Project N. 037110

NEAREST

Integrated observations from NEAR shore sources of Tsunamis: Towards an early warning system

Instrument: STREP

Thematic priority: 1.1.6.3 GOCE (Global Change and Ecosystems)

D19a: procedures, algorithms and methodologies for automatic and rapid determination of source parameters from a multi-parameter stream data

Due date of deliverable: August 2009
Actual submission date: August 2009

Start date of the project: 01/10/2006 Duration: 36 + 6 months

Organisation name of the lead contractor for this deliverable: UGR

Revision: Final

Project Co founded By the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (Including Commission Services)	
RE	Restricted to a group specified by the Consortium (Including Commission Services)	
CO	Confidential, only for members of the Consortium (Including Commission Services)	**CO**

WP5 - Data integration/ Integrated tsunami detection network

D.19a - Procedures, algorithms and methodologies for automatic and rapid determination of source parameters from a multi-parameter stream of data.

Task 5.2 Leader: UGR

Task 5.2 Responsible: José Morales

Authorship:

This report has been compiled by José Morales with the contributions from the main partners involved in the management of the national and regional seismic networks operating in the region of the SW Iberia: Instituto de Meteorologia at Lisbon (IM) as responsible of the national seismic network of Portugal, The National Geophysical Institute of Morocco of the Centre National pour la Recherche Scientifique (CNRST) as responsible of the national seismic network of Morocco and The Instituto Andaluz de Geofisíca of Granada University (UGR) as responsible of the broad band seismic network of southern Spain. Fernando Carrilho from the IM and Abdelouahad Birouk from CNRST completed the report with their contributions related with the seismic networks managed by their respective agencies.

Table of contents.

1. Introduction and objectives

Hypocentral parameters of large earthquakes are relatively well determined by global agencies using data from the first P waves at teleseismic distances (Δ>30º). Stable geographical location and depth of the seismic source can be obtained 15-20 minutes after the origin time (O.T.) of the earthquake. However, to make useful the hypocentral estimations with the purpose of a Tsunami Early Warning System (TEWS), the localization must go accompanied by a robust calculation of the real size of the seismic source. For the 2004 Sumatra-Andaman Mw=9.3 it showed the necessity to have other tools to calculate the size of the earthquake few minutes after the origin time. The conventional magnitude estimations Ms, Mw-CMT-Havard have the necessity to get the maximum value of ground motion of the surface-wave train or the complete seismograms for very long periods to evaluate magnitudes (Ms, Mw), which implies the impossibility of having robust estimations until several hours after O.T.. Is well know how during the Sumatra-Andaman 2004 earthquake the real Mw=9.3 was underestimated during the firsts hours while an undetected tsunami crossed the Indian Ocean and reached the coasts of India, the Bay of Bengal and Shri Lanka. Only several weeks after, the true size of the earthquake was fixed using free oscillation records (Stein and Okal, 2005). From this megaearthquake several lessons were learned: for one side, the need to develop an effective early warning systems against tsunami in regions with high tsunamigenic potential that include GPS-buoys, tide gauge and high density of real-time seismic stations and for another side, to investigate new methods able to calculate the true size of the seismic source as an indicator of potential tsunamigenic earthquake.

An effective TEWS with the purpose to give a fast emergency response to a tsunami hazard has mainly based in a robust real time acquisition with the support of the regional/global seismic networks that facilitate the quick access to their data. The joint management of the real time seismograms and procedures and algorithms that calculate, only few minutes after OT, the main parameters of the location and size of the seismic source is a crucial aspect for the design a prototype of TEWS. This seismic node must to be linked with the others components as: buoys, tide gauge, OBS's and ocean bottom pressure sensor in order to corroborate or not the generation of a tsunami due to a seismic event whose magnitude has been previously calculated for the seismic inland node algorithms.

After Sumatra-Andaman 2004 earthquake a large effort to obtain new and more effective procedures to accurate the magnitude estimate and size source characterization have been developed. The main challenge of this improvement to be efficient in a TWES is fix a robust size of the seismic source after few minutes the origin time.

In the last five years several algorithms based on different approximations have been proposed in order to calculate seismic moment or moment-magnitude Mw, which is directly related with the size of the source. Menke and Levin (2005) use a reference event on which compares the size of the earthquake "target" comparing teleseismic P-wave amplitudes on an arbitrary time window (at least several 200-s oscillations for each station). Results would be obtained after 30 minutes origin time. Lomax (2005a, b) proposed the use of the high frequency P-wave to estimate of the rupture time duration and calculate the rupture length which is related with the seismic moment (Mo). Lomax (2005b) tested his algorithm with data from the Sumatra 2004 earthquake obtaining results after 30 minutes origin time. Bormann and Wylegalla (2005) and Bormann and Saul (2008) proposed and new mB magnitude using the maximum displacement of the P-wave recorded on broad band seismometers. This magnitude is based on a point source and in the case of a complex rupture, the mB will give the magnitude of the higher subevent. This mB saturate at least one unit higher than short-period m_b became comparable with Ms and Mw for magnitudes up to around 8. A regression between mb-Mw allows the estimation of the moment magnitude Mw(mB) only 8-15 minutes after origin time. A recalculated calibration function $Q(\Delta, h)$ of the mB expression (Saul and Bormann 2007; Saul 2008) allows estimations of individual values of Mw(mB) for angular distancies > 5º, which means few minutes after origin time. For the case of megaearthquakes (Mw> 9) or large multi-source events, Saul and Bormann (2007; Bormann and Saul 2009) proposed a cumulative magnitude mBc based on the identification and summation amplitudes of discernable “subevents” in the P-coda. This technique used directly the unfiltered broad band seismograms and allows a high potential to have near real time evaluation of the seismic size even for Mw> 9.0, with unexpected long rupture duration earthquakes including slow earthquakes.

Lomax and Michellini (2009a and b) proposed also two new methodologies for rapid determination of the magnitude. Lomax and Michellini (2009b) present a duration-amplitude procedure for fast determination of the magnitude M_{wpd} using P-wave recordings. In this case robust values of magnitude can be reached after 20-30 minutes origin time. For coastlines near the source of the tsunamigenic region Lomax and Michellini (2009a) introduce the concept of apparent rupture duration *To*, which for values > 50 s has more importance for tsunami information than the Mw. They propose a procedure for its calculation in 3-10 minutes after origin time, depending of the density of seismic stations. The tracking of the seismic source rupture can be followed using different aperture array dimensions. Krüger and Ohrnberger (2005) analyzed the Sumatra 2004 earthquake using the German Regional Seismic Network as a seismic array showing that is possible to track the rupture front.

In the other hand, (Blewitt et. al, 2006) proposed other alternative, which do not require ground motion seismograms for rapid calculation of the size for tsunami alert. In this case they used geodetic methods using time series data from GPS’s to calculate the static displacement to get seismic moment Mo and moment magnitude of Mw. In this case it is possible to obtain robust results few minutes after the origin time depending of the resolution of the GPS and distances to the seismic source.

The objectives in task 5.2, which are joint, related also with the defined in the task 5.1 are:

a.- The use of real time seismic data from different networks for location.

b.- Fast estimation of the magnitude of the seismic source using different approximations.

2. Challenges for the Gulf of Cadiz.

The Pacific Tsunami Early Warning System (PTEWS) is a very well established and efficient system where the alarm response times are not necessarily so quick, except for the source region, as in the case of the Indonesia or in the Gulf of Cadiz, where lapse time to be able to calculate with more effectiveness the size of the seismic source is shorter. The recently inaugurated German-Indian Ocean Tsunami Early Warning System (GITEWS) (Hanka et. al, 2008) that operate in the Indonesia-Sumatra region has been designed with the purpose of giving a fast response to a hypothetical great earthquake that could generate a tele-tsunami similar to the 2004.

