# RADIO WAVE REMOTE SENSING BY CLUSTER AND REGATTA

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## ABSTRACT

The Cluster and Regatta missions provide unique opportunities for coordinated remote sensing studies of terrestrial radio emissions. The radio emission of primary interest is auroral kilometric radiation (AKR) which is a powerful radio emission generated over the Earth's auroral zones at frequencies from 100 to 500 kHz. Two types of coordinated measurements could be made: multi-point intensity measurements, and radio interferometry. Multi-point intensity measurements are the easiest to perform and would provide valuable new measurements of the instantaneous beaming pattern of the AKR source. Radio interferometry measurements are more difficult, since they involve the phase of the received signals. At separation distances up to several thousand km, the primary objective of radio interferometry measurements would be to determine motions of the AKR source. Source motion studies are best performed by the Cluster spacecraft, since the separation geometry of these spacecraft gives the best determination of variations in the direction of arrival. The larger Cluster-Regatta separation distances, which will be up to ten thousand km, or more, would be mainly useful for placing limits on the size and coherence of the AKR source.

Key words: Radio emissions; Remote sensing; Radio remote sensing; Auroral kilometric radiation.

## 1. INTRODUCTION

A coordinated Cluster/Regatta mission provides unique opportunities for remote sensing studies of terrestrial radio emissions. In this paper we describe the scientific questions that can be addressed by remote radio measurements from Cluster and Regatta, and comment on the technical issues involved.

There are basically three types of terrestrial radio emissions that could be studied by Cluster and Regatta. These are auroral kilometric radiation, continuum radiation, and upstream 2 $f_p$ radiation. Of these, auroral kilometric radiation is by far the most intense and offers the best possibilities for joint Cluster/Regatta observations. Auroral kilometric radiation, also abbreviated AKR, was first discovered by Benediktov et al. (Ref. 1) and has been studied by numerous investigators, including Dunckel et al. (Ref. 2), Gurnett (Ref. 3), Kaiser and Alexander (Ref. 4), Gallagher and Gurnett (Ref. 5), Mellott et al. (Ref. 6), and Bahnsen et al. (Ref. 7). Auroral kilometric radiation occurs primarily in the frequency range from 100 to 500 kHz. A typical spectrum of AKR is shown in Figure 1. Various direction-finding and radio occultation studies show that the radiation is generated at altitudes of about 1 $R_E$ along the auroral field lines. A sketch of typical ray paths is shown in Figure 2. Comparisons with auroral photographs (Ref. 3) show that the radio emission intensity is very closely correlated with the occurrence of discrete auroral arcs in the local evening sector of the auroral zone. The intensity is highly variable. During active periods the total power radiated is $10^7$ to $10^8$ Watts (Ref. 4), with peak intensities possibly as high as $10^9$ Watts (Ref. 3).

As presently understood, auroral kilometric radiation is believed to be generated by a cyclotron-maser instability at frequencies near or slightly above the electron cyclotron frequency (Ref. 8). The free energy source driving the instability is believed to be anisotropies in the auroral electron distribution. High resolution wideband spectrum measurements show that the emission spectrum consists of numerous narrowband components, typically with bandwidths of a few hundred Hz or less (Ref. 9). The center frequency

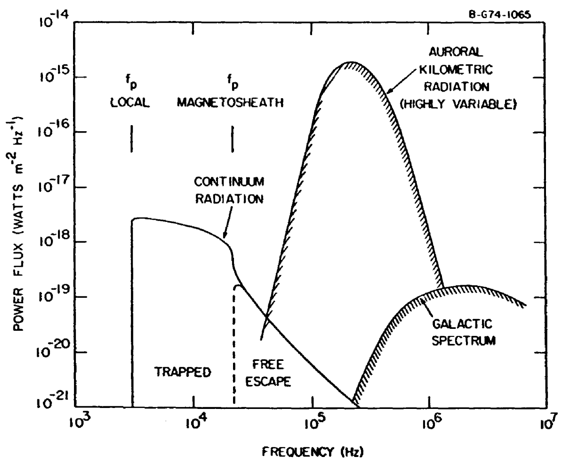


Fig. 1. A comparison of the spectrums of auroral kilometric radiation (AKR), continuum radiation, and galactic radio noise at a radial distance of 30 $R_E$.

