TEMPORAL AND SPATIAL VARIATIONS OF DISCRETE MAGNETOSPHERIC OSCILLATIONS DETECTED BELOW 1mHz

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***Keywords**: Earth's eigenmodes– ionosphere-Earth coupling – magnetic detection – interferences – SQUID magnetometer*

•Low frequency geomagnetic pulsations are detected below 2 mHz, using the underground ultra low-noise 3D superconducting magnetometer system [SQUID]^2 (SQUID with Shielding QUalified for Ionosphere Detection) in the Laboratoire Souterrain Bas Bruit in Rustrel (LSBB - France). The detection of the Earth’s eigen modes in the magnetic quiet background of the ionosphere has been established [1] **BUT**

From experimental data collected from ground-based stations and from sky satellites devoted to the study/survey of the magnetosphere, several power spectra of magnetic pulsations, entering the magnetosphere, have been identified.

•Scientific questions:

- **Nature of these waves: continuous? irregular? polarized? ....**
- **Origin of these waves**
- **Evaluation of the energy transfert**
- **autoconsistant theoretical model**

•Need:

- **Identification of the discrete frequencies spectrum**
- **Characterization**

[1] J. Marfaing, J. J. Bois, R. Blancon, E. Pozzo di Borgo, G. Waysand, S. Gaffet, M. Yedlin, P. Barroy, M. Auguste , D. Boyer, A. Cavaillou, , *Euro Phys. Lett.*, **88**, (2009) 19002; doi 10.1209/0295-5075/88/19002

- **Analysis of the 3D-magnetograms made for 72 consecutive hours in absence of major earthquakes and magnetic storms: same conditions as for detection of Earth's eigenmodes**

- **Use of 3 techniques:**
- **the Fast Fourier Transform (FFT) and Discrete Fourier Transform (DFT) : frequency signature**

- **DFT allows an adjustable resolution for a set of selected frequency peaks using the 2nd order Goertzel's algorithm (Beraldin and Steenaart, 1989)**

- **the Stockwell Transform (ST), extension of the short time Fourier Transform and a variant of the continuous wavelet transform: time-frequency décomposition.**

- **Advantage: modern tool for non-periodic and/or non-stationary signals with evidence of the discontinuous character of the signal.**

Discrete Fourier Transform (DFT): FT + 2nd order Goertzel algorithm
Resolution: df = 3.86 μHz

