A STUDY OF RELATIONSHIPS BETWEEN THE AURORA BOREALIS AND THE GEOMAGNETIC DISTURBANCES CAUSED BY ELECTRIC CURRENTS IN THE IONOSPHERE

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ABSTRACT

In high latitudes, magnetic disturbances attributable to intense electric currents in the upper atmosphere are known to occur simultaneously with visible aurora. With few exceptions past investigations have merely revealed statistically that the degree of magnetic disturbance is proportional to the intensity of auroral activity.

In the research reported here, magnetic records and auroral observations from College (Fairbanks), Alaska have been studied in detail to determine the manner in which these phenomena are related. It is found that the relationships are quite definite and that practically all, if not all, disturbances may be represented in terms of two closely related patterns describing sequences of auroral activity which accompany positive and negative "bay" disturbances. Disturbances may appear extremely complicated due to repetition and overlapping of bays; examples are given to illustrate that these disturbances can be easily separated into individual bays by examining the sequence of auroral activity. A discontinuity in auroral activity occurs simultaneously with the reversal in direction of electric currents during the midnight hours; this feature indicates a dependence between the aurora and the electromotive force and thus contradicts a common opinion that aurora merely augments the conductivity. The pattern of behavior during magnetic storms preceded by sudden commencements is the same as on other nights.

A preliminary analysis suggests that sudden commencements, reported on a world-wide scale, may be related to sudden changes from homogeneous to rayed aurora in the auroral zone.

(continued on next page)

Special attention is given to: (1) the spatial association of aurora and electric currents, (2) a previously undescribed interval of $+\Delta H$ disturbance following negative bays, (3) auroral pulsations and movements, and (4) the repetition of similar features on consecutive nights.

Theories and suggestions as to the cause of aurora and auroral zone currents are examined with reference to the present study.

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I. INTRODUCTION

In high latitude regions the coincidence of magnetic disturbance with the visual presence of aurora is a well known fact. Despite this fact, one finds that with few exceptions the investigations relating the two phenomena are of a statistical nature that merely reveal that the magnitude of the disturbance is proportional to the intensity of the auroral activity. Harang [1] has given a brief, but comprehensive, summary of the few exceptions to this statement. Meek [2] has very recently studied relationships between the magnetic horizontal component and auroral light intensities at Saskatoon, Saskatchewan in a more detailed manner than previous investigations.

The research reported here represents an attempt, first to find out if detailed relationships exist between aurora and magnetic disturbance, and second to organize the relationships, if found, into "patterns" which apply to a large majority, and perhaps all, of the nights on which the phenomena occur. From the magnetic disturbance one may infer the atmospheric electrical currents causing the disturbance; thus, indirectly the relationships sought are between the aurora and the electrical currents. The writer believes the attempt has been successful; the success, of course, is provided by the phenomena. It is found that only two patterns are necessary and they, in turn, are closely related. The patterns represent a sequence of simultaneous behavior which is distributed in time and in geomagnetic latitude. As such they do not indicate the exact time and latitude or the length of time and breadth of latitude of particular features. This is quite understandable; on any given night as a function of time and latitude one is confronted with the complex variations of the magnetic field and at least 12 forms of the aurora, each of varying intensity. Fortunately, it is possible to classify the auroral forms in only 7 groups without great loss of detail.

Once a pattern of behavior is determined, it is possible to "test" the great variety of theories and suggestions that have been put forth to explain the distribution and cause of the intense auroral zone currents and the aurora. "Testing" naturally leads to criticism and the reader will find that much of the criticism is directed toward the proposals of Dr. Chapman and his collaborators. This is unavoidable as these proposals are based on careful and extensive studies which have prevailed in the literature.

To many, it may seem presumptuous to construct patterns and draw conclusions on the basis of observations from only one station. Certainly it is a limitation. In starting the study, justification stemmed from the following. (1) In most cases, major changes in the aurora, in a given geomagnetic latitude zone, take place from horizon to horizon in less than 5 or 10 minutes and not unusually in less than one minute. For the common auroral heights the longitude range over which an observer at College, Alaska can identify the activity is more than 30° along his latitude. The range decreases with increasing latitude as will be noted in Figure 1. From this, it is apparent that longitudinal variations will be small except at times of significant change. The magnetic disturbance will thus be representative for the type of aurora over roughly 30° of longitude. In comparing College and Sitka, Alaska magnetograms it is surprising to see how well this assumption is borne out. Although Sitka is about 15° east and 5° south of College, major features on the horizontal component occur at the same universal time except during periods when different auroral forms exist between the latitudes of the stations. (2) As the type of auroral activity is zonal according to latitude the disturbance at one station will be affected principally by the activity nearest the latitude of the station. However, over a number of nights the distribution with latitude shifts relative to the station; for a large number of nights one thus gets a large sample of differences expected from the latitudinal zoning. In carrying out the investigation it was apparent that these elementary notions were justified. The ideal location of the station is one of the principal reasons. However, many problems arise which can only be solved by simultaneous observations at a number of stations spaced around the earth. These problems will probably be investigated during the International Geophysical Year 1957-1958, if not before.

The auroral observations were taken throughout the winters of 1950-1951 and 1951-1952 by the writer and co-workers at the Geophysical Institute, College, Alaska. The purpose at that time was to correlate auroral activity with ionospheric parameters and radio wave propagation conditions; this necessitated very detailed and complete observations of form and location. The necessity of equally detailed observations for the present study is especially evident considering Fuller and Bramhall's [3] conclusion that "no significant sequence in diurnal variation of the (auroral) displays could be detected". Their conclusion followed four years (1930-1934) of auroral studies at College, Alaska; however, they state clearly that their records were of a discontinuous nature. The quality of the observations used here permits one not only to detect sequences in the diurnal variation, but also to illustrate detailed features of the sequences. The quality of these observations has thus made the present study possible. The magnetograms were obtained from the permanent observatory of the U.S. Coast and Geodetic Survey at College, Alaska.

Some of the terminology may seem peculiar to the reader unfamiliar with this field of study; brief explanations may be found in the Parts where they first appear or in references [1,4,5,6]. "Nightly variations" are spoken of instead of the usual term "diurnal variations" as we are concerned with the night hours when most of the disturbance takes place. "Latitude" will always mean geomagnetic latitude and directions are relative to the geomagnetic meridian.

II. AURORAL OBSERVATIONS

In recording visual auroral observations the basic information desired is a record of the forms of the aurora, their intensities, and their positions in the observer's sky as a function of time. Additional information is obtained by recording colors, movements, and other distinctive features. Limitations imposed by cloudiness, moonlight, and twilight must also be specified. It is essential that this be done in a simple manner as the task of continuing observations through the usual period of 12 to 15 hours becomes quite tedious. The frequency of observations may vary with the degree of activity. At College, observations under clear sky conditions were, in general, taken at 15 minute intervals. At times of rapidly changing aurora, observations were often continuous.

Observations during the winter 1950-1951 were recorded by dividing the sky into sections and specifying the auroral activity in each section. Recognizing that this method often led to lengthy descriptions, drawing of diagrams, and limited accuracy in locating the positions of aurora, a different method was adopted for the winter 1951-1952. With this method each observation was taken on a separate sheet on which a zenith angle projection of the sky was plotted. Zenith angle circles were spaced to aid in correcting for the apparent flatness of the sky, and horizon markers helped in determining azimuths. Outlines of the positions of different auroral forms were sketched on these sheets along with notes as to intensities, colors, and distinctive movements.

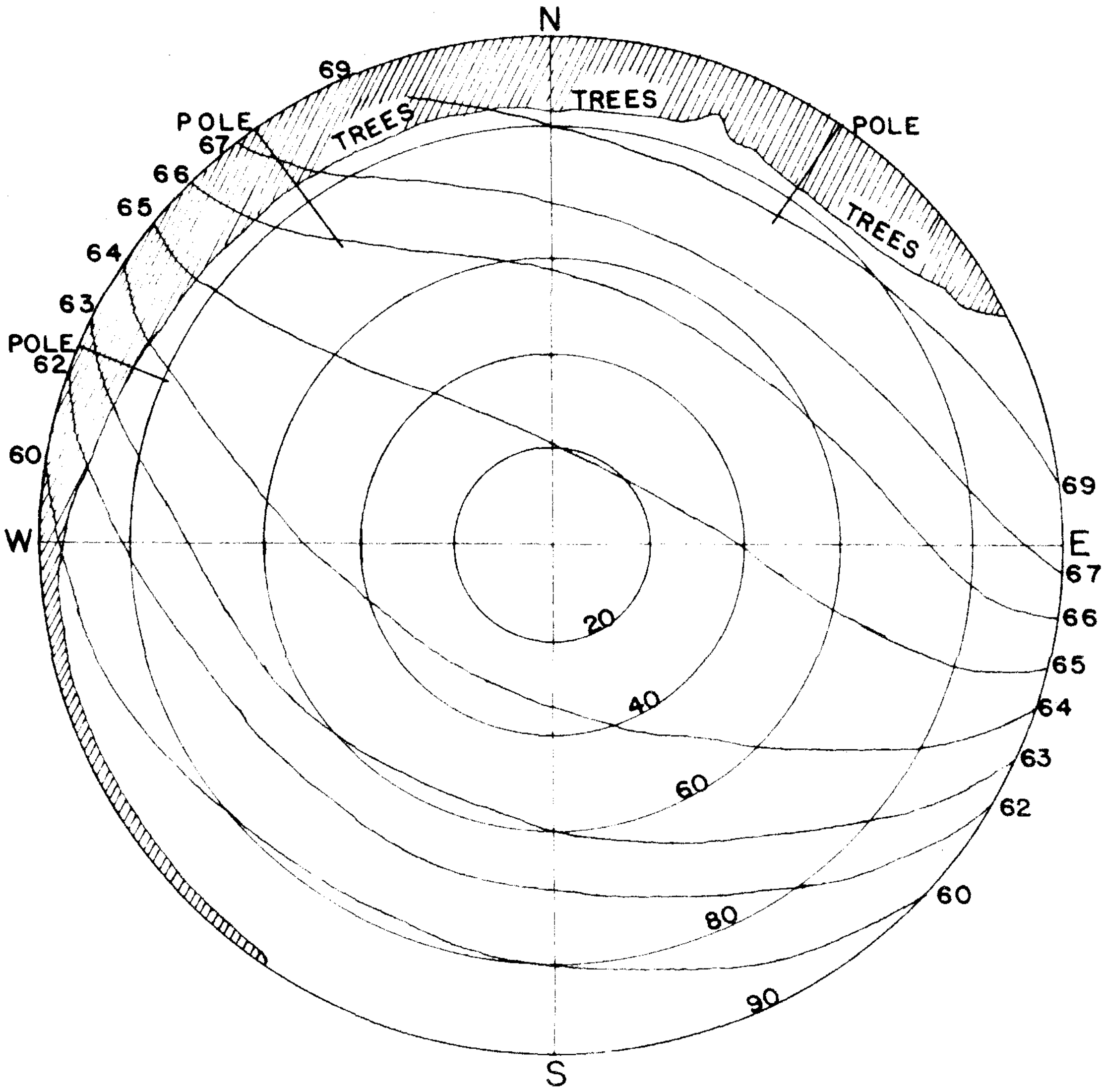

FIGURE 1--COLLEGE, ALASKA, AURORAL OBSERVATION SHEET WITH GEOMAGNETIC LATITUDES SUPERIMPOSED FOR AURORA AT A HEIGHT OF 115 KM.

For the present study this method has the added advantage that sky positions can be readily converted to geomagnetic latitude. Geomagnetic coordinate systems were computed with respect to the zenith angle projection for assumed auroral heights of 105, 115, and 150 kilometers. In Figure 1 lines of geomagnetic latitude, computed for a height of 115 km. have been superimposed on an observation sheet for illustration. In general, the assumed height is not critical except in cases of long rays and observations near the horizon. For example: latitudes 66.5° and 69° for a height of 150 km. correspond, respectively, to about 66° and 68° for a height of 105 km. Accurate identification of auroral forms is possible from the zenith down to altitudes of 5 to 10°; below this, identifications can often be made but are questionable. The decrease in longitudinal range of observation with increasing latitude is obvious from Figure 1. By use of diagrams like Figure 1 it has also been possible to reduce the 1950-1951 observations to geomagnetic location.

An excellent classification of auroral forms has been adopted by the International Geodetic and Geophysical Union [see 1,4]*. When properly used it reduces the variety of auroral forms to a simple set of words (or symbols) with which observers can communicate descriptions without ambiguity. A weak point in the classification is that the form "draperies" (D) becomes a catchall. This can be corrected by using the term "diffuse draperies" (DD) for relatively inactive, low intensity draperies and the term "pulsating draperies" (PD) for pulsating rayed patches, leaving draperies (D) to describe rayed patches of moderate and great intensity.

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* Photographic Atlas of Auroral Forms, International Geodetic and Geophysical Union, Oslo (1930).

In representing the auroral activity for entire nights on simple diagrams such as those shown in Plates 1 to 18, complete use of the international classification is cumbersome. For this purpose the grouping of auroral forms symbolized on the following page and described below was adopted on finding that magnetic variations could most consistently be related to it with a minimum of detail.

Homogeneous arcs and bands: quiet homogeneous arcs which extend from horizon to horizon are by far most common.

Rayed arcs and bands of faint to moderate intensity: like the homogeneous group but with obvious rayed structure.

Active, bright rayed forms: brilliant rayed bands, rayed arcs and draperies; usually with rapid movements and reddish colors.

Diffuse rayed patches: large and small, rayed patches of faint to moderate light intensity; primarily, diffuse draperies and rays.

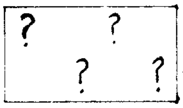
Diffuse surfaces: large and small, cloud-like patches without rays.

Pulsating aurora: any form which appears and disappears in a periodic manner; periods of five seconds to one minute predominate; pulsating surfaces are most common, pulsating arcs occur more frequently than pulsating draperies; flaming aurora is a form of pulsating aurora in which pulsations are directed toward the magnetic zenith.

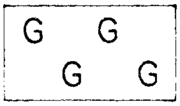
Glow: faint light with indistinct boundaries.

In Plates 1 to 18 (to be discussed in Parts VII, VIII, and IX), the auroral activity is represented in terms of the above groups as a function of 150th Meridian Standard Time and geomagnetic latitude.

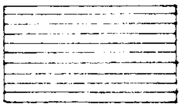
LEGEND OF AURORAL SYMBOLS



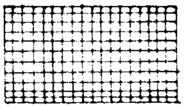
INCOMPLETE OBSERVATIONS



GLOW



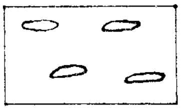
HOMOGENEOUS ARCS & BANDS



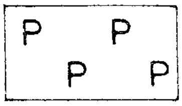
RAYED ARCS & BANDS OF FAINT TO MODERATE INTENSITY

ACTIVE BRIGHT RAYED FORMS

DIFFUSE RAYED PATCHES



DIFFUSE SURFACES



PULSATING AURORA

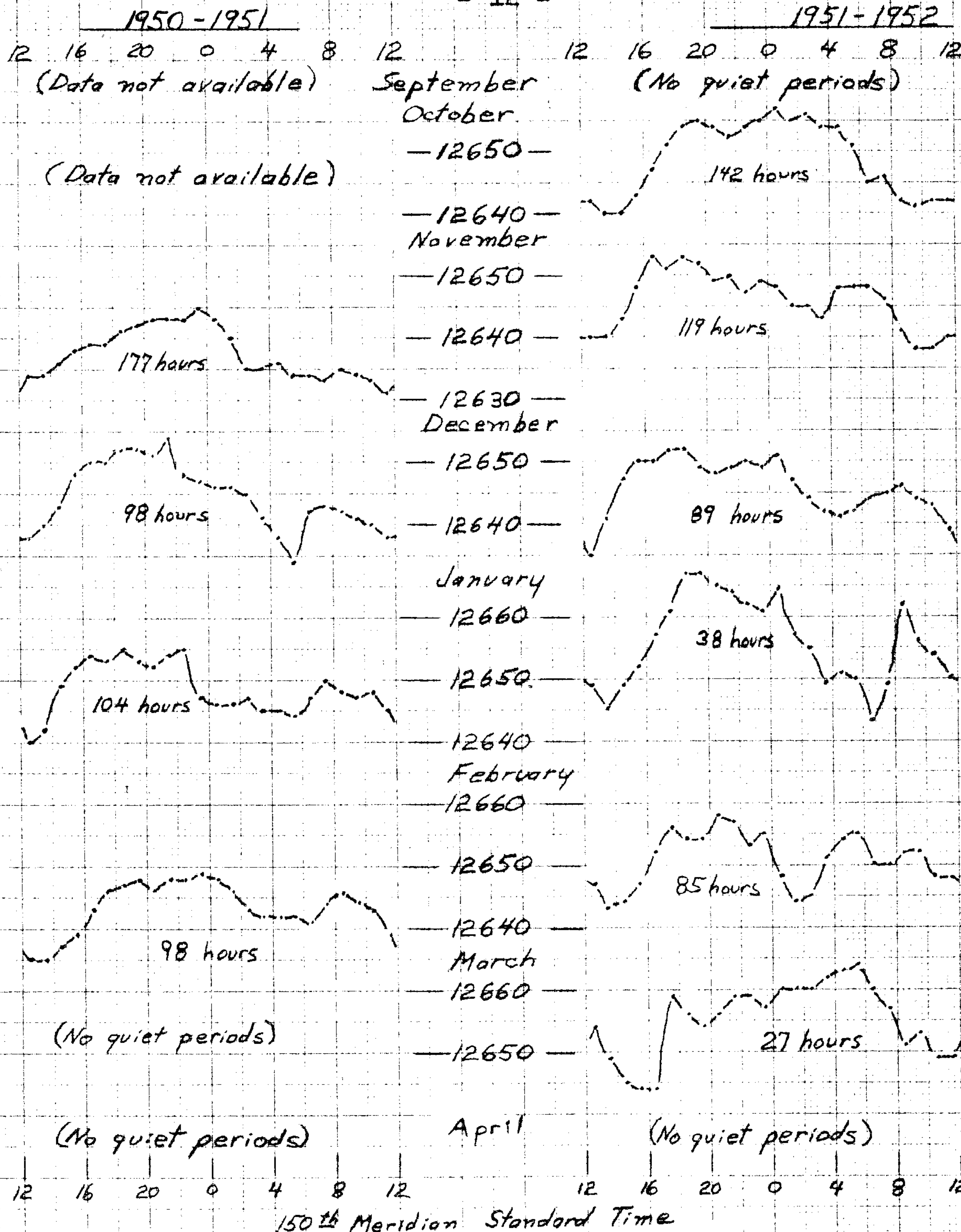
The meridian time lags local time by nine minutes. Limitations inherent in these diagrams are principally: (1) restriction of the amount of detail, (2) luminosity must be inferred from the type of activity, and (3) longitudinal variations are not represented. The diagrams do, however, illustrate: (1) the predominate type of activity at a given time and latitude, (2) the times and sequences of changes in the type of activity, (3) the southward advance of aurora during the first stage of activity, and (4) the tendency for the aurora to recede northward before dawn. Often several forms co-exist over a large area; this is especially true for the diffuse and diffuse pulsating forms. In such cases the symbols for both types of activity are used. The lines separating types of activity are, in general, interpolated between observations; when changes occurred during an observation, the lines are exact. Dashed lines are used where interpolation is uncertain.

III. COMPUTATION OF DISTURBANCE VECTORS

Magnetic disturbance may be defined as the difference between the instantaneous magnetic intensity and the mean value of magnetic intensity recorded at the same hour on magnetically quiet days occurring within the same month. In middle and low latitudes a common practice is to select the five quietest days of each month. Disturbance on other days is then determined by subtracting the hourly means for the five quiet days. In the vicinity of the auroral zone it is seldom possible to find five days per month which can reasonably be called "quiet"; consequently, a different procedure must be used in determining a quiet night baseline for computation of disturbance.

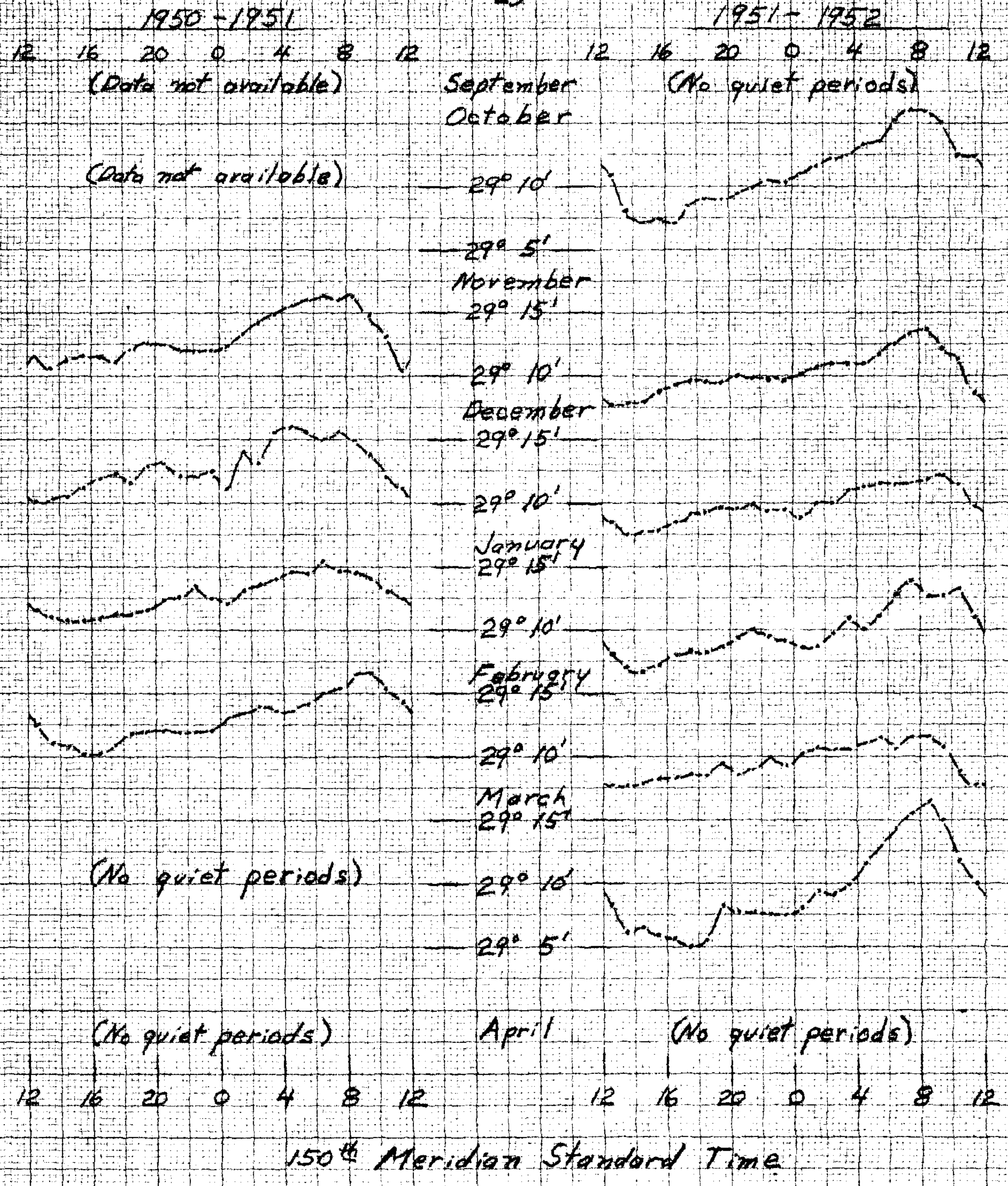
For the winters 1950-1951 and 1951-1952, quiet nights were selected by picking out periods of 26 or more successive hours in which the range in hourly values of H did not exceed 35 γ and 28 γ, respectively for the two winters. The first and last hours of each period were then excluded. For the 6 months, November 1950-April 1951, only 11 periods satisfied this condition and for the 8 months, September 1951-April 1952, only 13 periods satisfied this condition; thus they represent times of exceptional quiet. Curves showing the variations in H, D, and Z during these quiet periods are shown in Figures 2, 3, and 4. The auroral observations during these periods show that aurora is either absent or confined to glows and faint arcs near the north horizon.

Over a period of several months the quiet periods may be affected by seasonal variations and calibrations of the Z component



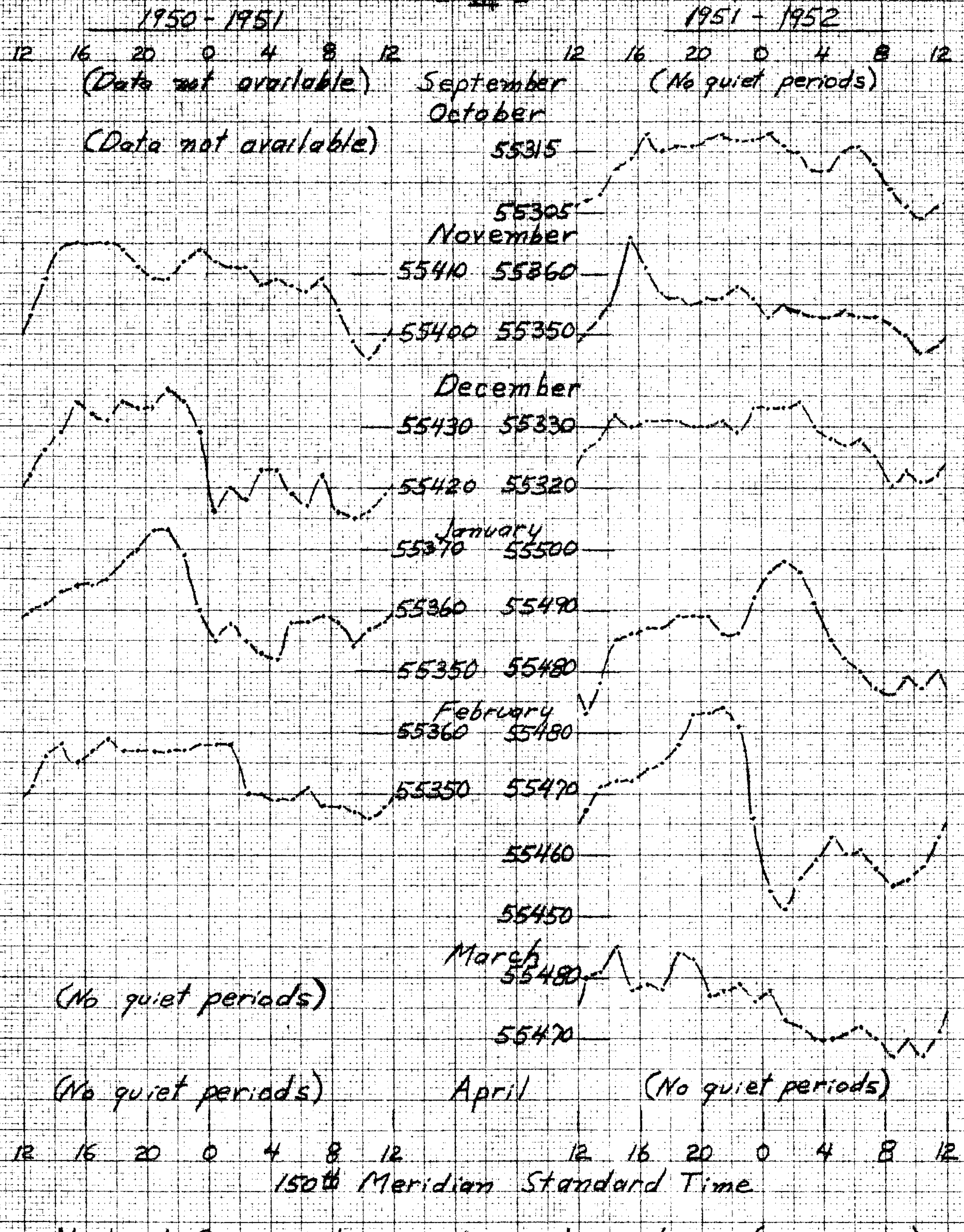
Horizontal Component: Quiet period variations (In gammas)
Averaged by months

Figure 2



Declination: Quiet period variations
Averaged by months

Figure 3



Vertical Component: Quiet period variations (In gammas)
Averaged by months
(For variability of baseline: See text)

Figure 4

may vary considerably. These variations would introduce errors if a mean annual quiet night baseline was used. To reduce such errors, only quiet periods occurring approximately within a month of the period of interest were used as a baseline for that period. For example, the quiet night baseline for the last half of January 1952 was obtained by averaging the quiet periods occurring in mid-January and early February. From Figure 4 it is obvious that determinations of the Z baseline may be erroneous. However, in determining ΔZ, errors can be minimized by fitting the quiet period Z baseline to the Z trace of quiet hours (usually daylight hours) occurring near the night for which disturbance is to be computed.

As the magnitude of disturbance is usually large compared to variations during quiet periods, use of a constant baseline averaged for all quiet hours would often be sufficient. However, the procedure followed here should give a more accurate picture of small disturbances.

In discussing disturbance it is convenient to use the following symbols for the magnetic elements, H, D, Z.

Let H, D and Z (without subscripts) represent the instantaneous horizontal component, declination, and vertical component.

Let H_q, D_q, and Z_q represent baseline values derived from quiet periods; then

$\Delta H = H - H_q$ (taken positive northward),

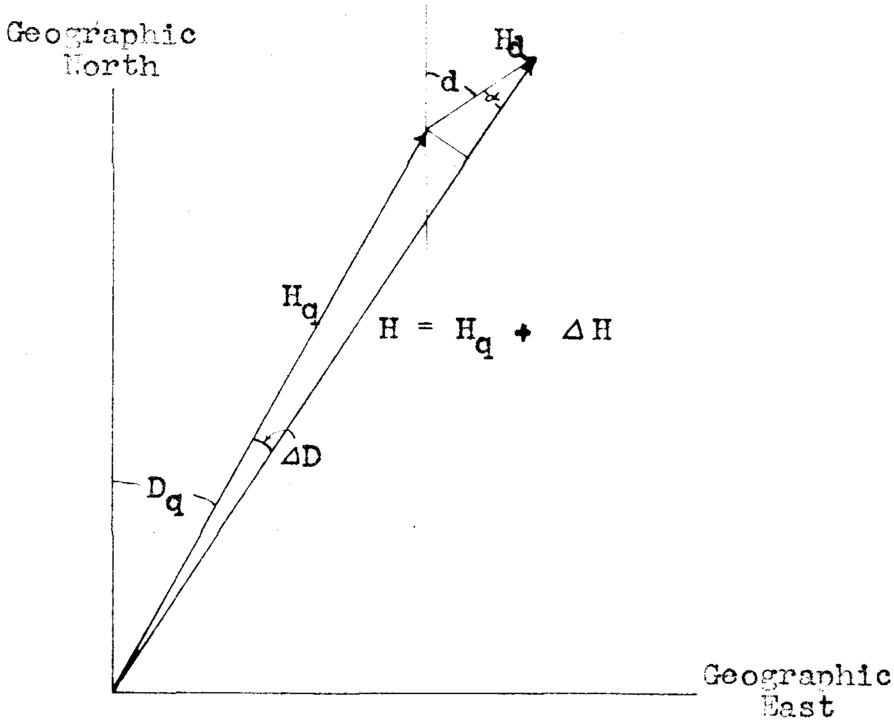
$\Delta D = D - D_q$ (taken positive eastward),

$\Delta Z = Z - Z_q$ (taken positive vertically downward)

are the disturbance values.

ΔD and ΔH may be combined trigonometrically to give H_d, the horizontal disturbance vector. This is illustrated in Figure 5.

In Plates1 to 18 (to be discussed later), horizontal disturbance vectors (H_d) and the signs and magnitudes of the vertical disturbance (ΔZ) are shown for various examples of auroral activity. During daylight hours and hours of very small or no disturbance the vectors are computed from hourly means. Where there is appreciable disturbance the vectors are usually computed from instantaneous values at 15 minute intervals. Where significant changes take place between 15 minute intervals, the intervals are altered to show these variations. The time scale is the same as for the auroral diagrams but is contracted between 07:00 and 17:00 to give more space to the dark hours. Azimuth angles are plotted with respect to the magnetic meridian. The corresponding magnetograms are numbered Plates 1' to 18'; as these are half-size tracings, minor fluctuations are only roughly indicated.



TO COMPUTE H_d (for $+\Delta H$, $+\Delta D$)

$$\tan\alpha = \frac{H_q \cdot \Delta D(\text{radians})}{\Delta H} = \frac{2.909(10^{-4})\ H_q\ \Delta D'}{\Delta H}$$

declination of $H_d = d = D_q + \Delta D + \alpha$

magnitude of $H_d = \dfrac{\Delta H}{\cos\alpha}$

Case	tan α	d	H_d
$+\Delta H, +\Delta D$	$\frac{2.909(10^{-4})\ H_q\ \Delta D'}{\Delta H}$	$D + \alpha$	$\frac{\Delta H}{\cos\alpha}$
$+\Delta H, -\Delta D$	$\frac{2.909(10^{-4})\ H_q\ \lvert\Delta D'\rvert}{\Delta H}$	$D - \alpha$	"
$-\Delta H, +\Delta D$	$\frac{2.909(10^{-4})\ H\ \Delta D'}{\lvert\Delta H\rvert}$	$180^\circ + D_q - \alpha$	"
$-\Delta H, -\Delta D$	$\frac{2.909(10^{-4})\ H\ \lvert\Delta D'\rvert}{\lvert\Delta H\rvert}$	$180^\circ + D_q + \alpha$	"

Figure 5 -- Horizontal disturbance vector, H_d

IV. DISTURBANCE VECTORS AS A MEASURE OF ELECTRICAL CURRENTS IN THE UPPER ATMOSPHERE.

In middle and low latitudes the existence of electrical currents in the upper atmosphere has been accepted for some time, primarily, on the basis of spherical harmonic analyses of the solar quiet day magnetic variations [4,6,7]. Theoretical reasoning as to the cause of these electrical currents has led to general acceptance of the "dynamo theory" of Stewart and Schuster [4,5,6]. Recent rocket measurements have directly established the existence of electrical currents in the E-layer near the equator [see Singer, Maple, and Bowen, 8].

In the auroral zone the simultaneous occurrence of aurora in the ionosphere and magnetic disturbance provides visible evidence for assuming that the disturbing currents lie in the ionosphere. In his classical study [1,4,6,9] Birkeland demonstrated that many "polar elementary storms" (now usually called "negative bays") could be attributed to the field of an infinite linear current situated 150 to 700 km. above the earth's surface. The disturbance field of such a current is given by $\Delta F = \frac{.2I}{R}$ gammas (1 gamma = 10^{-5} gauss), with I in amperes and R in kilometers. As the disturbance vector ΔF is tangential to the circular force lines, the intersection of perpendiculars drawn from ΔF at two stations lying along a line perpendicular to the current should locate the disturbing currents (see Figure 6).

