Toward a Euro Mediterranean tsunami warning system: The case of the February 12, 2007, Ml = 6.1 earthquake

Marco Olivieri[1] and Laura Scognamiglio[1]

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[1] UNESCO has made a commitment to the scientific community for the creation of the North East Atlantic and Mediterranean Tsunami Warning System (NEAMTWS). We wonder: "Is the European Seismological community ready to run an Euro Mediterranean tsunami warning system?" In this study we use the February 12, 2007 Ml = 6.1 earthquake, which occurred close to the epicenter of the 1755 Great Lisbon event, as a case study to verify and discuss our actual capability of alerting for a hypothetical tsunami. Starting from the available real-time data and tools, we emulate an automatic real-time processing to perform the source analyses needed for discriminating a tsunamigenic earthquake, and subsequently we evaluate the time shift between the release of results and the potential tsunami waterfront reaching the coasts. **Citation:** Olivieri, M., and L. Scognamiglio (2007), Toward a Euro Mediterranean tsunami warning system: The case of the February 12, 2007, Ml = 6.1 earthquake, *Geophys. Res. Lett.*, *34*, L24309, doi:10.1029/2007GL031364.

1. Introduction

[2] The 26/12/2004 Sumatra Earthquake, which generated the well-known destructive tsunami, attracted considerable attention in Europe regarding the risk of tsunamis in the countries that border the Mediterranean Sea and the Atlantic Ocean. Many studies have been carried out on the historical Euro-Mediterranean Tsunamis, both from scientific observations and historical felt reports [*Soloviev*, 1990]. The Mediterranean Tsunamis Catalogue (http://tsun.sscc.ru/htdbmed/), which goes back to 1628 B.C., reports more than 400 occurrences in the last five centuries, many of them resulting in fatalities and widespread damage, such as the 1755 Lisbon, and the 1908 Messina earthquake induced tsunamis. The knowledge of the past, and the media attention on the effects of the Sumatra Earthquake, motivated the European Commission and UNESCO to encourage the scientific community for developing a monitoring service specifically for the Euro-Mediterranean Region. Its aim would be to prevent damage on the coastlines of the European and North Africa countries, by warning in case of a potentially tsunamigenic earthquake. This multidisciplinary project called NEAMTWS (North East Atlantic and Mediterranean Tsunami Warning System) has set 2011 as the deadline for being fully operational, while the end of 2007 is the date for bringing to an end the "implementation of the initial architecture and functions of the tsunami warning system through regional and sub-regional watch centers" (http://unesdoc.unesco.org/images/0015/001509/150941e.pdf).

[3] A Tsunami Warning System (TWS) would exploit the speed difference between seismic body waves propagating in the Earth (3–7 Km/s), and the edge of the tsunami wave propagating in deep water ($\sim$200 m/s). This differential travel time is used for issuing an alert prior to flooding of the coasts. The size of the Mediterranean Basin, and the existence of tsunamigenic sources close to the European Atlantic coast, increases the complexity of the problem and it requires a bigger effort for shortening the "alert time," i.e. the elapsed time between earthquake occurrence and the release of the warning. The faster the determination of source parameters, the greater the portion of coast which can be saved.

[4] A feasibility study for a TWS requires merging different research fields e.g. the location of the next potential sources, the knowledge of seafloor bathymetry, and the capacity of the existing seismic networks to provide quick and reliable earthquake parameter determination.

[5] In this study we will focus on the latter topic by using the February 12th 2007, Ml 6.1 Horseshoe earthquake as a case study for creating a TWS.

[6] This earthquake occurred in the Atlantic Ocean beneath the Horseshoe abyssal plain, about 500km west of the Strait of Gibraltar. This area sets in a wide and complex deformation zone delineating the convergence of the Eurasian and African plates that move relative to each other at 4 mm/yr [*Argus et al.*, 1989; *Sartori et al.*, 1994]. This region is also a candidate source region for the 1755 Great Lisbon Earthquake [*Martinez-Solares and Lopez Arroyo*, 2004], which generated one of the most destructive tsunamis of the modern European history. This earthquake gives us the chance to explore the capability of VEBSN, the Virtual European Broadband Seismic Network [*van Eck et al.*, 2004] (Figure 1), to provide the required seismological information for discriminating between a tsunamigenic and non-tsunamigenic earthquake, and to understand, through a real case, how fast and accurate a potential Tsunami Warning System can be.

