

## FAST - Geotail correlative studies of magnetosphere ionosphere coupling in the nightside magnetosphere

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**Abstract.** Data from conjunctions between FAST and Geotail were used to examine the physical processes which mediate coupling between the magnetotail at 30  $R_E$  and the nightside auroral zone near 1.5  $R_E$ . During one conjunction, Geotail observed a large scale recovery of the plasma sheet and several partial thinnings. Two of these encounters with the plasma sheet boundary were recorded by Polar at high latitudes on the dawn flank, indicating the global nature of the plasma sheet motions. Wavelet analysis of the FAST and Geotail electric and magnetic field data revealed low frequency waves which may be involved in magnetosphere-ionosphere coupling. A brief electromagnetic pulse with a frequency of 0.9 Hz consistent with the Alfvénic structures discussed by Lysak [1997] was observed by FAST. Oscillations near this frequency were also observed in the Geotail electric field data. Signatures consistent with field line resonances in the frequency range 0.03 to 0.05 Hz were recorded by both FAST and Geotail. This is the first time these types of structures have been observed simultaneously in the auroral zone and the magnetotail.

### I. Introduction

Although the primary goal of the FAST mission is to use high time resolution data to study in detail small scale auroral plasma processes, such as wave-particle interactions and auroral electron acceleration, FAST also offers many opportunities to examine large scale magnetospheric processes. The current availability of data from many other satellites and ground stations, as well as theoretical support and numerical modeling, which can be used together with data from FAST, make it possible to perform a thorough global investigation of the aurora. In 1993, the International Auroral Study (IAS) was established to promote this type of study. Among the areas of focus for the IAS are the relationship between the structure and dynamics of visible auroral arcs and satellite

measurements of acceleration processes, large scale properties of electric fields and current systems in Earth's ionosphere, and the relationship between auroral arcs and magnetospheric substorms and boundaries in the magnetosphere. During the first broad IAS campaign period in January and February 1997, a number of conjunctions occurred between the FAST, Geotail and Polar satellites. These events provide an exciting new opportunity to examine the aurora and the relation of the aurora to the interaction of Earth's magnetosphere with the solar wind. Because the entire data set available for the January and February 1997 conjunctions is so large and diversified, a complete study of these events is beyond the scope of this letter. Therefore we will focus on the conjunction which occurred on January 18, 1997 between 03:00 and 08:00 UT as a typical example of the data set available. Detailed analysis of the other FAST-Geotail conjunctions will be presented in a future paper.

### II. Conjunction Selection and Analysis Techniques

The conjunction intervals of primary interest are time periods when Geotail was near midnight in the neutral sheet and FAST was above the nightside auroral zone. Although this letter will concentrate on one specific FAST orbit, the whole conjunction interval includes 4-6 hours centered on the time that Geotail was at midnight. Imaging of the auroral zone by the Polar Ultraviolet Imager, which operates in the wavelength range from 1300 Å to 1900 Å [Torr et al., 1995] was available during the longer interval. The Polar images were used to correlate auroral features with in situ particle observations by FAST and large scale magnetospheric reconfigurations as indicated by changes in the FAST and Geotail electric field data. The Polar images also provided a more continuous picture of what was happening at the foot of the field lines linking Geotail in the magnetotail and FAST in the auroral zone. When possible, the electric field data from Polar [Harvey et al., 1995], which has an apogee of 9  $R_E$ , were also used to identify large scale changes in the magnetospheric configuration at higher latitudes.

Magnetosphere-ionosphere coupling is thought to be mediated by waves [see, e.g. Lysak, 1997 and references therein] so the focus of our investigations will be examination of the low frequency electromagnetic waves observed by FAST and Geotail. By studying the nature of the waves observed in different regions of the magnetosphere we hope to gain an improved understanding of how processes in the magnetotail influence auroral plasma dynamics. The electric and magnetic fields from FAST [Ergun et al., 1997] and from Geotail [Tsuruda et al., 1994] were analyzed with both the continuous Morlet wavelet transform [Sigsbee et al., in progress] and the more traditional fast Fourier transform. Although the continuous wavelet transform is computationally slower than the FFT, the

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wavelet transform is better suited to analyzing non-stationary signals with sudden variations, such as those associated with substorms. The wavelet transform is not constrained by a fixed window size and as a result often reveals details that are not visible in a Fourier spectrogram.