Chapman [4,10] has pointed out that this method neglects currents induced in the earth and hence gives heights which are greater

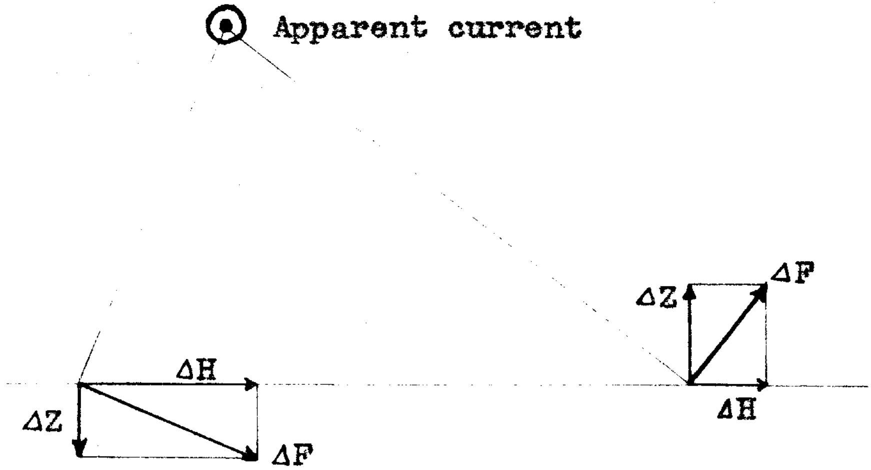


Figure 6 -- Birkeland's method of locating auroral zone currents

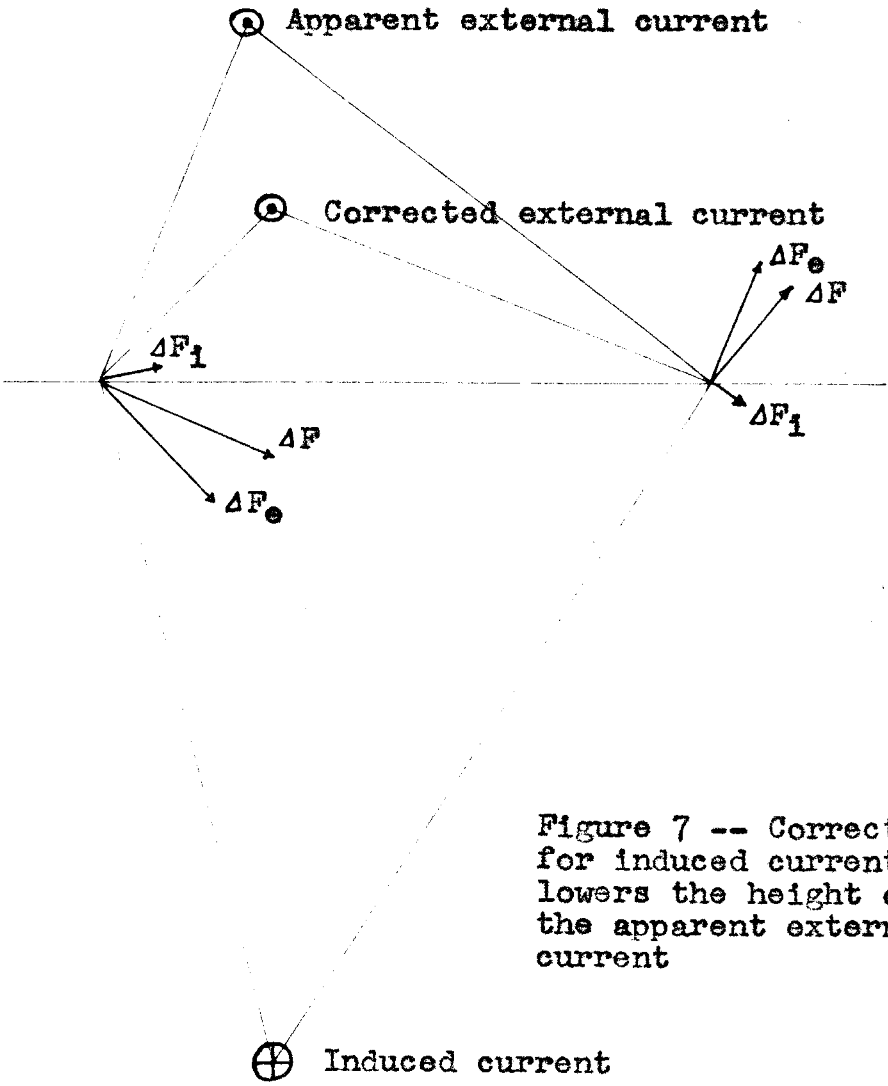


Figure 7 -- Correction for induced currents lowers the height of the apparent external current

than the true height. The induced currents will in general increase ΔH and decrease ΔZ. In Figure 7 this is illustrated by making the assumption that the induced current resembles the primary current and is therefore infinite, linear, and located at a depth in the earth which is thought to be highly conducting.

The problem of induced currents in the earth has been approached by numerous investigators but there appears to be little agreement. Theoretical studies [see Chapman, 4] are handicapped by the lack of information on the conductivity as a function of depth in the solid earth as well as limitations in assuming harmonic magnetic variations. From analyses of S_q variations, 0.6 to 0.7 of the total field is commonly attributed to external currents [4,6,7]. In the Carnegie Institute analyses [7, p. 359] reason was found to make this factor .9 near the center of the auroral zone, .7 near the zone, and .6 outside the zone. Harang [11] concluded that a factor .6 was implausible in the auroral zone but that .9 gave reasonable agreement between stations roughly along a meridian crossing the zone. McNish [6,12] calculated hypothetical current systems for the auroral zone using two-dimensional potential theory for both line and narrow sheet currents with factors of 0.6 to 0.8; he concluded that the currents must lie at an altitude of 100 to 200 km. In reviewing the literature pertaining to the heights of auroral zone currents, as determined from magnetic disturbance, it is quite striking to find that the heights determined are practically always above the usual auroral heights (i.e., >150 km.); this is in general true even when corrections for induced currents are made. [See Birkeland, Harang, Sucksdorff, 9,11,13.]

It is to be noted that in all the auroral zone investigations a single current, either a line or narrow sheet, has been assumed and mean rather than instantaneous values have been used. The validity of using mean values cannot readily be evaluated. However, on the basis of auroral behavior there is good reason to question the assumption of a single linear current. In general the aurora is not confined to one linear form. If we assume (see Part V) that the major part of the disturbing current coincides in space with aurora and there are, for example, several auroral arcs, a line current may then be located in each arc. In Figure 8 the disturbance vectors are illustrated for the simple case of two parallel arcs with equal currents. It is obvious that a single current located from the observed ΔF's would be considerably above the actual currents.

This argument may be extended to the hypothetical case where there is a continuous distribution of aurora with current distribution approximating an infinite uniform sheet. The disturbance is then given by $\Delta F = \Delta H = .2\pi I$, where I = amperes per cm., and is thus independent of height with $\Delta Z = 0$. This is a useful equation in low and middle latitudes but the large fluctuations in Z near the auroral zone demonstrate that the current is more linearly concentrated.

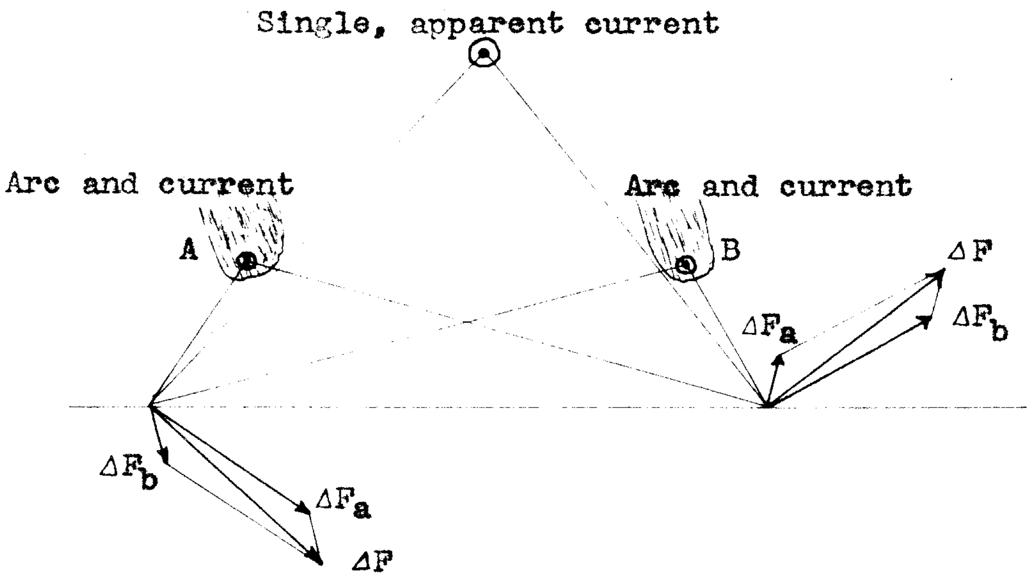


Figure 8 -- If a line current coincides with each auroral arc, the height of the apparent current, located from ΔF, will be too great.

V. THE ASSOCIATION OF ATMOSPHERIC ELECTRICAL CURRENTS AND AURORA

There are at least several good reasons for assuming that the greatest portion of the atmospheric disturbing current coincides fairly closely with visible aurora.

(1) Magnetic disturbance and the presence of aurora coincide in time and geographical position. This is well known but does not indicate, in a situation such as represented in Figure 8, whether currents are concentrated in the two arcs, or are distributed over the entire region.

(2) Maximum current densities should coincide with regions of greatest conductivity*. For a given height the maximum conductivity will coincide with regions of maximum ionization and electron density. There is good evidence that maximum electron densities coincide with aurora. From h'f (height vs. frequency) ionosphere records, the writer and others [14] have demonstrated that in the presence of different non-pulsating auroral forms sporadic-E electron densities vary with changes in auroral form in a manner similar to changes in light intensity. Also, variations in heights of maximum electron densities parallel variations in auroral heights. From photometric measurements at College, Alaska, the writer thinks the relationship

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

where N is the electron density, roughly expresses this correspondence. The standard ionosphere recorders referred to here receive reflections

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* Unless otherwise specified, "conductivity" refers to the d.c. conductivity in the absence of a magnetic field.

from a large area at the zenith. During the last few years a number of radar measurements in the frequency range, 30. to 106. Mc. per sec, have been made in Canada, Norway, Sweden, and England [for reviews and references, see 15,16]. On the basis of these measurements it has generally been argued that the electron densities associated with rayed auroral forms are much greater than indicated by standard h'f recorders. The most recent measurements and analysis of Harang and Landmark [16] indicate that this view may be erroneous. They conclude that the radar reflections are not coming directly from auroral structures and can only be explained as back scatter from land or sea after reflection from the intense E_s layer formed during aurora. From their analysis it now seems that the standard h'f ionosphere recorders, referred to above, remain the most reliable indicators of electron densities associated with aurora.*

(3) If the spatial positions of the current and aurora are identical, the perpendicular to ΔF should point to the aurora within the limitations of correcting for induced current. At Fort Rae, Stagg and Paton [18] found that the altitude angle of the perpendicular to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$ differed from the altitude angle of an auroral arc by 10° and 20° in 35 per cent and 60 per cent, respectively, of the cases studied. The presence of other, more distant aurora was not specified. Considering possible errors in Z and the neglect of induced currents, the coincidence is remarkable.

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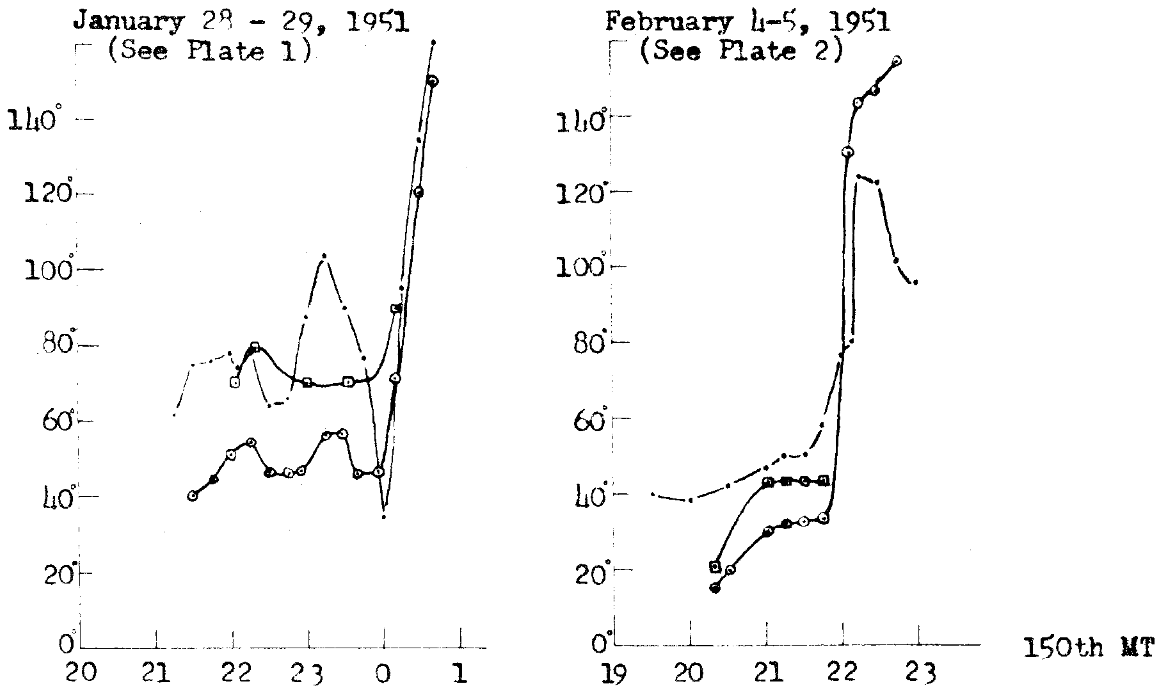
* The conclusion that radar reflections are not direct reflections from aurora is especially important in considering excitation processes in aurora. Most recent calculations of various possible processes are based on electron densities calculated from the radar measurements [for a review, see Seaton, 17].

To confirm and possibly add information to these results a number of examples of two cases were investigated in the present study. Differences between the altitude angles of perpendiculars to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$ and $\sqrt{(H_d)^2 + (\Delta Z)^2}$ and the altitude angles of (1) the southern edge of aurora north of College, and (2) isolated arcs, were examined. As the altitude angles for the aurora were taken from visual observations they are subject to error; this error, in general, will be of the order of 10°.

For case (1), when $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$ is used the altitude angles differ, most frequently, by 10° to 30° in good agreement with Stagg and Paton. The altitude angle of the aurora is nearly always less than that of the perpendicular to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$. Two examples are shown in Figure 9. Assuming that errors in Z are small, possible explanations are: (a) the difference is due to induced currents, and (b) there is considerable current flowing adjacent to the southern edge of the aurora. (a) is the most attractive explanation but (b) deserves consideration for the following reason. It has been pointed out by the writer, et.al.,[14] that Sporadic-E ionization adjacent to the southern edge of the aurora is peculiarly distributed such that h'f ionosphere traces show increasing ionization with height to an upper limit of 150 to 250 km. If interpreted literally this means that a conducting zone may exist above the usual auroral heights just south of the southern edge.

When the perpendicular to $\sqrt{(H_d)^2 + (\Delta Z)^2}$ is used, differences in the altitude angles become erratic whenever the declination is large

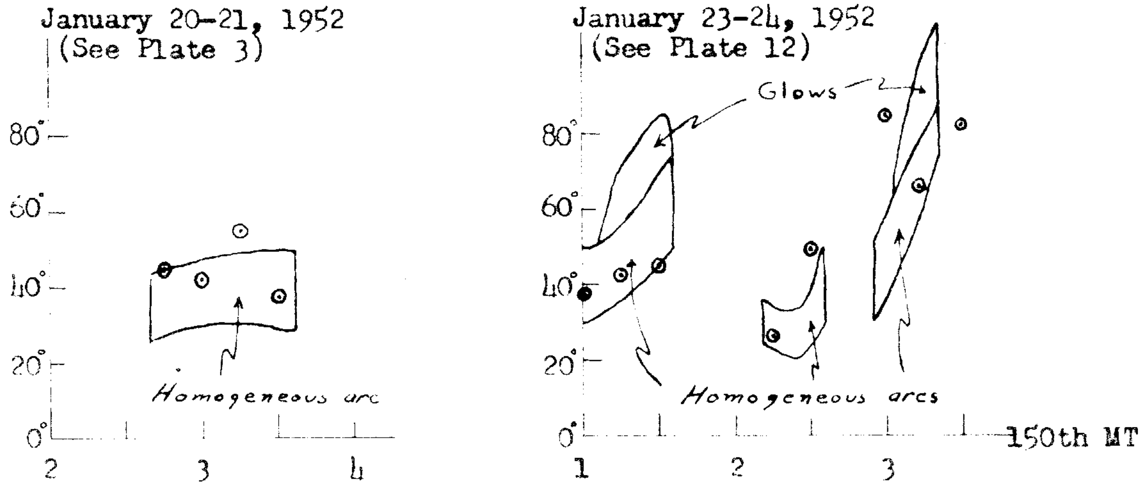


-·-·-·- Altitude angle of perpendicular to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$

⊙—⊙—⊙ " " " southern edge of auroral arc

⊡—⊡—⊡ " " " " " " " glow(approximate)

Figure 9



⊙ Altitude angle of perpendicular to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$

Figure 10

and changing. At these times the observations sometimes indicate changes in the orientation of the aurora but in general this is not the case. One explanation is that there are at times meridional currents not directly associated with the aurora.

The most striking feature in demonstrating the spatial coincidence of currents and aurora is the change in sign of ΔZ when an auroral arc at the southern edge moves south across the zenith. In many instances the times correspond almost exactly; this is especially true when ΔZ is large before and after changing sign and the aurora is moving rapidly southward.

The differences in altitude angles for the case (2) of isolated arcs are, in general, $< 30°$. Altitude angles of the aurora are more often below than above the perpendicular to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$ but this tendency is not as distinct as in case (1). Two examples are shown in Figure 10. Inasmuch as the disturbance accompanying isolated arcs is usually small enough to make the vector sensitive to errors in ΔZ, better agreement can hardly be expected.

In view of the work of Stagg and Paton and the examples studied here, the writer believes that there is little room to doubt that disturbance vectors indicate the spatial association of currents and aurora. With transit measurements of auroral altitudes and unquestionable calibrations of Z, the exactness of the association could be tested. Using the right-hand rule to approximate ΔH and ΔZ in Plates 1 to 18 the reader can roughly test the association for these and other examples.

VI. TWO BASIC PATTERNS RELATING AURORAL ACTIVITY AND MAGNETIC DISTURBANCE

High latitude magnetic disturbances are usually discussed with reference to the statistical idealized current systems, S_D, D_{st}, and D_i, which have been devised to explain disturbances. In the present study it has become evident that magnetic disturbances may be referred to two basic patterns of auroral activity which can be shifted in time and latitude to account for the important features of all varieties of disturbance occurring during dark hours. The symbolism, S_D, D_{st}, and D_i will not be necessary in this discussion and will be deferred to Part X where statistical current systems are reviewed with reference to these patterns.

The method of constructing the diagrams shown in Plates 1 to 18 has been discussed in Parts II and III. Auroral diagrams of this type have been drawn for 40 nights and disturbance vectors computed throughout 27 nights. Once familiarity with the magnetograms has been acquired the vectors can be roughly visualized by inspection when the appropriate quiet night baseline is placed on the magnetograms. Approximately, 45 additional nights of fairly complete auroral observations, and 50 nights of limited observations, have been examined in somewhat less detail. The quantity of information is thus large enough to include a number of examples of each degree and form of disturbance.

On examining a group of magnetograms from high latitude stations it is readily apparent that the disturbance often appears on the H trace after midnight as a simple depression lasting one to four hours. Birkeland called such periods, of simple $-\Delta H$ disturbance, "negative polar elementary storms." Now they are commonly called "negative bays."

Simple rises in the H trace giving a $+\Delta H$ disturbance before midnight are similarly designated "positive bays." At College, with few exceptions the horizontal component shows a $+\Delta H$ disturbance sometime between 16^h and 0^h and a $-\Delta H$ disturbance sometime between 0^h and 8^h local time. The change from $+\Delta H$ to $-\Delta H$ occurs most frequently between 23^h and 2^h local time; it is thus convenient to speak of the "midnight period" of change in sign of ΔH. The change in sign of ΔH during the "midnight period" is accompanied by a discontinuity in the auroral activity. This is the most important single fact presented here. There are two types of discontinuity in the auroral activity at this time: (I) the aurora undergoes a distinct change in form, and (II) the aurora disappears or recedes northward to a distance which makes the associated disturbance at the station inappreciable. (I) occurs more frequently than (II).

On the basis of the two types of discontinuities and the characteristic behavior of the aurora during a positive bay before and a negative bay after the discontinuities, the two patterns can be constructed; these will be referred to as Pattern I and Pattern II. Following the descriptions of the patterns it will be demonstrated how they may be used with reference to a variety of disturbances.

(a) Pattern I

The description of Pattern I, Figure 11, may be outlined with reference to the attached time scale as follows. The auroral symbols are explained on page 8. The parenthesized statements are included to indicate common variations not illustrated in the figure.

(1) 19:00-23:00. Following evening twilight a homogeneous arc with a glow paralleling its southern edge appears near latitude 70°. The arc and glow advance southward and additional arcs usually appear farther north. The magnetic disturbance indicates a predominant W to E current. On the average, H_d shows a small west declination indicative of a much smaller S to N component. (The arcs often have some rayed structure but the rays are very seldom bright and rapidly moving.)

(2) 23:00-00:20. The northernmost aurora undergoes a distinct transition to rayed auroral forms which fluctuate greatly in intensity, shape, and location. The transition progresses southward in an irregular manner. At the time the transition occurs in the north the southward movement of the homogeneous arcs is accelerated. The region between aurora which has passed through the transition and the aurora which has not, will be called a discontinuity. The dotted line AB in Figure 11 represents the discontinuity. When the station is several, or more, degrees south of the discontinuity ΔH is positive indicating that a W to E current is still associated with the arcs. When the station is north of the discontinuity ΔH is negative indicating that the current has changedto an E to W current. When the station is near the

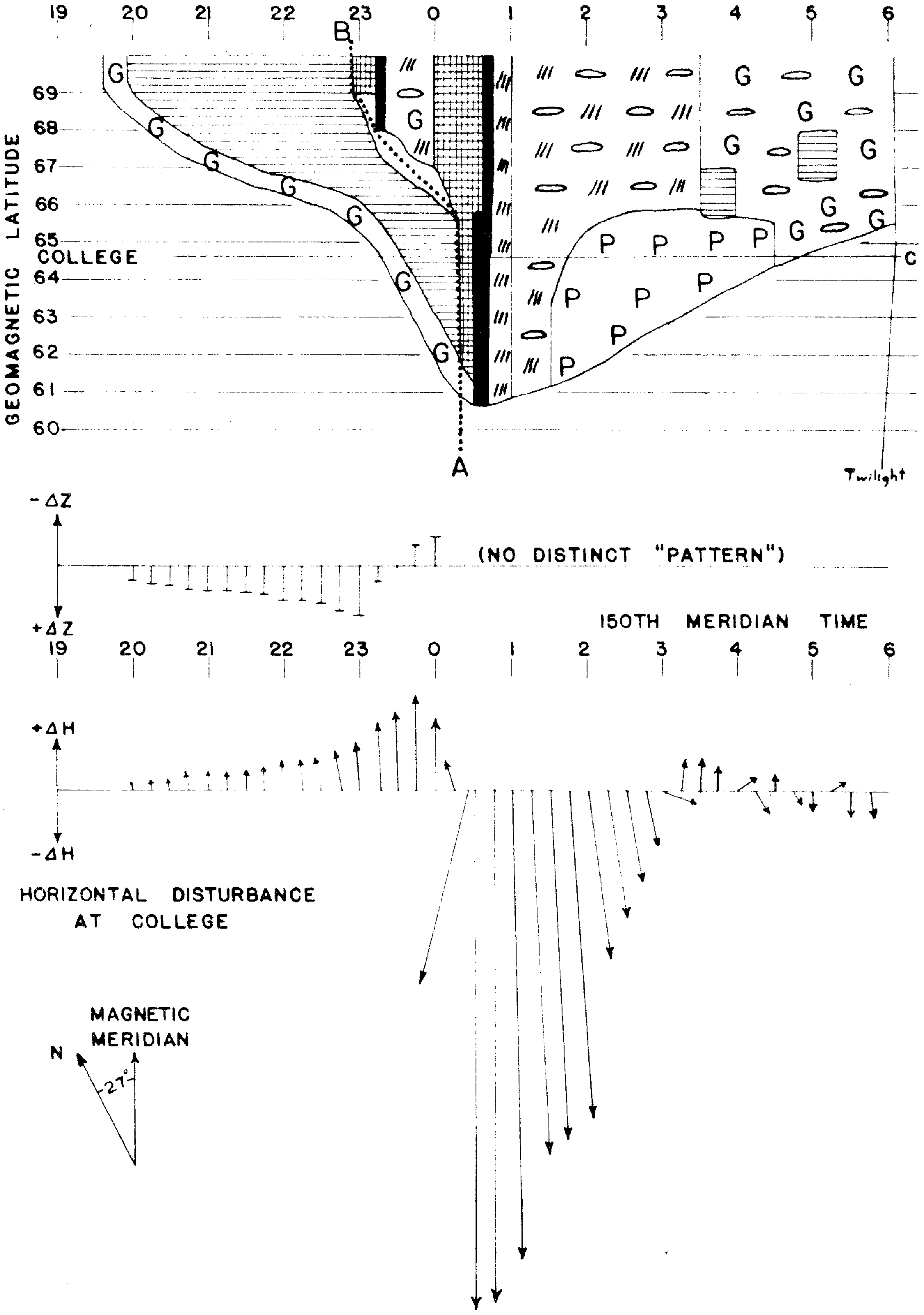


FIGURE II - PATTERN I

discontinuity ΔH may be positive or negative depending on the proximity of the discontinuity and the relative magnitudes of the W to E and E to W currents. In Figure 11 the disturbance vectors are drawn for a station south of the discontinuity; the reduced values of $+\Delta H$ at 00:00 and 00:15 indicate the influence of the current north of the discontinuity. (After an interval of transition homogeneous arcs may reappear, but the associated current remains E to W following the reappearance. On some nights the transition occurs almost instantaneously over the entire sky and this step may be omitted; the sequence then goes from step (1) to step (3).)

(3) 00:20-00:45. The arcs south of the discontinuity suddenly show marked rayed structure and within a brief interval break up into active, bright rayed bands and draperies, which are characteristically red along the lower border. The increased activity frequently spreads rapidly over the entire region including the areas which have already passed through the transition. At this time the display of colors and movements reaches its most magnificent proportions. The period of maximum activity commonly lasts only 5 to 15 minutes in any given area of the sky. Simultaneous with the transition to active rayed aurora, ΔH changes sign and rapidly reaches large negative values over the entire region. The discontinuity then extends to the southern limit of aurora. (The transition often occurs as a change from homogeneous arcs to diffuse draperies, or as a change to a variety of diffuse forms including pulsating aurora. In these cases step (3) should be omitted.)

(4) 00:45–01:30. As the active, bright rayed forms diminish in intensity they continue to break up into (or are replaced by) patches of diffuse rays. With time the rayed structure usually becomes less apparent and many patches appear in the cloud-like form, diffuse surfaces. During this period, ΔH may remain large and negative but usually decreases considerably. In most cases the disturbance vector, H_d, has a small east declination which increases as $-\Delta H$ decreases. The declination indicates that a small component of the disturbing current is N to S.

(5) 01:30–twilight. Diffuse patches along the southern margin of the aurora region commence pulsating and the pulsation spreads northward to approximately latitude 66°. The aurora north of the pulsating aurora, in general, persists in the form of diffuse patches but frequently the patches merge to form diffuse homogeneous arcs. Similarly, the pulsating surfaces may align themselves to form pulsating arcs. The orientation of these arcs is the same as for other arcs. While the pulsation continues, the southern limit of aurora recedes northward. The pulsation may continue until twilight, or cease as shown in Figure 11. When the pulsation ceases the aurora usually continues as diffuse surfaces and glows. Diffuse arcs may also be present. The negative ΔH disturbance decreases gradually to zero and is followed by a period of $+\Delta H$ disturbance. The $+\Delta H$ period may be very brief or continue for several hours; periods of a half hour are often observed. During the decrease of the $-\Delta H$ disturbance there is frequently a large east declination indicating that a N to S component of the disturbing

current is often prominent. Following the $+\Delta H$ disturbance, ΔH again becomes negative or changes sign in apparently a random manner. (The $+\Delta H$ disturbance is not necessarily dependent on the existence of pulsating aurora; it may also accompany diffuse surfaces and diffuse draperies following the decay of a negative bay.)

(b) Pattern II

The description of Pattern II, Figure 12, may be outlined with reference to the description of Pattern I, and the time scale attached to Figure 12 as follows:

(1) 19:00-21:00. (Same description as Pattern I(1).)

(2) 21:00-23:00. The southward advance of the arcs and glow stops. They then recede northward leaving the sky south of 70° free of aurora. The disappearance of aurora represents a discontinuity in the auroral activity. The horizontal disturbance remains positive but decreases to zero as the aurora disappears. (The disappearance of aurora may not be complete as a faint glow sometimes remains near 68°-70°.)

(3) 23:00-00:20. An arc (either homogeneous or rayed) reappears in the north and advances southward. North of the advancing arc additional arcs or other forms appear. The horizontal disturbance is negative. The change in sign of ΔH thus accompanies the discontinuity in auroral activity.

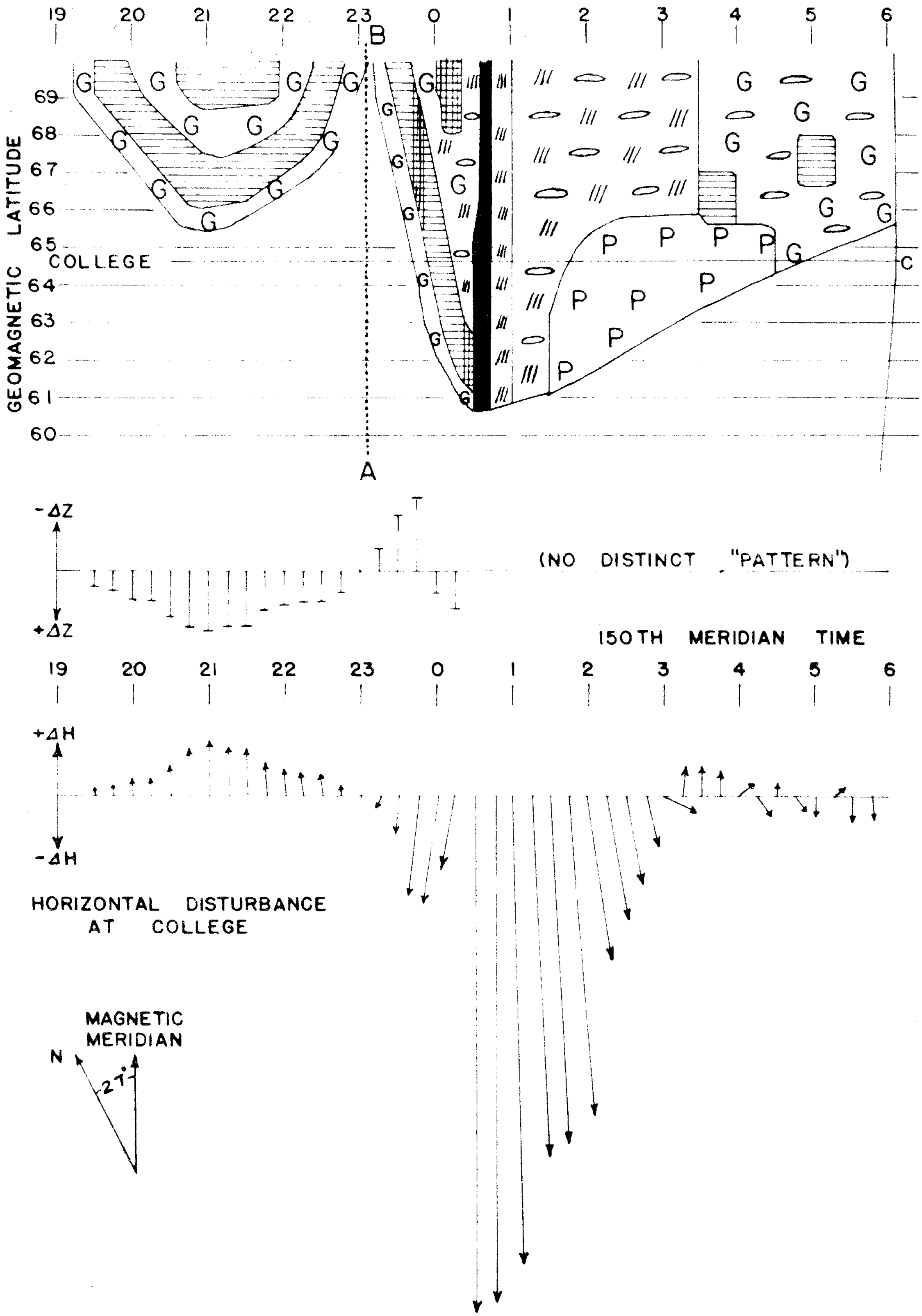


FIGURE 12 - PATTERN II

(4), (5), (6). 00:20-twilight. (See descriptions of Pattern I, (3), (4), and (5).) The auroral activity is the same as given for Pattern I. The horizontal disturbance is also the same as given for Pattern I with the exception that ΔH which is already negative does not change sign when the arcs break into active rayed forms.

(c) Positive and Negative Bays

As previously stated the midnight discontinuity separates positive and negative bays. In Pattern I, the positive bay begins with the first appearance of auroral arcs and ends when the auroral arcs break into rayed and diffuse forms; the end of the positive bay is also the beginning of the negative bay. In Pattern II, the positive bay begins as in Pattern I but ends when the aurora recedes northward and disappears; the negative bay begins with the reappearance of auroral arcs. On some nights a negative bay appears without being preceded by a positive bay (see Plate 9 and description); the negative bay is then represented by the portion of Pattern II occurring after the discontinuity.

