Magnetospheric Response to Solar Activity
September 9-12, 2003, Prague

MULTIPOINT OBSERVATIONS OF NONLINEAR WAVES AND ISOLATED ELECTROSTATIC STRUCTURES IN THE EARTH'S MAGNETOSPHERE: THE CLUSTER PERSPECTIVE

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A. Balogh, PI of Cluster FGM, for magnetic field data
T. Fritz for Cluster RAPID
NASA/GSFC support under Grant NAG5-9974

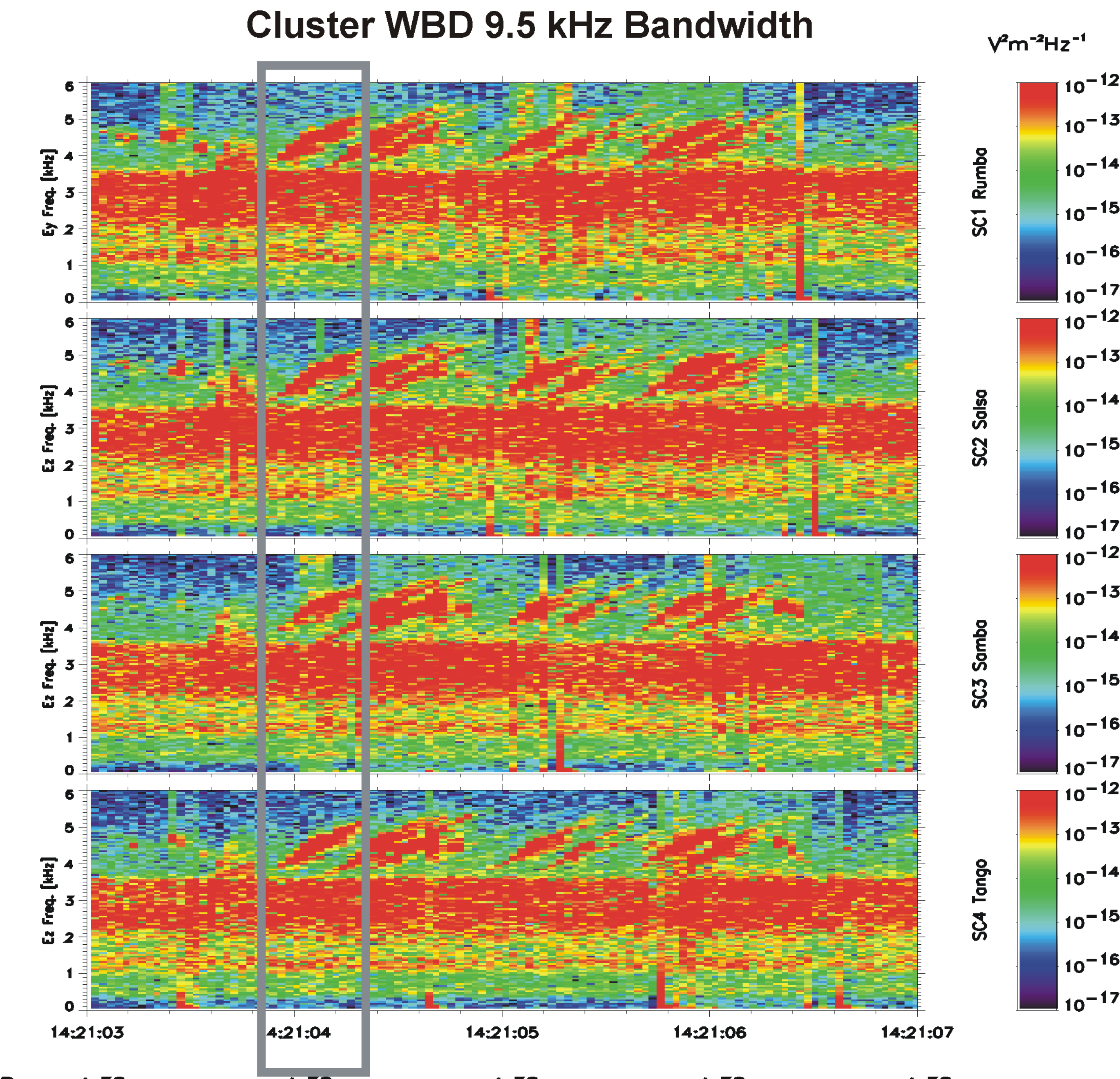
OUTLINE

- Electromagnetic VLF Triggered Emissions (VLF TE)
- Isolated Electrostatic Structures (IES)

QUESTIONS-VLF TRIGGERED EMISSIONS

- What do we mean by electromagnetic VLF triggered emissions?
- Where are VLF triggered emissions observed?
- What is the cross-spacecraft correlation distance for these emissions?
- What is the direction and velocity of propagation of these emissions?
- How are the VLF triggered emissions generated?

- *3.5-4.5 kHz fine-structured triggered emissions observed on all spacecraft for ~ 6 seconds*
- *Triggered emissions appear as risers*
- *Highlighted riser to be analyzed as to delay time of arrival at each spacecraft*

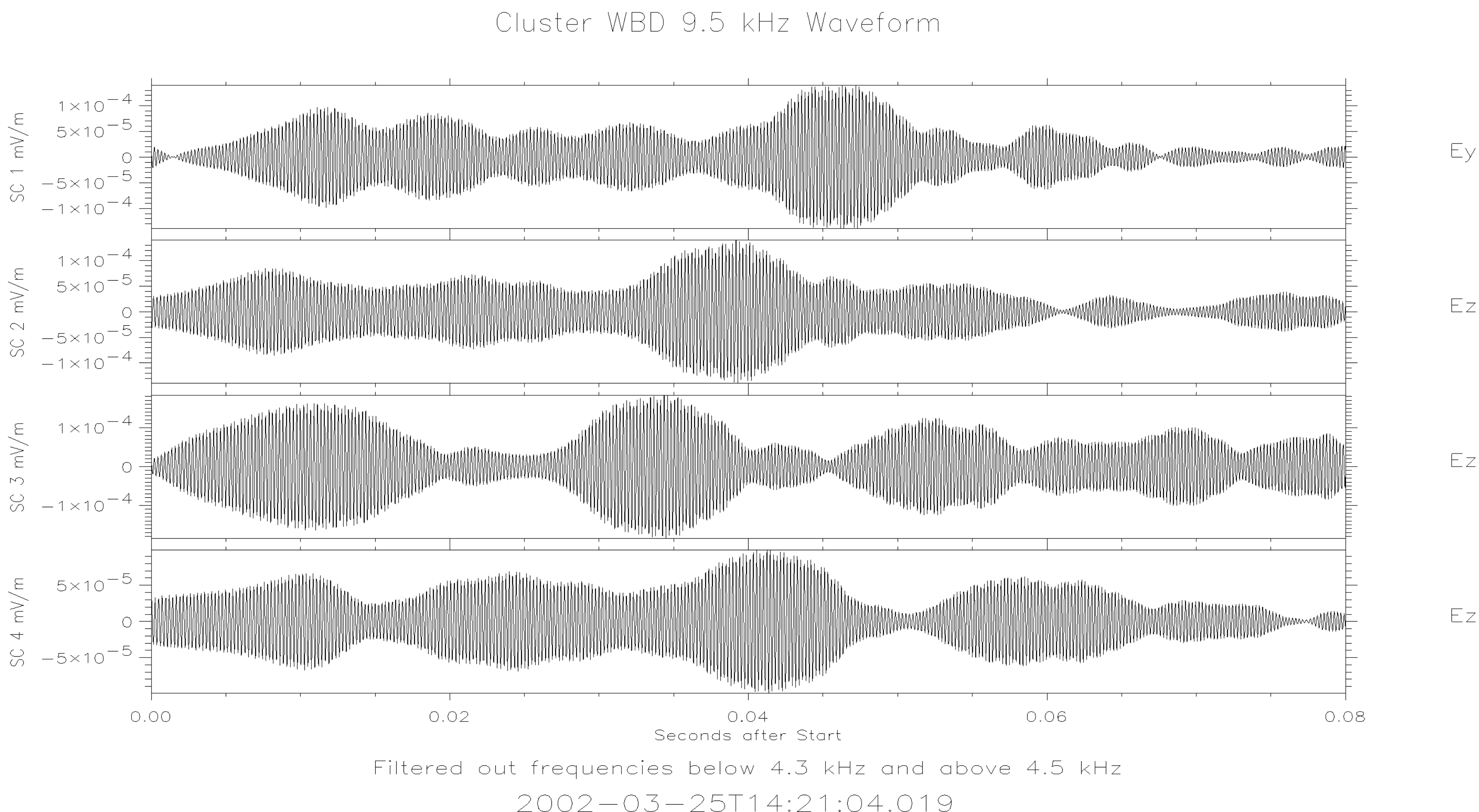


R_E	4.38	4.38	4.38	4.38	4.38
λ_m	4.50	4.51	4.52	4.53	4.54
MLT	22.50	22.50	22.50	22.50	22.50
L	4.40	4.40	4.40	4.40	4.40

UT_OBT: 2002-03-25T14:21:03 to 2002-03-25T14:21:07

- ***Fir digitally filtered (4.3 to 4.5 kHz) waveform of highlighted riser***
- ***Note the wave packet near the middle of the plot, which has been analyzed for delay time of arrival***
- ***Spacecraft order of observance: 3, 2, 4, 1***
- ***Delay times of arrival:***

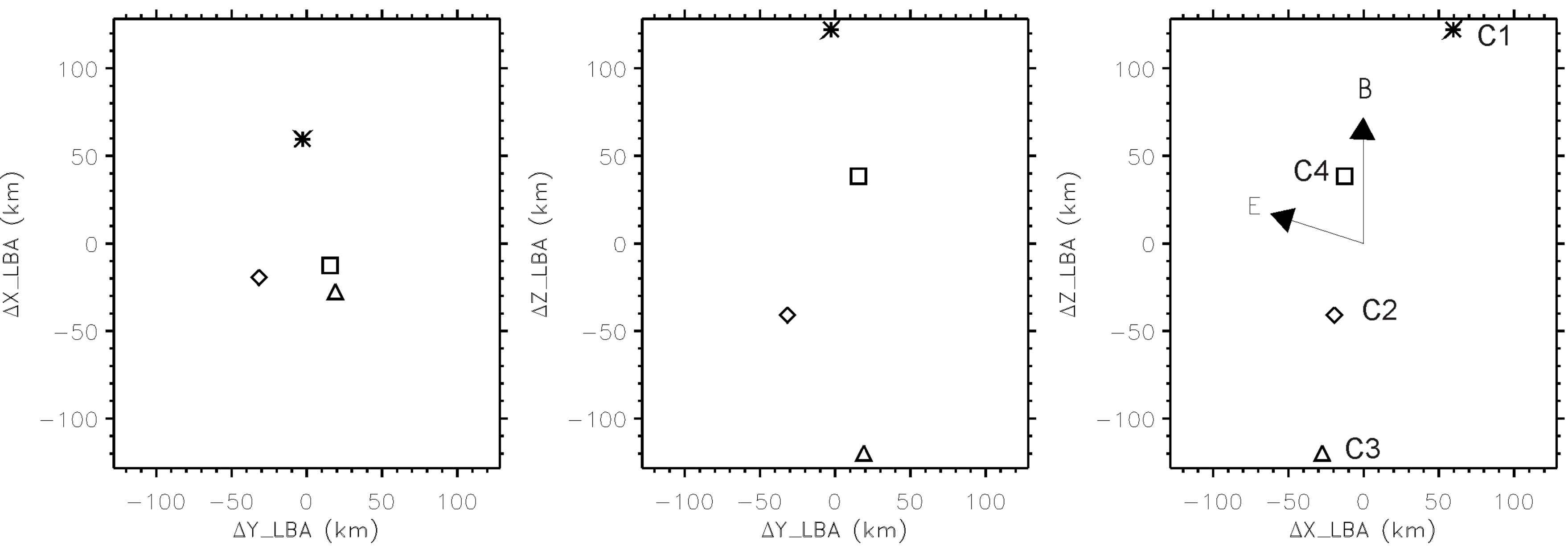
S/C Pair	Delay Time (milliseconds)
3/2	4.649
2/4	2.582
4/1	4.833