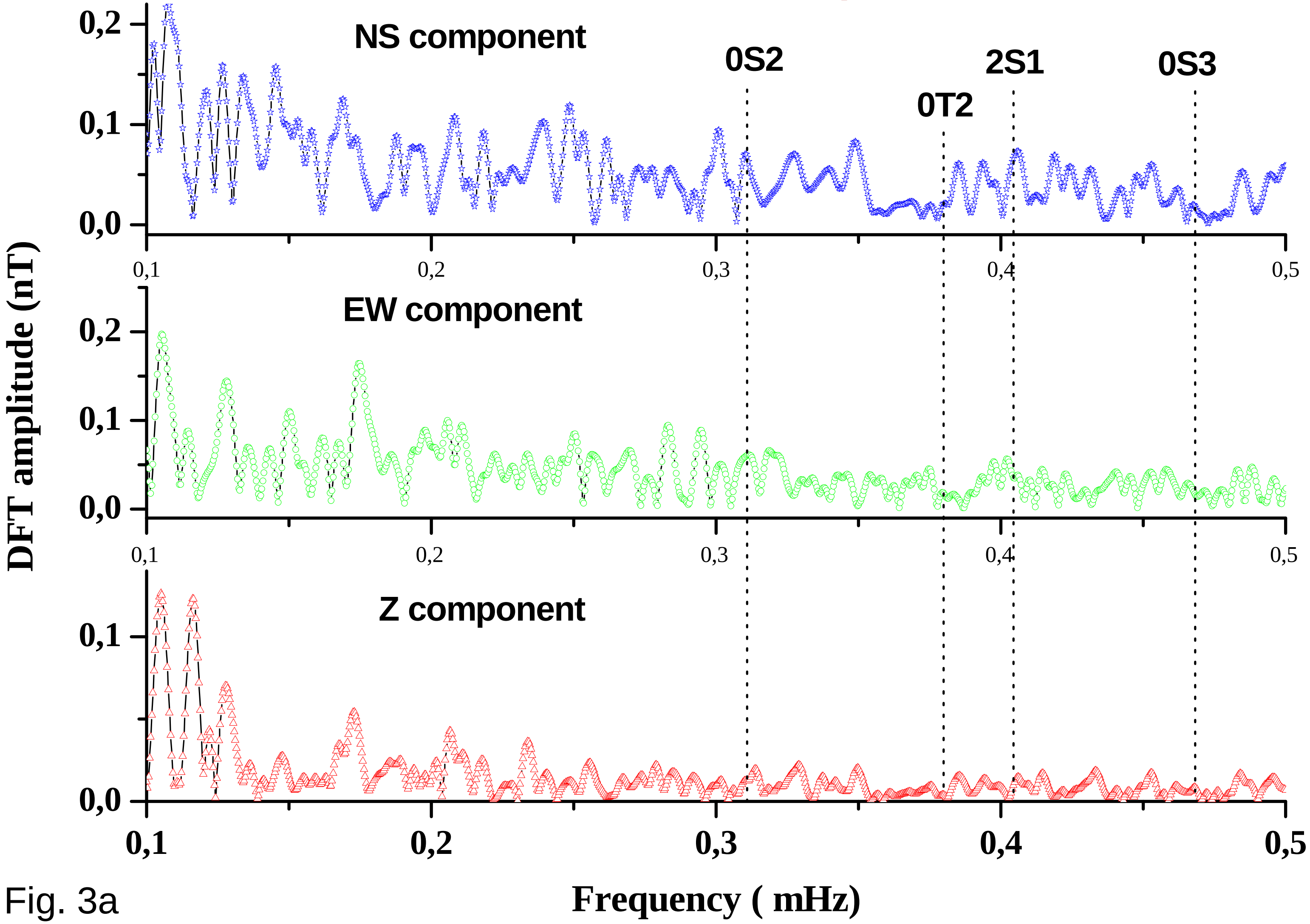


Fig. 3a

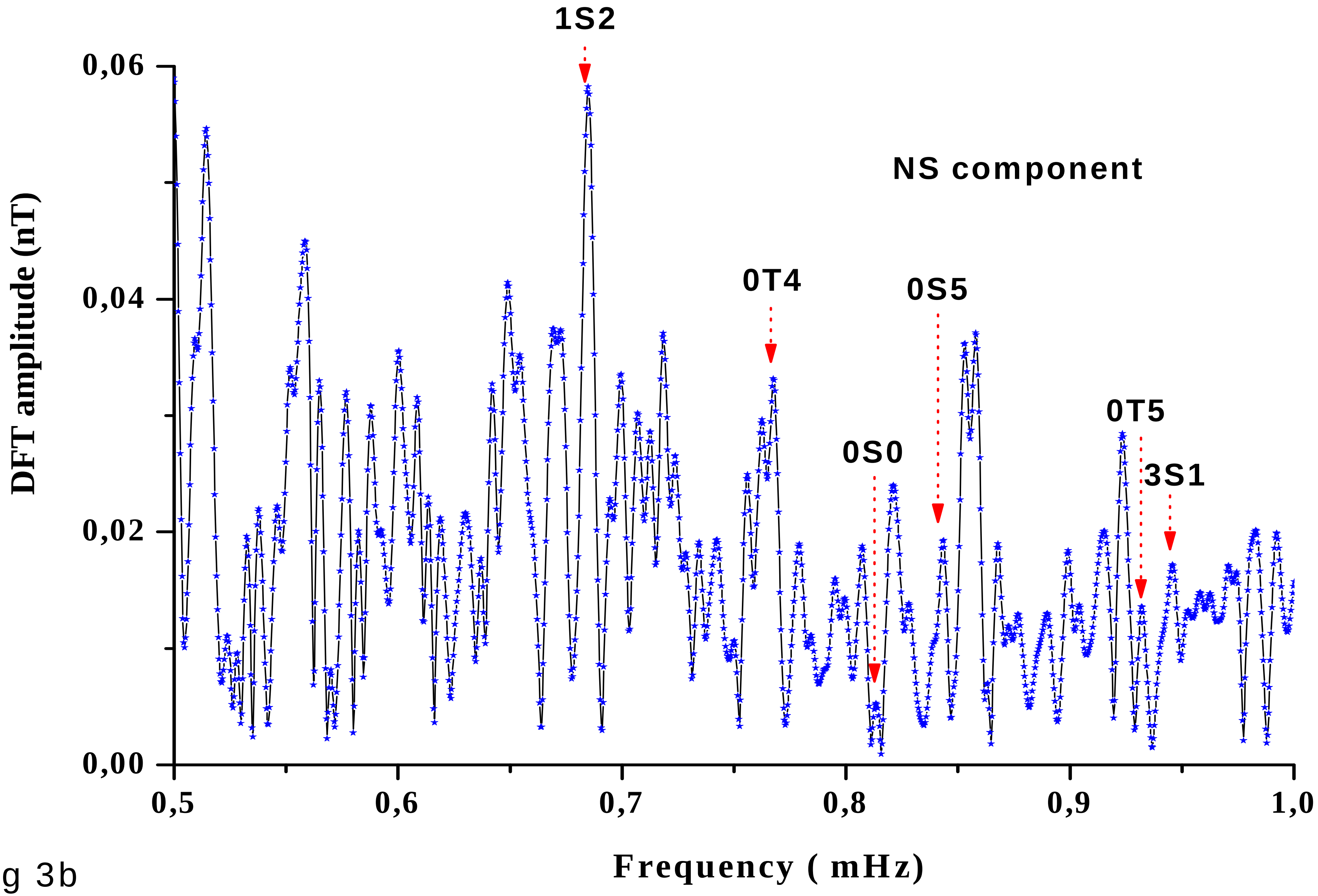
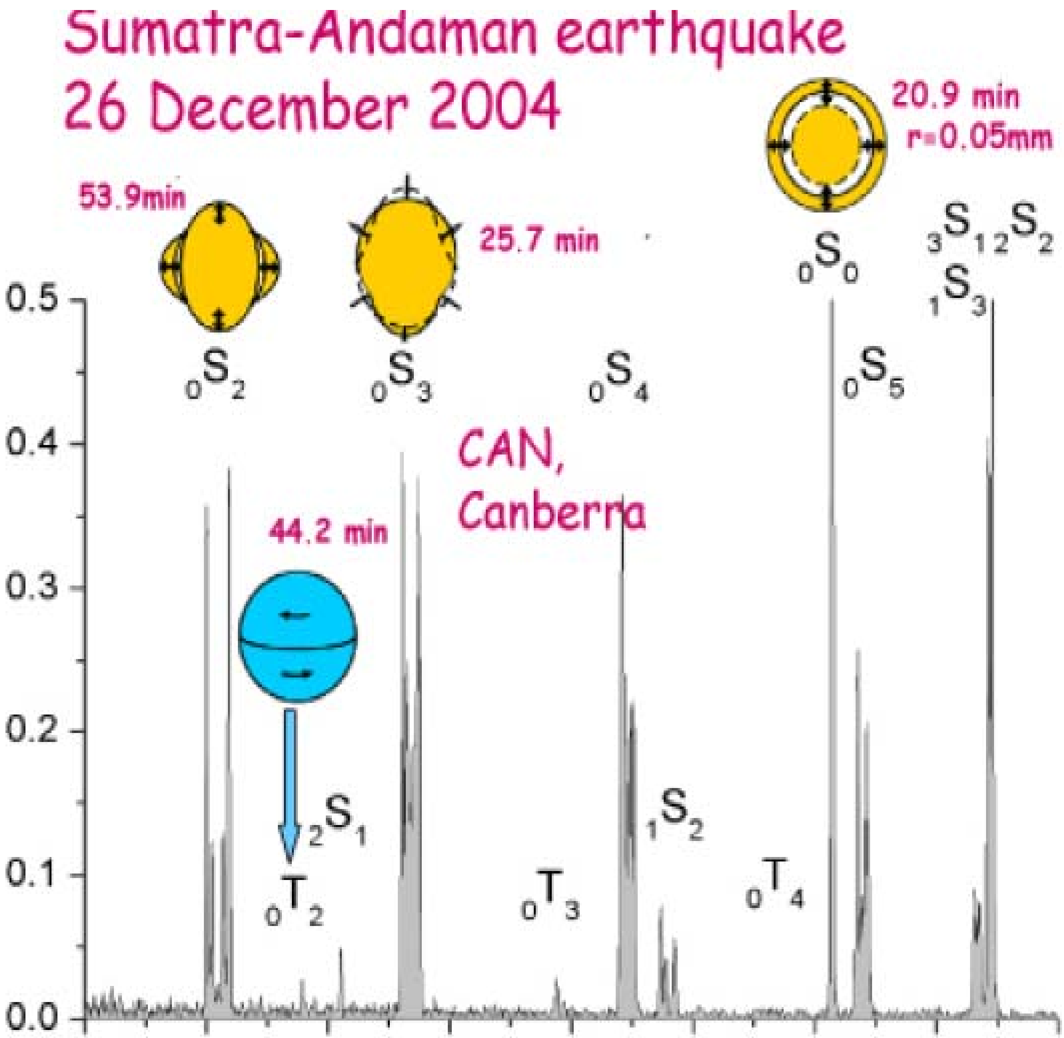

1S2
NS component
0T4
0S5
0S0
0T5
3S1
DFT amplitude (nT)
0,06
0,04
0,02
0,00
0,5
0,6
0,7
0,8
0,9
1,0
Frequency (mHz)

Fig 3b

Comparison with the seismic detection during a major earthquake (M_w =8)



Stockwell Transform (ST): is a variant of the continuous wavelet transform given by

$$W(b,a) = \int_{-\infty}^{\infty} f(x) \frac{1}{\sqrt{|a|}} \Phi\left(\frac{x-b}{a}\right)^{*} dx \qquad (1)$$

The Stockwell transform uses a particular complex mother wavelet – hence the conjugate.

