ULF wave observations in the topside ionoshere by the Swarm mission

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Outline

- **Introduction to the TFA tool**
  - Concept & objectives related to the tool
  - ULF waves
  - Wavelet transforms
  - Possibilities within the tool

- **Operational analysis of Swarm magnetic field data**
  - ULF waves
  - Plasma instabilities
  - Correlation of magnetic field & plasma measurements

Concept

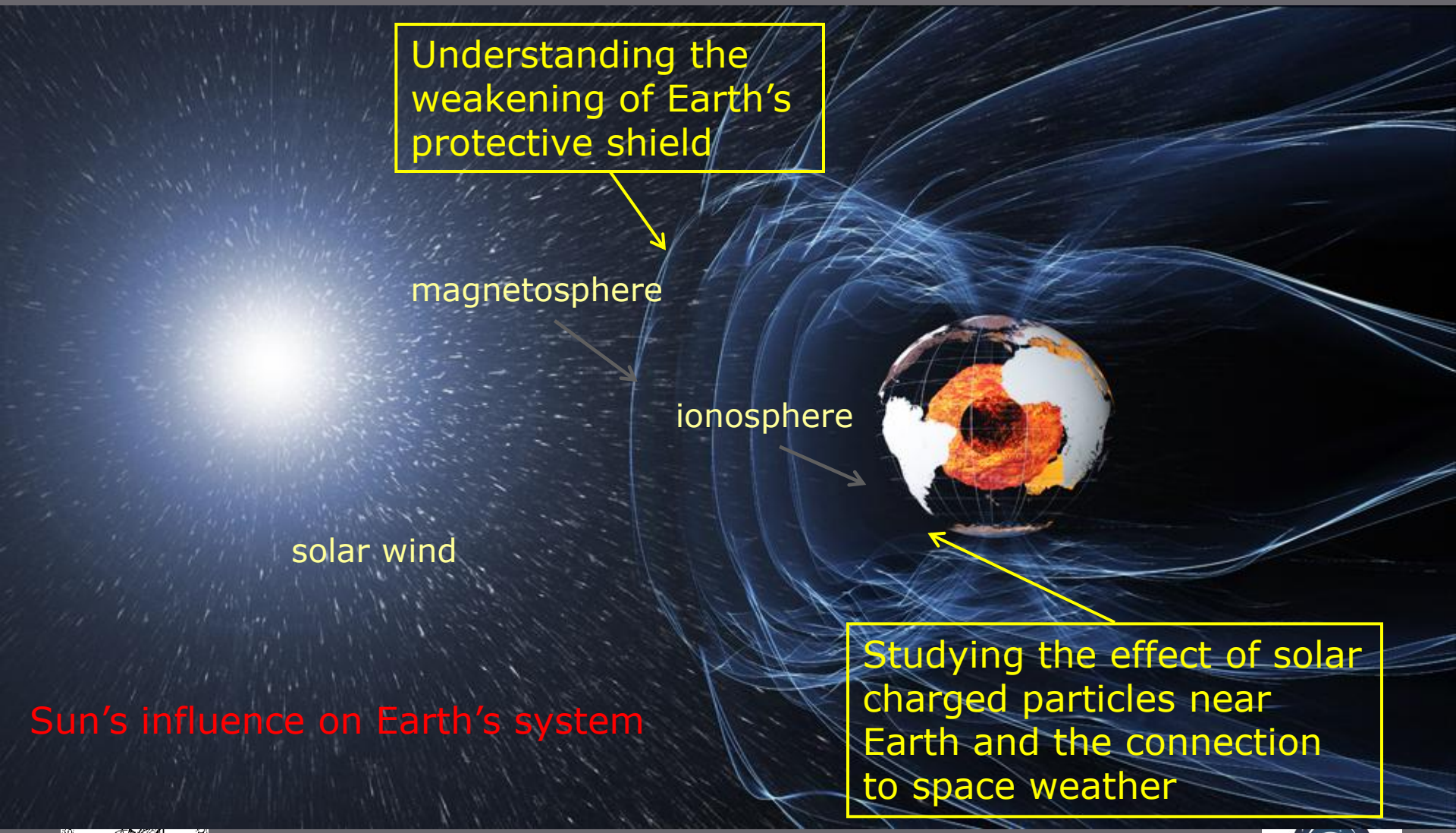
- The time-frequency analysis (TFA) tool has been developed within the frame of the **ULFwave** study (*"Multi-Satellite, multi-instrument and ground based observations analysis and study of ULF wave phenomena and products"*), which is an ESA funded study that has been exploited data from various magnetosphere and topside ionosphere missions (ESA's Cluster, JAXA's Geotail, NASA's ST5 and CHAMP), in combination with ground-based magnetometer data (e.g. IMAGE, CARISMA, GIMA arrays), with a focus on the scientific problem of **ultra low frequency (ULF) wave** generation and propagation.

- Thus, ULFwave also allows to geophysically validate some of **ESA's Swarm** data products, especially those related to the magnetic and electric fields in the magnetosphere.

Objectives

- Improved understanding of the wave activity / propagation and the underlying processes in different regions of the magnetosphere, topside ionosphere and on the ground.
- Analysis of existing satellite and ground data also in view of potential LEO satellite validation (test with *CHAMP* in preparation of ***Swarm***).
- Special focus on the additional opportunities that ***Swarm*** brings through magnetic and electric field (and density) data from a constellation of satellites also in view of potential new products/user tools.
- Projection of the ideas for the ***Swarm*** lifetime especially the expected combination with ***Cluster*** at that time.

External sources



Sun's influence on Earth's system

Swarm

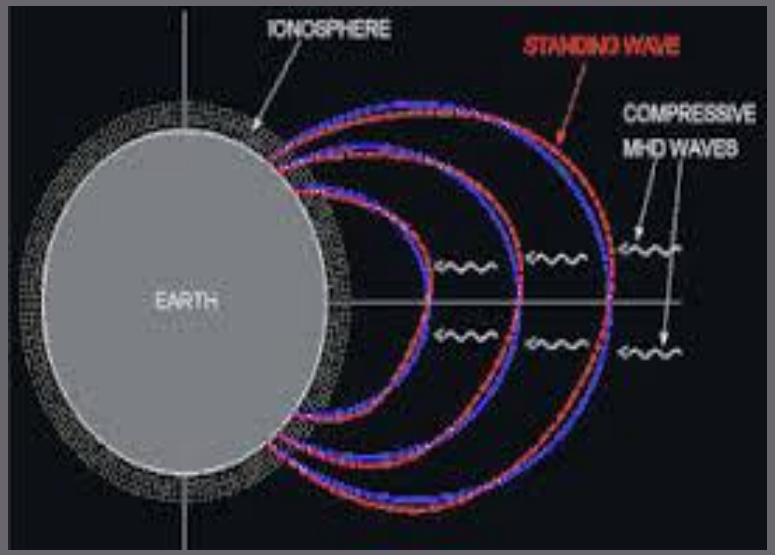
Each satellite is measuring:

- Strength and direction of the magnetic field
- Plasma conditions and characteristics
- Location

The Constellation:

- 3 identical satellites:
  2 side-by-side in low orbit (<460km)
  1 in higher orbit
  (< 530km)
- three orbital planes for optimal coverage in space and time
- **Launch 22 November 2013: 4 years operations**

ULF Waves



Pulsation classes

	Continuous pulsations					Irregular pulsations	
	Pc 1	Pc 2	Pc 3	Pc 4	Pc 5	Pi 1	Pi 2
T [s]	0.2-5	5-10	10-45	45-150	150-600	1-40	40-150
f	0.2-5 Hz	0.1-0.2 Hz	22-100 mHz	7-22 mHz	2-7 mHz	0.025-1 Hz	2-25 mHz

Compressional Pc3 dayside upstream relate to wave-particle interaction in the foreshock and shock

Toroidal Pc3 or multi-harmonics dayside upstream field line resonance harmonics in Pc3 / Pc4 range, compressional Pc3 as a driver (coupling with the fundamental toroidal mode)

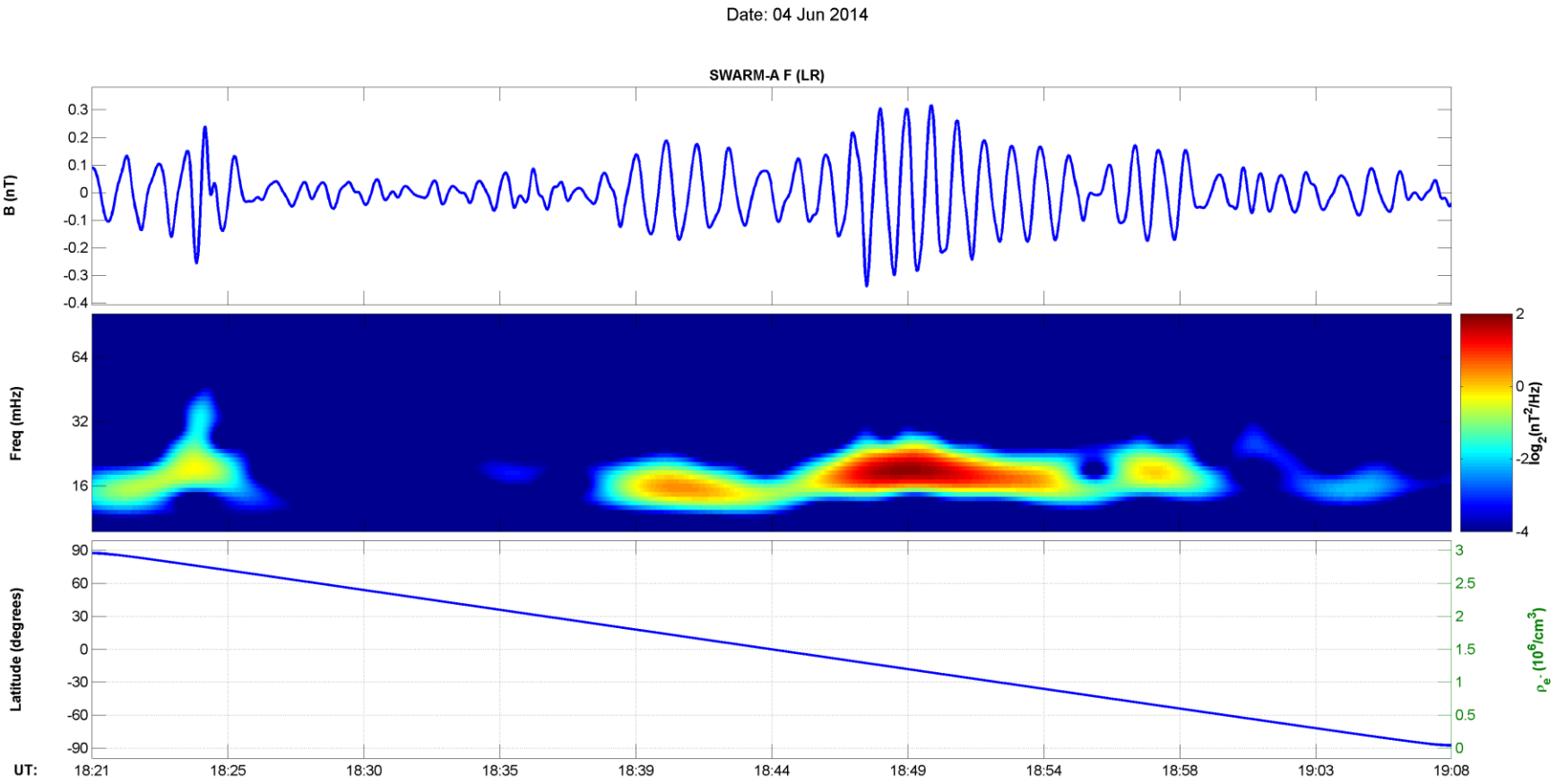
http://magbase.rssi.ru/REFMAN/SPPHTEXT/ulf.html

