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# Diagnosing the plasmapause with a network of closely spaced ground-based magnetometers

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**Abstract.**
Using cross-phase analysis on data from the closely spaced magnetometers of the BEAR array, we have obtained meridional frequency-latitude profiles of field line resonances (FLRs) from the inner plasmasphere, across the plasmapause and into the plasmatrough. The location of the plasmapause is indicated by the discontinuity in the frequency-latitude profile and is confirmed by a Kp-dependent model plasmapause position. We show that the cross-phase response from stations separated by <0.5 L is inhibited when the plasmapause is overhead. We are thus able to track the motion of the plasmapause polewards during the day by plotting the time development of the cross-phase spectra as a function of latitude. In addition we observe anomalous frequency values obtained from more widely separated station pairs (>1 L) spanning the plasmapause leading us to conclude that caution must be exercised when interpreting the cross-phase response from pairs of stations at mid-latitudes.

## 1. Introduction

The local eigenfrequency of a standing toroidal Alfvén wave in the magnetosphere can be diagnosed using cross-phase and related techniques applied to data from a pair of latitudinally spaced magnetometers [e.g., *Menk et al.*, 1994, and references therein]. When cross-phase is applied to data from a chain of magnetometers along a magnetic meridian, the form of the local Alfvén eigenfrequency continuum can be determined in both the plasmatrough [*Waters et al.*, 1995] and the plasmasphere [*Menk et al.*, 1999].

Both the plasmasphere and plasmatrough display natural Alfvén eigenfrequencies which monotonically decrease with increasing latitude or L-shell, being separated by the plasmapause region across which the density changes by a factor ~ 100 [e.g., *Chappell et al.*, 1970]. In general, the local Alfvén resonance response is dominated by the leading order variations in amplitude and phase expected at the resonance [e.g., *Southwood*, 1974] and for a pair of suitably closely spaced magnetometer stations spanning a slowly varying natural Alfvén frequency profile, the cross-phase response is dominated by a peak which indicates the resonance frequency approximately mid-way between the stations [e.g, *Menk et al.*, 1994]. However, if the stations span a region where the eigenfrequency varies more rapidly, there is likely to be a cross-phase response due to the local Alfvén speed variations as well as to the local resonance. Consequently, data from a dense network of magnetometers offers the possibility of diagnosing the position of the plasmapause and monitoring its motion with local and/or universal time.

The Baltic Electromagnetic Array Research (BEAR) project [*Korja*, 1998] was part of a multi-instrument geophysical study of the Baltic Shield region. The BEAR instrumentation, however, also provides coverage with unrivalled spatial resolution of the expected plasmapause region in the magnetosphere. In this letter, we use BEAR data to make high resolution cross-phase measurements of the plasmapause. We report on a range of signatures which can be used to infer the plasmapause location, and show how the motion of the plasmapause can be monitored. Further, we show that the station pairs spanning the plasmapause region can produce unexpected responses in the cross-phase spectra, and highlight that care should be taken when interpreting the cross-phase spectra from more widely spaced arrays in the vicinity of the plasmapause.

## 2. Data

The BEAR project involved the operation of 70 magnetometer and magnetotelluric stations between 15 June and 25 July 1998. Temporary installations supplemented by existing stations of the observatory network, the UK Sub-Auroral Magnetometer Network (SAMNET) and the International Monitor for Geomagnetic Effects (IMAGE), provided a dense array of closely spaced magnetometers covering an area of around 15° in latitude and 25° in longitude. The data was sampled at 2 seconds resolution, usually in the local magnetic (HDZ) coordinate system. Where the magnetometer was aligned with geographic (XYZ) coordinates, the data was preprocessed to rotate it into HDZ coordinates using the local value of declination.

To carry out the cross-phase analysis across the plasmapause, two subsets of BEAR stations were chosen lying close to magnetic meridians and with maximum station coverage. The first set comprises 8 stations lying within 0.75° of the 105° magnetic meridian (MM105) and with an average station separation of 1.5° in latitude. The second set comprises 7 stations, lying within 0.75° of the 102° magnetic meridian (MM102) with an average latitudinal separation of 1.7°. Figure 1 shows a map of the MM105 and MM102 stations and Table 1 gives their locations. The magnetic local time at MM105 is UT + 2 hours 48 minutes and at MM102 is UT + 2 hours 36 minutes. A day was selected for detailed analysis by examining the dynamic cross-phase spectrum of the H-component for each day of the BEAR project's operation using the station pair B36-B37. The day chosen for this initial study, 24th June 1998, showed a clear resonance response which persisted for more than 9 hours.