There are frequently several negative bays following the midnight discontinuity. When the first negative bay is represented by Pattern I, subsequent negative bays are represented by the negative bay of Pattern II. The first negative bay and the associated sequence of auroral activity may be completed to the short interval of $+\Delta H$ or may be interrupted at any time during steps (4) and (5). The interruption and the beginning of a second negative bay takes place when an arc forms and moves south; as the southward moving arc is accompanied by $-\Delta H$ the second negative bay is represented by Pattern II.

When a new bay begins before the previous bay is completed it is convenient to say that the bays "overlap."* It is also convenient to speak of the "cycle" of auroral activity when referring to the sequence from homogeneous arcs at the beginning of a bay to the pulsating and diffuse aurora at the end of a negative bay when ΔH again becomes positive. On nights when the disturbance appears exceedingly complex it is still possible to separate out individual bays by recognizing the sequence of auroral forms. The complexity is merely the consequence of the bays overlapping and the aurora simultaneously starting a new cycle of activity before the previous cycle is completed. When negative bays overlap in this manner the short interval of $+\Delta H$ obviously will not appear.

The generality of Patterns I and II and the terms "positive and negative bays" will be made clearer by considering the examples in the following sections.

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* Since the first writing of this thesis, Meek [2] has published a paper in which auroral light intensity along the Saskatoon magnetic meridian is compared to the shape of the H component at Saskatoon. His views on the bay character of disturbances are apparently the same as expressed here; to quote: "Magnetically disturbed nights may be thought of as variations due to a number of overlapping bays. Ionospheric and auroral characteristics are found to be related directly to the size and shape of these bays. The disturbances have been studied with this in mind."

VII. EXAMPLES RELATED TO PATTERN I

To avoid unnecessary repetition only prominent features of each example will be mentioned. In particular, the outstanding discrepancies between the examples and the pattern will be noted. Differences between the examples and Figure 11 which are mentioned in the description of Pattern I will not be pointed out. The examples are shown in Plates 1 to 7 at the end of the text. Selection of the examples is based on the quality and completeness of the auroral observations and on the different degrees of complexity. A dotted line (AB) is drawn on the auroral diagrams to indicate the discontinuity in auroral activity corresponding to the change in sign of ΔH. Note that the scale used for the disturbance vectors is not the same for all nights.

January 28-29, 1951 (Plate 1):

The similarity between this night and the pattern is quite striking. Several discrepancies merit mention. (1) At 00:00 an apparent discrepancy occurs as it will be noted that ΔH has temporarily dropped almost to zero; this coincides with a brief interval of rayed aurora. As this is not an unusual occurrence interpretation is desirable. The writer's opinion is that the coincidence with rayed aurora indicates that a discontinuity has started to form, but the conditions causing the homogeneous arcs and $+\Delta H$ are still prominent enough to prevent the discontinuity. (2) The declination during the decay of the negative bays does not agree with the pattern.

February 4-5, 1951 (Plate 2).

The following features merit special attention. (1) The southward acceleration of the homogeneous arcs at the time the discontinuity appears in the north is especially evident on this night at 22:00. (2) The length of time for the discontinuity to become complete is exceptionally long.

January 20-21, 1952 (Plate 3).

The behavior of H_d from 04:00 to 04:30 may or may not be considered a discrepancy. It is evident that a transition in ΔH is taking place without a change in the aurora but at the time (about 4:45) the transition becomes definite there is a discontinuity in the auroral activity.

January 21-22, 1952 (Plate 4).

On this night the disturbance after the discontinuity consists of two negative bays. The sequence of the first negative bay follows Pattern I quite closely. The second negative bay is represented by the negative bay of Pattern II, inasmuch as, the arc advanced southward accompanied by $-\Delta H$ before breaking into a rayed form. It appears that there are two alternatives in drawing the north part of the discontinuity line (AB); these are shown as (AB) and (AB'). If (AB) is correct, Pattern I applies. If (AB') is correct a combination of Patterns I and II applies. The possibility of (AB') is indicated by the reduction in $+\Delta H$ between 00:45 and 01:30. The behavior of H_d between 01:30 and 02:00 deviates somewhat from the usual. The discontinuity in the auroral activity at 01:30 is distinct but ΔH fluctuates in sign until 02:00 before becoming definitely negative.

January 22-23, 1952 (Plate 5).

The discontinuity (AB) is probably correct as the disturbance vectors between 23:00 and 01:00 indicate the influence of a W to E current south of the discontinuity. The possibility of A'B cannot, however, be excluded. It is evident that the disturbance in H after midnight may be separated into three major negative bays: approximately 00:30 to 2:15, 03:30 to 05:45, and 06:50 to 08:45. The first negative bay is well represented by Pattern I, but completion of the bay cycle to $+\Delta H$ was interrupted by the rayed activity at 02:15 and the onset of the second bay about 03:15. Had the pulsation continued uninterrupted it is reasonable to speculate that ΔH would have continued to decrease and change sign. As in the previous night the second negative bay is better represented by Pattern II. The cycle of this bay was completed to $+\Delta H$. The third negative bay began as dawn light interfered with observations, although brilliant rayed bands were observed despite the background light.

The arc located over College between 18:50 and 20:20 is notable because the coincident disturbance (less than 20 γ for the total field) was almost inappreciable. Such a lack of disturbance with aurora nearby is extremely rare. The occurrence of a similar arc without appreciable disturbance on the following night (see Plate 12), is a striking example of repetition on successive nights.

January 24-25, 1952 (Plate 6).

There is a question as to whether this night is best represented by Pattern I or Pattern II. The auroral observations, although not complete between 23:00 and 23:30, indicate that the arc did not disappear and hence Pattern I more likely applies to the discontinuity (AB). However, following this discontinuity a homogeneous arc reappeared coincident with $-\Delta H$ and the sequence that follows is better represented by Pattern II. The major onset of the negative bay between 01:15 and 01:30 follows Pattern II. However, the bay does not decay with the presence of pulsating aurora until about 04:30. This is understandable considering that the station is located near a boundary between pulsating and non-pulsating aurora. The variations between 02:00 and 04:30 appear to be related to latitude changes in this boundary. The pre-discontinuity positive bay is very irregular and small; the changes in declination are more prominent than changes in H.

<u>January 25-26, 1952 (Plate 7)</u>.

This night is well represented by Pattern I. The period of $+\Delta H$ following the negative bay is exceptionally long.

VIII. EXAMPLES RELATED TO PATTERN II.

When more than one negative bay occurred in the "Examples related to Pattern I," it was noted that the additional bays were represented by Pattern II. (See, e.g., the nights of January 21-22 and January 22-23, 1952.) On the basis of the ΔH discontinuity, these examples are grouped with Pattern I and need not be described in this section. The restriction of examples of Pattern II to exclude the repeated bays of Pattern I also restricts one, in general, to lower degrees of disturbance. The examples are shown in Plates 8 through 12.

February 9-10, 1951 (Plate 8).

Although the observations after 03^h are incomplete this example is included to illustrate that the prediscontinuity positive bay sometimes has considerable magnitude. During this period the H_d vectors are very irregular; the reason is not apparent from the auroral diagram. The discontinuity between 23^h and 0^h is obvious; glows may have been present north of 69° but their existence is very doubtful. The first negative bay agrees well with Pattern II with the exception of the declination. The auroral observations during the second bay are incomplete but the homogeneous arc between 03^h and 04^h and the pulsating aurora near 05^h indicates agreement.

March 1-2, 1951 (Plate 9).

The disturbance consists of a single negative bay which is represented by the negative bay cycle of Pattern II. Instead of a single break up of the homogeneous arcs to rayed and diffuse aurora the breakups occur gradually and intermittantly without great changes in the disturbance. The declination between 04:30 and 06:00 disagrees with the pattern.

March 3-4, 1951 (Plate 10).

The disturbance and auroral activity is very small. The variability of the declination compared to ΔH is not unusual at such times. The small negative bay coincides with a stable homogeneous arc which merely dissolves into glow as the bay decays.

March 4-5, 1951 (Plate 11).

The positive bay, the discontinuity, and the first negative bay closely resemble Pattern II (Figure 12) with the exception that pulsations were not noticed and a $+\Delta H$ period does not follow the negative bay, although ΔH does drop to zero. A second negative bay is also present but the auroral observations are limited by twilight.

January 23-24, 1952 (Plate 12).

The lack of disturbance coincident with the arc over College prior to 19:30 has previously been mentioned [see Part VII, January 22-23, 1952]. The positive bay just preceding the discontinuity is small and irregular. Following the discontinuity the auroral arcs were very faint until about 02:30 and $-\Delta H$ is small. In outline on the magnetogram the period 03^h to 07^h appears as one major bay. The auroral diagram indicates that this is actually a superposition of two bays. The onset of large $-\Delta H$ values coincides with the breaking up of the arc just before 04^h. As this bay started to decay accompanying pulsating aurora, a new arc formed to the north and moved south. The second arc broke into brilliant rayed forms about 05:50. This was followed by diffuse and pulsating aurora; simultaneously the bay decayed and was followed by a period of $+\Delta H$.

IX. EXAMPLES OF DISTURBANCES PRECEDED BY SUDDEN COMMENCEMENTS AS RELATED TO PATTERNS I AND II.

In the literature [see, e.g., 19] one finds sudden commencements defined in various ways. All definitions agree that a sudden commencement is an abrupt movement in H and usually in D and Z. Most commonly an abrupt increase in H occurs which may or may not be preceded by a smaller decrease. The abrupt movement is at times observed simultaneously (within a few minutes) at a large number of stations. Sudden commencements have received much attention in the literature as it is observed that they often precede great magnetic disturbances (or magnetic storms). Not all abrupt movements precede large disturbances; this has led to the subclassification: (s.s.c.) and (s.i.). (s.s.c.) denotes a sudden commencement followed by a magnetic storm or a period of storminess, and (s.i.) denotes a sudden impulse found on the magnetogramswhich is not followed by a period of storminess. Lists of the sudden commencements reported by various stations are published periodically in the Journal of Geophysical Research. Inspection of these lists shows, in general, that s.s.c.'s were reported simultaneously by more than six stations only several times, or less, during each month of the years 1950-1951-1952.*

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* In the Journal of Geophysical Research the list of stations reporting an s.s.c. is usually not quite complete. Complete lists are given in the Bulletin of the IATME. As the 1950-1952 bulletins have not been available to the writer, the numbers to be quoted here are taken from the "journal" unless otherwise noted. Walter E.Scott, Carnegie Institute, and J. Veldkamp, DeBilt, Holland, have kindly provided information on selected s.s.c.'s; these will be noted by (IATME).

Fortunately, fair to excellent auroral observations were obtained for a number of sudden commencements. The examples considered here are all of the type s.s.c. Two of the examples will be s.s.c.'s which were reported by a large number of stations and are clearly evident on the College magnetograms. For one of these, illustrations will also be given for a number of days following the s.s.c.

On examining the College magnetograms for the presence of s.s.c.'s at the times they were reported at other stations, it was noticed that they appeared coincident with the onset of negative bays on more occasions than would be expected by chance. The coincidence with the onset of negative bays indicates that some association may be present between s.s.c.'s and the transition between homogeneous arcs and rayed or diffuse forms. The coincidence will be indicated here in two illustrations: March 6-7, 1951 (Plate 14) and January 26-27, 1952 (Plate 18). In Part XII(b) the coincidence is discussed more thoroughly.

March 5-6, 1951 (Plate 13).

An s.s.c. was reported by 27 stations (IATME) on March 6, 1951 at 07:50 GCT. The 150th Meridian Time, 21:50, March 5, is indicated on the plate. The s.s.c. was preceded by a large positive bay coincident with southward advancing arcs until 21:00; between 21:00 and 21:50 the arc dissolved into glows and diffuse surfaces which began to recede northward. Coincident with the s.s.c. a new arc formed and the recession stopped; a second positive bay occurred as the arc moved southward. The sequence that follows is represented very well by Pattern I with the exception that there was a short interval of pulsation during the positive bay at 23:30. Pulsations are rarely observed during prediscontinuity positive bays.

March 6-7, 1951 (Plate 14).

The auroral activity and disturbance again follows Pattern I quite closely. The diagram indicates that the auroral activity probably extended considerably south of latitude 60°. During the decay of the first negative bay pulsating aurora was not observed; pulsations may have been obscured by twilight after 04:30 or been located south of 60°. A second negative bay occurred after twilight.

An s.s.c. was reported by 4 stations at 02:27, 150th Meridian Time, March 7th. The very distinct break up of homogeneous arcs shown in the illustration was recorded as occurring between 02:32 and 02:36. The stations and their geographical positions are:

Dombas	62° 05' N	9° 06' E
Wingst	53° 45' N	9° 04' E
Abinger	51° 45' N	0° 23' W
Vassouras	22° 24' S	43° 39' W

March 7-8, 1951 (Plate 15).

The positive bay, the discontinuity, and the first negative bay follow Pattern I except in the declination of H_d. The decay of the first negative bay was interrupted at 01:00 by the onset of another bay which is represented by Pattern II in the manner discussed in Part VI(c). Decay of the second negative bay had scarcely started when interrupted at 03:00 by the onset of a third negative bay. The third negative bay decayed after twilight.

March 8-9, 1951 (Plate 16).

This night is also well represented by Pattern I. Several features merit mention. (1) During the evening $+\Delta H$ period, ΔH was briefly negative or zero at several times. Within the accuracy of the observations the times coincide with the sudden appearance of homogeneous arcs. This happens often enough to suggest that such apparent discrepancies in the pattern behavior are related to the origin time of changes in the aurora. (2) At 03^h pulsating aurora extended farther north than usual. Following 04:15, a $+\Delta H$ period was apparently prevented by the beginning of a second negative bay.

March 9 through 14, 1951.

The degree of disturbance remained high until approximately midnight on the night of March 14-15, and then decreased abruptly. The disturbance and auroral activity remained similar to the nights illustrated. The degree of disturbance on 9-10 was similar to 8-9. On 10-11, the intensity increased again and reached a maximum on 12-13 although no new s.s.c.'s were reported.

March 2-3, 1952 (Plate 17).

An s.s.c. was reported by 25 stations (IATME) at 21:31, 150th Meridian Time, March 2, 1952. As the College magnetogram preceding the s.s.c. was perfectly quiet throughout the previous 18 hours, the s.s.c. stands out strikingly. The disturbance and auroral activity follows Pattern I very closely. The homogeneous arcs between latitudes 61° and 65° at 05^h are only an apparent discrepancy inasmuch as they could have been called pulsating arcs. As the arcs were not continually pulsating both symbols are used. Prior to 03^h a large area in the north was without aurora; this is often the case during large disturbances.

The magnetograms for the following six nights were highly disturbed. The disturbance decreased on the seventh and eighth nights.

January 26-27, 1952 (Plate 18).

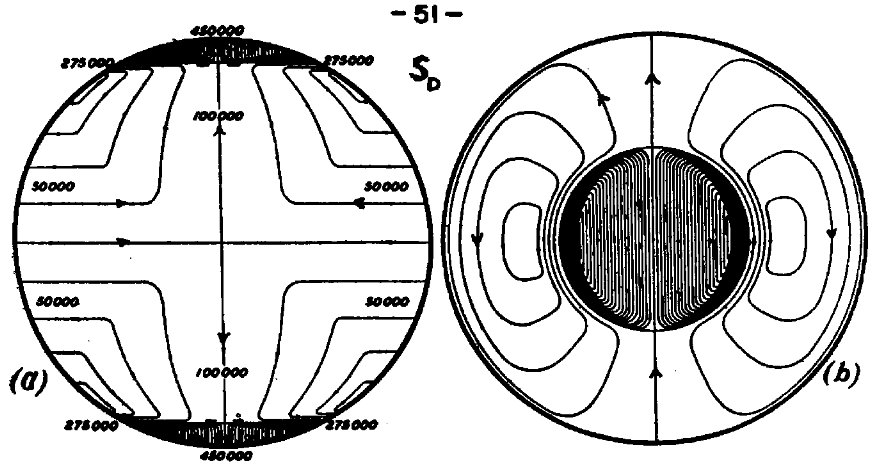
Lack of observations between 21:40 and 23:00 makes the discontinuity north of 65° uncertain. The discontinuity indicated between 23:00 and 02:00 is consistent with both the auroral activity and the magnetograms. The relatively small ΔH disturbance during this period suggests a W to E current to the south and an E to W current to the north of the discontinuity.

At 23:29, 150th Meridian Time, 4 stations reported an s.s.c. The brilliant rayed aurora began between 23:23 and 23:26 and reached maximum intensity about 23:30. The stations and their geographical positions are:

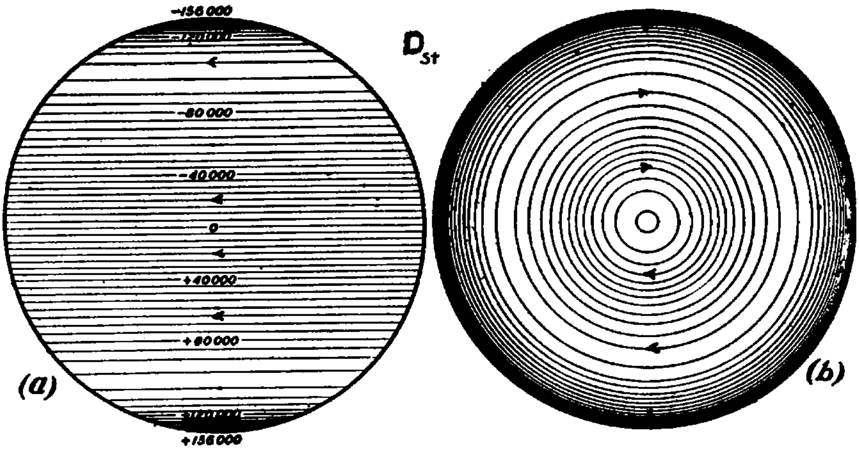
Wingst	53° 45' N	9° 04' E
Niemegk	52° 04' N	12° 40' E
Coimbra	40° 12' N	8° 25' W
Elisabethville	11° 40' S	27° 28' E.

X. STATISTICAL CURRENT SYSTEMS COMPARED WITH PATTERNS I AND II.

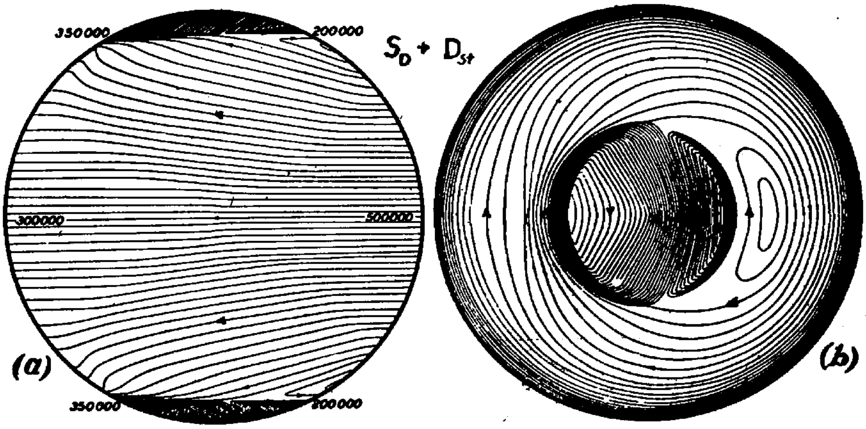
The idealized current systems derived by Chapman [20] and Vestine and Chapman [21] have become classics in the literature pertaining to magnetic disturbance. For reference, a copy of the diagrams for these current systems is given in Figure 13. The current systems were derived, primarily, by averaging 40 moderate magnetic storms and separating the resulting field into two parts S_D and D_{st}. S_D represents the part distributed with respect to solar time and D_{st} the part depending on storm time (i.e., time reckoned from the commencement of the storm). Being "idealizations" the current systems are open to criticism; the authors themselves have noted that the asymmetry of the geomagnetic poles [Vestine, 22] and the concentration of the current on the night side of the earth are not taken into account [Vestine, 7]. They have also recognized that a part of the disturbance is too irregular to explain with S_D and D_{st}; this irregular field has been given the symbol, D_i. In this classification an isolated bay represents a D_i disturbance but it is also found that D_i has a component which is considered to be D_{st} [7, p. 174]. Vestine, et.al. [7], have given examples of current systems computed for successive hours and average current systems for D_i. More recently, Chapman [23] has added another component called the "D_s field, or disturbance (solar) local-time inequality," which "varies with storm time in a manner materially different from D_{st}, developing more rapidly than the main phase of D_{st} and decaying much faster." To summarize, the disturbance field is considered to consist of four components: S_D, D_{st}, D_i, and D_s.



. Idealized atmospheric current systems producing S_D variations as deduced from forty magnetic storms of moderate intensity. (After Chapman.)
(*a*) View from the sun. (*b*) View from above the north pole.



Idealized atmospheric current systems producing D_{st} variations as deduced from forty magnetic storms of moderate intensity. (After Chapman.)
(*a*) View from the sun. (*b*) View from above the north pole.



Idealized combined atmospheric current systems producing both S_D and D_{st} variations (as depicted in Figs. 21 and 22) during magnetic storms of moderate intensity. (After Chapman.)
(*a*) View from the sun. (*b*) View from above the north pole.

FIGURE 13

Undoubtedly, with four variables, of which all may vary in magnitude, one is also irregular, and one is an inequality, it should be possible to represent any actual disturbance. However, a less formidable approach is desirable. In Part VI(c) it was stated that the pattern disturbances consist essentially of a positive bay followed by a negative bay, with a short interval of $+\Delta H$ following the negative bay. The two patterns differ in the manner in which the positive bay ends and the negative bay begins. Complex disturbances are attributed to the repetition and overlapping of bays. With this viewpoint, a comprehensive current system for auroral region disturbances should be obtainable by studying, simultaneously around the earth, the time, latitude, and intensity distribution of bays. This method would have the advantage, over the S_D, D_{st}, D_i, D_s method of being able to relate the disturbance directly to the auroral activity. A statistical analysis of magnetic bays, using 3-hour disturbance vectors, has been made by Silsbee and Vestine [24]. As would be expected from this broad averaging, the resulting systems very closely resemble a combination of the statistical S_D and D_{st}.

The averaging process in deriving the idealized current systems obviously cancels out all minor features which do not appear at exactly the same time every night. Thus, the short interval of $+\Delta H$ following a negative bay is not represented. In fact, this $+\Delta H$ period often occurs near 06^h which is the time of maximum $-\Delta H$ in the idealized system. The $+\Delta H$ interval will be discussed more thoroughly in Part XII(a).

On the basis of other analyses, discussed below, it seems that the idealized current systems should indicate the southward progression of the discontinuity between W to E and E to W currents occurring near midnight in Pattern I (for this discussion, the discontinuity of Pattern II may be neglected as it, in general, does not occur during magnetic storms of the degree used in deriving the current systems). However, the progression does not appear; this again illustrates that the averaging is more general than merely averaging hourly means. Harang [11] studied the mean disturbance field for a group of stations lying in a narrow longitude range but distributed in magnetic latitude between 55° and 75°. Disturbances were separated into four intensity ranges of which range III appears to correspond closest to the degree of storminess used by Chapman and Vestine. A copy of the "isopleth" curves (contours of equal ΔH, ΔD, and ΔZ) for range III is shown in Figure 14. Although hourly means were used and the post negative bay $+\Delta H$ does not appear, the southward progression of the $+\Delta H$ to $-\Delta H$ discontinuity is very definite near 21^{h} local-time. The local time is distinctly earlier than the most frequent time of the discontinuity at College; there are two reasons: (1) The time of the discontinuity - and other features - is related to the local geomagnetic time (time referred to a coordinate system in which the geomagnetic pole is used in place of the geographic pole); geomagnetic midnight at College occurs several hours after the geomagnetic midnight of the stations used by Harang. (2) In general, the $+\Delta H$ disturbance is considerably smaller than the $-\Delta H$ disturbance; consequently, in averaging a number of

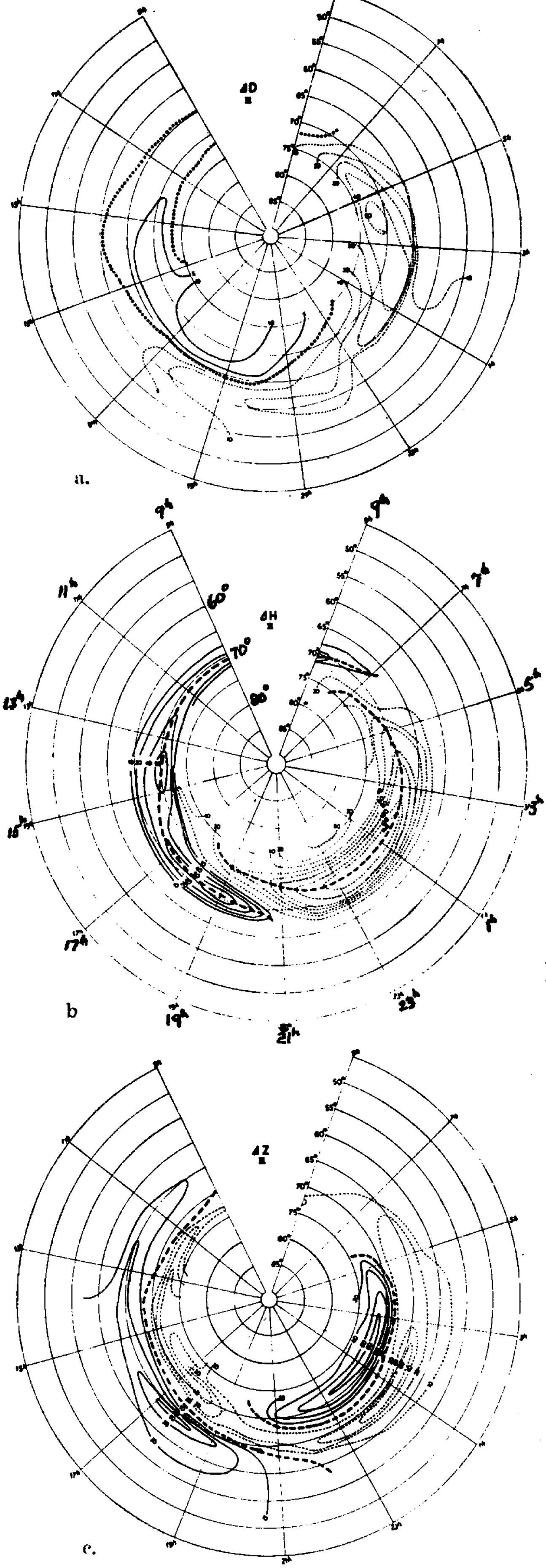


FIGURE 14: a, b and c. Variation of the three components ($\triangle D$, $\triangle H$ and $\triangle Z$) of the D-field with local time across the 120° geomagnetic meridian. *Range III.* **(AFTER HARANG)**

nights the discontinuity will be shifted to the evening hours. This is illustrated in Figure 15 by averaging three typical envelopes of ΔH displaced in time.

The southward progression of the discontinuity also appears in the average daily disturbance variation curves for the polar year 1932-1933. Figure 16 has been plotted from curves given in reference [7, p. 176] by marking the times at which the north component of H changed sign.

The discussion thus far applies to the auroral region only. For completeness it is desirable to also have knowledge of the simultaneous disturbance in other regions. The present study can contribute to this only at times when the auroral activity is considerably north of College. At these times, the disturbance vectors should indicate the meridional currents shown for S_D (Figure 13) if they exist; this assumes that D_{st} is absent, which should be the case when there is no magnetic storm and the auroral activity is low. Following Figure 13, the declination should be (1) westward during the first part of the positive bay, (2) eastward at the time ΔH is changing sign, and (3) westward toward the end of the negative bay. (1) is quite generally true. For (2), the opposite declination seems to occur just as frequently. For (3), eastward declination occurs more frequently than the expected westward declination. Thus, there is very little agreement; if, however, we assume D_{st} also exists the agreement is much better. The principal function of D_{st} in the diagrams of Chapman and Vestine is to account for the fact that the $+\Delta H$ disturbance is, in general, much smaller

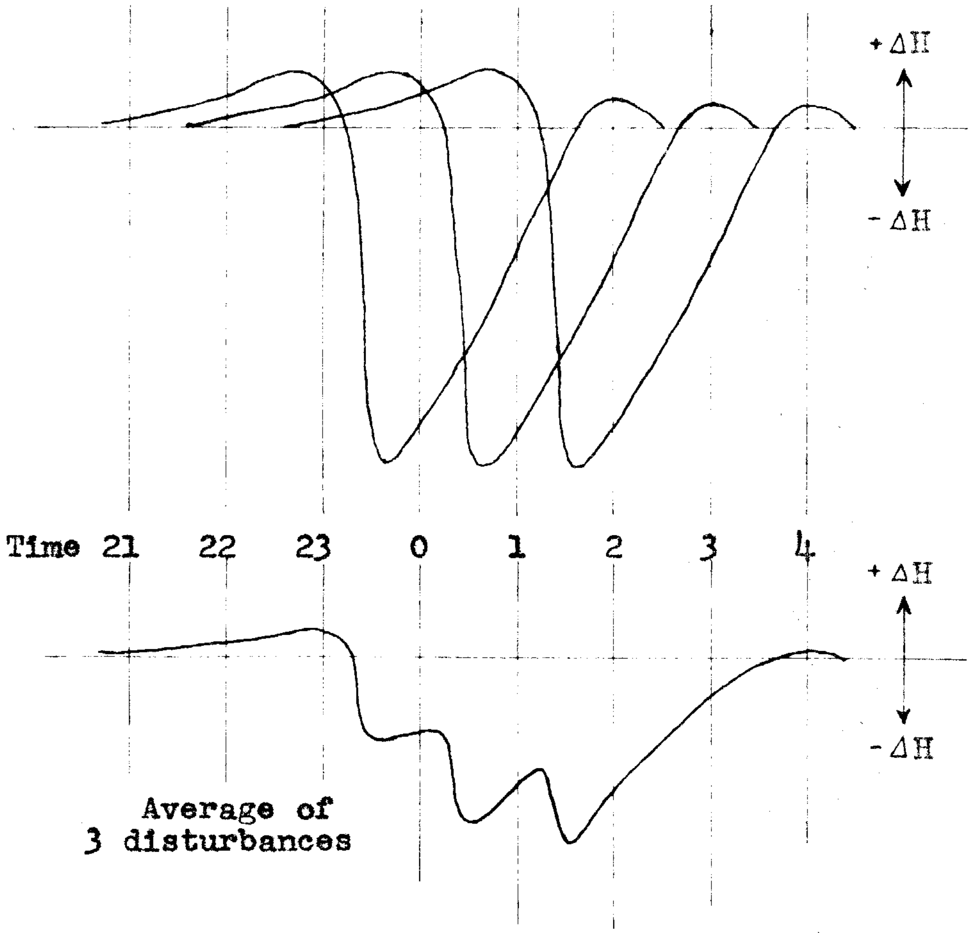


Figure 15 -- To illustrate the shift of the ΔH discontinuity as a result of averaging disturbances

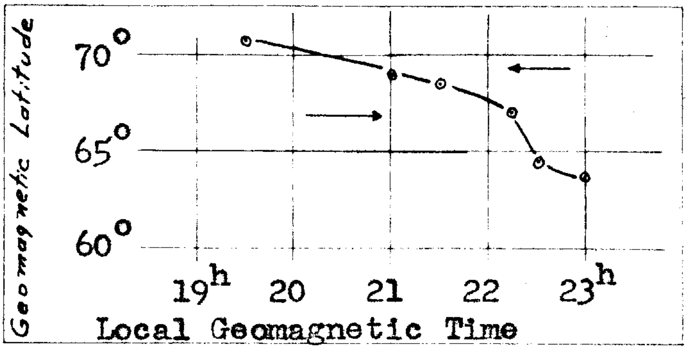


Figure 16 -- ΔH discontinuity plotted from average disturbance curves for the polar year 1932-1933.

than the $-\Delta H$ disturbance; this difference in magnitude is also obvious in Patterns I and II without assuming a "storm component" which increases in magnitude near the eqnator.

The question "where do the intense auroral zone currents complete their circuit" is still unanswered. In the systems of Chapman and Vestine the circuit is completed mainly over the polar cap although they state that adequate data to establish this is not available. The principal evidence is taken from several stations at latitudes greater than 75°. Mean values for those stations show that the sign of $+\Delta H$ is reversed from that in the auroral zone but of much smaller magnitude. In the early auroral theories of Birkeland and Stormer it was believed that the circuit was completed outside the atmosphere; this is also contained in the more recent proposals of Alfvén [25] and Martyn [26]. A third possibility is that the circuit is completed within the atmosphere but at a higher level in the ionosphere; this has been proposed by Goldie [27] and Wulf [28].

XI. ON THEORIES OF AURORA AND THE CAUSE OF AURORAL ZONE CURRENTS.

Ideas as to the cause of the intense linear currents in the auroral zone are closely allied with auroral theories. For the purpose here, it will be most effective to discuss the two subjects simultaneously. A comprehensive review of auroral theories would be extensive and will not be attempted; only the basic premises and major criticisms to be found in the literature will be mentioned. In contrast, once the auroral theory is stated, it requires very little space to summarize the still vague and undeveloped ideas on the cause of auroral zone currents. The theories and proposals will be outlined according to author and date; following each brief summary, the theory and (or) proposals will be examined with brief reference to the major criticisms found in the literature and a more extensive discussion based on the present study. Where the literature criticisms are adequately conclusive the discussion will be omitted.

(a) Birkeland-Störmer

Birkeland's "terrella" experiments and studies of magnetic disturbance, together with Störmer's mathematical analysis of the motion of a charged particle in a magnetic dipole field, led to the theory that aurora was created by charged particles from the sum which entered the earth's atmosphere under the influence of the magnetic field. Birkeland attributed the auroral zone currents to the paths of the charges in the earth's atmosphere. The charges individually spiralled into and then out of the atmosphere; the net current for a large number of charges was thus horizontal as the incoming and outgoing vertical components canceled. Störmer hypothesized a ring current encircling the earth at a great distance. The ring current was suppose to explain the deflection of particles to lower latitudes and the $-\Delta H$ disturbance in low latitudes during magnetic storms. [See 1,4,5,6.]

Although the theory laid the foundation for subsequent theories (especially the Chapman-Ferraro theory) it has been generally discarded. It was assumed that the charges were all of one sign; this has been adequately criticized on the grounds that electrostatic repulsion would disperse the particles before reaching the earth.

