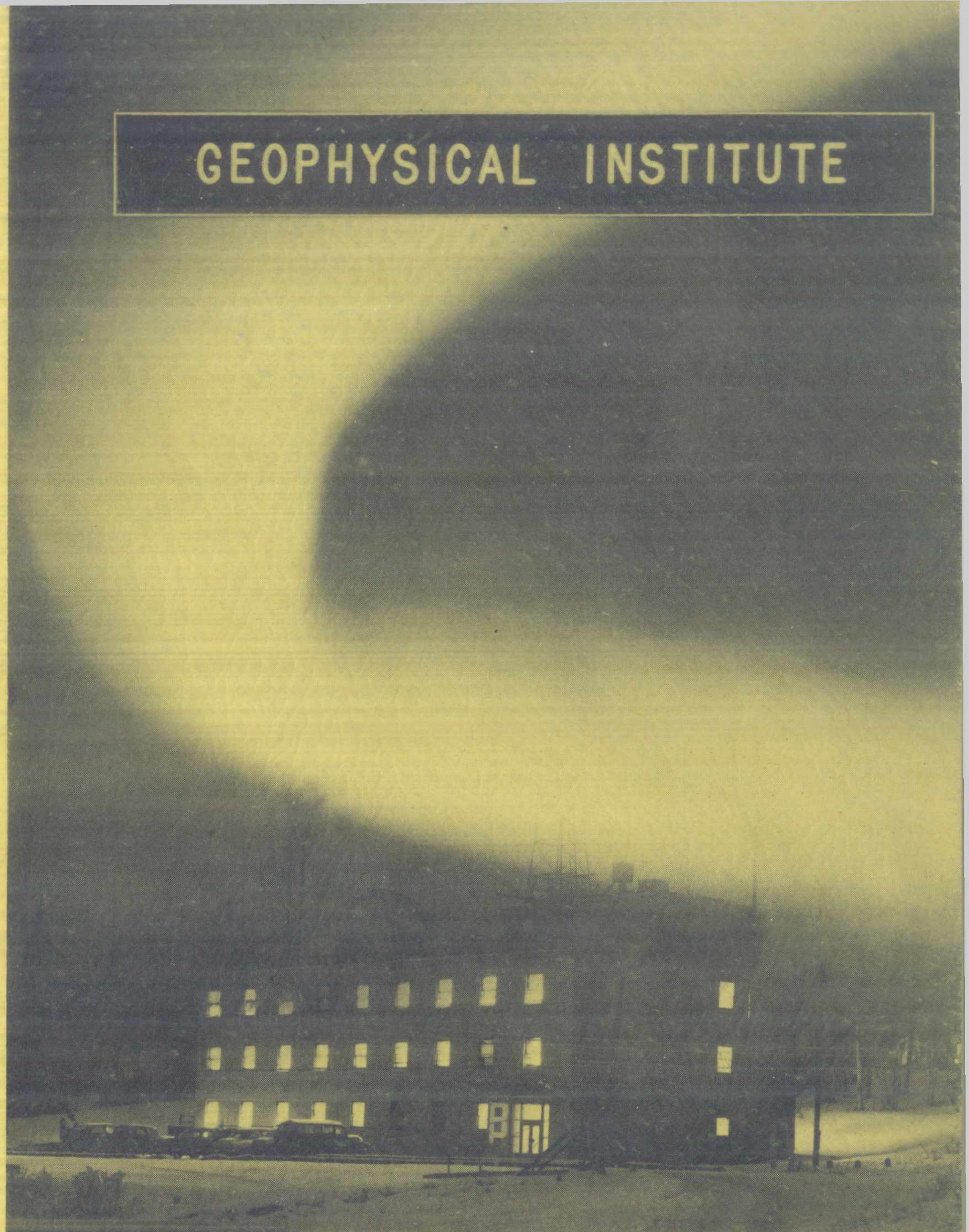

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Scientific Report No. 1

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July 1957

DRIFT MOTIONS OF AURORAL IONIZATION

by

B. Nichols

The research reported in this document has been sponsored by the Electronic Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command.

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The research reported in this document has been sponsored by the Electronic Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command. (This thesis was submitted in July, 1957, to the University of Alaska in partial fulfillment of the requirements for the degree of Doctor of Philosophy.)

C. T. Elvey
Director of the Institute

Date: July 1957

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Abstract

The primary subject of this report is the drift motions of auroral ionization. The existence of rapid motions of the ionization has been demonstrated in previous radar studies of the aurora, but neither the nature of the motions nor their explanation has been established until now. The purpose of our experimental observations was to determine the direction and speeds of the motions. In doing so, we obtained additional information concerning the general nature of the auroral ionization.

Measurements were taken at College, Alaska, during the winter and spring of 1956-57, using CW transmitters. By locating the transmitters at Eielson Air Force Base, it was possible to separate the transmitters and the receivers by 42 kilometers along a geomagnetically east-west line. The basic technique used was to examine the frequency spectra of radio echoes from the aurora at 106 Mc/s and 41.15 Mc/s. A comparison of the results obtained at 106 Mc/s and 41.15 Mc/s showed that the frequency shifts are proportional to the transmitted frequency, as would be expected of Doppler shifts.

By measuring the spectra of the echoes received from east and west of geomagnetic north at the same time, it was possible to determine the following:

(i) That the motions are generally horizontal and in the geomagnetic east-west plane; and

(ii) That the speeds of the motions vary from 350 meters per second to 2,000 meters per second.

On the basis of our experimental results and the published

literature, we show that the electron drift motions in the aurora are of the same order of magnitude and direction as the motions of the electrons in the ionospheric current system required to explain magnetic disturbances. These electron motions produce the Doppler shifts that are responsible for the well known rapid fading of auroral radio echoes. The fading of radar auroral echoes is therefore associated with the increased electric fields which drive the currents in auroral regions.

Following a review of the available information concerning general motions in the ionosphere, motions of the visible aurora, and motions inferred from magnetic storms, we show that the drift motions of auroral ionization do not constitute a separate and distinct group. Instead, they are found at the upper end of a continuous curve of increasing speed of motions with increasing magnetic disturbance. The intense ionospheric currents that produce the magnetic disturbances are found to be associated with both increased electron density and increased speed of motion.

In our examination of the amplitude of VHF radio auroral echoes, the basic premises of the theory of scattering by nonisotropic irregularities produced by turbulence [Booker, 1956] are found to be satisfactory. However, the numerical values of the parameters suggested by Booker require revision. In particular, our results indicate that the mean square fractional deviation of electron density is much greater than Booker conjectured on the basis of the then available evidence; in fact, it is greater by two to three orders of ten.

Introduction

This report is primarily concerned with the drift motions of auroral ionization. The aurora is an extremely complex, rapidly changing phenomenon that occurs over broad regions of the earth. No investigation made at a single place for a limited period of time could hope to present a complete picture of auroral motions. Moreover, before any such complete study is undertaken, it is important to understand the significance of the various measurements involved. The chief result of the present study has been to show that the rapid motions observed by radio means are a measure of the ionospheric current systems associated with the aurora.

The motions associated with auroras constitute a problem that remains to be solved fully. As seen visually or photographically, the auroral forms may move very rapidly across the sky. Even among experienced observers there is not complete agreement as to the character of these motions, much less as to their interpretation. Since 1940, and at a greatly accelerated pace following the second world war, radio means have been used to investigate the aurora. The chief method has been the use of radars at meter wavelengths, but information has been obtained also from the postwar studies of the scintillations of the so-called radio stars. All observers have agreed that the rapidity of the fading of radar echoes and of the scintillations must be caused by motions in the aurora whose speed is about a power of ten faster than is normally measured in other ionospheric observations.

The observers are not agreed as to the physical mechanism responsible for the radio echoes from aurora. It now seems clear, however, that the echoes arise from relatively weak backscatter of radio waves from nonisotropic irregularities of ionization in the auroral region. A theory that seems to fit most of the observed effects has recently been presented by Booker [1956]. In his conclusion, Booker points out that "the most serious objection to regarding turbulence as the cause of the irregularities required to explain auroral echoes is that the fading phenomena cannot possibly be explained in terms of wind-speed and turbulence." An additional aspect of our results has been to show that, while the general features of Booker's theory are probably correct, it is necessary to revise quantitatively his estimates of auroral ionization.

Auroral motions take place in the ionosphere, chiefly in the E region. In recent years the evidence concerning the speed and direction of motions--principally nonauroral motions--in the ionosphere has increased greatly. One striking feature of the radio observations from the point of view of the present investigation has been the association of increases in the speeds of motions with increases in magnetic activity. These magnetic disturbances can be explained in terms of current systems in the ionosphere and in high latitudes are associated with auroras. Unfortunately, most of the radio measurements have been made in lower latitudes, so the results will have to be used with some care in considering auroral motions. A study of the motion of auroral ionization should therefore consider general motions in the ionosphere, the motion of the visible aurora, and the disturbance current systems just mentioned.

In Chapter I we shall describe the various data on general motions in the ionosphere, except data derived from visually observed motions of auroras. It will be necessary to consider the relationship of wind speeds to the motion of charged particles in order to determine the significance of the radio data.

Chapter II will summarize the available information on motions of visual auroral forms. It will be shown that this information, while highly valuable, is still too incomplete to be conclusive.

The relevant parts of the extensive knowledge concerning magnetic storms and the ionospheric current system will be discussed in Chapter III. It will be seen that there is a close relationship between these current systems and the morphology of the aurora.

The experimental phase of the study described herewith took place at College, Alaska, from January to April 1957. It was concerned with determining the drift velocities of auroral ionization by using radio Doppler shift techniques. This method was first used by Bowles [1954, 1955], who was able to measure the radial components of the velocities. Bowles, however, was able only to conjecture as to the actual direction of the motions and therefore as to the actual velocities. He concluded that the motions involved were along the lines of force of the geomagnetic field and at speeds of 10 to 100 kilometers per second. Instead, the results to be described herewith indicate clearly that the motions are generally east-west and horizontal; their speeds are 350 to 2,000 meters per second.

These drift motions will be shown to be of the same order of magnitude and direction as the electrons in the ionospheric current system required to explain the magnetic disturbances. They are a factor of ten greater than the normally measured ionospheric winds. The rapid fading of auroral radio echoes can be associated with the increased electric fields which drive the currents in auroral regions.

The experimental equipment and procedure used in our experiment will be described in Chapter IV, and some typical records will be shown. The interpretation of these records will be discussed.

In Chapter V we shall review the various observations and explanations of auroral radio echoes in order to interpret our results properly. We shall compute estimates of the auroral ionization required to explain the strength of our echoes.

In Chapter VI the results of our measurements will be summarized. The relationship of the measured drift motions to magnetic observations will be discussed. Several examples of the comparison of our measurements to the simultaneous magnetic observations made at College and Point Barrow, Alaska, will be presented.

Chapter I. General Motions in the Ionosphere

An understanding of the motions of auroral ionization must inevitably be based to some extent upon a knowledge of the various motions taking place in the ionosphere. Unfortunately, only a quite limited picture of ionospheric motions can be given at the present time, particularly for high latitudes. Furthermore, even though some of the radio observations under magnetically quiet conditions probably map actual wind systems, this is not generally true. For the magnetically disturbed and auroral ionosphere, it is doubtful whether any of the radio observations refer directly to wind systems.

With these limitations in mind, we summarize the available facts in this chapter and discuss the interpretation of the facts. It is shown that auroral drift motions do not constitute a separate and distinct group. As a matter of fact, the measured speeds of motions constantly increase with the increase of magnetic disturbance. The high speeds of auroral motions are at the upper end of a continuous curve and are directly related to magnetic disturbances. At times, especially during auroras, the electric field in the ionosphere seems to increase simultaneously with an increase in ionization density and produces the currents responsible for magnetic disturbances. Since radio techniques measure the motion of charges, principally electrons, we conclude that the observed rapid auroral motions are associated with the increased electric field.

The many factors that would have to be considered in a complete study of ionospheric motions were fully described by Chapman [1953]. He pointed out the immensity of the task of relating and understanding the phenomena of the lower atmosphere—the various layers and belts, the general circulations, the trade and other wind systems, the larger features of cyclonic and anticyclonic areas, the topographical winds, the land and sea breezes, the detailed turbulence, the various clouds, monsoons, tornadoes, jet streams, etc. Moreover, the ionosphere is dynamically more active than the lower atmosphere; the general physical properties of its gases are less well known; and our observational knowledge is far inferior.

The ionosphere differs fundamentally from the lower atmosphere by the simple fact of its ionization. Motions of the ions and electrons, taking place in the presence of the geomagnetic field, will be influenced not only by the mass motion of the neutral gas but also by electrostatic and electromagnetic forces. The motions of the charged particles in turn may react on the mass motions of the air. Since most of our information about ionospheric motions comes from radio studies, it is important to remember that radio observations indicate the presence and motion of the electrons, both of which may differ from that of the main air mass. Ratcliffe [1954] in his excellent summary of irregularities and movements in the ionosphere suggested the use of the term "drift" for the movement of irregularities* of electron density to avoid confusion with the term "wind," which refers to the movement of the neutral air. Un-

* Ratcliffe points out, "If a radio wave were reflected from a uniform horizontally stratified ionosphere, there would be no way of using it to decide whether or not the electrons were drifting with any coherent motion. It is fortunate . . . that at all heights in the ionosphere there are irregularities in the electron density . . . ."

fortunately, some authors have not avoided this confusion.

1. Visual Observations of Ionospheric Motions

Measurements of ionospheric motions have been obtained from visual observations of the aurora, meteor trails, noctilucent clouds, and, most recently, of sodium clouds injected into the ionosphere from a rocket. Since the interpretation is uncertain, the motion of visual auroras will be reserved for discussion in the next chapter. There is little doubt that the other motions observed visually are directly caused by existing winds at the heights involved. Although the number of observations has been limited, it is obviously useful to summarize briefly the velocities measured.

The sodium-cloud wind observations thus far reported [Edwards, Dedinger, Mauring, and Cooper, 1955] took place in New Mexico at 1800 local time on October 12, 1955. By tracking the clouds with theodolites, the wind at the 85-km level was measured to be 80 m/s (180 mph) to the southeast; at the 100-km level, the wind was 45 m/s (100 mph) to the northwest. These shearing winds rapidly distorted the sodium trail.

Noctilucent clouds having heights between 74 and 92 km are observed at high latitudes in summer, some hours before sunrise and after sunset. The data on their motions has been summarized by Mitra [1952, pp. 334-335, 585]. Although early measurements gave higher speeds, the more recent information puts the average wind speed at around 50 m/s.

Many visual observations of long enduring meteor trails have been made over the years. Some 1,600 cases were examined by Olivier [1947]. The average speed deduced from these generally crude measurements was about 50 m/s. More recently, much more accurate measurements have been made using Super-Schmidt telescopes and photographic techniques [Liller and Whipple, 1954]. The velocities of five persistent meteor trains were measured as a function of altitude in the range 81 to 113 km. The winds changed rapidly with altitude at the rate of about 20 m/s per km. Winds separated by five km in height seemed uncorrelated. The maximum wind component reached about 100 m/s; the mean wind speed was 38 m/s.

Although the visual measurements of wind speeds have been limited to more or less isolated instances, they have yielded consistent results as far as the magnitude and character of the winds in the D and E regions of the ionosphere are concerned. The speeds may be as high as 100 m/s; the mean value is about 50 m/s. All observations indicate that the lower regions of the ionosphere are turbulent, the wind speeds varying rapidly and irregularly with height.

2. Radio Observations of Ionospheric Motions

Extensive radio measurements of ionospheric motions have been made in the past decade. The principal methods used have been as follows:

(i) Measurement, at closely spaced points, of time shifts in the amplitude pattern at ground level produced by vertically incident radio waves reflected from the E or F layer;

(ii) Measurement, at widely spaced points, of time shifts of large scale irregularities in the F region;

(iii) Measurement, at points separated by up to a few kilometers, of the time shifts in the scintillations of radio stars;

(iv) Measurement of the positions of meteor trails and the radial components of the velocity of drift of the ionized trails; and

(v) Measurement of the motions of auroral ionization.

An extensive summary of the results of the measurements using methods (i) - (iv) was compiled by Briggs and Spencer [1954]. A few of their major conclusions will be mentioned here. They reported that the mean velocity of the drift in the E region varies from time to time, but that it has an average value of 80 m/s. It contains a semi-diurnal component of about 30 m/s which has the general form expected from the theory of atmospheric oscillations produced by the thermal and tidal action of the sun. The velocities in the F region are somewhat higher, with directions toward the east by day and toward the west by night.

Of particular interest from the point of view of our study is the increase in the speeds measured during magnetic disturbances. Using method (i), Chapman [1953] reported that for the F region at Ottawa the mean drift velocity was independent of the K-index until K exceeded four. For a K-index of five or greater, the higher absorption commonly made echoes too weak for recording. Occasionally, however, echoes were obtained that invariably indicated drift velocities ranging from 200 to 500 m/s. For the F region Chapman reported a mean drift velocity that increased regularly with the K-index.

Briggs and Spencer [1954], using the same technique at Cambridge, England, reported that for the E region the velocity was independent of the K-index for values between one and five. High velocities of the order of 500 m/s were nevertheless recorded in the E region on one occasion during a severe magnetic storm. For the F region the velocity was independent of K-index until the value reached five, after which the velocity increased steadily. For the particular case in which F region motions were measured during a period of aurora, motions were observed first to the west and then to the east with speeds of up to 750 m/s. On one occasion a velocity of 1,000 m/s was observed during a magnetic storm.

The most complete studies of the variation of the drift velocity with the degree of magnetic disturbance [Little and Maxwell, 1952; Maxwell and Little, 1952; Hewish, 1952; Maxwell and Dagg, 1954; Maxwell, 1954] have been made by using method (iii). The results of all these studies showed that the increase in the drift speed is correlated with the increase in the K-index. Speeds up to 1,000 m/s were noted.

The radio star is a versatile tool for studying ionospheric motions, for as the elevation angle of the radio star under observation varies, its radiation penetrates the ionosphere at different latitudes. The radiation from different stars, observed at the same time, will traverse the ionosphere in different longitudes; at certain times the geomagnetic latitude will be the same. By taking advantage of this versatility, Maxwell and Dagg were able to determine that the drift motions near the auroral zone were twice as great as those overhead at Jodrell Bank. In general, the velocities in two areas separated by 800 km along the same geomagnetic latitude were substantially the same. Overhead motions at Jodrell Bank, particularly during magnetically disturbed conditions, were to the west before midnight and to the east after midnight. Near the auroral zone the reversal took place at about 2100. The north-south components of velocity were generally small.

There are two other significant observations in connection with the scintillation measurements. The first is that the size of the irregularities responsible for the scintillations does not change as the degree of magnetic disturbance and the speed of motion vary. The second is that the amplitude of the scintillations does not bear a one-to-one correspondence with the degree of magnetic disturbance. These facts lead directly to the conclusion that the character of the irregularities is not changed during magnetic disturbances but their speed is increased. Such would be the case if the irregularities were produced by turbulence and acted upon by increased electric fields during magnetic disturbances.

The chief difficulty in the interpretation of the radio star data concerning motions is that no firm conclusion has been reached as to the heights of the irregularities whose motions are being measured. While many workers in the field believe that the heights involved are greater than 400 km, the arguments supporting this belief are indirect. Recently Booker [1956, 1957] has argued on the basis of a turbulence theory that the height is much lower, of the order of 165 km. It is also possible that the measured direction of motions may be in error. Spencer [1955] demonstrated that the ionospheric irregularities which produce the scintillations are elongated along the earth's magnetic lines of force. The elongated shapes of the amplitude patterns on the ground are therefore approximately elliptical, with axis ratios greater than five to one. Under these conditions the apparent direction of motion lies very close to the minor axis of the ellipse. Even in the face of these uncertainties, it is possible to conclude from the scintillation measurements that at heights above the E region the magnitude of the drift motions is correlated with the degree of magnetic disturbance.

3. Motions of Auroral Ionization

We proceed now to examine more direct measurements of auroral ionization. Extremely rapid horizontal motions in the E region, apparently associated with aurora, have been deduced by Hagg and Hanson [1954] from the rapidly changing virtual height of echoes observed on the ionospheric sounders located at Fort Chimo and Baker Lake (their type III echoes). The average speed was about 1,200 m/s, but in several cases it was nearly four km/s.

The major studies of the drift motions of auroral ionization based on VHF radio echoes from aurora have been reported by Bowles [1954, 1955] and Bullough and Kaiser [1955]. The techniques used, and the conclusions reached, were quite different. Bowles measured the Doppler shift of CW auroral echoes at College and Kenai, Alaska, and Ithaca, New York. The measured radial components of velocity at College were typically about 600 to 1,000 m/s. At Kenai and Ithaca the radial components were typically about 300-500 m/s. Bowles noticed that the Doppler shifts of the CW echoes had no correlation with the range changes of radar echoes. At times when the radar range showed no change, the CW echoes continued to show Doppler shifts. Downward motions (upward shifts in frequency) were correlated with homogeneous forms of the visible aurora; rayed forms were correlated with upward motions (downward shifts in frequency). After ruling out east-west motions on the basis of several occasions when rotation of the antenna revealed "no large change in the shape of the spectrum," Bowles concluded that the drift motions were directed along the magnetic lines of force with speeds of 10 to 100 km/s. In Chapters IV and VI we shall show that the results of our experiment appear to rule out this interpretation.

Bullough and Kaiser [1955] deduced the speeds of motion of the reflecting regions from measurements of the change in range of radar echoes observed at Jodrell Bank, using an antenna directed 50 degrees west of the geomagnetic meridian. From geometrical considerations they showed that the motions were along a parallel of geomagnetic latitude. The motions were toward the west in the evening and toward the east in the morning, the reversal occurring between 2100 and 2200. The mean speeds at 1800 and 0600 were about 600 m/s to the west and east respectively. Speeds as high as three km/s were observed. On several occasions regular sequences of moving echoes were observed. In one case seven echoes with speeds of 500 m/s in the same direction passed through their antenna beam at intervals of 11 minutes.

Kaiser [1955] reported that a detailed analysis of the magnetic variation during individual auroras showed that for positive and negative bays the auroral motions were toward the west and east respectively. In addition, the time of reversal in direction of the motions corresponded to the time of reversal of the mean vertical component (ΔZ) of the magnetic disturbance at a station 10 degrees east of the reflecting region. Kaiser noted that a close relationship between the auroral motions and the atmospheric electric current system was clear. That close relationship is also confirmed by our results as described in Chapter VI, even though the Doppler shift measurements deal directly with the motions of the charges rather than with the motions of the reflecting regions.