In the case of the Mediterranean (Algeria coast earthquakes, Aegean arc or in the Gulf of Cádiz) the challenges are even higher due to the short time travel time of the tsunami wave. So, for these cases, an effective TEWS must to give very fast notifications about seismic parameters as location and magnitude in a brief short time window (less than 5-10 minutes after origin time) (Figure 1).

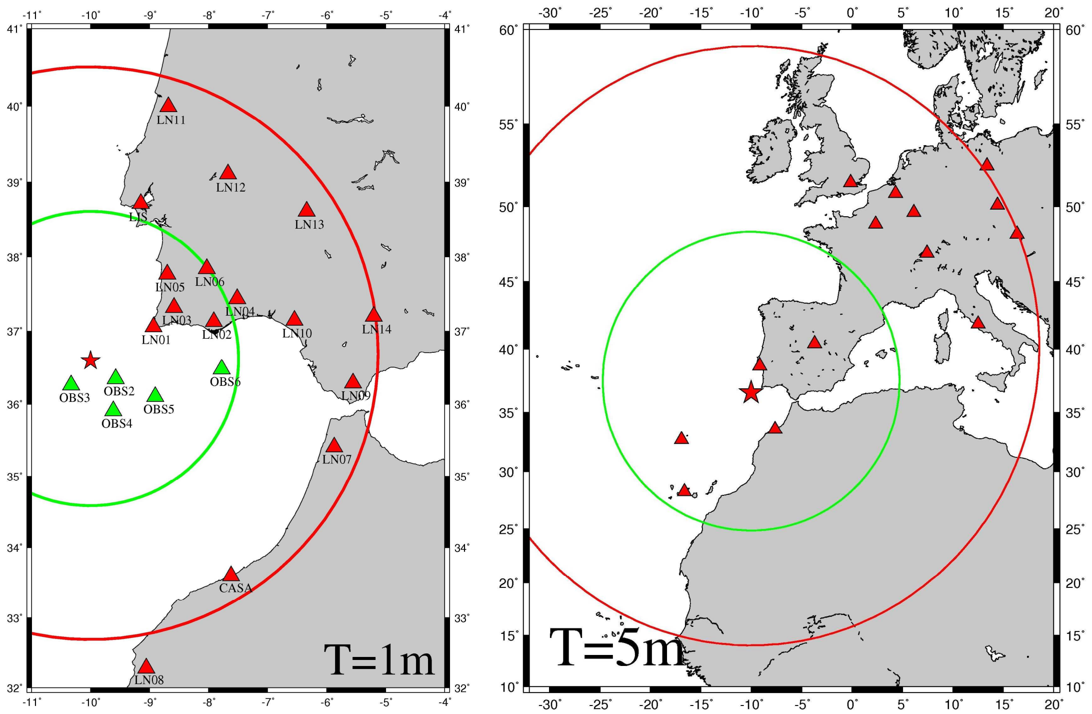


Figure 1. Theoretical wavefront location for P waves (red) and S waves (green). Origin Time plus 1 minute (left) and Origin Time plus 5 minutes (right) for a hypothetical earthquake located in the Saint Vincent Cape (star)

For the case of the Gulf of Cadiz the tsunami waves would attack in less than 20-30 minutes the Portugal, Spain and Morocco coasts, which mean a fast response in term of seismic information. The great challenge is be able the management of a large number of seismograms coming in real time from different national y/o regional seismic networks at angular distances less 20 degrees, which means than the TEWS has 5 minutes after origin time to collect a real time data set of seismograms, identify the main seismic phases (P and S), locate the event and get robust seismic magnitude to responds to the tsunami hazard (Figure 1)

3. Strategies for fast evaluation of the seismic source parameters (location and magnitude):

3.1. The case of the CNRST, Morocco with the Antelope System

The CNRST has acquired along with its new seismic network, the Antelope software for real time acquisition and processing of seismic data. As described by its designers, the Antelope Environment Monitoring Software is a distributed open-architecture UNIX-based acquisition, analysis and management software system. Antelope is provided by the Boulder Real Time Technologies (BRTT) and is designed to provide a comprehensive set of environmental monitoring data and processed information in real-time. Antelope is engineered as an all-in-one system, which aims to integrate state-of-the-art technology and scientific advances, making it possible to monitor seismic events from local/regional, national and global networks and arrays. Antelope largely takes advantage of the extensive support services provided by the UNIX environment and standard TCP/IP network utilities over multiple physical interfaces. Antelope runs on Sun Microsystems' Solaris operating system on both SPARC and Intel architectures.

The current generation of Antelope provides full functionality for seismic network and array operations and control, including real time data acquisition from field digitizers, interactive control of field equipment, system state-of-health monitoring and real time automated data processing such as detection, phase picking, seismic event association, seismic event location, archiving (Figure 2). It also offers interactive and batch processing, information system functions, automated distribution of raw data and processed results, batch mode seismic array processing and a powerful development toolkit for extending and customizing the system.

The Antelope Seismic Information System uses the relational database (RDBMS) formalism and the CSS v.3.0 schema for information organization. In addition to providing specific functionality for seismic monitoring systems, Antelope provides a robust and versatile substratum of generic functions that can be used to support other non-seismic monitoring applications.

Antelope Main Features:

- Open-architecture modular design concepts throughout
- Distributed real-time data acquisition and processing capability

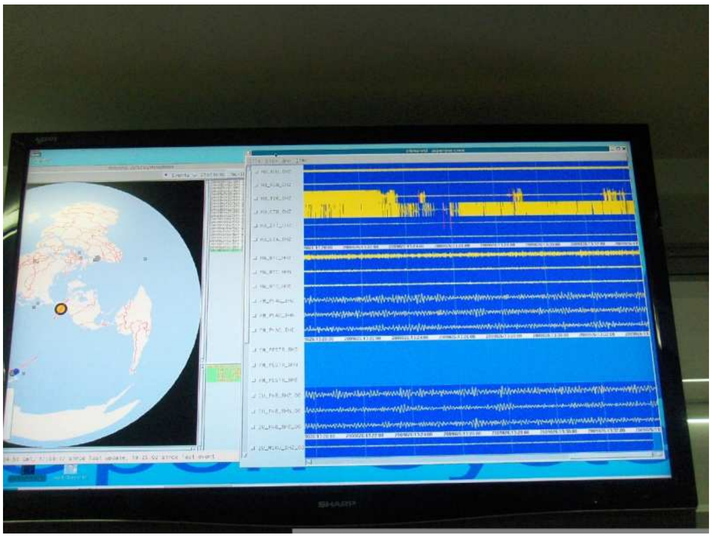


Figure 2. Graphical display that allows the control of the automatic and interactive phase picking as well as plotting the epicentral locations on different thematic maps.

- Distributed real-time system monitoring and control capability.
- Comprehensive automated seismic event information in near real-time.
- Network size independent (the system scales only with hardware used).
- Records data in real-time to non-volatile disk ring buffer.
- Size of ring buffer limited only by maximum file size.
- Unique set of on-line and off-line processing tools.
- Information system interfaces and functionality.
- Offers tools with RDBMS for rapid access to earthquake information.
- Provides a rich development toolkit.
- Highly configurable and adaptable to differing monitoring system requirements.

