THE INTERPLANETARY MAGNETIC FIELD and POLAR MAGNETIC DISTURBANCES[+]

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ABSTRACT

The Explorer 12 measurements of the magnetic field outside the magnetosphere are compared with ground magnetograms from Arctic observatories. Results indicate that an exterior field with a southerly component tends to be associated with ground disturbance while a northward field is associated with quiet conditions. Examples are presented showing how a north to south field direction change accompanies an increase in ground activity and also how south to north changes may produce quiet intervals between substorms. Results are discussed in terms of breaking and reconnection of the interplanetary field to the dipole field as the solar wind carries the variously directed interplanetary fields past the earth.

author

Introduction

Satellite measurements in recent years have detected the presence of a magnetic field outside the earth's magnetosphere which is carried from the sun by the solar wind, (Heppner et al, 1963; Cahill and Amazeen, 1963; Ness and Wilcox, 1964. Several workers (Dungey, 1963; Hines, 1963; Dessler and Walters, 1963; Piddington, 1963) have indicated that this exterior field may influence the ground magnetic disturbance that is recorded on magnetograms. Measurements of this exterior field by the Explorer 12 satellite provide the first opportunity to study exterior field-ground data relationships over an extended period of time.

The Explorer 12 data have already been used to study the geomagnetic events known as sudden impulses and micropulsations. Nishida and Cahill (1964) found times when the satellite data inside the magnetosphere show increases or decreases in field strength corresponding to positive or negative sudden impulses on the ground. They also presented evidence that the changes were produced by movements of the magnetospheric boundary, presumably due to the changing pressure of the solar wind. Patel and Cahill, (1964) have detected waves in the satellite data at times when the satellite is inside the magnetosphere. Furthermore, they found these waves corresponded to micropulsations observed simultaneously in the auroral zone, thus demonstrating that micropulsations are due to downcoming hydromagnetic waves.

The present paper relates to a third type of magnetic disturbance which is due to high latitude ionospheric currents. These currents flow virtually all the time (Nagata and Kakubun, 1962; Fairfield, 1963) and they produce some of the largest observed perturbations of the earth's field. Since these high latitude currents complete their circuit partially through low latitudes, this type of disturbance is the main contributor to the K_p index during disturbed periods. The present study differs from those cited above in that any relation between the exterior field changes and the ionospheric currents must be through some indirect cause-and-effect mechanism.

Satellite Data

Details of the orbit, magnetometer, and data analysis techniques have been described previously (Cahill and Amazeen, 1963), and only the most relevant points will be repeated here.

The Explorer 12 satellite was launched on August 16, 1961, and data transmission ceased on December 6, 1961. The satellite apogee of 83,600 km was near the earth-sun line (near the local noon meridian) at launch. As the earth moved around the sun the local time of apogee moved to about 0500 in December. The period of the satellite was 26.5 hours, and it spent about half of its time beyond $10 R_E$.

In ground processing the data are digitized, introducing a ± 12 gamma uncertainty in each component of the vector field. This fact is particularly critical in studying the field outside the magnetosphere where very low field values (10 to 60 gammas) occur. Individual field measurements are taken about three times a second and have an additional occasional uncertainty due to telemetry noise. The scatter in the data due to the uncertainty may be reduced by averaging individual points. The points on the figures presented here are twenty-point (approximately seven-second) averages.

At very low values (approximately $< 15\ \gamma$) these uncertainties in the magnitude of the components of the vector field mean that the vector direction is essentially unknown. Then no improvement in knowledge of the average direction is obtained by averaging individual data points. For larger field values ($> 25\ \gamma$) the vectors become increasingly more meaningful, and for fields larger than $35\ \gamma$ the direction is reasonably good.

In addition to digitization error the magnetometer is subject to errors caused by: 1) drift of the output voltage corresponding to zero magnetic field; 2) change of slope of the calibration curves ($\Delta V/\Delta B$). Of these errors the first is by far the more serious at the low field magnitudes under discussion here. Two of the three component magnetometers can be corrected for zero level drift by observation of the sinusoidal voltage variation produced as they rotate orthogonal to the satellite spin axis. During the lifetime of Explorer 12, the zero levels of these magnetometers were not observed to change by more than 5 gammas. Some assurance that the other component magnetometers did not drift was obtained by comparison of the magnetic field direction measured with the direction determined indirectly from a charged particle experiment on the same spacecraft. A conservative estimate of the maximum uncorrected zero level drift of any of the component magnetometers is 5 gammas. A drift of this magnitude would produce substantial errors in the measured direction of a 25-gamma field. It is unlikely, however, that zero level drift could be responsible for the abrupt changes in the field direction that constitute one of the principal arguments of this paper.

In the figures that follow, the seven-second average fields agree fairly well from point to point, and either change slowly over times of the order of tens of minutes or hours, or sometimes quite abruptly within a fraction of a minute. Good agreement among successive points suggests reliability of the individual points and helps demonstrate that the gradual changes are real. When successive points show greater variability during periods of low field value, it is impossible to tell if the changes are real or due to the digitization and noise. Times when successive vectors fail to show a tendency to point in some direction are rare, and there seems to be little reason to doubt that in most cases the vectors are a good representation of the real field.

Ground Magnetic Data

It is well known that the general pattern for current flow in high latitudes is that known as the DS type current pattern (Fairfield, 1963). This current pattern is illustrated by the figure of Vestine, (1947) reproduced as Figure 1. Under this pattern intense "electrojets" flow eastward and westward along the auroral zone on the evening and morning sides of the earth respectively and close partially over the polar cap and partially through lower latitudes. Increases in the intensity and/or distortions of this current pattern (or alternately the superposition of nearly similar current systems) produce "bay" events at individual auroral zone stations.

Since the auroral zone current systems complete their circuits largely over the polar cap, examination of magnetograms from a polar cap station such as Resolute Bay provides a reliable means of detecting high latitude activity. Virtually all auroral zone activity is accompanied by changes on the polar cap, but not conversely, since the smaller bay events or "substorms" affect only stations on the night side of the earth. For these reasons, Resolute Bay magnetograms are reproduced on all of the figures that follow, although many other magnetograms were examined.

On the polar cap both horizontal components of the field must be considered in contrast to auroral zone stations where the northward component of the field is most important since the currents generally flow perpendicular to the north component of the field.

Analysis and Results

In order to be able to determine the general pattern of high latitude disturbance, standard-run magnetograms were obtained from the twelve Arctic and four middle or low latitude observatories listed in Table 1. At the high latitude stations the approximate undisturbed field values were estimated from quiet days and drawn on the magnetograms as baselines, (Fairfield, 1964). When the magnetic field at, for example, Resolute Bay is close to the baseline then presumably the DS current flow is at a very low level both at Resolute Bay and in the auroral zone.