The correlation of the speed of motions measured by various radio methods with the degree of magnetic disturbance has already been noted above. In general, the various authors have plotted curves as a function of K-index. The nonlinear character of that index tends to obscure the direct relationship between the speeds of motion and the disturbance of the magnetic field. Accordingly, in Figure 1 we have replotted several of the published curves to show the variation in $\Delta\gamma$ as a function of the measured speeds. Since the K-figure at the different stations corresponds to a different range of $\Delta\gamma$, the percentage of the $\Delta\gamma$ corresponding to the highest K-figure, K-9, has been used. Curves A, B, and D refer to heights above the E region and show a smooth increase of $\Delta\gamma$ as speed of motion increases. The change in the field is nearly proportional to the square of the speed. Since the strength of the currents responsible for the magnetic variations would depend upon the product of the ionization density and the speed, it appears that both the speed of motion and the ionization density increase during magnetic disturbances. For K-figures

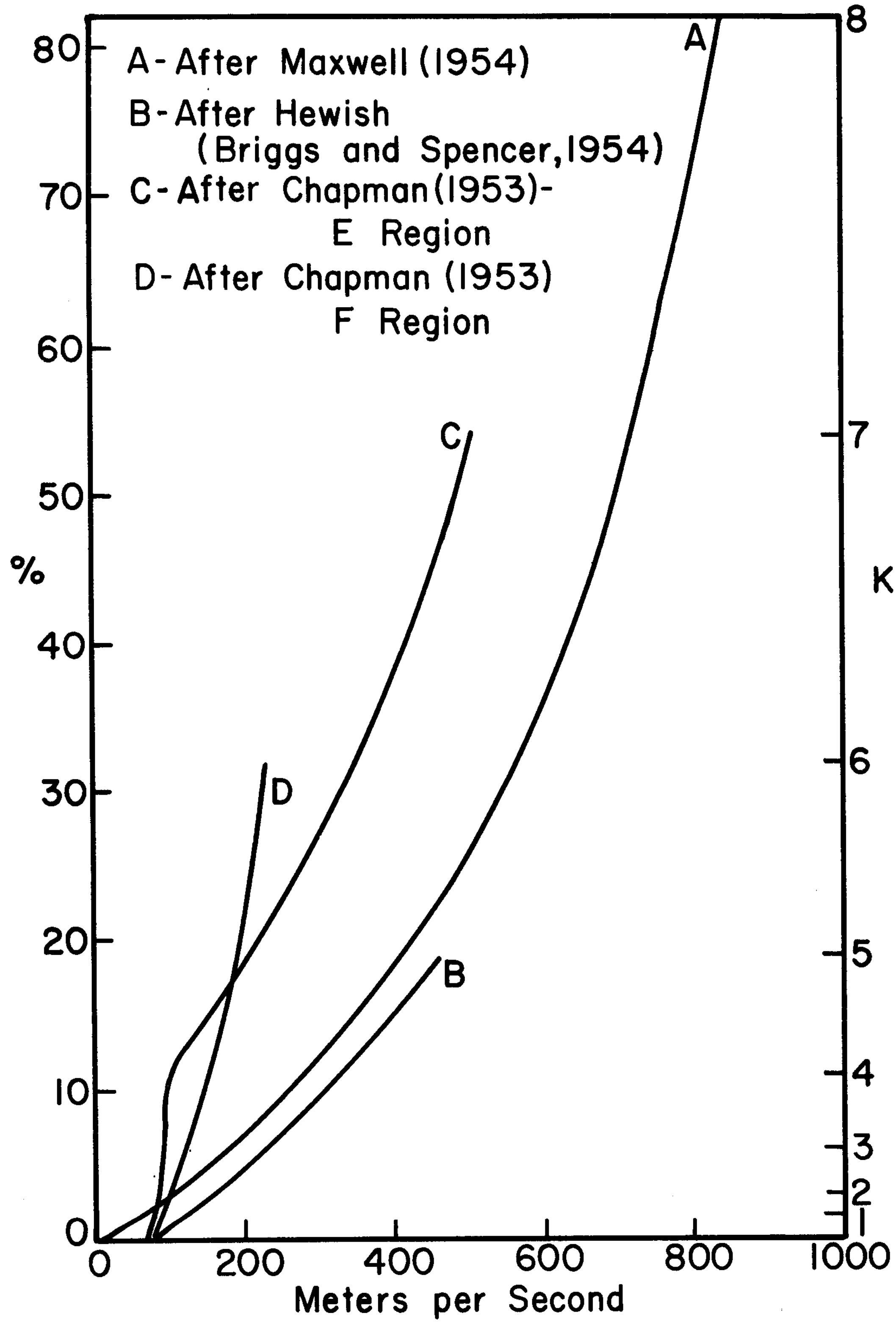

Figure 1. Percent of Disturbance Versus Speed ($\Delta\gamma$ For K9 = 100%)

less than four, the E-region speeds (curve C) seem to be independent of the magnetic disturbance, but for higher K-figures the shape of the E-region curve is very similar to that for the F region. The E-region curve gives one the impression that two mechanisms are involved and that, as the magnetic disturbance increases, the mechanism responsible for the increase in the currents predominates.

4. Winds and Electric Fields

The possible mechanisms responsible for the motions of charges in the ionosphere are winds and electric fields. These are not independent, for winds moving charges in the presence of the earth's magnetic field will generate electromotive forces. The probable motions of charges resulting from the wind systems and electric field in the ionosphere will be described in the remaining paragraphs of this chapter. The source of the additional electric field present during magnetic disturbances will be considered in Chapter III, where a discussion of the relationship of magnetic disturbances to the aurora will be found.

The relationship of ionospheric winds to electric currents in the ionosphere has been a subject of much interest since 1882, when B. Stewart suggested that the regular daily magnetic variations were due to electric currents in the upper atmosphere and that these currents were generated by conductors moving across the lines of magnetic force--the atmospheric dynamo theory. Over the years the dynamo theory has encountered quantitative difficulties. A major drawback was eliminated by the discovery that the tidal oscillations of the atmosphere at the ground were amplified by a large factor at ionospheric heights. The last obstacle has been removed by recent studies of the conductivity of the ionosphere [Baker and Martyn, 1952, 1953; Fejer, 1953] which show that the effective conductivity is increased by the polarization of the Hall current.

The so-called effective conductivity defines the flow of current in the direction of, and in terms of, the applied field. For an electric field applied perpendicularly to the earth's magnetic field, the conductivity is much reduced from that which applies when the electric field is parallel to the magnetic field. In the transverse case, however, an additional current may flow perpendicular to both the electric and magnetic field, namely the Hall current. If this current is inhibited from flowing, as it would be in the case of the ionosphere considered as a spherical sheet, the polarization built up would increase the effective conductivity.

On the basis of their detailed study of ionospheric conductivity, Baker and Martyn concluded that the dynamo theory is valid and that the region in which the currents flow is between 110-150 km in height. Their analysis also showed that, in the lower E region, ionization moves horizontally with substantially local wind velocity. In the upper E region, the horizontal motion of ionization may differ substantially in magnitude and direction from that of the local wind. In the F region ionization cannot be moved by winds transverse to the earth's magnetic field. There, high east-west drift velocities can be produced only by north-south electric fields communicated from elsewhere. These electric fields might originate in the E region by dynamo action and reach the F region along the highly conducting lines of magnetic force.

The conclusions of Baker and Martyn seem to fit the measurements previously described in this chapter. The various visual measurements of E-region winds gave results of similar magnitude to the E-region drift motions measured by radio means under magnetically quiet conditions. It appears very likely that for quiet conditions the E region radio measurements are actually measures of wind speed.

The continuous variation of the F-region speeds of drift motion with magnetic disturbances, even for very small disturbances, confirms the conclusion that the F-region motions are linked to the electric fields which drive the currents at lower heights.* In the E region, however, when the speeds measured are small, they refer to winds. The faster E-region drift motions are correlated with magnetic disturbances and undoubtedly are also associated with an increased electric field. It seems more than coincidental that during magnetic disturbances the E-and F-region drift motions have the same order of magnitude.

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* New evidence has very lately been presented by Dagg [1957], who showed that the F-region speeds measured by the drift of radio star scintillations are associated in detail with magnetic records taken at the same time. He also observed that on some occasions there was a close correlation between the scintillation amplitude and the magnetic variations.

Chapter II. Motions of Visible Auroral Forms

The fact that visible auroral forms move is well known to all auroral observers. There is considerable disagreement, however, both as to the actual character of these motions as well as to their proper interpretation. Perhaps the large-scale auroral photography program planned for the International Geophysical Year, 1957-58, will clarify some of the uncertainties. Meanwhile, as no summary of the data on auroral motions seems to exist in the published literature, we review the presently available information in this chapter.

There are of course motions associated with the development of an aurora. In many cases* the aurora first appears as a homogeneous arc which may be quiet for a time and then progress to the south. The arc may develop rayed forms and then break up into curtains and rays. Rapid motions and changes in the structure may be seen, followed by faint patches and pulsating forms. Finally the aurora may recede toward the north, leaving only a faint glow. One could describe these sometimes regular and sometimes random changes in the auroral structure as "motions." In general, however, the motions to be discussed here are not those associated with the movement of arcs or the creation of new forms, but those of particular features of the aurora, for example, the drift of a group of rays or of a bend in an arc. Even in these cases, it is not at all certain

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* Störmer [1955, p. 14] says, "During the 500 nights I have observed auroras in southern Norway, almost every big aurora was different from the others, with new fascinating colours and forms and only a few common characteristics." However, his description of the smaller auroras agrees with the summary given here.

that the apparent drift is in fact a mass motion. However, the use of the term "motion" leaves this question open.

The most general positive statement describing these motions was made by Meinel and Schulte [1953]. On the basis of wide-angle photographic sequence records taken at Yerkes Observatory during June 1952 they reported a general movement of auroral features that was westward in the evening and eastward in the morning. The drift speeds were maximum in the early evening, decreased to a minimum at local midnight, and increased again in the opposite direction in the early morning. The magnitude of the drifts varied between about 100 and 1,300 meters per second.

The simple picture of Meinel and Schulte was disputed by other experienced observers. [Meek 1954a], using similar equipment at Saskatoon, found that, for a five-month period (December 1953 - April 1954 inclusive), of 58 forms observed, 19 exhibited a definite easterly motion and 14 a definite westerly motion. The 14 cases of westerly motion all took place before 0200 local time. The remaining cases were scattered throughout the night. The estimated speeds of motion were about 200-500 meters per second.

On the basis of auroral movies taken at Ithaca, New York, since 1939 by Gartlein [Bless, Gartlein, and Kimball, 1955], it was found that, of 120 displays, 57 showed definite motion to the east or west. Of these 57 auroras, 45 showed a westward drift of rays, patches, and draperies and/or westward movement of bright patches and rays on arcs. Twenty-two displays showed similar motion to the east. In 8 displays a reversal of large-scale motion occurred between 2200 and 0200. Thirty-nine displays showed complex motions, mostly short periods of alternating east-west motion. The steady motions, when seen, were westward early in the night and eastward late in the night, but either or both ways in the middle of the night. Random motions occurred at any hour, and nearly always after arcs broke into rays. The authors concluded that the motions are not sharply controlled by local time.

In reply to the authors just cited, Meinel [1955] argued that the reversal from east-to-west drift to west-to-east drift during the night is not an exact relationship but a systematic one. He pointed out the similarity to the "reversal of ionospheric currents near midnight and noon during magnetic storms." These do not exhibit an abrupt reversal, and the local time of reversal varies from storm to storm; but the phenomenon as a whole does show a systematic reversal during the night.

A recent series of measurements of the directions of the motions of "180-degree bends" was made at College, Alaska [Geophysical Institute, 1955, pp. 34-37], using sequence photographs taken with an all-sky camera. The 180-degree bend is formed when an arc, either homogeneous or rayed, is bent through an angle of 180 degrees, forming two parallel arcs. Between January 1954 and April 1955, 105 of the 180-degree bends were found. Bends with open ends toward the west maximized at 2330 local time, while bends with open ends toward the east maximized at 0300 hours. Thirty of the bends were observed to move, 20 with westward drifts and 10 with eastward drifts. No systematic division of the westward and eastward drifts into evening and morning hours was found. The westward motions, however, were clustered around 2330.

Other descriptions of motions of auroras seem to be limited to specific instances rather than systematic variations, and of these only a few are based on actual measurements. Störmer [1955, pp. 119-122] described the motion of two cloudlike auroras.* One, on January 3, 1940, was observed from 1700 to 1940 local time. The drift velocity of a portion of the cloud was measured to be from 690 to 780 m/s in a westward direction. In another instance on March 25, 1933, between 0334 and 0408 the aurora moved in an easterly direction with a speed of the order of 200 m/s.

An early measurement using parallactic photographs [Krogness and Tönsberg, 1936] studied the movement of "auroral clouds" seen at Haldde Observatory. The height of the forms was determined to be between 106-110 km. Measurements were made on the night of March 8-9, 1915, from 2333 to 0105 local mean time. The speeds measured for different parts of the form varied between about 100 and 400 m/s. The direction of the drifts was mainly to the northeast. In geomagnetic coordinates the direction would have been quite close to geomagnetic east.

Other motions of visual aurora, observed at College, refer only to the directions of the motion. Fuller and Bramhall [1937] concluded that "the movement of rays generally, but not always, was easterly rather than westerly." Heppner [1954] made extensive visual observations which he correlated with magnetic records. He reported that the movements

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* Harang [1951, p. 49] pointed out that these "auroral clouds" are really faint diffuse or pulsating surfaces in which the "luminous particles often have a resemblance to clouds." In one case, he said, the auroral clouds were short draperies.

of discrete rayed forms during $-\Delta H$ disturbances, which generally occurred after midnight, were almost without exception from west to east. The movements during $+\Delta H$ disturbances (generally earlier in the evening) were uncertain because of insufficient data.

It is clear that the character of the motion of auroral forms has not been definitely established as yet. Most of the observations seem to fit into the general pattern of a westward drift in the early evening hours and an eastward drift in the early morning hours, but it is apparent that no rule for individual cases—if one exists—can be stated on the basis of evidence presently available.

Additional information of somewhat similar nature is available from the apparent motion of the forbidden oxygen radiation 5577 in the nightglow [Roach, Williams, and Pettit, 1952] observed at both Cactus Peak, California, and the Haute Provence Observatory on January 6-7, 1951, and November 19-20, 1952. The details of the motions were different on the two nights, but had the common features that before local midnight the apparent motion was east to west; at approximately midnight the motion stopped; after midnight there was a small component of motion from west to east and a large component southward. The maximum apparent speed was around 250 m/s.

Chapter III. High Latitude Electron Motions Inferred from Magnetic Storms

This chapter is concerned with the relationship between the auroras and the disturbances in the earth's magnetic field, caused by intense electrical currents in the ionosphere. The current systems that have been deduced by many workers from studies of the magnetic variations are described. Changes in the ionization of the lower ionosphere that accompany the magnetic storms are also considered. Finally, we compute the expected drift velocity of the electrons in the auroral ionization from estimates of the ionization density and the current density. The velocity computed agrees well with the velocities described in the previous chapter and with those found in our experiment.

The statistical agreement between the degree of magnetic disturbance and the intensity of auroral activity has long been known. More recently, detailed comparisons of magnetic and auroral variations have been made, and even more striking relationships have been found. Meek [1953, 1954] concluded that the maximum elevation of aurora above the northern horizon at Saskatoon was related closely to the magnetic variations. The absence of aurora always indicated the absence of magnetic disturbance (defined as a variation of greater than 200γ in the H component). The presence of aurora to the south of the zenith indicated large magnetic disturbances 95 per cent of the time. The aurora became brighter at the times of sharp deviation in the magnetic field.

Heppner [1954] showed that for auroral arcs the disturbing current was located approximately in the same space as the auroral light. The most striking feature in demonstrating this spatial coincidence was the change in sign of the vertical (ΔZ) component when an auroral arc at the southern edge of the aurora moved south across the zenith.

Heppner also found that the magnetic disturbances and simultaneous auroral activity could be represented by two patterns in which the changes in the horizontal (ΔH) component are correlated with changes in the auroral forms. In both patterns, the disturbances consist essentially of a positive bay—an increase in the horizontal component of the magnetic field lasting for several hours—followed by a negative bay—a similar decrease in H—with a short interval of $+\Delta H$ following the negative bay.

In the first pattern the transition from positive to negative bay occurs between 2300 and 0200 local time and is coincident with a transition of the aurora from quiet arcs and glow to rayed auroral forms that fluctuate greatly in intensity, shape, and location. The later $+\Delta H$ period, which may last for about half an hour, occurs at the same time that pulsating forms are observed. The second pattern occurs less frequently and differs in the manner in which the positive bay ends and the negative bay begins. The positive bay starts as in the first pattern but ends when the aurora recedes northward and disappears. The negative bay begins with the reappearance of auroral arcs, and ΔH continues to be negative when the arcs break into active rayed forms.

Both Meek and Heppner agreed that magnetic records on disturbed nights can be thought of as the resultant of a number of overlapping bays. On nights when the disturbance appeared to be exceedingly complex, Heppner was able to single out individual bays by recognizing the sequence of auroral forms. "The complexity is the consequence of the bays overlapping and the aurora simultaneously starting a new cycle of activity before the previous cycle is completed," he reported. Two other results of Heppner's study were as follows:

(i) The negative bays were usually of greater magnitude than the positive bays; and

(ii) The late evening discontinuity between the eastward and westward currents responsible for the positive and negative bays respectively took place first in the north and progressed southward. The transition in the auroral forms also started in the north and proceeded southward with the current discontinuity.

Heppner's observations provide a possible explanation for the simultaneous changes in the Doppler shift and the auroral form reported by Bowles (see Chapter I). If Bowles were receiving echoes only from east of north at the times in question, the shift in sign that he observed would then be consistent with the shift in the current directions observed by Heppner.

The close association of auroras with polar magnetic storms makes it desirable to examine the magnetic disturbances in more detail. Polar magnetic disturbances in general show very complicated variations of the geomagnetic field. Because of this complexity in the individual disturbances, many of the main studies of the worldwide morphology of the storms have been statistical. Such analyses have shown that the average disturbance field can be separated into two parts, one of which depends upon local time and the other of which depends upon the time measured from the worldwide commencement of the storm. In auroral regions the latter component is small compared to the one which depends upon local time [Chapman and Bartels, 1940, ch. IX]. Since for our purposes, however, we are chiefly interested in the character of individual storms, we shall not elaborate upon the statistical results.

A rather complete summary of the character of individual storms was presented by Fukushima [1953]. In his analysis Fukushima showed that the geomagnetic variations are composed of a number of elementary disturbances that take place intermittently or concurrently and last from several minutes to a few hours. These elementary disturbances can be linked with current systems which are similar to those responsible for magnetic bays. The similarity of Fukushima's conclusion, based on analyses of magnetograms taken by a worldwide chain of stations, to the statements of Meek and Heppner quoted above is obvious.

The average current system of a number of polar magnetic storms can be seen in Figure 2. The current system of Figure 2 has a number of characteristics that will prove important for later comparison with the records obtained in our experiment. For latitudes between 65 and 70 degrees, the current is eastward until about 2100 local time, becoming westward after 2200. For stations at these latitudes, therefore, a positive bay would be expected before 2100, a negative bay after 2200. Since the westward currents are more intense than the eastward ones, the negative bay would be the stronger

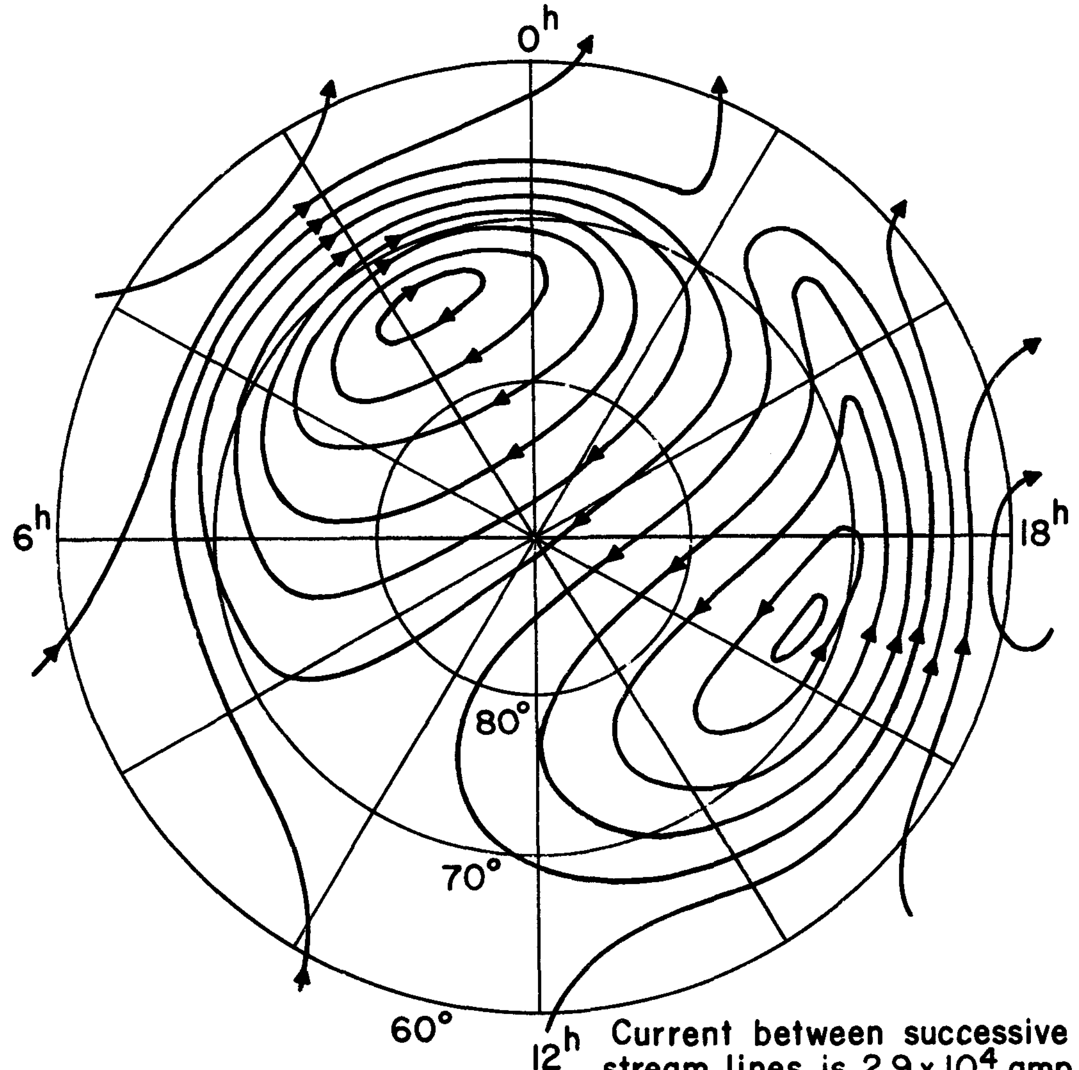

Figure 2. Mean Equivalent Current System for Polar Magnetic Storms During Second Polar Year (After T. Nagata)

one.

Silsbee and Vestine [1942] also noted in their fundamental study of the current systems of geomagnetic bays that the westward currents flowing along the auroral zone were much more intense than the eastward currents. In their average current system the ratio of intensities was considerably greater than that shown in Figure 2. The same is true for the elementary disturbances described by Fukushima.

The intense auroral zone current of individual elementary disturbances of polar magnetic storms generally is more localized than the average storm of Figure 2. The average storm is made up of a number of localized storms that take place around the auroral zone with their maximum number occurring around local midnight. Fukushima showed that the elementary disturbances can be represented by the current systems of electric doublets situated on the auroral zone. He gave additional quantitative arguments indicating that this doublet could be produced by a local increase in the ionization density, and therefore in the conductivity. The wind system, acting upon this region of increased conductivity, would produce an increased electric field by dynamo action. The observed total auroral zone current of between 5×10^5 and 8×10^5 amps could be produced by increases in conductivity of 10 to 100 over regions whose extent is of the order of 200 km in latitude and 600 to 1,000 km along the auroral zone. Such a zone of increased conductivity is not fixed, even for single storms. Nagata [1950], for example, computed the southward progression of the auroral zone currents as a magnetic storm became more intense.

The increases in ionization associated with magnetic disturbances have also been proved by measurements of increased absorption of radio waves and by observation of E_s echoes on ionospheric sounders. Wells [1947] found that at College high absorption of radio waves was coincident with each of 69 significant magnetic bays examined for the period January to September, 1942. The radio absorption was limited to the duration of the magnetic bay. More recent absorption measurements using extraterrestrial radiation at 30 Mc/s will be considered in Chapter V. From measurements using such techniques, it has lately been suggested that the zone of anomalous absorption coincides in latitudinal extent with the zone of maximum auroral occurrence [Leinbach and Little, 1957].

The increase of E_s ionization at College was examined by Heppner, Byrne, and Belon [1952], who concluded that in the presence of nonpulsating forms the E_s echoes varied in height and intensity in a manner similar to the changes in luminosity. From no aurora, to homogeneous arcs, to rayed bands, the maximum frequency of E_s reflections changes approximately from 3, to 6, to 9 Mc/s. Absorption was shown to be closely related to the forms with the minimum height of mean luminosity, namely, the pulsating forms.

