

1 **Advantage of wavelet technique to highlight the**
2 **observed geomagnetic perturbations linked to the**
3 **Chilean Tsunami (2010).**

V. Klausner,^{1,2,3} Odim Mendes,¹ Margarete O. Domingues,¹ Andres R. R.

Papa,^{2,4} Robert H. Tyler,⁵ Peter Frick,³ and Esfhan A. Kherani.¹

Corresponding author: V. Klausner, Space Geophysics Division - DGE/CEA, National Institute for Space Research, Av. dos Astronautas, 1758, Predio Sigma, Sala 41, CEP 12227-010, Sao Jose dos Campos, SP, Brazil. (virginia.oliveira@inpe.br)

¹National Institute for Space Research,
São José dos Campos, SP, Brazil.

²Department of Geophysics, National
Observatory, Rio de Janeiro, RJ, Brazil.

³Laboratory of Physical Hydrodynamics,
Institute of Continuous Media Mechanics,
Perm, Russia.

⁴State University of Rio de Janeiro, Rio
de Janeiro, RJ, Brazil.

⁵Department of Astronomy, University of
Maryland, Maryland, College Park, USA.

4 **Abstract.** The vertical component (Z) of the geomagnetic field observed
5 by ground-based observatories of the INTERMAGNET network has been
6 used to analyze the induced magnetic fields produced by the movement of
7 a tsunami, electrically conducting sea water through the geomagnetic field.
8 We focus on the survey of minutely-sampled geomagnetic variations induced
9 by the tsunami of 27th February, 2010 at Easter Island (IPM) and Papeete
10 (PPT) observatories. In order to detect the tsunami disturbances in the ge-
11 omagnetic data, we used wavelet techniques. We have observed a 85% cor-
12 relation between the Z-component variation and the tide gauge measurements
13 in period range 10 to 30 minutes which may be due to two physical mech-
14 anisms: gravity waves and the electric currents in the sea. As an auxiliary
15 tool to verify the disturbed magnetic fields, we used the maximum variance
16 analysis (MVA). At PPT, the analyses show local magnetic variations as-
17 sociated with the tsunami arriving in advance of sea-surface fluctuations by
18 about two hours. The first interpretation of the results suggests that wavelet
19 techniques and MVA can be effectively used to characterize the tsunami con-
20 tributions to the geomagnetic field and further used to calibrate tsunami mod-
21 els and implemented to real-time analysis for forecast tsunami scenarios.

1. Introduction

22 Ocean water is electrically conducting and as it flows through the Earth's magnetic field
23 small secondary magnetic fields are generated at the expense of some of the flow's kinetic
24 energy. Aside from being an interesting physical effect, there is currently great interest
25 from a practical perspective because of the potential for using these magnetic fields to
26 remotely sense ocean flows [*Stephenson and Bryan, 1992; Tyler et al., 1999, 2003; Manoj*
27 *et al., 2006*]. The magnetic fields generated by tsunami flow is a specific example of this
28 effect and is the application considered in this paper.

29 The geomagnetic field is described as a complicated function of space and time. Ground
30 based magnetic measurements show a repetitive diurnal variation on geomagnetically quiet
31 days. But there is a great variety of irregular variations that occur from time to time that
32 characterizes the "disturbance-time fields". Periods of great disturbance are called, by
33 analogy with the weather, "magnetic storms" [*Parkinson, 1983*].

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

43 *Manoj et al.* [2011] searched for the geomagnetic contributions due to the moderate
44 tsunami in the Pacific ocean generated by the 8.8 Chilean earthquake (2010) at three
45 different magnetic observatories (Papeete (PPT), Huancayo (HUA) and Easter Island
46 (IPM)). In their investigation, only IPM magnetograms presented a variation of 1 nT in the
47 vertical component of the magnetic field (Z) during the time of the tsunami propagation.
48 Also, *Utada et al.* [2011] observed a periodic fluctuation at CBI observatory (on Chichi-
49 jima Island) starting from around 7:00 UT due to the arrival of the Japanese tsunami on
50 11th of March, 2011. Considering quiet conditions, *Tyler et al.* [1999] discussed that the
51 major difficulty to determine the magnetic ocean generated signals are the weak values
52 compared to the signals from other sources.

53 In a short description, the induced magnetic field generated by the ocean can be clas-
54 sified by two components: toroidal and poloidal. The toroidal component is generated
55 by the electrical currents closing in the vertical plane and can reach up to 100 nT but is
56 confined to the ocean and the upper crust. The poloidal component is much weaker, be-
57 tween 1 and 10 nT, and arises from the electrical currents closing in the horizontal plane,
58 however it reaches outside of the ocean to remote lands and satellite locations [see *Tyler*
59 *et al.*, 2003; *Manoj et al.*, 2006, and references therein].

60 A theoretical description of the magnetic fields generated by tsunami flow was discussed
61 by *Tyler* [2005]. In this work, *Tyler* [2005] employed a simple relationship between
62 the tsunami generated magnetic field and the sea-surface displacement using the long-
63 wavelength assumption.

64 Another mechanism of the geomagnetic field induction is propagation of acoustic gravity
65 waves due to tsunamis. *Iyemori et al.* [2005] observed long period Pc5 pulsations with

66 a period of approximately 3.6 minutes and 9 minutes during the Sumatra tsunami and
67 also, they speculated about short period pulsation Pc3 (about 30 seconds) as a result of
68 magnetic field line resonance with a magnetosonic wave generated from the electric and
69 magnetic fields of the dynamo current caused by the Earthquake. According to *Iyemori*
70 *et al.* [2005], these pulsations were generated by the dynamo action in the lower ionosphere
71 set up by an atmospheric pressure pulse which propagated as an acoustic wave when the
72 ocean floor suddenly moved vertically. Also, *Artru et al.* [2005] detected gravity waves
73 with period range 10 to 30 minutes which propagate horizontally at approximately the
74 same speed as the tsunami observed in Peru on 2001, June, 23. As mentioned by *Artru*
75 *et al.* [2005] the tsunami waves are expected to couple with atmospheric gravity wave due
76 to the tsunami long wavelengths.

77 The mechanism of the acoustic and gravity-acoustic waves for generation of geomagnetic
78 variations consists of the vertical wind oscillation caused by the duct resonance set up
79 by the earthquake, a wide area at the epicenter suddenly lifted up or depressed and an
80 atmospheric pressure variation propagates upward as acoustic and gravity-acoustic waves.
81 These waves generate a electric field by polarization and by the dynamo current in an
82 east-west direction over the epicenter. The polarized electric field is mapped along the
83 geomagnetic field to the ionosphere. The electric field then generates the ionospheric
84 currents in both east-west and north-south direction by Pedersen and Hall ionospheric
85 conductivities causing geomagnetic oscillations on the ground [see *Iyemori et al.*, 2005,
86 and references therein].

87 For the Japan tsunami (2011), *Kherani et al.* [2012] have presented the detailed travel-
88 time diagram (TTD) of the magnetic field disturbances using a chain of magnetome-

89 ter stations. They have also presented a simulation of these disturbances based on the
90 tsunami-atmosphere-ionosphere (TAI) coupling mechanism, which was presented theoret-
91 ically for the first time by *Peltier and Hines* [1976] using an analytical approach based on
92 isothermal atmosphere hypothesis. Later, *Lognonné et al.* [1998] presented an additional
93 theoretical validation of TAI with a normal mode summation theory for a planet with
94 elastic ocean and viscous atmosphere. Finally, the TAI was theoretically discussed again
95 by *Occhipinti et al.* [2006] using a 3D pseudo-spectral propagator with an adiabatic and
96 non-isothermal atmosphere; additionally *Occhipinti et al.* [2006] introduce also the iono-
97 sphere, and supported the theoretical modeling with total electron content observations
98 by altimeters. More details and references about the tsunami and earthquake detection
99 by ionospheric sounding, as well as the coupling mechanism can be found in *Occhipinti*
100 *et al.* [2013].

101 In the TAI mechanism, Acoustic-Gravity-Waves (AGWs) are excited by the tsunami
102 which then drive the currents in the ionosphere and gives rise to the magnetic field dis-
103 turbances. *Kherani et al.* [2012] have presented a detailed synthetic TTD of the magnetic
104 field disturbances and found fairly good agreement with the observed TTD. By consider-
105 ing the full spectrum of the dissipative AGWs, an early development (within 10 minutes
106 from the tsunami initiation) of magnetic field and total-electron-content (TEC) distur-
107 bances in the ionosphere, were explained which otherwise could not be explained solely by
108 the slowly propagating gravity waves. In their work, most of the dominant wave features
109 such as the early arriving acoustic and late arriving gravity waves were identified in both
110 observed and synthetic TTDs which affirms that the complete dissipative AGWs, rather
111 than the pure gravity waves, should be considered in a TAI coupling mechanism.

112 In this work, we focused on the survey of geomagnetic variations induced by the tsunami
113 of 27th February, 2010. Wavelet transforms proved to be a useful tool in atmospheric
114 signal analysis [see *Domingues et al.*, 2005, and references therein]. The gapped wavelet
115 transform and discrete wavelet technique has been applied in order to detect the disturbed
116 magnetic fields in the geomagnetic data as used in *Mendes et al.* [2005]; *Mendes da Costa*
117 *et al.* [2011]; *Klausner et al.* [2013]. Thus, this work aims to evaluate the use of the
118 wavelet techniques as a way to identify the magnetic contributions related to tsunamis
119 on the geomagnetic field components, particularly in the Z-component. Also, we use the
120 maximum variance analysis (MVA) to verify the results and the disturbed magnetic fields
121 detected by the wavelet technique that may be associated with the tsunami propagation.