### III. January 18, 1997 Conjunction Example

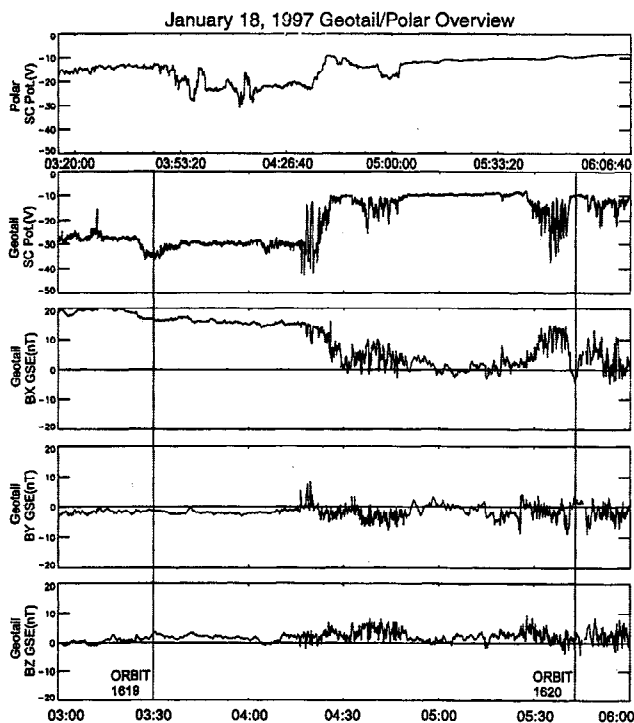
An overview of the Geotail data including spacecraft potential and the magnetic field in GSE coordinates during the time period from 03:00 to 06:00 UT when Polar imaging was available is shown in Figure 1. The times of the northern auroral FAST orbits 1619 and 1620 are marked. The Polar spacecraft potential is also shown in Figure 1.

At the start of the primary conjunction interval at 03:00 UT, Geotail was traveling towards midnight from an initial position of  $X_{GSE} = -30 R_E$  and  $Y_{GSE} = 2.5 R_E$ . Images from the Polar UVI instrument at this time show intense and active aurora. Geotail was in the northern tail lobe outside of a thinned plasma sheet during FAST orbit 1619. Around 04:20 UT, Geotail abruptly enters the plasma sheet and encounters the neutral sheet, and then briefly leaves again at about 04:30. These two crossings of the plasma sheet boundary were also recorded by the Polar electric field instrument about 15 minutes later, implying that the disturbance propagated at a speed on the order of 100 km/sec. During this time, the Polar images show the