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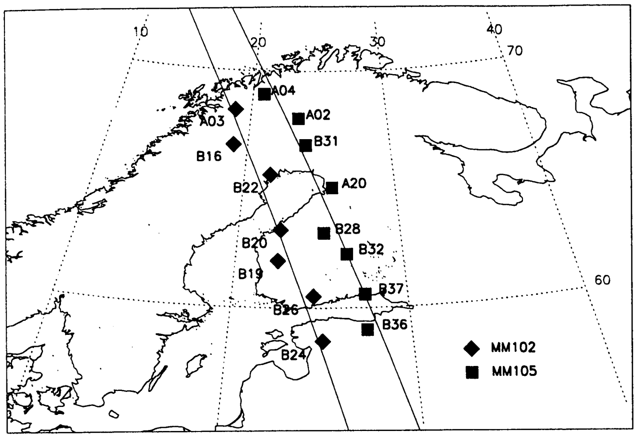


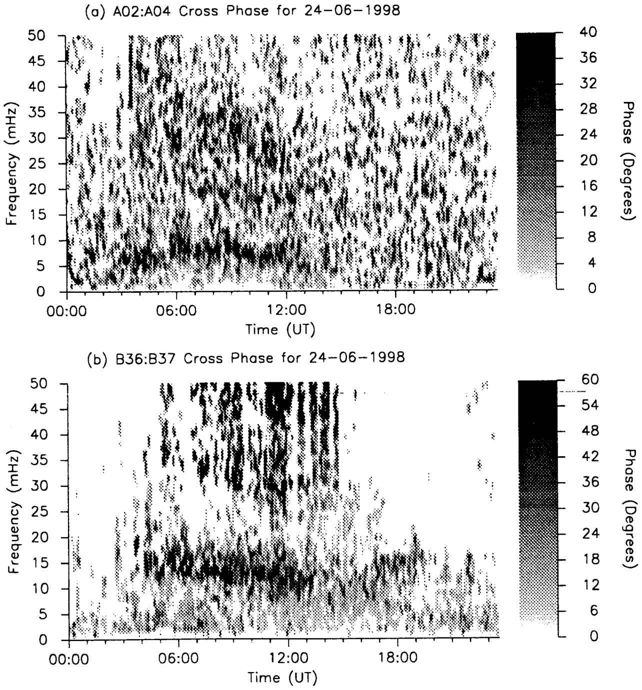
**Figure 1.** Map showing the location of the BEAR magnetometers along the 102° (MM102) and 105° (MM105) magnetic meridians (solid lines).

## 3. Analysis and Results

The dynamic cross-phase spectra from the immediately adjacent station pairs along MM105 were constructed by applying a 512 point FFT every 300 seconds through the day yielding a frequency resolution of ~0.98 mHz. The spectra obtained from the northernmost (A02-A04) and southernmost (B36-B37) pairs are shown in Figure 2. The monochrome representation of the spectra here shows only the positive values of phase difference, the negative phase values having been binned with zero phase (indicated by white). Full colour versions were used in the actual analysis, however, the duration and frequency of the continuous resonant response are still clearly seen in Figure 2. For the B36-B37 station pair the resonance is characterised by a cross-phase peak whose frequency decreases from 15 to 10 mHz between 0400 and 1300 UT. The resonance starts earlier at A02-A04 and ranges between 5 and 10 mHz with more of an "arch" structure. This difference in behaviour may be attributed to the different regimes sampled by the stations. The mid-point of B36-B37 is at L=3.3 and hence is expected to be within the plasmasphere for the prevailing Kp. The modelling work of *Poulter et al.* [1984] suggests that the local field line eigenfrequency within the plasmasphere steadily decreases between sunrise and sunset due to refilling from the ionosphere. At L~5.9 the A02-A04 pair is at a relatively high latitude and is probably sampling the plasmatrough. *Mathie et al.* [1999] observed the "arch" signature in cross-phase spectra from stations at L>4.5, confirming the results of *Waters et al.* [1995] and concluding that it is likely that the "arch" signature is at least partly generated by the diurnal variation in field line length in the outer magnetosphere.