As currently installed at the National Institute of Geophysics of the CNRST (Figure 3), Antelope allows the automatic detection and location of events using few Morocco stations along with a set of stations from the neighboring countries; Portugal and Spain and also other international stations; thus, making a relatively large virtual network. Using these stations, Antelope allows thus, a rapid hypocentral determination. For larger events, Antelope posts the NEIC hypocentral solution as well, allowing to compare it to the local solution. As expected, the NEIC solution is more precise for teleseismic events, while the solution of the local virtual network is more reliable for the events that take place within Morocco.

In general, an automatic detector is run and triggers a detection on each station separately. If a minimum number of detections, which is usually set by the antelope manager, is met then the software associates the phases and attempts a first automatic solution. This automatic solution is generated and made available by this software in less than a minute of reception of the first minimum seismic detections. Therefore, the CNRST staff who are present on site get the warning within a minute or so.

The system further allows sending warning messages to a pre-selected pool of selected people by SMS and by email. It however, takes few additional minutes for the SMS and email messages to reach their destinations. Thus, in principle, the people in charge of seismic warning should receive warning messages, in about 4 to 5 minutes after the occurrence of a local earthquake and in about 5 to 6 minutes, in the case of an event in the Atlantic Ocean such as within the Saint Vincent Cape.

The first automatic solution is further refined as seismic signals and detections are later received from farther stations. More warning messages are then sent. When necessary, the CNRST analysts intervene afterwards to control and readjust the phase picking.

Figure 3. Satellite communication receiving data in near real time (left). An analyst ontrolling and refining the phase pickings after event detection.

So far, the events magnitudes calculated by the Antelope software at the CNRST are M_L, M_S, and m_b. The Antelope manuals indicate that these magnitudes are calculated in real time by the orbampmag program without applying instrument deconvolution since it can cause instabilities. For broadband instruments, it is usually not necessary to apply instrument deconvolution since the instrument response is flat in the response band of the Wood-Anderson filter. In cases where the instrument is a 1 Hertz short period, it is usually not necessary to apply neither the deconvolution nor the Wood-Anderson filter. In all cases the responses are converted to displacement and the correct gains are applied to produce equivalent Wood-Anderson drum recorder displacement.

Recently in 2009, it was announced that a patch that allows the computation of the moment tensor magnitude Mw will soon be added to the Antelope software. As the Morocco new broadband network is still under deployment and as still most of its stations are not yet installed and linked to the central acquisition system, it is difficult to assess the performance of this network in terms of the reliability of the computed magnitudes.

3.2. The case of the IAG-UGR, Spain with the Seiscomp 3.0 platform

An important and essential goal in the feasibility of a TEWS is to have a fast and accurate determination of main seismic source parameters related with the potential generation of a tsunami (location, source depth and the size of the source given by the seismic moment (Mw)).

The particular case of the Gulf of Cadiz can resemble that of Sumatra in the sense that a hypothetical large earthquake generated a tsunami that would reach the coast of Africa and the Iberian Peninsula in less than 20 minutes. Therefore the measures of effectiveness in obtaining information to the main seismic parameters to provide a rapid response are similar to those used by the GITEWS. The core of GITEWS is the SeiscomP 3.0, (Hanka et. al, 2008, Saul et. al, 2008) a software developed by the GeoForschungsZentrum (GFZ), which was designed for automatic event detection and location. For the Sumatra region SeiscomP 3.0 (SC3) case can locate and evaluate the magnitude of major earthquakes in less than 5 minutes. An interesting example of the reliability of the system is in the Bengkulu September 12, 2007 earthquake of Mw = 8.4 in the Sumatra region, For this case SeiscomP 3.0 using mostly real-time data from more than 120 seismic stations in the network of seismic GITEWS, got the first location and evaluation only 2 and half minutes after origin time and with a robust evaluation of the magnitude Mw (mB) = 7.9, M_{WP} = 8.3 just 4 minutes after the time origin (Saul, 2008). This fast procedure would allow to a future focal point dedicate to the Early Warning in the Gulf of Cadiz to send alert message to the different organisms dedicated to Civil Protection.

For that reason it has taken SeiscomP 3.0 (Hanka et. al, 2008; Saul et. al, 2008) as the best automatic system for managing the identification and location of earthquake activity. The SC3 follows the philosophy of the earlier versions in terms of the SeedLink protocol used real time communication, but its modular design provides news of several modules developed for interactive and automatic data processing that provides the following characteristics: real time acquisition, data quality control, picking, location, amplitude calculation, magnitude calculation, waveform quality control and event parameter management. SC3 has a powerful and friendly graphical interface that allows the monitoring and control of the automatic and interactive processes related with the status of the seismic networks, acquisition of seismic data, the location and the magnitude evaluation.

Description of SC3:

The automatic data processing is composed by several modules:

1. A module dedicated to determine the quality parameters of real time seismic data streams. The graphical output gives the follow messages: delay, latency, offset, RMS, spike, gap and timing.

2. A module dedicated to the automatic seismic phases picking in real time (scautopick). This program is a combination of a Butterworth filter and a STA/LTA algorithm. The program search for waveform anomalies in form of changes in amplitude, applying the STA/LTA algorithm to the waveform seismograms which have been previously filtered with a pass band Butterworth filter of third order between 0.7-2 Hz. When the sta/lta ratio reaches a determined threshold value, the program picks the time value where this threshold is exceeded. Besides this module, also calculates amplitudes to be used in the estimation of different magnitudes types.

3. A module dedicated to the real time locating earthquakes (scautoloc). The program read the picks phases and try to associate with other previous picks to form, if it is possible, a consistent origin time. The location will be more stable and robust according with the increase of the numbers pickings from the different seismic stations when they reached by the P and S wavefronts. So, it is essential to include in the real time management, the maximum number of seismic station, overall in the source region, to have enough P and S data arrivals.

4. Module dedicated to compute magnitudes from amplitudes and origins. The implemented magnitudes in the SC3 platform are:

   MLv: local magnitude calculated on vertical component

   mb: Body wave magnitude using a Butterworth filter between 0.7-2.0 Hz frequencies.

   Mwp: Body wave magnitude of Tsuboi et. al, (1995).

   Mw(Mwp): Estimation of the moment magnitude Mw based on Mwp using the regression Mw-Mwp of Whitmore et. al, (2002)

   mB: Broad band body wave magnitude (Bormann and Saul 2008)

   Mw(mB): Moment magnitude based on mB, using the regression

   Mw-mB of Bormman and Saul (2008).

The interactive data processing dedicated to the graphic monitoring of the status of the seismic network, results from automatic location, the magnitude automatic estimation, can be summarized as follow:

1. A graphic module visualizes the information related with the quality status of the networks. In this case, the *Map Monitor* module show information about the ground motion level (in nm/s) of seismic station by different colour triangles, events (last earthquake with associated stations) and the network status which visualize the delay and latency of the whole seismic network. Another graphic module shows the real time seismograms with information about the station and network code, amplitude, etc.

2. The second module (*Event Summary*) is dedicated to show the information about the actual-last located earthquake (location including depth, time, magnitudes and origin info) together a map with the position of the epicentre and the world region associated. Also information about previous located earthquakes can be obtained from an event list.

3. A third graphic module (*Origin Locator*) This module is related with the manual/automatic processing and shows information about the different magnitudes estimated and their errors, location residuals, stations triggered, picking phases timing etc.. It is has the possibility to import the waveforms and proceed with a manual processing in the location, changing the time of the picks of the P and S phases for each station and proceed with a relocation of the event. The module also has an event list from where a specific earthquake can be recovered.

