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IONOSPHERIC AND MAGNETIC OBSERVATIONS AT 1000 KILOMETERS DURING THE GEOMAGNETIC STORM AND AURORA OF MAY 25-26, 1967

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GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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February 1969

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Abstract

Measurements of electron temperature and density and of transverse magnetic disturbances obtained at 1000 kilometers before, during and after the magnetic storm and aurora of May 25-26, 1967 are compared with visual observations of the aurora and a degree of correlation is apparent. Throughout the latitudinal region of visual aurora the electron temperature and its latitudinal variations were much greater than are observed under quiet conditions. Temperatures in excess of 6500°K and temperature variations of greater than 500°K within less than 4 km along the satellite path were measured. Temperatures this high suggest a heat source other than auroral electron bombardment. The electron density was also extremely structured through the region of visual aurora. Horizontal gradients were observed in which the density changed by greater than 50% in less than 100 meters along the satellite path. The greatest density measured was $\sim 6.5 \times 10^4$/cc (at $\Lambda = 53°$). The magnetometer recorded a number of disturbances (as large as 306γ) in the region of unusual density and temperature behavior.

INTRODUCTION

During the period 25-26 May 1967 an unusually great auroral event occurred. Visual observations were reported* from across the U. S. Continent throughout the night of the 26th. One observation from as far south as Alabama, and several nearly overhead observations from Washington, D. C. were reported.

The magnetic storm which accompanied the aurora was the most intense observed to that time in the present solar cycle with the daily planetary figure Ap reaching a peak of 146 on the 26th. The storm commenced during the 4th three-hour period of May 25th, continued through the 26th and into the first three-hour period of the 27th. Table 1 lists the magnetic indices for this period indicating the extent of the storm. The boxes indicate the 3 hour periods in which the satellite data reported here were taken.

Observations of electron temperature (T_e) and density (N_e) were obtained at 1000 kilometers before, during and after the auroral event from the Explorer XXII cylindrical electrostatic probe experiment. In addition, measurements of variations in the transverse component of the Earth's magnetic field were taken with an on-board magnetometer.

All data reported here represent passes recorded at the Applied Physics Laboratory in Howard County, Md. The observations covered the region from about 51° N invariant latitude (Λ = 51°) to about 75° N invariant latitude (Λ = 75°) centered over the eastern U. S. Figure 1 indicates the path of the satellite for the various passes from which data were obtained. The solid lines represent

*Communication from IGY World Data Center A.

the north bound passes, the broken lines southbound passes. The locations of stations from which visual aurora reports were received for this period are indicated by circles.

THE EXPERIMENTS

The Explorer XXII satellite is in a near circular orbit at 1000 km. It is a magnetically stabilized satellite with the axis of symmetry maintained parallel to the geomagnetic field. The two cylindrical probes are located on opposite ends of the spacecraft; one always pointing north along the field line and the other south. The probe experiment is described in detail elsewhere (Spencer, et al., 1965) (Brace, Reddy, 1965) (Brace, et al., 1967) thus only a brief outline is given here, emphasizing the aspects having the greatest bearing on this study.

In operation, a sawtooth voltage of -3 volts to +5 volts is applied to first one probe then the other, alternating each 2.6 seconds. The sawtooth is repeated at two sweeps per second. The resultant currents, or volt-ampere characteristics are linearly converted to telemetry signals to be transmitted to the ground. The current detector has two ranges, which are alternated each 5.5 seconds. In flight calibration checks are provided by substituting a known resistance for the collector for the first two sweeps of each range period. This sequence is demonstrated in Figure 2. The data are reduced as described by Brace and Reddy (1965); the electron temperature being derived from the slope of the exponential region corresponding to negative applied voltages and the electron density from the amplitude of the curve in the region os accelerating applied voltage. Note that telemetry saturation limits the amplitude of the more sensitive range. As indicated in Figure 2 the retarding potential region is best resolved on the more sensitive detector (.05μA full scale), while the accelerating voltage region can often only be seen on the less sensitive range (0.3μA full scale). The temperature range of the experiment is approximately 400°K to greater than 10,000°K. The absolute accuracy is believed to be better than 10% and the relative accuracy about ± 100°K. Densities are believed accurate to about 5% relative and 20% absolute. Normally the data-link is time-shared so that the probe data are sampled only 22 seconds every three minutes; however, for this study the satellite was operated in a mode which provided continuous probe data.

The transverse magnetic field variations were obtained from a Schonstedt Fluxgate Magnetometer. The fluxgate is mounted with its axis normal to that of the spacecraft stabilizing bar magnet, so that it measures the transverse component of the geomagnetic variation. The resolution and use of the instrument is similar to that on satellite 1968-38c (Zmuda et al., 1966).

THE NIGHTTIME DATA

Electron Temperature and Density

Figure 3 is a smoothed plot of the reduced data N_e, and T_e, from four nighttime passes and a quiet average profile, q, for this period. Pass 25 was taken between 0141:40 UT and 0150:05 UT, 25 May 1967; pass 26 between 0209:15 UT and 0217:10 UT on the 26th and passes 27a and 27b were taken between 0048:00 UT and 0100:15 UT and between 0236:20 UT and 0241:05 UT respectively on the 27th of May. The smoothing consisted of taking the average values of N_e and T_e

from each group of curves in a range sequence (of 5.5 seconds), plotting these average values and connecting them with a smooth line. Note that all data in figure 3 represent northbound passes at a local time of about 2000 hrs.