The magnetograms were then compared to records showing the exterior field vector projected in the earth-sun meridian plane and the equatorial plane of a solar ecliptic coordinate system. Additional days were investigated where the field was represented by plots against radial distance of the field magnitude and two angles in a coordinate system depending on the satellite spin axis. Since the solar wind is interacting with the dipole-like field of the earth and since the dipole axis differs from the rotational axis, geomagnetic coordinates are preferable to either of the above systems (Figure 2). Field vectors on several days were converted to geomagnetic coordinates to confirm conclusions

Table 1

Geomagnetic Observatories

High Latitude Station	Geomagnetic Latitude	Geomagnetic Longitude
Godhavn	79.8	32.5°
Leirvogur	70.2	71.0
Lerwick	62.5	88.6
Kiruna	65.3	115.9
Point Barrow	68.6	241.2
College	64.6	256.5
Sitka	60.0	275.4
Resolute Bay	83.0	278.6
Meanook	61.8	301.0
Baker Lake	73.8	315.2
Churchill	68.6	322.6
Thule	89.0	357.8
Mid and Low Latitude		
San Juan	29.9	3.2
Honolulu	21.1	266.5
Tucson	40.4	312.2
Fredericksburg	49.6	349.8

drawn in the other coordinate systems and for illustration here.

The important conclusion to be drawn from this work is that exterior fields with a southward component are associated with high latitude disturbance, while northward fields tend to be associated with quiet conditions. When a northward field is present at a time of relative quiet and is followed by a change (either gradual or practically instantaneous) to a southward field, an increase in polar cap disturbance (the DS current systems) invariably occurs in the records so far examined. Often large auroral zone bays corresponding to "polar substorms" are superposed on the more moderate DS disturbance associated with a north-south change, but exact conditions for their production are not clear. The typical situation seems to be that either a north to south change is followed almost immediately by a bay event, or else there is a small gradual increase in the polar cap disturbance with a bay event following after a time delay of up to an hour or more. The exact conditions setting off the substorms are not clear since there are sometimes, but not always, further direction changes at the time of this "delayed bay." In other words the presence of a southward component field appears to be necessary for the production of a bay but the sudden north-south switch does not necessarily produce the bay.

These relationships between exterior fields and ground-level changes are consistent with the idea of the solar wind carrying the exterior field past the earth. Time delays between sudden changes at the satellite and on the ground usually seem to be of the order of a few minutes, but they cannot be determined precisely using the standard-run magnetograms. Sometimes the time of the ground change is so gradual that it cannot be defined with an uncertainty less than 15 minutes.

Although the direction of the field appears to exhibit a controlling influence on the high latitude disturbance it does not determine the absolute magnitude of the disturbance. On quiet days the field may be southward and the ground disturbance fairly weak, yet this disturbance is always larger than that associated with a northward field on the same day. Similarly, on a highly disturbed day northward field may occur when the absolute magnitude of the ground disturbance is higher than that associated with southward field on a quiet day yet this northward field associated disturbance is small relative to the disturbance associated with a southward field on the same disturbed day. Since solar wind velocity has been shown to be correlated with magnetic disturbance as measured by the K_p index, (Snyder, Neugebauer and Rao, 1963) the solar wind is presumably a second parameter influencing high latitude disturbance.

Another important type of phenomena noticed is the south to north change in exterior field which seems to be responsible for the quiet intervals between polar substorms.

When this south-to-north change occurs the disturbance starts to decrease but may take up to an hour or more to reach a low value. This means that a northward exterior field may occur at a time of large (although decreasing) disturbance.

The above conclusions are illustrated in Figures 3 through 8 which show the magnetogram traces and the exterior magnetic field projections in the geomagnetic equatorial plane and the geomagnetic meridian plane containing the sun. The sun is toward the right and Universal Time is plotted horizontally. The plots have been made against time, since the position of the satellite does not seem to be important for the phenomena investigated as long as the satellite is outside the magnetosphere.

The magnetospheric boundary is generally clearly defined on radial plots (Cahill, and Amazeen, 1963) but shock waves have not been unambiguously detected in the Explorer 12 data. The average shock wave position as reported by Ness, Scearce and Seek (1964) is 13.4 R_E at the subsolar point which means the shock wave is generally further out than the apogee of Explorer 12. This means that the fields in Figures 3 through 8 were observed in the transition region between the magnetosphere boundary and the shock wave. It should be noted that these transition fields measured by Explorer 12 in 1961 are in general larger than those measured by IMP 1 in late 1963, (Ness, Scearce, and Seek, 1964). Although the IMP 1 results indicate that the transition region fields are more turbulent than the field outside the shock front, it should be stressed that the transition region fields, in 1961, are often steady enough that they have the same general direction over periods of the order of tens of minutes or even hours.

The observations shown are typical except in the following respects. Periods of higher than average exterior field magnitude have been studied since the directions are more reliable for these times. The observations may also be weighted to include times when the exterior field is more definitely north or south rather than near the equatorial plane. Also the abrupt transitions between northward and southward fields are not as frequent as examination of the figures would indicate.

Description of the Figures

Figure 3, October 26, 1961

At 0800 on this day DS type disturbance is present and the field is southward. At 0830 a bay occurs but this is a case where there is not appreciable change of the exterior field at the time of the bay. The bay disturbance reaches 1500γ at the auroral zone, but the disturbance decays to more moderate values after about an hour.

An exceptionally steady southward component field between 1000 and 1600 hours is accompanied by DS type current flow which produces disturbance of about 500 gammas at the auroral zone. This DS type disturbance is very steady except for the normal short period fluctuations of up to 100 γ magnitude. At 1600 the exterior field swings northward and a very quiet interval occurs at all high latitude ground stations. At about 1915 the field goes southward and at 1940 a sudden commencement storm begins.

Figure 4, September 12, 1961

Two events are illustrated in the figure for September 12. At 0133 the field switches from north to south, and a corresponding change occurs on the Resolute Bay magnetogram. After a break in the data a field with a small northward component field is again present, and the auroral zone is very quiet. This is a good example of a quiet interval between polar substorms. At 0945 the field goes suddenly southward, and the usual change is seen at Resolute Bay and a small change at Point Barrow corresponding to the evening positive disturbance. About 1015 the evening cell at Churchill increases slowly followed by disturbance at College and Sitka. Finally at about 1120 a very sharp negative bay occurs at Point Barrow. It may be significant that the field switches from one side of the earth-sun meridian plane to the other at this time.

