An extraordinary ULF wave episode during the 2003 Halloween superstorm revealed by wavelet transforms of multipoint observations

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Outline

- **Introduction**
  - **Motivation**
  - **ULF waves**
  - **Wavelet transforms**

- **Results**
  - **ULF wave activity during the 2003 Halloween superstorm: multipoint observations from CHAMP, Cluster and Geotail satellite missions as well as CARISMA, GIMA and IMAGE magnetometer arrays**

Motivation I

- 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 ***ESA's Swarm mission***).

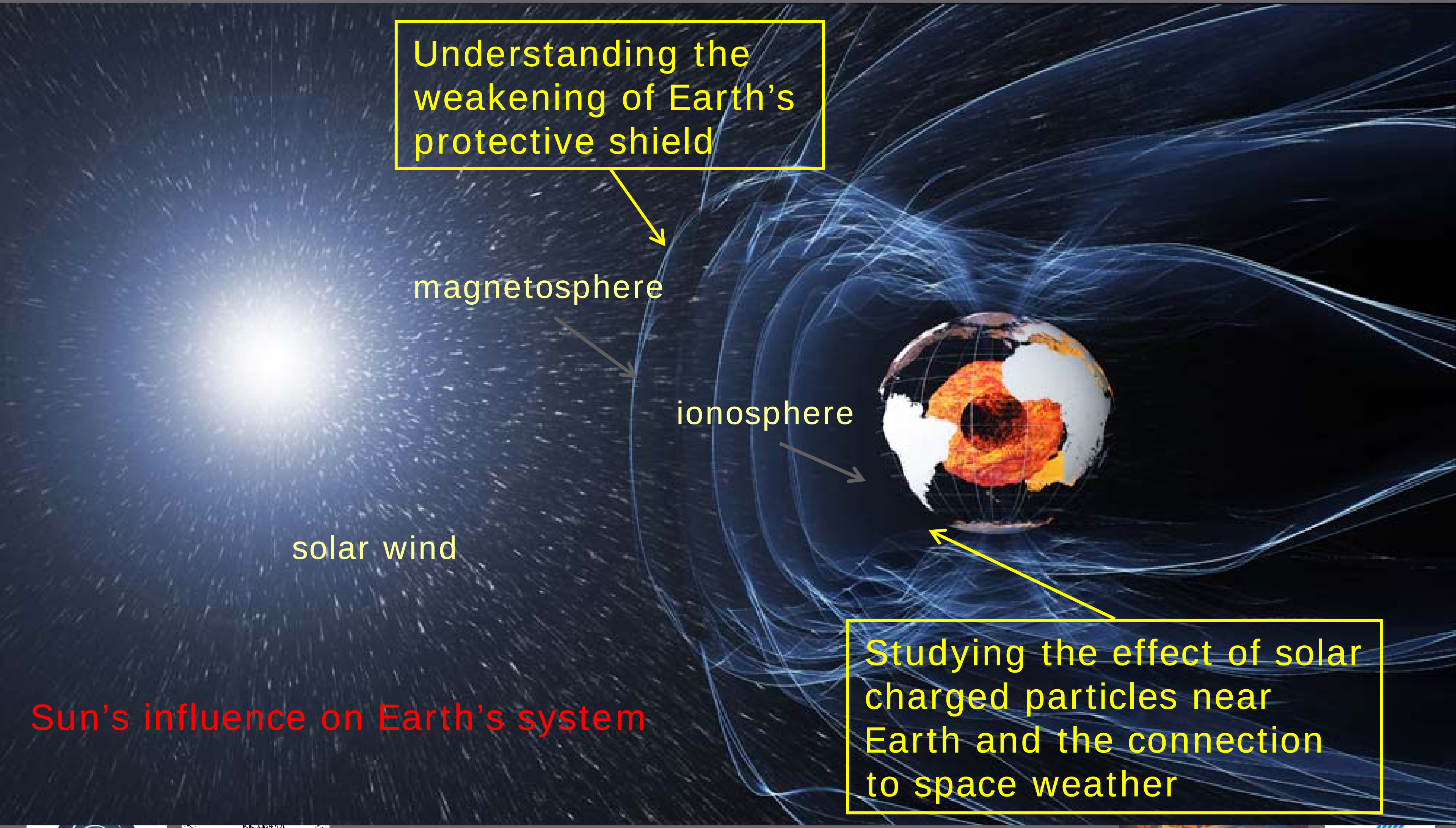
  [For a recent statistical study on CHAMP observations of ULF wave signatures, please attend the next talk of the session by **C. Papadimitriou et al.**]

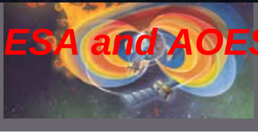
- Projection of the ideas for the ***Swarm*** lifetime especially the expected combination with ***Cluster*** at that time.

Earth's magnetic field

- produced to a large extend by a **self-sustaining dynamo**, operating in the fluid **outer-core,**
- also caused by **magnetised rocks** in the Earth's **crust**,
- electric currents flowing in the **ionosphere, magnetosphere** and **oceans**
- and by currents **induced in the Earth mantle** by time-varying **external fields**.

External sources





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 2013: 4 years operations

ULF waves

- Magnetospheric ULF waves are large-scale phenomena, and in principle, simultaneous observations at many locations are needed to understand in depth their generation and propagation.

- In particular, continuous pulsations with periods in the range 0.2 to 600 s, denoted as Pc 1-2 (0.2–10 s), Pc 3 (10–45 s), Pc 4 (45–150 s), and Pc 5 (150–600 s), have been extensively studied using measurements from both space-borne and ground-based instruments for many years.

(For a recent review see for example: Menk, F. W., "Magnetospheric ULF Waves: A Review" in The Dynamic Magnetosphere, IAGA Special Sopron Book Series, Vol. 3, Part 4, 223–256, DOI: 10.1007/978-94-007-0501-2_13, Springer, 2011).

Motivation II

- One of the gaps in the state-of-the-art knowledge of the wave background is how electromagnetic ion cyclotron (EMIC) waves in the Pc1-2 band (0.2-10 s) vary with altitude.

- The spatial extent of EMIC wave packets is critical to their potential role in **radiation belt electron loss**. The efficiency of EMIC waves in generating loss of relativistic electrons from the Van Allen belts to the atmosphere is determined by not only the resonance conditions and hence pitch angle diffusion rates of the particles, but also their spatial extent especially in L.

- The L-shell spatial extent of EMIC waves is essentially unknown, except for single event multiple satellite case studies such as Usanova et al. (GRL, 2008), since this cannot be determined from single satellites nor from arrays of ground-based magnetometers dues to Pc1 propagation in the Earth-ionosphere waveguide.

Wavelet transforms

- ULF wave events have been traditionally identified manually by examining a series of spectrograms based on the ***Fast Fourier Transform (FFT)***.

  Motivated by the continuously increasing amount of data collected by space missions and ground-based instruments, algorithms have been developed based on ***FFT spectra to automatically examine spectrograms*** and identify ULF waves. Therefore, a variety of automated FFT-based routines exists (e.g. Bortnik et al., 2007).

- Since the 1990s, the ***wavelet spectral analysis*** has become popular, as it allows the quantitative monitoring of localised variations of power within the time series data (see for example, Balasis et al., 2005, Balasis and Mandea, 2007).

  For instance, Balasis and Mandea (2007) used a wavelet analysis technique to look at CHAMP satellite data for ULF wave activity, while Heilig et al. (2007) developed an algorithm for the selection of possible ULF wave-related pulsation events (mainly Pc3) from both ground and space magnetometer data, separately.

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Halloween 2003 storm

- **ULF wave activity throughout the Halloween superstorm (27 October – 1 November 2003)**
- **Interval 1: Geotail - Cluster conjunction**

  (14:00 – 17:00 UT, 30 October 2003)
- **Interval 2: Geotail - CHAMP conjunction**

  (20:00 – 22:00 UT, 30 October 2003)

  (For the overall wave activity and for details on Events 1 & 2, please visit the poster *S1-8* by *Daglis et al.*)

