

Auroral Kilometric Radiation as an Indicator of Auroral Magnetic Disturbances

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Satellite low-frequency radio measurements have shown that an intense radio emission from the earth's auroral regions called auroral kilometric radiation is closely associated with auroral and magnetic disturbances. In this paper we present a detailed investigation of this relationship, using the auroral electrojet (AE) index as an indicator of auroral magnetic disturbances and radio measurements from the Imp 6 spacecraft. This study indicates that the mean power flux of the 178-kHz radiation tends to be proportional to $(AE)^{1.2}$ for $AE > 100 \gamma$ and, with less certainty, to $(AE)^2$ for $AE < 100 \gamma$. The correlation coefficient between $\log AE$ and the logarithm of the power flux is 0.514. Occasionally, a kilometric radiation event is detected which is not detected by the ground magnetometer stations, even though an auroral substorm is in progress. This study shows that the remote detection of kilometric radio emissions from the earth can be used as a reasonably reliable indicator of auroral substorm activity.

INTRODUCTION

In the past several years, low-frequency radio measurements have shown that the earth's magnetosphere is a very intense radio emitter, having characteristics very similar to those of other astronomical radio sources, such as Jupiter and Saturn [Kaiser and Stone, 1975]. From the very earliest measurements by Benediktov *et al.* [1968] and Dunckel *et al.* [1970] it was discovered that intense radio emissions in the several hundred kHz frequency range were closely associated with magnetic disturbances in the high-latitude auroral regions of the earth. Later studies by Gurnett [1974] showed that these radio emissions are closely associated with the occurrence of auroral arcs on the nightside of the earth. Direction-finding measurements and the angular distribution of the emitted radiation [Gurnett, 1974; Green *et al.*, 1977] indicate that the intense (up to 10^9 W of total radiated power) radiation is generated at relatively low altitudes ($\sim 3-R_E$ radial distance) over night and evening auroral regions. The radiation is presumably produced by the same intense fluxes of several keV electrons which cause the aurora and the currents responsible for the magnetic disturbances. Because of the close association with auroral phenomena and the wavelengths in the kilometer range these radio emissions have been called auroral kilometric radiation (AKR) [Kurth *et al.*, 1975].

Although auroral kilometric radiation is known to be associated with high-latitude magnetic disturbances, little has been done to study this relationship in detail. It is of interest to determine just how good the correlation is and whether there are any exceptions to the observed relationship. The relationship of the radio emission intensity to the currents flowing through the auroral zone may, for example, be helpful in developing a better understanding of how the auroral kilometric radiation is generated. Furthermore, since radio emissions from the entire auroral zone can be easily monitored by a single spacecraft, there is the question of whether the auroral kilometric radiation intensity could provide, on a near real time basis, a parameter which is comparable to the auroral

electrojet index AE without the need for a large array of ground stations with the attendant problems of information retrieval and processing. In this paper we present a detailed study of the relationship between the auroral kilometric radiation intensities observed by the Imp 6 spacecraft and the AE index computed from a series of high-latitude magnetometer stations. A description of the Imp 6 plasma and radio wave experiment is given by Gurnett [1974].

QUALITATIVE COMPARISON OF SOME TYPICAL EVENTS

Figure 1 shows the radio emission intensities detected by the Imp 6 spacecraft at 178 kHz and the corresponding variations in the auroral electrojet index AE for four 24-hour periods selected to illustrate the relationships typically observed between these two parameters. Since Imp 6 is in a highly eccentric orbit with an apogee radial distance of $33 R_E$, this spacecraft provides observations for long periods far from the earth where the auroral kilometric radiation intensities can be monitored nearly continuously without interruption. All of the enhanced radio emission intensities in Figure 1 are attributed to auroral kilometric radiation. The magnetic latitude, local time, and radial distance coordinates of Imp 6 are shown at the bottom of each panel.

The data in Figure 1 show the general type of correlation which is typically observed between the auroral kilometric radiation and auroral magnetic disturbances. Essentially every period of substantial magnetic activity, indicative of an auroral substorm, can be associated with a distinct period of enhanced auroral kilometric radiation intensity. Even during relatively quiet days, such as December 27, 1972, small magnetic disturbances are associated with an enhancement in the radio emission at 178 kHz.