**Table 1.** BEAR station locations in corrected geomagnetic coordinates for 1998.

| Code | Name | MM | MLAT | MLON | L |
|---|---|---|---|---|---|
| B36 | Peipsjarvi | MM105 | 55.21 | 104.46 | 3.07 |
| B37 | Virolahti | MM105 | 56.80 | 105.04 | 3.34 |
| B32 | Hankasalmi | MM105 | 58.62 | 104.98 | 3.69 |
| B28 | Kivijarvi | MM105 | 59.59 | 104.26 | 3.90 |
| A20 | Oulu | MM105 | 61.54 | 105.73 | 4.40 |
| B31 | Pello | MM105 | 63.46 | 105.38 | 5.01 |
| A02 | Muonio | MM105 | 64.62 | 105.69 | 5.44 |
| A04 | Kilpisjarvi | MM105 | 65.78 | 104.36 | 5.94 |
| B24 | Sindi | MM102 | 54.77 | 102.20 | 3.00 |
| B26 | Nurmijarvi | MM102 | 56.81 | 102.54 | 3.34 |
| B19 | Honkajoki | MM102 | 58.46 | 101.45 | 3.66 |
| B20 | Voltti | MM102 | 59.83 | 102.14 | 3.96 |
| B22 | Boden | MM102 | 62.67 | 102.73 | 4.62 |
| B16 | Jokkmokk | MM102 | 63.69 | 101.36 | 5.09 |
| A03 | Abisko | MM102 | 65.21 | 102.27 | 5.69 |


(a) A02:A04 Cross Phase for 24-06-1998

(b) B36:B37 Cross Phase for 24-06-1998

**Figure 2.** Dynamic cross-phase spectra derived from the MM105 station pairs (a) A02-A04 and (b) B36-B37.

Clearly we would expect to see a latitude at which the transition from the 'high-latitude' to the 'low-latitude' frequency characteristics occurs as we move equatorward from A02-A04 to B36-B37. Station pairs B31-A02 and A20-B31 display an "arch" structure similar in character to A02-A04. However, there is little resonant response from B28-A20, the cross-phase being close to zero until 1130 UT. The remaining pairs, B36-B37, B37-B32 and B32-B28, show no sign of the "arch" structure although the duration of the resonant response is different in each case.

More detailed analysis of the data from MM105 was undertaken at 09:30 UT, when a resonant response in the cross-phase from all of the closest station pairs, except B28-A20, was observed. Static cross-phase spectra were computed from 20 minutes of data centred on 09:30 UT, yielding frequency values with a resolution of 0.8 mHz. Together with the cross-phase peak, the gradient method indicators of a coincident zero crossing in the amplitude difference and a unity crossing in the power ratio [*Baransky et al.*, 1985] were examined as additional supporting evidence for the local resonance frequency. Any difference in frequency values determined by the cross-phase and gradient method was combined with the frequency resolution to produce an estimate of the error in the resonance frequency.

Figure 3a shows the derived resonance frequencies plotted as a function of latitude for MM105. The square, diamond and triangle symbols indicate a relative separation of 1, 2 and 3 stations respectively for the station pair used to derive each data point. For instance, station pair B36-B32 has

