Workshop on Nonlinear Plasma Waves
ISSI, Bern, Switzerland. 22-26 March 2004

CLUSTER OBSERVATIONS OF SHORT DURATION (<10 MS) SOLITARY WAVES: STATISTICS AND MULTI-SPACECRAFT PERSPECTIVE

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Acknowledgments:

L.-J. Chen and S. W. Kahler, The University of Iowa
D. A. Gurnett, PI of Cluster WBD Plasma Wave Receiver
A. Balogh, PI of Cluster FGM, for magnetic field data
NASA/GSFC support under Grants NAG5-9974 and NNG04GB98G

OUTLINE

- Instrumentation
- Sample bipolar and tripolar pulses representing phase space holes and weak double layers, and overview spectrograms showing the broadband emission associated with these pulses
- Potential change across bipolar and tripolar pulses
- Cross-spacecraft correlation study of the solitary waves
- Correlation of amplitude and time duration of the solitary waves
- Influence of the magnetic field on the solitary waves
- Concluding remarks

INSTRUMENTATION

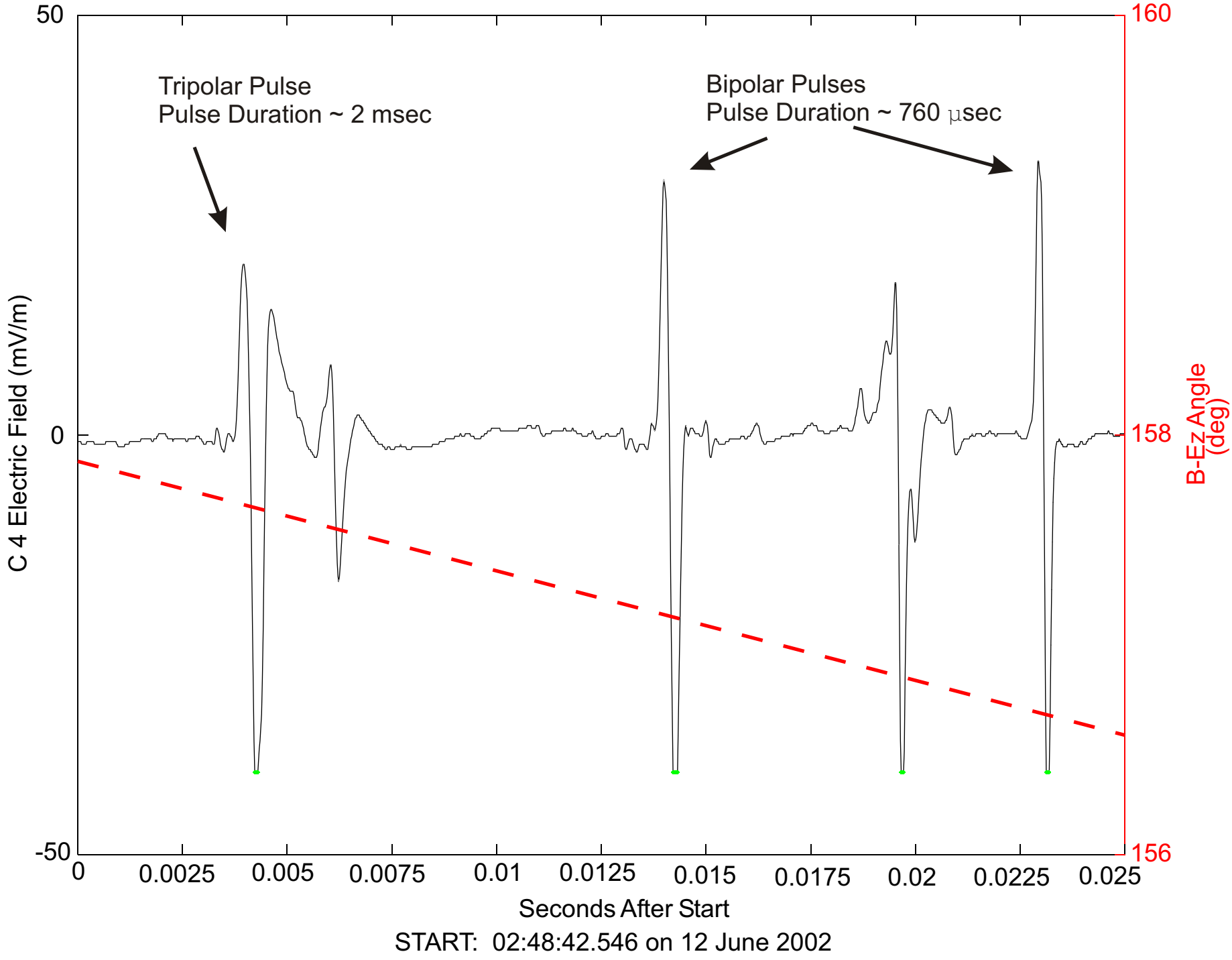
- The Cluster Wideband (WBD) plasma wave receiver obtains waveforms in one of three filter bandwidths: 1-77 kHz, 50 Hz to 19 kHz, 25 Hz to 9.5 kHz.
- WBD sample rates are 219.5, 54.8 and 27.4 kHz, respectively, providing time resolution between samples of 36.5, 18.2 and to 5 microseconds, respectively.
- The 19 kHz and 77 kHz bandwidth modes are duty cycled at one-half and one-eighth respectively, whereas the 9.5 kHz mode is sampled continuously.
- WBD makes one-axis measurement of ac electric field (average potential between the two electric field spheres) in the spin plane; thus, it cannot determine speed or direction of propagation of solitary waves on a single spacecraft or whether the solitary waves are ion or electron structures.
- The electric antenna provided by EFW is a double probe system of 88 m length (tip-to-tip).

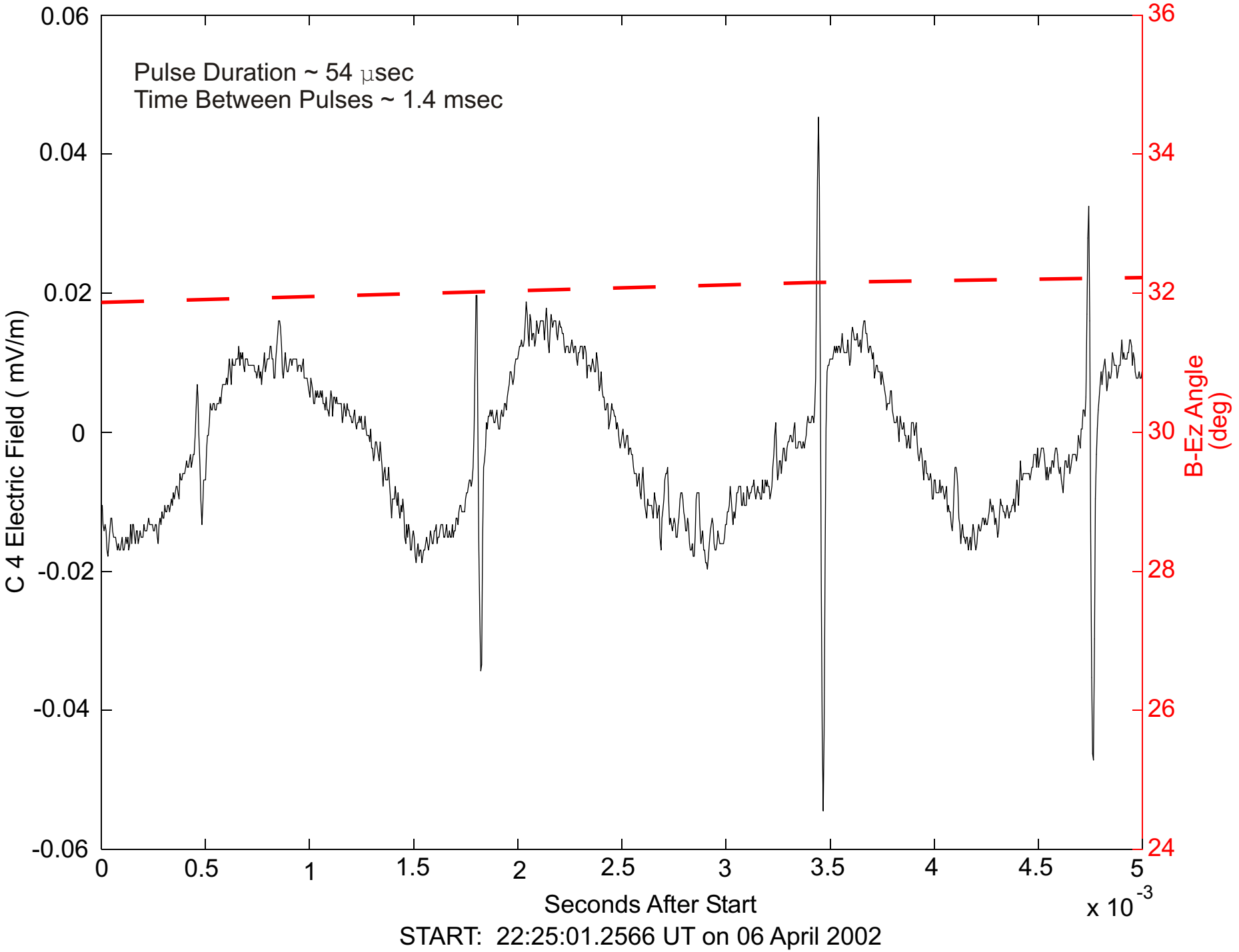
- The WBD receiver has an automatic gain control system (AGC) providing 75 dB of selectable gain in addition to the 48 dB of instantaneous dynamic range; gain update rate is once per tenth second.

- Receiver saturation will occur at the input at the 2 V level, providing a maximum peak-to-peak measurement of about 100 mV/m.

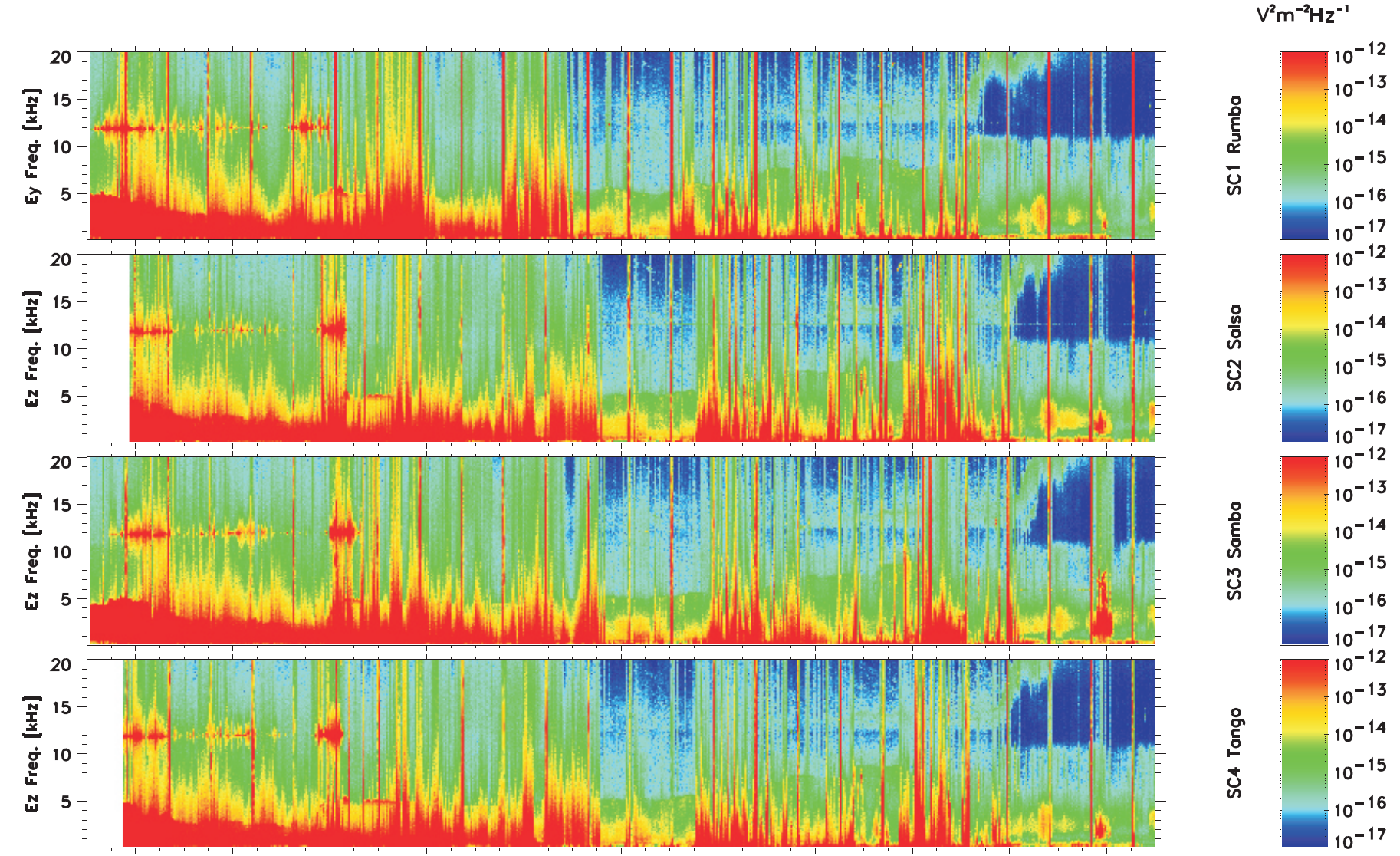
- Nonlinear effects due to saturation of the amplifiers are minimized by providing a maximum amplitude range that is greater than the maximum range of the digitized signal, i.e. clipped waveforms do not necessarily imply receiver saturation.