(b) Chapman-Ferraro

The theory is essentially a theory of neutral corpuscular streams and magnetic storms. The authors have conducted an extensive mathematical analysis of the properties of a neutral (electrons and positive ions) corpuscular stream and the conditions which would lead to a westward equatorial ring current outside the earth's atmosphere. The aurora is attributed to bombardment by corpuscles (primarily protons) which are ejected from the ring although the authors state that the manner in which this takes place has not been determined. Currents induced in the corpuscular stream at the time it contacts the earth's magnetic field have been calculated to explain sudden commencements. The D_{st} field (Figure 13) is attributed to the ring current which is either established or enhanced by the corpuscular stream. [See 4, 5,6,29,30,31.] With regard to the auroral zone current, Chapman [4,32] has expressed the opinion that the electromotive forces are continually present but the conductivity is augmented during aurora by corpuscular bombardment. The aurora and the electromotive force are thus considered to be independent. Chapman [4,33] has also suggested that the electromotive force is induced by the dynamo action of horizontal air flow across the earth's magnetic field. Several air circulation patterns were considered but he considers them to be purely hypothetical.

The authors have been their own critics in carefully stating the limitations of their analysis. The theory pertains to magnetic storms and thus is applicable only at special times. The illustrations of Parts VI-IX show that Patterns I and II are followed when there is a magnetic storm as well as when there is no evidence of storminess. The differences are that during periods of storminess, the aurora usually moves farther south, there is usually more rayed aurora, and bays usually occur more frequently. The difference is thus in the degree of auroral activity and magnetic disturbance; the sequence does not differ. The qualification "usually" is necessary above, as equivalent disturbances do occur on nights not preceded by s.s.c.'s (see Part IX) and not followed by nights of large disturbance. Following Störmer's idea and more recent calculations by Nagata [31,34], the radius and strength of the proposed ring current in the Chapman-Ferraro-Martyn theories determines the southward shift of the auroral zone with increased disturbance. It is obvious from Plates 1 to 18 that a southward shift is a nightly feature; thus for this explanation to have any validity it is necessary to assume that a ring current is practically always present. This is not in agreement with low latitude observations. To summarize, if the theory applies to magnetic storms it must also apply to all other times to explain the identical sequence of auroral activity and magnetic disturbance; this is not the case in the present form of the theory.

One of the principal, and most often quoted, points of the theory is its explanation for sudden commencements. A common objection has been that all sudden commencements (the s.i.'s) are not followed by magnetic storms. Very recently, Sugiura [35] has demonstrated that the amplitude of sudden commencements at Huancayo, Peru is greatly augmented relative to higher latitude stations during daylight hours; a confirmatory analysis has been made by Vestine [36]. They conclude that the source of the sudden commencement field must be within the upper atmosphere. In Part IX it was stated that a coincidence between s.s.c.'s and the break from homogeneous to rayed aurora appears on some nights. In Part XII(b) this is examined from the standpoint of coincidence between s.s.c.'s and the onset of negative bays. An association is clearly indicated; if verified on further analysis this would require an explanation quite different from that of the Chapman-Ferraro theory.

Chapman's suggestion that the aurora and the electromotive force causing the auroral zone currents are independent, is, to the writer, untenable in view of the present study. The discontinuities in auroral activity during the "midnight period" shown in Patterns I and II and in the illustrations are simultaneous with the change in direction of the electromotive force, as indicated by the sign change of ΔH. The few possible exceptions that have been found are very doubtful as they occurred at times when the auroral data was too incomplete to be meaningful. Also, changes in conductivity do not solely explain the $+\Delta H$ interval associated with diffuse and pulsating aurora following a negative bay.

(c) Hulburt-Maris and Bennett-Hulburt

The theory assumes that particles near the equator can rise to heights of 5 to 6 earth radii through superelastic collisions. They are then ionized by ultraviolet light and spiral along the magnetic lines of force to the auroral region where they create aurora. The theory has been thoroughly criticized by Chapman and McNish. [See references 4,5,6,37,38.]

Recently, Hulburt and Bennett [39,40] have revised the ultraviolet light theory. Changes in the ionosphere giving rise to magnetic storms are still attributed to ultraviolet light; however, high latitude magnetic disturbances and aurora are attributed to a stream of ions from the sun which becomes magnetically self-focused during passage to the earth. The theory is in a very abbreviated state and does not attempt to explain features such as the auroral zone currents.

(d) Alfvén

The theory is based on a neutral corpuscular stream which is laterally polarized as it approaches the earth by the sun's magnetic field. On contact with the earth's magnetic field electrons drift eastward and positive ions westward around the earth. The separation of charges is such that negative and positive space charges accumulate on the night and day sides, respectively. The space charges neutralize each other by discharge along the magnetic lines of force and the auroral zone. The net current is thus of the S_D type. A D_{st} current results from the paths of the charges in passing by the earth. The "auroral curve" (center of the auroral zone) is defined by the lines of magnetic force which intersect the space charge region at the boundary of the forbidden zone. The auroral curve, defined thus, is found to be farthest from the geomagnetic pole on the evening side and closest on the morning side; in the analysis this is the consequence of assuming that the electronic temperature is greater than the ionic temperature. [See 25.]

The assumptions concerning the sun's magnetic field are now thought to be incorrect. The neglect of electrostatic forces between electrons and ions and other features have been criticized by Chapman and Cowling. [See 5,31,41,42.]

The mathematical expression for the center of the auroral zone obviously disagrees with most observations of the diurnal variations of aurora. This is true for College as well as practically all published curves of auroral frequency as a function of time. At College, for example, the aurora at 18^h, if observed, is in most cases near the north horizon (this is the time aurora is farthest south according to Alfvén) whereas at 6^h (when it should be farthest north according to Alfvén) the aurora usually has not receded far north from its most southern position. Alfvén states that the expression for the center of the auroral zone agrees with observations but uses observations (taken in 1882-1886) from stations well north of what is usually called the auroral zone to illustrate the agreement. Considering the scarcity of observations north of latitude 70° Alfvén may not be incorrect; however, a re-examination with more comprehensive observations is desirable.

Despite the criticisms of Alfvén's theory, it contains several features which are especially attractive from the standpoint of the present study. (1) The aurora as well as the auroral zone current depends on an electric field and it seems likely that changes in the aurora would be expected when the electric field reverses. (2) Using the idealized symbols, an S_D type of current only exists when there is also a D_{st} type of current. In terms of bays, it is also easily imagined that the discharges take place intermittently, the time between bays being determined by the rate the space charge is built up.

However, as aurora occurs on at least 95 per cent of the nights, the theory fails completely unless it can be demonstrated that the space charge is almost continually present. This may necessitate the assumption that a corpuscular stream is almost continually passing the earth.

(e) Martyn

Martyn has proposed an extension of the Chapman-Ferraro theory to explain aurora and auroral zone currents. The ring current is placed such that its inner and outer radii intersect the magnetic lines of force extending to the south and north margins, respectively, of the auroral zone. Particles are ejected from the ring after being accelerated by a radial polarization within the ring; this also give them high enough velocity to penetrate to auroral heights. The polarization of the ring is thus transferred to the auroral zone. The auroral zone currents are attributed to the drift of ions under the crossed polarization (electric) and magnetic fields such that: (1) S_D currents flow during the first part of the storm, and (2) only D_{st} currents flow during the later stages of the storm. Bay disturbances "can be accounted for in the same manner as the main S_D-storm field, if they be considered as a manifestation of the process of closing the gap (in the ring current) behind the earth." [See 5,26,31.]

Criticisms have been directed by Chapman [23,31] and Alfvén [43].

The theory has the merit of relating the aurora to an electric field although little attention is given to the aurora. In concluding that only D_{st} currents flow in the later stages of the storm, the theory does not fit the observed facts. Even during storms preceded by an s.s.c. a positive bay appears in the evening hours; a D_{st} current gives only negative horizontal disturbance. The explanation for individual bays is also untenable unless it is assumed that the proposed ring current opens and closes with an approximate 24 hour period for a number of successive series of nights.

(f) Wulf

Wulf has suggested that a source of excitation for both the airglow and aurora is to be found in potential differences generated by zonal ionospheric winds cutting the earth's magnetic field. According to the "dynamo theory" such potential differences will be proportional to the product of horizontal wind velocity and vertical field intensity. It is thus proposed that an auroral zone results where this product is a maximum. Diurnal features in aurora are attributed to diurnal variations in upper atmosphere winds. [See 28,44.]

To date, details of wind systems and resulting polarization fields leading to auroral zone currents have not been published;* thus the suggestion can only be evaluated in a general way on the basis of the present study. From this standpoint the suggestion has two advantageous features: (1) the aurora is related to the electromotive force, and (2) the electromotive force caused by winds should vary diurnally and probably is present to some degree every night. The future of this suggestion will depend greatly on ionospheric wind measurements in the aurora zone.

(g) <u>Summary</u>: <u>Principal features to be explained.</u>

To the criticisms already stated, it could be added that none of the theories attempt to explain details of the aurora and disturbance currents. The details, such as the $+\Delta H$ following negative bays, the different forms of aurora, auroral movements and pulsations, etc., are unquestionably important as they occur systematically. However, as the theories are either very incomplete or incompatible with observations, explanations of details are hardly to be expected at present.

On the basis of this study an acceptable theory should explain the simultaneous sequences (illustrated as Patterns I and II) of auroral forms and the atmospheric electrical currents indicated by the magnetic disturbance. Neglecting details, the principal features to be explained are:

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* Recently, Vestine [45] has qualitatively considered several wind systems such as suggested by Wulf. A more complete presentation is to be given in the March 1954 issue of the Journal of Geophysical Research, not available at this writing.

(1) the initial occurrence of aurora and disturbance in the evening hours and the southward shift that follows;

(2) the simultaneous reversal of the electric field and the two types of discontinuities in the auroral activity during the "midnight period";

(3) the decay of the negative bay and the changes in electromotive force that follow the decay and give a $+\Delta H$;

(4) the frequent occurrence of several or more negative bays following the "midnight period" discontinuity;

(5) the usually greater magnitude for negative bays than positive bays even when the auroral light intensity is similar for the two bays;

(6) the changes in auroral form and intensity accompanying particular stages of the magnetic disturbance;

(7) the fact that the same patterns of behavior apply to all degrees of magnetic disturbance and auroral activity.

In Part XII additional features requiring explanation are discussed, many others, especially with regard to spectrographic observations and excitation processes, may be found in the literature. Relative to the past, the amount of literature on aurora within the last five years has grown to monstrous proportions. Although reports of observational results are remarkably consistent, interpretations and theories are seldom in agreement.

The outstanding gap in observational knowledge of the aurora is the lack of simultaneous investigations at stations suitably spaced around the globe. If viewed uncritically on an all-night basis, the patterns presented here appear to be roughly fixed such that they pass over College with the rotation of the earth. However, as stated in the introduction, changes in auroral form and magnetic disturbance within the pattern usually occur suddenly over a longitude range of at least several hours. It is apparent that time relationships between distinct stages of the patterns at various stations must be known before the patterns can be fully understood.

Throughout this study, auroral forms have been the principal "parameters" in attempting to establish relationships between aurora and magnetic disturbance. The writer believes that the importance of auroral forms cannot be overemphasized. This importance is now recognized by those concerned with radio wave propagation in high latitudes; however, practically no attention has been given to auroral forms in constructing auroral theories. In this respect, a peculiar situation is found on comparing corpuscular theories with the suggestion made by Wulf (p. 65) that winds may produce voltages adequate to cause auroral excitation. The principal evidence supporting corpuscular theories has been the existence of doppler-shifted H_{α} lines in auroral spectra. However, the measurements of Meinel [46], Dahlstrom and Hunten [47], and Wilson [48] indicate that the hydrogen lines are observed only in the form, homogeneous arcs. As evidence for high velocity winds during aurora, Wulf [28] has quoted the observations of Little and Maxwell [49] on the scintillation of radio stars during aurora. These observations indicate a considerable increase in the velocity of ionospheric winds during rapidly varying auroral forms such as diffuse patches and flaming aurora, but during homogeneous arcs the velocity is apparently unaffected.

Certainly more observations of associations of hydrogen lines and high velocity winds with particular auroral forms are needed before the significance can be determined. Noting that these associations occur, respectively, before and after the discontinuity of Pattern I one might postulate that there actually are two distinct mechanisms creating aurora. In fact, prior to these observations, Nikolsky [50] did postulate different causes for the evening and morning disturbances. There is, however, very little reason to do this as it is apparent that the post-discontinuity aurora of Pattern I depends on the previous existence of homogeneous arcs and in Pattern II the homogeneous arcs precede the rayed aurora without an intervening discontinuity.

In concluding that the aurora is related to the electromotive force producing the auroral zone currents, there is the alternative of creating the electromotive force outside (e.g., Alfven, Martyn) or within (e.g., Chapman, Wulf) the earth's atmosphere. Until it can be shown that a source of electromotive force exists every night outside the atmosphere it seems more reasonable to assume that the source is within the atmosphere. Taking this step, there is still the alternative of: (1) creating aurora by means of voltages generated by winds as suggested by Wulf, or (2) creating aurora by means of corpuscular bombardment. Alternative (2) is included as it is conceivable that electric fields generated within the atmosphere could alter the paths of incoming particle streams such that their configuration changes with changes in the electric field; this possibility has apparently not appeared in the literature.

There is an indirect argument which suggests a new approach to Wulf's proposal. The three regions of the globe which possess highly concentrated linear currents (sometimes called "electrojets") are the equator and the two auroral zones. Although generally recognized to be of "dynamo" origin, the large magnetic variations at the equator have only recently been explained; duplicate explanations have been given by Lucas, Hirono, Martyn and Baker, and Cowling [for a review, see 51,52]. This has been the result of considering the Hall conductivity in addition to conductivities perpendicular and transverse to the magnetic field. In Martyn's theory [26] of aurora the Hall conductivity plays an important role; however, the theory is objectionable in other respects (see p. 64). Considering the success in explaining equatorial variations, there is the possibility that similar analyses might aid in determining how wind systems could generate potential distributions consistent with the observed auroral zone currents.

XII. SPECIAL TOPICS.

(a) The $+\Delta H$ interval following negative bays.

To the writer's knowledge a $+\Delta H$ interval following negative bays has not previously been reported. It is therefore desirable to know how frequently the interval occurs on the College magnetograms. From visual examination of 180 magnetograms between 03^h and 09^h, the interval obviously occurred at least once on 55 per cent of the magnetograms. For 25 per cent an accurate subtraction of quiet hour values would be necessary to determine the sign. On the remaining 20 per cent the interval did not exist; the disturbance on these nights usually consisted of several overlapping bays. It should be noted that use of a constant mean value baseline instead of a variable quiet hour baseline would increase the length and magnitude of this interval.

In the opinion of the writer the $+\Delta H$ indicates a W to E current but the change from an E to W current should not be interpreted as a sudden 180° change in the electric field. In many cases, ΔZ does not change sign when ΔH does as would be expected for a sudden reversal of the electric field. Thus, if the previous E to W current was north of College, the W to E current should be located south of College; however, it is doubtful if the perpendicular to $\sqrt{(\Delta H)^2 + (\Delta Z)^2}$ is a good indicator of the location of the current at this time. The interval is usually preceded by a marked rotation of H_d. The vectors thus indicate that either a W to E current is established south of the previous (and perhaps still existent) E to W current, or the electric field rotates through 180°. It is quite possible that other explanations are just as reasonable. One possibility is that the $+\Delta H$ is caused by induction currents created during the negative bays. However, there does not seem to be any relationship between the lengths and magnitudes of the negative bay and the $+\Delta H$ interval as would be expected if it were an induction effect.

(b) <u>Coincidence of s.s.c.'s and the onset of negative bays at College, Alaska.</u>

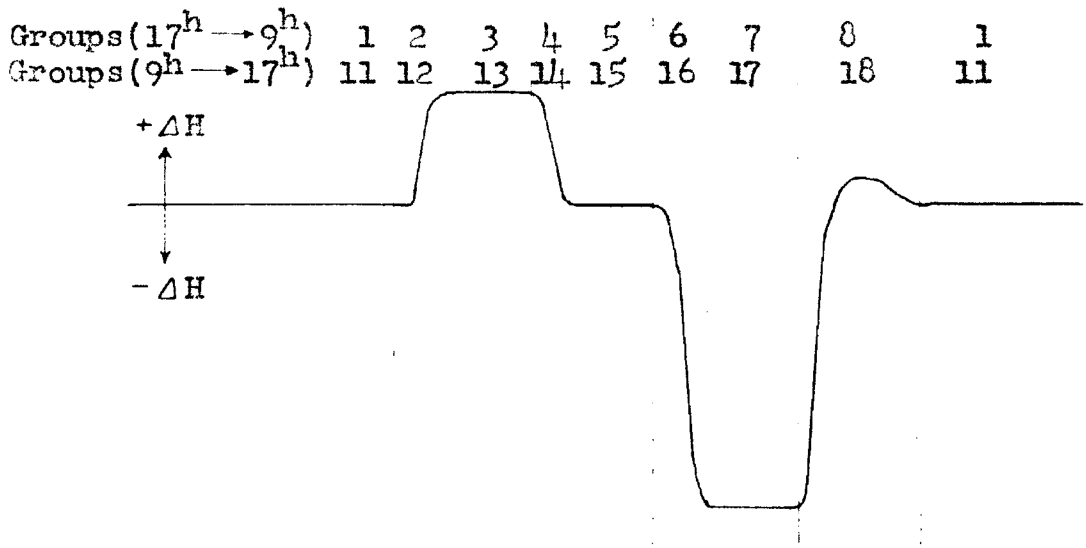
A diurnal variation in the frequency of occurrence of s.s.c.'s has been sought by numerous investigators. The general conclusion is that any local time dependence is very slight, if present at all. There is some possibility that s.s.c.'s occur most frequently in the afternoon hours with a maximum around 13^h local time [for a review, see 19].

On page 46 it was stated that internationally reported s.s.c.'s appeared coincident with the onset of negative bays at College on more occasions than would be expected by chance. Several examples, Plates 14 and 18, in which s.s.c.'s occurred at the time homogeneous arcs broke into brilliant rayed aurora were given. To gain further information on this coincidence, disturbance of the horizontal component at College was divided into 9 stages (see Figure 17). For the days covered by the 180 College magnetograms available, the times s.s.c.'s were reported (J. Geophys. Res., see footnote p. 45) were marked on the magnetograms. The s.s.c.'s were then classified in the 9 stages as follows:

The s.s.c. occurred during

(1) a period when H was comparatively quiet,

(2) the onset or increasing H stage of a positive bay,



Groups 9 and 19: s.s.c. occurred during large magnetic pulsations

Groups 10 and 20: s.s.c. not classifiable

"Night Hours" ($17^h \rightarrow 9^h$)

Groups	1	2	3	4	5	6	7	8	9	10
Number of s.s.c.'s reported (by 6 or more stations)	0	2	0	0	0	2	0	0	0	1
Number of s.s.c.'s reported (by less than 6 stations)	6	2	2	2	3	14	6	2	1	2

"Daylight Hours" ($9^h \rightarrow 17^h$)

Groups	11	12	13	14	15	16	17	18	19	20
Number of s.s.c.'s reported (by 6 or more stations)	4	0	0	0	0	0	0	0	0	0
Number of s.s.c.'s reported (by less than 6 stations)	8	3	0	0	0	2	0	0	2	0

Figure 17 -- Coincidence of reported s.s.c.'s and stage of magnetic disturbance at College, Alaska

(3) a period of large $+\Delta H$ for the particular night,

(4) the decay of a positive bay,

(5) a period separating a positive and negative bay,

(6) the onset or decreasing H stage of a negative bay,

(7) a period of large $-\Delta H$ for the particular night,

(8) the decay of a negative bay and the following period of $+\Delta H$,

(9) large pulsations in H of no particular sign.

Several s.s.c.'s did not fit this classification and were designated Group 10. The s.s.c. noted on Plate 13 between two positive bays is thus classified under Group 10. To distinguish between the often disturbed night hours and the often quiet day hours, the corresponding groups, 11 to 20, were used for s.s.c.'s occurring between 9^h and 17^h.

The results are shown in Figure 17. For the "night hours" the number under Group 6 is obviously large compared to other groups. From the fact that the onset of a negative bay may occur any time between roughly 22^h and 7^h it is apparent that a coincidence between the onset and s.s.c.'s would not show up as a diurnal variation of the type previously sought.

During the onset or decreasing H stage of a negative bay, a feature closely resembling an s.s.c. is often present on the College H component at the time it is reported by other stations. These are rarely reported by the College observatory as they are quite common. As the feature occurs either at the origin (within less than 10 minutes) or during the rapid decrease in H, the time relationships do not suggest that the s.s.c. precedes the change in aurora.

An attempt has been made to see if there is any particular geographical distribution of stations reporting the s.s.c.'s of Group 6. A tendency for the stations to be concentrated in Europe is present but this is of doubtful significance considering the overall concentration of stations in that region.

The number of s.s.c.'s studied here is too small to justify speculation on the cause of the coincidence. However, this approach to studying s.s.c.'s merits further attention. First, it would be desirable to make a more extensive study of the coincidence at College. Second, an auroral zone station located about 12 hours from College should be studied to see if a high percentage of the daytime s.s.c.'s at College occur in Group 6 at the selected station. If this proved to be the case, the study could be extended to other stations (especially to stations in the zone of the aurora australis) with a good possibility of establishing a definite relationship between s.s.c.'s and aurora.

(c) Repetition on successive nights.

The magnetic disturbance cycles of 11 years and of 27 days have received much attention in the literature. It is readily demonstrated, using three hour K-indices and auroral intensity scales that the 27 day cycle is also present in auroral activity.

In contrast, very little attention has been paid to the similar characteristics of magnetograms on two or more successive nights. A brief review is given in reference [4, p. 340] and Wells [53] has published a striking example for one degree of disturbance at College, Alaska. In working with the College magnetograms it is apparent that this tendency exists for large as well as small disturbance. This is illustrated in Figure 18 where the H trace has been copied for three pairs of nights. Often there is a gradual transition throughout a series of nights such that a given night has some of the characteristics of both the previous and the following nights.

The repetitive tendency also appears in the general pattern of auroral activity on successive nights. For example, the discontinuity shown for Pattern II does not occur as frequently as the discontinuity shown for Pattern I but when it occurs it tends to repeat for several consecutive nights. In the illustrations of Pattern II behavior this is apparent. Plates 10 and 11 are successive nights with a Pattern II discontinuity. The discontinuity on January 24-25, 1952 (Plate 6) was transitional (see page 40) between Patterns I and II and the previous night was represented by Pattern II. The series of nights January 20-21, 21-22, 22-23, 1952 (Plates 3,4,5) is a good example of a gradual transition; one, two, and three negative bays appeared, respectively, on the three nights. The preceding nights January 17 to 20 (not shown) were less disturbed than 20-21; thus the disturbance grew gradually from an almost perfectly quiet period on January 17.

The repetition is even more impressive when a peculiar or rare feature occurs on successive nights. For example, on January 22-23, 1952 (Plate 5) and January 23-24, 1952 (Plate 12) very faint homogeneous arcs crossed the College zenith before 20:00 when there was very little aurora elsewhere; in both cases there was practically no magnetic disturbance. For another interesting example of a faint homogeneous arc appearing briefly south of the rest of the aurora on successive nights, compare the times 00:00, 20:25, and 20:15 on Plates 14,15, and 16,

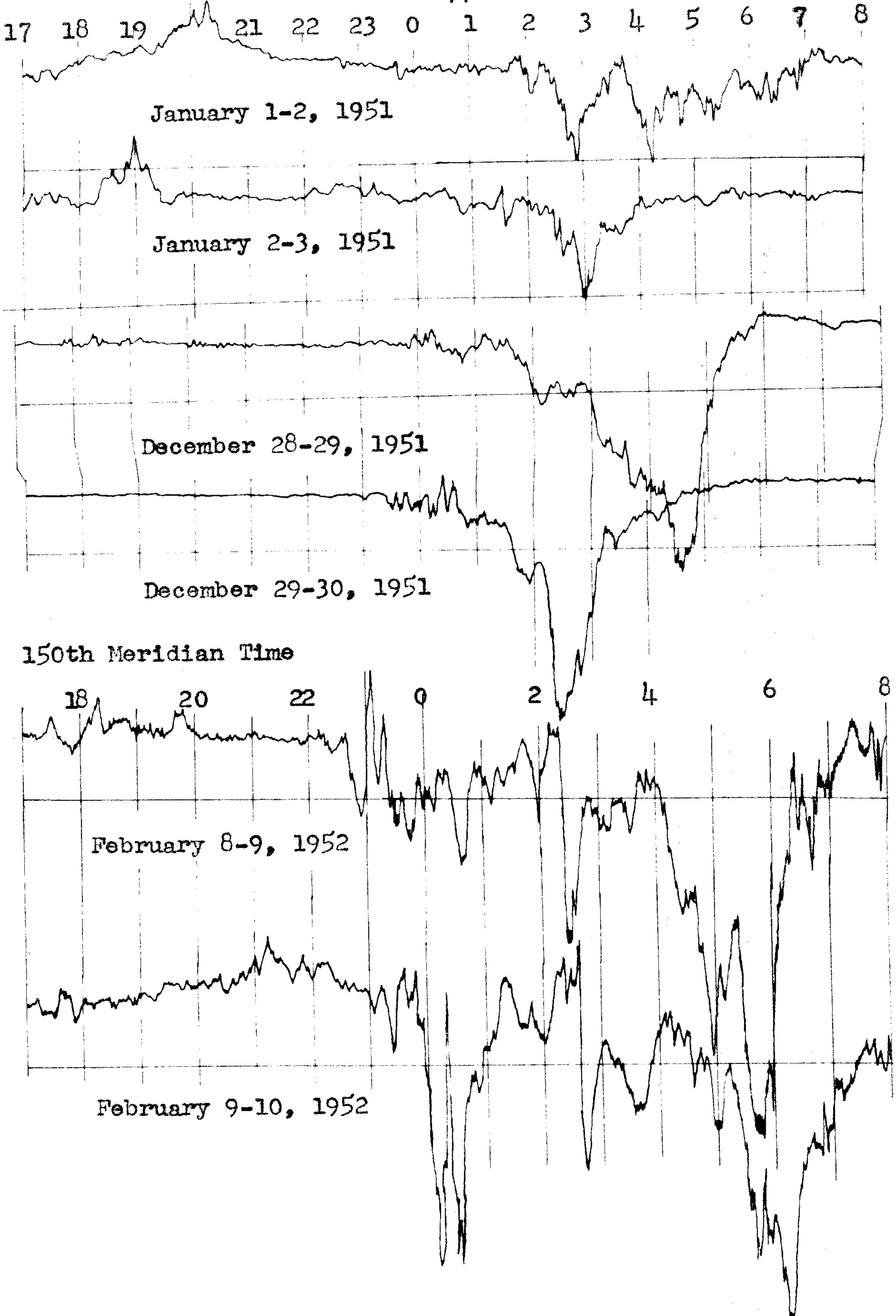


Figure 18 -- Repetition on successive nights, H component

respectively. The most striking example is the reoccurrence of a rare form of aurora which may be called a "horseshoe band" (the two ends of a nearly complete loop are close together at the west horizon). The "horseshoe" spreads eastward over much of the sky and then recedes back over practically the same path, the total process lasting about 15 to 30 minutes. Out of four good examples found in the College observations three occurred on the nights March 9-10, 10-11, and 12-13, 1951. Cloudy skies prevented observations on 11-12. The times of occurrence differed by only 45 minutes on the first two nights.

(d) Pulsating aurora.

The writer has for sometime taken a special interest in pulsating aurora. This interest resulted first from finding that complete absorption of radio waves is closely related to pulsations [14] and second from observing the spectrophotometric characteristics of the pulses. In the present study the special interest is in their distinct role in the nightly sequence and in their movements.

In Figure 19, the frequency of occurrence of pulsating aurora is plotted as a function of time and geomagnetic latitude from about three and one-half months observations; the observations are restricted to clear sky conditions. It is obvious that the relative frequency of pulsating aurora is quite low north of latitude 66° even though the overall frequency of aurora is much greater than near 64° where the maximum occurs. The time distribution increases abruptly after 01:00 which is to be expected from their association with the decay of negative bays.

The pulsations appear, primarily, in the three forms stated in Part II. They may also be classed as stationary, moving, and flaming

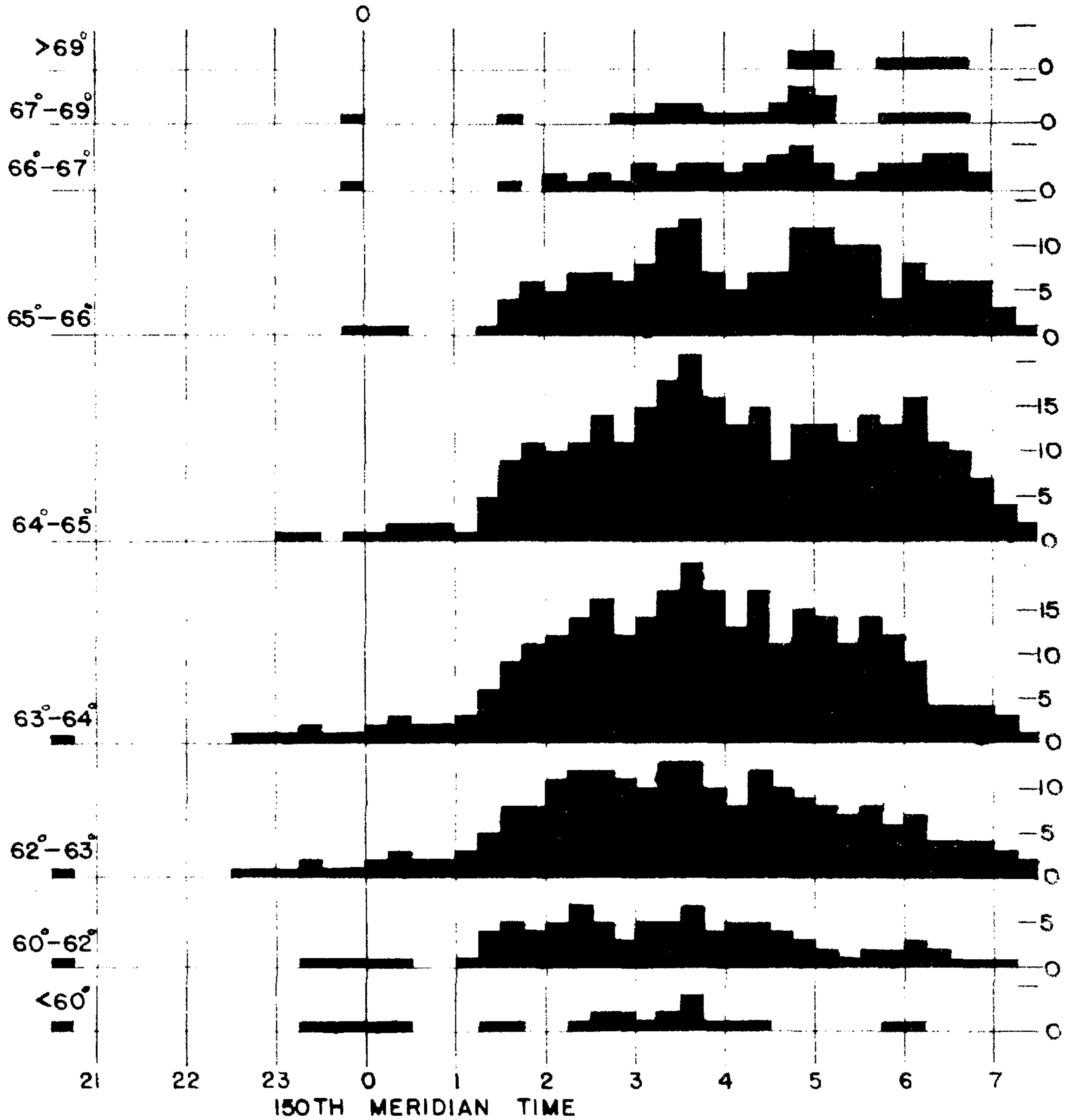


FIGURE 19 -- TIME VS. GEOMAGNETIC LATITUDE DISTRIBUTION OF PULSATING AURORA (PLOTTED ACCORDING TO OCCURRENCES WITHIN 15 MINUTE INTERVALS)

pulsations. The moving and flaming pulsations are of interest here as the writer thinks they may indicate discharge characteristics of aurora.

Flaming auroras will be considered first; descriptions may be found in references [1,4,6]. The distinguishing feature is that the pulsations are directed toward the observer's magnetic zenith; thus they are moving pulsations of a particular type. Observer's have long had the impression that these moving pulsations (or "waves") of light are passing upward in the atmosphere. When the moving pulsations converge toward the magnetic zenith from all sides simultaneously this impression cannot be attributed to perspective and can be regarded as real. The question is how far upward do the movements extend. Apparently accurate transit measurements have never been taken. In the routine observations at College angular estimates of the apparent lateral displacements occasionally appear. Rough calculations from these indicate upward movements of 100 to 300 km. To the writer this is indicative of movement from the E- to the F- region.

In routine observing, lateral movements are usually recorded only when they are so clearly evident that they impress the observer. Excluding N and S movements and cases where the pulsations were directed toward the zenith, it is found that pulsating surfaces move from W to E when ΔH is negative. The pulsating surfaces roughly maintain their shape and either appear, move, and disappear or appear successively in the eastward direction. As an example some excellent observations on the night of January 24-25, 1952 (Plate 6) will be cited. At 03:30 a pulsating multiple arc about 80° wide and extending from horizon to horizon in the usual arc direction was centered approximately at the College zenith; as shown in Plate 6 it was bordered on the north by a non-pulsating arc. The arc was pulsating violently with two distinct types of motion: (1) discrete surfaces appeared above the west horizon at intervals of 5 to 10 seconds and moved rapidly as a traveling pulse over the zenith to the east horizon, and (2) segments of the arc were ejected southward in a continuous manner resembling waves of light which died out with increasing distance. No time measurements were made of motion (2). For motion (1), the time for a pulse to travel from the point where first seen near the west horizon to the zenith was estimated by H. Leinbach to be 1 second or less at 03:30. The motion continued until slightly after 04:42. At 04:42 the writer estimated the time to be 1 to 2 seconds. With a reasonable assumption of the auroral height the times correspond to velocities of 300. to 900. km./sec. The velocity has no particular significance here as it is a measurement on one night only. However, the W to E motion is significant as it will be noted in the next section that the same direction is observed for other, much slower, motions.

(e) <u>Auroral Movements</u>.

Auroral movements of non-pulsating type will be discussed here with reference to recent measurements in middle latitudes by Meinel and Schulte [54]. During the post midnight hours they reported four measurements of rays and draperies which retained their shape during movement; W to E velocities ranging from about 100 to 1300 meters/sec. were found. The motion was attributed to transportation by an air circulatory system.

