Direction Finding Measurements of Auroral Kilometric Radiation

by

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MASTER'S THESIS

This is to certify that the Master's thesis of

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ABSTRACT

Plasma wave experiments using the rotating dipole antennas of the IMP-8 and HAWKEYE-1 satellites are used to obtain direction finding measurements of auroral kilometric radiation. This radiation is characterized by sporadic storms of very intense radiation lasting from tens of minutes to several hours with the frequency of peak intensity normally lying between 100 kHz and 300 kHz. The noise, which has been associated with bright auroral arcs, causes the earth to appear as a very bright radio source from positions outside the plasmasphere.

HAWKEYE-1 is in a highly elliptical polar orbit with an apogee radial distance of about 21 R_e over the northern polar region and IMP-8 is in a slightly eccentric orbit closer to the equatorial plane with perigee and apogee radial distances of 23 and 46 R_e respectively. When the source of auroral kilometric radiation lies near the plane in which the electric antennas rotate, the detected signal is strongly spin modulated so that accurate information on the position of the source region can be obtained. A source near the earth often lies near the planes of antenna rotation of both satellites so that two independent determinations of the source location can be made. The results of both determinations agree fairly well and place the source region about 0.9 R_e from the polar axis of the earth at a local time of

about 20 hours as projected into the equatorial plane. These results support earlier results in that the source must be in the region of the earth's evening auroral zones. The generation mechanism, although still unknown, must then be related to auroral electron precipitation events which are also closely related to bright auroral arcs.

I. INTRODUCTION

Direction finding measurements of auroral kilometric radiation are made in order to more directly relate this intense radiation to electron precipitation events in the earth's evening auroral zones. The auroral kilometric radiation is characterized by very intense, sporadic events of noise sharply peaked between 100 kHz and 300 kHz lasting from tens of minutes to several hours. The power flux at a distance of 30 R_e from the earth can range from 10^{-19} to 10^{-14} watts m^{-2} Hz^{-1}. The term sporadic is used here to mean that changes in power flux of greater than 20 db in a few minutes or less are often seen. At peak intensities, the total integrated power has been estimated at 10^9 watts [Gurnett, 1974].

Figure 1 is an example of what is termed auroral kilometric radiation. The figure is a display of the data from four electric channels of the HAWKEYE-1 plasma wave experiment with center frequencies of 42.2, 56.2, 100, and 178 kHz. The height of the vertical bars is roughly proportional to the logarithm of the electric field intensity where the distance between two ordinate tic marks represents approximately 20 db. The sporadic time structure is modulated by the rotating dipole antenna pattern which is the key to the direction finding method to be described in detail later. This radiation is not to be confused with other kilometer wavelength, near-earth spectral features such as the low level, non-thermal continuum as discussed by Brown [1973], Frankel [1973], and Gurnett [1975].

The first probable detection of auroral kilometric radiation was by Benediktov et al. [1965, 1968] using satellite measurements of radio emissions at 0.725 MHz and 1.525 MHz. Dunckel et al. [1970] also studied this radiation and refers to it as "high pass" noise. Dunckel et al. [1970] found a correlation between the detection of the noise and local time (LT) position of OGO-1 with which the emission was observed. The high pass noise was detected during local night time more often than during local day time. The radiation was observed by Brown [1973] using the IMP-6 GSFC radio astronomy experiment and was termed "midfrequency" radiation occurring at 150 kHz and 300 kHz. Stone [1973] commented that a sporadic component at 250 kHz appears to be coming from the tail region of the magnetosphere and that this radiation may be caused by particle precipitation into the auroral region, although no supporting data were presented.

Gurnett [1974] presented data from the IMP-6 plasma wave experiment which demonstrated the electromagnetic character of auroral kilometric radiation and showed a typical spectrum which consisted of a feature with a lower frequency limit of 20 kHz, peak at 150 kHz, and an upper frequency limit near 1 MHz. Also presented were frequency of occurrence studies showing conical radiation patterns centered on the earth and symmetric with the auroral ovals, in other words, tilted back toward the local night time. Correlation studies between bright auroral arcs and the occurrence of intense kilometric radiation using photographs from the DAPP satellite were also presented. Figure 2 is an example of the type of data used by Gurnett [1974] to support this correlation. In the top panel, data from the 178 kHz channel of the plasma wave experiment on board IMP-6 is displayed for a one day period in early January, 1973. The vertical bars indicate the average power flux for a five minute period while the dot represents the peak power flux during that same period. DAPP photographs from orbits 831 and 833 are shown below while the time each photograph was taken is marked by arrows above the IMP-6 data. Notice that the photograph from orbit 831 was taken during an intense auroral kilometric radiation event as detected by IMP-6 and shows an extensive display of bright auroral arcs. The north magnetic pole is near the top and center of these pictures. The photograph from orbit 833 was taken when the 178 kHz channel on IMP-6 was quiet. Notice that there is almost no auroral activity as seen in the photograph. More examples of this correlation can be found in Gurnett [1974]. This type of correlation strongly implies the radiation is generated by the same precipitating electrons which produce the bright auroral arcs. The conclusion of Gurnett [1974] is that the evidence presented is compatible with a source region located on an auroral field line about 1.0 to 1.5 R_e above the earth in the local evening.

The present paper is concerned with making direct measurements of the position of the source region of auroral kilometric radiation. The goal behind locating the source region of auroral kilometric radiation falls into a much larger scheme of relating the radiation to "inverted V" electron precipitation events [Frank and Ackerson, 1971]. From the total estimated power emitted by an intense auroral kilometric radiation event given by Gurnett [1974] as about 10^9 watts and a calculation by Akasofu [1968] of the maximum power dissipated by charged particles in the auroral zone during a substorm of about 10^{11} watts it is clear that if these two phenomena are related, a very efficient mechanism must generate the kilometric radiation. Gurnett [1974] pursues this argument in greater detail and concludes that this mechanism is indeed important to understand since it may have broad application to other events such as Jupiter emissions at decametric wavelengths. In fact, Brown [1974] has detected a feature in the Jovian decametric spectrum at about 900 kHz which could possibly be analogous to terrestrial kilometric radiation from the auroral zones. Brown [1975] has also detected radio emission from Saturn at 1.1 MHz with a secondary peak at 400 kHz which may also have characteristics and origin similar to that of the auroral kilometric radiation.

The firm establishment of a source position for auroral kilometric radiation is, therefore, an important step in understanding the mechanism of the emission. Although the previous work cited is consistent with an evening auroral zone location, there is some evidence to the contrary and the literature produces some questions on the true source location of this spectral component at 200 kHz. Initial comments on the source position by Stone [1973] are apparently in accord with Gurnett's [1974] implication that the source is located near the evening auroral region but using measurements from the IMP-6 and RAE-2 satellites, Stone et al. [1974] identified a spatially compact source on the dayside of the earth which was described to have the sporadic time structure and other features which are descriptive of auroral kilometric radiation. A dayside location of the average source region is, of course, not in agreement with Gurnett [1974]. It is the purpose of this paper to resolve this discrepancy.

II. DIRECTION FINDING MEASUREMENTS WITH HAWKEYE-1

A. Description of the Instrument

The HAWKEYE-1 satellite was launched on June 3, 1974, into a highly eccentric earth orbit with initial perigee and apogee radial distances of 6,847 km and 130,856 km, respectively. The orbit is inclined 89.79° to the equator and the period was initially 49.94 hours. The initial argument of perigee is 274.6° so that apogee is almost directly over the north pole. The orbit is depicted in Figure 3 which also shows the attitude of the spacecraft with respect to the orbit plane and the earth. The satellite is spin stabilized with a spin period of about 11.00 seconds and is oriented such that the spin axis lies in the plane of the orbit and nearly parallel to the equatorial plane. The plane perpendicular to the spin axis containing the electric dipole antennas (which are parallel to the spacecraft y axis) will often be referred to in this paper as the spin plane. Figure 3 demonstrates that the earth is close to the spin plane throughout a large part of the orbit, i.e., when the satellite is at large radial distances.

The plasma wave experiment on board HAWKEYE-1 consists of a very-low-frequency (VLF) receiver which is connected to an electric dipole antenna. The electric dipole antenna is extended perpendicular to the spin axis to a tip-to-tip length of 42.45 m. The intensity of the signal from the electric antenna is measured periodically through each of 16 narrow band frequency channels with center frequencies ranging from 1.78 Hz to 178 kHz. The lower eight frequencies are sampled once per 23.04 seconds while the upper eight channels are sampled once every 11.52 seconds. The effective noise bandwidths of the eight lower frequency filters are about ±15% of the center frequency and the bandwidths of the eight upper frequency filters are approximately ±2.5% of the center frequency. There is also a magnetic search coil on HAWKEYE-1 oriented with its sensitive axis parallel to the spacecraft spin axis which provides a signal proportional to the magnetic field intensity to the lower eight filters (1.78 Hz to 5.62 kHz) so that alternate measurements of magnetic and electric field intensities are made by the lower eight filters.

In addition to the outputs from the spectrum analyzer described above, the experiment has a wideband analog output with selectable bandwidths of 10 kHz or 45 kHz. Either the electric or magnetic antenna can be switched to the wideband receiver. The output of the wideband portion of the experiment can be used to make high resolution, frequency-time spectrograms. The wideband receiver is automatic-gain-controlled (AGC) to provide good intensity resolution over a given spectrum yet large dynamic range.

This paper is primarily concerned with the output of the higher frequency discrete filters, especially the 178 kHz channel since the peak in the auroral kilometric radiation spectrum usually lies between 100 kHz and 300 kHz. The output of the discrete filters goes into a log compressor which compresses approximately 100 db of dynamic range into an output from 0 to 5 volts. This voltage is approximately proportional to the logarithm of the field intensity with a change of output voltage of 1 volt representing a change of about 20 db in field intensity.

B. Method of Analysis

The rotating dipole antenna pattern provides a simple method of determining the direction to a source of electromagnetic radiation which lies near the plane of rotation. Referring again to Figure 1, one will easily see a periodic modulation especially in the 178 kHz channel. The deep nulls occur when the antenna is most nearly parallel to the propagation vector of an electromagnetic wave since the electric vector is perpendicular to the propagation vector. If the source were a point source directly in the plane of rotation and the antenna pattern were that of a true dipole, the detected signal intensity would drop all the way to the receiver noise level when the antenna was oriented parallel to the propagation vector. When the source subtends a solid angle of finite size or lies out of the rotational plane, the depth of the nulls decreases. Since the errors in the direction finding procedure are less for more strongly modulated signals, it is important for the source to lie close to the spin plane. Recalling Figure 3, one can see that a source near the earth lies close to the plane of rotation of the electric antenna for most of the orbit of HAWKEYE-1. Errors will be discussed in greater detail near the end of this section.

