10th Hellenic Astronomical Conference, Ioannina, Greece, 5-8 September 2011

"A wavelet spectral analysis tool for multipoint space and ground-based observations of ULF wave activity"

I. A. Daglis[(1)], G. Balasis[(1)], M. Georgiou[(1,2)], C. Papadimitriou[(1,2)], E. Zesta[(3)], and A. Anastasiadis[(1)]

(daglis@noa.gr)

(1) Institute for Space Applications and Remote Sensing, National Observatory of Athens, Greece
(2) Section of Astrophysics, Astronomy and Mechanics, Department of Physics, University of Athens, Greece
(3) Space Vehicles Directorate AFRL/RVBXP, USA

Abstract

Magnetospheric ULF waves influence radiation belt dynamics and are therefore of particular relevance for space weather nowcasting and forecasting efforts. We have used novel algorithms based on wavelet spectral methods to analyze multipoint observations of ULF wave activity by the Cluster and THEMIS missions and by ground-based magnetometers. Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By decomposing a time series into time-frequency space, we are able to determine both the dominant modes of variability and how these modes vary in time. The advantage of analyzing a signal with wavelets as the analyzing kernel is that it enables us to study features of the signal locally with a detail matched to their scale. Owing to its unique time-frequency localization, wavelet analysis is especially useful for signals that are non-stationary, have short-lived transient components, have features at different scales, or have singularities. The results are rather promising for the development of automatic identification tools, which will allow the detection and classification of various categories of ULF waves from multipoint magnetospheric observations according to well-defined criteria.

Introduction

The 4 Cluster spacecraft [Escoubet et al., 1997] and the 5 THEMIS spacecraft [Angelopoulos, 2008] represent a very suitable tool to analyze magnetospheric ULF pulsations as shown in recent studies [Eriksson et al., 2005; Schaefer et al., 2007, Sarris et al., 2009]. Compared to previous missions with one or two spacecraft the advantage of the Cluster and THEMIS missions consists in the availability of 4 or 5 measurement points either close to each other within the same region of interest or located in different regions. The instrumentation of THEMIS five-probe constellation and the alignment at distances $<1R_E$ among some of the THEMIS probes, particularly in the first period of the mission, provides unique opportunities to study ULF pulsations in the magnetosphere [Sarris et al., 2009]. A low-Earth orbit (LEO) mission, such as CHAMP satellite, presents an interesting and useful opportunity to study ULF waves closer to Earth.

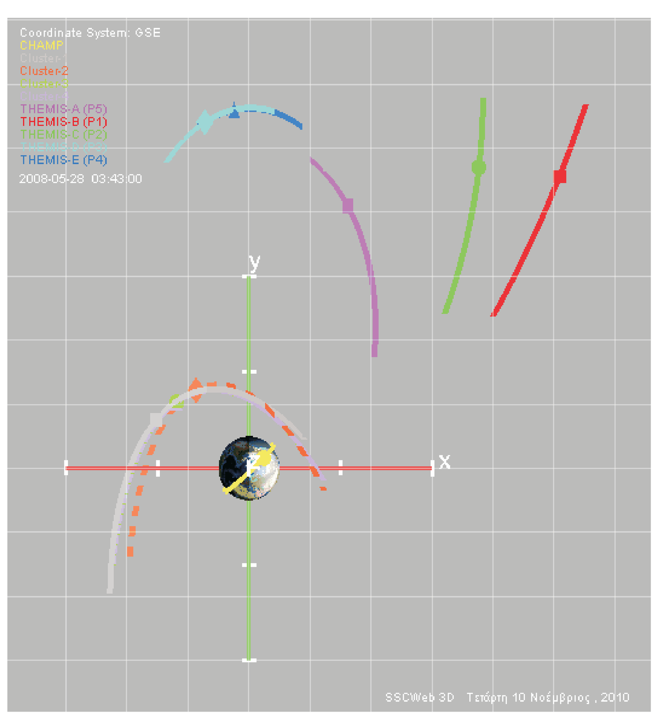
To analyze the highly accurate Cluster and THEMIS magnetic field data as well as CHAMP geomagnetic measurements, we have used specific codes based on wavelet transforms. The wavelet transform is superior to the Fourier spectral analysis, providing excellent decompositions of transient, non-stationary signals. It has the ability of providing a representation of the signal in both the time and frequency domains. In contrast to the Fourier transform, which provides a description of the overall regularity of signals, the wavelet transform identifies the temporal evolution of various frequencies. This property suits the signals under investigation, because they are not stationary by their nature, and have a time varying frequency content.