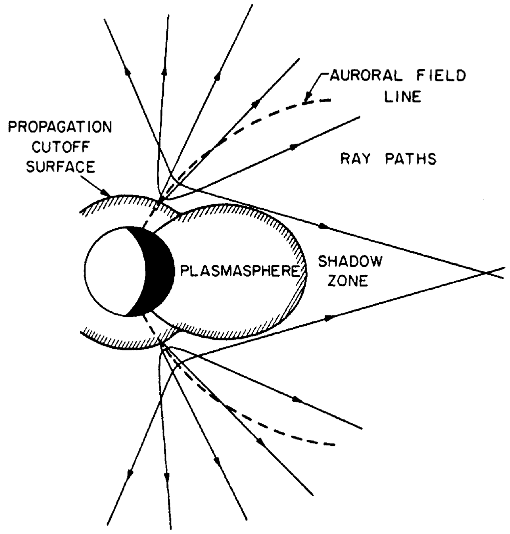


Fig. 2 Representative ray paths of auroral kilometric radiation. This radiation is produced at an altitude of about 1 $R_E$ over the nighttime auroral regions.

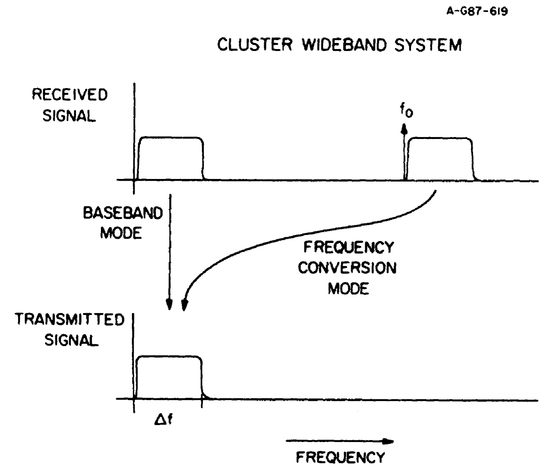


Fig. 3. The frequency conversion system used in the Cluster wideband plasma wave instrument.

of these emissions typically drifts upward in frequency, suggesting that the source is moving downward along the auroral field line. Emissions drifting upward in frequency are also occasionally observed. Typical source velocities, computed assuming that the emission frequency is at the local electron cyclotron frequency, range from ten to several hundred km/sec (Ref. 10). The mechanism responsible for the source motion is not known. One possibility is that the motion may be associated with an acoustic-like disturbance (soliton or shock wave) propagating along the magnetic field line. The inferred velocities are on the order of the ion acoustic speed. Another possibility has been suggested by Calvert (Ref. 11), who has developed a wave feedback model for explaining the fine structure of the AKR. In his model, the characteristic frequencies are determined by reflections from the walls of the auroral plasma cavity, in the same way that the frequency of a laser is determined by reflections from the mirrors at the ends of the laser cavity. Calvert suggests that frequency variations are caused by changes in the plasma density at the walls of the auroral plasma cavity.

## 2. RADIO WAVE REMOTE SENSING INSTRUMENTATION ON CLUSTER AND REGATTA

The only wave instrument on Cluster with an upper frequency limit sufficiently high to study auroral kilometric radiation is the wideband plasma wave instrument. For a description of this instrument see Gurnett et al. (Ref. 12). The purpose of the wideband plasma wave instrument is to transmit waveforms of plasma waves and radio emissions over relatively wide bandwidths. Three bandwidths can be selected, 10 kHz, 25 kHz, or 100 kHz. The waveforms can be sampled at baseband (with no frequency conversion), or in a frequency conversion mode of operation in which the passband is offset by 125 kHz, 250 kHz, or 500 kHz. These modes of operation are illustrated in Figure 3. The waveforms are sampled by an analog-to-digital (A/D) converter and can be transmitted real-time, or stored on the on-board tape recorder. The frequency conversion signal and A/D conversion are phase locked to the spacecraft clock, thereby preserving the phase of the sampled signal.

