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A Regional Approach for Earthquake Early Warning in South West Iberia: A Feasibility Study

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Abstract A Spanish ALERT-ES project was set up to study the feasibility of setting up an earthquake early warning system to warn of potentially damaging earthquakes that can occur in the Cape of San Vicente (SV)–Gulf of Cadiz (GC) area, located in the south west of the Iberian Peninsula, such as the 1755 Lisbon earthquake. Four events, located close to the epicenters of the largest earthquakes in the area, were simulated using different seismic software packages (Earthworm, SeisComP3, and PRobabilistic and Evolutionary early warning SysTem [PRESTo]) and the errors were analyzed. In addition, a study about the blind zone and the lead time at six selected targets was carried out. The results show a blind zone in the southwest corner of Portugal for SV earthquakes and also a blind zone in the coastal area, from Portimao to Cadiz, for the GC earthquakes.

Introduction

The south of the Iberian Peninsula is located in a complex plate boundary between Eurasia and Africa, where seismicity is characterized by the occurrence of moderate earthquakes at shallow or intermediate depths (Buforn *et al.*, 1988, 2004). However, some very large earthquakes have been registered, especially in the Cape of San Vicente (SV)–Gulf of Cadiz (GC) area. The largest one, the 1755 Lisbon earthquake M_w 8.5 (Martínez Solares and López Arroyo, 2004) with a big associated tsunami, caused more than 15,000 casualties and very significant damage in the southwest of the Iberian Peninsula and in northwest Morocco (Fig. 1). But this is not an isolated case; in the last 50 years, large earthquakes have occurred, such as GC 1964 (M_s 6.5) and SV 1969 (M_s 8.1). Earthquakes of smaller size in this area can also produce some damage and a considerable social alert because they are felt in a wide region, as it happened in the 2009 earthquake M_w 5.5 felt in a wide zone of the southwest of the Iberian Peninsula and as far as Madrid (Instituto Geográfico Nacional [IGN], 2014). For this reason, southwest Spain and south Portugal areas have particular need for the development of an earthquake early warning system (EEWS).

The basic hypothesis of most of EEWS is that the early arrival and low-energy *P* wave carries information about earthquake size and seldom causes damage, whereas the *S* wave is primarily responsible for earthquake-shaking damage. This makes it possible to determine the earthquake parameters from a quick analysis of the initial portion of the *P* wave and provides a few seconds warning before the more severe shaking produced by *S* waves, thus allowing for short-term damage mitigation. Generally, EEWS use two parameters for the real-time magnitude estimation: the predominant period (τ_c) (Kanamori, 2005; Wu *et al.*, 2007), and the peak displacement (Zollo *et al.*, 2006; Satriano *et al.*, 2010).

In the regional EEWS approach, the earthquake hypocenter and the M_w magnitude are estimated using as few *P*-wave picks as possible, providing a quick warning about the *S*-wave arrival time at the targets (lead time), the expected peak ground motion, and so on. Nevertheless, there will be areas where the *S* wave will have already arrived (blind zone), and a warning is not possible. The main goal of ALERT-ES project was to study the feasibility of setting up a regional EEWS for southwest Iberia. In this article, four representative events, located in the same area where the largest events have occurred (see Fig. 1), have been simulated using three different seismological software packages. The location and origin time errors were analyzed as well as the blind zone and the lead times at targets, the time since a warning is declared until the *S* wave arrives at the target.

Database

A waveform database for SV–GC area earthquakes was created using data from 105 events, with magnitudes bigger than m_b 3.8, recorded in the 2006–2011 period by 24 broadband (BB) selected stations (see Fig. 1) that belonged to Western Mediterranean, IGN and Instituto Português do Mar e da Atmósfera networks. Most of these earthquakes have epicenters located offshore at distances around 200 km from the coast for SV and 50 km for GC events. This situation is similar to Mexico, where they take advantage of an EEWS that is operating with the earthquakes located about 300 km away from Mexico