The Stockwell transform defined in Stockwell et al. 1996, is given by

$$S(b,\xi) = \int_{-\infty}^{\infty} f(x) |\xi| \frac{e^{-\frac{(x-b)^2 \xi^2}{2}}}{\sqrt{2\pi}} e^{-2\pi i \xi x} \, dx$$

where *b* corresponds to time, *t* and ξ corresponds to the frequency. If we factor out the phase modulation corresponding to

$$S\left(b,\frac{1}{a}\right)=\frac{1}{\sqrt{|a|}}e^{-2\pi i\frac{1}{a}b}\int_{-\infty}^{\infty} f(x)\frac{1}{\sqrt{|a|}}\frac{e^{-\frac{(x-b)^2}{2a^2}}}{\sqrt{2\pi}}e^{-2\pi i\frac{1}{a}(x-b)}\,dx$$

$$=\frac{1}{\sqrt{|a|}}e^{-2\pi i\frac{1}{a}b}\int_{-\infty}^{\infty} f(x)\frac{1}{\sqrt{|a|}}\left[\frac{e^{-\frac{1}{2}\left(\frac{x-b}{a}\right)^2}}{\sqrt{2\pi}}e^{-2\pi i\left(\frac{x-b}{a}\right)}\right]dx$$

where the term in the square brackets is of the form $\frac{1}{\sqrt{|a|}}\Phi\left(\frac{x-b}{a}\right)^{*}$

when F is chosen to be the complex Morlet wavelet given by: $\Phi(x)=\frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}x^2}e^{2\pi i x}$

Thus, we see that **the Stockwell transform is a continuous wavelet transform given by**

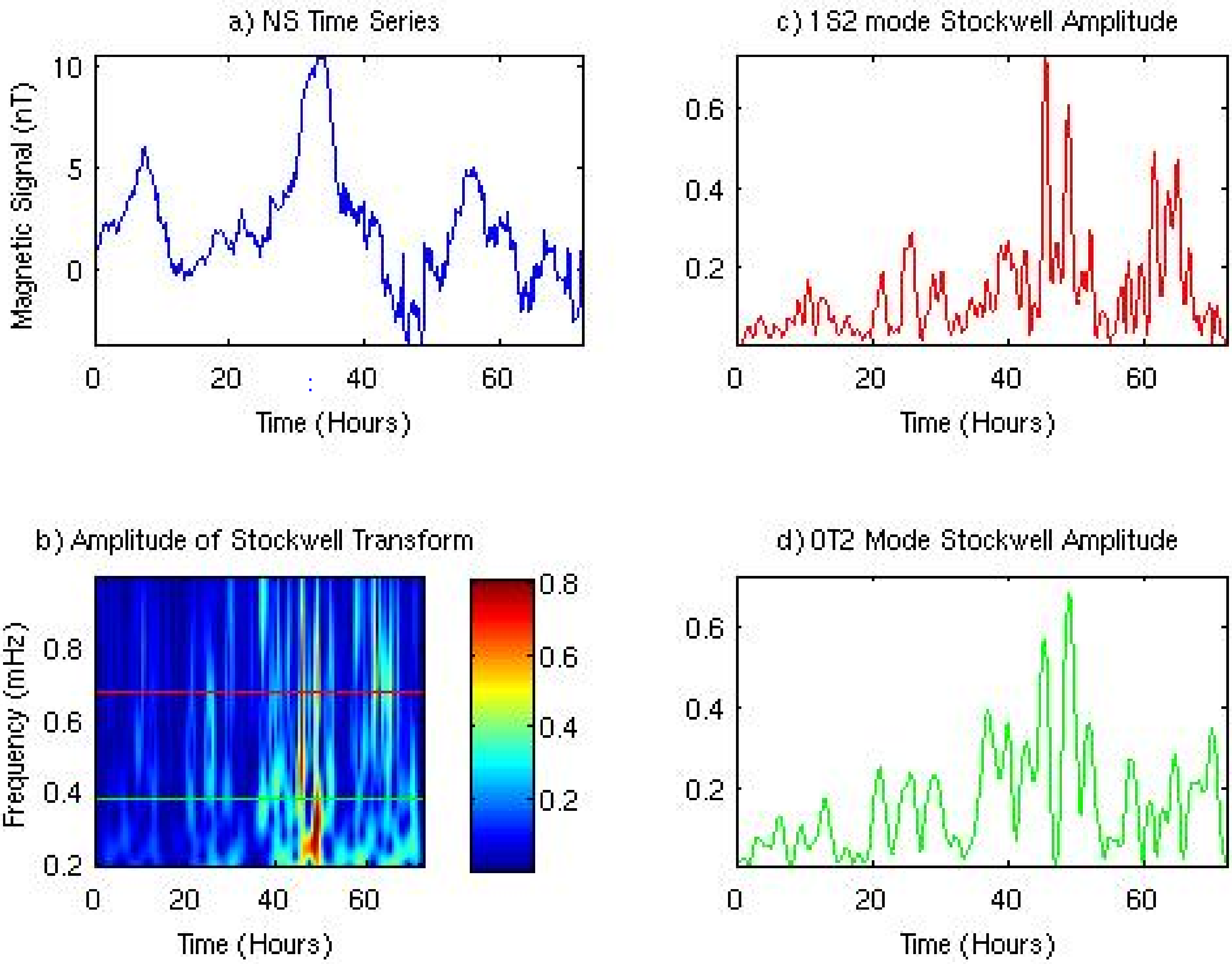
$$S\left(b,\frac{1}{a}\right)=\sqrt{\frac{1}{|a|}}e^{-2\pi i\frac{b}{a}}\,W(b,a)$$

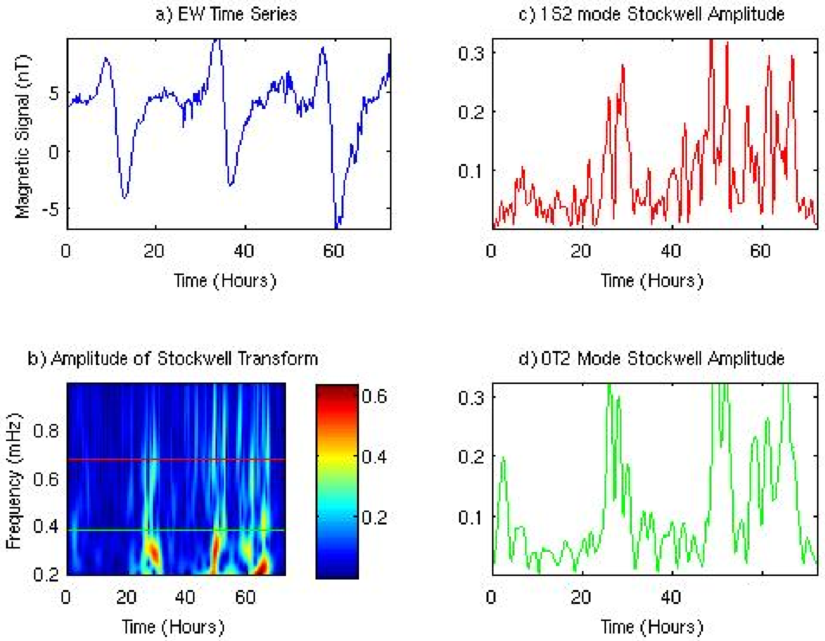
Appropriate low-pass filtering, .

