SM43A-2275. New advanced tools for combined ULF wave analysis of multipoint space-borne and ground observations: application to single event and statistical studies

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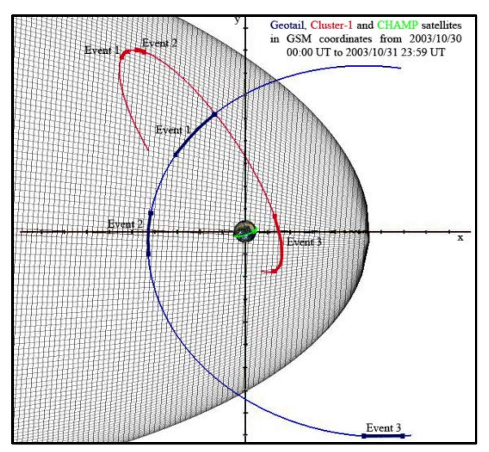
ABSTRACT: In the past decade, a critical mass of high-quality scientific data on the electric and magnetic fields in the Earth's magnetosphere and topside ionosphere has been progressively collected. This data pool will be further enriched by the measurements of the ESA/Swarm mission, a constellation of three satellites in three different polar orbits between 400 and 550 km altitude, which was launched on the 22nd of November 2013. New analysis tools that can cope with measurements of various spacecraft at various regions of the magnetosphere and in the topside ionosphere as well as ground stations will effectively enhance the scientific exploitation of the accumulated data.

Here, we report on a new suite of algorithms based on a combination of wavelet spectral methods and artificial neural network techniques and demonstrate the applicability of our recently developed analysis tools both for individual case studies and statistical studies of ultra-low frequency (ULF) waves. First, we provide evidence for a rare simultaneous observation of a ULF wave event in the Earth's magnetosphere, topside ionosphere and surface: we have found a specific time interval during the Halloween 2003 magnetic storm, when the Cluster and CHAMP spacecraft were in good local time (LT) conjunction, and have examined the ULF wave activity in the Pc3 (22-100 mHz) and Pc4-5 (1-22 mHz) bands using data from the Geotail, Cluster and CHAMP missions, as well as the CARISMA and GIMA magnetometer networks. Then, we perform a statistical study of Pc3 wave events observed by CHAMP: the creation of a database of such events enabled us to derive valuable statistics for many important physical properties relating to the spatio-temporal location of these waves, the wave power and frequency, as well as other parameters and their correlation with solar wind conditions, magnetospheric indices, electron density data, ring current decay and radiation belt enhancements.

Event Study (Halloween Storm – 2003)



Satellites' Position

The Geotail, Cluster-1 and CHAMP locations in GSE coordinates on the xy plane on the 30 and 31st of October 2003. The event discussed here is Event 3.

