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EUGENE M. WESCOTT
JOHN D. STOLARIK
JAMES P. HEPPNER

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Electric Fields in the Vicinity of Auroral Forms From Motions of Barium Vapor Releases

By

Eugene M. Wescott*

John D. Stolarik

and

James P. Heppner

Laboratory for Space Sciences

NASA-Goddard Space Flight Center

Greenbelt, Maryland

* National Academy of Sciences, Resident Research Associate

ABSTRACT

In August - September, 1967, eleven barium vapor clouds were released during evening twilight between invariant magnetic latitudes of 67.3° to 68.1° from Andøya, Norway. Two flights (8 releases) occurred during moderate negative bays in H, while the third flight (3 releases) took place during a positive bay in H. Visual auroral displays were observed in the vicinity during all flights. In the negative bay situation, barium ion cloud motions were eastward, and closely parallel to auroral arc alignments. Electric fields transverse to the magnetic field with intensities of 10 to 130 mv/m directed southward were observed. During the positive bay event the barium clouds spanned the breakup transition region, with the two equatorwards clouds moving westward while the poleward cloud went east. Observed reversals in direction were closely correlated with magnetic variations. North directed electric fields of up to 50 mv/m were found in the positive bay sector. In all events the ion cloud motions revealed that $\underline{E}$ was perpendicular to the ionospheric current, hence we conclude that the auroral electrojets, both eastward and westward, are essentially Hall currents. The results illustrate that the magnitude of $\underline{E}$ driving ionospheric currents cannot be deduced solely from ground magnetic observations because of the variable ionospheric electrical conductivity. There is evidence that while $\underline{E}$ is large near an auroral arc, the field within is very low. Large gradients and/or irregularities in the $\underline{E}$ field are found to exist most of the time. These are revealed on three different time-space scales: from differences in velocity for parallel moving clouds, from velocity changes along the path of a given cloud, and in the form of rayed structure within a cloud.

INTRODUCTION

The development of a method for producing visible ion clouds in and above the ionosphere has given geophysicists a powerful tool for investigating ion drift motions, the fine structure of the ionosphere, electric fields, ionospheric conductivity and magnetospheric convection. Investigators at the Max Planck Institut, [Föppl et al., 1967] discovered that barium vapor produced in a thermite reaction and released in the ionosphere under solar ultraviolet radiation will form a long lasting ion cloud with strong resonant lines in the visible spectrum. Such ion clouds can be formed with uncomplicated payloads from sounding rockets above about 130 km altitude, and they can be observed and photographed under twilight conditions as long as they are illuminated by solar radiation in the visible band.

The growth of the ion cloud after release along the magnetic field line is controlled by gravity and collisions with the ambient atmosphere, while growth perpendicular to the field line is controlled by ambipolar diffusion, collisions, and inhomogeneities in the electric field. The bulk motion of the cloud is a function of gravitational fall, interaction with the ambient neutral wind, and of the magnetic and electric fields. If an ion cloud is formed at an altitude where the collision frequency of the Ba^+ ions with the ambient atmosphere is low and where the ion density in the cloud is not large enough to create a large anomaly in electron density, then the motion of the cloud is essentially due to the $\underline{E} \times \underline{B}/B^2$ drift and gravity. As $\underline{B}$ is known to a fraction of one percent and the expected vertical motion attributable to gravitational fall is usually checked by comparison of the neutral and ion fall rates, the electric field $\underline{E}$, perpendicular to $\underline{B}$, is deduced from $\underline{E} = -\underline{v} \times \underline{B}$ by measuring the horizontal velocity $\underline{v}_\perp$ of the ion cloud. The high conductivity along $\underline{B}$ usually permits one to treat magnetic field lines as lines of equipotential such that magnetospheric potentials are transferred unattenuated to the ionosphere or vice versa. An electric field which can be shown not to originate in an ionospheric process forms the basis for the deduction of magnetospheric convection [e.g., Axford and Hines, 1961; Taylor and Hones, 1965]. Because so many important presumably magnetospheric induced phenomena, (aurora, magnetic disturbances, ionospheric irregularities, and particle precipitation) occur in the auroral zone, electric field measurements in this region are of extreme interest. The determination of the electric fields associated with auroral displays and electrojets is a requisite for formulating a tenable theory of these phenomena.

This paper deals with the observations of the motions of eleven barium vapor clouds released from three Nike-Tomahawk rockets during the fall of 1967 from the auroral zone rocket range at Andøya, Norway (69°, 17' 42"N, 16° 01' 24"E). During all flights visual auroral forms were observed in the vicinity of the barium releases, with two flights during negative magnetic bays and one during a positive magnetic bay in H. Each barium rocket launch was followed within minutes by an instrumented Nike-Tomahawk with various energetic particle detectors, magnetometers, and a set of three-axis long extendable booms for making direct $\underline{E}$ field measurements.

INSTRUMENTATION

The basic chemistry and experimental background for generating barium vapor clouds has been discussed extensively by Föppl et al., [1965, 1967]. Basically barium is partially burned with CuO in a container producing the heat required to evaporate excess barium. The chemical reaction is:

$$(1 + n)\ Ba + CuO \rightarrow BaO + Cu + nBa_{vapor} \qquad (1)$$

where n is excess barium. The reaction and ionization process are not very efficient, perhaps 5% of the barium metal is initially ionized. Strontium is usually present as an impurity or is added to produce a bright neutral cloud which persists much longer than the neutral barium component.

For the releases described here, each canister contained a 3 kg mixture of 25% CuO, 74% Ba metal, and 1% Sr metal. This provides 7.5 moles of excess barium for ionization. Each payload weighing about 137 pounds contained four canisters with timers set to produce releases at 220 km and 285 km on ascent and at 310 km and 220 km on the descent of the Nike-Tomahawk. The field lines in the release area dip at 77°, and the release altitudes were chosen to produce clouds approximately evenly spaced in invariant magnetic latitude from 67.3° to 68.5° on an azimuth of 315°.

Ionization of the barium vapor is not fully understood but does require solar ultraviolet radiation. Initially (within a few seconds) atoms raised to one of two metastable levels are ionized by ultra violet radiation of about 3200 Å. Further ionization from the ground state population via the metastable levels proceeds more slowly with an observed time constant of about 31 sec at altitudes above 240 km [Rosenberg et al., 1968]. At lower altitudes the time constant appears to be less because of the competing oxidation process. Föppl et al. [1967] have reported that following the rapid ionization which forms the main ion cloud, ionization continues to take place at the location of the neutral cloud, but with a characteristic time most recently reported as about 100 sec. A large number of emission lines fall within the visible spectrum with the principal Ba^{+} resonant lines in twilight occurring at 4554.03 and 4934.09 Å

To photograph the clouds and aurora for triangulization purposes a total of nine K-46 aerial cameras with 7" focal lengths were set up at three sites: the launch site at Andøya, the Auroral Observatory at Tromsø, and at Gravdal. In addition an image orthicon television system was in operation at Andøya. Kodak film, type 2498, was used without filtering. Some data were lost from cloud cover and aurora being photographically mixed with the barium clouds but overall excellent pictures were produced. Six frames per minute were taken with exposure times of 3, 6, and 12 sec with all stations synchronized to within one second. Additional pictures in color and black and white were taken with conventional cameras.

THEORETICAL CONSIDERATIONS

In a collision free region of very low β (i.e., ratio of plasma and magnetic field energy densities $\ll 1$) and large $\underline{B}$, such that plasma pressure gradients have an insignificant effect on the magnetic field, the hydromagnetic approximation $\underline{E} = -\underline{v} \times \underline{B}$ provides an accurate description of convective motions [Hines, 1964]. At ionospheric altitudes these conditions are readily met, even in auroral conditions, with the exception that the medium is not collision free, and the electric conductivity perpendicular to the magnetic field lines is important. Haerendel et al. [1967], have derived an approximate expression for the transverse external electric field at infinity, $E_\perp$, using a finite cylindrical ion cloud model. In mks units

$$E_\perp \approx \frac{\lambda^* + 1}{2} B \left[\frac{\underline{B}}{B} \times v_\perp + \frac{1}{\varkappa} (\underline{v_\perp} - \underline{v_n}) + \frac{\lambda^* - 1}{\lambda^* + 1} (\underline{v_n} \times \frac{\underline{B}}{B}) \right] \qquad (2)$$

where $\underline{v_\perp}$ is the ion cloud motion, $\underline{v_n}$ is the neutral wind motion, $\varkappa = \omega/\nu$ is the ratio of the barium ion gyro to collision frequency and $\lambda^* = \frac{\Sigma P_c}{\Sigma P_o}$

is the ratio of height integrated Pedersen conductivity including the cloud to that without the cloud. Equation 2 reduces to $-\underline{v}_\perp \times \underline{B}$ if $\lambda^* \approx 1$ and $\kappa \gg 1$. Consider the second term inside the bracket which involves the vector difference of $\underline{v}_\perp$ and $\underline{v}_n$, and κ. At 200 km $\kappa \approx 100$, and at 240 km $\kappa \approx 500$ [Haerendel et al., 1967] so this term represents at most one percent of the first term. For the third term to be negligible the released barium must not significantly alter the integrated Pedersen conductivity, i.e., $\lambda^* \approx 1$. Therefore for the ideal measurement one releases the minimum amount of barium which still produces a cloud bright enough for tracking. During the three flights the Tromsø ionograms indicated E layer electron densities of up to 10^5 electrons/cc, suggesting that the clouds would contribute only a small increment to the integrated Pedersen conductivity. One can also argue that the conductivity parallel to the magnetic field lines is sufficiently high so that they connect to the conjugate ionosphere, hence one should include the integrated conductivity through the conjugate ionosphere, essentially further reducing the clouds contribution. Haerendel et al. [1969] have discussed the electron density measurements during two barium release experiments from Churchill where 24 kg of mixture was used. Under conditions of much lower electron density than indicated during our flights and with 8 times the barium ejected they found that $\lambda^* \approx 1.5$ in one case. This suggests that with the smaller 3 kg releases and higher ambient electron density in our three flights we are justified in taking $\lambda^* = 1$. The fact that the observed motions showed $v_\perp \gg v_n$ gives us additional confidence that $\underline{E}_\perp = -\underline{v}_\perp \times \underline{B}$ is a valid approximation.

Where the magnetic field is nearly vertical, as is the situation in the auroral zone, the effect of gravity is to cause the cloud to fall with a velocity given by $v_z = g/\nu_i$, where g=gravity and ν_i=ion collisional frequency. At 300 km this corresponds to about 50 meters per second and at 200 km only 5 m/sec. Thus clouds released between 200-300 km will remain at useful altitudes for several hours, and if illuminated could provide drift motion information over this period.

The question as to the existence of electric field components parallel to magnetic field lines, particularly in shells with auroral displays, is one of great interest to those interested in a viable auroral theory. Low energy electrons could be energized to auroral electron energies by dropping through a parallel E field. Electrons gain no energy from a perpendicular field which merely changes their direction. Mende [1968] has considered the effects of a parallel electric field on the equilibrium scale height of a barium vapor cloud, while ignoring possible effects of the polarization field. Based upon his formulation and photometric observations of a series of barium releases by the Max Planck Institute from Kiruna in 1967, Mende [1968] found no evidence for a parallel field of more than 6 μv/m, and suggested an upper limit of 60 μv/m. However, the barium clouds he was able to observe were several hundred km south of auroral activity [Föppl et al., 1968]. The accuracy, or applicability, of analyses such as Mende's are difficult to judge at the present level of understanding of what the effects of a parallel E field would be. Extrapolating from the behavior of single particles one would predict some vertical diffusion or bulk motion of the cloud in the direction of the field. Owing to the inherent uncertainties in picking identical points on barium cloud photographs and the scatter introduced by other errors it would be difficult to see small departures from the expected vertical fall rate. However, for all eleven ion clouds described here there was no evidence of abnormal vertical motion which could not be attributed to triangulation scatter.