[7] We will determine location, magnitude, depth and focal mechanism acting as if we were running different procedures in real-time and automatically. Those are the fundamental parameters needed to figure out the real capability of an earthquake to generate a tsunami wave, given that a tsunamigenic source can be defined as an offshore shallow large magnitude earthquake that ruptures at the surface with a non strike-slip faulting style. We will finally give an overview on time delays for different results

[1]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

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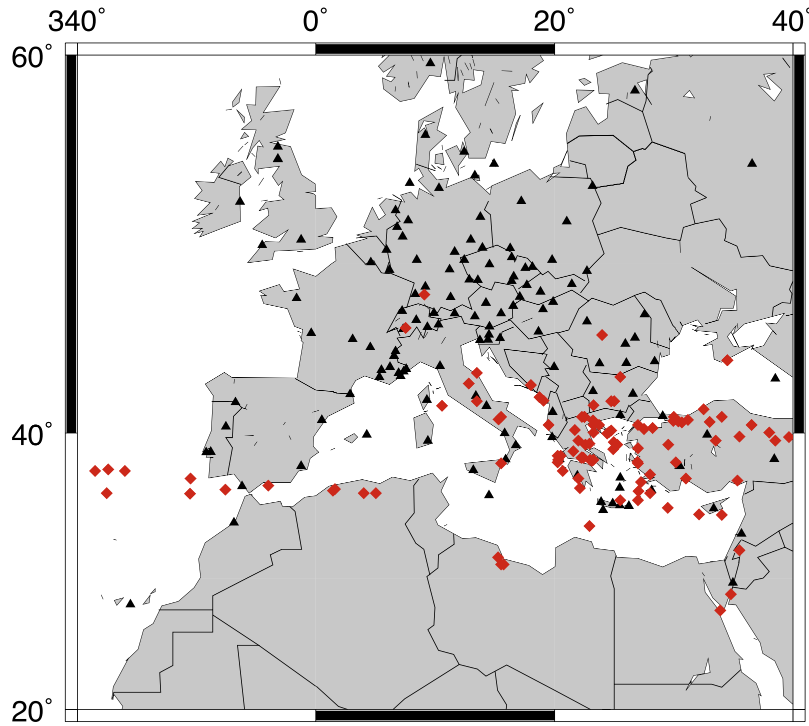

Figure 1. VEBSN broadband network (black triangles) in the region sized as the input grid for NLL. Red diamonds are the M $\geq$ 6.0 earthquakes that occurred between 1900 and 2000 as from the ISC catalogue (International Seismological Centre, On-line bulletin, http://www.isc.ac.uk, 2001).

to understand how an automatic system can be considered effective.

2. Analysis and Results

[8] We study the Horseshoe earthquake by using the four closest broadband stations contributing in real-time to the VEBSN: PACT.IP, SFS.GE, RTC.MN and MTE.GE. Their epicentral distance ranges from 342 Km for PACT to 553Km for MTE (Figure 2a). Four stations is the minimum data-set necessary for producing an alert following the chosen techniques that include standard hypocentral location.

3. Hypocentral Location

[9] We search for the hypocentral determination by using the NonLinLoc algorithm [*Lomax et al.*, 2000, hereinafter NLL] and setting the grid as large as the Euro Mediterranean region plus part of the Atlantic Ocean (Figure 1), with the seismogenic layer thickness equal to 660 km. The first location, using just P wave arrival times, gives: latitude 35.86, longitude −10.67 and depth 59.96 Km. The non-linear grid-search location performed by NLL is represented by a "cloud" of samples (dots in Figure 2) drawn from the spatial Probability Density Function (PDF). The extent and density of this PDF cloud indicates the non-linear confidence region for the event location (for a detailed description see *Lomax et al.* [2000]). As mentioned above, a four station data-set is the minimum requirement for getting the first hypocentral location and, considering that we are dealing with an "out of the network", earthquake, it is unrealistic to set a minimum azimuthal coverage rule that waits for later arrivals to reduce the azimuthal gap. The PDF associated to the location indicates that the epicenter is not well constrained and the depth, crucial for tsunami discrimination, is not reliable. The inclusion of the S wave arrival times reduces the locational uncertainty, and it fixes the depth at 36.0 km, while latitude and longitude become respectively 35.93 and −10.48 (Figure 2b). When compared to the IMP (Instituto de Meteorologia, Portugal) location (lat. 35.97, lon. −10.25, and depth 67 km), our epicenter results mislocated of about 40 km for P arrivals and 21 km for P and S arrival.