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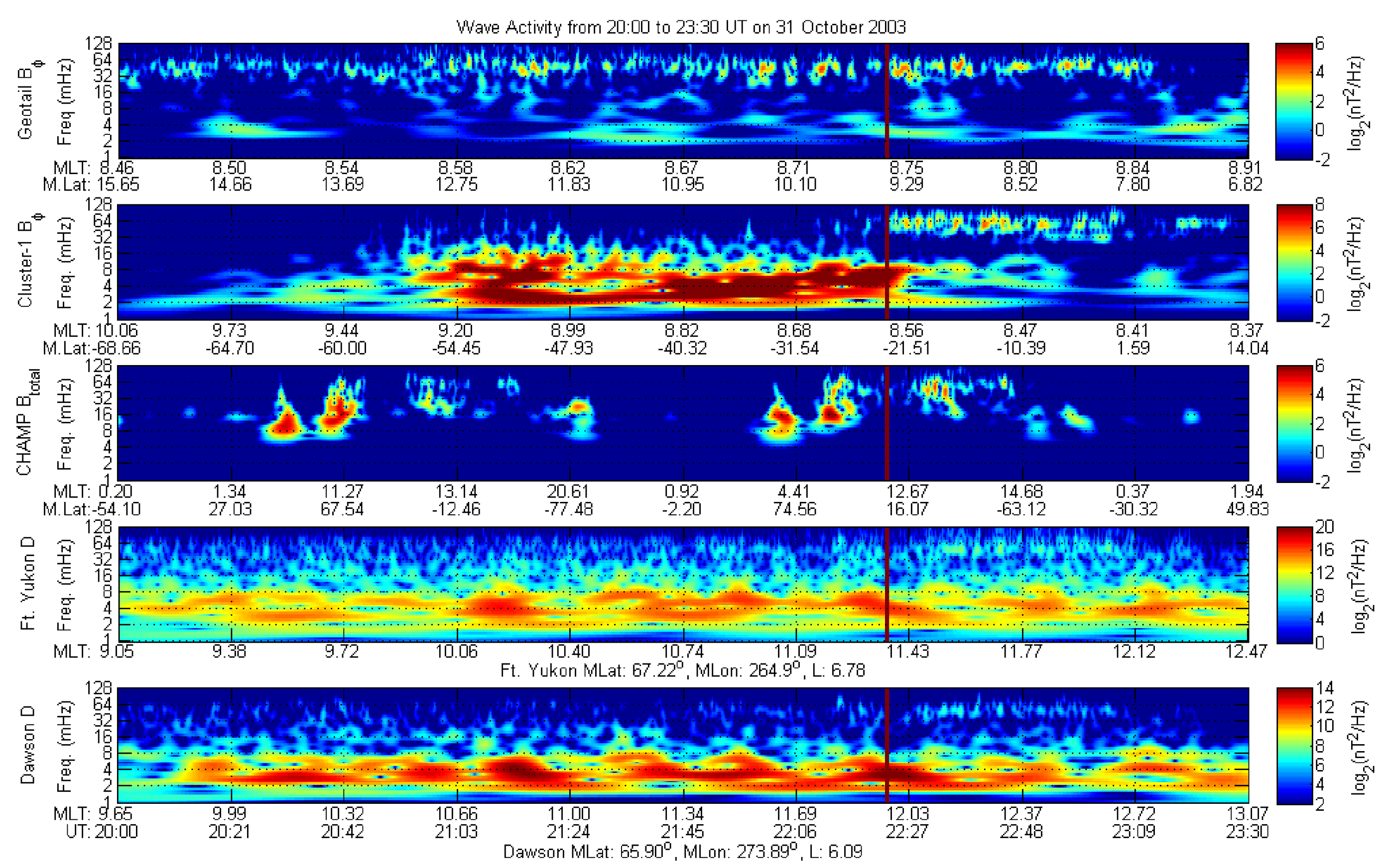
(These plots are modified versions of the graphs derived the Tool for Interactive Plotting, Sonification, and 3D Orbit Display – TIPSOD provided by NASA.)



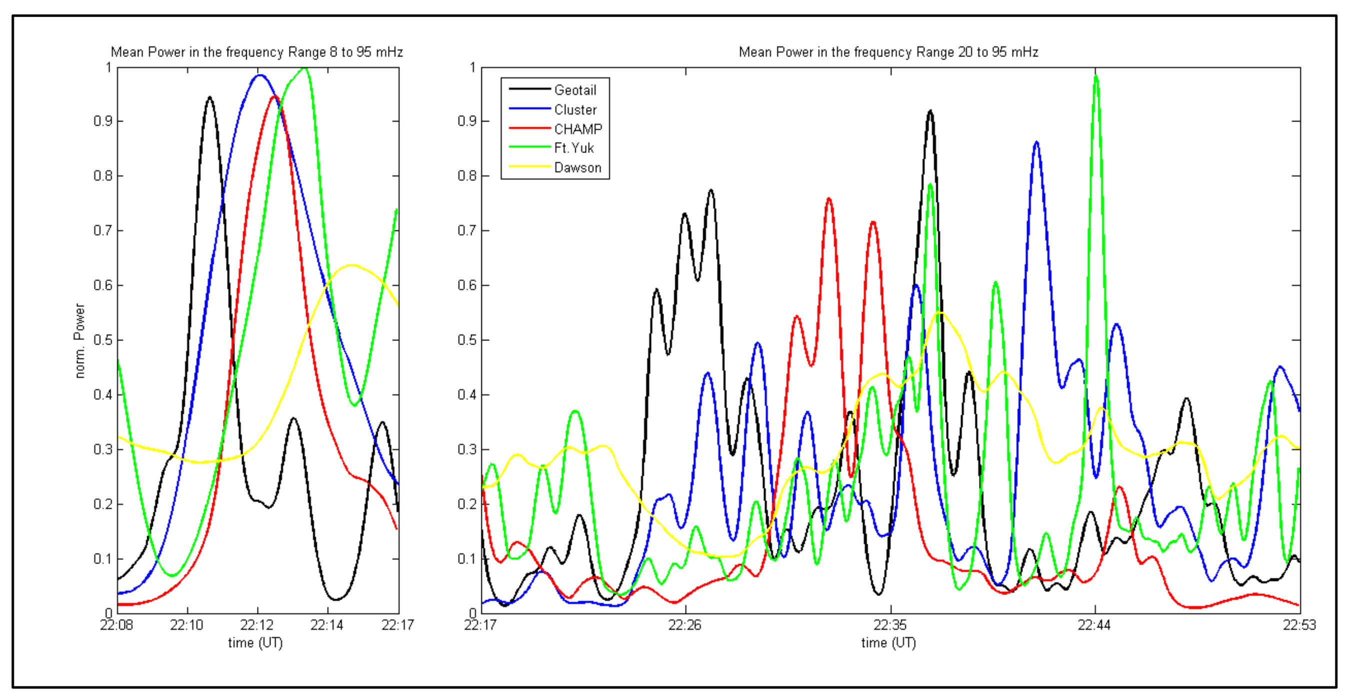
Combined wave observations (20:00 – 23:30 UT, 2003/10/31)