On the basis of the close association of the visual, magnetic, and radio observations, the conclusion seems inescapable that the visual luminosity takes place in a region of increased ionization and increased currents. The intensity of the currents is directly related to the intensity of the aurora. Even the changes in the auroral forms correspond to changes in the current directions. The magnitude of the current density J (neglecting the motion of ions) is given by

$$J = N e v \quad , \tag{3.1}$$

where N is the electron density, v is the speed of the electrons, and e is the electron charge.

In Chapter I we demonstrated that the current intensity increases as approximately the square of the electron drift speeds.* The increased current density during auroras is therefore caused by increases in v as well as N. On the basis of arguments which will be presented in Chapter V, a probable value for N is about 3×10^5 per cm^3, corresponding to a plasma wavelength of about 60 m. The current density J can be estimated from the current systems derived from magnetic observations and an assumed height range. The measured auroral zone current intensities are of the order of 5×10^5 amps in a five-degree range of latitude, or about 10^5 amps per 100 km. From the conductivity arguments of Baker and Martyn [1953] previously cited, we assume a height range of 30 km. From these assumptions we conclude

$$v = 700 \text{ m/s} \quad . \tag{3.2}$$

The direction of the electron velocities is, of course, in the direction opposite to that of the currents, i. e., the electrons drift to the west in the evening and to the east in the morning. The value computed in Equation (3.2) is obviously not constant and depends upon the intensity of the current and on the ionization

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* Heppner [1954] stated, "From photometric measurements at College, Alaska, the writer thinks the relationship

$$\text{Brightness} \propto N^2$$

roughly expresses this (E_s electron density to light intensity, B. N.) correspondence."

density. It agrees well, however, with the speeds found in radio measurements during magnetic disturbances as described in Chapter I. In Chapter VI it will be shown that it also agrees well with the speeds measured in our experiment.

Chapter IV. Outline of Our Experiment and Sample Data

The basic technique used in this experiment was the measurement of the frequency spectrum of radio waves received at College, Alaska (geographic co-ordinates 147.8° W, 64.9° N; geomagnetic co-ordinates 256.5° E, 64.7° N), from a single frequency (CW) transmitter. A direct groundwave signal at the transmitted frequency was always received. Since echoes from auroral ionization are spread in frequency and generally show a mean shift with respect to the transmitted frequency, these frequency shifts may be used to measure the motions of the echoing sources. By observing simultaneously in two directions, the approximate speeds and directions of motions may be deduced. The magnitude of the echo power may also be measured.

The following discussion of the experimental procedure includes descriptions of the transmitter, the antennas, the receivers, the recorder, and the method of analysis. Samples of the data obtained are presented, and the interpretation of the records is discussed. A brief description of a special auxiliary experiment using interferometric techniques is also included.

1. The Equipment

Previous radar experiments at College (described in the next chapter) have shown that VHF auroral echoes are received from a broad sector centered about 700 kilometers geomagnetically north of College. Almost all the echoes arrive from azimuths less than 45 degrees from the geomagnetic meridian and at angles of elevation less than 12 degrees. Since in our case CW transmission was being used, it was necessary to separate the transmitter and receiver and to orient the transmitting antenna to send only a very weak signal toward the receiver. The above requirements led to the choice of locations shown on the map in Figure 3. A simple folded half-wave horizontal dipole was used as the transmitting antenna to provide almost uniform illuminations over the desired azimuth angles and little radiation toward College. The transmitter site and the transmitting antennas are shown in Figure 4.

The transmitter, a Wilcox 99C (seen in Figure 5), permitted simultaneous CW crystal controlled operation at the two frequencies used, 106.0 Mc/s and 41.15 Mc/s. Delay in securing a licence from the Federal Communications Commission restricted operation at 41.15 Mc/s to the period starting March 19, 1957. The transmitter was unattended and, except for a few breakdowns and regular half-hourly code identifications, transmitted continuously. As manufactured, the 99C is designed for the frequency ranges 2-20 Mc/s (RF head) and 108-132 Mc/s (VHF head). No difficulty was encountered in tuning the VHF head to 106 Mc/s. The RF head had to be modified for operation at 41.15 Mc/s, the major change being a conversion of the final power amplifier to frequency-doubler operation and 52-ohm coaxial output.

The impedances of the transmitting dipoles and associated half-wave baluns were carefully adjusted to match the 52-ohm RG 8/U coaxial cable used as transmission lines. The power outputs of the transmitter were measured with an M. C. Jones 251N1 RF Power and VSWR Meter. At 106 Mc/s the power into the transmission line was

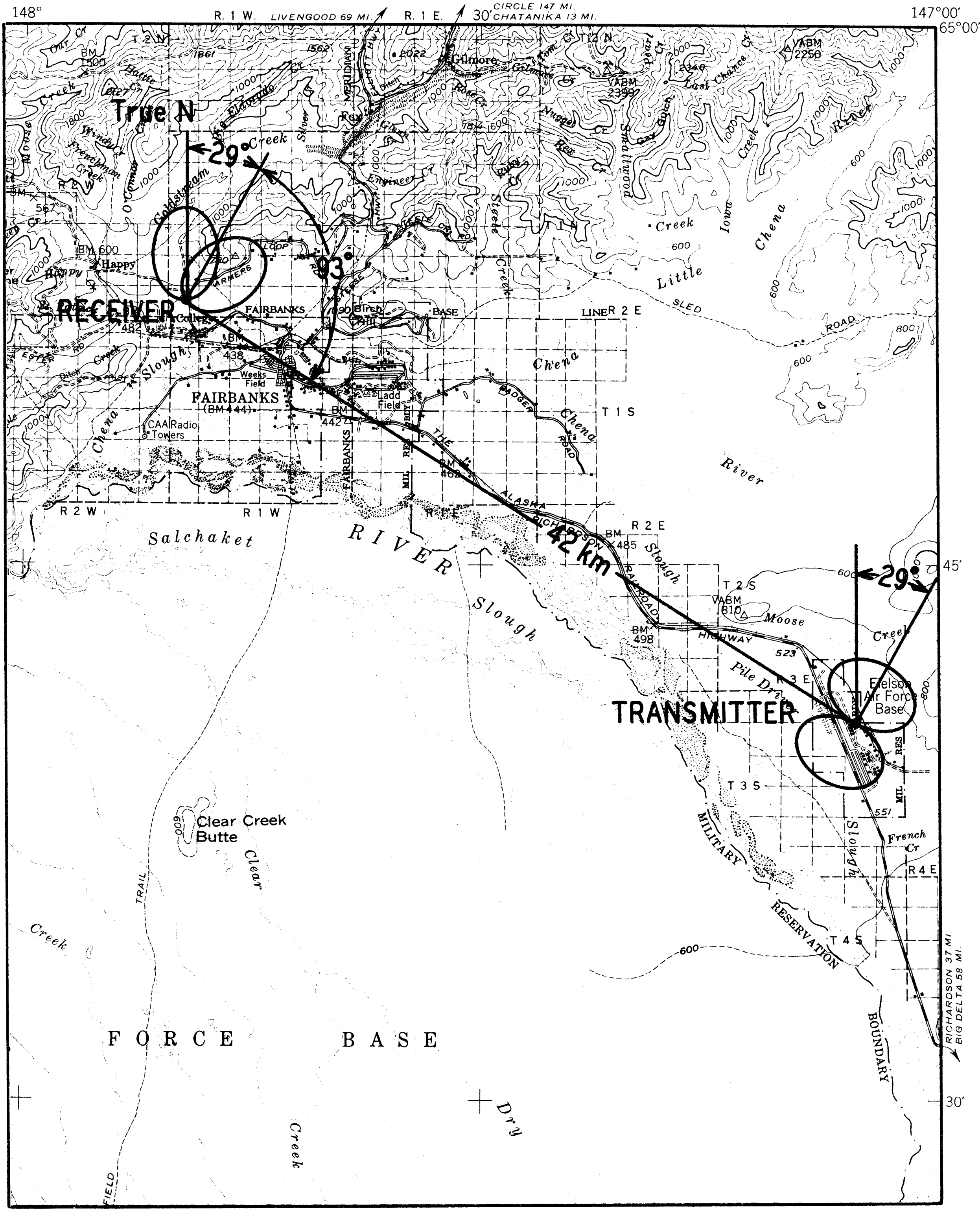


Figure 3. Antenna Locations and Orientations

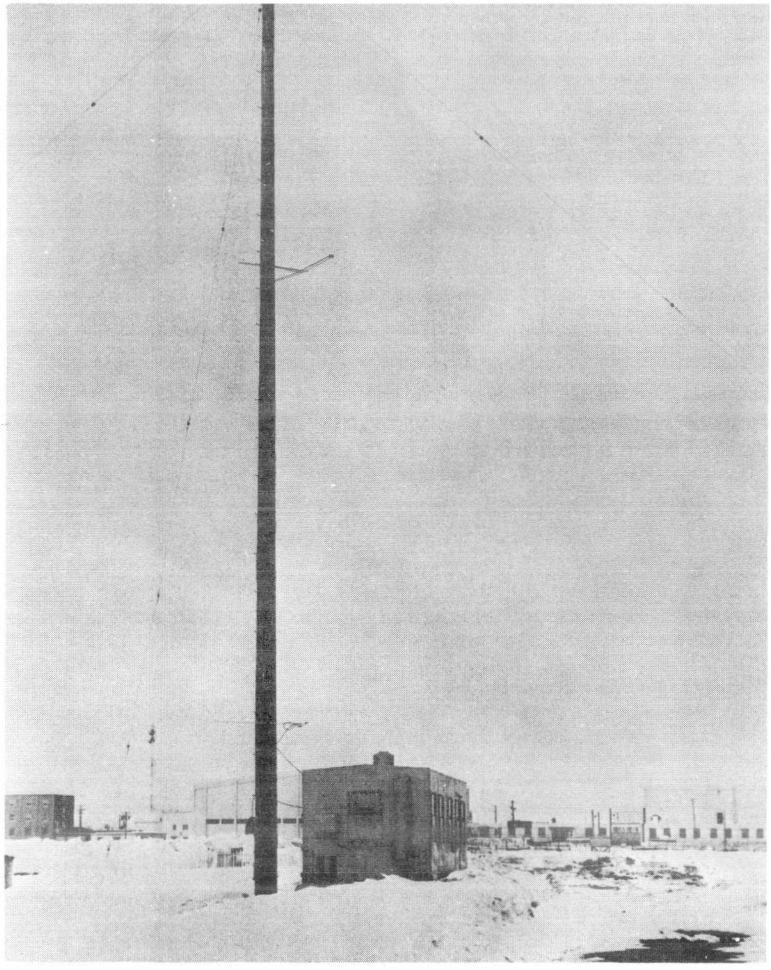


Figure 4. Transmitter Site and Antennas

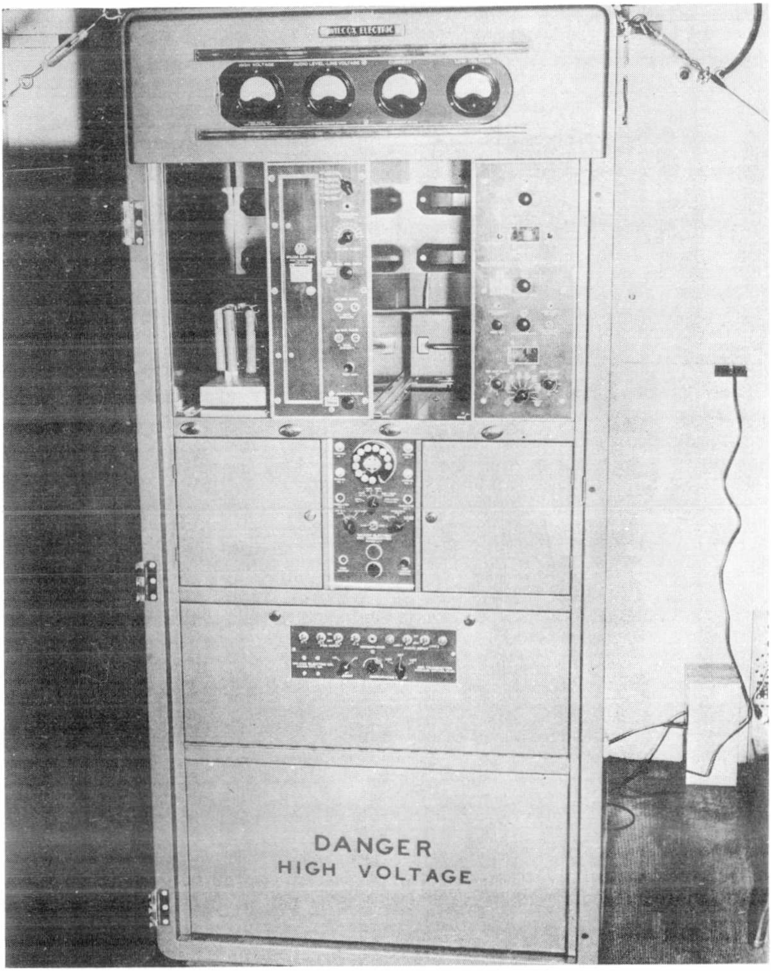


Figure 5. The Transmitter

300 watts; the reflected power was 1.5 watts. The corresponding figures at 41.15 Mc/s were 92 watts and 1.0 watts. The transmission line attenuations at 106 Mc/s and 41.15 Mc/s were estimated to be 0.7 and 1.0 decibel respectively, resulting in antenna input powers of 255 and 72 watts. Although the transmitter was unattended, the power outputs appeared to remain almost constant for periods of several weeks. The above figures can be regarded as accurate to within 10 per cent.

The arrangement of the receiving antennas was based on the fact that the frequency shift is determined only by the radial component of the motion of the echoing source. Ideally the true velocity should be found by restricting the observations to a small area of the sky. The impractability of such a technique at meter wavelengths and the initial uncertainty as to the character of the motions led to the use of a simpler, but cruder, method. Assuming that the mean motions in the aurora are roughly the same throughout its volume, an examination of the frequency shifts of echoes arriving from east and west of geomagnetic north will discriminate among various directions of motion. Components of the motion symmetrical with respect to the meridian, i. e., motions along the geomagnetic lines of force or in the north-south direction, will have identical radial components. East-west components, on the other hand, will have radial components which are opposite in sign. It was decided to look first for this possible assymmetry.

The examination of the frequency shifts of echoes from different azimuths could presumably be performed with a rotating antenna. This method was used for a short time at 106 Mc/s. However, the rapidly changing character of auroras and the desire for simultaneous observations in different directions led to the use of fixed antennas with main beams directed east and west of north respectively. At 106 Mc/s the fixed and the rotating antennas were 7-element Yagis with folded dipole driven elements and a half-wave balun to the RG 8/U coaxial transmission line. At 41.15 Mc/s a similar system of fixed antennas was used, except that the Yagis had only four elements. The azimuth polar diagrams were measured using the direct signal from the transmitter and are shown in Figures 6 and 7.

The elevation polar diagrams of the antennas at low angles of elevation were determined chiefly by the interference pattern produced by ground reflection since the free-space vertical beamwidths were greater than 60 degrees. For horizontal polarization at the frequencies used, the ground reflection coefficient can be taken as -1. Thus the power gain at an elevation angle θ for an antenna at height h above ground is

$$4 \sin^2 \left(\frac{2\pi h}{\lambda} \sin \theta \right) . \qquad (4.1)$$

At 106 Mc/s the transmitting and receiving antennas were located at 1.5 and 2 wavelengths above ground respectively. At 41.15 Mc/s the transmitting and receiving antennas were 2 and 1.5 wavelengths above ground respectively. The products of the power gains of the transmitting and receiving antennas were therefore the same for each frequency and are given by

$$16 \left[\sin^2 (3\pi \sin \theta) \right] \left[\sin^2 (4\pi \sin \theta) \right] . \qquad (4.2)$$

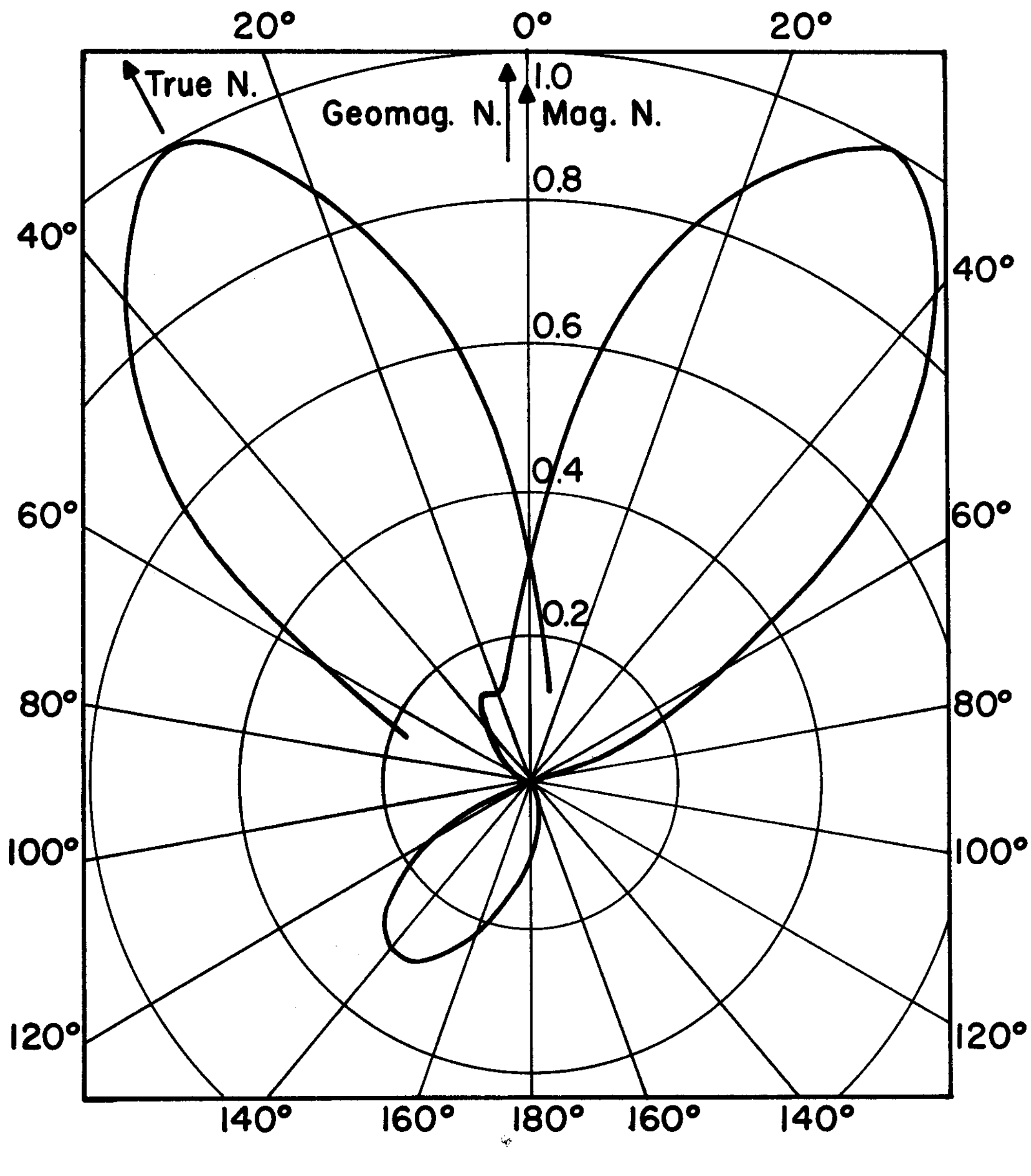


Figure 6. 106 Mc/s Receiving Antennas Measured

Azimuth Power Polar Diagrams

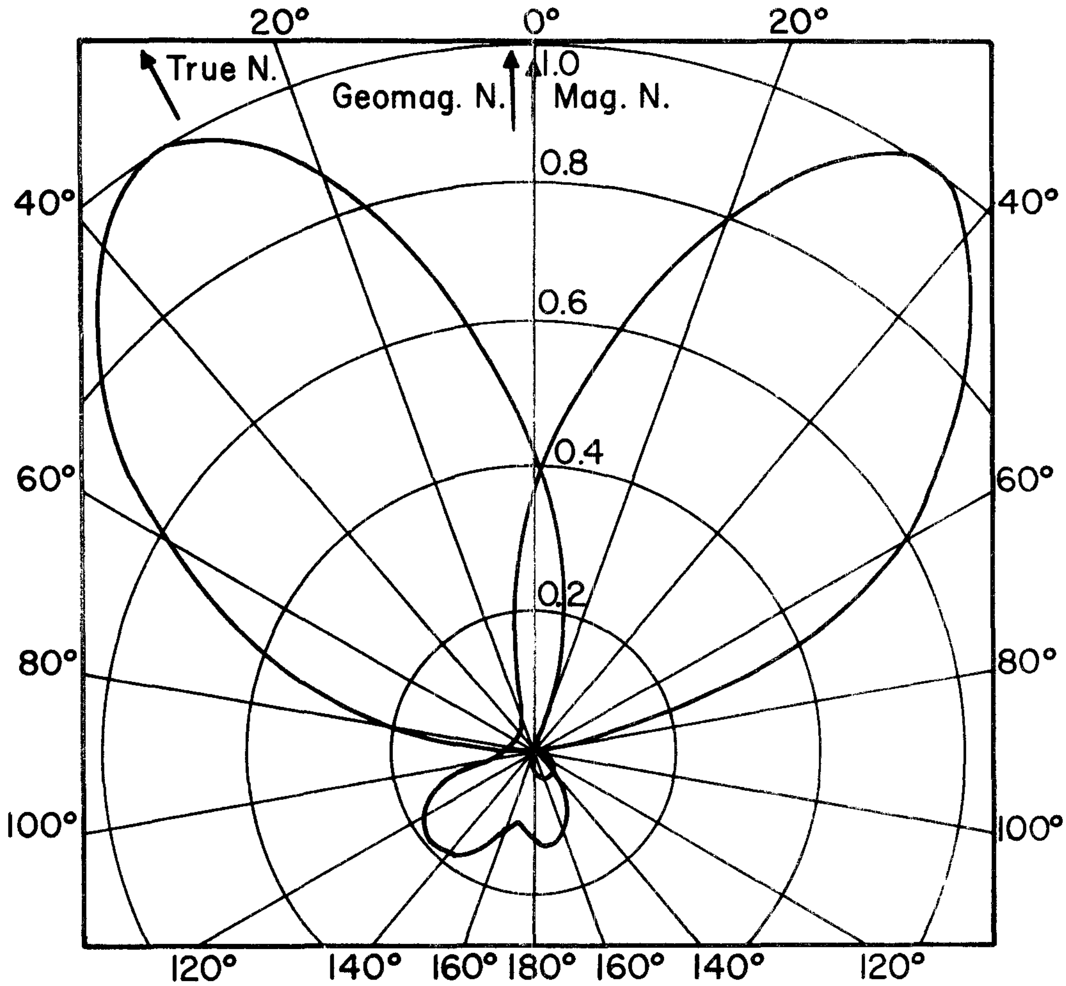


Figure 7. 41.15 Mc/s Receiving Antennas Measured Azimuth

Power Polar Diagrams

Equation (4.2) is plotted in Figure 8. The receiving site and the receiving antennas can be seen in Figure 9. The physical arrangement of the receiving, recording, and analyzing equipment can be seen in Figure 10. A block diagram of the system is shown in Figure 11. The pre-amplifiers used two stages of RF amplification with cascode input circuits and had measured input impedances, as installed, of 52 ± 1 ohm at phase angles of 0 ± 3 degrees. The noise figures were measured to be 7 db for the 106 Mc/s pre-amplifiers and less than 3 db for the 41 Mc/s pre-amplifiers. The local oscillators were crystal controlled.

The Collins 51J-4 receivers were found to be particularly suitable for this experiment. The 3 kc/s mechanical filters in their IF stages resulted in an extremely uniform response over the desired frequency range. Their frequency stability was better than that of the transmitter, permitting operation over long periods of time without retuning. The beat frequency oscillators were adjusted to operate on the high frequency side of the 3 kc/s passband, with the direct signal producing a tone of about 1,200 cps. The sketch on page 45 illustrates the amplitude frequency diagram for an assumed echo. The audio frequency spectrum is clearly the mirror image of the RF spectrum. The beat frequency oscillators might equally well—or perhaps better—have been adjusted to operate on the low frequency side of the passband. The sketch presented on page 45, however, shows the actual situation as checked on both receivers using the Measurements Corporation Model 80 signal generator.

