Japanese tsumani 2011 effects on the geomagnetic field: Preliminary results.

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Abstract

The vertical component of the geomagnetic field observed by ground-based observatories of the INTERMAGNET network has been used to analyze the effects of the Japanese tsumani, 2011. The purpose of this work is to observe the geomagnetic variations induced by a tsunami resulting from the strong earthquake on 11 February 2011. We choose four stations that were influenced or more direct affected by the tsumani. The stations considered in this analysis were: Kanoya (KNY), Memambetsu (MMB), Guam (GUA) and Charters Towers (CTA). To detect these disturbances in the geomagnetic data, the discrete wavelet technique have been used in three levels of decomposition. We were able to detect the localized behavior of the geomagnetic variations induced by the movement of electrically conducting sea-water through the geomagnetic field, *i.e.*, the identification of transients related to the tsunamis. As well, using the minutely magnetogram data, it was able to localize the inicial phase and time of the tsunami maximum height. The first interpretation of the results suggests that discrete wavelet transform can be used to characterize the tsumanis effects on the geomagnetic field, but need further study.

Introduction

Gilbert showed as early as 1600, in his treatise “De Magnete”, the predominately dipolar character of the terrestrial magnetic field. In the early nineteen century, Gauss (1848) introduced improved magnet field observation techniques and the spherical harmonic method for geomagnetic field analysis. Also, in this same period, Gauss developed a mathematical method for separating the external and internal contributions to the surface field by a unique global analysis of the Earth’s main field, called the “Spherical Harmonic Analysis” (see Campbell, 1997, and references therein).

The geomagnetic field is a complicated function of space and time. Ground based magnetic measurements show a repetitive diurnal variation on geomagnetically quiet days. But there is a great variety of irregular variations that occur from time to time, the “disturbance fields”. Periods of great disturbance are called, by analogy with the weather, “magnetic storms” (Parkinson, 1983).

Some evidence of the influence of oceanic tides on the magnetic daily variation has been obtained by Larsen and Cox (1966). They found small semidiurnal variations of the Z component at a coastal site (Cambria, California) and at two island stations (Honolulu and San Miguel) that could not be explained by the atmospheric tidal theory. They suggested that these variations must be due predominantly to oceanic tides. It is important to mention here that the conductivity of the ocean does not vary significantly with time, unlike the ionospheric conductivity. As a consequence, the seasonal variation of the oceanic contribution is expected to be smaller than the ionospheric contribution (Cueto et al., 2003).

Manoj et al. (2011) observed the geomagnetic contribuitions due to the moderate tsumani in the Pacific ocean provoked by the Chilean earthquake of 8.8 in magnitude at three different magnetic stations (PPT, HUA and IPM). Their observations presented a variation of 1 nT in the vertical component of the magnetic field (Z) during the time of the tsumani effects. Movement of electrically conducting sea-water through the geomagnetic field generates an electromotive force that induces eletric fields, currents and secondary magnetic fields. In other words, tsunamis can produce perturbations in the Earth’s magnetic field by electro-magnetic induction (see Manoj et al., 2011, and references therein).

In this work, we focused in the geomagnetic variations induced by the Japanese tsunami of 11th of March, 2011. For detect the small singularities in the geomagnetic data, the discrete wavelet technique have been used in three levels of decomposition. The purpose of this work is to validate the wavelet technique as a way to identify the effects related to tsunamis in the Z-component of the Earth’s magnetic field.

Methodology

Discrete Wavelet Transform (DWT)

The wavelet transforms were better and broadly formalized thanks to mathematicians, physicist, and engineers efforts (e.g., Morlet, 1983). In space geophysics applications, the main characteristic of the wavelet technique is the introduction of time-frequency decomposition (e.g., Domingues et al., 2005; Mendes et al., 2005; Mendes da Costa et al., 2011). In the 1990s several important ideas and applications concerning wavelet were developed (e.g., Daubechies, 1992; Chui, 1992a,b, 1994).