122 The outline of this paper is as follows: Section 2, Dataset, ground magnetic measure-
123 ments set; Section 3, the applied methodology; Section 4, the results achieved by the
124 analysis; and Section 5, the conclusions of our work.

2. Dataset

125 In this section, we first describe the data used to study the geomagnetic variations due
126 to the tsunami-generated magnetic fields. The tsunami event of 27th of February, 2010 is
127 presented. For this event, we have chosen two ground magnetic measurements. We have
128 also selected the tide-gauge measurements at or nearby the chosen magnetic observatories.

129 We selected magnetic observatories belonging to the INTERMAGNET program
130 (<http://www.intermagnet.org>) that were influenced or more directly affected by the
131 tsunami. By international agreement, there are two usual systems that can represent
132 the Earth's magnetic field: the XYZ and the HDZ system [see *Campbell*, 1997, and ref-
133 erences therein]. The X, Y and Z stand for northward, eastward and vertical into the

134 Earth directions, the H, D and Z stand for horizontal component, declination (angular
135 direction of the horizontal component related to the geographical north) and vertical (into
136 the Earth). The H-component is more affected by the solar-magnetospheric interactions,
137 consequently, also the X- and Y-component. These variations, specially those associated
138 with the ring current, are a major contribution to the magnetograms at observatories
139 located at low and mid-latitude regions. Because the Z-component is less affected than
140 the H-component at the low latitudes of the observatories selected, we decided to use the
141 Z-component to detect the geomagnetic variations induced by the tsunami.

142 Regarding geomagnetic conditions, the 27 February, 2010 corresponded to a very quiet
143 day. The Dst index presented the minimum of -2 nT and the maximum of 4 nT and the
144 SYM-H index presented the minimum of -9 nT and the maximum of 5 nT, both of which
145 show smooth variations (see Fig. 1). When the magnetosphere is under quiet conditions
146 the behavior of the recorded Z-component should be much smoother than its behavior
147 in the disturbed periods, making easy the identification of the variations induced by the
148 propagation of the tsunami. The SYM-H index is essentially the same as the traditional
149 hourly Dst index. The main characteristic of the 1 minute time resolution SYM-H index
150 is that the solar wind dynamic pressure variation is more clearly seen than through indices
151 with lower time resolution. Its calculation is based on magnetic data provided by eleven
152 observatories of low and medium latitudes. Only six of these eleven observatories are used
153 for its calculation of each month, some observatories can be replaced by others depending
154 on data conditions.

155 Near the coast of central Chile, on the 27 th of February, 2010 at 06:34 UT occurred
156 an earthquake with magnitude 8.8 M_w . The epicenter was located on Lat. -36.1° and

157 Long. -72.6° at 55km depth. As reported by *Pararas -Carayannis* [2010], shortly after
158 the earthquake, tsunami waves hit the coastal area of the Central Chile. The tsunami
159 overtook the coastal cities as Talcahuano, Coquimbo, Antofasta and Caldera, as well as
160 the Juan Fernández Islands. The NOAA Pacific Warning Center released a bulletin of
161 number 018 and a tsunami warning was issued at 00:12 UT on 28 February, 2010 for a
162 large number of islands and countries in (or near) the Pacific basin.

163 In the region of Callao La Punta, Peru, the observed and computed tsunami time arrival
164 were coincident, both at 10 : 34 UT with amplitude of up to 0.69 m. We used the sea
165 level measured at this region as a guide to the arrival tsunami at IPM (see Fig. 2). For
166 PPT, the observed tsunami initial arrival time was at 17:33 UT and the computed time
167 was at 17:47 UT with amplitude up to 0.22m (see Fig. 3).

168 In this work, the magnetic observatories considered for this event were: Easter Island
169 (IPM) and Papeete (PPT), with the geographic and geomagnetic coordinates presented
170 in Table 1. Fig. 4 display the localization of tide gauge and magnetic stations with
171 their respectively IAGA codes. We selected the same two observatories used by *Manoj*
172 *et al.* [2011] to study the geomagnetic contributions due to the Chilean tsunami (2010)
173 and excluded the observatory of HUA located in Peru due to the equatorial electrojet
174 effects. In their study, only the IPM observatory showed a periodic variation of 1 nT in
175 the vertical component (Z) caused by the tsunami started at 11:35 UT, and the other two
176 observatories did not show concurrent variations.

3. Methodology

177 We apply in this work both continuous and discrete wavelet transform. For the contin-
178 uous, we used the Gapped wavelet technique introduced by *Frick et al.* [1997] due to its

179 property of dealing with gaps and the algorithm of Discrete Wavelet Transform (DWT)
 180 described by *Mendes et al.* [2005]. We detected there the disturbed transients on the H
 181 (or X) component of the magnetic field due to geomagnetic storms. Here, we use a similar
 182 technique during a geomagnetically quiet period in the Z component of the magnetic field
 183 to characterize the magnetic variations supposed to be produced by the propagation of
 184 tsunamis. However, we used as an auxiliary tool, the maximum variance analysis (MVA),
 185 to be sure that these variations are really associate with the tsunamis. The MVA is
 186 able to verify the changes in the direction of the magnetic field due to the poloidal com-
 187 ponent of the induced magnetic field generated by the ocean due to the tsunami water
 188 displacements.

3.1. Gapped Wavelet Analysis

189 In this work, we applied the gapped wavelet technique which was first introduced by
 190 *Frick et al.* [1997] and afterwards improved in *Frick et al.* [1998]. The leading idea of the
 191 gapped technique is to restore the admissibility condition which is broken when applied
 192 on data gaps.

193 Following *Frick et al.* [1997], we separate the analyzing wavelet in two parts, the oscil-
 194 latory part $h(t)$ and the envelope $\varphi(t)$,

$$\psi(t) = h(t) \varphi(t), \quad (1)$$

$$h(t) = \exp(i\omega_0 t), \quad (2)$$

$$\varphi(t) = \exp\left(\frac{-t^2}{2}\right). \quad (3)$$

195 When the wavelet is disturbed by the gap, we can restore the admissibility condition
 196 by including a function $\mathbf{K}(\mathbf{a}, \mathbf{b})$ in the oscillatory part of the wavelet,

$$\tilde{\psi}(t, b, a) = \left[h \left(\frac{t-b}{a} \right) - \mathbf{K}(a, b) \right] \varphi \left(\frac{t-b}{a} \right) \quad (4)$$

197 and requiring,

$$\int \tilde{\psi}(t) dt = 0 \quad (5)$$

198 The introduced function $\mathbf{K}(a, b)$ can be determined for each scale a and position b from
 199 (4) and (5).

200 It was shown that this technique not only suppresses the noise caused by the gaps and
 201 boundaries, but improves the accuracy of frequency determination of short or strongly
 202 gapped signals [*Frick et al.*, 1998].

203 3.1.1. Wavelet Cross-correlation Analysis

204 The approach of this work is to use the wavelet cross-correlation to study the correlation
 205 between a pair of datasets from different locations as a function of scale (see *Nesme-Ribes*
 206 *et al.* [1995] and *Frick et al.* [2001] for more mathematical details):

$$\mathcal{C}(a) = \frac{\int \mathcal{W}_1(a, t) \mathcal{W}_2^*(a, t) dt}{\left(\int \mathcal{W}_1(a, t)^2 dt \int \mathcal{W}_2(a, t)^2 dt \right)^{\frac{1}{2}}} \quad (6)$$

207 where $\mathcal{W}_i(a, t) = |W_i(a, t)| - \overline{|W_i(a, t)|}$, W_i are the wavelet coefficients and $\overline{W_i}$ is the
 208 arithmetic mean in time for $i = 1$ or 2 .

209 The wavelet cross-correlation allows us to check the interaction between two sets of
 210 data for each considered scale. In order to determine the dominating periods, we choose

211 the scales where the correlation has the maximum value in the geomagnetic correlation
 212 spectrum.

3.2. Discrete Wavelet Transform (DWT) methodology

213 The discrete wavelet transform (DWT) is a multi-level linear transform based on a
 214 multiresolution analysis construction [Daubechies, 1992]. This analysis produces the so-
 215 called wavelet coefficients at different levels and it is proved that their amplitudes can
 216 be used to study the local regularity of the analyzed data [Mallat, 1999]. If the wavelet
 217 coefficient amplitude is very small, it means that more regular is the analyzed data.
 218 Therefore, where the amplitudes are large we can associate it to some disturbance on the
 219 signal [Mendes et al., 2005].

The wavelet transform in level $j + 1$ is given by

$$d_k^{j+1} = 2 \sum_m g(m - 2k) c_m^j, \quad (7)$$

where g is a high-pass filter, d_k^{j+1} is the wavelet coefficient at level $j + 1$, and c_m^j are the scale coefficients at level j . In this transform,

$$c_k^{j+1} = 2 \sum_m h(m - 2k) c_m^j, \quad (8)$$

220 and h is a low-pass filter.