Figure 3 defines various angles which are used in the direction finding analysis. The angle ϕ_y is the orientation angle of the +y antenna measured from the spacecraft-sun line projected into the spacecraft spin plane. ϕ_y is determined from data from the spacecraft optical aspect system. A knowledge of the spacecraft attitude and position with respect to the earth and sun can allow the angle ϕ_E to be calculated. The angle ϕ_E is the angle between the spacecraft-sun line and spacecraft-earth line, both projected into the spin plane. For specific satellite positions, this calculation can be verified by the optical aspect system using the earth telescopes. Subtracting ϕ_E from ϕ_y gives the angle δ_y which is the basic angle used in the analysis, and is the angle from the spacecraft-earth line projection into the spin plane to the y antenna. In addition to the geometrical phase angles computed, a correction phase angle due to the receiver time constant must also be included. For the higher frequency channels on the HAWKEYE-1 experiment using the nominal spin period, this correction is about $1.3° \pm 0.2°$.

For the channel used in this analysis, the sampling interval is slightly greater than the spin period so that consecutive samples are obtained every 360° plus about 17° depending on the actual spin rate. Therefore, on the order of 21 rotations of the satellite are required to sample through 360°. The period of time needed to sample through 360° will be referred to as a sampling cycle. During a sampling cycle a sporadic emission like auroral kilometric radiation is likely to change amplitude. For ease in handling data which varies sporadically in amplitude within one sampling cycle, the samples are normalized by subtracting the average of all the samples obtained during a sampling cycle from each of the individual samples. Each sample is a voltage which is proportional to the logarithm of the field strength, hence, subtracting the average voltage is equivalent to dividing by the average field strength. To reduce the effect of fluctuations, the measurements from several of these 360° sampling cycles are combined by sorting normalized samples into 10° angle bins and averaging within the bins. The data from $90° < \delta_y \leq 270°$ are shifted into the range $-90° < \delta_y \leq 90°$ since the dipole pattern is assumed symmetric. Usually after an hour of this averaging process, the resulting averaged points will yield a modulation pattern smooth enough to give on the order of 1° accuracy in a fit routine that will be discussed below.

Figure 4 shows the result of a one hour averaging period from an auroral kilometric radiation direction finding analysis. For this example HAWKEYE-1 is at a radial distance of 18.9 R_e and at a magnetic latitude of 78.3°. The small drawing in the upper right hand corner of this figure shows the relative positions of the earth, sun, and satellite. The spacecraft spin axis projects out of the plane of the page. In the lower part of the figure, the normalized electric field amplitude has been plotted as a function of δ_y. It is obvious that the null direction angle δ is very close to 0°, that is, the null is in the direction of the earth.

An accurate determination of δ can be found by doing a least squares fit of the normalized field strengths E/E_o to a theoretical expression for the modulation pattern:

$$\left(\frac{E}{E_o}\right)^2 = (1 - \frac{m}{2}) - \frac{m}{2} \cos\left[2(\delta_y - \delta)\right] \quad (1)$$

The parameter, m, is the modulation factor which gives a measure of the null depth such that if m is zero there is no modulation and if m is one the maximum modulation exists. The result of this analysis for the case in Figure 4 is that $\delta = 3.4° \pm 1.4°$.

There are several potential sources of systematic error in the determination of the null direction for HAWKEYE-1 data. The receiver time constant correction may be in error, but the correction is quite small (1.3°) and is known to about $\pm$ 0.2° so that the receiver time constant correction error is not a major one. On the order of one degree error or less is the desired accuracy in determining a direction from the apogee of the HAWKEYE-1 satellite's orbit. The optical aspect provides data on the angle, ϕ_y and the orientation of the spin axis. The orientation of the spin axis is used in conjunction with data on the position of the spacecraft in space to determine the angle ϕ_E. The errors involved in the computation of both of these angles is considered to be less than 1°. Perhaps the most troublesome error is the misalignment of the electric dipole antenna because its magnitude is unknown and also it is possibly the largest error involved in the analysis. Although the manufacturing specifications of the antenna required an antenna misalignment of no more than 1°, there are no directly measured data on the actual alignment error. The method of data analysis presented later in this study is essentially unaffected by this alignment error and actually gives an estimate of the misalignment of about 1.5°.

The polarization of the source, under certain circumstances, could lead to errors. If the source position were collinear with the spin axis, the null angle would correspond directly to the angle of the smallest transverse electric field vector. Of course, a randomly or circularly polarized source would produce no null due to polarization. There is no direct evidence on the polarization of auroral kilometric radiation, therefore, to avoid contamination of the analysis with polarization effects, measurements have been made only during times when the earth is close to the spin plane where polarization effects are absent or minimal.

C. Results

Since the peak in the auroral kilometric radiation spectrum usually occurs in the frequency interval from 100 kHz to 300 kHz, the 178 kHz channel is used for all measurements presented in this paper. To reduce the statistical error in the null angle δ to the approximate level of one degree, averaging intervals on the order of one hour or greater in length are required. During the averaging interval the power flux in the 178 kHz channel must remain greater than 10^{-18} watts m^{-2} Hz^{-1} to insure that the low level continuum which may also be spin modulated [Gurnett, 1975] does not contaminate the modulation pattern of the auroral emission. Averaging intervals are chosen during times when the amplitude of the radiation (averaged over a 360° sampling cycle) remains fairly constant. Some of the HAWKEYE-1 satellite's orbits yield enough 178 kHz data which is fairly constant at power fluxes greater than 10^{-18} watts m^{-2} Hz^{-1} to provide up to 20 individual determinations of the null angle δ. Other orbits may yield no useable data.

It should be pointed out that for any one determination of δ, only one component of the source position has been measured. That component is perpendicular to the plane defined by the spin axis and the spacecraft-earth line, i.e., the plane of the orbit. Another component may be eliminated from the problem by projecting into the equatorial plane. Although Gurnett [1974] predicts that the actual source region lies 1.0 to 1.5 R_e above the earth on an auroral field line, it is thought that the effects of choosing the equatorial plane here are minimal, certainly less than other errors involved and that the position of the source projected into this plane is still of scientific interest.

The measurement of the perpendicular distance, d, from the polar axis of the earth to a line through the projection of the source into the equatorial plane can be computed from the null angle δ and the distance of the satellite above the equatorial plane, R.

$$d = R \tan(\delta) \tag{2}$$

The line through the projection of the source into the equatorial plane is defined by the intersection of the equatorial plane and the plane of the spacecraft spin axis and electric antenna (spacecraft y axis) when the electric antenna orientation angle, δ_y, equals the null angle δ. The third component must be obtained using the fact that the orbit plane rotates 360° with respect to the dawn-dusk meridian plane in one year. Therefore, if the source is assumed to remain fixed in space to some degree over the course of several months, a different component can be measured for each orientation of the orbit plane. Figure 5 demonstrates how two components of the source region can be determined by combining the data from two orbits separated in time by two or three months. In the center of the figure, a diagram shows the projection of orbits 5 and 42 on the equatorial plane as seen from above the north pole. On either side of the figure are constructions showing the results of several determinations of the null angle for the two orbits. These displays show the view as seen by an observer at positions A and B in each of the planes looking edgewise into those planes. A line is drawn from the position of the satellite above the earth at an angle δ with respect to the orbit plane to the equatorial plane. The average position of the source region as determined by orbit 5 appears to be in the orbit plane. For orbit 42, however, there is a clear trend favoring a source to the right of the orbit plane as observed from A. Again referring to the diagram at the center, we can see that if the source lies in the plane of orbit 5 and to the right of the plane of orbit 42, the source region must be on the night side of the earth as projected into the equatorial plane and specifically at a local time of about 2 hours. Using a rough estimate for the average distance, $\bar{d}$, from the polar axis to the source in orbit 42 of 1.0 R_e it is easily seen how the source position can be determined in two dimensions.

Figure 5 also demonstrates the large variability in the source position determinations during one orbit. These fluctuations are larger than the statistical errors and are probably due to fluctuations in the position of the source on a time scale greater than the averaging interval. There is no reason to rule out spatial fluctuations on a time scale of less than an hour, although those could not be detected with the method used here. Data will be presented later which averages about three months of data, hence averaging out even very long time scale drifts in the position so that what is obtained is truly a time averaged position of the source region.

It is important to explain what is meant by "position of the source". As just discussed, this is a time averaged position, but more correctly, the result is the position only of the centroid of the source region. Since the angle δ is the phase factor in the sine wave fit, no information is obtained about the brightness distribution other than the position of its center. The modulation factor does not provide source size directly since the point source out of the spin plane may produce a modulation factor identical to that of an extended source centered directly in the spin plane. Only after the source position is known in two dimensions can the modulation factor be used to derive angular size information.

By expanding the idea of using information from two orbits to arrive at a source location to using a large number of orbits, a better average position can be determined. For any one orbit, an average perpendicular distance, $\bar{d}$, for that orbit can be found, weighting the individual determinations of d as $1/\sigma_i^2$ where σ_i is the error of the i^{th} determination of d in the orbit. The average perpendicular distance $\bar{d}$ defines a line in the equatorial plane which is parallel to the spin axis projection and passes through the projection of the average source position in the equatorial plane. The perpendicular distance between this line and the polar axis is $\bar{d}$. Figure 6 illustrates the superposition of these lines for most of the first 43 orbits of HAWKEYE-1. Several orbits are not represented because there was too little auroral kilometric radiation present to establish an average. The lines are superimposed on a sketch of the earth as viewed from above the north pole. It is evident that most of the lines pass through the local evening and nighttime sector. A qualitative estimate of the average source position would place it somewhere in the local evening quadrant on the order of 0.5 to 1.0 R_e from the center of the earth. The error bars drawn for one of the lines indicate the typical rms spread (plus and minus the standard deviation) in the distribution of the null positions observed during a particular orbit.