4. Magnitude Evaluation

[10] To provide a rapid estimate of the size of the earthquake we use the Mwp technique [*Tsuboi et al.*, 1995; *Tsuboi et al.*, 1999]. This methodology, routinely used at the Pacific Tsunami Warning Center, has the capability of giving reliable estimates of the moment magnitude both at regional and teleseismic distances just using the first seconds of seismograms after the P onset. Other rapid magnitude estimation methods used in Earthquake Early Warning are not usable in this contest because those apply just for station-event distances closer than 50Km in the case of P peak ground displacement [*Zollo et al.*, 2006], or 100 km for the P dominant period [*Allen and Kanamori*, 2003].

[11] We compute Mwp for all the stations using the P wave location as this is the only one available at this stage. Mwp results: 6.35 (PACT), 6.42 (SFS), 6.15 (RTC) and 5.75 (MTE), with an average estimate of Mwp = 6.2 ± 0.4. It is noteworthy that the approximated scalar moment M_0, used to compute Mwp, is proportional to the epicentral

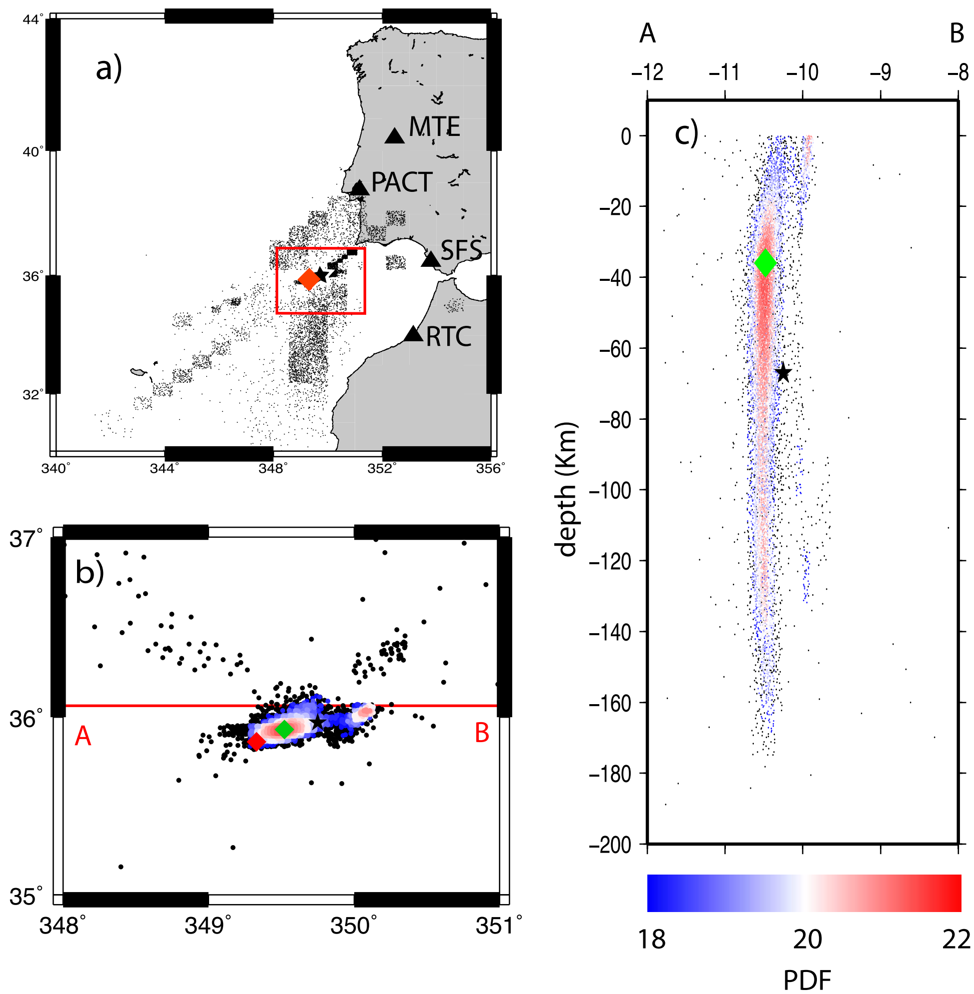

Figure 2. (a) Map showing the NLL epicentral location (red diamond) obtained by using only P arrival, the shape of the Probability Density Function (black dots), and the VEBSN stations used (black triangles). As a reference we also plot the IMP location (black star). (b) Zoom of the epicentral region (red rectangle in Figure 2a) for the case of P and S arrival time location (green diamond). The shape of the PDF is scaled in colour to evidence the higher PDF values (in red) in the denser area wrapping the NLL resulting epicenter. (c) East-west vertical section (A-B in Figure 2b) showing the NLL and IMP hypocentral depths.