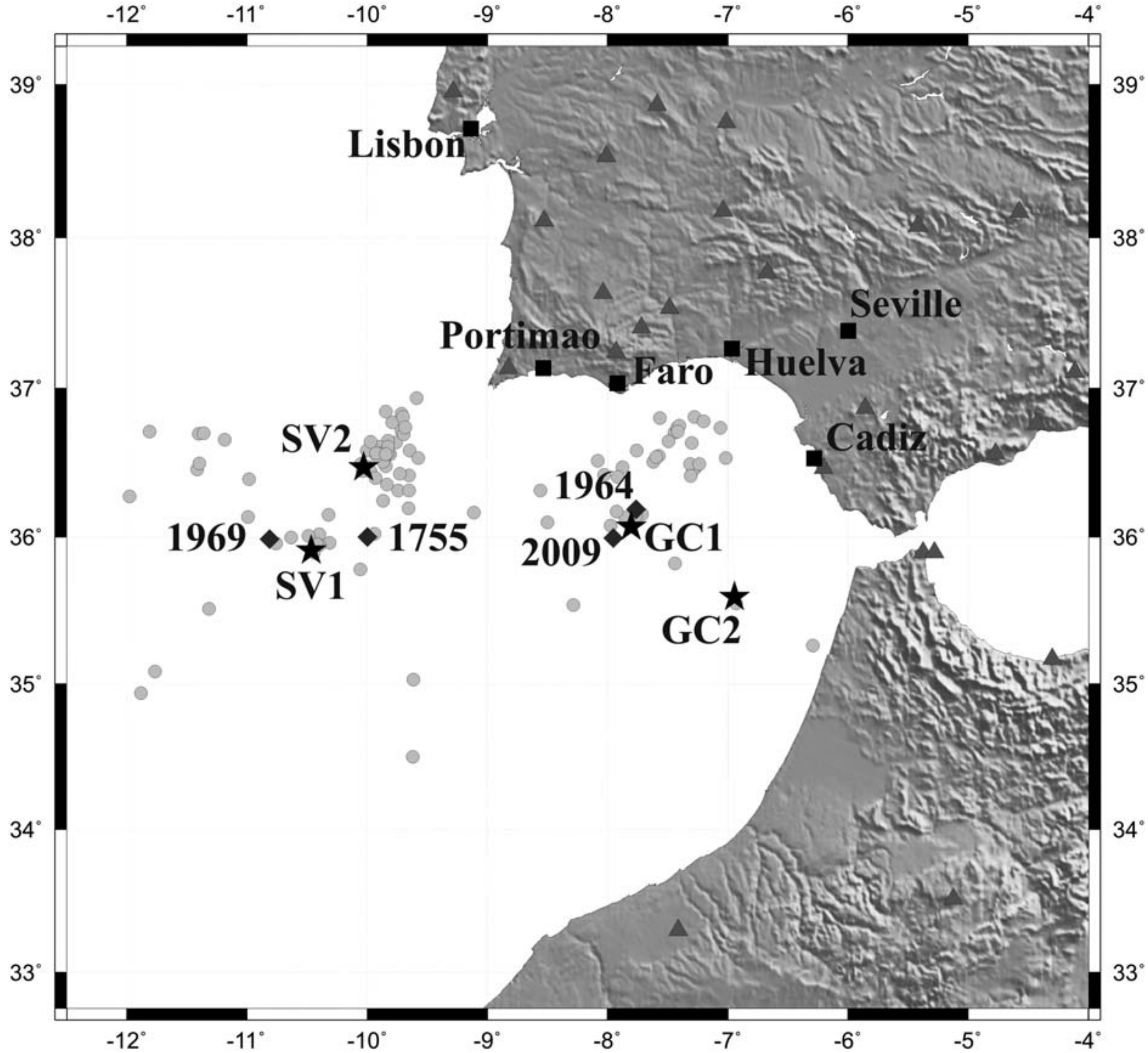

Figure 1. Database earthquakes (dots) in the test zone, San Vicente (SV)–Gulf of Cadiz (GC) area, in the 2006–2013 period, with magnitude larger than or equal to 3.8. The biggest earthquakes occurred in the area (gray diamonds), the four selected earthquakes (stars) for simulation, the selected broadband stations (triangles), and the targets (squares) are shown.

City (Espinosa-Aranda *et al.*, 1995). However, in this article, this advantage is reduced by the current poor density, poor azimuthal coverage, and the geometry of the available seismic stations deployed in the region.