The curves labeled 25 represent the electron density and temperature of the quiet pre-storm ionosphere, when K_p was 2-. There is general agreement with the quiet average, q, in both N_e and T_e at $\Lambda < 64°$. Between $\Lambda = 64°$ and $\Lambda = 73°$ we see a profile which, though structured, is normal for this latitude region. The individual passes used for the quiet average also exhibited variations through this region but these were removed in averaging. At $\Lambda > 73°$ both N_e and T_e are in agreement with the quiet average.

The data labeled 26 correspond to the peak of the storm when the aurora was observed overhead near Washington, D. C. Both N_e and T_e were extremely structured below $\Lambda = 65°$. Unusually high temperatures (including the highest ever measured by this experiment at any latitude) were measured in the region $52° < \Lambda < 57°$ and $64° < \Lambda < 65°$. Higher than normal densities were seen from turn-on up to $\Lambda = 60°$, and below normal densities at $\Lambda > 61°$. Both N_e and T_e appear unstructured at $\Lambda > 66°$.

27a and 27b are consecutive passes one day later. In these passes at $\Lambda < 62°$, T_e remains significantly above the quiet background whereas N_e has essentially returned to normal. Conversely, at higher latitudes T_e is approximately at the background level while N_e is depressed.

Correlation with Visual Aurora

The night time pass of the 26th, during the aurora, is shown separately in figure 4 together with a summary of visual auroral observations. This summary is based upon the hourly reports of visual observations before and after the pass centered at 0212 UT. The bars represent regions of observed aurora. The triangles indicate that there were clear skies but no aurora at that time. These observations were made from stations in the region 70° West to 92° West. None were directly under the path of the satellite. In spite of this one might expect some correlation between visual observations and ionospheric effects along the same L shells, and the data seem to bear this out. All 0300 visual observations fall in the region of greatest structure in the ionospheric data ($52° < \Lambda < 66°$); conversely, reports of clear skies and no aurora were received only from stations outside this region. In the region $\Lambda > 58°$ there are disturbances even though clear skies and no aurora were reported at 0200; however, there were observations of aurora reported at 0225 and 0230 from Ottawa ($\Lambda = 58.5$). These were seen as rays and rayed arcs to the west, the direction of the satellite pass. This suggests that even though the skies were clear and no aurora was present at 0200 in this region, by the time of the satellite pass (0210-0217) there may very well have been aurora.

The high degree of correlation between the observations of visual aurora at about 100 km altitude and the unusually high electron temperatures and structure measured nearly 1000 km above, but on the same field lines, is strong evidence that they are part of the same phenomenon.

Although not shown, we would like to point out that visual observation reports for the 25th and 27th indicate clear skies but no aurora throughout the same regions.

Correlation with Magnetometer Data

Figure 4 also includes observations of significant transverse magnetic disturbances measured simultaneously by the onboard magnetometer. The amplitudes noted are disturbance peak amplitudes; that is with the effects of satellite orientation removed. The horizontal extent of each disturbance is indicated by the length of the bar. The bar also denotes polarity relative to the undisturbed field; the bars above the line represent one polarity and those below the line represent the opposite; however, absolute polarity could not be determined. Comparison between transverse magnetic disturbances and probe data shows excellent correlation between structure in T_e and magnetic disturbance. There seems to be less direct correlation with N_e. Correlation between magnetometer data and visual observations is also excellent if one uses both the 0200 UT and 0300 UT reports.

THE DAYTIME DATA

Electron Temperature and Density

Figure 5 is a plot of daytime data smoothed in the same manner as that in Figure 3. These are the southbound passes and are about 11 hours in local time from the northbound nighttime passes. The curves labeled 26 represent the electron density and temperature at about 1133 UT May 26, on a pass just east of the U. S. The curves labeled 27 correspond to a pass at about 1150 UT on the 27th and nearly overhead.

The most apparent feature of the temperature data for pass 26 is that it is much less structured than the corresponding nighttime pass. The temperature is significantly above normal throughout the pass, and there is a region of large variations in T_e centered at $\Lambda = 64°$ with peak values of about 5200°K.

The density, though more structured than normal, is much less structured than that through the corresponding nighttime pass. There is an inverse relation between N_e and T_e throughout this pass. This is in contrast to the nighttime auroral pass where N_e and T_e vary directly below $\Lambda = 60°$.

As in the nighttime data from the 27th, the post storm daytime data (pass 27) show that both N_e and T_e have essentially returned to normal.

Correlation with Visual Auroral Observations

There was no possibility of simultaneous observation of aurora for pass 26 (1150 UT) because of daylight. However, visual observations reported at 0900 UT and 1000 UT from stations in the Western U. S. are plotted in Figure 5. This provided for some comparison along L shells although its significance is questionable because of the difference in time and because the observations of aurora were in the longitude range 83°W to 117°W and the satellite pass was at about 65°W.

Correlation with Magnetometer Data

The magnetometer data showing transverse magnetic disturbances for the pass of the 26th are also plotted in Figure 5. As in the case of the nighttime pass there is excellent correlation between the position of magnetic disturbance data and the position of greatest structure in T_e and N_e.