- ***Relative locations of the 4 Cluster spacecraft in a magnetic field-aligned coordinate system (origin at center of mass)***
- ***Separations:***

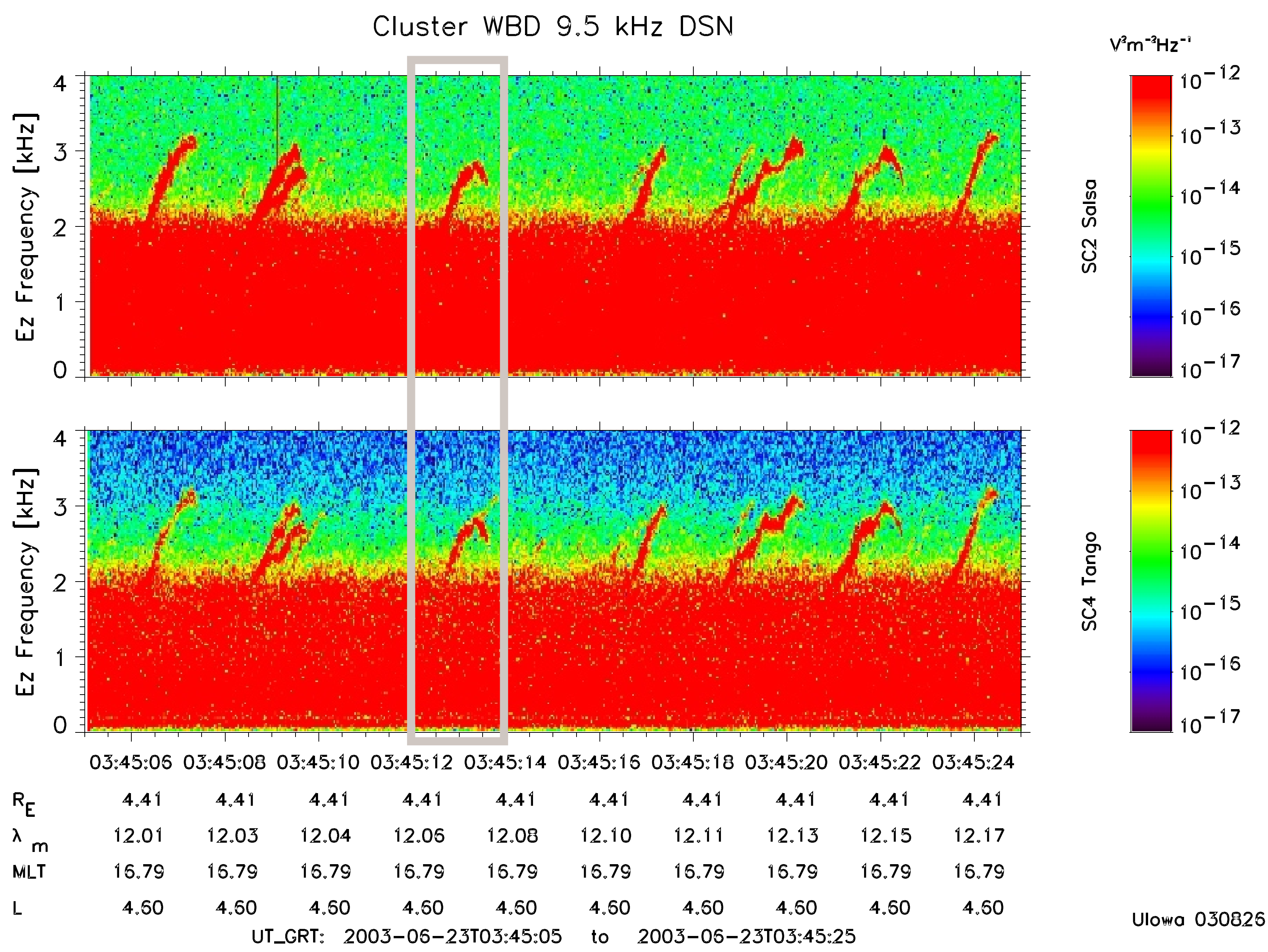
S/C Pair	Along B (km)	Across B (km)
3/2	78.8	52.5
2/4	79.4	47.7
4/1	83.7	74.5

SCET: 2002-Mar-25T14:21:04

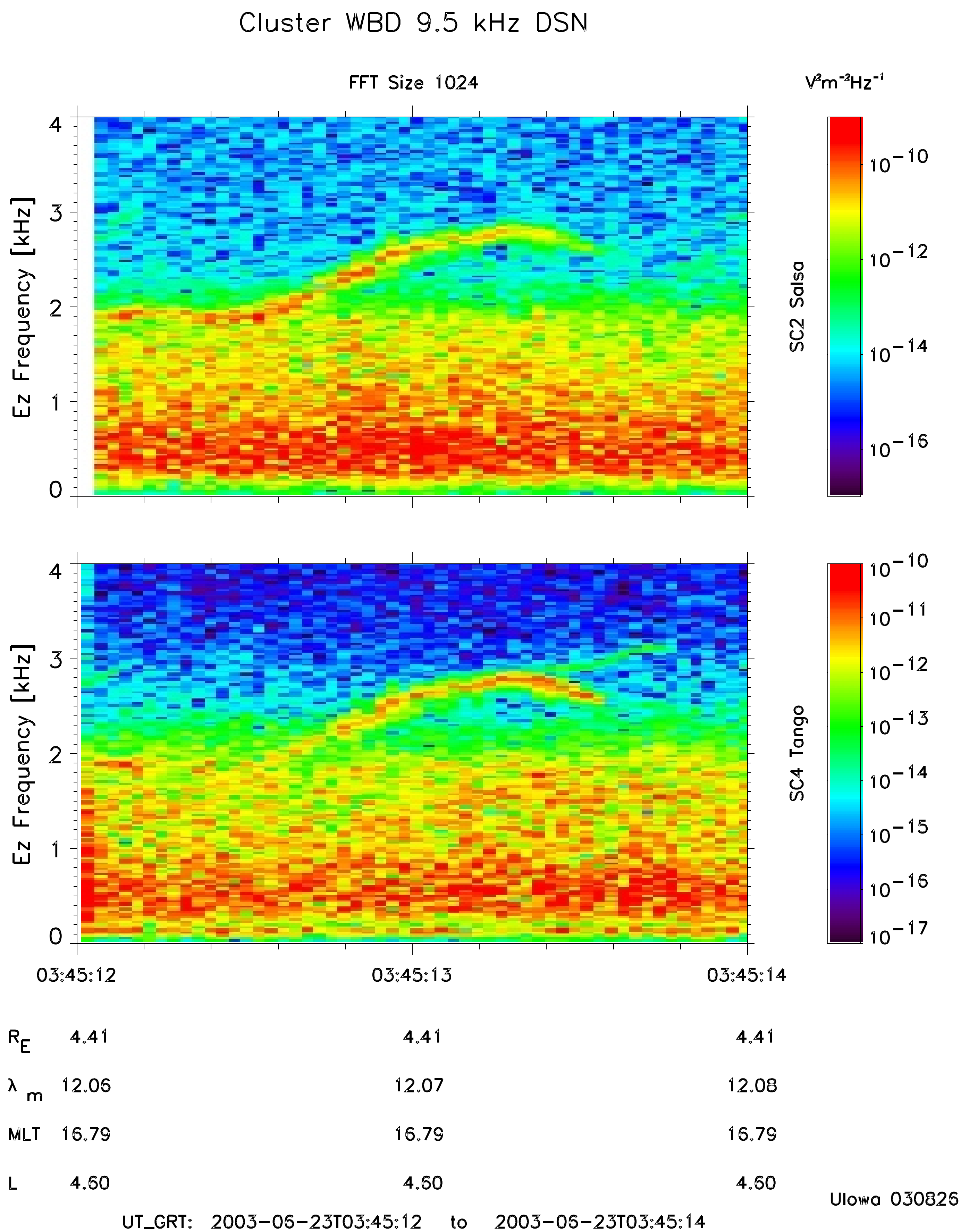


Cluster	1 *	2 ◇	3 △	4 □
GMLat	4.72°	4.35°	4.19°	4.51°
Re	4.38	4.38	4.38	4.38
L	4.41	4.40	4.40	4.40
MLT	22.29	22.29	22.29	22.29

- 2.2-3.2 kHz fine-structured triggered emissions observed on C2 and C4 for ~ 20 seconds
- Triggered emissions appear as risers and hooks
- Highlighted riser will be analyzed in detail.

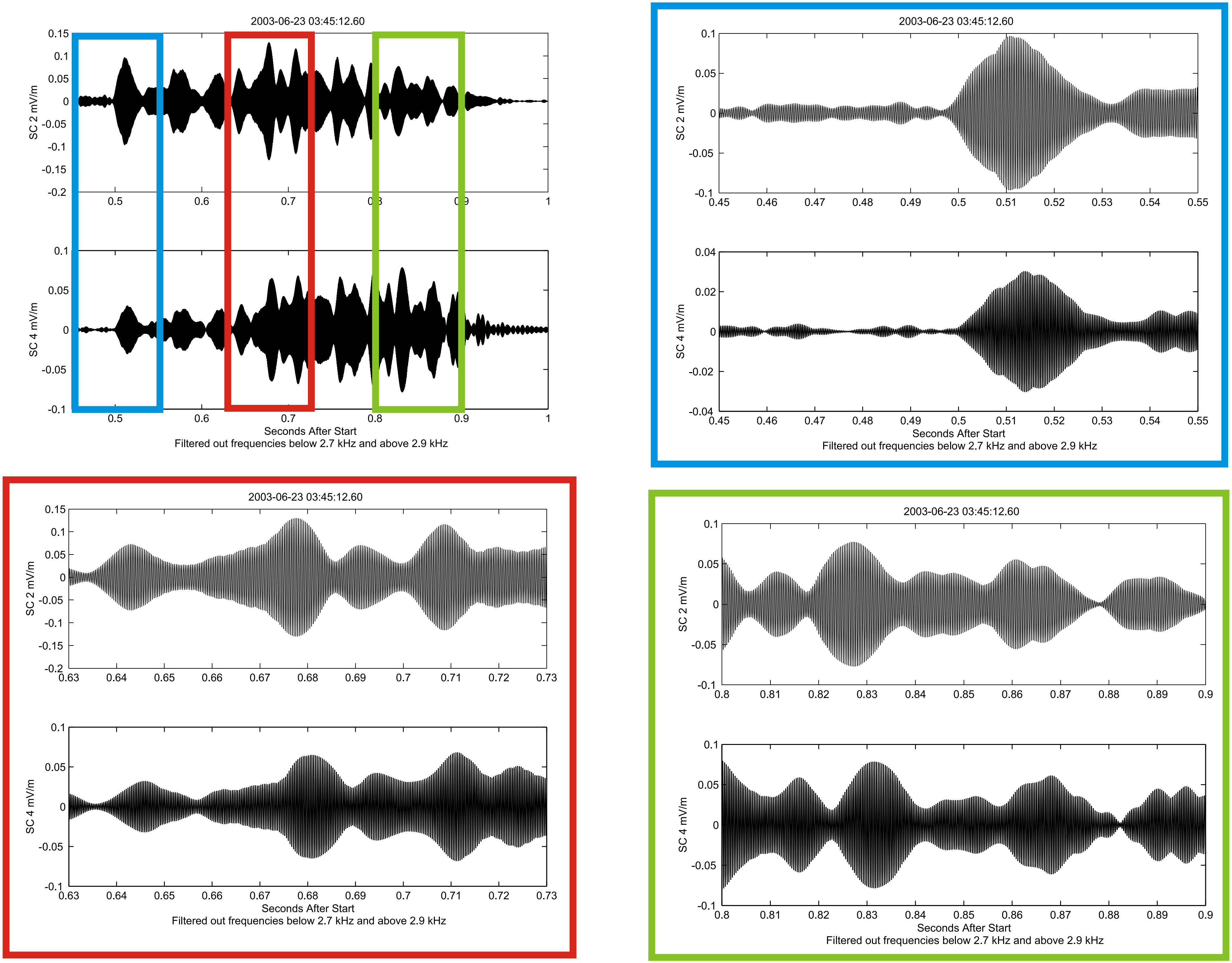


- Triggered Emission on C2 and C4 in form of riser and hook in frequency band ~ 2 to 3 kHz covering ~1 second.
- Additional trigger off of triggered emission on C4.