- WBD data are transmitted directly to DSN ground stations in Canberra and Goldstone; thus, orbit coverage is limited to 2 hours per spacecraft per 57 hour orbit.


AURORAL ZONE (4.8 R_E 53.5 λ_m, 16.9 MLT, 13.5 L)
Tripolar Pulse
Pulse Duration ~ 2 msec
Bipolar Pulses
Pulse Duration ~ 760 μsec
C 4 Electric Field (mV/m)
B-Ez Angle (deg)
50
0
-50
160
158
156
0
0.0025
0.005
0.0075
0.01
0.0125
0.015
0.0175
0.02
0.0225
0.025
Seconds After Start
START: 02:48:42.546 on 12 June 2002


MAGNETOSHEATH (13.4 R_E, 26.4 λ_m, 9.5 MLT) BIPOLAR PULSES
Pulse Duration ~ 54 μsec
Time Between Pulses ~ 1.4 msec
C 4 Electric Field (mV/m)
B-Ez Angle (deg)
Seconds After Start
x 10^-3
START: 22:25:01.2566 UT on 06 April 2002

Cluster WBD



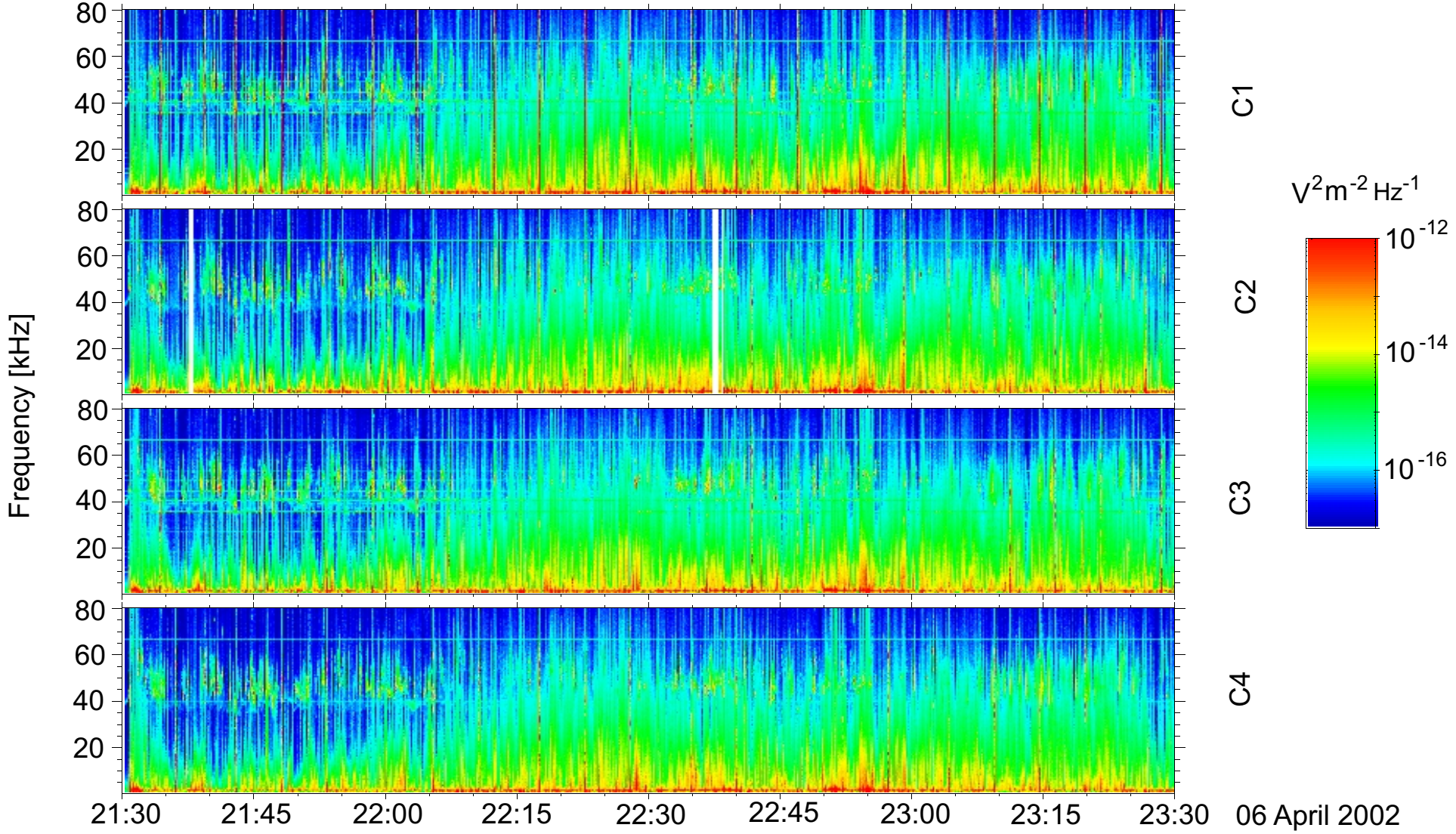
R_E	5.08	5.06	5.03	5.00	4.98	4.95	4.92	4.90	4.87	4.85	4.83
λ_m	−49.13	−48.32	−47.50	−46.68	−45.84	−44.99	−44.13	−43.26	−42.38	−41.48	−40.58
MLT	18.86	18.84	18.82	18.80	18.79	18.77	18.75	18.74	18.72	18.71	18.70
L	11.90	11.40	11.00	10.60	10.30	9.90	9.60	9.20	8.90	8.60	8.40

UT_OBT: 2002-05-26T08:35:00 to 2002-05-26T08:57:00

CLUSTER WBD

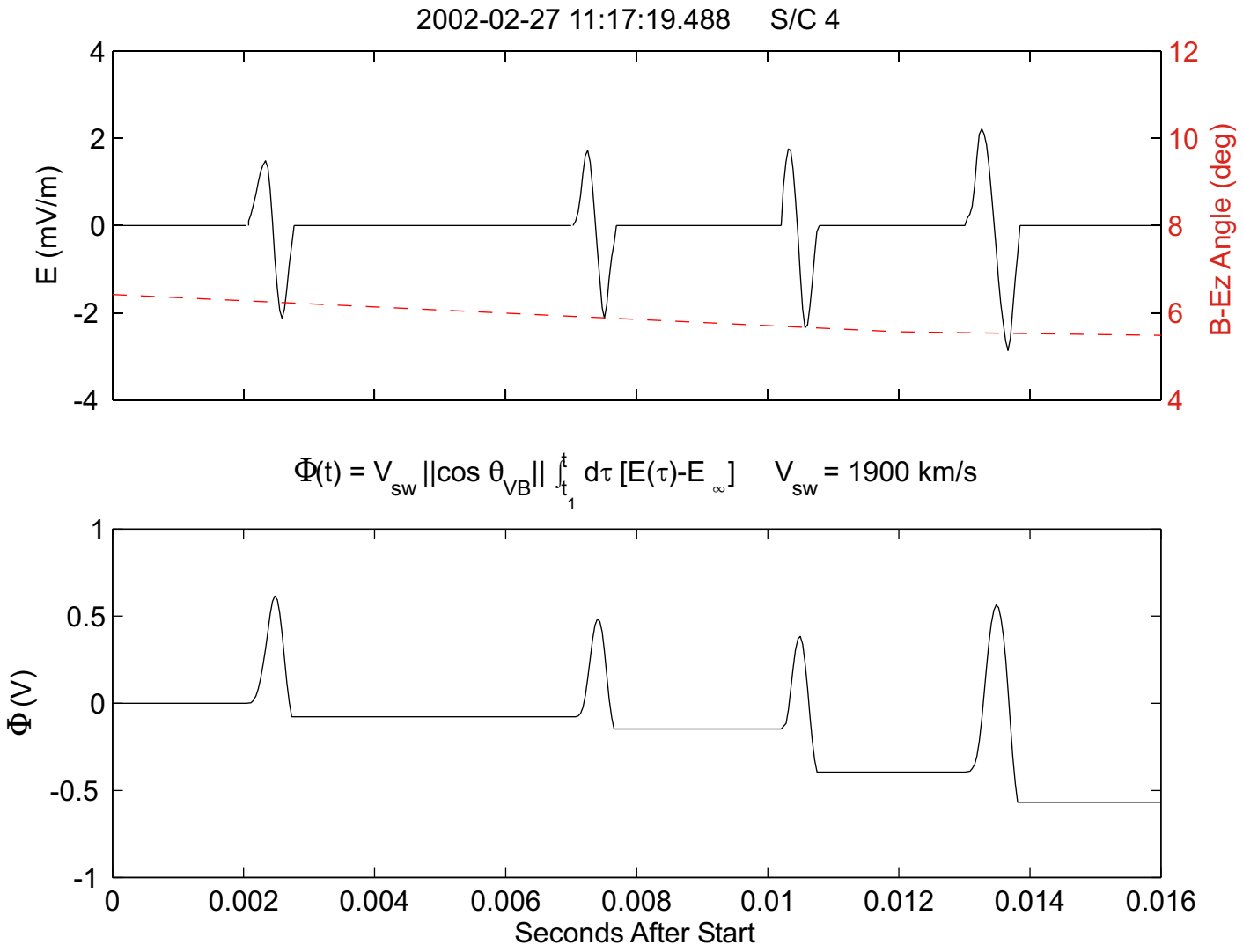
DAYSIDE MAGNETOSHEATH

(SPACECRAFT SEPARATION ~ 100 KM)