3.2.1. SEISCOMP 3.0 at IAG-UGR node. Experiences.

The SeiscomP3.0 pack software was installed in a server *"Istar"*, which is specifically dedicated to the management of the real time processes related with the identification, picking of the seismic phases, estimation of the location parameters (geographic coordinates and depth) of the seismic activity and the calculation of the size of the seismic source by a fast procedure algorithm that estimate mLv, mb, Mwp, Mw(Mwp), mB and Mw(mB) magnitudes (Tsuboi et. al, 1995; Whitmore et. al, 2002; Bormann and Saul 2008, 2009; Saul et. al, 2008). This server was installed in a preliminary version in July 2008 and in a final version in January 2009 with some updates during the same year. During this time the system has been incorporating both, broad band seismic stations and short-period from the IAG-UGR seismic networks as other national or regional networks that operate mainly in the Iberian Peninsula area and surrounding. During this time the server, which receive in real time waveforms from the *Dagobah* server, has increased the number seismic stations coming from private servers belonging to national and regional seismic network operating mainly in the Iberian Peninsula area as the Meteorological Institute of Lisbon in Portugal, the CNRST of Morocco, the Spanish National Seismic Network, Ebro Observatory, Institute of Catalan Studies and also for the rest of seismic stations globally distributed belonging or managed by the public seismic server as IRIS and GEOFON. In fact now, *Istar* is managing more than 516 seismograms worldwide distributed, of which around 40 seismic stations are in the region (Iberian Peninsula and north of Africa). There is no doubt that to be most effective in the future TEWS, the density of seismic stations available in real time should increase. It requires an effort to standardize communication and share protocols, mainly with networks installed in the north of Africa.

In the figure 4 we can see the *MapView* graphic module of the CS3 installed in the *Istar* server, where appear all seismic stations received in real time in the system, which are conforming a *Virtual Seismic Network*. Figure 5 shows the *Real Time Trace View* graphic module of the SC3 where part of the waveforms received in real time, particularly those belonging to the IAG-UGR seismic network, are visualized.

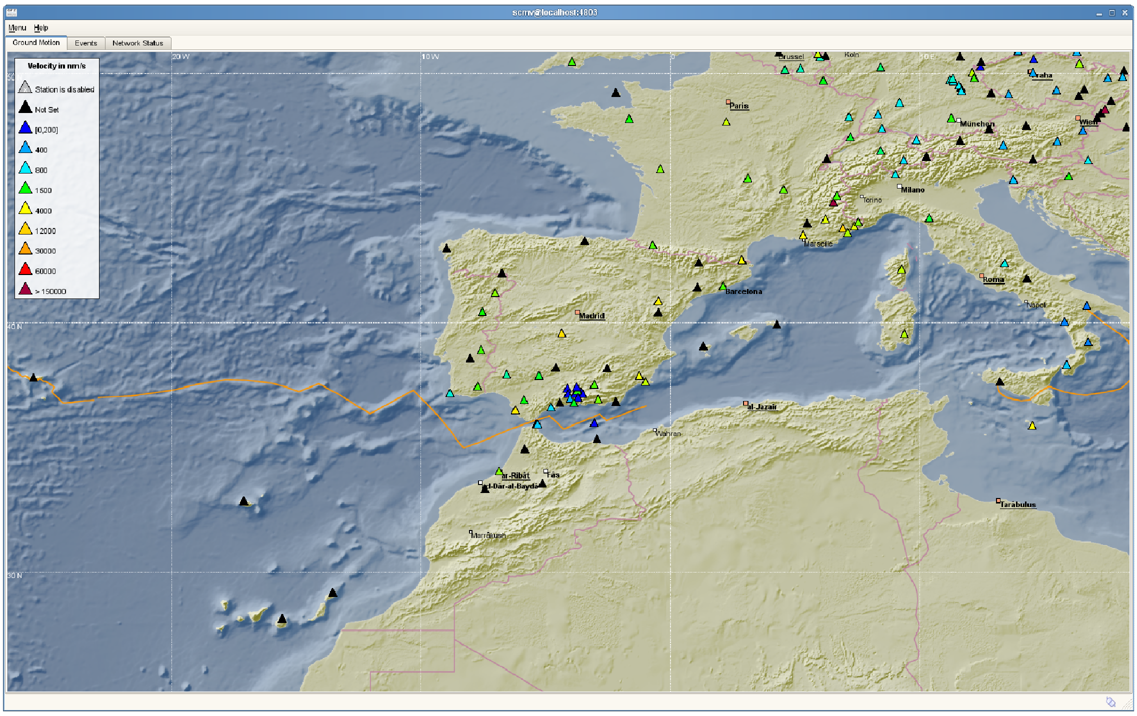


Figure 4. MapView graphic module of the Seiscomp3 installed at UGR where is shown the seismic stations distributed in the Iberian Peninsula, which are been received in the Istar server for the automatic processes. The seismic stations can be monitorized by the ground motion level, the delay of the network status and also if has been declared some event.

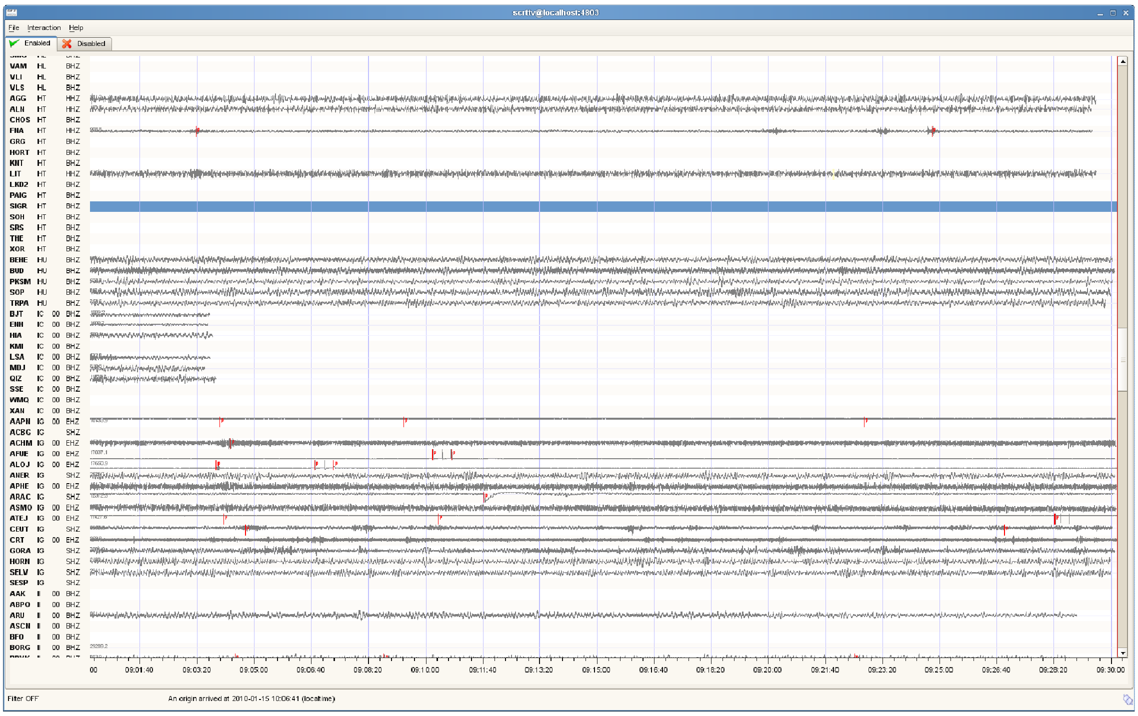


Figure 5. Real Time Trace View graphic module of the Seiscomp3 installed at UGR where is shown part of the real time seismograms of a stream belonging to the IAG-UGR seismic networks.