A more satisfactory method for determining a quantitative source position involves plotting the average perpendicular distance, $\bar{d}$, determined for each orbit as a function of local time of the spin axis. The local time of the spin axis is the angle in hours from the spacecraft-sun line to the angular momentum vector, both projected into the equatorial plane. Twelve hours is added to this angle such that the anti-sunward direction is local midnight. The $\bar{d}$ values are plotted in Figure 7. It is not immediately obvious from this plot that the data follow any particular trend. To realize that there should, indeed, be a pattern and in fact that the pattern is a sinusoid, one can imagine a point source fixed in time which is not centered on the center of the earth. Assume the point is at 1.0 R_e from the center of the earth at 21 hours local time and that several position measurements can be made with good precision. If the spin axis points in either the 21 hours or 9 hours local time direction, d should be equal to zero. If, on the other hand, the spin axis pointed toward 15 hours or 3 hours local time d would equal $\pm$ 1.0. (Recall Equation 2 in which d is a function of tan δ where δ has a sense determined by the direction of satellite rotation. Hence, d may be positive or negative.) It can be seen that a plot of this hypothetical source position, d, as a function of spin axis local time would result in a cosine curve of amplitude 1.0 R_e and phase shift of 225° or 15 hours local time. Now, if the source were generalized to an extended source which fluctuates in position, the datum points would no longer lie directly on the sine wave, but would be scattered on either side of it.

Following the above analysis scheme, a cosine curve is fitted to the data in Figure 7 using standard, least squares fitting techniques. The curve drawn in Figure 7 is the resulting curve. The amplitude is 1.1 $R_e \pm 0.7$ R_e and the phase angle (local time) is 13.6 $\pm$ 1.3 hours. Thus the average source position is at 1.1 R_e from the polar axis at a local time of 19.6 hours. Recall that d is perpendicular to the spin axis projection, hence a shift of 90° or 6 hours is added to the phase shift of the curve to get the position of the source. The scatter in the data is due mostly to time variations, but also to statistical uncertainties. The error bar is typical of the standard deviation of the mean defined by:

$$\sigma_{\bar{d}} = \left(\frac{1}{\Sigma\, 1/\sigma_i^{2}}\right)^{1/2} \qquad (3)$$

where σ_i is the uncertainty in the i^{th} determination of d. This error is an estimate of the statistical error in $\bar{d}$ for a particular orbit.

Perhaps the most significant deficiency of the data presented in Figure 7 is the lack of data throughout a wide range of local times. Unfortunately the optical aspect system on board the satellite ceased functioning after three months making measurements at other local times impossible. With more data, a more accurate determination of the antenna misalignment can be made using the fact that the average d measured from orbits separated by 180° or 12 hours in local time should be zero. The fact that the curve in Figure 7 is offset from $\bar{d}$ = 0.0 R_e by approximately 0.7 R_e indicates that there is, in fact, a misalignment of approximately 1.5°. For the purpose of this study, however, the misalignment affects only the offset of the curve, not the phase angle and amplitude which give the source position.

In summary, the time averaged centroid of the source region of auroral kilometric radiation is found using the data from HAWKEYE-1 to be at 19.6 ± 1.3 hours local time, 1.1 ± 0.7 R_e from the center of the earth when projected into the equatorial plane.

III. DIRECTION FINDING MEASUREMENTS WITH IMP-8

A. Description of the Instrument

The IMP-8 spacecraft was launched on October 26, 1973, into a slightly eccentric earth orbit with initial perigee and apogee radial distances of 147,434 km and 295,054 km, respectively. The orbit inclination is 28.6° and period is 11.98 days. IMP-8 is spin stabilized with its spin axis perpendicular to the ecliptic plane and with a spin period of about 2.59 seconds.

The University of Iowa plasma wave experiment on IMP-8 is very similar to the experiment on HAWKEYE-1. IMP-8, however, has a much longer electric dipole antenna extended perpendicular to the spacecraft spin axis with a tip-to-tip length of 121.8 meters. IMP-8 has 15 discrete bandwidth channels ranging from 40 Hz to 178 kHz for electric measurements. There are triaxial search coil magnetometers on the spacecraft for the detection of magnetic signals which are sampled at 8 frequencies from 40 Hz to 1.78 kHz.

B. Method of Analysis

The IMP-8 data are analyzed using the same method as for determining the null angle δ with HAWKEYE-1 data. One major area of difference to consider, however, is due to the geometrical differences imposed by the IMP-8 orbit. Since IMP-8 has its spin axis perpendicular to the ecliptic plane and an orbit inclined only 28.6° to the equator, the data can be used to determine roughly the same components of the source position of auroral kilometric radiation as HAWKEYE-1, but from a different perspective. The HAWKEYE-1 measurements are made from above the north pole and the IMP-8 measurements from a position close to the equatorial plane. At various times during its orbit, IMP-8 is situated so that the earth is close to the spin plane of the satellite. Each individual determination will be a line from the satellite through the source position projected into the ecliptic plane. It will be argued later that for the purpose of this study the line through the source projected into the ecliptic plane can be thought of as a line through the projected source location in the equatorial plane with no correction. It will be seen that the errors involved with this uncorrected translation will not systematically shift the determined source position. The second component is obtained by measuring the position of the source from another local time position of the satellite. Again, d is the perpendicular distance from the polar axis of the earth to the line through the source. Another major difference is that IMP-8 is usually about two times as far from the source as HAWKEYE-1, thus greater accuracy in the determination of δ is required to give reasonable perpendicular distance determinations. This is accomplished in two ways. Since the radiation is sporadic, better average modulation patterns are obtained if the averaging period is extended to, in some cases, 12 hours or longer. Also, if the modulation factor is large, the statistical errors will be less than for cases where the factor is small. This is true because a strong modulation pattern is not dominated by the sporadic power flux of the event as greatly as a weakly spin modulated case, i.e., the relevant signal-to-noise ratio is the ratio of the modulation amplitude to the sporadic fluctuation amplitude. Large modulation factors are obtained by using events during times when the earth is very close to the spin plane of IMP-8. Using events with large modulation factors, hence, events during times when the source is very close to the spin plane of IMP-8 also reduces errors due to measuring polarization angles instead of direction angles. Recall that polarization errors are minimized by studying sources close to the spin plane. Events with modulation factors of .766 or larger have been used in this study.

The same errors encountered in the HAWKEYE-1 determination of the null angle are encountered with IMP-8, however, the most significant ones are the uncertainty in the receiver time constant and antenna misalignment. The phase shift due to the receiver time constant at the nominal spin rate is thought to be $7.16° \pm 2.0°$. A comparable phase shift due to antenna misalignment may also be present. Since data is available from IMP-8 taken from a wide variety of local times, it is possible to determine the total phase shift correction while in orbit. The method used is to require that the average perpendicular distance, $\bar{d}$, for a large number of auroral kilometric events as determined from satellite positions on opposite sides of the earth be zero. The best estimate for the total phase correction due to the receiver time constant and antenna misalignment is 11.96°.

This phase shift has been included in all IMP-8 data presented in this paper, but, as was the case for HAWKEYE-1 data, the position can be determined independent of this correction.

C. Results

To show the geometry of an IMP-8 direction finding determination and how the position of the satellite in its orbit allows more than one component to be measured, Figures 8 and 9 will now be discussed. The diagram in the upper right corner of Figure 8 is a sketch of the relative positions of the sun, earth, and IMP-8 as seen from above the north pole during a 14-hour averaging interval. IMP-8 is 32 R_e from the earth at a local time of 2.76 hours. The data are plotted as in Figure 4. Although measured in a different plane, δ_y still represents the angle of the antenna with respect to the earth so the null angle $\delta = 1.0° \pm 0.4°$ still represents the angle from the earth to the source as seen from IMP-8. For this determination the source would be on the evening side of the earth since an angle $\delta = +1.0°$ places the source to the left of the earth as seen by IMP-8. Figure 9 shows the results of an event studied from IMP-8 while the satellite is more or less on the other side of the earth at a local time of 16.85 hours. For this case, $\delta = -1.1° \pm 0.4°$ which also suggests a source on the evening side of the earth.

Figure 10 is a qualitative illustration of the data obtained from IMP-8 as seen from above the north pole. Each line is drawn from the satellite through the source region as determined by individual averaging intervals. It is clear that most of the lines pass through the local evening sector and that there is also a fair amount of spread in the region of the intersections of the lines. Almost no determinations can be made from local morning positions since auroral kilometric radiation is not usually detected at those local times from near the equator [Gurnett, 1974].

Again, these results may be analyzed using the same least squares fit to a cosine method as used to summarize the HAWKEYE-1 data. Figure 11 is a plot of the perpendicular distance d as a function of the local time of the satellite. The error bar is the typical error in a determination of d for the IMP-8 data. The cosine curve represents the best fit to the data and has an amplitude of 0.9 $\pm$ 0.2 R_e and a phase shift of 2.6 $\pm$ 1.1 hours in local time. Hence the time averaged centroid of the source position as determined by IMP-8 is at a local time of 20.6 hours and at a distance of 0.9 R_e from the polar axis of the earth. Again, the 90 degree or 6 hour shift in local time is due to the fact that d is always measured in the direction perpendicular to the spacecraft-earth line. As was mentioned earlier, this result is actually independent of the phase shift correction since that correction only shifts the whole curve up or down such that the amplitude and phase are unchanged.

The results obtained with IMP-8 are actually found in the spacecraft's spin plane which is parallel to the ecliptic plane. So far no mention has been made of the consequences of using ecliptic plane measurements to arrive at a source position as projected into the equatorial plane with no correction. Under worst case conditions the error incurred is on the order of the standard deviation of a typical determination of d, about 0.6 R_e. Virtually no error is involved, however, if radiation from roughly complement sources in opposite hemispheres is received simultaneously. Using the results of frequency of occurrence studies of kilometric radiation as a function of magnetic local time done by Gurnett [1974] one can assume that if the satellite is within 15° of the magnetic equator while at a local time between afternoon and early morning, radiation will be received from sources in both hemispheres. The conditions under which datum points plotted in Figure 11 were computed have been analyzed to check whether the conditions were close to the worst case. The data which were thought to be suspect were studied as to whether they deviated from the sinusoid in a manner predictable from errors incurred by mapping from the ecliptic to equatorial plane. The suspect points fell in random fashion on either side of the fitted curve indicating that no bias had been introduced by them. Therefore, it appears unlikely that using the ecliptic plane results for IMP-8 as equatorial plane results have caused any systematic error in the results from Figure 11.

IV. DISCUSSION

The position of the time averaged centroid of the source region of auroral kilometric radiation for 178 kHz events greater than 10^{-18} watts m^{-2} Hz^{-1} has been determined to be in the local evening at about 20.0 hours and at a distance of about 0.9 R_e from the polar axis of the earth as projected into the equatorial plane. Two independent determinations using data from the HAWKEYE-1 and IMP-8 satellites give very consistent results for this position. Each of the satellite's data is limited by errors and shortcomings of some nature. The HAWKEYE-1 data only determined the position in a local time range of less than three hours and has not been corrected for antenna misalignment. The IMP-8 satellite is so far from the earth that even errors of less than 1° result in a large displacement of the perpendicular distance and the data also must be evaluated for antenna misalignment. The misalignment problem has been avoided in both cases by fitting a sinusoid to the data whose amplitude and phase is unaffected by the offset caused by misalignment. The large degree of consistency between the two independent determinations is evidence that any systematic errors have been eliminated or kept small.