Figure 5, September 24, 1961

Early on this day the magnetograms are very quiet and the exterior field is near the geomagnetic equatorial plane with a small northward component. After a break in the satellite data the field has a southward component and the disturbance is slightly higher. A rather small substorm begins just before 0900 with no noticeable change in the field. At 1040 a very large substorm occurs. The field vector appears to swing through the meridian plane at this time but the reliability of this single vector is not certain. At 1140 a northward field is again present and is accompanied by a large decrease in disturbance current intensity. In Alaska the H trace even goes positive corresponding to a current reversal. This is a phenomenon noted by Heppner (1954) where during the recovery from a negative bay the H trace overshoots the quiet day baseline and reverses direction. When the satellite data resume after a break in the data the field is still north. This interval of northward field again corresponds to a quiet interval between polar substorms. At 1300 the field becomes southward and another polar substorm begins shortly thereafter.

Figure 6, September 30, 1961

At the beginning of this day the magnetograms are fairly quiet and the field appears to be slightly southward although the magnitude is quite small which makes the direction rather uncertain. At about 0225 the field suddenly becomes directed northward for five minutes, then goes back southward and a bay event follows almost immediately. This is a case where a bay may be related to a change in the exterior field. A southward field and disturbance continue until the satellite enters the magnetosphere just after 0600.

Figure 7, August 29-30, 1961

On August 29th the field is southward and the disturbance rather large before 2000. About 2000 the field swings slowly northward and the magnetograms show that the normal DS type current toward the sun decreases but then increases in a direction away from the sun. At this particular local time Resolute Bay (geomagnetic latitude 83°) is near the earth-sun meridian plane in a location (in respect to the sun) notable for magnetic agitation and current flow not in agreement with the DS pattern (Fairfield, 1963). The erratic variation in the exterior field at this time may be related to the ground variation, but it is difficult to find correlations between the rapid changes. The remainder of this day, after 2200 shows a southward component field and appreciable disturbance with a southward swinging of the field apparently corresponding to a current increase at 2230, 29 August, and again at 0015, 30 August.

Figure 8, October 11, 1961

Here, the predominantly northward field before 0800 corresponds to a relatively quiet period at all stations. The field abruptly becomes southward at 0752 and disturbance begins shortly thereafter at Resolute Bay. A further change in direction as the field swings through the meridian plane at 0900 is followed by a substorm.

Interpretation

An explanation of the mechanism through which the exterior field controls disturbances has been given by Dungey, (1963). He has considered the effect that an interplanetary field would have on the solar wind-geomagnetic field interaction. He concluded that with a generally southward interplanetary field, the interplanetary field lines could join high latitude earth dipole lines, forming an "open" magnetosphere. According to one interpretation, an electric field $\vec{E} = -\vec{V}\times\vec{B}/c$ is associated with the solar wind plasma moving past the earth, and this field is fed into the polar cap ionosphere along the equipotential lines of force connecting to space. Similar fields are fed to the auroral zone by circulation of plasma in the magnetosphere tail. These electric fields are supposed to drive the DS current system, with the currents flowing along the equipotential surfaces in the ionosphere due to the Hall conductivity.

With a northward interplanetary field the situation is quite different. Now the interplanetary field is opposed to the polar cap dipole field lines coming down to the earth in high latitudes and the interplanetary field can no longer become connected to these earth lines. In this situation the field connection does not occur and no electric field is available to drive the currents as in the case of a southward field. A prolonged occurrence of northward field would tend to produce a closed magnetosphere.

A similar plasma flow within the magnetosphere and resulting polar current system is predicted by Axford and Hines, (1963). In their model a viscous interaction at the magnetosphere surface is the mechanism for causing magnetosphere plasma flow rather than field connection.

Recent satellite measurements in the tail of the magnetosphere indicate that the tail extends to great distances with a "neutral sheet" region at zero magnetic field extending along the central plane of the tail (Heppner etal, 1963; Cahill, 1964; Ness, 1964). These observations can be interpreted as supporting the concept of an open magnetosphere.

Although the field connection model appears to explain the general properties of the observed results, the question of the origin of the bays or polar substorms seems to be in doubt. Since a moderate increase in disturbance -- but not always a large bay event -- accompanies the switch to southward field and the presumed resumption of reconnection of field lines, the bay events may require a separate explanation. The dramatic suddenness with which bay events often begin seems to suggest some kind of instability. Dungey (1965) envisages a buildup of the flux connected to the polar cap until an instability in the tail produces rapid disconnection of the interplanetary lines with a resulting substorm.

An additional result that may have relevance for this discussion is that of Akasofu(1964). He has presented examples of instances where low latitude magnetograms show an apparent sudden commencement, but no main phase or other disturbance follows the event. Akasofu's conclusion is that the sudden influx of solar plasma is a necessary but not sufficient condition for a magnetic storm. Apparently, some additional parameter is necessary to produce the storm. It is here suggested that this parameter is a southward component magnetic field.

One event of this type was found in the ground data during the Explorer 12 period. On October 17, 1961, the four available low latitude stations exhibited an apparent sudden commencement, yet no storm followed. Stations at the auroral zone and above were not affected. Unfortunately, no satellite data exist at this time, but it can be pointed out that this event occurred during a period of several days that was the most quiet at high latitude, of the Explorer 12 interval. In view of the relation between field direction and disturbance, it seems possible that the field may have been northward at this time.

Conclusion

We believe that the satellite and ground magnetic data presented, and many other cases examined but not discussed here, make a persuasive case for a strong influence by the transition region magnetic field direction on the polar region ionospheric current system (DS). Explanations of this influence other than the field connection model of Dungey suggested here may ultimately be shown correct; at present this model appears the most plausible. The evidence presented here does not constitute a final and convincing case. It should be supplemented with further study of Explorer 12 and Explorer 14 transition region data. The more precise directional data of the IMP 1 satellite in the transition region should also be examined for evidence of these relations. Finally, other methods of investigation of the relation between transition region field directions and magnetosphere processes may be rewarding. Observing the magnetic field connection process directly at the magnetopause has been suggested by Sonnerup, 1964. An attempt to accomplish this observation is in progess at UNH although it is hindered considerably by directional uncertainties in the field.

The proposed opening and closing of the magnetosphere, if correct, ought to have far-reaching implications on many high latitude phenomena. Low energy particles ought to be able to reach the polar cap when there is a southward field and the magnetosphere is open, but not when the field is north and the magnetosphere closed. This, in turn, would affect the ionosphere and resulting phenomena such as sporadic E, spread F, and the measurements of riometers.