distance. At such distances (300–500 km), the mislocation between the two computed epicenters and the IMP one results in a Mwp variation not exceeding 0.1.

[12] After recording the S wave train it becomes possible to compute the local magnitude Ml [*Richter*, 1935]. The two regional networks that routinely provide automatic Ml estimates, MedNet (http://mednet.rm.ingv.it), and Geofon (http://geofon.gfz-potsdam.de/db/eqinfo.php), both give Ml = 6.8, while the result from IMP Ml is 6.1. The reason of this discrepancy could be found in the way MedNet and Geofon evaluate Ml which is without using an appropriate, regionally calibrated predictive relationship for the earthquake area. It would also be interesting to compare our Mwp estimate with the energy-duration magnitude M_{ED} proposed by *Lomax et al.* [2007] that gives a good fit to the CMT Mw over a wide range of magnitudes and does not underestimate the size of the 2004 Sumatra earthquake, as occurs for Mwp. However, as pointed out by the authors, at present M_{ED} works for epicentral distances larger than 30 degrees and it will probably requires attenuation and filtering calibration when used at local or regional distance.

5. Moment Tensor Solution

[13] As outlined above, understanding the fault style of the earthquake is crucial for discriminating if it could generate a tsunami or not. Only normal and reverse fault earthquakes have the capability of being tsunamigenic, due to their vertical motion component. Strike-slip faults, characterized by horizontal motion are considered unfavorable for directly causing tsunamis because the water is not affected by horizontal shearing motion.

[14] We estimate the moment tensor solution for the Horseshoe earthquake by using the long period full waveform 1D Time-Domain INVerse Code (TDMT_INV *Dreger* [2003]) wrapped with an automatic procedure developed by Scognamiglio et al. (manuscript in preparation, 2007). This procedure uses 500 second waveforms from the origin time (OT), and performs a signal-to-noise analysis to select the

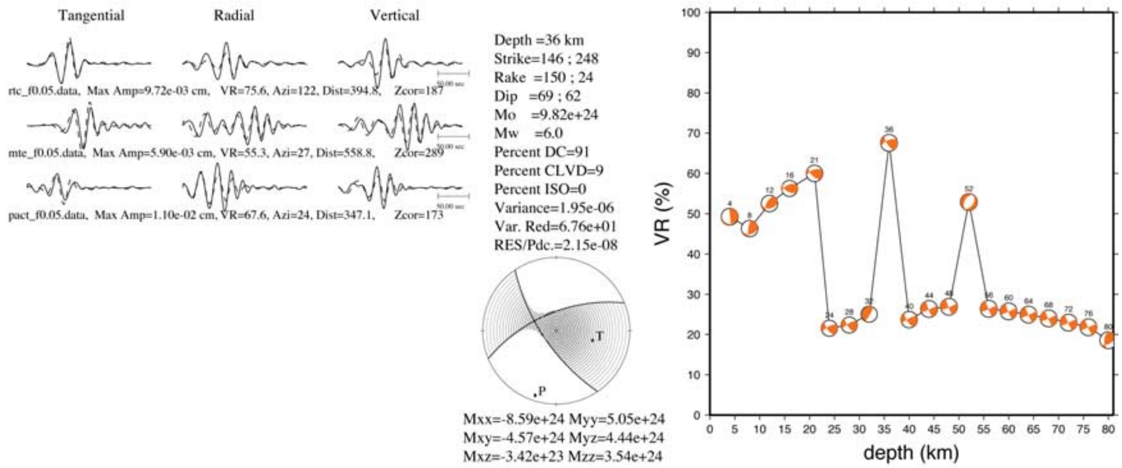

Figure 3. (left) Moment tensor solution obtained with 500s waveforms after the earthquake origin time, fixing the depth to the one obtained from the NLL with P and S waves hypocentral location. (right) Focal mechanism variation in a VR-depth plot. The highest variance reduction is obtained by inverting at 36 km depth.