A source position near 20 hours local time, about 0.9 R_e from the polar axis strengthens evidence given by Gurnett [1974] supporting a source region near the evening auroral zone about 1.0 R_e above the earth. This height was assumed since the radiation must be generated in a region where the greater of the local plasma frequency or gyrofrequency is close to but less than the detected frequencies. This means the region is above the propagation cutoff surface for 178 kHz. Assuming a source region at about 1.0 R_e above the earth on an auroral field line of 70° invariant latitude, the projection of this region into the ecliptic plane would give a displacement from the polar axis of .96 R_e consistent with the position determined in this study. Figure 12 is a qualitative view of the position of both the expected source centroid and its projection into the equatorial plane as measured in the present work. The position of the actual source in Figure 12 is inferred from Gurnett [1974]. The local time of the source also agrees well with the location of very bright auroral arcs in the local evening [Akasofu, 1968; Snyder et al., 1974] and with the location of the most numerous and most intense "inverted V" events [Frank and Ackerson, 1972].

In addition to agreeing with Gurnett's [1974] predicted position of the source region, the results indicating an average source centroid located in the local evening about one earth radius from the polar axis are consistent with Stone's [1973] paper. The results, however, are in general disagreement with the dayside location reported by Stone et al. [1974]. Auroral kilometric radiation probably does originate in the local day time, since "inverted V" events are detected there [Frank and Ackerson, 1972], but the average position of the radiation as determined in this papers falls on the evening side since the multiplicity of occurrence and intensity of the kilometric events are both greater in the local evening. After the original results of this thesis [Kurth et al., 1975] were presented at the URSI Meeting in Boulder, Colorado, in October, 1974, Kaiser and Stone [1975] presented data which both supported Kurth et al. [1975] and cleared up the contradiction related to the dayside source [Stone et al., 1974]. Kaiser and Stone [1975] agree that there is a source located in the local evening with power fluxes greater than 10^{-18} watts m^{-2} Hz^{-1} as measured at radial distances of 20 to 30 R_e but added that there is also a source at the same frequency but at much lower intensity which is located on the late local morning side of the earth. This lower intensity radiation probably correlates well with the lower intensity, local daytime "inverted V" events studied by Frank and Ackerson [1972].

Now that there is increasing evidence that the source region location of auroral kilometric radiation coincides roughly with that of discrete auroral arcs and electron precipitation events progress can be made on determining the source mechanism of the radiation and its relation to particle precipitation. Benson [1975] has made a step in that direction by describing a possible mechanism which is driven by plasma oscillations near the upper hybrid frequency produced by precipitating electrons. The energy in longitudinal electrostatic waves can be converted into transverse electromagnetic waves through a process of reflections off of constant density surfaces. This mechanism may have applications to Jovian decametric radiation [Oya, 1974] and also for the newly discovered Saturnian bursts [Brown, 1975].

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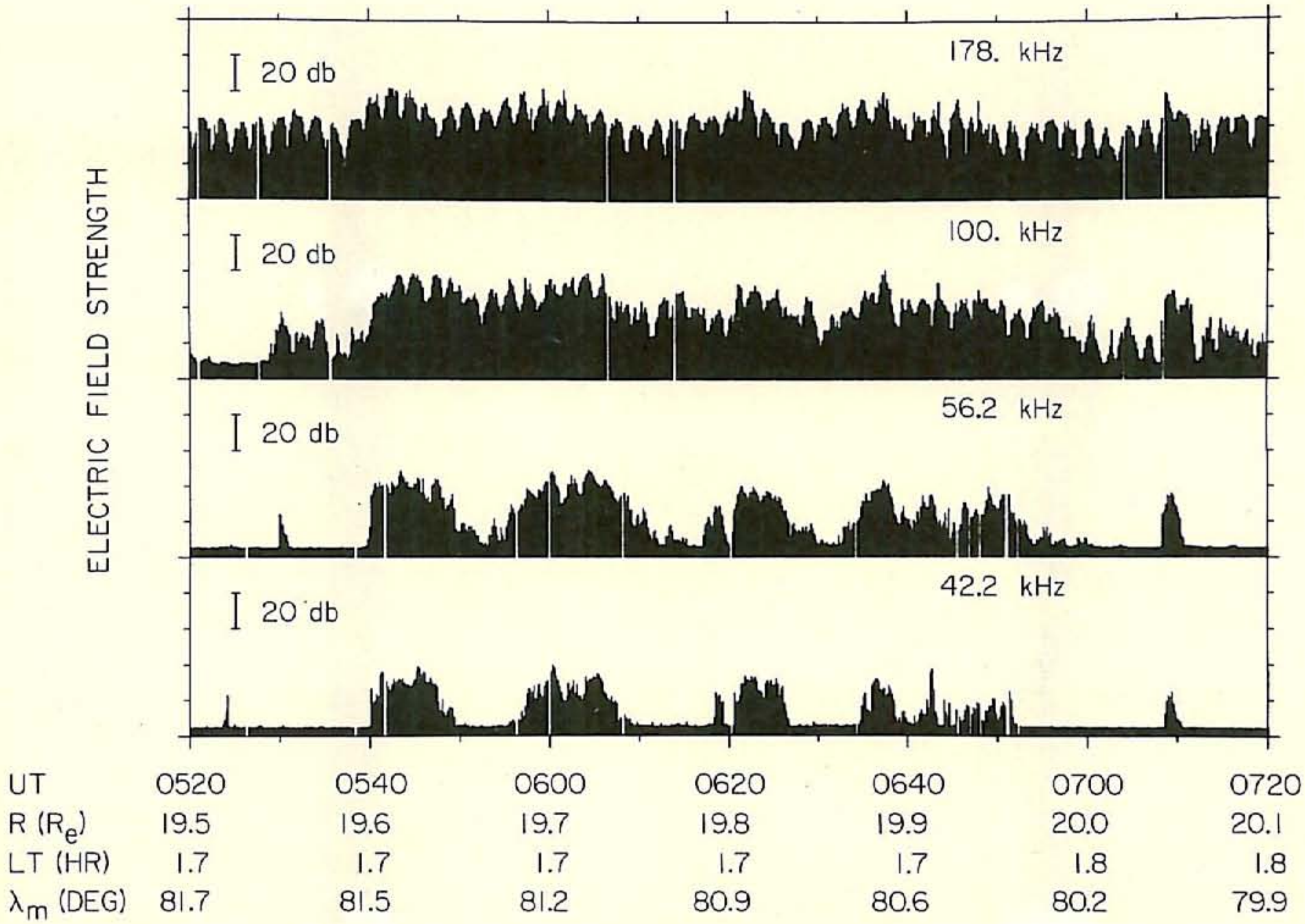
APPENDIX: FIGURES

Figure 1 Data from the upper four frequency channels of the HAWKEYE-1 experiment showing intense auroral kilometric radiation events. Notice the strong spin modulation especially in the 178 kHz channel.

C-G75-99-1



HAWKEYE-1 JUNE 28, 1974

Figure 1

Figure 2 Simultaneous observations of auroral kilometric radiation far from the earth by IMP-6 and low altitude auroral photographs obtained on two polar passes with the DAPP satellite. The intense burst of 178 kHz noise during orbit 831 is seen to be closely associated with discrete auroral arcs in the local evening and midnight regions of the auroral zone.

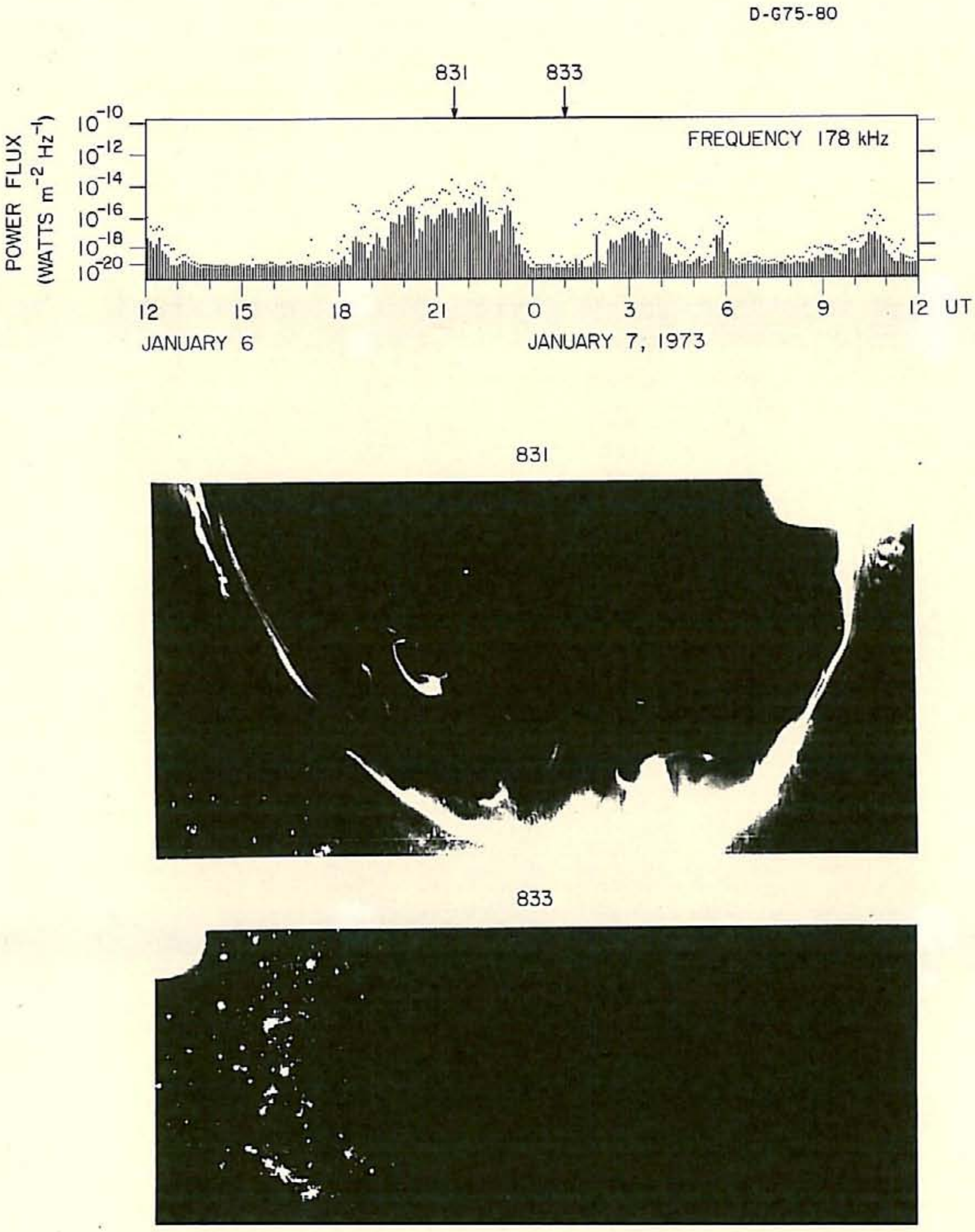

D-G75-80
831
833
POWER FLUX
(WATTS m^{-2} Hz^{-1})
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
FREQUENCY 178 kHz
12
15
18
21
0
3
6
9
12 UT
JANUARY 6
JANUARY 7, 1973
831
833

Figure 2

Figure 3 The HAWKEYE-1 orbit and spin axis orientation relative to the orbit plane. The angle δ_y is the angle from the projection of the satellite-earth line into the spin plane to the antenna. The angle δ_y at which a null occurs determines a meridional plane through the spin axis in which the source must be located.