IONOSPHERIC STRUCTURE SCALE

To better demonstrate the scale of the structure seen in the storm-time data, a section of raw data is shown in Figure 6. The top strip represents typical non-structured data, while the lower strip represents an extreme case of structure. These variations in collected current are thought to represent density variations along the satellite path (Dyson, 1969). The horizontal scale is time; each data curve is about a half second long. As the satellite velocity is constant, the horizontal scale also represents distance along the satellite path. A scale representing one kilometer is included for reference. Based upon this scale the particular disturbance shown in Figure 6 appears as a depression in N_e (dashed line) of about 10-15 km width with fine-structure greater than 50% over a distance less than 100 meters. The deepest point in the depression is to less than 10% of the density just adjacent to the depression.

Figure 7 is a photo of a section of raw data demonstrating the scale of temperature variations. This curve was taken from the nighttime pass of the 26th in the region of highest and most variable temperature. The details of determining temperature from the data are found elsewhere; (Spencer, et al., 1965; Brace, Reddy, 1965) it is sufficient to note here that temperature is inversely proportional to the slope of the log of the exponential portion of the curve. Two adjacent portions of this curve indicate a temperature change of about 500° over a distance of less than 75 meters. This example demonstrates the degree of isolation between adjacent field tubes at this altitude.

DISCUSSION

Transverse magnetic disturbances at 1100 km in the auroral oval have been treated by Zmuda et al. (1966, 1967) and related to field-aligned currents by Cummings and Dessler (1966). Currents of this type were proposed by Birkeland (1913) and by Alfvén (1939) and have applicability to the auroral-current models discussed by Bostrom (1964, 1967) and Schield et al. (1968), which also include current flow across the auroral field lines in the lower ionosphere. Schield et al, developing a model of Alfvén, (1939) proposed a mechanism for generating the current which contains charge separation in the Alfvén layer, forming the inner boundary to which energetic plasma drifts from the tail. The expected width of the Alfvén layer is in good agreement with that computed from the width of the magnetic disturbance region at 1100 km. (Schield, 1968).

The scale of the structure seen in the electron temperature and density is similar to the scale of magnetic disturbances. This suggests that heating from currents related to these disturbances may be significant.

On the basis of a recent theoretical study, Walker and Rees (1968) have concluded that the high temperatures reported here for 1000 km would not result from auroral electron bombardment. With the energy spectrum considered by Walker and Rees (1968) virtually all the energy of the incident flux is deposited at much lower altitudes and heating at 1000 km results only from conduction upward. On this basis an additional source of heating at 1000 km would be required to explain the observation presented here. One possibility is that the incident spectrum includes a significant number of lower energy electrons which could cause local heating at 1000 km.

Another possible source of heating at this altitude is heat conduction from the magnetosphere (Cole 1965). Walker and Rees (1968b) have concluded that this mechanism would produce temperatures as high as those reported here in the region of stable auroral red arcs. While no red arc was reported during the night of the 25th-26th of May, it is possible that one was present but that conditions were not suitable for observation at the stations equipped to observe red arc. It should be noted however, that the latitudinal region over which the high temperatures were measured is considerably greater than the width of red arcs described by Roach and Roach (1963) and Cole (1965).

CONCLUSION

The degree of correlation between the ground based and satellite data presented above demonstrate a strong relation between the transverse magnetic disturbances and variations in the electron density and temperature at 1000 km, and the visual aurora. Observed electron temperatures are higher than predicted on the basis of auroral electron bombardment alone. It is possible that the observations relate to a combination of aurora and stable red arc; however, we believe that for the most part they relate to the aurora. If this is the case, then it is likely that there is a significant very low energy component (order of 10 ev) in the auroral flux.

ACKNOWLEDGMENT

We are grateful to George Carignan and Tuck Bin Lee of the University of Michigan for their efforts in the design and implementation of the instrumentation, to the members of the APL tracking station crew for their special efforts in obtaining these special passes, and to James C. G. Walker for his helpful discussions. We also thank World Data Center A for the use of visual auroral data.

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GEOMAGNETIC ACTIVITY INDICES

DATE (MAY)		Kp THREE HOUR RANGE INDICES								Ap
24		2−	1+	2−	2−	2+	3+	4+	2+	11
25	D	[2−]	2	1	5+	8+	7+	8−	9	130
26	D	[9]	9−	7+	[7−]	7−	4−	4	5−	146
27		[4]	3+	3+	[2+]	3	2−	4+	4+	20
28	D	3−	3−	4+	6−	6−	7−	6	5+	55

Table 1–Geomagnetic Activity Indices Kp and Planetary Amplitude Figures Ap for the Period 24–28 May 1967. Boxes Indicate Three Hour Periods in Which Satellite Data Were Obtained.