Unfortunately the regional seismic activity in the last year has been low with earthquakes with magnitudes Mw <4.0. Furthermore, as the automatic system need a minimum number of picks (10) to proceed with the location and magnitude estimation, the trigger level of our virtual seismic network is not enough for small earthquakes. However this threshold in the trigger level is expected decrease in the next months to earthquakes around M= 3.0 in parallel with the increase of the number of seismic station incorporated to the Seiscomp3.0.

However it has been possible to test the automatic system for low-moderate regional earthquakes with 3 events happened in the south of Spain in October 2008, one of them took place in the area of Morón de la Frontera (Seville) in October 2th, and other two earthquakes in October 21th located in the Alboran Sea (Gulf of Almería). Although the number of stations of IAG-UGR connected to the system in this moment was minimal (only three), the inclusion of seismic stations of other institutions through their public or private servers made it possible to verify in a first approximation the feasibility of the automatic system in the location and magnitude evaluation procedure. The figure 6 shows the *Event Summary* graphic module of the example of the first automatic location developed by the SC3 for the regional earthquake of October 2, 2008. It is shows the different magnitudes calculated automatically (MLv, Mw(mB), mB and mb). A further improvement in the magnitude evaluation by inverting the seismic moment tensor solution using the complete waveform of regional broad band seismogram (Stich, 2003) fixed the moment magnitude in Mw = 4.7, close to Mw (mB) = 4.8 given by the automatic system. Figure 7 show more details of the location and magnitude calculation.

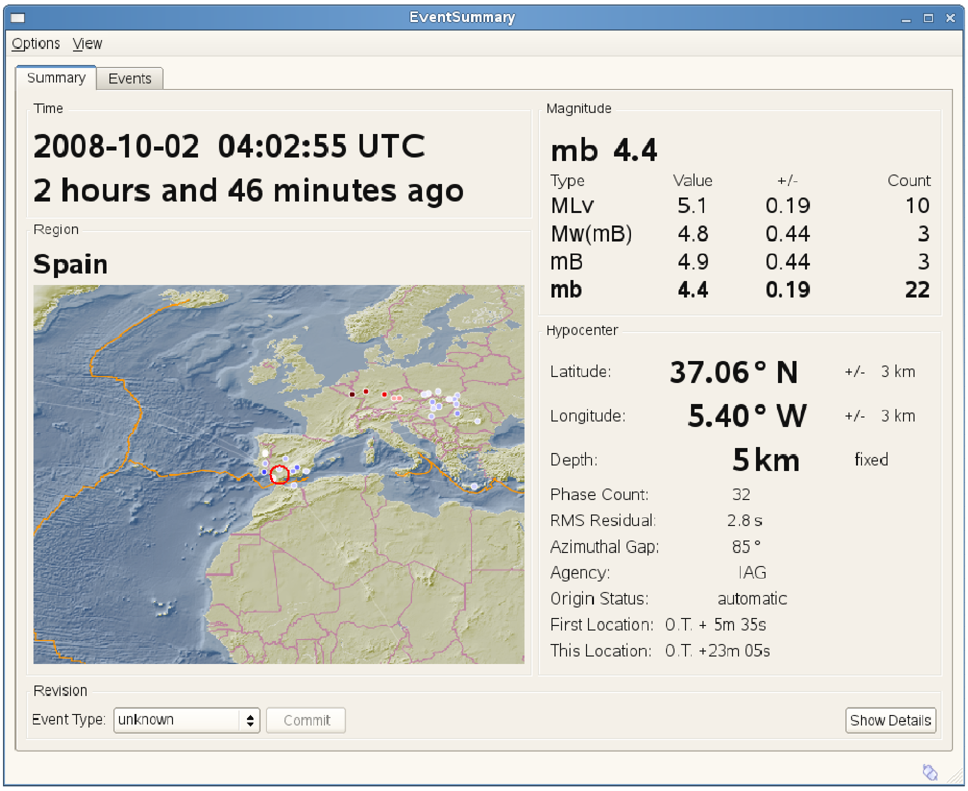


Figure 6. Event Summary graphic module of the SC3 for the first regional earthquake automatically recorded. It is observed the information provided related with the magnitude and location parameters. In the output format appear also information about the errors, number of phases, residuals, RMS, azimuthal gap, time of the first location and the actual

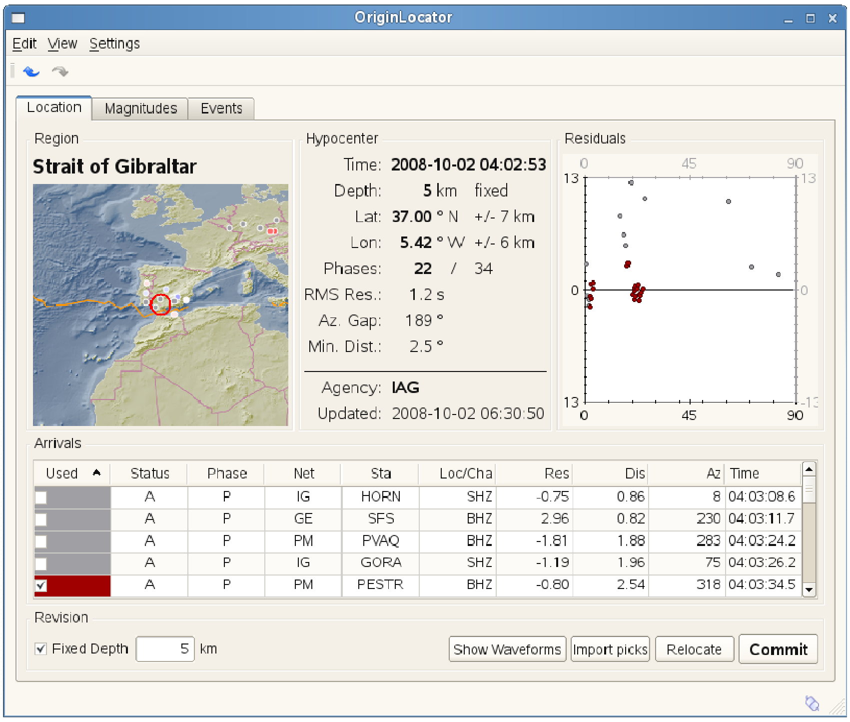


Figure 7.- OriginLocator graphic module of the SC3 for the first regional earthquake automatically recorded by the SC3. It is observed detail information related with the location parameters. In the output format appear the seismic station involved in the location, residuals, picking, distance, RMS and a graphic with the residuals versus distances.