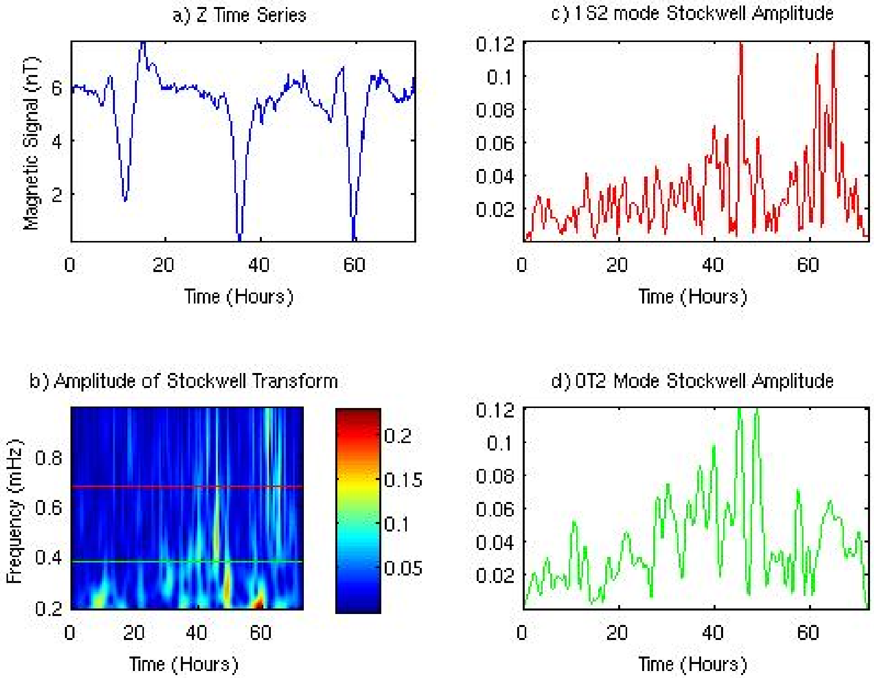
Resampling of the data at 1 minute intervals, which corresponds to a Nyquist rate of 1/120 Hz which is 8.33 mHz.

Frequency analysis using the Stockwell transform : between 0.2 and 1 mHz, well below the Nyquist rate for the resampled data.

For the data length of 72 hours, the time series will be over 4000 points long

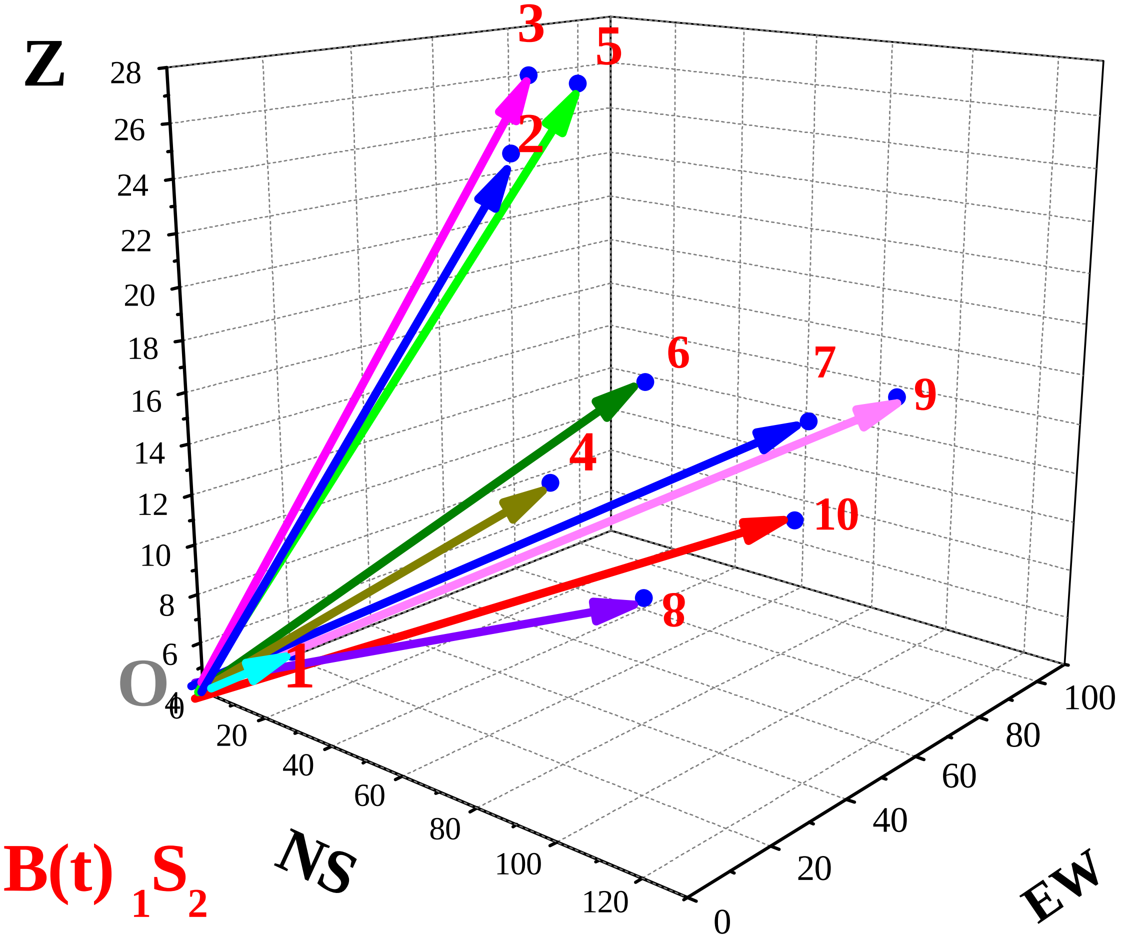

a) NS Time Series
Magnetic Signal (nT)
10
5
0
0
20
40
60
Time (Hours)
c) 1S2 mode Stockwell Amplitude
0.6
0.4
0.2
0
20
40
60
Time (Hours)
b) Amplitude of Stockwell Transform
Frequency (mHz)
0.8
0.6
0.4
0.2
0
20
40
60
Time (Hours)
0.8
0.6
0.4
0.2
d) 0T2 Mode Stockwell Amplitude
0.6
0.4
0.2
0
20
40
60
Time (Hours)


a) EW Time Series
Magnetic Signal (nT)
5
0
-5
0
20
40
60
Time (Hours)
c) 1S2 mode Stockwell Amplitude
0.3
0.2
0.1
0
20
40
60
Time (Hours)
b) Amplitude of Stockwell Transform
Frequency (mHz)
0.8
0.6
0.4
0.2
0
20
40
60
Time (Hours)
0.6
0.4
0.2
d) 0T2 Mode Stockwell Amplitude
0.3
0.2
0.1
0
20
40
Time (Hours)


a) Z Time Series
Magnetic Signal (nT)
6
4
2
0
20
40
60
Time (Hours)
c) 1S2 mode Stockwell Amplitude
0.12
0.1
0.08
0.06
0.04
0.02
0
20
40
60
Time (Hours)
b) Amplitude of Stockwell Transform
Frequency (mHz)
0.8
0.6
0.4
0.2
0
20
40
60
Time (Hours)
0.2
0.15
0.1
0.05
d) 0T2 Mode Stockwell Amplitude
0.12
0.1
0.08
0.06
0.04
0.02
0
20
40
60
Time (Hours)

