SEARCHING FOR POSSIBLE SEISMOGENIC SIGNATURES IN IONOSPHERE BY AN ENTROPY-BASED ANALYSIS OF MAGNETIC SATELLITE DATA: A CASE STUDY

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Abstract - The importance of detecting possible electromagnetic signatures due to large earthquakes is self-evident, signatures which can be either anticipating, simultaneous or subsequent with respect to the main shock.
Taking advantage of the present low Earth's orbiting CHAMP satellite, we apply an “ad hoc” technique based on the Information Theory [1], to the satellite magnetic data with the aim at extracting eventual time anomalies. This technique has small time-space resolution using a preliminary wavelet analysis in order to detect shorter-wavelength anomalies. Some examples are given for magnetic satellite data taken over periods including the times of two large earthquakes, one being the Sumatra region event on 26 December 2004 (M=9.1).

INTRODUCTION

When studying earthquakes we cannot consider seismograms only, but also some other information. We take advantage of a new way to see the Earth System. Indeed Geosystemics [2] consider the Earth system from a holistic point of view focusing on relations among parts of the system (in terms of Information production and transfer). We expect that during earthquake the Solid Earth transfers some information to ionosphere with an increase of organisation in the coupled system lithosphere-ionosphere. To measure the possible change of organisation we search for possible electromagnetic (EM) effects looking at the behaviour of the system entropy by means of the wavelet analysis technique. The search for anomalous geophysical signals preceding the main seismic event would be of great importance in future to both a possible prediction of such an event and a better understanding of the physics behind its generation. For this reason many papers have appeared on this subject, reporting observations on sensible variations in electric, magnetic and electromagnetic fields during, after or even just before seismic or volcanic events [3-13]. Nowadays, the presence of those kinds of signals, ranging over a wide interval of frequencies (from ELF to VHF), is broadly accepted. The main purpose of this research focuses on the possibility to discover some early-warning electromagnetic signals, even in limited but highly seismic or volcanic vulnerable areas. Two examples of application of wavelet analysis are shown, one of which is about the Sumatra large earthquake of 26 December 2004.

SUMATRA 2004-2005 LARGE EARTHQUAKES

The large earthquake of 26 December 2004 (hypocentre coordinates 3.316°N, 95.854°E and 30 km depth) occurred at 00:58:53 UTC between the subducting India plate and the overriding Burma plate. Its magnitude was $M = 9.1$ (even if this value is still debated, e.g. see [14-15]) and can be considered the biggest earthquake after the one with the magnitude 9.2, i.e. the 1964 Alaska earthquake [14]. The main shock occurred as the result of thrust faulting on the western Burma-plate boundary, although many strike-slip faulting aftershocks occurred on the eastern plate boundary.

Another big earthquake, although of less magnitude ($M = 8.6$) occurred on 28 March 2005 16:09:36 UTC shocking almost the same area (coordinates 2.074°N, 97.013°E, 30 km depth).
The width of the $M = 9.1$ 2004 earthquake rupture, measured perpendicular to the Sunda trench, has been estimated of about 150 kilometres with maximum displacement on the fault plane of about 20 meters. As a result of the earthquake, the seafloor overlying the thrust fault would have been uplifted by several meters. It was this uplift to cause the huge tsunami that devastated all the coasts reached by the anomalous waves produced after the earthquake and causing so many damages and victims.

SATELLITE DATA

High quality satellite data are very important in order to observe physical events due to earthquakes [e.g. 16]. Satellites make high quality contemporaneous measurements of magnetic and ionospheric parameters together with a global coverage. Recent accessible satellite data acquiring several and diverse physical observables (e.g. magnetic and electric fields) are provided (or will be provided) by the following satellites:
- CHAMP, a German satellite in orbit since July 2000, still provides measures of vector and scalar magnetic field, electric field and total electron content (TEC) data.
- DEMETER, launched in 2004 with a 2-year planned mission time (but still operating at time of writing) in order to measure ionospheric disturbances (as ion density and ELF signals in the magnetic field) related to seismogenic areas and seismic events.
- SAC-C, an Argentina-USA satellite that since 2000 monitors the condition and dynamics of the Earth's environment and, among other things, the magnetic field in relationship with the Sun.
- ØRSTED, a Danish satellite that has been operating since 1999 at higher altitude than CHAMP, performing accurate scalar and vector measurements of the Earth's magnetic field and the flux of fast electrons, protons and α-particles around the satellite.
- Swarm, a planned constellation satellite mission by the European Space Agency (ESA). The constellation will be formed by three satellites: two will fly at the same (initial) altitude (450 km) separated by almost one hundred kilometres; they will allow to measure the east–west gradient of the magnetic field with unprecedented high-accuracy. The altitude of the third satellite will be greater (530 km) and with different orbital parameters in terms of local time from the lower satellites.