Although the magnetic disturbances associated with an individual magnetic substorm usually have a close correspondence to a period of enhanced radio emission, the detailed short time scale (< 1 hour) intensity variations often do not have a close association with variations in the AE index. The onset time of the radio emission at the start of a magnetic substorm is sometimes significantly delayed with respect to the onset time of the magnetic disturbance. For example, delays of this type

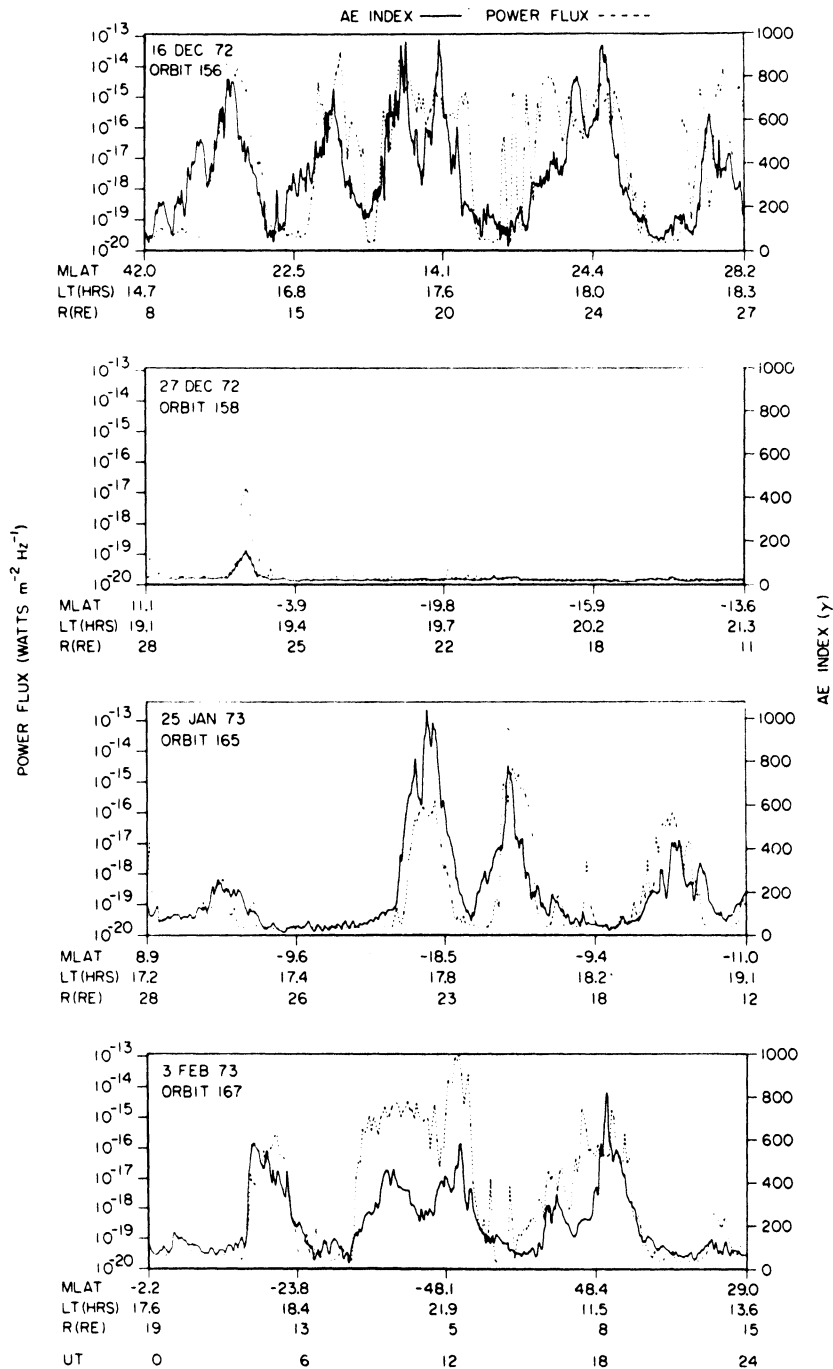


Fig. 1. Simultaneous measurements of the auroral kilometric radiation intensity at 178 kHz by the Imp 6 satellite and the auroral electrojet index AE for a selection of days in which a close correlation is observed. The coordinates of Imp 6 are shown at the bottom of each panel.

can be seen at about 0200 and 0600 UT on December 16, 1972, and at 1330 UT on January 25, 1973.