From top to bottom we show the wavelet power spectra for the Pc3 to Pc5 frequency range for the Geotail toroidal component, Cluster-1 toroidal component, CHAMP total field and the two ground stations, Ft. Yukon and Dawson, D components. Additional lines below each panel inidicate the MLT of all observatories and especially for the case of the three satellites, the magnetic latitude. The actual time, in UT, is given in the last horizontal axis at the bottom. The vertical red line indicates the time for which the Cluster constellation crosses the plasmapause, which coincides with it observing an increase in high frequency Pc3 waves and a simultaneous decrease in the activity at lower frequencies. The sudden emergence of this high-frequency band indicates 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 FAC , i.e. shear mode wave.

The two panels present the mean power with respect to time, with the averaging being performed on two different ranges, across frequencies 8 to 95 mHz (left panel) and 20 to 95 mHz (right panel) and focusing on the consecutive time intervals 22:08 to 22:17 (left) and 22:17 to 22:53 (right). In order to have a direct comparison of wavelet spectra of widely different values, each time series is normalized with respect to its maximum value. Additionally, a smoothing filter was applied (1-min moving average) to reduce the irregularities in the series.

From the first panel, it is obvious that all platforms detect an almost simultaneous increase in the Pc3 and Pc4 wave activity, that causes them to achieve their (local) maximum value. Of special interest is the fact that they seem to reach their peak consecutively, in order of distance from the earth (or L shell). The same can be seen in panel two, for a longer time interval, for which in many occasions multiple platforms seem to record near simultaneous increases in the activity of Pc3 waves (i.e. the multiple peaks at approx. 22:37 by Geotail, Cluster, Dawson and Ft. Yukon).

Performing a correlation study on these time-averaged time series, for the Pc3 range (20 to 95 mHz) and the entire time span (20:00 to 23:30 UT) yields the obvious strong relation between the two ground stations (~0.7), but more interesting, albeit weaker (between 0.25 to 0.5), correlations arise when we introduce a time shift of ± 10 minutes. In that case, Geotail series correlate with the future shifted Cluster series (+5') and they in turn with the future shifted Ft. Yukon series (+4'), while CHAMP also exhibits weak correlations with both ground stations (+2')., thus giving some indication for the inwards propagation of Pc3 ULF waves that arise at the outer magnetosphere.



Normalized average power (22:08 – 22:53 UT, 2003/10/31)

DATA PROCESSING:

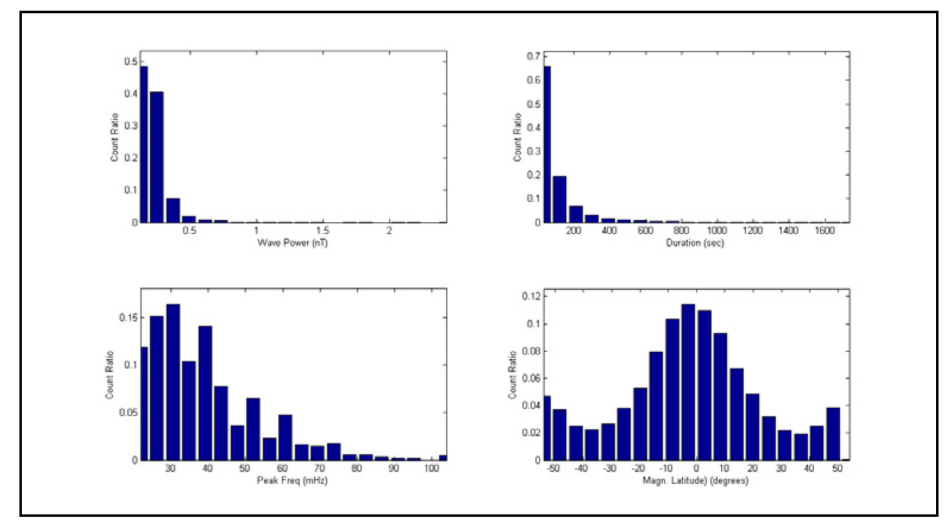
- We have considered fluxgate magnetometer (FGM) measurements from Geotail, Cluster and CHAMP missions, as well as Fort Yukon station of the GIMA network in Alaska and Dawson station of the CARISMA array in Canada. The time resolution of these time series is 1 s for CHAMP, 3 s for Geotail and 4 s for Cluster measurements, while the ground stations in Alaska and Canada provide data with 5 and 1 sec resolution respectively.
- We use a Mean Field-Aligned (MFA) coordinate system in the analysis of the Cluster and Geotail observations, in order to separate ULF field variations perpendicular to as well as along the magnetic field direction.
- We use the CHAMP total magnetic field measurements as they are considered to be a fairly good approximation of its compressional component for studying ULF waves (e.g., Heilig et al., 2007).
- Measurements from the ground stations are being analyzed in the native H,D,Z system.
- We apply the continuous wavelet transform with the Morlet wavelet as the basis function to the time series under investigation (see for details Balasis et al., 2012).

Statistical Analysis of CHAMP data

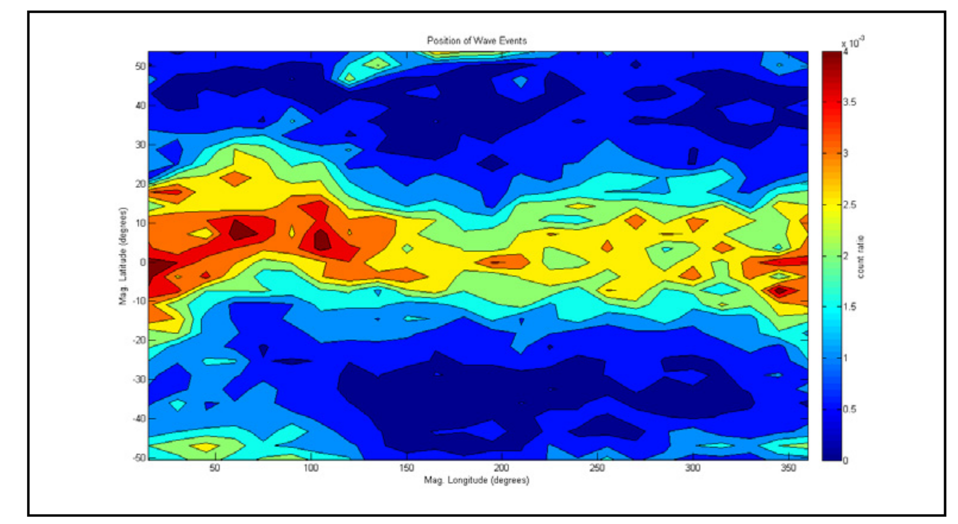
For a statistical analysis we employ our automated wave detection routines on data from the CHAMP mission. We apply the wavelet analysis on each track (half-orbit) of the satellite, limiting it further to measurements performed when the satellite's position was within +/- 55 degrees in magnetic latitude, in order to avoid perturbations due to the auroral currents and the polar cusps. After that, the algorithm detects parts of the spectra that exhibit enhanced power and performs a series of tests. If such a candidate signal is tested successfully against all criteria, it is considered a valid wave event and its characteristics are saved in an event catalogue, from which useful statistics can be extracted. If not, the algorithm classifies the candidate event into two other categories, namely Non-Events (if the candidate was too short, or too weak to pass the corresponding criteria) or False Positives (spikes, gaps in the data and/or preprocessing errors). For more details see Balasis et al., 2013.

In parallel to that, we have used a detection scheme based on the adaptive neuro fuzzy inference systems (ANFIS) class of neural networks, that have been trained on datasets, including signals from all three categories, prepared by both a human operator and the wavelet detection method described above. After the training, the ANFIS networks are able to perform the detection of all three categories of signals (Events, Non-Events & False-Positives) and thus are used in tandem with the wavelet techniques for accurate Wave Event detection.