In the case of the other two regional earthquakes located by the system in October 21th, 2008, there are more discrepancies between the magnitudes given by the automatic system and calculated by inverting the tensor solution. This discrepancy is clearly associated with the lowest number of seismic stations involved in the automatic process, due mainly to the lower density of stations in the incorporated in the system and overall to the lower magnitude of earthquakes. In the figure 8 it is shows the output graphic format of the EventSummary module of the SC3 for both earthquakes

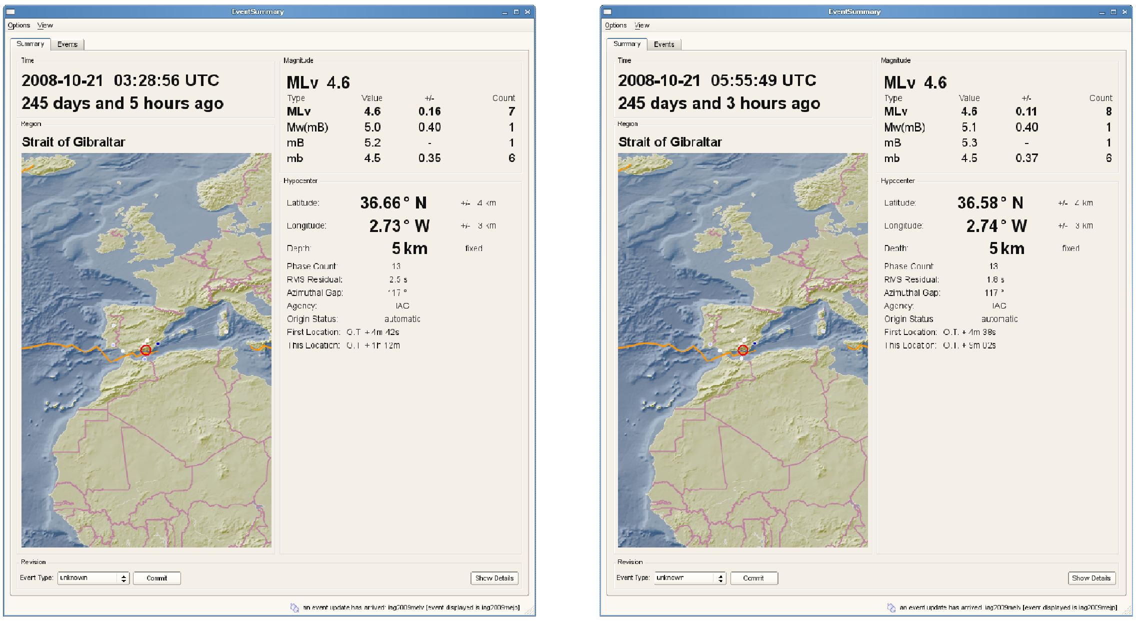


Figure 8. Graphic outputs of the EventSummary module of the SC3 installed in IAG-UGR for two small earthquakes located in Alborán sea (Almeria Gulf) in October 21th, 2008 with less than three hours of differences between them. Main parameters of the location and magnitude calculation given by the automatic system appear for each earthquake is shows in each panel.

Since the time of the earthquakes mentioned (October 2008) to the present (date of this document) the number of stations available in the area in real time has significantly increased but the seismic activity has been low with earthquakes with M<4.0. It is hoped that with the increase in the number and density of stations is expected when all the seismic stations of the IAG-UGR be incorporated, the threshold of detectability of the *Virtual Network* will be include also earthquakes with magnitudes M<3.0 or even smaller.

Regarding the locations, we can say that in all three cases the geographic coordinates provided by the automatic system and the depth, have low errors respect to the locations provided by the seismic operator in the location routine. Response times in the location have been around Origin time + 5 minutes. The response time to a robust location is also expected to be faster with the increase of seismic stations available by the system.

December 17th, 2009 Saint Vincent earthquake example

During the elaboration of the present report an earthquake located in the SW Iberia (close to the Saint Vincent Cape) with magnitude Mw(mB)=5.3 took place the December 17th, 2009 with origin time 01h:37m:50s (Universal Time). The automatic process responded to the event given fast information of the main parameters of the event: hypocentral location and magnitudes (figures 9 and 10). As consequence of the increase during the last months of seismic stations include in the real time processing the response to the event by the SC3 is doing more stable and faster. In this case a stable and robust location was established by SC3 only five minutes after origin time. The Mw(mB)=5.3 calculated by the SC3 was very close to the Mw=5.5 inverted, several hours after, by some agencies using inversion of the moment tensor by waveform modelling (http://www.emsc-csem.org/Images/MT/GQYU6.jpg). The location and magnitude was more or less stable when the number of data (seismograms) reach values around 80, only 5 minutes and a half after O.T..

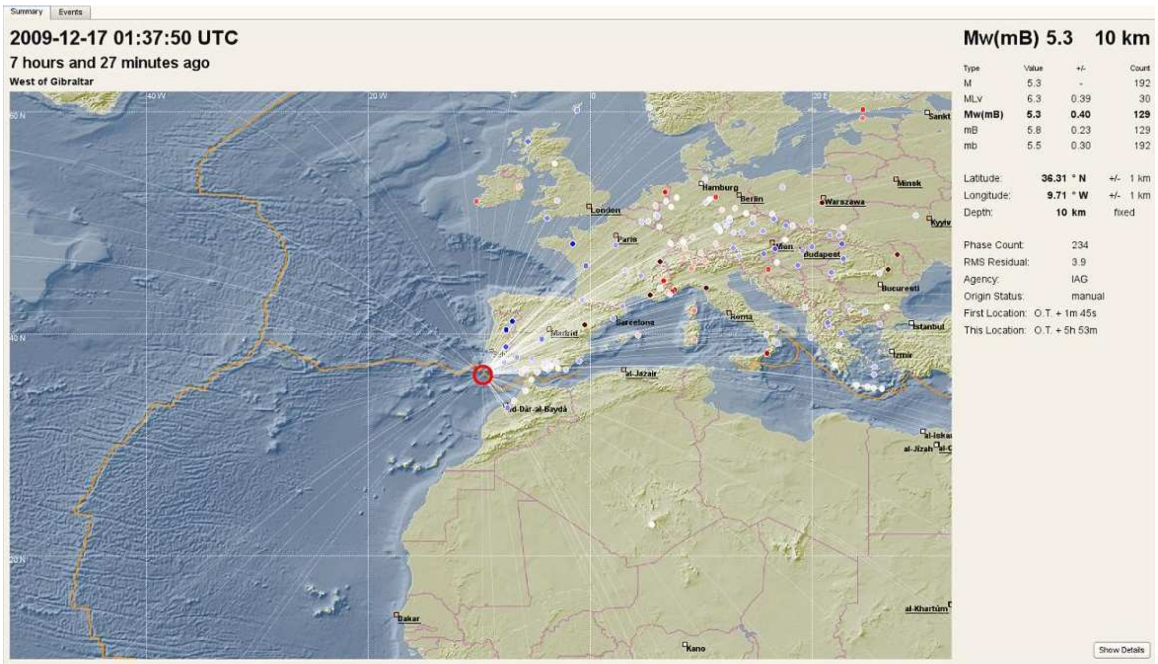


Figure 9. EventSummary graphic module of the SC3 installed at UGR where it is shows the information related with magnitude and location parameters of the Saint Vincent Cape of December 17th, 2009 earthquake with Mw(mB)=5.3.