In this paper we analyse CHAMP magnetic data only.

WAVELET ENTROPY AND SEISMIC EVENTS

From Fourier analysis, reference [17] defined the *spectral entropy*

$$S = -\sum_r P_r \ln P_r \tag{1}$$

where

$$P_r = \frac{|f_r|^2}{\sum_{r'} |f_{r'}|^2} \tag{2}$$

is the probability associated to frequency f_r.

Equation (1) is a measure of the frequency dispersion degree of the Fourier power spectrum, i.e. how energy concentrates about a narrow or a broad range of frequencies, giving rise to a low or high entropy value respectively. The natural extension of spectral entropy to wavelet analysis is the wavelet entropy [18].
Wavelet analysis is a powerful method for decomposing signals $f(t)$ both in time and scale (or frequency): this make it possible to control the appearance of transients in the frequency domain and, in general, spectral evolution in time. Wavelet analysis results in a set of coefficients $W(s,\tau)$ (the wavelet coefficients) depending on the scale s and dilatation (time) τ. Hence, the wavelet power spectrum

$$E(s,\tau) = |W(s,\tau)|^2 \tag{3}$$

and, as [18], the wavelet entropy at time τ

$$WH = -\sum p_{s,\tau} \log_2 \left(p_{s,\tau} \right) \tag{4}$$

where $p_{s,\tau} = \dfrac{E(s,\tau)}{\sum_s E(s,\tau)}$, are defined.

Unlike Fourier transform, wavelet analysis can capture localized changes with time in the power spectrum of a signal. The technique used here analyses directly the magnetic data along segments of orbit by using the wavelet analysis [16]. After a high-pass filtering stage, the modulus B(t) of the magnetic field is analysed and decomposed into wavelet coefficients. Fig. 1 shows the typical distribution of one-day of recording, in particular the day of the big Sumatra earthquake.

Each part of Fig. 2 is composed essentially by three panels: on the top, the wavelet energy content of the filtered modulus B(t) (in the bottom panel), measured along the track in ±75° latitude range, represented in the right-most panel; the panel in the middle is the wavelet entropy.

Clockwise from the left, the sequence in Fig. 2 shows a typical evolution of a pulsation in ionosphere: it appears as a small patch in the wavelet spectrum (here in the south auroral region at the beginning of the track) of the first (left) track with a very small frequency range content (low entropy). It grows in amplitude and then disappears after some hours. Its persistence in contiguous tracks (here distant 13° in longitude each other) shows its long life time and spatial extension.

Fig. 3 shows instead two distinct coupled "pulsations" whose evolution (dynamics) is rather different from that usually encountered and showed in Fig. 2. Their behaviour differs in the sense that they both *suddenly* (if compared with Fig. 2) appear and disappear *as couples* of "pulsations". In addition, what is more important is that each "pulsation" occurs in regions which are not so far from epicentral areas: indeed they appear a few days before and in the same interval of latitude of two earthquakes (see Tab. 1), whose magnitudes are greater than 8.