DATA REDUCTION

Determination of E depends upon the calculation of ion cloud velocity. The primary data are pictures of the clouds taken on film $4\frac{1}{2}$ inches square. with about 35° field of view to a time accuracy of better than one second. Angular information is obtained by use of the star background, with a program using a 7 coefficient star fit. Usually 50 stars are read from a contact print or an isodensity plot for the fitting program. Wild star readings are automatically thrown out in successive fits until all stars fit within a preselected error residual. Cloud positions are determined from triangulation using two or three stations by a computer program. For a well-defined point such as the rocket motor track or an initial release point the uncertainty in triangulation is of the order of 100 meters or less. However, the barium clouds are usually extended diffuse forms quite often striated and presenting a different shape to observers at different stations. The difficulty in accurately selecting plate coordinates for the extremities or center of a cloud produces positional uncertainties of the order of one km and in some cases several km. Because of the location of the triangulation sites and the angles to the clouds the vertical position is generally subject to more scatter than the horizontal position. Often the ion clouds evolve into rayed or striated forms, which is troublesome because the rays do not remain fixed with the cloud as a whole and change position and relative intensity. Furthermore as the rayed forms become extended sometimes over several tens of km horizontally, different portions are moving with different velocities as compared to the cloud center. This is indicative of interesting nonuniformity of the electric field in that region and also of the fine structure of ionospheric density but it also makes for complexities in triangulation.

On several occasions where E was evidently very high, ions appeared within seconds of release as a diffuse horizontal jet projecting from the neutral cloud and moving with velocities of about 2 km/sec. The diffuseness and motion smearing on the photographic plates makes for scatter in positioning of these rapid clouds.

The position of auroral forms were primarily determined from all sky camera pictures from the Tromsø Auroral Observatory with an assumption of 110 km for the height of the lower border. For certain critical occasions auroral arcs were located more accurately by triangulation using the K-46 plates. All sky camera frames were also used occasionally for cloud tracking using height extrapolation where they had become lost by K-46 cameras.

FLIGHT 1, AUGUST 31, 1967

In terms of the complexity of the observed ground magnetic variations and the barium ion cloud motions, the results of this first flight are the most straight forward to explain, and offer a very good determination of the relative contributions of the integrated Hall and Pedersen conductivities. The Ba rocket was launched at 2206:00 UT as an extensive negative bay in H was developing. At lift off at Andøya, the launch site, ΔH was -150 gammas.

H continued generally to decrease during the time the barium clouds were observed, and at 2222:45 UT when the last cloud disappeared at the eastern horizon ΔH at Andøya was -340 gammas. The bay reached a maximum of -450 gammas ten minutes later.

Figure 1 shows the magnetograms from Kiruna, Sweden, and Tromsø and Andøya, Norway. Inspection of the vertical component deflection, ΔZ, indicates a westward line current located to the south of both Tromsø and Andøya but north of Kiruna. From the behavior of the barium clouds and data from a rubidium vapor magnetometer flown in the instrumented payload near 2250 UT one can deduce that a wide spread sheet current also existed in the region.

During the period of observations a fairly stable east-west oriented auroral arc was situated south of Andøya and Tromsø but north of Kiruna. It seems very likely that the line current was principally flowing in this arc. More active and bright auroral forms typical of the post break-up phase were observed at various times after lift-off to the north of Andøya and Tromsø in the barium release area. These forms were not persistent or stationary.

The alignment of the auroral arcs on this evening tended to be east-west geographic which is also the approximate alignment of the local iso-dip angle lines. However, the statistical auroral zone in this region agrees well with the invariant magnetic latitude lines, which are oriented similar to geomagnetic latitude lines. The invariant latitude lines as shown in subsequent figures are inclined to the geographic latitude lines by about 15 degrees.

Since the barium clouds are released between 200-300 km altitude, and the magnetic field lines are inclined at about 77° it is clear that an auroral display at about 100 km and a barium cloud at the same geographic location would not be on the same L shell, or field line. Thus to make comparisons of the E fields with auroral forms it is necessary to project barium cloud locations down magnetic field lines to the 100 km altitude. In making the projection it is not clear whether to project perpendicular to the L shells, or along the dip angle. Since auroral electrons most likely follow the local magnetic field lines, the most pursuasive argument is to use the best mathematical fit to the local magnetic field for projection. We have used the GSFC(12/66) field model [Cain et al., 1967].

Figure 2 illustrates the 100 km projected positions vs. time of the four ion clouds on a geographical grid map which also includes the invariant magnetic latitude lines (dashed). The launch site is shown as A while T and K denote Tromsø and Kiruna. G indicates a camera site at Gravdal. As one can clearly see in Figure 2, all the ion clouds travelled with a predominantly geographical eastward direction and became distributed in a track about 50 km in width. Each cloud was eventually lost from view at the eastern horizon. The arrows indicate the velocity in meters/second of the four neutral clouds. One sees that the neutral wind was predominantly southward with an average speed near 200 m/sec.

The ion cloud velocities were much higher. Clouds 1 and 2 were observed to form within seconds of release, moving rapidly eastward (about 700 m/s) with a horizontal ion tail from the neutral clouds. The horizontal tailing is a result of the high field causing the ions produced first to move eastward while new ions were still being produced for a period of 10 or more seconds. Ion cloud 2 moved obviously faster than cloud 1 and though released 54 seconds after 1, overtook and passed 1 within 150 seconds. Clouds 3 and 4 developed into more typical field aligned cigar shapes without horizontal tails. Their velocity generally increased with time. Positional times along each cloud track are indicated by minute and seconds in the 22nd UT hour (e.g., the time 0816 given at the release point of cloud 1 is $22^h08^m16^s$ UT). Positions were usually calculated 4 to 6 times per minute and where possible, are indicated at one minute intervals, along the tracks.

The electric field is perpendicular to both $\underline{B}$ and $\underline{v}$, and in the case of eastward motion in the northern hemisphere $\underline{E}$ is directed southward. $\underline{E} = -\underline{v} \times \underline{B}$ was computer calculated in terms of both geographic components and total field. The ion velocity components were computed from the differential motion between adjacent positions, with v_z set equal to zero as an approximation to eliminate the gravity fall term. $\underline{B}$ was calculated at the midpoint position from the GSFC(12/66) field model [Cain et al., 1967]. Figure 3 shows the total magnitude of $\underline{E}$ in millivolts per meter vs. time as determined from the four cloud motions. In comparing the time sequence E(t) of one cloud with another, one must remember that because of the high velocities observed the clouds were separated in space by 200-300 km; thus one cannot expect close coherence in the variations of E. The previously mentioned uncertainties in triangulating on cloud positions produces some random scattering of the E points in Figure 3. One can place the most reliance on the points determined from the longer time intervals. A few obviously wild position points have been removed from the data before calculating E. Careful scrutiny of the remaining data indicate that $\underline{v}$

and thus $\underline{E}$ is not smooth and constant. For instance the sharp increase in E seen by I_3 at 2212:30 seems to be based on solid data and also represents a change in direction at that time. As one can see the electric field averages between 30 to 50 mv/m through the observations.

Throughout the observation time the direction of $\underline{E}$ was predominately southward as was the associated magnetic perturbation seen on the ground magnetometer records. Because the $\underline{E}$ measurements were spread spatially over 500 km from west to east, and ground magnetometers were not densely spaced, one cannot make much of the detailed variation seen in E as compared to variations in $\underline{B}$. However as the first two clouds passed very close to Tromsø we can make a very important observation. Computing the direction of the horizontal magnetic perturbation at that time, as close as one can read the magnetogram and determine a good quiet day base line, $\Delta\underline{B}$ is within 5 degrees of being parallel to $\underline{E}$. In other words $\underline{E}$ is nearly perpendicular to the ionospheric current implying that the integrated Hall conductivity predominates in the westward auroral electrojet.

Figure 4 illustrates an abridged history of the aurora with corresponding instantaneous ion cloud velocities. The numbers beside the arrows indicate the horizontal speed in m/sec. The magnitude of $\underline{E}$ is approximately v/20 [mv/m] and the direction is about 90° clockwise of $\underline{v}$. The equatorward arc was located at about $\Lambda = 65.5^{\circ}$. At 2211:15 auroral arcs could be seen in the all sky camera frame east of the barium clouds. By 2212:00 a bright arc appeared to the west of Andøya and all velocities increased. The motion was essentially parallel to the auroral alignment. At 2212:30 the aurora became more active, with pronounced loops and a sinuous form east of cloud 3. The increase in $\underline{v}$ experienced by cloud 3 at that time, which was previously mentioned, is shown as well as some non-parallelism of the direction. The final map illustrates the situation several minutes later with cloud velocities parallel to the faint auroral forms. At times during the observations no auroral forms could be seen on the all sky camera frame, yet there was no apparent diminution of the ion velocities during these periods. However, owing to film and optical limitations some weak aurora may have been present in the region but not detected.

As one can see in Figure 3, the first and second clouds slowed considerably during the latter minutes of observation. As a consequence of angular coincidence of aurora and faint barium clouds on the photographs we do not have full confidence in the exact relative locations of the barium clouds and the auroral band in the same area. However, our best estimate is that the barium was very close to, if not actually in the auroral shell at these times, and the suggestion from this data is that the low velocity coincides with close proximity to the aurora shell. This would agree with observations made by Aggson [1969] on several flights with direct probes which penetrated auroral forms and showed low E inside the aurora.

The instrumented Nike-Tomahawk flight which was to follow the barium releases by about 10 minutes was not launched at that time because the aurora had faded. It was fired at 2247:52 when the aurora consisted of patches and diffuse glows over much of the sky. Unfortunately all the barium ion clouds had disappeared from view at the eastern horizon so that no direct comparison of barium derived $\underline{E}$ and the direct probe measured $\underline{E}$ could be made. The $\underline{E}$ probe measurements at this later time averaged about 30-40 mv/m during the flight. The rubidium vapor magnetometer flown in the instrumented payload showed a sheet current, quite similar on the up leg and down leg with a current maximum at 105 km.

We have looked carefully for evidence of an electric field component parallel to the magnetic field in the vertical motions of the ionized clouds. The lower portion of Figure 5 illustrates the altitude vs. time plots of the centers of the four neutral clouds. The fall rates agree well with the theoretical rate g/ν. In the upper portion of Figure 5 the altitudes of the tops, centers and bottoms of the four ionized clouds vs. time are shown together with the observed neutral fall rates. There are no obvious anomalous vertical motions of the ion clouds beyond what might be expected from triangulation scatter.

FLIGHT 2, SEPTEMBER 2, 1967

The second barium release flight began under very similar conditions to those existing during flight 1. There was a negative bay in H, with ΔH at Andøya and Tromsø of -150 gammas, however this was the maximum excursion of the bay. The magnetograms from Kiruna, Tromsø and Andøya, shown in Figure 6, also indicate a current concentrated north of Kiruna, but south of Tromsø and Andøya. (The Andøya magnetic East component was inoperative.)

At the time of the first release a bright arc extended east-west from horizon to horizon, passing just north of the Tromsø zenith. As projected the first release came 26 km north of the auroral shell. During the time the barium clouds were observable transitory auroral arc segments were observed around the same general latitude but exact limits on their extent was indefinite as a consequence of relatively bright twilight conditions.

The observed velocities of the first two clouds were much higher than any seen during the first (31 August) flight. Four seconds after the first release a horizontal ion jet could be seen extending several km beyond the expanding neutral ball. The ion clouds 1 and 2 moved with average speeds of about 2000 m/s eastward, and closely parallel to the auroral arc.

Figure 7 illustrates the cloud positions projected to an altitude of 100 km as a function of time, and also neutral wind vectors. The number beside positions indicates the minutes and seconds during the 20th hour UT. As one can see clouds 1-3 all moved essentially geographically eastward to the horizon. Cloud 1 could be seen for only 4½ minutes, and cloud 2 for less than 3 minutes before disappearing. The initial velocity of cloud 3 was much less than that of 1 and 2 but eventually became about 1000 m/sec as it followed in essentially the same track as cloud 2. Cloud 4 however had a much different history. After release it drifted slowly south and east. After 2044:00 it became very much broken up into magnetic field aligned rays the extent of which is indicated by the hashed area, Figure 7. At around 46:00, the rayed cloud was extended east-west and began to drift back to the north and west. At the time of this reversal of direction the cloud was about 180 km northwest of the magnetometer at Andøya and even further away from Tromsø; neither of these stations show any magnetic indication of a large current direction change.