List of Figures

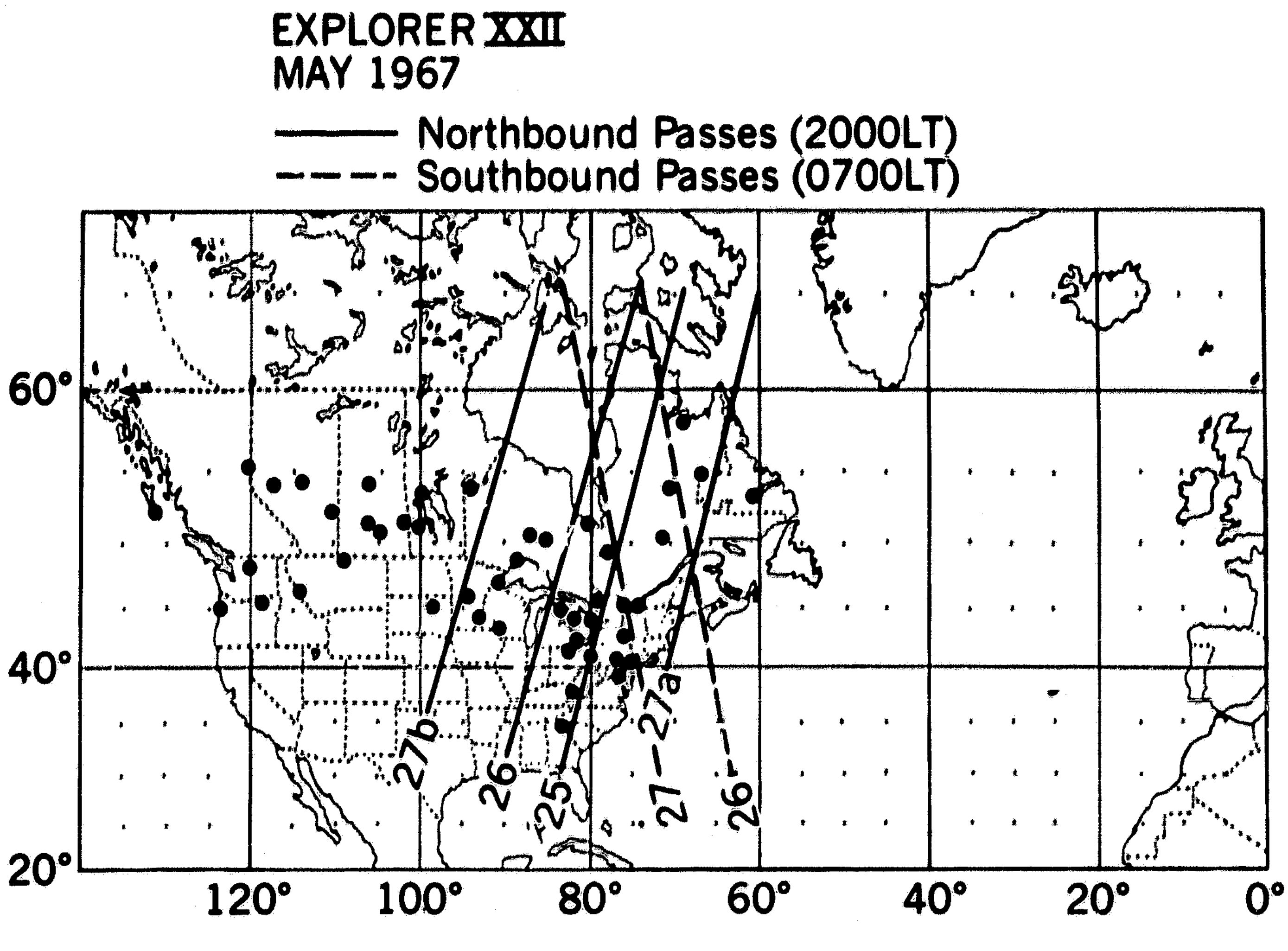

Figure 1. Sub-satellite paths of Explorer XXII passes discussed. Numbers indicate date of pass. Passes labeled 26 correspond to most disturbed conditions. Large dots indicate locations of stations from which reports of visual observations were used.