Automatic Detection of Events

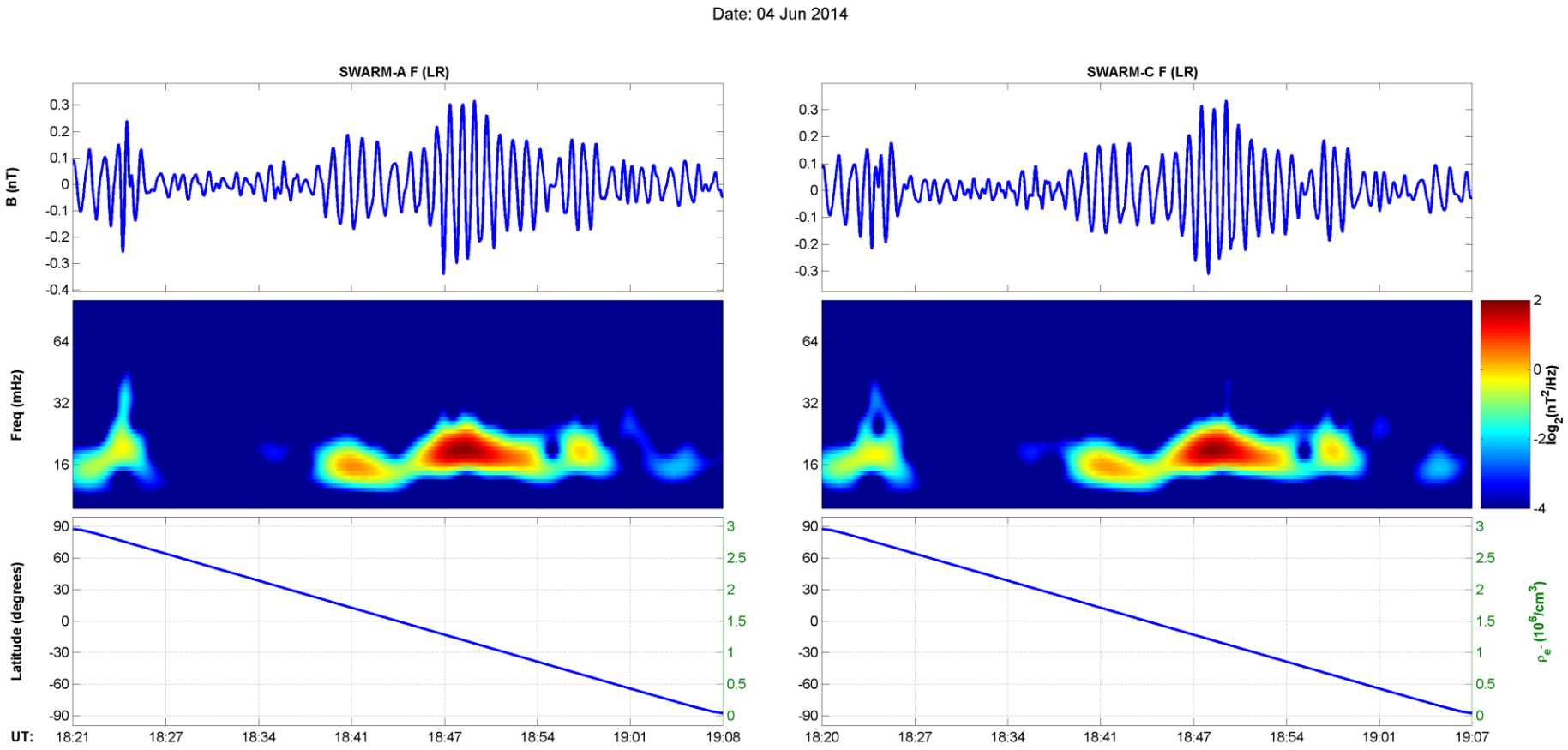
- Perform the Wavelet Analysis according to the current methodology
- Scan the wavelet spectrum along the temporal dimension
- Find consecutive times for which the wavelet power exceeds a certain threshold
- Mark these intervals as "Candidate Events" and extract important parameters
- Using the Classification Schema, examine if the Candidate passes all required tests to be marked as an actual Event
- In case of failure, identify the Candidate as a False Positive or Non-Event
- Plot the Track with the appropriate flags, classify it and save relevant statistics.

- Onset
- Duration
- Max Amplitude of the Filtered Signal
- Number of Points above a Threshold
- Peak Frequency
- Peak Frequency Power
- Time of Peak Frequency
- First Derivative of Wavelet Power at the Highest Frequency
- Frequency Range
- Total Wavelet Power
- Average Wavelet Power
- Signal Roughness
- Ion Density Roughness
- Magnetic Latitude
- Magnetic Local Time