Z

Dependence in time of the mode 1S2 over 10 hours



B(t) $_1S_2$

UNIDENTIFIED PULSATIONS BELOW 1 mHz

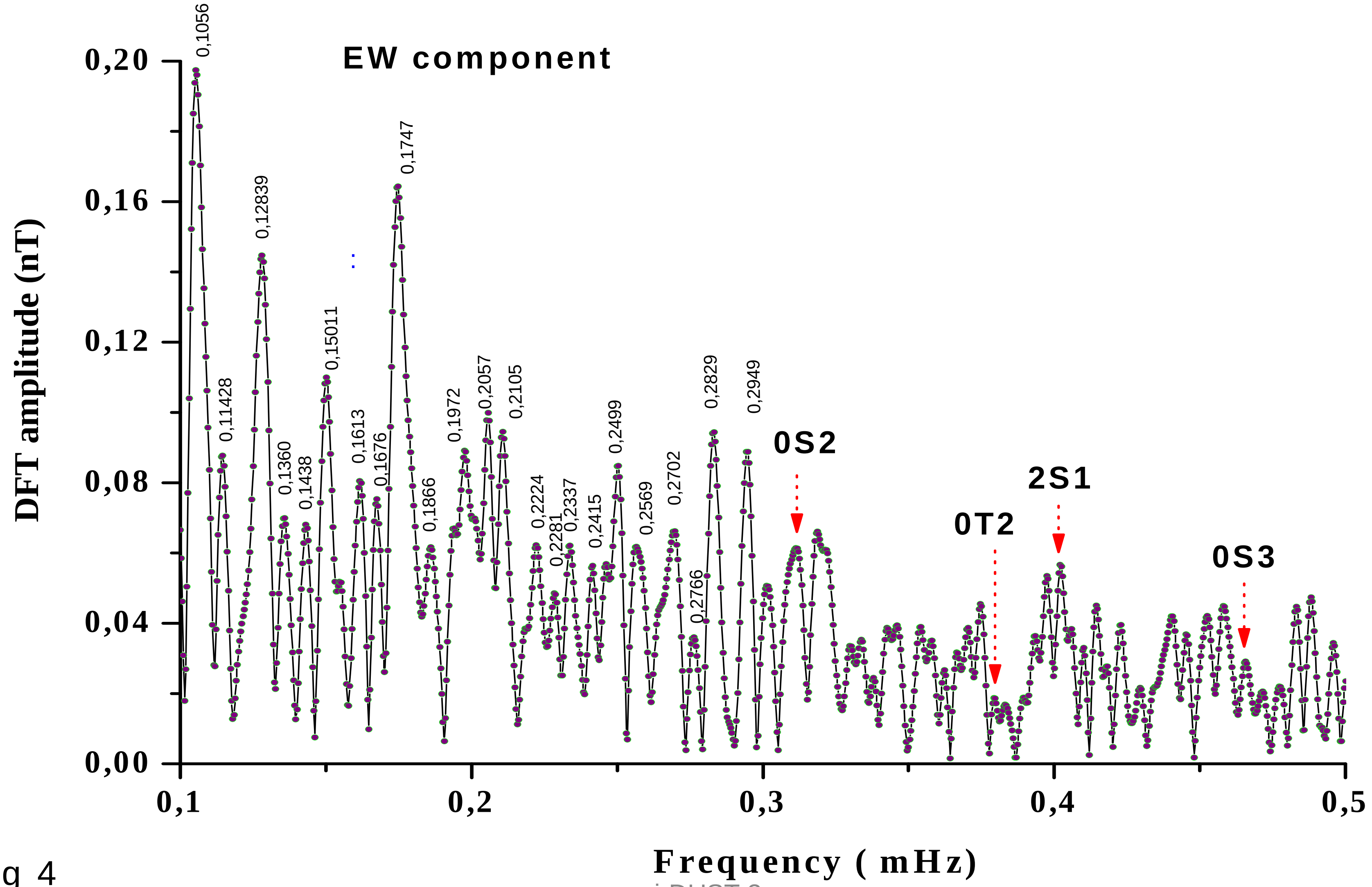


Fig 4

AND ALSO BELOW 0.1 mHz

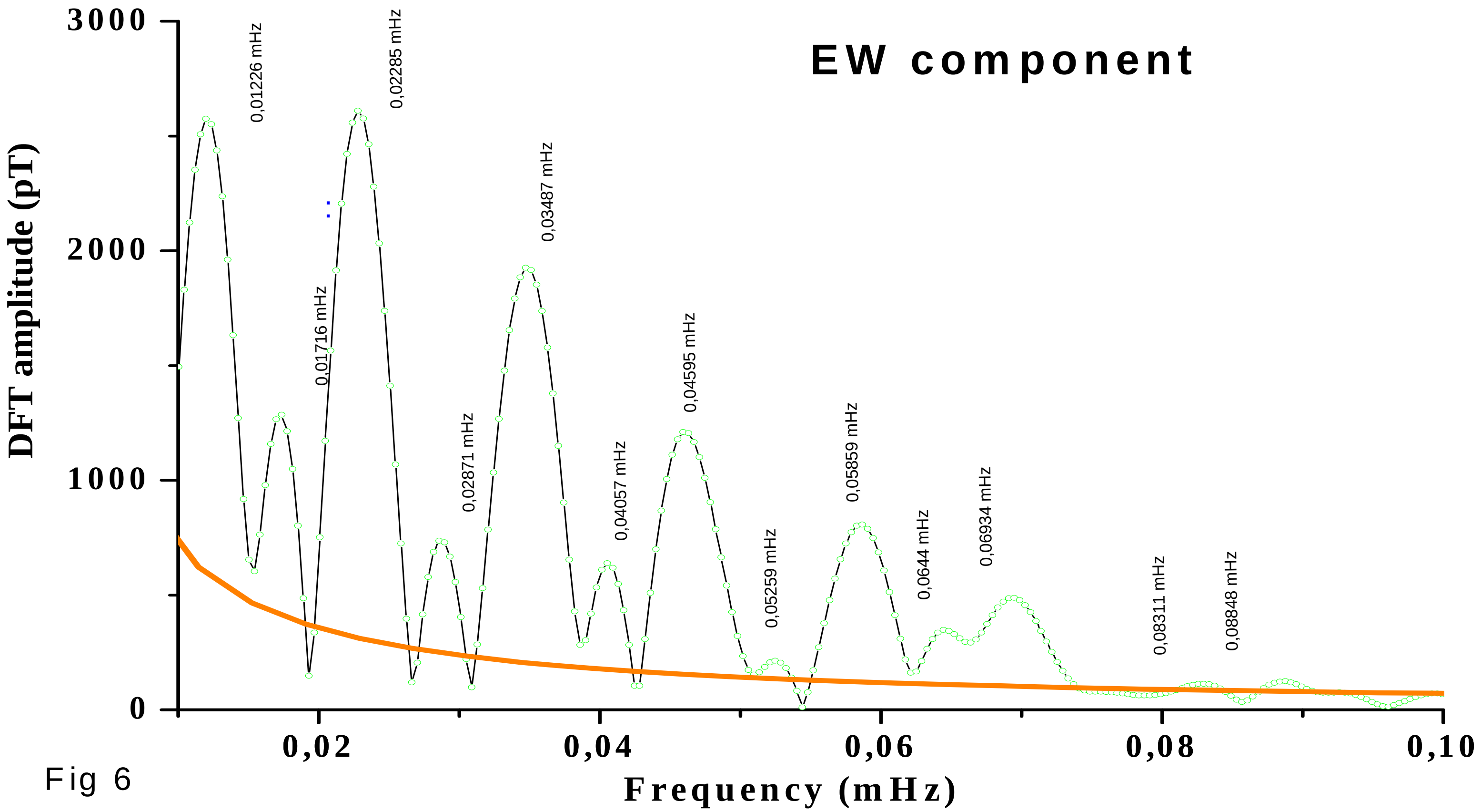
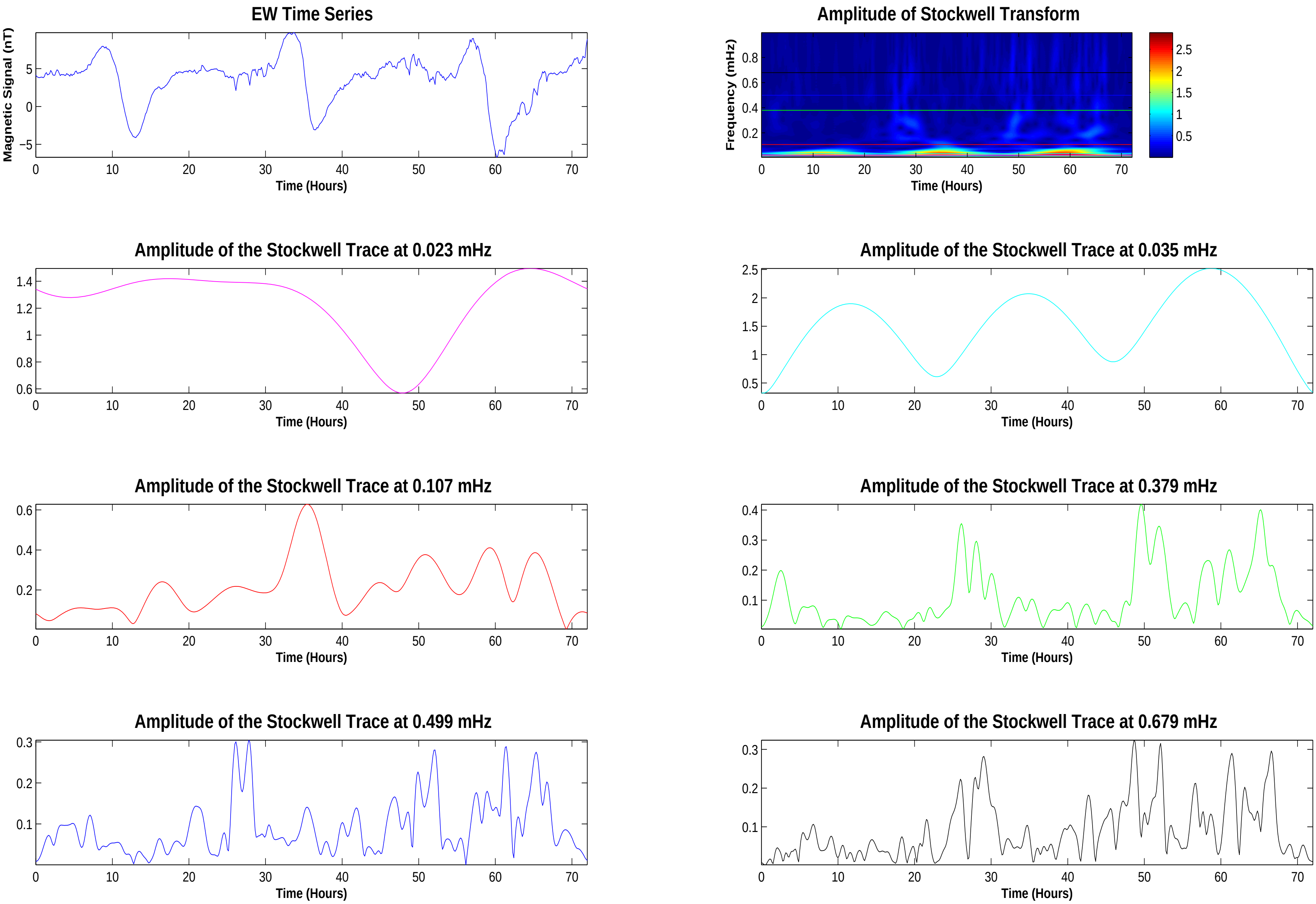


Fig 6


EW Time Series

Amplitude of Stockwell Transform

Amplitude of the Stockwell Trace at 0.023 mHz