C-G74-769

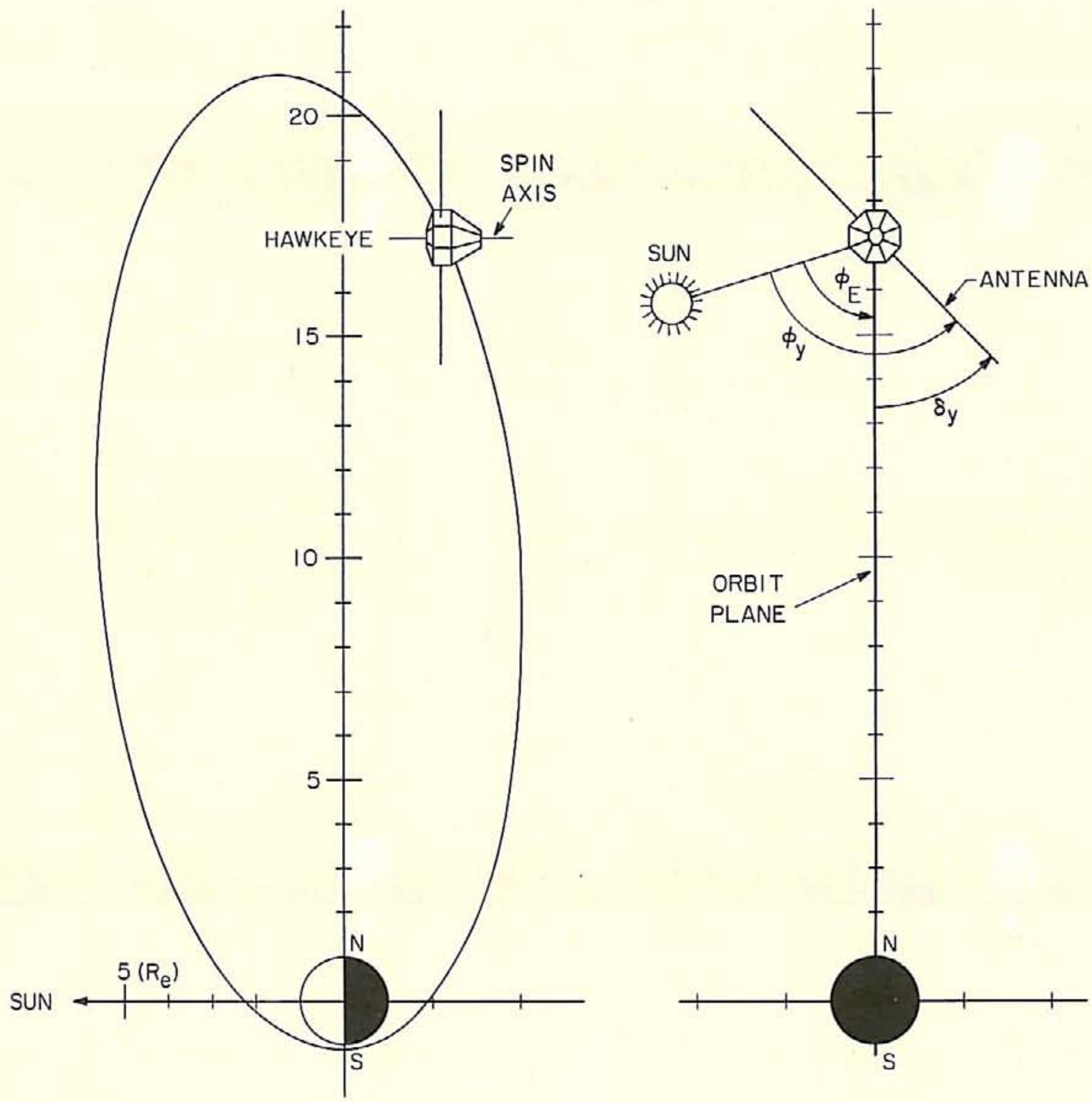


Figure 3

Figure 4 The average normalized electric field amplitude parallel to the antenna axis of auroral kilometric radiation at 178 kHz detected by HAWKEYE-1 as a function of the antenna orientation angle, δ_y. The angle δ is the position of the null as determined by a least squares, sine wave fit.

C-G74-768-1

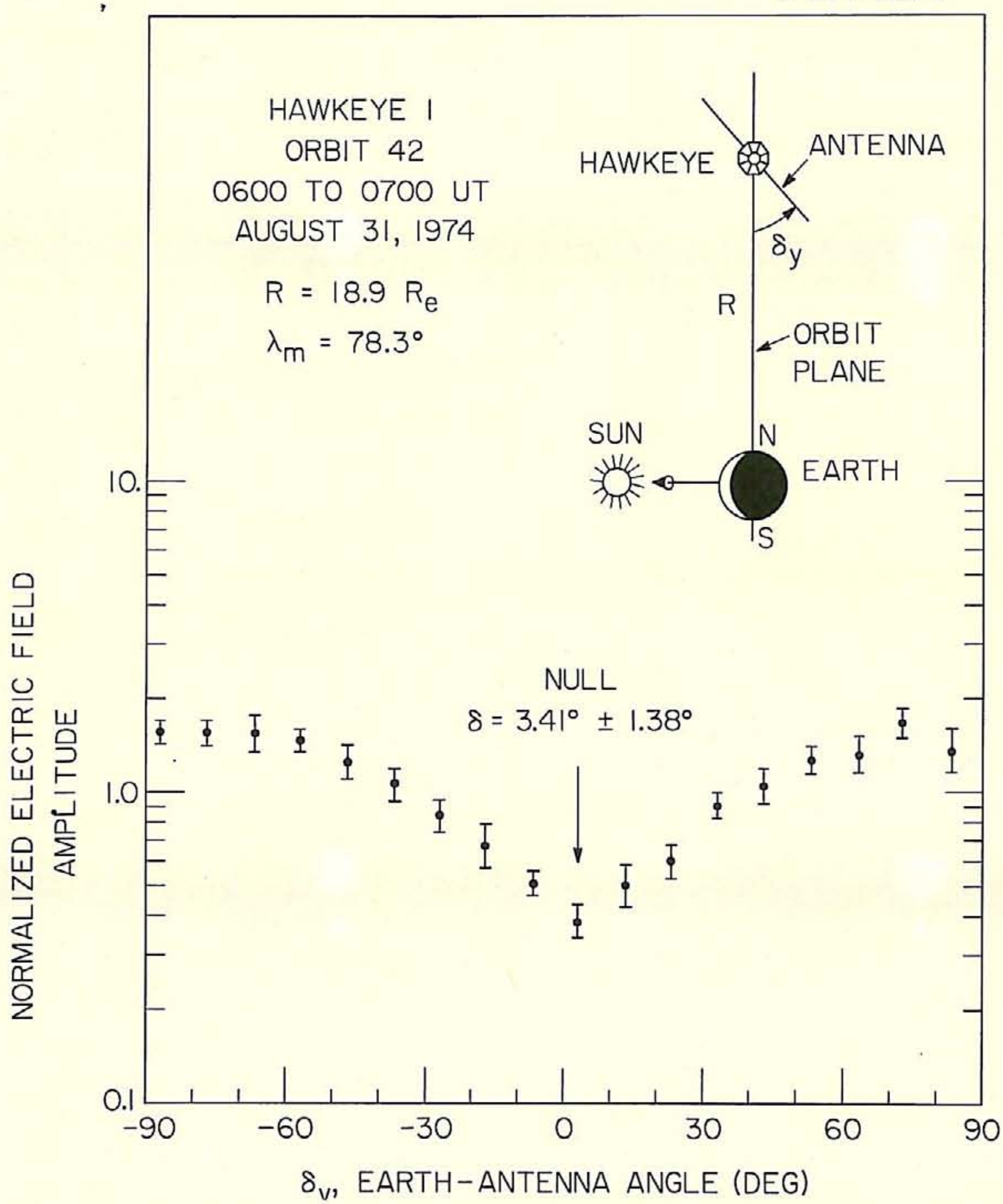
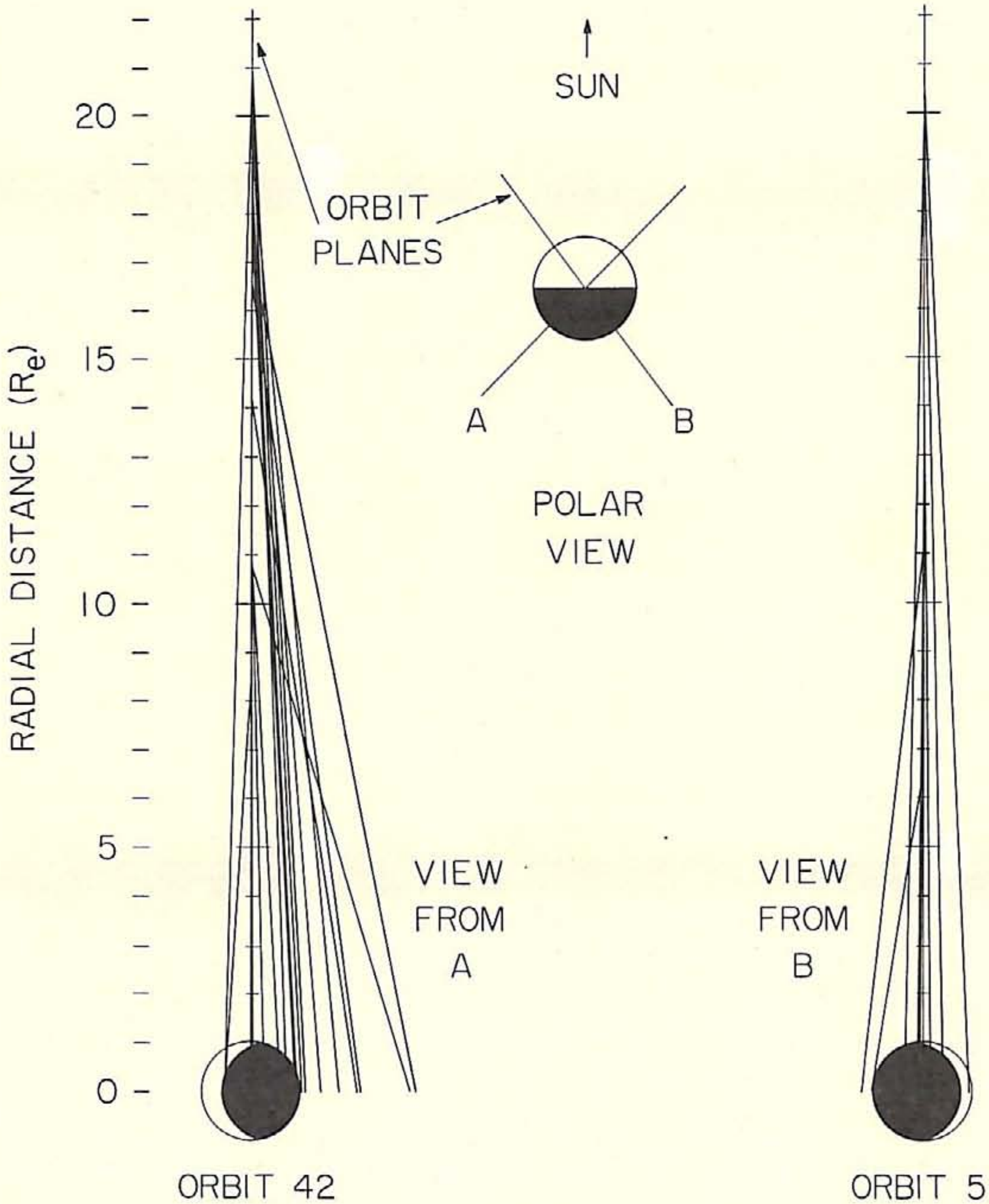