The audio frequency outputs of the Collins receivers were recorded simultaneously on the two outside channels (thus avoiding

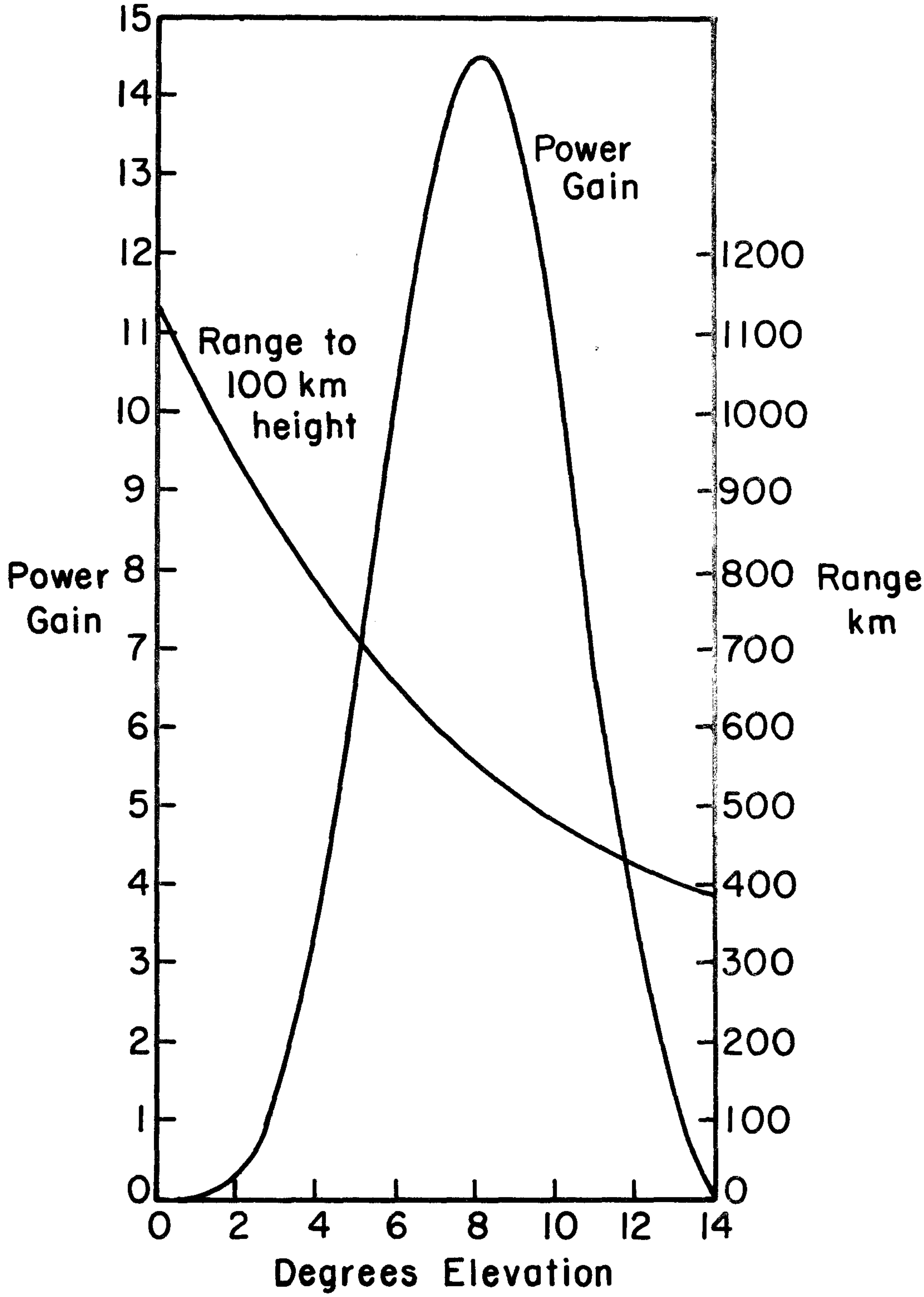


Figure 8. Elevation Power Gain (transmitter + receiver).

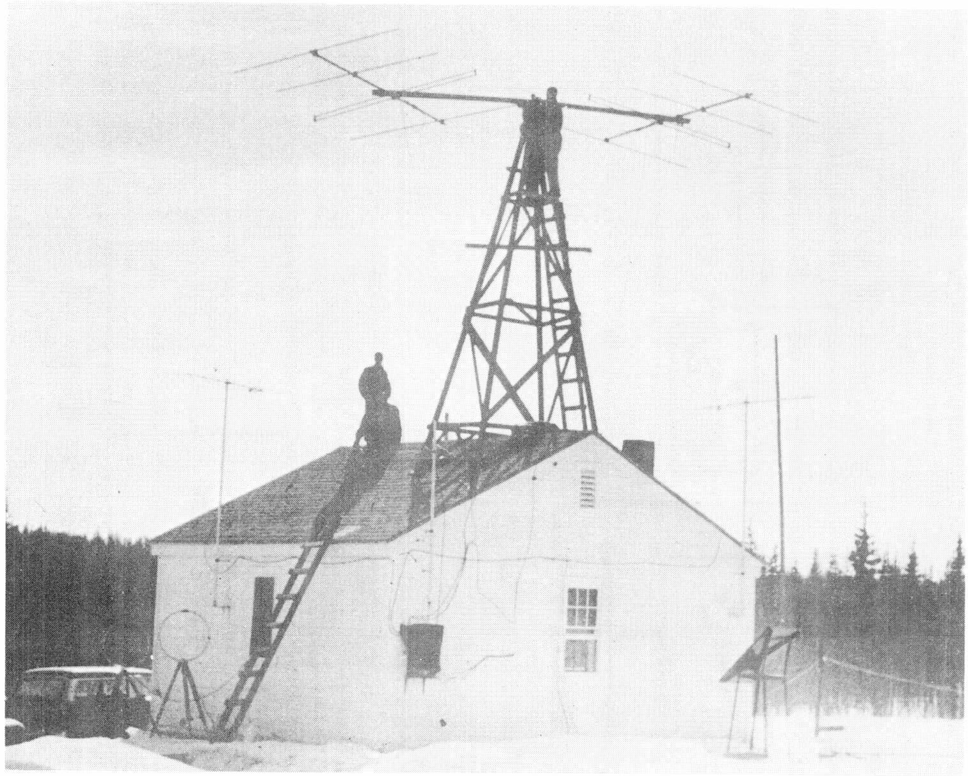


Figure 9. Receiving Site and Antennas

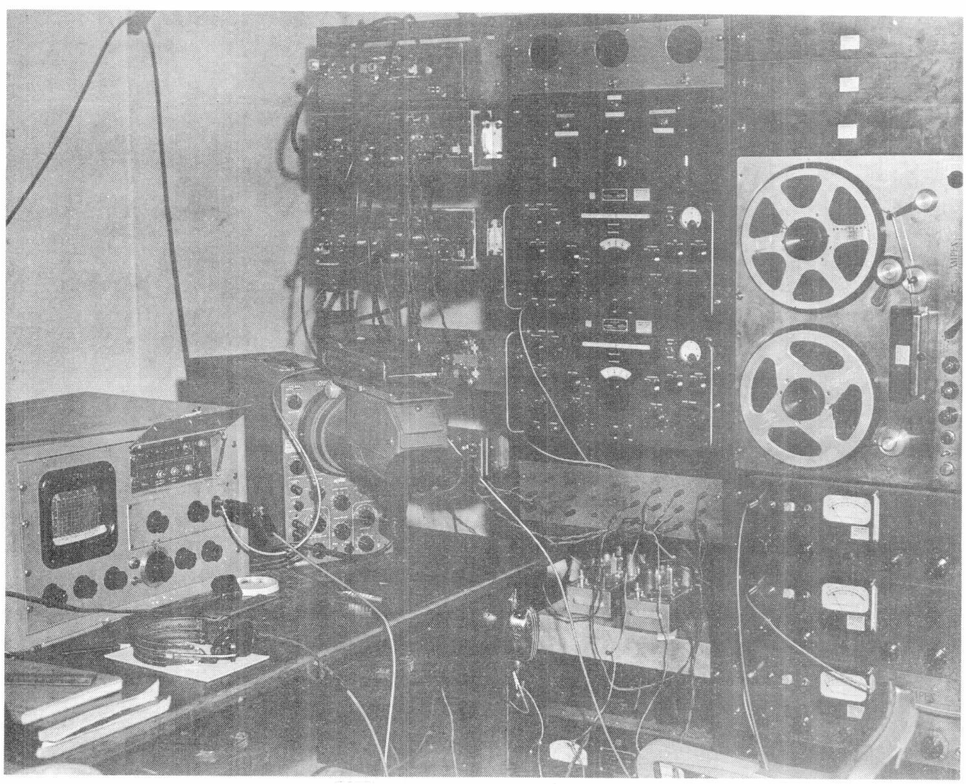


Figure 10. Receiving, Recording, and Analyzing Equipment

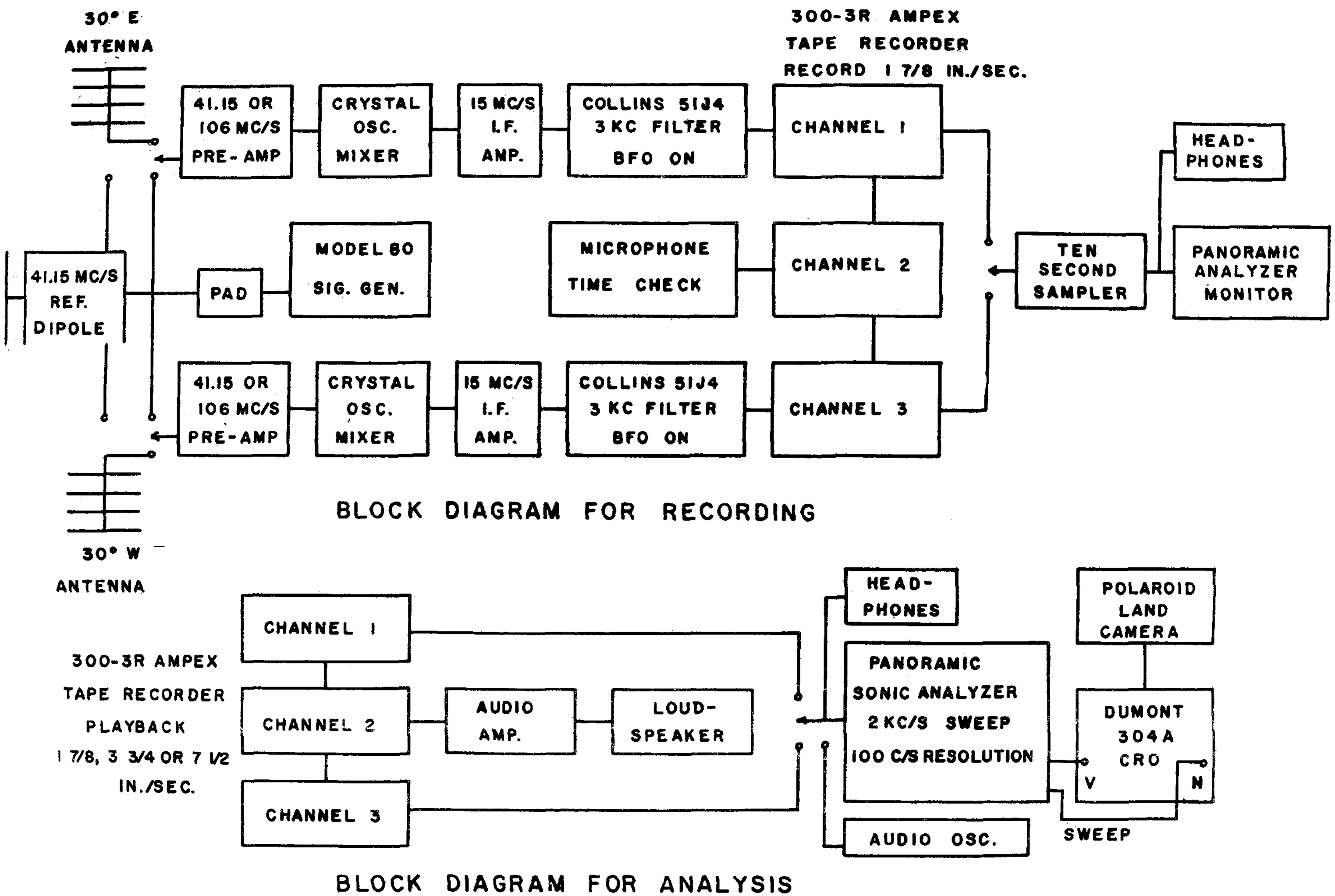
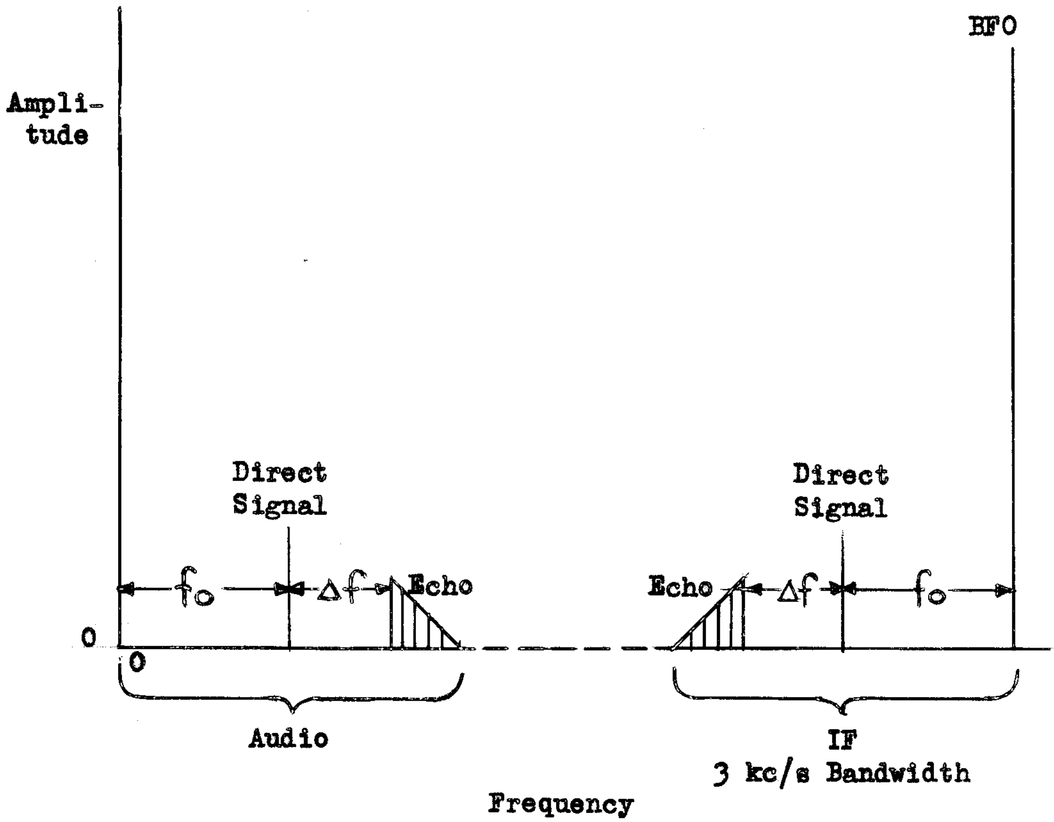


Figure 11. Block Diagrams



Amplitude Frequency Diagram for an Assumed Echo

cross-talk) of a three-channel, three-speed Ampex tape recorder. Recording was always done at the lowest speed, 1 7/8 in/s, to allow for frequency expansion in playback and to provide the longest possible unattended recording time. At that speed, 6 1/3 hours of record can be put on a 10 1/2 inch reel of Scotch # 190 magnetic tape. The middle channel was used for simultaneous voice recordings of time and other information.

Although some of the records were taken with the equipment unattended, in most cases the writer was present. It was possible to monitor the record visually on the same Panoramic Sonic Analyzer which was later used for the analyses. Each receiver channel was alternately sampled for ten seconds. By listening to the receiver outputs on headphones, it was possible to detect occasions when ignition or powerline noise was present.

The over-all response of the equipment was checked periodically with the Model 80 signal generator. The input voltage on each channel was measured by adjusting the signal generator output to produce the same deflection on the Panoramic analyzer as was produced by the direct signal. The linearity of the response was also checked.

At 106 Mc/s it was always possible to see the direct signal as a frequency reference. However, during strong auroral echo conditions, this reference was sometimes obscured on 41.15 Mc/s. A dipole aligned with its maximum gain toward the transmitter was therefore installed, and during strong signal occasions the dipole was substituted briefly for the Yagi antennas. Using the reference dipole, the ratio of the direct signal to the auroral signal was always very large.

On most of the nights when records were taken, a 41 Mc/s auroral radar was being operated at the Geophysical Institute by R. S. Leonard. The A-scope video output of the radar was brought to the field site over telephone lines and presented on an auxiliary oscilloscope. During the nights when both the 41.15 Mc/s CW transmitter and the 41 Mc/s radar were in operation, the radar was turned on and off at 30-second intervals.

The method of analyzing the tape recordings is illustrated in the block diagram of Figure 11. Each channel was examined separately on the Panoramic analyzer. The output of the analyzer was displayed on an oscilloscope, and pictures of the oscilloscope screen were taken with a Polaroid Land camera. The sweep of the analyzer was generally adjusted to bring the direct signal to the middle of the oscilloscope screen. The frequency scale was calibrated with a General Radio 1304-A audio oscillator.

The output of the middle channel of the tape recorder was fed into an audio amplifier and loudspeaker. After photographic records were taken of one of the outside channels, the tape was re-wound, and records were taken of the other outside channel at the identical times as determined from the (voice) time references.

The analyzer sweeps through a 2 kc/s range in one second and has a resolution of about 50 cps. This resolution could be effectively increased by doubling or quadrupling the playback tape speed. The sweep range is of course proportionally reduced. In most cases the pictures taken were exposed for ten seconds.

2. Sample Data and Interpretation

In this section examples of the records obtained are presented in Figures 12-16 inclusive, and their interpretation is discussed. The methods used in determining the directions and speed of the motion of auroral ionization are described and justified. Records of auroral echoes of the type shown in this section were used in the analyses of the strengths of the echoes (see Chapter V) and the velocities of the drift motions (see Chapter VI).

The response of the analyzer to an audio frequency signal generator is shown in Figure 12a. The horizontal sweep was adjusted so that the separation between the thin vertical scale lines was 100 cps (500 cps between the heavy vertical scale lines). The analyzer bandwidth appeared to be about 50 cps. For evaluation of the subsequent records, the width of the line traced by the cathode ray beam should be noted. In some of the records the noise level barely increases this width.

Successive records of an airplane echo are shown in Figure 12b. In this case the playback speed was twice the speed used in recording. Since each picture was exposed for ten seconds, each represents 20 seconds of record, and the frequency scale is expanded by a factor of two. In addition, the sweep was expanded so that the separation between the thin vertical scale lines for an audio frequency source was 70 cps. Thus the effective separation between the thin vertical lines is 35 cps (175 cps between the heavy vertical lines). For all records shown, the "scale" refers to the effective frequency separation of the thin vertical scale lines. In Figures 12b-16 the vertical trace in the center of the frequency spectra is the transmitted frequency.

The frequency shift (Δf) of the airplane echo is a Doppler shift produced by the changing path length from transmitter to receiver and can be computed in the following manner. For a sinusoidal source $e_t = A \cos (\omega t + \phi)$, the returned echo from an object at a distance R_t from the transmitter and R_r from the receiver will have the form

$$e_r = A' \cos \left(\omega t - \frac{2\pi \left(R_r + R_t\right)}{\lambda} + \phi' \right) \quad . \qquad (4.3)$$

Letting $t = 0$ when $R_r + R_t = R_o$, and assuming that the airplane is moving with a constant velocity whose component producing a decrease in $R_r + R_t$ is v_r, then

$$e_r = A' \cos\left\{\left(\omega + \frac{4\pi v_r}{\lambda}\right) t - \frac{2\pi R_o}{\lambda} + \phi'\right\} \quad . \qquad (4.4)$$

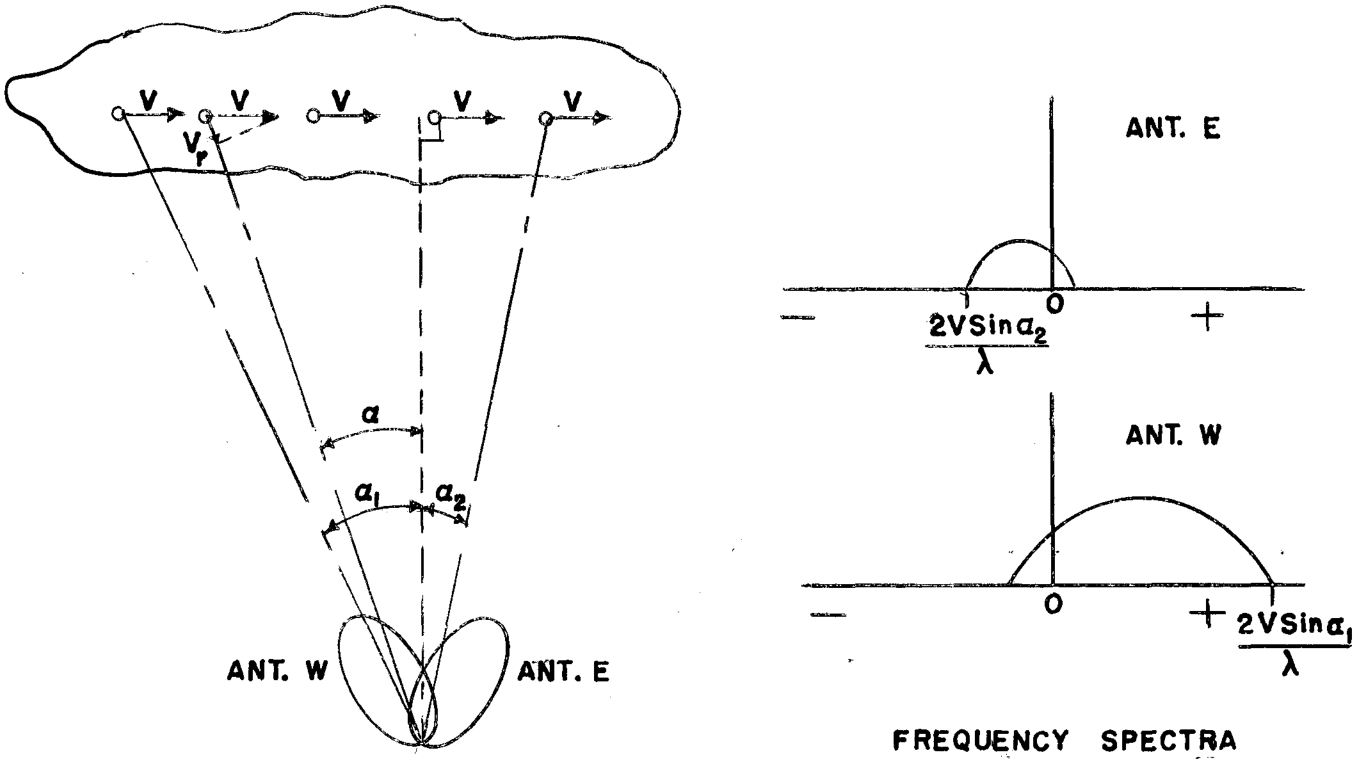
The Doppler shift in frequency Δf is thus given by

$$\Delta f = 2\,\frac{v_r}{\lambda} \quad . \qquad (4.5)$$

If the transmitter and receiver are at the same point, v_r is simply the inward radial component of the motion. The effect of the separation of the transmitter and receiver in our case will be considered in the next section of this chapter, and the error made in considering them both to be at the same point will be shown to be very small insofar as it affects our results.