An examination of the College observations confirms the direction of movement noted by Meinel and Schulte. The recorded movements of discrete rayed forms during $-\Delta H$ disturbances are almost without exception from W to E. Only very rough estimates of the velocities can be made from the observations; if anything, they indicate somewhat greater velocities than reported by Meinel and Schulte. This may be the result of the observers overlooking the slower movements. From their observations at College, Fuller and Bramhall [3] concluded that "the movement of rays generally, but not always, was easterly rather than westerly." Although it is not stated whether the rays were complete forms or rays within a rayed arc or band, the direction suggests agreement with the present study.

At College a west to east effect is also present during $-\Delta H$ disturbances in the mode with which homogeneous arcs are transformed to brilliant rayed forms. (Note: this corresponds to negative bays of the type represented by Pattern II.) Often the transformation occurs in a manner such that no directional effect is noticed. Excluding these cases, rays, wavy motions, and increased light intensity within the arc, appear first near the west horizon and then propagate eastward (one well recorded and several questionable exceptions to this statement have been found so it is not always the case). A transformation from horizon to horizon frequently takes place in several minutes. However, due to the fact that the change is also observed to occur instantaneously or may stop at a particular eastern limit, no distinctive velocity range can be assigned when observed at only one longitude.

Meinel and Schulte also reported two measurements of E to W movements during premidnight hours. In the College observations the writer has not found enough examples to either add confirmation or question the generality of the direction. The observations give some information on the mode with which homogeneous arcs transform to brilliant rayed forms at times corresponding to the discontinuity of Pattern I. The homogeneous arc often breaks off near the east end and bends back toward the north thus forming a homogeneous band which is convex toward the east. Rays may appear at any time within the arc or band such that they may appear as a rayed arc followed by a more intense rayed band. When the rayed band stage appears the linear appearance rapidly disappears and rapid movements begin. In a sense this is an E to W effect if the rays appear first at the east end; some observations clearly indicate that this is the case but a much greater proportion indicates rays appearing at the same time all along the arc or band; consequently, no decision can be made here. Detailed studies of these and other transformations are needed.

From the above, there is good evidence for W to E movements and effects during negative bays; the movements during positive bays remain uncertain. In the previous section W to E movements of pulsations were also noted but at velocities much greater than seems possible for winds. Considering the differences in the various phenomena it is improbable that they have a common cause; however, the possibility that they all may be due to motions in an electric field cannot be neglected.

XIII. CONCLUSIONS

(1) For cases of simple auroral arcs, Birkeland's method of locating linear currents in the auroral zone indicates that the disturbing current is located approximately in the same space as the auroral light. The accuracy of the method is limited by uncertain corrections for induced currents, the presence of more than one auroral form, and meridional currents which may be either components of the principal current or distinct from the principal current.

(2) When the aurora is moving southward during the evening hours there is some indication that currents adjacent to the southern edge are especially intense.

(3) The magnetic disturbance and simultaneous auroral activity on a large majority, and perhaps all, nights may be represented by means of two patterns which apply individually or in combinations. This is a consequence of recognizing that magnetic disturbances are made up of individual bay disturbances and that coincident with each bay there is a distinct sequence of auroral activity.

(4) During periods of large disturbances (magnetic storms) preceded by sudden commencements the pattern of behavior is the same as on other nights. That is, the disturbance is still made up of bays and coincident with each bay the same sequence of auroral activity is observed.

(5) The reversal of the electric current during the "midnight period," indicated by the change in sign of ΔH, occurs simultaneous with a discontinuity in the auroral activity. Therefore, there is good reason to believe that the aurora and the electromotive force are related.

(6) On nights represented by Pattern I the "midnight" discontinuity in auroral activity and the simultaneous change in sign of ΔH progress with time from north to south. The change in sign of ΔH is in good agreement with the current system derived by Harang [1,11].

(7) Following a negative bay a short $+\Delta H$ interval is observed. The time of occurrence of this interval is associated with the presence of diffuse and pulsating aurora. This also suggests a dependence between the aurora and the electromotive force.

(8) Negative bays are usually of greater magnitude than positive bays even when the auroral luminosity is similar for the two bays. The most promising explanations are: (a) that the conductivity has increased during the auroral activity preceding the negative bay, and (b) that there is an additional atmospheric current with an east to west component during both bays. If (b) is the case it must be assumed that the additional current is in the general region of the auroral zone; otherwise negative ΔH disturbances would be observed almost every night in lower latitudes.

(9) The results of a preliminary study indicate that s.s.c.'s, reported on a world-wide scale, appear simultaneous with the onset or decreasing H stage of negative bays at College on more occasions than would be expected through chance.

(10) There is commonly a gradual transition in the auroral activity and magnetic disturbance throughout a series of nights such that a given night will have some of the characteristics of both the previous and the following night. The transition is sometimes so slight that two successive nights may be roughly identical.

(11) The characteristics of flaming aurora suggest, but by no means prove, that discharges between the E- and F-regions of the ionosphere may exist.

(12) During negative bays, movements of rayed forms which retain their shape, movements of pulsating surfaces, and transitions from homogeneous to rayed aurora all tend to take place from west to east. Directional effects during positive bays remain uncertain.

(13) The theories which have been put forth to explain, individually or collectively, the cause of auroral zone currents and aurora, are either very incomplete or incompatible with observations. The present study will favor theories that relate the aurora to the electromotive force causing the auroral zone currents. This electromotive force must be present on more than 95 out of 100 nights.

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PLATES

Plates 1' through 18': Half-size tracings of College, Alaska magnetograms.

Plates 1 through 18: Horizontal disturbance vectors (H_d), ΔZ variations, and auroral diagrams. (For index to auroral symbols, see p. 9.)

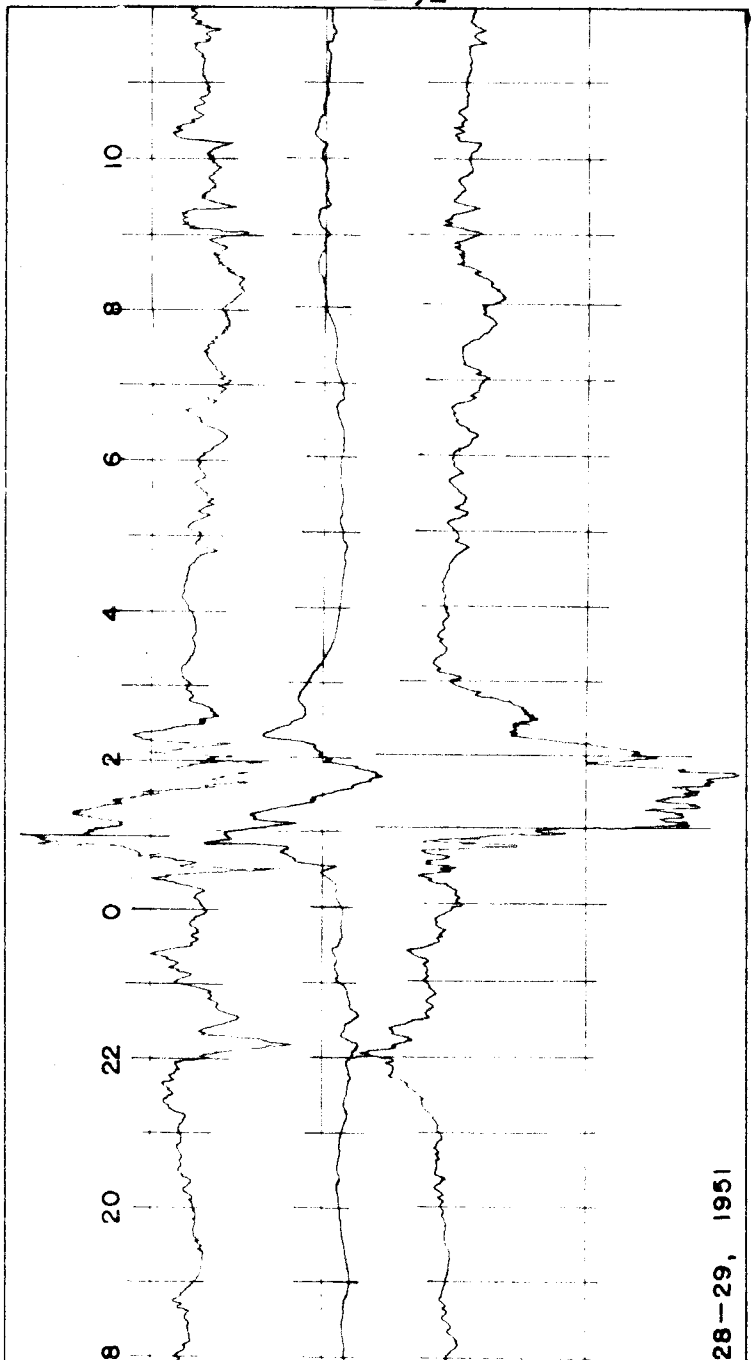


PLATE I': JANUARY 28–29, 1951

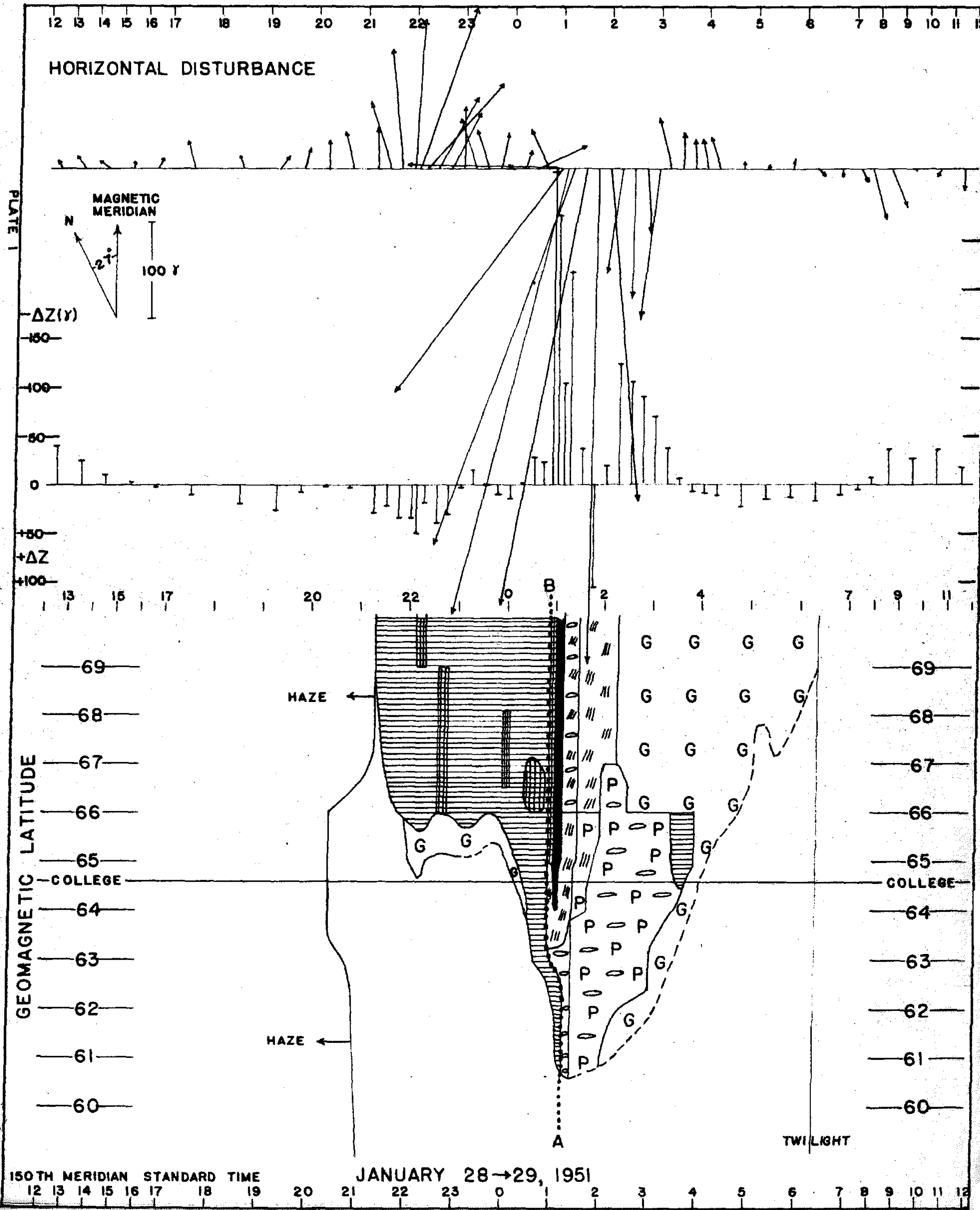


PLATE I
HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ(γ)
-150
-100
-50
0
+50
+ΔZ
+100
HAZE
HAZE
GEOMAGNETIC LATITUDE
COLLEGE
B
A
TWILIGHT
150TH MERIDIAN STANDARD TIME
JANUARY 28→29, 1951

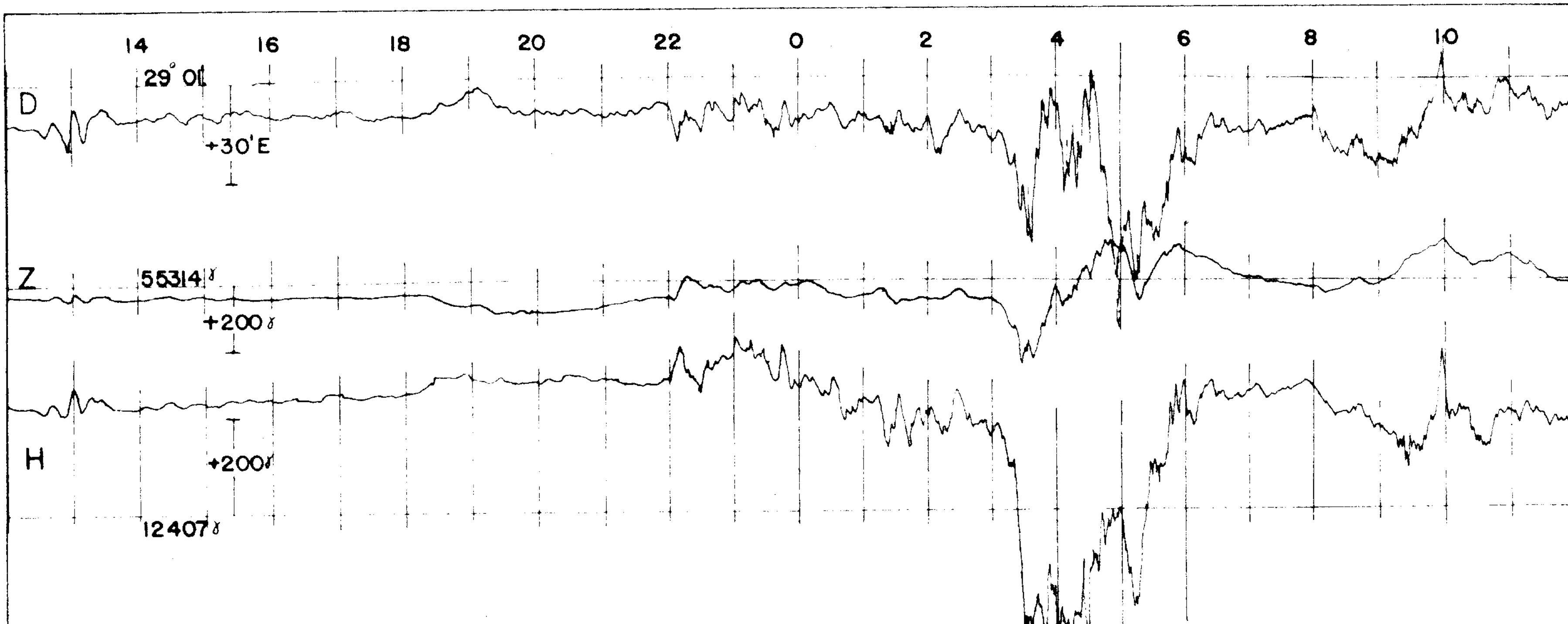
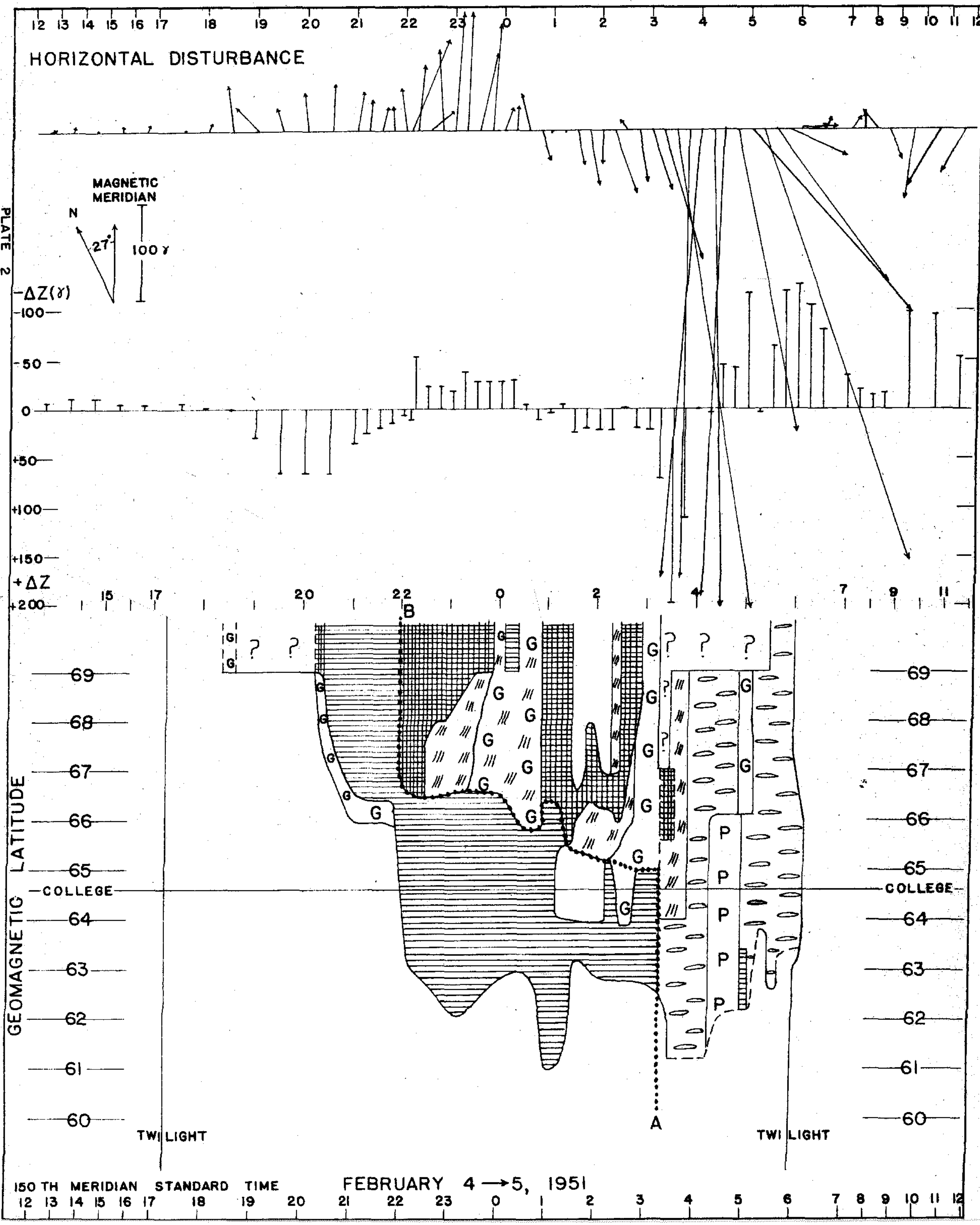


PLATE 2': FEBRUARY 4–5, 1951



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
−ΔZ(γ)
+ΔZ
GEOMAGNETIC LATITUDE
COLLEGE
TWILIGHT
A
B
150 TH MERIDIAN STANDARD TIME
FEBRUARY 4 → 5, 1951

PLATE 2

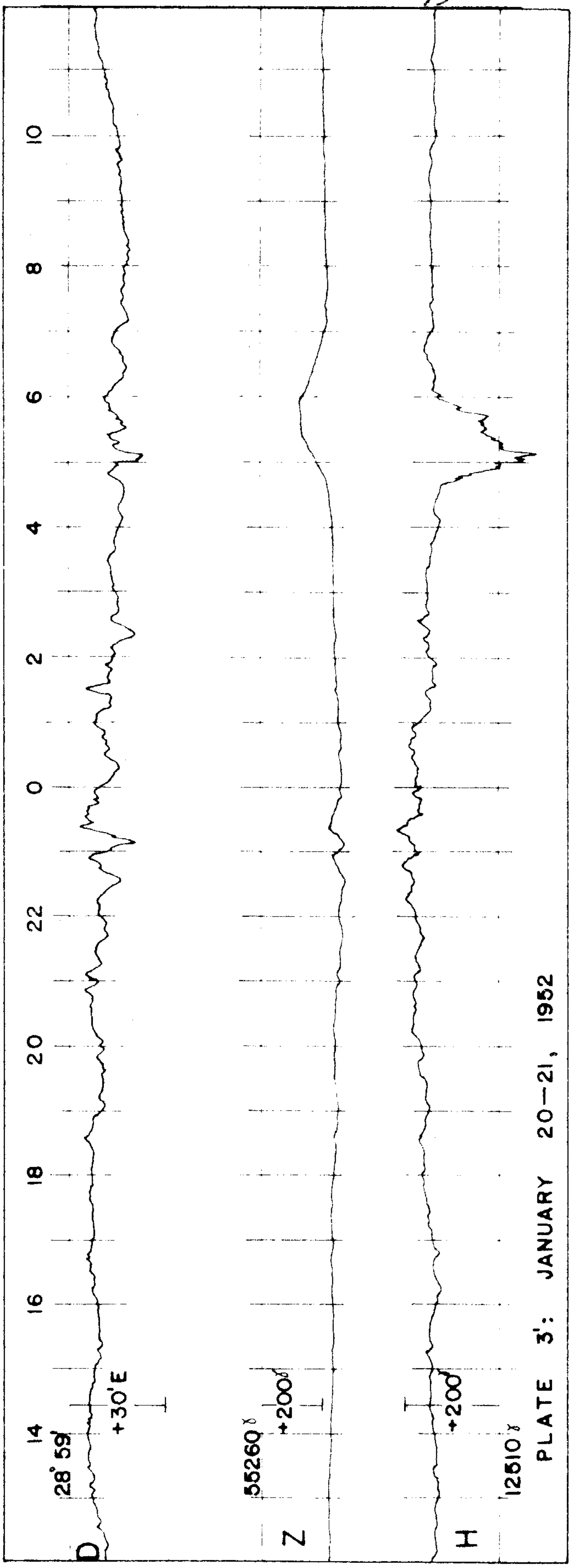
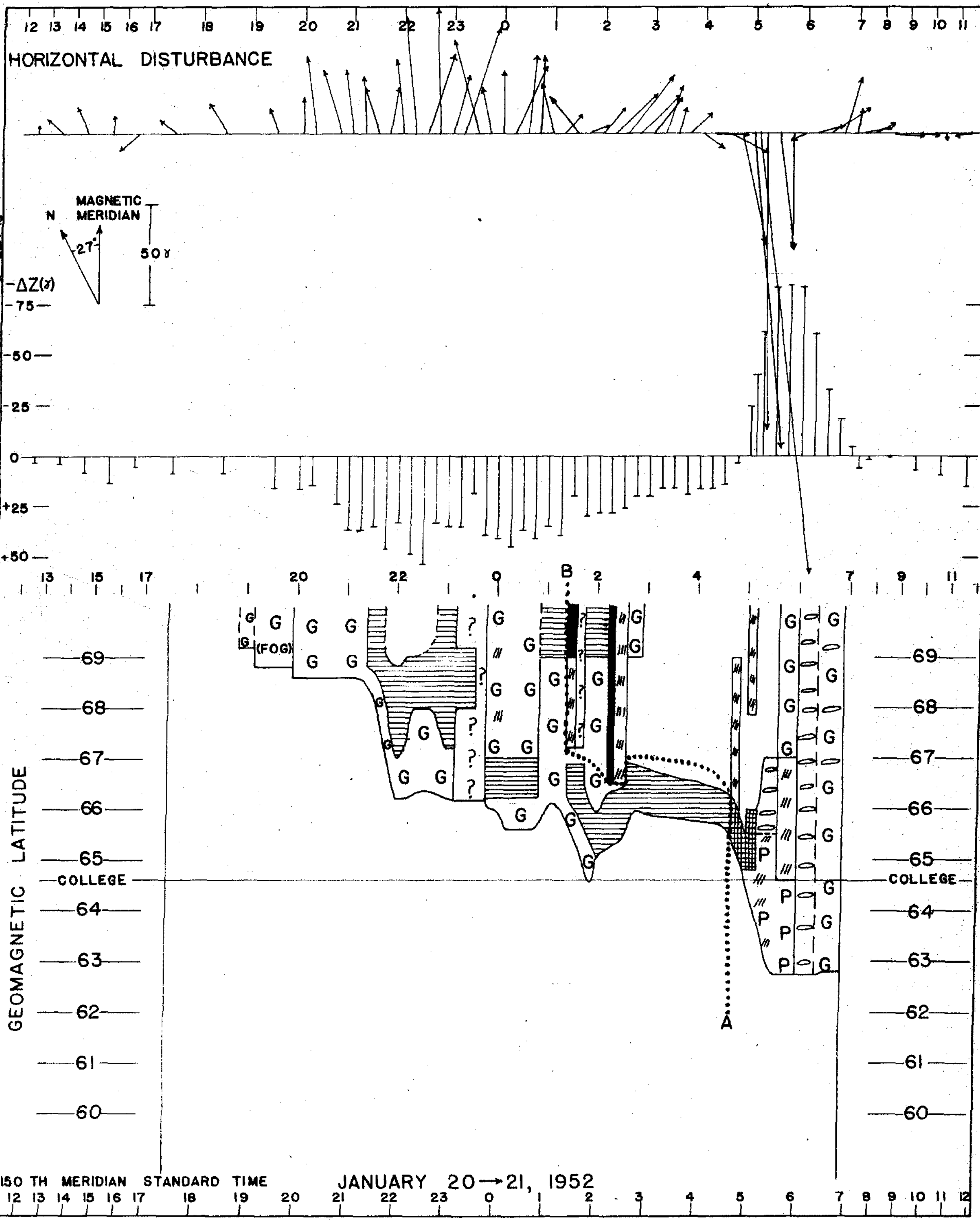


PLATE 3': JANUARY 20—21, 1952

PLATE 3


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
50 γ
-ΔZ(γ)
-75
-50
-25
0
+25
+50
B
A
G
(FOG)
P
COLLEGE
GEOMAGNETIC LATITUDE
69
68
67
66
65
64
63
62
61
60
150 TH MERIDIAN STANDARD TIME
JANUARY 20→21, 1952

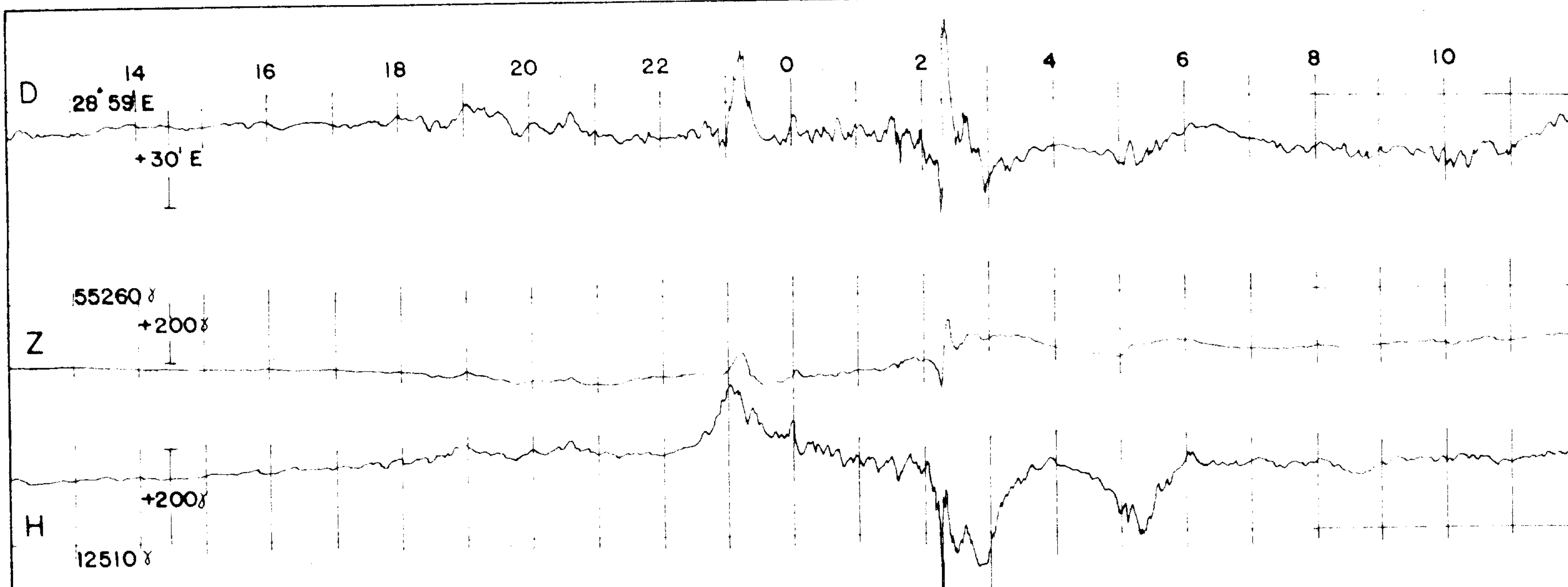
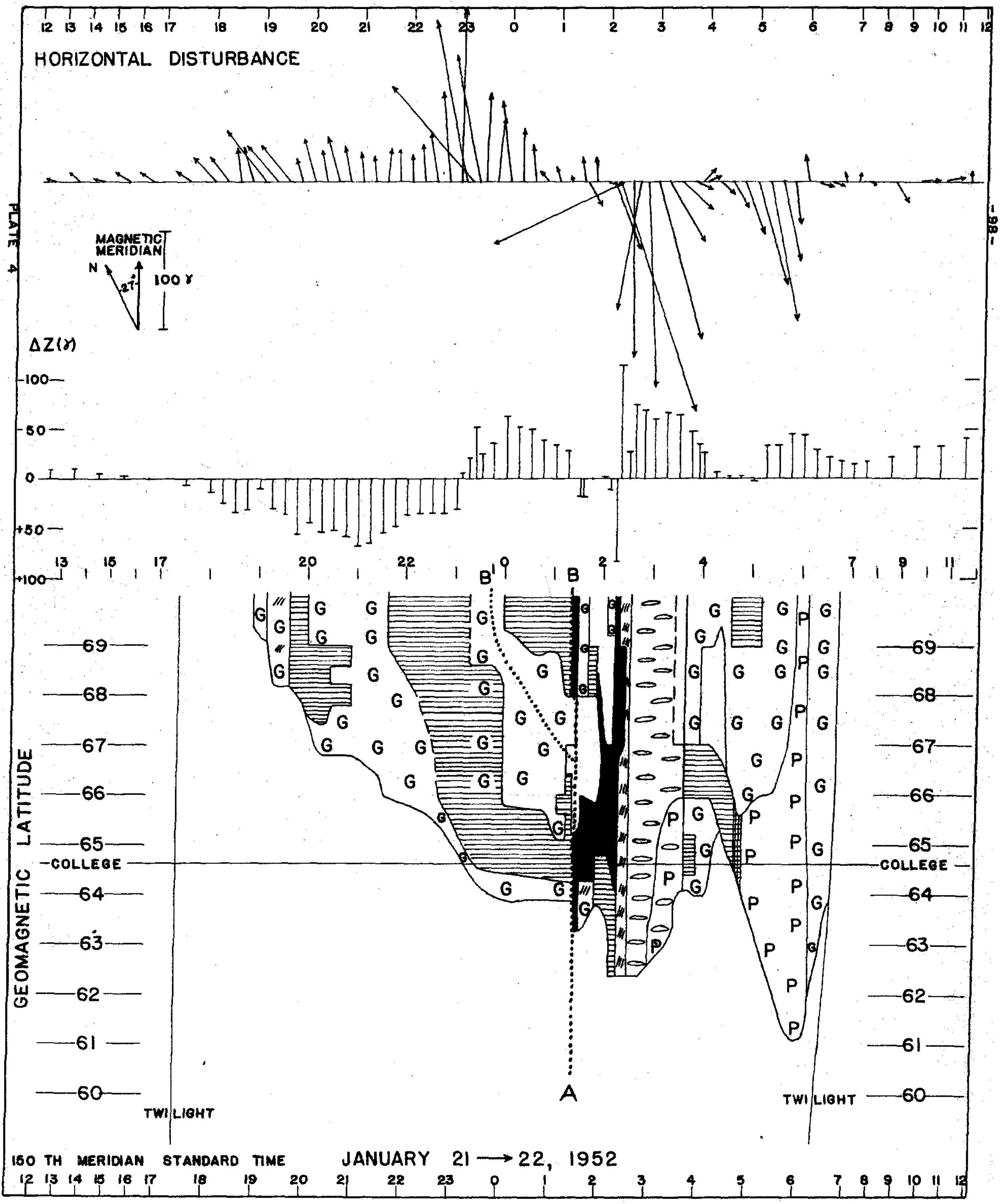


PLATE 4': JANUARY 21—22, 1952

PLATE 4



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ(γ)
100
50
0
50
100
A
B
B'
GEOMAGNETIC LATITUDE
69
68
67
66
65
COLLEGE
64
63
62
61
60
TWILIGHT
TWILIGHT
160 TH MERIDIAN STANDARD TIME
JANUARY 21 → 22, 1952
12 13 14 15 16 17 18 19 20 21 22 23 0 1 2 3 4 5 6 7 8 9 10 11 12

