

Isolated Electrostatic Solitary Structures Observed Throughout the Cluster Orbit: Relationship to Magnetic Field Strength

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Abstract. Isolated electrostatic structures are observed throughout much of the 4 R_E by 19.6 R_E Cluster orbit. These structures are observed in the Wideband plasma wave instrument's waveform data as bipolar pulses (one positive and one negative peak in the electric field amplitude) and tripolar pulses (two positive and one negative peak, or vice versa). These structures are observed at all of the boundary layers, in the solar wind and magnetosheath, and along auroral field lines at 4.5-6.5 R_E . Using the Wideband waveform data from the various Cluster spacecraft we have carried out a survey of the amplitudes and time durations of these structures in all of the various regions and compared these quantities to the local magnetic field strength. We find that there is a general trend for the amplitudes of the structures to increase as the strength of the magnetic field increases over a range of 5 to 500 nT. We also note that a range of amplitudes is observed at any specific magnetic field strength. We provide a possible explanation for this trend that relates to the structures being Bernstein-Greene-Kruskal mode solitary waves. There is no corresponding dependence of the duration of the structures on the magnetic field strength, although a plot of these two quantities reveals the unexpected result that with the exception of the magnetosheath, all of the time durations for all of the other regions are comparable, whereas the magnetosheath time durations clearly are in a different category of much smaller time duration. We speculate that this implies the structures are much smaller in size, or less likely, that their velocity is much greater. The distinct pulse durations for the magnetosheath pulses indicate the possibility that the pulses are generated by a mechanism which is different from the mechanism operating in other regions.

1 Introduction

Cluster began its mission operations phase on February 1, 2001 following a five-month commissioning phase. The Cluster quartet is in an approximate polar orbit with an apogee of about 19.6 R_E and a perigee of 4 R_E . This allows Cluster to cross all of Earth's boundaries and spend considerable amounts of time in the near-Earth solar wind, magnetosheath, magnetotail and auroral zone. The Cluster orbit precesses through all 24 hours of Magnetic Local Time (MLT) in one Earth-year. Thus, the Cluster spacecraft are

always in the same local time sector for any given month each year as described in Escoubet et al. (2001) and as depicted in their Figure 1. Although not important for the current study, the inter-spacecraft separations of the four satellites have been changed on a 6- to 12-month time frame since operations began, with the smallest ideal tetrahedron separation being 100 km and the largest 5,000 km as of this date.

The Cluster WBD instrument obtains high resolution waveforms in three different filter bandwidths, providing time resolution between samples varying from 5 to 36.5 μ sec (see Gurnett et al., 1997 and Pickett et al., 2003a for a full description of the WBD instrument and its sampling characteristics). This allows for the resolution of periodic or single period (pulse) waveforms with extremely short durations. Since WBD makes only a single axis electric field measurement, it is not possible to transform the waveforms into any other coordinate system. However, it is possible to transform three axis measurement and position vectors into the antenna coordinate system used by WBD, thus providing the antenna's position at any moment in time in some reference system, such as a magnetic field-aligned coordinate system. The WBD instrument is unique among all the Cluster instruments in that it does not record its data onboard. Rather, the spacecraft transmits the WBD data in real time to a Deep Space Network ground station. This allows WBD to obtain extremely high time resolution measurements with tens of μ sec accuracy in absolute time. In order to obtain these unique capabilities, WBD data are only obtained for a total of 8 hours across all 4 spacecraft (or about 2 hours per spacecraft) for each 57-hour Cluster orbit.

The combination of the Cluster spacecraft and the WBD instruments on each spacecraft thus provides the unique capability for the first time to obtain high resolution digital waveform data from multiple spacecraft from all regions near Earth in which isolated electrostatic structures (IES) are observed. Although wave instruments on several single spacecraft such as Freja, Geotail, WIND, Polar and FAST have observed IES, none of them explore as many of the regions where IES are observed as Cluster does. Furthermore, most of the waveform instruments on these spacecraft are unable to observe the extremely short duration IES as WBD does, or those that do cannot sample as many of the IES regions. As will be shown below, IES are observed along magnetic field lines that map to the auroral zone, in the magnetosheath and near-Earth solar wind, and at all boundary layers. In general, wherever there is turbulence or a mixing of plasmas, IES are observed.

As previously mentioned, several recent studies of IES have been carried out using waveform data from Earth-orbiting spacecraft, eg., see Kojima et al. (1999) and Cattell et al. (2003) for references to these observations. Some studies have provided surveys of the characteristics of the IES, such as their potential and velocity, and thus size, in the regions where they made measurements, eg., Franz (2000) and Cattell et al (2003). Tsurutani et al. (2003) and Lakhina et al. (2003) have analyzed a bipolar pulse train onset and have argued that the IES may be created by counter streaming electron beams accelerated by wave parallel electric fields. However, none of these investigators have analyzed the amplitude and time duration of the IES specifically with respect to the strength of the magnetic field over a broad range of field strengths. Below we provide

the results from the first such study. We begin by providing samples of the IES of interest, followed by the results of the survey, specifically the amplitude and time duration of the IES vs. the magnetic field strength, and conclude with some possible explanations for the results that were obtained.

2 IES Examples

Figure 1a shows a typical 6-minute spectrogram of data obtained by WBD on June 26, 2003 on all four spacecraft in the auroral zone at about $4.8 R_E$ and 53° magnetic latitude. This spectrogram has increasing time, in UT, plotted on the horizontal axis and frequency, in kHz, on the vertical axis with color indicating power spectral density, in $\text{mV}^2/\text{m}^2/\text{Hz}$. The spectrogram was created by taking 1024 samples of the time series and transforming these data to the frequency domain by using a Fast Fourier Transform. The white line in the spectrogram is the electron cyclotron frequency as determined from the Fluxgate Magnetometer, FGM (see Balogh et al., 1997). Figure 1b shows a 25 msec line plot of the waveform beginning at 02:48:42.548 UT obtained by WBD on C4 (Cluster 4) from the 6-minute interval seen in the spectrogram. The line plot in Figure 1b has increasing time, in sec from 02:48:42.548 UT, plotted on the horizontal axis and electric field amplitude, in mV/m, plotted on the vertical axis. The total angle of the electric field antenna to the local magnetic field using transformed FGM data is shown on the right vertical scale. The spectrogram at the time of the waveform in Figure 1b shows only a broad band signal ranging in frequency from the lower cutoff of the filter around 50 Hz, where its greatest intensity is observed, up to its higher cutoff around 19 kHz, where a much lower intensity is observed. The broad band signal results from the fact that the pulses observed in the waveform in Figure 1b contain all frequencies. When one or more of these pulses are dominant in a 1024 point sample and are transformed to the frequency domain via Fast Fourier Transform, the expected result is a broad band signal as observed.