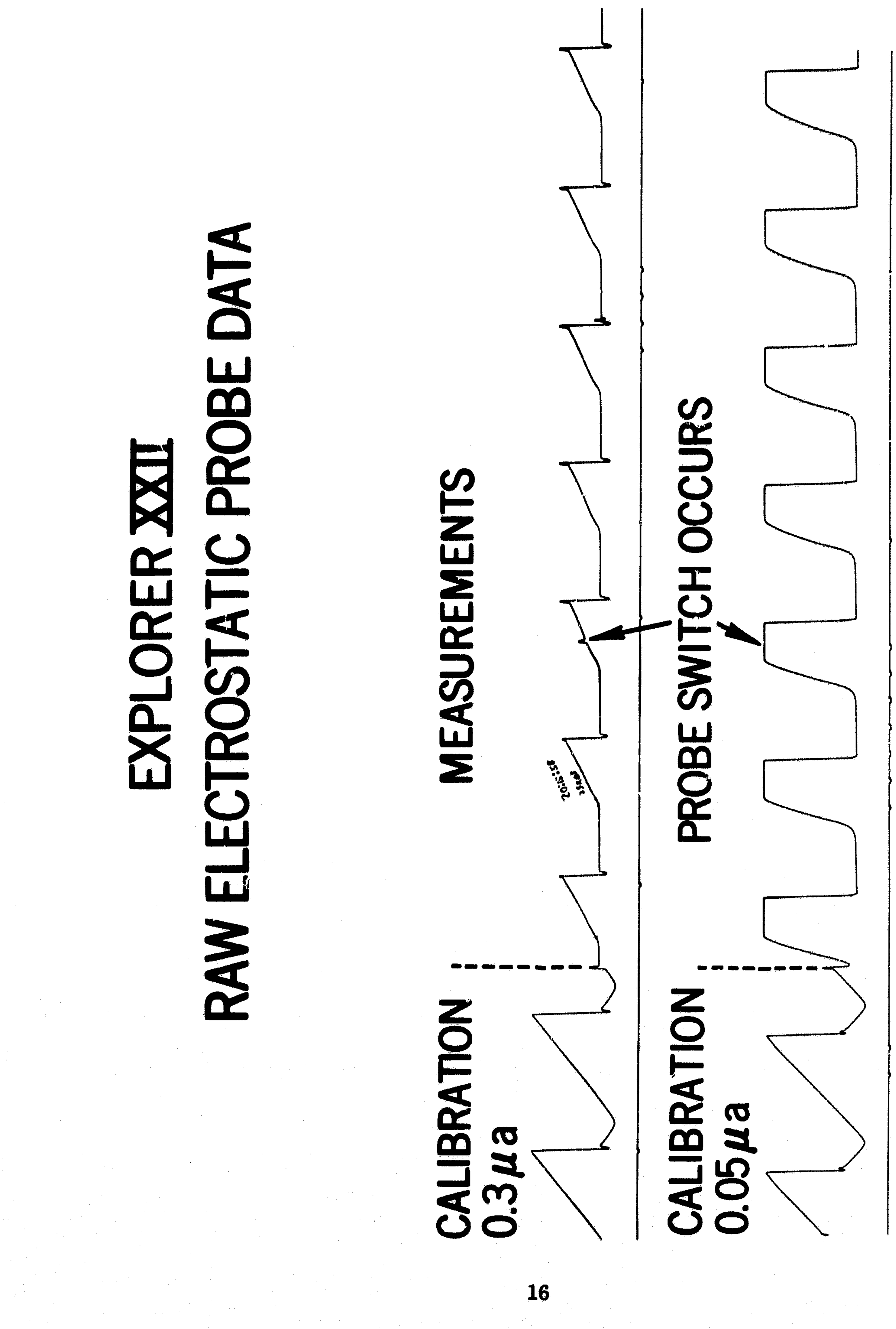

Figure 2. Cylindrical probe data indicating data sequence and calibrations.

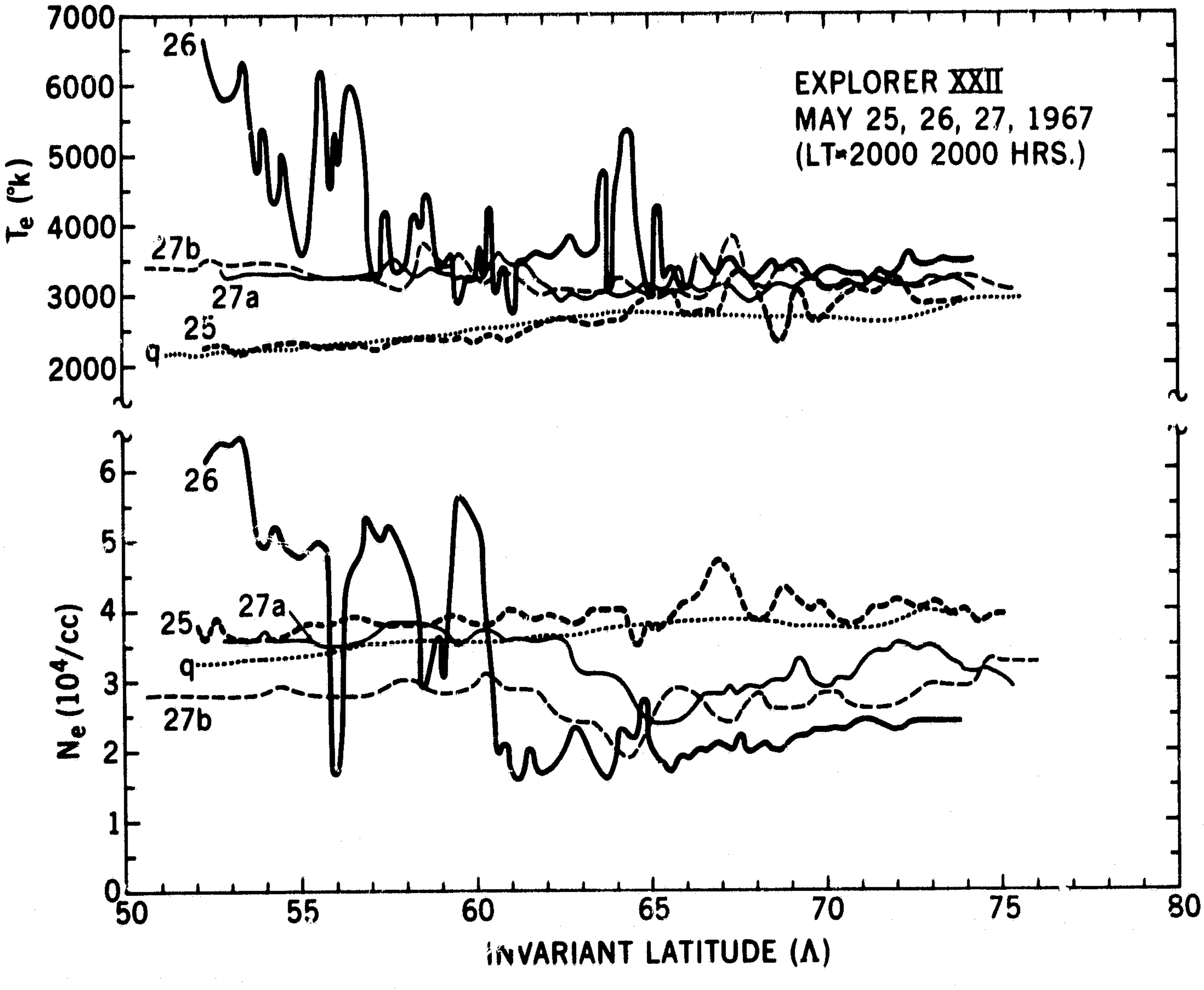

Figure 3. Variations in nighttime electron temperature and density through the period May 25-27, 1967.