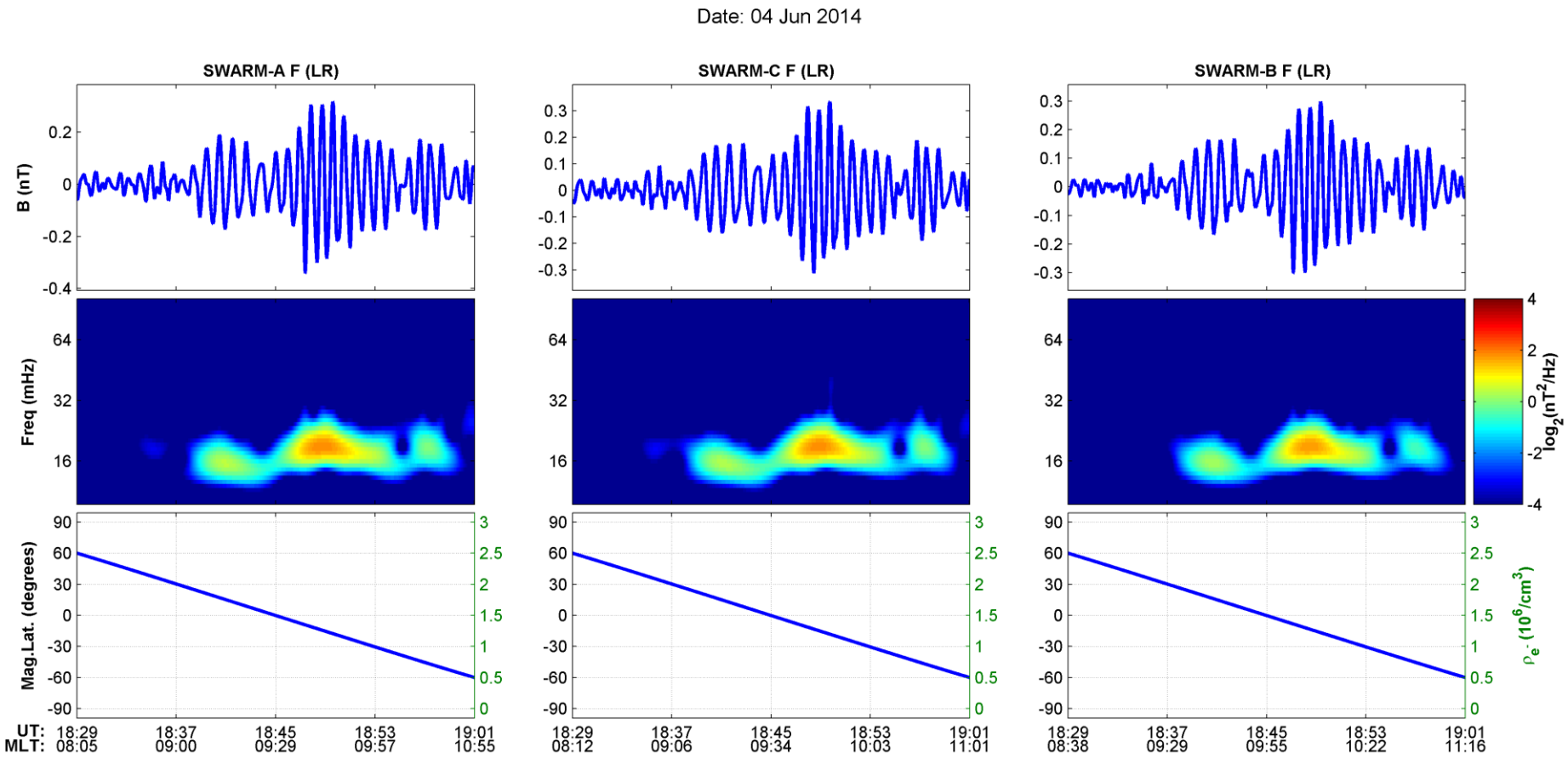
The Time-Frequency Analysis (TFA) Tool



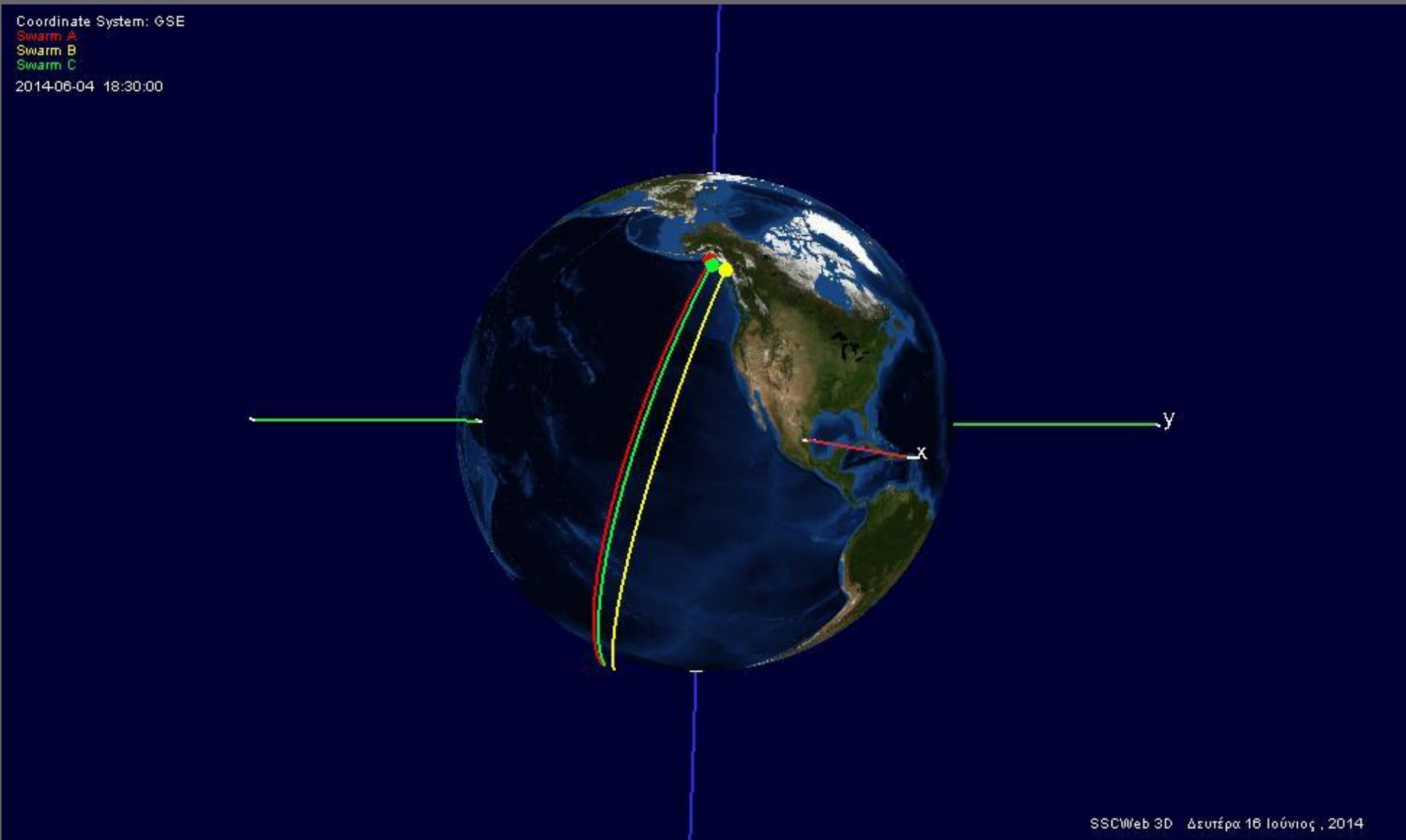
TFA tool: 2-Column Case



TFA tool: 3-Column Case

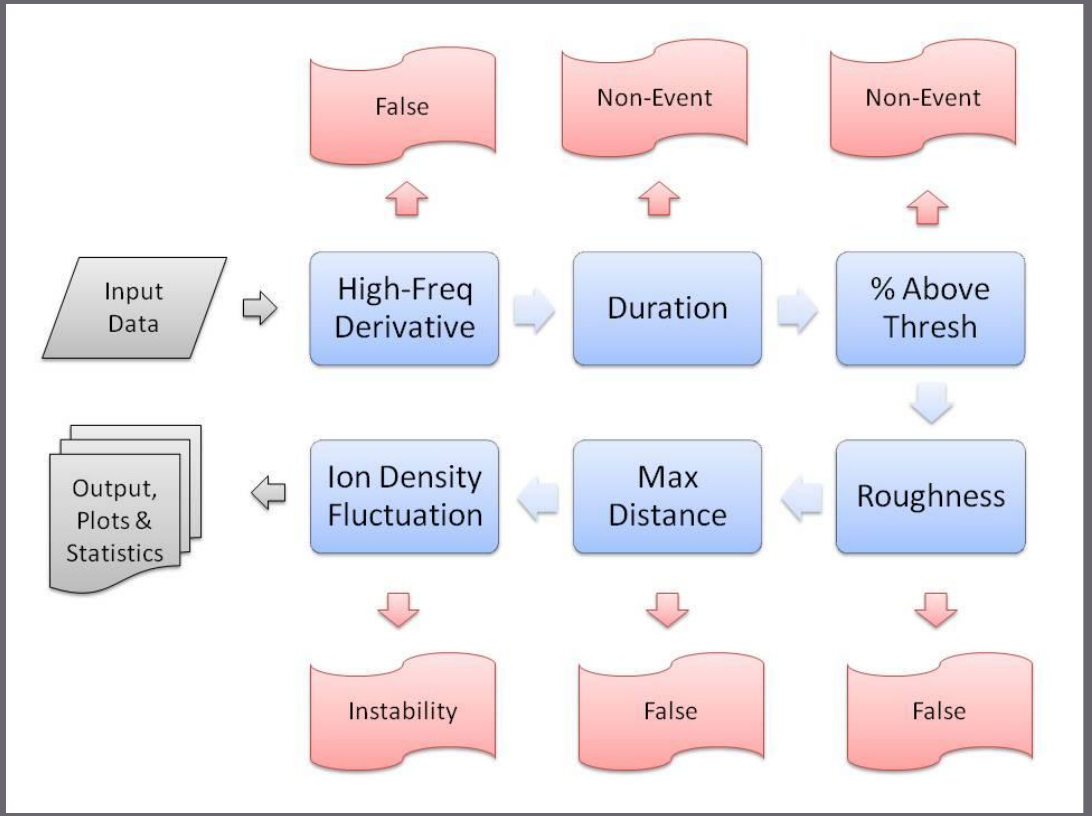


NASA 4D Orbit Viewer



Classification Schema

- **Input**: Candidate Segments, namely parts of the Track that exhibit activity greater than that attributed to background noise
- **Criteria**
  - First time derivative of Wavelet Power at a frequency of 250 mHz
  - Duration
  - %of segment points that have values higher than the threshold
  - Time series roughness (average absolute value of the second derivative at local extrema)
  - Distance of maximum from mean, measured in standard deviations
  - Roughness of the Ion Density time series



Balasis et al., Magnetospheric ULF wave studies in the frame of Swarm mission: a time-frequency analysis tool for automated detection of pulsations in magnetic and electric field observations, Earth, Planets and Space, 65, 1385–1398, 2013.

Application of the TFA tool to satellite data (CHAMP) and ground-based data (IMAGE)

- Papadimitriou et al. (September 17, 2014, 12:00)
- Dimitrakoudis et al. (September 17, 2014, 12:15)

SWARM DATA PROCESSING STEPS

- Reading data (extended time interval to avoid edge effects)
- Checking for Data Gaps or flagged data and set to NaN
- Correct spikes and discontinuities (DEACTIVATED FOR CAL/VAL)
- Interpolate missing data
- High-pass filtering with a Chebysev filter at 10 mHz
- Calculating Wavelet Power Spectral Density matrix at frequencies from 10 to 100 mHz (logarithmically spaced)
- Remove extended intervals
- Perform coordinate transforms to get Magnetic Latitude *
- Separate to Tracks (according to Mag. Lat. limits)
- For each Track:
  - Calculate additional parameters (MLT, geomagnetic indices etc)
  - Perform Wave Detection (DEACTIVATED FOR CAL/VAL)

* Magnetic latitude & magnetic local time calculations are performed through ONERA IRBEM Library

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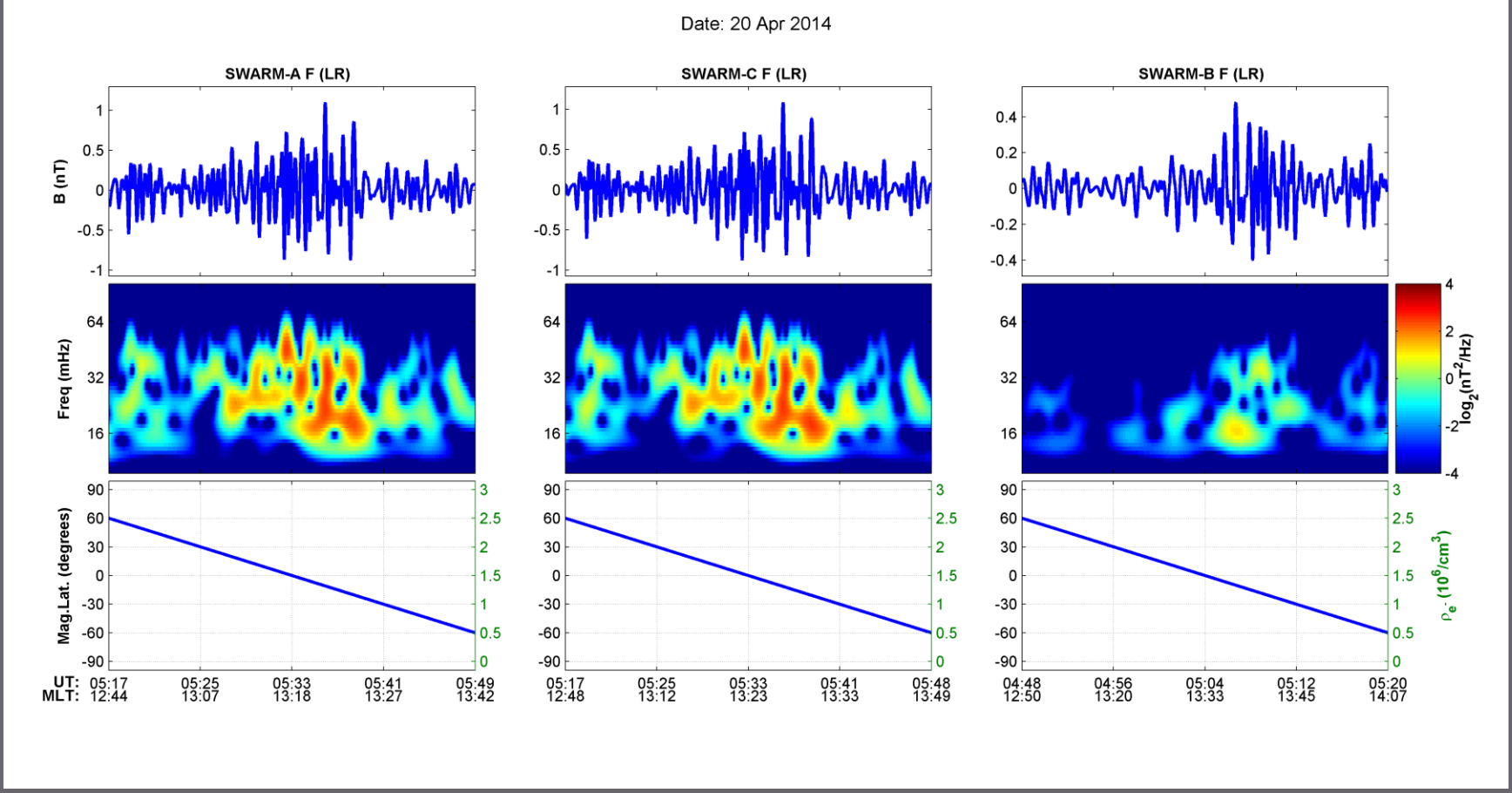
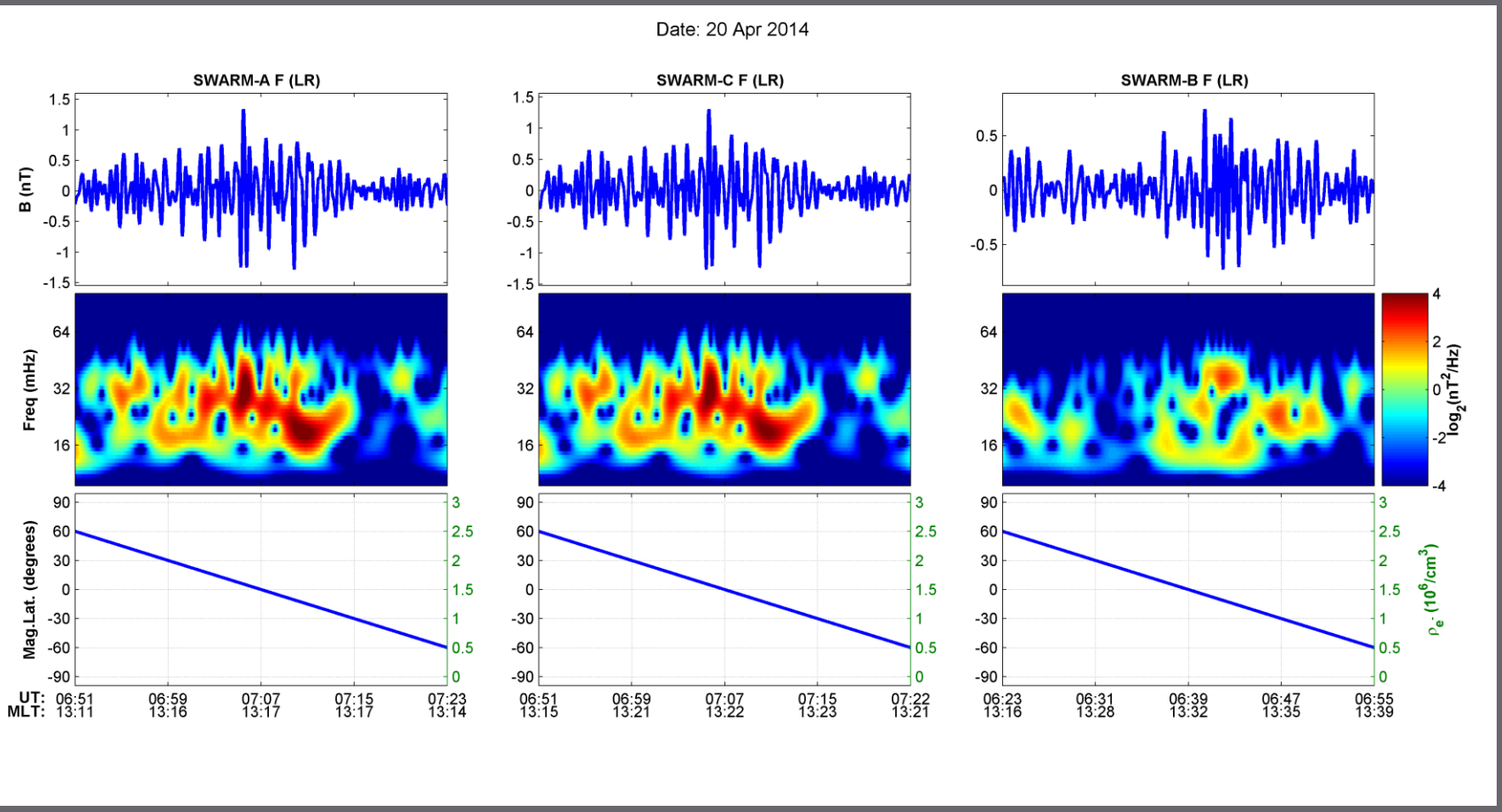
Intense pulsations (Dayside events)