The wavelet analysis could show that the larger amplitude of the wavelet coefficients are associated with abrupt signal locally. In the recent works (Domingues et al., 2005; Mendes et al., 2005; Mendes da Costa et al., 2011), the transition region and the exactly location of this discontinuities due to the geomagnetic storms are detected. The multiresolution analysis is a mathematical tool used to build up wavelet functions (e.g., Daubechies, 1992; Mallat, 1991).

In the multiresolution analysis (AMR) is possible to build up wavelet funstions using a pair of vectors $\{V^j, \phi^j\}$, in such way that there are a sequence of embedded approximating spaces and the functions $V^j \subset V^{j+1}$ and ϕ_k^j form a Riesz basis for V^j, being $V^j = span\{\phi_k^j(t)\}$. In this technique, a mother-wavelet is generated from a scaling function. Its obeys the following scale relation, more details in Mallat (1991):

$$\phi(t) = 2\sum_{k\in Z} h(k)\phi(2t-k) \quad \text{(Scale relation)} \tag{1}$$

and $h(k)$ is called scale filter coefficients. The family of scale relations are represented by:

$$\phi_k^j(t) = 2^{j/2}\phi(2^j t - k), \qquad j,k \in Z \tag{2}$$

They are called scale functions and in frequency domain is given by:

$$\hat{\phi}(\xi) = H(\xi/2)\hat{\phi}(\xi/2) \tag{3}$$

where $H(\xi) = \sum_{k\in\ h(k)} e^{-\imath k\xi}$ is a low pass filter associate to ϕ. The following relation holds:

$$V^{j+1} = V^j \oplus W^j \tag{4}$$

The spans W^j have the difference of information between V^j and V^{j+1}. If the ψ function form a Riez base of W^j, it is called wavelet function:

$$\psi_k^j(t) = 2^{j/2}\psi(2^j t - k) \qquad \psi(t) = 2\sum_{k\in Z} g(k)\psi(2t-k) \tag{5}$$

where $g(k) = (-1)^{k+1}h(-k+1)$ is a high pass filter.

The wavelet and scale functions satisfy the orthogonality condition, $\langle\phi_k^j, \psi_l^j\rangle = 0$, $\langle\psi_k^j, \psi_l^m\rangle = \delta_{j,m}\delta_{k,l}$. The AMR tool is useful to study the function in $L^2(\Re)$. The difference of information between V^j and V^{j+1} is given by W^j, *i. e.*,

$$\left(\Pi^{j+1} - \Pi^j\right) f(t) = Q^j f(t), \tag{6}$$

where the projections in V^j and W^j are, respectively:

$$\Pi^j f(t) = \sum_k \langle f, \phi_k^j\rangle \phi_k^j(t) \qquad Q^j f(t) = \sum_k \langle f, \psi_k^j\rangle \psi_k^j(t), \tag{7}$$

We obtain in multi-level $j_0 < j$ the coefficients expression:

$$c_k^j = \langle f, \phi_k^j\rangle \qquad d_k^j = \langle f, \psi_k^j\rangle \tag{8}$$

We can obtain with a change of base $\{\phi_k^{j+1}\} \leftrightarrow \{\phi_k^{j_0}\} \cup \{\psi_k^{j_0}\} \ldots \cup \{\psi_k^j\}$, the equation:

$$\sum_k c_k^{j+1}\phi_k^{j+1}(t) = \sum_k c_k^{j_0}\phi_k^{j_0}(t) + \sum_{m=j_0}^{j}\sum_k d_k^m \psi_k^m(t) \tag{9}$$

In the DWT the equation (8) is manipulated jointly with to the scale relations:

$$c_k^j = \sqrt{2}\sum_m h(m-2k)c_m^{j+1} \qquad d_k^j = \sqrt{2}\sum_m g(m-2k)c_m^{j+1} \tag{10}$$

In this work we use the Daubechies(db1) wavelet function of order 1 (Haar wavelet). In this case the coefficients $h = [\frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2}]$ and consequentely, $g = [\frac{\sqrt{2}}{2}, -\frac{\sqrt{2}}{2}]$.