Halloween 2003 storm

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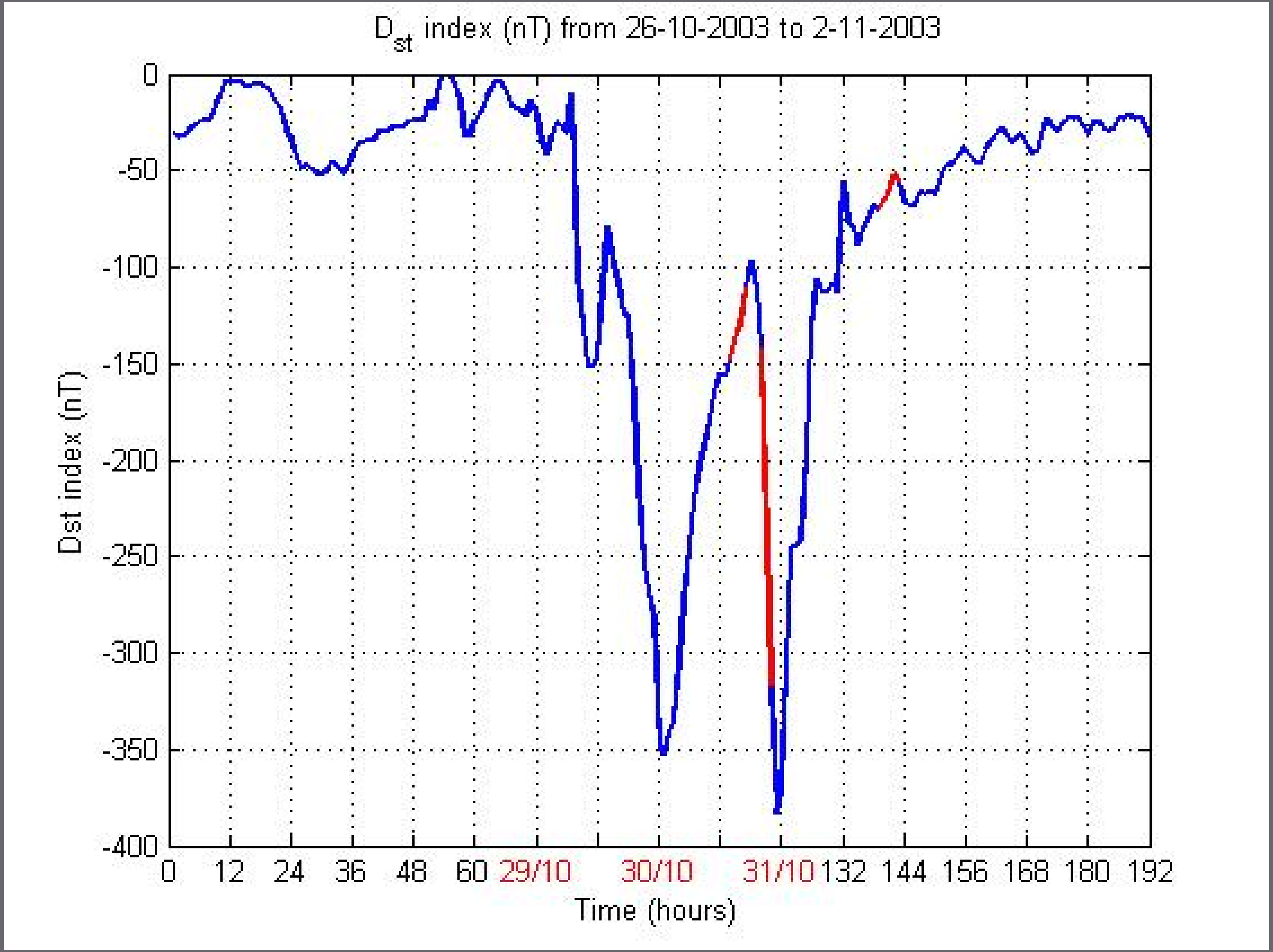
- **Interval 2: Geotail - CHAMP conjunction**

  (20:00 – 22:00 UT, 30 October 2003)
- **Interval 3: Cluster - CHAMP conjunction**

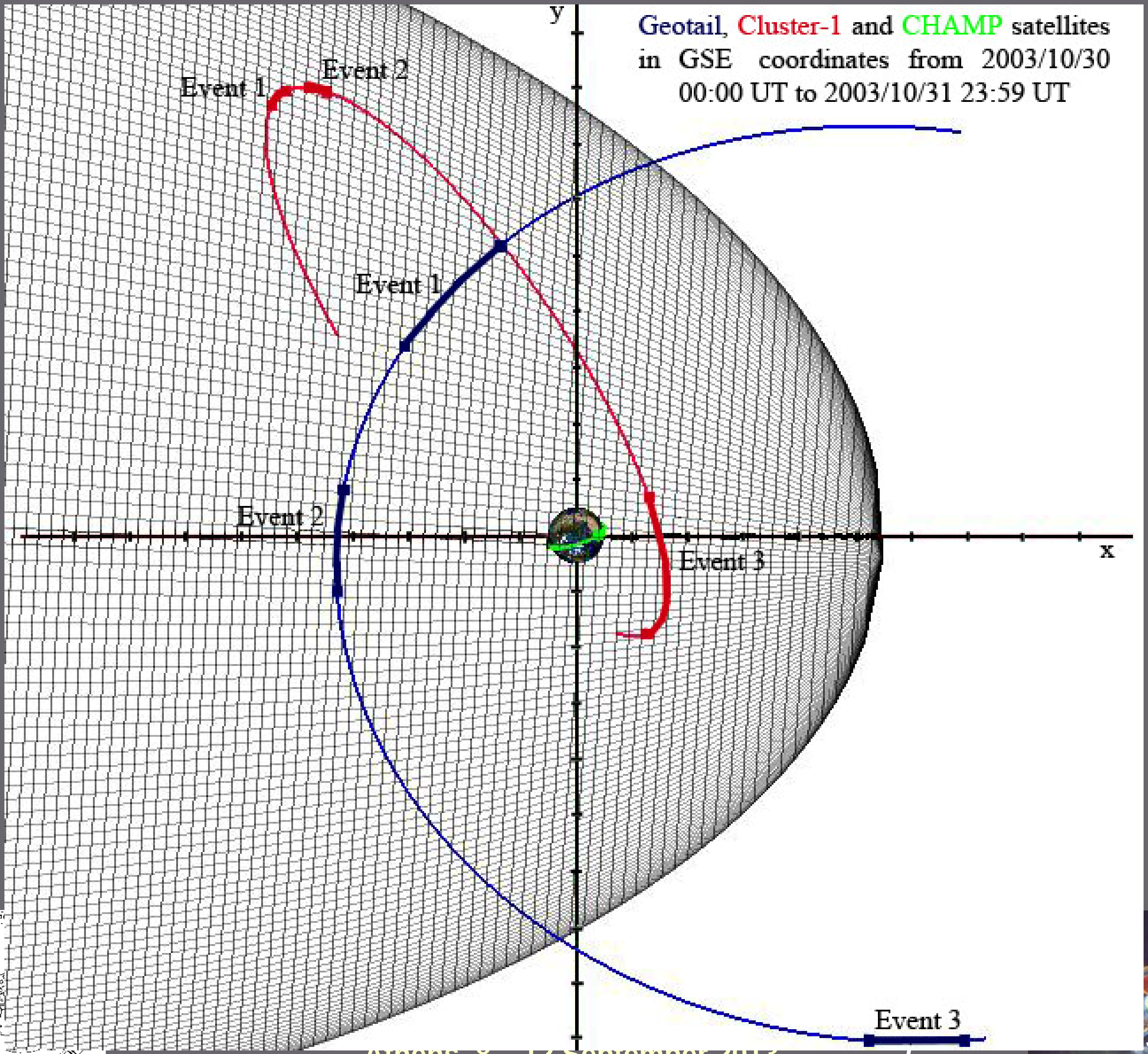
  (19:00 – 23:30 UT, 31 October 2003)

Halloween 2003 superstorm



11th Hellenic Astronomical Conference
Athens, 8 – 12 September 2013

Satellite locations during Halloween 2003 storm



Satellite locations

- The Cluster and CHAMP satellites were in good local time (LT) conjunction in the time interval from 19:00 to 23:30 UT, near the dayside noon-midnight meridian, on 31 October 2003, during the recovery phase of the Halloween 2003 superstorm.

- Geotail was on the morning-side magnetosheath at the same time period.

A few technical issues

Data processing

- We have analyzed fluxgate magnetometer (FGM) measurements from Geotail (3 s data), Cluster (4 s data), CHAMP (1 s data) and CARISMA and GIMA magnetic networks (1 s data). The following preliminary processing steps were then applied:
- Time series for the Cluster and Geotail spacecraft were transformed in a mean field-aligned (MFA) coordinate system in order to separate ULF field variations perpendicular to as well as along the magnetic field direction.
- The parallel component in the coordinate system is obtained from a 20-minute running average of the instantaneous magnetic field, while the azimuthal component is positive eastward, and the meridional component points radially outward at the magnetic equator. ULF waves in these directions are referred to as compressional, toroidal and poloidal, respectively.