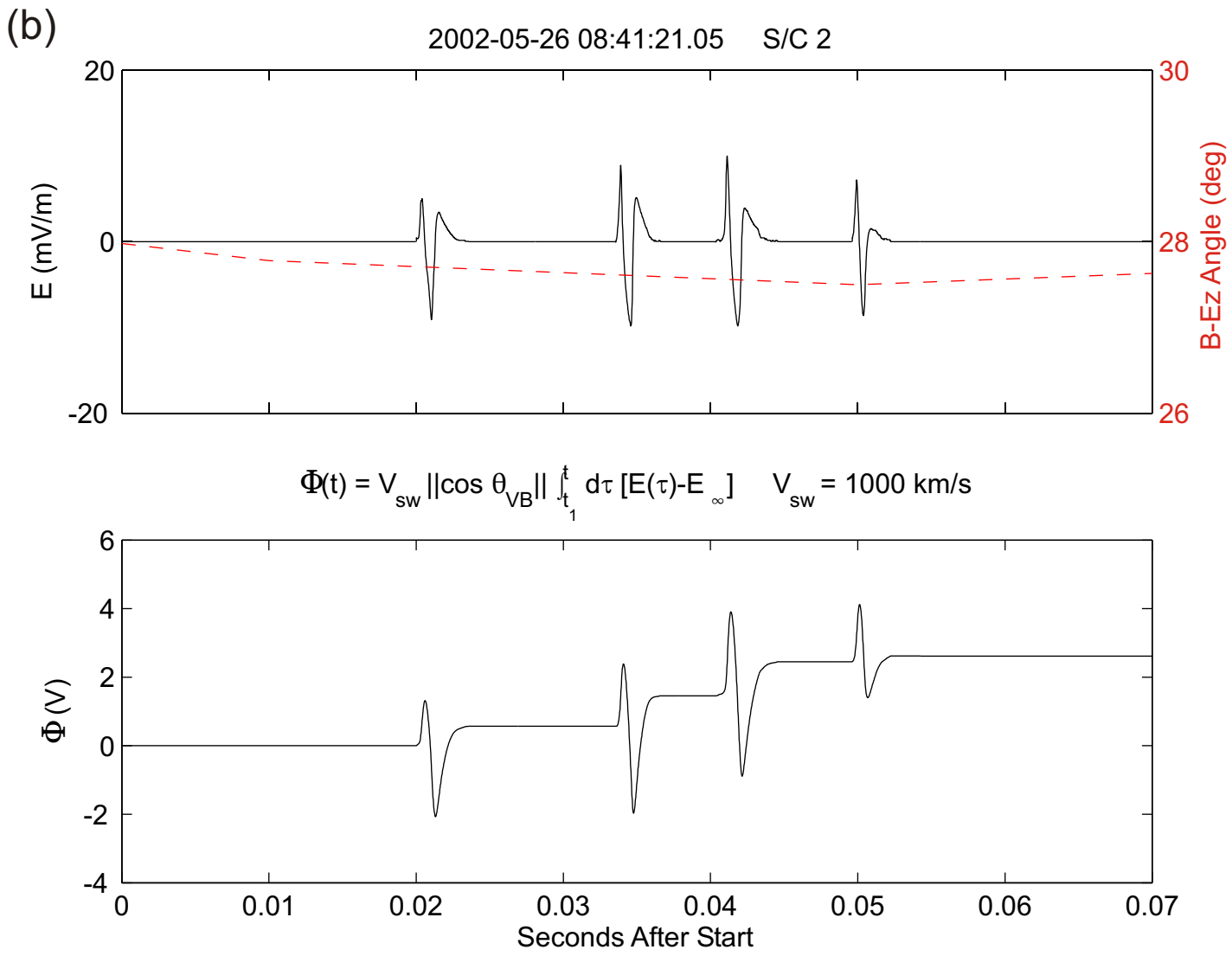


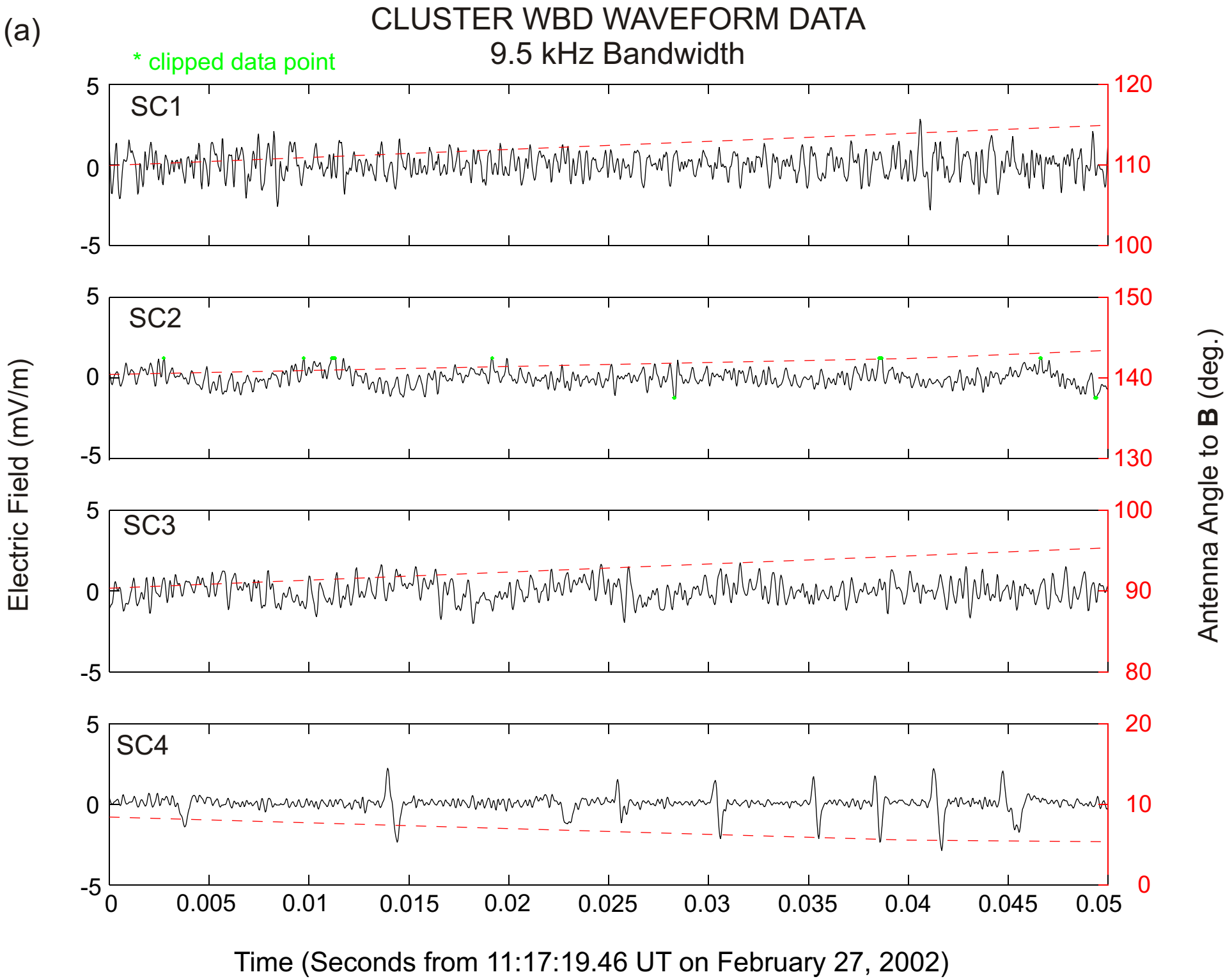
R_E	12.86	13.05	13.23	13.41	13.58	13.75	13.92	14.08	14.25
λ_m	32.20	30.57	28.99	27.44	25.95	24.49	23.08	21.71	20.39
MLT	9.41	9.44	9.47	9.50	9.52	9.55	9.57	9.60	9.62
L	18.00	17.60	17.30	17.00	16.80	16.60	16.40	16.30	16.20

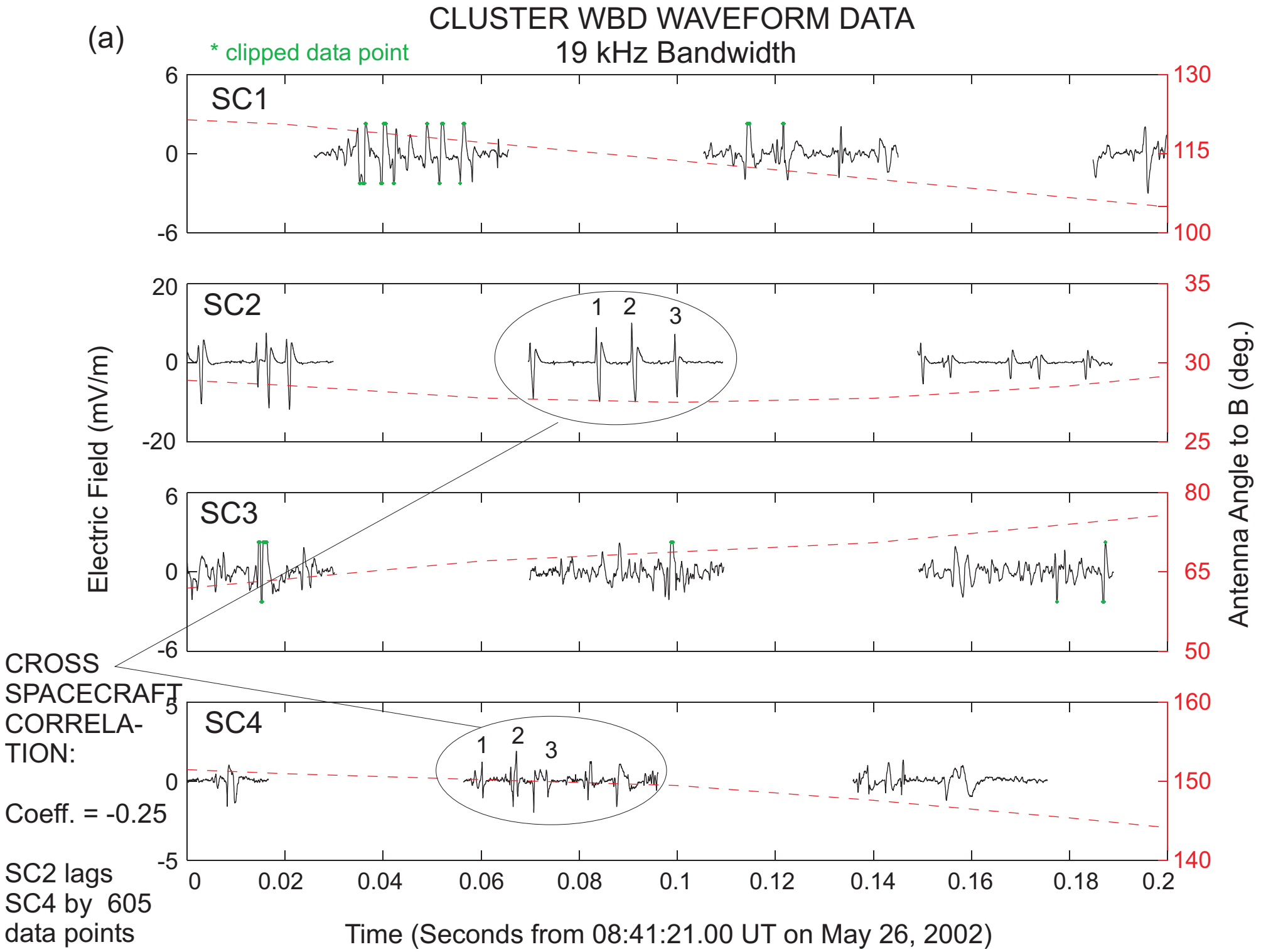
POTENTIAL CHANGE ACROSS BIPOLAR PULSES



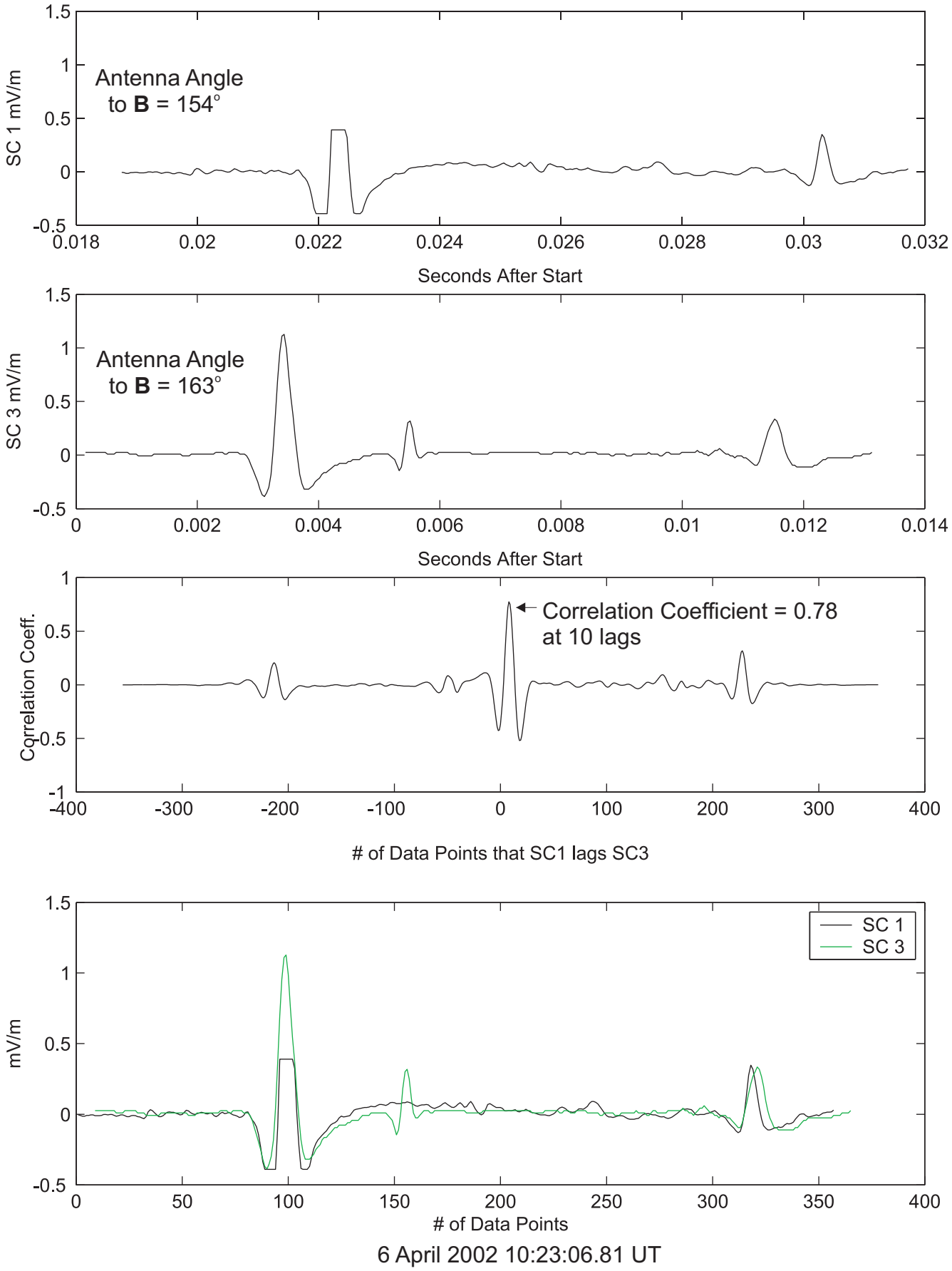
POTENTIAL CHANGES ACROSS TRIPOLAR PULSES




(a)
CLUSTER WBD WAVEFORM DATA
9.5 kHz Bandwidth
* clipped data point
SC1
SC2
SC3
SC4
Electric Field (mV/m)
Antenna Angle to B (deg.)
Time (Seconds from 11:17:19.46 UT on February 27, 2002)
5
0
-5
120
110
100
150
140
130
90
80
20
10
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05


(a)
CLUSTER WBD WAVEFORM DATA
19 kHz Bandwidth
* clipped data point
SC1
SC2
SC3
SC4
1
2
3
Electric Field (mV/m)
Antenna Angle to B (deg.)
CROSS SPACECRAFT CORRELA-TION:
Coeff. = -0.25
SC2 lags SC4 by 605 data points
Time (Seconds from 08:41:21.00 UT on May 26, 2002)

CROSS SPACECRAFT CORRELATION OF TRIPOLAR PULSES
AURORAL ZONE AT 4.8 Re, -36 DEG. MLAT, 22:09 MLT



6 April 2002 10:23:06.81 UT

ANALYSIS OF CROSS SPACECRAFT CORRELATIONS

- Only tripolar pulses have been correlated across spacecraft; no cases of bipolar pulses correlating across spacecraft have yet been found

- May 26, 2002, SC2 and SC4:

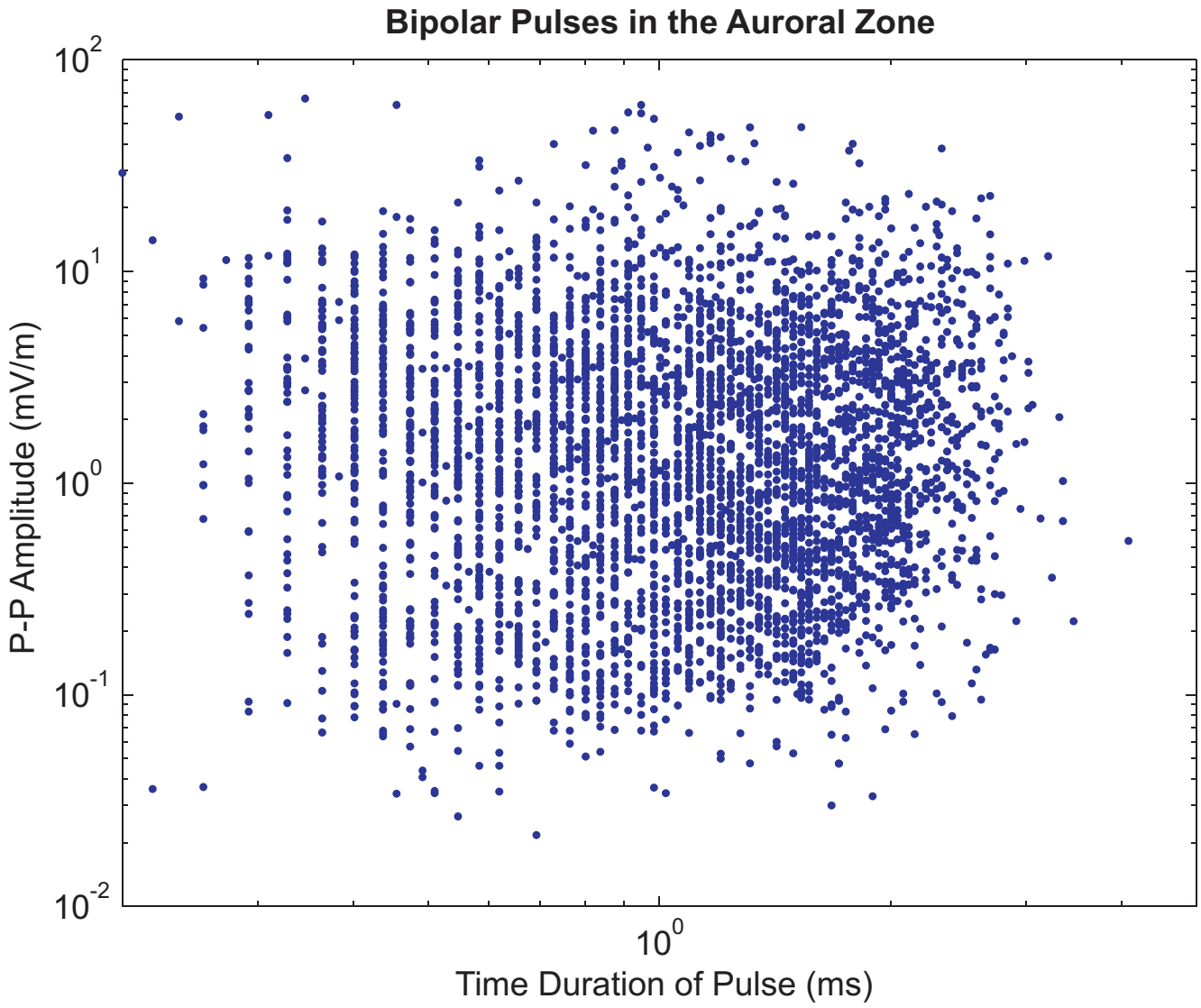
  Distance along field: 25 km
  Distance across field: 50 km
  Detection delay time from SC4 to SC2: 0.027 s
  Speed along magnetic field: 926 km/s
  Direction: Away from earth
  Time Duration of Pulse: 2.5 ms
  Parallel width: 2 km
  Perpendicular width: at least 50 km

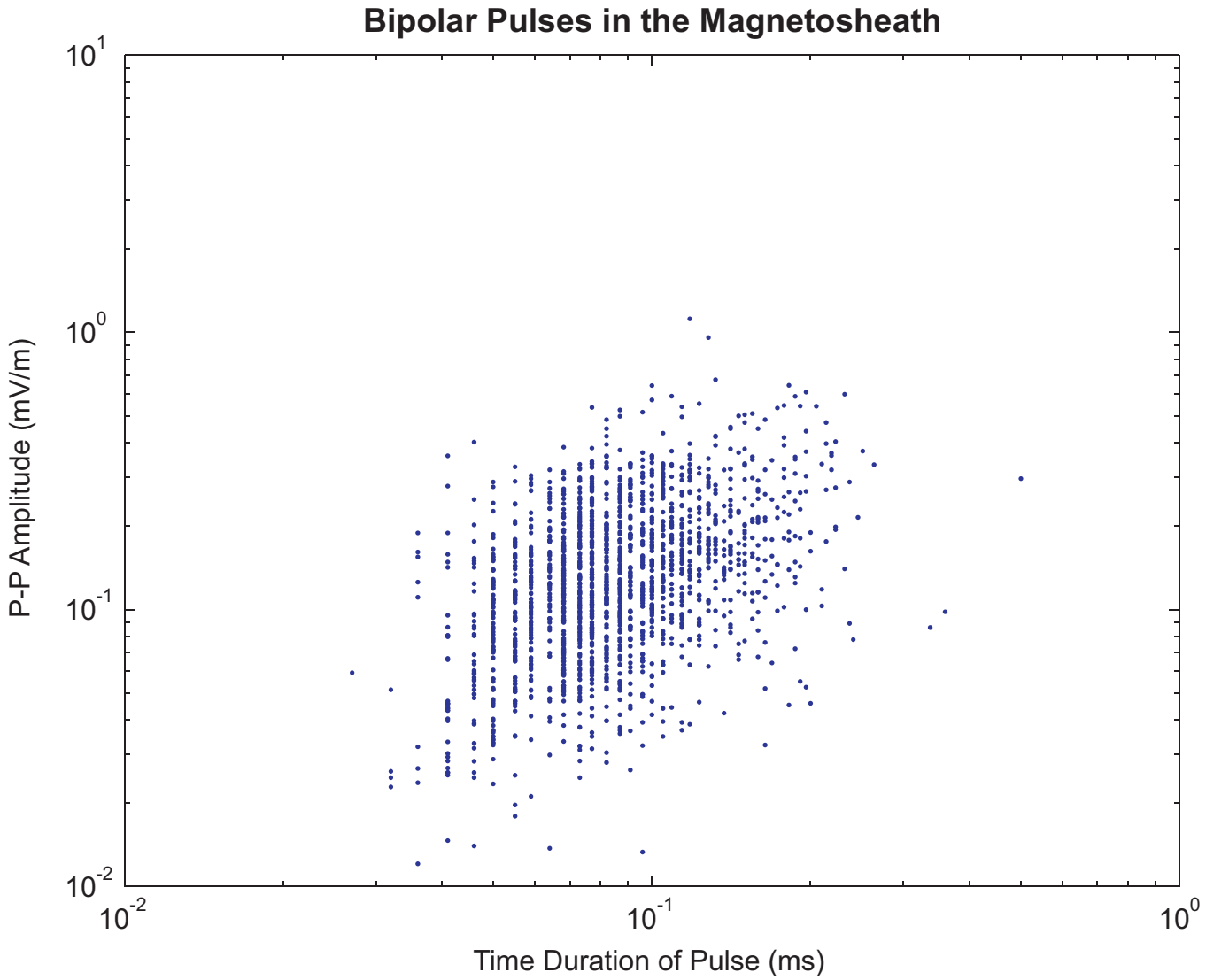
- April 6, 2002, SC1 and SC3:

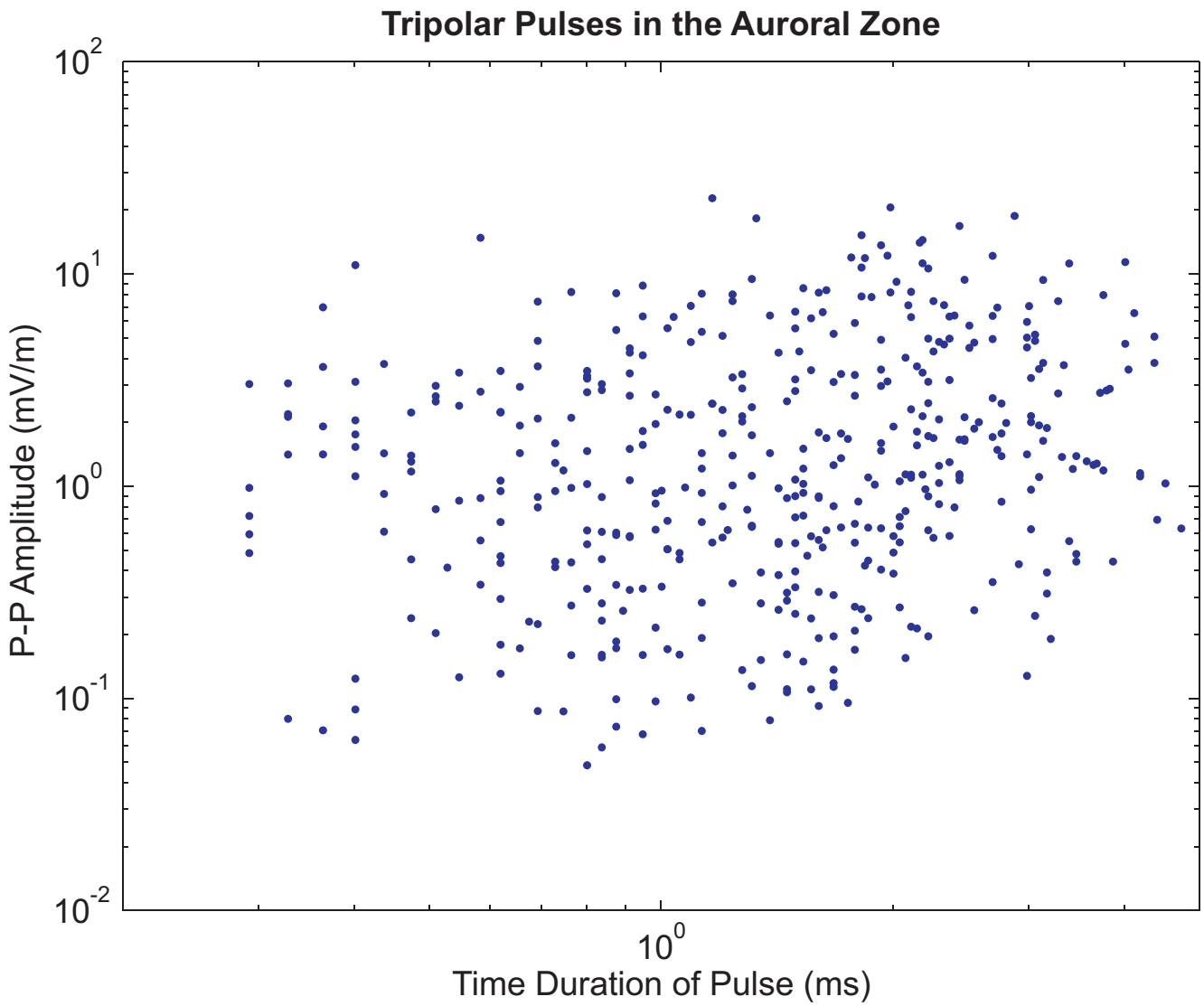
  Distance along field: 56 km
  Distance across field: 251 km
  Detection delay time from SC3 to SC1: 0.02 s
  Speed along magnetic field: 2800 km/s
  Direction: Toward earth
  Time Duration of Pulse: 1.6 ms
  Parallel width: 4.5 km
  Perpendicular width: at least 251 km

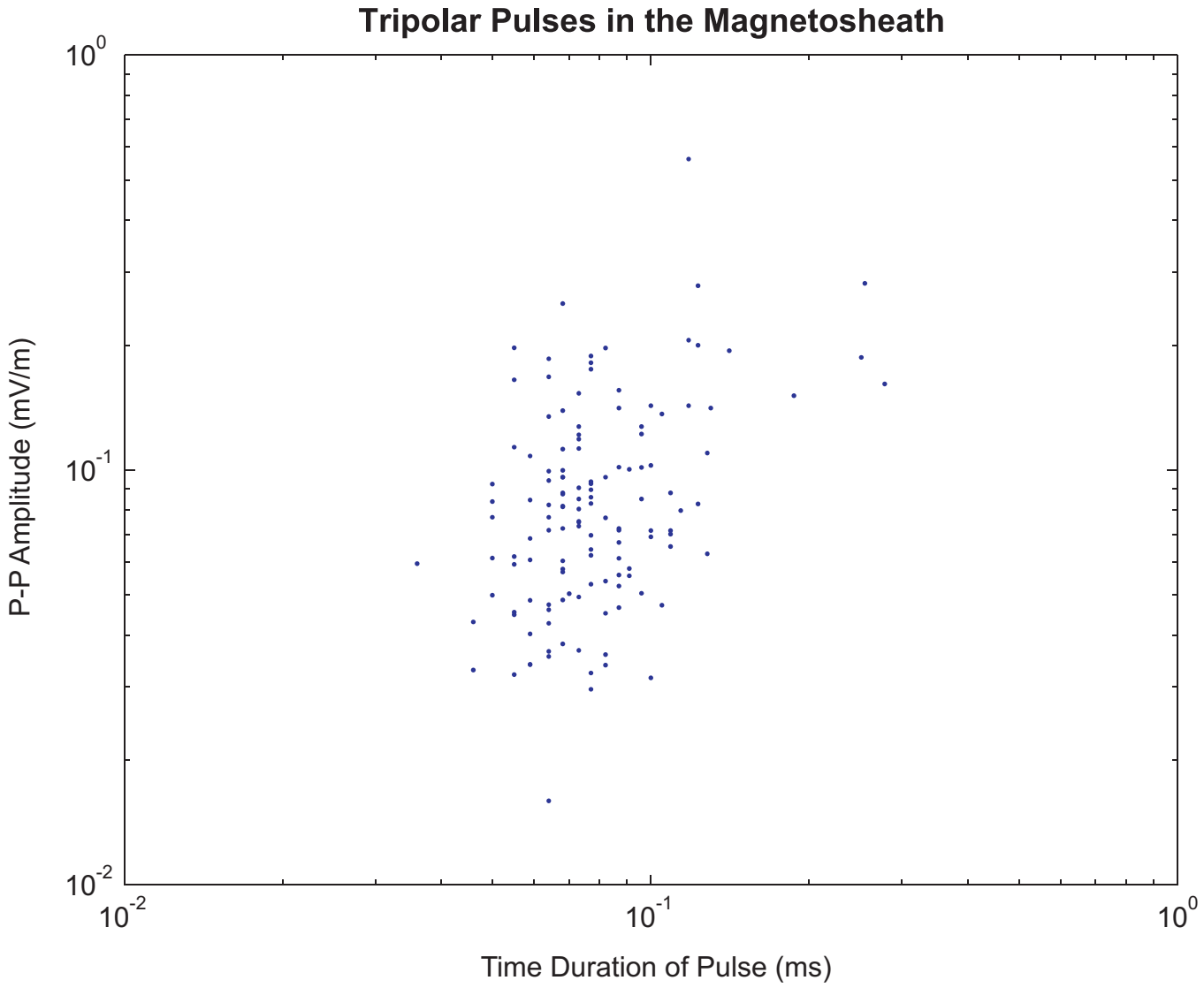
- Cross spacecraft correlation is complicated by several factors:

  - the spacecraft are not often lying along the same magnetic field line;
  - the angles of the antennas with respect to the magnetic field are often not identical, a requirement for good correlations;
  - the solitary waves observed close in time may be traveling in opposite directions.