221 In this study, we considered $j = 0$ as the most refined level of the multi-level decom-
 222 position which is associated with one minute data resolution. In other words, $c_k^{j=0}$ is the
 223 mean time fluctuation computed from the raw magnetogram data.

224 We choose the Haar wavelet, therefore the non-zero filter values are $h = [\frac{1}{2}, \frac{1}{2}]$ and
 225 $g = [\frac{1}{2}, -\frac{1}{2}]$. This choice is based on the property of this wavelet to reproduce constant

226 functions locally, this means that it is very sensitive to local variations. This property
227 is the key point of this study of local regularity. Choosing the order of the analyzed
228 wavelet you decide the local polynomial approximation, consequently, with the choice
229 of Daubechies wavelet of order 1, we focus our study in local constant polynomial ap-
230 proximation. Therefore, the amplitude of the wavelet coefficient are related to the local
231 approximation error [*Mallat*, 1991].

232 With the choice of Haar wavelet and sampling rate of one minute, the first three multi-
233 levels are associated with pseudo-periods (central-periods) of 2, 4, and 8 minutes. On the
234 physical point of view, these periods are related to the tsunami wave arrival and the sea
235 water displacements.

3.3. Maximum variance analysis

236 We used the maximum variance analysis (MVA) to verify the identification done by the
237 discrete wavelet technique, as an alternative way to analyze the influence of the tsunami
238 on the geomagnetic field. The maximum variance analysis (MVA), in the case of this work,
239 uses a set of magnetic field components to determine the direction to minimize the stan-
240 dard deviation of the magnetic field component in that direction. MVA has been applied
241 to magnetometer data to define a new set of vectors relative to some natural boundary
242 such as the magnetopause or the bow shock [*Sonnerup and Cahill*, 1967; *Sonnerup*, 1976].
243 In that context, the main purpose of MVA was to find an estimate of the orientation of a
244 nearly one-dimensional discontinuity such as current sheet or wave front.

245 The boundary normal coordinates system (LMN system) is defined as having its M-
246 direction along the direction with minimum variance in the magnetic field, its L-direction
247 along the medium variance and its N-direction along maximum variance, see *Russell and*

248 *Elphic* [1978] for more details. In our case, the M-direction is along the direction of the
249 electrical current on the horizontal sea sheet, the L-direction and N-direction are along
250 the tsunami velocity propagation perpendicular to the geomagnetic field line and along
251 the vertical sea sheet.

252 It is the custom to construct a curve in this new space defined by the MVA vectors
253 in two projections called magnetic hodograms. A tutorial on the main properties and
254 applications of the MVA can be found, for instance, in *Paschmann and Daly* [1998].

4. Results and analysis

255 In this section, we present first the results concerning the wavelet techniques and after
256 those concerning MVA.

4.1. Results using GWT

257 In order to detect the same geomagnetic tsunami contributions observed by *Manoj*
258 *et al.* [2011], we applied the continuous gapped wavelet transform (GWT) on IPM mag-
259 netograms. One of the reasons for using GWT is that the geomagnetic data can include
260 gaps up to one minute length. Fig. 5 shows the geomagnetic behavior for the days 26 to
261 28th of February, 2010 using GWT. The GWT can be used in the analysis of geomag-
262 netic signal to obtain information on the frequency or scale variations about ionospheric
263 and/or magnetospheric phenomena due to its properties of detecting the localization of
264 these structures in time and/or in space [see *Klausner et al.*, 2013, for more details]. It is
265 possible to analyze a signal in a time-scale plane, the so called wavelet scalogram. In anal-
266 ogy with the Fourier analysis, the square modulus of the wavelet coefficient, $|W(a, b)|^2$,
267 is used to provide the energy distribution in the time-scale plane. Each panel shows: a)

268 the Z -component (top) and b) the wavelet square modulus (bottom). In the scalogram,
269 areas of stronger wavelet power are shown in dark red on a plot of time (horizontally) and
270 period time scale (vertically). The areas of low wavelet power are shown in dark blue.

271 Before applying the GWT to the magnetograms, we removed the daily variations from
272 the data. We calculated the smooth average from 30 days of quiet day daily variations
273 using days belonging to the same season in order to prevent the ionospheric dynamo
274 seasonal changes. Also, we eliminate a Gaussian white noise from the data, since it is the
275 simplest to be modeled. The signal was estimated by isolating the coherent structures
276 which have a high correlation with the signal components of the wanted data. The method
277 of extraction of coherent structures consists in using a wavelet basis which approximates
278 piecewise smooth functions efficiently but does not correlate well with high frequencies
279 oscillations. It is inspired by a theorem of Donoho which states that the way to denoise
280 a signal f , sampled on N points and perturbed by an additive Gaussian noise of variance
281 σ^2 , is to take its discrete wavelet transform. The method selects only those wavelet
282 coefficients with absolute value larger than the threshold $\epsilon = (2\sigma^2 \log(N))^{\frac{1}{2}}$ and sets all
283 the other coefficients to zero. After that, the signal is reconstructed with the remaining
284 wavelet coefficients (see *Farge et al.* [1999] for more details). For the estimation of these
285 coherent structures we use some packages from the free software WaveLab (available on-
286 line in the URL <http://www-stat.stanford.edu/wavelab/>) to filter the data.

287 On the 27th February, 2010, the scalogram shows a strongest wavelet power area from,
288 approximately, 11:00 UT to 14:00 UT. The physical phenomena responsible for wavelet
289 power area appear to have period of a few minutes, mainly from 8 to 16 minutes. [The](#)
290 [same period range of geomagnetic pulsations were detected by *Iyemori et al.* \[2005\] due](#)

291 to tsunami related gravity wave. For the Japan tsunami, 5-10 minutes geomagnetic pul-
292 sations were detected by *Kherani et al.* [2012], and these pulsations were shown to be
293 associated with the gravity waves. The presence of periodicities ~ 8 minutes was ex-
294 plained on the basis of mesospheric ducting of the gravity waves which is the region of the
295 atmosphere around 90-110 km altitude that oscillates with the Brunt-Vaisala frequency
296 ~ 8 minutes. The presence of this period in Fig. 5 which can only be associated with the
297 mesospheric duct, suggests that the magnetic field perturbations detected in Fig. 5 are
298 partly caused by the ionospheric currents driven by the gravity waves Moreover, *Kherani*
299 *et al.* [2012] have found the early arrival of unducted large vertical wavelength gravity
300 waves followed by the late arrival of the ducted short-wavelength gravity waves into the
301 ionosphere. In this context, Fig. 5 shows the development of ducted (with period ~ 8
302 minutes) disturbances later than the unducted (period >15 minutes) disturbances. This
303 feature is consistent with the mechanism discussed by *Kherani et al.* [2012] and thus it
304 may be said that the magnetic disturbances presented in Fig. 5 are partly arising from
305 the TAI coupling mechanism.

306 On the scalograms of the day of 26th February, 2010, these pulsations were not detected.
307 On the day of 28th February, 2010, these pulsations were detected between 05:00 to 09:00
308 UT. However, these pulsations were also detected at the same day at the same time on the
309 PPT scalogram (see Fig. 6) showing that the physical phenomena responsible for these
310 pulsations affected the magnetosphere globally and it was not a local phenomena as the
311 tsunami.

312 The pulsations due to the propagation of the gravity wave generated by the tsunami
313 was also detected on PPT magnetograms (Fig. 6). Period range between 10 and 30

314 minutes were detected between 16:00 and 21:00 UT on the PPT scalogram. Around this
315 time the ionosphere was the quietest and the SYM-H geomagnetic index did not indicate
316 any magnetic storm or unusual solar activity. However, at PPT the daily ionospheric
317 variations start about 16:00 UT and the ionospheric dynamo (Sq) starts around this time
318 but we filtered the daily variations from the data. In order to eliminate any doubts from
319 tsunami-induced magnetic fields due to the propagation of the acoustic wave around 16:00
320 UT, we applied GWT on the PPT tide gauge dataset and after we analyzed the wavelet
321 correlation between the PPT magnetogram and PPT tide gauge dataset.

322 On Fig. 7, the tsunami waves were detected on the scalogram with period range between
323 10 and 30 minutes from 18:00 to 22:00 UT. Comparing Fig. 6 to Fig. 7, the square
324 modulus of the wavelet coefficients with stronger power than the background in period
325 range between 10 and 30 minutes were detected about two hours in advance.

326 As mentioned by *Artru et al.* [2005], the typical tsunami wave period range is approx-
327 imately the same period as the tsunami related gravity wave. In this case, we applied
328 wavelet cross-correlation to check the interaction between these two waves for period range
329 between 10 and 30 minutes.

330 During the tsunami propagation, the correlation coefficient has a value up to 0.85 for
331 the wave period range between 10 and 30 minutes (see Fig. 8). In contrast, the correlation
332 coefficient value remains below 0.54 in a period previous the tsunami arrival.

4.2. Results using DWT

333 Fig. 9 shows the wavelet signatures for the three first decomposition levels. Panels (a)
334 to (b) correspond to magnetic observatories of IPM and PPT, respectively. In each panel,

335 from top to bottom are displayed the magnetogram (Z -component), and the $d^j = (d^j)^2$
336 for $j = 1, 2, 3$ wavelet decomposition levels.