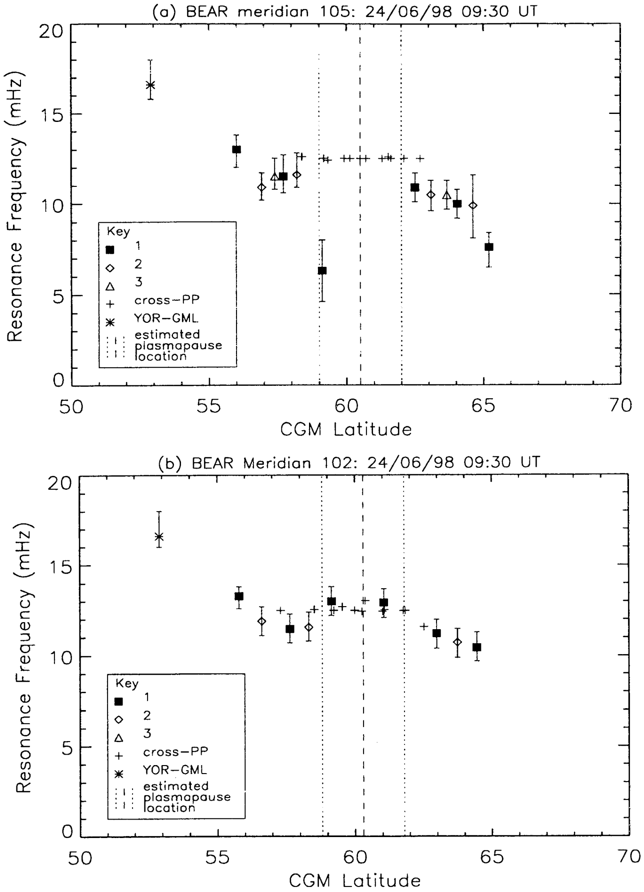


**Figure 3.** Resonance Frequency versus CGM latitude for (a) MM105 and (b) MM102.

a separation of 2. The value derived from the SAMNET stations YOR (50.9°N, 79.0°E CGM) and GML (54.9°N, 78.2°E CGM) is indicated by an asterisk. Although well to the west of the region of interest, this data point is shown for comparison as being representative of the inner plasmasphere with a mid-point at L∼2.8. Station pairs which span the region defined by the pair B28-A20 produce values marked by a plus symbol ('cross-PP' in the key); the significance of these values will be discussed later. The frequency-latitude curve displays a discontinuity at which the monotonic decrease in frequency with increasing latitude is interrupted by an increase in frequency as expected at the plasmapause [*Orr*, 1975]. The resonance frequency variation at MM102 (Figure 3b) is broadly similar (within experimental error) to that from MM105 across the latitude range, confirming the location of the plasmapause.

An independent estimate of the location of the plasmapause can be derived from the Kp values prevailing up to 18 hours prior to any local time using the technique described by *Yeoman et al.* [1989] and references therein. Although not as accurate as direct satellite measurements it can give realistic estimates for Kp<4. The average Kp in the 18 hours prior to 09:30 was nearly 3, indicating moderately disturbed geomagnetic conditions. The Kp-derived plasmapause location at 09:30 UT for the two meridians MM105 and MM102 is shown in Figures 3a and 3b as a dashed vertical line. The dotted lines represent the associated error of ±0.4 L in the estimated plasmapause position [*Orr and Webb*, 1975]. The coincidence of the Kp-derived plasmapause location with the discontinuity in the cross-phase resonance profiles confirms that we are observing the effects of the plasmapause on the FLR eigenfrequencies.

As discussed in relation to Figure 2, a clear cross-phase peak was not apparent in the dynamic spectra for all nearest-neighbour station pairs at all times; it is possible that this could be related to the location of the stations relative to the plasmapause. To test this hypothesis, Figure 4 shows the timelines of the continuous resonant response from each adjacent station pair to give a latitude vs MLT plot of the resonance signature observed at MM105 (Figure 4a) and MM102 (Figure 4b). The horizontal lines indicate the times at which clear, continuous dynamic and static cross-phase spectral peaks were observed for each station pair. At latitudes below 61° there is a marked trend for the response to start at later times with increasing latitude. At higher latitudes, the cross-phase response is seen more continuously in the morning sector. This behaviour can be compared with the time development of the Kp derived plasmapause which is again shown by the dashed and dotted lines. As expected for periods of moderate activity, the plasmasphere expands and the plasmapause moves poleward through the day. Our results show clearly that as the plasmapause moves between two stations the cross-phase response is inhibited until both stations are once again clear of its influence.

The 'cross-PP' frequency values (marked with a plus symbol in Figure 3) were obtained using station pairs spanning the latitude of the Kp-derived plasmapause location and the discontinuity in resonance frequency. Figures 3a and 3b appear to show that this cross-plasmapause signature has a remarkably constant frequency of 12.5 mHz and is approximately independent of both the separation and the mid-point location of the station pairs. This is in contrast to the variations in cross-phase frequency values derived from station pairs entirely within either the plasmasphere or the plasmatrough.