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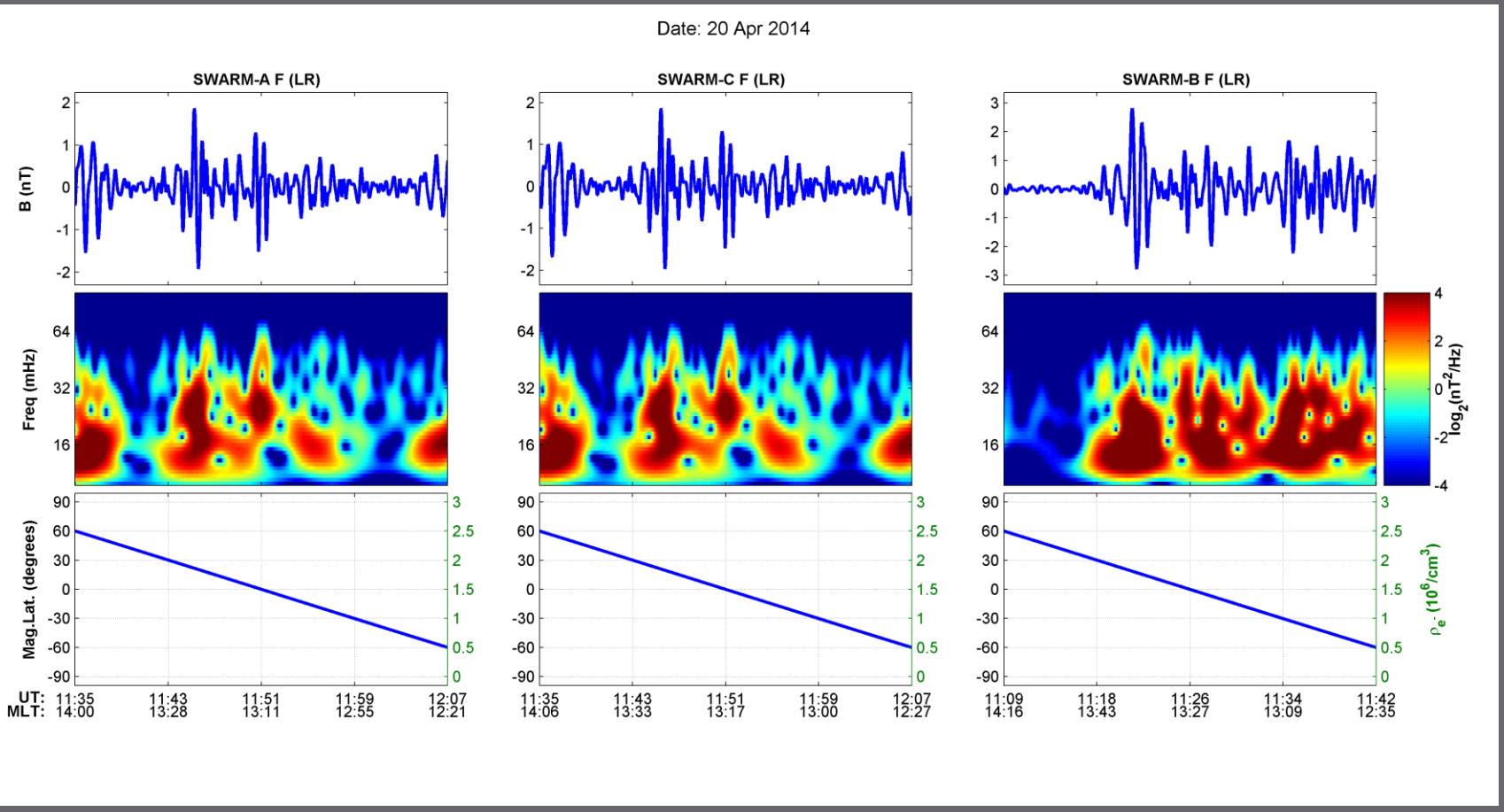
SWARM-A F (LR)
SWARM-C F (LR)
SWARM-B F (LR)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
$\log_2(nT^2/Hz)$
ρ_e (10^6/cm^3)
UT: 06:51 06:59 07:07 07:15 07:23
MLT: 13:11 13:16 13:17 13:17 13:14
UT: 06:51 06:59 07:07 07:15 07:22
MLT: 13:15 13:21 13:22 13:23 13:21
UT: 06:23 06:31 06:39 06:47 06:55
MLT: 13:16 13:28 13:32 13:35 13:39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SWARM-C F (LR)
SWARM-B F (LR)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
ρ_e (10^6/cm^3)
$\log_2$(nT^2/Hz)
UT: 11:35 11:43 11:51 11:59 12:07
MLT: 14:00 13:28 13:11 12:55 12:21
UT: 11:35 11:43 11:51 11:59 12:07
MLT: 14:06 13:33 13:17 13:00 12:27
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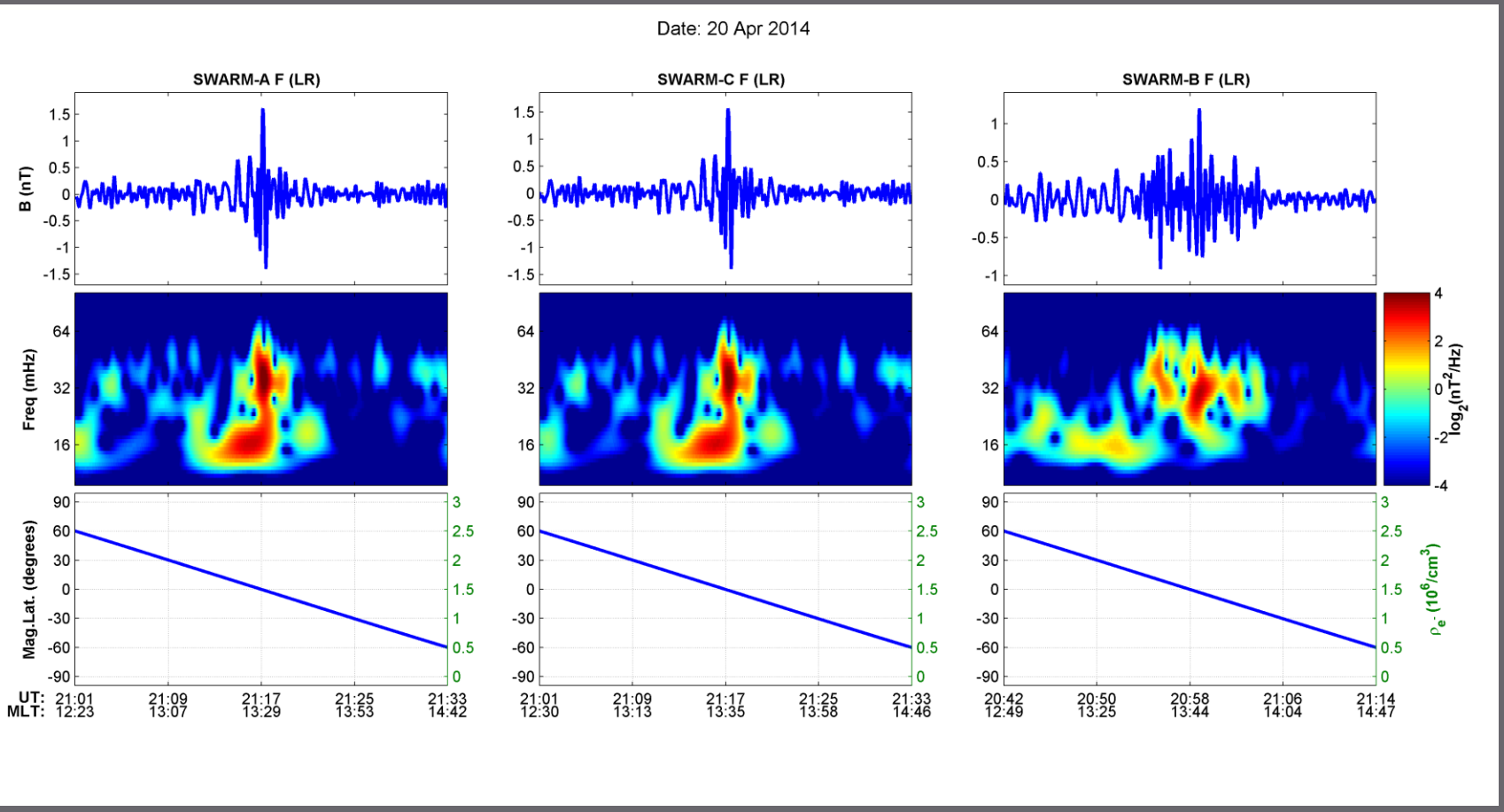
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SWARM-A F (LR)