Two types of IES are pointed out in Figure 1b. The first is a tripolar pulse, defined as having either two positive peaks and one negative peak in the electric field, as in this case, or two negative peaks and one positive. This tripolar pulse has a fairly typical duration of about 2 msec and amplitude of 55 mV/m peak-to-peak. As shown in Pickett et al. (2003b), when the electric field of these pulses is integrated over the duration of the pulse, a significant potential shift is obtained. The second type of pulse pointed out in Figure 1b is the bipolar pulse (one positive and one negative peak). Likewise, the bipolar pulses have typical durations of 760 μsec and amplitudes of 75 mV/m peak-to-peak. No potential shift will result from integrating the electric field of the bipolar pulse over the duration of the pulse. Figure 1b also shows that the total angle of the electric antenna being used by WBD to the local magnetic field is around 157° , or nearly antiparallel.

We now highlight some of the differences between the IES in the near-Earth auroral zone presented in Figure 1, and the magnetosheath. Figure 2 (same format as Figure 1 with the exception that the electron cyclotron frequency, plotted as a white line, has been omitted in Figure 2a as it would appear at the very bottom of the frequency band) contains WBD data taken during a pass through the dayside magnetosheath at $13\text{-}14 R_E$ and $20^\circ\text{-}30^\circ$

magnetic latitude. Figure 3a shows the spectrogram for a two-hour period of time on April 6, 2002 when the spacecraft were separated by about 100 km. Note that the horizontal lines seen around 40 kHz and 65 kHz in all panels are spacecraft interference and the numerous horizontal lines seen in the C1 and C3 panels are interference from the Cluster EDI experiment. Although the signatures of the IES, i.e., the broad band signals, in this spectrogram, are observed to be very similar from one spacecraft to the next, we have been unable to conclusively correlate any one structure as propagating from one spacecraft to the next, but this is the subject of ongoing work and not pertinent to this study. Here we see that the broad band signals extend up to about 40-60 kHz, which is indicative of the pulses being much shorter in duration (see Pickett et al., 2003a) than those from the auroral zone. Indeed, when we look at the 5 msec sample waveform from C4 beginning at 22:25:01.2566 UT, we see that the duration of these bipolar pulses is 54 μ sec. The interesting aspect of these bipolar pulses is that they are seen almost every 1.4 msec at a certain phase of the lower frequency, nearly sinusoidal, wave. This would imply that the pulses are being created through some mechanism that involves the low frequency wave, but this topic is also left to future work. In addition we observe that the amplitudes of the pulses, 0.02 to 0.10 mV/m, are much lower than in the auroral zone.

3 IES Survey

Since the primary purpose of this paper is to provide a geophysical basis, in this case the local magnetic field strength, for the various amplitudes and time durations of the pulses, we resort to a survey of the IES observed in various parts of the Cluster orbit. Because it would be computationally prohibitive at this time to run an automatic IES detection program on all of the data obtained to date, we have instead turned to choosing representative events from the various regions that Cluster traverses in which IES are observed, and only then analyzing the first second of every minute of data.

The automatic bipolar and tripolar IES detection algorithm works as follows. First the range of the background noise is determined by taking the standard deviation of the raw count values over 2 or 3 minor frames of data (approximately 80-120 μ sec). Then looking within this span of data, the program finds the first data point that falls outside the noise range. For this data point, a local minimum and maximum raw count value are found. The following tests are now run to determine if the data represent a bipolar pulse:

1. Ensure that the maximum and minimum raw count values for the pulse do not occur at the beginning or ending of the pulse,
2. Ensure that the slope of a linear best-fit line between the peaks of the pulse is greater in magnitude than the slope of a linear best-fit line between the start and the first peak and the slope for the line between the second peak and the end of the pulse.
3. The ratio of the amplitudes for the two peaks (amplitude measured from the mean of the pulse) must be smaller than 2:1.
4. There are no significant raw count values within 1/4 the period of the pulse. A significant value is one whose amplitude (measured from the mean of the pulse) is greater than 10% of the pulse's peak-to-peak amplitude.

5. The time duration of each peak must be roughly the same. The largest ratio accepted for the time duration of each individual peak is 14:11.

If all the above five conditions are met, the pulse is confirmed to be a bipolar pulse. If any one of conditions 3 through 5 is NOT met, then another local minimum or maximum (ie., if the second peak found previously was a minimum, then we are looking for a maximum) is identified. The following tests are now run to determine if the data represent a tripolar pulse:

1. Ensure that the maximum and minimum raw count values for the pulse do not occur at the beginning or ending of the pulse.
2. Ensure that the slopes of a linear best-fit line between the first and second peaks and the line between the second and third peaks are the greatest in magnitude for the pulse, ie., the same as test applied above for bipolar pulses.
3. Ensure that the second peak (center peak) is the farthest removed from the mean raw count value of the pulse.
4. There are no significant raw count values within 1/4 the period of the pulse. A significant value is one whose amplitude (measured from the mean of the pulse) is greater than 10% of the pulse's peak-to-peak amplitude.
5. The amplitudes (measured from the mean of the pulse) of the two peaks on one side of the mean of the pulse individually should at least be 1/4 the amplitude of the single pulse on the other side of the mean.
6. The time duration of the two peaks on the same side of the pulse's mean raw count value must be similar. The largest ratio accepted for the time duration comparison of these two individual peaks is 3:1.

If all the above six conditions are met, then the pulse is confirmed to be a tripolar pulse. This method of pulse detection will not result in false positives. However, because of the various fluctuations naturally present in the data, ie., other plasma waves and electrostatic turbulence, some pulses may be missed. Since many of these missed pulses are questionable, they are best left out of this survey. The pulses that are confirmed have been extensively checked manually for authenticity. In addition, the confirmed pulses are also labeled as “clipped” if the instantaneous dynamic range of the instrument is insufficient to provide an accurate amplitude. In the plots that follow below, all “clipped” pulses have been omitted.

The results of the IES survey are shown in Figures 3 and 4 for the bipolar and tripolar pulses, respectively. These plots contain 7,104 confirmed bipolar pulses and 668 confirmed tripolar pulses. First we examine the bipolar pulses. Figure 3a shows the amplitude, in mV/m, on the horizontal axis vs. the total magnetic field strength, in nT, on the vertical axis, color coded according to the region in which the bipolar pulses were detected. Although there is a range in the observed amplitudes of the bipolar pulses at any given magnetic field, as shown by the black guiding parallel dashed lines, the trend for the amplitude to be larger as the strength of the magnetic field increases is clearly evident. One possible explanation for this trend will be provided in the next section. From this figure we also see that the range of amplitudes varies from a few hundredths

mV/m to several tens of mV/m. Since WBD employs an automatic gain function implemented in its hardware to add and remove gain in 5 dB steps at an update rate of once every tenth of a second, it should not be missing many structures over the 1 second interval because the gain will adjust 9 times in this period if necessary to keep the amplitudes within its dynamic range. If, however, all of the gain has been taken out of the system and the structures are still being clipped, WBD would be unable to determine the full amplitude. As can be seen from Figure 3a, this is most likely to occur in the auroral zone where the largest magnetic fields are observed for the Cluster orbit. As stated previously, structures with clipped waveforms are not plotted in Figure 3.