Figure 8 shows the calculated magnitude of E vs. time. The position of cloud 1 for the first minute could be calculated with assurance because it was followed from all three camera stations, thus we feel the calculated peak of 130 mv/m is a valid measurement of the field at about 2033:30. The motion of cloud 2 was harder to follow because from two camera stations a barium neutral cloud interferred with unfiltered photography of the early motion. It is definite however that the velocity of cloud 2 was higher overall and that E averaged over 100 mv/m for the few minutes it was followed.

Peak values of 180 mv/m were obtained, with less certainty than the 130 mv/m of cloud 2. The E deduced from the motion of cloud 3 was much lower, approaching only 50 mv/m towards the end of the observation. For the first three minutes of observation cloud 4 was influenced by an E of less than 10 mv/m and for the rest of the time by no more than 30 mv/m. The turn around to northwestern motion was accompanied by a slight increase in E.

The pertainent and typical auroral and ion velocity situations are illustrated in Figure 9 for four different times. At 2033:20 one can see the very close parallelism of the ion velocity to the auroral arc. Both cloud 1 and 2 were observed to follow the curve of this arc very closely as they drifted rapidly eastward as illustrated at time 2035:20. By 2039:50 clouds 1 and 2 had disappeared in the east and cloud 3 was moving at about 800 m/s in the same direction, while cloud 4 was moving at about 50 m/s (in the upper left corner of the map). At 2040:50 cloud 3 increased in velocity to 980 m/s and changed direction southward at the same time as the aurora became brighter, more active and sinuous. Since a similar direction change was seen during Flight 1 (Figure 4 at 2212:30) one might suggest that the instability seen as a sinusoidal activity of the aurora is also seen as disturbing the general d.c. electric field pattern in the region adjacent (i.e., within 100 km of the active aurora.)

Figure 10 illustrates detailed fall rate data for ion cloud 3 compared with the rate of neutral 3. The neutral cloud cannot be followed for more than a few minutes at this altitude because of the rapid diffusion and low density. As one can see however the ion center continues to fall at a rate in good agreement with extrapolation of the neutral data. No anomalous behavior was seen in any of the other clouds to suggest that they are influenced by a parallel electric field. The 50 to 60 km vertical extent of the ion cloud is a typical dimension.

Owing to the insight into the amount of time that auroral zone barium clouds might be observed in the launch sector it was planned to launch the second instrumented rocket more closely after the barium rocket than on August 31. However at "I" lift-off at 2042:35 clouds 1 and 2 had disappeared eastward and 3 was well east of the instrumented trajectory. If cloud 4 had continued southeast instead of turning north and west there would have been some overlap. The E probe measurements along azimuth 325^{o} did reveal two peaks of about 100 mv/m in the same general projected area crossed by clouds 1 and 2, and the field in the region beyond agreed with the field which influenced cloud 3. The rubidium vapor magnetometer experiment showed the existence of a partial sheet current with current maximum at about 125 km, or about 20 km higher than during the first flight. This suggests that the conductivity was less on the second flight than on the first and probably explains why the magnetic disturbance during the second flight was weaker than during the previous flight even though the E field was stronger. This illustrates the necessity of knowing the conductivity when estimating E fields from surface disturbances.

When cloud 1 passed nearly overhead at Tromsø the magnetograms indicated that the magnetic perturbation vector $\Delta\underline{B}$ was very close to being perpendicular to $\underline{v}$ at that time. This agrees with the observations of flight 1 that the westward electrojet must be predominately Hall current. If this current was located at the same altitude, 125 km, as the current encountered 12 minutes later by the rocket magnetometers north of Andøya the usual conductivity models which give roughly equal Hall and Pedersen conductivities at this altitude would have to be questioned. The time and spatial separation of this example does not, however, provide adequate justification for quantitatively questioning the model calculations.

FLIGHT 3, SEPTEMBER 12, 1967

The results of this third and last flight of the 1967 series are the most interesting because of the complexity of the auroral zone electric fields revealed. At the time of lift-off a small positive bay (about 50 gammas) in H was seen on the Tromsø and Andøya magnetograms, Figure 11. There was a very slight indication of the positive bay at Kiruna, farther to the south and east. There was very little indication of the current in Z at Andøya or Tromsø, but the Kiruna Z trace suggested the presence of a current concentration to the north, perhaps nearly overhead at Tromsø.

Unfortunately the Tromsø all sky camera was not in operation on this evening so definite documentation of the auroras in the area is lacking. From observer notes taken during the flight and narrow field color photographs we can say generally that during the first increase in H, weak, fairly active aurora was seen overhead and to the north of Andøya and Tromsø. More auroral activity occurred during the second maximum near 2120.

Figure 12 shows the projected cloud tracks on the area map. Note the location of Andøya - "A" at the extreme eastern edge of the map. The times shown are minutes and seconds of the 20th and 21st hours UT. Only three tracks are shown as the fourth scheduled cloud was not observed, perhaps due to a timer malfunction in the payload.

Cloud 1 moved rapidly (about 1000 m/s) westward immediately after release and was lost from view at 2105:50. Presumably it continued westward, as it was not seen to reappear. Cloud 1 was slightly rayed or striated. Cloud 2 also began to move westward, at about 900 m/s, but slowed down gradually and reversed motion to the east at about 2105:00.

It eventually continued westward until lost from view at about 2114:20. The cloud broke up into three or four prominent rays, the motions of which are shown as separate tracks from about 2101:00 to 2107:20. Cloud 3 moved more slowly westward until about 2105:50 when it moved north and then towards the east. Eastward motion continued until about 2115:50 when an abrupt reversal to rapid westward motion occurred. The cloud moved westward at around 1000 m/s until lost from view at 2123:20. The motions of all three clouds tended to be more nearly parallel to the invariant magnetic latitude lines than to geographic east-west lines.

The rather complicated paths followed by the barium ion clouds seems to relate well to the magnetic variations seen by the closest magnetometer at Andøya. In Figure 13 the Andøya magnetic H component is plotted with its quiet day base line and the ion cloud velocities parallel to the invariant magnetic latitudes. The magnetic H trace shows a positive deflection throughout the observation time, with two general increases in H. The first "bay" or increase began at about 2055:00 reaching a maximum of about 50 gammas and then began to decrease towards the base line at around 2106:00. The trace remained near the base line until around 2116:00 when a second larger (75 gammas) bay began. The cloud motions seem to correlate quite well with the increases or decreases of Andøya H, particularly the cloud 3 motions. It is quite apparent from the cloud 1 and 2 motions that a positive bay corresponds to a northward E, in this case of about 50 mv/m. It would also seem that because cloud 2 was moving west while cloud 3 was moving east, we have for a time observed the division region between the positive and negative bay currents. During the second positive bay from about 2116:00 onward the boundary apparently moved northward, as evidenced by the abrupt westward motion of cloud 3. As one can see there is good correlation between the cloud 3 velocity and Andøya H, but with an apparent time lag of about one to two minutes. Without further magnetic data to the north of Andøya detailed speculation on this correlation is not justified.

Unfortunately the magnetic east component recorder at Andøya was inoperative during the flight so the horizontal perturbation vector $\Delta\underline{B}$ cannot be determined at that closest station. However from the Tromsø magnetograms it would seem that $\Delta\underline{B}$ was nearly perpendicular to the cloud motions, implying that the eastward electrojet was predominantely Hall current in this example. This flight showed the complexity of the $\underline{E}$ field in the auroral zone, with northward and southward fields existing within short distances of each other.

No data were obtained from the instrumented flight on this evening due to a structural failure in the payload.

STRIATIONS IN BARIUM CLOUDS

One of the most interesting aspects of barium release experiments is the development of field aligned striations or ray structures in the ionized clouds. Striations have been observed in both large and small releases and at various altitudes. They develop in low and mid-latitude releases but apparently at a much slower rate than in the auroral zone. In many cases the rayed structures in the ionized clouds are very similar to the rayed forms in adjacent auroral forms. In fact unless one knows the time history of a particular rayed form, views the display through a BaII interference filter, or is looking at a color photograph it is often impossible to distinguish between rayed barium or rayed aurora. This fact strongly suggests that many of the details of rayed auroral forms are determined by some ionospheric field aligned fine structuring rather than by magnetospheric ordering of the incoming auroral electrons.

The cause of the ray formation is unknown. Some of our ionized barium clouds, those moving very rapidly, appeared as a jet, with horizontal tailing and a small field aligned head. Others, particularly cloud 3 of flight 1 remained nearly as a field aligned cigar shape. The rest of the clouds exhibited the formation of field aligned rays or striations to varying degrees. In an extreme case a cloud became separated into rays which were distributed over a horizontal distance of 30 km. All of our barium releases used identical chemistry, and probably produced the same number of ions. The ambient background electron and neutral densities, integrated conductivity and $\underline{E}$ field varied considerably, however there is no consistent pattern to suggest how, or even that, the introduction of the barium clouds is in itself a cause of the fine structure.

If field aligned irregularities already existed in the ionosphere, even much lower down in the E region, current flowing through the irregularities would produce irregular polarization electric fields extending to greater altitudes. The barium ion cloud would be affected by the fine structure of the field. Conversely if the magnetospheric $\underline{E}$ field has a fine structure, then as projected down to the ionosphere the non-uniform $\underline{E}$ would produce corresponding ion density irregularities.

A conductivity anomaly introduced by a barium cloud might trigger a plasma instability (e.g., the $\underline{E} \times \underline{B}$ instability discussed by Simon [1963]) which would result in the rayed structure. However, electron density gradients characteristic of a barium cloud are easily within the range of anomalies produced naturally by auroral electrons and other ionospheric processes. Thus if plasma instabilities cause the field aligned structures to develop in barium clouds, it is quite reasonable to assume that such structures are produced without artificial injection and in fact would be a normal feature of the high latitude ionosphere. This appears to be confirmed by the OV 1-10 satellite measurements of E field irregularities [Heppner, 1969]. The satellite measurements further indicate that the existence of extensive irregularities with similar dimensions depends on the presence of a larger scale E field. The $\underline{E} \times \underline{B}$ instability, Simon [1963], thus provides an attractive foundation for further study. If this instability explains the rayed structure, the origin is most probably in the E-region of the ionosphere where the differential drift between ions and electrons, required by the theory, becomes significant.

Pending further theoretical and experimental work, we tend to regard the striations in barium clouds from low density releases as a visualization of ambient field aligned fine structures in the ionosphere, and suggest that many of the rayed features of aurora are similarly caused.

CONCLUSIONS

Of three barium release rocket flights in the auroral zone in 1967 two were during moderate negative bays in H and one during a smaller positive bay in H. There were auroral arcs in the vicinity of the barium clouds during all three flights, but no unequivocal examples of barium directly in auroral shells.

The most striking observation made was the close parallelism of barium ion cloud motion to the alignment of auroral arcs. Since it is very likely that much of the electrojet current flows in the region of auroral arcs where the conductivity is enhanced, one can suggest that the parallel motion of barium clouds indicates that $\underline{E}$ is perpendicular to the current. Strong evidence to support this hypothesis was found from the ground magnetograms at Tromsø during negative bays; when several ion clouds were nearly overhead the magnetic perturbation $\Delta\underline{B}$ was nearly perpendicular to $\underline{v}$. During a positive bay the electric field was in the opposite direction and as well as one can determine was also perpendicular to the current. Although the number of observations is limited we feel that we have strong evidence for concluding that the auroral electrojets, both westward and eastward are predominately Hall current.

Within 26 km of a well-defined arc we measured a perpendicular $\underline{E}$ field of 130 mv/m which probably extended tens of km further away. While $\underline{E}$ may be large outside the auroral form it appears to go to very small values inside where the conductivity is high. Aggson [1969] has found with long probe E field measurements, from several rockets which penetrated auroral forms, a strong anti-correlation of $\underline{E}$ and aurora. Our barium cloud observations do not conflict with these findings, and in the one case where Ba clouds apparently coincided with an auroral form the evidence is also for low $\underline{E}$. The weak $\underline{E}$ field inside the form could be caused by enhancement of the Pedersen and Cowling conductivities which would act as short circuits on the potential field and present an electrical load on the mechanism producing E.

