GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.15, PAGES 3027-3030, AUGUST 1, 1998

Auroral kilometric radiation and the auroral electrojet index for the January 1997 magnetic cloud event

W. S. Kurth,[1] T. Murata,[2] G. Lu,[3] D. A. Gurnett,[1] and H. Matusmoto[4]

Abstract. Auroral kilometric radiation (AKR) observations by Polar and Geotail are compared with the auroral electrojet index for the January 1997 magnetic cloud event. These two-spacecraft measurements are complementary in covering the AKR emission cones throughout the event and, together, reasonably represent the auroral electrojet A_E index. We point out, however, limitations of both the AKR index and the A_E index in providing truly global measurements of substorm activity.

1. Introduction

A correlation between auroral kilometric radiation and magnetic disturbances (as characterized by K_p) was first demonstrated by *Benediktov et al.* [1968] and a direct relationship between AKR and auroral substorm activity was shown by *Gurnett* [1974] and *Voots et al.* [1977]. However, its use as an index in the study of magnetic substorms or related events in magnetospheric physics has been limited [*Murata et al.*, 1997; *Kurth and Gurnett,* 1998]. Some of the earliest studies of this radio emission in the frequency range of a few hundred kHz demonstrated a direct relationship between AKR emission and discrete aurora [*Gurnett,* 1974; *Kurth et al.*, 1975] and the cyclotron maser instability has been invoked as the generation mechanism [*Wu and Lee*, 1979] operating on auroral field lines at distances of $\sim$ 2 to 4 R_E. *Voots et al.* [1977] demonstrated a good correlation between the intensity of AKR at 178 kHz and A_E. *Murata et al.* [1997] developed an index based on the AKR intensity as measured by Geotail integrated over frequency range of 50 to 800 kHz. *Kurth and Gurnett* [1998] developed a similar index using the integrated power flux of AKR in the same frequency range as observed by the Polar plasma wave instrument. The frequency range of 50 to 800 kHz covers most of the AKR spectrum, although the emission does exceed both of these limits on rare occasions. Given that the studies of *Voots et al.* [1977] and *Murata et al.* [1997] showed reasonable correlations between AKR power flux and magnetic indices such as A_E and K_p, it follows that integrating over the entire AKR spectrum for such an index would more accurately capture the full power emitted in the radio regime. This is especially important since the frequency of peak of the AKR spectrum is known to vary with magnetic activity [*Kaiser and Alexander,* 1977] and since the AKR spectrum varies greatly in bandwidth with time.

In this paper, we compare the Geotail AKR index, the Polar AKR integrated power flux, and A_E for the time period of January 10-11, 1997, when a coronal mass ejection (CME) originating on January 6 interacted with the terrestrial magnetosphere [*Carlowicz,* 1997; *Peredo et al.*, 1997]. The purpose of this paper is twofold. First, since this event has attracted the attention of the International Solar Terrestrial Physics community, the combined availability of multi-spacecraft observations of AKR in addition to A_E may be useful in other studies of this particular event by providing global information on the level of auroral substorm activity. Second, we demonstrate that the correlation of these three data sets is not perfect; each has its own limitations. The differences between the AKR observations can be explained primarily by existing and ongoing studies of the beaming characteristics of AKR. Observations are from the plasma wave instruments on Polar [*Gurnett et al.*, 1995] and Geotail [*Matsumoto et al.*, 1994].

2. Observations

The event of interest as described by *Carlowicz* [1997] was driven by a coronal mass ejection first observed by SOHO at 1730 UT on January 6, 1997. The resulting magnetic cloud reached Earth on January 10, 1997, resulting in a peak in auroral activity at 1100 UT. The magnetosphere was compressed by a large pressure pulse at the end of the magnetic cloud on January 11. Since the primary effects on the terrestrial magnetosphere were observed during January 10-11, we concentrate on this period.

Figure 1 shows the observations of AKR for January 10-11, 1997, from Geotail (bottom panel) and Polar (top panel) using spectrograms with similar linear frequency scales up to 800 kHz. In each case, the intensity of AKR is plotted by the use of a false color scheme, however, since the spacecraft are at different and varying distances with respect to the source, we have made no attempt to try to normalize the amplitude scales with respect to each other or as a function of distance for a given platform. We do compare these data sets in a quantitative fashion below, however. The observations from the two spacecraft are similar for much of the latter portion of the plotted interval, but differ in significant ways. For example, prior to about 1800 UT on January 10, Geotail observes only weak, low-frequency emissions in contrast to Polar. Later on January 10 the frequency

[1]Dept. of Physics and Astronomy, University of Iowa.
[2]Dept. of Computer Science, Ehime University, Matsuyama, Japan.
[3]High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado.
[4]Radio Atmospheric Science Center, Kyoto University, Uji, Japan.