The survey of the time durations of the same sample of bipolar pulses is shown in Figure 3b. Here we have plotted the time duration of the pulse on the horizontal scale, in msec, vs. the strength of the magnetic field, in nT, on the vertical axis, color coded by region. We observe that there is no dependence of the time duration of the pulses on the magnetic field. However, we do observe that there appears to be two distinct classes of time durations: 1) those greater than 100 μ sec up to about 5 msec, and 2) those less than 100 μ sec down to the lowest duration that WBD can resolve at about 20 μ sec. Clearly the magnetosheath structures fall into category 2 and all others into category 1. The reason for this distinction will be discussed in the next section and simply point out here that for a typical flow velocity of a few hundred km/sec in the magnetosheath and a time duration less than 100 μ sec, we obtain a scale size on the order of tens of meters.

We have also examined the tripolar pulse amplitudes and time durations for dependences on the magnetic field strength. The survey results are provided in Figures 4a and 4b. Although fewer tripolar structures are observed in any sample interval, similar trends, or lack thereof, to the bipolar structures are seen, i.e., the amplitudes increase as the magnetic field strength increases over a finite spread of amplitudes, and the time durations show no dependence on the magnetic field strength. However, just as for the bipolar pulses, the tripolar pulses in the magnetosheath are from a different, shorter time duration class. Similar results for the tripolar pulses as for the bipolar ones point to the conclusion that they are created out of the same kinds of mechanisms. The fact that the tripolar pulses are sometimes observed in groups without the presence of bipolar pulses (see, for example, Figure 2b of Pickett et al., 2003b) indicates that they are themselves coherent structures and less likely to be an intermediate stage in the generation of bipolar pulses. It is possible that structures with an unusual shape, perhaps those that are partly concave as opposed to spherical, ellipsoidal or pancake-shaped, could produce the tripolar pulses out of a similar mechanism as for the bipolar pulses. We will leave discussion of this topic to future work.

4 Discussion

We will first discuss one possible explanation for the dependence of the amplitudes of the bipolar and tripolar IES on the strength of the magnetic field. Chen et al. (2003) have derived a complete width-amplitude relation for three-dimensional Bernstein-Greene-Kruskal (BGK) solitary waves in the limit of strong magnetic fields. Due to the kinetic nature of the waves, a continuum of allowed potential amplitudes and widths are allowed

according to a set of inequality relations between the amplitudes and the widths. When effects of finite magnetic fields are taken into account, the stability requirements lead to the following conditions:

$$\omega_b / \omega_c \ll 1 \rightarrow \frac{\sqrt{m\Psi/e}}{B\delta_z} \ll 1 \quad (1)$$

$$r_c / r_U \ll 1 \rightarrow \frac{\sqrt{2m\Psi/e}}{B\delta_r} \ll 1 \quad (2)$$

where ω_b is the frequency of electron bounce inside the solitary potential, r_c is the electron cyclotron radius, ω_c is the electron cyclotron frequency, r_U is the inhomogeneity length of the solitary wave electric field $E(x,y,t)$, Ψ is the peak potential amplitude, B is the magnetic field strength, δ_z is the parallel size, δ_r is the perpendicular size, and e, m are the charge and mass of electrons, respectively.

The above conditions show that when we move to a weaker magnetic field region, either the potential amplitude has to decrease or the size has to increase in order to keep the same conditions satisfied, and this results in smaller electric field amplitudes. The Cluster observational results shown in Figures 3 and 4 are consistent with this, i.e., the average electric field amplitude for a particular magnetic field strength decreases with decreasing magnetic fields. We note that at any fixed magnetic field strength a broad range of electric field amplitudes are observed. Some of this broad range of amplitudes can be explained by the orientation of the antenna to the magnetic field and the orientation of this antenna with respect to the structure as it propagates across the spacecraft. In addition, this broad range feature further supports that the solitary waves we observed are of the BGK mode, since the most outstanding property of BGK solitary waves is their inequality width-amplitude relation allowing a continuous range for widths and potential amplitudes (Chen et al., 2003).

We now discuss why there is no dependence of the average time durations of the IES in different regions on the magnetic field strength. The time duration that a pulse is observed scales with the ratio of its size to its velocity. If the pulses are generated by the two-stream instability, this ratio would be roughly constant. The reason is as follows. The typical size of these pulses is determined by the wavelength of the fastest growing mode in the linearly unstable stage, and this wavelength is proportional to the relative streaming velocity of the two beams (Gurnett and Bhattacharjee, 2003). On the other hand, the velocities of the pulses generated by the two-stream instability are roughly half of the two stream velocity with some deviation, if the observing frame is taken to be one of the two streams. Hence, the average ratio of size to the velocity of the pulses would stay roughly the same for different regions.

This leads into our last problem of explaining why the time durations of the magnetosheath bipolar and tripolar IES are much shorter than those in all other regions. Smaller time duration implies smaller size or larger velocity or a combination of both. We have proposed in the last paragraph one scenario whereby all the regions other than the magnetosheath produce IES through the two-stream instability with similar typical time durations. The magnetosheath IES could be produced spontaneously through turbulence as proposed in a general case in Chen et al. (2003), and the much smaller time durations could then be simply due to the small fluctuation lengths of the magnetosheath turbulence, since these IES would have similar flow velocity as the turbulent flow there. Assuming that the size is smaller for IES in the magnetosheath, this now leaves us with the problem of why they fit so nicely into the amplitude-magnetic field strength curve. The answer is that no matter how the IES are generated, the conditions required for their stability are the same, namely, their size and potential amplitudes have to adjust accordingly such that the cyclotron radius is always much less than the size of the solitary structures.

5 Conclusions

We have observed isolated electrostatic structures in the form of bipolar and tripolar pulses in all of the following regions crossed by the Cluster quartet: numerous boundary layers, the near-Earth solar wind, magnetosheath, magnetotail and auroral zone. These IES have amplitudes ranging from a few hundredths of mV/m up to almost 100 mV/m, and time durations from about 20 μ sec, the shortest time duration that can be resolved, up to about 5 msec. The amplitudes of the IES show a clear dependence on the strength of the magnetic field, i.e., the amplitude increases as the strength of the magnetic field increases. No dependence is found for the duration of the IES pulses on the strength of the magnetic field. However, plotting the time durations of the IES vs. the magnetic field clearly points out that the magnetosheath IES come from a different class of structures than those found in all other regions. We have speculated that the IES are BGK mode and that the amplitude/magnetic field dependence comes from the stability requirements of the BGK mode in finite magnetic fields. The lack of dependence of the time duration (or size/velocity) is indicative of the generation mechanism in most regions (except the magnetosheath) being the two-stream instability. The difference in the time durations of the magnetosheath IES vs. all other observed IES is most likely due to a much different generation mechanism.