It is quite obvious from our observations that one cannot deduce the magnitude of the electric field driving an auroral zone ionospheric current from the ground magnetic perturbations. For instance we found with a negative bay of about -200 to -350 gammas, fields of around 50 mv/m. During a smaller negative bay fields of 130 mv/m or higher were observed, and during a much smaller positive bay in H, of abcut 50 gammas we also saw fields of 50 mv/m. Thus it is clear that the ionospheric current is strong function of the ionospheric conductivity as well as the applied E field both of which may change with time. This makes it impossible to estimate the electric field magnitude from surface magnetograms as is often attempted. However, demonstration that the electrojet currents are Hall currents does permit surface magnetic data to be used to deduce the direction of the applied E field -- at least under conditions analogous to those present during these 3 flights.

The question as to the configuration of the D_p current system has been argued for many years. Our data are of course limited, but the cloud motions during the September 12 positive bay event do indicate the existence of an eastward electrojet which overlaps equatorwards of the westward electrojet as discussed in detail by Heppner [1967].

The irregular motions of a given Ba^+ cloud along its path and the contrasts in velocity between parallel moving clouds clearly illustrate the time and space variability of the general E field. Even when visual aurora is not apparent in the proximity of the clouds, factor of two changes in velocity over tens of seconds and differences between parallel moving clouds are frequently observed. Irregularities on this scale appear to be distinct from the field aligned irregularities seen as rayed structure within a cloud which have characteristics that are more likely to be related to plasma instabilities. These irregularities and other facets of the observations, such as the implications of the supersonic ion bulk motions, present interesting problems for future study.

ACKNOWLEDGMENTS

The rockets were launched through the cooperation and assistance of the Royal Norwegian Council for Scientific and Industrial Research. The Tromsø Auroral Observatory generously made facilities available for the observation of the releases. The Astro-met Division of the Thiokol Chemical Company was responsible for the payload development, fabrication, and the payload preparations at the launch site. We particularly thank Mrs. M. Miller for her efforts in programming and reducing the star and barium plates in the analysis, and Drs. R. F. Benson and N. Maynard who provided timely assistance in photographing the clouds.

REFERENCES

Aggson, T. L., Probe measurements of electric fields in space, Proc. NATO Adv. Study Inst. "Aurora and Airglow, 1968, Ås, Norway, in press, 1969.

Axford, W. I. and C. O. Hines, A unifying theory of high latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433-1464, 1961.

Cain, J. C., S. J. Hendricks, R. A. Langel and W. V. Hudson, A proposed model for the international geomagnetic reference field - 1965, J. Geomagnet. and Geoelec., 19(4), 335-355, 1967.

Föppl, H., G. Haerendel, J. Loidl, R. Lüst, F. Melzner, B. Meyer, H. Neuss and E. Rieger, Preliminary experiments for the study of the interplanetary medium by the release of metal vapour in the upper atmosphere, Planet. Space Sci. 13, 95-114, 1965.

Föppl, H., G. Haerendel, L. Haser, J. Loidl, P. Lütjens, R. Lüst, F. Melzner, B. Meyer, H. Neuss and E. Rieger, Artificial strontium and barium clouds in the upper atmosphere, Planet. Space Sci., 15(2), 357-372, 1967.

Föppl, H., G. Haerendel, L. Haser, R. Lüst, F. Melzner, B. Meyer, H. Neuss, H.-H. Rabben, E. Rieger, J. Stöcker and W. Stoffregen, Preliminary results of electric field measurements in the auroral zone, J. Geophys. Res., 73(1), 21-26, 1968.

Haerendel, G., R. Lüst and E. Rieger, Motion of artificial ion clouds in the upper atmosphere, Planet. Space Sci., 15, 1-18, 1967.

Haerendel, G., R. Lüst, E. Rieger, and H. Völk, Highly irregular artificial plasma clouds in the auroral zone, Proc. of the NATO Adv. Study Inst. "Aurora and Airglow, 1968", in press, 1969.

Heppner, J. P., High latitude magnetic disturbances, "Aurora in Airglow", ed. by B. M. McCormac, Reinhold Publishing Corp., N.Y., 75-92, 1967.

Heppner, J. P., Magnetospheric convection patterns inferred from high latitude activity, Pro. of the NATO Adv. Study Inst., "Aurora and Airglow, 1968", in press, 1969.

Hines, C. O., Hydromagnetic motions in the magnetosphere, Sp. Sci. Rev., 3, 342-379, 1964.

Mende, S. B., Experimental investigation of electric fields parallel to the magnetic field in the auroral ionosphere, J. Geophys. Res., 73(3), 991-998, 1968.

Rosenberg, N. W., G. T. Best, F. P. Delgreco, M. M. Klein, M. A. Macleod, T. M. Noel, W. K. Vickery, AFCRL barium release studies 1967, Project Secede Special Rept. No. 4, Stanford Res. Inst., 1968.

Simon, A., Instability of a partially ionized plasma in crossed electric and magnetic fields, Phys. Fluids, 6, 382-388, 1963.

Taylor, H. E. and E. W. Hones, Adiabatic motion of auroral particles in a model of the electric and magnetic fields surrounding the earth, J. Geophys. Res., 70, 3605-3628, 1965.

FIGURE CAPTIONS

Figure 1. Magnetograms: Kiruna, Sweden, Tromsø and Andøya, Norway for Flight 1, 31 Aug. 1967. Ba and I indicate lift-off time of the barium and instrumented rockets. Base lines are derived from quiet day values.

Figure 2. Tracks of four ionized barium clouds, Flight 1, projected along magnetic field lines to 100 km datum altitude on geographic coordinates. Arrows indicate average neutral cloud velocities in meters/second. Numbers along tracks are minutes and seconds of 22nd hour UT. Dashed grid lines are invariant magnetic latitude. K=Kiruna, T=Tromsø, A=Andøya, and G=Gravdal.

Figure 3. Electric field magnitude perpendicular to $\underline{B}$ vs. time from four ionized cloud motions, Flight 1.

Figure 4. Time sequence of typical auroral situations and barium ion cloud locations and velocities, (m/s), during Flight 1. Cloud positions have been projected down magnetic field lines to 100 km altitude. Note the general cloud motion parallel to arc alignments and the increase in velocity with time. $\underline{E}$ is 90° clockwise of $\underline{v}$ and approximately given by v/20 (mv/m).

Figure 5. Plots of barium cloud altitudes vs. time, Flight 1. At bottom the neutral Ba and Sr. cloud fall rates are plotted. At the top are shown ion cloud extremities and center altitudes with the corresponding neutral data given as a solid line.

Figure 6. Magnetograms: Kiruna, Sweden, Tromsø and Andøya, Norway for Flight 2, 2 Sept. 1967. Ba and I indicate lift-off times for the barium and instrumented rockets. Base lines are derived from quiet day values.

Figure 7. Tracks of four ionized barium clouds, Flight 2, projected along magnetic field lines to 100 km datum altitude on a geographic grid. Arrows indicate average neutral cloud velocities in meters/second. Numbers along tracks are minutes and seconds of 20th hour UT. Dashed grid lines are invariant magnetic latitudes. See text for explanation of cloud I4 track in hashed area.

Figure 8. Electric field magnitude (mv/m) perpendicular to B vs. time from four ionized cloud motions, Flight 2.

Figure 9. Time sequence of typical auroral situations and ionized barium cloud positions and velocities (m/s) during Flight 2. Cloud positions have been projected down magnetic field lines to 100 km datum altitude. Note the high velocities of I_1 and I_2 and the motion parallel to the auroral arc alignment. E is 90^o clockwise of v and approximately = v/20 (mv/m).

Figure 10. Detailed plot of altitude vs. time for neutral cloud 3 and ion cloud 3, Flight 2.

Figure 11. Magnetograms: Kiruna, Sweden, Tromsø and Andøya, Norway for Flight 3 showing the positive bay in H. Barium and instrumented rocket lift-off times indicated. Base lines are derived from quiet day values.

Figure 12. Tracks of three ionized barium clouds, Flight 3, projected along magnetic field lines to 100 km datum altitude. Numbers along tracks are minutes and seconds of 20th and 21st hour UT. Cloud 2 became separated into three prominent rays shown by separate tracks. Note the reversal of direction of cloud 3.

Figure 13. Plot of the ionized cloud velocity in the invariant magnetic east-west direction with the H magnetic component at Andøya. Note the close correlation of the cloud 3 motion with changes in H. E is approximately given by v/20 (mv/m).