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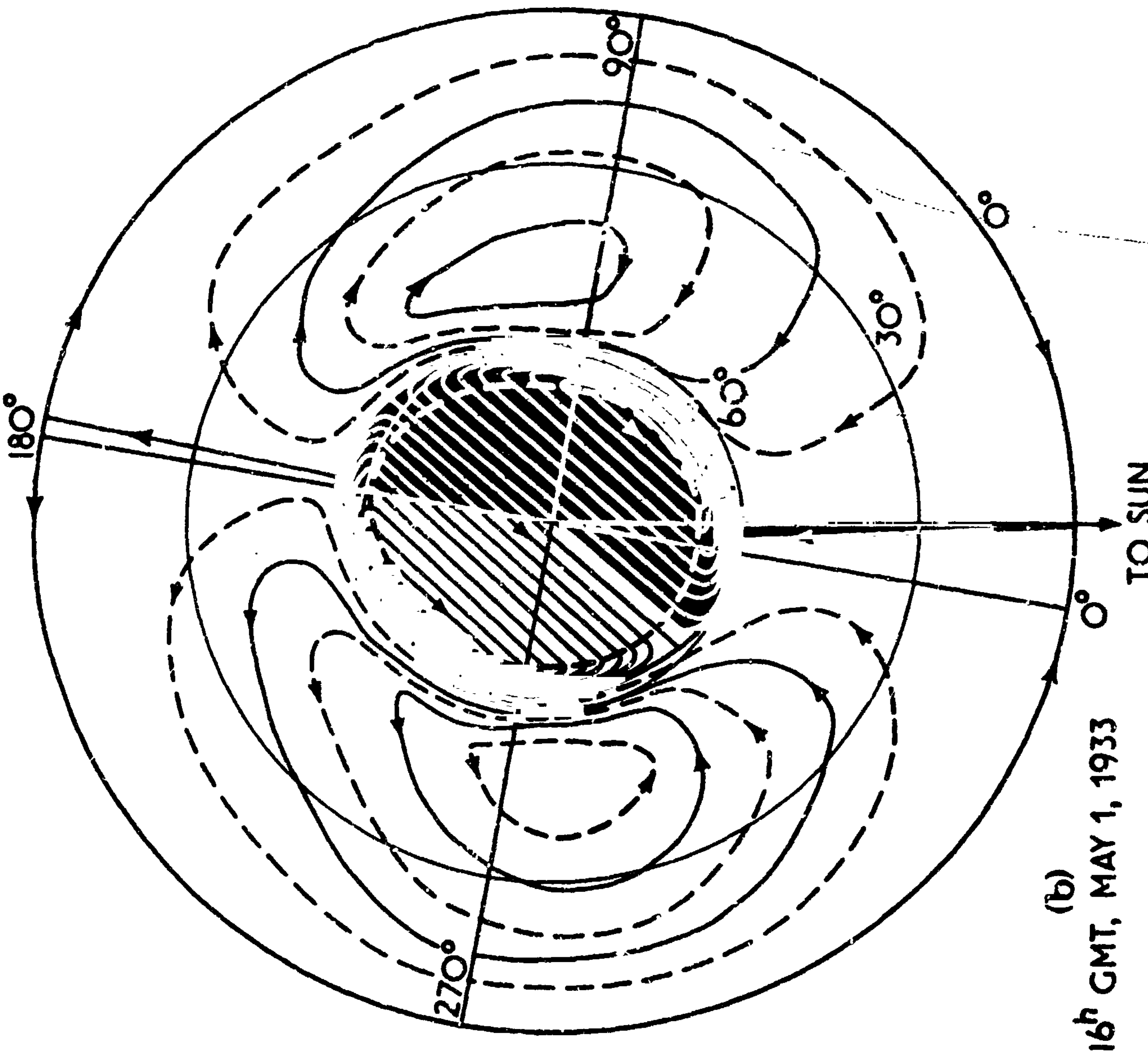
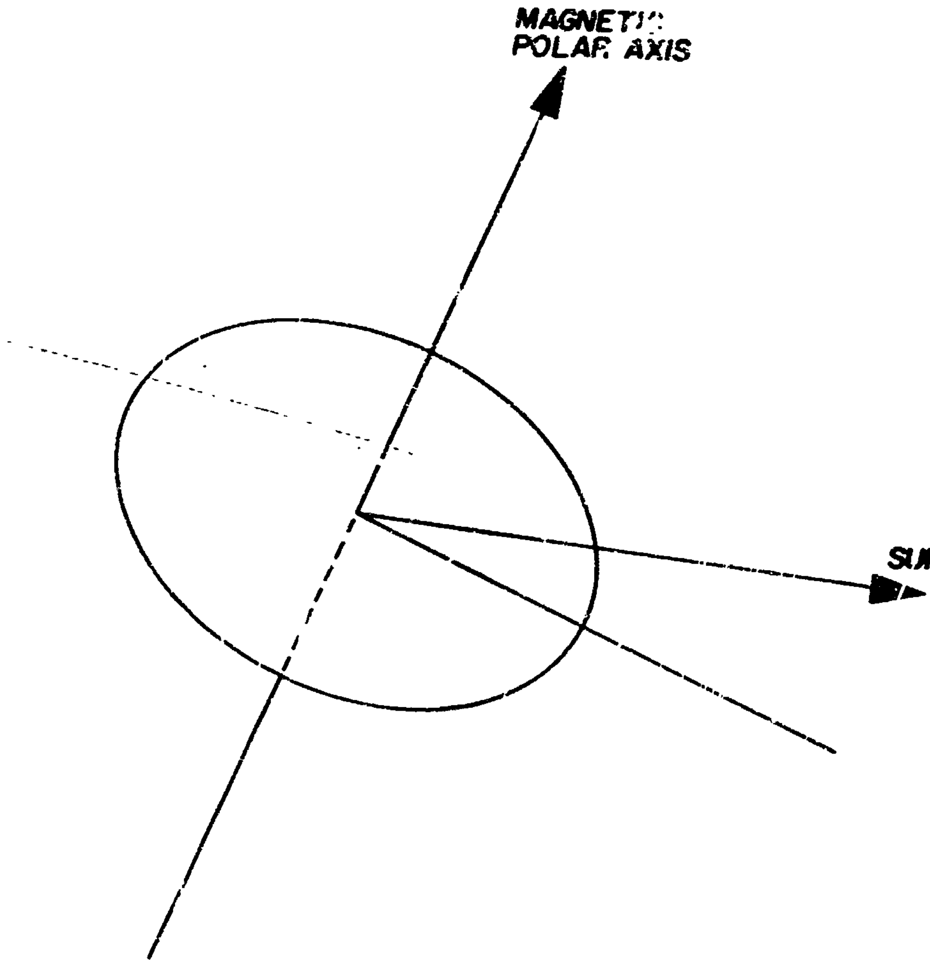