best stations to invert. Among the 4 stations selected for this earthquake, 3 satisfy the imposed signal-to-noise ratio condition. Waveforms from those stations were inverted using the hypocentral location given by the NLL location with P and S waves (Figure 3). Meanwhile, to provide a further constraint to the hypocentral depth estimate, the inversion is run for 36 different depths between 4 and 80 km. Among all the moment tensor solutions obtained, the procedure selects the one with the largest overall variance reduction (Figure 3, right). In this case the best solution is given at the same depth as that resulting from the hypocentral location.

[15] Synthetic tests show that this technique is almost insensitive to inaccuracies in epicentral location: mislocation up to 0.15 degrees introduces changes on the fault plane orientation smaller than 10° [*Dreger and Helmberger*, 1993; *Kubo et al.*, 2002].

6. Discussion

[16] For the case of the February 12th 2007 Horseshoe earthquake, the four closest stations to the epicenter can provide sufficient information for determining the source parameters and discriminating between tsunamigenic and non-tsunamigenic earthquakes. The stations' distribution will be also crucial for determining the alert time, which is a function of the distance of the fourth closest station. Considering that this earthquake was located out of the VEBSN network, this is an odd case when monitoring the Euro Mediterranean region, as compared with events within the Mediterranean basin.

[17] For this specific case and assuming a P wave velocity of 5.8 km/s, and S-wave velocity of about 3.7 km/s we can expect to have the P picks at the four closest stations about 100 seconds after the OT, and the S-picks with an extra delay of 50 seconds. As shown in Figure 2a, even if the P waves location is close to the IMP one, the constrain is very poor when compared to the result obtained by using both P and S waves. However, due to the fact that it is still not trivial to accurately pick S waves using automated methods, we cannot argue that waiting for an extra 50 seconds will certainly improve the locational accuracy.

[18] With an average latency of about 10 seconds and a computation time shorter than 1 minute we can expect to release the first hypocentral determination 2 minutes after the OT and, if possible, the P and S one after about three minutes.

[19] Mwp gives an average value of 6.2 ± 0.4, which agrees well with the Mw estimate obtained some minutes later from the Moment Tensor inversion and with the IMP Ml. This result will be available few seconds after the P location (Figure 4).

[20] The automatic moment tensor analysis results in a strike-slip focal mechanism, with a small compressional component, and a moment magnitude Mw = 6.0, the same as the QuickCMT (www.globalcmt.org). The preferred depth is 36 km, the same found by the P and S waves hypocentral location. Comparing our automatic solution with the moment tensor solutions obtained by *Stich et al.* [2007] we found consistency in magnitude, hypocentral depth, and the fault orientations, while there is a poor agreement regarding the kinematics of the source. We found a wider strike-slip faulting style that is not unusual for the studied area (see global CMT catalogue, www.globalcmt.org). Moreover, the small observed discrepancies lay within the uncertainties associated with the different moment tensor methodologies.

[21] We have verified that the difference between the IMP epicentral location and that of the NLL for P and S waves, does not affect the focal mechanism solution. As shown by the synthetic tests [*Dreger and Helmberger*, 1993; *Kubo et al.*, 2002], larger mislocations result in erroneous fits of the seismograms and lead to unreliable and potentially wrong moment tensors. This problem could be overcome by implementing a MT spatial grid search over the region of interest, as suggested by *Kawakatsu* [1998] and *Tajima et al.* [2002]. This automatic system, which simultaneously

