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Entropy based analysis of satellite magnetic data for searching possible electromagnetic signatures due to big earthquakes

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Abstract: - The importance of detecting possible electromagnetic signatures due to big 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 orbiting CHAMP satellite, we apply two "ad hoc" techniques both based on the Information Theory (after the seminal monograph by Shannon [1]) to the satellite magnetic data with the aim at extracting eventual time anomalies. These techniques have different time-space resolutions: the first technique requires a preliminary spherical harmonic analysis of daily magnetic data and, potentially, detects long-wavelength variations, while the second uses a preliminary wavelet analysis and can detect shorter-wavelength anomalies. Some examples are given for magnetic satellite data taken in correspondence with the two big earthquakes occurred in the Sumatra region on 26 December 2004 $(M = 9.1)$ and 28 March 2005 $(M = 8.6)$.

Key-Words: - Earthquake precursors, Magnetic field, Satellite data, Wavelet Analysis, Shannon Entropy

1 Introduction

Big earthquakes continue to shake our planet: according to a global Gutenberg-Richter relationship we expect about 20 earthquakes with magnitude $M > 7$ every year [2]. One of the biggest occurred on 26 December 2004, in Sumatra and surrounding area, with $M = 9.1$ causing huge damages and more than two hundreds of thousands of deaths; after few months (28 March 2005) it was followed by another strong shock with $M = 8.6$. 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. A strong challenge of the present research is the definition of models that can explain electromagnetic phenomena related to earthquakes or volcanic events and how to discriminate them among signals in the same frequency ranges. The main purpose of this research is the discovery of some early-warning electromagnetic signals, even in limited but highly seismic or volcanic vulnerable areas. An example of application of these techniques will be the case of the two Sumatra big earthquakes of 26 December 2004 and 28 March 2005. In this paper we will recall the main mechanisms that can produce some electromagnetic (e.m.) effects from an earthquake, and we will introduce the characteristics of the two big earthquakes occurred in Sumatra area. We will then describe two techniques applied to satellite magnetic data in order to detect some possible e.m. signatures of those earthquakes; these techniques are based on the information theory [1]. Some signatures emerge that will deserve particular attention and discussion.

2 Possible mechanisms

Park et al. [10] and Johnston [11] provide a complete review of possible mechanisms and effects during or preceding main tectonic events: pressure induced mass movements (gas, fluids) or stress loading and cracks of fluid-saturated crustal rocks during volcanic eruptions or earthquakes can lead to magnetic and electric rock property changes which can be summarised as the followings:

Volcanic phenomena

- *Piezomagnetic effects.* Laboratory experiments show that, when a stress σ is applied to a rock, its magnetization, M, changes as $\Delta M/M \approx k\sigma$ (k is an appropriate constant). In active volcano areas pressure loading can result in anomalies of few nT effectively found during some eruptions [12].
- *Demagnetization by thermal effects.* When Curie point is exceeded, crustal rocks lose their magnetization that reappears again when they cool below that point. In volcanic regions, fluid or gas movements transport rapidly a large amount of heat causing local magnetic anomalies.
- *Magnetized matter rotations or movements* due to fluid pressure can result in detectable changes.

Seismic events

- *Piezomagnetic effects.* They occur as in volcanic areas, except that anomalies arise from loading due to tectonic stress.
- *Electrokinetic effects.* In the solid-fluid interface in high fractured and salt-water saturated crustal rocks, a double layer (electrons and positive ions) is formed. Magnetic and electric fields arise from the ion flux of the fluid inside the fractures caused by pressure gradients.
- *Resistivity changes.* Experiments show that resistivity, ρ, of some crystalline rocks increases with compression because of pore closure with the resulting fluid expulsion; instead shear stress lowers ρ as a consequence of crack opening. Also for resistivity change we can write a formula relating it with stress σ such as $\Delta\rho/\rho \approx k_r\sigma$, where k_r is a constant whose changes depend on various rock characteristics as porosity, fluid saturation or degree of fracturing.