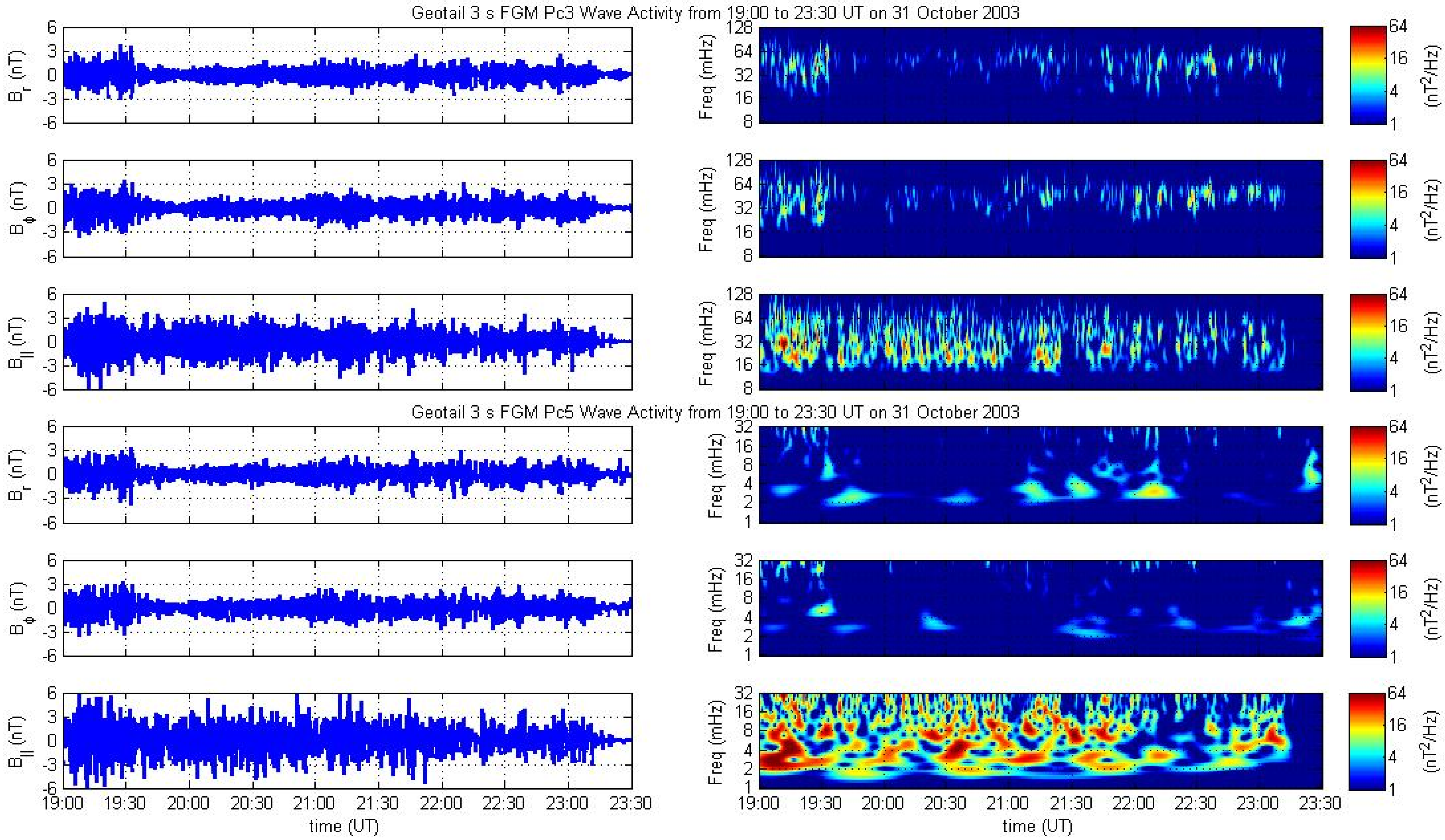
- [see also Balasis, Daglis, Zesta et al., *AnnGeo* 2012]

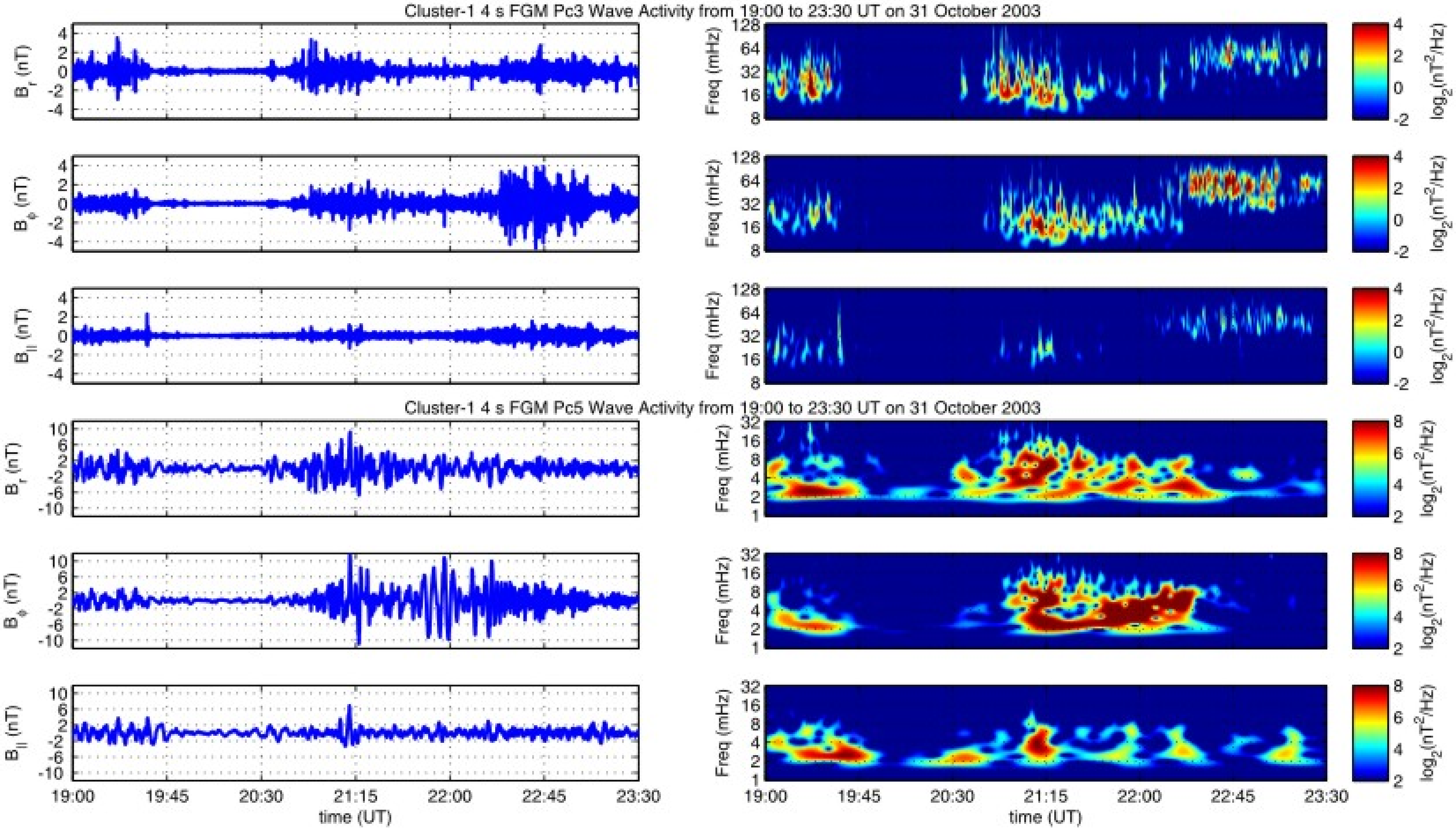
Data processing cont.

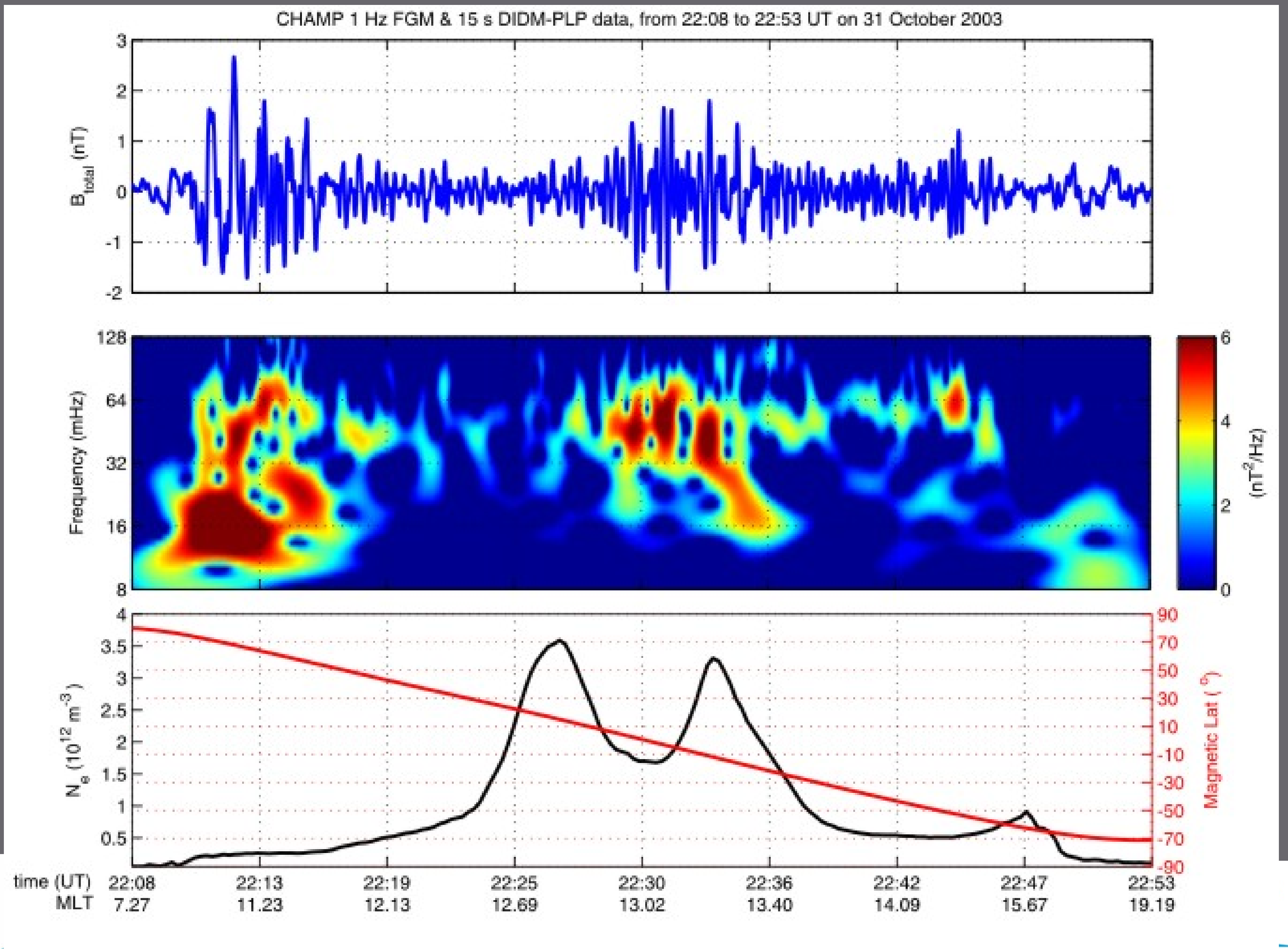
- CHAMP total field was computed from the three vector components as it is considered a fairly good approximation of its compressional component for studying ULF waves (e.g., Heilig et al., 2007).