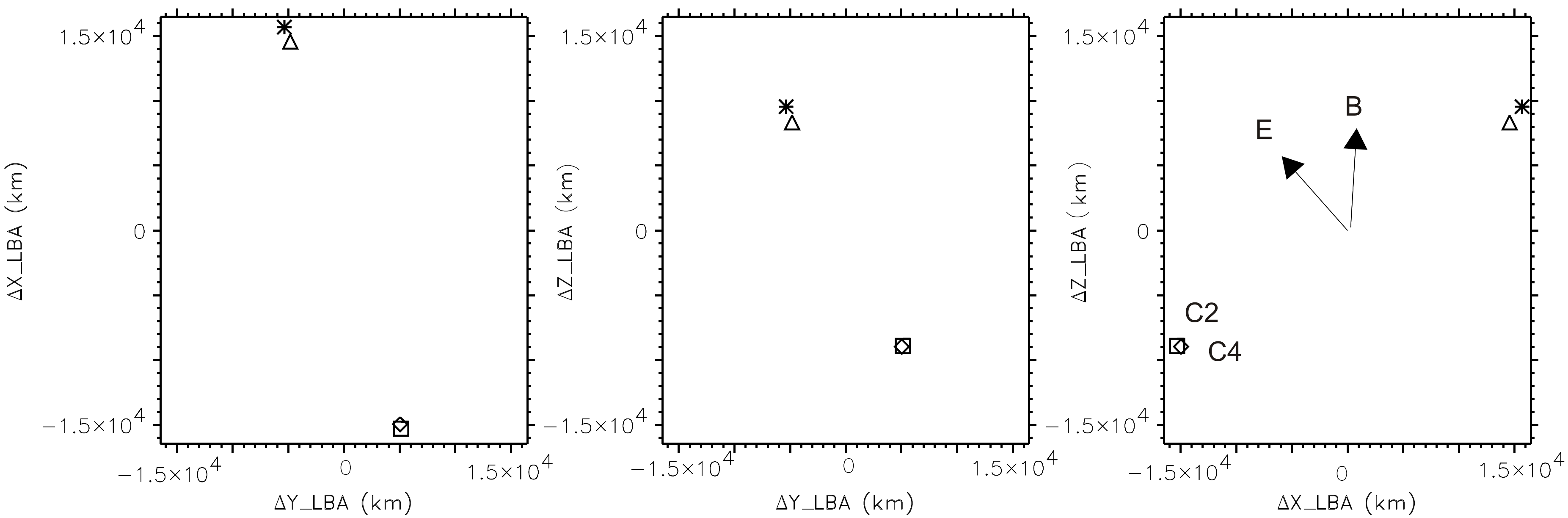
Fir digitally filtered 2.7 to 2.9 kHz riser/hook on C2 and C4

Average Delay C2-->C4: 3.2 msec



- Relative locations of the 4 Cluster spacecraft in a magnetic field-aligned coordinate system (origin at center of mass)
- Separation of spacecraft pair C2/C4: Along B: 33.5 km Cross B: 118.6 km

SCET: 2003–Jun–23T03:45:12.000



Cluster	1 *	2 ◇	3 △	4 □
GMLat	78.15°	12.77°	76.47°	12.09°
Re	5.69	4.43	5.57	4.42
L	135.14	4.66	101.65	4.62
MLT	13.68	16.78	14.22	16.79

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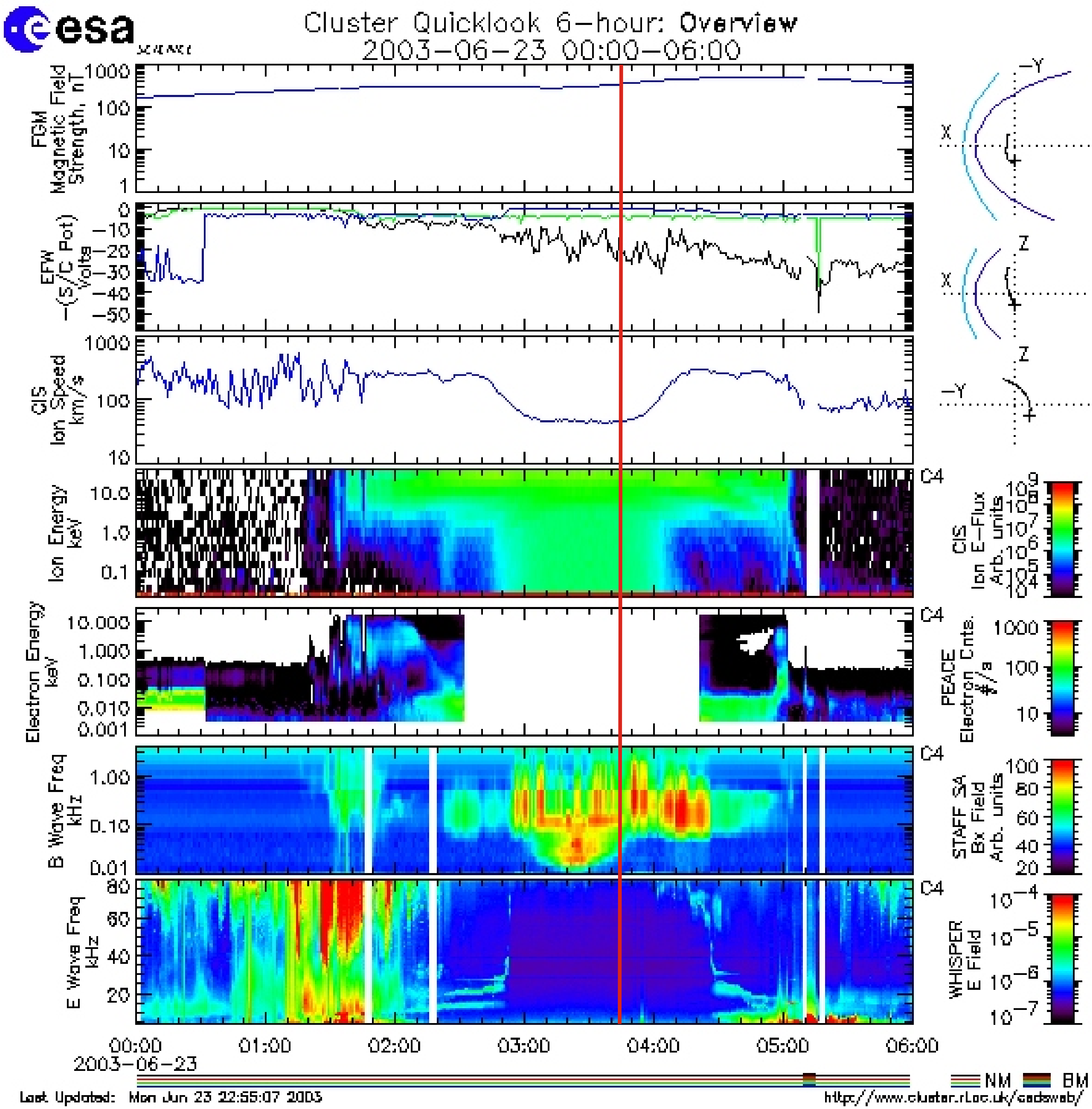
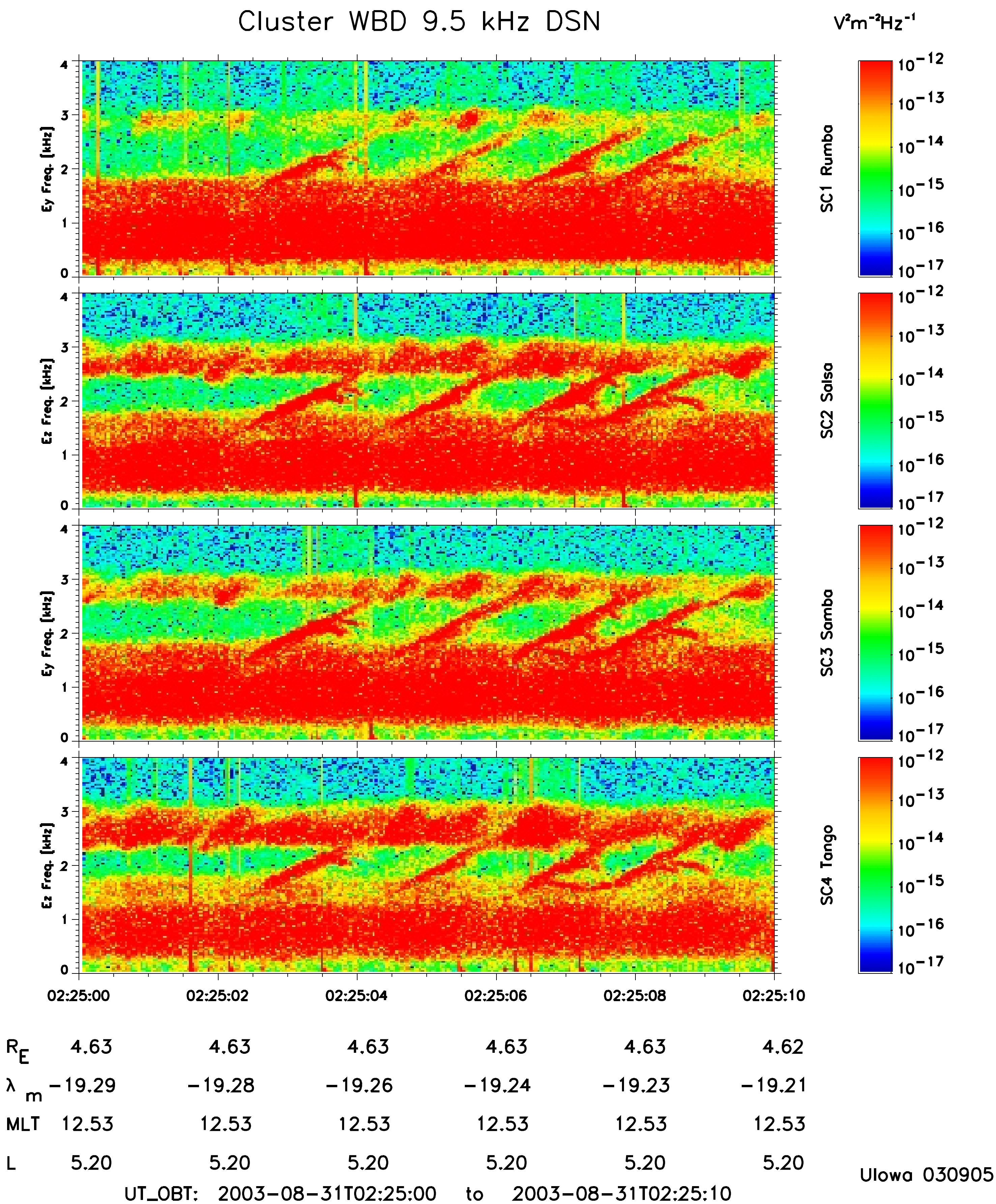


