Phase coherence analysis of a field line resonance and solar wind oscillation

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[1] Discrete field line resonances (FLRs) are a common occurrence in the magnetosphere. However, the source of the stable, discrete FLR frequencies is still an unresolved problem. Recent work has proposed that discrete, continuous oscillations in the solar wind directly drive magnetospheric FLRs. However, these studies have only concentrated on common frequency and amplitude comparisons. This paper presents a new technique which utilizes either Fast Fourier Transform or wavelet cross-phase measurements to demonstrate a high degree of phase coherence between a 1.7 mHz FLR observed with the SuperDARN Kodiak radar and ACE SWE oscillations in solar wind plasma density. A statistical analysis which simulates the solar wind as red noise indicates with 99% confidence that the FLR oscillation is the same as the solar wind plasma density variation. **Citation:** Fenrich, F. R., and C. L. Waters (2008), Phase coherence analysis of a field line resonance and solar wind oscillation, *Geophys. Res. Lett.*, 35, L20102, doi:10.1029/2008GL035430.

1. Introduction

[2] Field line resonances (FLRs) are standing MHD Alfvén waves along geomagnetic field lines [Dungey, 1967; Radoski, 1967]. They are known to be associated with auroral arc formation [Lotko *et al.*, 1998] and energization of radiation belt electrons [Rostoker *et al.*, 1998; Degeling *et al.*, 2008], both current topics of scientific study and debate. FLRs are also used for remotely sensing magnetospheric plasma densities [Waters *et al.*, 2006]. Thus it is important to understand all aspects of this phenomenon. However, the source of the stable, monochromatic FLR frequencies remains an unresolved problem. Most often the discrete FLR frequencies are attributed to their coupling with magnetospheric cavity/waveguide modes [Kivelson and Southwood, 1985; Samson *et al.*, 1992] or Kelvin-Helmholtz instabilities on the magnetospheric flanks [Southwood, 1974; Chen and Hasegawa, 1974]. However, these sources cannot reconcile the variable nature of the magnetosphere with the observed multiple discrete FLR frequencies [Fenrich *et al.*, 1995].

[3] Recent work has proposed that discrete compressional MHD oscillations [Stephenson and Walker, 2002; Eriksson *et al.*, 2006] and Alfvénic oscillations [Prikrýl *et al.*, 1998] in the solar wind may directly drive magneto-

spheric FLRs. Other studies have shown similarities between individual discrete solar wind compressional oscillations and global magnetospheric pulsations observed in geosynchronous magnetic fields [Kepko and Spence, 2003] and in low latitude ground based magnetometer measurements [Villante *et al.*, 2007]. Kessel *et al.* [2004] reported that total Pc5 power of Alfvénic and compressional fluctuations in high speed solar wind streams was correlated with total Pc5 power of ground-based magnetic field pulsations. Furthermore, during individual high speed events they observed discrete frequency ULF fluctuations in the 1–4 mHz band in the solar wind but no one-to-one correspondence with the ground-based frequencies. Except for Villante *et al.* [2007] who included some coherence spectra results, all of these studies have used frequency, amplitude, and direct time series comparisons. However, spectral cross-phase is an additional parameter which can be exploited. If solar wind oscillations drive FLRs then they should exhibit phase coherence with the FLR during the wave event. In this paper we present a new technique that utilizes either Fast Fourier Transform or wavelet cross-power and cross-phase measurements to determine the degree of phase coherence between a 1.7 mHz FLR observed with the Super Dual Auroral Radar Network (SuperDARN) Kodiak HF radar [Greenwald *et al.*, 1995] and oscillations in solar wind plasma density observed by the SWEAP instrument on the ACE spacecraft [McComas *et al.*, 1998]. A statistical analysis simulating the solar wind with red noise is included to determine the statistical significance of the cross-power and cross-phase results.

2. Data Analysis

[4] The FLR event under investigation occurred from 01:30 to 02:45 UT on 21 November, 2003. The magnetosphere was in the recovery phase of a large magnetic storm which began on 20 November, 2003. For the four hour interval surrounding the FLR event the ACE spacecraft measured above average magnetic fields, flow speed and density. The level 2, 64 second resolution, solar wind proton density data measured by the ACE SWEAP instrument is shown with symbols in Figure 1a. A time lag of 65 min has been applied to the data based on the minimum variance method of Weimer *et al.* [2003]. The minimum variance method yielded a ~50 min delay to the location of the bowshock plus an additional 15 min was added to account for wave propagation through the magnetosheath and magnetosphere. Timing of the sharp increase in solar wind density at 01:30 UT to sharp positive deflections in GOES 10 B_z and dayside 210 Magnetic Meridian magnetometer measurements yielded the same delay time. Note that delay times between 51 min to 80 min yield similar results.