Figure 12b shows that for a single echoing source, the airplane, Δf has a single value, which in this case remains almost constant for periods of 20 seconds. For an auroral echo, however, there are many echoing sources, and if these have different values of v_r, a spread in values of Δf is obtained. For broad beam antennas the spread of Δf does not necessarily imply a spread in values of the actual speeds or directions of motion. As illustrated in the sketch on the following page, $v_r = v \sin\alpha$. Assuming equal echo power from each echo source, the frequency spread will be determined by the spread in $\sin\alpha$ and the polar diagram of the receiving antenna.

Auroral echoes are shown in Figures 12c-16. The rapidly changing character of auroral echoes can be seen in Figure 12c, which shows successive records taken on the 30° E antenna. No echoes were seen on the 30° W antenna at the time. The echo, after being strong



Effect of Antenna Beams on Frequency Spectra

at 2037, had disappeared by 2041, but then was strong again at 2042. It will be recalled that the frequency spectra recorded are mirror images of the true spectra, so that the frequency shifts in Figure 12c are actually positive, indicating inward radial components of velocity. The radial velocities can be found by inverting Equation (4.5). Then

$$
\begin{aligned}
v_r &= \lambda/2\,\Delta f \\
&= 1.42\,\Delta f \quad \text{m/s} \quad \text{for 106 Mc/s} \qquad (4.6)\\
&= 3.65\,\Delta f \quad \text{m/s} \quad \text{for 41.15 Mc/s} \quad .
\end{aligned}
$$

The maximum value of Δf at 2037 is about + 800 cps; the

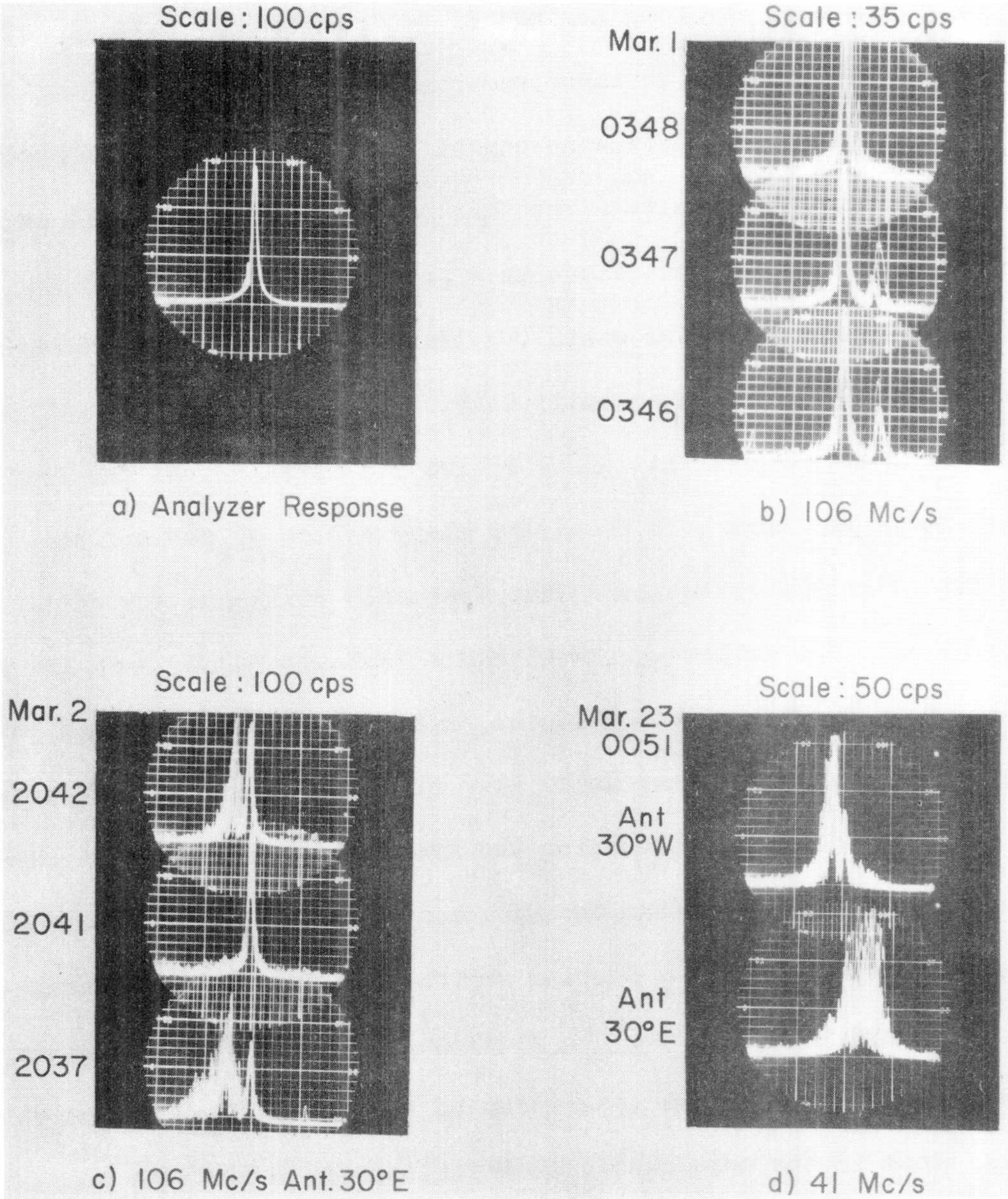


Figure 12. Sample Frequency Spectra

a) Response of analyzer to audio oscillator.
b) Successive spectra of airplane echo.
c) Successive spectra of auroral echo showing rapid variations in intensity.
d) Spectra of simultaneous auroral echoes on east and west antennas.

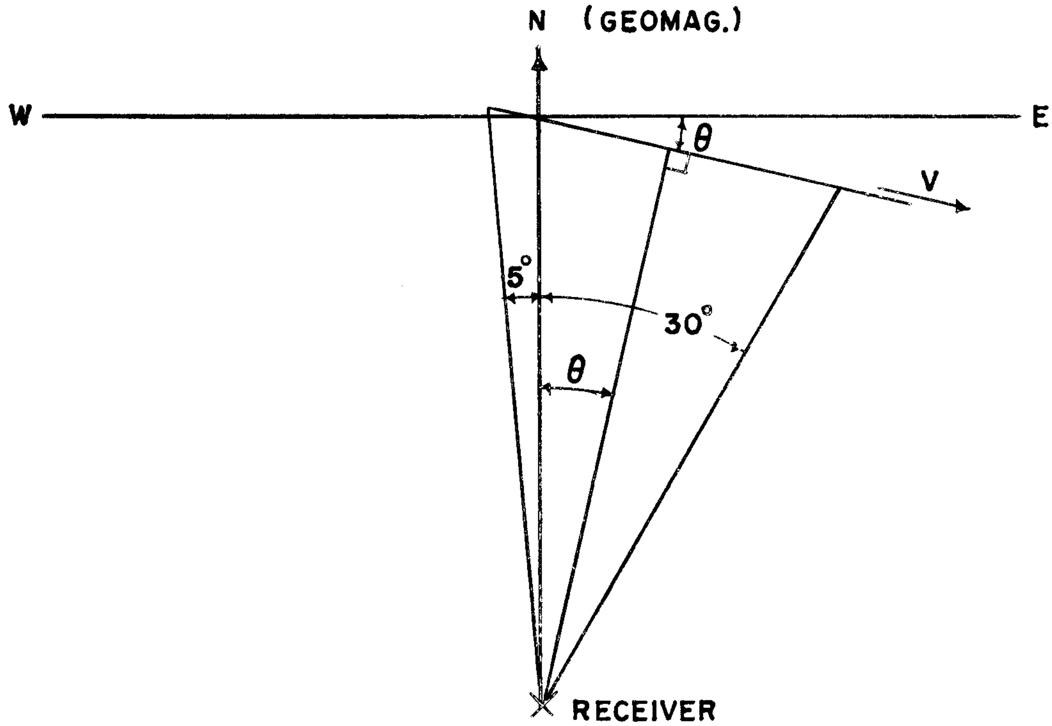
maximum value of v_r is therefore 1,140 m/s. The maximum speed must be greater than 1,140 m/s by a factor depending upon the direction of motion.

The most striking feature of the records taken is illustrated in Figures 12d and 13. In those records it is quite clear that, for the times involved, simultaneous echoes from east and west of geomagnetic north showed opposite directions of frequency shift. It is reasonable to suppose that there is a general drift motion of the echoing sources toward the east. On the night in question, March 22-23, 1957, this motion continued until 0145.

A closer examination of Figure 12d reveals that the drift motion could not have been precisely along a line of geomagnetic latitude since the echoes near zero frequency shift are not antisymmetrical. The following sketch and calculation illustrate how a general motion over a limited region, making a small angle with respect to the latitude line, would give rise to records of this type.

The accuracy with which the frequency spectra can be read and the obviously oversimplified assumption that the velocity is exactly the same everywhere in the echoing region make any precise measurements of v and θ impossible. In addition, an accurate calculation would have to consider the separation of the transmitter and receiver, as explained in the next section. Nevertheless, the values of v and θ can be estimated in the following way.

For the sketch shown on the following page, the effect of the antenna beams will maximize the amplitude of the frequency shift components received on the 30° E antenna and the 30° W antenna at azimuth angles of 30° E and 5° W respectively. (The value of 5° was



Probable Condition for Record of Figure 12d

chosen to fit the shapes of the frequency spectra.) The radial components of the velocity at 30° E and 5° W, found by using Equation (4.6) are therefore about -450 m/s and +225 m/s respectively. Thus

$$\begin{aligned} v \sin(\theta + 5^\circ) &= 220 \\ v \sin(30^\circ - \theta) &= 450 \quad . \end{aligned} \qquad (4.7)$$

Solving Equation (4.7) simultaneously gives values of about 1,120 m/s and 6.5° for v and θ. As previously stated, no claim is made for the accuracy of these figures. However, many of the records taken show characteristics similar to those of Figure 12d, and it is well known that visual auroral arcs are tilted with respect to lines of magnetic latitude by angles of the order of 10 degrees [Harang,

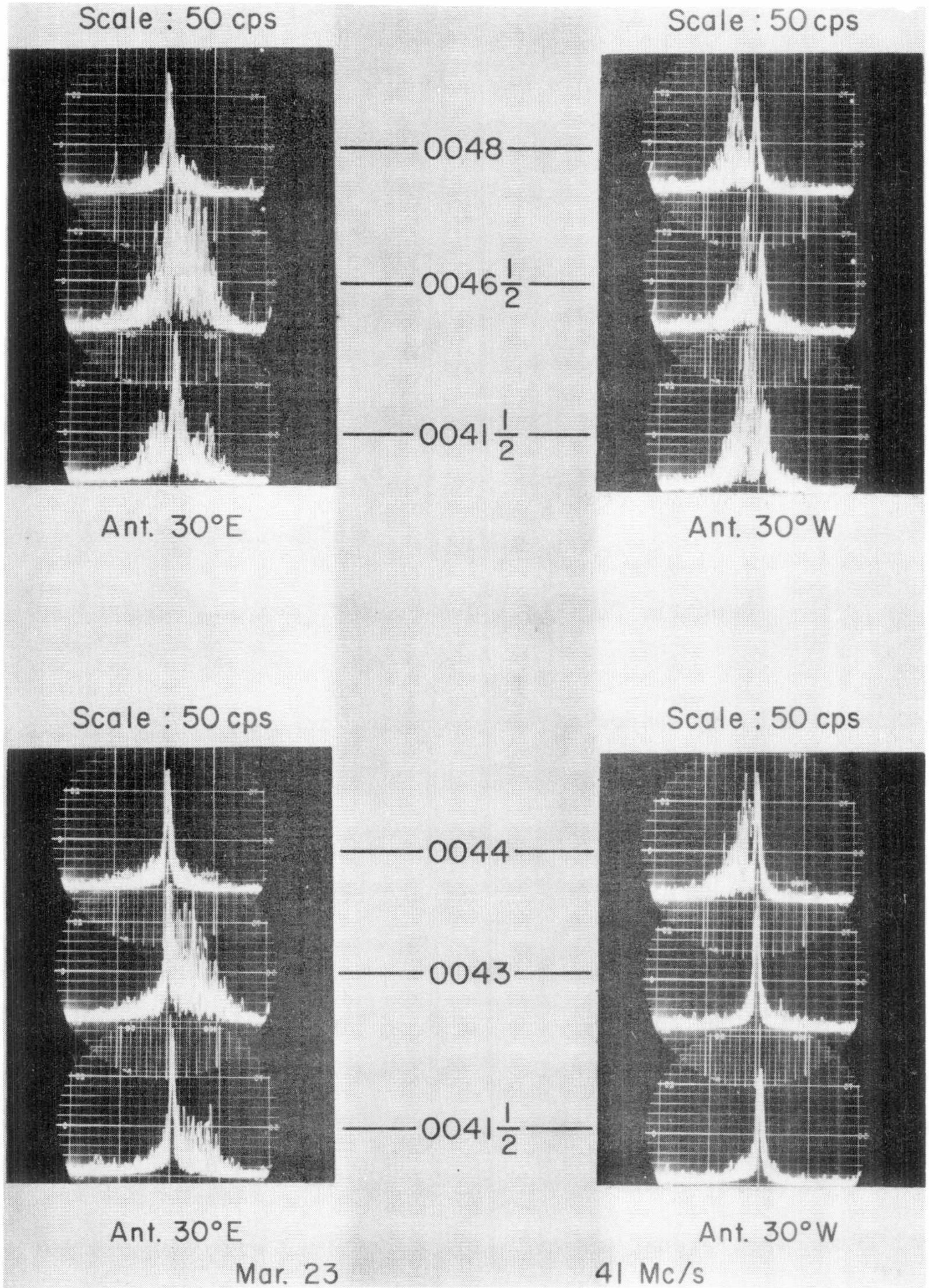


Figure 13. Simultaneous Frequency Spectra on 30° E and 30° W antennas. The transmitted frequency is at the center of each spectrum.

1951].* Furthermore it would be impossible to explain the measured frequency spectra by assuming even a small vertical component of motion or a component along the magnetic lines of force. If present, such components would produce equal frequency shifts on both channels since the elevation polar diagrams of both antennas are identical.

Another frequently observed phenomenon can be seen in Figure 13. At 0043 an echo was being received only from the east. By 0044 it had shifted to the west. Similarly, between 0046½ and 0048 the echo disappeared in the east and remained in the west. A deceptive feature of some of the records can be seen at 0045½ in Figure 13, where the frequency shifts appear to be in the same direction. The small component of positive frequency shift seen on the 30° E channel is undoubtedly caused by the finite gain of this antenna toward the west. It should be noted that the gains on the two channels are not the same since the received amplitudes of the direct signal on the two channels were almost equal. A more striking example of this effect will be discussed later in reference to Figure 16.

Examples of somewhat unusual records are given in Figure 14. Figure 14a shows the strongest echoes recorded at 106 Mc/s. The analyzer gain was reduced in taking the successive records shown. This was the only case observed in which the linear range of the system was exceeded, producing the small harmonic content seen on the right-hand side of the records at 2053 and 2054.

Figure 14b illustrates some particularly strong echoes

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* Similar radar auroral observations will be described in Chapter V.

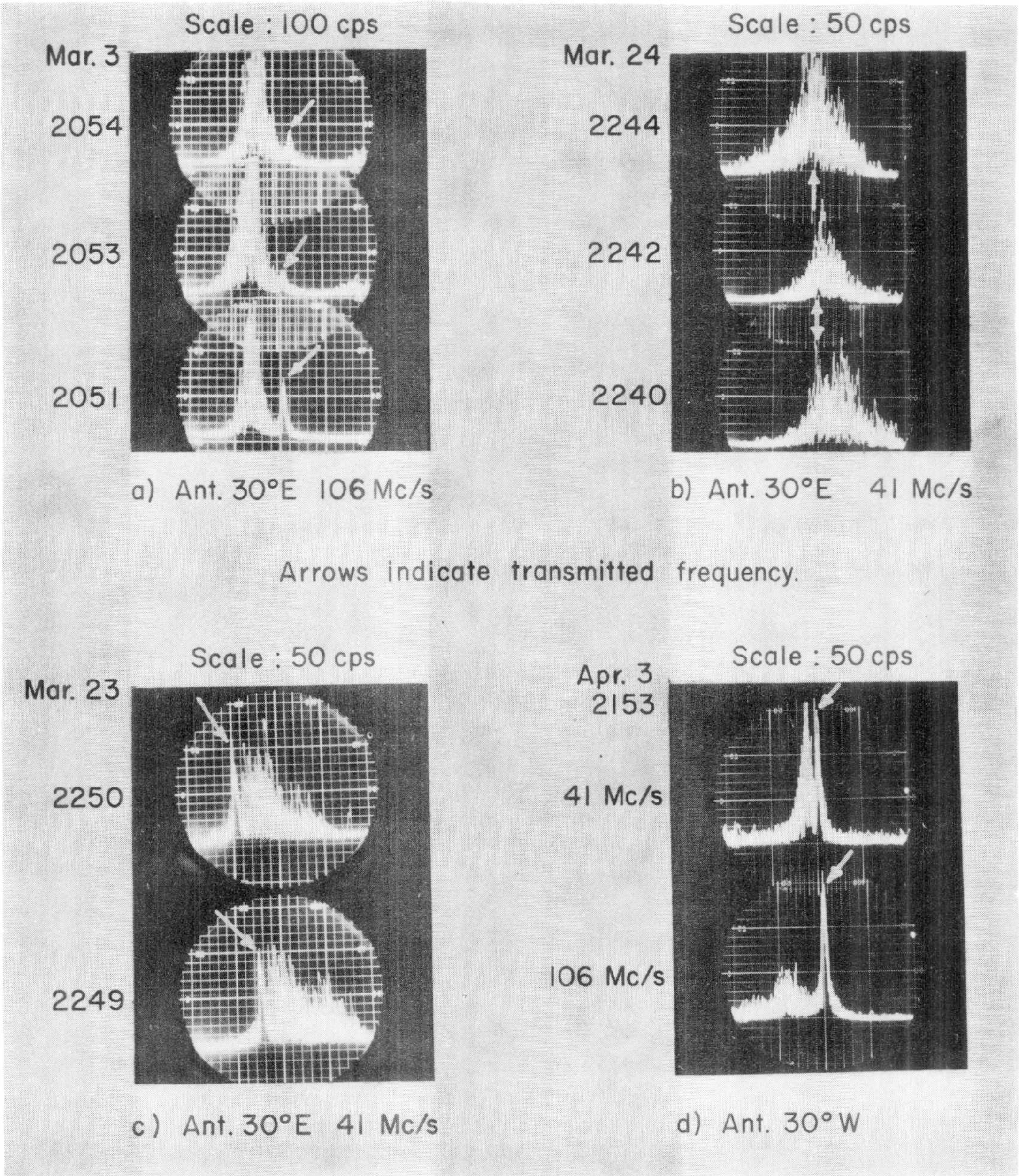


Figure 14. Some Examples of Frequency Spectra

a) Successive spectra of strong echo. b) Successive spectra of strong echo. Transmitted frequency obscured by echo. c) Successive spectra showing wide spread. d) Spectra of simultaneous echoes at 41 Mc/s and 106 Mc/s showing shifts proportional to transmitted frequency.

received at 41.15 Mc/s. These echoes completely obscure the direct signal component. In Figure 14c are shown examples of some widely spread frequency spectra observed at 41.15 Mc/s. The highest frequency shift shown corresponds to a radial component of velocity of 2 km/s. No echoes were received on the 30° W antenna at the time.

In Figure 14d an example of records taken simultaneously at 41.15 Mc/s and 106 Mc/s is shown. The Doppler shift interpretation requires that the frequency shift of echoes from the same moving source be proportional to the transmitter frequency. Thus the ratio of the frequency shifts should be 2.58. To the accuracy with which the frequency shifts can be read, the measured ratio is equal to that value.

Drift motions were observed which were directed both to the east and to the west. In several cases a reversal of the motion was detected. An example of such a reversal is shown in Figure 15. Before 2146 the motion was observed to be toward the west. At about 2146 the reversal began; it was completed by 2210. The direction of motion remained to the east until midnight, after which the echoes were too weak for measurable records to be taken.

As previously stated, the fact that the antenna beams overlapped caused some confusion in interpretation at times when the echo was really being received from azimuths on one side of north. An example of a record of this type can be seen in Figure 16 at 2325. At first glance it appears that the frequency shifts are in the same direction for echoes received from east and west of north, indicating that the major component of motion is not east-west. A closer examination reveals that the echo on the 30° E

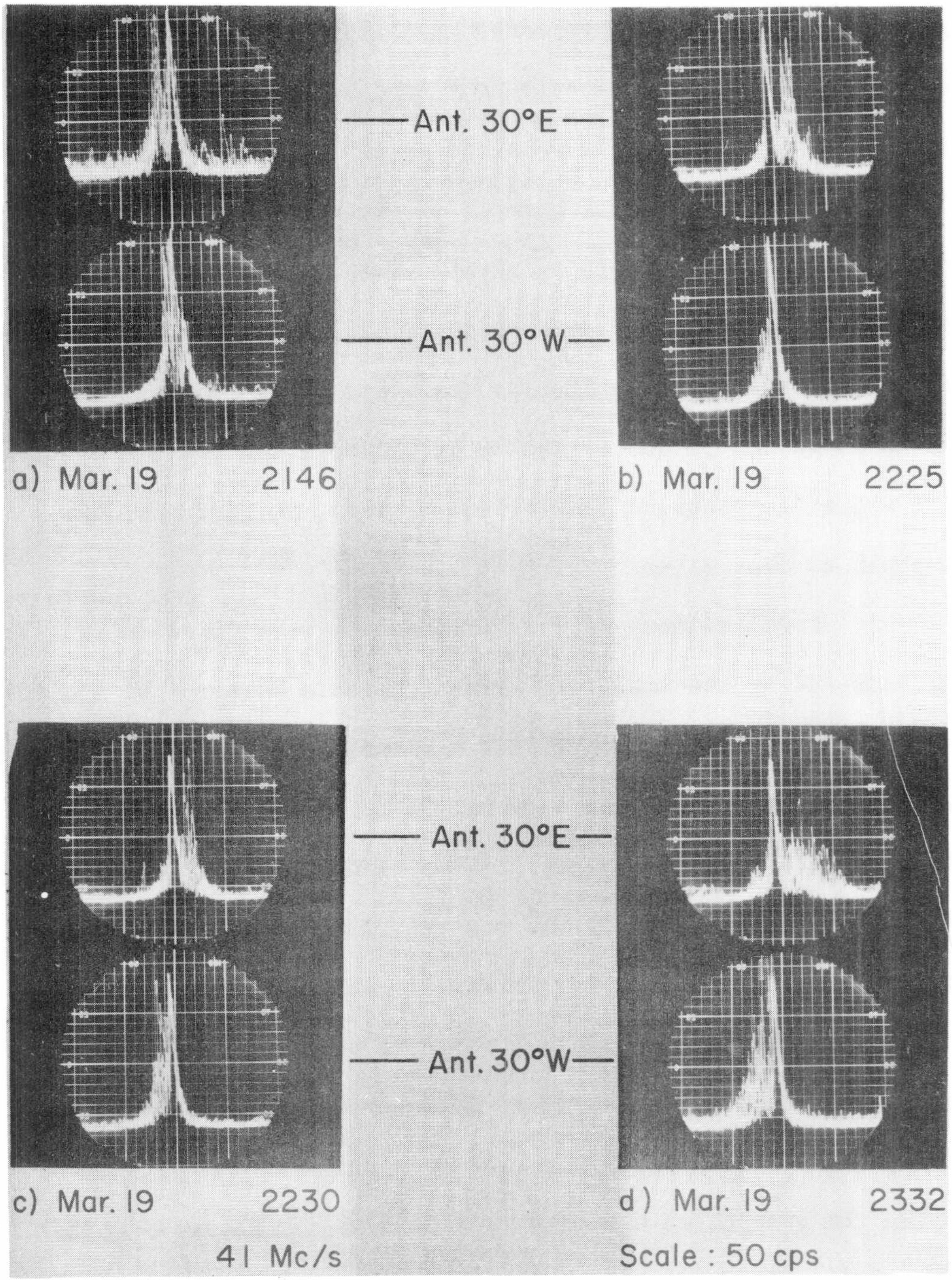


Figure 15. Frequency Spectra Showing Reversal of Drift Motion

(Spectra of simultaneous echoes on east and west antennas at times indicated. Transmitted frequency is thin vertical trace near center of each spectrum.)