Copyright 1998 by the American Geophysical Union.

Paper number 98GL00404.
0094-8534/98/98GL-00404$05.00

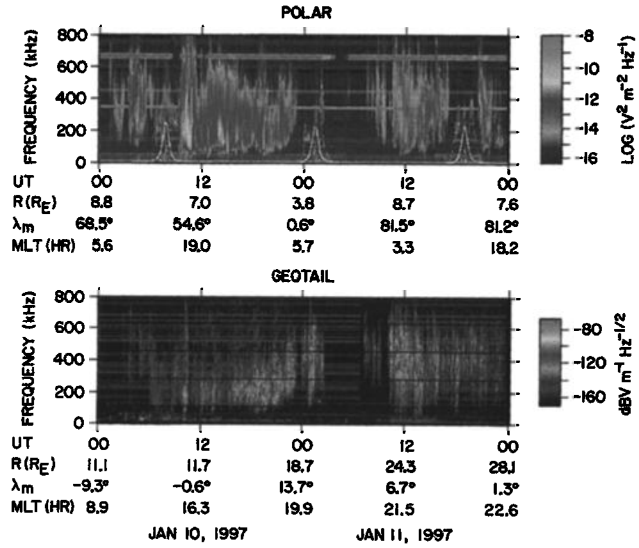

Figure 1. Frequency-time spectrograms showing the Polar (top) and Geotail (bottom) observations of auroral kilometric radiation for January 10-11, 1997. The three intervals in the Polar spectrogram where a white contour is superimposed on the spectrogram are perigee passes; the contour gives the electron cyclotron frequency.

extent of AKR as oberved by Geotail increases with time; the opposite is generally true for the Polar observations. Also, Polar periodically drops into the plasmasphere or lies close enough to the plasmapause to be in a shadow zone for AKR. On the other hand, other features appear somewhat similar. The paucity of emission near mid-morning of January 11 is common to both data sets as is the intensification shortly after noon on this day.

The differences can be explained by the positions of the spacecraft with respect to Earth. Early on January 10, Geotail is on the dayside at low latitudes where earlier studies have shown a shadow zone for AKR [*Green et al.*, 1977]. Near the bottom of the Polar spectrogram, near 0800 on January 10, and near 0200 and 1900 on January 11, we have superimposed the electron cyclotron frequency to indicate times when Polar approaches perigee and is likely to either be directly in the plasmasphere or close enough to it and at low enough latitudes to be in an AKR shadow zone. Below we elaborate further on the specific times when each spacecraft is properly positioned to detect AKR.

Murata et al. [1997] have defined an AKR index which is the result of integrating the power flux of AKR emissions in the frequency range of 50 to 800 kHz, dividing by the 750-kHz bandwidth, and normalizing to 25 R_E. They use units of dBV/m/$Hz^{1/2}$. Specifically, the Geotail index is defined by

$$\epsilon = 20\log_{10}\frac{r}{r_0} + E(r)\mathrm{dBV/m/\sqrt{Hz}}$$

where r is the radial distance to Geotail, r_0 is 25 R_E, and $E(r)$ is the square root of the integrated power flux from 50 to 800 kHz divided by 750 kHz.

Kurth and Gurnett [1998] use a similar scheme with which to indicate the magnitude of the AKR emissions. They integrate the power flux from 50 to 800 kHz and normalize to 9 R_E. Neither group attempts to remove the contribution from type III solar bursts, but these are not important in the time interval plotted here. Also, plasma waves such as upper hybrid resonance bands and the shadow zone near the plasmasphere make the AKR integrated power flux unreliable in the low altitude regions. The Polar AKR integrated power flux is defined as

$$P_I = \left(\frac{r}{9R_E}\right)^2 \sum_{i=M}^{N} P(f_i)\Delta f(f_i)$$

where $P(f_i)$ is the power flux in W/m^2Hz measured in channel i, $\Delta f(f_i)$ is the portion of the spectrum in Hz

