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Source spectrum for the Algerian tsunami of 21 May 2003 estimated from coastal tide gauge data

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[1] On 21 May 2003 a submarine earthquake occurred near Algiers producing a tsunami that propagated northward and reached the Balearic Islands and the Levantine coast of the Iberian Peninsula within an hour. Despite that the generated tsunami was moderate, sea level variations inside certain harbors at the Balearic Islands were significant, producing severe damage to moored boats. Available tsunami records in the affected harbors are examined to estimate amplifications factors of arriving waves and spectral characteristics of the source. Comparison between background and tsunami oscillations at various sites allowed separation of the tsunami source properties from local topographic effects. The fundamental period of the reconstructed source spectrum is 21 min, which is in close agreement with that found by Alasset et al. (2006) based on modeling the tsunami initiation. **Citation:** Vich, M., and S. Monserrat (2009), Source spectrum for the Algerian tsunami of 21 May 2003 estimated from coastal tide gauge data, *Geophys. Res. Lett.*, *36*, L20610, doi:10.1029/2009GL039970.

1. Introduction

[2] North Algeria is a known active and hazardous seismic zone in the western Mediterranean basin. Seismic activity in this region is associated with the boundary between the Eurasian and African plates [*Hamdache et al.*, 2004]. On 21 May 2003 at 18:44 UTC a strong submarine shallow thrusting earthquake occurred at 7 km to the north of Zemmouri, about 50 km northeast of Algiers (Figure 1) producing a tsunami that affected the nearby coastal countries (i.e., Spain, France and Italy), but did not affect the Algerian coast [*Meghraoui et al.*, 2004]. The earthquake claimed 2271 human lives and injured more than 10000 while the tsunami sunk 10 boats and 10 more were damaged in the Balearic Islands (Spain) harbors. Due to its high social impact several studies have been done primarily focused on the earthquake [*Hamdache et al.*, 2004; *Bouhadad et al.*, 2004; *Delouis et al.*, 2004]. *Alasset et al.* [2006] modeled the tsunami initiation and propagation in order to test different seismic sources for the event. Synthetic waves were compared with coastal observations and concluded that the most plausible tsunami source should have a period of 20 min. However the authors compared model outputs with in situ coastal observations when they are surely strongly influenced by the local topographic response. The same tsunami event recorded at different places, even at nearby locations, may have completely different spectra, being these spectra mainly controlled by the natural resonance response of the bay or inlet where the tsunami is measured. On the other hand, different tsunamis events recorded at the same place usually present similar spectral contents. This fact has been confirmed by many authors (e.g., *Miller* [1972], *Soloviev and Kulikov* [1987] and *Baptista et al.* [1992], among many others) suggesting that the energy related to the tsunami source is mostly shaded by the usually more energetic topographic contribution.

[3] Furthermore, the particular characteristics of the damages produced by this tsunami, being only relevant in some very specific locations, reinforce the hypothesis of the major role played by the local harbor topography in the amplification of the sea level oscillations.

[4] The aim of this paper is to study the 21 May 2003 tsunami through the wave data recorded during the event on the coastline stations in the north-western Mediterranean region with the purpose to separate source and topographic effects. *Rabinovich* [1997] proposed a simple and ingenious method to separate source effects from topography by simply estimating the spectral ratios of tsunami to background spectra. This technique removes the major contribution of local resonance effects and provides as a result those energetic contents which are not associated with local topography. A very similar technique was applied successfully by *Monserrat et al.* [1998] to atmospherically generated seiches (meteotsunamis).

[5] The data set used for this study, along with a brief description of the spectral analysis techniques is presented in section 2. In section 3, the topographic response for every location is obtained and compared with the tsunami energy contents. The spectral ratios between tsunami and background are also used to compute the best estimation of the external tsunami source reaching the Balearic Islands and the Levantine coast of the Iberian Peninsula. A summary and some major conclusions are outlined in section 4.