At present it is not known what wave instrumentation will be selected for flight on Regatta. For the purposes of this discussion we will assume that an instrument comparable to the Cluster wideband receiver will be included on Regatta. Since the orbits of both Regatta-A and Regatta-E are presently contemplated to have high inclinations, greater than 50°, either or both of these spacecraft could be used to make observations of auroral kilometric radiation in coordination with Cluster. Regatta-A probably offers the best possibilities, since its orbit will be closely matched with Cluster. However, as will be described below, Regatta-E also offers attractive possibilities for coordinated operations.

## 3. MULTI-POINT STUDIES OF AURORAL KILOMETRIC RADIATION

The auroral kilometric radiation studies that can be carried out with Cluster and Regatta can be grouped into two categories: multi-point intensity measurements, and radio interferometry. The results that can be achieved in each of these categories will be discussed separately.

### 3.1 Multi-Point Intensity Measurements

Multi-point intensity measurements are the simplest and least demanding comparisons that can be made between Cluster and Regatta. The geometry involved is illustrated schematically in Figure 4. Since the basic plan is to have Cluster rendezvous with Regatta-A, it is anticipated that the separation distance between Cluster and Regatta-A will be closely coordinated, probably at a distance somewhat larger than the typical Cluster-to-Cluster separation distances. As presently planned, the Cluster separations are expected to range from about 1000 to 5000 km. It is probably reasonable to assume that the Regatta-Cluster separation will be on the order of five times the Cluster separations. At apogee (22 $R_E$) this geometry would provide instantaneous measurements of the radiation pattern of the auroral kilometric radiation with angular separations ranging from 0.4° to 10°.

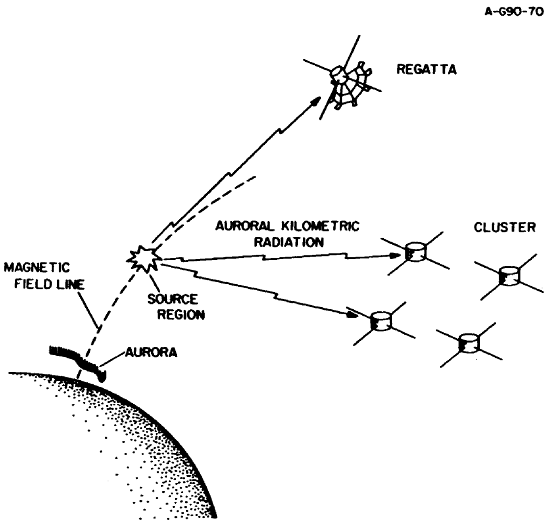


Fig. 4. A schematic illustration of auroral kilometric radiation being simultaneously detected by the Cluster and Regatta spacecraft.

Since Regatta-E is in an entirely different orbit, the separation distance between Regatta-E and Cluster will vary over a large range. Depending on the relative phasing, times will occur when Regatta-A, Regatta-E, and Cluster will all be over the northern polar region at the same time. During these periods, multi-point intensity measurements could be made of the radiation pattern over a very broad range of angular separations, from a few tenths of a degree to as much as ninety degrees or more.

Significant questions still remain concerning the beaming pattern of auroral kilometric radiation. Figure 5 shows two simultaneous spectrums of auroral kilometric radiation obtained by ISEE 1 and 2 at an angular separation of about 2° (Ref. 13). These spectrums show the previously mentioned fine structure of auroral kilometric radiation. Each discrete feature in these spectrograms is believed to represent a separate distinct source. The auroral kilometric radiation apparently consists of a large number (probably hundreds to thousands) of isolated sources distributed over the auroral zone. As can be seen the spectrums at the two spacecraft are quite similar, but some differences are apparent. The differences tend to increase with increasing separation. At the maximum angular separation achievable with ISEE 1 and 2, which in the available data set is about 5°, the spectrums often show substantial differences, indicating that the beamwidth of the discrete features is probably only a few degrees. We have no idea of the beam structure of the individual sources. The beams could be narrow pencil beams, or cone-shaped sheets sweeping across the sky. With two-point