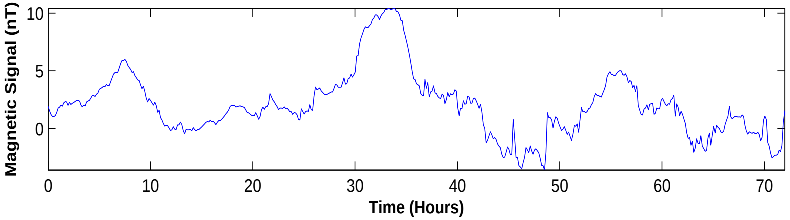
Amplitude of the Stockwell Trace at 0.035 mHz

Amplitude of the Stockwell Trace at 0.107 mHz

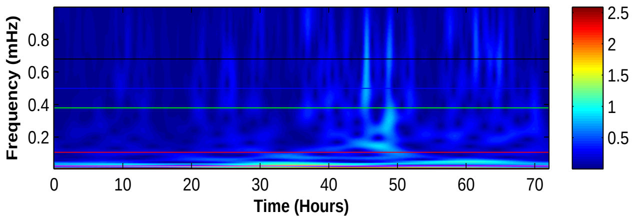
Amplitude of the Stockwell Trace at 0.379 mHz

Amplitude of the Stockwell Trace at 0.499 mHz

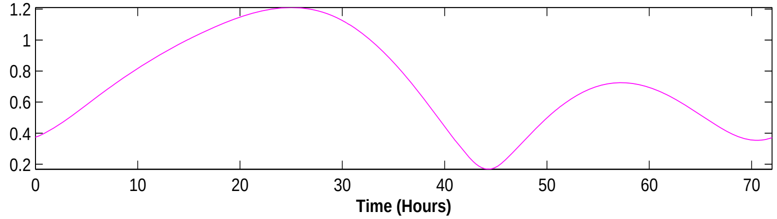
Amplitude of the Stockwell Trace at 0.679 mHz