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Figure Captions

Figure 1: Cluster WBD data taken on 12 June 2002 in the auroral zone. a) Spectrogram showing the frequency and power spectral density of the emissions. The broad band signals ranging up to about 10 kHz are indicative of times when IES are observed. b) Representative waveform from a time of the broad band signals, showing the two types of IES: bipolar and tripolar pulses.

Figure 2: Cluster WBD data taken on 06 April 2002 in the dayside magnetosheath. a) Spectrogram showing the frequency and power spectral density of the emissions. The broad band signals in this region, unlike the auroral zone, range in frequency from the lowest frequency measured up to 40-60 kHz. b) Representative bipolar pulse waveforms from a time of the broad band signals, showing that the pulses are much shorter in duration in this region and that they are tied to a certain phase of the low frequency wave.

Figure 3: Survey of the bipolar pulses observed by Cluster WBD over a two-year period. a) Electric field amplitude vs. magnetic field strength showing a trend of increasing amplitude with increasing field strength. b) Pulse duration vs. magnetic field strength showing no trend between the two, but pointing out the obvious difference of the time durations of the magnetosheath pulses to pulses in all other regions.

Figure 4: Survey of the tripolar pulses observed by Cluster WBD over a two-year period. a) Electric field amplitude vs. magnetic field strength showing a trend of increasing amplitude with increasing field strength, just as for the bipolar pulses. b) Pulse duration vs. magnetic field strength showing no trend between the two, but pointing out the obvious difference of the time durations of the magnetosheath pulses to pulses in all other regions, just as for the bipolar pulses.

CLUSTER WBD
 AURORAL ZONE
 (SPACECRAFT SEPARATION ~ 100 KM)

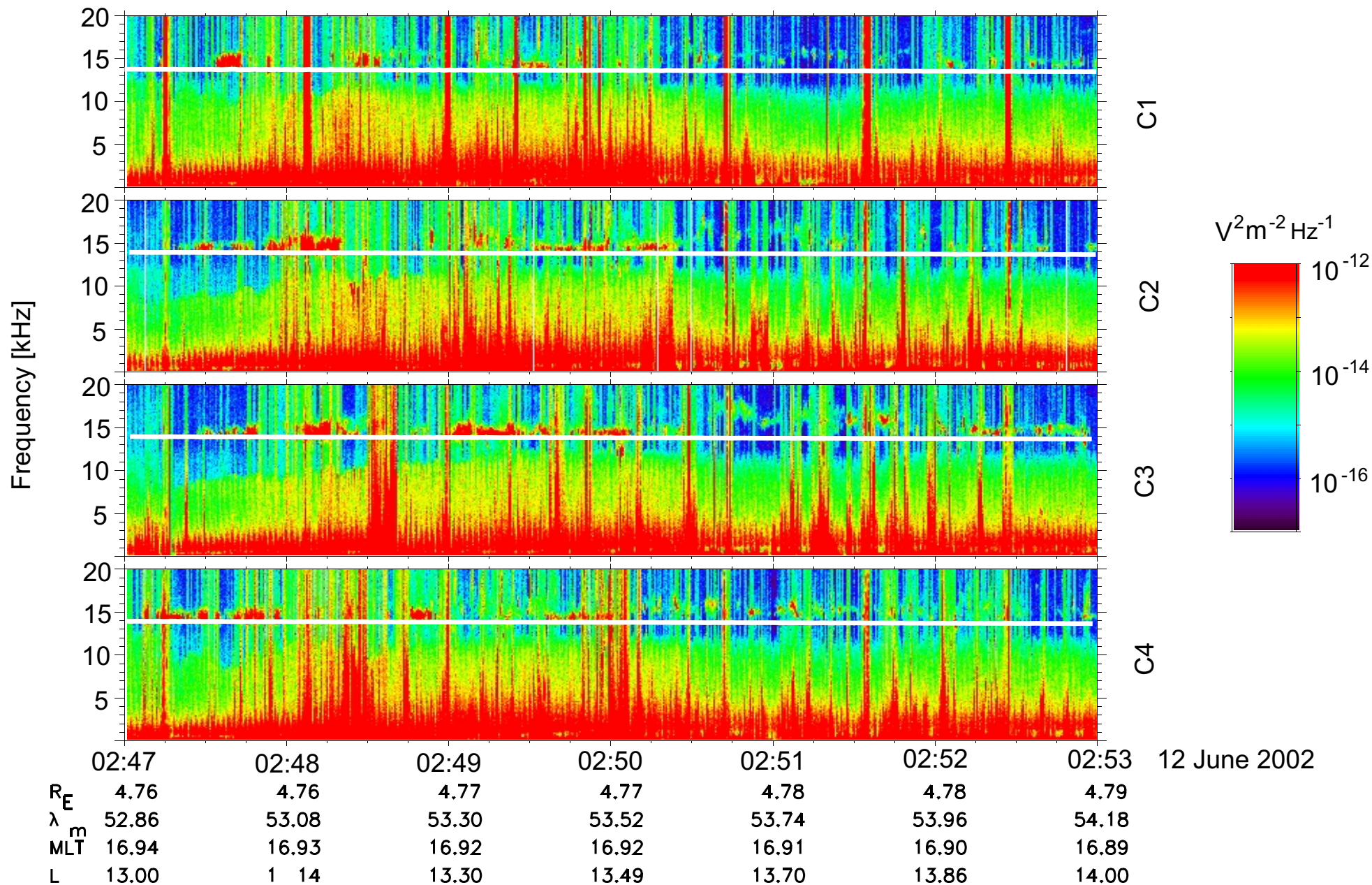
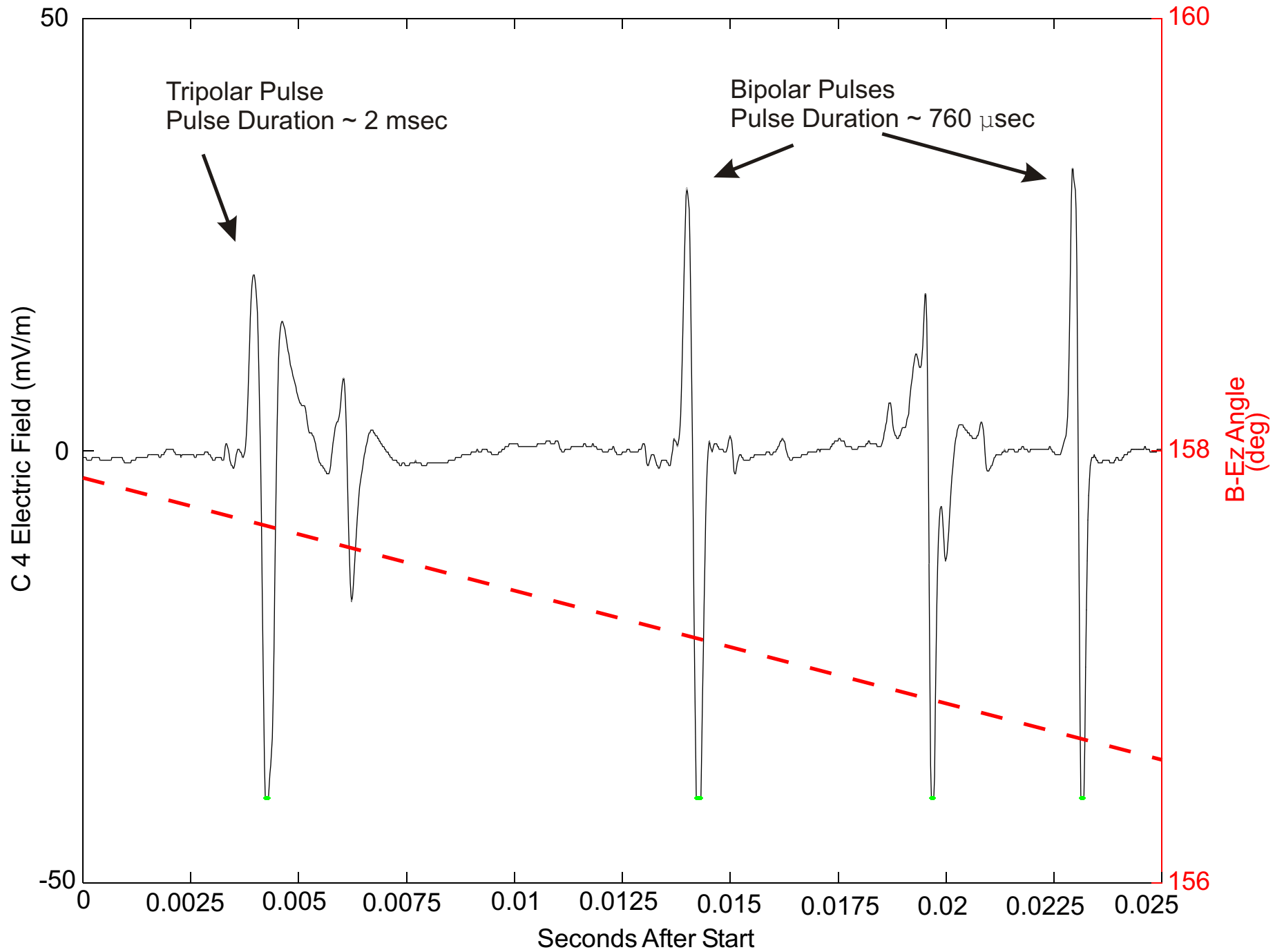