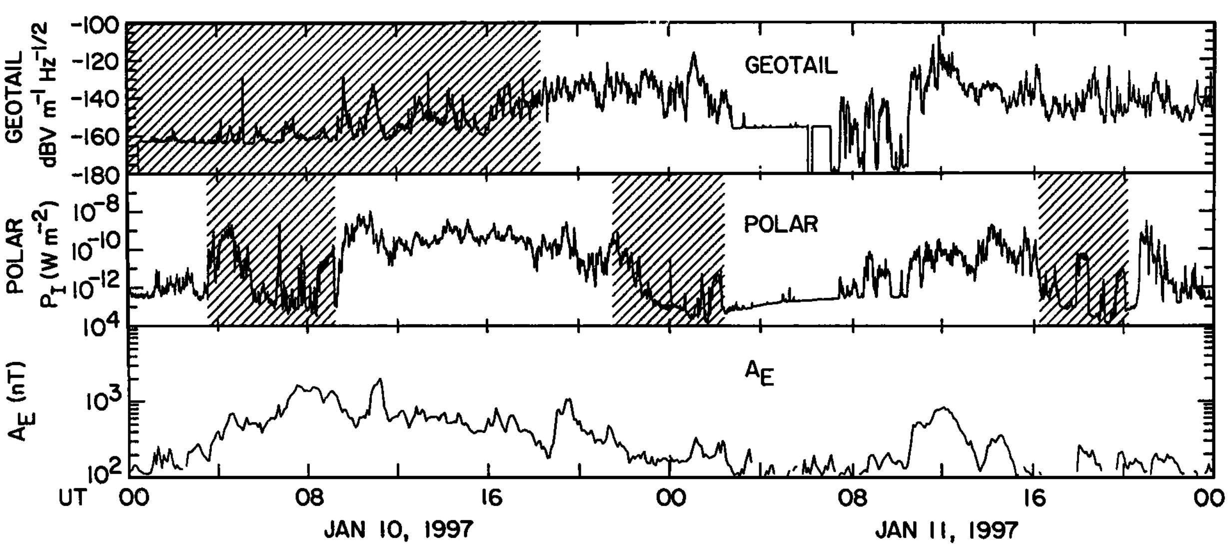

Figure 2. The auroral electrojet index (bottom), integrated AKR power flux from Polar (middle) and the Geotail AKR index for the January 10-11 interval. The hatched regions represent times when one of the spacecraft is outside of the nominal 178-kHz emission cone and when the integrated power flux is not expected to accurately represent AKR activity, in general.

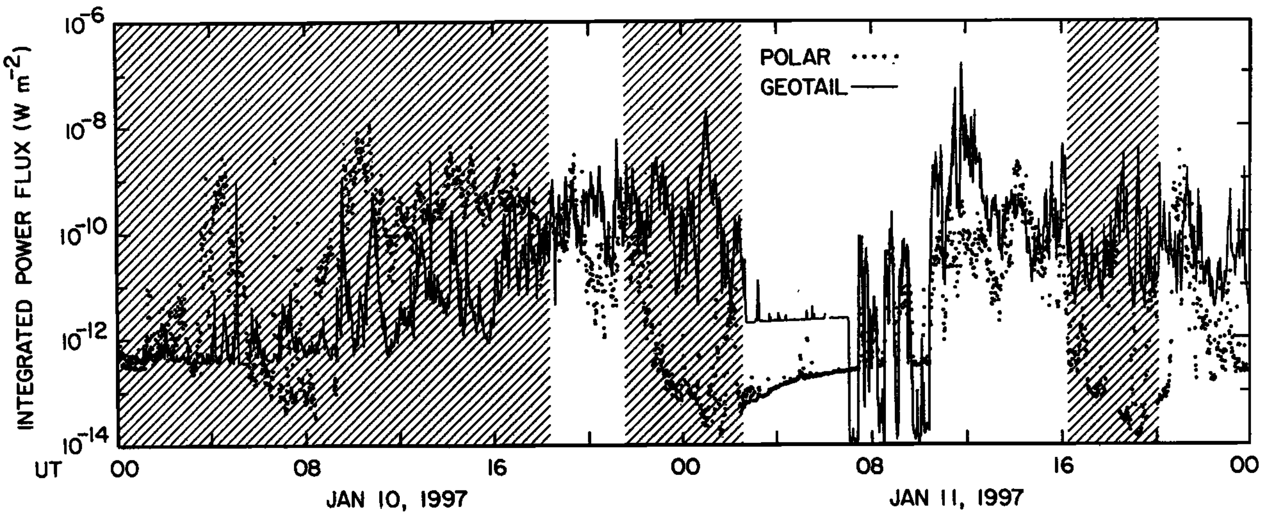

Figure 3. The Polar integrated power flux (dots) from Figure 2 and the Geotail AKR index converted into similar units and normalized for direct, quantitative comparisons. Again, the hatched intervals indicate times when either Polar or Geotail is not within the nominal AKR emission cone.

represented by channel i, and r is the radial distance of Polar in Earth radii. M and N are Polar sweep frequency receiver channel numbers covering the frequency range from 50 to 800 kHz.