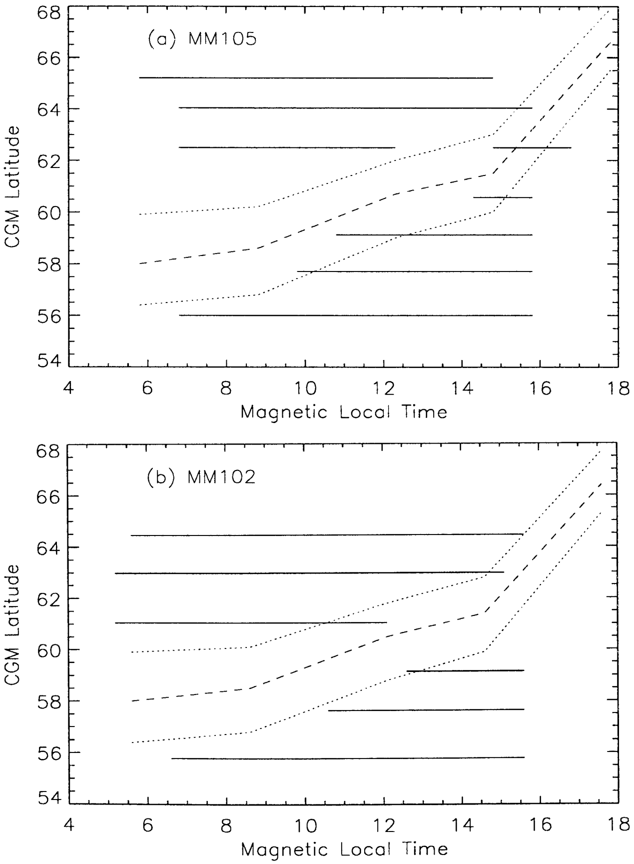


**Figure 4.** Times of continuous resonant cross-phase response (solid lines) compared with the Kp derived plasmapause location (dotted and dashed lines) plotted as a function of Magnetic Local Time for (a) MM105 and (b) MM102.

## 4. Discussion and Conclusions

Using data from the BEAR magnetometer array, we have presented the first direct cross-phase measurements of the discontinuous change in the local Alfvén eigenfrequency across the plasmapause. The resonance frequencies inferred from the cross-phase analysis between the most closely spaced station pairs, show the expected decrease with latitude of the FLR eigenfrequencies on either side of the discontinuity. Moreover, the latitudinal movement of the plasmapause with local time was monitored and found to be in good agreement with the predictions of a model using the variation of Kp to estimate the plasmapause location. Our measurements confirm the value of the cross-phase technique in measuring the local field line resonance frequencies. However, they also indicate potential problems with the interpretation of data from more sparsely distributed magnetometers at mid-latitudes.

The presence of the plasmapause between the most closely-spaced stations is seen to suppress the detection of a peak in the dynamic cross-phase spectrum. It is possible that there could still be a weak resonance signature in the spectra, however, the amplitude of the cross-phase peak is sufficiently close to the background phase fluctuations to make it very difficult to resolve. This effect is observed for station separations in the range ~0.1–0.5 L which is comparable to the expected width of the plasmapause for the prevailing Kp [e.g. *Chappell et al.*, 1970]. The anomalous 12.5 mHz signal is obtained only from station pairs spanning the plasmapause with a separation of >1 L. We infer that this represents an upper limit on the width of the plasmapause at this time. It is clear that the assumption of a monotonic and slowly varying background Alfvén frequency profile is not valid in the region of the plasmapause as the resonance frequency profile passes rapidly through 2 turning points with a spatial scale of the same order as the typical FLR width of 0.1–0.3 L at these latitudes [*Menk et al.*, 1999]. The situation may be further complicated by the existence of structures such as detached plasma regions within the plasmapause. For station pairs with a separation of the same order as the width of the plasmapause we might expect the cross-phase response to be very sensitive to location when in the vicinity of the plasmapause. This could explain why the frequency estimate of 7 mHz at 59° from B32-B28 on MM105 is not substantiated by the estimate of 13 mHz from B19-B20 at a similar latitude on MM102 (Figure 3).

The responses obtained from more widely separated stations (>1 L) which span the plasmapause yield a much clearer cross-phase peak, however, this is at a remarkably constant frequency which is independent of the separation and the mid-point latitude of the station pairs used. This anomalous response is seen up to the maximum station separation of ~3 L. For station pairs spanning a slowly varying monotonic Alfven frequency profile, the cross-phase response should be characterised by a phase peak whose amplitude increases with station separation and whose frequency is representative of the local resonance frequency near the station pair mid-point. If the stations span a region with a rapidly varying background Alfvén speed, additional features in the cross-phase spectrum may be expected. In this case, spectral characteristics and phase variations from the driving fast mode waves might become important in addition to the natural local resonances [c.f., *Pilipenko and Fedorov*, 1994], particularly if the background variations have the same spatial scale as the local Alfvén resonance widths. The presence of two turning points in the background non-monotonic Alfvén frequency profile may also affect the cross-phase signatures. It is not clear whether either of these effects can generate a cross-phase peak at a frequency which is independent of station separation across the plasmapause and this remains a subject for future work.

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