337 The NOAA Pacific Warning Center predicted the tsunami time arrival at 12:05 UT
338 for the Easter Island, IPM. In Fig. 9(a), the first decomposition level presented a main
339 structure of coefficients between 11:58 UT and 13:24 UT and a secondary spike at 15:36
340 UT. Also, it presented a sequence of small structures between 16:54 UT and 24:00 UT. The
341 $(d^j)^2(j = 2)$ showed the highest coefficients at 12:28 UT and 12:40 UT and $(d^j)^2(j = 3)$
342 at 12:00 UT. On the other hand, $(d^j)^2(j = 2, 3)$ presented less structured features than
343 $(d^j)^2(j = 1)$. In $(d^j)^2(j = 3)$ it was possible to notice four peaks, one at 12:00 UT, a
344 second one at 12:15 UT, a third one at 12:32 UT and the last at 13:35 UT, followed by
345 two main structure of coefficients between 14:30 UT and 16:30 UT and between 20:30 UT
346 and 22:30 UT. These wavelet coefficients with higher amplitudes than the background
347 ones determine the time interval candidates of the magnetic contribution to the tsunami
348 propagation.

349 In Fig. 9(b), the main wavelet coefficient structures are restricted to the period between
350 15:36 UT and 21:52 UT. The $(d^j)^2(j = 1, 2, 3)$ presented surprisingly similar wavelet sig-
351 natures. These wavelet coefficients might be associated with the abrupt variations on the
352 magnetic field associated with the tsunami activity. The tsunami-induced electromagnetic
353 candidates were detected about two hours in advance.

354 The DWT can improve the hard task of visual inspection developed by *Manoj et al.*
355 [2011] and *Utada et al.* [2011]. The proposed technique has also the advantage to detect
356 objectively local variations on the analyzing data.

357 The same analysis shown on Section 4 was performed on the day before and on the day
358 after the tsunami arrival using PPT observatory for comparison purposes. Fig. 10 shows
359 the magnetogram (Z component) and the $dj = (d^j)^2$ for $j = 1, 2, 3$ decomposition levels
360 for PPT the day before, (a) 26th February, 2010, and the day after, (b) 28th February,
361 2010.

362 The 26th February, 2010 was a geomagnetically quiet day, Fig. 10(a). The SYM-H
363 index presented the minimum of -16 nT and the maximum of -3 nT with very smooth
364 variations, similar to the 27th February, 2010, see Fig. 1. It is possible to notice that
365 the wavelet coefficients with high amplitudes only appears between 19:00 to 21:00 UT.
366 The reason is that, when the magnetosphere is under quiet conditions, the geomagnetic
367 signal can be considered as smooth, and therefore, the local approximation of the wavelet
368 analyzing function is good and, consequently, the wavelet coefficients which are the local
369 errors of this approximations are negligible. However, the increase of the wavelet coeffi-
370 cient amplitudes between 19:00 to 21:00 UT might be explained by the passage of the solar
371 terminator (ST) which causes the generation of gravity waves, turbulence and instabilities
372 in the ionosphere plasma. As discussed by *Afraimovich* [2008], the ST passage generates
373 wave processes in the ionosphere which have duration of about 1–2 hours and a time shift
374 of about 1.5–2.5 hours after the ST appearance.

375 On the other hand, on 28th February, 2010, Fig. 10(b), the SYM-H index presented the
376 minimum of 0 nT and the maximum of 16 nT, see Fig. 1. Usually the positive variations
377 on the Dst index, consequently on the SYM-H index, are mostly caused by magnetospheric
378 compressions due to interplanetary shocks. As mentioned by *Karinen and Mursula* [2005],
379 it often corresponds to the initial phase of geomagnetic storms. The wavelet coefficients

380 amplitude is associated with abrupt signal variations. In this case, the highest amplitudes
381 of the wavelet coefficients indicate the disturbed magnetic fields due to a development of
382 a geomagnetic storm. The wavelet coefficient structures appear between 06:00 UT and
383 08:00 UT, 12:00 UT and 14:00 UT, 16:00 UT and 20:00 UT and 22:00 and 24:00 UT at
384 the three decomposition levels. This coefficients are related to these positive variations
385 on the Dst index.

386 In this work, we were able to distinguish the magnetic variations induced by the tsunami
387 from geomagnetic activity because the 27th February, 2010 was a geomagnetically quiet
388 day. During geomagnetic storms, it is difficult to connect the observed perturbations to the
389 tsunami propagation, due to the dynamic variations produced by magnetospheric activity.
390 However, Z-component monitoring could potentially be used in concert with ionospheric
391 measurements [Occhipinti et al., 2006, 2011, 2013; Rolland et al., 2010; Kherani et al.,
392 2012] and applied in a future tsunami early warning system.

4.3. Results using MVA

393 Fig. 11 and Fig. 12 show the time series of the filtered geomagnetic field measurement
394 (Z-component) and its transformation to boundary normal coordinates (LMN), respec-
395 tively, both for the IPM event. We applied MVA on the wavelet filtered data because it
396 allows us to analyze the LMN relations on a given range of scales. The hodogram was
397 made using a cycle of the sinusoidal signal (peak to peak) measured on the Z-component
398 from 11:00 UT until 14:00 UT, as shown in Fig. 11. The peaks were measured at the
399 following time intervals of 12:20 UT – 12:31 UT and 12:31 UT – 12:42 UT.

400 Fig. 12 presents the hodogram obtained from the analysis of Fig. 11. It shows a
401 polarized magnetic field variation induced by tsunami wave in the boundary normal com-

402 ponents. In the plane of maximum variance, we can notice a signature of polarized
403 magnetic field that occurs during the time of tsunami propagation which might be due to
404 the electric currents induced in the sea. This polarized magnetic field has approximately
405 the variation of 0.5 nT which corresponds to the magnitude order expected from tsunamis
406 disturbances.

407 As *Utada et al.* [2011] calculated in their work, we also applied the Biot-Savart law
408 (ignoring the electromagnetic induction) to calculate the induced magnetic fields by the
409 tsunami wave propagation. Considering the distance between the site and the source
410 current of 100 km, the tsunami height of 0.5 m, the tsunami wavelength of 100 km, the
411 propagating velocity of the tsunami 220 m/s, and the vertical geomagnetic component at
412 IPM of 19,000 nT, the intensity of the induced magnetic field field is estimated to be as
413 large as 1.4 nT.

414 The same analysis was done for the data from the magnetic observatory of PPT. Fig. 13
415 shows the time series of filtered Z-component and Fig. 14 shows its transformation to
416 boundary normal coordinates (LMN) for PPT observatory using the day of the tsunami
417 arrival at Papeete. Once more, the hodogram was made using a cycle of the sinusoidal
418 signal (peak to peak) measured on the Z-component due to the tsunami propagation,
419 shown in Fig. 13.

420 Fig. 14 is very similar to Fig. 12. The graphics corresponding to the peak time interval
421 of 18:23 UT – 18:38 UT and 18:38 UT – 19:03 UT. Here, the maximum variance plane
422 also shows a signature of polarized magnetic field presenting approximately the variation
423 of ± 0.5 nT.

5. Conclusions

424 In this study, we have examined the Chilean tsunami, 2010, using an improved anal-
425 ysis methodology based on wavelet techniques and MVA applied to the Z-component of
426 magnetogram data when no geomagnetic storms were present. We select the IPM and
427 PPT magnetic observatories to determine the magnetic contribution of the tsunami wave
428 propagation through the geomagnetic field.

429 Our results showed oscillations with a period range from 10 to 30 minutes which can
430 be associated with gravity wave propagation induced by tsunamis. In these conditions,
431 after removing the daily variations from the data, we observe that: (1) the gravity waves
432 observed at PPT has the same period range of the tsunami waves and (2) the ionosphere
433 was very quiet before the tsunami arrival.

434 Also, at PPT the Z-component variation and the tide gauge measurements showed a
435 maximum of correlation above 85% between 22 to 30 minutes. In this work, we showed
436 a very good correlation between the Z-component variation and the tide gauge measure-
437 ments in period range from 10 to 30 minutes, and this correlation may be due to two
438 physical mechanisms which are the gravity waves and the electric currents in the sea.

439 In response to the Chilean tsunami, 2010, the DWT results show that the increase
440 of wavelet coefficient amplitudes associated with the Z-component observed at IPM are
441 well correlated with the arrival of the tsunami waves. A similar increase in the wavelet
442 coefficient amplitudes was also detected at PPT, where a signal was not apparent in the
443 previous analysis using simpler inspection methods. These wavelet amplitudes at PPT
444 appear, however, with about a two-hour lead over the arrival of the sea-surface displace-
445 ments. A lead of this amplitude is expected because of the closure of electric currents in

446 the sea [Tyler , 2005]. The tsunami flow, through motional induction, excites electric cur-
447 rents along the axis of the crests/troughs of the wave (i.e. perpendicular to the tsunami
448 wave fronts). But the current density induced is uniform along the direction of electric
449 current flow only in highly idealized situations (e.g. cylindrical symmetry of all sources
450 and parameters). More generally, there will be convergences/divergences in this directly
451 induced component of the electric current. Because of this, to conserve electric charge
452 there will also be electric currents that close along paths including extensions through the
453 water ahead of the wave. The length scale for this forward closure of electric current may
454 involve all scales over which the flow, main magnetic field, and ocean-layer conductance
455 vary. Additionally, one expects a higher concentration of this forward electric current (and
456 the associated magnetic fields) when the curvature of the wave crest/trough is positive
457 toward the direction of propagation. Inspection of the animated tsunami simulation cal-
458 culated with MOST forecast model (provided on-line by the NOAA Center for Tsunami
459 Research) shows that at IPM, the tsunami crests/troughs are negative toward the di-
460 rection of propagation (i.e. there is a concentric wave form propagating away from the
461 source). But by the distant location of PPT, one sees that the wave form has changed and
462 the crests/troughs arrive at this location with positive curvature over a scale of roughly
463 2000 km.