- The low Earth orbit of CHAMP allows a global view of the topside ionosphere within the relatively short time of a full orbit. Due to the fast motion through field lines in a LEO orbit we are only able to reliably detect Pc3 waves (frequency 15–100 mHz) from CHAMP, but not Pc 4-5 waves (frequency 1–10 mHz).

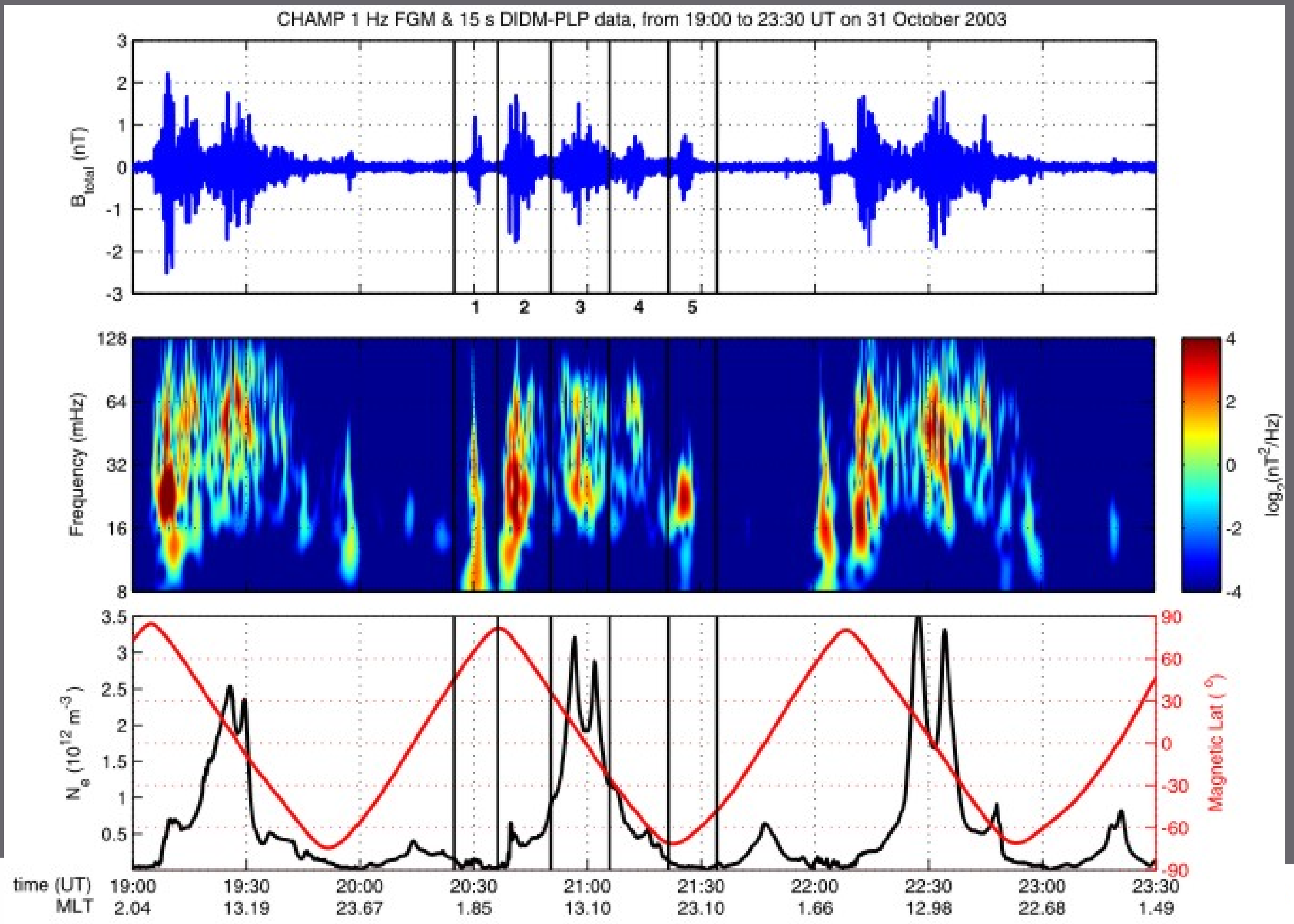
- Continuous wavelet transform with the Morlet wavelet as the basis function was applied to the time series under investigation [see for details Balasis et al., 2005, 2006, Balasis & Mandea, 2007; Mandea & Balasis, 2006].


Geotail 3 s FGM Pc3 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
Geotail 3 s FGM Pc5 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
B_r (nT)
B_φ (nT)
B_|| (nT)
Freq (mHz)
(nT²/Hz)
time (UT)
19:00 19:30 20:00 20:30 21:00 21:30 22:00 22:30 23:00 23:30


Cluster-1 4 s FGM Pc3 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
Cluster-1 4 s FGM Pc5 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
B_r (nT)
B_ϕ (nT)
$B_{||}$ (nT)
Freq (mHz)
$\log_2(nT^2/Hz)$
19:00
19:45
20:30
21:15
22:00
22:45
23:30
time (UT)



CHAMP 1 Hz FGM & 15 s DIDM-PLP data, from 22:08 to 22:53 UT on 31 October 2003
B_total (nT)
Frequency (mHz)
(nT²/Hz)
N_e (10¹² m⁻³)
Magnetic Lat (°)
time (UT) 22:08 22:13 22:19 22:25 22:30 22:36 22:42 22:47 22:53
MLT 7.27 11.23 12.13 12.69 13.02 13.40 14.09 15.67 19.19



CHAMP 1 Hz FGM & 15 s DIDM-PLP data, from 19:00 to 23:30 UT on 31 October 2003
B_total (nT)
3
2
1
0
-1
-2
-3
1
2
3
4
5
Frequency (mHz)
128
64
32
16
8
log10(nT²/Hz)
4
2
0
-2
-4
N_e (10^12 m^-3)
3.5
3
2.5
2
1.5
1
0.5
Magnetic Lat (°)
90
60
30
0
-30
-60
-90
time (UT) 19:00 19:30 20:00 20:30 21:00 21:30 22:00 22:30 23:00 23:30
MLT 2.04 13.19 23.67 1.85 13.10 23.10 1.66 12.98 22.68 1.49