Figure 1



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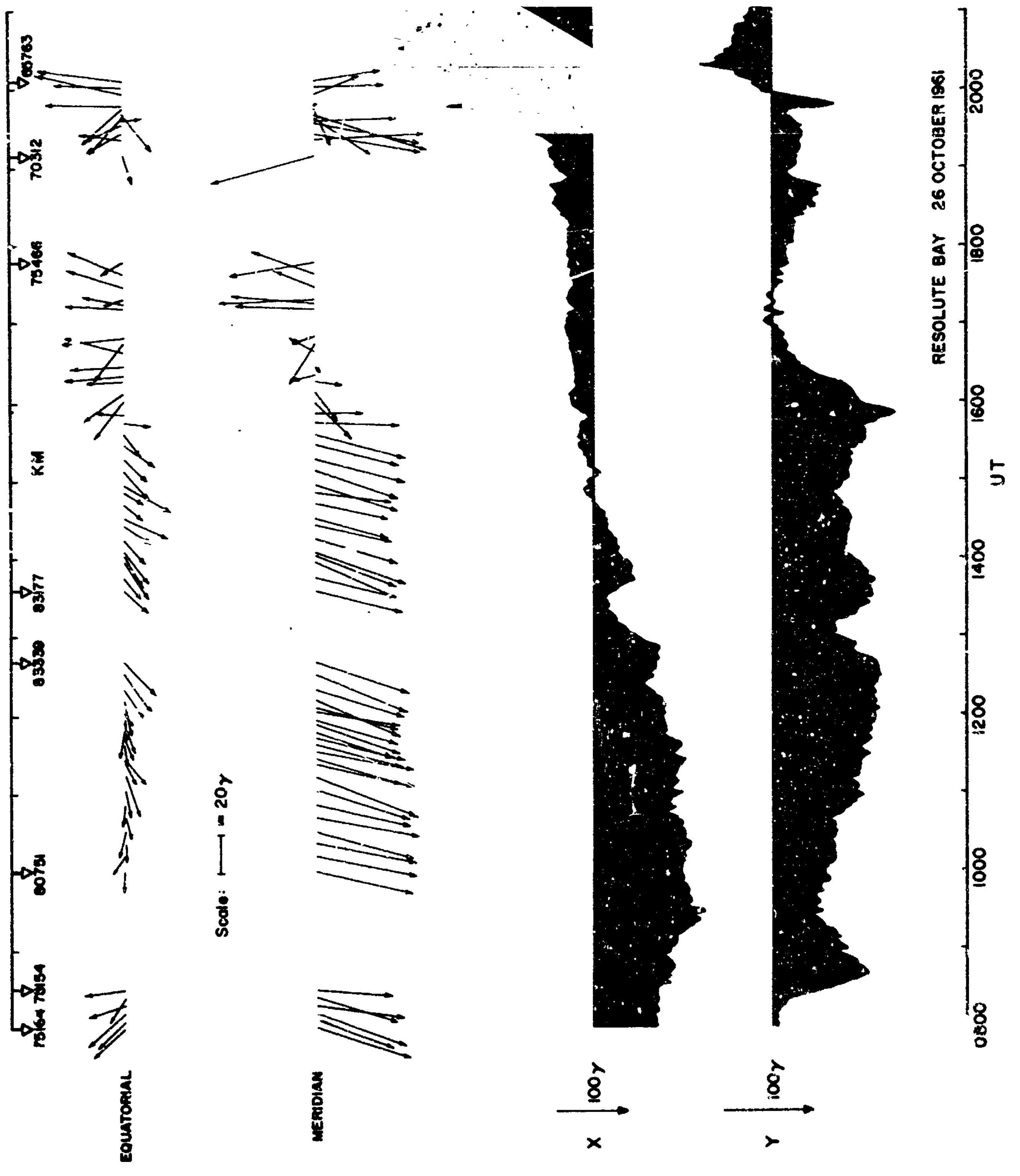

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Figure 3

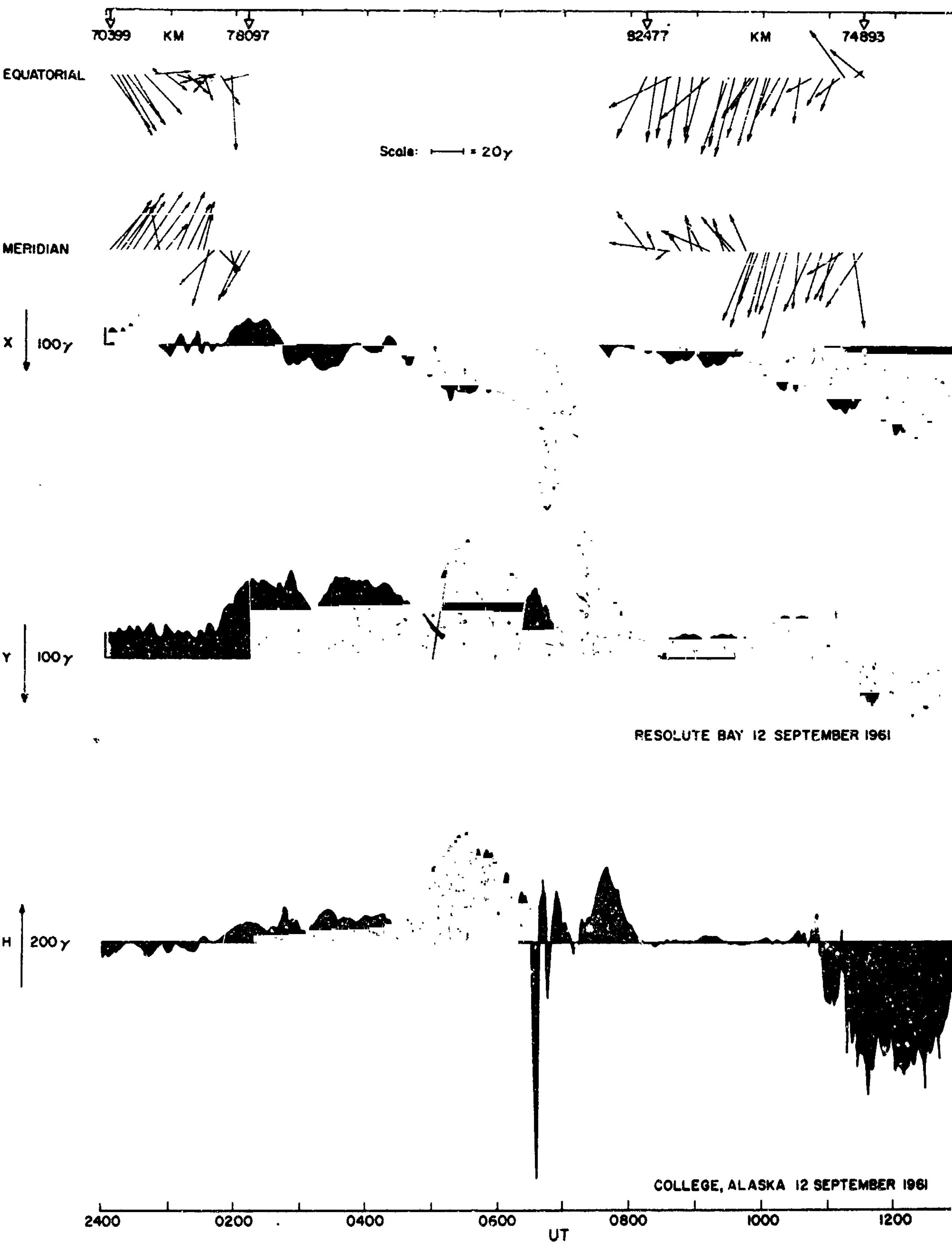
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Figure 4