Figure 4

Figure 5 Null directions of auroral kilometric radiation determined in two orbits oriented at nearly right angles. The data from orbit 42 show a clear tendency for the radiation to originate from the night side of the earth. Time and statistical variations in the source position are also evident.

C-G74-770-I



HAWKEYE I

Figure 5

Figure 6 An equatorial plane projection of the average null directions of auroral kilometric radiation at 178 kHz for several HAWKEYE-1 orbits at various local times. The lines intersect in the region of the source, near local evening about 1.0 R_e from the center of the earth.

A-G75-117

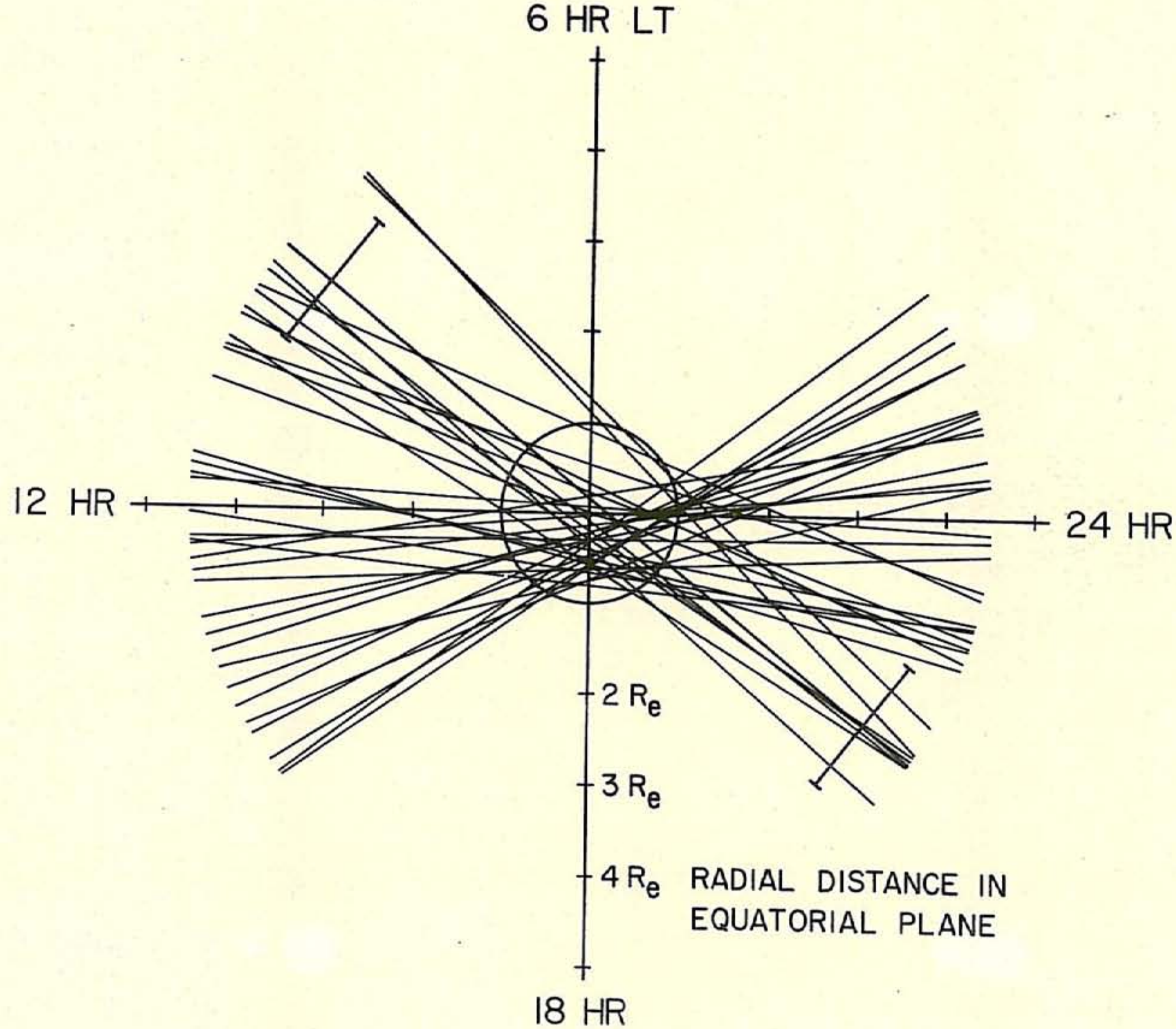


Figure 6

Figure 7 A plot of the average perpendicular distances, $\overline{d}$, measured for several HAWKEYE-1 orbits as a function of the local time of the spin axis. The sinusoidal relation is expected from the relation of $\overline{d}$ versus local time for a point source not centered on the earth. The amplitude and phase of this curve are directly related to the source position.

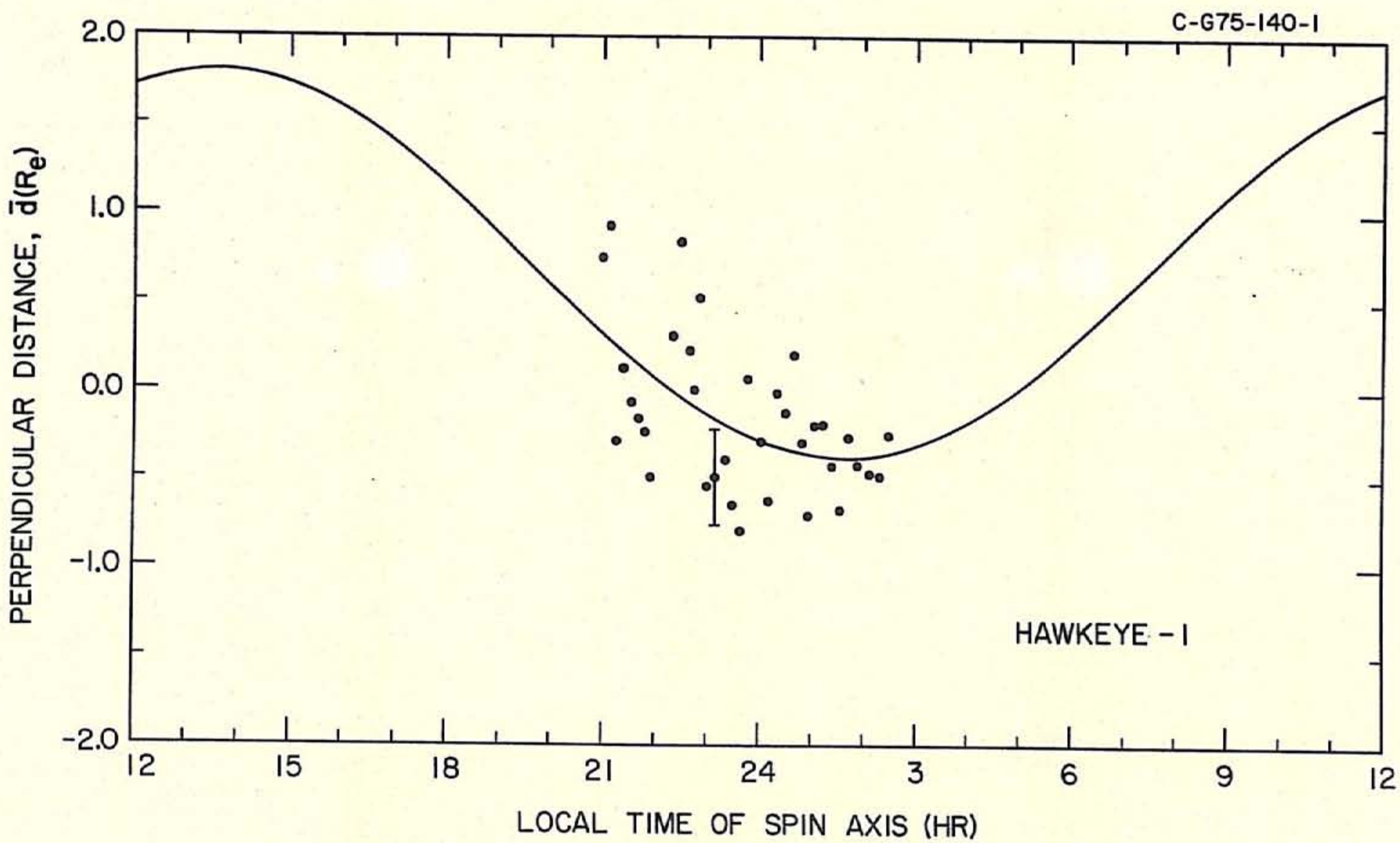

C-G75-140-1
2.0
1.0
0.0
-1.0
-2.0
PERPENDICULAR DISTANCE, $\bar{d}(R_e)$
HAWKEYE - 1
12
15
18
21
24
3
6
9
12
LOCAL TIME OF SPIN AXIS (HR)

Figure 7

Figure 8 The average normalized electric field strength as a function of the antenna orientation angle δ_y for a period when intense auroral kilometric radiation at 178 kHz was being detected from a local time of 2.76 hours by the IMP-8 satellite. The averaging period is very long, 14 hours, to reduce the statistical error in the determination of δ to only $\pm$ 0.4°. The null position is slightly to the left of the earth's polar axis as viewed by the satellite and, hence, on the night side of the earth.