CHAMP observations

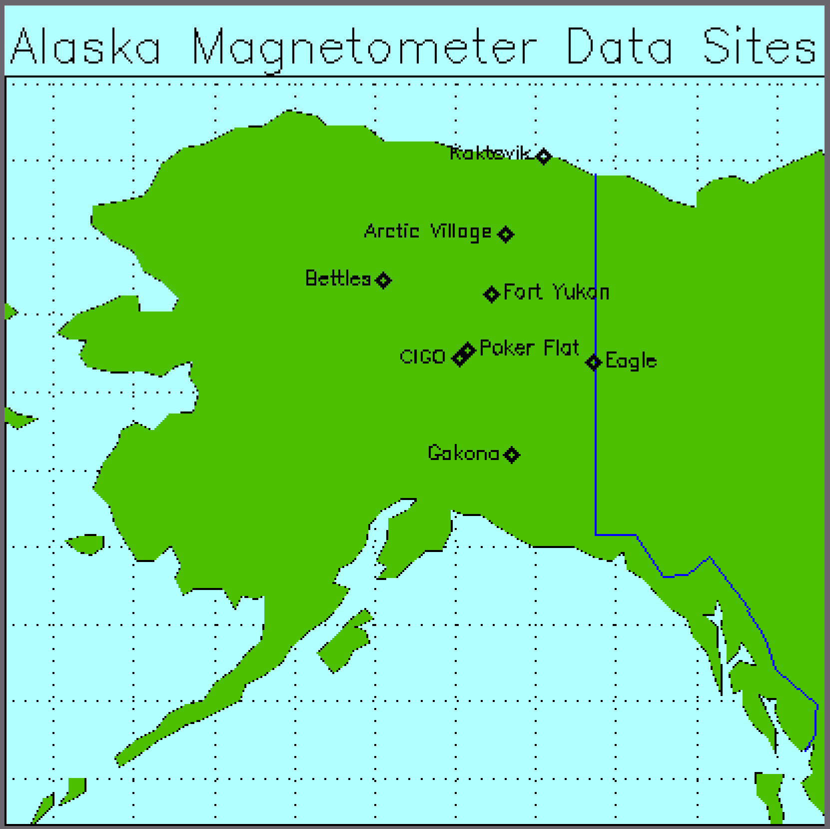
- Pc3 waves are observed over the auroral zones (intervals 1 and 2 correspond to the North a.z., while intervals 4 and 5 to the South a.z.) and the day-side equator (interval 3), while wave power decreases significantly at mid-latitudes; a profile that we attribute to strong ionospheric Hall and Pedersen currents there.

- Furthermore, a dramatic N to S asymmetry in the Pc3 waves is observed over the a.z., with the wave activity being more pronounced over the N auroral oval.

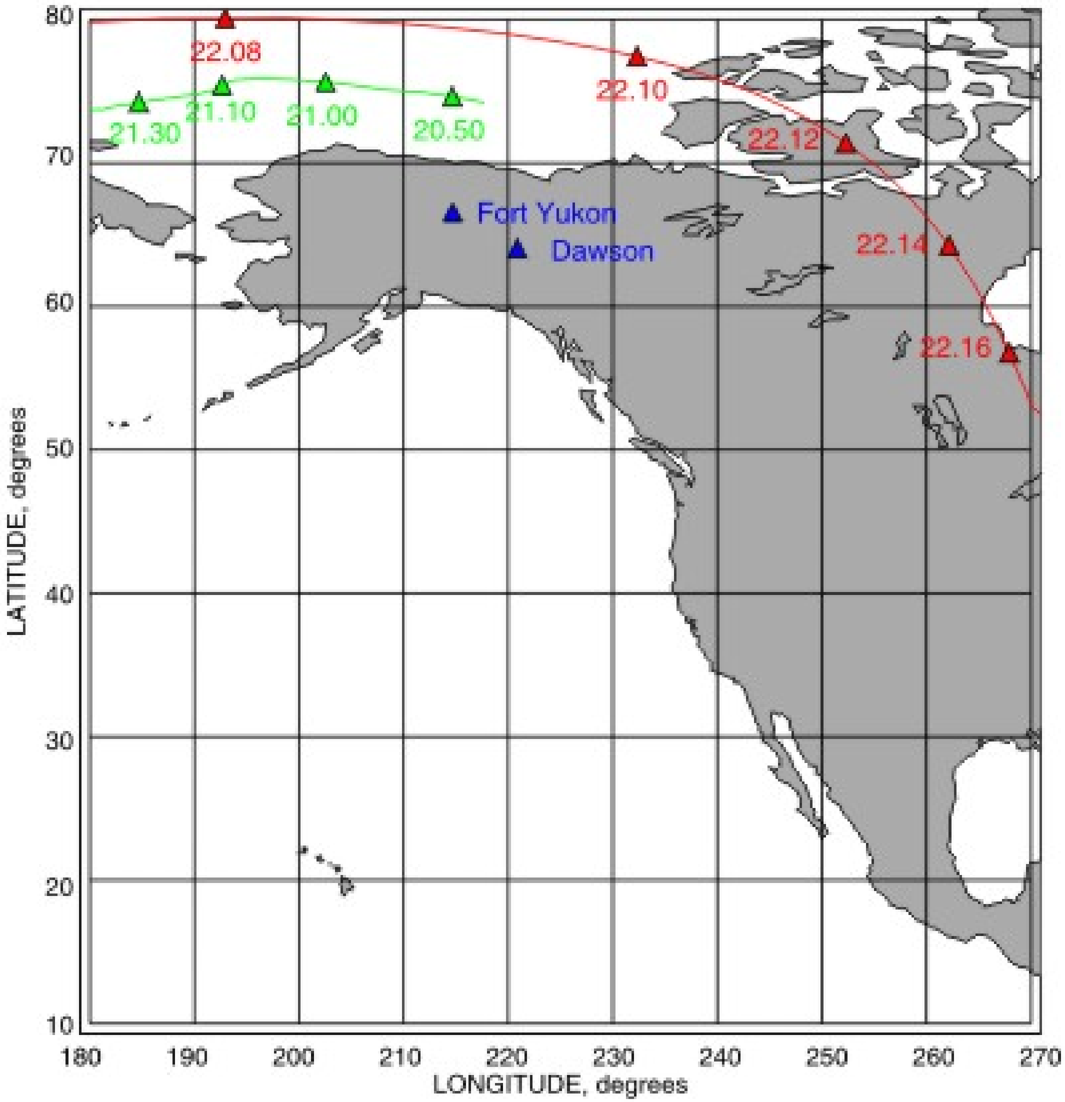
- A nightside/ dayside auroral oval asymmetry is also evident, with most of the wave power on the dayside auroral oval (see intervals 2 and 4 vs. intervals 1 and 5).

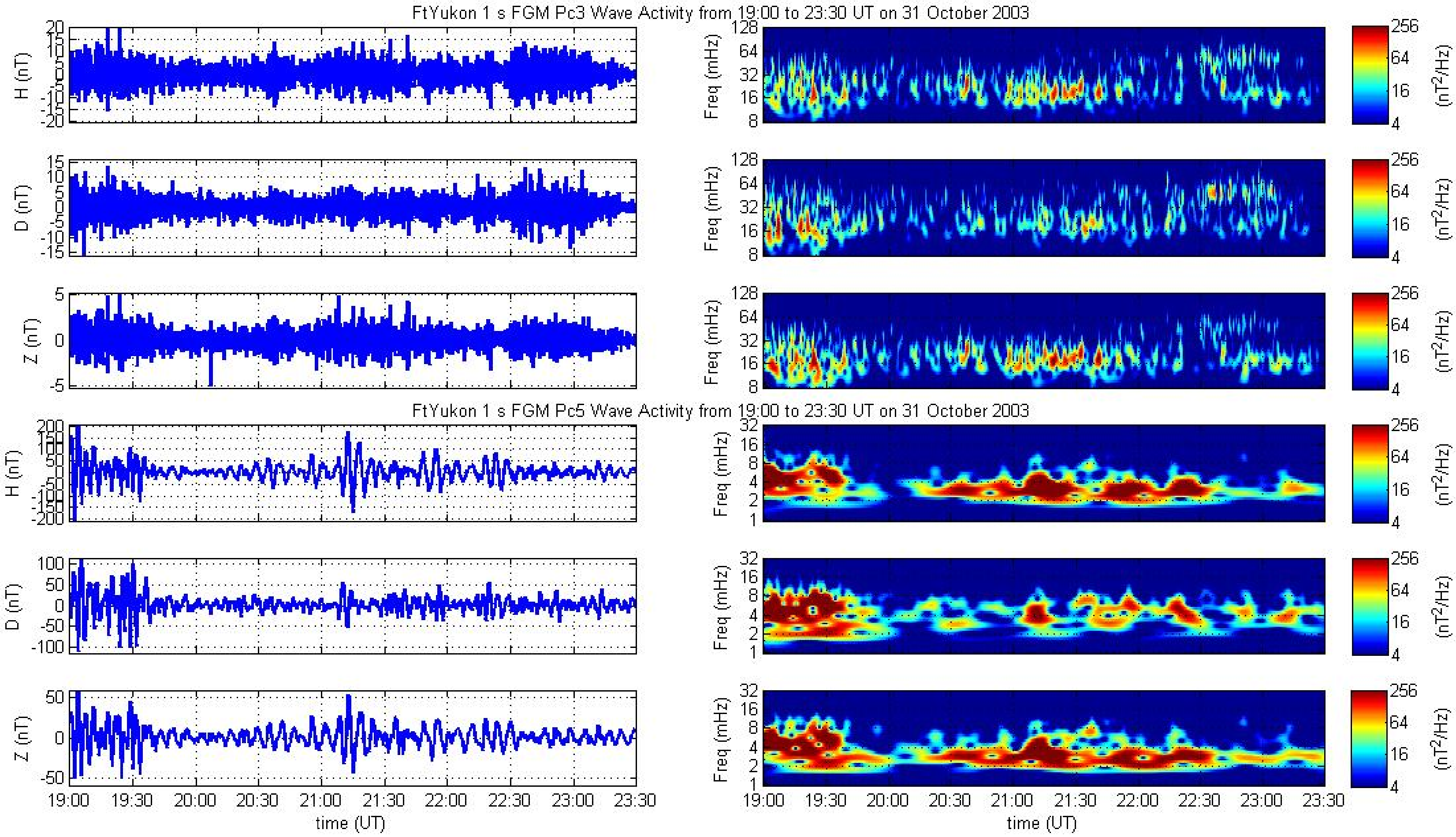
- Because the equatorial electrojet disappears in the nightside, wave power has significantly decreased over the nightside equator. Wave activity that is sporadically observed in the nightside is likely due to phenomena like currents enhanced during substorms or the propagation of Pi2 waves from the magnetotail.