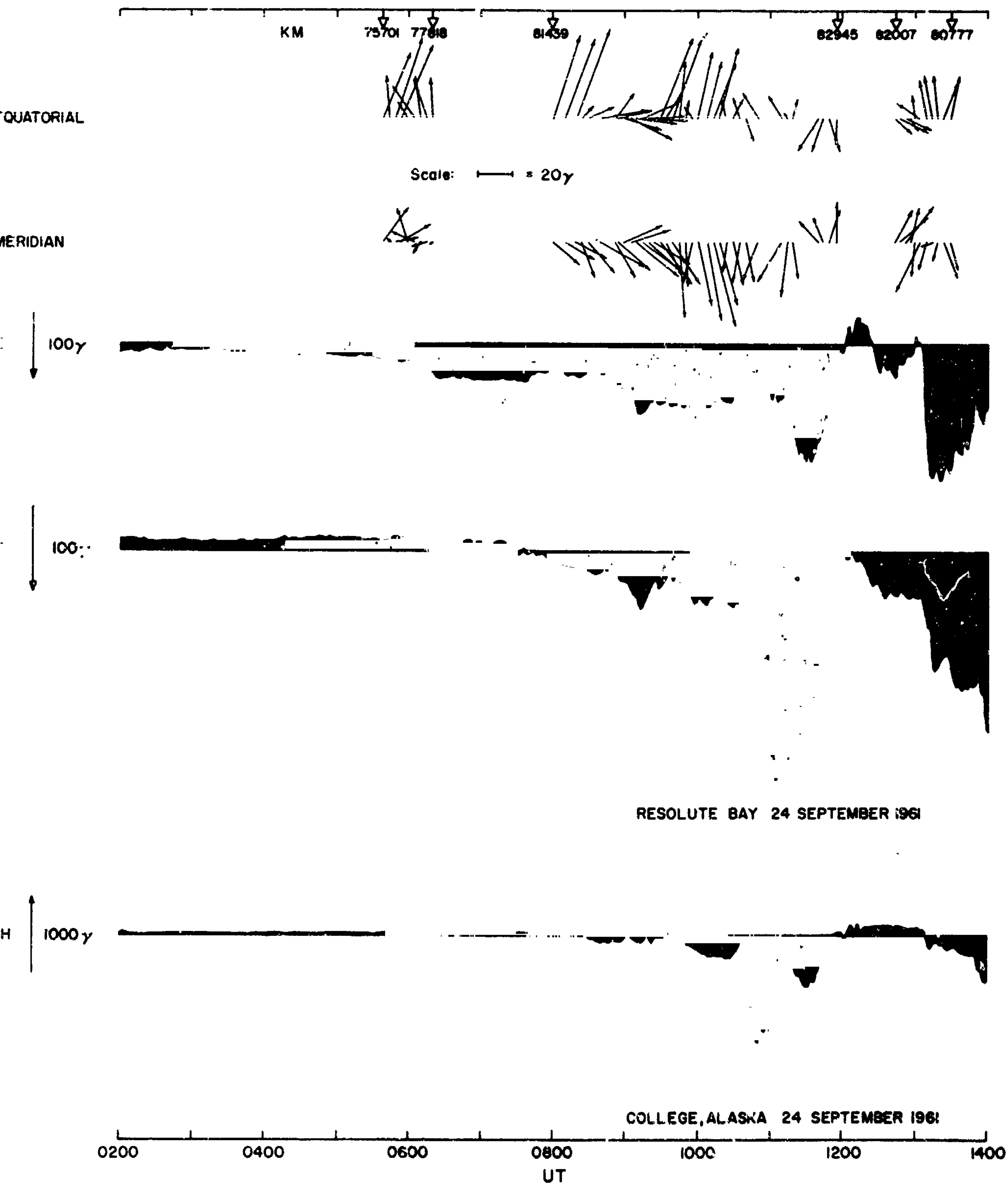
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Figure 5