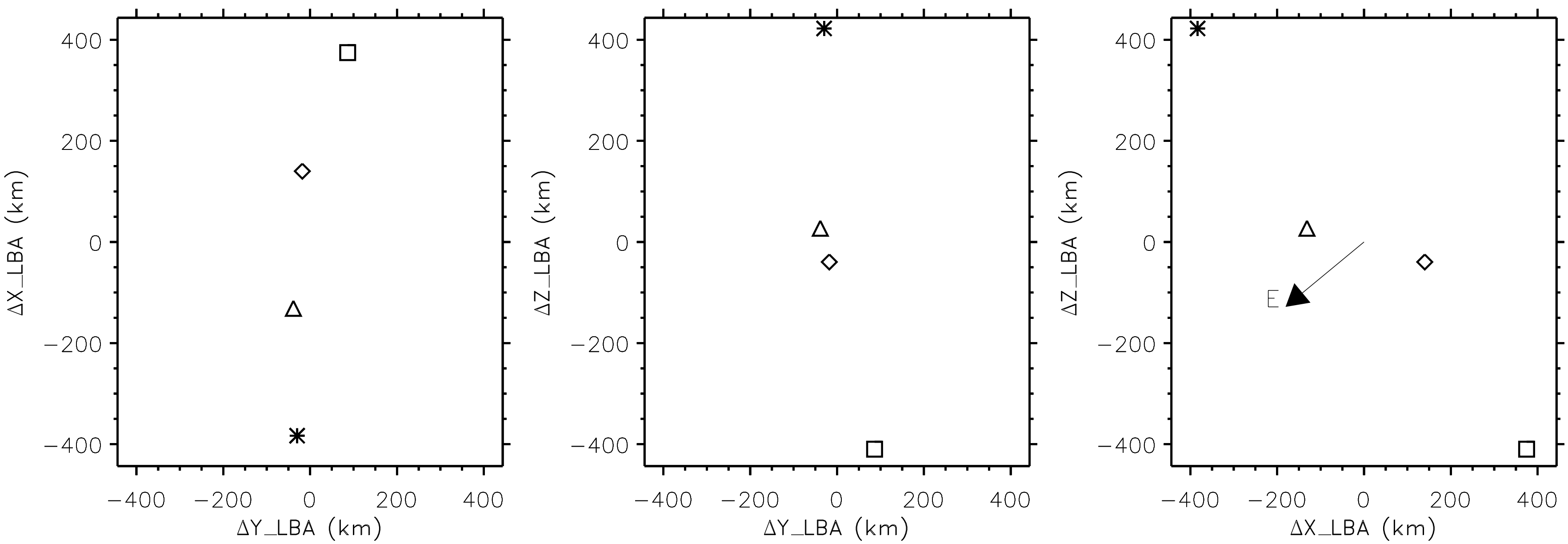
esa
Cluster Quicklook 6-hour: Overview
2003-06-23 00:00-06:00
FGM Magnetic Field Strength, nT
EFW -(S/C Pot) Volts
CIS Ion Speed km/s
Ion Energy keV
CIS Ion E-Flux Arb. units
Electron Energy keV
PEACE Electron Cnts. #/s
B Wave Freq kHz
STAFF SA Bx Field Arb. units
E Wave Freq kHz
WHISPER E Field
C4
00:00
01:00
02:00
03:00
04:00
05:00
06:00
2003-06-23
NM
BM
Last Updated: Mon Jun 23 22:55:07 2003
http://www.cluster.rl.ac.uk/csdsweb/

- 1.5-2.5 kHz fine-structured triggered emissions observed on all 4 spacecraft for ~ 10 seconds
- Triggered emissions appear as risers and hooks.



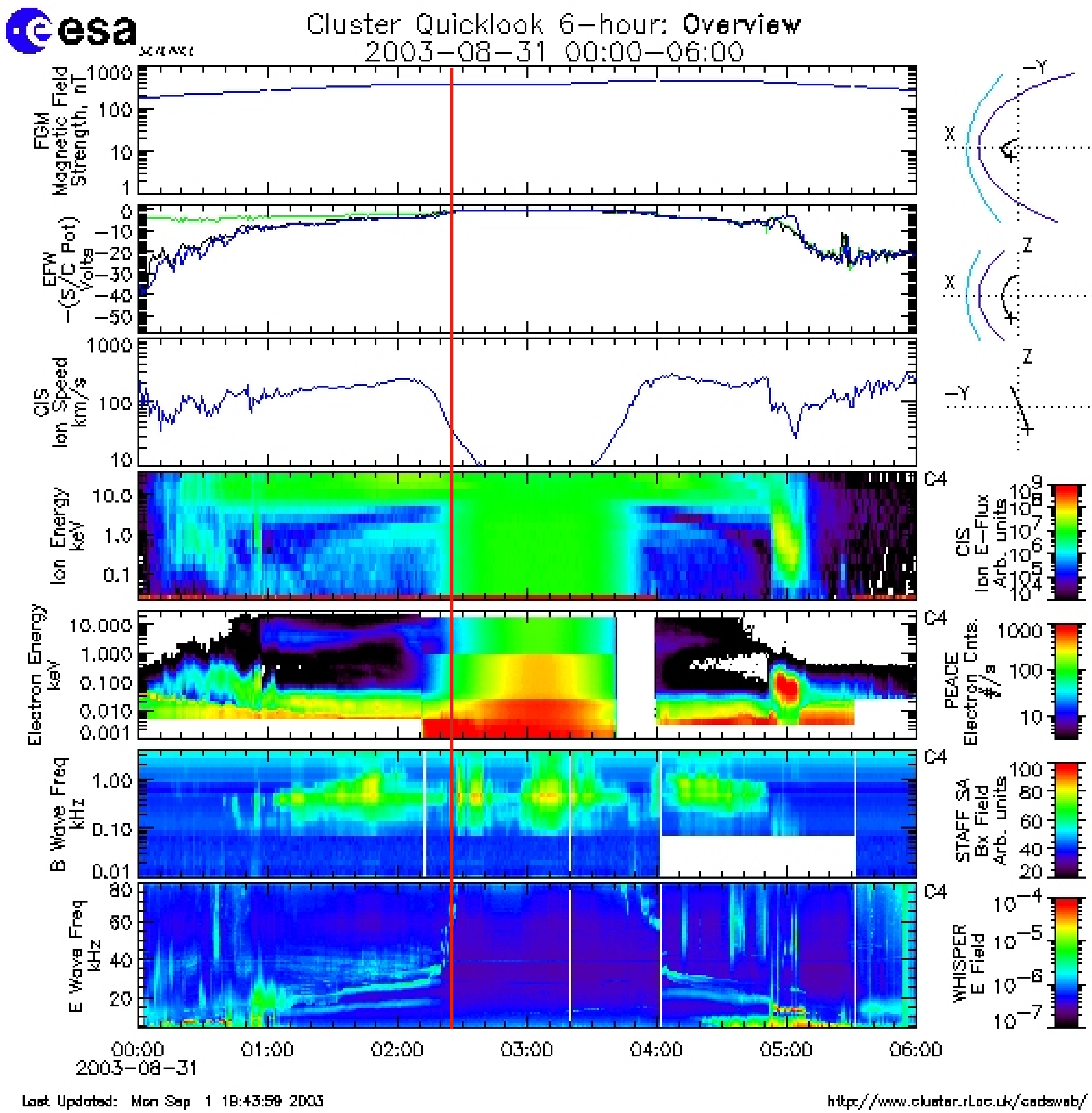
Cluster Relative Positions

SCET: 2003−Aug−31T02:25:00.000



Cluster	1 ∗	2 ◇	3 △	4 □
GMLat	−17.39°	−18.72°	−18.30°	−19.56°
Re	4.61	4.64	4.61	4.63
L	5.07	5.17	5.11	5.22
MLT	12.52	12.52	12.52	12.54

UIowa 030905



esa
Cluster Quicklook 6-hour: Overview
2003-08-31 00:00-06:00
FGM Magnetic Field Strength, nT
EFW -(S/C Pot) Volts
CIS Ion Speed km/s
Ion Energy keV
Electron Energy keV
B Wave Freq kHz
E Wave Freq kHz
C4
CIS Ion E-Flux Arb. units
PEACE Electron Cnts. #/s
STAFF SA Bx Field Arb. units
WHISPER E Field
00:00
2003-08-31
01:00
02:00
03:00
04:00
05:00
06:00
Last Updated: Mon Sep 1 18:43:59 2003
http://www.cluster.rl.ac.uk/csdsweb/

DISCUSSIONS AND CONCLUSIONS- VLF TE (1)

- Electromagnetic VLF Triggered Emissions are observed on Cluster as fine-structured risers, fallers and hooks in the Fourier-transformed spectrograms.
- The triggered emissions are observed within 20 degrees north and south of the magnetic equator at around 4-5 Re.
- Correlation distances are as great as 800 km both along and cross B.
- These emissions are seen propagating both toward and away from the magnetic equator at group velocities around 1×10^7 m/s.

DISCUSSIONS AND CONCLUSIONS- VLF TE (2)

- Data from the HYDRA and PWI instruments on the POLAR spacecraft within the plasmasphere have demonstrated that VLF emissions are triggered near the magnetic equatorial plane during times when the energetic electron flux near 20 keV exceeds 10^6/cm^2-s-sr-keV and the energetic electron pitch angle distribution is highly anisotropic [Bell, et al. 2000]. It is believed that the emissions are generated through a gyroresonance interaction between the energetic electrons and the VLF input waves.

- The available Cluster RAPID energetic electron data during some of the triggered emission events suggest that the flux of energetic electrons near 20-30 keV exceeded 10^6/cm^2-s-sr-keV. Thus there is reason to believe that the triggered emissions may also be generated through gyroresonance.

- To test this hypothesis we calculate the total amplification that a VLF wave would experience as it propagates across the magnetic equator in the presence of the measured RAPID energetic electron fluxes.

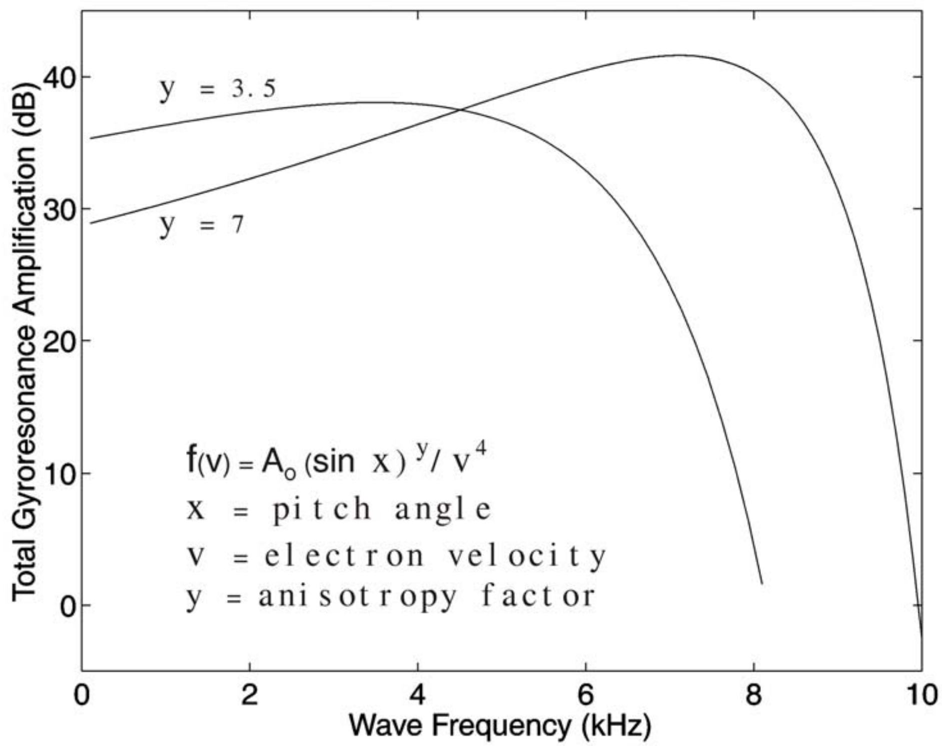
DISCUSSIONS AND CONCLUSIONS- VLF TE (3)

- To calculate the amplification we need to know the form of the energetic electron distribution function. Since we cannot determine the energetic electron distribution function directly from the RAPID data, we assume the form is similar to that observed on POLAR during triggered emission events. The general form is shown in the Figure.