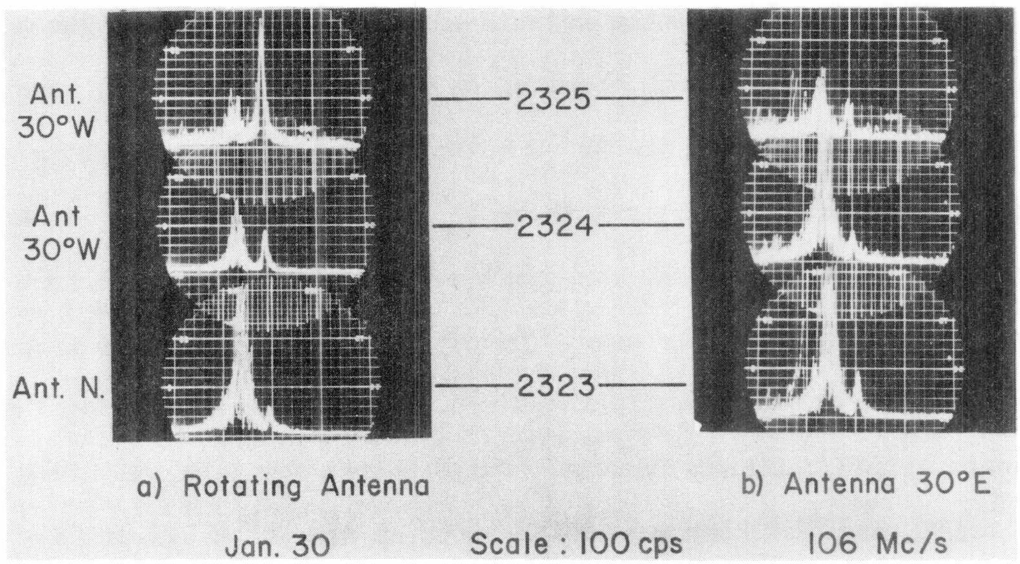


Figure 16. Effect of Antenna Beams on Frequency Spectra

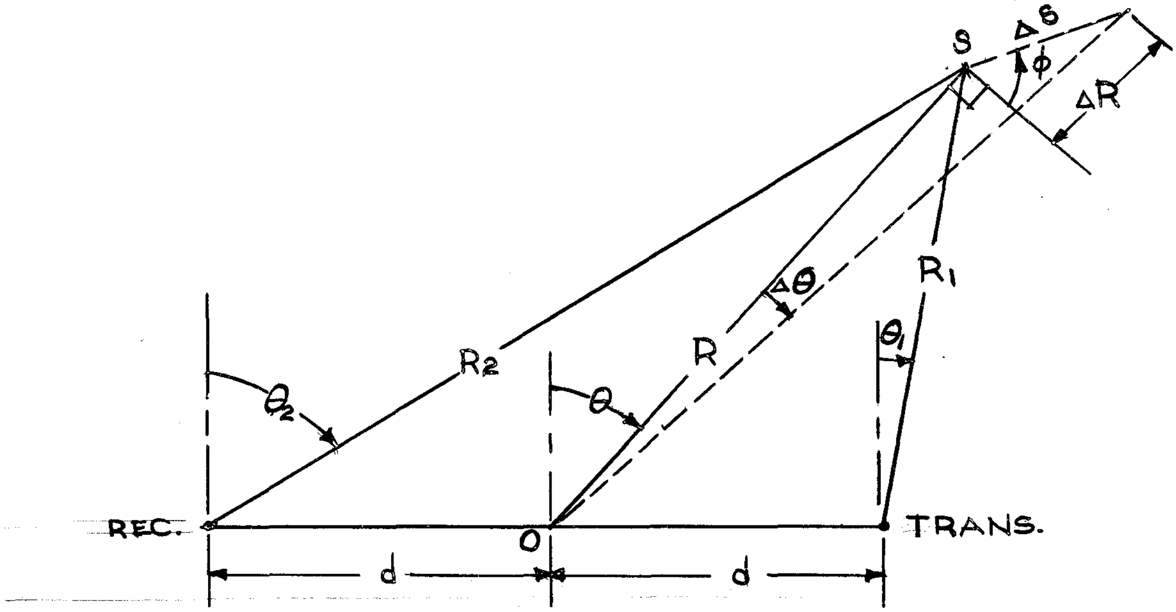
The spectra of simultaneous echoes on rotating and fixed antennas at times indicated. The transmitted frequency is at the center of each spectrum.

antenna is much stronger than that on the 30° W antenna (remembering that the direct signal components have approximately the same received amplitude). In most of the records no other information would be available. However, as previously mentioned, a rotating antenna of identical construction and height to that of the fixed antennas was available at 106 Mc/s. On the occasion illustrated in Figure 16, records were being taken on one of the channels with the rotating antenna. At 2323 this antenna was pointed toward magnetic north. The gain of the rotating antenna would therefore be equal to that of the 30° E antenna at the azimuth angle of about 15° E. The amplitude of the direct signal received on the rotating antenna, however, was about half that on the 30° E antenna. At 2324 the rotating antenna was pointed at an azimuth of 30° W. The increase in the amplitude of the direct signal component and the decrease in the echo amplitude can be clearly seen. Simultaneously on the 30° E antenna the echo amplitude actually increased. The interpretation of the record at 2325 is then obvious. The echo was arriving only from east of north, and the frequency shift shown on the 30° W antenna is caused by its finite gain at azimuths east of north.

3. Effect of Finite Transmitter-Receiver Spacing

The Doppler shift produced by an echoing source when the transmitter and receiver are separated by a distance 2d will be calculated using the sketch following.

The ranges to the echoing source at position S are given by



Effect of Transmitter-Receiver Separation

$$R_1^{\,2} = R^2 + d^2 - 2\,Rd\sin\theta$$
$$R_2^{\,2} = R^2 + d^2 + 2\,RD\sin\theta \quad . \qquad (4.8)$$

When the echoing source moves a distance ΔS at an angle ϕ with respect to the normal from point 0, the range from point 0 increases by ΔR where

$$R\Delta\theta = \Delta S\cos\phi \qquad (4.9)$$
$$\Delta R = \Delta S\sin\phi \quad .$$

The increase in range from transmitter to receiver is given by the sum of ΔR_1 and ΔR_2 where

$$\Delta R_1 = \frac{\partial R_1}{\partial R}\Delta R + \frac{\partial R_1}{\partial \theta}\Delta\theta$$
$$\Delta R_2 = \frac{\partial R_2}{\partial R}\Delta R + \frac{\partial R_2}{\partial \theta}\Delta\theta \quad . \tag{4.10}$$

Performing the indicated operations and letting $x = d/R$,

$$\Delta R_1 = \frac{\Delta R[1 - x \sin\theta] - \Delta S(\cos\phi \cos\theta)x}{\left(1 + x^2 - 2x\sin\theta\right)^{\frac{1}{2}}} \quad ,$$
$$\Delta R_2 = \frac{\Delta R[1 + x \sin\theta] + \Delta S(\cos\phi \cos\theta)x}{\left(1 + x^2 + 2x\sin\theta\right)^{\frac{1}{2}}} \tag{4.11}$$

For our conditions $x \ll 1$. (For a range of 600 km, $x = 0.033$.) For small x, adding R_1 and R_2 and simplifying gives

$$\Delta R_1 + \Delta R_2 = 2\,\Delta R\left[1 - \frac{x^2}{2}\left(1 + \frac{\cot\phi \sin 2\theta}{2}\right)\right] \tag{4.12}$$

The separated transmitter and receiver, compared with a hypothetical transmitter and receiver both located at point 0, introduce a fractional error in the change of range (and frequency shift) of

$$\frac{x^2}{2}\left(1 + \frac{\cot\phi \sin 2\theta}{2}\right) \quad . \tag{4.13}$$

For east-west motion, with which we are concerned, $\phi = \theta$, and the fractional error becomes

$$x^2\left(1 - \frac{\sin^2\theta}{2}\right) \quad . \tag{4.14}$$

The fractional error is always less than x^2 and therefore negligible. However, this statement refers to a comparison with a transmitter and receiver at point 0, for which there would be no shift produced by east-west motion of a source located north of point 0. Such a source, at a range of 600 km, would be at an azimuth angle of 2° E measured from the receiver. The major effect of the transmitter-receiver separation, therefore, would be to introduce an apparent, small north-south component into the measurements of motion that was truly east-west. As shown in the preceding section, this effect would not be sufficient to explain the north-south components that were observed.

4. An Interferometer Experiment

In section 2 we pointed out that the broad antenna beams used had a pronounced effect on the frequency spectra measured. To see if this effect could be decreased without constructing extremely large antennas, an interferometer experiment was attempted. The results obtained, while not definitive, serve to illustrate some aspects of the nature of the motions.

If two identical fixed antennas, each of which is pointed toward geomagnetic north, are separated by a distance ℓ along a geomagnetic east-west line and the received signals are brought together over transmission lines of equal length and added, it is well known that the azimuth power polar diagram of the system is

$$A_o(\psi) \left[1 + \cos \frac{2\pi \ell \sin\psi}{\lambda}\right] \tag{4.15}$$

where $A_o(\psi)$ is the polar diagram of the individual antennas and ψ is the azimuth angle measured from geomagnetic north. This interferometer arrangement has maxima of gain (neglecting A_o) at $\sin\psi = \frac{n\lambda}{2\ell}$ (n even) and nulls at $\sin\psi = \frac{n\lambda}{2\ell}$ (n odd).

The two receiving antennas previously used for 30° E and 30° W on 41.15 Mc/s served again for an interferometer arrangement of the above type, with a separation ℓ equal to 4λ. The physical setup is shown in Figure 17. The antenna impedances were carefully adjusted to be equal to within one ohm in resistance and one degree in phase angle, and equal-length transmission lines were used. The azimuth polar diagram would be expected to have maxima at $\psi = 0^\circ$, $\pm 14.5^\circ$, $\pm 30^\circ$, and $\pm 48.6^\circ$. The last maximum would of course be suppressed by the rapid decrease in A_0 at azimuth angles greater than 30 degrees. Nulls would be expected at $\psi = \pm 7.2^\circ$, $\pm 22^\circ$, and $\pm 38.7^\circ$.

For a region in which all the echoing sources have the same east-west motion v, we have previously shown that

$$\Delta f = \frac{2v}{\lambda} \sin \psi \quad . \tag{4.16}$$

The power frequency spectra, assuming that each echoing source returns equal power, would be

$$A_0 (\Delta f) \left(1 + \cos \frac{4\pi\lambda\Delta f}{v}\right) \tag{4.17}$$

The frequency spectra should therefore exhibit maxima at $\Delta f = 0$, $\pm \frac{v}{2\lambda}$, and $\pm \frac{v}{\lambda}$ as well as nulls at $\Delta f = \pm \frac{v}{4\lambda}$, $\pm \frac{3v}{4\lambda}$, and $\pm \frac{5v}{4\lambda}$. For $v = 160\lambda$ (about 1,160 m/s), these figures would correspond to maxima at 0, ± 80 cps, and ± 160 cps, with nulls at ± 40, ± 120, and ± 200 cps.

The above calculations were made on the assumption that all the echoing sources have identical velocities, are distributed uniformly over the echoing region, and return equal powers. A variation of two to one in the velocities would completely suppress the nulls and zeros.

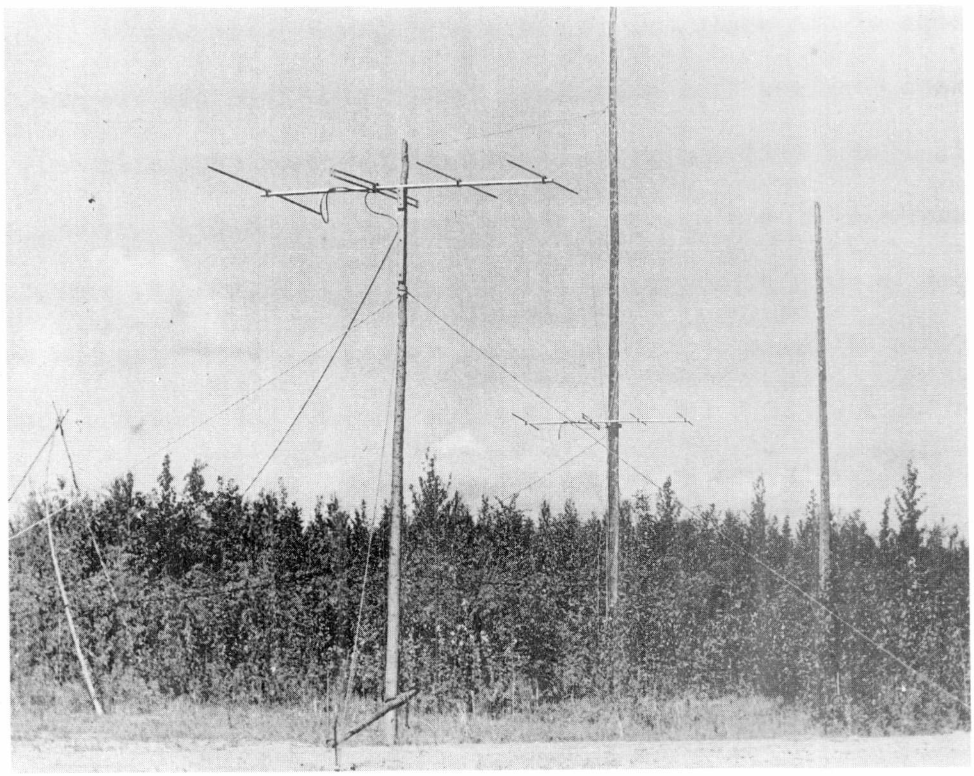


Figure 17. Interferometer Antennas

Sample records taken with our interferometer are shown in Figures 18 and 19. They indicate that the variation in velocities is too great to produce the simple frequency spectra calculated above, but the variation cannot be so great as two to one.

Figure 18 presents records taken on the morning of April 19, 1957. Figure 18a contains a record taken at 1023 using the reference dipole to show the transmitted frequency. The record at 1025 was of two sweeps of the analyzer. Since the playback speed was $7\frac{1}{2}$ in/s, each sweep consumes four seconds of record time, and the frequency scale is 25 cps (125 cps between the heavy vertical scale lines). The transition of the spectra, which takes place in four seconds of time, can be seen by comparing the two sweeps. Figure 18b illustrates the effects of these transitions added together over 40 seconds on records taken at 1034 and 1036. Figures 18c and 18d show the changes that took place in the spectra within about two minutes. In Figure 18c each sweep again represents four seconds of time. In Figure 18d each of the sweeps takes two seconds, and the frequency scale is compressed.

The records presented in Figure 18 are obviously complex. The records for 1029, 1030 1/2, and 1030 3/4 show that there is some consistency in the spectra, as well as some tendency for the expected nulls and maxima to appear. There was reason to think that a comparison of records of this type with records taken from a single antenna would show whether the maxima and minima were real effects. Accordingly, a coaxial switch was installed so that at periodic intervals records could be taken with only one of the antennas. In addition, another coaxial switch made it possible from time to time to

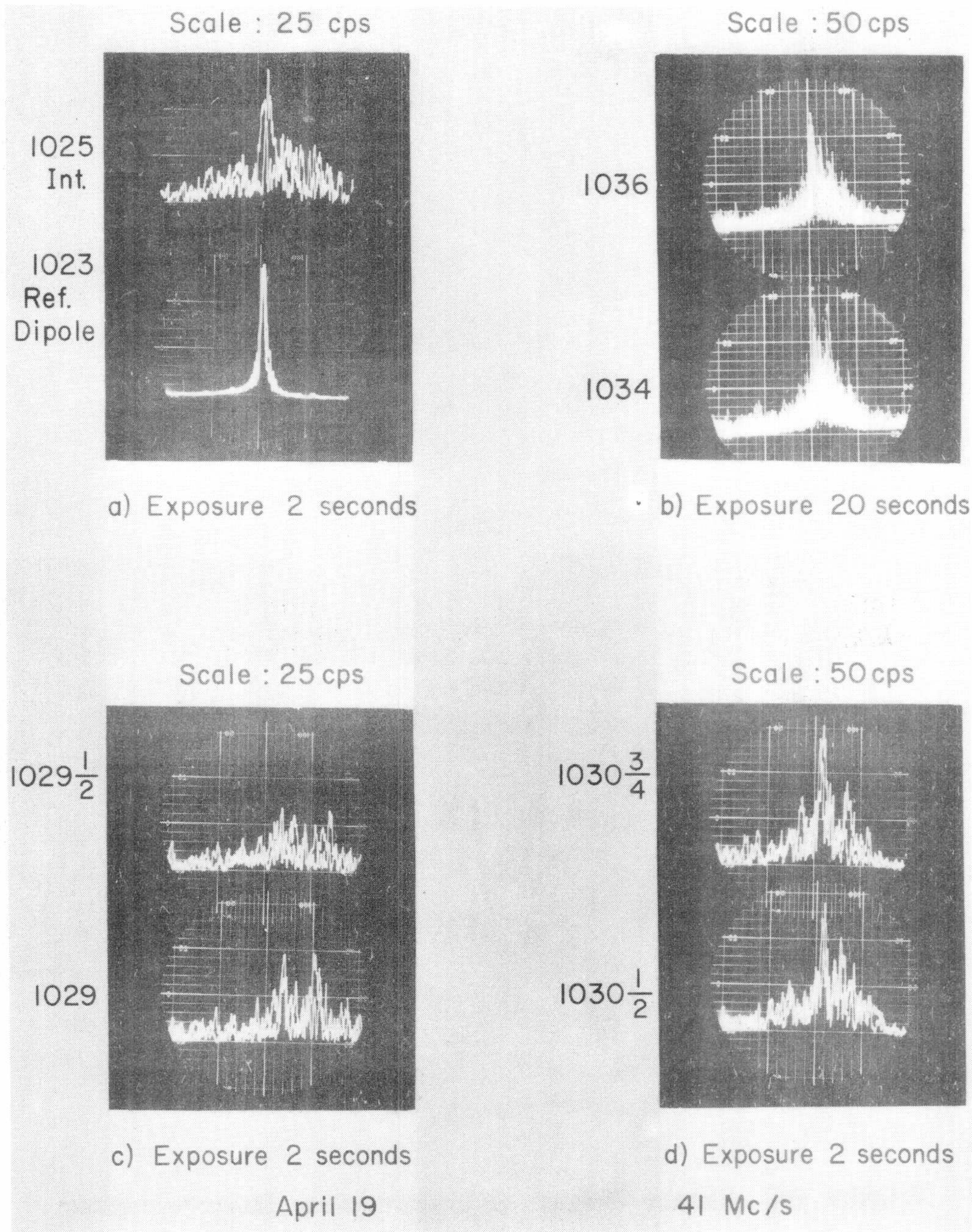


Figure 18. Sample Frequency Spectra of Echoes Received on Interferometer. Lower spectrum of (a) shows signal received on reference dipole.

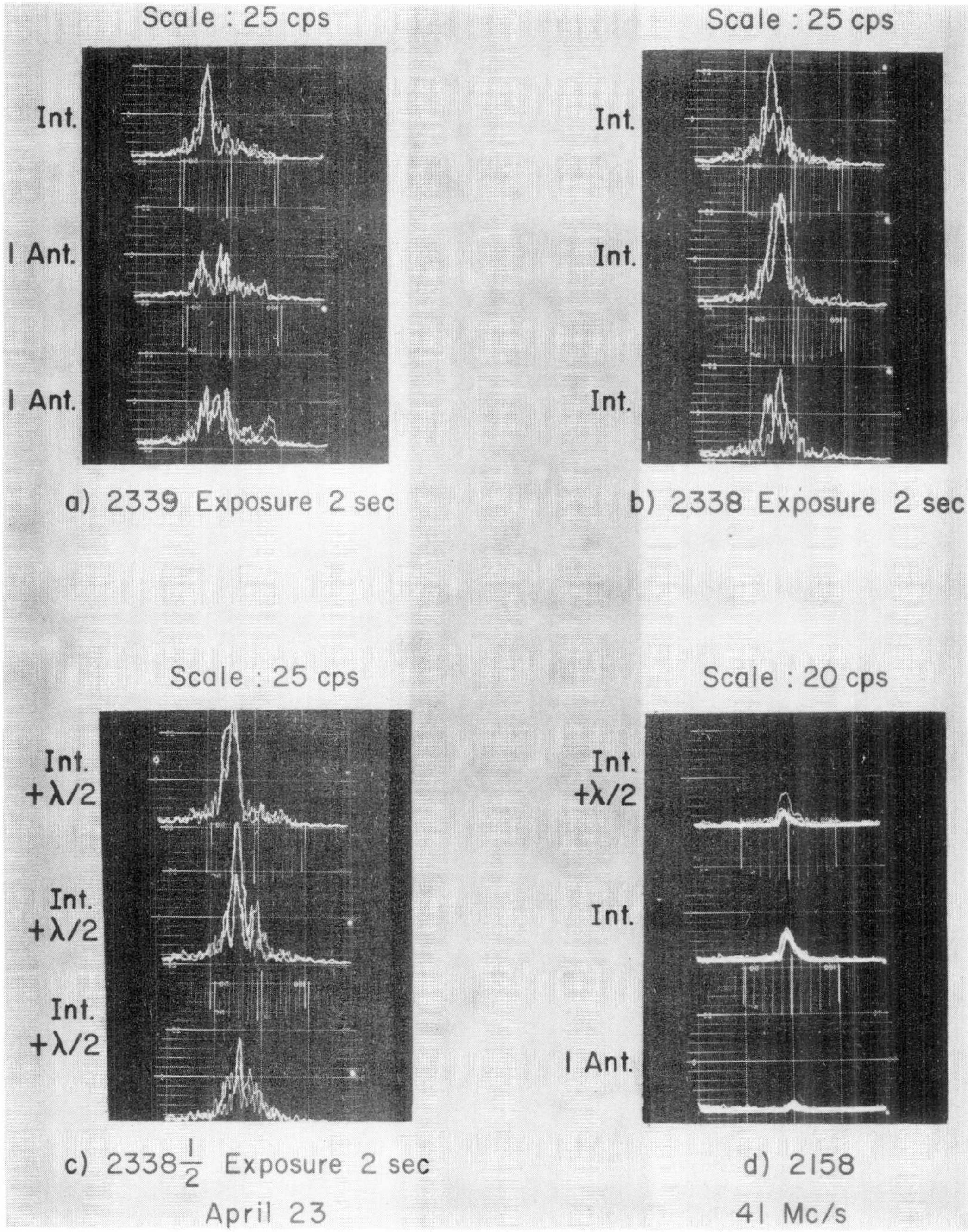


Figure 19. Sample Frequency Spectra from Interferometer and Single Antenna

a) Successive spectra on single antenna and interferometer. b) Successive spectra on interferometer. c) Successive spectra on interferometer with added half wavelength in one transmission line. d) Spectra of signals in absence of auroral echo with same amplitude scale as in a, b, and c.

add an extra half-wavelength into the transmission line from one of the antennas. The addition of this transmission line served to reverse the positions of the maxima and minima in the interferometer polar diagram.

Records taken in this manner are shown in Figure 19. For these records the playback speed was 3 3/4 in/s, so that each sweep consumed only two seconds of record time. The 25-cps scale was achieved by spreading out the sweep width on the oscilloscope. Figure 19a shows that the sharp maxima seen on many of the interferometer records are a real effect. Typically, the frequency spectra observed on the single antenna were broader and more uniform than those seen using the interferometer. Samples of successive records using the normal interferometer and the interferometer in which an extra half-wavelength was added to one of the transmission lines—labelled + $\lambda/2$ in the photograph—are shown in Figures 19b and 19c. The amplitude of the direct signal component seen on the various antenna arrangements is shown in Figure 19d to the same amplitude scale.