Tab. 1 – Seismic events with magnitude greater than 8 occurred in an area close to the appearance of the couples of "pulsations"

Date	Orig. time UT)	Lat.	Lon.	Depth	M
2004-12-23	14:59:04.41	-49.31	161.35	10	8.1
2004-12-26	5:08:53.45	3.3	95.98	30	9

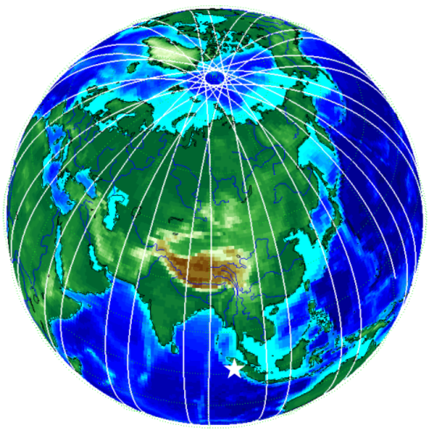

Fig. 1 – Spatial distribution of CHAMP magnetic data on 26 December 2004. The small star in the lower part of the globe indicates the position of the earthquake epicentre.

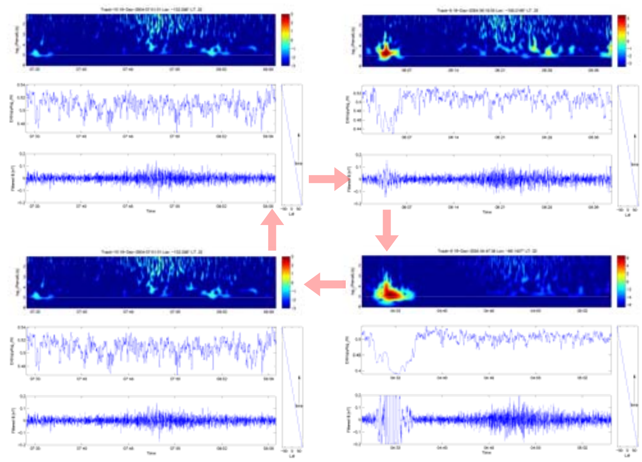

Fig. 2 – Clockwise, **t**he sequence of a typical "pulsation" appearing in the magnetic signal. It shows persistence both in space and time.

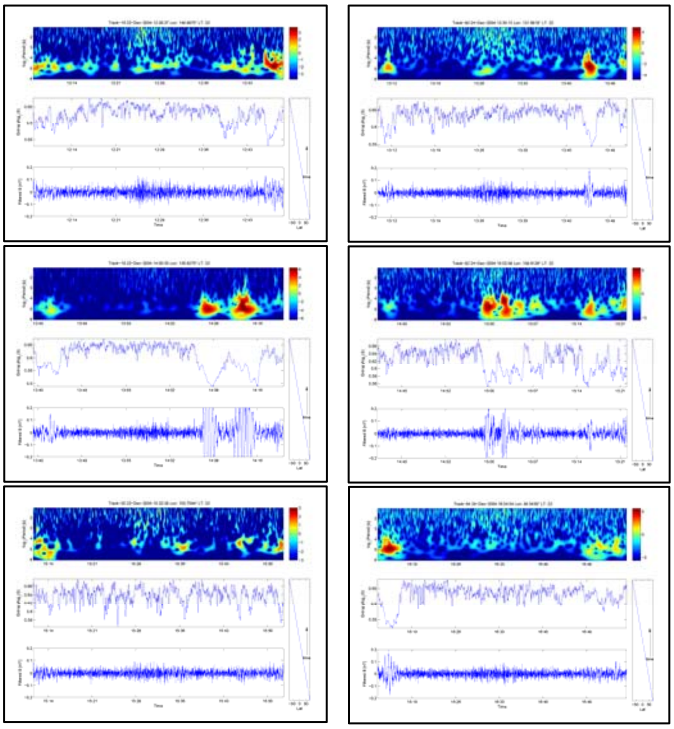

Fig. 3 – From top to bottom, each sequence shows the appearance of two "coupled" pulsations not so far from the region where few time later a big earthquake occurred (see Tab. 1**).**

CONCLUSIONS

We have shown here a method to analyse satellite magnetic data in order to reveal important signatures that can be possibly correlated with large earthquakes. To do this, we have described an innovative technique based on Information Theory with some preliminary results. This technique detects some anomalous behaviour in the satellite magnetic signal, in terms of some entropy decreasing (related to some magnetic features in the magnetic field measured at the ionospheric altitude) preceding large earthquakes, that must be further analysed and investigated. With this aim, the future Swarm data will be crucial in order to refine the search for features in the magnetic field that can be related to occurrence of large earthquakes.

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