Occasionally, events can be found in which a large magnetic disturbance is clearly evident in the AE index but for which no corresponding radio emission is detectable and vice versa. Events of each of these types are shown in Figure 2. The event on March 31, 1973, at the top of Figure 2 illustrates a case in which a large magnetic disturbance ($AE \approx 1000\text{--}1500 \gamma$) occurs with only a negligible enhancement in the radio emission. This type of event, consisting of a large magnetic disturbance characteristic of a substorm with only a small or undetectable

increase in the radio intensity, occurs most frequently when the spacecraft is on the dayside of the earth. The absence of a detectable radio emission in most of these cases is thought to be caused by a propagation cutoff effect which prevents the radiation generated in the nighttime auroral regions from being detected at low latitudes on the dayside of the earth. This propagation cutoff effect is illustrated by the bottom panel of Figure 3, from Green *et al.* [1977], which shows the frequency of occurrence of auroral kilometric radiation at 178 kHz as a function of magnetic latitude and magnetic local time. This frequency of occurrence distribution, which is analyzed in

greater detail by *Green et al.* [1977], shows that a distinct latitudinal cutoff occurs, below which the radiation is much less frequently detected. The magnetic latitude of this cutoff varies from about 60° on the dayside of the earth to about 20° on the nightside of the earth. The cutoff is not sharp but occurs over a transition region about 20° wide in latitude. This cutoff effect is almost certainly caused by refraction effects in the ionosphere which cause the radiation to be beamed into a conical-shaped region, with a half angle of about 60° , directed upward from the nighttime auroral region. Comparison of the magnetic latitude and local time (14.7° and 12.4 hours LT) of Imp 6 during the intense magnetic disturbance on March 31, 1973, in Figure 2 with the frequency of occurrence contours in Figure 3 shows that no radio emission should be detected during this event. The top panel of Figure 3 shows the approximate boundaries of the northern and southern illumination regions within which the auroral kilometric radiation at 178 kHz can be detected essentially free of propagation effects. It should be noted that the boundaries of the illumination region are frequency dependent [*Green et al.*, 1977], so that even

though the radiation cannot be detected at 178 kHz, it is still possible that the radiation could be detected at higher frequencies. Effects of this type may account for some of the local time variations of the emission frequency reported by *Kaiser and Alexander* [1976]. If all of the data are examined when the spacecraft is in the northern illumination region (about 40 days of data), no large AE index enhancements are evident unless a corresponding enhancement in AKR also occurs at some time during the event. There may be periods during an event when the AE index is high and the AKR values are low, but at some time during the event the AKR is also enhanced.

Events for which enhanced auroral kilometric radiation intensities occur with no clear enhancement in the AE index are not uncommon. In most cases some minor disturbances can be identified in the AE index for an enhanced radiation intensity, although they are far from typical in indicating the occurrence of substorms. Almost complete breakdown of the correlation occurs, however, very infrequently. Of a total of 146 days which have been examined, two substorm events of this type have been clearly identified. We suggest that the lack of corre-