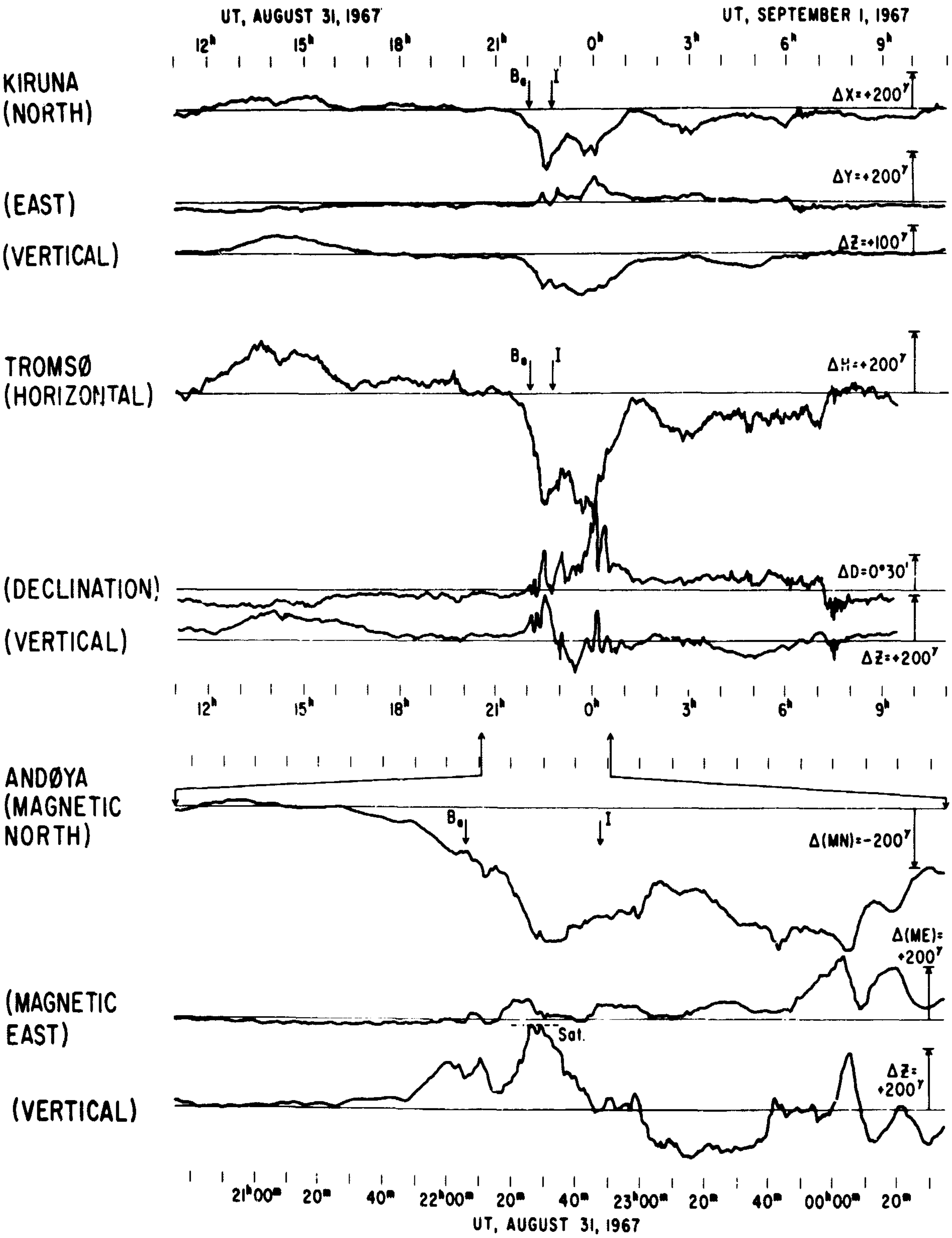
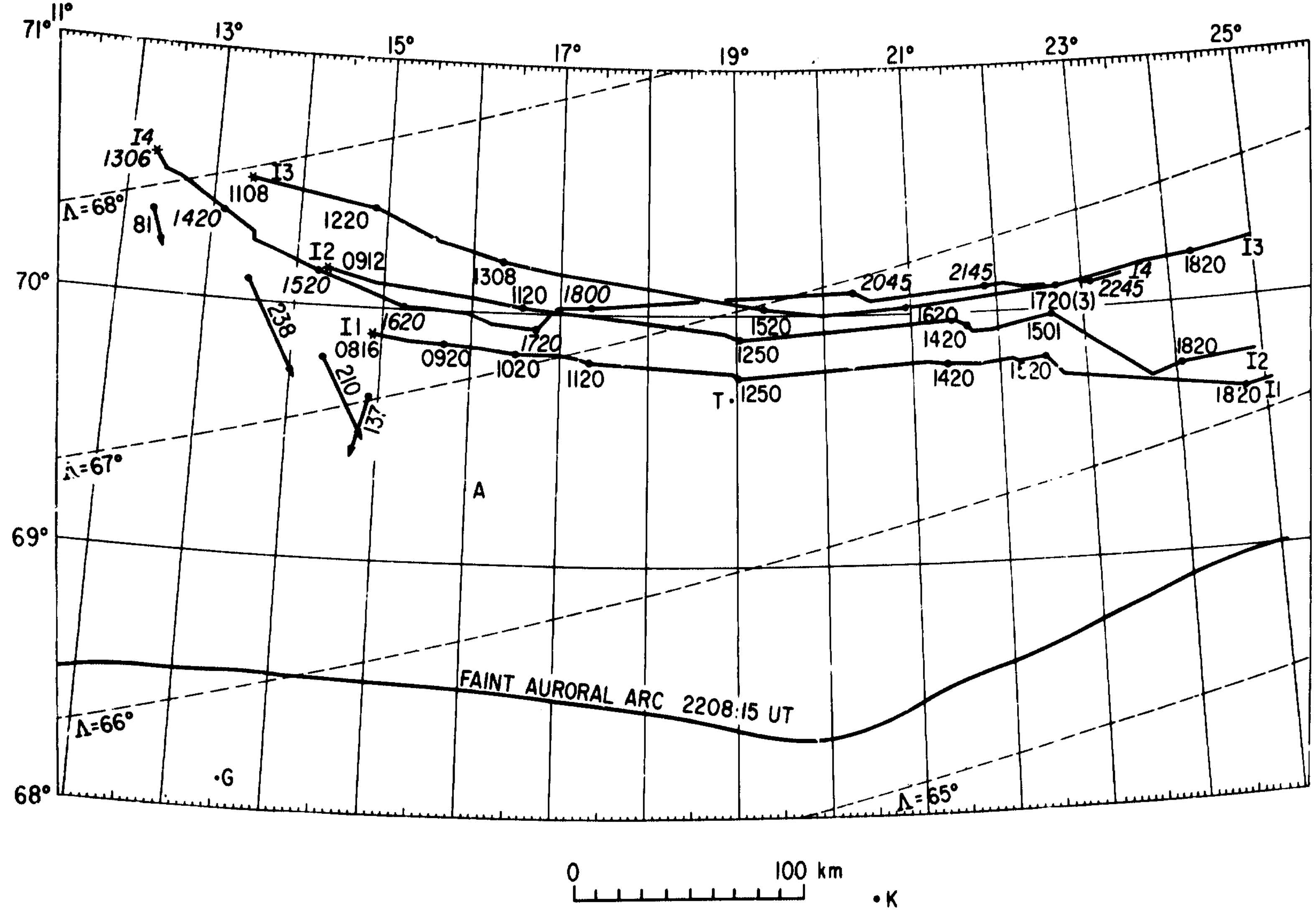
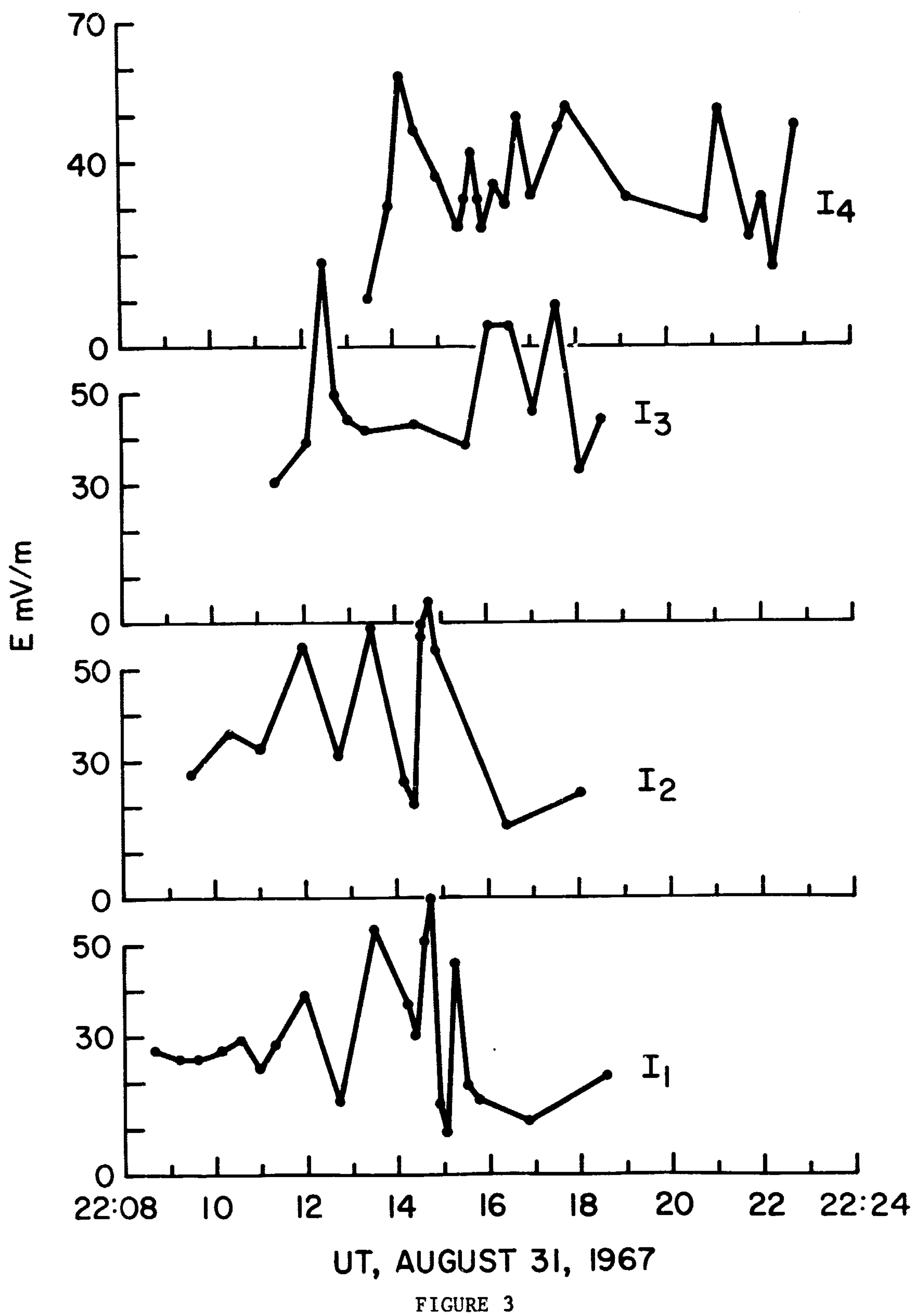

UT, AUGUST 31, 1967
UT, SEPTEMBER 1, 1967
12h
15h
18h
21h
0h
3h
6h
9h
KIRUNA (NORTH)
B_e
I
ΔX=+200γ
(EAST)
ΔY=+200γ
(VERTICAL)
ΔZ=+100γ
TROMSØ (HORIZONTAL)
ΔH=+200γ
(DECLINATION)
ΔD=0°30'
(VERTICAL)
ΔZ=+200γ
ANDØYA (MAGNETIC NORTH)
Δ(MN)=-200γ
(MAGNETIC EAST)
Δ(ME)=+200γ
Sat.
(VERTICAL)
ΔZ=+200γ
21h00m
20m
40m
22h00m
23h00m
00h00m
UT, AUGUST 31, 1967