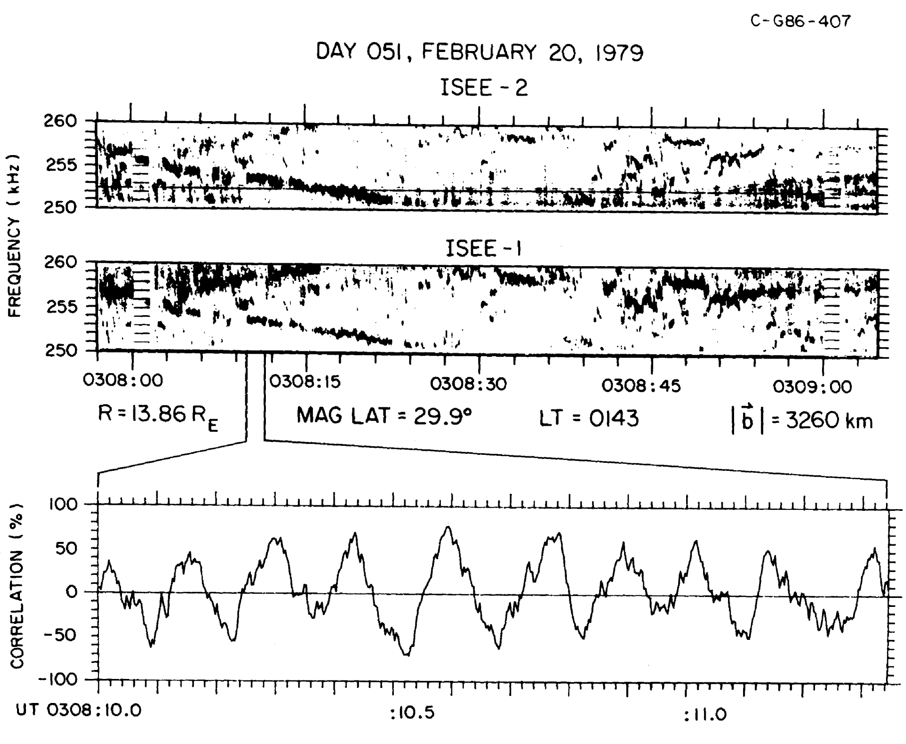


Fig. 5 The top two spectrograms show the spectrum of AKR detected simultaneously by ISEE 1 and 2 (Ref. 13) at a separation distance of 3,260 km. The bottom panel shows the fringe pattern detected in the cross-correlation between the two signals.

measurements there is no way to resolve the instantaneous shape of the beam. With multi-point measurements from Cluster and Regatta it should be possible to make important advances in our understanding of the radiation pattern of auroral kilometric radiation. The structure of the beam is directly linked to the mechanism by which the radiation is generated. For example, if the radiation is generated by laser-like reflections in the auroral plasma cavity, as suggested by Calvert (Ref. 11), then very narrow beams (laser spots) should be detected sweeping across the sky in response to changes in the plasma density at the walls of the auroral cavity. If mirror-like reflections are not important, the radiation is more likely to be generated in a cone-shaped pattern that is azimuthally symmetric around the magnetic field.

### 3.2 Radio Interferometry

If the phase of the received signal is preserved, radio interferometric measurements of auroral kilometric radiation can be performed using Cluster and Regatta. The Cluster wideband waveform system has been specifically designed to provide this capability. Since such measurements require very carefully matched conversion frequencies, filter passbands, and sampling rates, the wideband receiver on Regatta would have to be essentially identical to the wideband receiver being flown on Cluster. The possibility of performing interferometric measurements of auroral kilometric radiation has already been demonstrated by Baumback et al. (Ref. 13) using data from wideband receivers on ISEE 1 and 2. These measurements were first suggested by Shawhan (Ref. 14).