- The total gyroresonance amplification across the magnetic equator is shown in the Figure for a range of wave frequency and two values of the anisotropy factor y. The value of y must exceed 2 in order for amplification to take place. The amplification rate is an increasing function of y. However as y increases, the energetic electrons are confined to a smaller region about the magnetic equator. This results in a smaller interaction region, and thus the total gain at some frequencies can decrease as y increases.

- It is clear from the Figure that the RAPID fluxes could provide enough gyroresonance amplification to grow the VLF triggered emission elements from the background noise.

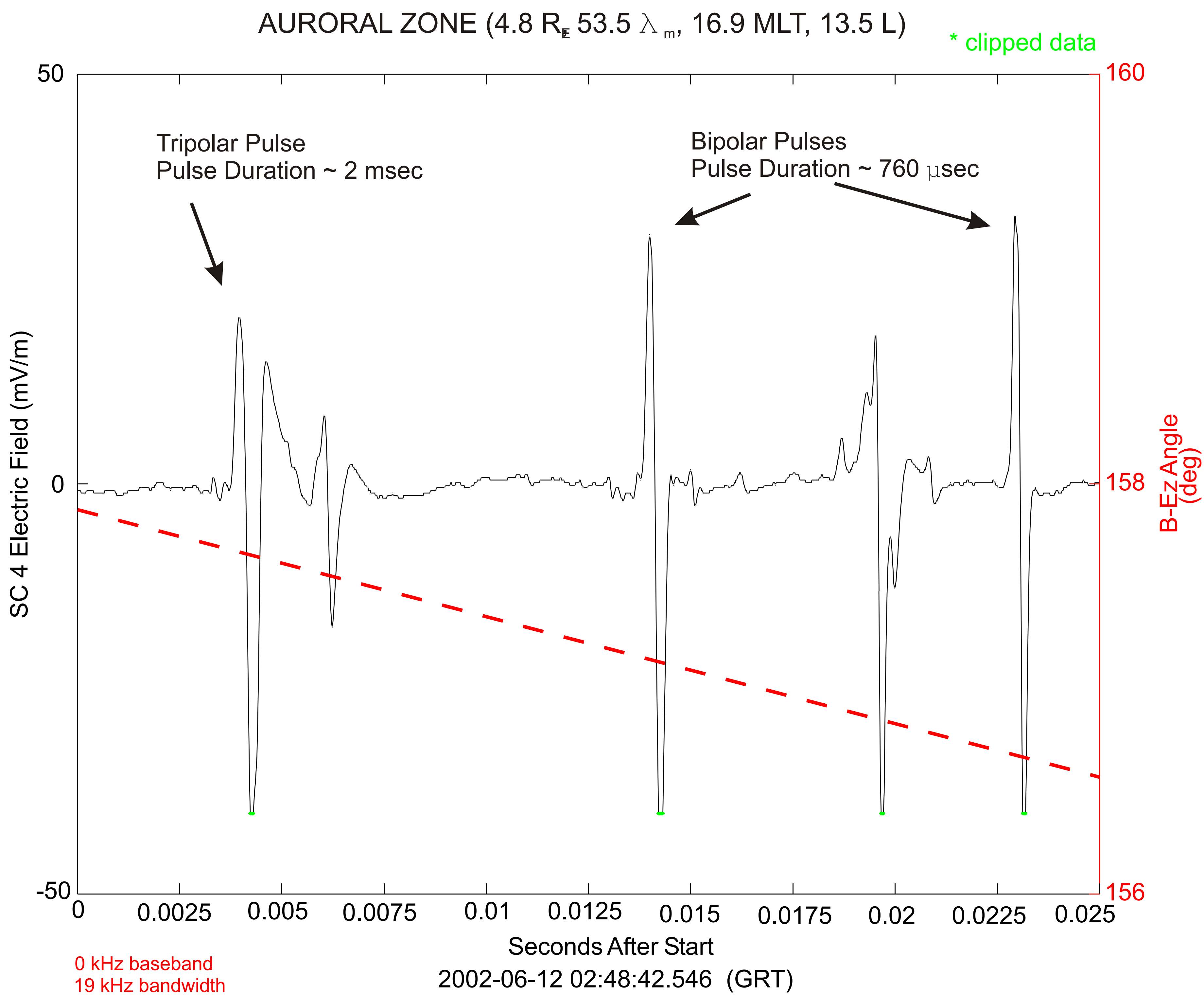
DISCUSSION AND CONCLUSIONS-VLF TE (4)



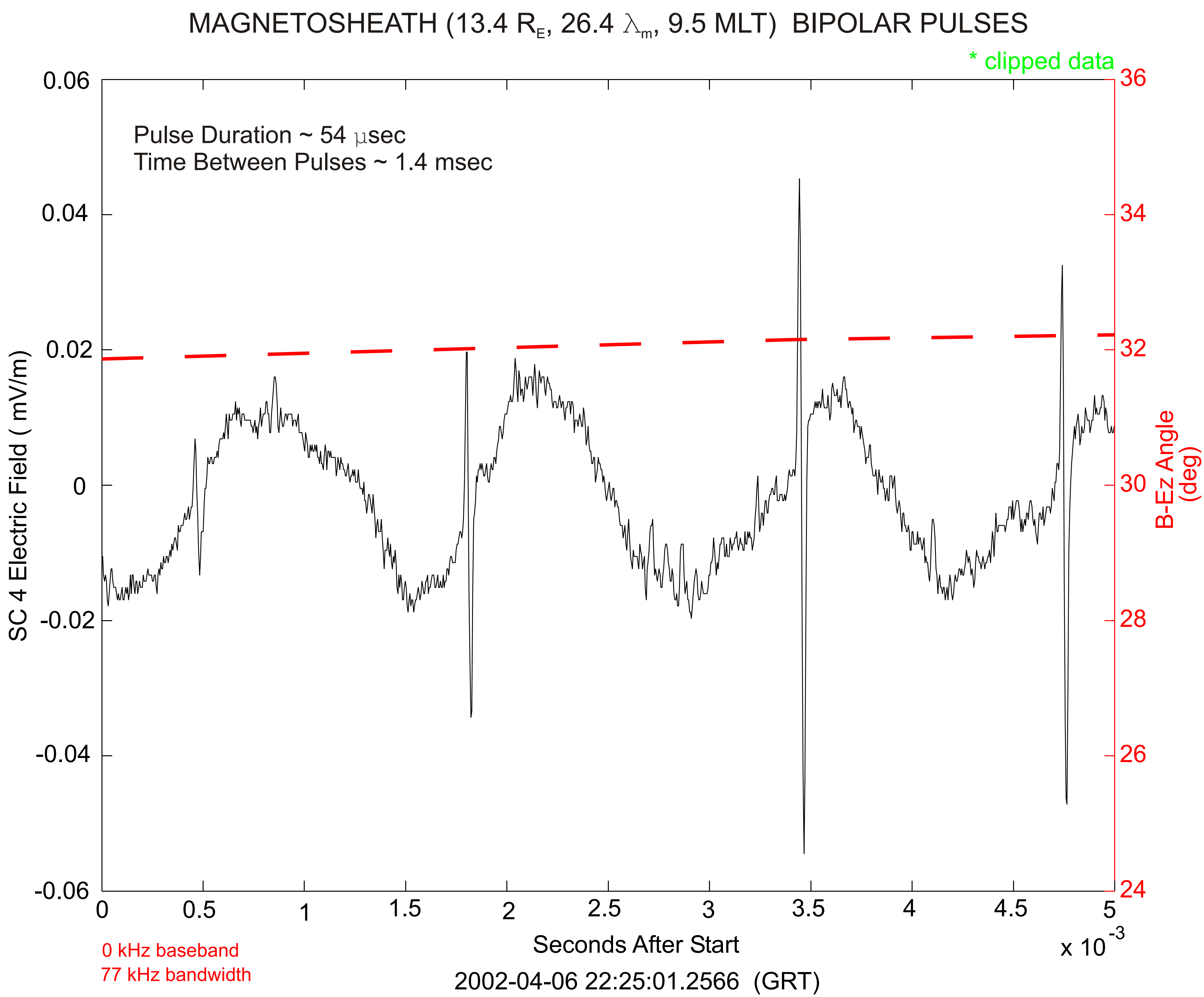
Total gain due to gyroresonance which propagates across the magnetic equator at L=4.1 in the presence of a flux of energetic electrons equal to 10^6 /cm^2-s-sr-keV at 20 keV and varying with x, v and y as shown. This flux is consistent with RAPID fluxes during VLF triggered emission events