Just before significant seismic events, according to some authors [5, 14-18], several satellites flying over the investigating areas measured intense electromagnetic phenomena with possible sources on ground, in the ionosphere and in the magnetosphere. Recent studies [19] show that the vertical component of the surficial electric field penetrates into ionosphere when seismogenic area on the Earth surface has a radial length R greater than or equal to the altitude h of the most conductive ionospheric layer (E-layer), i.e. $R \geq 100$ km; for the *Dobrovolsky law* [1] this would happen for earthquakes with magnitude $M > 4.7$ [19].

Among the measurable effects in ionosphere due to phenomena occurring below it, we mention:

1. geomagnetic pulsations, i.e. magnetospheric plasma waves that can be observed as oscillations in electromagnetic field measurements (range 1 mHz-10 Hz) with various shapes and amplitudes [e.g.20-21].
2. ULF, ELF, VLF emissions [14-16], emerging as anomalies in the magnetic and electric field measurements, or changes in VLF signal characteristics [22].
3. Irregularities in ionospheric plasma such as ionospheric TEC (Total Electron Content) and ionic concentration deviation [e.g. 23], changes in characteristic frequencies [24-25].

There are several source models proposed as explanations for the above phenomena. Some of them are

- charged particles injection from near-Earth space radiation belt related to e.m. emission generated in the epicentre area [26-27];
- electromagnetic waves emission due to microcurrents generated by charge relaxation during microcrack opening due to an earthquake preparation stage [28-29];
- acoustic gravity waves - first observed after the 1964 Alaska earthquake - and possibly generated by seismic surface waves [30-32] or excited by lithospheric gas emissions [33-34] that in turn can enhance vertical electric fields penetrating into ionosphere [35-36] and leading, by means of a chain of processes (e.g. photochemical heating at ionospheric altitude [36]) to irregularities in the ionosphere region.

As complex above processes are, recently Pulinets [37] identifies the two main causes in:

- acoustic gravity waves, though they probably cannot justify the strong variations measured;
- anomalous vertical electric field, proposed as a plausible hypothesis.

In this paper we are not interested on the kind of mechanism behind the possible e.m. effects from an earthquake but we deals with some specific techniques which can in principle allow to detect eventual signatures possibly correlated with big earthquakes.

3 Sumatra 2004 – 2005 big earthquakes

The big 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

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[1] $R = 10^{0.43M} \Rightarrow M = \left.\frac{\log R}{0.43}\right|_{R=100\text{ km}} \simeq 4.7$

plate. Its magnitude was $M = 9.1$ [2] and can be considered the biggest earthquake after the magnitude 9.2 1964 Alaska earthquake [38]. 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.

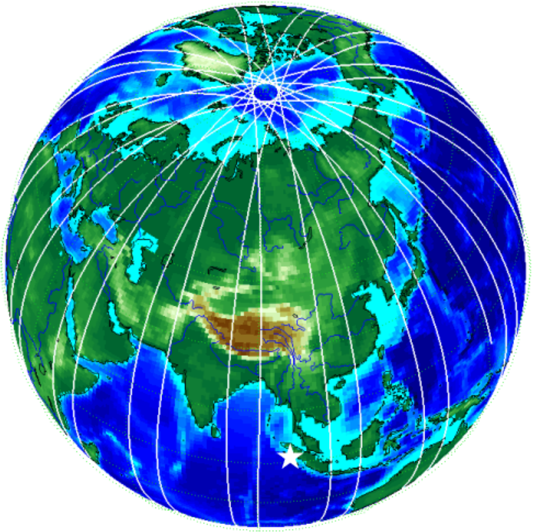

Fig. 1 Spatial distribution of CHAMP magnetic data on 26 December 2004. The small star in the lower part of the globe indicates the position of the earthquake epicentre.

The aftershocks occurred over 1000 km of distance, suggesting that main-shock fault-rupture may have extended north of the epicentre by a comparable amount [38].