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SWARM-B F (LR)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
$\log_2(nT^2/Hz)$
ρ_e (10^6/cm^3)
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MLT: 12:23 13:07 13:29 13:53 14:42
UT: 21:01 21:09 21:17 21:25 21:33
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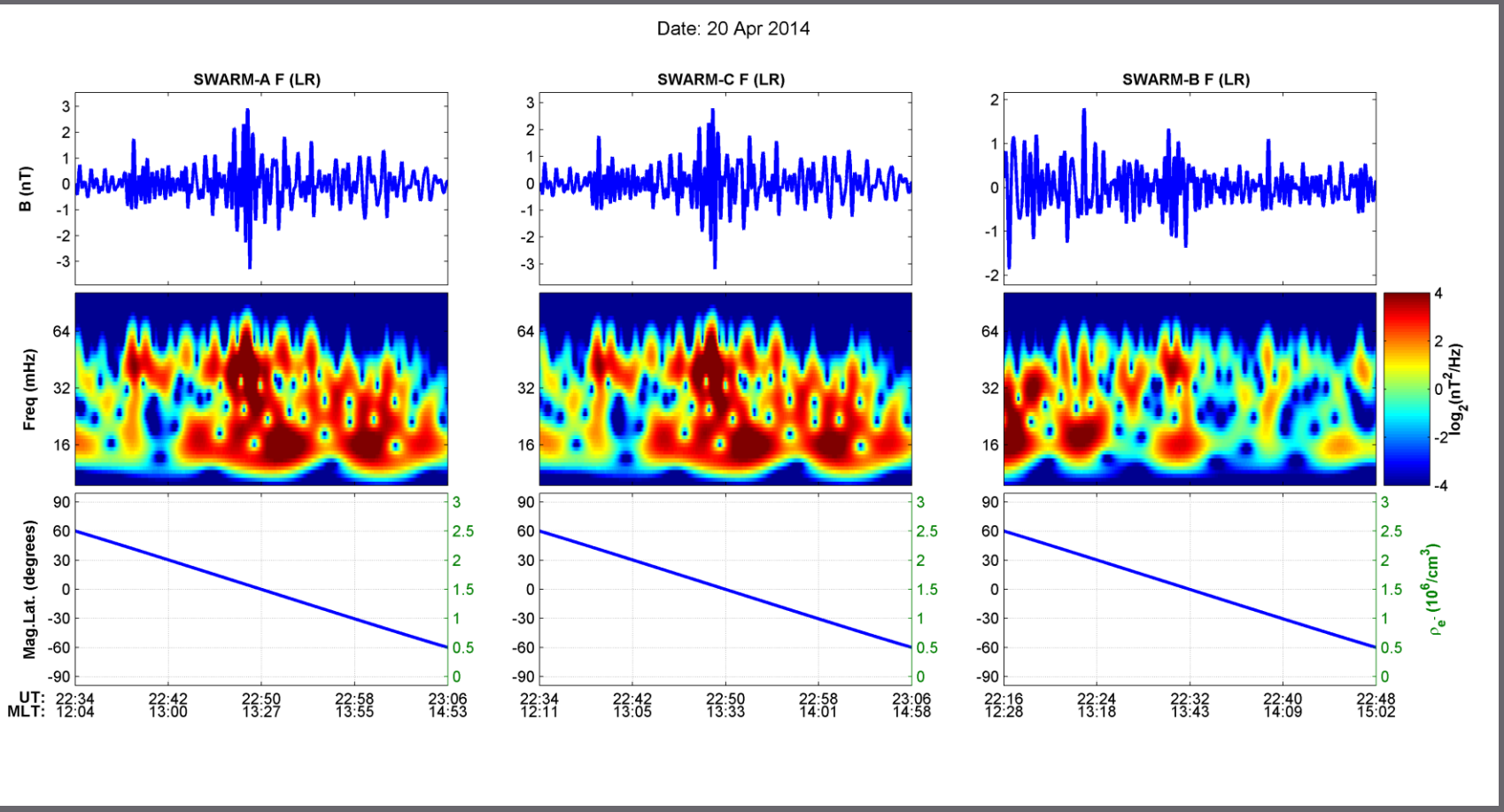
Date: 20 Apr 2014
SWARM-A F (LR)
SWARM-C F (LR)
SWARM-B F (LR)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
ρ_e (10^6/cm^3)
$\log_2$(nT^2/Hz)
UT: 22:34 22:42 22:50 22:58 23:06
MLT: 12:04 13:00 13:27 13:55 14:53
UT: 22:34 22:42 22:50 22:58 23:06
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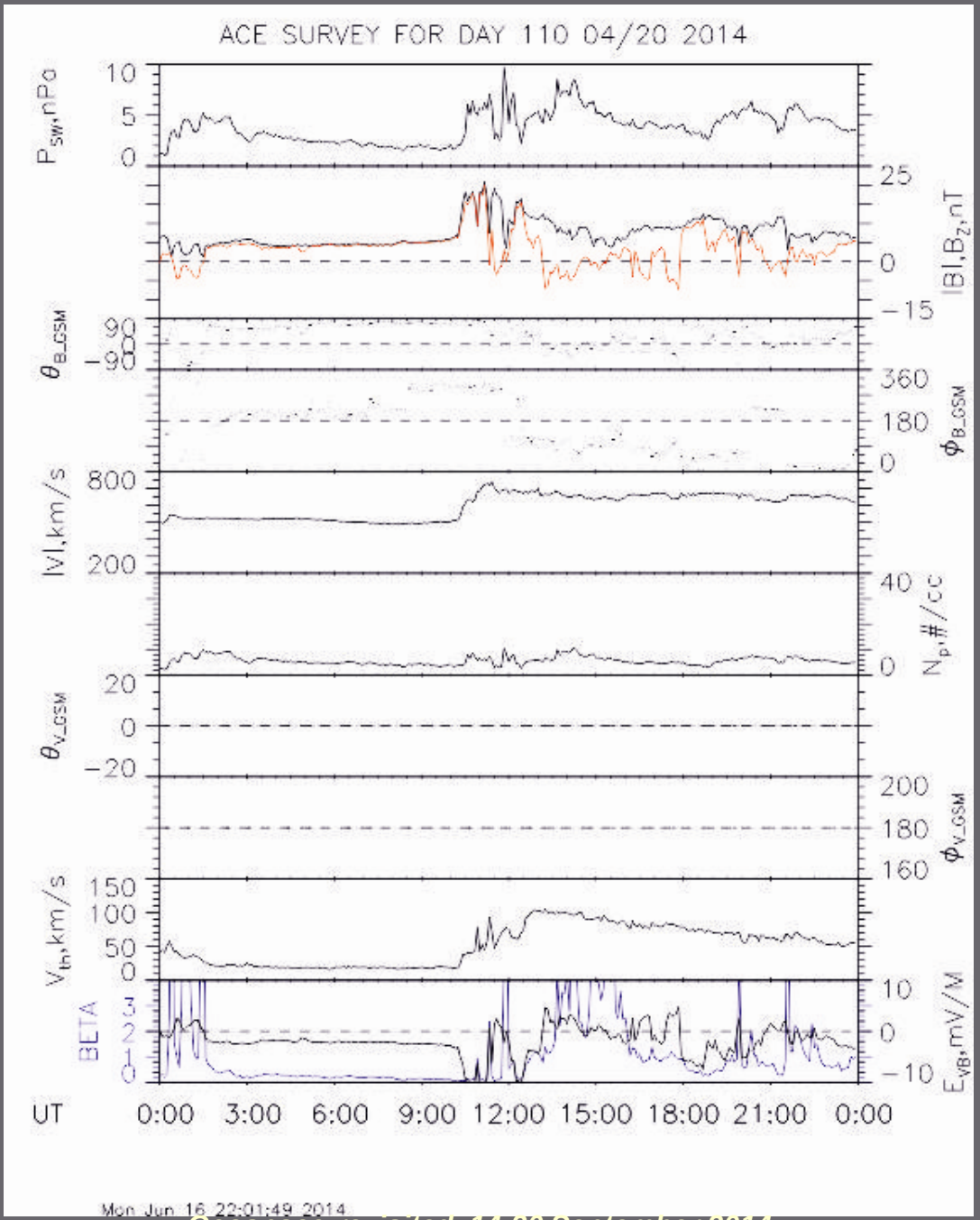
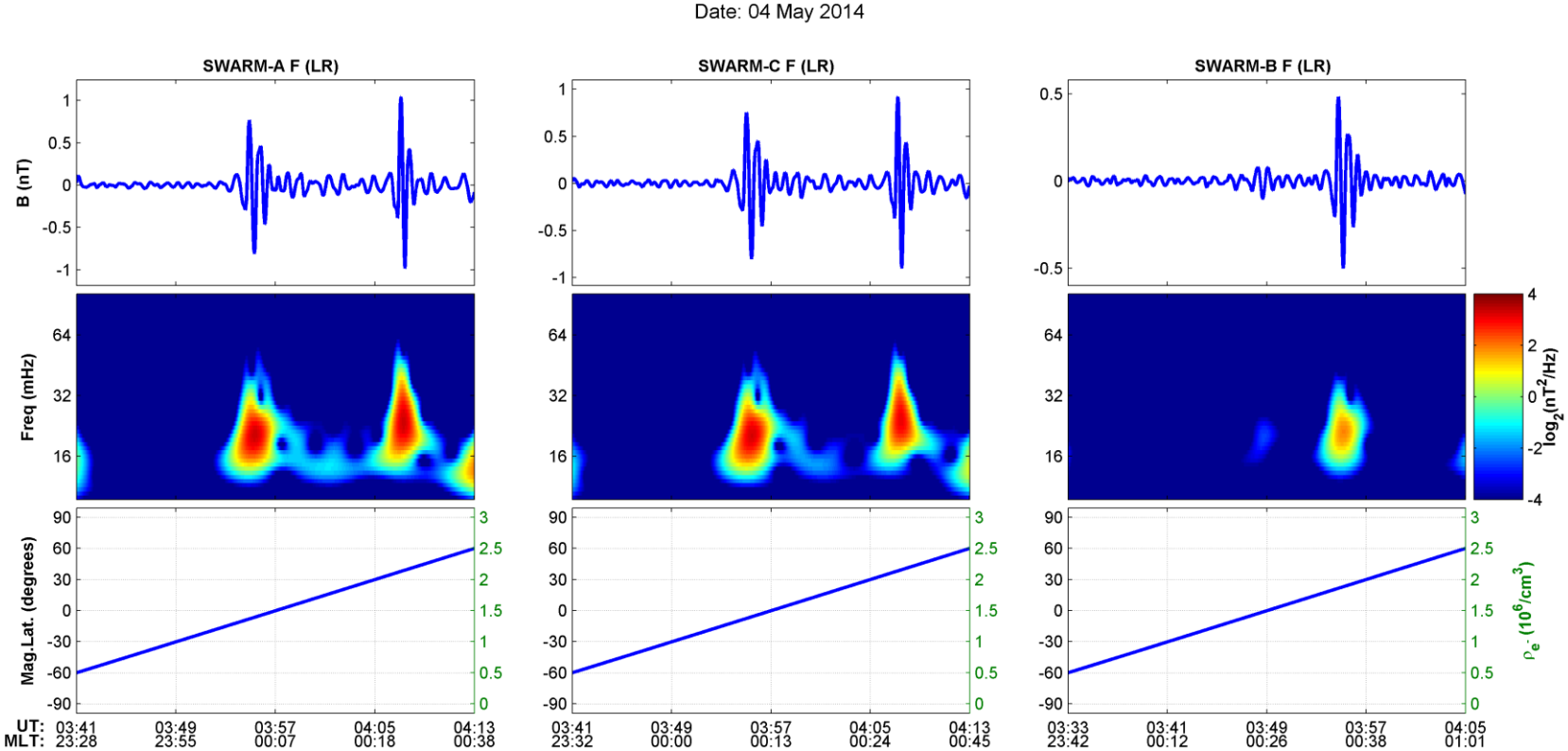
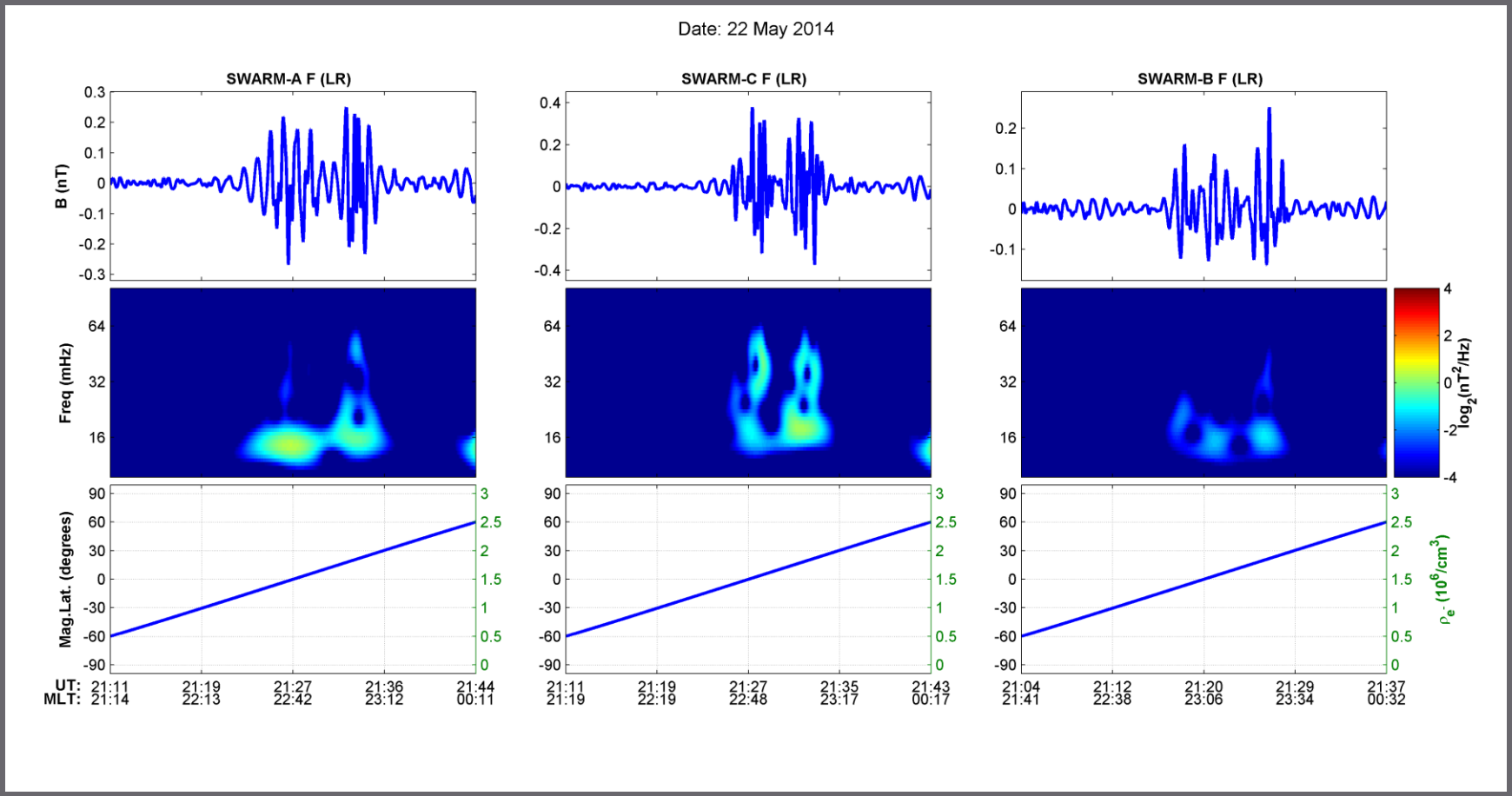
MLT: 12:28 13:18 13:43 14:09 15:02