2. Available Data and Methodology

[6] After the earthquake occurred in 21 May 2003 near Algiers, tsunami waves propagated northwards reaching the Balearic Islands and the Levantine coast of the Iberian Peninsula approximately 60 min after the main shock in the earthquake epicenter. Observed sea level oscillations reached at one specific location (Sant Antoni harbor, Balearic Islands) peak-to-through amplitude of more than 2 m. The sea level variations produced during this event are available at three sites in the Balearic Islands (Sant Antoni, Ibiza and Palma) and at two other sites in the Iberian Peninsula (Malaga and Valencia) (see Figure 1 for the location of the instruments). The sampling interval is of

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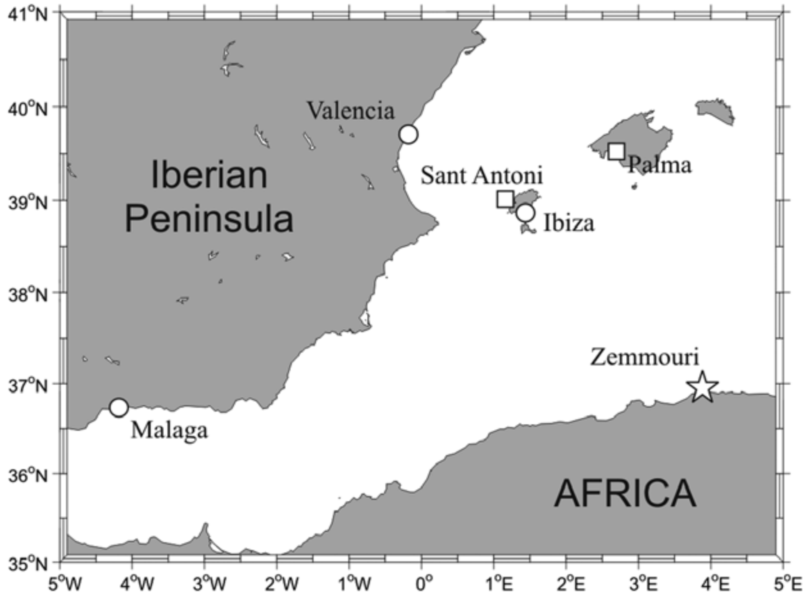

Figure 1. Zone of interest of the Western Mediterranean. The star denotes the epicenter location (Zemmouri) of the 21 May 2003 earthquake that produced the tsunami. The tide gauges locations are represented by circles for the 5 min sample interval instruments and by squares for the 2 min ones.

5 min for those tide gauges owned by *Puertos del Estado* (Ibiza, Malaga and Valencia) and 2 min for Sant Antoni (property of the University of the Balearic Islands) and Palma (from the mareograph network property of the *Instituto Español de Oceanografía*).

[7] Raw data, available from April to June, 2003, is pre-processed to identifying outliers and discontinuities, afterwards is also de-trended and tides (67 components) subtracted. Figure 2 shows two days of sea level residuals recorded at the five available stations at the time of the tsunami. The major tsunami characteristics as recorded at the five sites are summarized in Table 1.

[8] The duration interval of the tsunami event has been selected to be of 2 days (2880 min), which implies a length series of 1440 points for those instruments with 2 min sampling interval and 576 points for those sampled every 5 min. Since the records have different sampling intervals, the duration interval selection implies a compromise between having a time series long enough to still have significant degrees of freedom when spectral techniques are applied while the interval of significant oscillations occupies a significant part of the tsunami event (see Figure 2). When comparative analyses are required the time series with 2 min sampling interval should be re-sampled or, alternatively, the 5 min sampling interval time series interpolated every 2 min. As the second option would require artificially including non measured data in the analysis with the only advantage of increasing the Nyquist frequency up to 4 min^{-1}, the first option has been selected implying that all the spectra are computed with a Nyquist frequency of 10 min^{-1}.

[9] When applying the method suggested by *Rabinovich* [1997] to separate source from topographic effects, a background spectrum needs to be defined for every station. In order to minimize the possible effects that could arise from the selection of this background period, a set of six intervals with weak atmospheric activity and no seismic forcing with the same duration of the tsunami event are selected. These background intervals have been selected when sea level amplitudes remain small during the whole interval.

3. Data Analysis

[10] Spectra of the six backgrounds are estimated for each location using a Kaiser-Bessel window of 128 points with half-window overlapping resulting in 21 degrees of freedom. In principle background spectra may differ if the harbor response is sensitive to the characteristics of the forcing conditions, such as the angle of incidence of ocean waves. Harbors may oscillate differently under varying conditions. However, it is found that the six spectra are very similar for each station, which suggests that using their mean value as the background spectrum for every location will introduce minor effects in the purpose of computing the event-background spectral ratios.