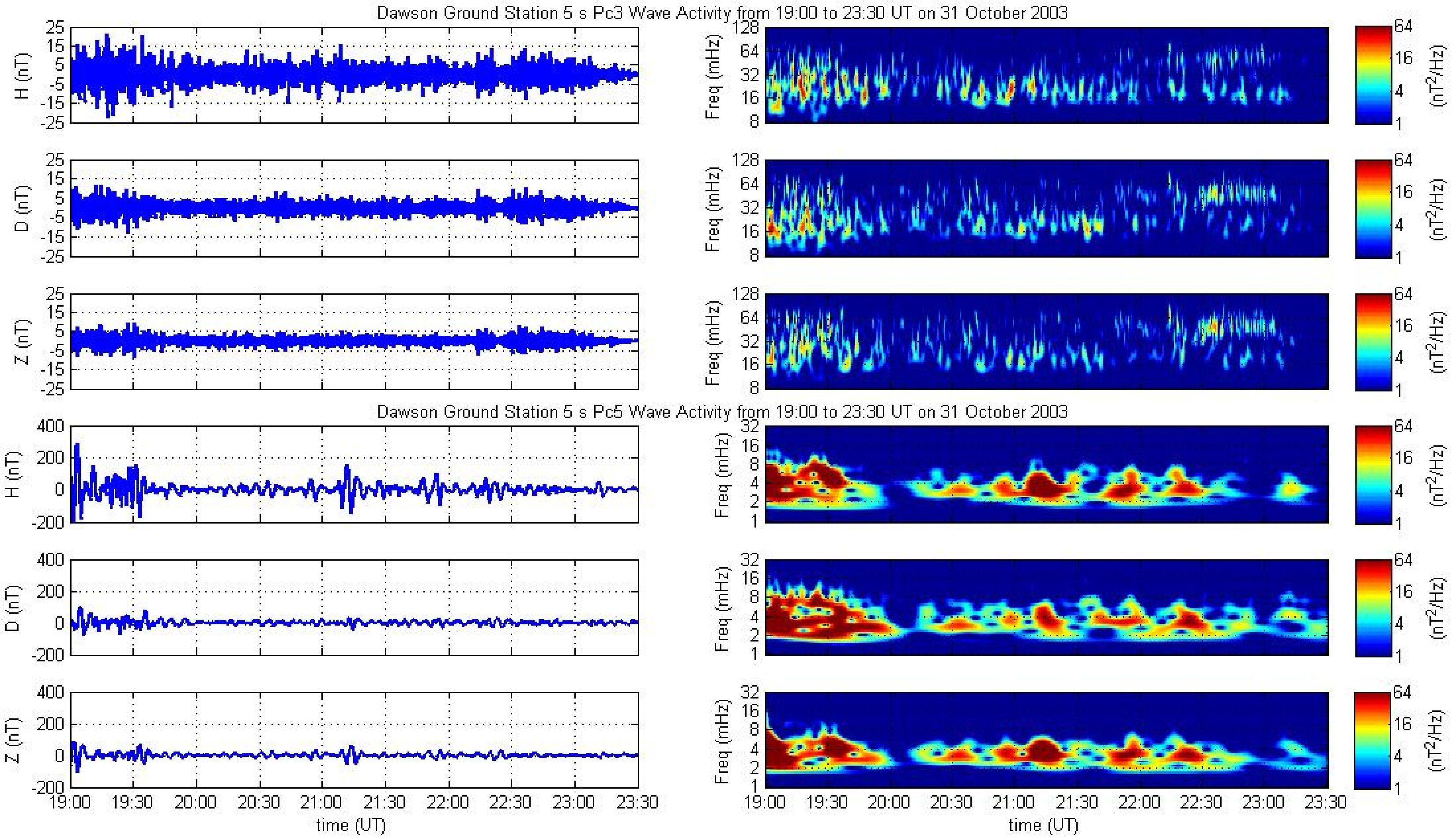
GIMA network



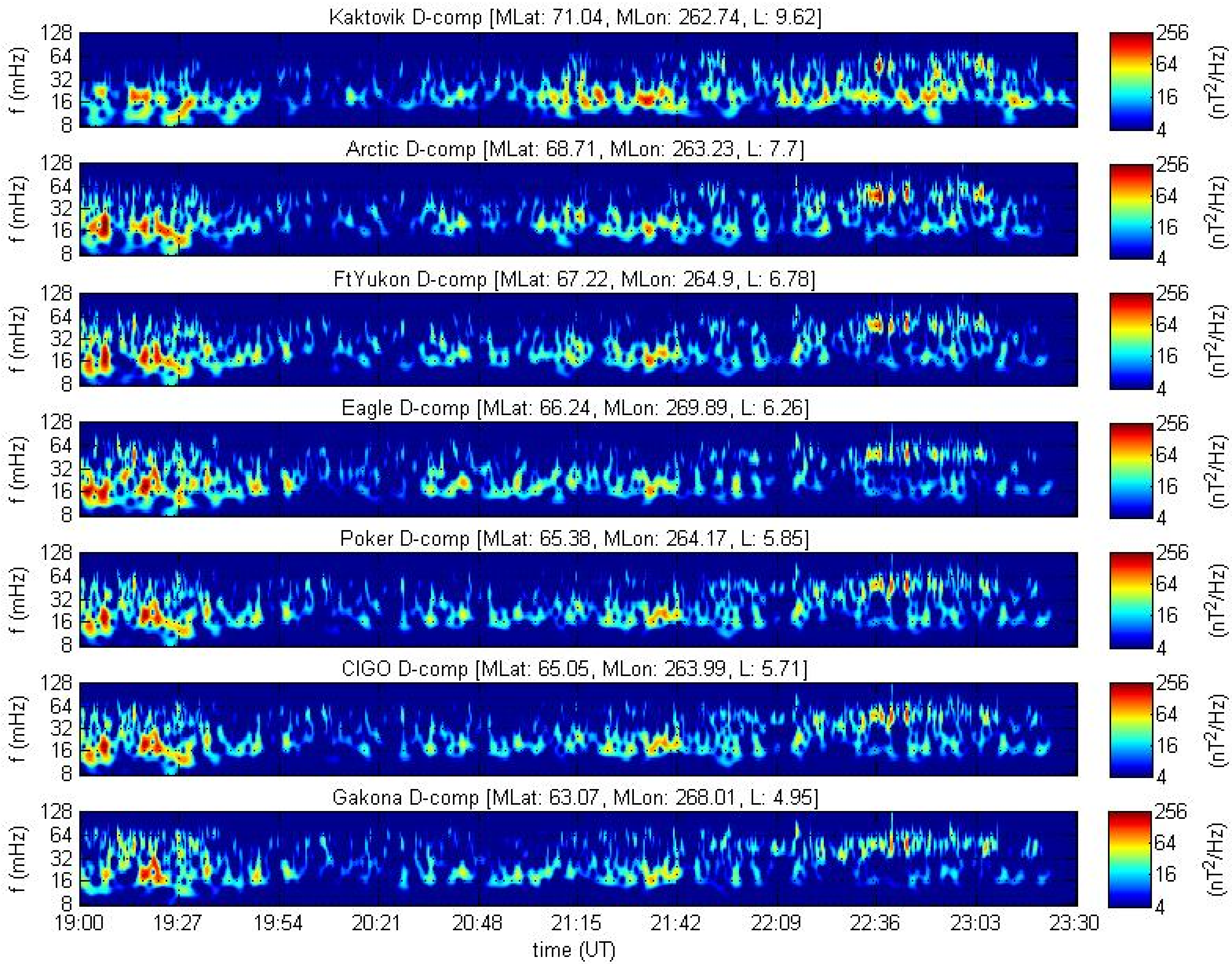
CARISMA network

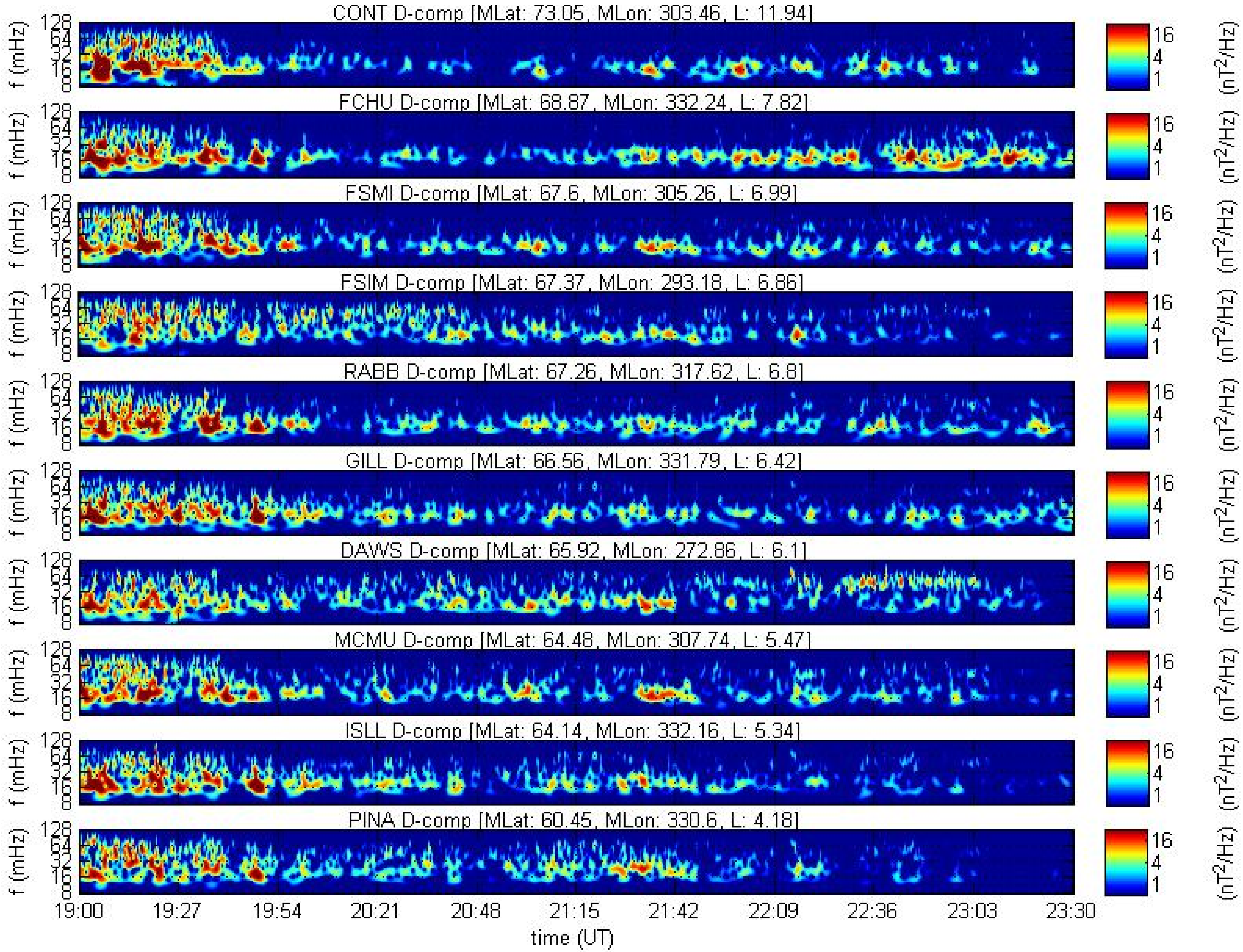

22.08
22.10
22.12
22.14
22.16
21.30
21.10
21.00
20.50
Fort Yukon
Dawson
LATITUDE, degrees
LONGITUDE, degrees
80
70
60
50
40
30
20
10
180
190
200
210
220
230
240
250
260
270


FtYukon 1 s FGM Pc3 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
FtYukon 1 s FGM Pc5 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
H (nT)
D (nT)
Z (nT)
Freq (mHz)
(nT2/Hz)
19:00 19:30 20:00 20:30 21:00 21:30 22:00 22:30 23:00 23:30
time (UT)