464 It is then expected that while the leading electric currents (and associated magnetic
465 signals) may be negligible at IPM, they may be significant at PPT. An observed two-hour
466 lead at PPT corresponds to a forward leading distance of roughly 1600 km when one
467 assumes a propagation speed of 220 m/s (this is obtained from the wave speed $(gH)^{1/2}$,
468 where g is the gravitational acceleration and $H \approx 5$ km is taken to be the average water

469 depth). A realistic simulation of the hydrodynamics and electrodynamic elements of the
470 tsunami are required for clear demonstration of this leading effect (i.e. that the tsunami
471 flow generated magnetic signals at PPT arrive two hours earlier than their flow sources.)
472 But the fact that the two-hour lead corresponds with a leading distance of 1600 km, and
473 that this distance is similar to the 2000 km length scale of the wave curvature seen in
474 the simulated tsunami provides an adequate provisional explanation. Indeed, as stated
475 above, in all but highly idealized geometries one should expect return electric currents
476 cast through the water ahead of the tsunami front, and the maximum length scales for this
477 closure increase as the tsunami wave broadens in time. But note that the density of the
478 electric current involved decreases as the length scale for these return currents increase.

479 Changes on the geomagnetic field due to a presence of a polarized magnetic field were
480 observed during the tsunami propagation at IPM and PPT and it was estimated to be
481 of amplitude 0.5 nT which is consistent with theoretical expectations. The signature of
482 polarized magnetic field corresponds to the poloidal component of the induced magnetic
483 field generated by the tsunami wave.

484 Our methodology could be used in a semi-automatic way to characterize the tsunami
485 induced magnetic field. Previous studies of *Manoj et al.* [2011] and *Utada et al.* [2011],
486 employed mainly visual inspection. An automatic detection and classification of tsunami-
487 genic magnetic signals may also be useful to the understanding of the physical processes
488 involved in the tsunami propagation and could be implemented to real-time analysis for
489 forecast scenarios.

490 **Acknowledgments.** V. Klausner wishes to thanks CAPES for the financial support
491 of her PhD (CAPES – grants 465/2008) and her Postdoctoral research (FAPESP – grants

492 2011/20588-7 and 2013/06029-0). The authors would like to thank the NOAA and the
493 INTERMAGNET program for the datasets used in this work, V. Menconi (FAPESP
494 208/09736-1, CNPq 312486/2012-0 and 455097/2013-5) for his helpful computational as-
495 sistance and the comments by G. Occhipinti and anonymous referee which led to improve-
496 ment of this paper.

References

- 497 Afraimovich, E. L. (2008), First GPS-TEC evidence for the wave structure excited by the
498 solar terminator *Earth, Planets and Space*, *60*, 895–900.
- 499 Artru, J., V. Ducic, H. Kanamori, P. Lognonné and M. Murakami (2005), Ionospheric
500 detection of gravity waves induced by tsunamis, *Geophysical Journal International*,
501 *160*(3), 840–848.
- 502 Campbell, W. H. (1997), Introduction to Geomagnetic Fields, *Cambridge University*
503 *Press, New York*.
- 504 Cueto, M., D. McKnight, and M. Herraiz (2003), Daily geomagnetic variations on the
505 Iberian peninsula, *Geophysical Journal International*, *152*(1), 113–123.
- 506 Daubechies, I. (1992), Ten lectures on wavelets, *In: CBMSNSF Regional Conference*
507 *Series in Applied Mathematics, SIAM*, Philadelphia, PA. Vol. 61.
- 508 Domingues, M. O., O. J. Mendes, and A. Mendes da Costa (2005), Wavelet techniques in
509 atmospheric sciences, *Advances in Space Research*, *35*(5), 831–842.
- 510 Farge, M., K. Schneider, and N. Kevlahan (1999), Non-Gaussianity and coherent vortex
511 simulation for two-dimensional turbulence using an adaptive orthogonal wavelet basis,
512 *Physics of Fluids*, *11*(8), SYMPOSIUM PAPERS, 2187 (15 pages).

- 513 Frick, P., S. L. Baliunas, D. Galyagin, D. Sokoloff, and W. Soon (1997), Wavelet analysis
514 of stellar chromospheric activity variations, *The Astrophysical Journal*, *483*(1), 426–434.
- 515 Frick, P., A. Grossmann, and P. Tchamitchian (1998), Wavelet analysis of signal with
516 gaps, *Journal of Mathematical Physics*, *39*(8), 4091–4107.
- 517 Frick, P., R. Beck, E. M. Berkhuijsen, and I. Patrickeyev (2001), Scaling and correlation
518 analysis of galactic images. *Monthly Notices of the Royal Astronomical Society*, *327*(4),
519 1145–1157.
- 520 Iyemori, T., M. Nose, D. Han, Y. Gao, M. Hashizume, N. Choosakul, H. Shinagawa,
521 Y. Tanaka, M. Utsugi, A. Saito, H. McCreadie, Y. Odagi, and F. Yang (2005), Geo-
522 magnetic pulsations caused by the Sumatra earthquake on December 26, 2004, *Geophysical*
523 *Research Letters*, *32*(20), L20807.
- 524 Karinen, A., and K. Mursula (2005), A new reconstruction of the Dst index for 1932-2002,
525 *Annales Geophysicae*, *23*, 475–485.
- 526 Kherani, E. A., P. Lognonné, H. Hébert, L. Rolland, E. Astafyeva, G. Occhipinti, P. Coïsson,
527 D. Walwer, E. R. de Paula (2012), Modelling of the total electronic content and
528 magnetic field anomalies generated by the 2011 Tohoku-Oki tsunami and associated
529 acoustic-gravity waves, *Geophysical Journal International*, *191*(3), 1049–1066.
- 530 Klausner, V., M. O. Domingues, O. Mendes, and A. R. R. Papa (2013), Tsunami effects on
531 the Z component of the geomagnetic field, *Journal of Atmospheric and Solar-Terrestrial*
532 *Physics*, *92*, 124–136.
- 533 Larsen, J., and C. Cox (1966), Lunar and solar daily variation in the magnetotelluric field
534 beneath the ocean. *Journal of Geophysical Research*, *71*(18), 4441–4445.

- 535 Lognonné, P., E. Clévéde, H. Kanamori (1998), Computation of seismograms and atmo-
536 spheric oscillations by normal-mode summation for a spherical earth model with realistic
537 atmosphere *Geophysical Journal International*, 135(2), 388–406.
- 538 Mallat, S. (1991), Multiresolution approximations and wavelets orthonormal bases, *Trans-*
539 *actions of American Mathematical Society*, 315, 334–351.
- 540 Mallat, S. (1999), A Wavelet Tour of Signal Processing, *Academic Press, Elsevier Science*,
541 *ISBN 9780080520834*.
- 542 Manoj, C., A. Kuvshinov, S. Maus, H. Luhr (2006), Ocean circulation generated magnetic
543 signals. *Earth, Planets and Space*, 58, 429–437.
- 544 Manoj, C., S. Maus, and A. Chulliat (2011), Observation of Magnetic Fields Generated
545 by Tsunamis, *EOS, Transactions American Geophysical Union*, 92(2), 13–14.
- 546 Mendes, O. J., M. O. Domingues, A. Mendes da Costa, and A. L. Clúa de Gonzalez
547 (2005), Wavelet analysis applied to magnetograms: Singularity detections related to
548 geomagnetic storms, *Journal of Atmospheric and Solar-Terrestrial Physics*, 67(17–18),
549 1827–1836.
- 550 Mendes da Costa, A., M. O. Domingues, O. Mendes, and C. G. M. Brum (2011), In-
551 terplanetary medium condition effects in the south atlantic magnetic anomaly: A case
552 study, *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(11–12), 1478–1491.
- 553 Nesme-Ribes, E., P. Frick, D. Sokoloff, V. Zakharov, J. C. Ribes, A. Vigouroux, and
554 F. Laclare (1995), Wavelet analysis of the maunder minimum as recorded in solar diam-
555 eter data. *Comptes rendus de l'Académie des sciences, série II, Mécanique, physique,*
556 *chimie, astronomie*, 321(12), 525–532.