Bipolar Pulses in the Auroral Zone
P-P Amplitude (mV/m)
Time Duration of Pulse (ms)
10^2
10^1
10^0
10^-1
10^-2
10^0


Bipolar Pulses in the Magnetosheath
P-P Amplitude (mV/m)
Time Duration of Pulse (ms)
10^1
10^0
10^-1
10^-2
10^-2
10^-1
10^0


Tripolar Pulses in the Auroral Zone
P-P Amplitude (mV/m)
Time Duration of Pulse (ms)
10^2
10^1
10^0
10^-1
10^-2
10^0

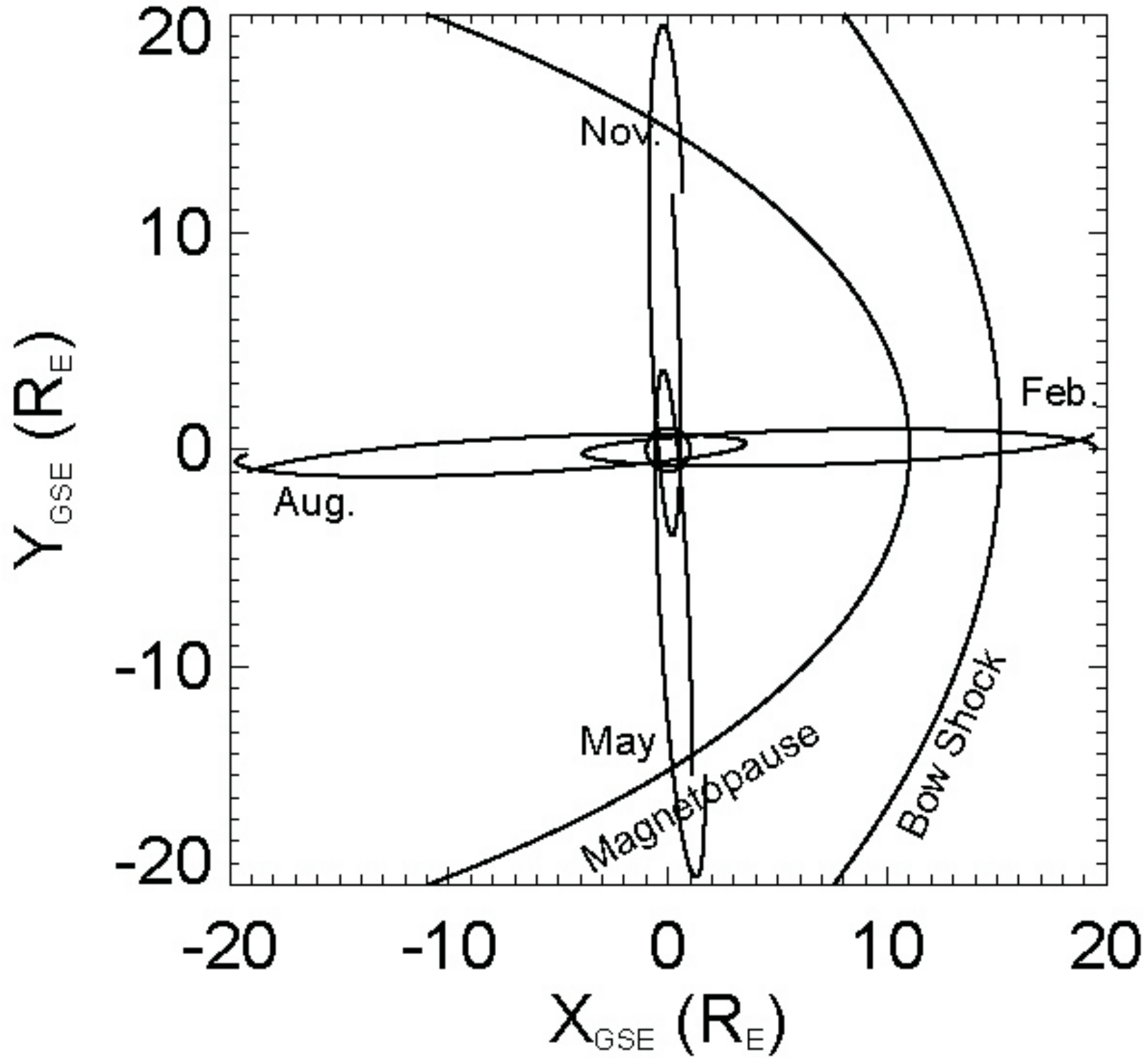

Tripolar Pulses in the Magnetosheath
P-P Amplitude (mV/m)
Time Duration of Pulse (ms)
10^0
10^-1
10^-2
10^-2
10^-1
10^0

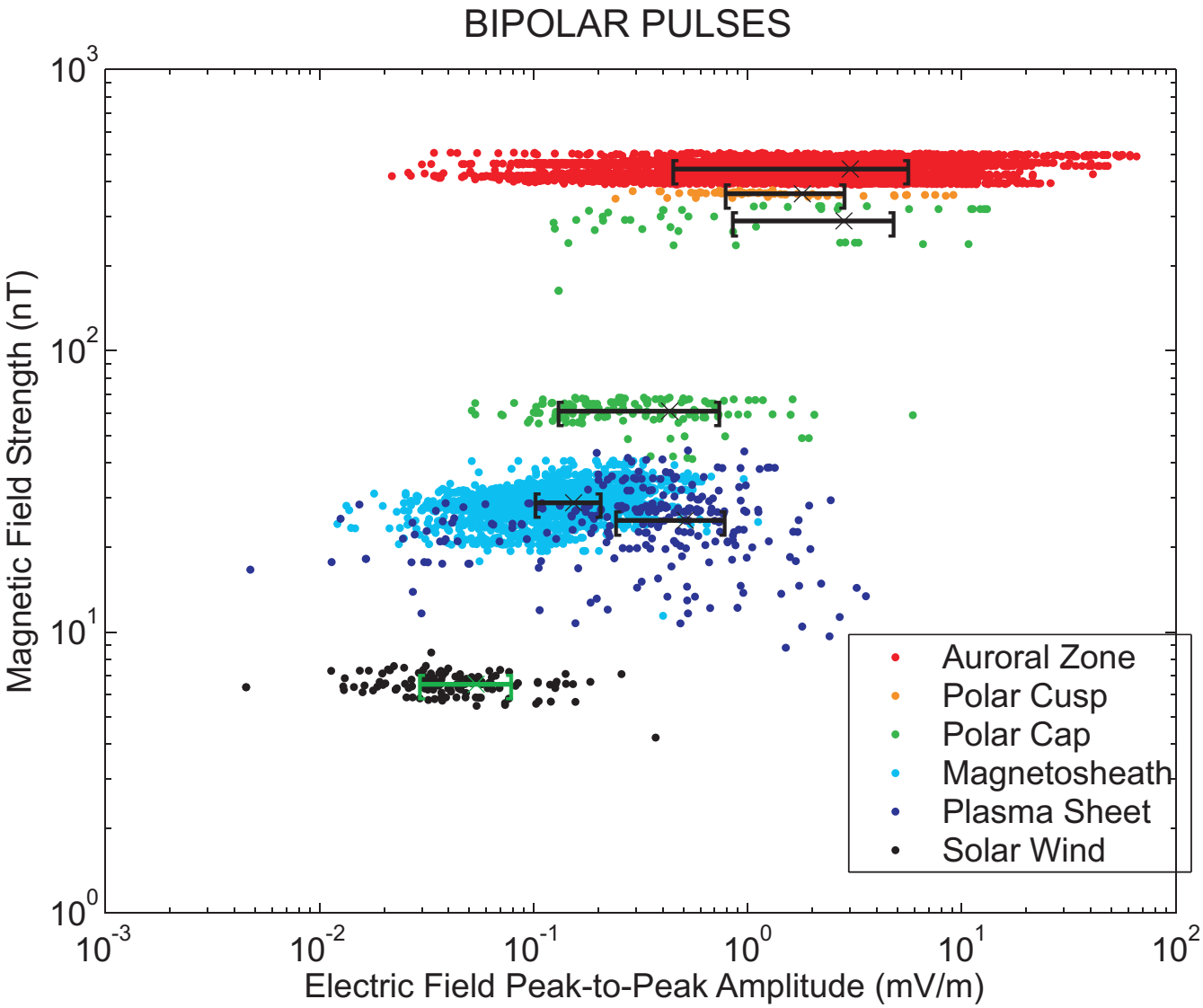
ANALYSIS OF AMPLITUDE VS. TIME DURATION PLOTS

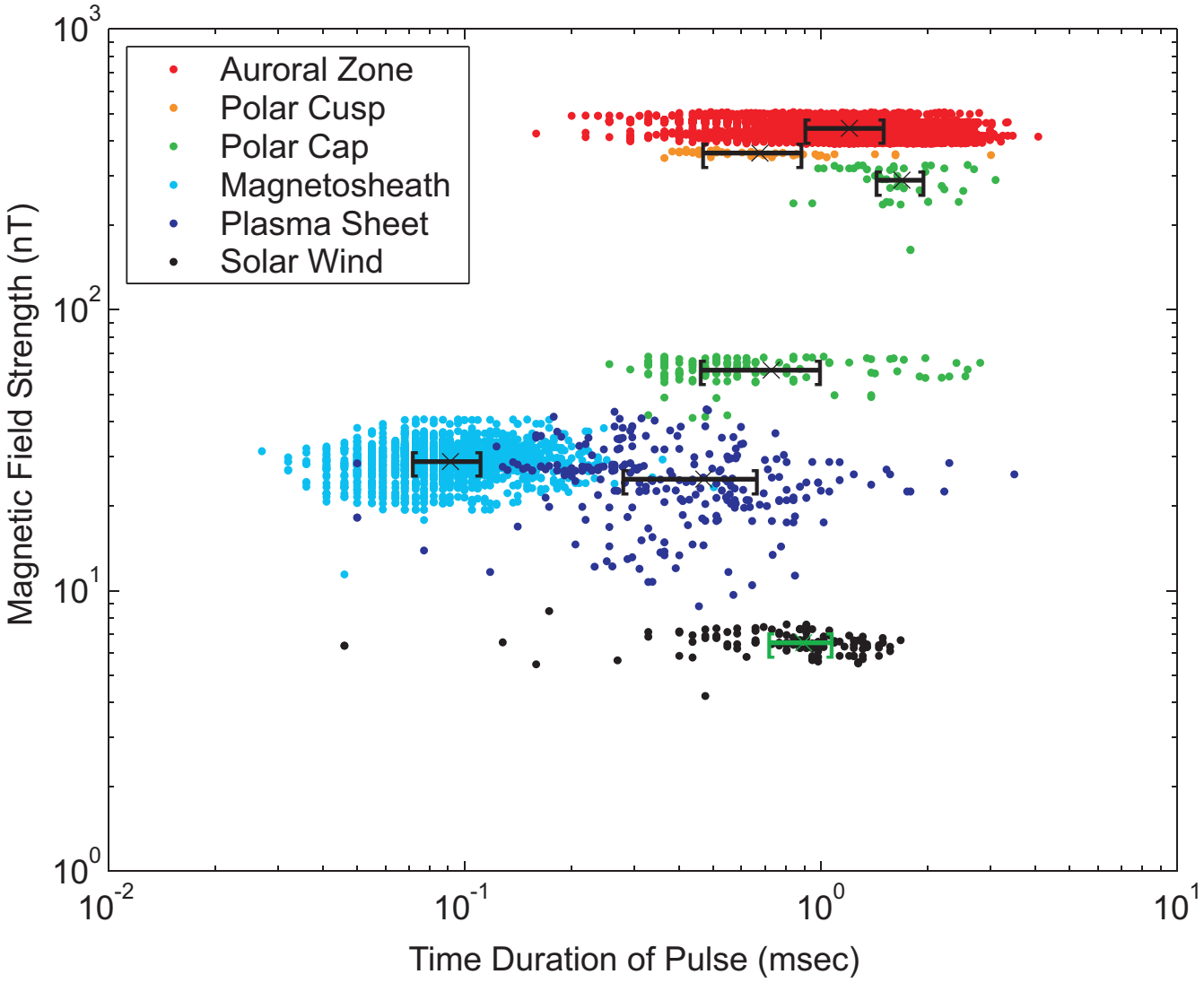
- Time duration of a pulse is related to either its size (width) or speed, or both.
- We assume that all pulses in a given region are propagating at about the same speed since they are probably created by a similar mechanism, so that time duration of a pulse for a given region is related to its size.
- For the auroral zone and magnetosheath, there is no relationship between the amplitudes and time durations of the pulses, i.e., all plots for tripolar and bipolar pulses produce scatter plots.
- This lack of relationship leans more heavily to the solitary waves being created out of an instability that produces nonlinear Bernstein-Green-Kruskal (BGK) type isolated potentials as opposed to KdV solitons because:

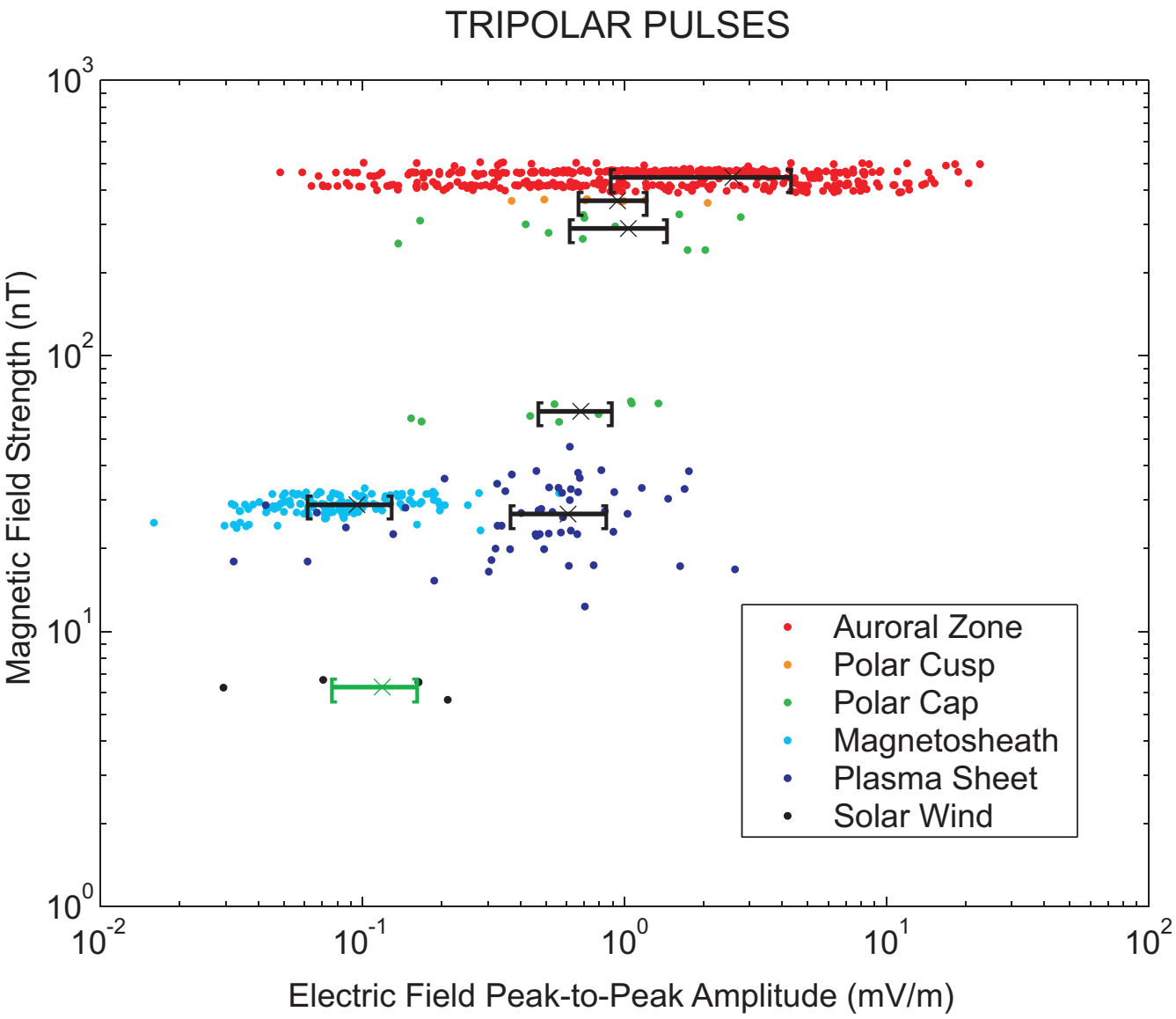
- For KdV solitons, including ion acoustic and shallow water, we expect that their widths will increase with decreasing potential amplitudes (thus decreasing electric field amplitudes) [“Solitons”, by P. G. Drazin]

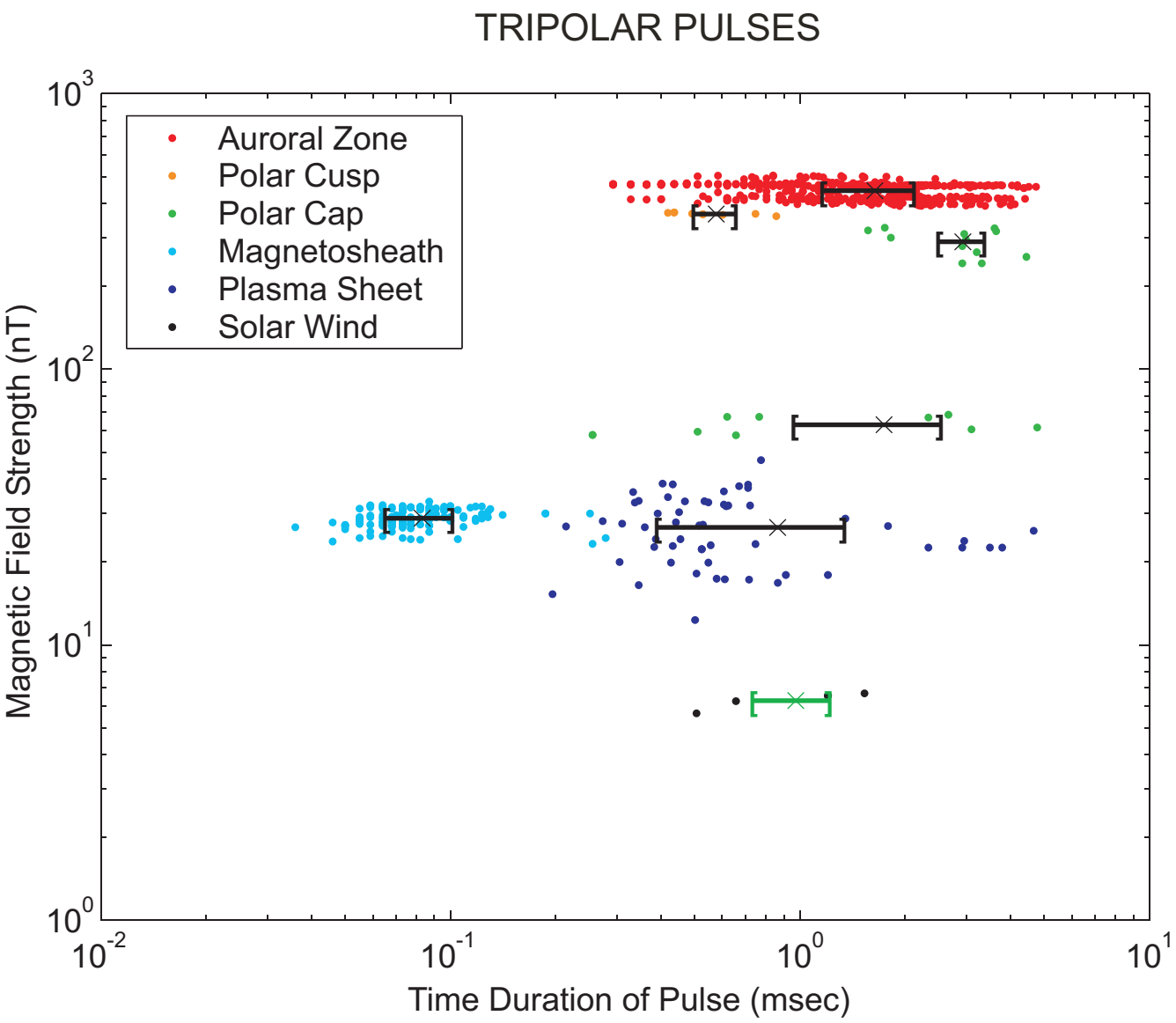
- For BGK solitary waves, their widths and potential amplitudes (electric field) are constrained by inequalities so that we expect no relationship between the two quantities
  [Chen et al., http://arxiv.org/abs/physics/0303021, 2003]


20
10
0
-10
-20
-20
-10
0
10
20
Y_{GSE} (R_E)
X_{GSE} (R_E)
Nov.
Feb.
Aug.
May
Magnetopause
Bow Shock


BIPOLAR PULSES
Magnetic Field Strength (nT)
Electric Field Peak-to-Peak Amplitude (mV/m)
10^3
10^2
10^1
10^0
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
Auroral Zone
Polar Cusp
Polar Cap
Magnetosheath
Plasma Sheet
Solar Wind


BIPOLAR PULSES
Auroral Zone
Polar Cusp
Polar Cap
Magnetosheath
Plasma Sheet
Solar Wind
Magnetic Field Strength (nT)
Time Duration of Pulse (msec)
10^3
10^2
10^1
10^0
10^-2
10^-1
10^0
10^1


TRIPOLAR PULSES
Magnetic Field Strength (nT)
Electric Field Peak-to-Peak Amplitude (mV/m)
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
10^2
Auroral Zone
Polar Cusp
Polar Cap
Magnetosheath
Plasma Sheet
Solar Wind


TRIPOLAR PULSES
Auroral Zone
Polar Cusp
Polar Cap
Magnetosheath
Plasma Sheet
Solar Wind
Magnetic Field Strength (nT)
Time Duration of Pulse (msec)
10^3
10^2
10^1
10^0
10^-2
10^-1
10^0
10^1

ANALYSIS OF AMPLITUDE/TIME DURATIONS VS. B-FIELD STRENGTH PLOTS

- For the amplitude vs. B-field strength (5 to 500 nT) plots, both bipolar and tripolar pulses show:

  - ❖ a broad range of amplitudes at any specific magnetic field strength;
  - ❖ a general trend for the amplitudes to increase as the magnetic field strength increases.

The following two conditions have been found to provide a ground for understanding the general observational trend [Chen et al., 2003]:

(1) $\frac{\sqrt{m\Psi/e}}{B\delta_z} << 1$ (2) $\frac{\sqrt{2m\Psi/e}}{B\delta_r} << 1$

WHERE:

Ψ Peak potential amplitude

δ_z Parallel Size

δ_r Perpendicular Size

B Magnetic field strength

e,m Charge and mass of electrons

- For the time duration vs. B-field strength plots, both bipolar and tripolar pulses show:
  - ❖ no dependence;
  - ❖ all regions sampled have comparable time durations with the exception of those found in the magnetosheath, which have smaller time durations;
  - ❖ the smaller time durations of the magnetosheath solitary waves may imply that they are generated by a different mechanism.