FIGURE 1



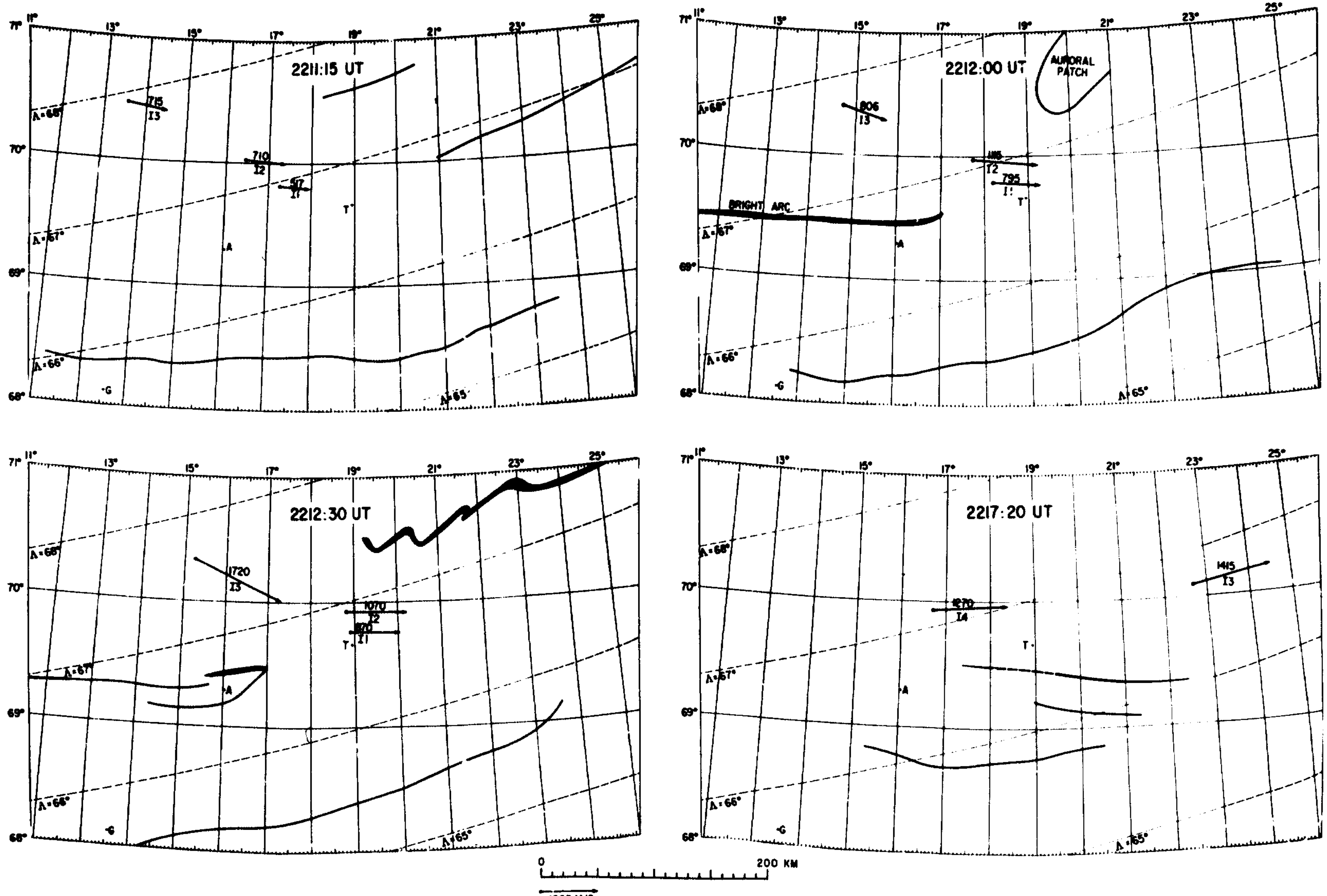
31 AUG 1967

FIGURE 2



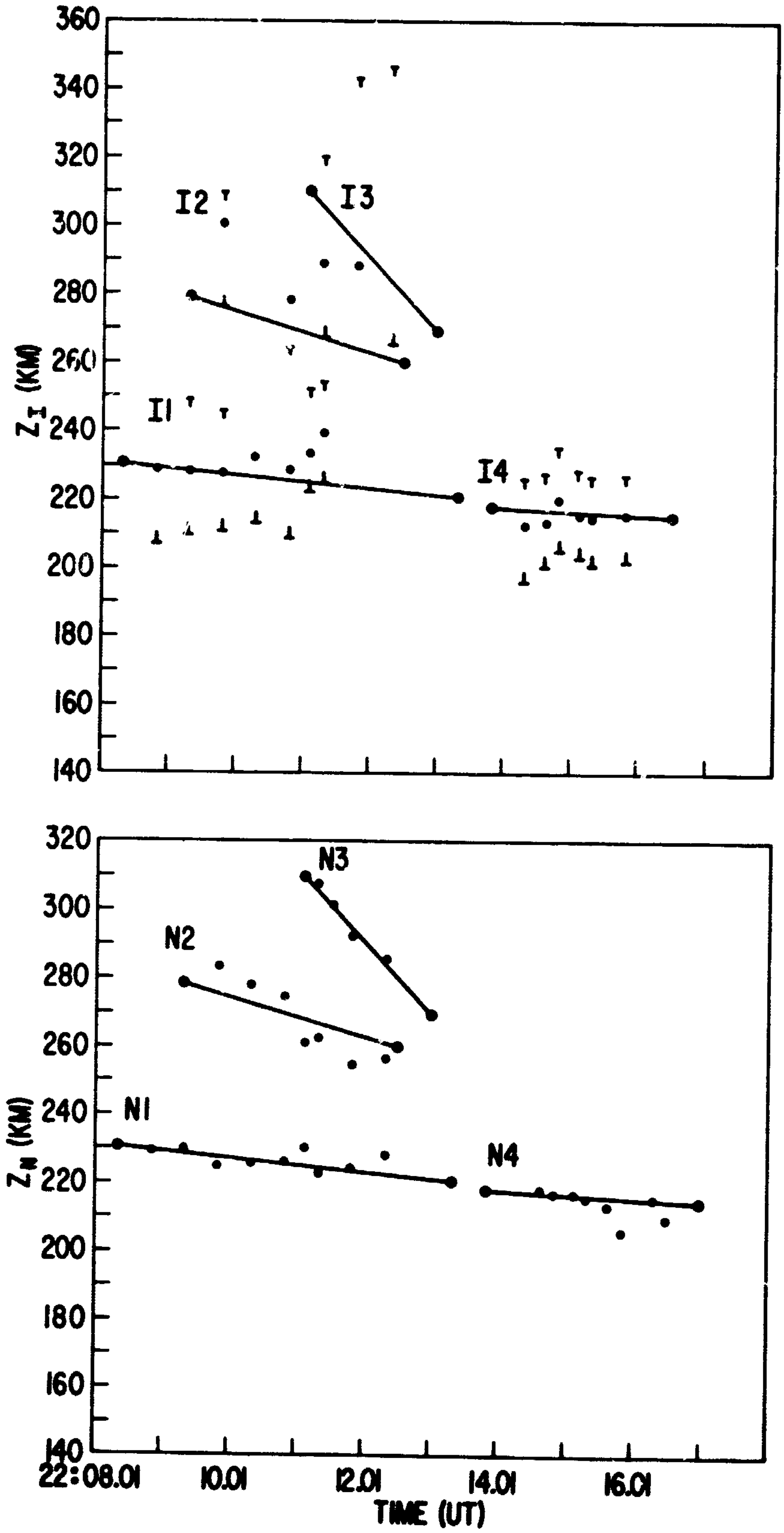
70
40
0
50
30
0
50
30
0
50
30
0
E mV/m
I4
I3
I2
I1
22:08
10
12
14
16
18
20
22
22:24
UT, AUGUST 31, 1967