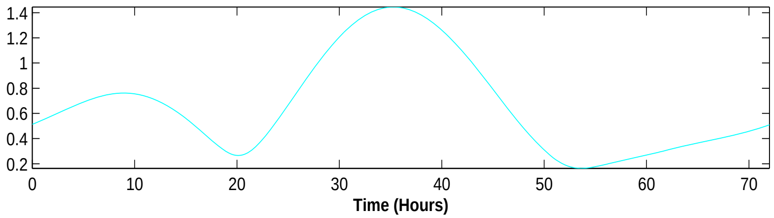
NS Time Series



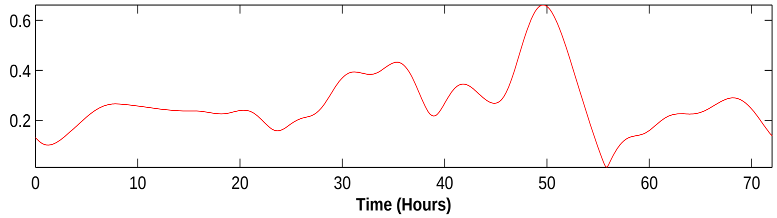
Amplitude of Stockwell Transform



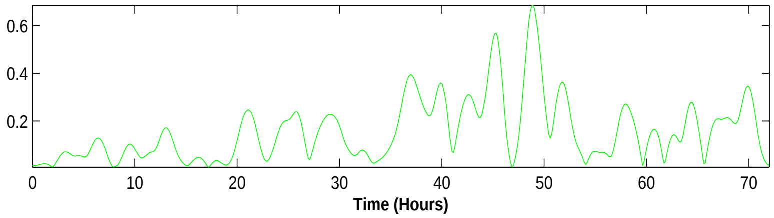
Amplitude of the Stockwell Trace at 0.023 mHz



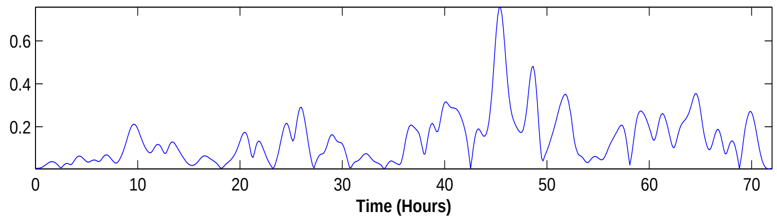
Amplitude of the Stockwell Trace at 0.035 mHz



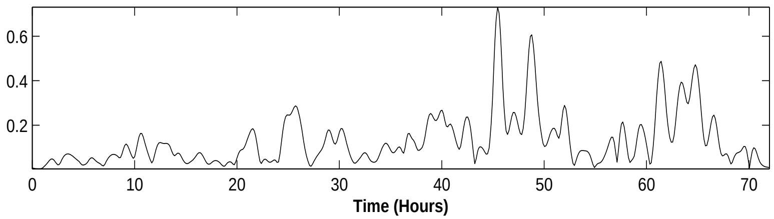
Amplitude of the Stockwell Trace at 0.107 mHz



Amplitude of the Stockwell Trace at 0.379 mHz

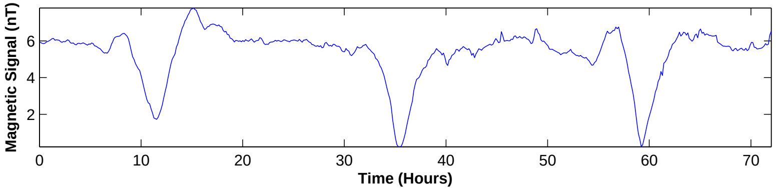


Amplitude of the Stockwell Trace at 0.499 mHz

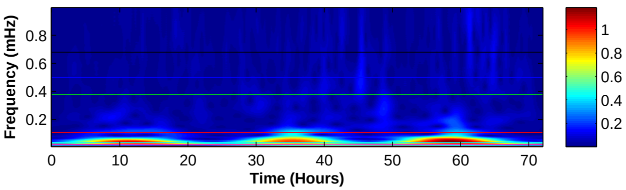


Amplitude of the Stockwell Trace at 0.679 mHz

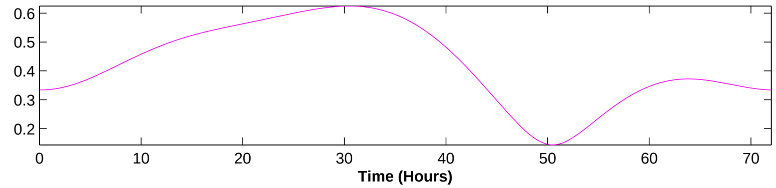
Z Time Series



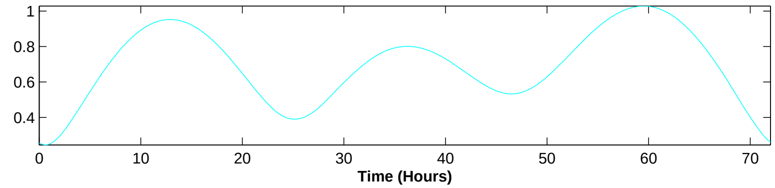
Amplitude of Stockwell Transform



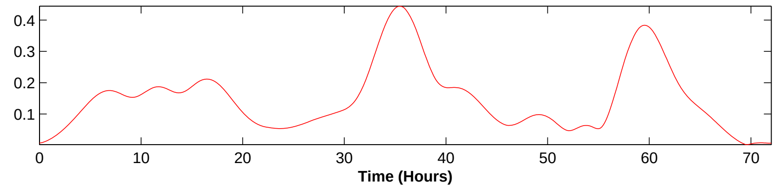
Amplitude of the Stockwell Trace at 0.023 mHz



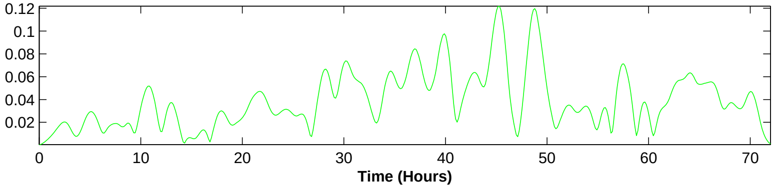
Amplitude of the Stockwell Trace at 0.035 mHz



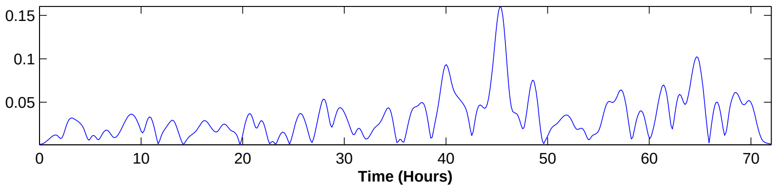
Amplitude of the Stockwell Trace at 0.107 mHz



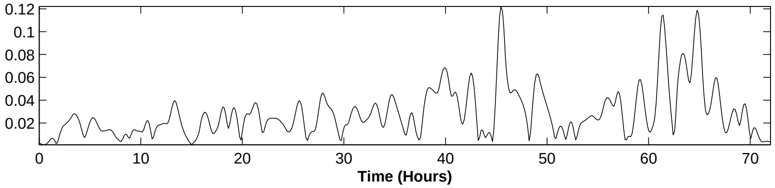
Amplitude of the Stockwell Trace at 0.379 mHz