Wavelet transforms

Wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By decomposing a time series into time-frequency space, one is able to determine both the dominant modes of variability and how those modes vary in time. The advantage of analyzing a signal with wavelets as the analyzing kernel is that it enables one to study features of the signal locally with a detail matched to their scale. Owing to its unique time-frequency localization, wavelet analysis is especially useful for signals that are non-stationary, have short-lived transient components, have features at different scales, or have singularities. The decomposition pattern of the time-frequency plane is predetermined by the choice of the basis function.

We have used the methodology that has been developed over the last years for analyzing magnetic field time series by Balasis et al. [2005, 2006], Mandea and Balasis [2006] and Balasis and Mandea [2007] for various purposes. More precisely, we have applied the continuous wavelet transform with the Morlet wavelet as the basis function [Torrence and Compo, 1998]. Our results have been checked for consistency using the Paul and DOG (derivative of a Gaussian) mother functions. We should also stress that there are several parameters of the wavelet transform (e.g., frequency range, power spectral density amplification factor, etc.), which need to be correctly adjusted in order to capture different kind of interesting characteristics of the signal. This tuning of the wavelet transform is quite time consuming, but is an important step of our analysis.

Satellites' position (XY plane) on 28/05/2008 at 3:43 UT.



Satellites' position (ZY plane) on 28/05/2008 at 3:43 UT.