FIGURE 3



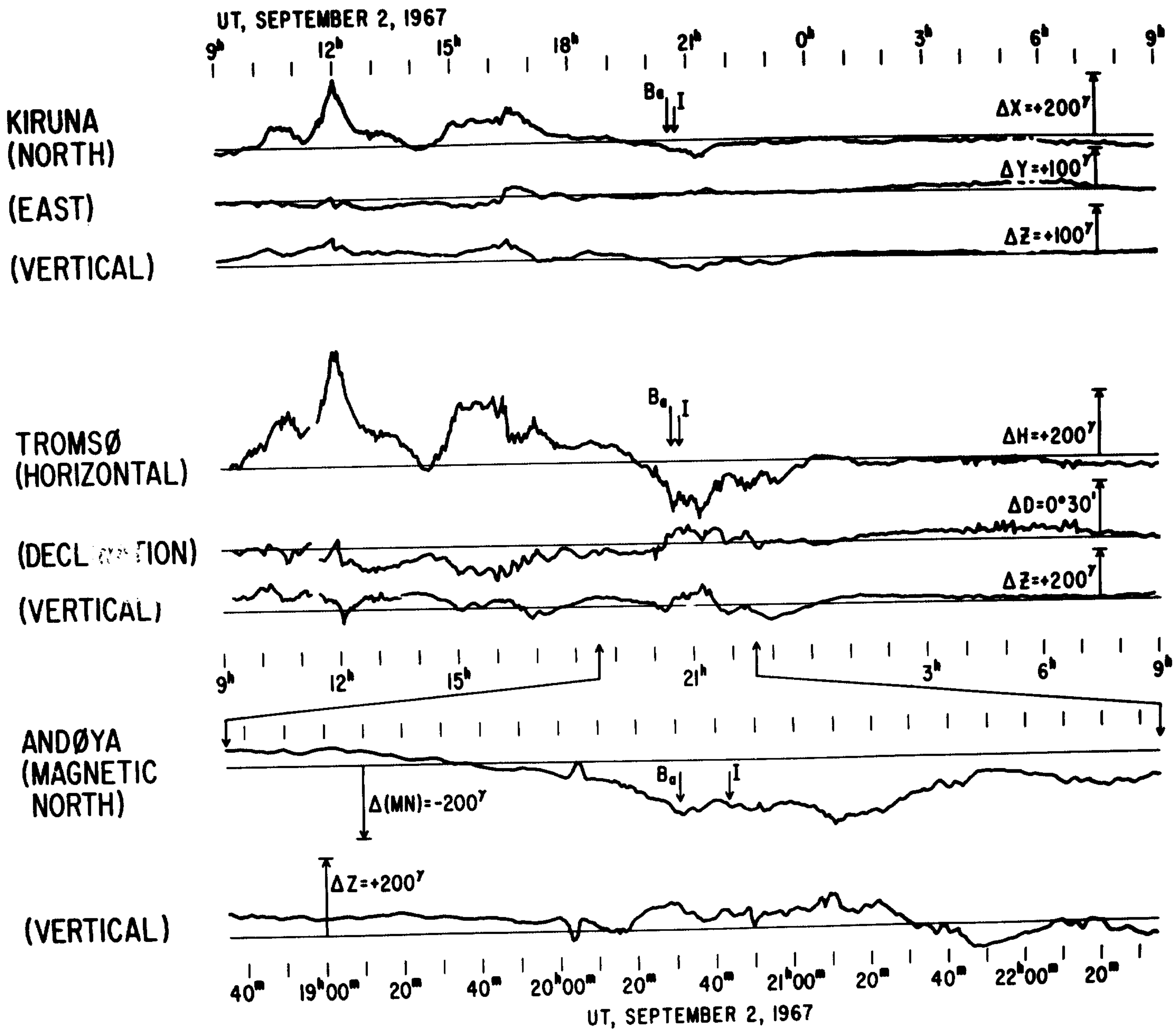
31 AUG 67

FIGURE 4



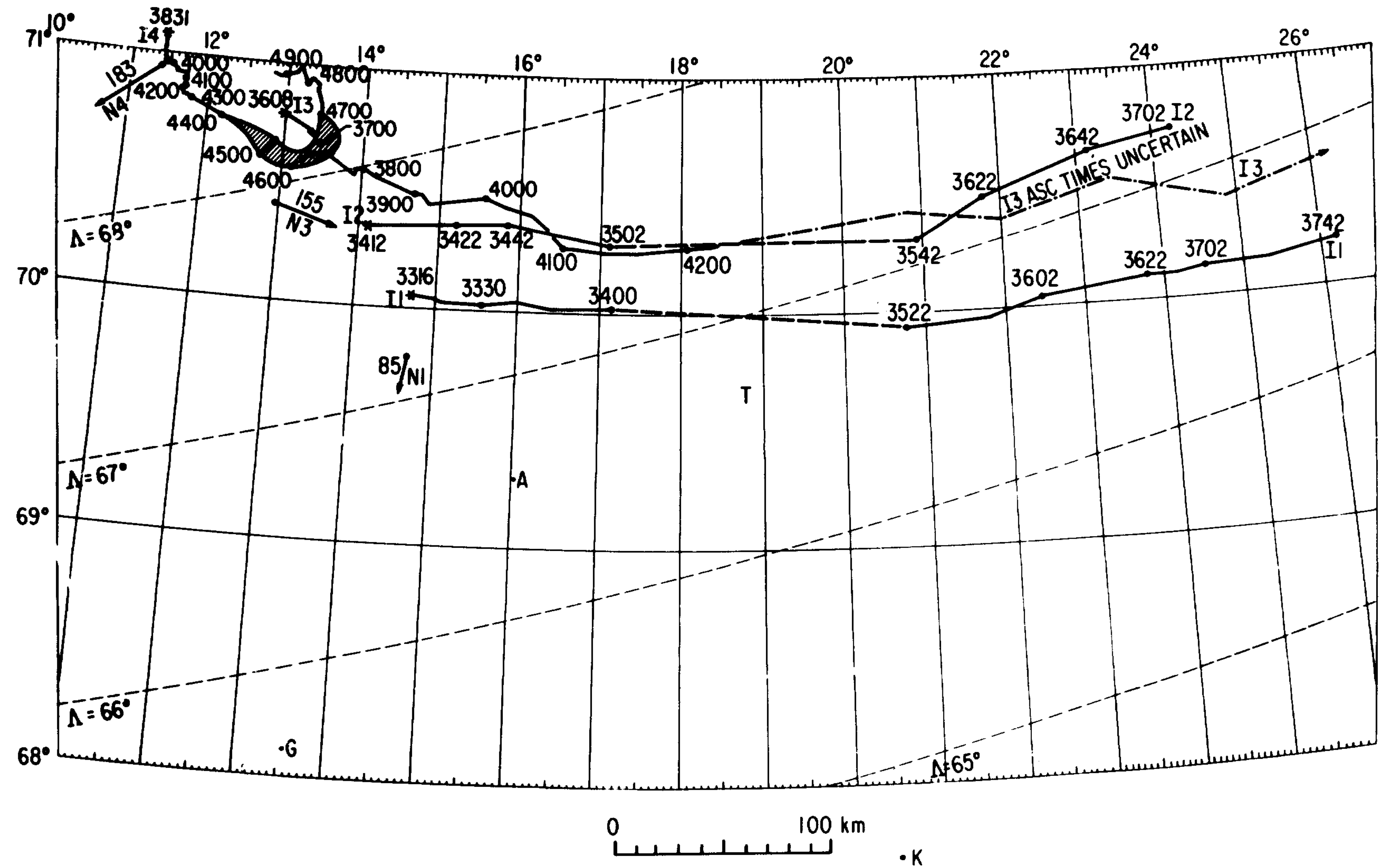
AUG. 31, 1967

FIGURE 5



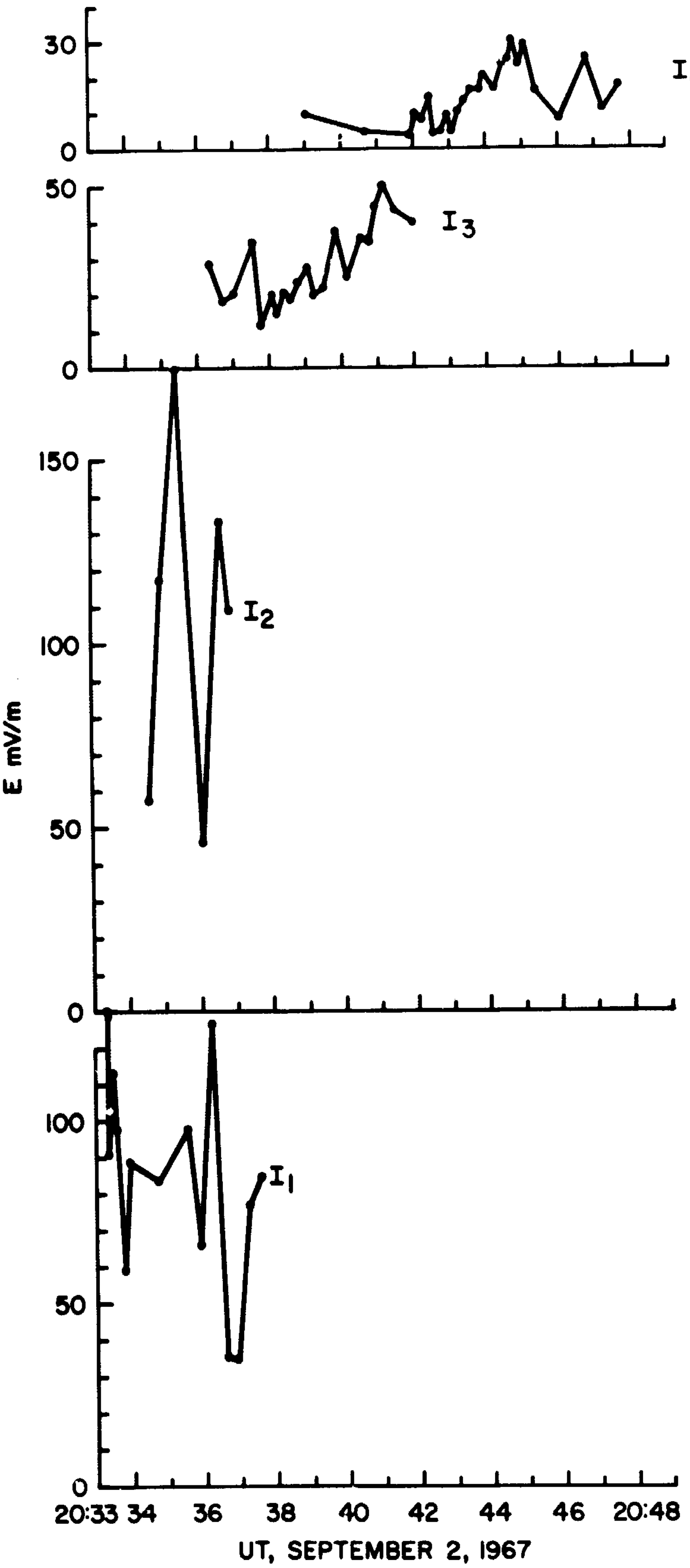
UT, SEPTEMBER 2, 1967
9h
12h
15h
18h
21h
0h
3h
6h
9h
KIRUNA (NORTH)
(EAST)
(VERTICAL)
Ba
I
ΔX=+200γ
ΔY=+100γ
ΔZ=+100γ
TROMSØ (HORIZONTAL)
(DECLINATION)
(VERTICAL)
ΔH=+200γ
ΔD=0°30'
ΔZ=+200γ
ANDØYA (MAGNETIC NORTH)
(VERTICAL)
Δ(MN)=-200γ
ΔZ=+200γ
40m
19h00m
20m
40m
20h00m
20m
40m
21h00m
20m
40m
22h00m
20m
UT, SEPTEMBER 2, 1967

FIGURE 6



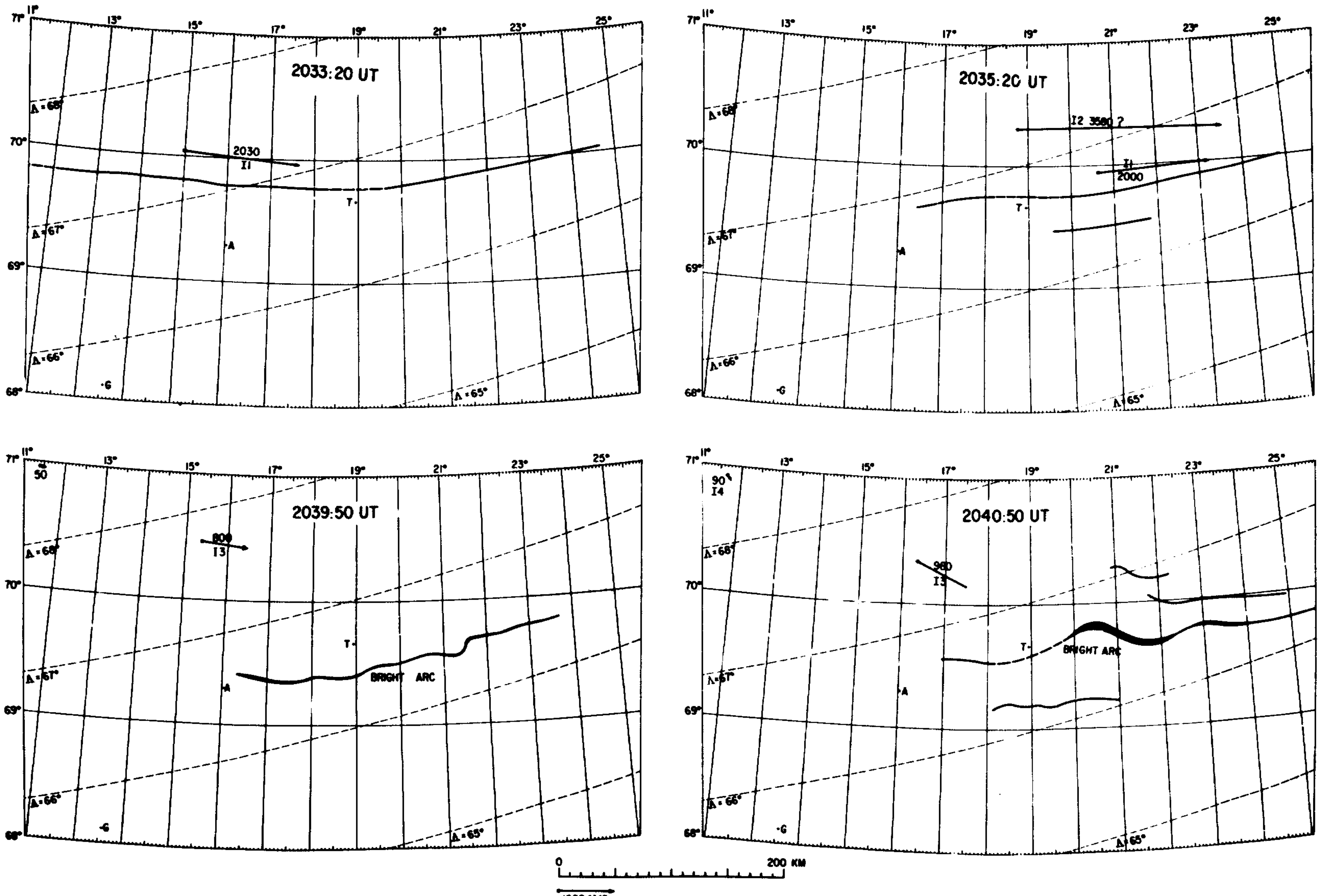
2 SEP 1967

FIGURE 7



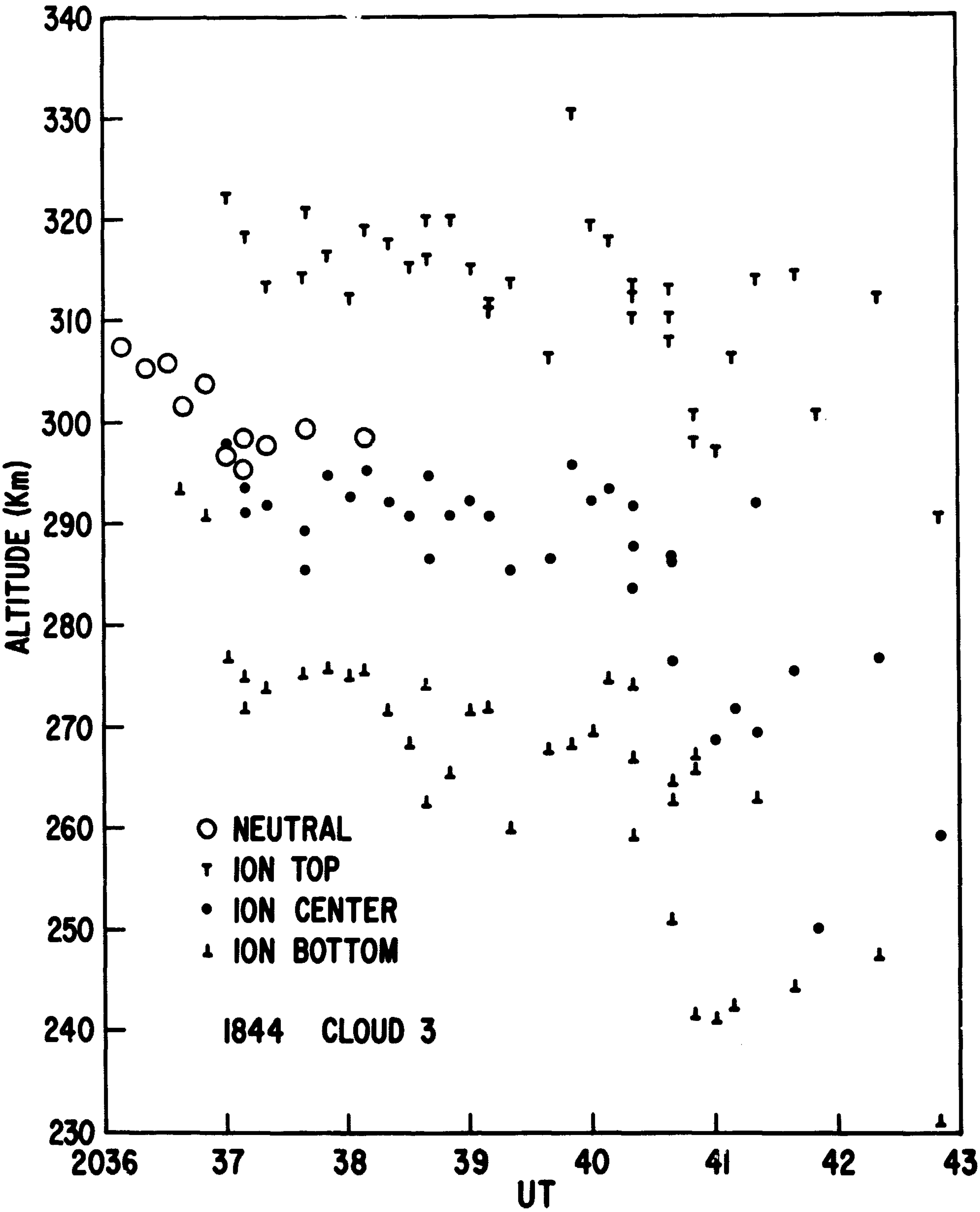
30
0
50
0
150
100
50
0
100
50
0
E mV/m
I_4
I_3
I_2
I_1
20:33 34 36 38 40 42 44 46 20:48
UT, SEPTEMBER 2, 1967