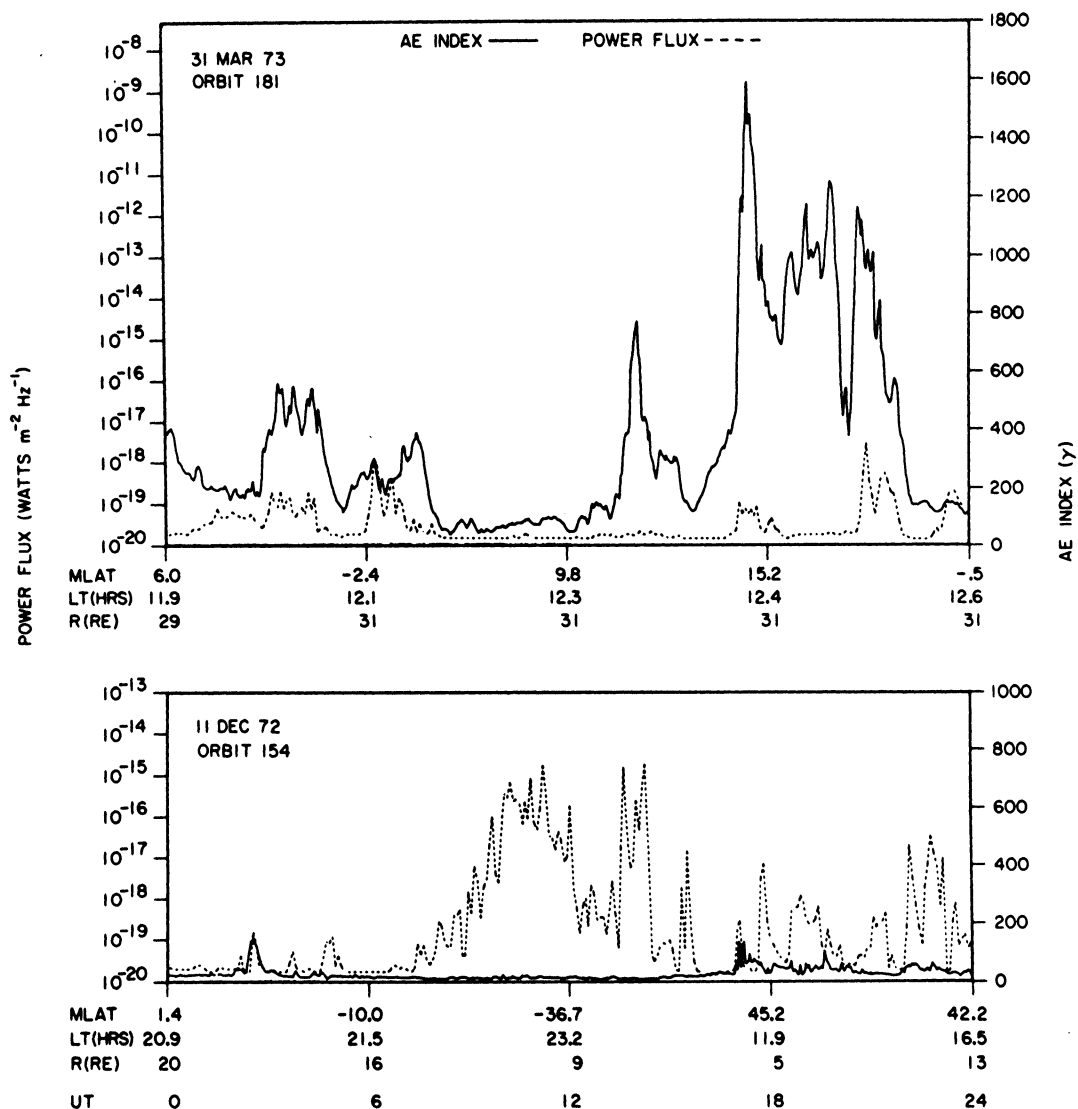


Fig. 2. Two days selected to illustrate cases in which no correlation is evident between the radio emission and the AE index. (Top) An intense auroral kilometric radiation event occurs with essentially no variation in the AE index. (Bottom) A large enhancement in the AE index occurs with only minor variations in the radio emission. Events of this type occur very infrequently.

lation in these cases results from the distribution of ground magnetometer stations being insufficiently dense to detect all the magnetic substorms which occur, in particular, small isolated disturbances at very high magnetic latitudes. This explanation is confirmed for the December 11, 1972, event at the bottom of Figure 2 by the photograph shown in Figure 4, which was taken by the Defense Meteorological Satellite Program (DMSP) spacecraft over the north pole near the time (1100 UT) of maximum radio emission intensity. Although no magnetic disturbance is evident in the *AE* index, the DMSP photograph clearly shows that an auroral substorm was occurring during this event. The intense surge apparent in Figure 4 is traveling westward and lies off the eastern Siberian coast.

High-quality DMSP photographs were not available for the other event, occurring at 1230–1330 UT on March 4, 1973 (not shown). All-sky camera photographs from the Alaska meridian chain (College, Fort Yukon, Inuvik, Sachs Harbour) indicate that auroral activity during that period was confined mostly between Fort Yukon (dip latitude 67°) and Inuvik. Auroras were quite active between 1130 and 1200 UT and then shifted poleward; they were seen near Inuvik until about 1440 UT (through clouds).