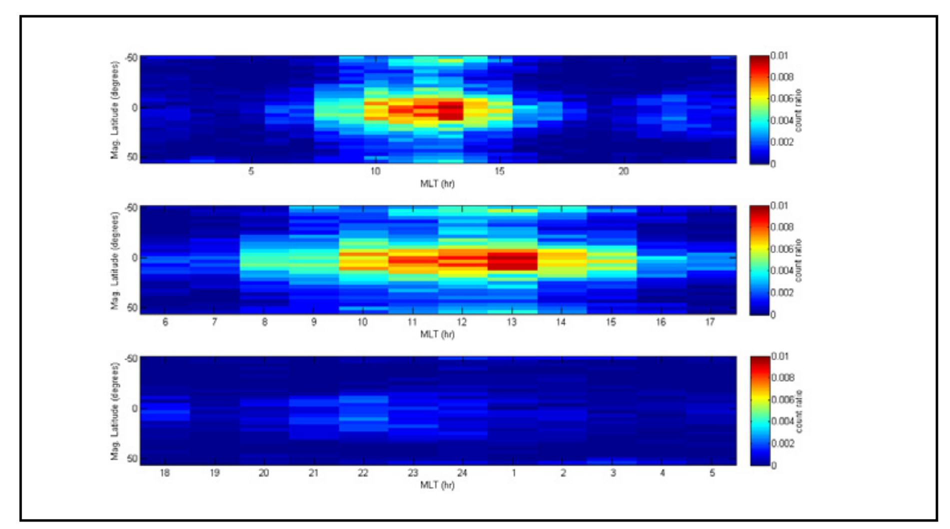
Analysis of wave events observed by CHAMP for the years 2003 – 2005



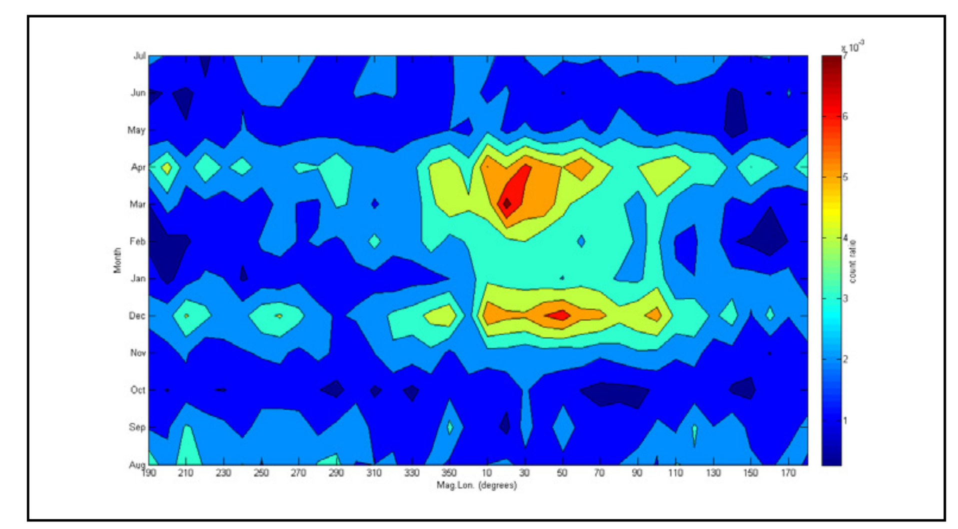
Distributions of Wave Power, Duration, Peak Frequency and Magnetic Latitude



Position of wave events in magnetic coordinates



Diurnal Variations in the occurrence rates for wave events location
Top Panel: All events – Middle: Daytime Only – Bottom: Nighttime Only



Monthly variations on the occurrence rates for wave events location

Conclusions

We have developed a set of tools, based on wavelet analysis and artificial neural networks, that enable us to detect magnetic wave activity by both space-borne and ground magnetometers. The application of these tools is relevant to the recovery phase of the Halloween super storm of 31 Oct 2003. We have looked at a specific interval when Cluster and CHAMP satellites were in good local time conjunction and examined ULF wave activity in the range of 1 mHz to over 100 mHz and its concurrence in the different regions of the magnetosphere, down to the topside ionosphere and on the ground. We have made a rare concurrent observation of a wave event on board three different satellite missions (from the outer through the inner magnetosphere, down to the topside ionosphere) and on the earth's surface on two ground magnetic networks.

In addition, our tools are able to perform wave event detection for long time intervals, thus enabling the creation of event catalogues which facilitate statistical studies on ULF waves and their physical properties.

References

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Acknowledgment

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