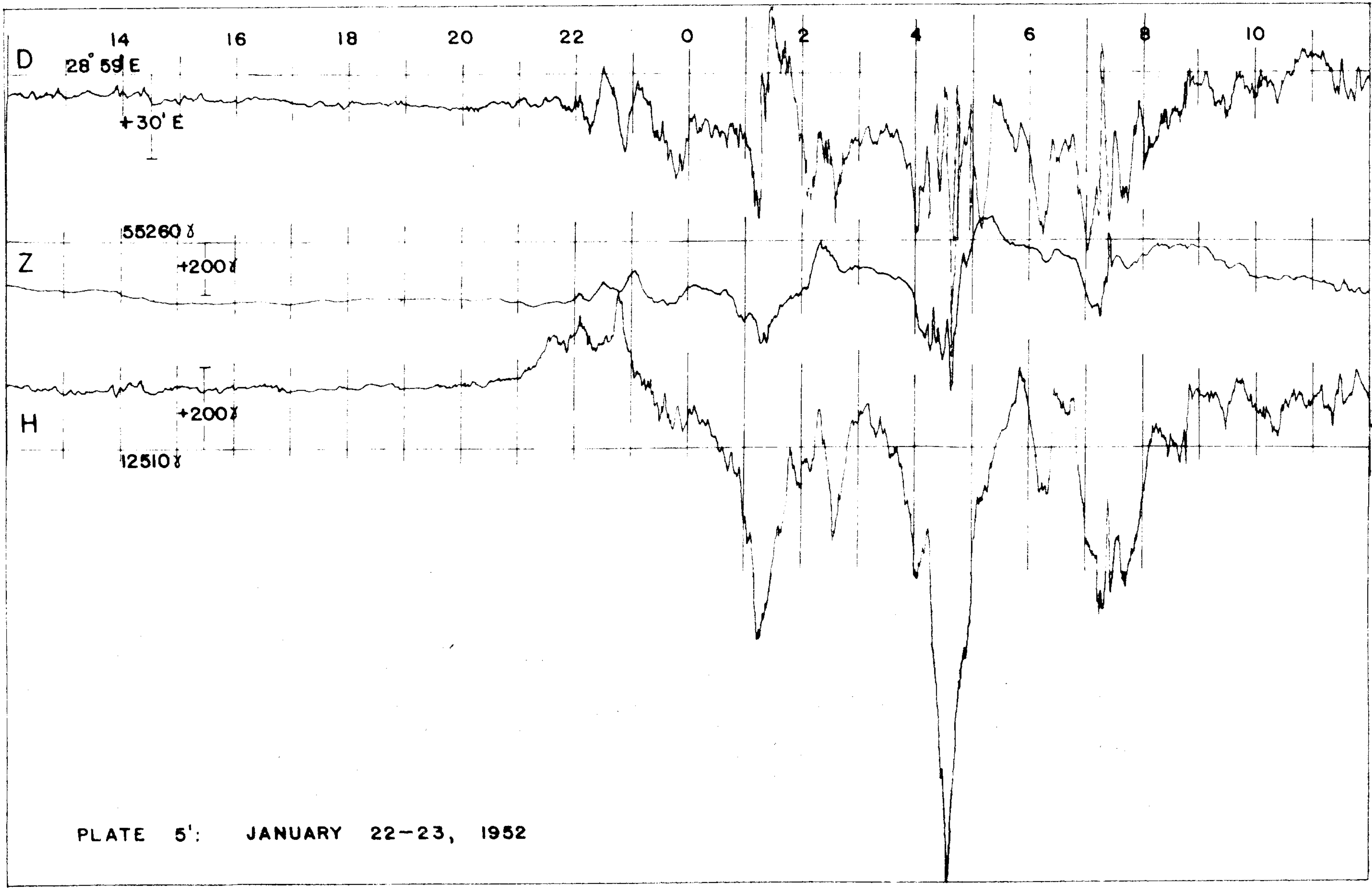
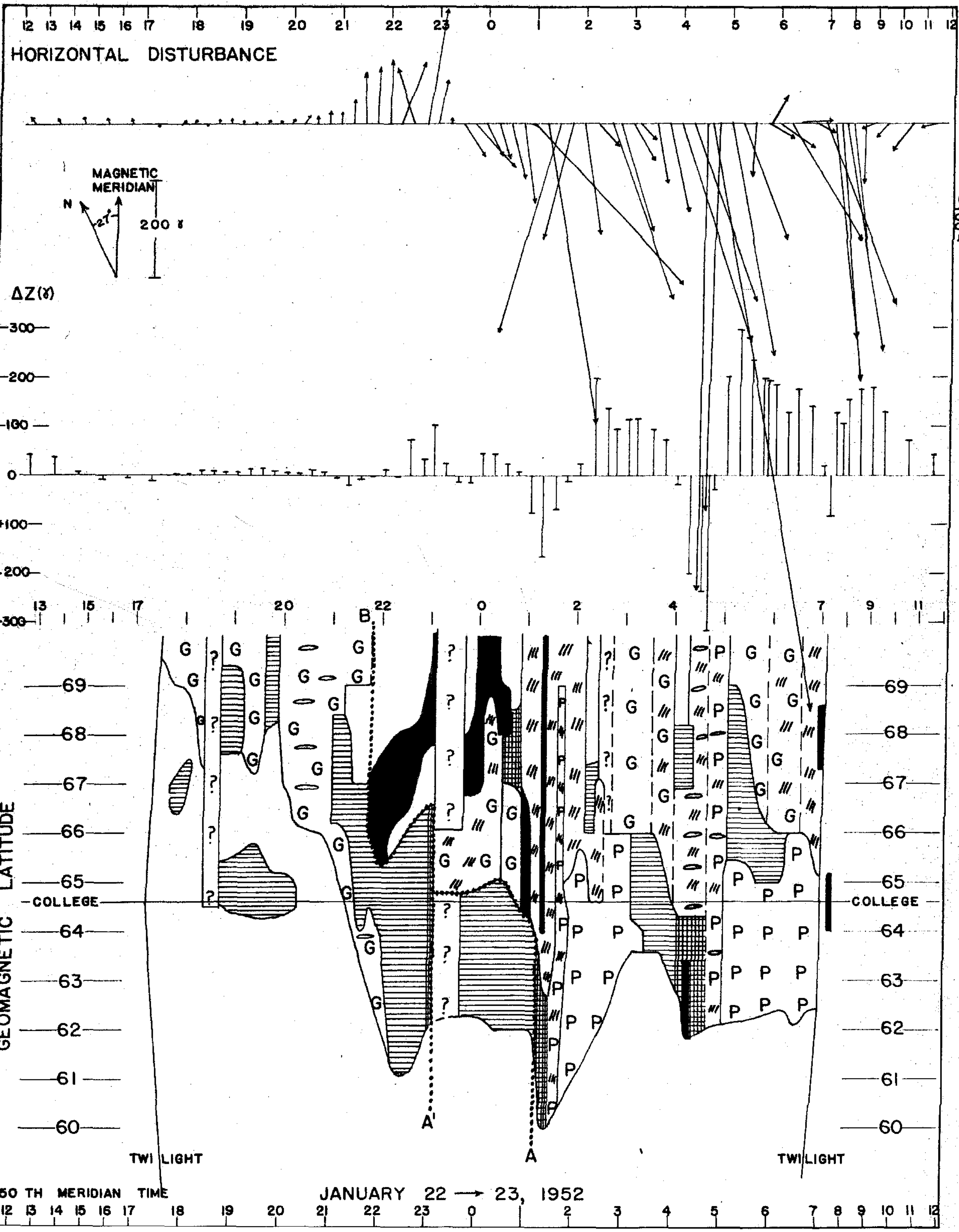


PLATE 5': JANUARY 22–23, 1952

PLATE 5


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
200 γ
ΔZ(γ)
GEOMAGNETIC LATITUDE
COLLEGE
TWILIGHT
TWILIGHT
A
A'
B
150 TH MERIDIAN TIME
JANUARY 22 → 23, 1952

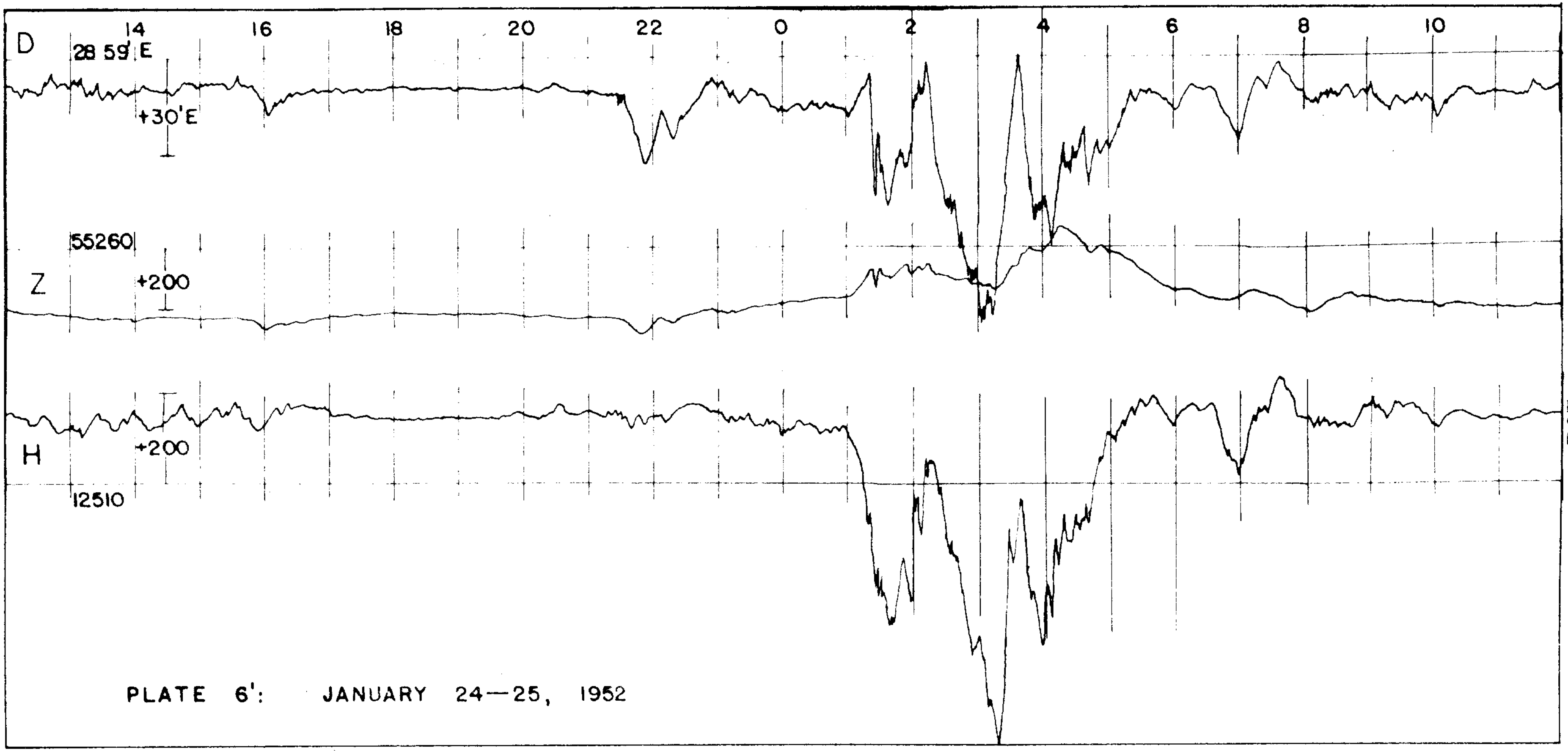
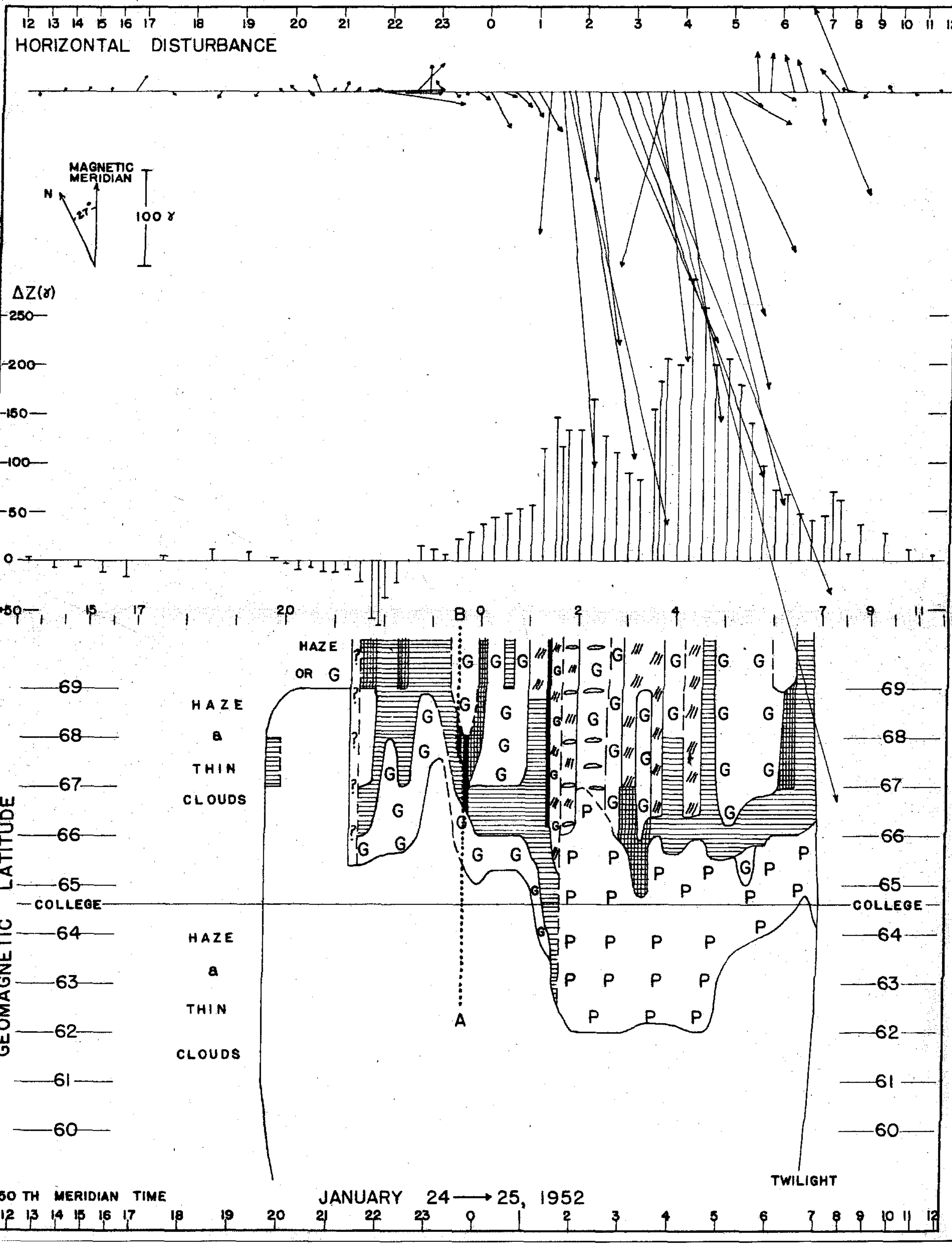


PLATE 6': JANUARY 24—25, 1952

PLATE 6



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ(γ)
250
200
150
100
50
0
50
HAZE OR G
HAZE & THIN CLOUDS
HAZE & THIN CLOUDS
B
A
G
P
COLLEGE
GEOMAGNETIC LATITUDE
69
68
67
66
65
64
63
62
61
60
TWILIGHT
150 TH MERIDIAN TIME
JANUARY 24 → 25, 1952
12 13 14 15 16 17 18 19 20 21 22 23 0 1 2 3 4 5 6 7 8 9 10 11 12

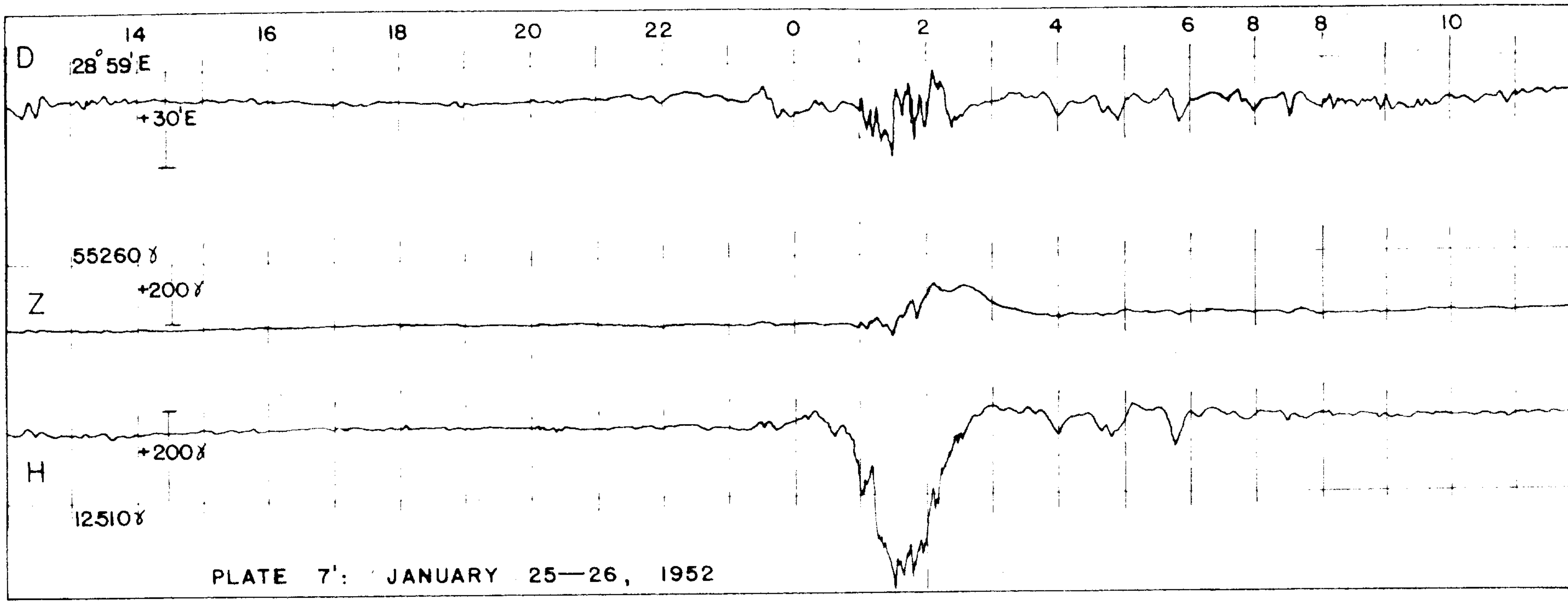
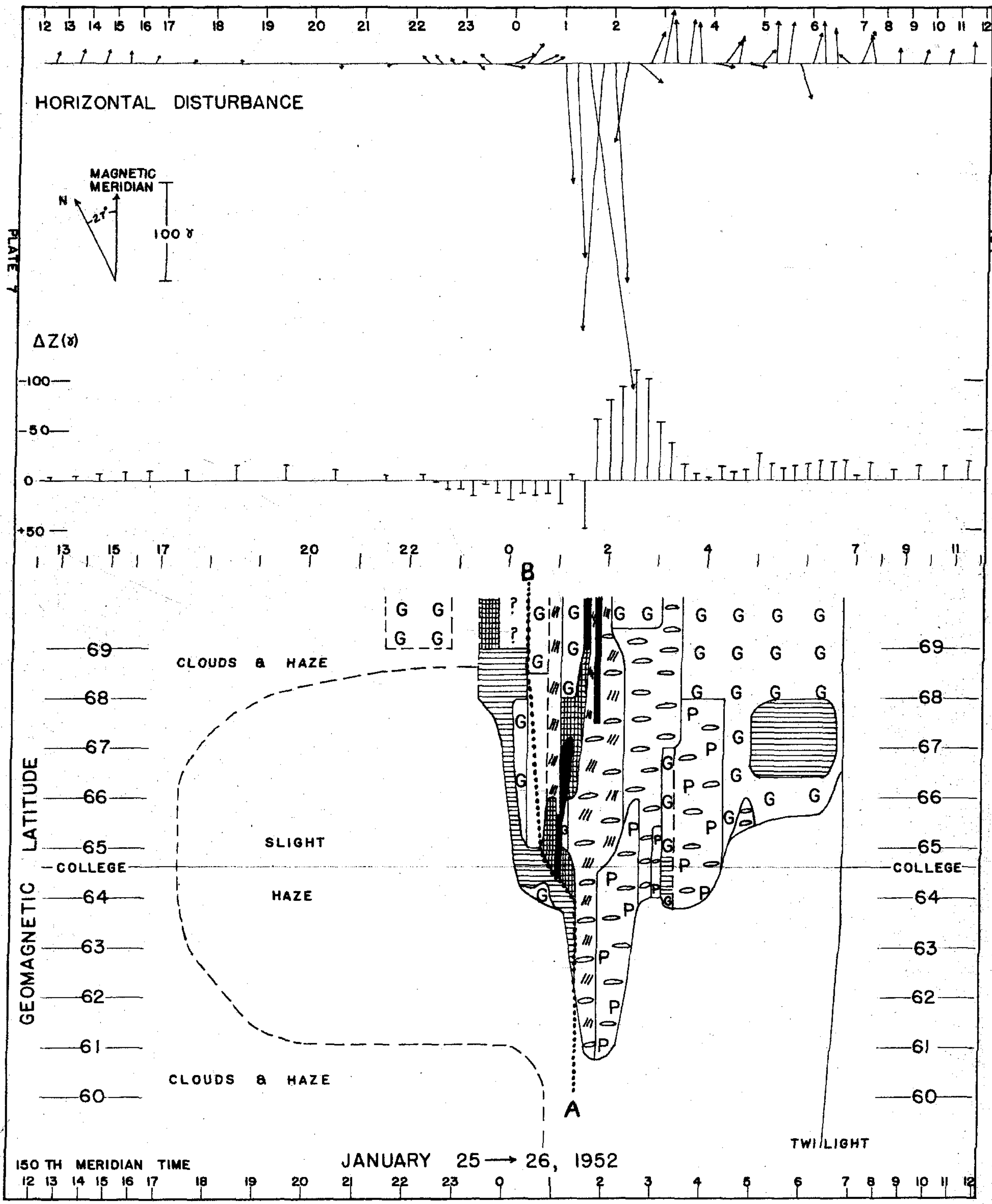


PLATE 7': JANUARY 25—26, 1952

PLATE 7


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ(γ)
-100
-50
0
+50
B
A
CLOUDS & HAZE
SLIGHT
HAZE
CLOUDS & HAZE
GEOMAGNETIC LATITUDE
COLLEGE
TWILIGHT
150 TH MERIDIAN TIME
JANUARY 25 → 26, 1952

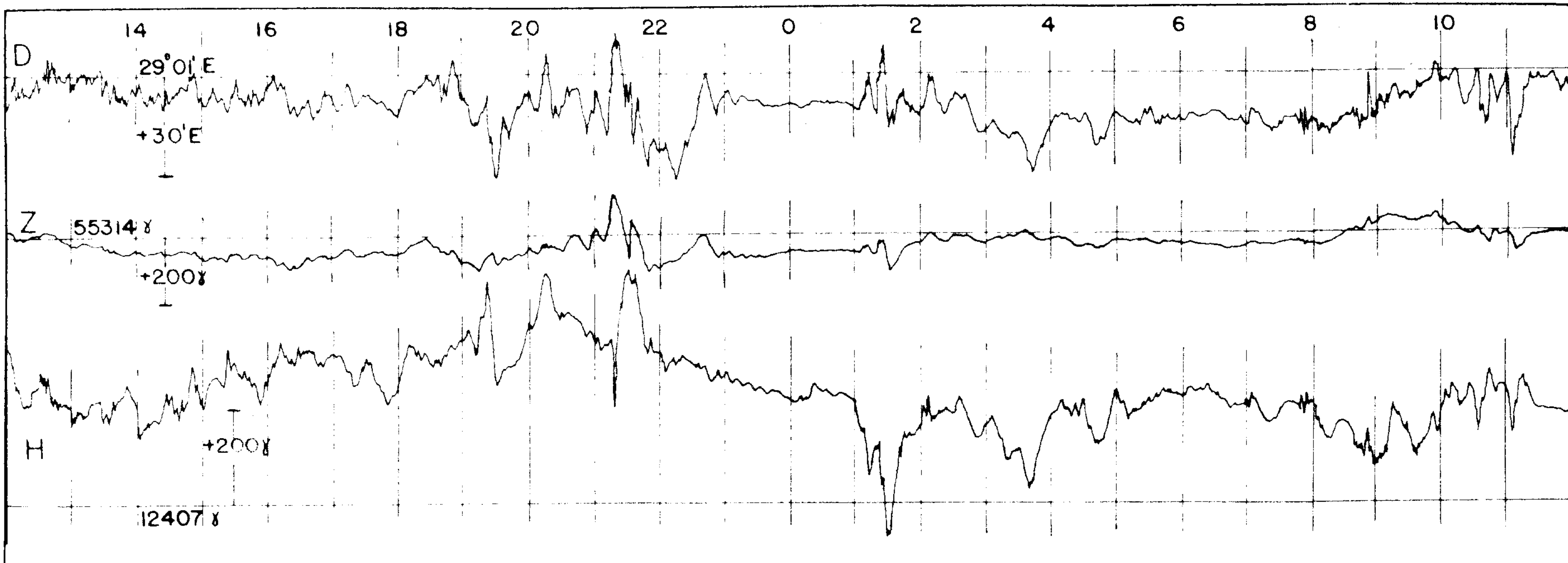
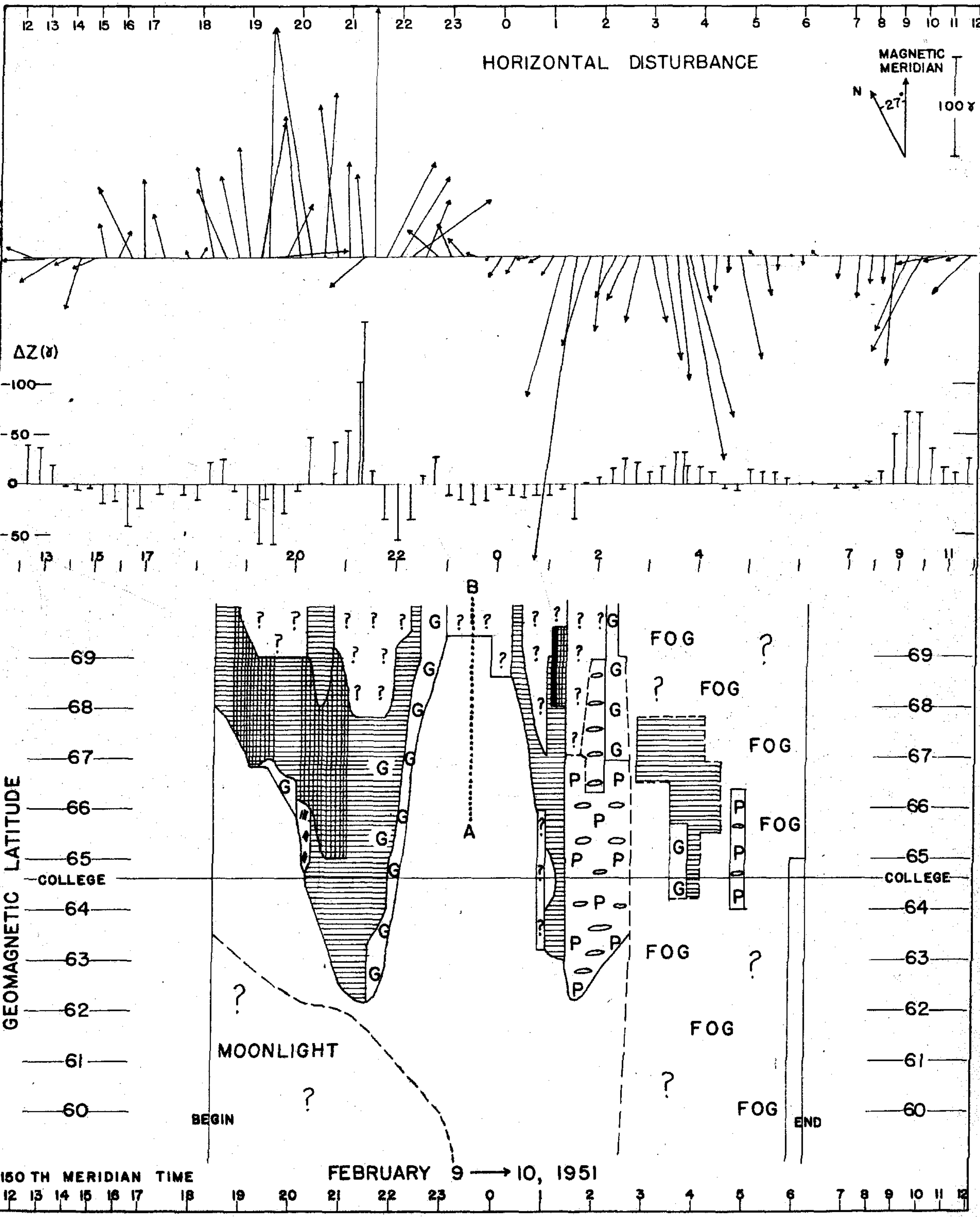


PLATE 8': FEBRUARY 9—10, 1951

PLATE 8


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ (γ)
-100
-50
0
-50
GEOMAGNETIC LATITUDE
69
68
67
66
65
COLLEGE
64
63
62
61
60
FOG
MOONLIGHT
BEGIN
END
A
B
G
P
150 TH MERIDIAN TIME
FEBRUARY 9 ⟶ 10, 1951

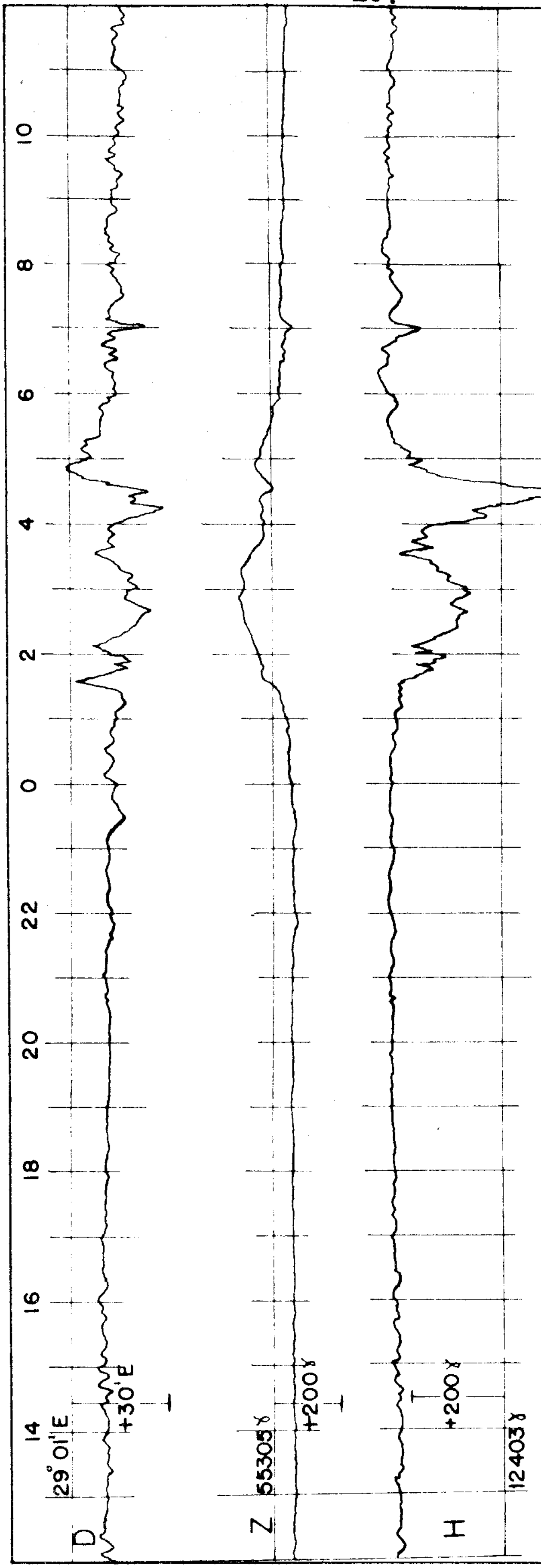
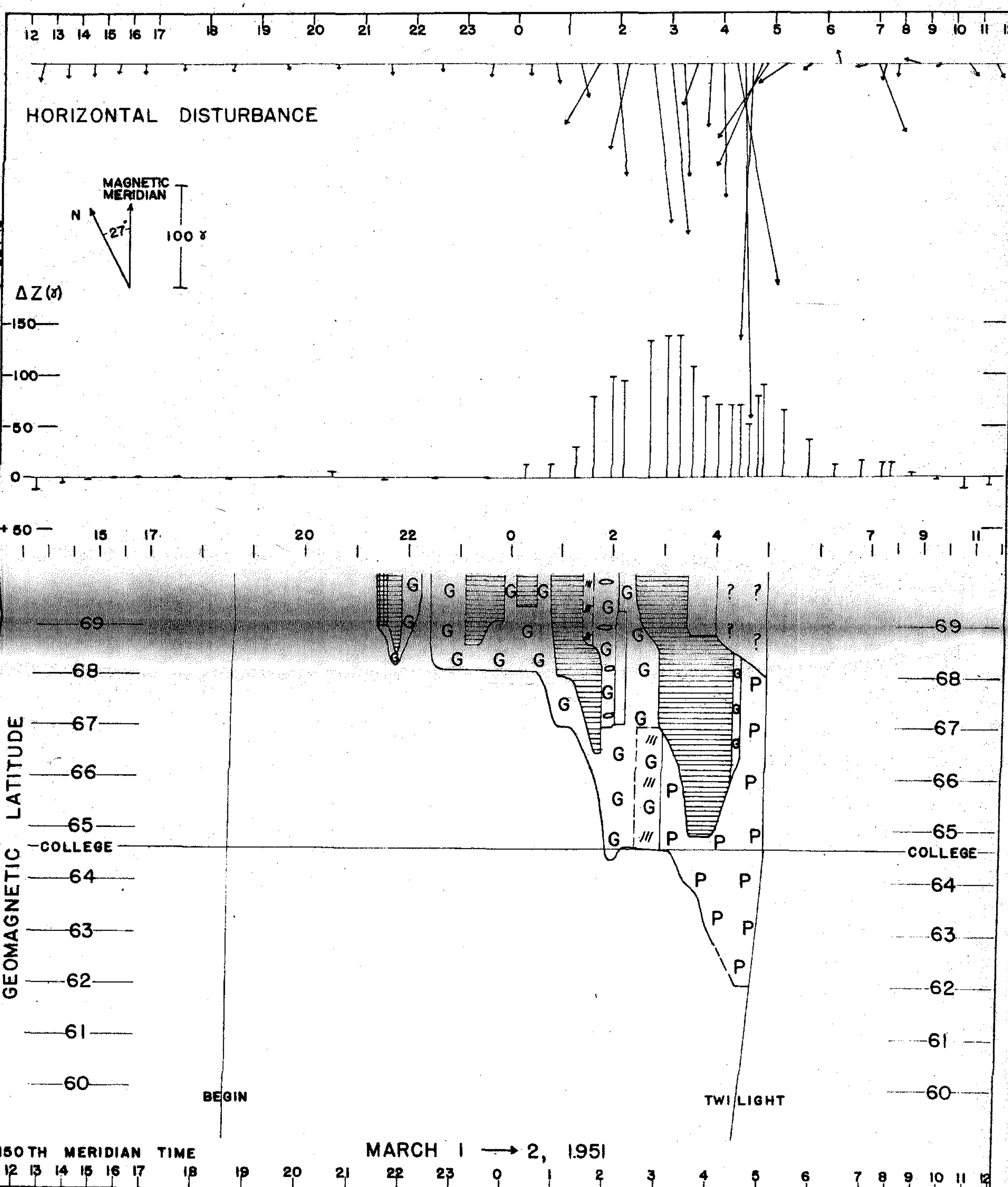