4 Satellite data analysis

Recently, several techniques have been applied to satellite data in order to observe physical events due to earthquakes [e.g. 40-42]. Satellites make high quality contemporaneous measurements of magnetic and ionospherical parameters together with a global coverage.

Recent accessible satellite data acquiring several and diverse physical observables (e.g. magnetic and electric fields) are from the following satellites:

- CHAMP in orbit since July 2000, still provides measures of vector and scalar magnetic field, electric field and TEC.
- DEMETER (*D*etection of *E*lectro-*M*agnetic *E*mission *T*ransmitted *from E*arthquake *R*egion) launched in 2004 with a 2-year planned mission time 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 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 operating since 1999 at higher altitude than CHAMP, performs accurate scalar and vector measurements of the Earth's magnetic field and the flux of fast electrons, protons and α-particles around the satellite.

In this paper we will analyse CHAMP magnetic data only.

When the objective is to detect possible e.m. signatures from data, some typical analysing techniques are usually applied:

- Cross correlation between "ground-based" and satellite data [40-41].
- Wavelet analysis [42-44].
- Fractal analysis [45-47].
- Neural networks and Pattern Recognition [48].

In this short paper we show some preliminary results applying two original kinds of entropy based analyses. For some connections among Entropy, chaos and complexity in general, please look at [49].

The first type of analysis requires a preliminary spherical harmonic analysis (SHA) of the vector magnetic data (X,Y,Z components) taken every single day. Fig.1 shows the orbits of the satellite in the day of the biggest Sumatra seismic event. The small star in the lower part of the globe indicates the position of the earthquake epicentre. Data from a single day have the minimum time resolution and spatial coverage needed for Gauss coefficients computation.

After the SHA we can apply the definition given by De Santis et al. [50] to estimate the information

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[2] Magnitude value is still debated. Stein et al. [38] indeed think that slow slip was not detectable from the surface waves. Some authors report M=9.3 [39].

content (or Shannon information) from Gauss coefficients.

The Shannon information $I(t)$ of the geomagnetic field **B**(t), characterized by a spherical harmonic expansion with maximum degree N (which represents also the maximum number of states of the Earth magnetic dynamical system), can be defined as [50]:

$$I(t) = \sum_{n=1}^{N} p_n(t) \cdot \ln p_n(t) \qquad (1)$$

where $p_n(t)$ is the probability to have a certain *n*-degree spherical harmonic contribution instead of another:

$$p_n = \frac{\langle B_n^2 \rangle}{\langle B^2 \rangle} = \frac{(n+1)\sum_{m=0}^{n}(c_n^m)^2}{\sum_{n'=1}^{N}(n'+1)\sum_{m=0}^{n'}(c_{n'}^m)^2} \qquad (2)$$

and $(c_n^m)^2 = (g_n^m)^2 + (h_n^m)^2$; with $\sum_n p_n = 1$, and $p_n \ln p_n = 0$ if $p_n = 0$. Then Shannon Entropy, *H*, can be defined as simply as $H = -I$. To have a number between 0 and 1, we can also define a normalised entropy [51] dividing *H* by $\log N$, i.e. by the maximum entropy for a system whose *N* states have all the same probability distribution $p_n = 1/N$. Definition (2) is in the case of Schmidt quasi-normalised spherical harmonics, typically used in geomagnetism, and it can be interpreted as the n-degree contribution of the energy density at time *t* with respect to the total value $\langle B^2 \rangle$ of the magnetic field of the Earth. This contribution comes from all $n \cdot (n+2)$ terms associated to the Gauss coefficients g_n^m and h_n^m of degree *n*. The top curve of Fig.2 shows the behaviour of $I(t)$ from around a month before to a month after 26 December, 2004 earthquake, whose occurrence is indicated by a star; the bottom curve represents the daily sum of the planetary magnetic K_p index, which is a measure of the external (mainly solar) magnetic activity. Inspection and comparison of the mutual behaviour of the two quantities in Fig.2 is necessary in order to check whether external sources influence $I(t)$ and to what extent. First, we can notice that the information minimum is in correspondence with the maximum of the solar activity: this behaviour could let think us about a strong counter-phase influence. But this is not a general rule: notice the in-phase $I(t)$ minimum just a day after the event.