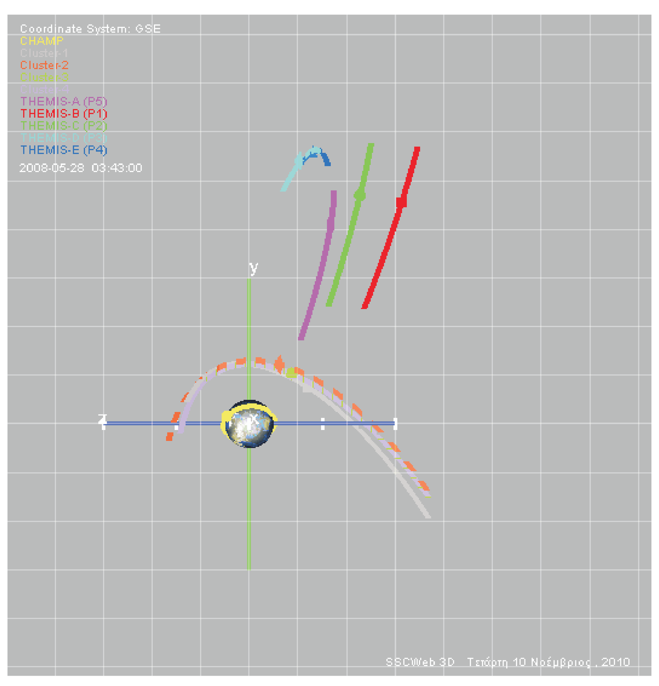


Figure 1: THEMIS-D 4 Hz FGM data

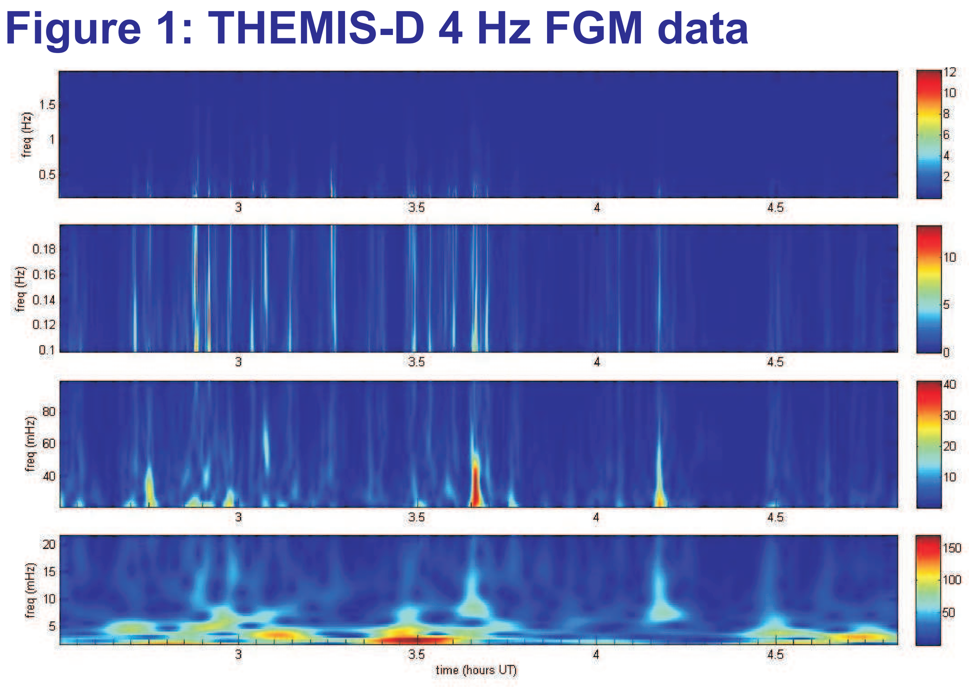


Figure 2: THEMIS-E 4 Hz FGM data