Motivated by the work of *Voots et al.* [1977], we have plotted in Figure 2 the Geotail AKR index, the Polar AKR integrated power flux, and the log of the A_E index for the period January 10-11, 1997. Based on the work of *Green et al.* [1977] and *Voots et al.* [1977], we have hatched those intervals in Figure 2 when Geotail or Polar are not within the 178-kHz emission cone. The hatched intervals should not be regarded in an absolute sense, however. AKR is observed albeit weakly by Geotail for most of the period from about 0900 to 1820 on January 10, even though it is not within the nominal emission cone. Also, Polar observes AKR near 0400 and 2200 on January 10, even though it is not within the emission cone. It is entirely likely that the impinging coronal ejecta distorts the magnetosphere in such a way as to significantly change the AKR emission cone, temporarily.

Notice that when the spacecraft are in good position to observe AKR, they provide a good indication of increased magnetic activity as indicated by the A_E index. According to *Zhao and Hoeksema* [1997], the CME originated from a disappearing solar filament between about 1300 and 1500 UT on January 6. The Wind spacecraft observed a shock at 0100 on January 10 and a magnetic cloud between 0500 on January 10 and 0400 on January 11. This cloud contained continuous southward interplanetary magnetic fields for about 12 hours [*Peredo et al.*, 1997] which triggered a geomagnetic storm at about 0600 on January 10. Neither Geotail or Polar was well situated to see the onset of this storm, but increased AKR power was observed by Polar beginning at about 0330 on January 10 and both spacecraft saw increased AKR emission in the interval from about 0930 to 1130. Once Polar entered the AKR emission cone shortly after 0900 on January 10, the observed AKR power flux was elevated and qualitatively tracked the A_E index until after it left the nominal AKR emission cone near 2200 on this day. The Geotail observations after 1820 were elevated and generally featureless until about 0130 on January 11 when there was a dramatic increase in AKR power. All three indicators Geotail, Polar, and A_E show very quiet conditions between about 0230 and about 1000 on January 11. This quiet period probably is due to the northward-directed IMF during the latter half of the magnetic cloud passage [*Peredo et al.*, 1997]. The cloud is followed by a large pressure pulse [*Peredo et al.*, 1997] which evidently results in the large substorm beginning around 1000 on January 11. This is seen by all three indicators in Figure 2, but less clearly in the Polar record. The magnetic activity (according to A_E) tapered off during the remainder of January 11 and was limited by a series of small substorms; AKR activity was apparent throughout the remainder of the day.

Given that the Geotail and Polar investigators have chosen nearly identical integrals of power flux as the bases of their respective indices, but have expressed the results in different units, we can convert the Geotail index into the Polar units of integrated power flux in order to more quantitatively compare the Polar and Geotail AKR observations in Figure 3. Basically, we have converted the Geotail index to $Vm^{-1}Hz^{-1/2}$, squared it, multipled by 750 kHz, and re-normalized the result to 9 R_E. During most intervals when both spacecraft are in the AKR emission cone (non-hatched intervals), the integrated power fluxes from the two spacecraft are quantitatively very similar, such as between 1800 and 1930 UT and near 2130 UT on January 10 and near 0900, between 1330 and 1600 UT, and near 2100 on January 11. However, there are periods when both spacecraft are evidently in good position to observe AKR, but the integrated power fluxes are significantly different. For example, the power flux observed by Geotail is greater near 1800 on January 10, near the intense substorm centered near 1200 UT on January 11, and also near 2330 on this day. There is no clear indication by comparing the spectrograms in Figure 1 for 1800 on January 10 why there should be a significant difference. However for the two differences noted on January 11, it appears the emission seen at Geotail is most intense at higher frequencies, contrary to what is observed by Polar. Such a difference might be surprising given the *Green et al.* [1977] and *Green and Gallagher* [1985] results that the beaming patterns of AKR between 56 kHz and 178 kHz are filled cones centered on auroral field lines near 70 degrees invariant latitude with lower frequency waves resulting in cones with smaller half-angles. However, *Benson and Calvert* [1979] and *Calvert* [1981] both argue that the emission cone may be hollow at higher and lower frequencies. More recent studies by *Murata et al.* [1998] indicate that AKR is not seen much above 500 kHz at high magnetic latitudes. Hence these differences may be due to hollow emission cones at both high and low frequencies.