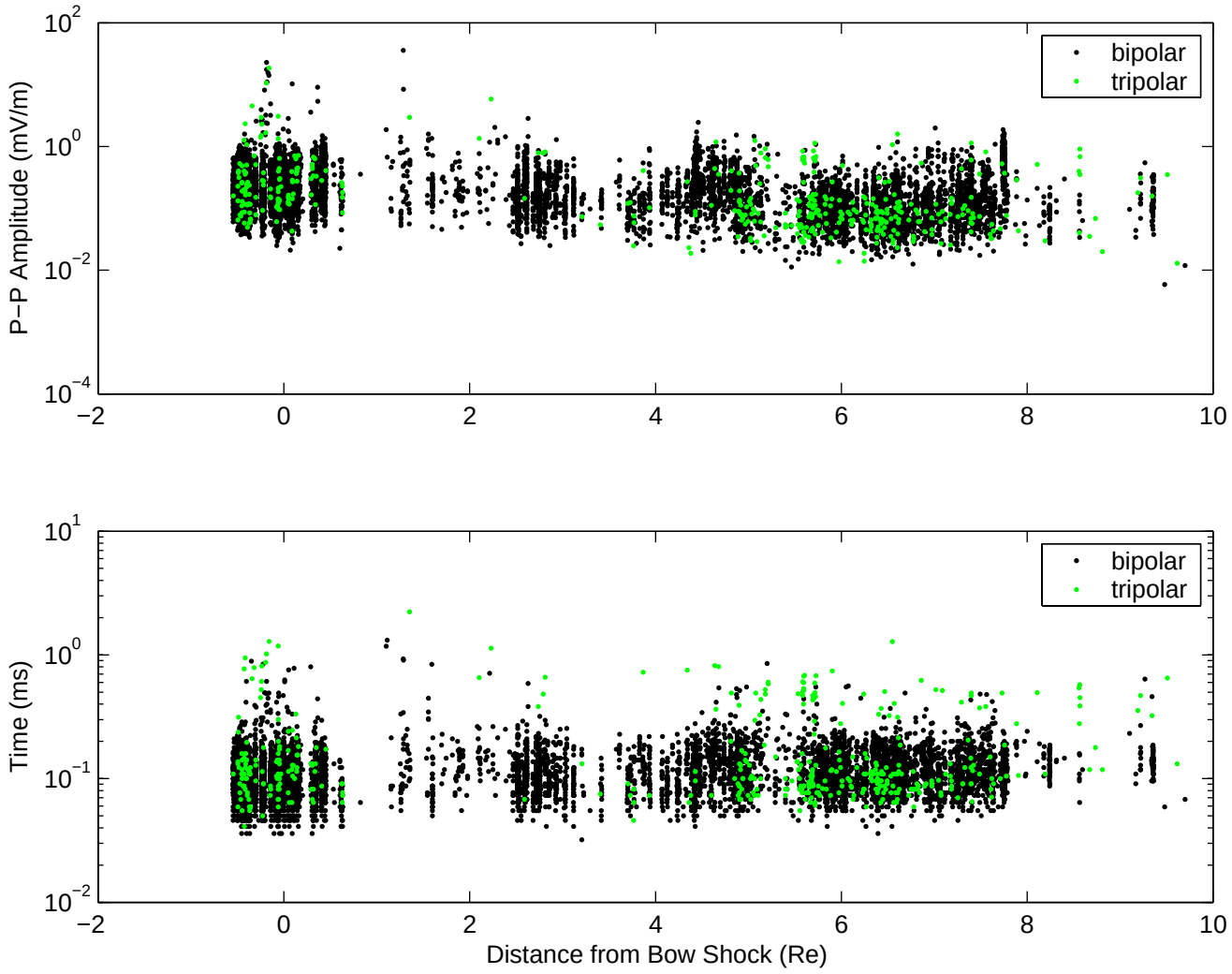
CONCLUDING REMARKS

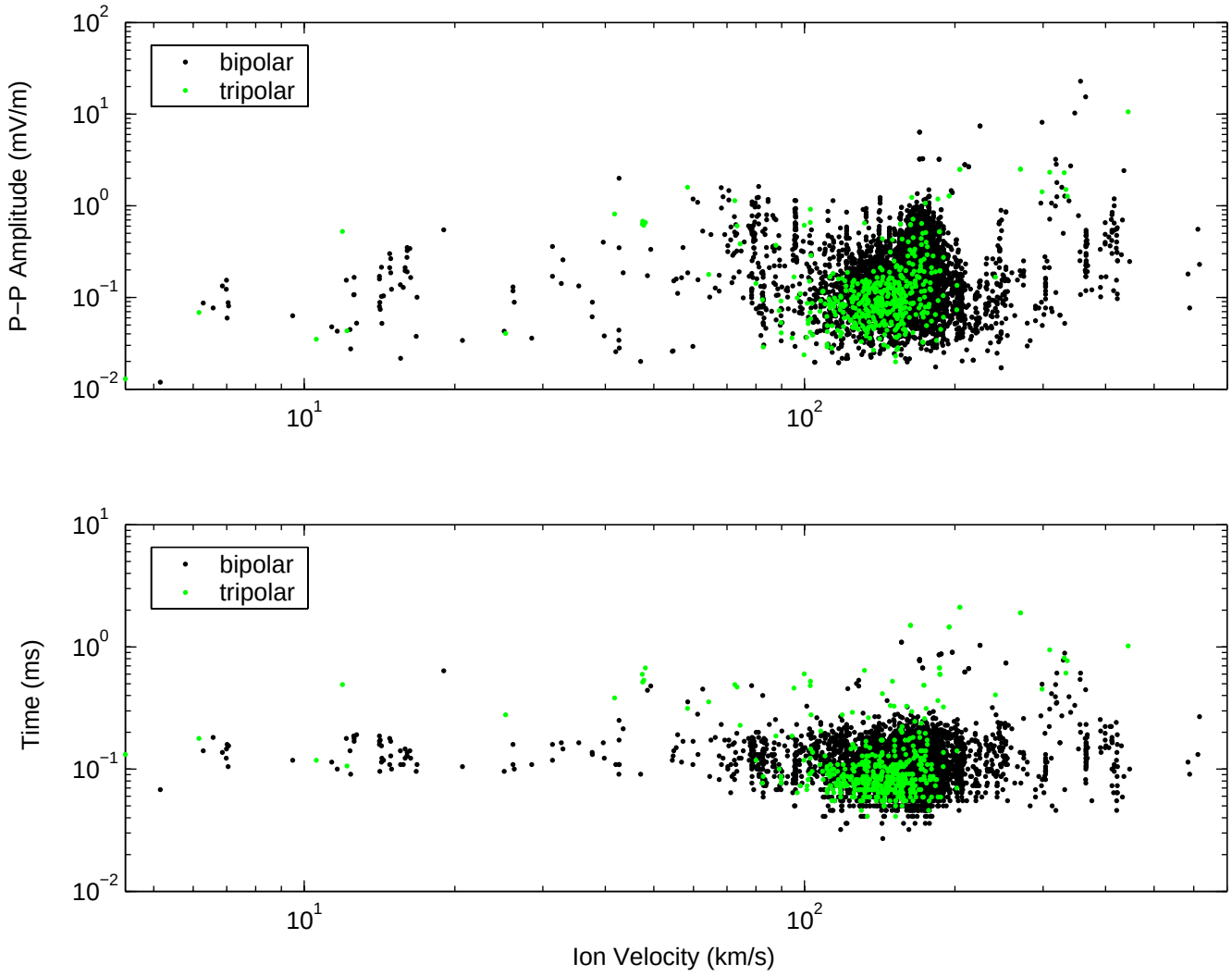
- Solitary waves are observed at all of the boundaries crossed by Cluster (bow shock, magnetopause, polar cap, cusp, LLBL), as well as in the solar wind, magnetosheath and along auroral field lines at 4.5-6.5 R_E.

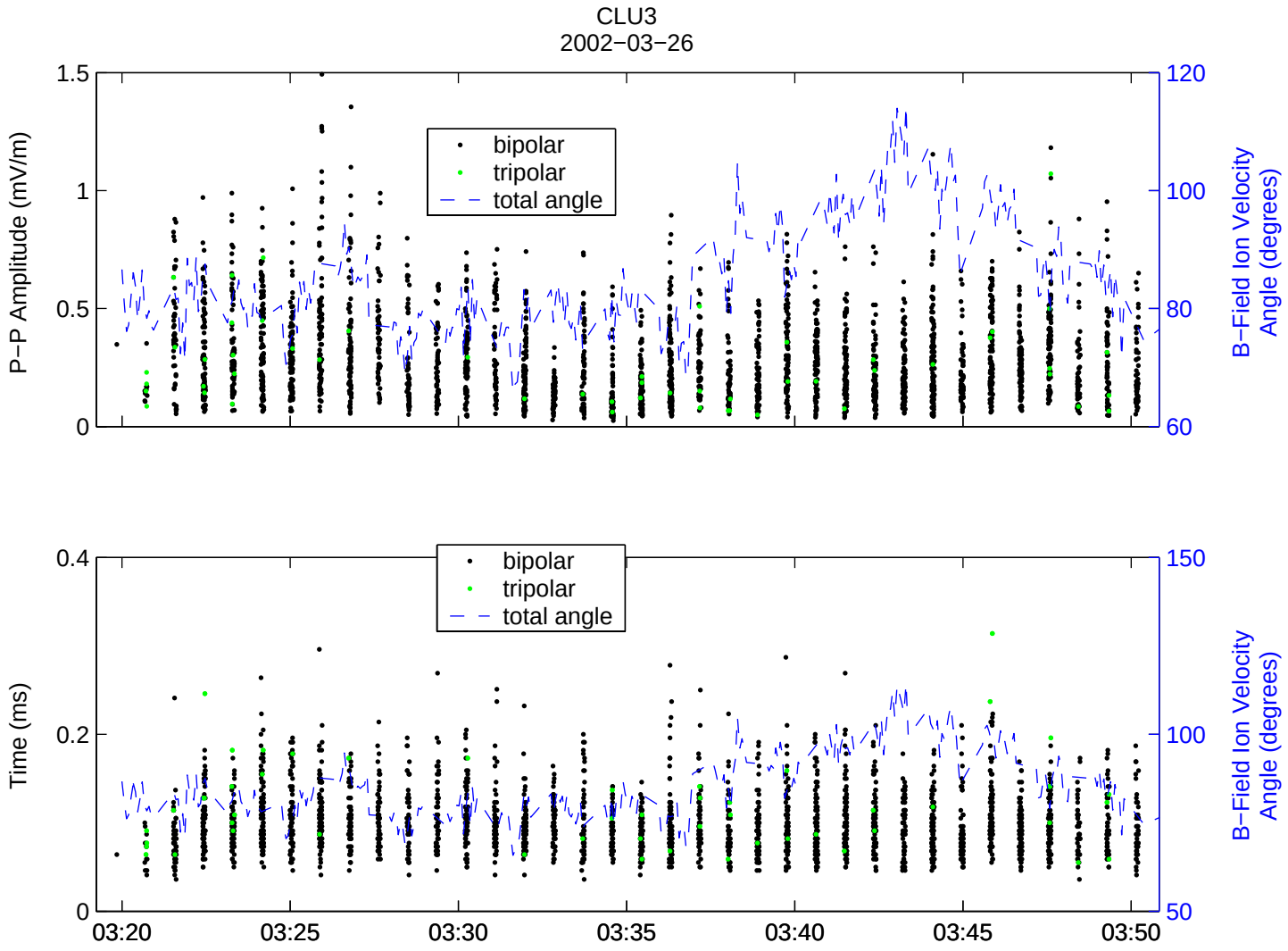
- A general study of the generation mechanism (beam instability; electrostatic turbulence) of the solitary waves, as well as the effect of solitary waves on particle populations in these regions has just begun.

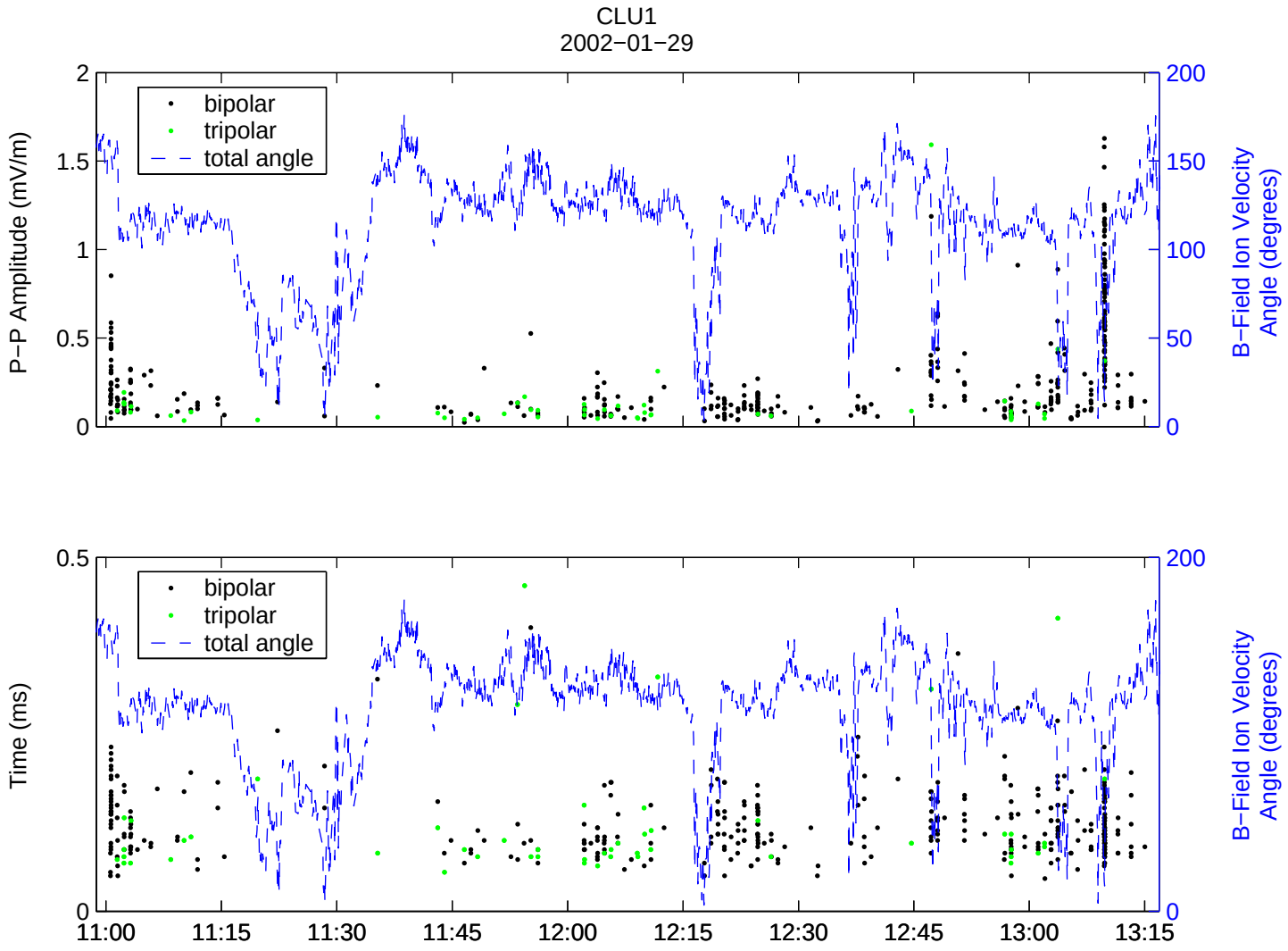
- The time resolution of Cluster particle data, both electron and ion, is insufficient to perform time correlations of solitary waves with beams, etc.; thus, regional statistics will be compiled.