The interferometer measurements indicate that, while the velocities of the echoing sources over the whole region observed were neither identical nor steady, the range of velocities was probably not more than 1.5 to 1.

Chapter V. Auroral Radio Echoes and Our Power Measurements

In this chapter the characteristics of auroral radio echoes are described, and the probable mechanism by which such echoes are produced is considered. Those results of our experiment which relate to the amplitude of auroral echoes are presented and compared with theoretical predictions. The theoretical discussion is based chiefly on the work of Booker [1956]. It is shown that the explanation of the strength of our echoes requires the modification of the values of the parameters used by Booker.

Since excellent summaries of most of the literature on auroral radio echoes are already available [Little, Rayton, and Roof, 1956; Kaiser, 1955], only the brief review necessary for the present purpose is given here. In addition, some more recent results are included. Finally, a comparison of our experimental results with those obtained during the same period by other experimenters at 398 Mc/s is presented.

1. General Nature of Auroral Echoes

While the aurora is undoubtedly effective in producing radio echoes at frequencies below 30 Mc/s, the study of auroral echoes at these frequencies is complicated by severe absorption effects and reflections from the normal ionospheric layers. In a recent study by Owren and Stark [1956, pp. 8-18] it was shown that, in addition to the direct echoes, auroral radar echoes are obtained at 12 Mc/s over paths that include at least one reflection from the F_2 layer and one reflection from the ground.

It is not uncommon for the absorption of natural radiation from celestial sources at 30 Mc/s to reach three decibels in auroral regions [Chapman and Little, 1956]. The three-db figure refers to one-way passage through a broad zone centered on the zenith. If the absorbing region is traversed twice at an oblique angle, the absorption at 30 Mc/s might typically be 12 db. Furthermore, since the nondeviative absorption in decibels is almost proportional to the wavelength squared, the corresponding figure at 10 Mc/s for reasonable values of the collisional frequency would be of the order of 80 db.

At frequencies above 30 Mc/s the situation is more straightforward. While absorption undoubtedly plays some role in the lower VHF range, its effect decreases rapidly as the frequency is increased. Thus 12 db of absorption at 30 Mc/s would result in 6.4 db absorption at 41 Mc/s and 1 db at 106 Mc/s.

The maximum frequency at which auroral radar echoes have been observed has only recently been extended to about 400 Mc/s [Peterson, Leadabrand, and Dyce, 1957; Fricker, Ingalls, Stone, and Wang, 1957]. The 400 Mc/s experiments used narrow-beam steerable antennas which made it possible for the first time to determine directly the height of the reflecting region from measurements of the range and elevation angle. Peterson et al. reported heights between 80 and 130 km, with an average height of 105 km. Fricker et al. found the maximum height to be 165 km. These heights agree well with the heights at which the maximum luminosity is observed in the visible aurora.

The connection between the radio echoes and the visible aurora was obscured for some time by the fact that auroral ionization is effective in producing radar echoes only when the incident radar beam is nearly perpendicular to the earth's magnetic field in the auroral region. Since auroras are most frequently observed in high latitudes, where the earth's magnetic field is nearly vertical, radio echoes in the northern hemisphere are obtained only from regions near the northern horizon. Comparisons must therefore be made only with visible aurora in that region. When the analysis is restricted to these regions, fairly good correlations between visual and radar auroras are obtained, although the intensity of the echoes is not always proportional to the brightness of the visual forms.

The aspect sensitivity of auroral radio echoes has been the subject of much investigation. It is clear that the number and intensity of echoes decrease as the angle from perpendicularity with the geomagnetic field increases. The perpendicularity requirement becomes less critical as the frequency is decreased. The contours of off-perpendicular angles at a 100-km height for College, Alaska*, are plotted in Figure 20. Bowles [1955] found that at College the contours of the expected probability of obtaining auroral echoes at 106 Mc/s had shapes very similar to the contours shown in Figure 20. Less than 5 percent of his echoes were received from points corresponding to off-perpendicular angles greater than 6 degrees. Similarly, Dyce [1955] showed that at 51.7 Mc/s almost all the echo centers fell within the 8-degree contour.

Bullough and Kaiser [1954, 1955] concluded that, as viewed

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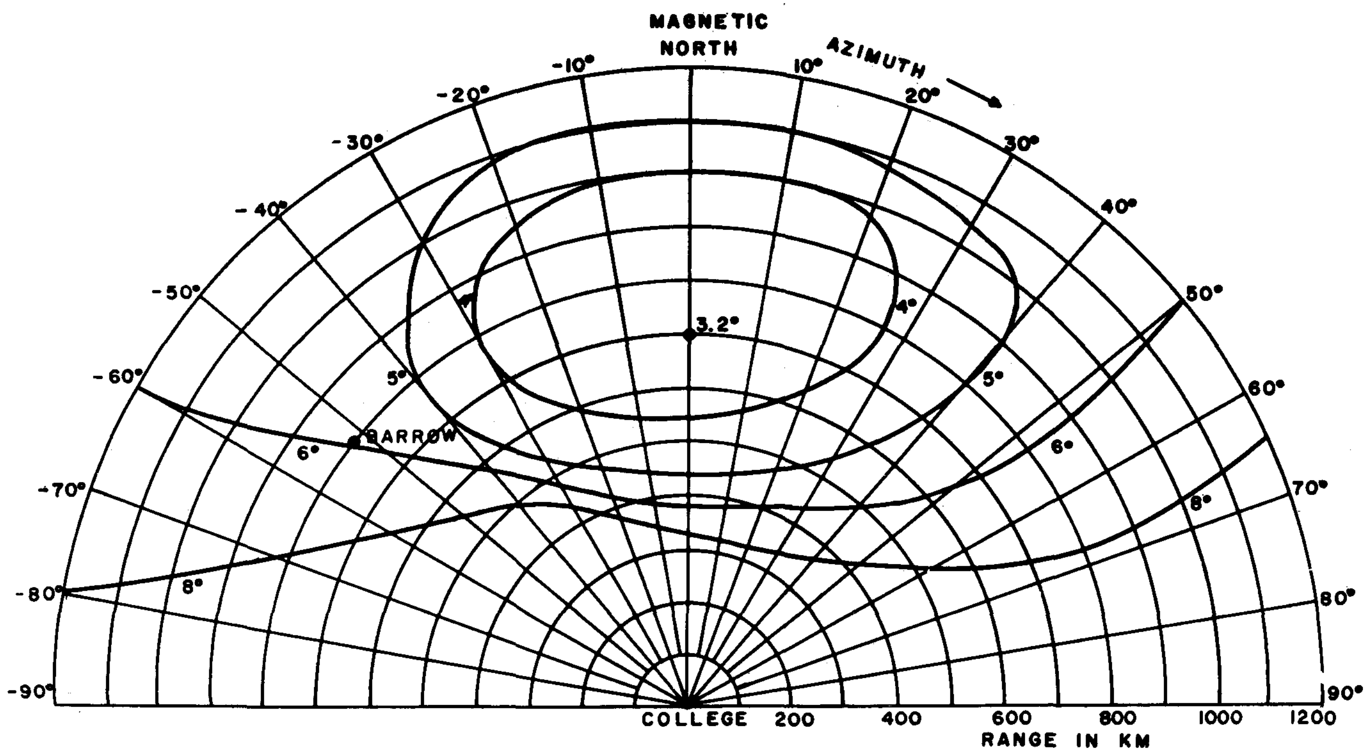
* Courtesy of R. L. Leadabrand, Stanford Research Institute



CONTOURS OF OFF-PERPENDICULAR ANGLE AT 100 KM

Figure 20. Contours of Off-Perpendicular Angle at 100 Km

from Jodrell Bank, the reflecting ionization during an individual aurora was closely confined to an arc along a parallel of magnetic latitude. Bowles [1955] found similar orientations at College, but was able to show that the reflecting ionizations were rotated slightly clockwise during the 6-hour period before local midnight and slightly counterclockwise during the 6-hour period after local midnight. For ionization distributed along a parallel of latitude, the range spread measured will be a function of the antenna beamwidth in azimuth. Nevertheless, many workers have found that the echoes can be separated into two types in terms of the spread in range exhibited. Echoes showing great spread in range are called diffuse; those with narrow range spreads are called discrete. Bullough and Kaiser [1955] pointed out that their diffuse echoes were generally observed before 2100 local time, and their echoes showing discrete structure generally occurred after 2100 local time.

The use of the term "discrete" does not imply that auroral radio echoes have ever been found to have the characteristics of an echo arising from a single source such as an airplane. The received signals are always complex; they have the characteristics that would be expected of echoes arising from many randomly positioned, moving sources.

2. The Booker Auroral Echo Theory

The character and strength of echoes from auroral ionization have been explained by Booker [1956] in a theory of scattering by nonisotropic irregularities. According to Booker's theory, the irregularities of electron density are created by atmospheric turbulence and made nonisotropic by the action of the earth's magnetic field. The irregularities mainly responsible for the VHF radar echoes would have dimensions of the order of 40 meters along the earth's magnetic field and one meter normal to the field. These dimensions, particularly the length, would explain the aspect sensitivity observed. The effect of the aurora was supposed to increase the electron density in the E region by a factor of about a hundred, to a value of about 10^6 per cm^3. Booker concluded that for this mean electron density N, and the dimensions stated above, a mean square deviation of electron density $\overline{\left(\frac{\Delta N}{N}\right)^2}$ of the order of 3×10^{-7} in the scattering region would explain the strength of the echoes. He suggested however that a permissible modification of the theory would raise the values of $\overline{\left(\frac{\Delta N}{N}\right)^2}$ by about two powers of ten.

Since the proper interpretation of any experiment involving echoes from auroral ionization necessarily depends upon the source of the echoes, it seems desirable to examine the basis of Booker's theory critically. The least controversial part of the theory relates to the calculation of the scattered power from a region containing nonisotropic irregularities, postulating that the irregularities make no first-order change in the field strength of the incident wave. Considering only the case of backscattering (the radar case) from an ionized medium, the backscattered power per unit solid angle, per unit incident power density, per unit volume reduces to

$$\sigma_B = \overline{\left(\frac{\Delta N}{N}\right)^2} \; \frac{\pi^2}{\lambda_N^{\,4}} \; P\,(2\,k\,\ell,\; 2\,k\,m,\; 2\,k\,n), \qquad (5.1)$$

where

λ_N is the plasma wavelength corresponding to the mean electron density N;

k is the propagation constant of the medium in the absence of irregularities;

P (ℓ, m, n) is the Fourier transform of the spatial autocorrelation function of $\frac{\Delta N}{N}$, $\rho(x, y, z)$;

and ℓ, m, n are the direction cosines of the incident beam.

To calculate the backscattered power, one must know the (statistical) way in which $\frac{\Delta N}{N}$ varies throughout the volume in the directions x, y, z (i.e., the spatial autocorrelation function of $\frac{\Delta N}{N}$), the mean ionization in the region, the mean square deviation of ionization, and the extent of the volume. At this stage a more controversial point enters. An autocorrelation function must be chosen. In the interest of simplicity Booker chose a Gaussian autocorrelation function with axial symmetry about an axis z,

$$\rho(x, y, z) = \exp\left\{-\frac{1}{2}\left(\frac{x^2}{T^2} + \frac{y^2}{T^2} + \frac{z^2}{L^2}\right)\right\}. \qquad (5.2)$$

After taking the Fourier transform of ρ, Equation (5.1) becomes for L $\gg$ T and small ψ,

$$\sigma_B = (2\pi)^{3/2}\, \pi^2\, \frac{\overline{\left(\frac{\Delta N}{N}\right)^2}}{\lambda_N^{\,4}}\, T^2 L \exp\left(-\frac{8\pi^2 T^2}{\lambda^2}\right) \exp\left(-\frac{8\pi^2 L^2}{\lambda^2}\,\psi^2\right), \qquad (5.3)$$

where ψ is the complement of the angle between the direction of incidence and the axis of symmetry. For application to the ionosphere, the axis of symmetry would lie along the earth's magnetic field in the element of volume involved.

The total scattered power can be calculated by integrating σ_B over the total volume, taking into account the variation of ψ throughout the total volume and the antenna polar diagrams in elevation and azimuth. The aspect sensitivity would depend only upon the term involving ψ; for a given location and given antenna beams the aspect sensitivity is therefore a function only of the ratio of L to the wavelength. Booker found that assigning a value of 6.8 meters to L ($2\pi L = 43$ m) explained the major features of the experimental aspect-sensitivity results.

The major drawback of the above approach is the assumption of the Gaussian autocorrelation function. Booker further showed that the value of L found above was consistent with the scale of the small eddies at 100 km deduced from a turbulence theory. Turbulence theory, however, would lead to a quite different autocorrelation function and therefore to a different expression for the aspect sensitivity and scattered power.

The effect of a change in the autocorrelation function would be most pronounced at large values of $\frac{L}{\lambda}$. For the problems that Booker considered, the values of $\frac{L}{\lambda}$ were comparatively small. However the recent detection of auroral echoes at 400 Mc/s proves that the scattered power cannot fall off so rapidly as would be predicted from the term

$$\exp\left(-\frac{8\pi^2 L^2}{\lambda^2}\psi^2\right).$$

The scale normal to the earth's magnetic field T is even more uncertain. Booker found that for a value of L of 6.8 meters at 100 km the effect of the field would cause T to be about 6 cm.

The effect of the term exp $\left(-\frac{8\pi^2 T^2}{\lambda^2}\right)$ would therefore start to be appreciable only at frequencies above about 500 Mc/s.

3. Parameters Obtained from Our Experiment

Let us proceed to compare the scattered power measured in our experiment with the theoretical predictions just outlined. For $L = 6.8$ m and $\psi = 0.07$ (about four degrees in Figure 20), the values of the term exp $\left(-\frac{8\pi^2 L^2}{\lambda^2}\psi^2\right)$ at 106 Mc/s and 41.15 Mc/s are 0.11 and 0.7 respectively. Since, as noted above, that term predicts too rapid a decrease with frequency, it is likely that the true reduction in the scattered power due to aspect sensitivity for our stronger echoes ($\psi \approx 4^\circ$) would be smaller.

As auroral echoes are spread in frequency and consist of many components adding in random phase, they have the statistical characteristics of random noise passed through a band-pass filter. The total power in an auroral echo can therefore be found by adding the powers received over the frequency spectrum.

The amplifying, recording, and analyzing systems used in our experiment were linear in voltage. The relative echo power was found by squaring the amplitude at each frequency, plotting the power frequency spectrum, and measuring the resultant area. To convert this area into an absolute power measurement, the known power of the signal received directly from the transmitter was used. The ratio of the power echo area to the power direct signal area determined the absolute echo power. Since computations were done only on the stronger echoes, those with signal-to-noise ratios greater than 20 db, the error made by neglecting the noise power was negligible.

Using the method outlined above, we have computed the echo powers for the records shown in Figures 14a, 14b, and 14c. On March 3, 1957, at 2053 the echo power at 106 Mc/s was about 5×10^{-13} watts. At 41.15 Mc/s the echo powers at 2249 on March 23 and at 2244 on March 24 were 1.3×10^{-14} watts and 1×10^{-12} watts respectively. In the latter case the direct signal power was estimated from a nonauroral record taken the same evening. The transmitted powers (see Chapter IV) have already been given as 250 watts at 106 Mc/s and 72 watts at 41.15 Mc/s.

Assuming that the transmitting and receiving antenna power gains, G_T and G_R, and the range R are constant over the volume, the ratio of the echo power received, P_R, to the power transmitted, P_T, is given by

$$\frac{P_R}{P_T} = \left(\frac{G_T}{4\pi R^2}\right)\left(\frac{\lambda^2 G_R}{4\pi R^2}\right) \int_{\text{Volume}} \sigma_B \, d\,v \qquad (5.4)$$

In the examples mentioned above the echo was being received only on the 30° E antenna. We can therefore assume that the direction of arrival was near the maximum of the antenna polar diagram. If the sacttered power originates at a 600 km range where the gains of the antennas are maximum in azimuth and elevation, then for the very strong echoes at both frequencies

$$\int_{\text{Volume}} \sigma_B \, d\,v \gtrsim 5 \times 10^7 \ m^2 \quad . \qquad (5.5)$$

The volume involved was limited by the receiving antenna beams in azimuth, as well as by aspect sensitivity. It seems reasonable to assume the following dimensions for the volume: height, 30 km; width, 300 km (30° in azimuth); and depth, 200 km (range variation of 500-700 km) and to consider σ_B constant over this volume. The value of σ_B thus obtained is 4×10^{-8} per meter. Using Equation (5.3) and the aspect sensitivity factors previously estimated,

$$\frac{1}{\lambda_N^4} \overline{\left(\frac{\Delta N}{N}\right)^2} \approx \begin{matrix} 10^{-7} \text{ (106 Mc/s)} \\ 1.5 \times 10^{-8} \text{ (41.15 Mc/s)} \end{matrix} \quad . \tag{5.6}$$

The above calculations were for the strongest echoes received. More normal echoes would correspond to a value of

$$\frac{1}{\lambda_N^4} \overline{\left(\frac{\Delta N}{N}\right)^2} \approx 10^{-10} \tag{5.7}$$

On the other hand, using the previous experimental auroral radar results available to him, Booker deduced

$$\frac{1}{\lambda_N^4} \overline{\left(\frac{\Delta N}{N}\right)^2} \approx 4 \times 10^{-13} \quad . \tag{5.8}$$

He then assumed a value of λ_N of 30 m to conclude that $\overline{\left(\frac{\Delta N}{N}\right)^2}$ was 3×10^{-7}.

The result quoted in Equation (5.7) depended upon our assumptions of volume and range. To reduce the value, it would be necessary to assume an even larger scattering volume and/or shorter range. Changes in these assumptions, however, would necessarily involve decreasing the antenna gains and increasing ψ, both of which would tend to increase the value given in (5.7).

It also seems probable that 30 m is too low a value for λ_N. The 30 Mc/s absorption measurements at College, combined with the information obtained from the C-3 ionospheric sounder at the

Geophysical Institute, lead to the conclusion that the average electron density in the auroral region corresponds to a λ_N of more than 50 m.*

Using λ_N = 50 m, we are therefore left to conclude that our normal auroral echoes correspond to a value of

$$\overline{\left(\frac{\Delta N}{N}\right)^2} \approx 6 \times 10^{-4} \quad . \tag{5.9}$$

This value, while considerably higher than that deduced by Booker—letting λ_N equal 50 m in Equation (5.8) results in a $\overline{\left(\frac{\Delta N}{N}\right)^2}$ of 2.5×10^{-6}—does not seem unreasonably great. Bailey et al. [1952], for example, used a value of 10^{-4} for the same parameter in explaining the original VHF long distance ionospheric observations. The concept that the normal auroral echoes arise through scattering from small irregularities in the ionization density would still seem to be valid.

The explanation for the great strength of our strongest echoes, corresponding to Equation (5.6), is less certain. Even for $\overline{\left(\frac{\Delta N}{N}\right)^2}$ as high as 10^{-2}, λ_N would have to be as small as 18 m to obtain the result quoted for 106 Mc/s. It is doubtful that values of $\overline{\left(\frac{\Delta N}{N}\right)^2}$ as high as 10^{-2} could be expected to be produced by normal turbulence. It is more probable that the turbulence model in auroral regions must be modified to take into account the sharp gradients in luminosity, and presumably therefore in ionization density, seen in auroras. Under these conditions it may not be so unlikely that

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* This value is due to C. G. Little and is based on the fact that the limited absorption measured at 30 Mc/s would not prevent the reception of C-3 echoes at higher frequencies if the critical frequency exceeded 6 Mc/s.

values of $\overline{\left(\frac{\Delta N}{N}\right)^2}$ might be as high as 2×10^{-2}. If so, the strongest echoes could be explained by a λ_N of 36 m.

One interesting sidelight of our results is the fact that, for the strongest echoes, the scattering coefficients computed in Equation (5.5) are the same at 41.15 Mc/s and 106 Mc/s. Although the measurements refer to different nights, a possible deduction based upon their equality is that the value for ψ must have been close to zero on those occasions. Such almost exact perpendicularity could have been achieved if the aurora were at a height of 80 km. Another possibility is that at times the local magnetic field in the auroral region is sufficiently distorted by the disturbance current system to make perpendicularity possible at the 100-km height. On the assumption of perpendicularity, the highest value of $\frac{1}{\lambda_N^4}\overline{\left(\frac{\Delta N}{N}\right)^2}$ deduced from our records would be 10^{-8}; such a value would be achieved by a λ_N of 32 m combined with a $\overline{\left(\frac{\Delta N}{N}\right)^2}$ of 10^{-2}.

4. Comparison with Echo Strengths at 400 Mc/s

A significant factor emerges from the comparison of the strength of our echoes with those observed at College during March 1957 by Peterson et al. [1957] at 398 Mc/s. They reported that auroral echoes 27 db above noise were received on a radar with 60 kw peak power, 0.5 millisec pulse, receiver bandwidth of 3 kc/s, and receiver noise figure of 6 db. The antenna used was a large paraboloid with 3 degree beamwidth. The volume of scattering region involved may be found by assuming that the volume was limited by the beamwidth and pulse length. Assuming that the backscattering coefficient was constant over the scattering volume——the same assumption that was made for our echoes—Equation (5.4) may be rewritten for the 398 Mc/s experiment

$$\sigma_B = \frac{4\pi R^2}{G\lambda^2 p}\left(\frac{P_R}{P_T}\right) , \qquad (5.10)$$

where p is the pulse width.

For the same range of 600 km used in deducing the backscattering coefficient from our echoes, and for an antenna gain of 5,000

$$\sigma_B = 4.3 \times 10^{-15} \text{ per meter} \quad . \qquad (5.11)$$

The ratio of the backscattering coefficient at 106 Mc/s to that at 398 Mc/s is therefore 10^7.

It is apparent that the Gaussian autocorrelation function is an incorrect assumption from the fact that on the basis of the term $\exp\left(-\frac{8\pi^2 L^2}{\lambda^2}\psi^2\right)$ the ratio of the backscattering coefficients should be 10^{13}.

It is instructive to determine the power law of wavelength dependence that would fit the measurements at 106 Mc/s and at 398 Mc/s.

$$\frac{\sigma_B(106)}{\sigma_B(398)} = \left(\frac{\lambda(106)}{\lambda(398)}\right)^n = 3.75^n = 10^7 \quad . \qquad (5.12)$$

From Equation (5.12) we deduce that a value of 12 for n would fit the observations. It is interesting that Villars and Weisskopf [1954], on the basis of a theory of isotropic turbulence computed a power-law wavelength dependence corresponding to a value for n of from 4 1/3 to 11. According to the theory, the eleventh-power law should be applied in cases where the wavelength is small compared to the smallest eddy size. The 106 Mc/s and the 398 Mc/s measurements undoubtedly refer to such a situation insofar as the comparison of the wavelength to the eddy size along the magnetic field line is concerned. Furthermore, we have previously shown that, for the nonisotropic case at frequencies below 500 Mc/s, it is the size along the magnetic field line that controls the wavelength dependence.

It appears that a theory of scattering by nonisotropic irregularities produced by turbulence is capable of explaining the amplitude of VHF auroral radio echoes as well as their wavelength dependence. However, the parameters used in such a theory would have to be quite different from those inferred by Booker from the data available to him. The turbulence theory applied to the aurora would have to take into account the sharp gradients of luminosity--and presumably of ionization density--observed in auroral forms. Turbulence acting on these gradients might very well produce the high values of $\overline{\left(\frac{\Delta N}{N}\right)^2}$ deduced by us.