STATISTICAL ANALYSIS

To provide a quantitative evaluation of the correlation between the auroral kilometric radiation and the *AE* index, a

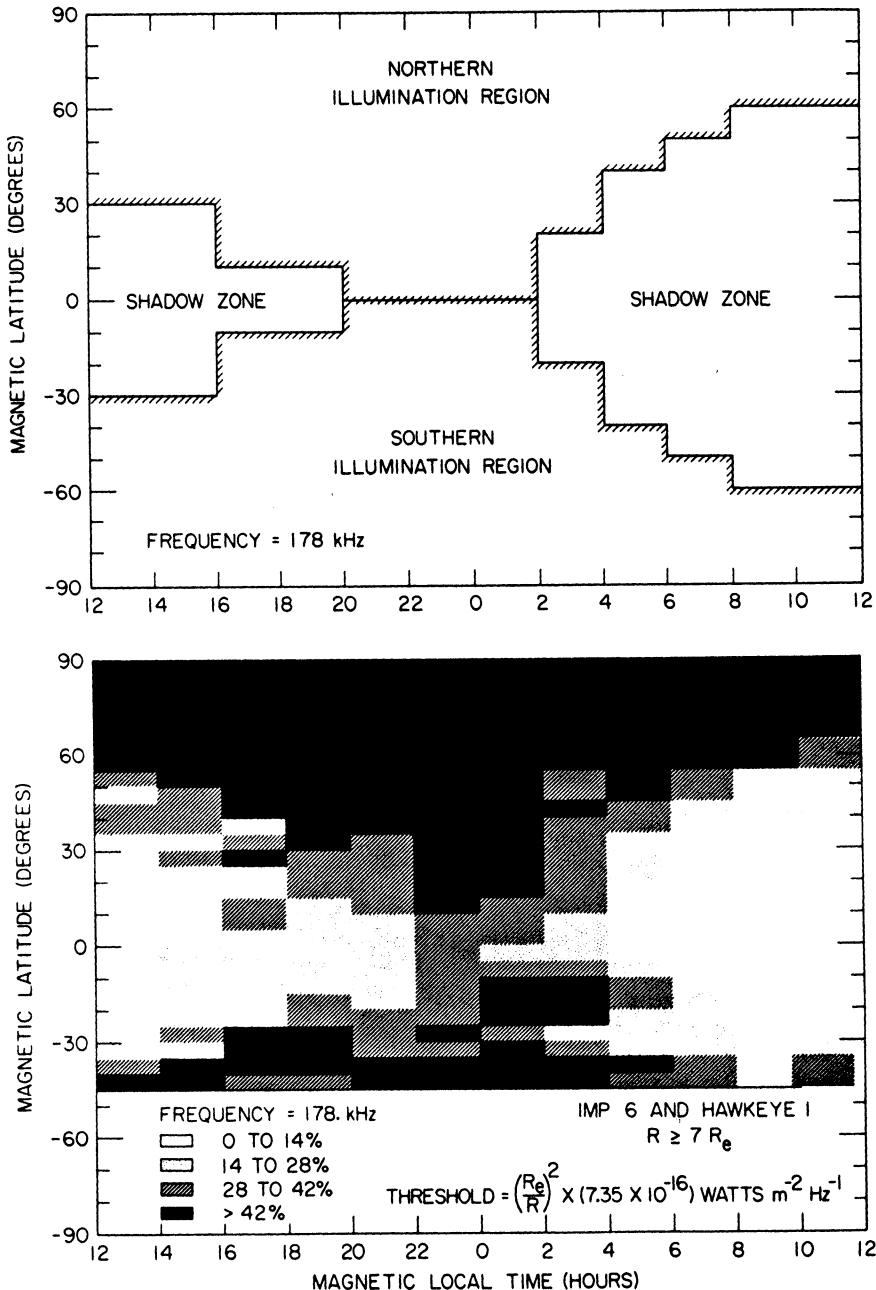


Fig. 3. (Bottom) Frequency of occurrence of auroral kilometric radiation at 178 kHz as a function of magnetic latitude and magnetic local time. A distinct latitudinal boundary is evident in the frequency of occurrence, most of the radiation being beamed into a conical-shaped region over the northern and southern polar regions. (Top) Approximate boundaries of the northern and southern illumination regions.



Fig. 4. DMSP 2 photograph (orbit 457) taken over the northern polar region for December 11, 1972, showing the occurrence of an auroral substorm during the auroral kilometric radiation event shown at the top of Figure 2. The absence of a detectable magnetic disturbance during this event is due to the limited spatial coverage of the ground magnetometer network.