[11] The spectra for the Zemmouri 2003 tsunami event and the mean background for the five available stations are shown in Figure 3. Tsunami and background spectrum shapes at any given location are very similar, although tsunami spectra are clearly more energetic. On the other hand, the spectra of different sites have significant differences at high frequencies, showing the resonance influence of local topography.

[12] Topographic response for every site is better identified in the background spectra where the natural oscillations are not obscured by the energetic characteristics of the forcing. Tide gauge at Sant Antoni is located inside an inlet with a fundamental resonant mode of 18 min. Ibiza spectrum is a little more complicated with major peaks at 58, 25 and 15 min. Palma shows a major peak at 75 min with some minor response at 20–30 min. Valencia presents two major peaks at 32 and 15 min and Malaga does not show

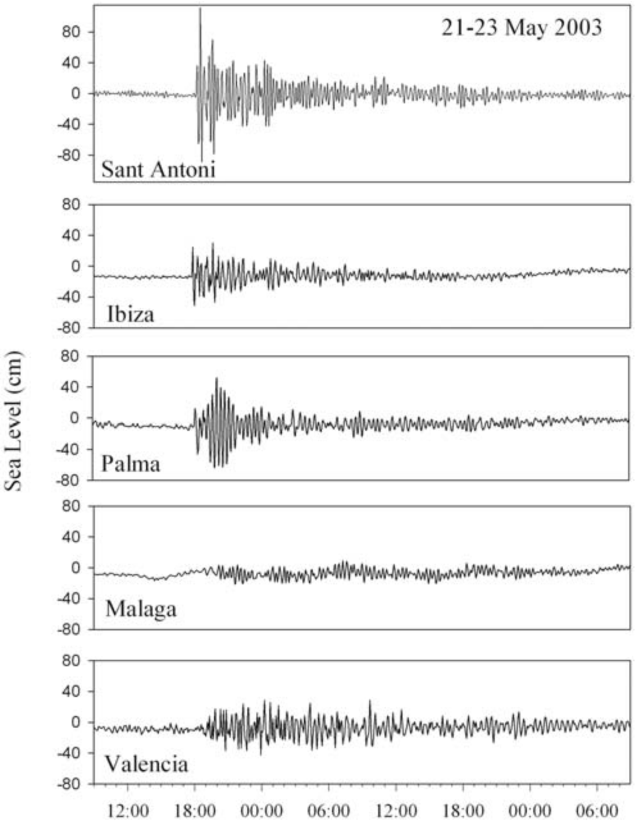

Figure 2. De-tided (residual) sea level variations at Sant Antoni, Ibiza, Palma, Malaga and Valencia at the time of the tsunami (UTC).

any clear resonant peak at its background spectrum. Tsunami spectra energetic contents results as a combination of topographic response and the tsunami forcing.

[13] Following *Rabinovich* [1997] the ratio between the tsunami spectrum and the one of the corresponding background gives information on the external tsunami source. The method is explained with detail by *Rabinovich* [1997] and is only briefly outlined here.

[14] The observed spectrum during the tsunami ($S_{OBS}(\omega)$) as a function of frequency (ω) may be considered as the sum of the energy associated with the tsunami source ($S_T(\omega)$) and the energy of the background oscillations ($S_B(\omega)$)

$$S_{OBS}(\omega) = S_T(\omega) + S_B(\omega) \tag{1}$$

If we assume that the topographic responses $T(\omega)$ are the same during the tsunami and background periods (this may be not strictly true and should be confirmed at posteriori), then:

$$\begin{aligned} S_T(\omega) &= T(\omega)E_T(\omega) \\ S_B(\omega) &= T(\omega)E_B(\omega) \end{aligned} \tag{2}$$

Where $E_T(\omega)$ and $E_B(\omega)$ represent the external forcing during the tsunami and background conditions respectively.

[15] The spectral ratio between the tsunami and background period is then:

$$R(\omega) = \frac{S_{OBS}(\omega)}{S_B(\omega)} = \frac{E_T(\omega)}{E_B(\omega)} + 1 \tag{3}$$

Therefore assuming that $E_B(\omega)$ is a universal function of frequency

$$E_B(\omega) = C\omega^{-2}, \tag{4}$$

where C is a constant increasing with decreasing water depth and depending on atmospheric activity, the spectral ratio may be considered as an estimation of the energy content of the external incoming waves during the tsunami.