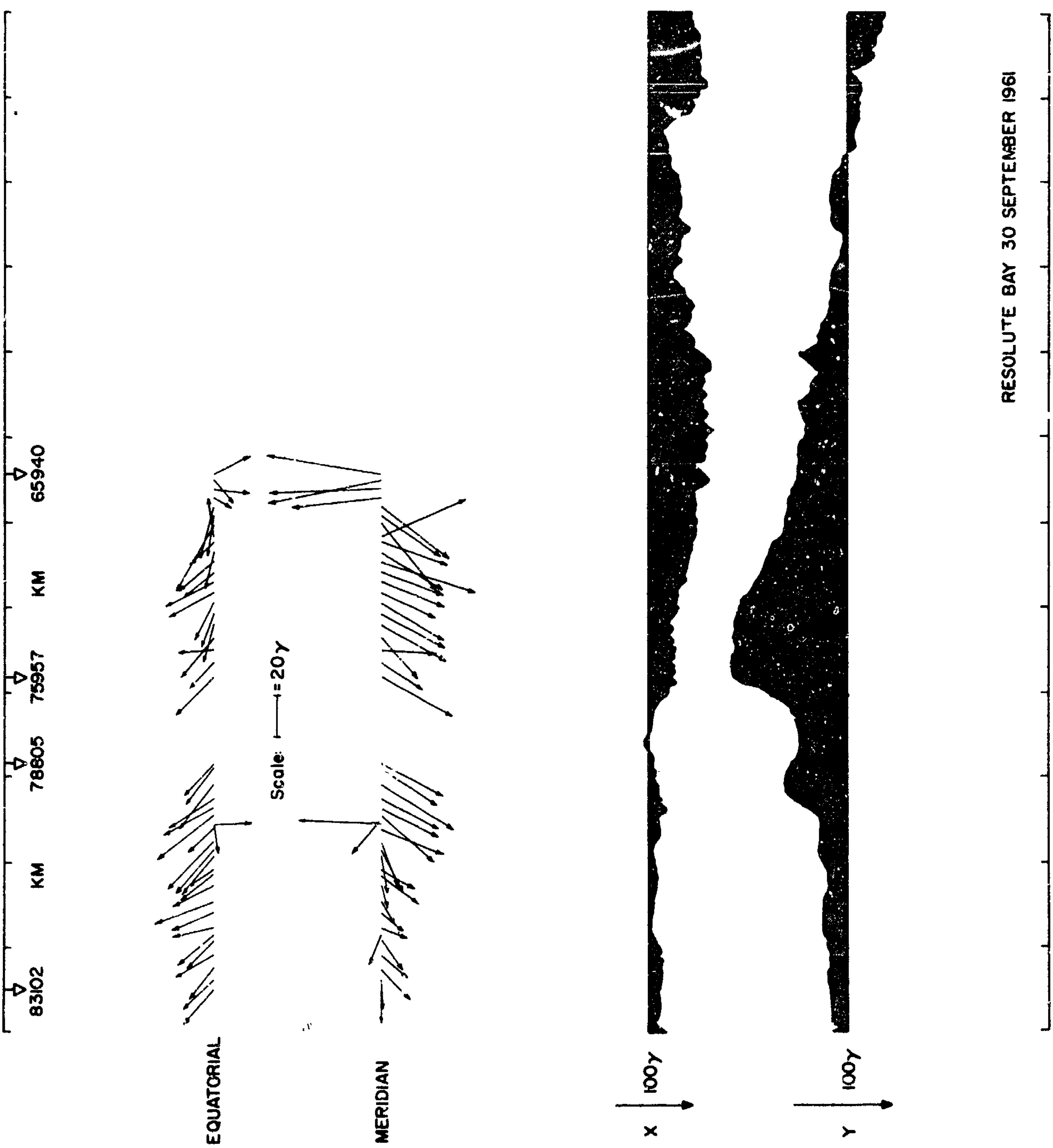
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Figure 6