- 557 Occhipinti, G., P. Lognonné, E. A. Kherani, and H. Hébert (2006), 3D Waveform modeling
558 of ionospheric signature induced by the 2004 Sumatra tsunami. *Geophysical Research*
559 *Letters*, *33*, L20104.
- 560 Occhipinti, G., P. Coisson, J. J. Makela, S. Allgeyer, A. Kherani, H. Hébert, and
561 P. Lognonné (2011), Three-dimensional numerical modeling of tsunami-related inter-
562 nal gravity waves in the Hawaiian atmosphere. *Earth Planets Space*, *63*(7), 847–851.
- 563 Occhipinti, G., L. Rolland, P. Lognonné, and S. Watada (2013), From Sumatra 2004 to
564 Tohoku-Oki 2011: The systematic GPS detection of the ionospheric signature induced
565 by tsunamigenic earthquakes. *Journal of Geophysical Research: Space Physics*, *118*(6),
566 3626–3636.
- 567 Parkinson, W. D. (1983), Introduction to geomagnetism, *Scottish Academy Press, Edin-*
568 *burg and London*.
- 569 Pararas -Carayannis, G. (2010), The Earthquake and tsunami of 27 February 2010 in Chile
570 - Evaluation of source mechanism and of near and far-field tsunami effects, *Science of*
571 *tsunami hazards*, *29*(2), 96–126.
- 572 Paschmann, G., and P. W. Daly (1998), Analysis Methods for Multi-Spacecraft Data,
573 *ISSI Scientific Reports Series, ESA/ISSI, 1, ISBN 1608-280X*.
- 574 Peltier, W. R., and C. O. Hines (1976), On the possible detection of tsunamis by a
575 monitoring of the ionosphere, *Journal of Geophysical Research*, *81*(12), 1995–2000.
- 576 Rolland, L., G. Occhipinti, P. Lognonné, and A. Loevenbruck (2010), Ionospheric gravity
577 waves detected offshore Hawaii after tsunamis. *Geophysical Research Letters*, *37*(17),
578 L17101.

- 579 Russell, C. T., and R. C. Elphic (1978), Initial ISEE magnetometer results: magnetopause
580 observations, *Space Science Reviews*, 22(6), 681–715.
- 581 Stephenson, D., and K. Bryan (1992), Large-scale electric and magnetic fields generated
582 by the oceans, *Journal of Geophysical Research*, 97(10), 15467–15480.
- 583 Sonnerup, B. U. O., and L. J. Jr Cahill (1967), Magnetopause Structure and Attitude
584 from Explorer 12 Observations, *Journal of Geophysical Research*, 72(1), 171–183.
- 585 Sonnerup, B. U. O. (1976), Magnetopause and boundary, in *Physics of Solar-Planetary*
586 *Environments*, American Geophysical Union, ed. D.J. Williams, 541–557.
- 587 Tyler, R. H., J. M. Oberhuber, and T. B. Sanford (1999), The potential for using ocean
588 generated electromagnetic fields to remotely sense ocean variability. *Physics and Chem-*
589 *istry of the Earth, Part A: Solid Earth and Geodesy*, 24(4), 429–432.
- 590 Tyler, R. H., S. Maus, and H. Luhr (2003), Satellite observations of magnetic fields due
591 to ocean tidal flow. *Science*, 299, 239–241.
- 592 Tyler, R. H. (2005), A simple formula for estimating the magnetic fields generated by
593 tsunami flow. *Geophysical Research Letters*, 32, L09608, 4 pp.
- 594 Utada, H., H. Shimizu, T. Ogawa, T. Maeda, T. Furumura, T. Yamamoto, N. Yamazaki,
595 Y. Yoshitake and S. Nagamachi (2011), Geomagnetic field changes in response to the
596 2011 off the Pacific Coast of Tohoku Earthquake and Tsunami, *Earth and Planetary*
597 *Science Letters*, 311(1–2), 11–27.

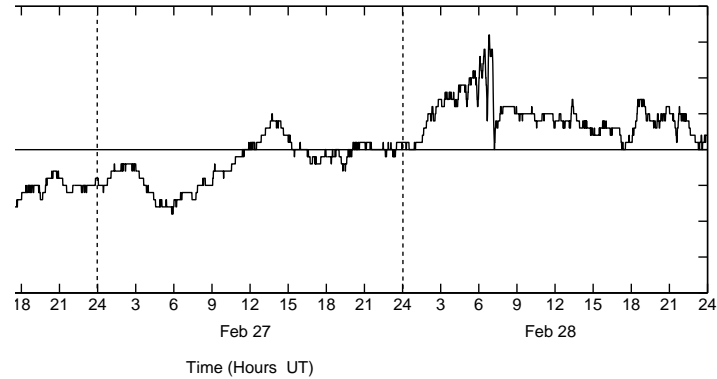


Figure 1. Minutely variation of the SYM-H index from the 26 to 28th of February, 2010. The vertical axis shows the provisional SYM-H signature and the horizontal axis shows the corresponding Universal time. The vertical dashed lines divide the tsunami event (February 27, 2010) from the previous day and the day after.

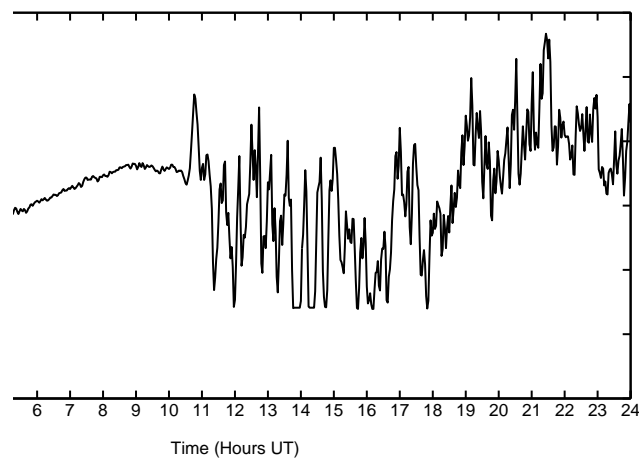


Figure 2. Variation of sea level at Callao La Punta, Peru, on the 27th of February, 2010.

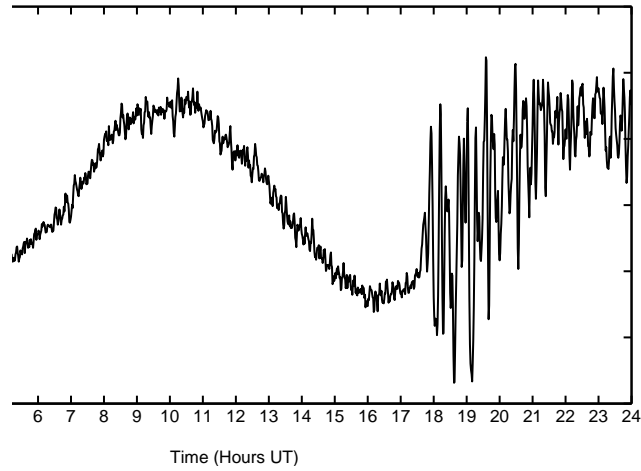


Figure 3. Variation of sea level at Papeete, French Polynesia, on the 27th of February, 2010.

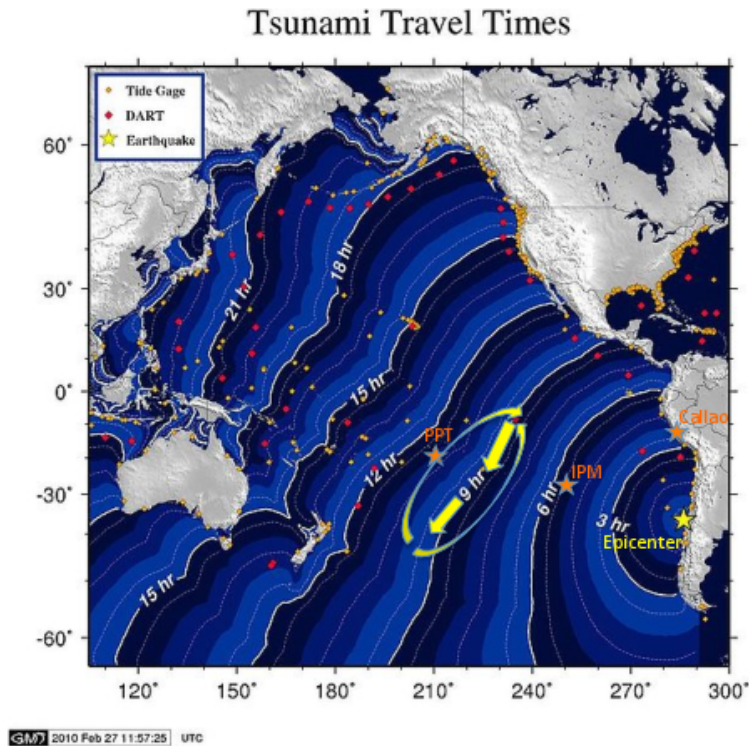


Figure 4. Adapted map of tsunami arrival times (courtesy of NOAA) showing the locations of Pt. Callao, and the PPT and IPM magnetic observatories. Also included is a diagrammatic example of tsunami-flow generated electric currents in the ocean: When the primary front has reached the 9-hr contour, motionally induced electric currents are generated in the sense of the straight yellow arrows. Because this induction is not uniform along the contour, and because electric charge must be conserved, electric currents such as shown by the curved arrows develop. Note that these electric currents (and the associated magnetic field) arrive in advance of the tsunami (see the animated tsunami simulation calculated with MOST forecast model provided on-line by the NOAA Center for Tsunami