[16] If this reasoning is correct, the tsunami-background spectral ratios should be therefore independent of the instrument location and entirely related to the forcing. In fact those aspects common to all the spectral ratios may be interpreted as a signal of the initial tsunami disturbance after the earthquake and the differences as any modification of the original forcing during the propagation. Thus spectral ratios for nearby stations are expected to be more similar than those obtained for relatively far away instruments.

[17] The spectral ratios for the three instruments at the Balearic Islands are shown in Figure 4a and those computed for the instruments at the Levantine coast of the Iberian Peninsula in Figure 4b. Spectral ratios are more energetic at the Balearic Islands as a result of the expected loose of energy as the tsunami travelled towards the northwest. The five spectral ratios present many similarities, mostly between nearby stations but even between relatively far away sites. These similarities give confidence to the methodology used. The clearest signal reflected in the spectral ratios is the presence of a significant peak at 21 min together with two secondary ones at 42 and 14 min. The strong similarities found between relatively far away instruments suggest that tsunami spectral contents were only slightly distorted during the propagation and that tsunami properties for different angles of propagation are for this case very similar.

[18] In order to highlight those aspects of the spectral ratios related to the forcing and separate them from any

Table 1. Properties of the 21 May 2003 Tsunami as Recorded at the Different Stations[a]

	Tsunami Arrival Time (UTC)	Tsunami Travel Time (min)	Maximum Wave Height (cm)	Time Maximum Waves (UTC)	Tsunami Periods (min)
Sant Antoni	19:44	60	201.2	21:04	21,18
Ibiza	19:29	45	76.3	21:19	58, 40, 25, 15
Palma	19:34	50	116.6	21:34	75, 40, 21
Malaga	21:50	186	24.9	23:30	35, 20
Valencia	20:10	86	52.8	23:20	32, 15

[a] Tsunami travel times have been computed assuming the earthquake occurred at 18:44 UTC.

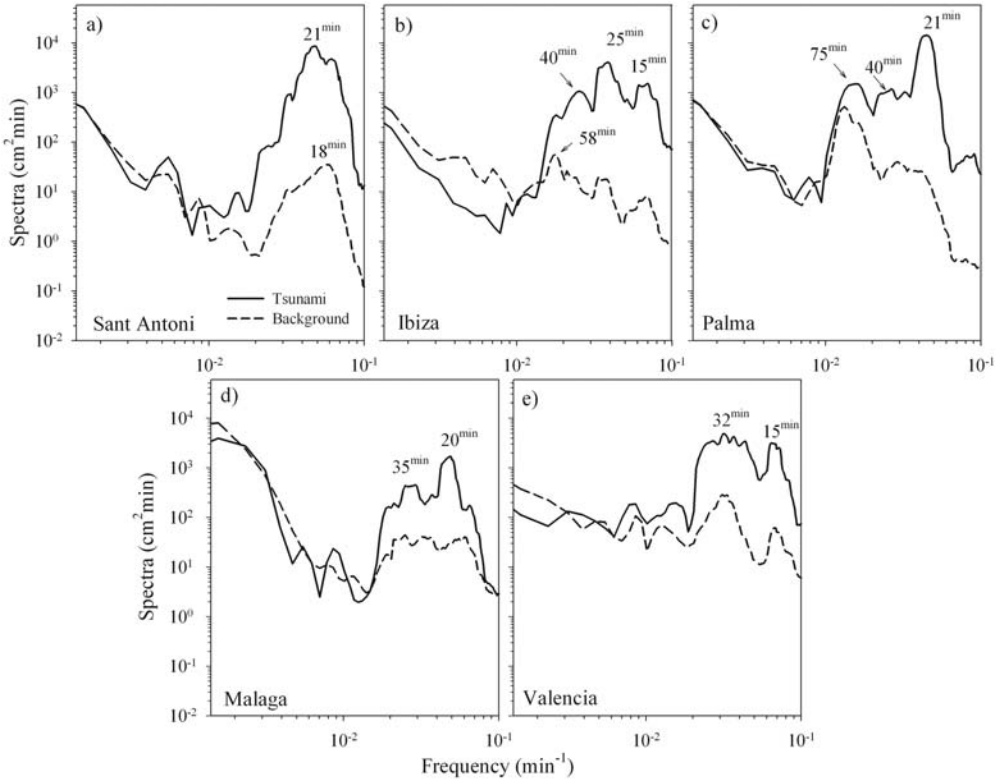

Figure 3. Spectra at each tide gauge for the tsunami (solid) and background (dashed). The main peaks are marked with their corresponding period.

signal associated with the tsunami propagation, a mean value of these spectral ratios has been computed. It should be noticed that the most energetic signal influences the mean value computation, for this reason the mean spectral ratio is also computed separately for the instruments at the Balearic Islands and for those located at the Iberian Peninsula. The comparison between the regional and the global mean spectra (Figure 4c) emphasizes similarities in the forcing.