Amplitude of the Stockwell Trace at 0.499 mHz

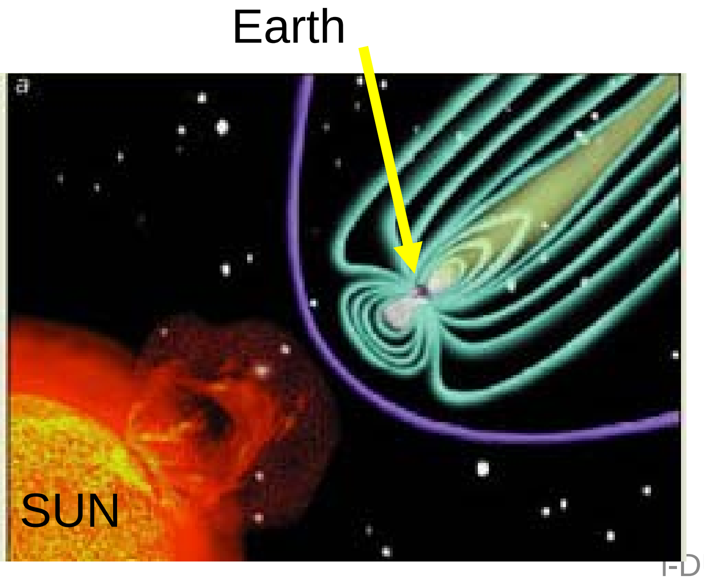


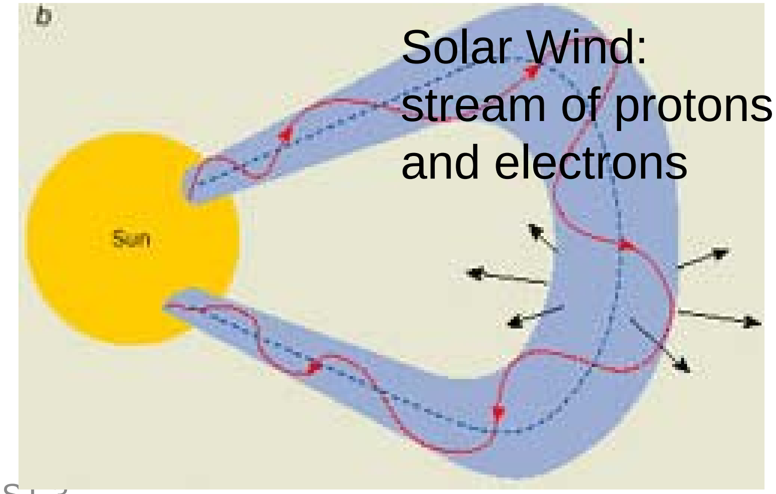
Amplitude of the Stockwell Trace at 0.679 mHz



• PROBABLE ORIGIN

- Several sources of ULF waves are known in the millihertz band, originating
- either from the **incessant seismic activity of the Earth** which induces the free oscillation modes of the Earth generally detected by the seismographs between 2 and 7 mHz (Tanimoto 2005)
- or from the **ionosphere and the magnetosphere**, resulting for example from the Kelvin-Helmholtz, Rayleigh-Taylor …instabilities at the magnetosphere boundary (Kivelson & Russell 1995).





Solar Wind: stream of protons and electrons

Tanimoto, T.,. *Geophys. J. Int.*, **160**, 2005, 10.1111.

Kivelson , M.G., Russell, C.T., 1995, Introduction to Space Physics, Cambridge University Press, Cambridge.

ULF waves originating from ionosphere, especially of type Pc5 are detected during intense magnetic storms, due to changes in the solar activity and correlated with solar wind parameters (Vichare *et al.* 2009; Kleimenova & Kozyreva, 2007).

Spectral peaks in the 0.5 – 4 mHz frequency range (Stephenson & Walker 2002; Kepko & Spence 2003): near 0.5-0.6, 0.8, 1-1.5, 1.2-1.4, 1.6, 1.8, 2.0, 2.6,…3.4 mHz.

However, up to now, no accurate values or complete list of such ULF waves are known from experimental observations or ionospheric models.

Vichare, G., Alex, S. and Lakhina, G.S., *J. Atmospheric and Solar-Terrestrial Physics*, **71**, 2009, 1814-1823, doi:10.1016/j.jastp.2009.06.015

Kleimenova, N.G. and Kozyreva, O. V., “*Physics of Auroral Phenomena*”, Proc. XXX Annual Seminar Apatity, 2007,, pp. 30-33.

Stephenson, J.A.E., and Walker, A.D.M., *Goephys. Res. Lett.* **29,** 2002, 121297, doi:10.1029/2001GL014291,2002

Kepko, L. and Spence,H.E., *J. geophys.Res.*, **108** (A6), 2003, 1257; doi : 10.1029/2002JA009676,2003

Another origin can be speculated:

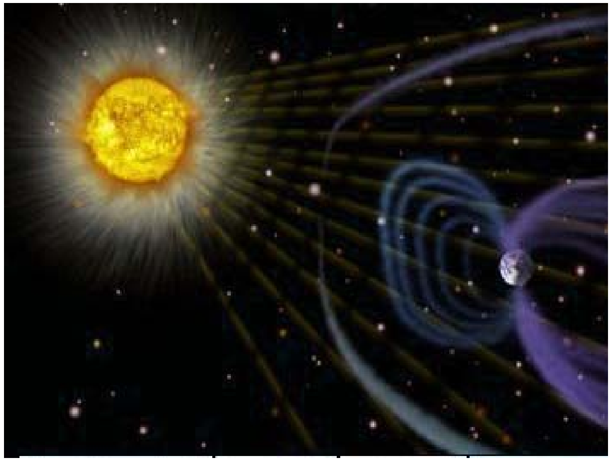
- **beat frequencies** : **simple difference between two close** Earth's eignemodes **frequencies** that can be easily identified from the calculated PREM values.

- **50 frequencies, deviating by less than 1% from the eigenmodes of Earth, have been magnetically detected below 2 mHz (54 theoretical values).**
  Implicitly, interference exists if the waves present similar amplitude and frequencies.

In the lowest frequency range, from 0.01 to 0.3 mHz, it has been verified that:

i) **all the unidentified peaks in the range 0.01 to 0.3 mHz may correspond to interferences between [SQUID]²-identified modes, whether S or T modes**

there is an excellent agreement between the observed and "calculated" interferences.
their amplitudes can be high as several modes can present the same difference in frequency, and hence produce constructive signals.



'Earth's magnetosphere is a very large, complex and variable system. This makes the understanding of ULF waves, together with the mechanisms for the energy transfer from space to ground, a very difficult matter,' says Philippe Escoubet, ESA's Cluster and Double Star Project Scientist.

?

Using the data from GEOS-2 satellite, YOMOTO et al. 1984 have proposed that the Pc3-4 wave energy is convected through the magnetosheath to the magnetopause, transmitted deep into the magnetosphere without significant changes in spectra, and then couple with various hydromagnetic wave modes in the magnetosphere (Ansari 2006).

Other track: Study of integrated flux variations of four lines (N _ O _ Ne) - search of periodicities in the fluxes of the lines (power spectra from FFT and wavelets methods). Frequencies detected at 0.09 mHz, 0.25 mHz, 0.38 mHz; 0.83 mHz, 1.44 mHz, (N, and O ions) ; 0.17 mHz, 0.92 mHz (Ne ions) [Popescu et al., 2004].