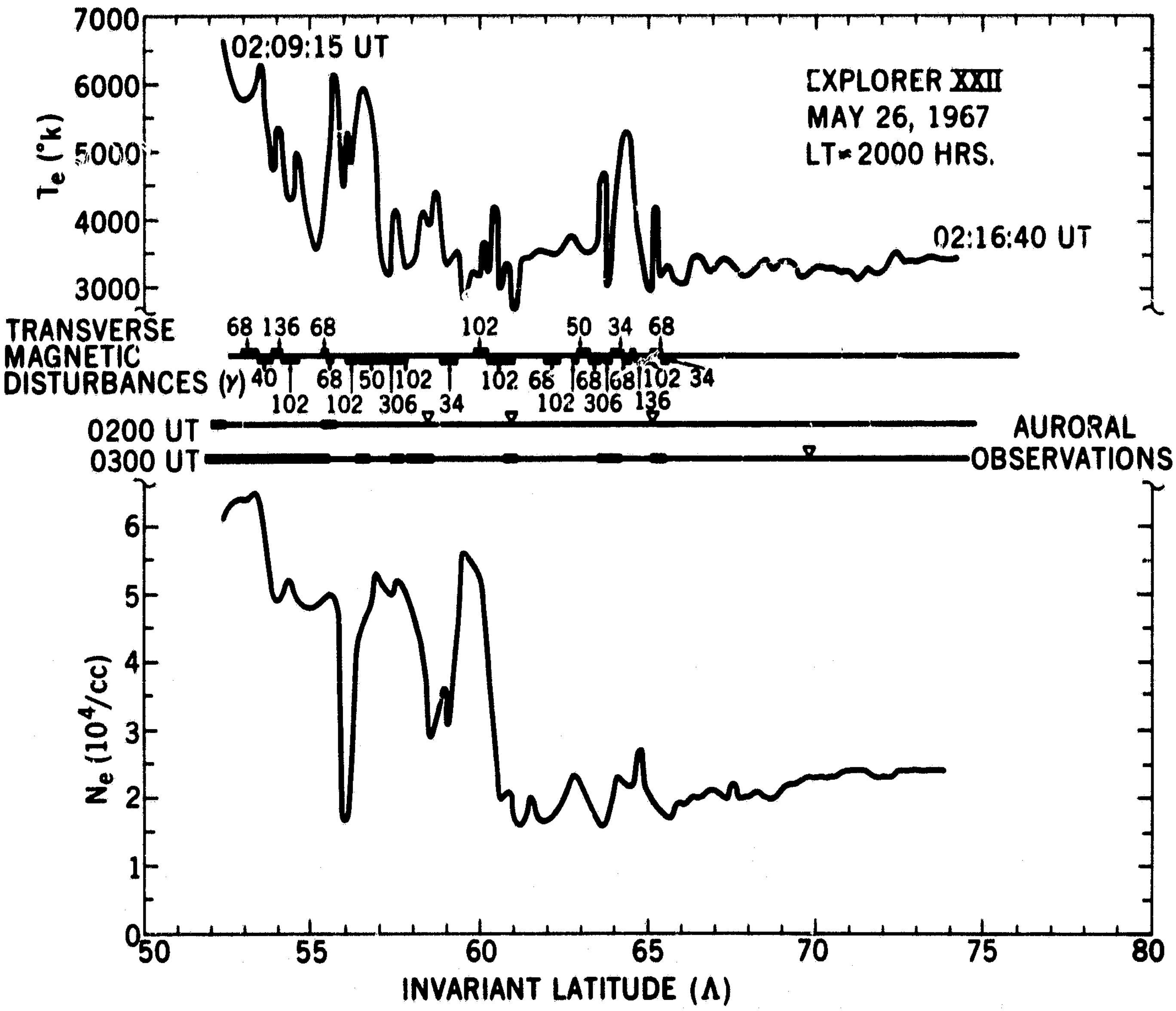

Figure 4. Cylindrical probe and magnetometer data and latitudinal location of auroral observations [illegible] the time period of pass 26. Triangles indicate observations of clear skies and no aurora.