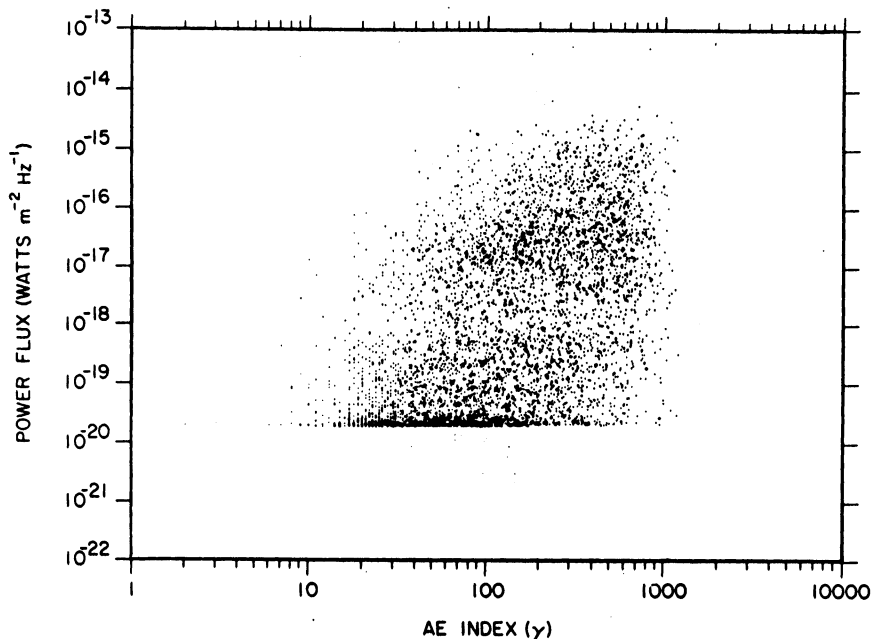


Fig. 5. Scatter plot of simultaneous measurements of the auroral kilometric radiation intensity (normalized to $30 R_E$) and the auroral electrojet index *AE* using 40 days of data from the Imp 6 spacecraft. Each point represents a 10-min average obtained while the spacecraft was in one of the two primary illumination regions shown in the top panel of Figure 3.

statistical analysis has been performed on simultaneous radio intensity measurements from Imp 6 and *AE* measurements from a network of ground magnetometer stations. Simultaneous data were available for 146 days, occurring in the periods from August 31, 1971, to December 3, 1971, and from December 1, 1972, to March 31, 1973. During these periods the local time of apogee moved from ~ 0100 to ~ 2000 hours and from ~ 2000 to ~ 1200 hours, respectively. The data used in the statistical analysis are selected from these periods. To obtain the best correlation, as many as possible of the known factors which could affect the auroral kilometric radiation intensity have been taken into account. To account for the latitudinal cutoff caused by propagation effects, comparisons have been made only when the spacecraft is within the northern illumination region shown in the top panel of Figure 3 and only at radial distances greater than $7 R_E$. Since the radiation intensity varies approximately as $1/R^2$, where R is the geocentric radial distance to the spacecraft, the intensities have been normalized to a radial distance of $30 R_E$ by multiplying the observed power flux by $(R/30)^2$.

To provide directly comparable measurements, the radio emission intensity at 178 kHz and the *AE* index have been averaged over corresponding 10-min intervals. A total of 5702 ten-minute intervals are included in this analysis. A scatter plot of all of these data points is shown in Figure 5. Although a considerable amount of scatter is evident, a very clear correlation can be seen, the mean of the power flux P increasing as the *AE* index increases. For the data points used in this plot the median value of the normalized power flux (at $30 R_E$) is $6.31 \times 10^{-19} \text{ W m}^{-2} \text{ Hz}^{-1}$, and the median value of the *AE* index is 158 γ . If *AE* is greater than 158 γ , then 69.2% of the power flux values are greater than $6.31 \times 10^{-19} \text{ W m}^{-2} \text{ Hz}^{-1}$; whereas if *AE* is less than 158 γ , then 68.7% of the power flux values are less than $6.31 \times 10^{-19} \text{ W m}^{-2} \text{ Hz}^{-1}$. The percentage distributions above and below the median values are summarized in Table 1. (For computational reasons the values used as the medians are not exactly the true medians, but this has no effect

on the significance of a chi-square analysis.) A chi-square test performed on these data shows that a hypothesis of no correlation is rejected at a level of 0.001. The linear correlation coefficient, computed for $\log(P)$ versus $\log(AE)$, is 0.514.