Finally, four representative earthquakes (Table 1), located close to the epicenters of the large events occurred in the area, with a very well constrained location, a well-known M_w magnitude, and a signal-to-noise ratio (SNR) bigger than

Table 1
Selected Earthquakes in the Test Area

	Date (yyyy/mm/dd)	Origin Time (hh:mm:ss.ss)	ERR (s)	Latitude (°)	Longitude (°)	SMAJ (km)	SMIN (km)	AZ (°)	Depth (km)	ERRZ (km)	M_w	NSTA	GAP (°)
SV1	2007/02/12	10:35:24.44	0.42	35°.9100	−10°.4684	5.4	3.8	114	30	16.3	6.1	161	129
SV2	2009/12/17	01:37:49.74	0.51	36°.4702	−10°.0318	5.8	3.9	101	36	17.3	5.5	144	145
GC1	2009/08/18	06:56:04.23	0.10	36°.0689	−7°.8024	1.0	0.5	45	50	2.2	3.9	106	150
GC2	2013/12/16	07:06:23.19	0.82	35°.5932	−6°.9431	8.4	4.7	24	40	fixed	4.8	62	161

The hypocenter location parameters are taken from the Instituto Geográfico Nacional (IGN) catalog. ERR, the error of the origin time in seconds; SMAJ, the major axis of the error ellipse; SMIN, the minor axis; AZ, the azimuth of the major axis; ERRZ, the error in depth; NSTA, the number of associated stations; and GAP, the azimuthal gap.

20 dB, were chosen (see Fig. 1) to study the feasibility of a regional EEWS for the southwest Iberian Peninsula.

Seismic Software

Three real-time seismic software packages have been used, the widely distributed SeisComP3, Earthworm, and the PRobabilistic and Evolutionary early warning SysTem (PRESTo), all of them configured with the optimal parameters for this seismic area. A similar grid and the same earth velocity model (IGN, Mezcua and Martínez Solares, 1983, for the crust and International Association of Seismology and Physics of the Earth's Interior 1991 [IASPEI91] for the mantle) were used to compare the results.

For Earthworm software (U.S. Geological Survey, 2005), the key of the optimization of the system is focused on the processing modules to get a first location. The picking module (pick_ew), based on Allen (1978), was tuned and tested for a total of 18 BB stations (with a pick mean error below 0.2 s), using the vertical components of registers, with an SNR bigger than 10 dB, from a total of 93 earthquakes available in the database. For the picks association and location module (binder_ew), a minimum of six *P*-waves picks association was fixed to declare events to assure their coherence and supplies a rough and quick hypocentral location.

In the case of SeisComP3 software (Hanka *et al.*, 2010), the recent Jakarta 2014.248 (version 1.4.0) was used. The scautopick module (with a detector based on Allen's algorithm) was optimized by filtering the vertical records with a four-poles Butterworth band-pass filter (4–16 or 1–10 Hz for HHZ channels and 2–8 Hz for BHZ channels); also, a repicking algorithm based on the nonautoregressive Akaike information criterion method of Maeda (1985) (also see Zhang *et al.*, 2003) was selected, although this introduces 2–3 s of processing delay. In addition, there is another delay because, in playback mode, the time to process a pick varies depending on when data enter the scautopick module and the number of stations configured for the simulation. The location module (scautoloc) uses the location program LocSat (Bratt and Naggy, 1991) and has been configured by setting a maximum residual of 5.0 s and a root mean square less than 2.0 s. In addition, the default 30 s processing delay was drastically reduced to a few seconds, by changing the default amplitude type.

PRESTo is a real-time EEWS software developed by the RISSC Lab (Naples, Universitá Federico II) and is under testing in Southern Italy at the Irpinia Seismic Network (Satriano *et al.*, 2010), using acceleration signals, so that velocity records available from BB stations must be previously differentiated to get accelerations. The parameters of the picking algorithm, developed by Lomax *et al.* (2012), were configured with a filter window of 32 s, long-term window of 10 s, and the thresholds of 15 and 20 s. The binder was configured with 15 s for coincidence and 90 s for association. This software also provides a quick estimation of the magnitude based on the *P*-wave peak displacement and a probabilistic Bayesian method (Lancieri *et al.*, 2011) configured as default.