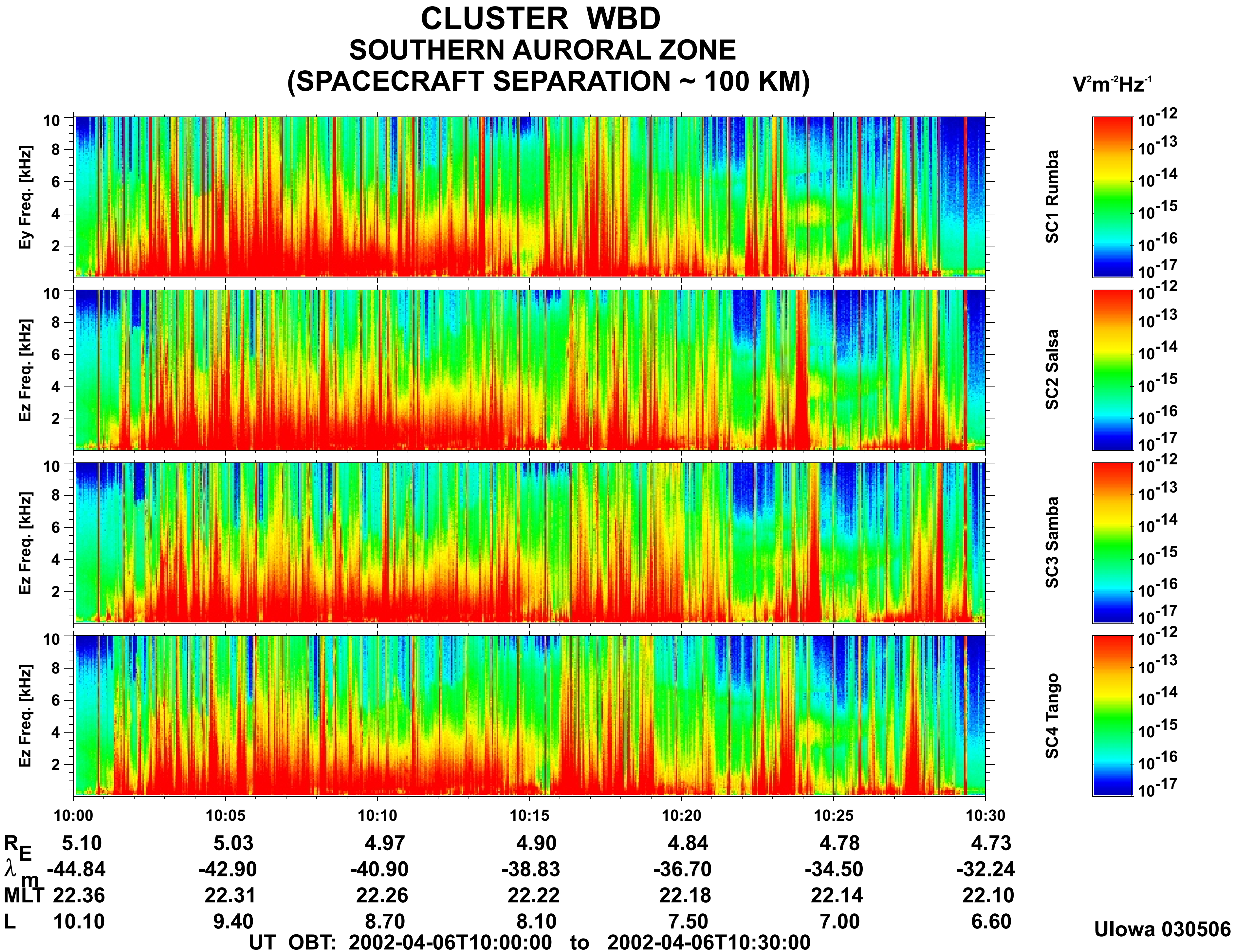
QUESTIONS-IES

- What do we mean by Isolated Electrostatic Structures (IES)?
- Where are the IES observed?
- Do the IES propagate, and if so, over what distances?
- What do we know about the generation of the IES?
- What geophysical parameters provide order to the IES observed throughout the Cluster orbit?



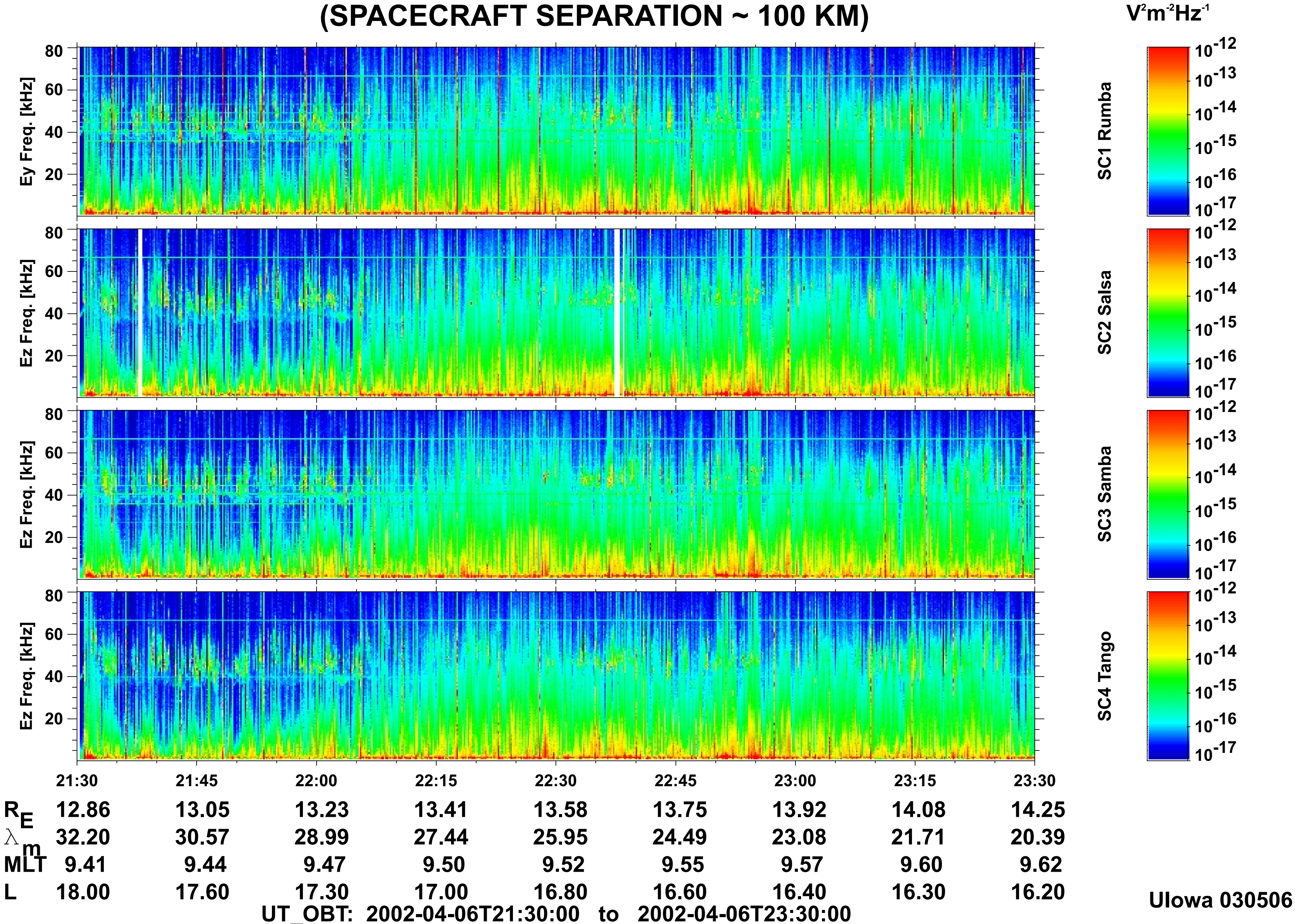
AURORAL ZONE (4.8 R_E, 53.5 λ_m, 16.9 MLT, 13.5 L)
* clipped data
Tripolar Pulse
Pulse Duration ~ 2 msec
Bipolar Pulses
Pulse Duration ~ 760 µsec
50
0
-50
SC 4 Electric Field (mV/m)
160
158
156
B-Ez Angle (deg)
0
0.0025
0.005
0.0075
0.01
0.0125
0.015
0.0175
0.02
0.0225
0.025
Seconds After Start
2002-06-12 02:48:42.546 (GRT)
0 kHz baseband
19 kHz bandwidth

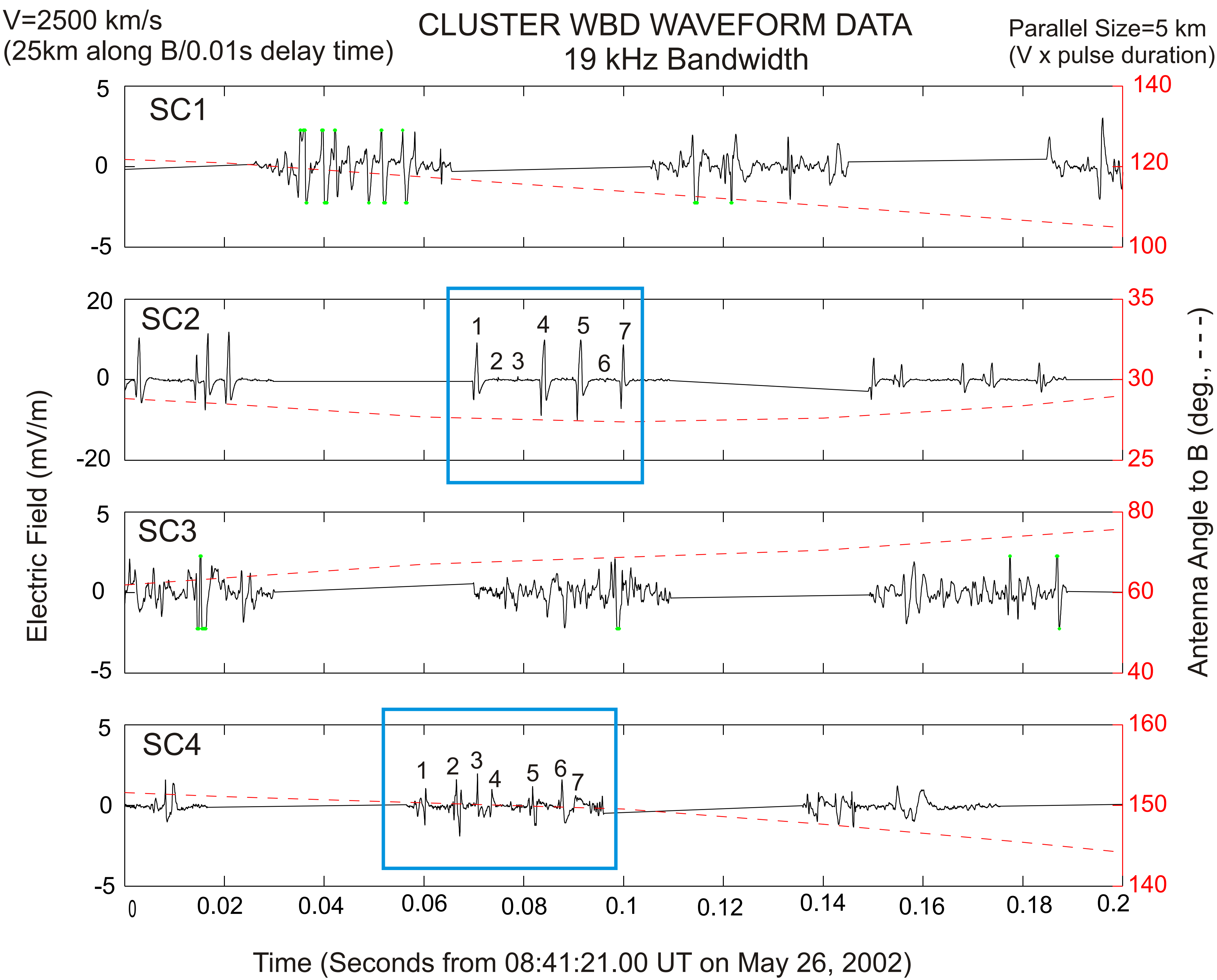

MAGNETOSHEATH (13.4 R_E, 26.4 λ_m, 9.5 MLT) BIPOLAR PULSES
* clipped data
Pulse Duration ~ 54 μsec
Time Between Pulses ~ 1.4 msec
SC 4 Electric Field (mV/m)
B-Ez Angle (deg)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
36
34
32
30
28
26
24
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
x 10^-3
Seconds After Start
2002-04-06 22:25:01.2566 (GRT)
0 kHz baseband
77 kHz bandwidth



CLUSTER WBD
SOUTHERN AURORAL ZONE
(SPACECRAFT SEPARATION ~ 100 KM)
V²m⁻²Hz⁻¹
Ey Freq. [kHz]
Ez Freq. [kHz]
Ez Freq. [kHz]
Ez Freq. [kHz]
SC1 Rumba
SC2 Salsa
SC3 Samba
SC4 Tango
10⁻¹² 10⁻¹³ 10⁻¹⁴ 10⁻¹⁵ 10⁻¹⁶ 10⁻¹⁷
10:00 10:05 10:10 10:15 10:20 10:25 10:30
RE 5.10 5.03 4.97 4.90 4.84 4.78 4.73
λm -44.84 -42.90 -40.90 -38.83 -36.70 -34.50 -32.24
MLT 22.36 22.31 22.26 22.22 22.18 22.14 22.10
L 10.10 9.40 8.70 8.10 7.50 7.00 6.60
UT_OBT: 2002-04-06T10:00:00 to 2002-04-06T10:30:00
UIowa 030506