C-G74-777-1

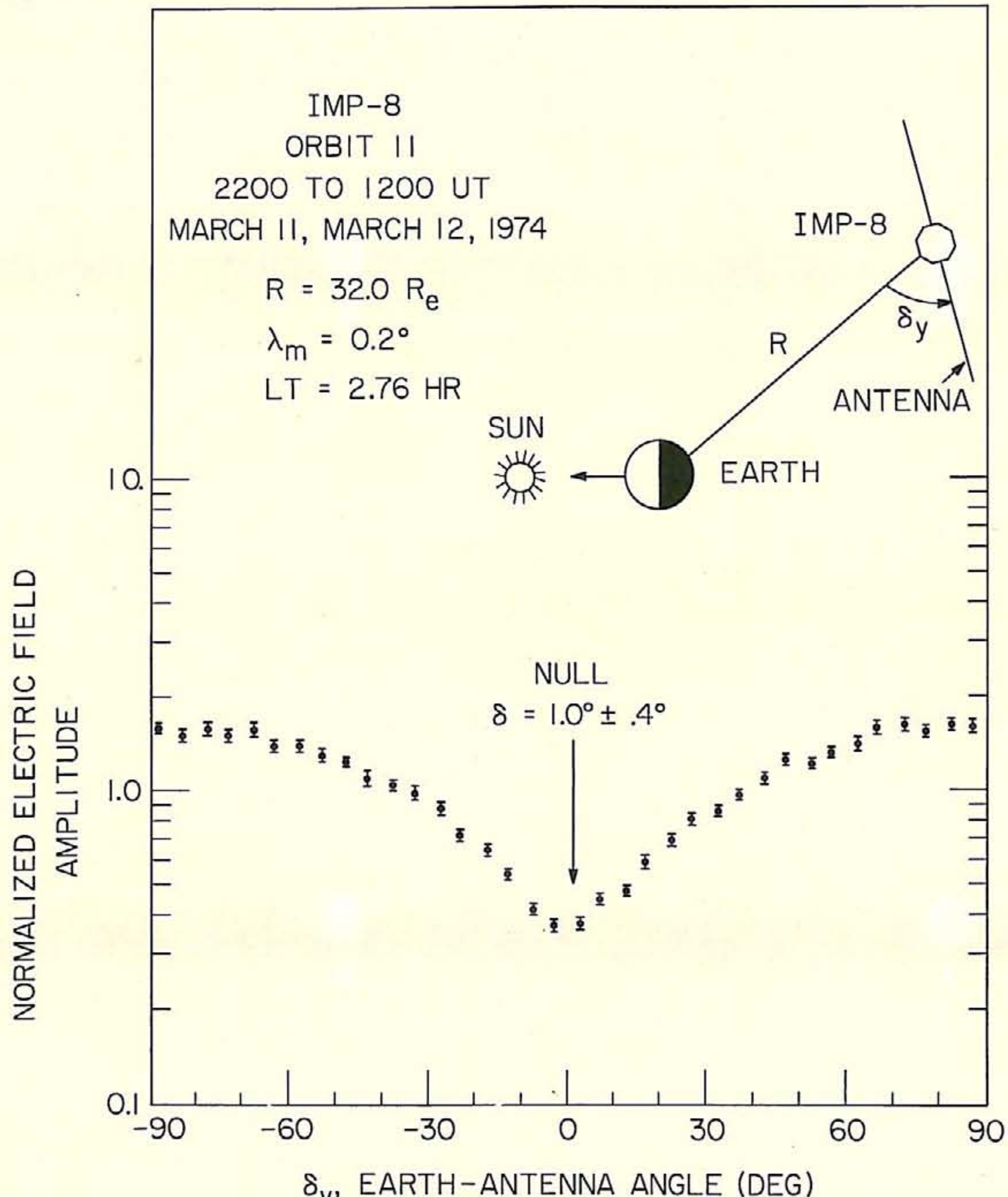


Figure 8

Figure 9 Another null determination using IMP-8 data similar to the case in Figure 8, but at a local time of the satellite of 16.85 hours. The null position in this case is slightly to the right of the earth's polar axis, again on the night side of the earth, as viewed from the spacecraft.

B-G74-778-1

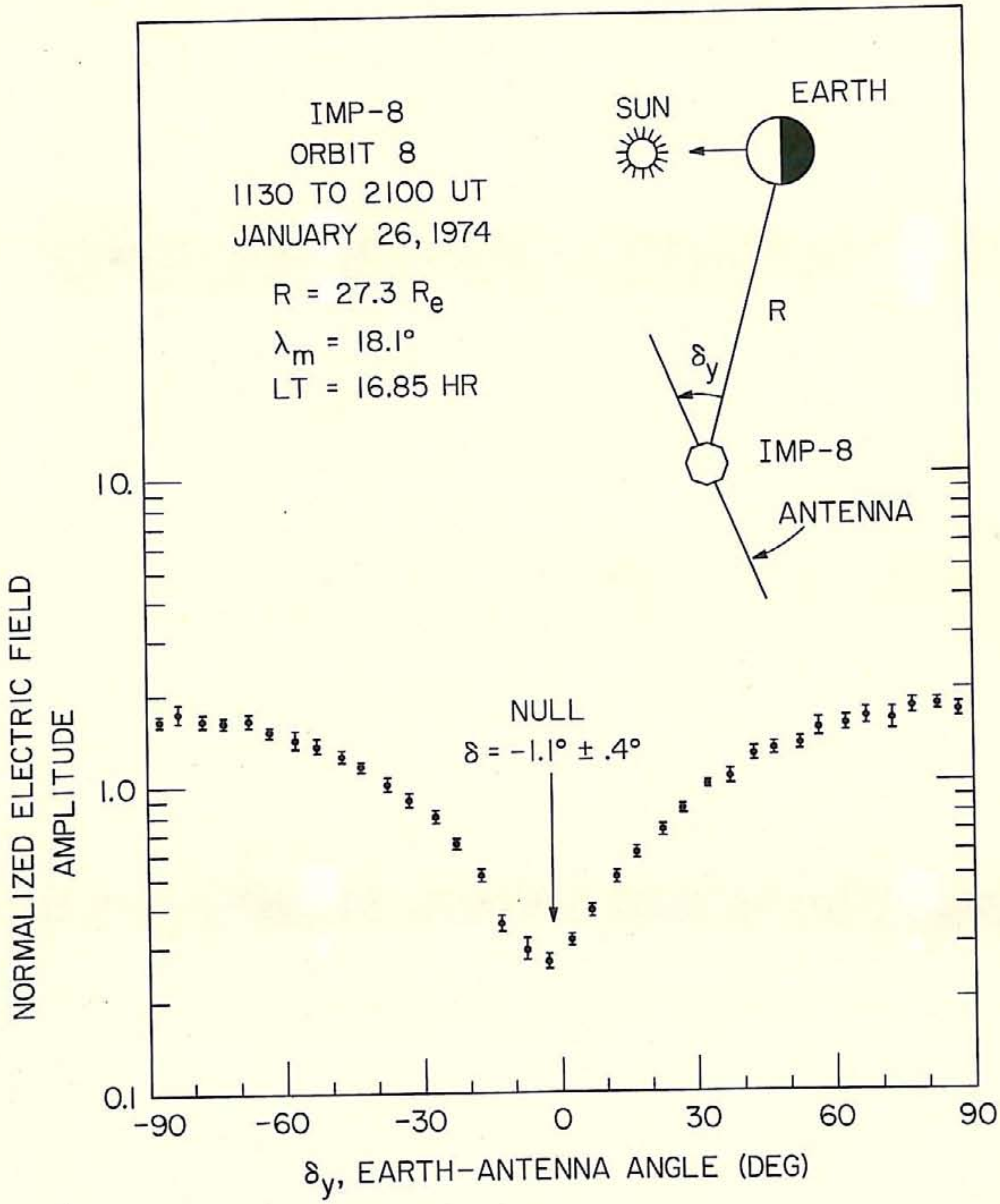


Figure 9

Figure 10 A view from above the northern polar region of several direction determinations of auroral kilometric radiation from IMP-8 data. The arrows indicate the direction from the spacecraft to the source. The intersection of the lines qualitatively shows the source region to be about 1 R_e from the polar axis of the earth in the local evening.