During the software configuration process, all 105 events from the database were simulated to study the optimal number of picks for providing an initial epicenter within a 50 km radius centered on the IGN location or the final location of the system. Waiting for a large number of picks, however, increases the elapsed time and the blind zone, and a compromise between location precision and elapsed time is needed. As results of these previous simulations, in which false picks were rejected, the 45% of the initial locations with four picks were farther than 50 km relative to the IGN location, 25% with five picks and less than 5% with six-pick association, which was chosen to configure the three systems.

It should be noted that the more picks used for association the more azimuthal coverage is obtained. For SV earthquakes, in general, the azimuthal coverage varies from 10° to 45° when the number of picks is increased from 4 to 6; meanwhile for the GC earthquakes, the azimuthal coverage varies from 85° to 115°.

Finally, the three software packages were configured for a minimum of six-pick association for providing a location.

Methodology

The first step was to simulate with these seismic software packages the four selected events. Then, an error analysis of the onset picks, the hypocenter location and the origin time were carried out. Also, the elapsed time (seconds elapsed between the origin time and the instant in which an event is declared) and the blind zone were estimated. Finally, the lead times at targets were computed.

Simulations

The four representative events selected were simulated over these three seismic real-time processing systems and the automatic *P*-wave picks, taken from the log files, were compared with manual picks provided by an analyst, as well as the origin times, and hypocentral locations were confronted with the reference (IGN catalog and the simulation final solution).

The elapsed time T_w was first computed as the seconds between the origin time and the instant in which an event is declared and can be formulated as

$$T_w = T_r^i + T_l^i + T_p^i + T_a^i + T_e + T_m, \qquad (1)$$

in which the superscript i refers to each station; T_r is the *P*-wave propagation time needed to reach the station; T_l corresponds to the communication system latency (note that a fix value of 8 s, close to the average of the delays for IGN and Institut Cartogràfic i Geològic de Catalunya VSAT stations, was assumed); T_p is the consumed time for the picking module; T_a corresponds to the time that the pick is waiting for association; T_e is the time consumed by the event and

Table 2
Location Errors (Simulation—IGN Reference) for Six-Station Configuration and the Final Solution, Taking into Account All Stations

		Δ Origin Time (s)		Δ Latitude (km)		Δ Longitude (km)		Δ Distance (km)		Δ Depth (km)	
		6ST	All	6ST	All	6ST	All	6ST	All	6ST	All
SV1	Earthworm	11.2	9.9	76	62	49	48	90	78	8	8
	SeisComP	−2.7	0.3	−6	2	−11	2	12	3	−20	63
	PRESTo	−0.5	−0.3	3	4	−9	−4	10	6	8	10
SV2	Earthworm	1.7	1.4	5	4	1	8	5	9	32	32
	SeisComP	16.9	0.9	90	2	108	2	140	3	−26	38
	PRESTo	−10.2	0.3	−52	−1	−68	2	86	2	3	3
GC1	Earthworm	−5.7	−5.2	−37	−41	5	1	37	41	−22	−22
	SeisComP	−5.7	−3.1	−25	−2	−2	2	26	3	−40	−40
	PRESTo	0.4	0.1	10	7	3	2	11	8	−11	−10
GC2	Earthworm	−0.6	0.4	−9	2	−7	−1	12	2	8	8
	SeisComP	0.01	−0.8	13	−5	−1	−2	13	5	−30	47
	PRESTo	−0.9	−0.4	7	−4	−1	−1	7	5	−2	0

Positive errors mean that the simulation result has a later origin time, more toward the north, more toward the east, or a deeper location than the reference (IGN catalog).

location modules; and, finally, T_m is the execution time for the magnitude module. Although the T_m value cannot be estimated with the current magnitude modules in Earthworm and SeisComP3 software, because they do not use the *P*-wave parameters to estimate the magnitude, it was fixed to 0.05 s (the mean value obtained in the PRESTo simulations).

However, there is another simple way to compute the elapsed time by subtracting the location message time of the system from the origin time and adding the executing time of the magnitude module and the latency of the communication system.

The blind zone corresponds to a circle centered in the epicenter location and radius of the *S*-wave propagation distance during the T_w time, calculated as follows:

$$R_{bz} = V_S \times T_w, \quad (2)$$

in which V_S is the *S*-wave velocity (assumed as 3.4 km/s). Therefore, the elapsed time and the blind-zone radius are proportional.