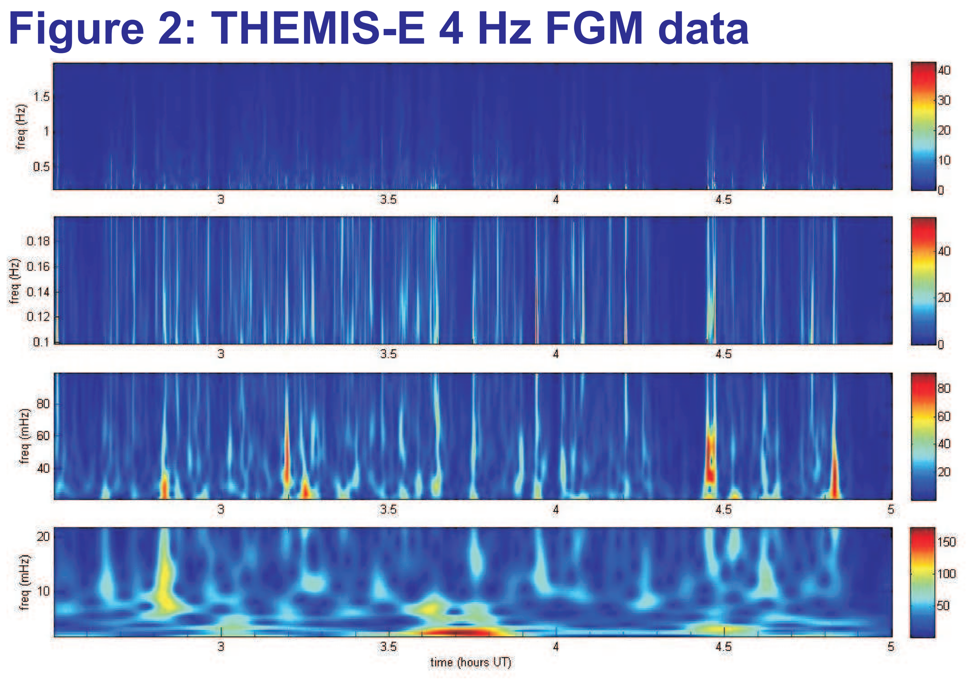


Figure 3: THEMIS-A 4 Hz FGM data

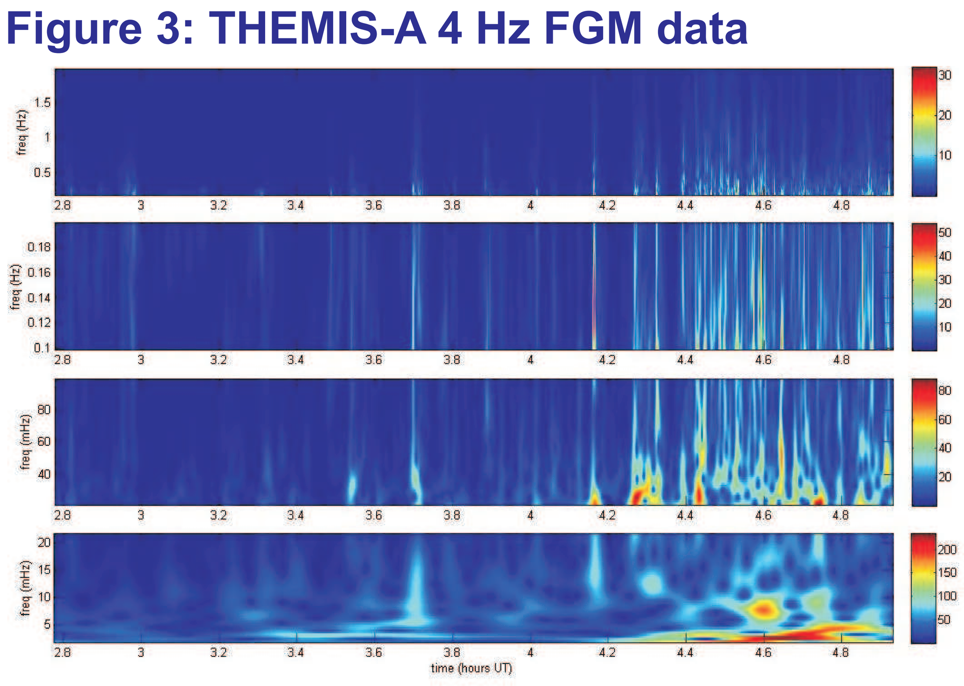