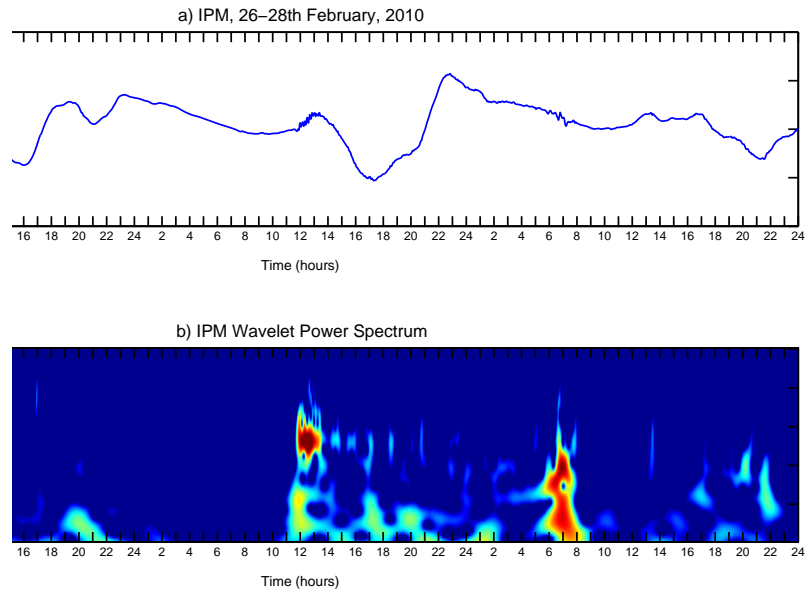


Figure 5. The GWT of IPM magnetograms for the days 26 to 28th of February, 2010. The top panel shows the filtered Z-component and the bottom panel presents the scalogram using Morlet wavelet, logarithmic scaled representing $\log_2(|W(a, b)|)$.

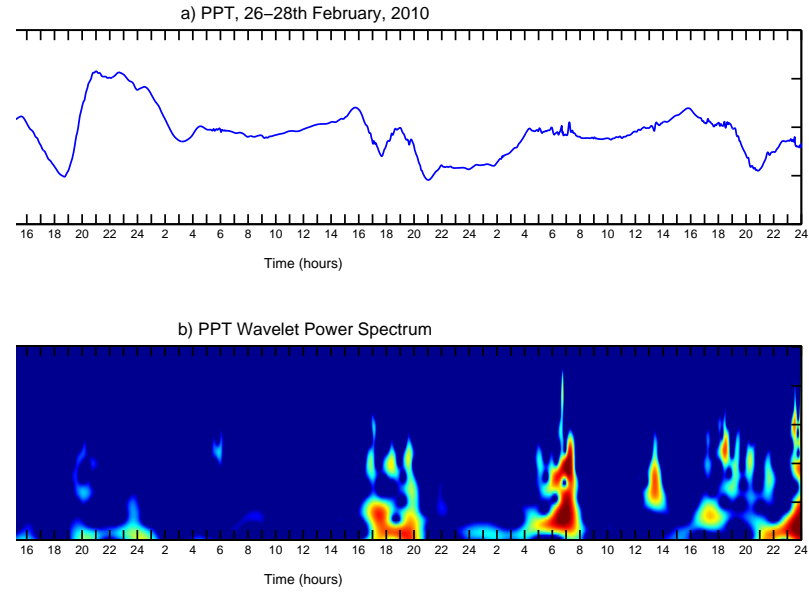


Figure 6. The GWT of PPT magnetograms for the days 26 to 28th of February, 2010. The top panel shows the filtered Z-component and the bottom panel presents the scalogram using Morlet wavelet, logarithmic scaled representing $\log_2(|W(a, b)|)$.

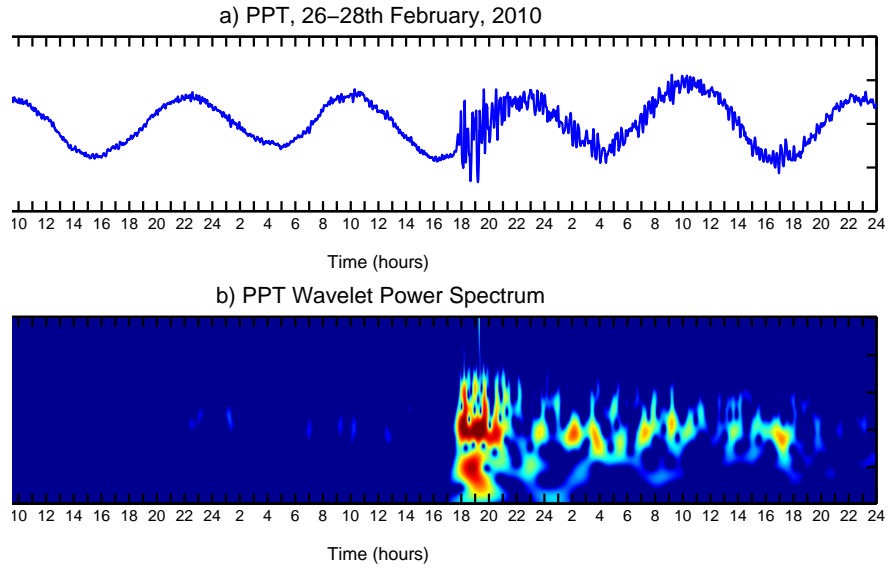


Figure 7. The GWT of PPT tide gauge dataset for the days 26 to 28th of February, 2010. The top panel shows the tide gauge data and the bottom panel presents the scalogram using Morlet wavelet, logarithmic scaled representing $\log_2(|W(a, b)|)$.

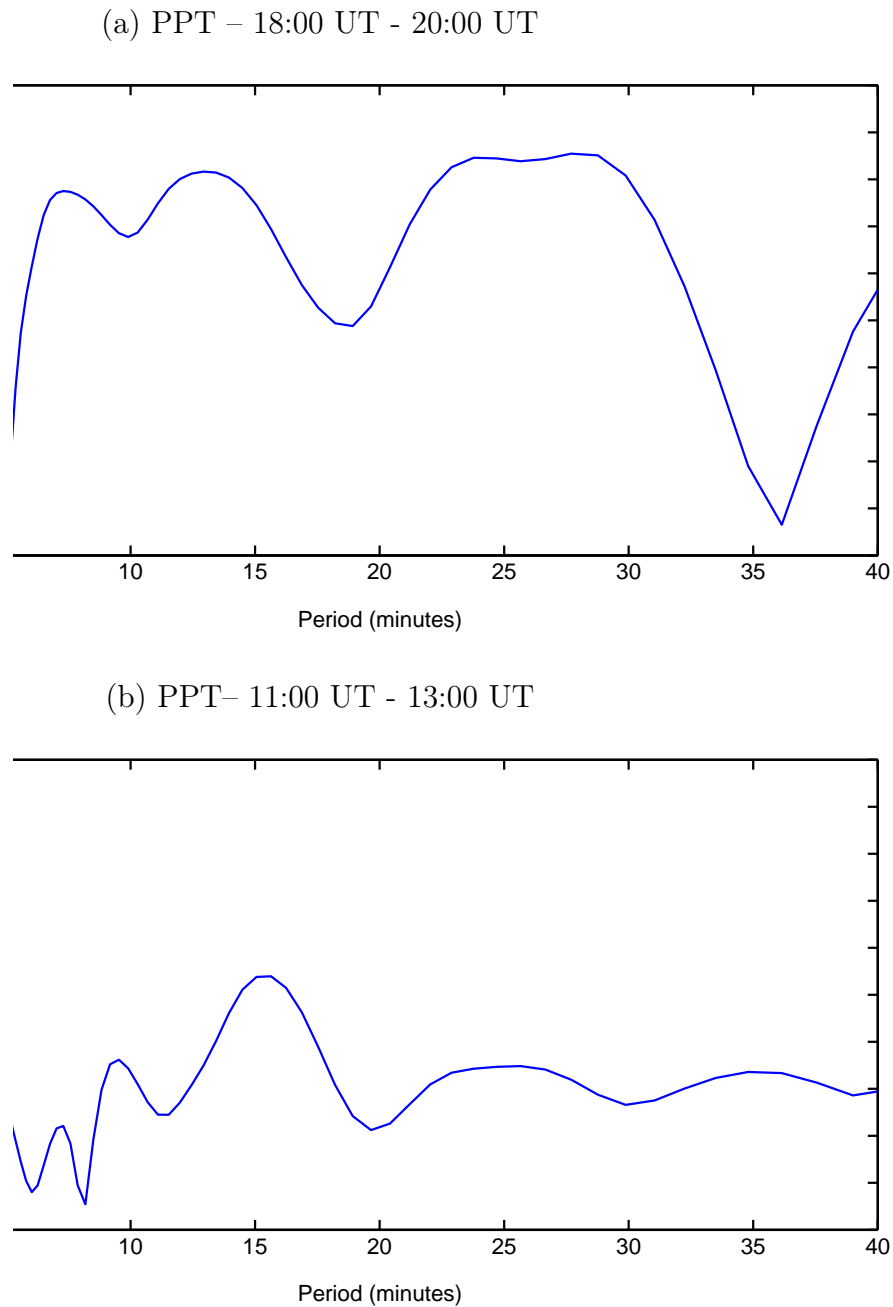
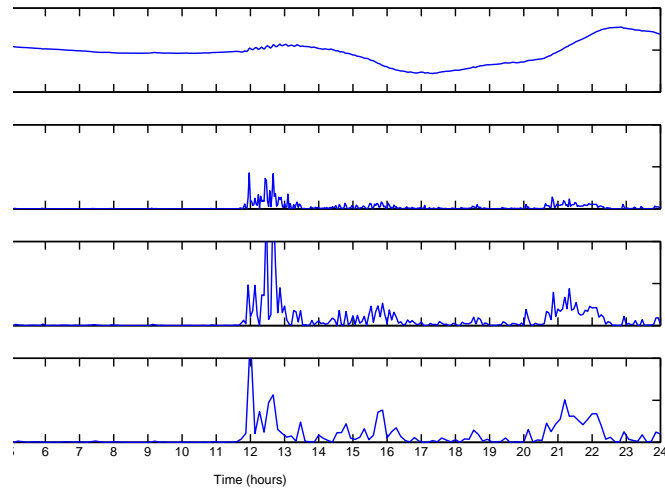


Figure 8. Modulus of the wavelet cross-correlation functions for PPT magnetogram and PPT tide gauge during the tsunami propagation (top panel) and the period before the tsunami arrival (bottom panel).