Lead Time at Targets

There are several criteria used to select targets taking into account the seismic hazard: population, tourist zones, important buildings, big infrastructures, and so on. We have selected a total of six targets (see Fig. 1), three in southwest Spain (Huelva, Seville, and Cadiz) and three in Portugal (Portimao, Faro, and Lisbon), that fulfill those criteria simultaneously.

To calculate the lead time at targets, the following equation was used:

$$T^j = \frac{R^j}{V_S} - T_w, \quad (3)$$

in which the superscript j refers to each target, T^j is the lead time at target for the *S*-wave arrival, and R^j is the hypocentral distance to target.

Results and Discussion

This section describes the results obtained in the simulations. For each simulation and each software system, the accuracy of picking, the origin time, and the hypocentral location errors were first analyzed, and second, the elapsed time and the blind zone followed by the analysis of the lead time to targets. In this analysis, not only the location and origin time from the reference catalog were taken into consideration but also the final results obtained by the simulations.

Picking Accuracy

From the simulations, the *P*-wave pick errors were analyzed for the three software packages. Taking into account all stations, the mean error remains less than 0.1 s with a standard deviation of 0.2 for the four events; meanwhile if only the six first picks are considered, the mean error is always less than 0.05 s and the standard deviation 0.07 s.

For PRESTo and SeisComP3 software, all pick errors remained below 0.1 s, and, only for the SV2 event, the Earthworm software raised a maximum pick error of 0.2 s. This means that the picking errors should not have a large influence on either the earthquake location or in the ulterior magnitude estimation.

Location Errors

In Table 2, the origin time and location errors for each earthquake and each seismic software package are shown (for a six-station configuration as well as considering all stations). These errors were calculated subtracting the reference value (IGN catalog) from the simulation value, so positive errors mean that the simulation result has a later origin time, more toward the north, more toward the east, or a deeper location than the IGN reference hypocenters. In addition, in Figure 2, the evolution of the epicenters for the three

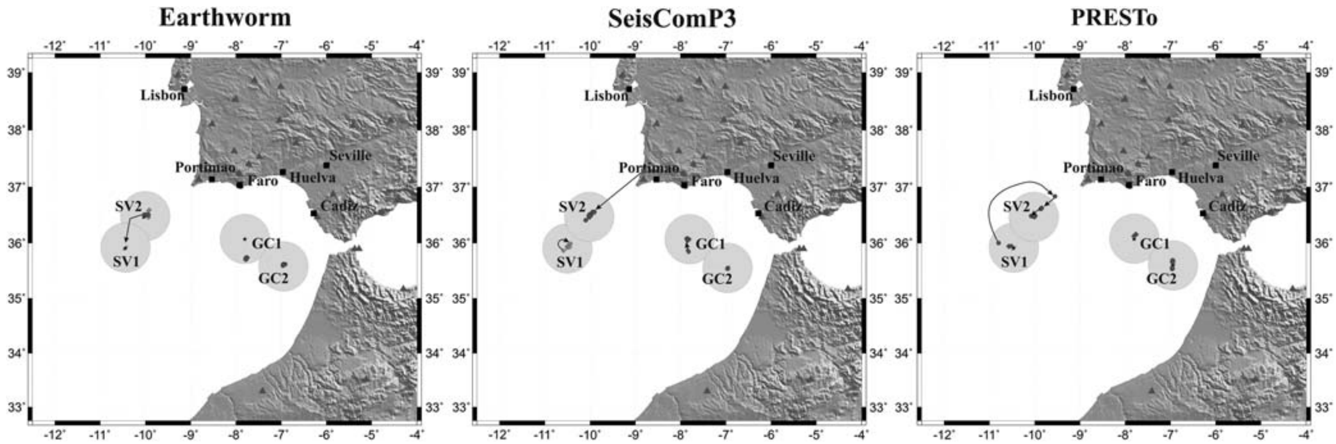

Figure 2. Epicenter evolution of the selected events for each seismic software package. Gray circles show the 50 km distance from epicenter. The Instituto Geográfico Nacional (IGN) location references and the error ellipses (less than 10 km) are also shown.

software programs is shown. These results confirm the goodness of the IGN location to be used as reference.

SeisComP3 and PRESTo present a similar behavior. Both software packages show a location error lower than 30 km with a six-pick configuration except for the SV2 event (larger than 80 km). Earthworm location error is larger than 50 km for the SV1 event, close to 40 km for the GC1 event, and lower than 10 km for the SV2 and GC2 events.