CLUSTER WBD
DAYSIDE MAGNETOSHEATH
(SPACECRAFT SEPARATION ~ 100 KM)

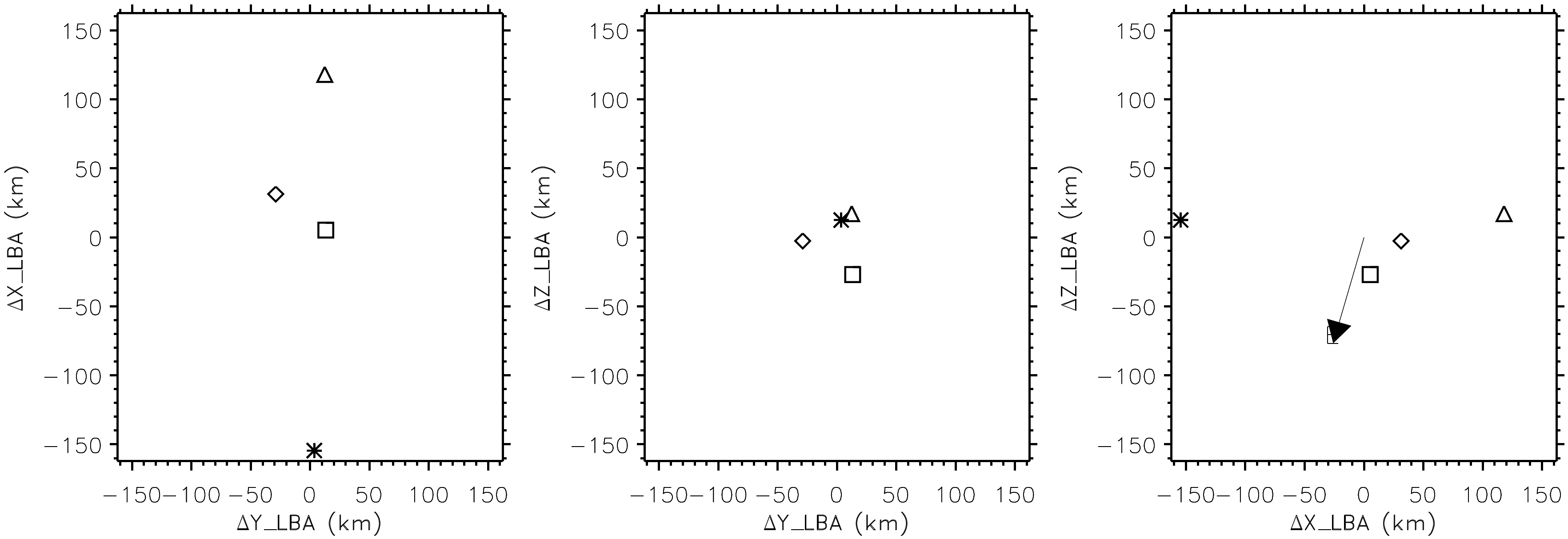




V=2500 km/s
(25km along B/0.01s delay time)
CLUSTER WBD WAVEFORM DATA
19 kHz Bandwidth
Parallel Size=5 km
(V x pulse duration)
SC1
SC2
SC3
SC4
1 2 3 4 5 6 7
1 2 3 4 5 6 7
Electric Field (mV/m)
Antenna Angle to B (deg., - - -)
5 0 -5
20 0 -20
140 120 100
35 30 25
80 60 40
160 150 140
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Time (Seconds from 08:41:21.00 UT on May 26, 2002)

Cluster Relative Positions

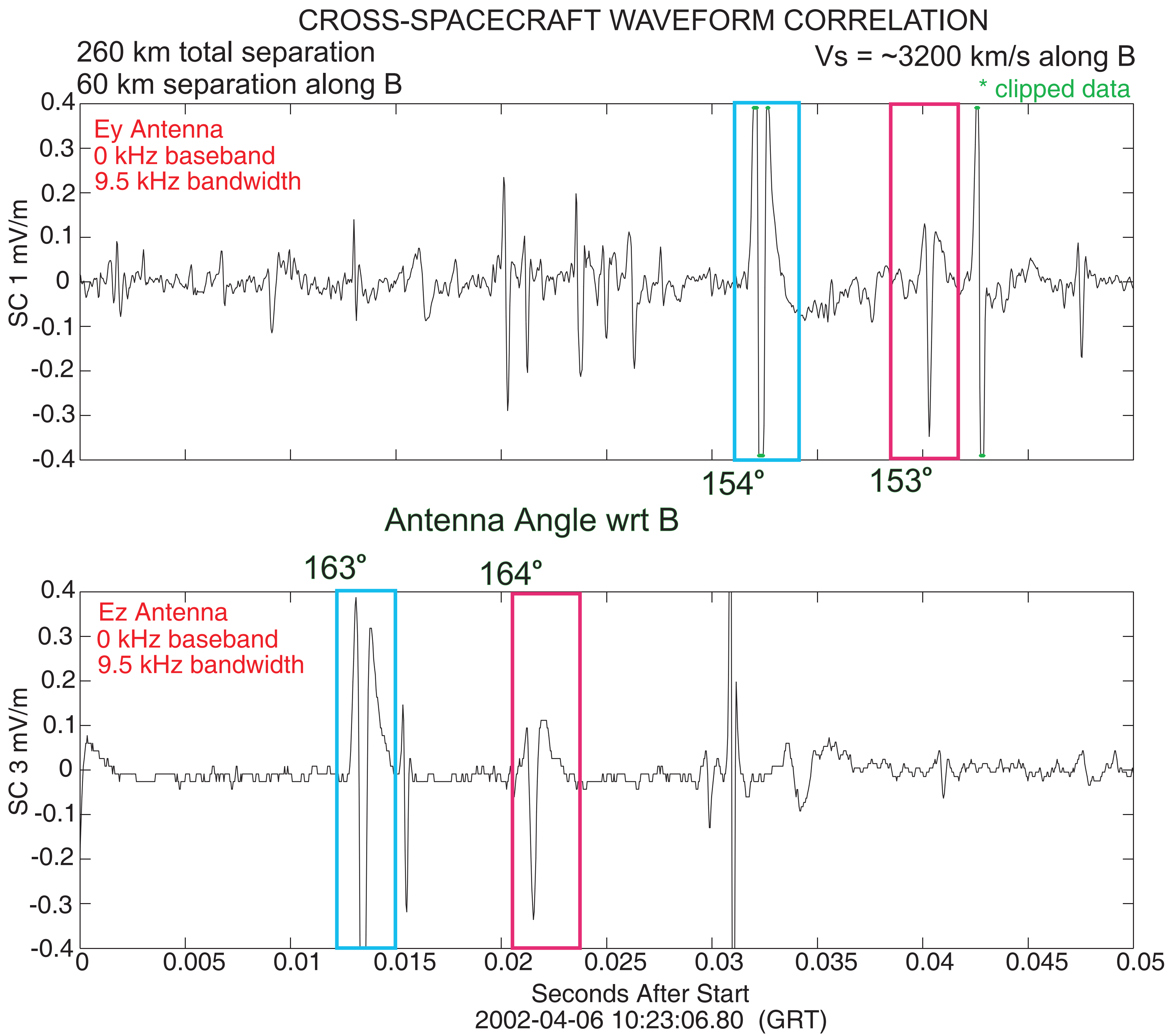
SCET: 2002-May-26T08:41:21.000



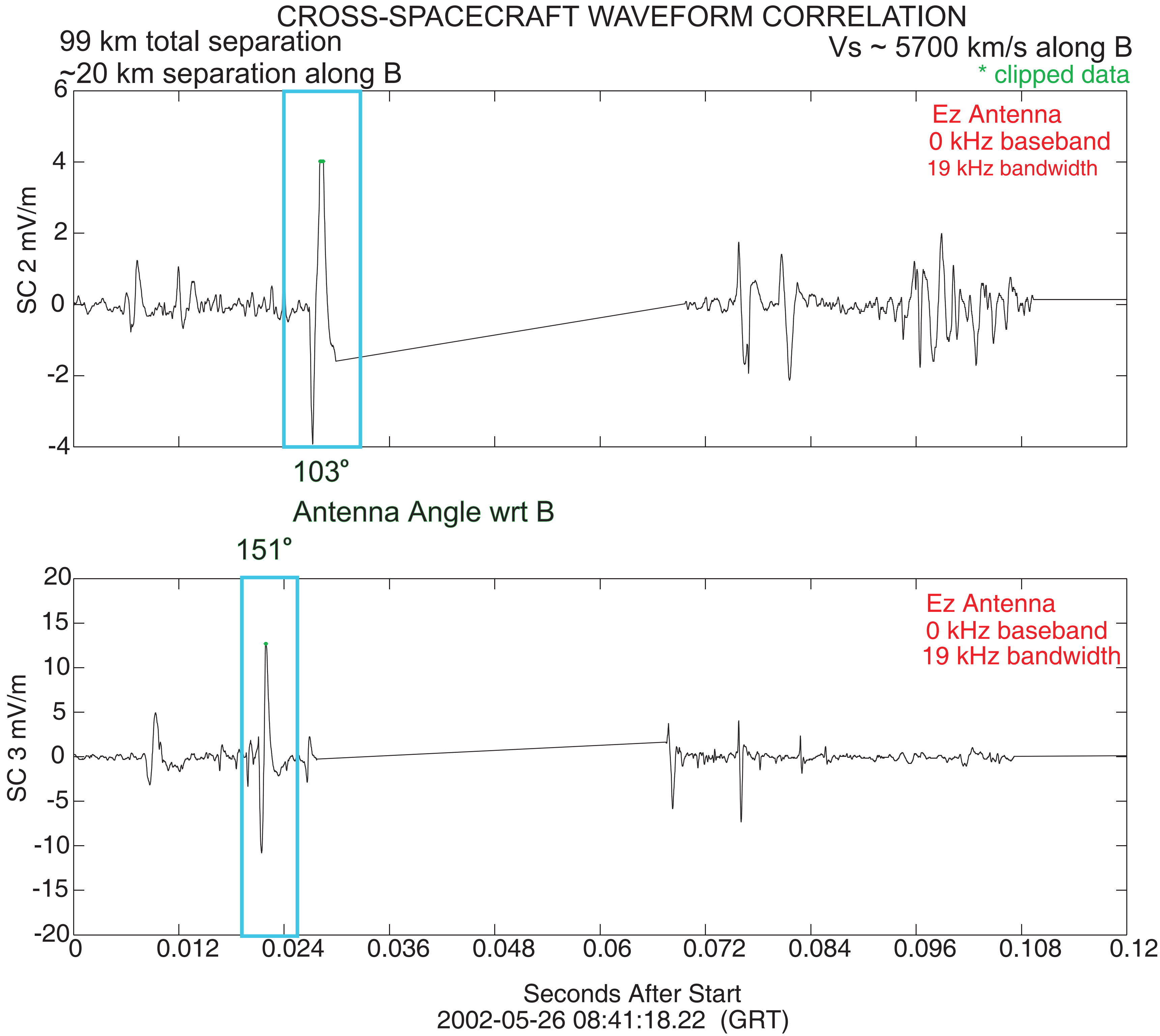
Cluster	1 *	2 ◇	3 △	4 □
GMLat	−46.66°	−46.99°	−47.11°	−46.95°
Re	5.01	5.02	5.02	5.01
L	10.63	10.78	10.85	10.75
MLT	18.48	18.48	18.48	18.48