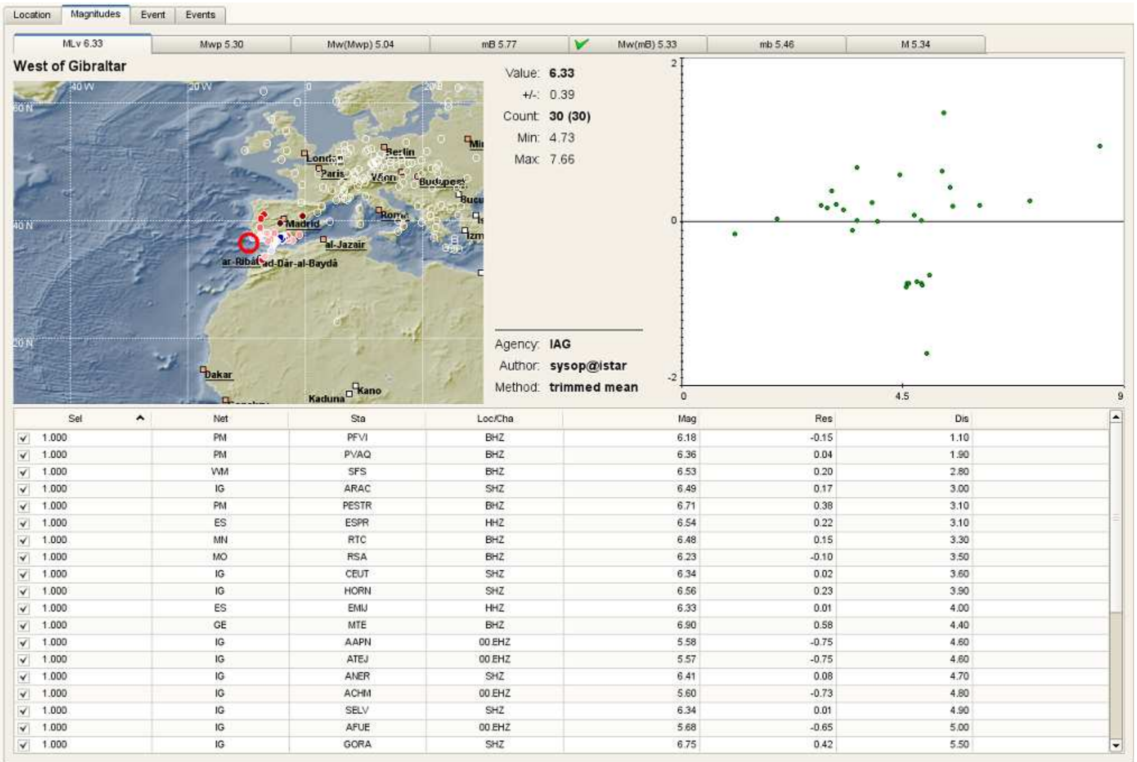


Figure 10.- OriginLocator graphic module of the SC3 for the Saint Vincent earthquake of December 17th, 2009. It is observed detail information related with the different magnitudes estimated.

Because the SC3 installed at *Istar* is also receiving in real time seismograms from seismic station deployed around the world through the IRIS and GEOFON servers, we can also test the potential of the automatic response of the SC3 platform for larger earthquakes in other regions of the world. So, as an example of reliability of the system can take two examples: The L'Aquila April 6th, 2009 earthquake and the May 28th 2009 in Honduras earthquake. In figures 11 and 12 is observed, in the *Event Summary* graphic format, for both cases, the locations and magnitudes obtained by the SC3 are related with the configuration of seismic stations that had the IAG-UGR in that dates. In the L'Aquila earthquake the moment magnitude provided by the system was Mw(mB)=6.4, only 0.1 higher that the inverted by several international institutions several hours after (http://www.emsc-csem.org/Images/MT/GMSS2.jpg). The first location was developed by the SC3 only 2 minutes and 10 seconds after O.T..

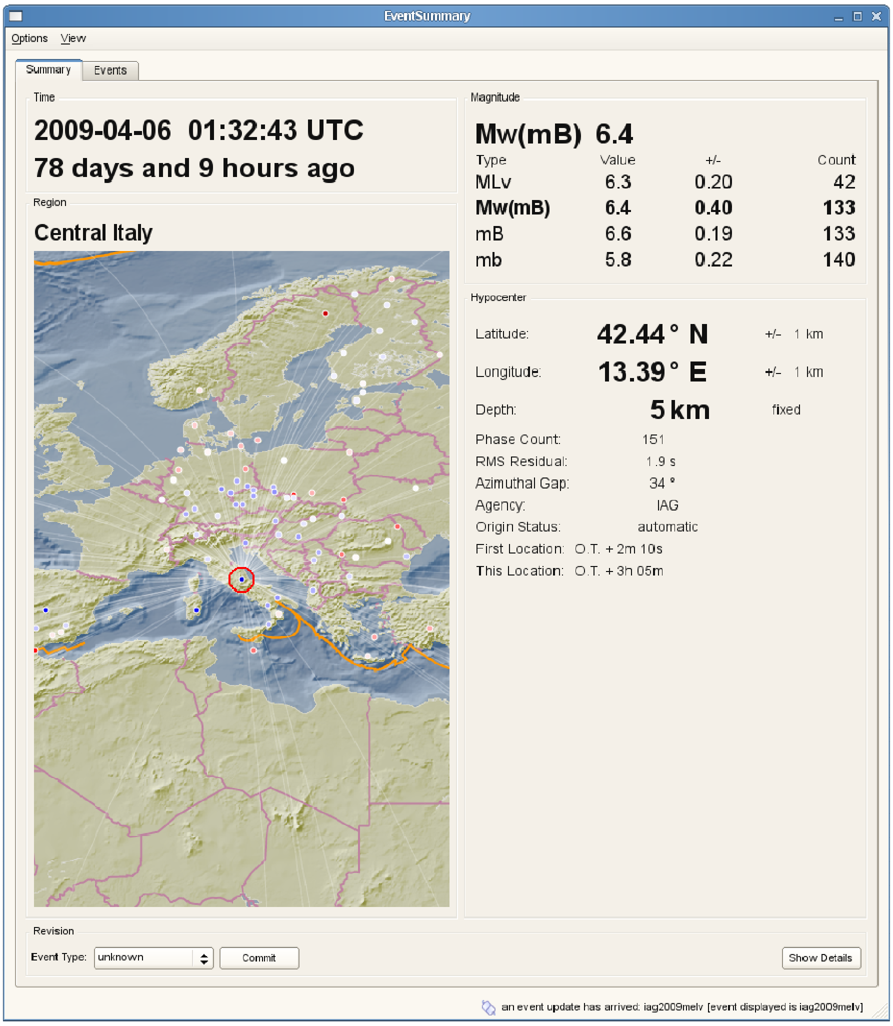


Figure 11. EventSummary graphic module of the SC3 installed at UGR where it is shows the information related with magnitude and location parameters of the L'Aquila April 6th, 2009 earthquake.

In the case of the earthquake in Honduras May 28, 2009, the magnitude Mw of the automatic system was Mw (mB) = 7.4 and the response was OT + 5 minutes. The location given by the USGS show a magnitude of M = 7.3 (http://earthquake.usgs.gov/eqcenter/recenteqsww/Quakes/us2009heak.php).

The inverted Mw by the USGS from different techniques shows solutions between 7.2-7.3.