Chapter VI. Summary of the Results of Our Drift Motion Measurements

In the preceding chapters we have attempted to establish a broad experimental and theoretical context into which the results of this experiment can be placed. The methods by which our data were obtained were described in Chapter IV. In that chapter we also explained the basis of our interpretation of the records. In essence, the interpretation depends upon the simultaneous recording of the frequency spectra of auroral echoes from a CW transmitter, received on antennas directed east and west of geomagnetic north. It was assumed that the frequency shifts were caused by motions of the echoing centers through Doppler action. That assumption was justified by simultaneous recordings on two frequencies (see Figure 14d) and by the average shifts measured on the two frequencies. We now proceed to examine the observed motions in more detail. We also compare them with the previous measurements mentioned in Chapters I, II, and III, as well as with magnetic records taken concurrently.

1. Summary of Results

Observations were made on 53 nights during the period January through April, 1957. Auroral echoes were obtained for some periods on 33 of the nights, with durations varying from several minutes to four hours. A total of 32 hours of auroral echoes were recorded and analyzed. Photographs of about 800 different frequency spectra of these echoes were taken.

In most cases the echo was received with measurable spectra on only one of the antennas—that is, from one side of geomagnetic north. In some instances the echo was much stronger on one antenna than on the other, and the frequency spectra were almost identical. Since the antenna beams overlapped, such records may be interpreted as indicating that both antennas were receiving echoes from the same portion of the sky. In Chapter IV we discussed an example of this type (see Figure 16), for which we were able to prove, by using a rotating antenna, that such an interpretation was correct.

When echoes are being received from only one side of north, it is not possible to determine the direction of motions positively. However, on 11 different nights, for a total of 4 hours of auroral echoes, the signals on both antennas were of almost equal strength, and the frequency spectra were displaced in opposite directions. Examples of these spectra are shown in Figures 12, 13 (at 0046 ½), and 15. For those periods the direction of motion must have been generally east-west although, as explained in Chapter IV, a small north-south component was also present. On six nights, for a total of six hours of auroral echoes, echoes were received for alternate periods on the two antennas with frequency spectra that were consistently displaced in opposite directions. It seems unquestionable that records of that type could be produced only by east-west motions. In only one instance, and for a period of five minutes, did we see any records in which the spectra on both channels were so similar as to rule out a generally east-west motion.

From this evidence, we concluded that the motions were for the most part east-west and interpreted all our records in that way, even for the times when the echoes were being received on only one antenna. The nocturnal variation of the directions of motions has been plotted in Figure 21. The number of occurrences of motion to the east or west observed during the hours indicated may be noted. Along the top border of Figure 21 are given the number of times that observations were made during the hour specified. For example, between 2300 and 2400 Alaska Standard Time observations were made on 43 nights. Auroral echoes were obtained during that hour on 14 of the nights. Of these, ten showed electron drift motion to the east and four to the west. It is apparent from Figure 21 that westerly drift motions were observed chiefly in the evening hours. The transition from predominantly westerly motions to predominantly easterly motions occurred around 2200 local time. That result checks very well with the average current system shown in Figure 2, where we saw that the transition from easterly currents (westerly motion of electrons) to westerly currents (easterly motion of electrons) also occurs around 2200. The result also agrees with the auroral zone scintillation motions of Maxwell and Dagg [1954] described in Chapter I. Maxwell and Dagg reported a transition from westerly to easterly motions in the auroral zone at 2100.

The determination of the speed of motion is more difficult than establishing the direction. As previously shown, for east-west motion the speed v is determined from the frequency shift Δf by

$$\begin{aligned} v &= 1.42\ \Delta f \csc \alpha \qquad \text{for } 106 \text{ Mc/s} \\ &= 3.65\ \Delta f \csc \alpha \qquad \text{for } 41.15 \text{ Mc/s}, \end{aligned} \tag{6.1}$$

where α is the azimuth angle.

The frequency spectra are of course spread as a result of the variation in α. In addition, there is undoubtedly a variation

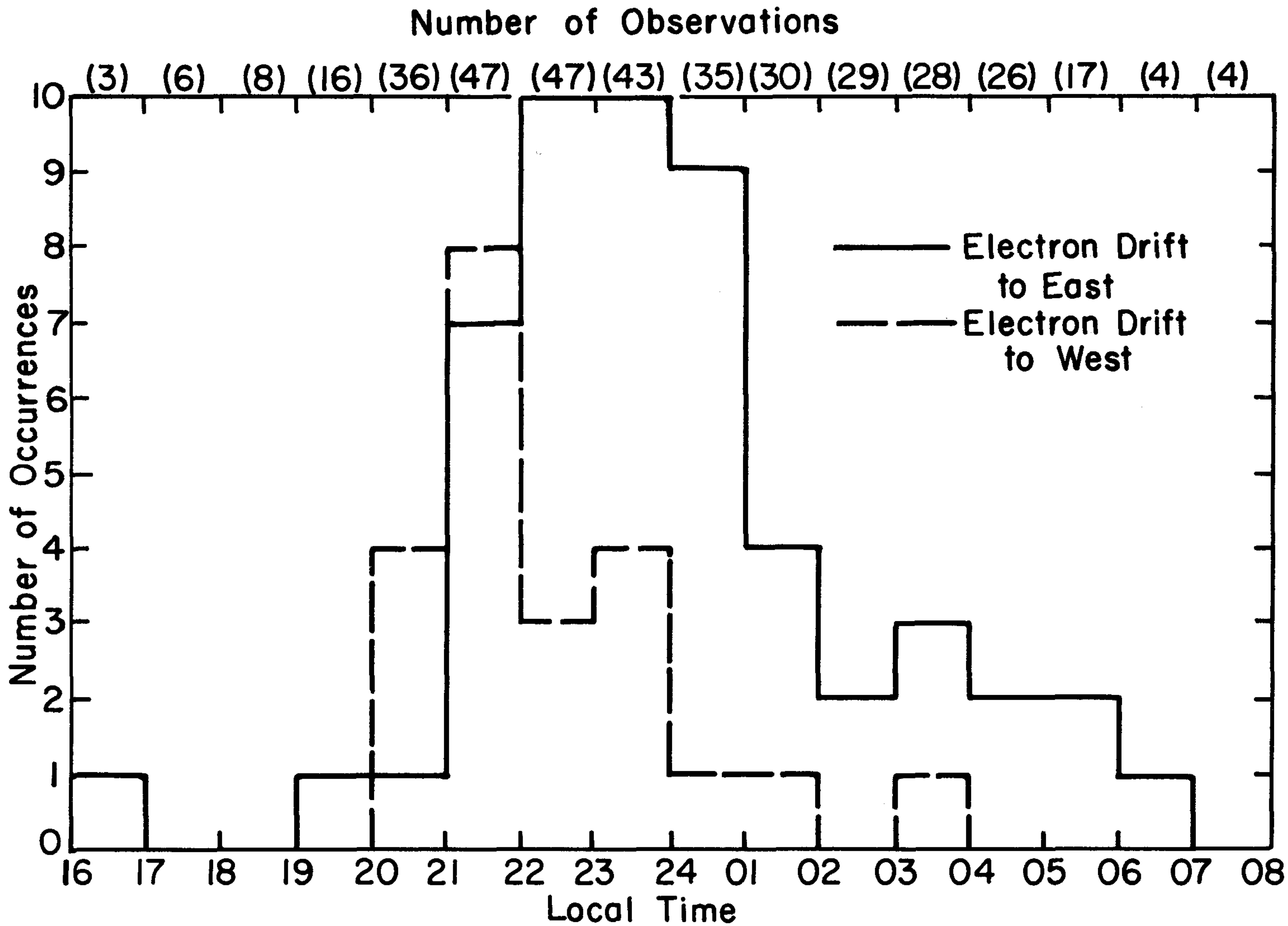

Figure 21. Nocturnal Variation of Drift Motions to East and West

in the velocities of the electrons in the auroral region. In the discussion of our interferometer results (see Chapter IV), it was shown that the variation in velocities was probably not greater than 1.5 to 1. Upon the assumption of uniform velocities, a speed can be calculated from an examination of the spectra. An example was presented in Equation (4.7), for which a speed of around 1,100 m/s was found. Such a calculation, however, is impossible for the records where echoes were received from only one side of north.

A cruder computation of the speed can be made by estimating the mean frequency shift (Δf_m) from the recorded spectrum. Since the gain of the antennas is greatest at an azimuth angle of 30 degrees, the mean shift may be assumed to be associated with echoes from that direction. On that basis, Equation (6.1) may be rewritten

$$\begin{aligned} v &= 2.84 \ \Delta f_m \quad \text{for 106 Mc/s} \\ v &= 7.30 \ \Delta f_m \quad \text{for 41.15 Mc/s} \quad . \end{aligned} \tag{6.2}$$

The observed frequency shifts at 106 Mc/s varied from 0 to 800 cps; the mean shifts varied from 125 to 500 cps. At 41.15 Mc/s the observed frequency shifts varied from 0 to 500 cps; the mean shifts varied from 50 to 200 cps. Using Equation (6.2), the velocities measured at 106 Mc/s ranged from 360 to 1,425 m/s; at 41.15 Mc/s they ranged from 365 to 1,460 m/s. It should be emphasized that most of the measurements at the two frequencies were not made on the same nights, so it is all the more astonishing that the results should be so nearly equal. The median speed measured at 106 Mc/s was 720 m/s; at 41.15 Mc/s, for 153 measurements, the median was 730 m/s.

Although the accuracy of the figures quoted above is probably not better than + 50 per cent or - 25 per cent, it is also doubtful that the errors can be much greater. The method used to estimate the speeds possibly leads to values that are somewhat too small, since the effect of aspect sensitivity would increase the amplitudes of components arriving from small azimuth angles. Again it is somewhat surprising that the results at the two frequencies should have the same average value of about 725 m/s. That value can be compared with the 700 m/s value (see Equation (3.2)) that we computed by considering the average current systems described in Chapter III. It is also of the same order of magnitude as the speeds measured in the E and F regions during magnetic storms by the radio means described in Chapter I.

Comparison of the auroral Doppler shift measurements with magnetic observations made concurrently at College and Point Barrow by the United States Coast and Geodetic Survey can at best be only qualitative. It will be recalled from the discussion in Chapter V that the radio echoes observed are obtained from a zone 400 to 800 km geomagnetically north of College. The disturbances in the magnetic field at any single station depend of course on the total current system and are strongest when the intense currents are overhead at that station. Point Barrow, as shown in Figure 20, is about 52 degrees west of geomagnetic north from College.

The actual current systems can only be derived from magnetograms taken at many stations. This is particularly true since, as mentioned in Chapter III, many of the disturbances are quite localized.

2. Description and Interpretation of Sample Records

It is not surprising, of course, that the nights on which auroral echoes were observed were also nights of visual auroras and magnetic activity. A selection of sample nights will be described. The nights selected were ones on which echoes were obtained from both east and west of geomagnetic north. The strength of the current can be judged from the fact that an infinite linear current at a distance r (meters) is related to the total disturbance field $\Delta\gamma$ by

$$I = 5 \times 10^{-3} \, r \, \Delta\gamma \text{ amps} \quad . \qquad (6.3)$$

Thus for a $\Delta\gamma$ equal to 10^3, the current at a range of 100 km is 5×10^5 amps, the same order of magnitude as the intense currents described in Chapter III. In most cases the greatest disturbance is in the horizontal component H. For the order-of-magnitude comparisons made here, ΔH may be considered to be $\Delta\gamma$. In addition, there should be a correction for the effect of the earth currents. Since Harang [1946] showed that near the auroral zone taking account of the earth currents would reduce the computed value by only about 10 per cent, this correction is negligible for our purpose.

In the descriptions which follow, it should be noted that a positive bay in H would be caused by an eastward current or a westward drift of electrons. A negative bay in H would be associated with an eastward drift of electrons. In all cases the times quoted are Alaska Standard Time. The directions referred to are in geomagnetic co-ordinates.

<u>January 29-30, 1957</u>

Description: Auroral echoes were obtained from 2045 to 2115 and from 2210 to 2235. In both cases the drift motion was to the east. The College magnetogram shows a small positive bay in H from 1800 to 2100 and a negative bay from 2100 to 2230. The maximum ΔH occurred between 2220 and 2240 with a magnitude of 880 γ. At Point Barrow the disturbance in H began suddenly at 2210. A large bay with a magnitude of 1,250 γ lasted until 2220; it was followed by a small negative bay that lasted until 2320.

Interpretation: In general, the large negative bays observed are consistent with the eastward drift motion measured. While our auroral echoes indicated drift motion to the east from their onset at 2045, the College magnetogram indicates that the transition from westward electron motion to eastward started at 2100. It will be recalled, however, that the current discontinuity progresses southward and would be expected to occur earlier in the region from which the echoes are obtained. Again, the radio echoes disappeared before the time of maximum ΔH at College, when the current system was closest to College. The beginning of the disturbance at Point Barrow coincided with the beginning of our second echo period. The end of the large negative bay shown on the magnetic record for Point Barrow at 2320 is consistent with the fact that after that time all our echoes were received from the east.

March 19-20, 1957

Description: Auroral echoes were obtained from the beginning of observations at 2058. Measurements from 2140 to 2205 showed that the drift motions were to the west. From 2225 to 2345 the motions were to the east. The frequency shifts were greater on the east antenna, indicating that the auroral region extended only slightly west of north. The College magnetogram shows a positive bay of about

300 γ from 1940 to 2200 and a negative bay of about 300 γ from 2200 to 2300. An additional small negative bay was present from 2310 to 2345. The Barrow magnetogram shows only small, high frequency fluctuations in H of about 100 γ from 2100 to 0110. The main disturbance in the field at Point Barrow was in its declination.

Interpretation: The transition of electron drift motions from westward to eastward checks very well with the transition from a positive bay to a negative bay. The echoes disappeared at the same time that the negative bay ended. The fact that the major disturbance at Point Barrow was in declination is consistent with the observation that the echo region extended only somewhat west of north.

March 22-23, 1957

Description: Auroral echoes began at 2235 from east of north. The drift motion was to the west until 2355, when it reversed toward the east. From 2359 to 0007 the echoes were received from both east and west of north; but from 0007 to 0041 the echoes were all from the west. From 0041 to 0145 echoes were again received from both east and west of north. The drift motion was always to the east after 2355. The College magnetogram shows slightly positive ΔH before 2400 followed by a large negative bay of up to 600 γ from 2400 to 0145, and a small negative bay from 0156 to 0300. At Point Barrow the negative bay started at 0030 and continued until 0200 with a maximum ΔH of about 750 γ. Again large changes in declination occurred at Point Barrow.

Interpretation: The westward electron drift motions observed before 2355 appear to be associated with only a very small +ΔH at College. However, the fact that echoes were received only from east of north until that time suggests that the current region was quite localized. At 2355, the transition to eastward electron motions correlates well with the large magnetic bay at College. The fact that echoes were received from west of north from 0007 to 0041 is consistent with the late start of the negative bay at Point Barrow. The localized region appeared to progress westward along the auroral zone.

March 24-25, 1957

Description: Auroral echoes were obtained from the beginning of observation at 2052. The echoes were from the east and indicated westward motion until 2120. Between 2120 and 2230 the motions were mixed with echoes from both east and west starting at 2202. After 2230 the drift motion was always to the east, the echo from west of north being strong from 2312 to 2332. After 2332 the echo was from the east until 0014, after which the echo disappeared. At College there was a positive bay in H from 1530 to 2230, with the major disturbance ending at about 2115 and only a small disturbance continuing until 2230. At 2230 a large negative bay began, reaching 600 γ at times. At 0009 there was a sharp recovery in H with a small negative bay continuing until 0400. After 0300 the ΔZ component was positive until 0400, indicating that the major current was south of College. The Point Barrow magnetogram shows a negative bay in H of up to 600 γ from 2230 to 2330.

Interpretation: The large positive bay in H at College before 2120 agrees with the westward auroral drift motions until that time. The mixed motions coincide with a period of transition between the positive bay and the negative bay beginning at 2230.

The fact that after 2230 the auroral motions were only to the east checks well with the negative bay observed. The sharp recovery of the negative bay at 0009 coincides with the decrease and final disappearance of the echoes at 0014. The current region again appears to have progressed westward, the later appearance of echoes from the west after 2202 and the large west amplitude from 2313 to 2332 correlating with the negative bay at Point Barrow from 2230 to 2330.

March 28-29, 1957

Description: Auroral echoes were present from the beginning of observations at 0847. The motion was always to the east. Echoes were received on both antennas until the echoes disappeared at 0906. The College magnetogram shows a series of negative bays starting at 0320. The last negative bay started at 0805 and reached a maximum ΔH of about 860 γ. By 0900 the H field was returning to normal, and it reached its normal value by 0915. At Point Barrow a series of negative bays in H started at 0315. The last negative bay started at 0815, reached 1,100 γ between 0836 and 0845, and had returned almost to normal by 0915.

Interpretation: In this case, radio observations were made only at the end of the disturbance. The eastward motions correlate with the negative bay in H. The disappearance of the echoes coincides closely with the end of the magnetic bay.

3. Conclusions

The analysis of our results, as described in this chapter, shows an excellent statistical agreement with the motions deduced from the current systems responsible for magnetic disturbances. The speeds and directions measured by the Doppler shift method also agree very well with those measured by other radio techniques during magnetic disturbances. We have included more detailed descriptions of particular nights to demonstrate the substantial qualitative agreement of our measurements with the magnetic observations. We conclude therefore that the electron motions in radio auroral regions are produced by the electric fields that drive the currents responsible for magnetic disturbances.

The most intense currents are ordinarily east-west, even though north-south components are present. A probable explanation for the relatively few times that we detected motions that were not approximately east-west is that the auroral echoes come from the region of most intense currents (see Figure 2). The technique used unfortunately did not lead to an accurate determination of the north-south component.

From the information gained in this experiment, the general nature of the motions of auroral ionization appears to be established. The uncertainty as to the cause of the rapid fading rates observed in radar auroral studies is now resolved. Booker's statement, quoted in the Introduction to this report, that the rapid fading could not be explained in terms of windspeed and turbulence is undoubtedly correct. The explanation lies in the electric fields set up in auroral regions. These fields cause the charges to move rapidly, thus producing large Doppler shifts in the echoes. The addition over the radar passband of these randomly phased, frequency shifted echoes produces the rapid fading.

We believe that this study has led to a better understanding of the Doppler shifts of auroral radar echoes and of the electron drift motions that cause them. By applying this increased knowledge, it may be possible to improve high latitude radio communications. To define and localize the motions more exactly, further work in this field should be conducted with narrow beam antennas.

References

Bailey D. K., Bateman R., Berkner L. V., Booker H. G., Montgomery G. F., Purcell E. M., Salisbury W. W., and Wiesner J. B.	1952	PHYS. REV. 86, 141
Baker W. G. and Martyn D. F.	1952	NATURE 170, 1090
Baker W. G. and Martyn D. F.	1953	PHIL. TRANS. ROY. SOC. (LONDON) A 246, 281
Bless R. C., Gartlein C. W., and Kimball D. S.	1955	AP. J. 122, 205
Booker H. G.	1956	J. ATMOS. TERR. PHYS. 8, 204; J. GEOPHYS. RES. 61, 673
Booker H. G.	1957	Paper presented at Spring URSI meeting, Washington, D. C., May 22-25
Bowles K. L.	1954	J. GEOPHYS. RES. 59, 553
Bowles K. L.	1955	Cornell University School of Electrical Engineering Research Report EE 248
Briggs B. H. and Spencer M.	1954	REP. PROG. PHYS. 17, 245
Bullough K. and Kaiser T. R.	1954	J. ATMOS. TERR. PHYS. 5, 189
Bullough K. and Kaiser T. R.	1955	J. ATMOS. TERR. PHYS. 6, 198
Chapman J. H.	1953	CANAD. J. PHYS. 31, 120
Chapman S.	1953	Proceedings of Conference on Motions in the Upper Atmosphere, University of New Mexico, September 7, 8, 9
Chapman S. and Bartels J.	1940	Geomagnetism, vol. I. Oxford: Clarendon Press
Chapman S. and Little C. G.	1957	J. ATMOS. TERR. PHYS. 10, 20
Dagg M.	1957	J. ATMOS. TERR. PHYS. 10, 194

Dyce R. B.	1955	Cornell University School of Electrical Engineering Research Report EE 249
Edwards H. D., Bedinger J. F., Manring E. R., and Cooper C. D.	1955	_The Airglow and the Aurorae._ Proceedings of Symposium at Belfast, September, 1955. London and New York: Pergamon Press, p. 122
Fejer J. A.	1953	J. ATMOS. TERR. PHYS. _4_, 184
Fricker S. J., Ingalls S. M., Stone M. L., and Wang S. C.	1957	Paper presented at Spring URSI meeting, Washington, D. C., May 22-25
Fukushima N.	1953	J. FAC. SCI. TOKYO UNIV. _8_, part V, 293
Fuller V. R. and Bramhall E. H.	1937	_Auroral Research at the University of Alaska, 1930-1934._ Misc. Publ. Univ. of Alaska 3
Geophysical Institute	1955	Interim Scientific Report No. 1, Contract AF CRC-TN-55-579. August 15, 1955
Hagg E. L. and Hanson G. H.	1954	CANAD. J. PHYS. _32_, 790
Harang L.	1946	TERR. MAG. _51_, 353
Harang L.	1951	_The Aurorae._ New York: John Wiley and Sons
Heppner J. P.	1954	Ph. D. Thesis, California Institute of Technology; J. GEOPHYS. RES. _59_, 329
Heppner J. P., Byrne E. C., and Belon A. E.	1952	J. GEOPHYS. RES. _57_, 121
Hewish A.	1952	PROC. ROY. SOC. A _214_, 494
Kaiser T. R.	1955	_The Airglow and the Aurorae._ Proceedings of Symposium at Belfast, September, 1955. London and New York: Pergamon Press, p. 156
Krogness O. and Tönsberg E.	1936	GEOF. PUBL. _11_, no. 8 (1934-1937)

Leinbach H. and Little C. G.	1957	Paper presented at Spring URSI meeting, Washington, D. C., May 22-25
Liller W. and Whipple F. L.	1954	Rocket Exploration of the Upper Atmosphere. London: Pergamon Press; New York Interscience Publishers, p. 112
Little C. G. and Maxwell A.	1952	J. ATMOS. TERR. PHYS. 2, 356
Little C. G., Rayton W. M. and Roof R. B.	1956	PROC. I.R.E. 44, 992
Maxwell A.	1954	OCCAS. NOTES ROY. ASTRON. SOC. LONDON 3, no. 16, 65
Maxwell A. and Dagg M.	1954	PHIL. MAG. 45, 551
Maxwell A. and Little C. G.	1952	NATURE 169, 746
Meek J. H.	1953	J. GEOPHYS. RES. 58, 445
Meek J. H.	1954a	AP. J. 120, 602
Meek J. H.	1954b	J. GEOPHYS. RES. 59, 87
Meinel A. B. and Schulte D. H.	1953	AP. J. 117, 454
Meinel A. B.	1955	AP. J. 122, 206
Mitra S. K.	1952	The Upper Atmosphere, 2nd ed. Calcutta: The Asiatic Society
Nagata T.	1950	J. GEOPHYS. RES. 55, 127
Olivier C. P.	1947	PROC. AM. PHIL. SOC. 91, 115
Owren L. and Stark R.	1956	Quarterly Progress Report No. 3, Contract DA-36-039-sc-71137. Geophysical Institute, Univ. of Alaska, 1 September to 1 December, 1956
Peterson A. M., Leadabrand R. L., and Dyce R. B.	1957	Paper presented at Spring URSI meeting, Washington, D. C., May 22-25

Ratcliffe J. A.	1954	Report of the Physical Society Conference on the Physics of the Ionosphere, Cambridge, Sept. 1954. London: The Physical Society, 1955, p. 88
Roach F. E., Williams D. R., and Pettit H.	1953	AP. J. 117, 456
Silsbee H. C. and Vestine E. H.	1943	TERR. MAG. 47, 195
Spencer M.	1955	PROC. PHYS. SOC. B 68, 493
Störmer C.	1955	The Polar Aurora. Oxford: Clarendon Press
Villars F. and Weisskopf V. F.	1954	PHYS. REV. 94, 232
Wells H. W.	1947	TERR. MAG. 52, 315