Figure 4: Cluster-1 40 Hz STAFF data

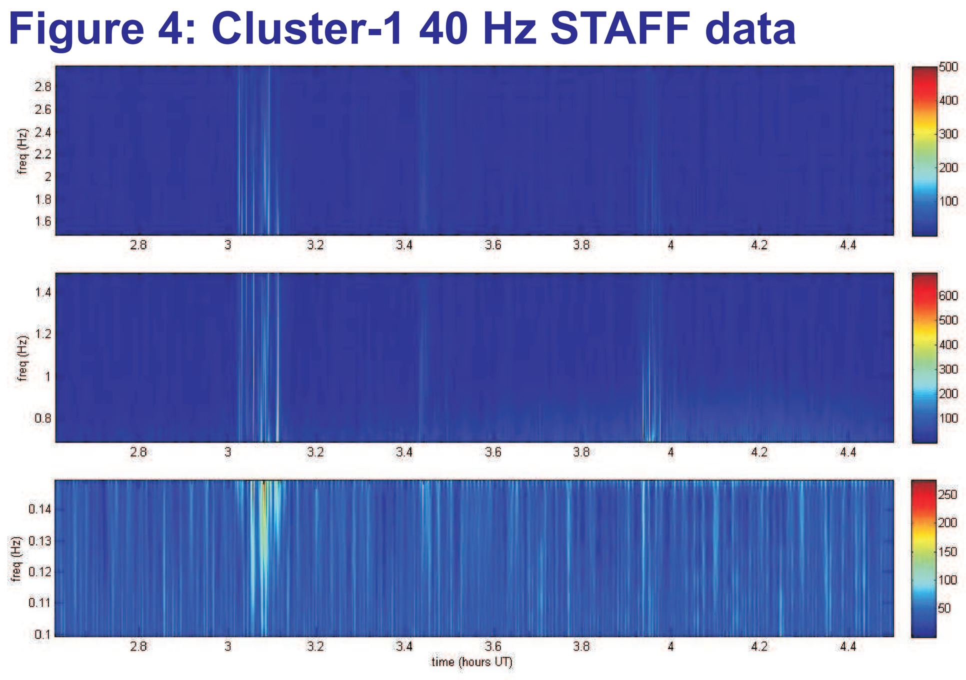
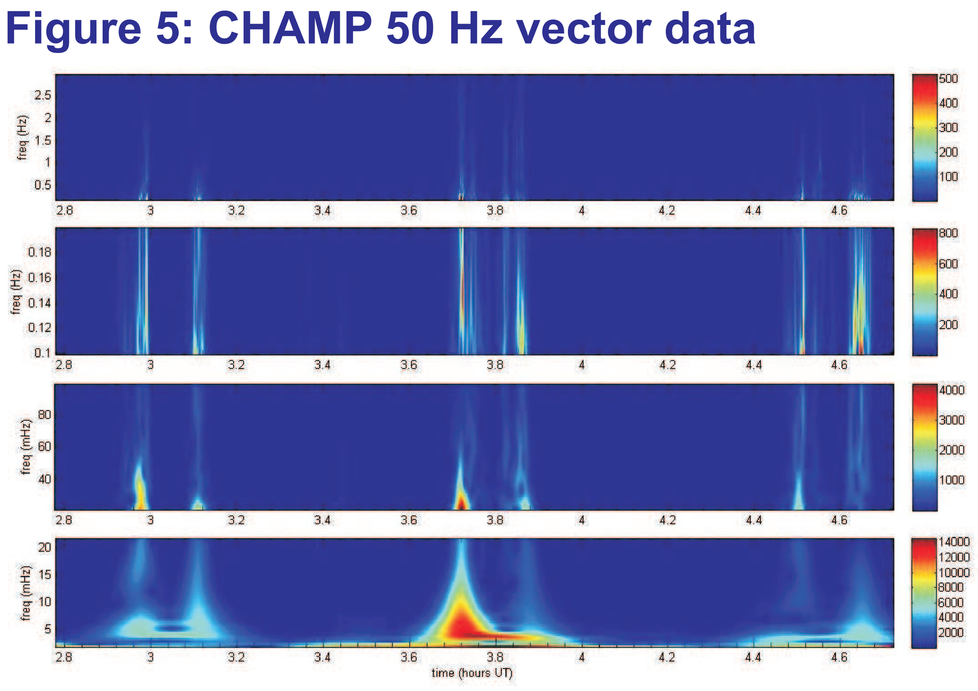
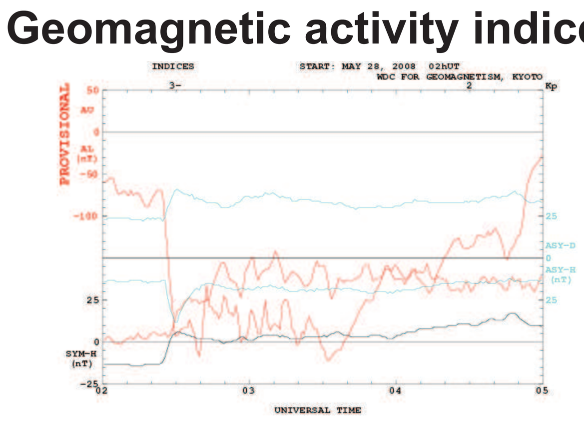