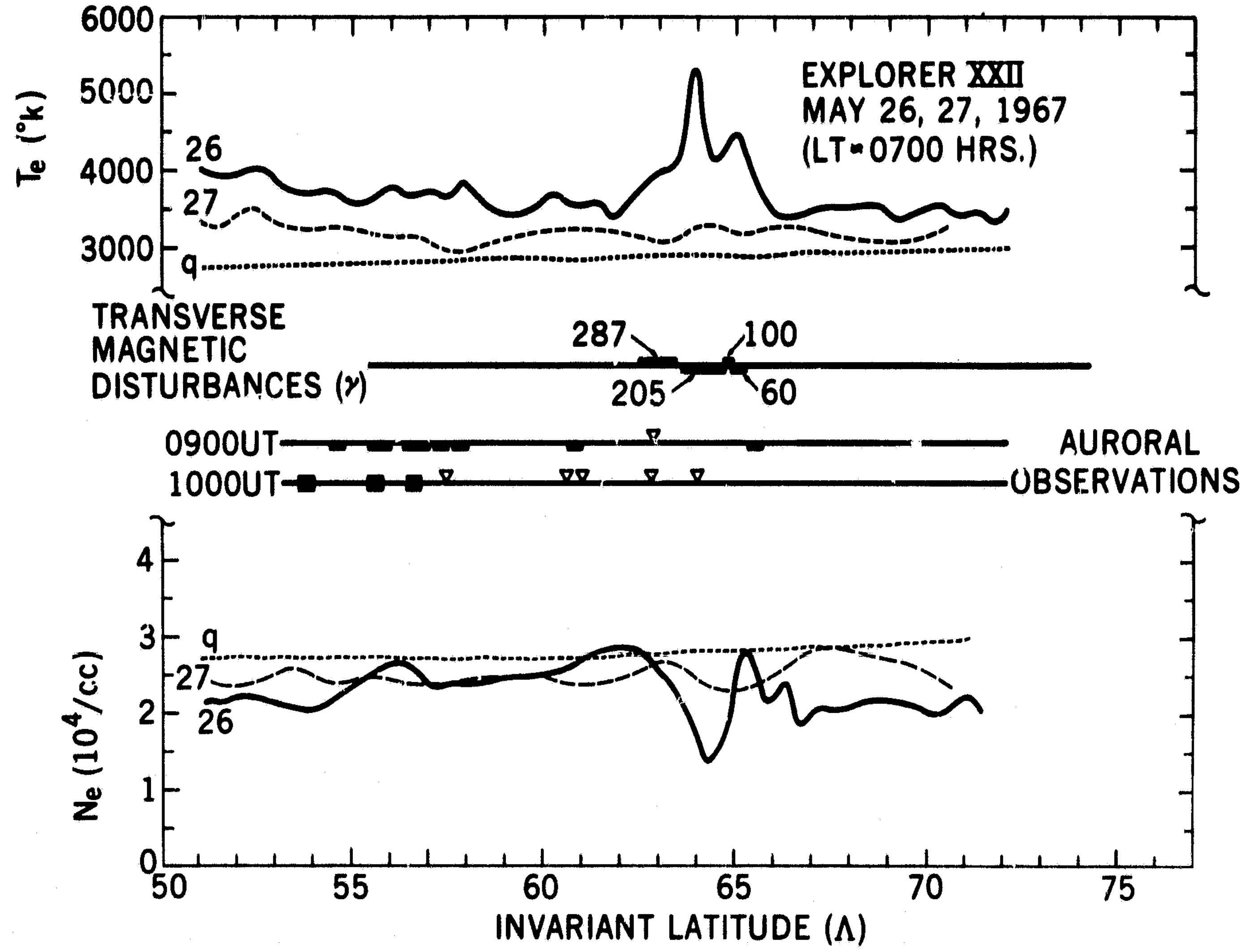

Figure 5. Variation in daytime electron temperature and density through storm period along with transverse magnetic disturbances measured on the pass of the 26th. Included are latitudinal locations of auroral observations most nearly corresponding to pass labeled 26.