Figure 1a

AURORAL ZONE (4.8 R_E 53.5 λ_m, 16.9 MLT, 13.5 L)



START: 02:48:42.546 on 12 June 2002

Figure 1b

CLUSTER WBD
 DAYSIDE MAGNETOSHEATH
 (SPACECRAFT SEPARATION ~ 100 KM)

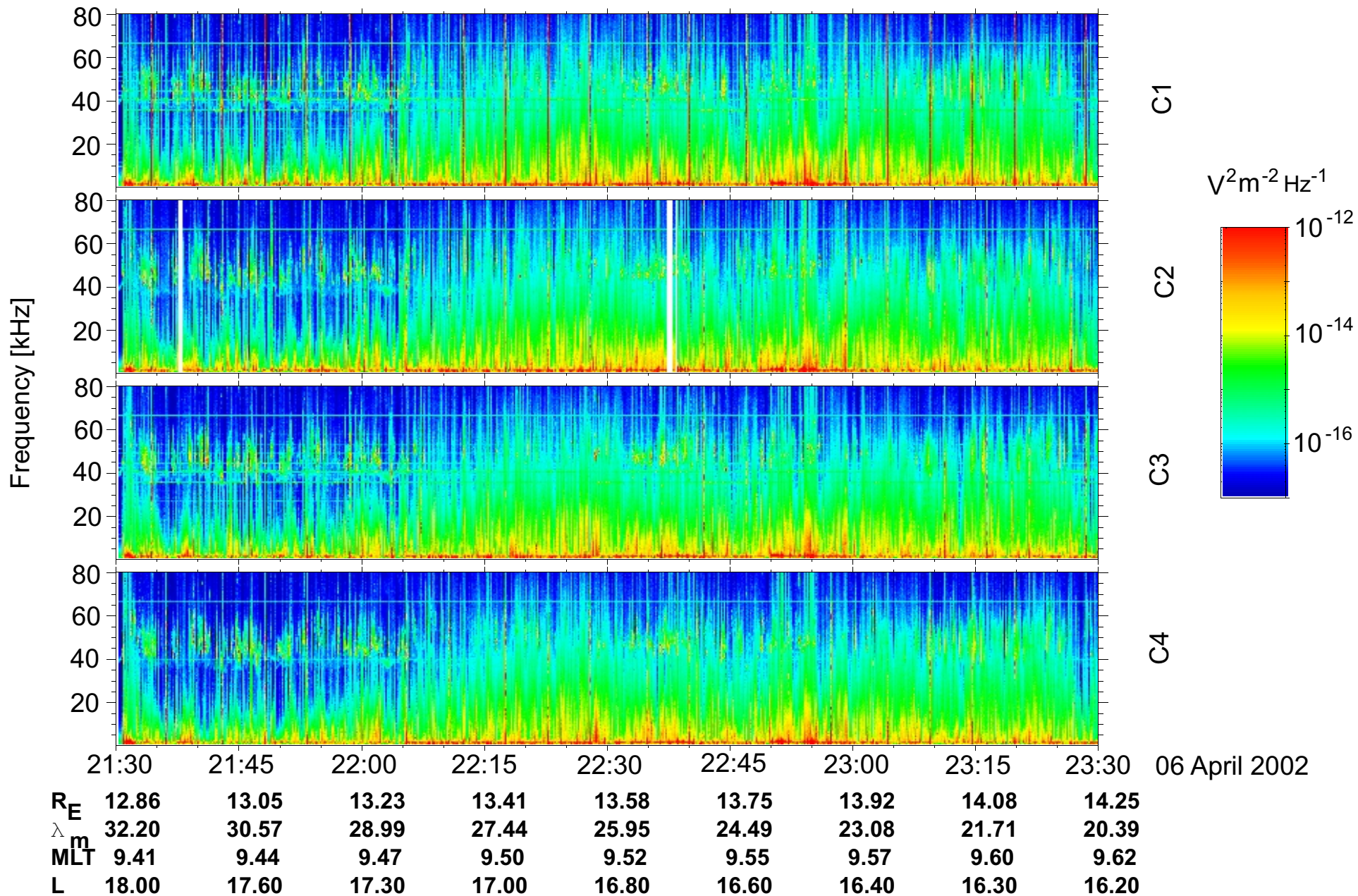
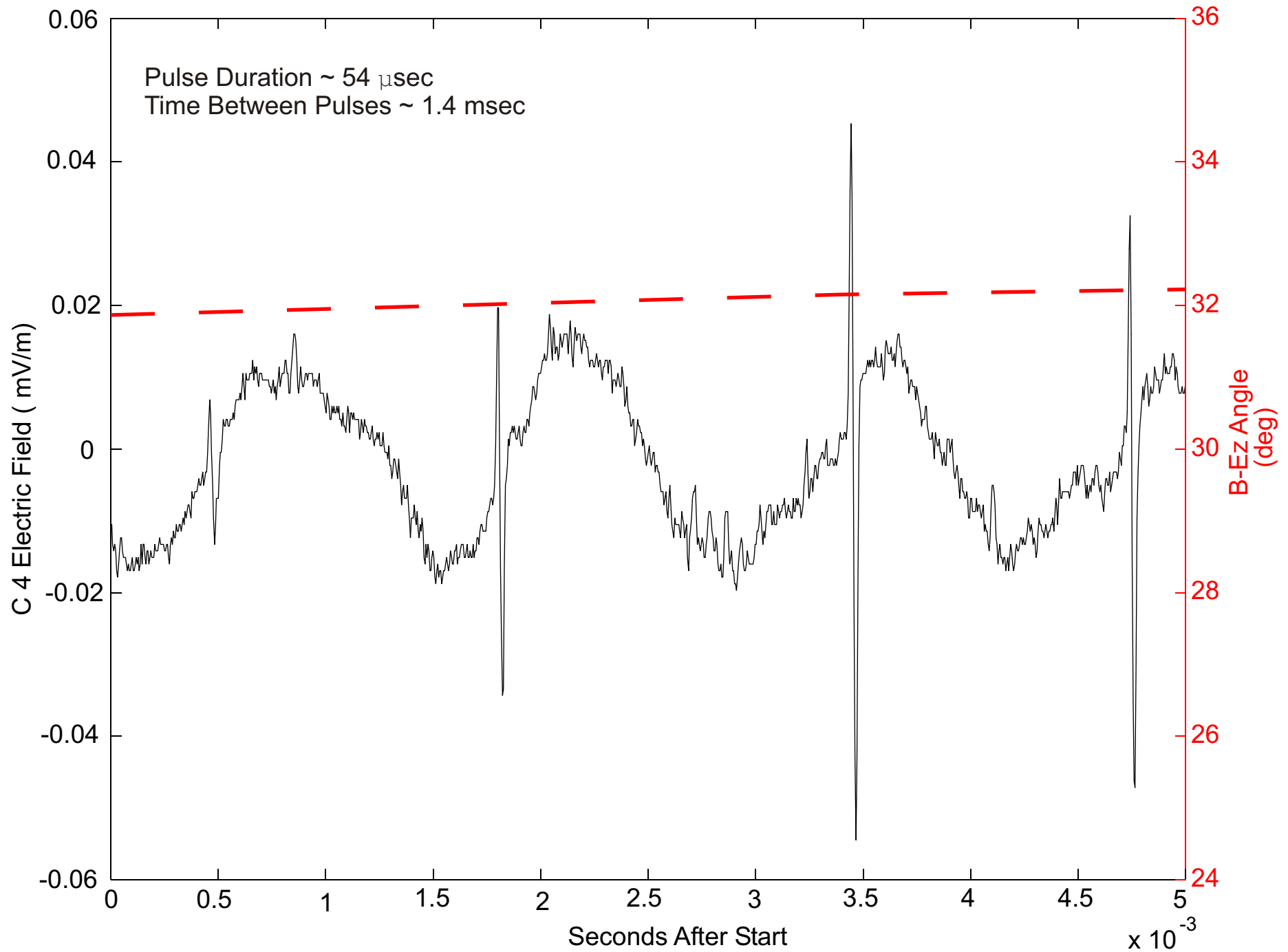