[19] As expected, the Balearic mean is more similar to the global mean than the Iberian one, due to its higher energy, but they all present almost the same shape with very defined peaks at the same periods of 14, 21 and 42 minutes. The difference in spectral ratio values between Balearic and Iberian coast is most probably due to the already mentioned propagation energy loss.

4. Summary and Concluding Remarks

[20] The methodology developed by *Rabinovich* [1997] to separate source and topographic effects from coastal measurements is applied to the coastal data recorded at the Balearic Islands and Iberian Peninsula after the 21 May 2003 Algerian tsunami. The sea level spectra during the

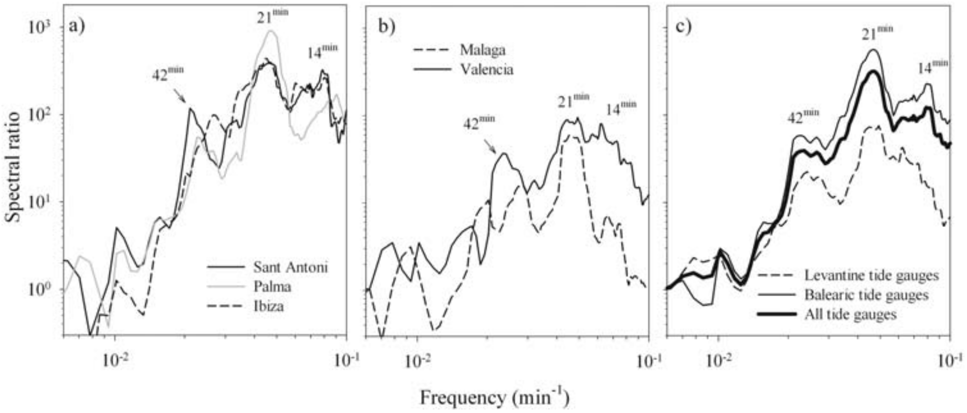

Figure 4. Tsunami-background spectral ratios for (a) the Balearic Islands stations and (b) the Levantine coast at Iberian Peninsula. (c) Mean values are computed for each region and for the total.

tsunami show the expected topographic influence. However, tsunami-background spectral ratios show many resemblances between stations despite some instruments were located relatively far away.

[21] Once topographic effects have been removed, spectral ratio similarities should be related to the tsunami source characteristics and the differences addressed to the tsunami changes experienced during propagation. The most relevant differences between computed ratios are in the total energy content. This is probably due to the expected energy loss associated with the tsunami propagations since the Levantine stations are farther away than the Balearic from the earthquake epicenter. On the other hand all the ratios present the same relevant peaks, the major one at 21 min, and two weaker ones at 14 and 42 min. This 21 min main peak is consistent with the 20 min period obtained by *Alasset et al.* [2006] when modeling the initial tsunami properties with seismical models.

[22] As a way to highlight the common aspects in the spectral ratios an averaged has been computed for the region of the Balearic Islands, the Iberian Peninsula coasts and the full region. This average may be considered as the best estimation of the external tsunami source affecting the coast and should be taken into account when seeking the best fit between synthetic and observed data by the modelers.

[23] Lastly, despite the fact that the response of a tsunami around an island group can be extremely complex and many factors may play a key role, such as the position of the harbor or its orientation [*Fritz and Kalligeris*, 2008; *Fritz et al.*, 2008], the results presented here give a clue to explain why the observed tsunami waves were particularly large at Sant Antoni when compared with other harbors in the region. The resonant normal mode for this harbor is about 18 min, very close to the tsunami source main peak, so the external tsunami energy may have been optimally amplified at this site by resonance.

[24] **Acknowledgments.** The data from Ibiza, Malaga and Valencia were kindly provided by *Puertos del Estado* in Spain. José Luis López Jurado from the *Instituto Español de Oceanografía* provided the Palma record.

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