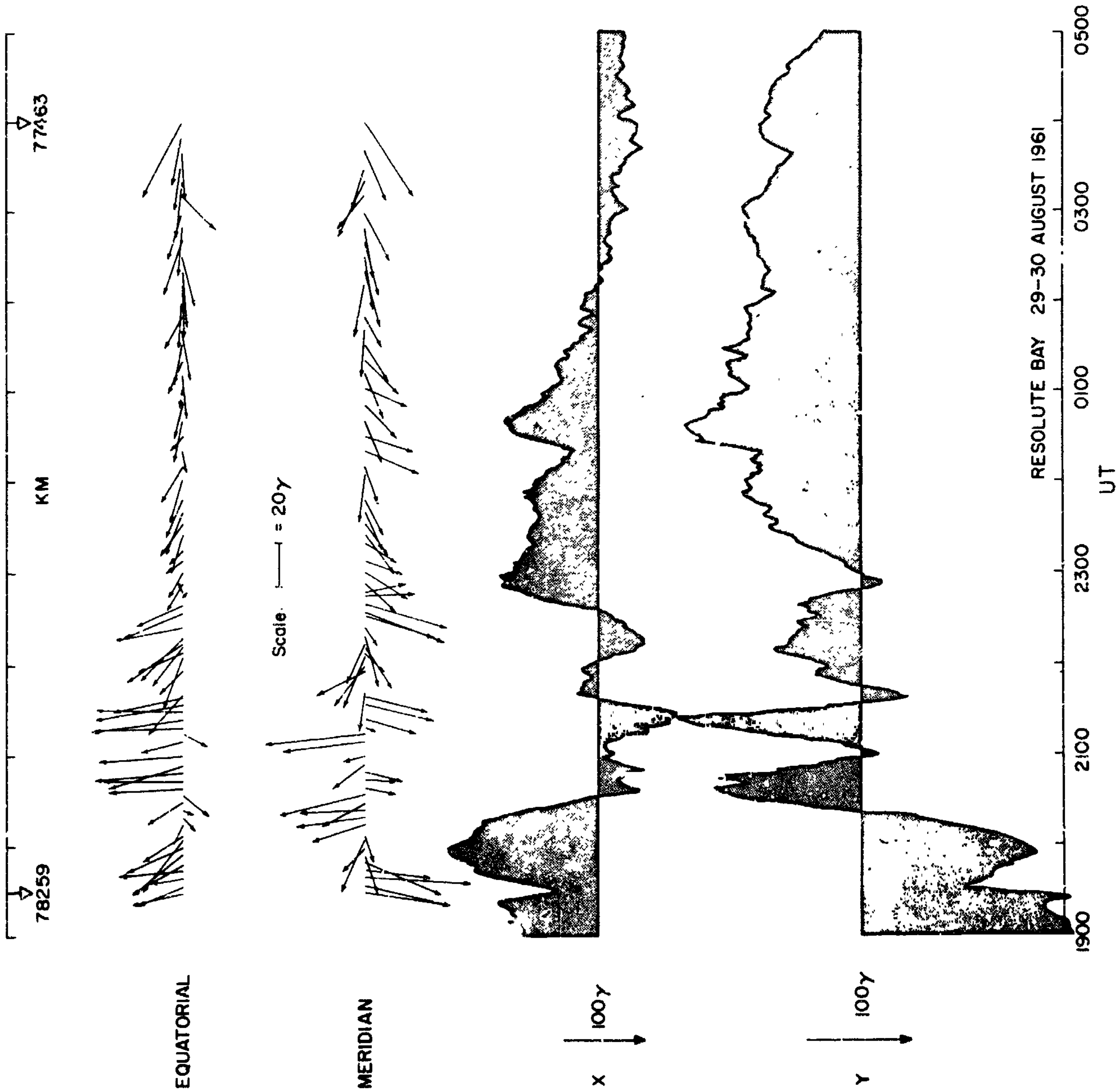

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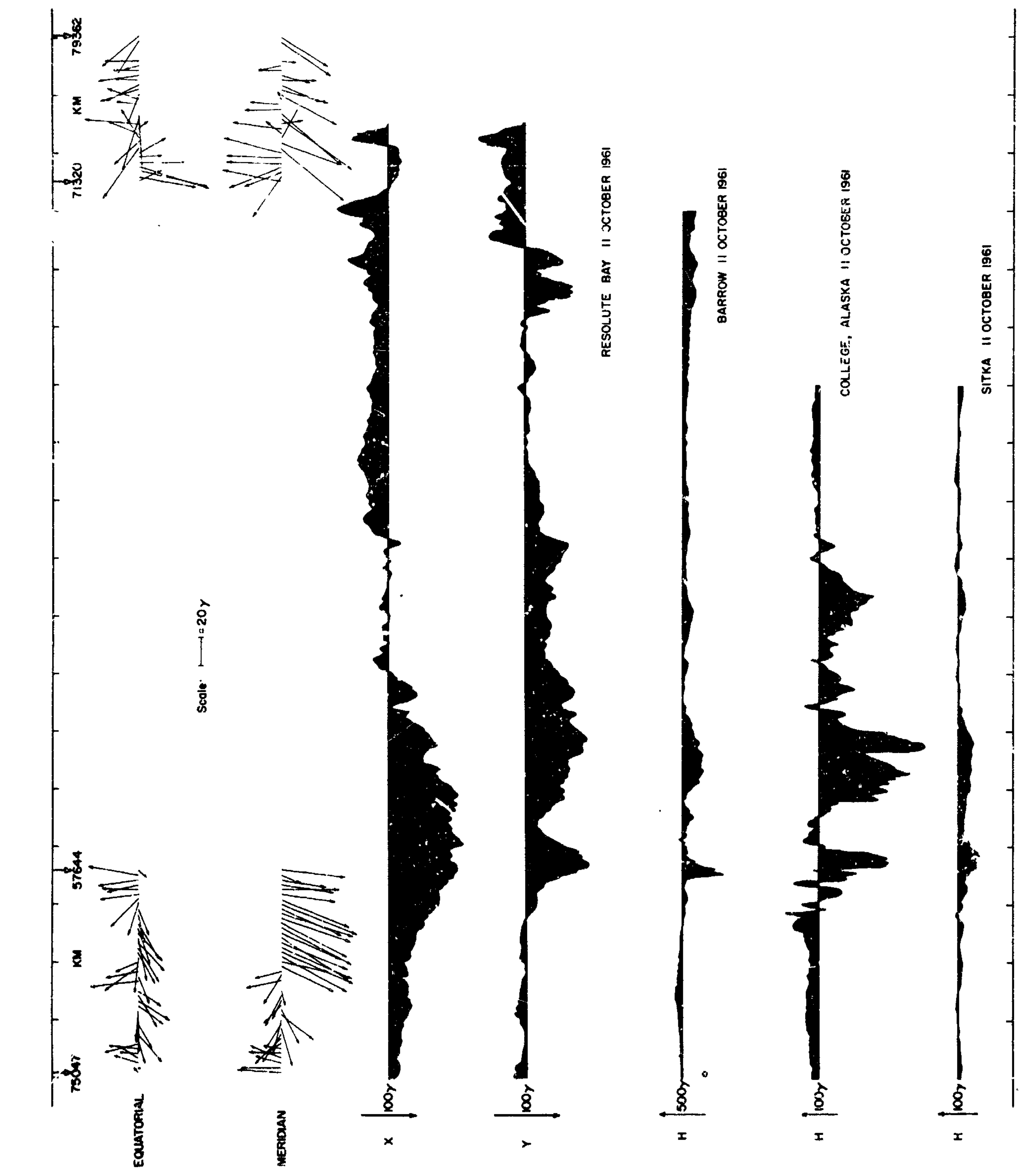
Figure 7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79362
Scale = 20γ
RESOLUTE BAY 11 OCTOBER 1961
BARROW 11 OCTOBER 1961
COLLEGE, ALASKA 11 OCTOBER 1961
SITKA 11 OCTOBER 1961

Figure 8

Figure Captions

Figure 1. Current system deduced as responsible for ground magnetic fluctuations (DS) at 1600 UT during the magnetic storm of May 1, 1933. The center of the diagram is at the north magnetic pole, and the zero meridian is through the geographic north pole. Current direction is shown by arrows; 100,000 amperes flow between each solid current line (after Vestine, 1947).

Figure 2. Diagram showing the two planes on which the transition region magnetic field vectors were projected for illustration of this paper. The geomagnetic north pole is represented by an arrow and the geomagnetic equatorial plane by the ellipse. The geomagnetic meridian plane containing the sun is described by the radius vector pointing to the sun, and the projection of this radius vector onto the equatorial plane. In the figures that follow the equatorial vectors are obtained by projecting the measured vector onto the geomagnetic equatorial plane. The meridian vectors are obtained by projection onto the meridian plane containing the sun.

Figure 3. October 26, 1961, 0800 to 2300 UT; the transition region magnetic field is shown projected onto the geomagnetic equatorial plane and onto the meridian plane containing the sun together with the horizontal components of the magnetic field at Resolute Bay. Universal Time of the observations is plotted in hours on the bottom and top scales.

Captions

For the equatorial projections shown, the sun is to the right of the figure, east is toward the top, and westtoward the bottom. For the meridian projections north is up, south is down and the sun is toward the right. Both the X, north, component and the Y, east, component of the horizontal field at Resolute Bay are shown. The scale of the vectors and of the ground variations are shown on the figure. Radial distances from the earth for the satellite observations are shown by occasional arrows superimposed on the top time scale.

Figure 4. September 12, 1961, 2400 to 1300 UT; the transition region field is shown with the Resolute Bay and College magnetograms. Description of the figure is the same as for Figure 3.

Figure 5. September 24, 1961, 0200 to 1400; the transition region field is shown with Resolute Bay and College magnetograms.

Figure 6. September 30, 1961, 2400 to 1200; transition region field and Resolute Bay magnetogram.

Figure 7. August 29, 1900, to August 30, 0500, 1961; transition region field and Resolute Bay magnetogram.

Figure 8. October 11, 1961, 0600 to 2400; transition region field and magnetograms from Resolute Bay, Barrow, College and Sitka.