Magnetic Field Courtesy of Cluster FGM

UIowa 030624

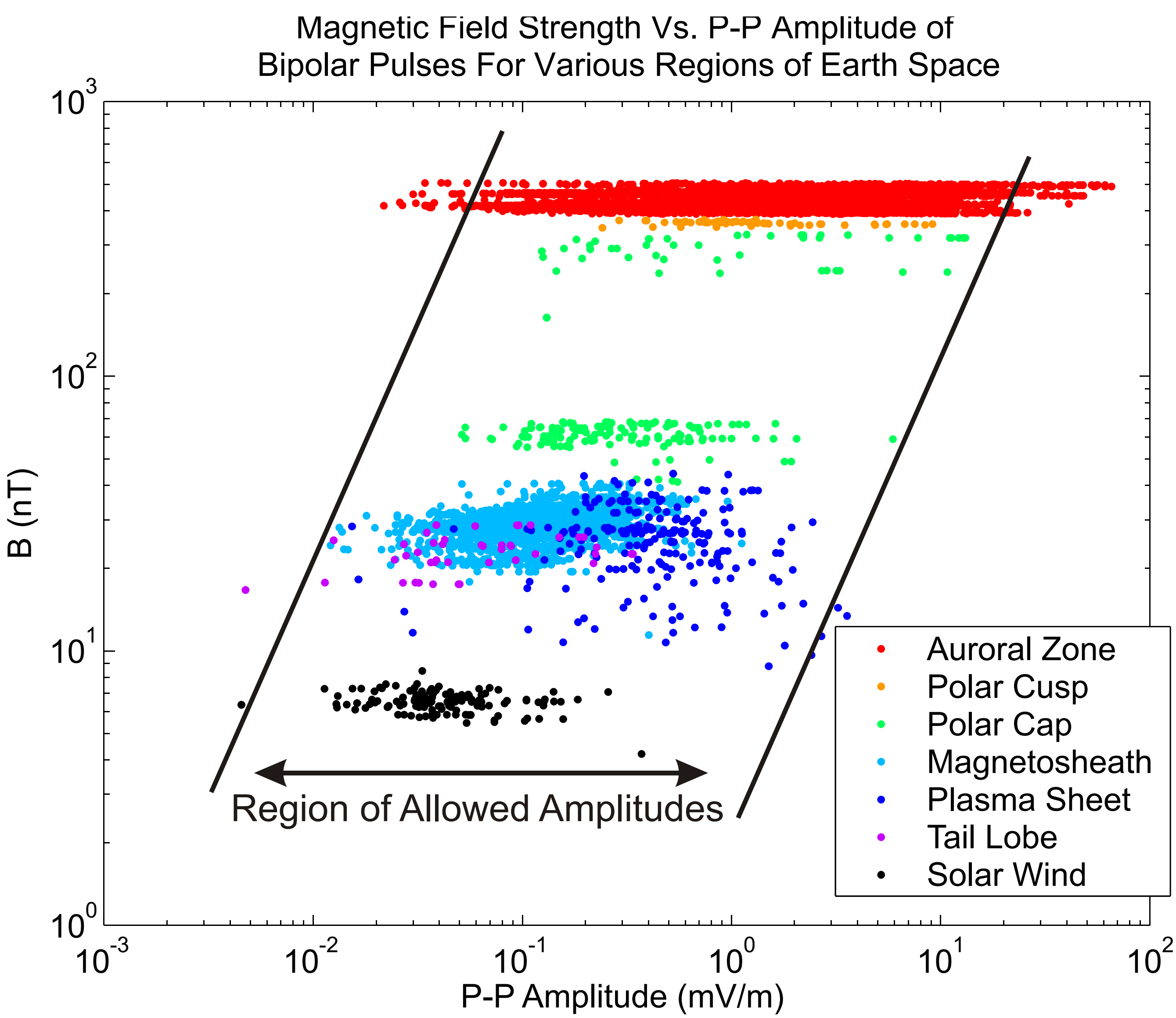


CROSS-SPACECRAFT WAVEFORM CORRELATION
260 km total separation
60 km separation along B
Vs = ~3200 km/s along B
* clipped data
Ey Antenna
0 kHz baseband
9.5 kHz bandwidth
SC 1 mV/m
154°
153°
Antenna Angle wrt B
163°
164°
Ez Antenna
0 kHz baseband
9.5 kHz bandwidth
SC 3 mV/m
Seconds After Start
2002-04-06 10:23:06.80 (GRT)


CROSS-SPACECRAFT WAVEFORM CORRELATION
99 km total separation
~20 km separation along B
Vs ~ 5700 km/s along B
* clipped data
Ez Antenna
0 kHz baseband
19 kHz bandwidth
SC 2 mV/m
6
4
2
0
-2
-4
103°
Antenna Angle wrt B
151°
SC 3 mV/m
20
15
10
5
0
-5
-10
-15
-20
Ez Antenna
0 kHz baseband
19 kHz bandwidth
0
0.012
0.024
0.036
0.048
0.06
0.072
0.084
0.096
0.108
0.12
Seconds After Start
2002-05-26 08:41:18.22 (GRT)

Primary Trend: As the magnitude of B increases, the allowed amplitude range (minimum and maximum) of the bipolar pulses increases.

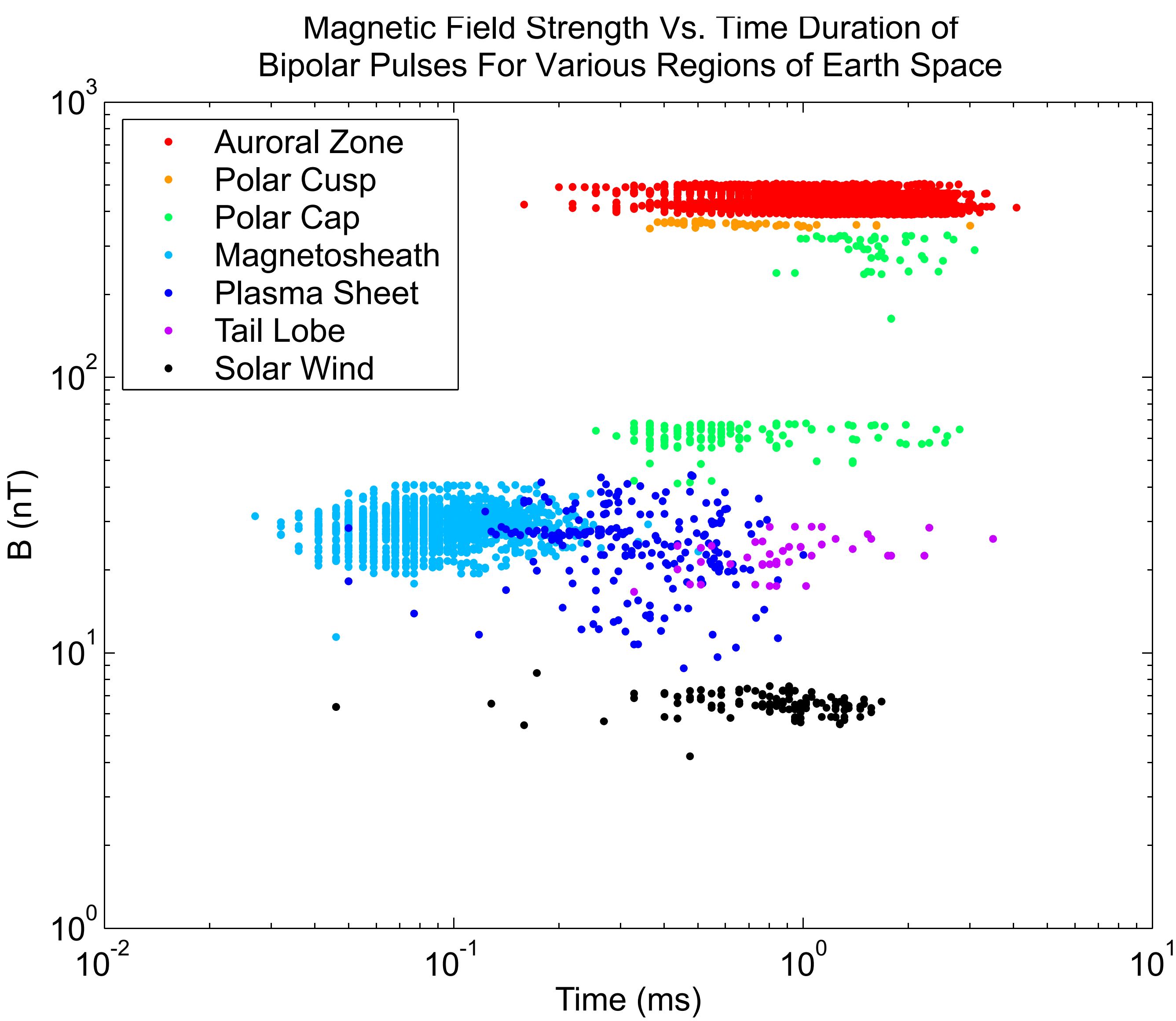
Same trend is observed for the tripolar pulses.



No relationship appears to exist between the magnitude of B and time duration (which is an indication of size and/or velocity).

Magnetosheath structures are clearly different from those in all the other regions sampled.

Tripolar pulses show the same trend.



DISCUSSION AND CONCLUSIONS-IES (1)

- Identification of the same structures on more than one spacecraft, which would be indicative of their propagation over distances of 20-60 km:

  - ➢ is inconclusive:
    - o it is highly likely that the structures evolve (grow) over such distances so that they no longer have the same characteristic shape as observed from one spacecraft to the next, or they decay;
    - o only tripolar pulses have shown any possibility of correlation in the auroral zone (5 R_E), implying propagation at about 2200 km/s away from earth, with a parallel (to **B**) size of 5 km and a perpendicular size of 50 km, and growth and evolution to tripolar form.

  - ➢ is complicated in space by several factors:
    - o the spacecraft are not often lying along the same magnetic field line;
    - o the angles of the antennas with respect to the magnetic field are often not identical, a requirement for good correlations
    - o all, or some, of the IES observed close in time may be traveling at different speeds and/or in different directions and be evolving.

DISCUSSION AND CONCLUSIONS-IES (2)

- Onset, intensity, and time durations are often very similar from one spacecraft to the next over separations of a few hundred km, implying that:
  - the IES are being generated locally in response to similar conditions along the various field lines; or
  - the IES are being generated at remote sites consistent with propagation over a time period of a few hundred plasma oscillation periods.
- In the magnetosheath:
  - Onset of the IES are consistent with processes occurring at the bow shock and propagating to the spacecraft at the ion acoustic speed;
  - Bipolar IES are sometimes found to be locked in phase with ion acoustic waves, implying a generation mechanism involving these waves.

DISCUSSION AND CONCLUSIONS-IES (3)

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

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

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

WHERE:

ω_b Electron Bounce Frequency
ω_c Electron Cyclotron Frequency
Ψ Peak potential amplitude
δ_z Parallel Size
δ_r Perpendicular Size

r_c Electron cyclotron radius
r_U Inhomogeneity length of **E**(x,y,t)
B Magnetic field strength
e,m Charge and mass of electrons

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; the observational results are consistent with this, i.e., the electric field amplitudes are smaller in weaker magnetic fields.

DISCUSSION AND CONCLUSIONS-IES (4)

- The IES are observed as bipolar and tripolar waveforms 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.

- The generation mechanism (beam instability; waves; electrostatic turbulence) of the IES, as well as their effect, if any, on particle populations in these regions (ion heating) is just getting underway.

- The electron holes, in sufficient numbers, could alter the bulk properties of the plasma, such as the dc resistivity and temperature [Chen et al., Phys. Rev. Lett., submitted, 2003].

- The tripolar pulses (weak double layers) could provide an entire series of small potential changes along field lines sufficient to explain some of the potential difference between the ionosphere and magnetosphere [Pickett et al., Nonlinear Processes in Geophys., submitted, 2003].