PLATE 9': MARCH 1—2, 1951

PLATE 9



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ (γ)
150
100
50
0
+50
GEOMAGNETIC LATITUDE
COLLEGE
BEGIN
TWILIGHT
150TH MERIDIAN TIME
MARCH 1 → 2, 1951

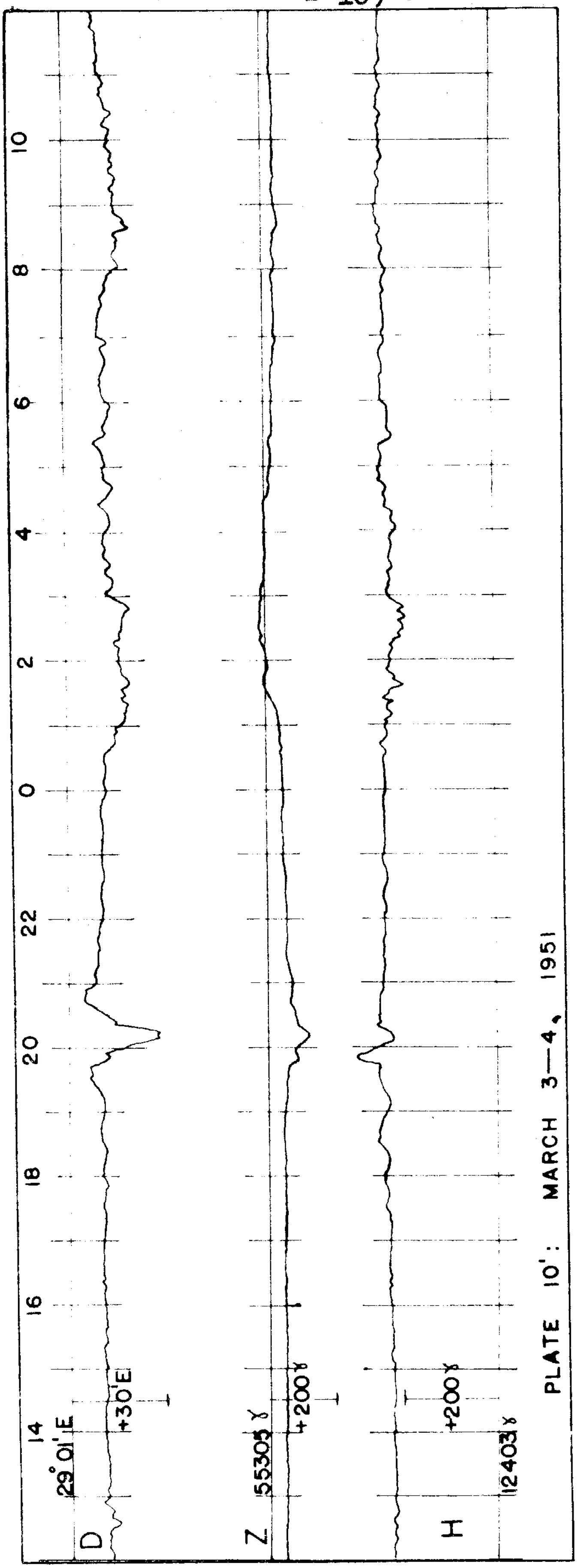
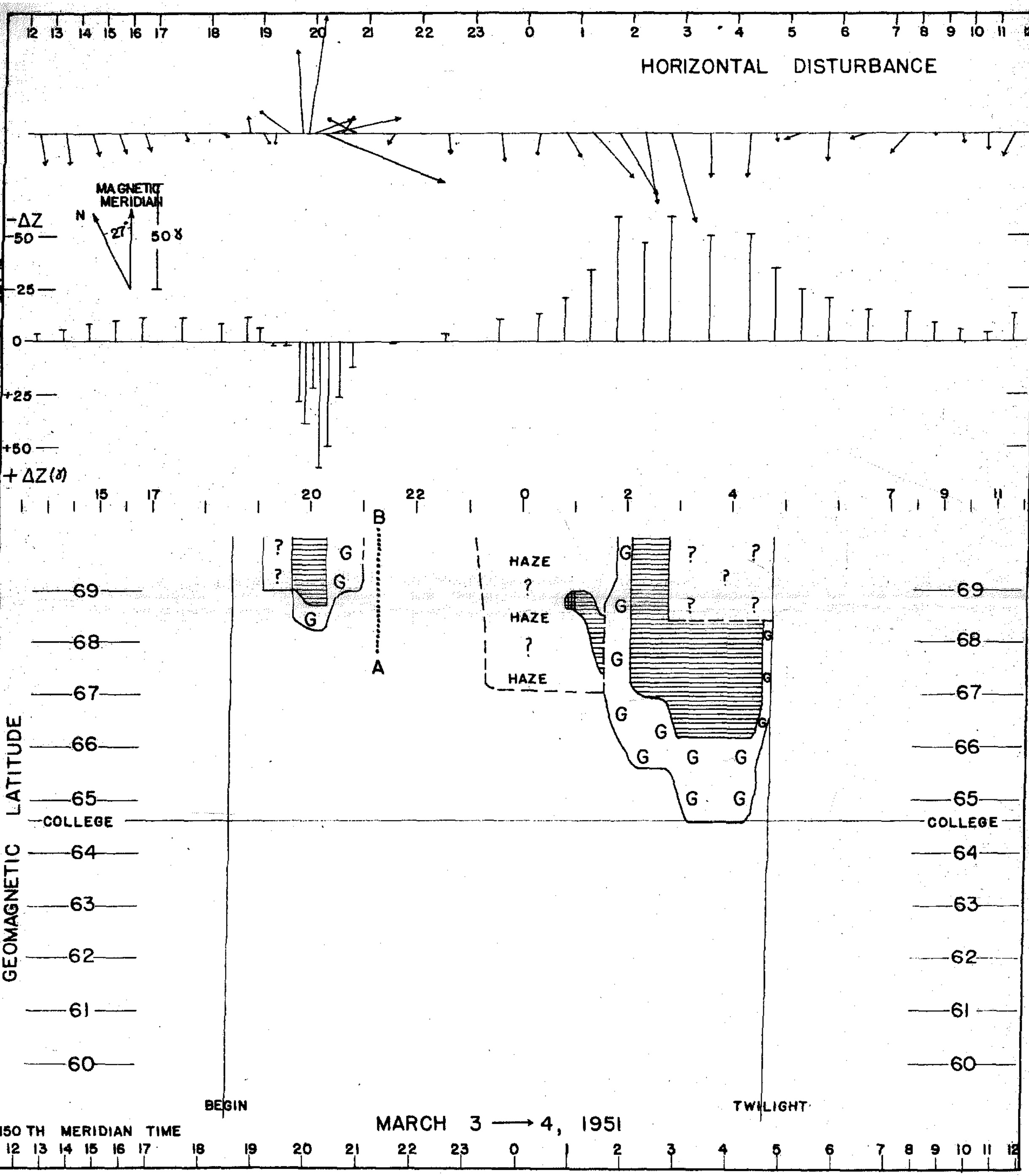


PLATE 10': MARCH 3—4, 1951

PLATE 10



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
50 γ
−ΔZ
+ΔZ(γ)
B
A
HAZE
?
G
COLLEGE
GEOMETRIC LATITUDE
BEGIN
TWILIGHT
MARCH 3 ⟶ 4, 1951
150 TH MERIDIAN TIME

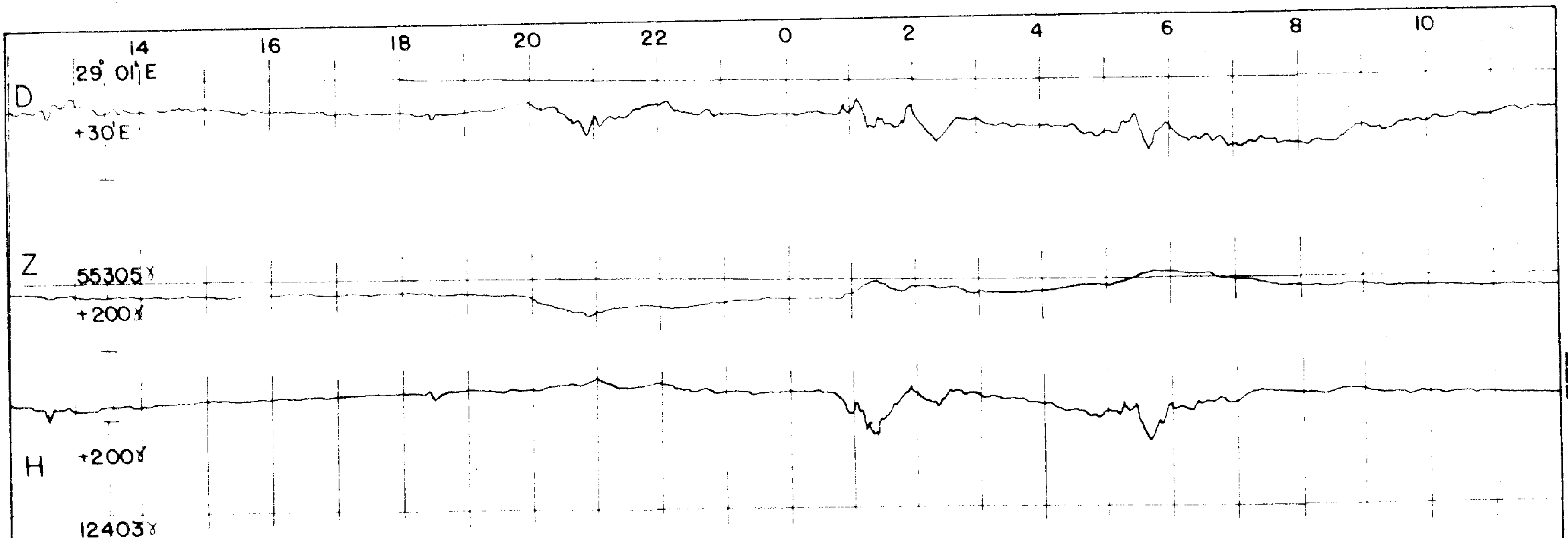
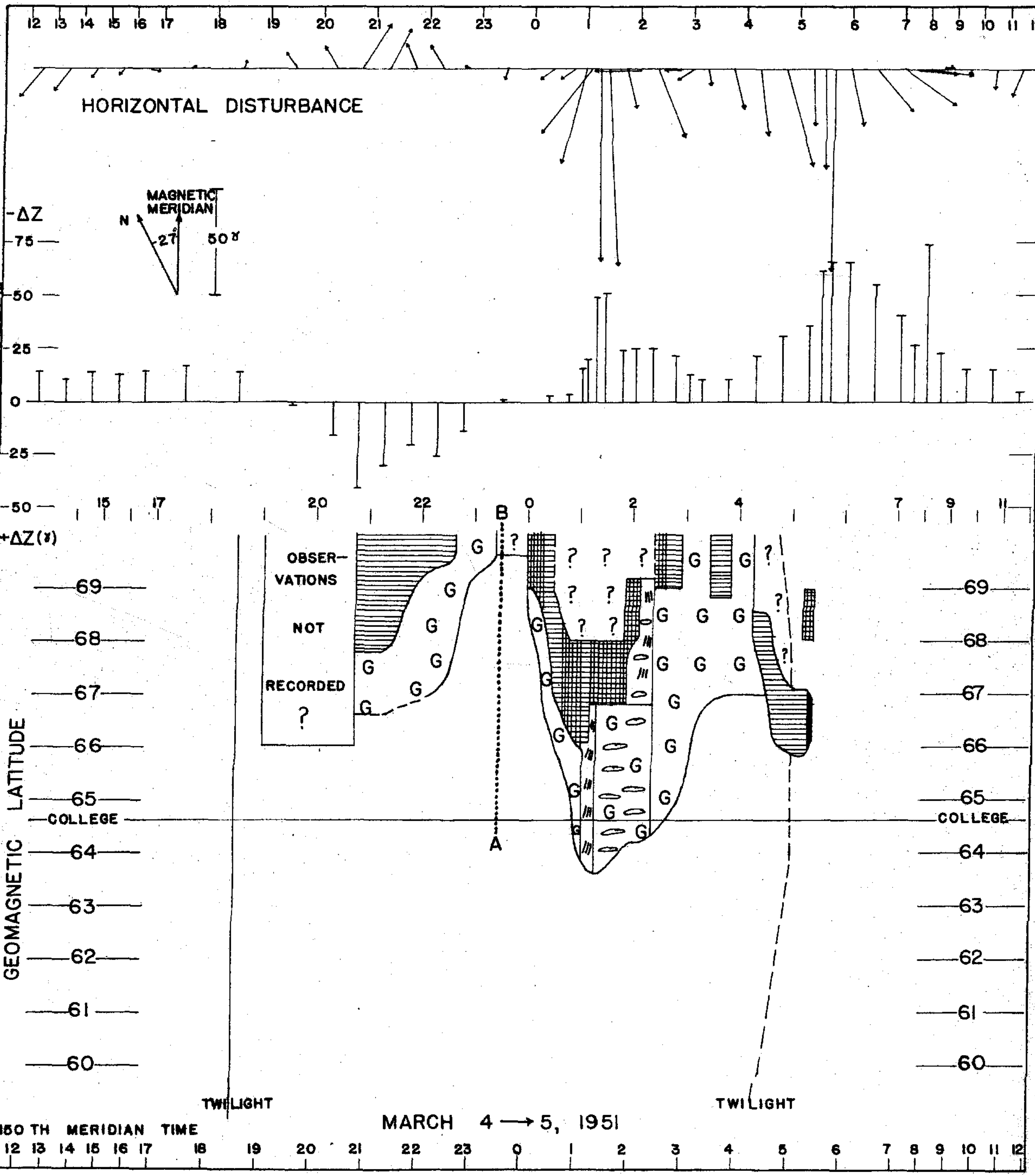


PLATE II': MARCH 4—5, 1951

PLATE 11



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
50γ
-ΔZ
+ΔZ(γ)
OBSER-VATIONS NOT RECORDED ?
COLLEGE
GEOMAGNETIC LATITUDE
TWILIGHT
TWILIGHT
B
A
MARCH 4 → 5, 1951
150 TH MERIDIAN TIME

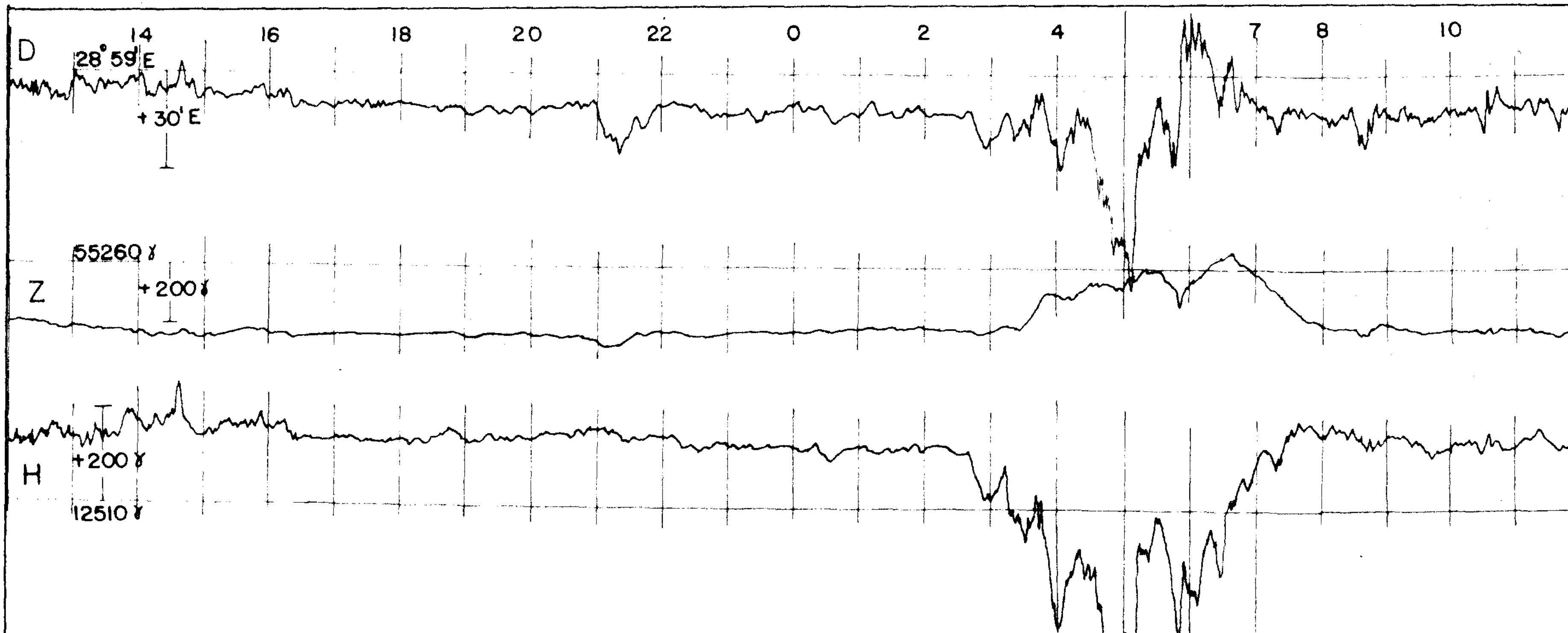
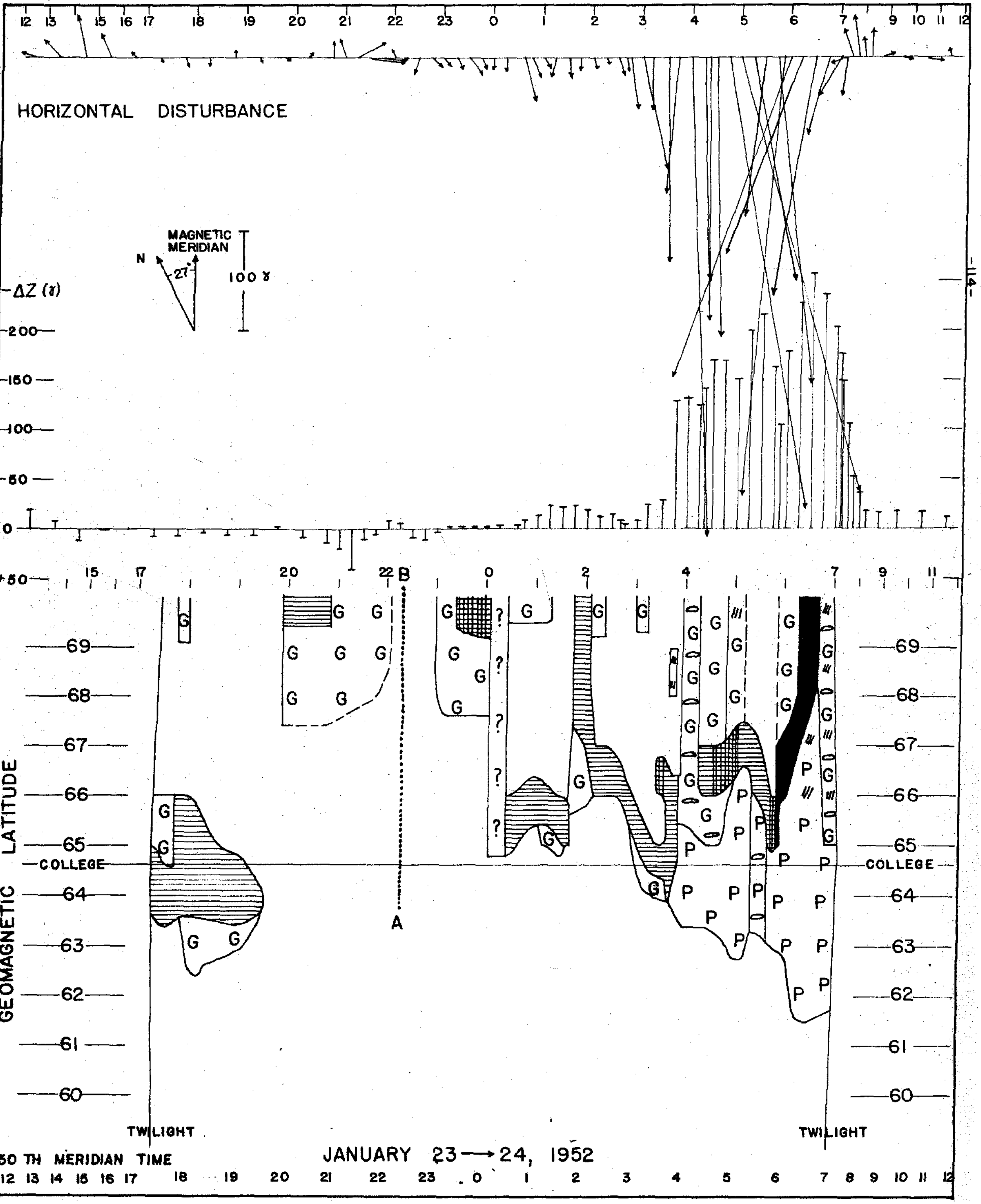


PLATE 12': JANUARY 23—24, 1952

PLATE 12


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
100 γ
ΔZ (γ)
GEOMAGNETIC LATITUDE
COLLEGE
TWILIGHT
150 TH MERIDIAN TIME
JANUARY 23 → 24, 1952

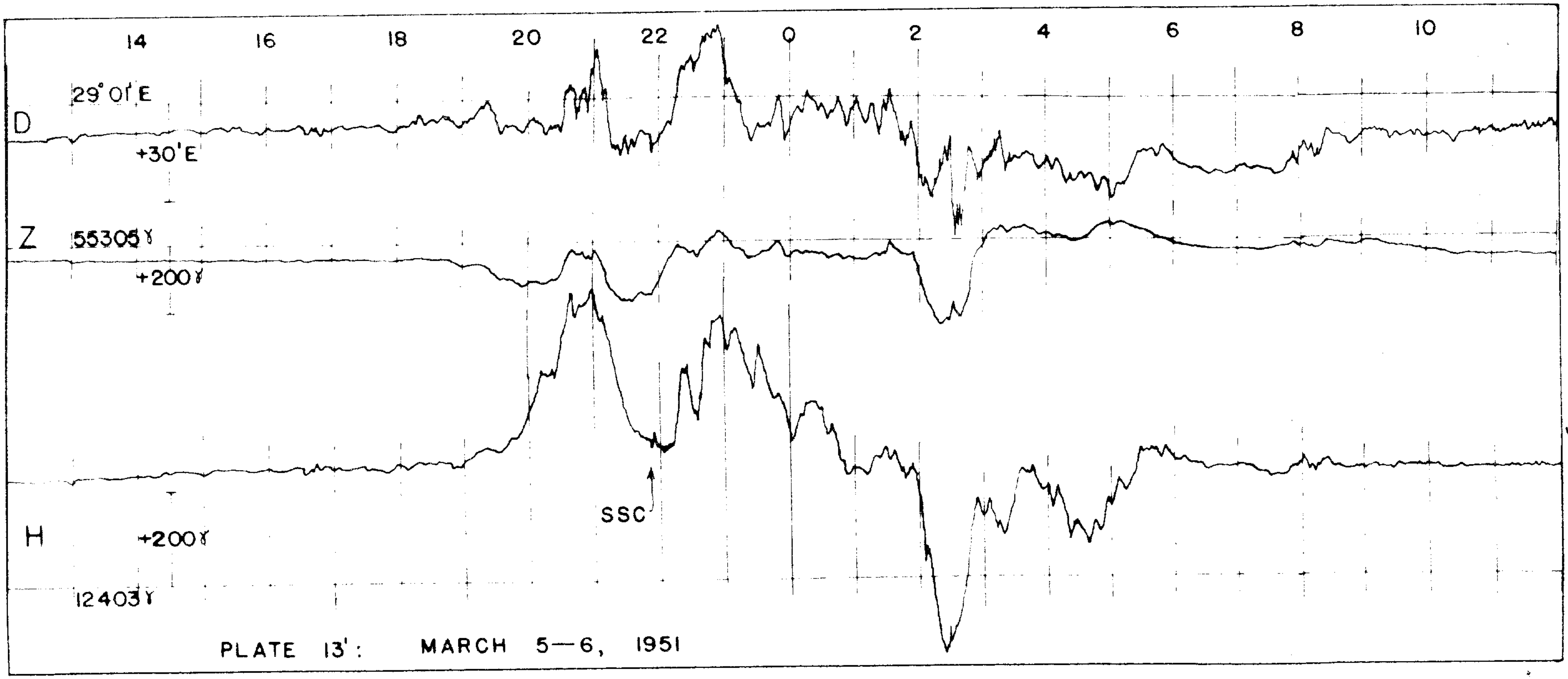
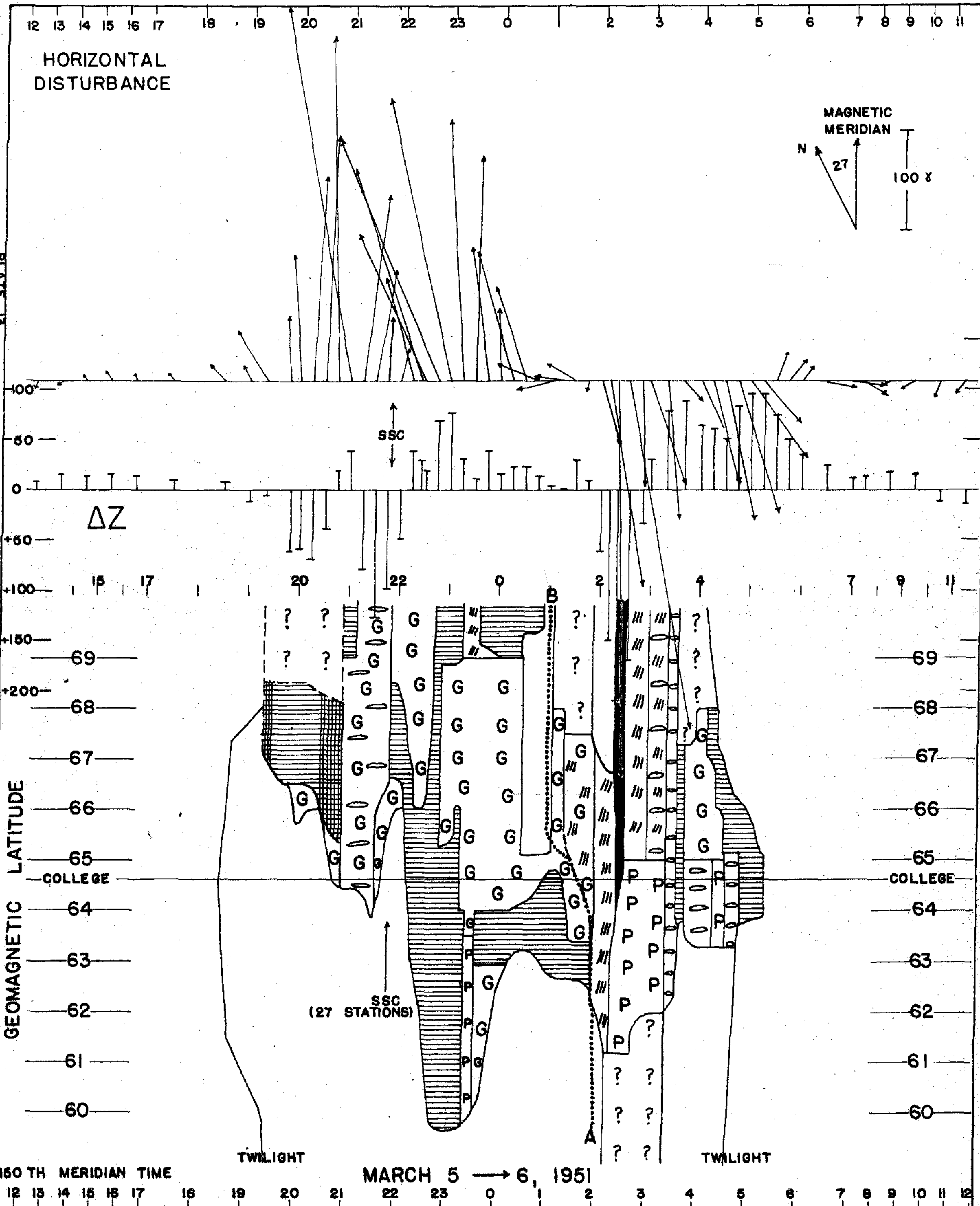


PLATE 13': MARCH 5—6, 1951


HORIZONTAL
DISTURBANCE
MAGNETIC
MERIDIAN
N
27
100 γ
SSC
ΔZ
B
A
GEOMAGNETIC LATITUDE
COLLEGE
SSC
(27 STATIONS)
TWILIGHT
TWILIGHT
160 TH MERIDIAN TIME
MARCH 5 → 6, 1951

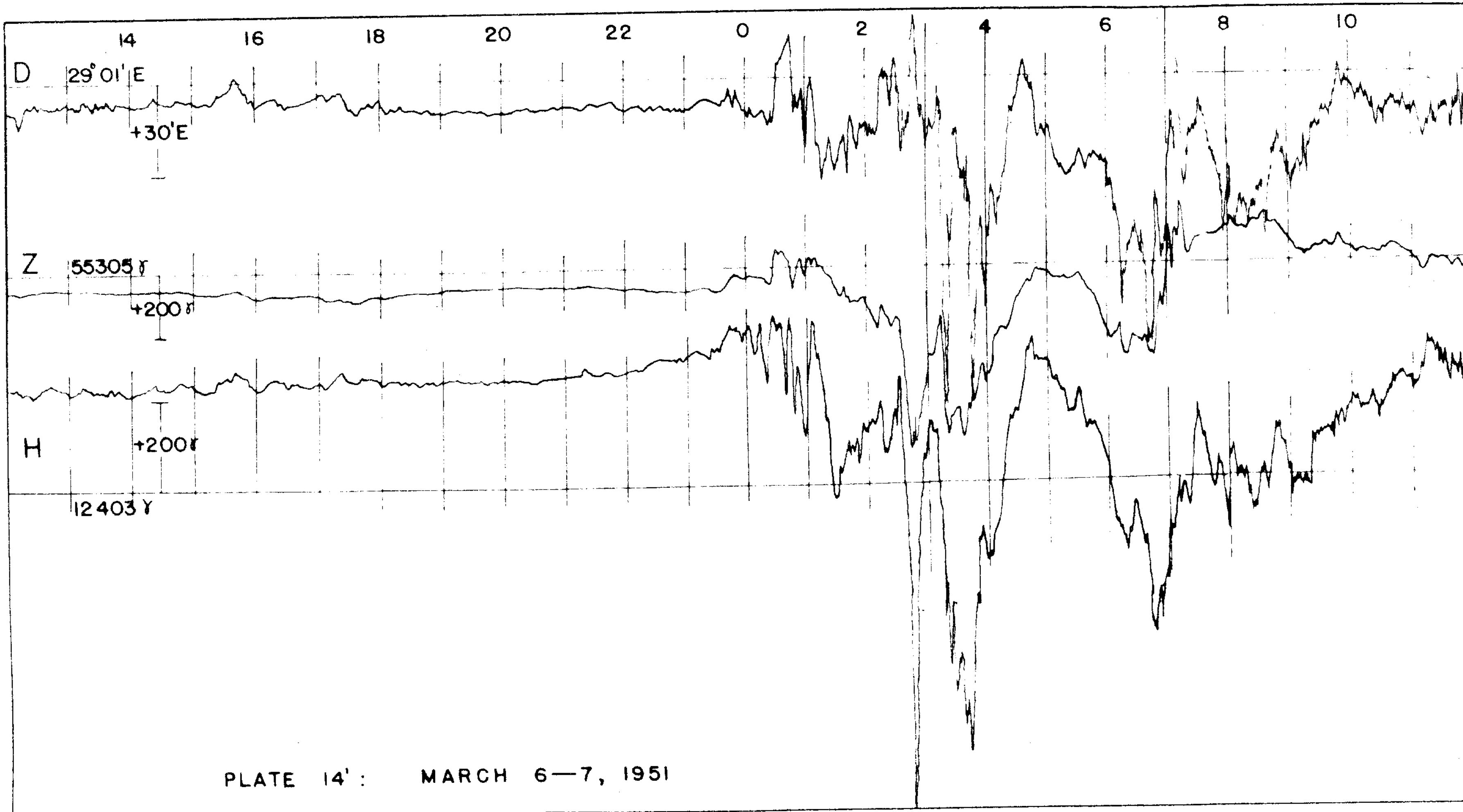
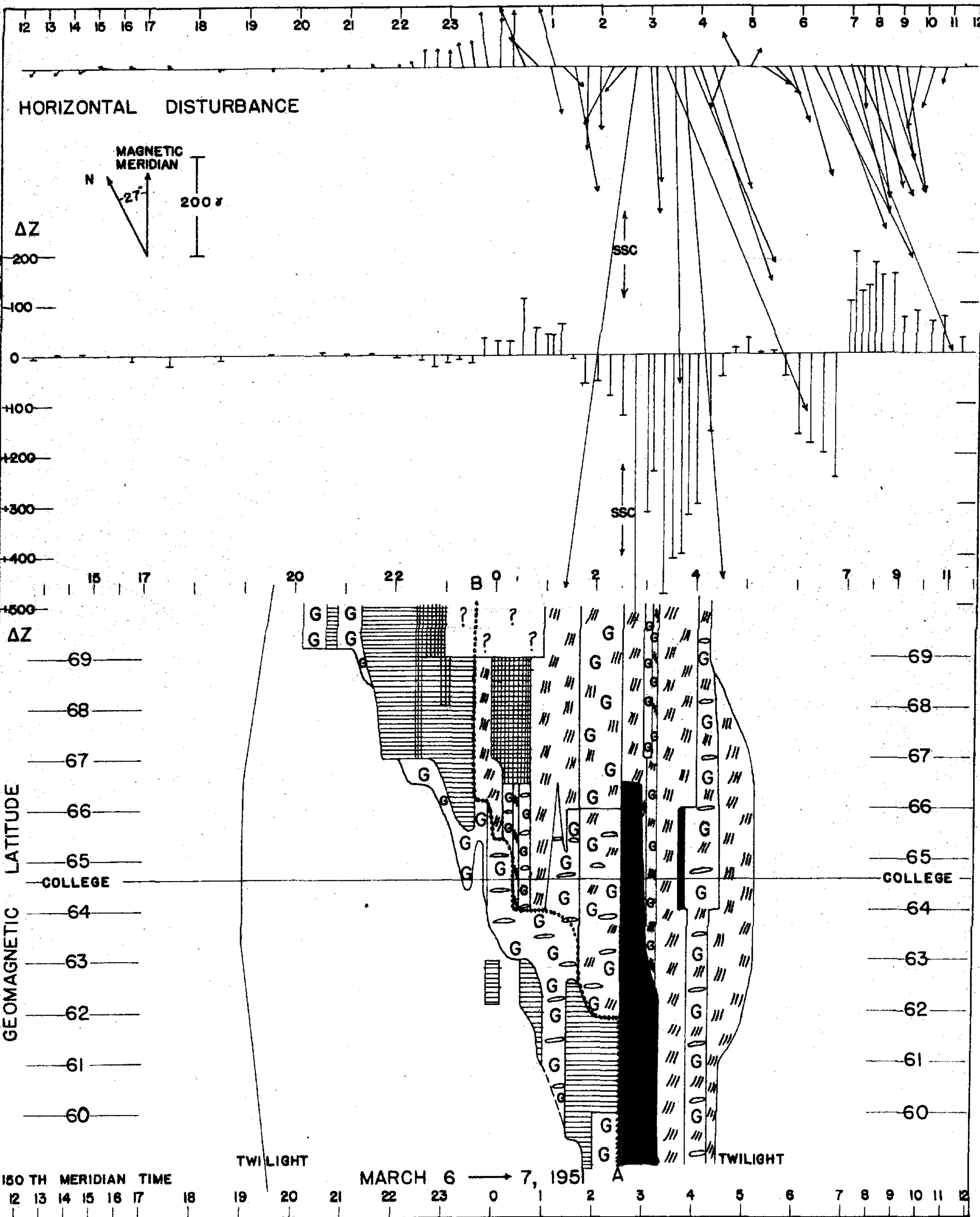