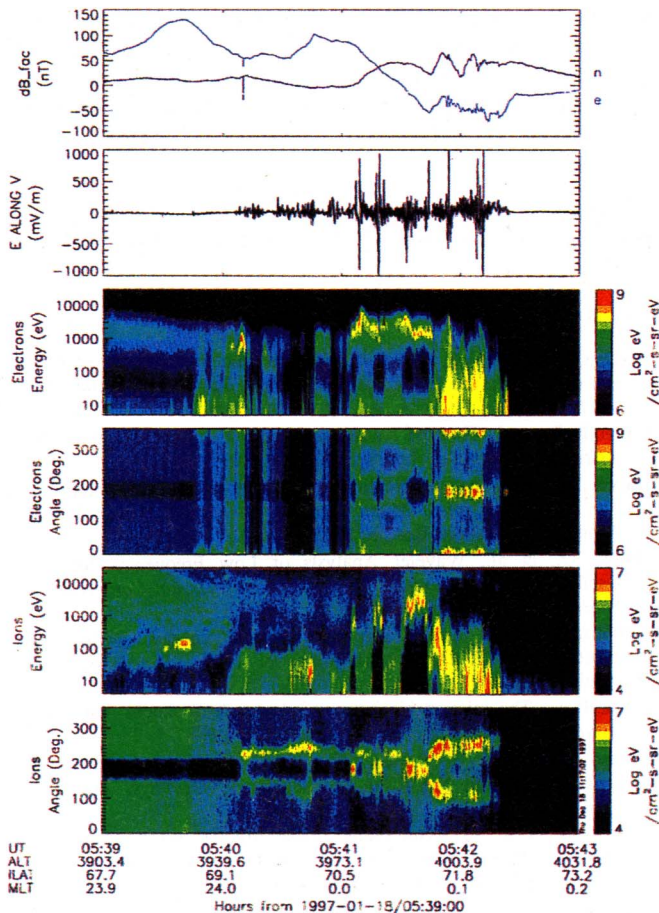
growth of a pronounced bright region in the poleward region of the auroral oval extending from about 20:00 LT to midnight. A few minutes later, the region breaks up into a series of smaller spots and moves slightly duskward. Geotail re-entered the plasma sheet at 04:35 UT and left ten minutes later at 04:45 UT. A second encounter with the plasma sheet boundary was also recorded by Polar from 04:50 to 05:00 UT. The structure and timing of these two partial thinnings of the plasma sheet as recorded by the spacecraft potential on Geotail ( $X_{GSE} = -30 R_E$ ,  $Y_{GSE} = 2.0 R_E$ ) and Polar (near apogee at 6.3 MLT) is remarkably similar considering the differences in the locations of the two spacecraft.

At the time of the next FAST auroral pass, the plasma sheet recovered and Geotail once again encountered the current sheet at 05:30 UT. Using the Tsyganenko 89 field model with a  $K_p$  of 3, the FAST and Geotail footpoints during FAST orbit 1620 were traced down to an altitude of 100 km in the ionosphere. During orbit 1620, the Geotail footpoints remained more or less stationary, moving only approximately  $0.1^\circ$  in latitude. FAST came within a few degrees of the Geotail footpoint on this pass through the northern auroral zone. The simultaneous ultraviolet images show a persistent recovery remnant located between  $70^\circ$  and  $73^\circ$  geomagnetic latitude and 0 to 0.5 MLT. Although the bright region dimmed slightly, it remained stationary during this FAST pass through the nightside auroral zone. An overview of the FAST data with the despun electric field, magnetic field data in field aligned coordinates, the electron energy and pitch angle spectrograms, and the ion energy and pitch angle spectrograms is shown in Figure 2. The alternating ion conics and ion beams observed from 05:40 to 05:42 UT are features typical of many FAST passes through the auroral zone, even during fairly quiet times. FAST traveled through a region of upward and downward going electrons [Carlson et al., 1997] between  $71.4^\circ$  and  $72.3^\circ$  geomagnetic latitude at 0.1 MLT, which corresponds reasonably well to the bright region observed by Polar.

Several regions of field-aligned currents can be seen in the eastward component of the FAST magnetic field data. Immediately after the sudden change associated with the field aligned currents, both the magnetic field and the electric field began to undergo rapid fluctuations. Wavelet scalegrams of the Geotail and FAST electric field data showing the oscillations near 1 Hz are presented in Figure 3. When the oscillations observed on FAST were analyzed with the Morlet wavelet, a short electromagnetic pulse with a frequency of 0.9 Hz at 05:41:54 was seen in the component of the electric field along the spacecraft velocity and the spin axis (eastward) component of the magnetic field. This sinusoidal pulse was also easily identifiable in the time series of the electric and magnetic field data and lasted for 2.5 periods. The ratio of the perpendicular field components  $\delta E_{ALONG V} / \delta B_{EAST}$  was  $2.8 \times 10^4$  km/sec for this wave packet. This is close to the local Alfvén speed calculated from FAST magnetic field and ion composition data [Klumpp et al., 1997] which was  $3.5 \times 10^4$  km/sec during the wave pulse. The large amplitude electric field spike in the center of this wave packet appears in the scalegram as an intense, narrow peak at all frequencies above 1 Hz. A spike such as this one is similar in form to a delta function, and therefore has a very broad spectrum. Another brief oscillation lasting for 4 periods at a slightly higher frequency was seen 12 seconds later. These two wave pulses occurred on the edges of a region of low energy counterstreaming electrons in the middle of a long ion conic. Wavelet analysis of the Geotail data was per-