Regarding the depth, all three systems provide large errors, but the depth has the major uncertainties in the hypocentral solutions. As expected, depth errors for regional earthquakes with large distances to the stations have a small influence for the elapsed time and the blind-zone radius estimation.

Because the error on phase picking should not have a large influence on the location, its uncertainties are most likely due to the poor azimuthal coverage of available stations, between 25°and 45° for SV events and 85°–115° for GC earthquakes.

Finally, relative to the origin time errors, PRESTo shows time differences less than 1 s regarding the IGN catalog, except for the SV2 event (−10.2 s) with a six-station configuration. SeisComP3 shows differences less than 6 s for six-station configuration except for the SV2 event. Earthworm differences are less than 2 s for the SV2 and GC2 events and about 10 s for the SV1 event and 5 s for the GC1 event.

Elapsed Times and Blind Zones

The computed elapsed times and the blind radius, referred to the IGN catalog solutions as well as for the six-picks configuration, are given in Table 3. As can be observed, Earthworm provides the smallest elapsed-time values for SV earthquakes (SV1 and SV2), and PRESTo for the GC1 and GC2 events. Meanwhile, SeisComP3 always provides the largest elapsed times due to the delay problem already mentioned in the configuration section, when it operates in playback mode and the repicker is used. However, taking the IGN solution as reference, PRESTo and Earthworm show similar elapsed times and SeisComP3 is about 3–5 s delayed.

To analyze the blind zone (Fig. 3), two parameters must be considered: the radius (see Table 3) and the earthquake location. On one hand, the radius is proportional to elapsed time (equation 2) and, therefore, has proportional variations and errors as elapsed time. On the other hand, the area depends on the epicentral location. Here, the first solution (six picks) from the seismic software packages is analyzed and compared with the true situation (taking the IGN parameters as reference).

For SV events, the southwest corner of Portugal is inside the blind zone, although, for the SV1 event, Earthworm places the epicenter closer to the coast but the radius is smaller than the real situation. For the SV2 event, PRESTo places the epicenter farther and underestimates the blind zone, and meanwhile SeisComP3 localizes the event inside the coast, close to Portimao, and shows a large overestimation.

For the GC events, the blind zone affects the coastal areas of the GC (Cadiz, Huelva, and southeast Portugal coasts) when the epicenter is localized in the northern part (GC1 event) and the Morocco and Cadiz coasts when it is localized to the southern part (GC2 event).

Table 3
Elapsed Times (Seconds) and Blind-Zone Radius (Kilometers) for the Selected Software Packages Considering as Reference the Six-Station Configuration (System) and the IGN Hypocenter (Real)

		Earthworm		SeisComP3		PRESTo	
		System	Real	System	Real	System	Real
SV1	T_w (s)	48.8	59.9	65.6	62.9	59.0	59.8
	R_{bz} (km)	165.9	203.8	222.9	213.9	200.6	203.4
SV2	T_w (s)	45.9	47.3	36.1	52.9	57.0	46.8
	R_{bz} (km)	156.2	160.8	122.6	179.9	193.8	159.2
GC1	T_w (s)	43.6	38.4	48.7	43.1	38.6	38.1
	R_{bz} (km)	148.2	130.5	165.7	146.5	131.5	129.6
GC2	T_w (s)	43.3	42.8	45.3	45.3	39.4	40.6
	R_{bz} (km)	147.3	145.3	153.9	153.9	134.0	138.1