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Figure 1. Raw data (symbols) and interpolated data (solid line) for (a) ACE SWE proton density and (b) SuperDARN Kodiak beam 14 Doppler velocity averaged over gates 9–11 for the 00:00–04:00 UT interval on November 21, 2003. The ACE SWE data has been time lagged by 65 min.

Following the sharp increase at 01:30 UT, the proton density clearly exhibits a 10 min period oscillation with peak to peak values of the order of 5 cm^{-3} . One ‘spike’ in the data just after 02:20 UT has been removed. This point and 7 other single point gaps in the data were linearly interpolated and the resulting data are shown as the solid line in Figure 1a.

[5] Between 01:30 and 02:45 UT the SuperDARN Kodiak HF radar observed a 1.7 mHz (10 min period) pulsation in the backscattered Doppler velocity. Each SuperDARN HF radar scans along 16 different azimuthal beam directions in succession with each beam spanning 3.2 degrees in azimuth while simultaneously sampling 75 range gates at 45 km resolution. The 1.7 mHz pulsation observed by the Kodiak radar peaked in amplitude on range gates 9–11 and was observed on all 16 radar beams. This pulsation was identified as a field line resonance with peak amplitude localized between ~ 62 – 63 degrees AACGM latitude and an azimuthal wave number of ~ 4 . To facilitate cross-power and cross-phase analyses, the 60s sampled radar data from beam 14 were spatially averaged over range gates 9–11 and then linearly interpolated to the same 64s time points as the ACE data. The interpolated radar Doppler velocity data are shown as the solid line in Figure 1b. The symbols in Figure 1b indicate the 60s Doppler velocity data after spatial averaging.

[6] Before spectral analysis both data sets were detrended with a 30 min running average to remove low frequency trends. Dynamic Fast Fourier Transform (FFT) cross-power and cross-phase between the ACE SWE and Kodiak beam 14 data sets were calculated using a one hour FFT window with a Hanning weighting and a 1 point shift. Note that the cross-power spectrum of two time series is the discrete Fourier transform of their cross-correlation and the cross-phase yields the phase difference between the two time series at each frequency [Ramirez, 1985]. If two data sets are correlated and exhibit a high degree of phase coherence at a specific frequency then the cross-phase measurement will be approximately constant with time. In order to provide a quantitative measure of the degree of phase coherence, the variance in cross-phase over one hour intervals at each frequency and time were calculated. The

cross-power and variance in cross-phase between ACE SWE proton density and Kodiak Beam 14 data are shown in Figures 2a and 2b, respectively. The lower values of the variance in cross-phase indicate coherent phase between the two time series.

[7] Given that random noise might generate low cross-phase variance with the sliding FFT window method, we have used a red noise model to determine the statistical probability that the observed cross-power and phase coherence could be due to random noise in the solar wind. Note that red noise is characterized by a $1/f^2$ power law, similar to that of the solar wind [Goldstein and Roberts, 1999]. Thus 5000 four hour, red noise data sets were simulated for the solar wind using the equation $x_i = x_{i-1} + \text{random}(\text{seed}) \times \sigma \times 0.65$, where σ is the standard deviation of the detrended four hour ACE SWE data set. The 0.65 multiplication factor was applied to match the standard deviations of the detrended red noise and solar wind data sets. The simulated red noise data sets were then cross-spectra analysed with the Kodiak Beam 14 radar data and the 5% significant levels calculated at the times and frequencies when the radar data exhibited strong power. The 5% significance levels correspond to the cross-power and variance in cross-phase values that will be reached or exceeded by simulated red noise data sets only 5% of the time. The black contour lines in Figures 2a and 2b indicate these 5% significance levels with respect to red noise.

[8] For the FFT analysis used here a 1 hour FFT time interval has been used which limits the temporal resolution of the analysis. In order to improve this, we have repeated the processing using a wavelet analysis. The wavelet cross-power and cross-phase analysis between the ACE SWE and Kodiak Beam 14 data used the six hour interval from 23:00 UT on 20 Nov to 05:00 UT on 21 Nov using a Morlet wavelet at $1/4$ octave frequency intervals [Waters et al., 2006]. The wavelet cross-power and variance in cross-phase results for the 00:00–04:00 UT interval and 0.5–4 mHz band are shown in Figures 3a and 3b. Note that in this wavelet transform the minimum frequency is 0.5 mHz and the variance in cross-phase decreases with decreasing frequency unlike the FFT method. The solid black contour lines show the 5% significance level with respect to red noise.

Figure 2. Plots of FFT (a) dynamic cross-power and (b) dynamic variance in cross-phase between ACE SWE density and Kodiak beam 14 Doppler velocity. The black contours correspond to the 5% significant level with respect to red noise.