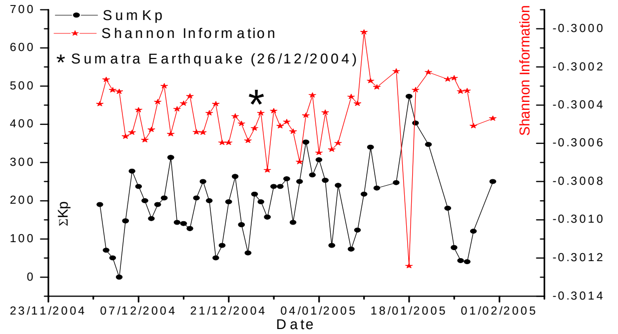

Fig.2 Shannon information (top curve) deduced from Gauss coefficients of a spherical harmonics inversion of daily geomagnetic satellite (CHAMP) data, together with the *rescaled* daily sums of the planetary magnetic index K_p (bottom curve). The star indicates the day of 9.1 Sumatra earthquake.

From the same figure, besides the point-to-point behaviour, what we also notice is a general decreasing trend of the Shannon information till the occurrence of the big earthquake, together with an almost general increase after. On the basis of this analysis only, we cannot say whether this feature is related to the earthquake or to other contemporary external magnetic activity, although the sum of the K_p index does not follow the two trends. This is an interesting aspect that will deserve further detailed study.

The other technique analyses directly the magnetic data along complete segments of orbit by using the wavelet analysis [42]. Wavelet analysis is a powerful method of decomposing signals both in time and scale (or frequency): in this way, it is possible to control the appearance of transient signals in the frequency domain. After a high-pass filtering stage, the modulus B(t) of the magnetic

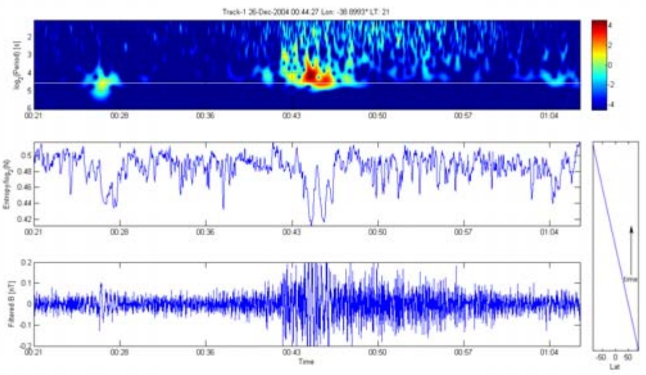

Fig.3 Wavelet analysis (top panel) of 26 December 2004, together with normalised Entropy (middle panel) and filtered geomagnetic field intensity (bottom diagram). Right vertical panel shows the latitude of satellite orbit.

field is analysed and decomposed into wavelet coefficients. From the latter, we then define the Shannon entropy in an analogous way to the case of SHA, but using each wavelet instead of each spherical harmonic [52].
Fig.3 shows the results for an interval around the time of the 26 December 2004 earthquake.
It is interesting to notice an anomalous behaviour in both wavelet and entropy diagrams 10-15 minutes before the main big earthquake. Also this deserves special attention and further study.

5 Discussion

We have shown how it is possible to analyse satellite magnetic data in order to reveal important signatures that can be possibly correlated with earthquakes. We have described two innovative techniques based on Information Theory with some preliminary results. Both techniques detect some anomalous behaviour of the satellite magnetic signal that must be further analysed and investigated. This is just a preliminary step in the wide and difficult realm of possible correlation between seismic activity and magnetic field.

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