Figure 2a

MAGNETOSHEATH (13.4 R_E , 26.4 λ_m , 9.5 MLT) BIPOLAR PULSES



START: 22:25:01.2566 UT on 06 April 2002

Figure 2b

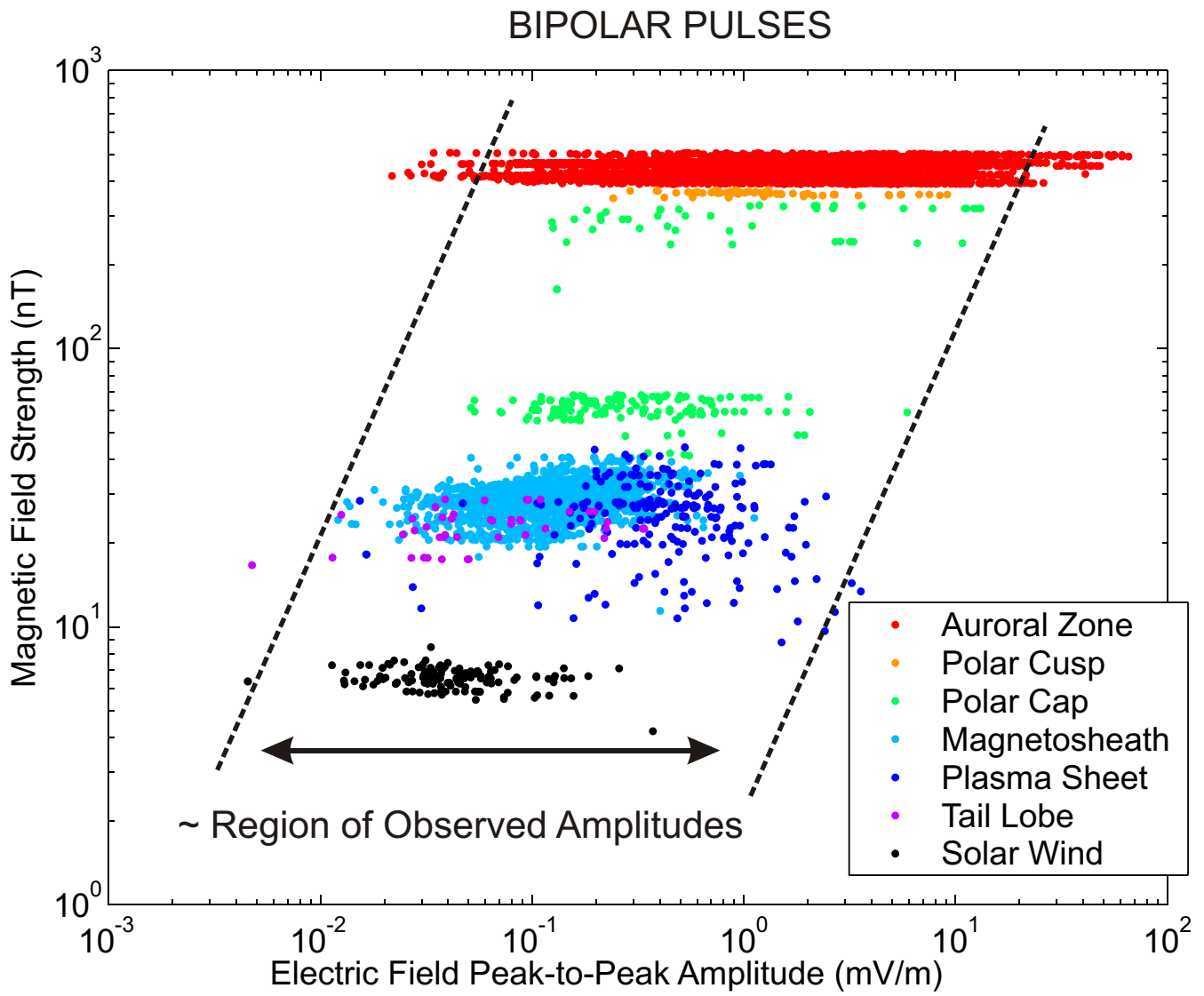


Figure 3a

BIPOLAR PULSES