**Figure 1.** Overview of data from Geotail and Polar for the January 18, 1997 conjunctions between FAST and Geotail from 03:00 to 06:00 UT. The starting times of the northern auroral zone FAST passes on orbits 1619 and 1620 are marked with vertical lines. The Polar spacecraft potential has been offset by 15 minutes from the Geotail spacecraft potential to allow for the travel time between these two spacecraft. Note the similarity between the structure of the crossings of the plasma sheet boundary as seen in the Geotail spacecraft potential at 04:20 and in the Polar spacecraft potential 15 minutes later.



**Figure 2.** Overview of FAST fields and particles data for orbit 1620 with the despun electric field along the spacecraft velocity, magnetic field data in field aligned coordinates, the electron energy and pitch angle, and the ion energy and pitch angle.

formed on an interval starting several minutes before FAST was in the auroral zone to allow for the Alfvén travel time from Geotail to FAST, which was estimated to be 10 minutes. Electric field oscillations close to 1 Hz were also seen in wavelet analysis of the Geotail electric field measured along the spinning booms. These observations are consistent with the propagation of an Alfvén wave from Geotail to FAST, as described in more detail in the next section.

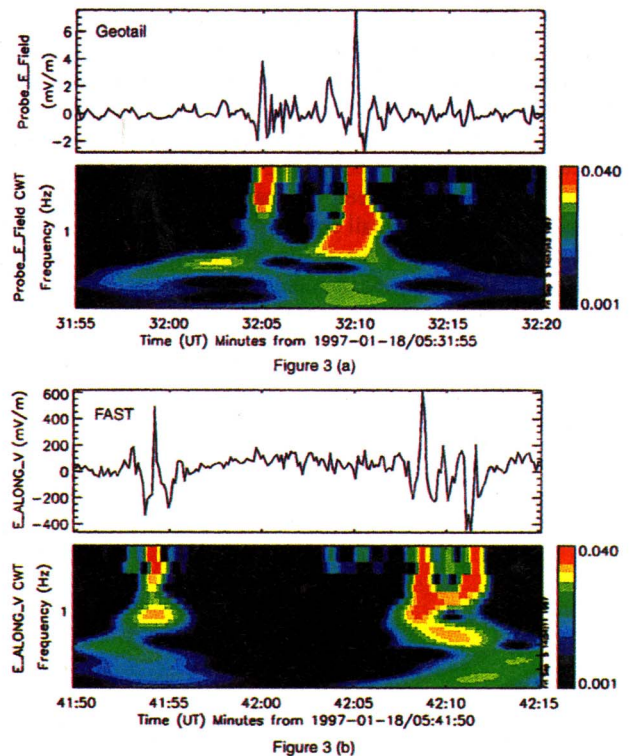
Lower frequency oscillations of the fields were also recorded by both FAST and Geotail. Wavelet analysis of the Geotail spin averaged (3 second resolution) electric and magnetic fields within the plasma sheet from 05:30 to 05:40 shortly before FAST was in the auroral zone shows peaks in the spectra of  $B_x$  GSE and  $E_y$  GSE in the Pi 2 range between 0.01 and 0.02 Hz similar to those observed on GEOS-2 by Holter et al. [1994]. Higher frequency oscillations were observed between 0.03 and 0.05 Hz and close to 0.1 Hz. Geotail was traveling at 1 km/sec through the magnetotail, so peaks from 0.03 to 0.05 Hz could represent the transit of the satellite through spatial structures on the order of 20 to 30 km. Power is also seen in the frequency range 0.03 to 0.05 Hz and near 0.1 Hz in the wavelet scalegrams of FAST spin averaged (5 second sampling rate) fields data for orbit 1620. Because FAST is moving at close to 6 km/sec through the auroral zone, the low frequency peaks between 0.03 to 0.05 Hz seen in the wavelet scalegrams

could actually represent spatial structures on the order of 120 to 200 km. Spatial structures of this size in the auroral zone should map to spatial structures on the order of  $1 R_E$  at Geotail, assuming that they are on the same flux tube. The fact that power is observed at the same frequencies at both FAST and Geotail is consistent with the idea that the observed variations are temporal, and not due to the Doppler shifting of a spatial structure.