The correlation between the normalized power flux and *AE* is illustrated even more clearly in Figure 6, which shows the average power flux and the standard deviation of the average as a function of the *AE* index. The slope of the best-fit straight line through these points indicates that the power flux P increases approximately as the 1.5 power of the *AE* index. A slight change in the slope of the $\log(P)$ versus $\log(AE)$ curve takes place at about 100 γ , the power flux increasing more rapidly with increasing *AE* at low *AE* values. A computer fit to these averages that weights each point according to its uncertainty indicates that the power flux is proportional to $(AE)^2$ for the points under 100 γ and is proportional to $(AE)^{1.5}$ for the points above 100 γ . The fit for the higher points is much better than the fit for the lower points, possibly because of the uncertainty in the *AE* index determination for *AE* values less than 100 γ .

One factor that might affect the values of these slopes should also be discussed. It has been observed that the frequency at which the peak of the emission spectrum occurs tends to decrease with increasing *AE* [Kaiser and Alexander, 1976]. Since the 178-kHz channel is usually below the peak in the spectrum, there could be an increase in the power flux at 178 kHz due to this downward frequency shift. It appears that this effect would generally be less than 1 order of magnitude and

TABLE 1. Distribution of Power Flux Values as a Function of the Corresponding *AE* Index Value (%)

$P = 6.31 \times 10^{-19}$ $\text{W m}^{-2} \text{ Hz}^{-1}$	Below $AE = 158 \gamma$	Above $AE = 158 \gamma$	Entire Range of <i>AE</i>
Above P	31.3	69.2	48.4
Below P	68.7	30.8	51.6
Total	100	100	100

would make the slopes of the fitted lines in Figure 6 somewhat steeper than they might be if the data were taken at the peak of the spectrum.

DISCUSSION

This study has shown that satellite measurements of auroral kilometric radiation can be used as a sensitive and reliable indicator of auroral magnetic disturbances. Detailed comparisons of the auroral kilometric radiation intensity and AE index variations show that periods of enhanced radio emission intensities at 178 kHz are very closely associated with magnetic disturbances indicative of auroral substorms. Occasionally, events are detected in which no typical substorm features in the AE index can be detected even though greatly enhanced radio emission intensities are being observed. Investigation of cases of this type shows that the lack of correlation is usually due to a failure of the ground station magnetometer network to detect an auroral substorm because of the limited spatial coverage of the magnetometer network. Cases also occasionally occur in which a large magnetic disturbance is detected with no corresponding enhancement in the radio emission. Cases of this type usually occur because the spacecraft is located at a latitude too low to be within the primary illumination region of the auroral kilometric radiation. The number of such cases can be greatly reduced by using only measurements obtained when the spacecraft is within the illumination regions given at the top of Figure 3. A statistical analysis shows that if the auroral electrojet index AE exceeds the median value of 158γ , then the auroral kilometric radiation intensity (normalized to $30 R_E$) has a 69% probability of exceeding the median value of $6.31 \times 10^{-19} \text{ W m}^{-2} \text{ Hz}^{-1}$. The correlation coefficient

between $\log P$ at 178 kHz and $\log AE$ is 0.514. This relatively low correlation coefficient, despite the qualitatively good association of individual radio emission events with magnetic substorms, is apparently due to the poor short time scale (< 1 hour) correlation and to the variable proportionality factor between the radio emission intensity and the AE index from event to event. Long-term averages of the power flux show a very consistent correlation with AE , the power flux increasing approximately as the 1.5 power of the AE index overall. It appears that for lower values of AE the power flux increases as the 2.0 power of AE and for higher values of AE it increases as the 1.2 power of AE . Since AE is directly proportional to the auroral electrojet current, on the assumption that spatial effects average out, the change in the slope of $\log \overline{AE}$ versus $\log \overline{P}$ may suggest that some type of nonlinear saturation effect may occur in the AKR-generating mechanism in high electrojet currents.