The wavelet transform can be used in the analysis of non-stationary signals to rescue information on the frequency or scale variations of those signals and to detect the localization of its structures in time and/or in space. Due to the double localization property of the wavelet function, the wavelet transform is said to be of local type in time-frequency, with time and frequency resolutions inversely proportional. As a property of the wavelet analysis, it is possible to show that the wavelet coefficients amplitude is associated with abrupt signal variations or "details" of higher frequency (Meyer, 1990; Chui, 1992b). Selecting a wavelet function which closely matches the signal to be processed is of utmost importance in wavelet applications. A tutorial on the main properties and applications of the wavelet analysis can be found, for instance, in Domingues et al. (2005) and Mendes et al. (2005).

A hard thresholding process has been applied to the wavelet coefficients for the first three decomposition levels to identify the storm time in the magnetograms, as has been discussed by Mendes et al. (2005). Thresholding concerns the process of setting to zero certain coefficients in an effort to highlight significant information, in this case the shock-like transient phenomena that appear in the main phase of the magnetic storms. It was found that 2^{j-1} could be used as threshold sets for the decomposition levels $(d_j)^2$, because according to Meyer theorem, the multilevel threshold sets may have a multiplicity of 2 (Meyer, 1990).

In this analysis, we choose to use the Haar wavelet and the sampling rate of 1 min, the pseudo-periods of the first three levels are 2, 4 and 8 min. The most simple orthogonal analyzing wavelet function is the Haar wavelet. The discrete wavelet transform (DWT) using Haar wavelet detects abrupt variations, *i. e.*, one localization feature in the physical space. For instance the Haar wavelet has a compact support in physical space and a large support in Fourier space. In another words, Haar wavelet have a better localization on time than on frequency what is expected by the Heisenberg's uncertainty principle (as discussed in Daubechies, 1992).

Dataset

In this paper, we used ground magnetic measurements to study the geomagnetic variations during the Japanese tsunami of March 11, 2011. We choose four stations that belong to the INTERMAGNET programme (http://www.intermagnet. org) that were influenced or more directly affected by the tsunami. The stations considered in this analysis are: Kanoya (KNY), Memambetsu (MMB), Guam (GUA) and Charters Towers (CTA). The geographic and geomagnetic coordinates of these magnetic stations are given in Table 1.

Discussion

On the 11th of March, 2011 ocurred in the Japanese coast an earthquake at 05:46 UT (Universal Time) with

Table 1: INTERMAGNET network of geomagnetic stations used in this study.

Station	Geografic coord.		Geomagnetic coord.	
	Lat.(°)	Long.(°)	Lat.(°)	Long.(°)
CTA	-20.10	146.30	-27.64	-138.65
GUA	13.28	144.45	05.18	-144.20
KNY	13.42	130.88	04.13	-157.50
MMB	35.44	144.19	35.44	-148.23

Source: http://wdc.kugi.kyoto-u.ac.jp/igrf/gggm/index.html (2010)

8.9 of magnitude. The epicenter located at $38.3°$N and $142.4°$E, near east coast of Honshu, at 24 km depth. This earthquake induced a "major" tsunami that affected all the Japanese coast and transversed the Pacific Ocean eastward. Fig. 1 shows the areas affected by the tsunami and the estimated heights of the tsunami maximum readings. In the city of Kushiro, near to the magnetic station of MMB, the inicial phase of the tsunami started at $06:34$ UT and reached the maximum height ($+2$m) at $06:51$ UT. Near to the KNY station, in the city of Nichinan, the tsumani started at $08:05$ UT and the maximum height ($+1$m) was measured at $09:57$ UT.