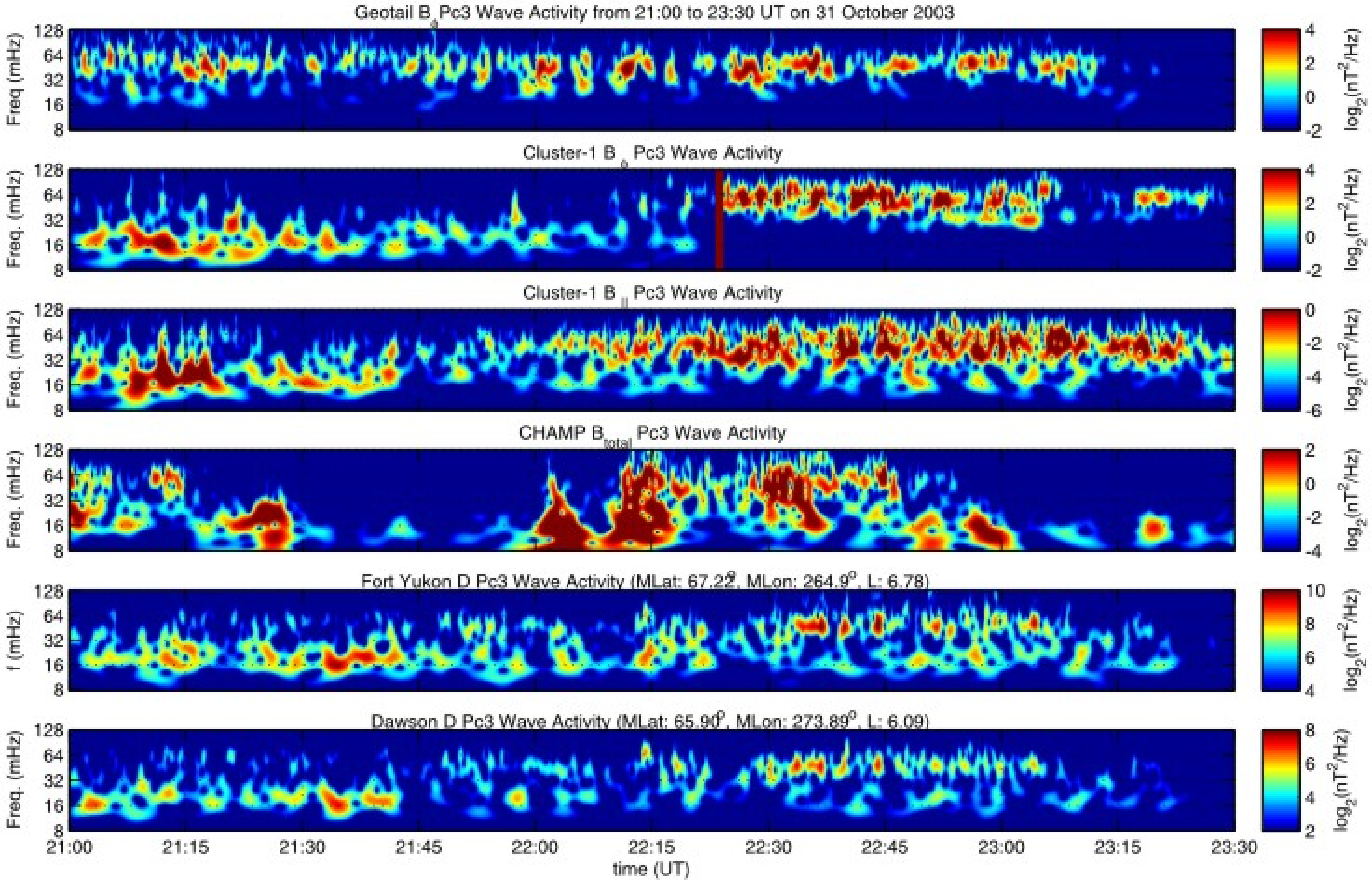


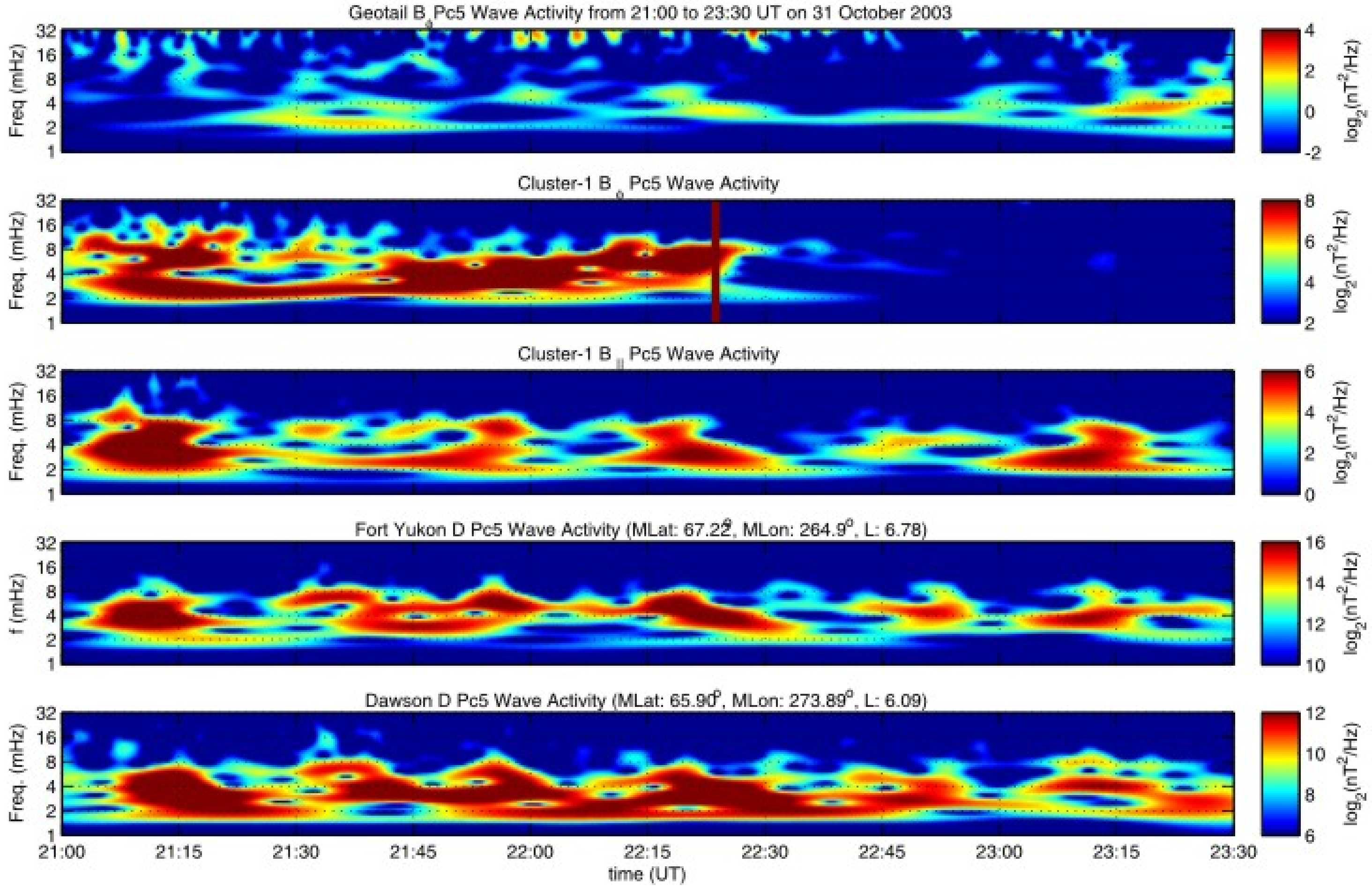
Dawson Ground Station 5 s Pc3 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
H (nT)
D (nT)
Z (nT)
Freq (mHz)
(nT^2/Hz)
Dawson Ground Station 5 s Pc5 Wave Activity from 19:00 to 23:30 UT on 31 October 2003
19:00 19:30 20:00 20:30 21:00 21:30 22:00 22:30 23:00 23:30
time (UT)


Kaktovik D-comp [MLat: 71.04, MLon: 262.74, L: 9.62]
Arctic D-comp [MLat: 68.71, MLon: 263.23, L: 7.7]
FtYukon D-comp [MLat: 67.22, MLon: 264.9, L: 6.78]
Eagle D-comp [MLat: 66.24, MLon: 269.89, L: 6.26]
Poker D-comp [MLat: 65.38, MLon: 264.17, L: 5.85]
CIGO D-comp [MLat: 65.05, MLon: 263.99, L: 5.71]
Gakona D-comp [MLat: 63.07, MLon: 268.01, L: 4.95]
f (mHz)
128
64
32
16
8
256
64
16
4
(nT^2/Hz)
19:00
19:27
19:54
20:21
20:48
21:15
21:42
22:09
22:36
23:03
23:30
time (UT)



CONT D-comp [MLat: 73.05, MLon: 303.46, L: 11.94]
FCHU D-comp [MLat: 68.87, MLon: 332.24, L: 7.82]
FSMI D-comp [MLat: 67.6, MLon: 305.26, L: 6.99]
FSIM D-comp [MLat: 67.37, MLon: 293.18, L: 6.86]
RABB D-comp [MLat: 67.26, MLon: 317.62, L: 6.8]
GILL D-comp [MLat: 66.56, MLon: 331.79, L: 6.42]
DAWS D-comp [MLat: 65.92, MLon: 272.86, L: 6.1]
MCMU D-comp [MLat: 64.48, MLon: 307.74, L: 5.47]
ISLL D-comp [MLat: 64.14, MLon: 332.16, L: 5.34]
PINA D-comp [MLat: 60.45, MLon: 330.6, L: 4.18]
f (mHz)
128
64
32
16
8
16
4
1
(nT²/Hz)
19:00
19:27
19:54
20:21
20:48
21:15
21:42
22:09
22:36
23:03
23:30
time (UT)


Geotail B Pc3 Wave Activity from 21:00 to 23:30 UT on 31 October 2003
Cluster-1 B Pc3 Wave Activity
Cluster-1 B Pc3 Wave Activity
CHAMP B total Pc3 Wave Activity
Fort Yukon D Pc3 Wave Activity (MLat: 67.22°, MLon: 264.9°, L: 6.78)
Dawson D Pc3 Wave Activity (MLat: 65.90°, MLon: 273.89°, L: 6.09)
Freq (mHz)
Freq. (mHz)
f (mHz)
log2(nT2/Hz)
21:00
21:15
21:30
21:45
22:00
22:15
22:30
22:45
23:00
23:15
23:30
time (UT)



Geotail B_ϕ Pc5 Wave Activity from 21:00 to 23:30 UT on 31 October 2003
Freq (mHz)
$\log_2(nT^2/Hz)$
Cluster-1 B_ϕ Pc5 Wave Activity
Freq. (mHz)
Cluster-1 $B_{||}$ Pc5 Wave Activity
Fort Yukon D Pc5 Wave Activity (MLat: 67.22°, MLon: 264.9°, L: 6.78)
f (mHz)
Dawson D Pc5 Wave Activity (MLat: 65.90°, MLon: 273.89°, L: 6.09)
21:00 21:15 21:30 21:45 22:00 22:15 22:30 22:45 23:00 23:15 23:30
time (UT)

Spaceborne observations I

- Waves are in the sheath on the morning side, where Geotail is. Geotail has a weaker band before 22 UT, and a stronger, higher frequency band >=64 mHz starting just after 22 UT in the azimuthal component.

- That band starts immediately in the compressional component at Cluster, which is at small negative z but on the morning side as is Geotail. Cluster toroidal sees an abrupt onset of that wave band later and when the satelite enters the plasmasphere, which means that this band did not couple to the shear Alfven waves until Cluster cleared the plasmasphere boundary layer (PBL), probably because that is where it found the right pressure gradients to generate the right amount of field-aligned currents (FAC), i.e. shear mode wave.