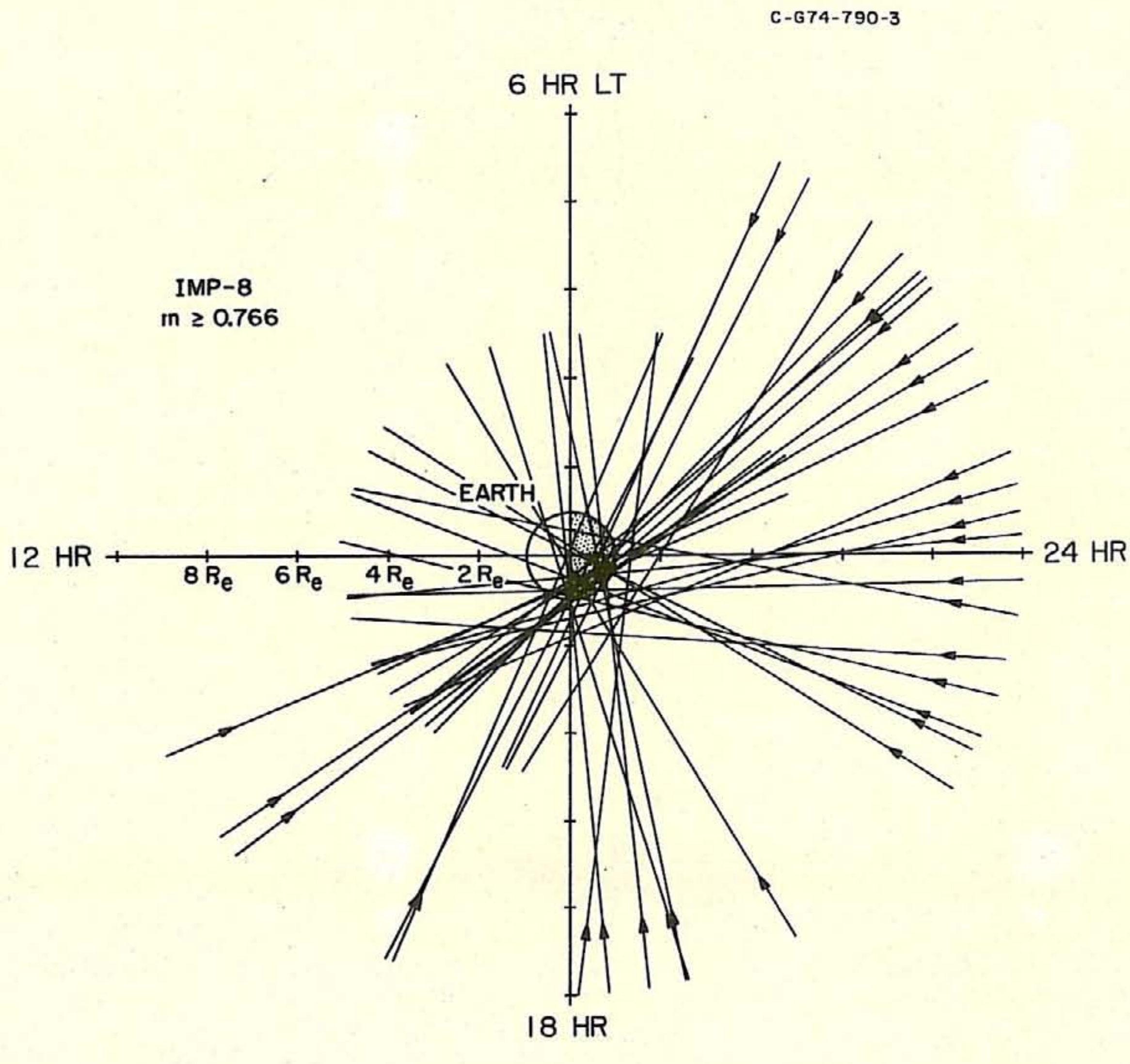

C-G74-790-3
6 HR LT
IMP-8
m ≥ 0.766
EARTH
12 HR
8 Re
6 Re
4 Re
2 Re
24 HR
18 HR

Figure 10

Figure 11 A series of null directions as measured from IMP-8 plotted as perpendicular distance from the polar axis of the earth to a line through the source as a function of the spacecraft position in a local time. As in Figure 7 a sinusoid is fitted to the data. The amplitude and phase of the sinusoid are related to the actual source position.

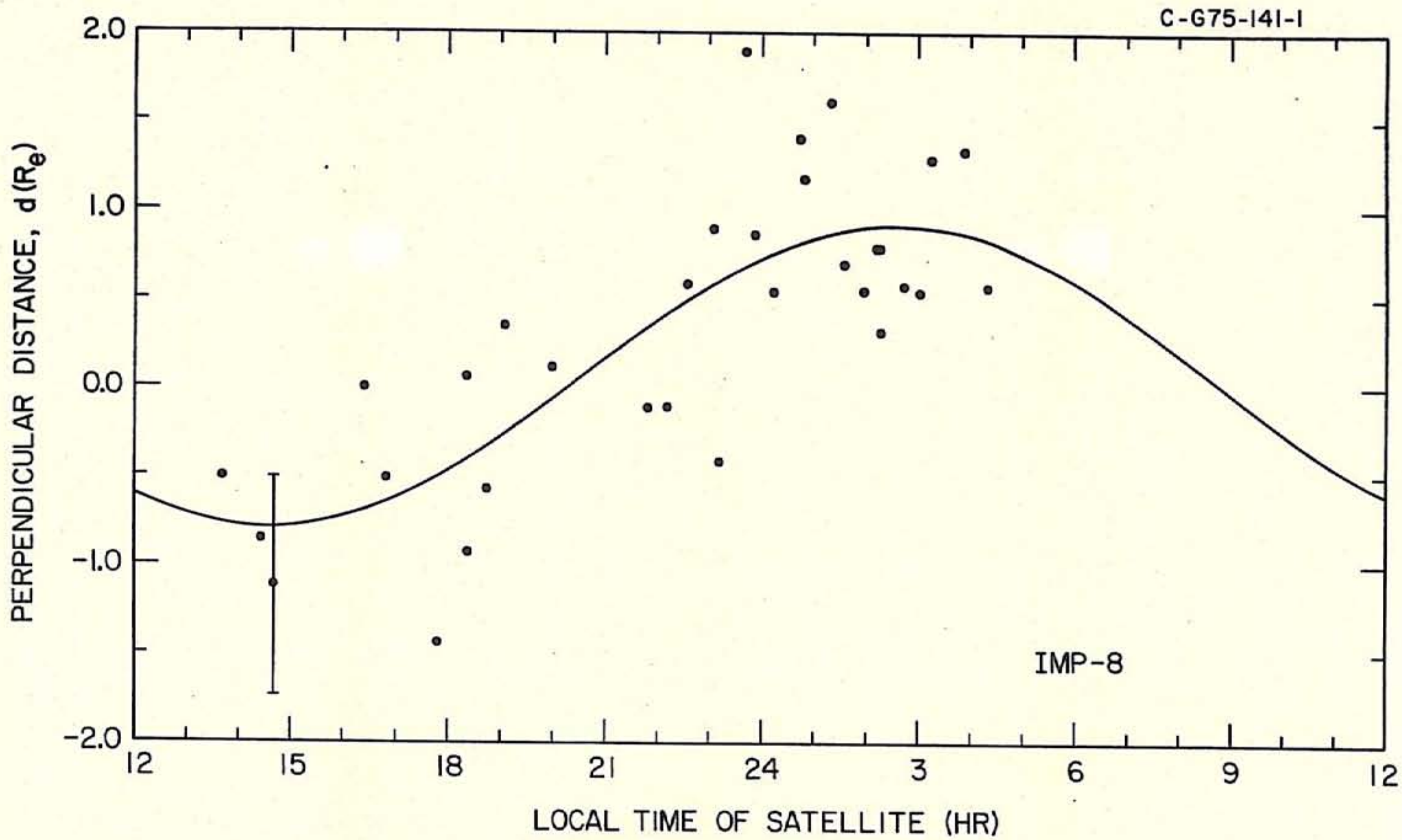

C-G75-141-1
PERPENDICULAR DISTANCE, d(R_e)
2.0
1.0
0.0
-1.0
-2.0
12
15
18
21
24
3
6
9
12
LOCAL TIME OF SATELLITE (HR)
IMP-8

Figure 11

Figure 12 A three dimensional view of the expected auroral kilometric radiation source centroid and its projection into the equatorial plane. Notice that the position of the projection of the source is compatible with a source region located on an auroral field line in the local evening.

C-G75-170

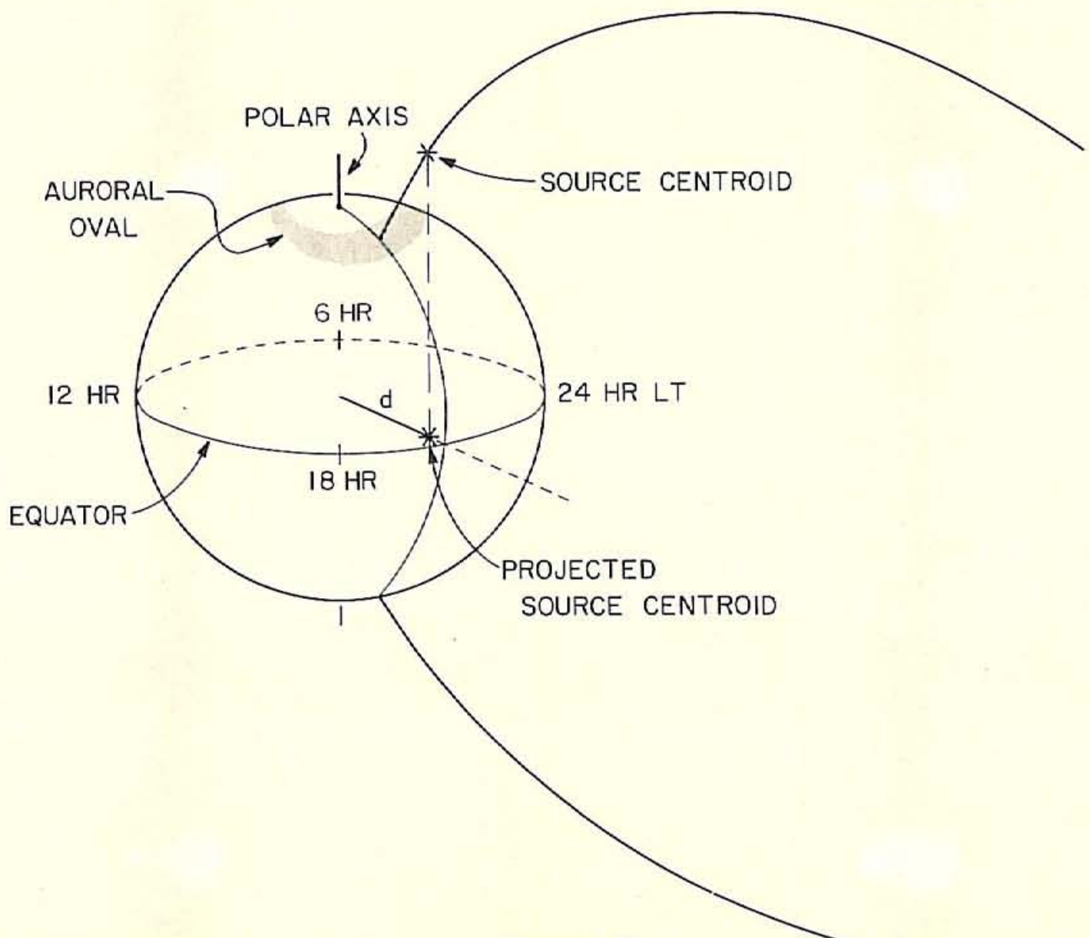


Figure 12