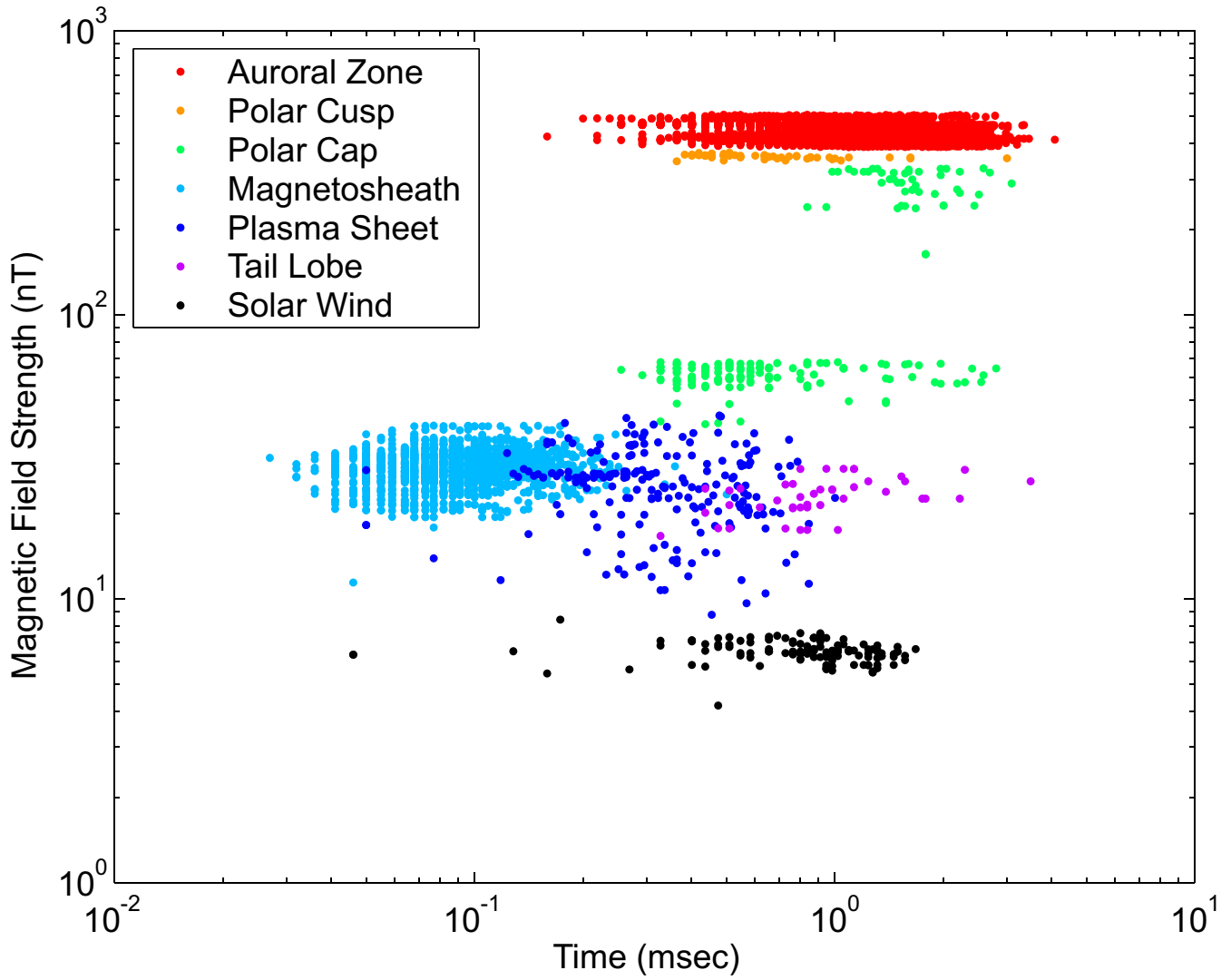


Figure 3b

TRIPOLAR PULSES

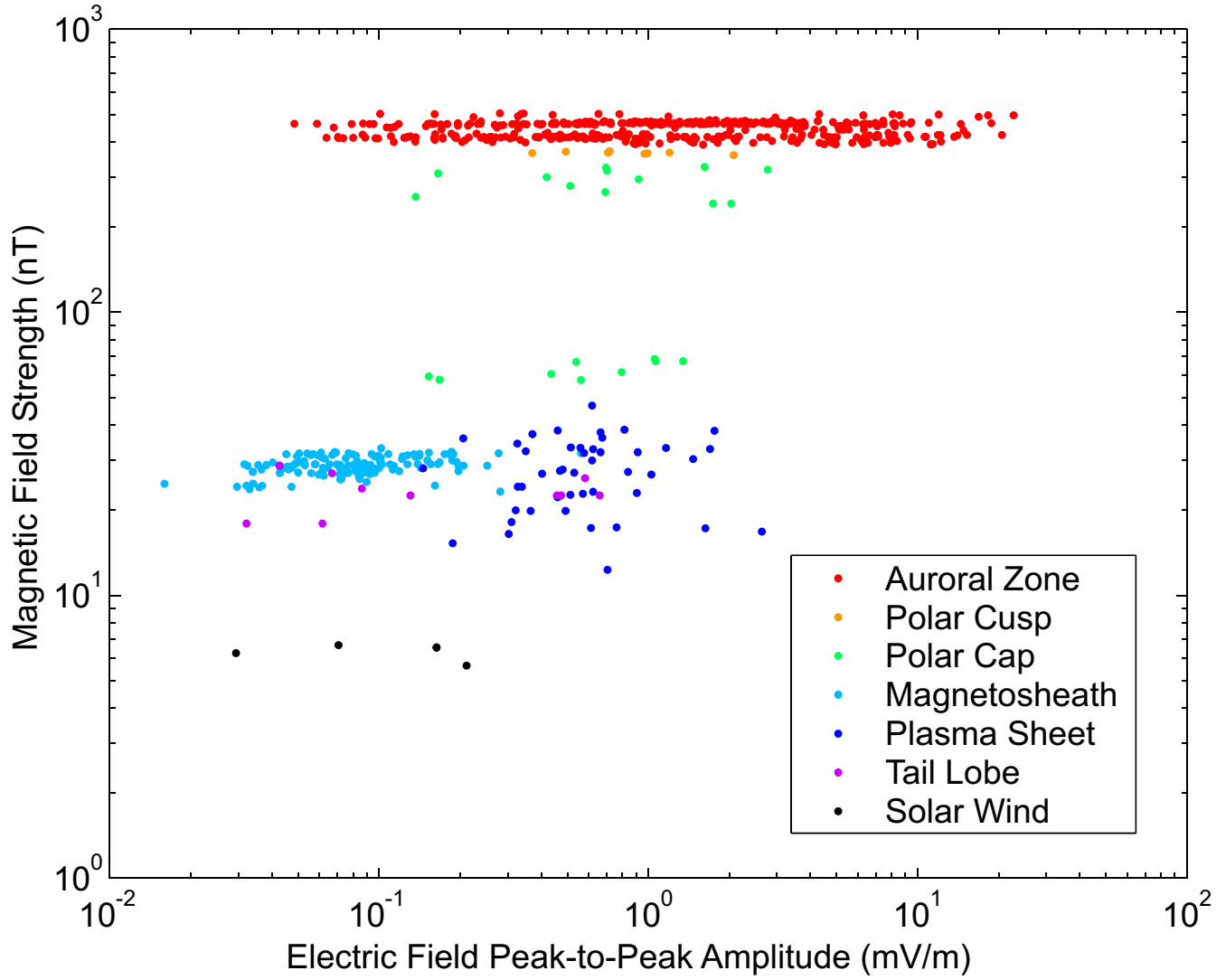


Figure 4a

TRIPOLAR PULSES

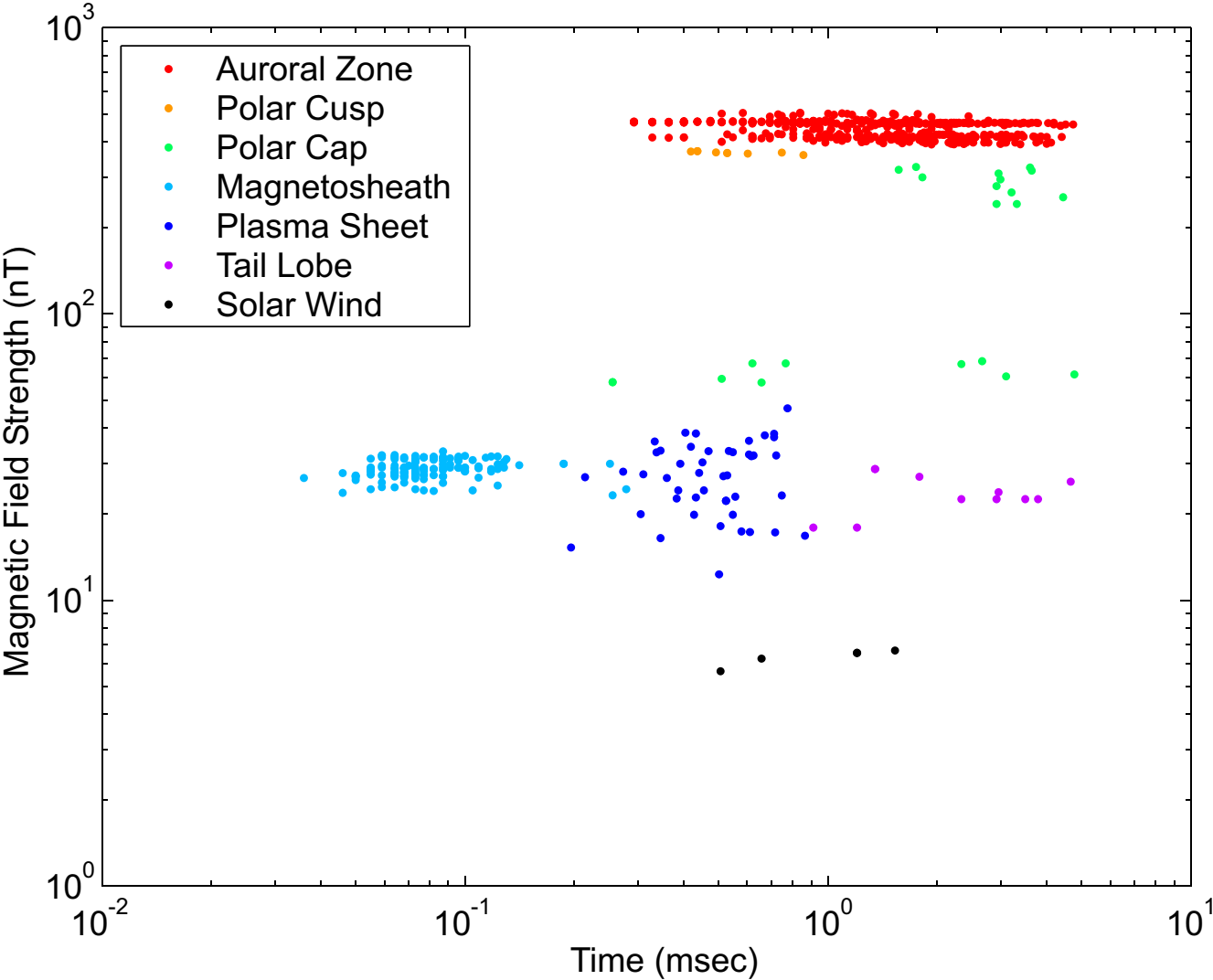


Figure 4b