Spaceborne observations II

- CHAMP sees the high band only when it is in the northern dayside auroral zone and equatorial zone. When the high band intensification starts at Geotail, just after 22 UT, that is when CHAMP can see the waves through the whole dayside, not only aurora and equatorial zones, presumably because then the waves are driven directly from the magnetosheath and are stronger.

- We still need to solve the problem of why there is such a stong north-south asymmetry, but generally a nice conclusion comes out. Namely, that the topside ionosphere namifests the waves only where there is strong conductivity, i.e. dayside and regions of strong currents (equatorial, auroral). Only when the waves are stronger and driven can they be seen at sub-auroral and mid-latitudes and then only on the illuminated dayside.

Ground-based observations

- The Alaska stations (GIMA network), closer to the Cluster footpoint and on the morning side, all show the onset of the strong high band sometime after 22 UT and after it is seen at Geotail and at Cluster. The only difference is Gakona that seems to have a strong band even before, but there is an intensification around 2210 UT or so.

- Furthermore, Dawson is perhaps CARISMA's westernmost station and it sees the same waves and intensification as well. Interestingly enough, the Churchill line station, which are at about 14-15 MLT at that time, see no such waves in the afternoon. So this band is clearly a morning side phenomenon and directly driven from waves in the sheath.

EMIC Waves & RBs Loss

- Input:

Pc1 magnetic field data from Cluster (and THEMIS), from CHAMP in LEO, and from arrays of ground-based magnetometers under the satellite passes within the electron radiation belts. [see also **Van Allen Probes** (former RBSP)]

- Output:

Discover the statistical radial extent of EMIC in the magnetosphere using multi-point satellite data, and supporting ground-magnetometer data. This is essential for establishing the potential importance of these waves for radiation belt electron loss, since the L-shell width determines the extent of the outer radiation belt which could be affected.

EMIC Waves & RBs Loss cont.

- Science Discovery:

Establish the potential importance of EMIC waves for radiation belt loss based on a characterisation of their L-shell width, and hence the predicted potential strength of their role in radiation belt loss. The width of emission regions is predicted in coupled ring-current-plasmasphere-radiation belts models (see e.g., the modelling and review by Jordanova (2007) and the modelling by Khazanov et al., (2006) and Khazanov and Gamayunov (2007)), but has not been characterised observationally.