ACE SURVEY FOR DAY 110 04/20 2014
P_{SW},nPa
|B|,B_z,nT
θ_{B_GSM}
ϕ_{B_GSM}
|V|,km/s
N_p,#/cc
θ_{V_GSM}
ϕ_{V_GSM}
V_{th},km/s
BETA
E_{VB},mV/M
UT
0:00 3:00 6:00 9:00 12:00 15:00 18:00 21:00 0:00
Mon Jun 16 22:01:49 2014

Equatorial Spread-F (Nightside events)

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SWARM-C F (LR)
SWARM-B F (LR)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
ρ_e (10^6/cm^3)
$\log_2$(nT^2/Hz)
UT: 21:11 21:19 21:27 21:36 21:44
MLT: 21:14 22:13 22:42 23:12 00:11
UT: 21:11 21:19 21:27 21:35 21:43
MLT: 21:19 22:19 22:48 23:17 00:17
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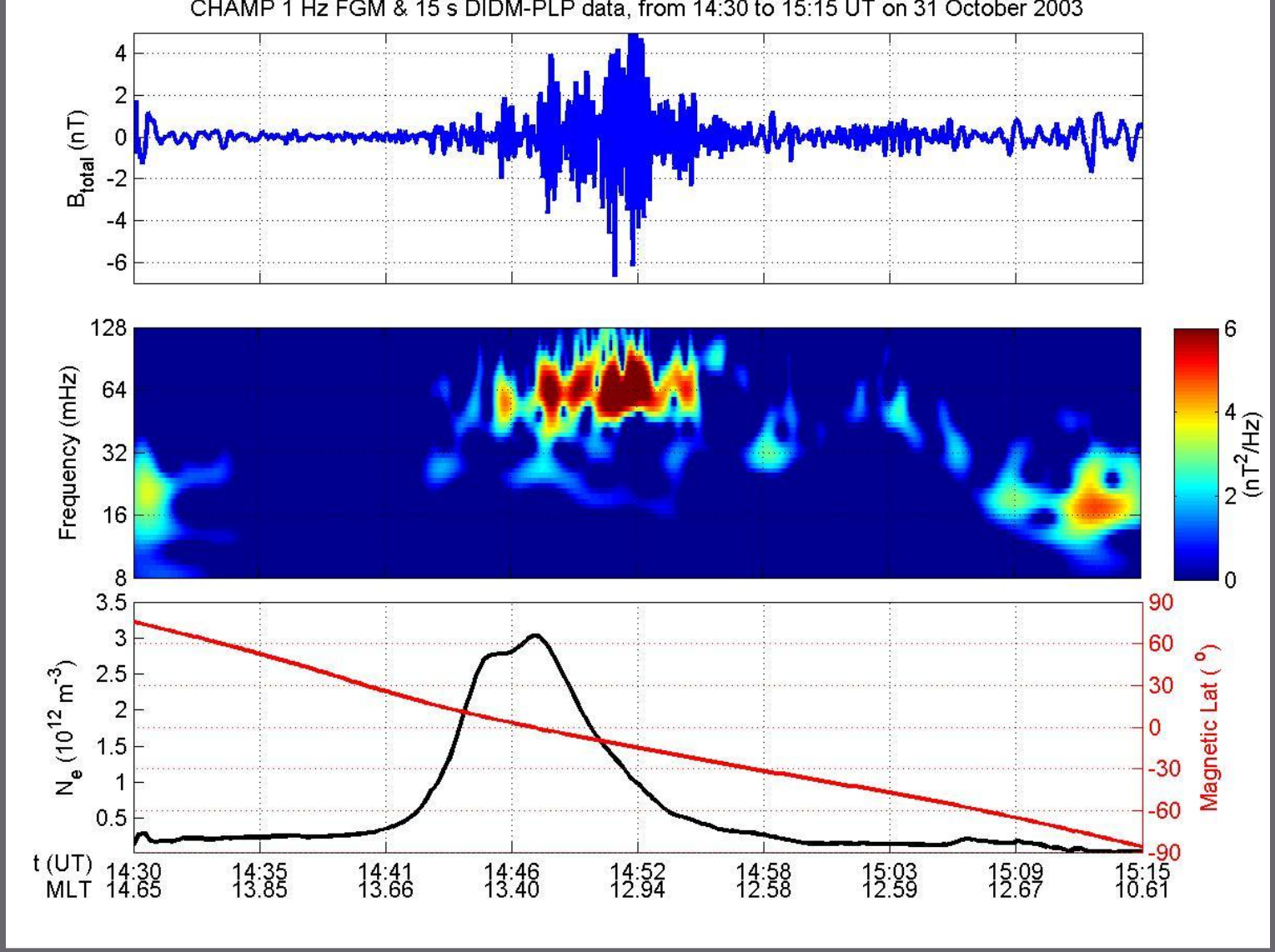
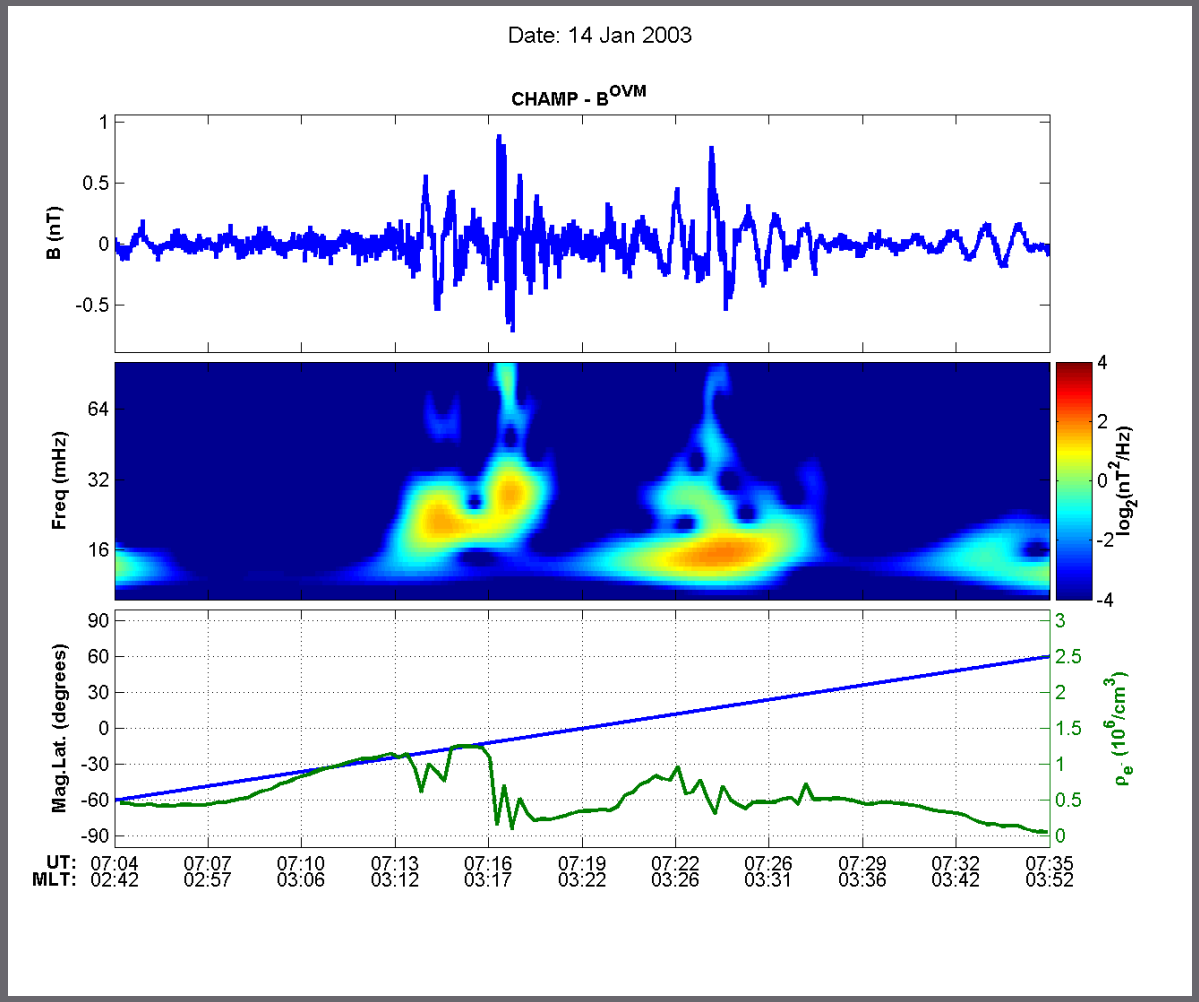
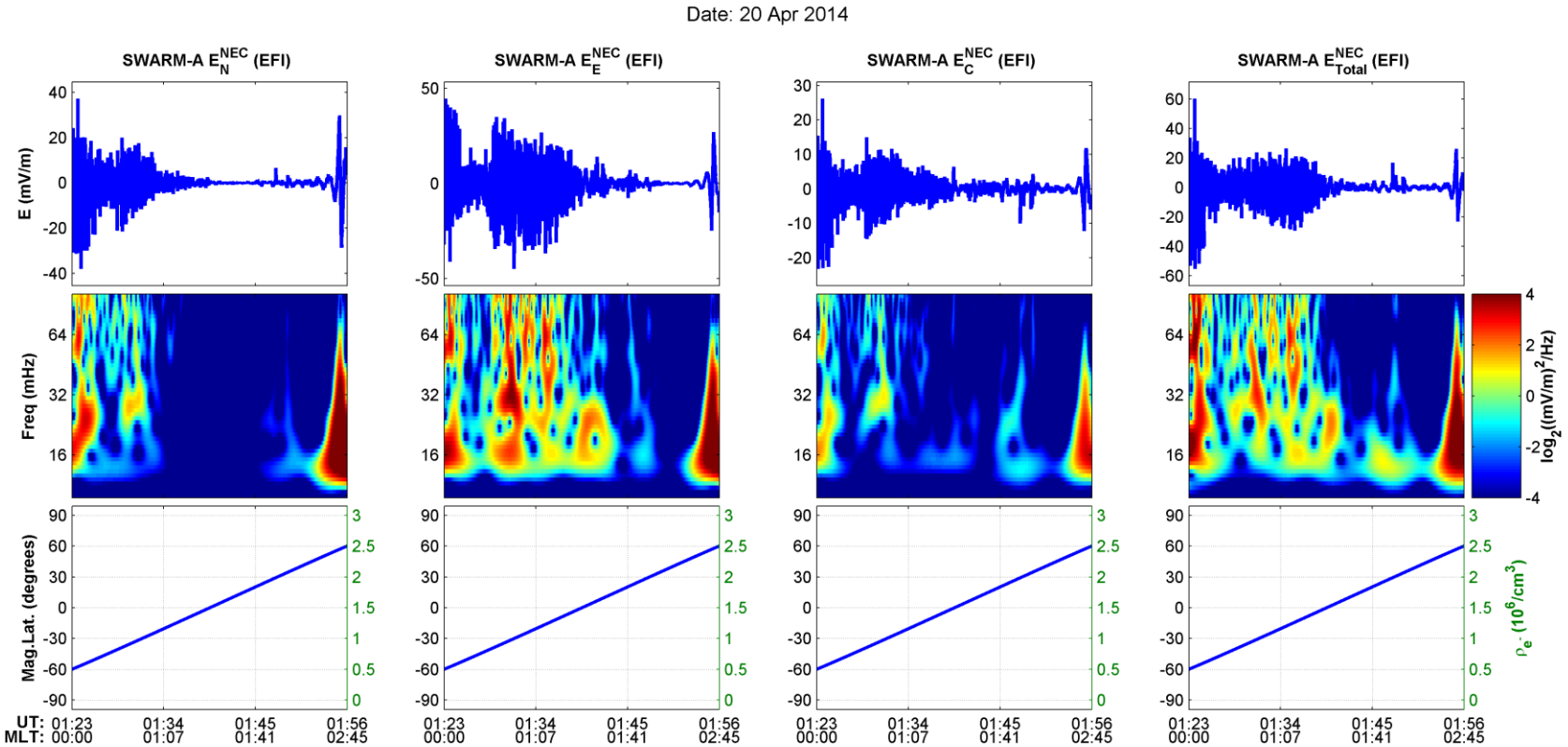
MLT: 21:41 22:38 23:06 23:34 00:32



Balasis et al., ULF wave activity during the 2003 Halloween superstorm: multipoint observations from CHAMP, Cluster and Geotail missions, *Ann. Geophys.*, 30, 1751-1768, 2012.