(a) IPM



(b) PPT

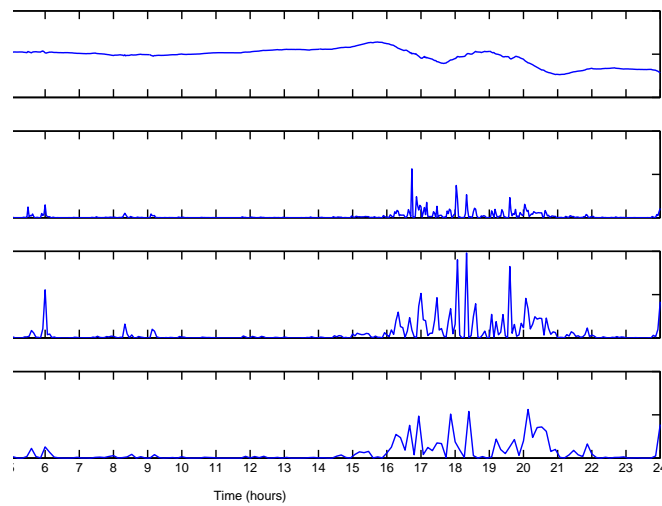


Figure 9. Magnetogram of the Z-component and the first three wavelet decomposition levels $d_j = (d^j)^2$ where $j = 1, 2, 3$ with pseudo-periods of 2, 4 and 8 minutes, for IPM (a) and PPT (b), respectively.

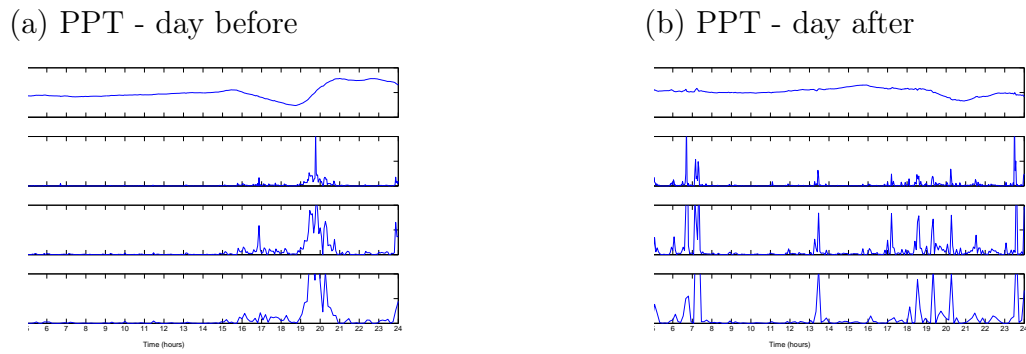


Figure 10. Magnetograms and the wavelet decomposition levels $d_j = (d^j)^2$ for $j = 1, 2, 3$ for PPT: (a) for the day before of the tsunami arrival (26th February, 2010) and (b) the day after (28th February, 2010), respectively.

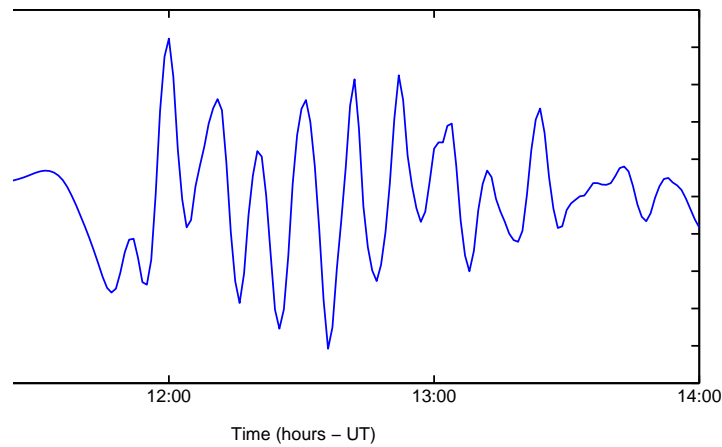


Figure 11. Variation of the filtered Z-component from 11:00 UT until 14:00 UT for IPM. Period of time corresponding to the tsunami propagation.

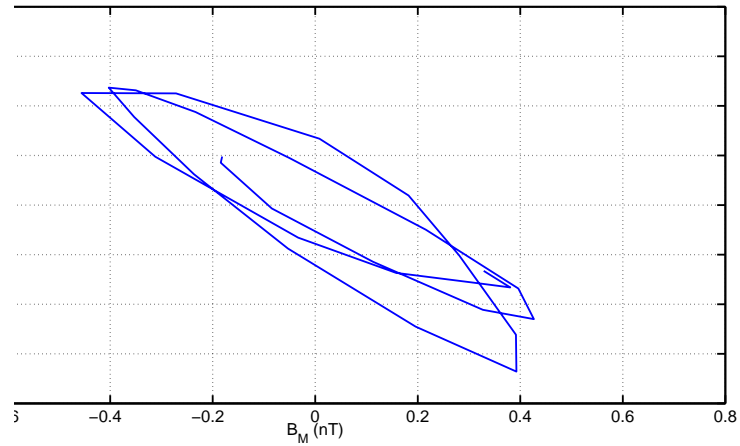


Figure 12. The transformation to the system of LMN coordinates for IPM on 27th February, 2010.

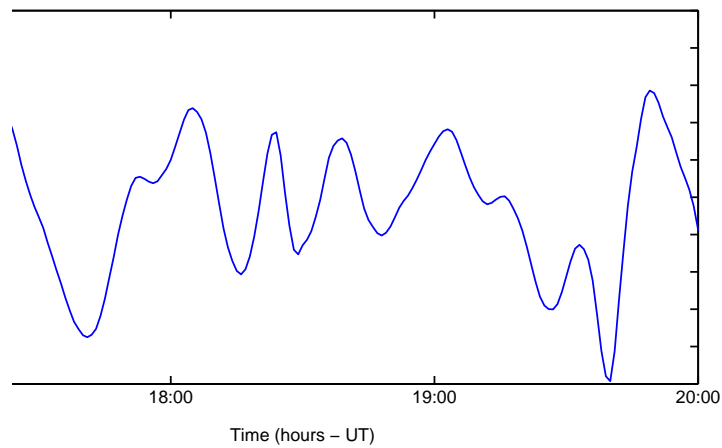


Figure 13. Variation of the filtered Z-component from 17:00 UT until 20:00 UT at PPT. Period of time corresponding to the tsunami propagation.

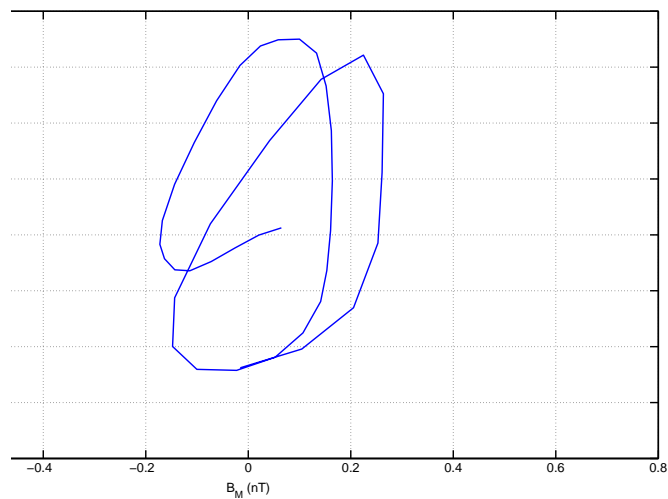


Figure 14. The transformation to the system of LMN coordinates for PPT on 27th February, 2010.

Table 1. INTERMAGNET network of geomagnetic observatories for the study of the Chilean tsunami, 2010.

Observatory	Geographic coord.		Geomagnetic coord.	
	Lat.(°)	Long.(°)	Lat.(°)	Long.(°)
IPM	-27.90	-109.25	-19.63	-34.47
PPT	-17.57	-149.58	-15.03	-74.53