The *National Oceanic and Atmospheric Administration* (NOAA) reported about the tsunami as follow: "The highest wave from the March 11, 2011 tsunami was 13 meters reported by an eyewitness at Minami Sanriku town. Tide gauge recordings in Japan range from 1 to 7 meters. Three meter waves were observed by eyewitnesses in the Kuril Islands, Russia. Two meter waves were observed at tide gauges in South America, Hawaii, and the west coast of the United States. The highest wave ever recorded by an ocean-bottom sensor was measured at 1.08 meters by DART station 21418 located 450 nautical miles northeast of Tokyo"(Source:http://www.ngdc.noaa.gov /hazard /tsunami /pdf /2011-0311.pdf).

The predicted time of the tsunami's arrival by NOAA at Cairns (Australia) was at $15:35$ UT and at the coast of Guam at $09:17$ UT. Cairns is located near to the magnetic station of CTA.

Figs. 2, 3, 4 and 5 show the discrete wavelet decomposition applied to geomagnetic minutely data using Daubechies orthogonal wavelet family 1. From top to bottom in these figures, the Z-component and the first three levels of wavelet coefficients for the hours between $05:30$ and $16:00$ UT of 11th of March, 2011.

Also in 11th of March, 2011 ocurred a geomagnetic storm which corresponds to a moderate storm with minimum Dst $= -82$ nT at $06:00$ UT and a second energy injection at $18:00$ UT with minimum Dst $= -67$ nT at $22:00$ UT. Geomagnetic activity is classified by "size" and usually described by the variation of indices to distinguish between a quiet and an active day (occurrence of storm or substorm). The characteristic signature of a magnetic storm is a depression in the horizontal component of the Earth's magnetic field H at middle to low latitude ground stations. The index most used in low latitudes is the Dst index. It represents the variations of the H component due to changes of the ring current (Gonzalez et al., 1994).

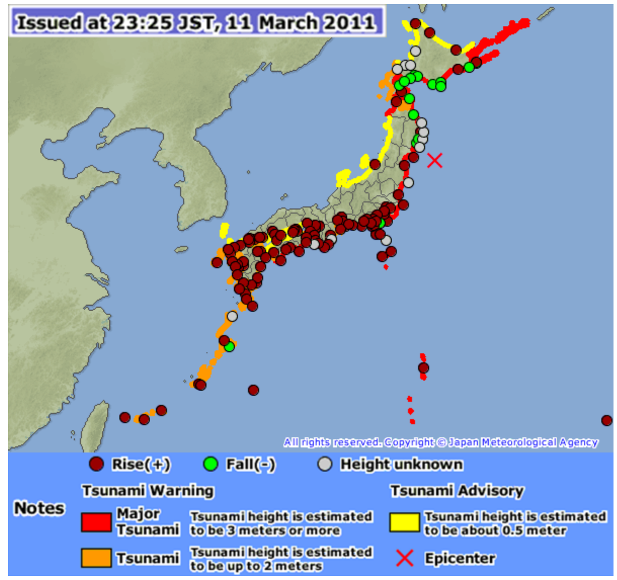

Figure 1: Map with the tsunami information of affected areas and maximum height. The X corresponds to the epicenter.
Source:http://www.jma.go.jp/en/tsunami/observation-04-20110311232516.html

The wavelet coefficients allow the identification of quiet and disturbed periods because it can detect the physical discontinuities in the vertical component of the geomagnetic field. When the magnetosphere is under quiet conditions the behavior of the Z-component recorded is much smoother than its behavior in the disturbed periods, such as storms. Therefore, the amplitude of wavelet coefficients is larger in the main phase of storm. Nevertheless, using a very localized wavelet (Haar wavelet), we were able to detect the small geomagnetic variations induced by the Japanese tsunami of 11th of March, 2011. The Haar wavelet present a short compact support that provides a better local chacterization of the signal and it may be the most convenient to represent times series with abrupt variations or steps.