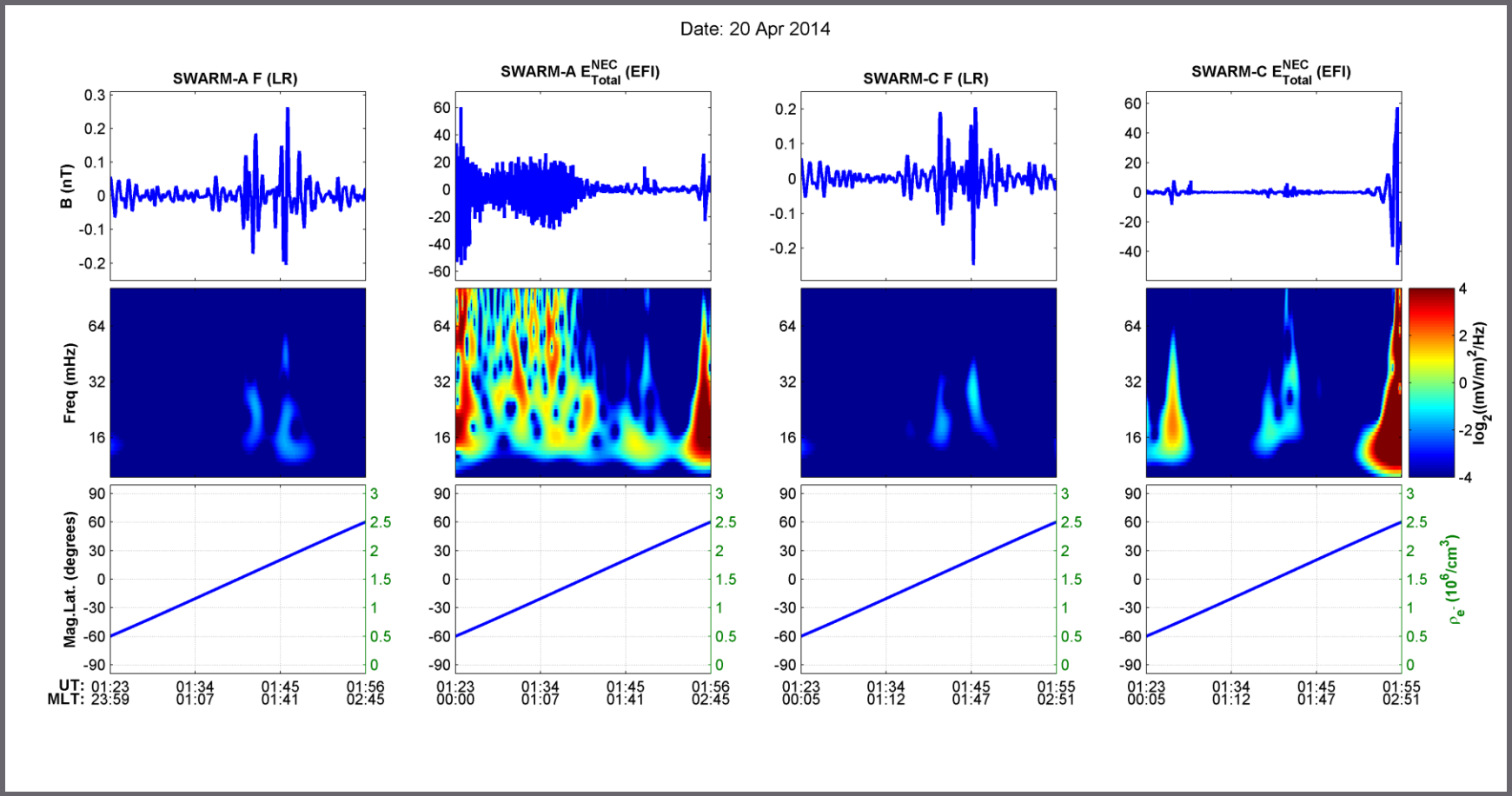
Plasma bubble (CHAMP)





EFI measurements

[Courtesy of Dave Knudsen & Johnathan Burchill, University of Calgary, Canada]