PLATE 14': MARCH 6—7, 1951

PLATE 14


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
200 γ
ΔZ
SSC
SSC
B
A
ΔZ
GEOMAGNETIC LATITUDE
COLLEGE
COLLEGE
TWILIGHT
TWILIGHT
180 TH MERIDIAN TIME
MARCH 6 ⟶ 7, 1951

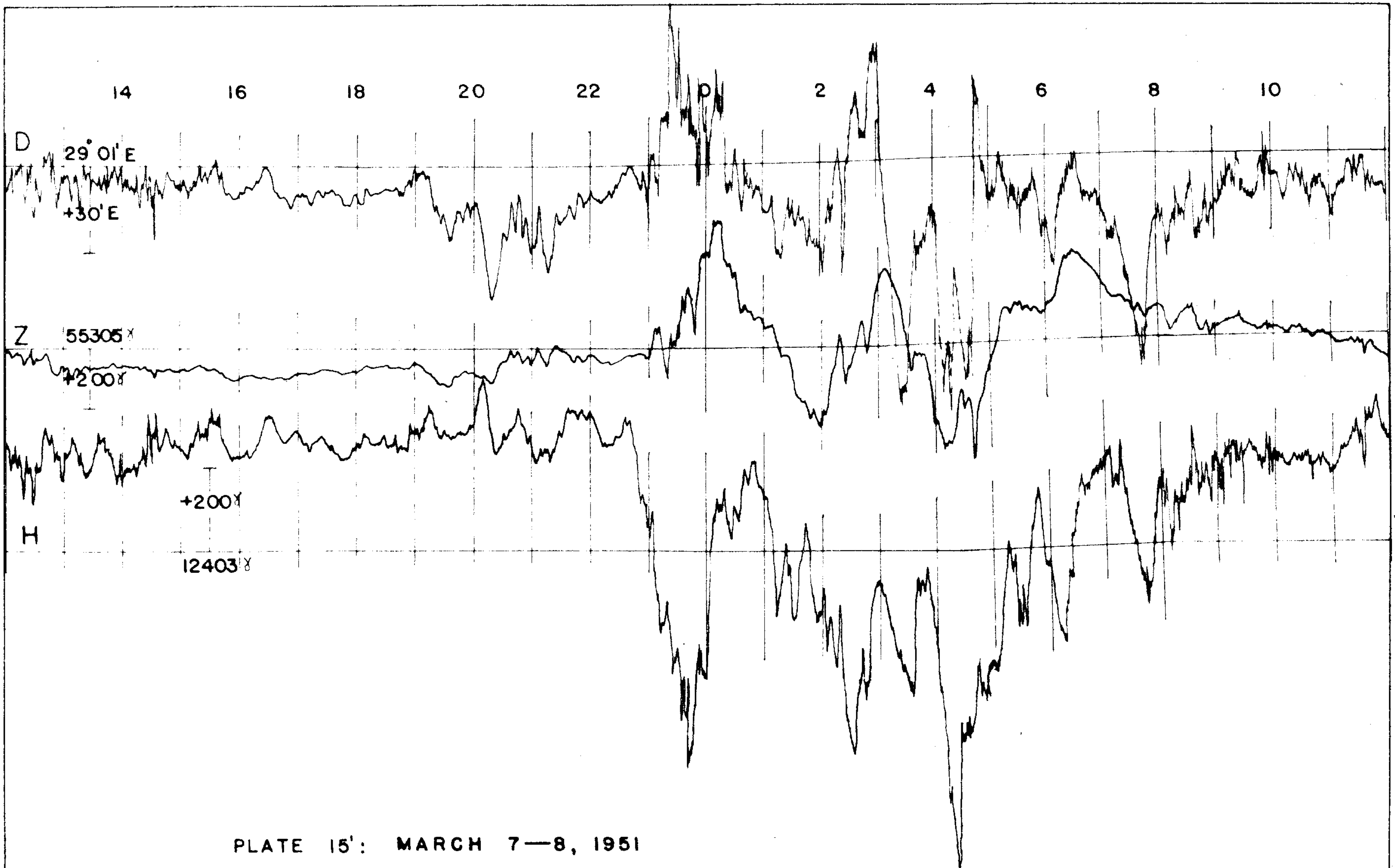
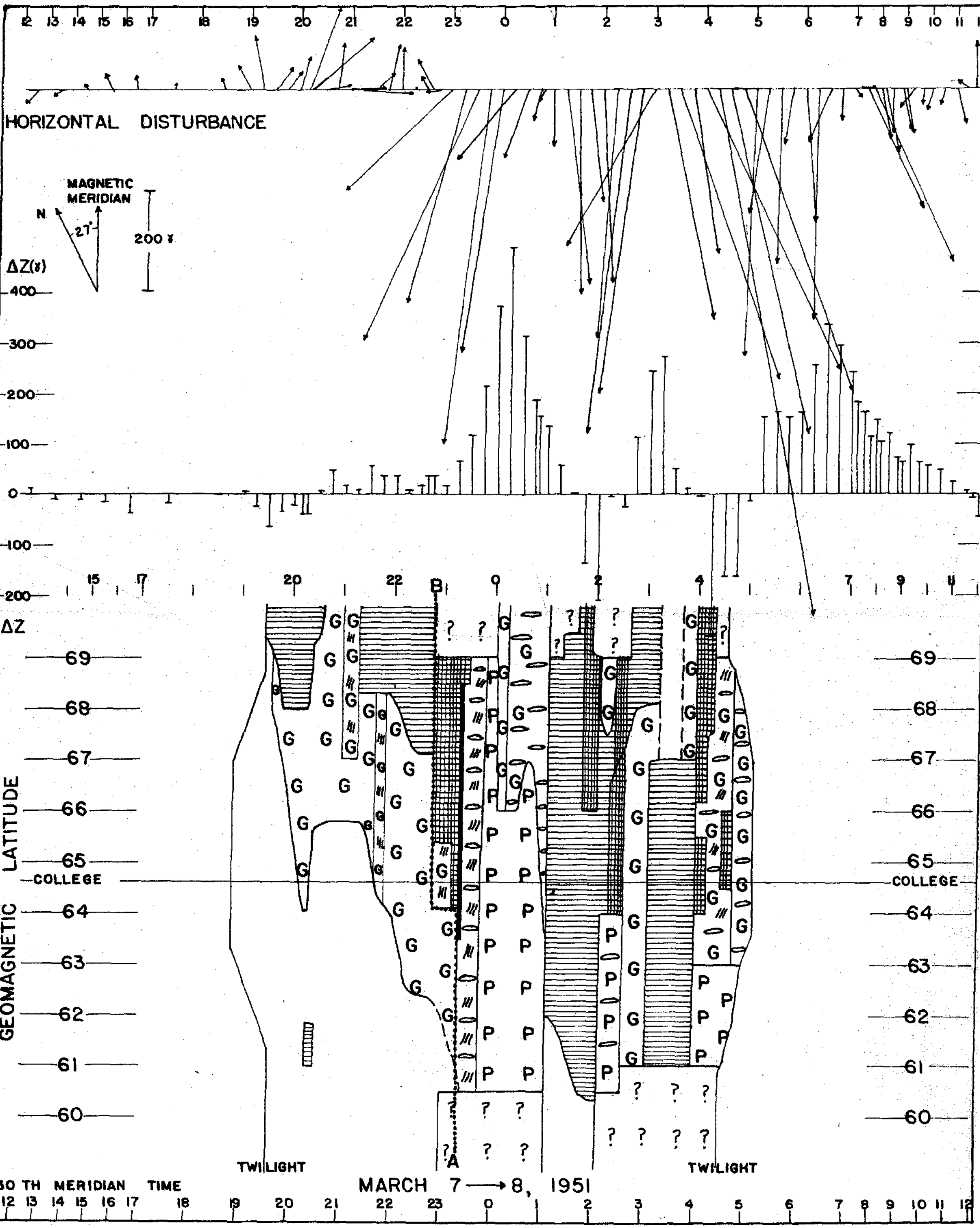


PLATE 15': MARCH 7—8, 1951

PLATE 15


12 13 14 15 16 17 18 19 20 21 22 23 0 1 2 3 4 5 6 7 8 9 10 11 12
HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
200 γ
ΔZ(γ)
400
300
200
100
0
100
200
15 17 20 22 B 0 2 4 7 9 11
ΔZ
69
68
67
66
65
COLLEGE
64
63
62
61
60
GEOMETIC LATITUDE
TWILIGHT
A
TWILIGHT
150 TH MERIDIAN TIME
MARCH 7 → 8, 1951
12 13 14 15 16 17 18 19 20 21 22 23 0 1 2 3 4 5 6 7 8 9 10 11 12

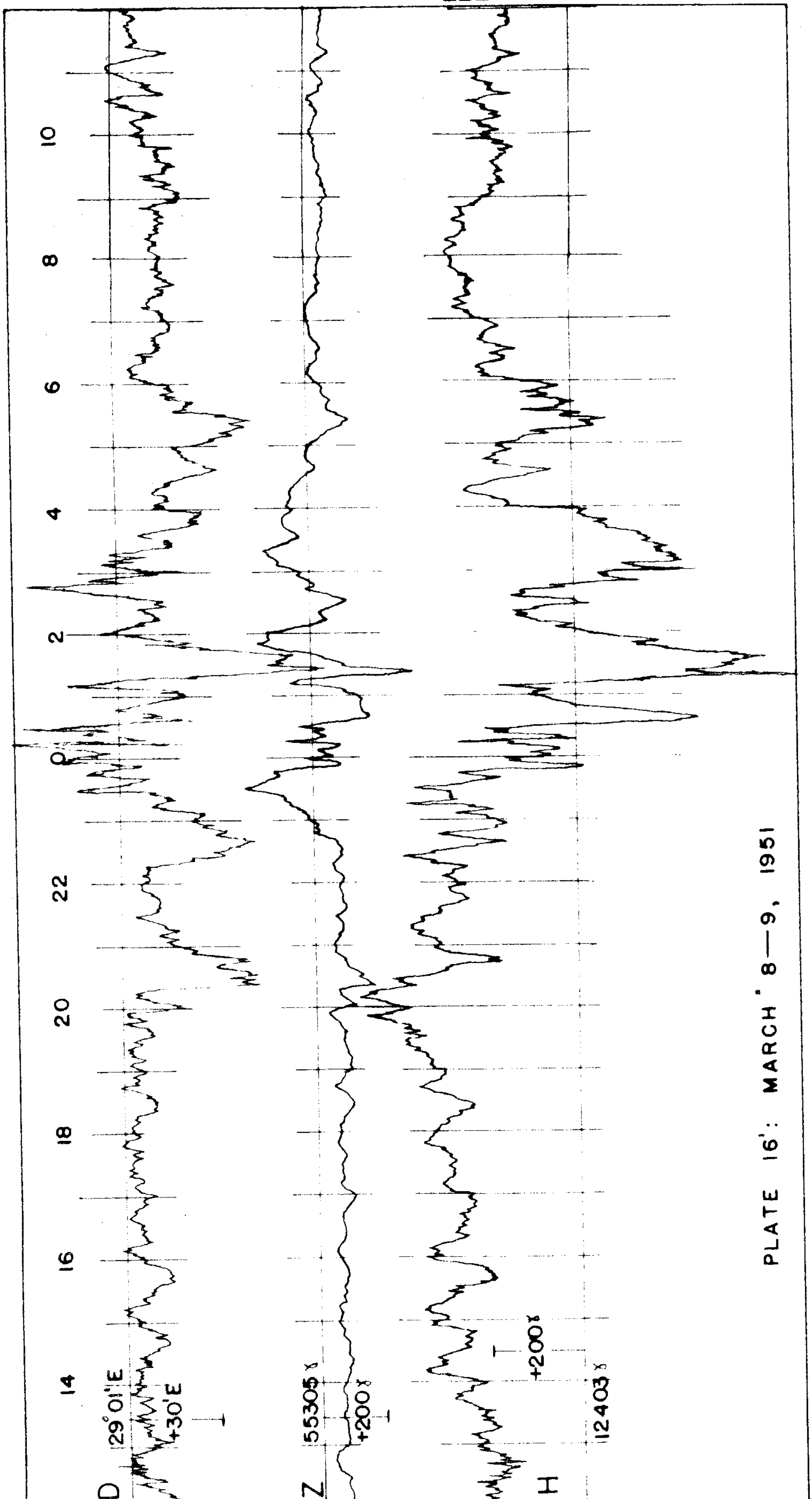
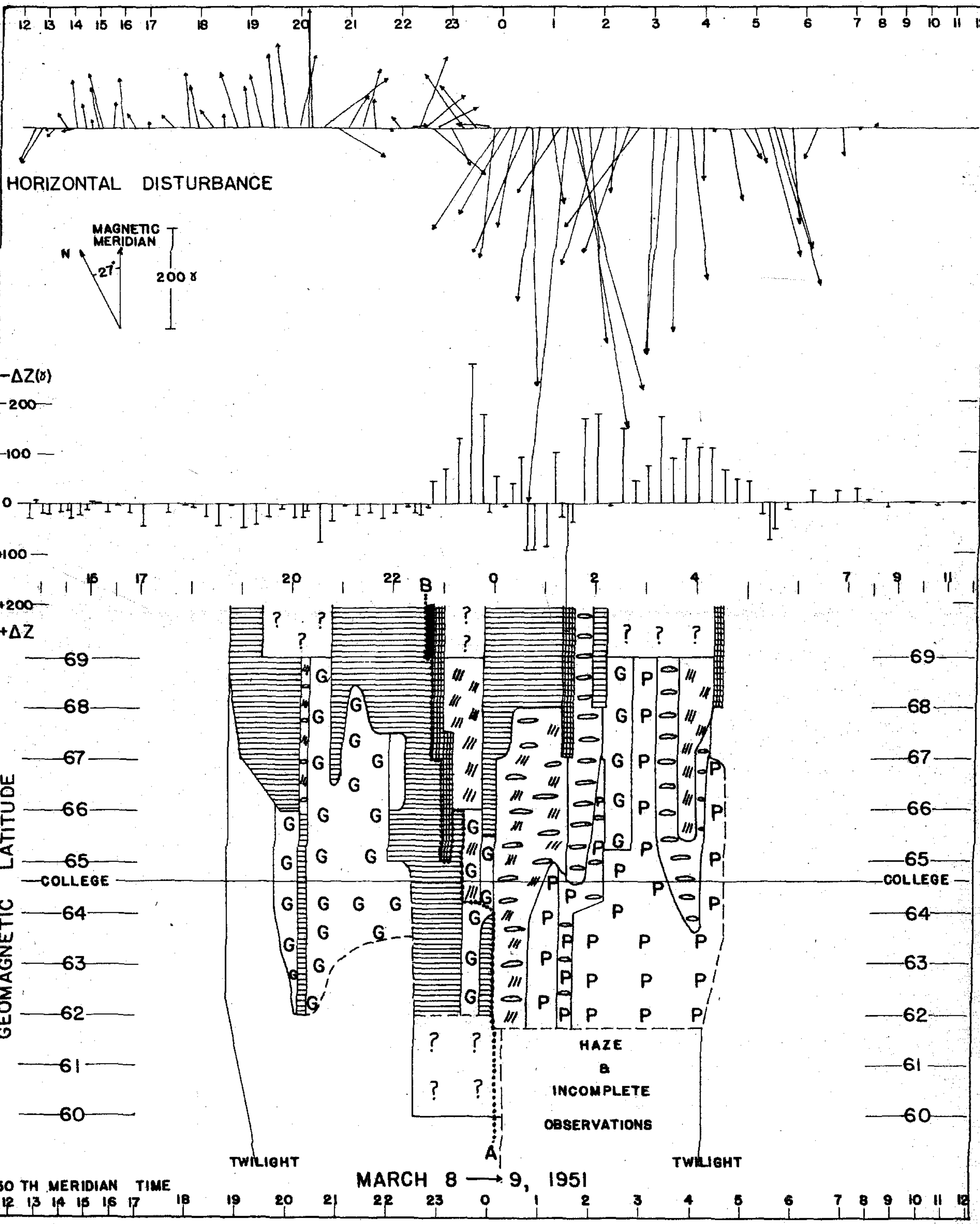


PLATE 16': MARCH 8—9, 1951

PLATE 16


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
200 γ
−ΔZ(γ)
200
100
0
+100
+200
+ΔZ
B
A
COLLEGE
GEOMAGNETIC LATITUDE
HAZE & INCOMPLETE OBSERVATIONS
TWILIGHT
TWILIGHT
MARCH 8 → 9, 1951
150 TH MERIDIAN TIME

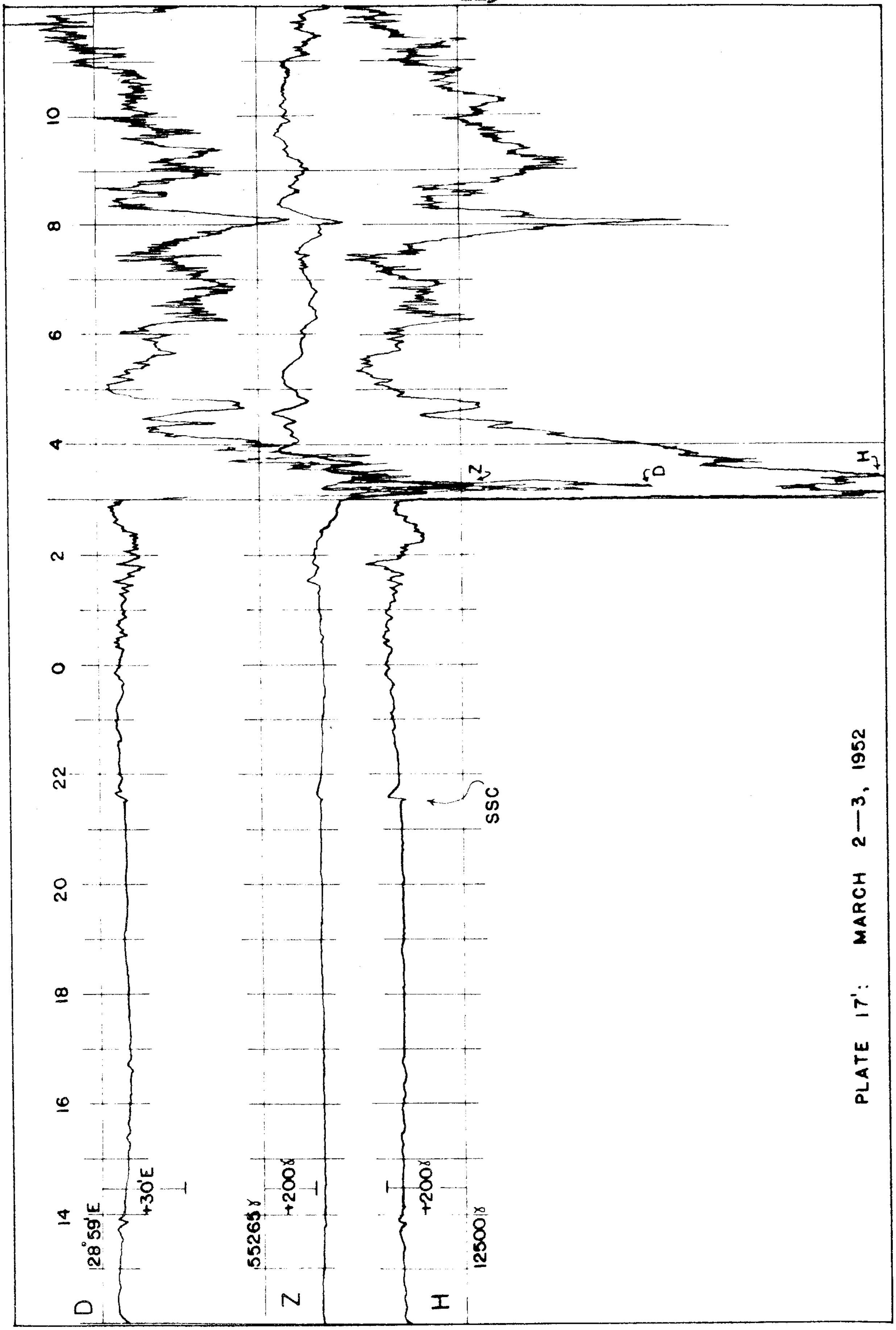
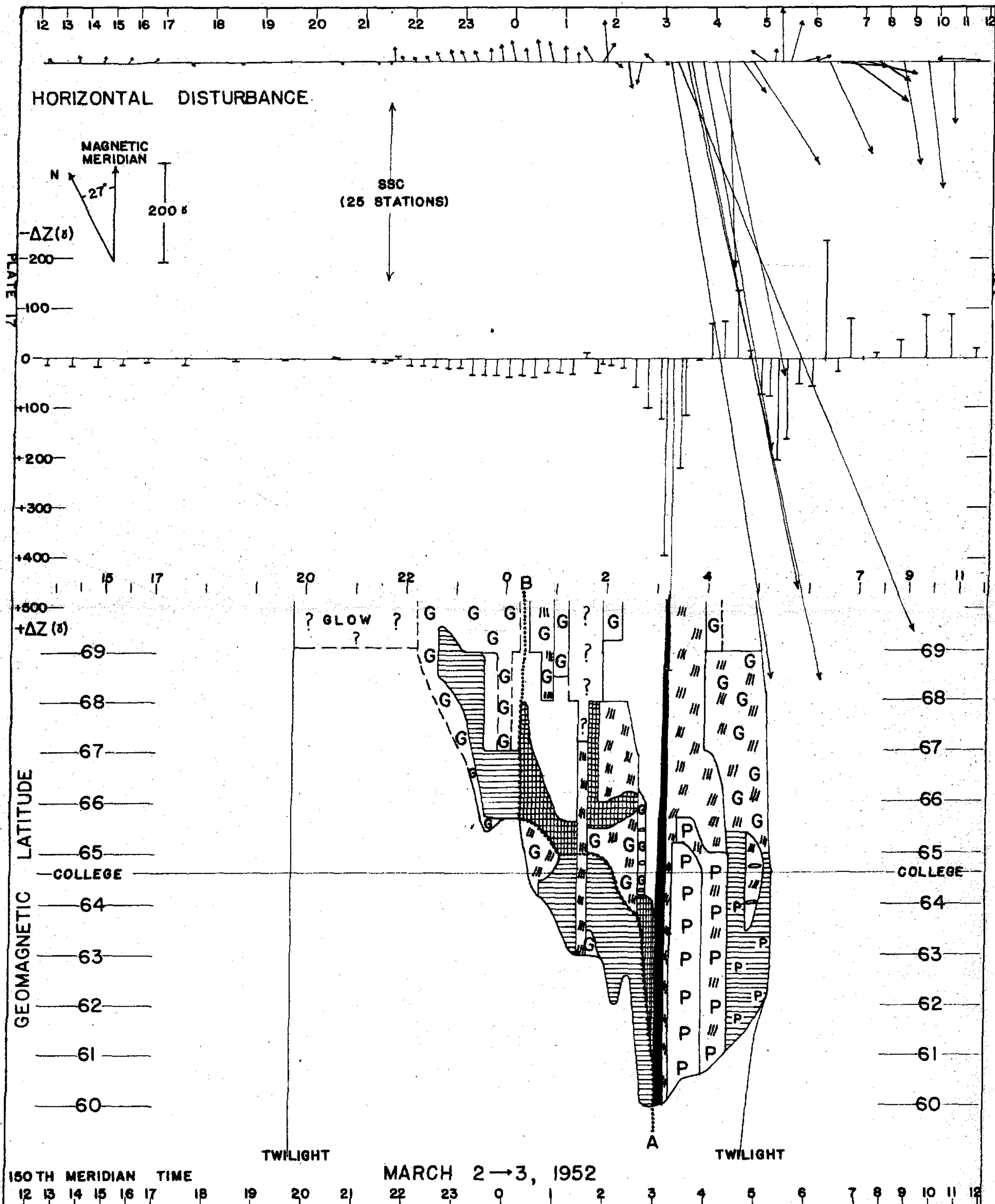


PLATE 17': MARCH 2—3, 1952



HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
200 γ
SSC
(25 STATIONS)
-ΔZ (γ)
+ΔZ (γ)
PLATE 17
-124-
? GLOW ?
G
P
B
A
COLLEGE
GEOMAGNETIC LATITUDE
TWILIGHT
TWILIGHT
150TH MERIDIAN TIME
MARCH 2→3, 1952

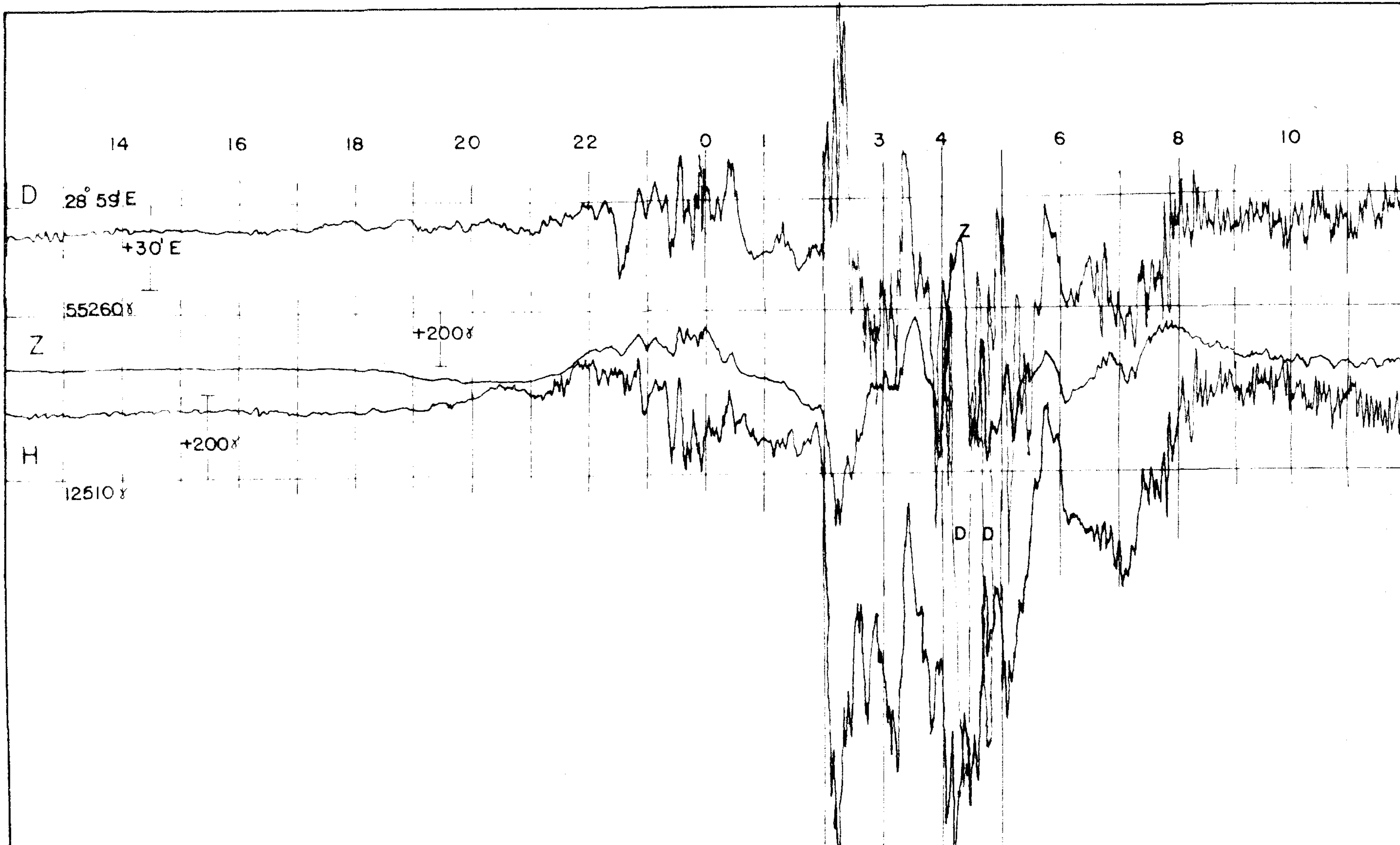
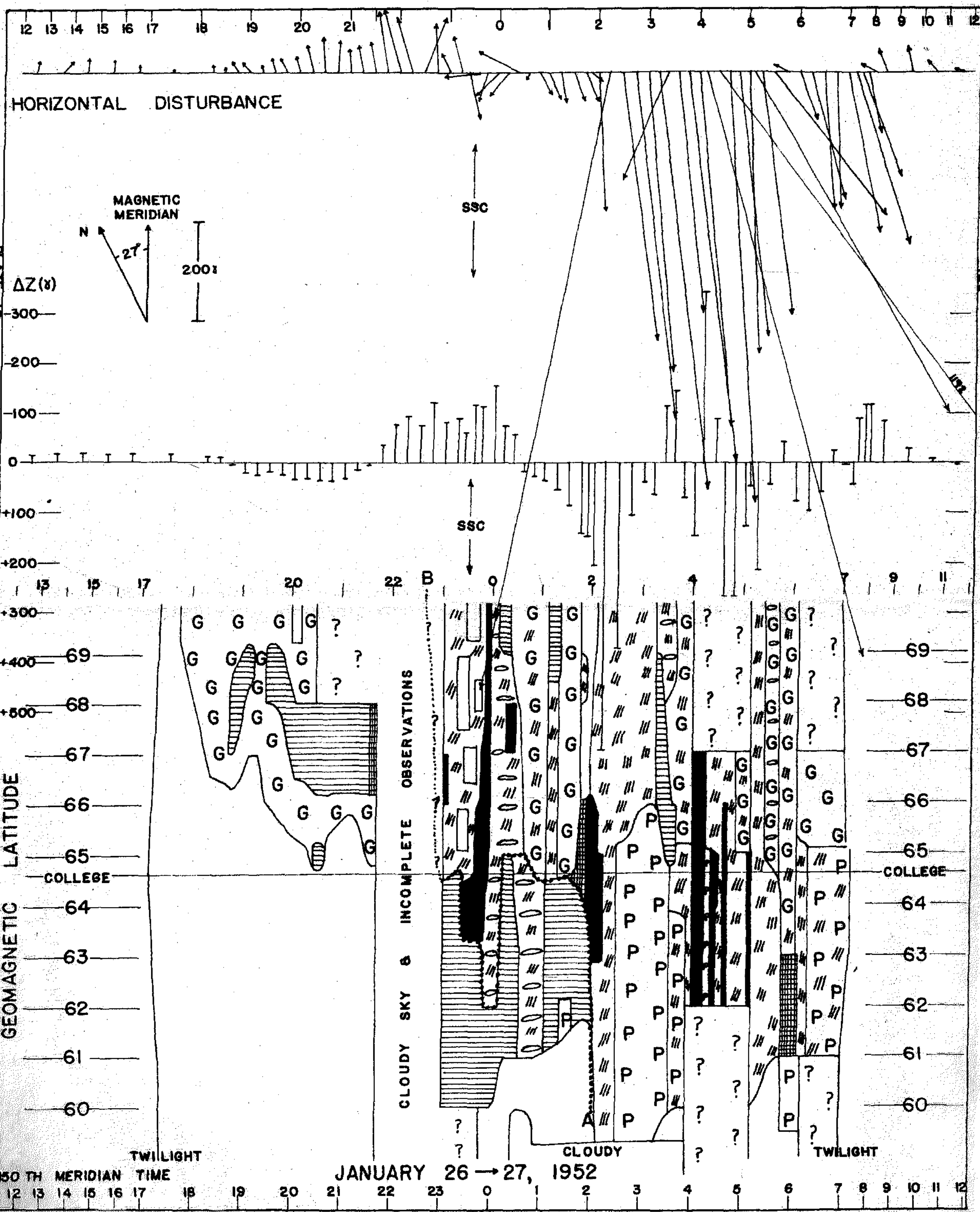


PLATE 18': JANUARY 26—27, 1952


HORIZONTAL DISTURBANCE
MAGNETIC MERIDIAN
N
27°
200γ
SSC
ΔZ(γ)
-300
-200
-100
0
+100
+200
+300
+400
+500
B
A
CLOUDY SKY & INCOMPLETE OBSERVATIONS
GEOMAGNETIC LATITUDE
60
61
62
63
64
65
66
67
68
69
COLLEGE
TWILIGHT
CLOUDY
JANUARY 26 → 27, 1952
150 TH MERIDIAN TIME
12 13 14 15 16 17 18 19 20 21 22 23 0 1 2 3 4 5 6 7 8 9 10 11 12