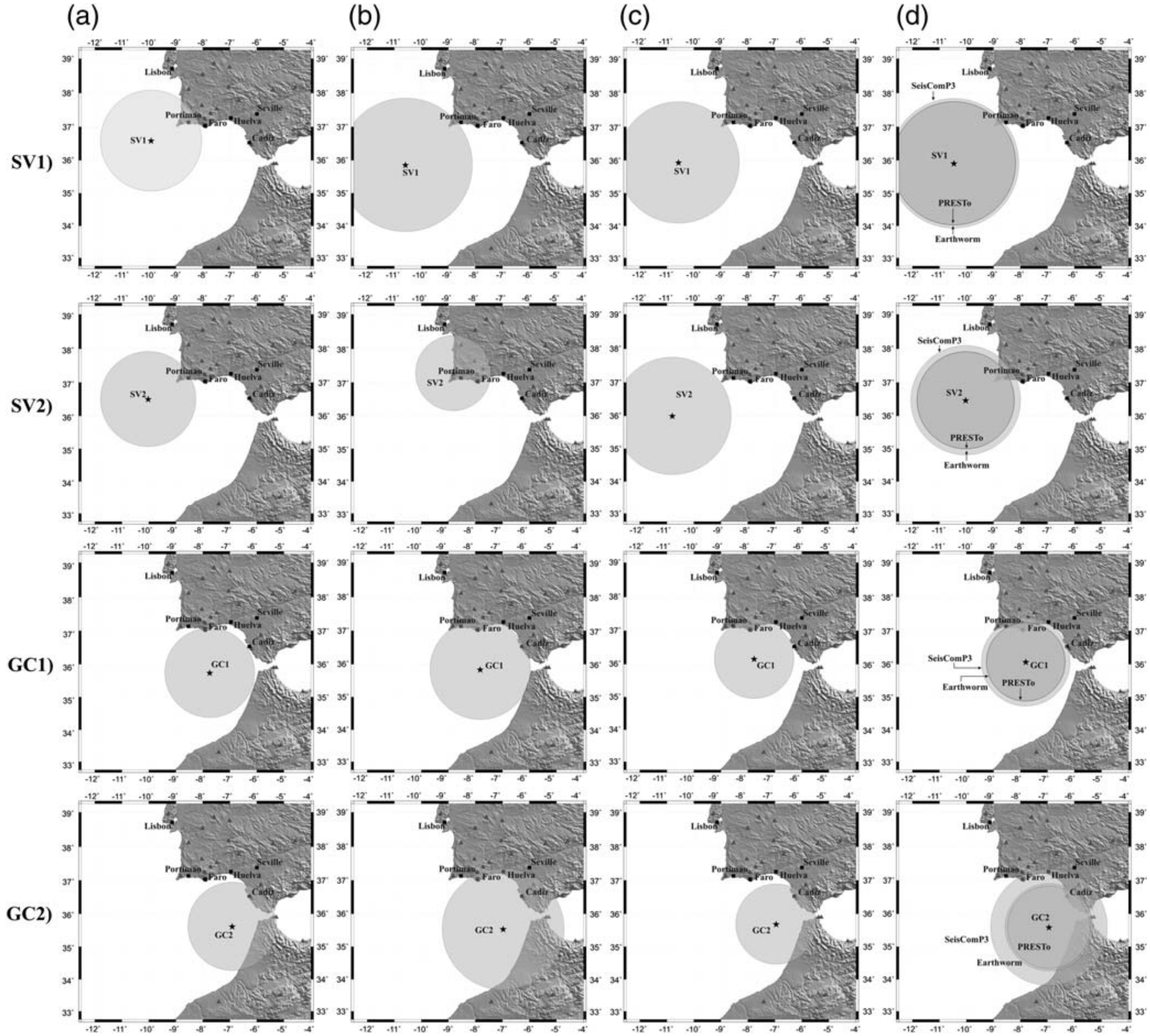

Figure 3. Blind zone for the four selected events for a six-station configuration. Column (a) Earthworm, (b) SeisComP3, (c) PRobabilistic and Evolutionary early warning SysTem (PRESTo), and (d) estimated blind zone for the referenced IGN hypocenter.

Lead Time to Targets

Lead times at selected targets taking as reference the IGN catalog (real) and also taking as reference the first output (six picks) of the simulation (sim) are shown in Table 4. SeisComP3 provides the shortest lead times in all cases due to the delay problem previously mentioned.

The resulting lead times are useful for all southwest Spain and South Portugal, with the exception of some coastal zones, which depend on the earthquake epicenter area. On one hand, for SV earthquakes, only the Cape of SV area is inside the blind zone and lead times are too short to be useful (except for automatic-warning applications); for example, Portimao is inside the blind zone or has a lead time less than 5 s. In the remaining region, lead times are large enough to be considered for damage mitigation, for example, 5–15 s for Faro, 30–40 s for Huelva and Lisbon, 40–50 s for Cadiz, and 55–65 s for Seville. Carranza *et al.* (2013) estimated these lead times for the 1755 Lisbon earthquake for different configurations and obtained similar conclusions taking into account that only theoretical velocities and arrivals for *P*- and *S*-waves were used for the estimation and no transmission and software delays were computed.