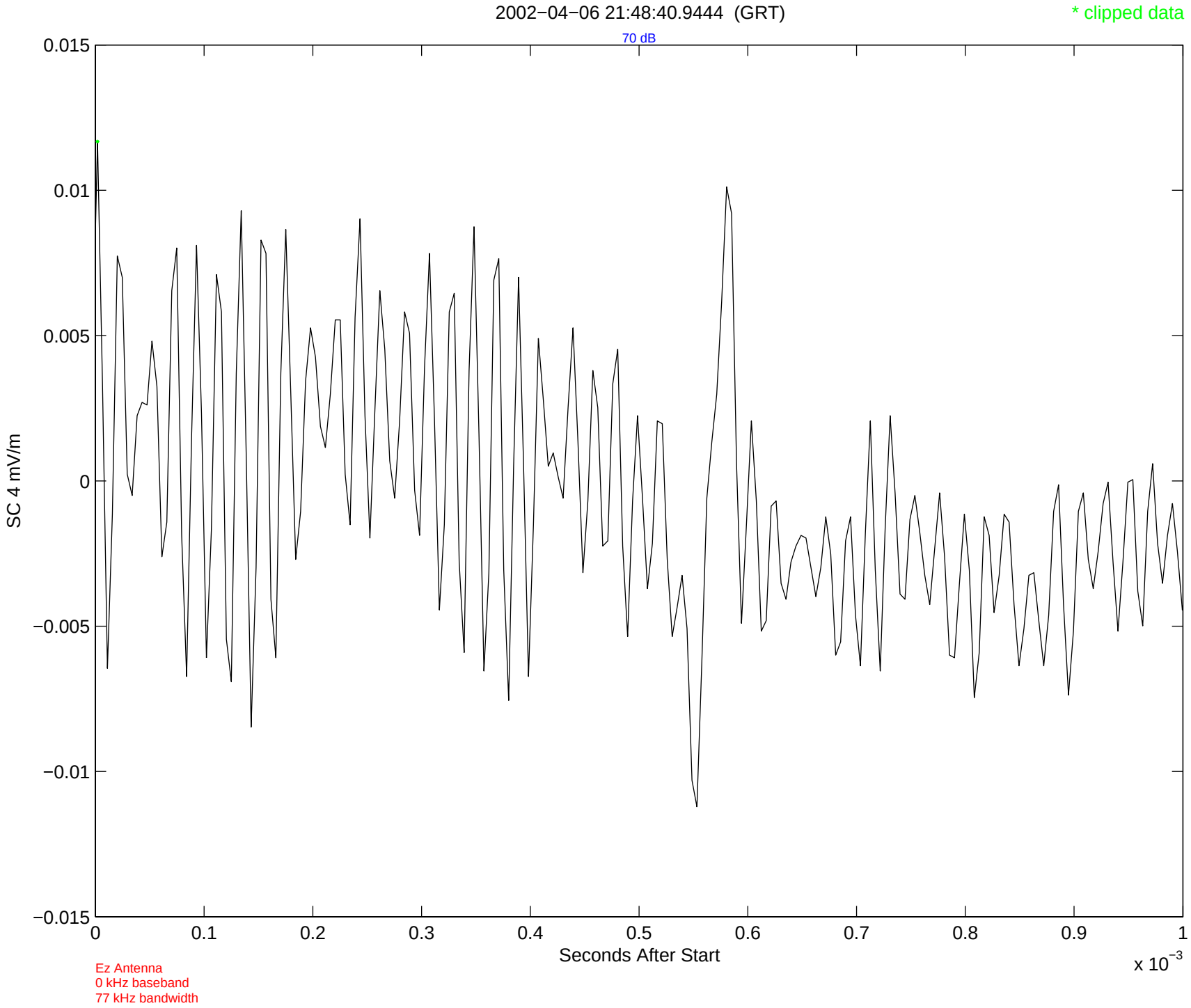
- Magnetosheath solitary waves are being investigated in more detail due to their uniquely smaller time durations.

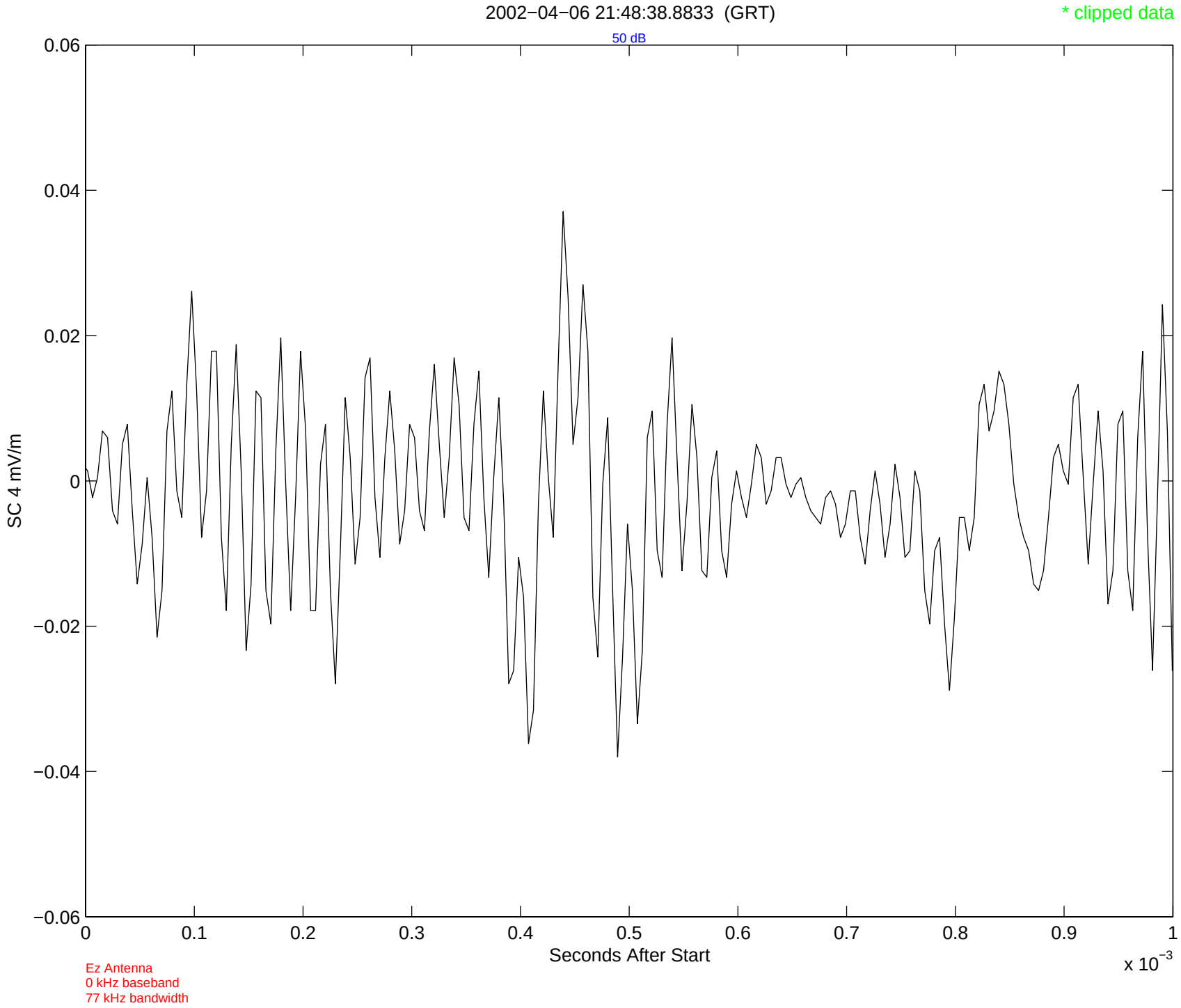

P−P Amplitude (mV/m)
bipolar
tripolar
Time (ms)
bipolar
tripolar
Distance from Bow Shock (Re)

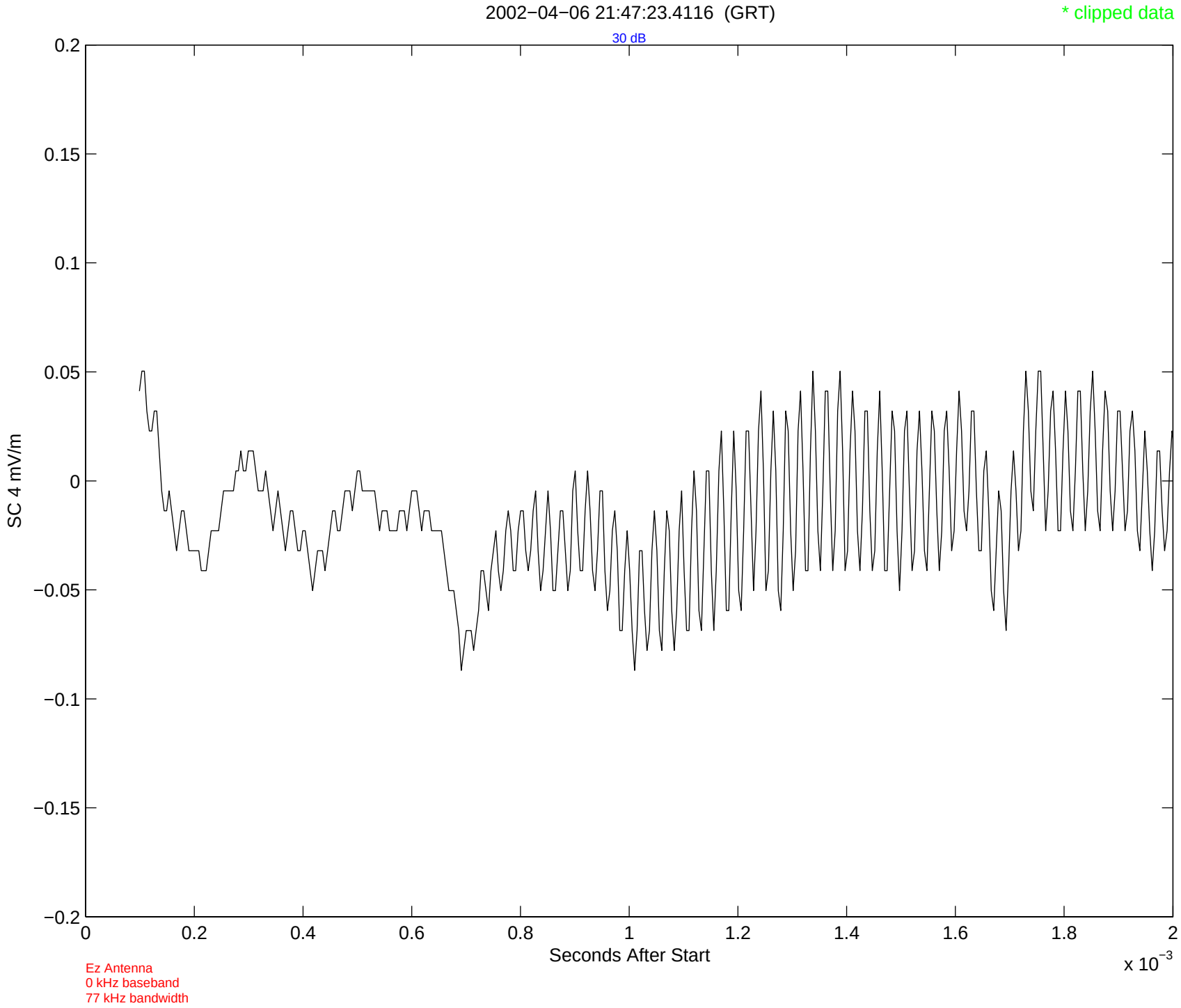

bipolar
tripolar
P–P Amplitude (mV/m)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{1}
10^{2}
bipolar
tripolar
Time (ms)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{1}
10^{2}
Ion Velocity (km/s)


CLU3
2002−03−26
P−P Amplitude (mV/m)
B−Field Ion Velocity Angle (degrees)
bipolar
tripolar
total angle
1.5
1
0.5
0
120
100
80
60
Time (ms)
0.4
0.2
0
150
100
50
03:20
03:25
03:30
03:35
03:40
03:45
03:50


CLU1
2002−01−29
P−P Amplitude (mV/m)
B−Field Ion Velocity Angle (degrees)
bipolar
tripolar
total angle
Time (ms)
11:00
11:15
11:30
11:45
12:00
12:15
12:30
12:45
13:00
13:15


2002−04−06 21:48:40.9444 (GRT)
* clipped data
70 dB
0.015
0.01
0.005
0
−0.005
−0.01
−0.015
SC 4 mV/m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Seconds After Start
x 10−3
Ez Antenna
0 kHz baseband
77 kHz bandwidth


2002−04−06 21:48:38.8833 (GRT)
* clipped data
50 dB
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
SC 4 mV/m
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Seconds After Start
x 10−3
Ez Antenna
0 kHz baseband
77 kHz bandwidth


2002−04−06 21:47:23.4116 (GRT)
* clipped data
30 dB
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
SC 4 mV/m
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Seconds After Start
x 10−3
Ez Antenna
0 kHz baseband
77 kHz bandwidth