To illustrate the basic principles involved in radio interferometry, a schematic diagram of a radio interferometer is shown in Figure 6. In this system an electromagnetic wave of wavelength $\lambda$ is received by two antennas separated by a distance L. The signals from the two antennas, $E_1$ and $E_2$, are multiplied and averaged to produce a cross-correlation $\langle E_1 E_2 \rangle$. The sign and amplitude of the cross-correlation is determined by the angle of arrival $\theta$ relative to the symmetry axis of the interferometer. If the wavelength of the radiation is much less than the separation distance between the antennas, $\lambda \ll L$, then the cross-correlation

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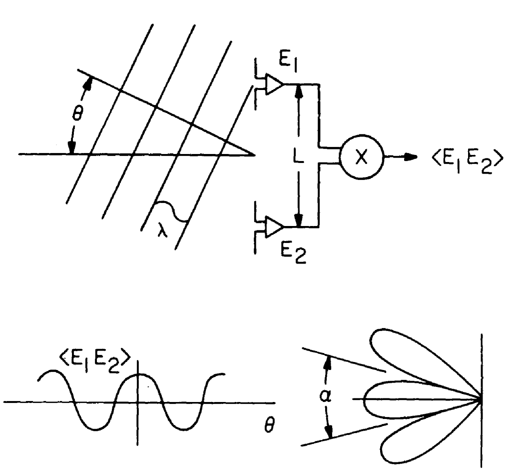


Fig. 6. An illustration showing the angular response of a two-point radio interferometer. The response consists of a series of lobes, each with a beamwidth, $\alpha = \lambda/L$.

varies as the cosine of the angle of arrival. The antenna pattern of the interferometer system then has a series of lobes, each with a beamwidth $\alpha$. For small angles of arrivals, and $\lambda \ll L$, the beamwidth is approximately $\alpha = \lambda/L$. If the separation distance is large, this angle can be quite small. For example, using a typical Cluster separation distance of L = 1000 km, and $\lambda$ = 1 km, $\alpha$ = 0.06°. If a source moves through this fan-shaped antenna pattern, a sinusoidal modulation is produced in the cross-correlation. This modulation pattern is called a fringe. The bottom panel of Figure 5 shows the fringe pattern detected by ISEE 1 and 2 for an isolated burst of auroral kilometric radiation. In this case the signals from the two satellites were received independently on the ground and then combined to produce the cross-correlation.

With Cluster, radio interferometry can be performed using two modes of data collection: burst-mode and real-time. In the burst-mode of operation the data is stored in the on-board tape recorder at a bit rate of about 83 kbit/s (the exact rate is yet to be determined). The burst mode has the advantage that data can be simultaneously recorded from all four Cluster spacecraft, but the disadvantage that the absolute timing accuracy is only a few milliseconds. Since the period of the auroral kilometric signal is only a few microseconds, the absolute phase of the received signal cannot be preserved. However, since the short term stability of the spacecraft clock is very good, $\Delta t/t$ better than $10^{-8}$, the relative phase is well preserved over periods of several minutes. This means that interference fringes can be easily detected and source motions can be measured down to angular rates possibly as low as 0.001°/sec.

In the real-time mode of operation, the data is transmitted directly to the ground at a rate of about 230 kbit/sec (the exact rate is yet to be determined). This mode has the advantage of producing very good timing accuracy, but the disadvantage that a separate ground antenna is required for each spacecraft. In principle, by correlating the arrival time of the telemetry signal with a stable clock in the ground station it should be possible to obtain a timing accuracy of one microsecond or less, which after correcting for the various propagation delays would provide absolute phase measurements. If one microsecond timing accuracy could be achieved, it would be possible to operate the antennas as an array, so that the well-known radio imaging techniques of very-long-baseline-interferometry (VLBI) could be employed. However, at present there are several technical difficulties with real-time VLBI operation and no commitment has been made by ESA or NASA to carry out VLBI operations with Cluster. The most serious problem is that the spacecraft positions cannot be determined with sufficient accuracy (less than 1 km) to permit VLBI imaging. This problem does not affect the burst-mode source motion studies, since absolute phase measurements are not necessary for these types of studies.

Source motion studies are of considerable importance for understanding the mechanism involved in producing the rapidly drifting narrowband features that are so characteristic of the AKR spectrum. It seems most likely that these rapid frequency drifts are caused by a motion of the source along the auroral field line. This hypothesis can be checked by measuring the angular motion of the source and determining whether the motions are consistent with a source moving along the auroral field lines. To perform these measurements it is essential that wideband measurements be obtained from at least three spacecraft. As illustrated in Figure 7, three-point measurements are necessary to determine the plane of a wavefront.