#### IV. Discussion and Conclusions

The multiple encounters with the boundary of the plasma sheet recorded by Geotail near the equatorial plane at  $30 R_E$  close to midnight on January 18, 1997 are indicative of a period of plasma sheet expansion with several partial thinning. The observation of two of the same plasma sheet boundary crossings by both Geotail and Polar is a dramatic reminder of the global nature of the processes producing substorms and the aurora.

Examination of the low frequency waves during this time period using the continuous Morlet wavelet transform revealed field fluctuations at similar frequencies in the magnetotail and the auroral zone. This is a significant result because it has long been believed that MHD waves and field line resonances



**Figure 3.** Wavelet scalegrams of FAST and Geotail electric field data from January 18, 1997 for frequencies between 0.2 Hz and 4 Hz. Panel (a) shows the time series of the Geotail electric field measured across the spinning booms of the spacecraft and the corresponding wavelet scalegram. Approximately 10 minutes before FAST was in the nightside auroral zone, oscillations of the electric field close to 1 Hz were observed by Geotail at  $30 R_E$  in the magnetotail. Panel (b) shows the component of the electric field along the spacecraft velocity measured by FAST in the auroral zone on orbit 1620 and the corresponding wavelet scalegram. Two wave packets with frequencies close to 1 Hz are clearly visible.

which propagate towards Earth can be excited by reconfigurations of the magnetotail. The  $E/B$  ratio  $2.8 \times 10^4$  km/sec for the 0.9 Hz oscillation observed by FAST during orbit 1620 agrees reasonably well with the results of the model presented by Lysak [1997] to describe Alfvénic structures resulting from the superposition of an incident wave and a wave reflected off the ionosphere. The model assumes a maximum Alfvén speed of 140,000 km/sec at an altitude of 3000 km. The ratios of the wave electric and magnetic fields predicted by this model depend heavily on the perpendicular wavelength in the ionosphere, but are not strongly affected by the conductivity except very close to the ionosphere at low frequencies. The 0.9 Hz wave packet observed by FAST is consistent with a perpendicular wavelength intermediate between the 1 km and 100 km cases presented by Lysak [1997]. The model was recalculated using an Alfvén speed profile with maximum of 80,000 km/sec at 6000 km and a value of 28,000 km/sec at 4000 km to match the local Alfvén speed observed by FAST. An eigenmode of the ionospheric Alfvén resonator with  $E/B$  ratios close to the FAST observations at 0.9 Hz was obtained for a conductivity of 10.0 mho and perpendicular wavelength of 100 km.

The electric and magnetic field oscillations below 0.1 Hz observed by both FAST and Geotail are in the frequency range of the field line resonances which can be excited by disturbances of the near-Earth plasma sheet [Streltsov and Lotko, 1996]. The peaks seen by FAST and Geotail between 0.03 to 0.05 Hz are within the frequency range of the first four odd harmonics of the nonradiative field line resonances discussed by Streltsov and Lotko [1996] and are quite close to 0.048 Hz, the frequency of the third harmonic. The peaks in the wavelet scalegrams below 0.1 Hz could also represent spatial structures which appear at these frequencies due to the motion of the satellites. The relation between the maximum electric field amplitudes measured by Geotail and FAST appears consistent with electrostatic mapping of the fields, assuming there is no potential drop between the magnetotail and the auroral zone. Further analysis of this data and comparison with the other FAST-

Geotail conjunctions will be required to accurately characterize the whether the observed features in this frequency range are primarily spatial structures, temporal variations, or some combination of the two, and to determine the relationship between the electric and magnetic field structures observed by the two satellites.

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