Date: 20 Apr 2014
SWARM-A F (LR)
SWARM-A E NEC Total (EFI)
SWARM-C F (LR)
SWARM-C E NEC Total (EFI)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
log2((mV/m)2/Hz)
ρe- (10^6/cm^3)
UT: 01:23 01:34 01:45 01:56
MLT: 23:59 01:07 01:41 02:45
UT: 01:23 01:34 01:45 01:56
MLT: 00:00 01:07 01:41 02:45
UT: 01:23 01:34 01:45 01:55
MLT: 00:05 01:12 01:47 02:51
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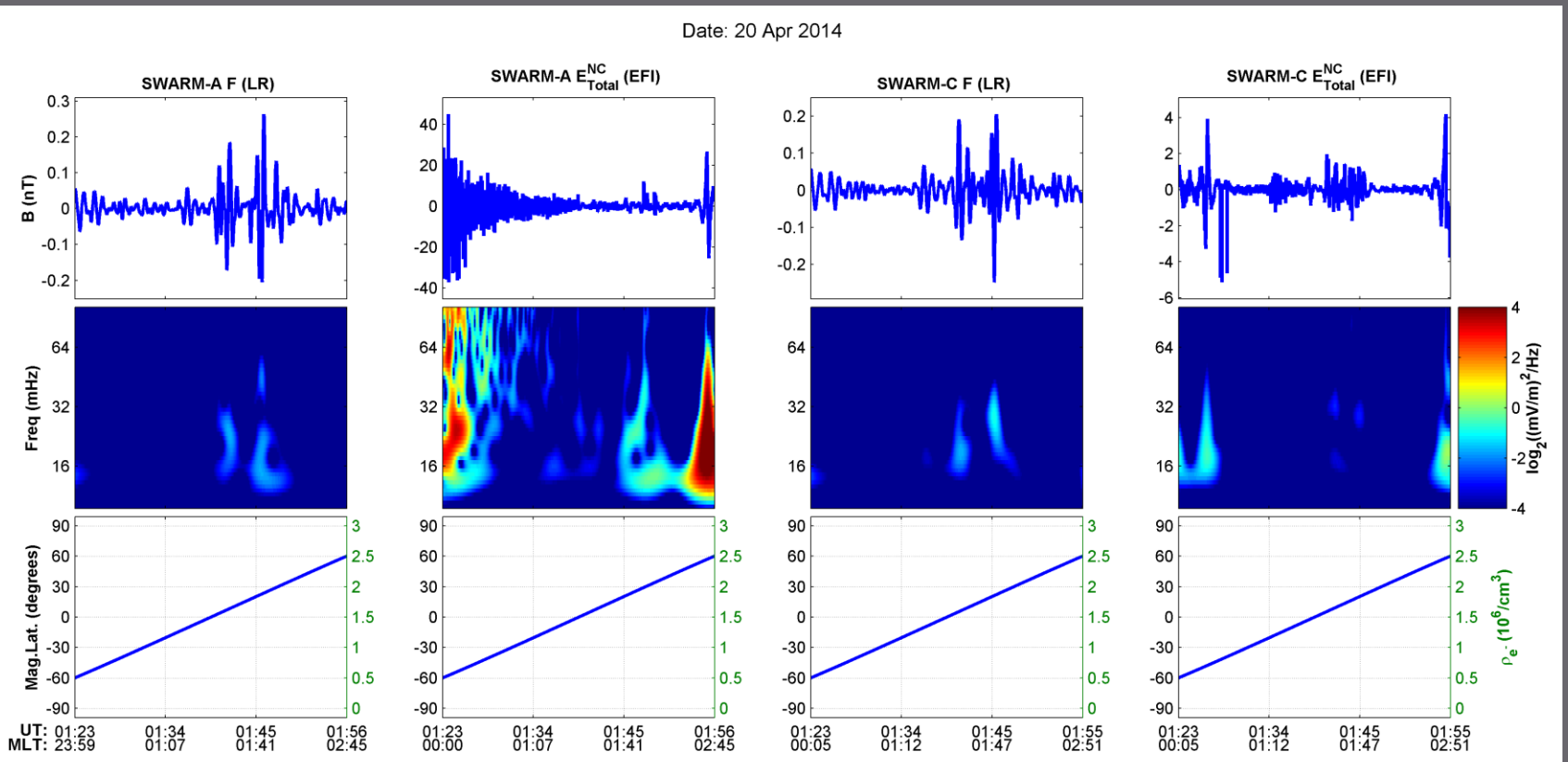
MLT: 00:05 01:12 01:47 02:51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SWARM-A F (LR)
SWARM-A E NC Total (EFI)
SWARM-C F (LR)
SWARM-C E NC Total (EFI)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
ρe- (10^6/cm^3)
log2((mV/m)^2/Hz)
UT: 01:23 01:34 01:45 01:56
MLT: 23:59 01:07 01:41 02:45
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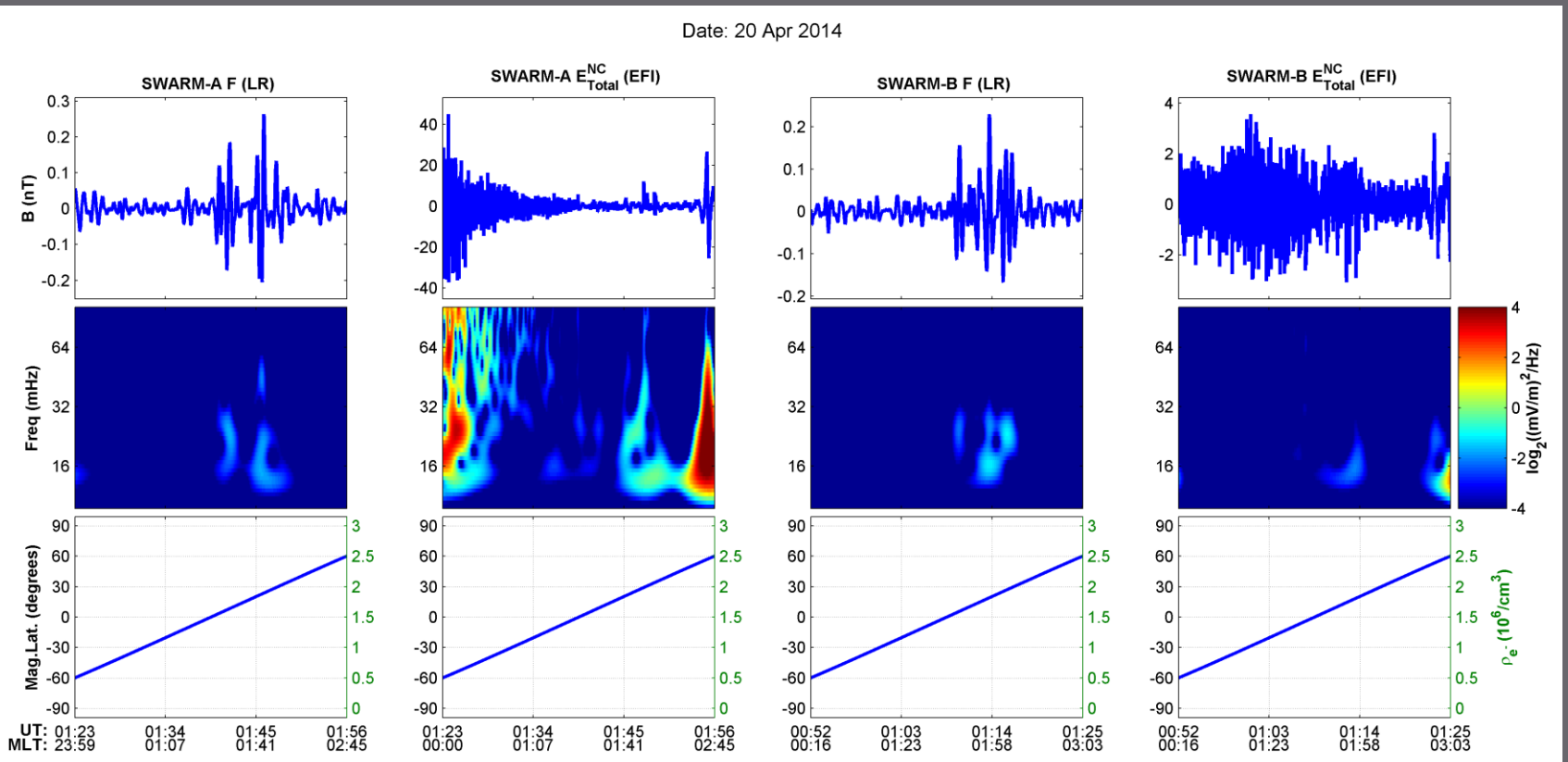
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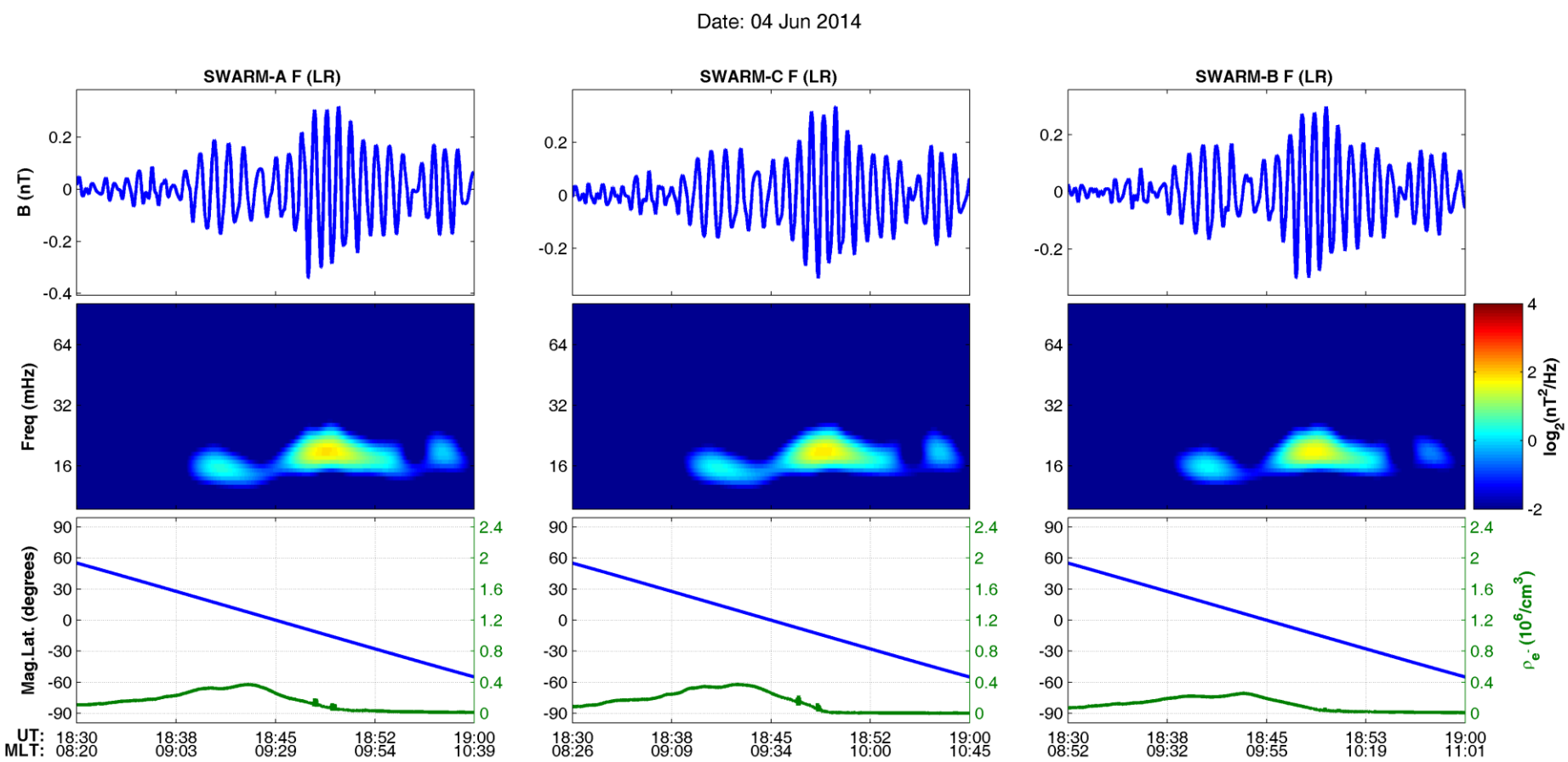
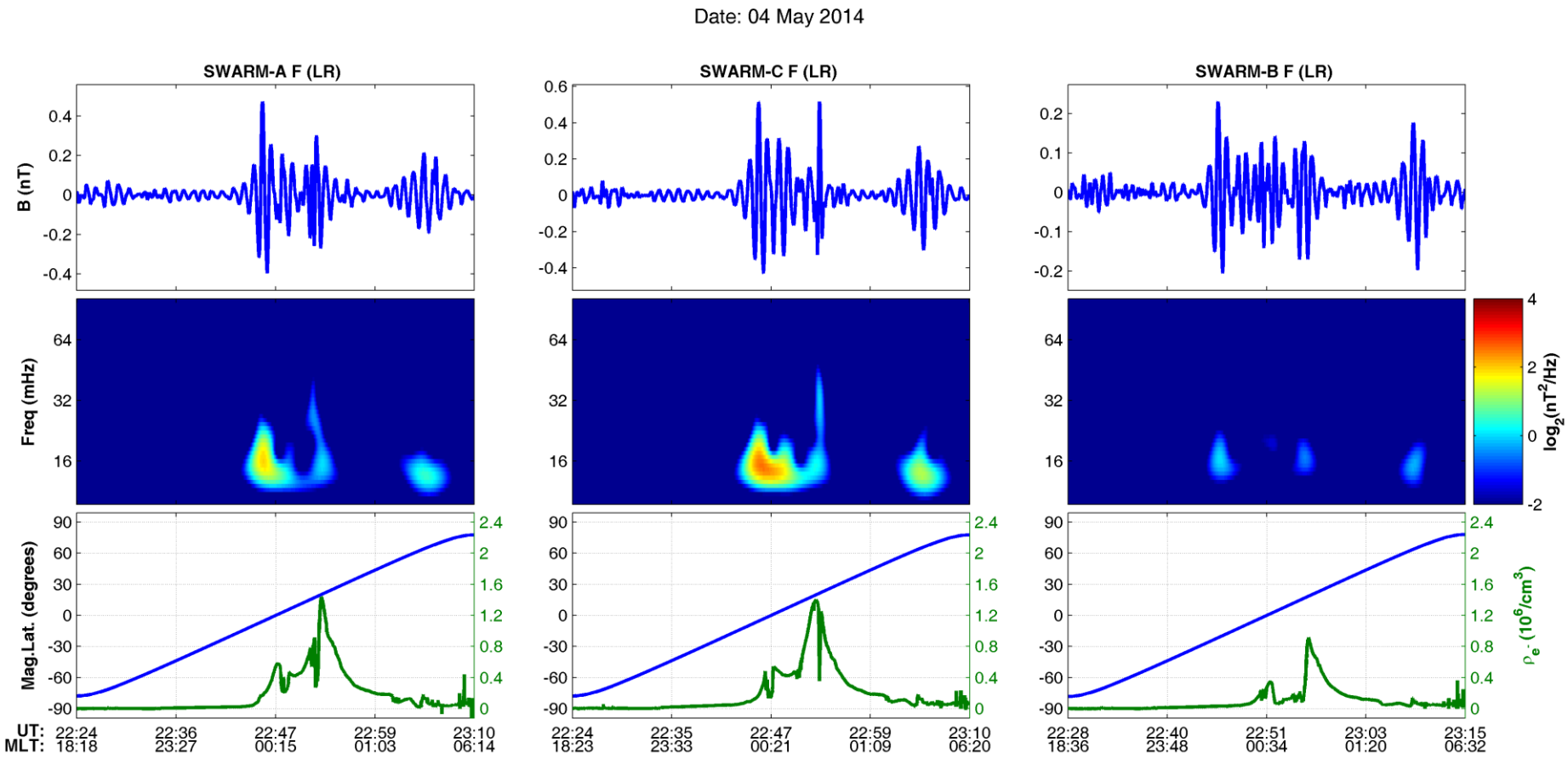
SWARM-A F (LR)
SWARM-A E NC Total (EFI)
SWARM-B F (LR)
SWARM-B E NC Total (EFI)
B (nT)
Freq (mHz)
Mag.Lat. (degrees)
log2((mV/m)2/Hz)
ρe- (10^6/cm^3)
UT: 01:23 01:34 01:45 01:56 | 01:23 01:34 01:45 01:56 | 00:52 01:03 01:14 01:25 | 00:52 01:03 01:14 01:25
MLT: 23:59 01:07 01:41 02:45 | 00:00 01:07 01:41 02:45 | 00:16 01:23 01:58 03:03 | 00:16 01:23 01:58 03:03



PL measurements

[Courtesy of Stephan Buchert, IRF Uppsala, Sweden]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B (nT)
Freq (mHz)
Mag.Lat. (degrees)
log2(nT2/Hz)
ρe- (10^6/cm^3)
UT: 22:24 22:36 22:47 22:59 23:10
MLT: 18:18 23:27 00:15 01:03 06:14
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MLT: 18:23 23:33 00:21 01:09 06:20
UT: 22:28 22:40 22:51 23:03 23:15
MLT: 18:36 23:48 00:34 01:20 06:32

Next steps

- Combine Swarm with Cluster and ground-based magnetometer arrays' observations in order to be able to understand spatial and temporal characteristics of the features observed (e.g. source of origin, wave propagation properties)

- Systematically compare magnetic field (ASM, VFM experiments) and plasma measurements (EFI and PL experiments) on board Swarm satellites for wave studies and other purposes

- Use higher sampling rate Swarm data and ground-based coils' recordings (e.g. CARISMA array) in order to be able to detect EMIC/Pc1 events as well as IAR signatures

(collaboration with Ian Mann, Univ. of Alberta)

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Radiation Belt Loss & Energization (MAARBLE)

FP7-SPACE-2011-1 Collaborative Project