3. Conclusions

Auroral kilometric radiation provides a good indication of magnetic activity associated with the magnetic cloud event of January 10-11, 1997. While both Geotail and Polar were in poor position to observe the onset of the interaction early on January 10, the later measurements of the integrated AKR power flux show the extended magnetic activity associated with the prolonged southward IMF as well as very quiet conditions associated with the northward IMF during the latter portion of the interaction. The AKR also reflects the intense substorm activity associated with the pressure pulse following the cloud on January 11. Observations of the integrated power flux of auroral kilometric radiation are consistent with the A_E index provided the spacecraft is within the AKR emission cone. It is clear, though, that a single spacecraft in Earth orbit spends considerable time outside of the nominal AKR emission cone and that multiple observation platforms improve the coverage of the radio emissions. Differences observed between the two satellites appear to be related to hollow AKR emission cones at extremely high and low frequencies.

Acknowledgments. The research at The University of Iowa was supported by NASA through Contract NAS5-30371 with Goddard Space Flight Center.

References

Benediktov, E. A., G. G. Getmansev, 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*, 791-794, 1968.

Benson, R. F., and W. Calvert, ISIS 1 observations at the source of auroral kilometric radiation, *Geophys Res. Lett.*, *6*, 479-482, 1979.

Calvert, W., The AKR emission cone at low frequencies, *Geophys. Res. Lett.*, *8*, 1159-1162, 1981.

Carlowicz, M., Satellites, scientists track storm from Sun to surface, *Eos*, *78*, 49-50, 1997.

Green, J. L, and D. L. Gallagher, The detailed intensity distribution of the AKR emission cone, *J. Geophys. Res.*, *90*, 9641-9649, 1985.

Green, J. L., D. A. Gurnett, and S. D. Shawhan, The angular distribution of auroral kilometric radiation, *J. Geophys. Res.*, *82*, 1825-1838, 1977.

Gurnett, D. A., The Earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, *79*, 4227-4238, 1974.

Gurnett, D. A., et al., The Polar plasma wave instrument, *Space Sci. Rev.*, *71*, 597-622, 1995.

Kaiser, M. L., and J. K. Alexander, Terrestrial kilometric radiation 3. Average spectral properties, *J. Geophys. Res.*, *82*, 3273-3280, 1977.

Kurth, W. S., and D. A. Gurnett, Auroral kilometric radiation integrated power flux as a proxy for A_E, *Adv. Space Res.*, in press, 1998.

Kurth, W. S., M. M. Baumback, and D. A. Gurnett, Direction-finding measurements of auroral kilometric radiation, *J. Geophys. Res.*, *80*, 2764-2770, 1975.

Matsumoto, H., et al., Plasma wave observations with the Geotail spacecraft, *J. Geomagn. Geoelectr.*, *46*, 59-95, 1994.

Murata, T., W. Kurth, K. Hashimoto, H. Matsumoto, and H. Yamaguchi, AKR propagation in the vicinity of the Earth, *Geophys. Res. Lett.*, in preparation, 1998.

Murata, T., H. Matsumoto, H. Kojima, and T. Iyemori, Correlations of AKR index with K_p and D_{st} indices, in *Proc. NIPR Symp. Upper Atmos. Physics*, *10*, 64-68, 1997.

Peredo, M, N. Fox, and B. Thompson, Scientists track solar event all the way to Earth, *Eos*, *78*, 477-483, 1997.

Voots, G., D. A. Gurnett, and S.-I. Akasofu, Auroral kilometric radiation as an indicator of auroral magnetic disturbances, *J. Geophys. Res.*, *82*, 2259-2266, 1977.

Wu, C. S., and L. C. Lee, A theory of the terrestrial kilometric radiation, *Astrophys. J.*, *230*, 621-626, 1979.

Zhao, X. P., and J. T. Hoeksema, Is the geoeffectiveness of the 6 January 1997 CME predictable from solar observations?, *Geophys., Res. Lett.*, *24*, 2965-2968, 1997.

D. A. Gurnett, W. S. Kurth, Dept. of Physics and Astronomy, University of Iowa, Iowa City, IA 52242. (e-mail: donald-gurnett@uiowa.edu; william-kurth@uiowa.edu).

T. Murata, Dept. of Computer Science, Faculty of Engineering, Ehime University, Matsuyama, Japan. (e-mail: murata@sp.cs.ehime-u.ac.jp).

G. Lu, High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307. (e-mail: ganglu@ncar.ucar.edu).

H. Matsumoto, Radio Atmospheric Science Center, Kyoto University, Uji, Japan. (e-mail: matsumot@kurasc.kyoto-u.ac.jp).

(Received October 15, 1997; revised January 8, 1998; accepted January 20, 1998.)