Figure 5: CHAMP 50 Hz vector data



Geomagnetic activity indices



Description

The analysis was performed on the GSE-Y component of the THEMIS fluxgate magnetometer (FGM) data. For Cluster and CHAMP, there is no publicly available GSE decomposition of the signal; therefore we have used the STAFF instrument Y component and FGM Y component, respectively, of the satellites' own coordinate system. Because of that, we also had to limit in the case of Cluster the spectral analysis to frequencies higher and lower than the satellite's own rotation frequency (15 rpm = 0.25 Hz).
The four wavelet power spectrum plots in Figures 1,2,3 and 5 (THEMIS and CHAMP satellites) correspond to the frequency range of Pc pulsations in the following manner: 1st panel: Pc1, 2nd panel: Pc2, 3rd panel: Pc3 and 4th panel: Pc4 and Pc5.
In Figure 4 (Cluster-1 satellite), the three wavelet power spectrum plots correspond to pulsations in the frequency range of Pc1 and Pc2 waves: 1st panel: Pc1 high, 2nd panel: Pc1 low and 3rd panel: Pc2.

Future work

In the future, our main task will be the establishment of an automatic wave detection algorithm based on our previously developed wavelet tools that can be applied generally to a variety of wave types and frequency regimes, for spacecraft and ground-based measurements. Additionally, after the particular time series has been converted into a wavelet power scalogram format, our technique will proceed in a standard way through the analysis. This can be achieved regardless of the frequency range or type of wave under consideration, making this technique fairly general and independent of the type of wave and platform upon which it is measured. To achieve this frequency band identification through spectral peak detection, temporal grouping of the peaks into discrete wave events and continuity in wave parametersl will be involved similar to Bortnik et al. (2007).

Conclusions

We have developed time series analysis tools based on wavelet transforms, to be employed for studying magnetospheric ULF wave activity through multipoint magnetic field observations, in the framework of understanding and monitoring ULF wave influence on radiation belt dynamics.

We have shown that our method is capable of detecting and categorizing ULF waves' signatures in data from magnetometers onboard the Cluster and THEMIS missions. Additionally, we have demonstrated the applicability of the technique in magnetic field measurements from CHAMP, a low-Earth orbit (LEO) mission.

As a next step, we will proceed to examine ground-based magnetometer measurements at the same time intervals, as well as electric field data from the aforementioned space missions.

References

Angelopoulos, V. (2008), Space Sci. Rev., 141: 5–3, doi: 10.1007/s11214-008-9336-1.
Balasis G., Maus S., Lühr H. and Rother M. (2005), Wavelet analysis of CHAMP flux gate magnetometer data, in Earth Observation with CHAMP, ed. by C. Reigber, H. Lühr, P. Schwintzer and J. Wickert, 347–352, Springer, New York.
Balasis G., I. A. Daglis, P. Kapiris, M. Mandea, D. Vassiliadis, and K. Eftaxias (2006), Annales Geophysicae, 24, 3557–3567.
Balasis, G., and M. Mandea (2007), Tectonophysics, 431, doi:10.1016/j.tecto.2006.05.038.
Bortnik, J., J. W. Cutler, C. Dunson, and T. E. Bleier (2007), J. Geophys. Res., 112, A04204, doi:10.1029/2006JA011900.
Eriksson, P. T. I., Blomberg, L. G., Walker, A. D. M., and Glassmeier, K.-H.: Ann. Geophys., 23, 2679–2685, 2005.
Escoubet, C. P., Schmidt, R., and Goldstein, M. L.: Space Sci. Rev., 79, 11–32, 1997.
Mandea M., and G. Balasis (2006), Geophys. J. Int., doi: 10.1111/j.1365-246X.2006.03125.x (see report http://www.sciencemag.org/content/vol314/issue5798/twil.dtl).
Sarris, T. E., et al. (2009), Geophys. Res. Lett., 36, L04104, doi:10.1029/2008GL036732.
Schaefer, S., Glassmeier, K. H., Eriksson, P. T. I., Pierrard, V., Fornacon, K. H., and Blomberg, L. G.: Ann. Geophys., 25, 1011–1024, 2007.
Torrence, C. and Compo, G. P.: Bull. Am. Meteor. Soc., 79, 61–78, 1998.