The results of this study show that auroral kilometric radiation can be used with good reliability to identify magnetic substorms, provided the radio measurements are taken within the regions of primary illumination for the auroral kilometric radiation and at distances sufficiently remote ($R > 7 R_E$) from the earth to avoid local propagation cutoff effects. In certain situations, auroral kilometric radiation intensity measurements may provide a more useful index of auroral activity than some of the more conventional parameters, such as the AE index. This is particularly true when a near real time monitoring of global auroral activity is needed. Measurements of this type can be obtained on a limited basis from the presently operating Hawkeye 1, Rae 2, and Imp 8 satellites and should be possible on the forthcoming Isee-A, Isee-B, and Dynamic Explorer satellites.

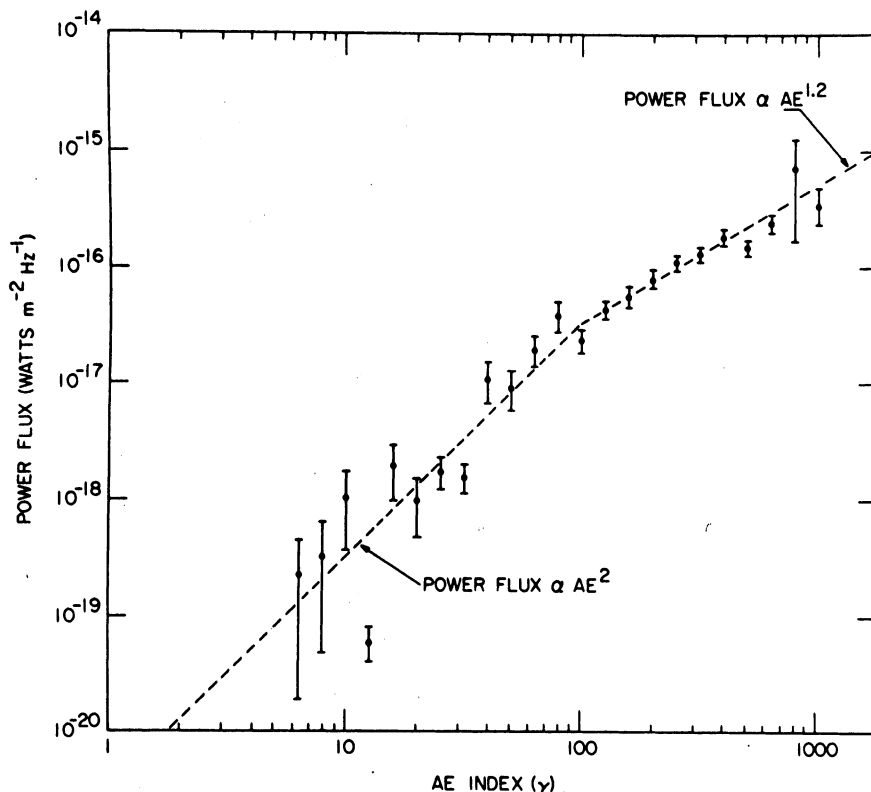


Fig. 6. The average power flux and the standard deviation of the average for the data points shown in Figure 5. The monotonic increase in the average auroral kilometric radiation intensity with increasing AE is clearly evident.

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REFERENCES

- Benediktov, E. A., G. G. Getmantsev, N. A. Mityakov, V. O. Rapoport, and A. F. Tarasov, Relation between geomagnetic activity and the sporadic radio emission recorded by the electron satellites, *Cosmic Res., Engl. Transl.*, 6, 791, 1968.
- Dunckel, N., B. Ficklin, L. Rorden, and R. A. Helliwell, Low-frequency noise observed in the distant magnetosphere with Ogo 1, *J. Geophys. Res.*, 75, 1854, 1970.
- Green, J. L., D. A. Gurnett, and S. D. Shawhan, The angular distribution of auroral kilometric radiation, submitted to *J. Geophys. Res.*, 1977.
- Gurnett, D. A., The earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, 79, 4227, 1974.
- Kaiser, M. L., and J. K. Alexander, Terrestrial kilometric radiation: 3-average spectral properties, *NASA X Doc. 695-76-255*, 1976.
- Kaiser, M. L., and R. G. Stone, Earth as an intense planetary radio source: Similarities to Jupiter and Saturn, *Science*, 189, 285, 1975.
- Kurth, W. S., M. M. Baumbach, and D. A. Gurnett, Direction-finding measurements of auroral kilometric radiation, *J. Geophys. Res.*, 80, 2764, 1975.

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