[9] For comparison FFT cross-power and variance in cross-phase were calculated between Kodiak beam 14 and the other beams of the radar which also observed the 1.7 mHz field line resonance. The cross-power and variance in cross-phase between beam 14 and beam 1 are shown in Figure 4. The 5% significant level shown in Figure 4 is calculated in the same manner as that described above for the solar wind density, however the standard deviation in this case corresponds to the four hour detrended Kodiak beam 1 data set. Figure 4 shows significant cross-power and variance in cross-phase values during the 1.7 mHz FLR between $\sim 02:00$ – $02:45$ UT. Similar values of significant cross power were seen between beam 14 and other beams of the radar during the 1.7 mHz FLR. Significant values of variance in cross-phase were also seen between beam 14 and the other radar beams during the 1.7 mHz FLR with the strongest levels of phase coherence found between beam 14 and adjacent beams for which minimum log of variance levels reached values of ~ 1.0 .

3. Discussion

[10] Figure 1 clearly shows a 1.7 mHz (10 min period) oscillation in ACE SWE density at the same time the 1.7 mHz field line resonance is observed by the SuperDARN Kodiak radar between 01:30–02:45 UT. The FFT and wavelet cross-power and variance in cross-phase in Figures 2 and 3 show that the 1.7 mHz FLR interval is the only interval that simultaneously exhibits both cross-power and variance in cross-phase above the 5% significance levels. Since power and phase are independent, the probability of this occurring randomly for a simulated red noise data set is only 1%. Furthermore, the minimum level of variance in cross-phase with beam 14 during the 1.7 mHz FLR is as low for the solar wind oscillation (Figure 2b) as it is for Kodiak beam 1 (Figure 4b). This indicates that the phase coherence between the solar wind plasma density oscillation and the 1.7 mHz FLR is similar to the phase coherence between two extreme beams of the Kodiak radar.

[11] These results indicate that a high degree of phase coherence exists between the solar wind proton density oscillation and the 1.7 mHz FLR. The observed values of phase coherence and cross-power are statistically unlikely to occur due to random chance. The 1.7 mHz FLR pulsation begins at approximately the same time as the solar wind

Figure 3. Wavelet (a) cross-power and (b) variance in cross-phase between ACE SWE density and Kodiak beam 14 Doppler velocity. The black contours correspond to the 5% significant level with respect to red noise.

Figure 4. Dynamic plots of FFT (a) cross-power and (b) variance in cross-phase between Kodiak beam 1 and Kodiak beam 14 Doppler velocity. The black contours correspond to the 5% significant level with respect to red noise.

oscillation given an appropriate time delay and ceases approximately two cycles after the solar wind oscillation ends which suggests that the solar wind oscillation directly drives the FLR which decays away soon after the solar wind oscillation ceases.

[12] ACE total magnetic field measurements (not shown) also indicate a 1.7 mHz oscillation that is coherent with the FLR and 180° out of phase with the proton density oscillation suggesting this particular solar wind oscillation is a slow mode type compressional MHD wave. MHD waves are known to be modulated and amplified at the bowshock [Kessel *et al.*, 2004] and can be transmitted through the magnetopause, preferentially when the magnetopause is open [Kwok and Lee, 1984]. For the 20–21 Nov, 2003 event the solar wind has a dominant IMF B_y component making conditions favourable for magnetic reconnection on the flanks of the magnetopause. The 1.7 mHz FLR observed by the Kodiak radar occurs at $\sim 15:30$ MLT and exhibits a westward or sunward phase propagation which is consistent with a source such as solar wind MHD compressional wave transmission through a dusk flank reconnection region. In addition, alignment of the solar wind compressional wave fronts along the spiral IMF direction can also result in westward phase propagation from dusk [Sibeck *et al.*, 2003].

4. Conclusions

[13] A variance in cross-phase technique combined with cross-power and red noise statistics has been described. This method can identify FLRs that have similar discrete continuous oscillations in the solar wind with a high degree of confidence. For the 21 Nov, 2003 interval presented the analysis yields significant levels of cross-power and phase coherence between ACE SWE plasma density and Kodiak Doppler velocity data during a 1.7 mHz FLR at 01:30–02:45 UT suggesting that the FLR may be directly driven by the oscillation in the solar wind. For the 1.7 mHz FLR event the degree of phase coherence is the same between two extreme beams of the radar as it is between the solar wind data and a single beam of the radar. In future more FLR events will be analyzed with this technique to determine the occurrence statistics of discrete FLRs associated with solar

wind MHD waves, and to pinpoint any special conditions required for these events to occur.

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