Finally, for GC earthquakes, lead times are useless for most of the coastal targets (from Portimao to Cadiz). Nevertheless, for inner regions lead times are large enough for an early warning; for example, Seville has 20–25 s available.

Table 4
Lead Times (in Seconds) at Selected Targets for the Selected Software Packages

		Cadiz		Huelva		Seville		Faro		Portimao		Lisbon	
		Sim.	True	Sim.	True	Sim.	True	Sim.	True	Sim.	True	Sim.	True
SV1	Earthworm	46.7	52.3	31.5	42.2	56.8	66.8	5.6	16.5	−8.4	4.8	23.5	38.0
	SeisComP3	50.1	49.3	40.1	39.2	64.8	63.8	14.5	13.5	2.7	1.8	35.0	35.0
	PRESTo	55.7	52.4	45.1	42.3	69.9	66.9	19.4	16.6	7.3	4.9	39.1	38.1
SV2	Earthworm	52.4	51.2	37.9	37.0	63.1	62.3	11.9	11.1	−1.8	−2.5	29.8	29.6
	SeisComP3	34.5	45.6	12.2	31.4	37.4	56.7	−11.2	5.5	−27.3	−8.1	11.5	24.0
	PRESTo	63.2	51.7	51.7	37.5	76.7	62.8	25.9	11.6	13.1	−2.0	41.6	30.1
GC1	Earthworm	2.9	4.4	10.2	6.4	27.0	25.5	−1.2	−6.7	6.5	1.4	60.1	54.7
	SeisComP3	−2.3	−0.3	3.0	1.7	20.8	20.8	−9.6	−11.4	−2.3	−3.3	51.3	50.0
	PRESTo	2.3	4.7	3.1	6.7	22.5	25.8	−9.9	−6.4	−0.9	1.7	52.1	55.0
GC2	Earthworm	−9.1	−7.5	10.5	11.8	19.2	20.8	10.0	10.8	22.2	22.8	73.3	74.1
	SeisComP3	−8.1	−10.0	11.0	9.3	20.1	18.3	9.5	8.3	21.2	20.3	72.8	71.6
	PRESTo	−6.7	−5.3	12.0	14.0	21.4	23.0	11.3	13.0	23.6	25.0	74.6	76.3

Sim. refers to the simulation origin, and true refers to the IGN hypocenter.

Conclusions

A study of the feasibility of an EEWS for the southwest of the Iberian Peninsula was carried out, simulating four representative selected events and comparing the results of three seismic software packages (SeisComP3, Earthworm, and PRESTo) to the reference solution taken from the IGN catalog.

The resulting location errors are due mainly to the poor azimuthal coverage and low density of the available land stations. The pick errors are small enough for the three tested seismic software not having a large influence on the location errors. During the software configuration stage a minimum of six-station association was chosen, being the best compromise between precision and elapsed time for the actual available stations deployed in the area.

The resulting lead times estimations for all southwest Spain and south Portugal, except some restricted areas, show the feasibility of an EEWS for the southwest Iberian Peninsula. For SV earthquakes, only the Cape of SV region is inside the blind zone and the lead times are too short to be useful, whereas for the other areas, lead times are large enough to be considered for damage mitigation. For GC earthquakes, the lead time is useless for most of the coastal targets from Portimao to Cadiz. Nevertheless, for inner regions lead times are also useful for early warning. This is why we conclude that a local EEWS should be developed to warn areas inside the blind zone.

In summary, an EEWS is indeed feasible for the southwest of the Iberian Peninsula, but it should be ensured that the system improves the azimuthal coverage of available stations, to get better location accuracy and also a shorter elapse time, having a smaller blind zone and greater lead times to targets. Any of the three software packages used in the simulations could be configured for this purpose. However, it is recommended that for Earthworm and SeisComP3 new magnitude modules should be developed and incorporated. For the SeisComP3 and for the SeisComP3, the delay of the picking and location modules in playback mode should be resolved.

Data and Resources

Records used in this study were collected from three different broadband seismic networks: Western Mediterranean and Instituto Geográfico Nacional networks from Spain and the Instituto de Meteorología from Portugal. Access to the waveforms records can be obtained from the owners on request.

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