FIGURE 8



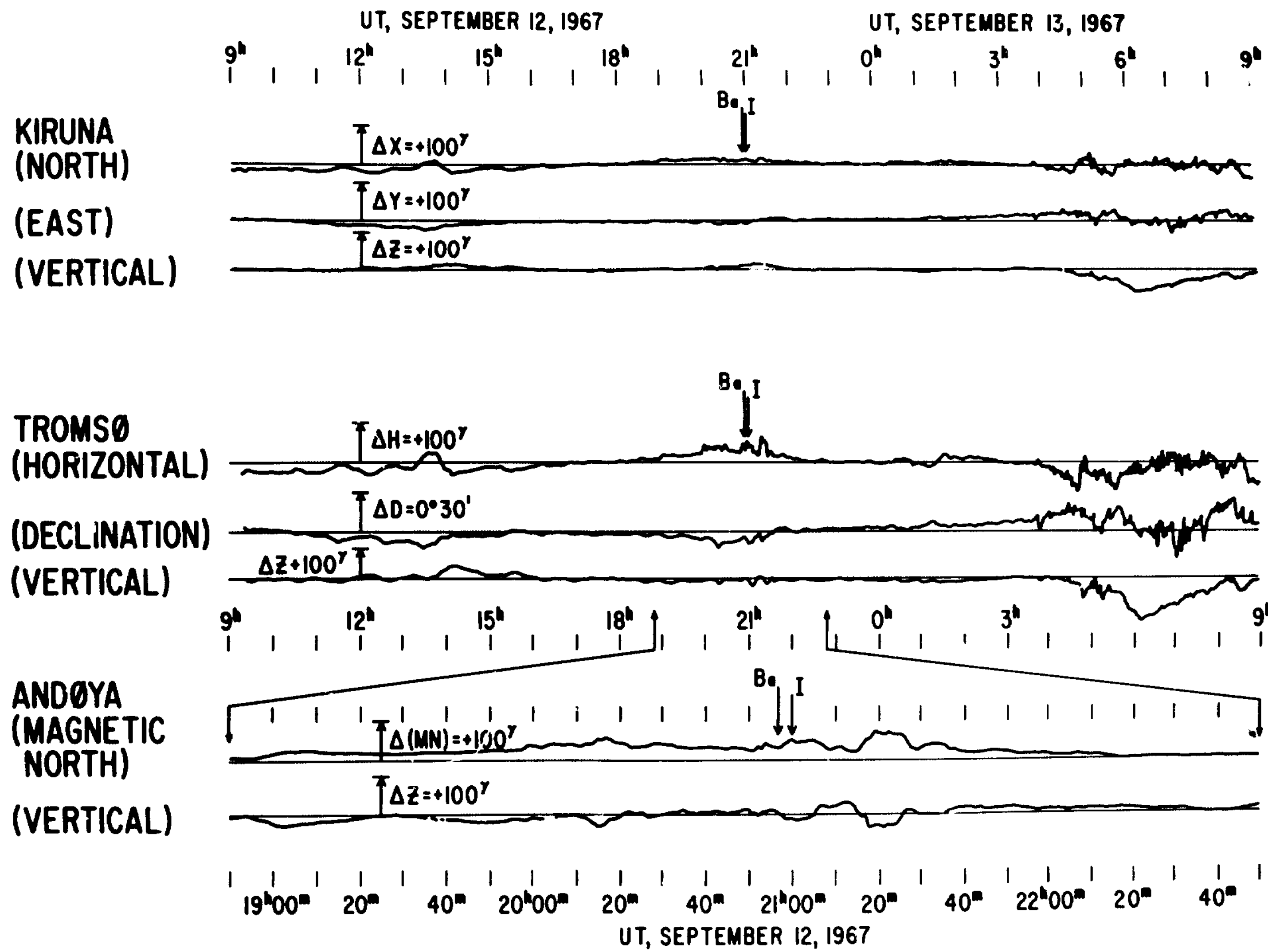
2 SEPT 67

FIGURE 9



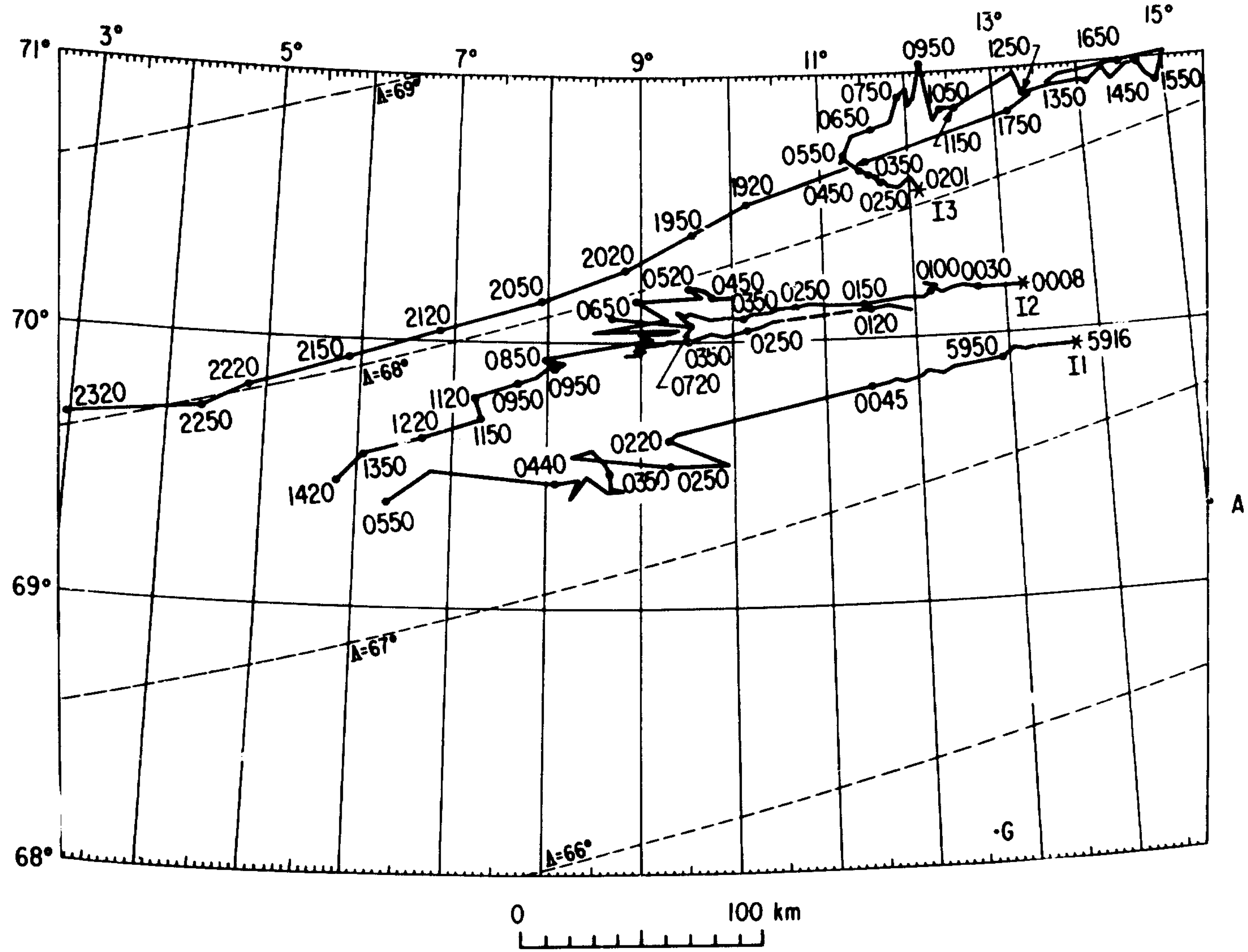
SEPT. 2, 1967

FIGURE 10



UT, SEPTEMBER 12, 1967
UT, SEPTEMBER 13, 1967
9h 12h 15h 18h 21h 0h 3h 6h 9h
Be I
KIRUNA (NORTH)
ΔX=+100γ
(EAST)
ΔY=+100γ
(VERTICAL)
ΔZ=+100γ
Be I
TROMSØ (HORIZONTAL)
ΔH=+100γ
(DECLINATION)
ΔD=0°30'
(VERTICAL)
ΔZ+100γ
9h 12h 15h 18h 21h 0h 3h 9h
Be I
ANDØYA (MAGNETIC NORTH)
Δ(MN)=+100γ
(VERTICAL)
ΔZ=+100γ
19h00m 20m 40m 20h00m 20m 40m 21h00m 20m 40m 22h00m 20m 40m
UT, SEPTEMBER 12, 1967

FIGURE 11



12 SEP 1967

FIGURE 12

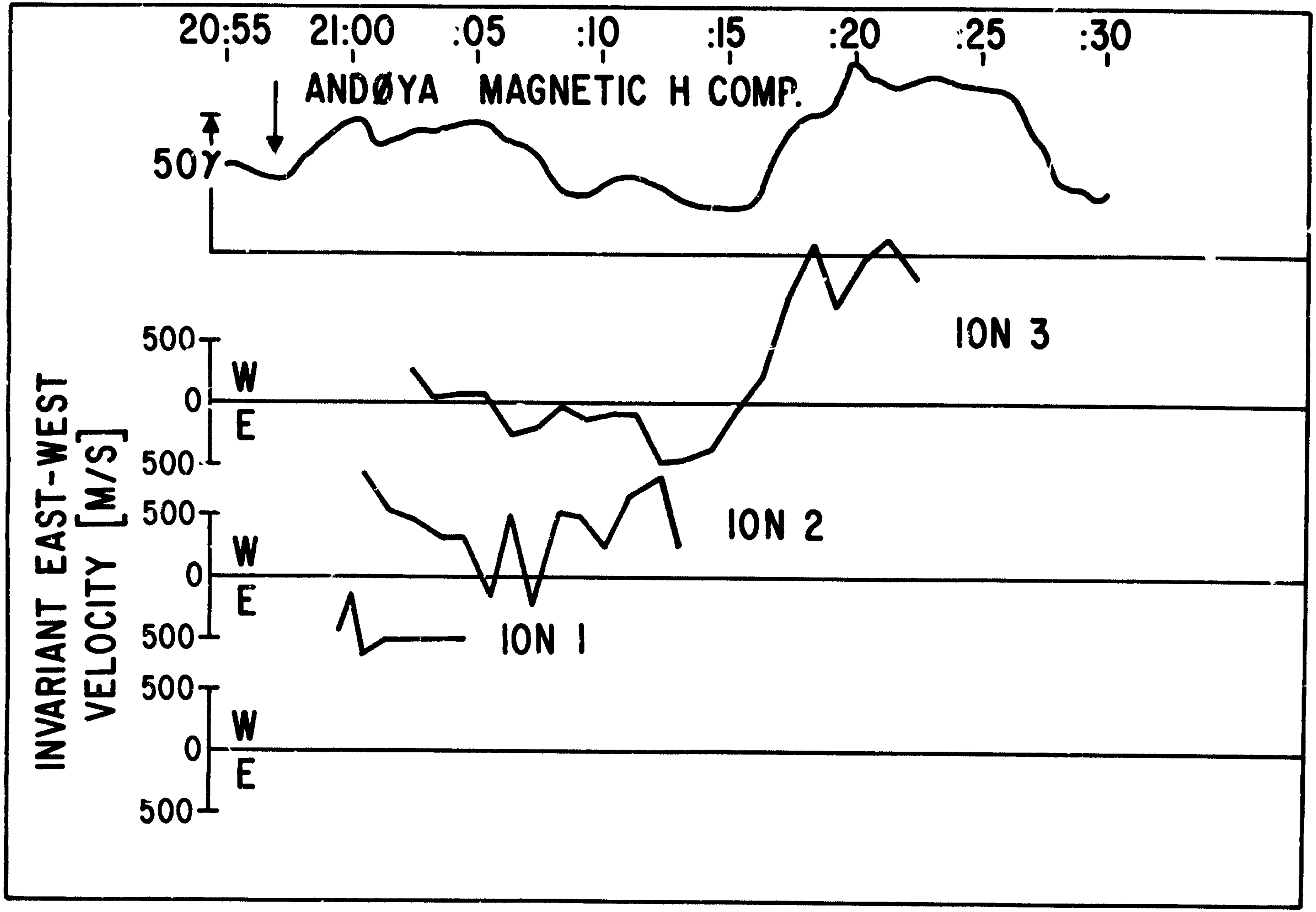

20:55
21:00
:05
:10
:15
:20
:25
:30
ANDØYA MAGNETIC H COMP.
50γ
INVARIANT EAST-WEST
VELOCITY [M/S]
500
W
0
E
500
ION 3
ION 2
ION 1

FIGURE 13