In Figs. 2, 3, 4 and 5, for this event, it is possible to notice the presence of the highest wavelet coefficients for the first three levels of decomposition in association with the geomagnetic storm. The abrupt variations of the vertical component of the geomagnetic field are emphasized by the highest amplitudes of the wavelet coefficients. On the other hand, the smooth variations due to the magnetosphere under quiet conditions, present very small amplitude of wavelet coefficients. In Mendes et al. (2005), it was found that, "when a geomagnetic storm is under development (disturbed periods) the wavelet coefficients are significantly large", specially during the inicial and main phase. The inicial phase and the maximum height of the tsunami nearby MMB occurred after the main phase of the geomagnetic storm. In Fig. 2, we can observe at the first level of wavelet decomposition, an increase of the amplitude of the coefficient at $06:34$ UT which corresponds to the inicial phase of the tsunami. At $06:51$ UT, when tsunami reached the maximum height, we also could notice the presence of an increase in the coefficient amplitude, but smaller than the coefficient at the inicial phase. Meanwhile,

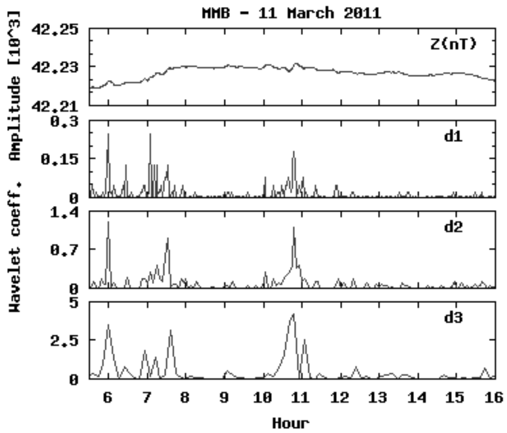

Figure 2: Geomagnetic field dataset for Memambetsu (MMB) station. The panels show from top to bottom, the Z-component of the geomagnetic field and the wavelet coefficients amplitudes at levels 1, 2 and 3 for the 11th of March, 2011.

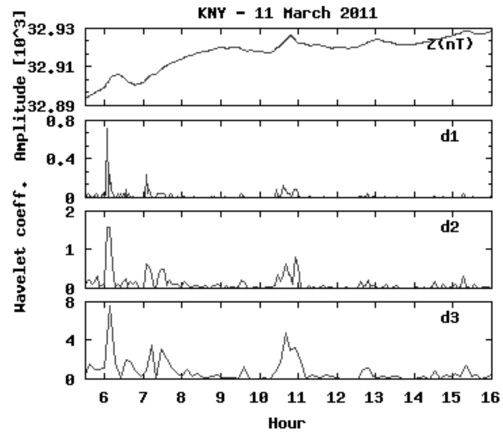

Figure 3: Geomagnetic field dataset for Kanoya (KNY) station. The panels show from top to bottom, the Z-component of the geomagnetic field and the wavelet coefficients amplitudes at levels 1, 2 and 3 for the 11th of March, 2011.

at the second and third levels, in the coefficients associated to the tsunami, the higher amplitude corresponds to its maximum height.

Fig. 3 shows the geomagnetic data and the wavelet decompositions for KNY. This japanese magnetic station does not show any coefficient in the first decomposition due to the tsunami. At the same time, in the second and third level of decomposition, we could observe the presence of small coefficients but noticeable at 08 : 05 UT (inical phase) and at 09 : 57 UT (maximum height).

Fig. 4 and 5 show that the further areas surrounding the epicenter are also affected by the tsunami. The arrival of the tsunami at Guam (GUA) was 09 : 17 UT. In Fig. 4 (GUA station), we observed a very perceptible wavelet coefficient in the three levels of decomposition at 09 : 17 UT. Although, the first level has presented the coefficient with the highest amplitude.