At present, the wideband plasma wave instrument has only been approved for flight on two of the Cluster spacecraft. Therefore, to carry out source motion

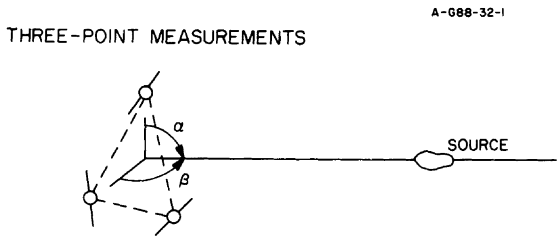


Fig. 7. Three point measurements are required to determine a wavefront, and therefore a line through the source.

studies of AKR, it is essential that a third instrument be flown, either on Cluster, or on Regatta. For this purpose the highest priority should be given to flying the third instrument on Cluster. The reason is that the baseline separations between the three spacecraft should be comparable, and not too large. As can be seen from Figure 7, the angles α and β are not accurately determined if one of the baselines is much smaller than the other two baselines. Thus, a Cluster-Cluster-Regatta combination would not provide good measurements of source motions (this assumes that the Cluster-Regatta separation is much larger than the typical Cluster-Cluster separations). Also, from ISEE 1 and 2, we know that significant differences in the AKR spectrum start to occur at baseline separations of more than a few thousand km. For the relatively large baseline separations expected between Regatta and Clsuter, it is possible that the phase correlation may not be good enough to determine source motions.

Although the highest priority should be given to radio interferometry measurements between the Cluster spacecraft, this does not mean that radio interferometry between Cluster and Regatta is uninteresting. With the ISEE 1 and 2 spacecraft, we were only able to carry out measurements of the two-point correlation out to projected baseline separations of about 3,000 km. A plot of the correlation (visibility) as a function of projected baseline is shown in Figure 8. Large baseline separations are important because they give information on the source size. When the separation distance becomes so large that the beamwidth, $\alpha = \lambda/L$, is smaller than the angular size of the source, then the visibility (correlation) must decrease. As can be seen from Figure 8, the visibility of auroral kilometric radiation remains high (> 90%) out to projected baseline separations of at least 3,000. These visibility plots imply a source diameter of less than 9 km. Because the separation distance betweenRegatta and Cluster will probably range up to ten thousand km or more, coordinated radio interferometry measurements between Regatta and Cluster can be used to provide projected baseline separations significantly larger than were available from ISEE 1 and 2. These measurements will provide improved limits on the source size and coherence of the auroral kilometric radiation.

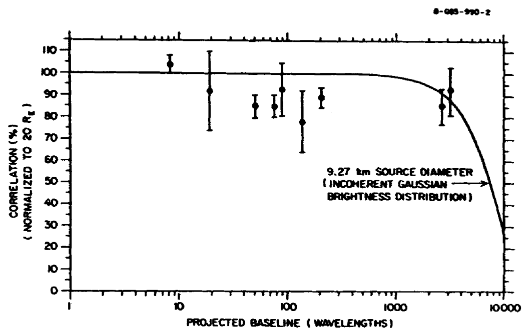


Fig. 8. The two-point correlation as a function of the projected baseline separation from ISEE 1 and 2 (Ref. 13). The correlation remains high out to at least 3,000 km, which indicates that the source is either very small (< 9 km), or highly coherent.

## 4. CONCLUSIONS

The conclusions of this paper are summarized as follows.

- Simultaneous measurements by Cluster and Regatta provide a unique opportunity for performing multi-point studies of auroral kilometric radiation.
- Multi-point intensity measurements are most easily achieved. These measurements would provide valuable new information on the instantaneous radiation pattern of AKR.
- Radio interferometer measurements are more difficult to achieve. These measurements would provide unique new information on AKR source motions. In particular, they would tell us whether the narrowband components are associated with disturbances propagating along the auroral field lines.
- For source motion studies, the highest priority should be given to wideband measurements from three or more Cluster spacecraft, since these spacecraft have the most favorable separation geometry for carrying out source motion studies.
- Radio interferometric measurements between Cluster and Regatta would be mainly useful for determining the two-point correlation at separation distances of several thousand km, or more. These measurements would provide improved limits on the size and coherence of the AKR source.

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