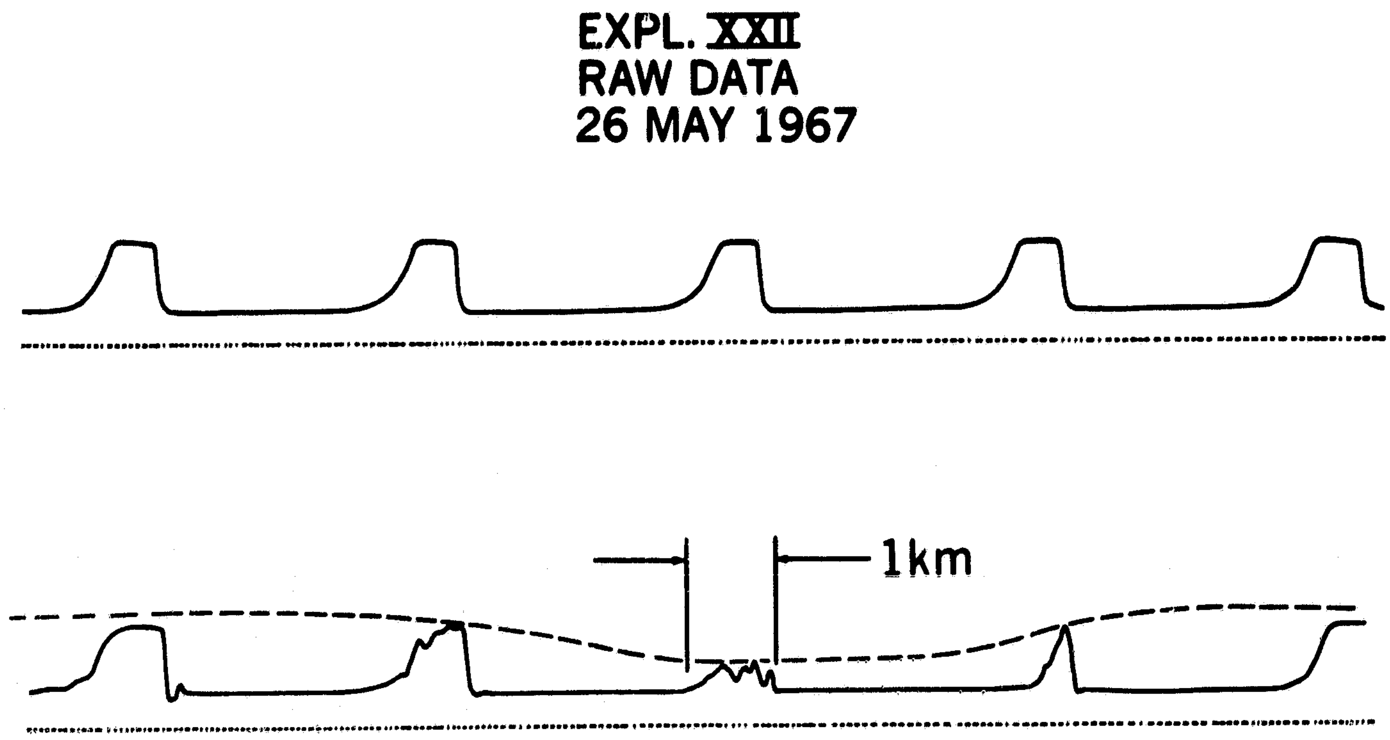

Figure 6. Raw data indicating scale of structure in density during storm.

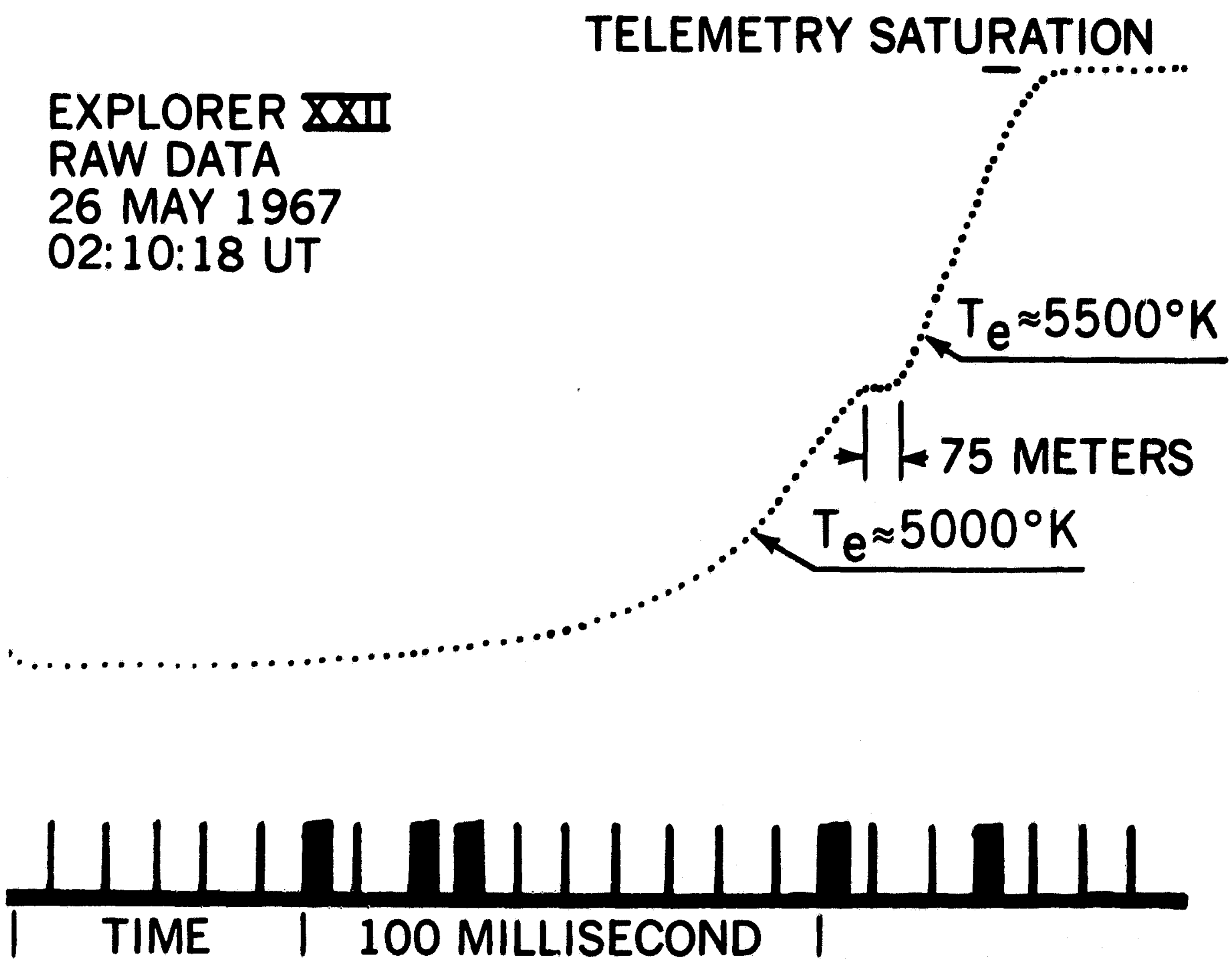

Figure 7. Volt-ampere curve showing case of abrupt increase in electron temperature of about 500 degrees in less than 75 meters indicated by sudden decrease in slope of collected current vs applied voltage.