The tsumani arrival at the Australian coast (CTA) was 15 : 35 UT. The CTA magnetic station (Fig. 5) does not show any coefficient in the first and second decompositions due to the tsunami. In the third level appeared to have a small wavelet coefficient at 15 : 35 UT.

In summary, the wavelet coefficient of the first three levels of decomposition showed a good time localization of the inicial phase and the maximum height of the Japanese tsunami at 11th of March, 2011 and they, also, were locally associated with the geomagnetic variations present in the signal due to the secondary magnetic fields induced by the movement of electrically conducting sea-water through the geomagnetic field.

Final Remarks

The preliminary remarks in this analysis can be summarized as follows:

- The wavelet technique is useful to "zoom in" the localized behavior of the geomagnetic variations induced by the movement of electrically conducting sea-water through the geomagnetic field; *i. e.*, the identification of transients related to the tsunamis. As well, in the magnetogram data, it was able to localize the inicial phase and maximum height of the tsunami.

- The discrete wavelet transform (Daubechies - db1) provides a better local chacterization of the signal and it may be the most convenient to represent times series with abrupt variations or steps, *i. e.*, very small and localized variations as the discontinuities in the Z-component due to the tsunamis.

- The discrete wavelet transform is an alternative way to analyze the global influence of the tsunamis on the geomagnetic field and it could be used as a sophisticated tool in the geomagnetic signal analysis.

- The study of the tsumani effects on the geomagnetic field still remains an important issue, that is far from being fully understood.

The results obtained are encouraging. But the present study dealt with just one tsunami event and few magnetic stations. In the next step, we will present a further study using more events and more stations to do a complete analysis. The first interpretation of the results suggests that discrete wavelet transform can be used to characterize the tsumanis effects on the geomagnetic field, but need further study.

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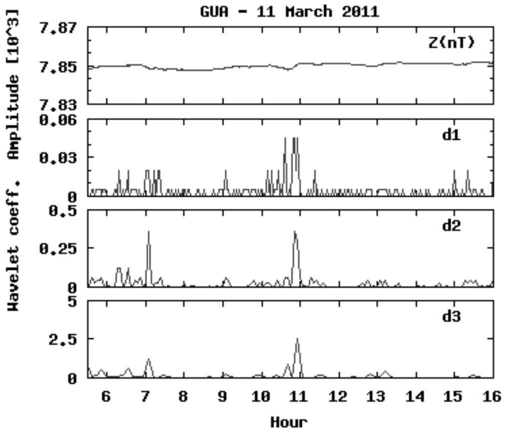

Figure 4: Geomagnetic field dataset for Guam (GUA) station. The panels show from top to bottom, the Z-component of the geomagnetic field and the wavelet coefficients amplitudes at levels 1, 2 and 3 for the 11th of March, 2011.

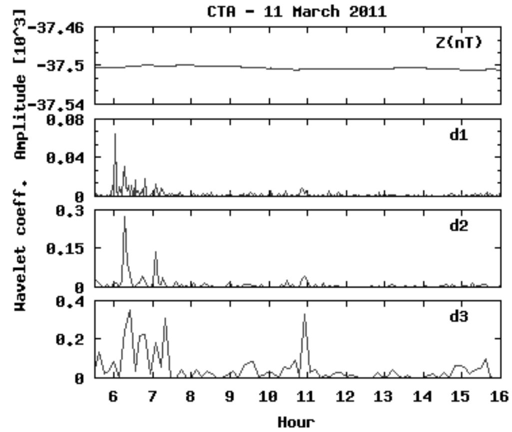

Figure 5: Geomagnetic field dataset for Charters Towers (CTA) station. The panels show from top to bottom, the Z-component of the geomagnetic field and the wavelet coefficients amplitudes at levels 1, 2 and 3 for the 11th of March, 2011.

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