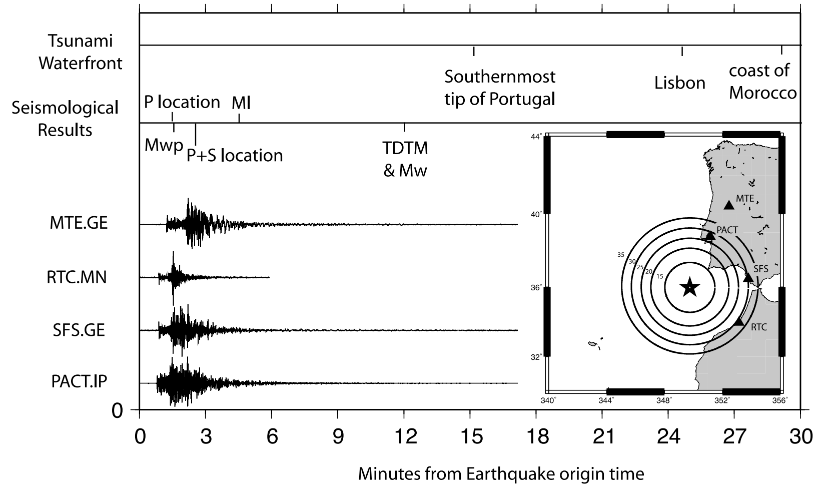

Figure 4. Starting from the top: time delays of the waterfront as expected at some relevant places around the epicenters; markers indicating the time at which each earthquake parameter can be estimated; time history of seismic data as recorded at the 4 closest stations used in this study. Circles in the map show the tsunami waterfront at 15, 20, 25, 30, and 35 minutes after the origin time.

determines centroid source location and seismic moment tensor for regional earthquakes, could significantly reduce the warning time [*Tajima et al.*, 2002] but it would require a detailed knowledge of the velocity structures, and very powerful computational capabilities. Given the use of 500 seconds of seismogram, the MT solution will be released 12 minutes after the origin time.

[22] Investigating the possibility that the studied earthquake fault is the one which produced the 1755 Lisbon earthquake is beyond the scope of this paper. The debate is still open on the precise location of the earthquake, and on the potential of the main tectonic structures active in the region to generate a $M_w > 8$ earthquake [*Stich et al.*, 2007; *Gracia et al.*, 2003].

[23] For the case of the Horseshoe earthquake, we were able to compute reliable estimates of the location depth and magnitude within 2 or 3 minutes by using the four closest stations and the NonLinLoc algorithm and Mwp technique. Local magnitude Ml takes longer to be released and can be inaccurate when not calibrated for the specific region. About 12 minutes after the earthquake occurrence we obtained the moment tensor solution that also confirms both the Mw predicted by Mwp, and the hypocenter depth. All these results can be considered sufficient for discriminating between tsunamigenic or non-tsunamigenic earthquakes leaving a time window of 3 minutes for warning the southernmost part of Portugal, about 8 minutes in the case of Lisbon, and 13 minutes for the coasts of Morocco (Figure 4). Generally speaking, the efficiency of a Tsunami Warning System will benefit both from accurate estimates of the source parameters and from rapid release of such information.

[24] The results presented in this paper are encouraging in terms of our capability to quickly estimate source parameters, obtaining robust and unrevised results. The data and techniques have been shown to be appropriate for meeting the preliminary NEAMTWS objective which is, in the case of earthquakes within the Mediterranean basin or in the Northern Atlantic Ocean, to protect not the closest coasts but the other side of the basin. This study supports the idea of using the Virtual European Broadband Seismic Network as the backbone for the forthcoming European Tsunami Early Warning System. The average latency (the time delay between the actual time and the last received sample) for fully functioning stations using seedlink protocol [*Hanka and Kind*, 1994] over an Internet connection is smaller than 20s. This induces a small and almost negligible extra-delay on the evaluation of the warning time. Further efforts, currently in place on several seismic networks, to increase the number of real-time open broad-band stations in the region will increase the robustness of the solutions reducing the alert time and possible false alarms. In parallel, a number of efforts (such as the European Commission project NEAREST) are in place for deploying OBS (Ocean Bottom Seismometers) networks in the Mediterranean and in the Atlantic Ocean to close the gaps of inland seismic networks. The availability of such data in real time would help to better estimate the earthquake source and to reduce the required time for this estimate.

[25] The future availability of datasets of potentially tsunamigenic earthquake sources will be used to provide real estimates of delays, and through identifying savable areas based on the results of this work this will also help to release worst case scenarios for the region.

[26] **Acknowledgments.** BSL "Earthquake of the week" meeting triggered this idea, thanks to the SeismoLab people of UCBerkeley. VEBSN waveforms are from www.orfeus-eu.org. L. Scognamiglio was supported by EC project "NERIES" (contract 026130). The manuscript was improved with the help of A. Michelini, Rachel Cassidy, and the two anonymous reviewers.

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M. Olivieri and L. Scognamiglio, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, I-00143 Roma, Italy. (olivieri@ingv.it)