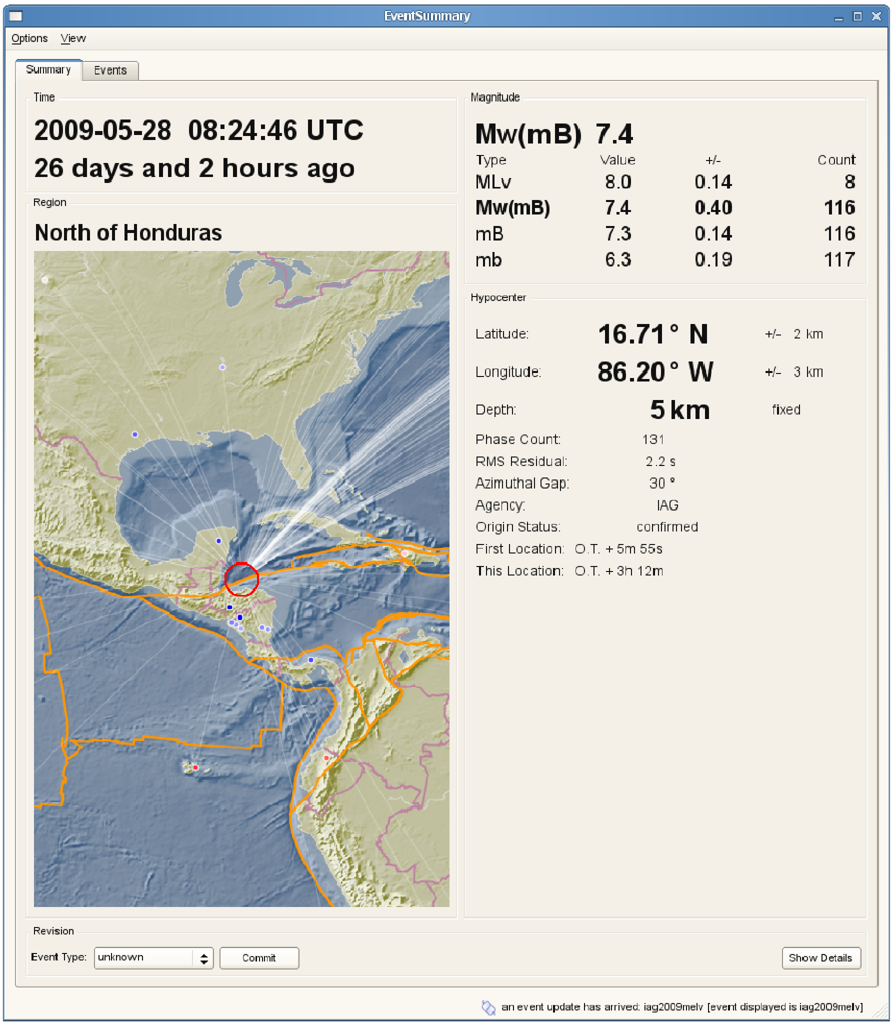


Figure 12. EventSummary graphic module of the SC3 installed at UGR where it is shows the information related with magnitude and location parameters of the Honduras May 28th, 2009 earthquake.

3.3. The case of the IM

As stated before, for a TEWS is fundamental the capability to quickly obtain an accurate determination of the hypocenter and a good evaluation of the magnitude, which are the parameters that are used for an initial evaluation of the potential for the earthquake to cause a tsunami, usually to be feed into a decision matrix.

For the Cadiz Gulf area, a typical tsunami scenario, with a source located Southwest of San Vicent Cape, implies that the first tsunami arrivals will hit the coast within 15 to 20 minutes. The standard requirements for a TEWS demand that the initial solution (hypocenter and magnitude) should be available within less than 5 minutes.

At IM two parallel solutions were implemented: a first one based on Seiscomp 2.6, SEISAN and DATA_EXTRACT (IMSOL), with some extra software developed inside IM; a second one based on SeiscomP3.0.

3.3.1. IMSOL

Seiscomp 2.6 has an automatic data processing built on two basic tools: AutoPick and Autoloc:

- The first one is the responsible for the real time P arrival detection's, which is basically done by applying STA/LTA algorithm to the seismic traces previously band pass filtered (at IM the bandpass is 0,7Hz to 5Hz). When a the sta/lta ration exceeds a certain threshold value, a detection is assigned. This tool is also capable to measure different amplitude values to be used in the computation of mb and MLv magnitudes.

- The second tool, Autoloc, is the one that performs the automatic near-realtime earthquake location and magnitude estimation. The program listens to the AutoPick outputs and try to associate different P arrivals that might form a consistent origin time. The program uses the IASP91 travel time tables. Because automatically the system is only able to detect P arrivals, it is fundamental to have as much as possible real-time seismic stations, in order to minimize the possibility to form false events or compute inaccurate source parameters.

The Autoloc solution proved to work reasonably well, when considering the 5.9Mw earthquake of 2007.02.12, located SW of San Vicent Cape. After 2 minutes upon origin time, the Autoloc program released a solution which was not too far from the one computed manually after 20 minutes. We found an epicentral difference of 12km and depths difference of 6 km. The computed magnitude was 6.2ML (0.3 more then the internationally reported Mw and manual revised ML).

The SEISAN system (Ottemöller and Havskov, 1999) is a well known software package for seismic data processing, supporting, among others, tools for interactive analysis, automatic detection, hypocenter location and magnitude evaluation. Some of the tools have been modified at IM:

- The AutoPic module was changed having now the capability to also detect S waves and measure amplitudes. Amplitudes can be automatically measured on displacement traces, for ML computations, but also on velocity and acceleration, allowing automatic measurements of PGA and PGV (very usefull for ShakeMap computations).

- The Hypocenter program was also modified in order to automatically compute hypocenter solutions by eliminating arrivals that do not fit into the solutions. This process is performed on an automatic iterative schema.

The connection between the Seiscomp2.6 and the SEISAN platform is established by the DATA_EXTRACT software (developped at IM), which is used to check the triggers and to export valid events it into SEISAN data base. This DATA_EXTRACT software (Figure 13) listens to the AutoPick outputs and generates alarms to the on duty analyst, which can then activate the automatic processing and validate the locations using a specific environment build around SEISAN package.

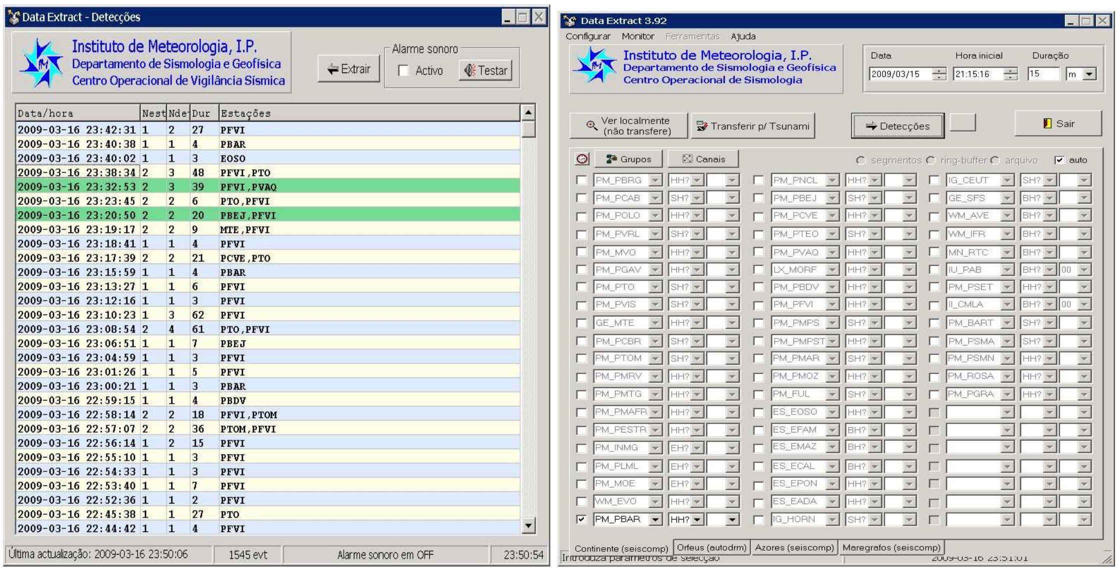


Figure 13. Data_Extract software

With this implemented schema is possible to very accurately compute hypocenter parameters and estimate magnitude ML values for local and regional events occurred in the Cadiz Gulf area as well in the remaining Portugal Mainland and Adjacent areas. In the period from August 2008 to December 2009 this system allowed to systematically obtain the basic source parameters, validated by the on duty staff, within 4 minutes after origin time. For example, the 2009.12.17 event, located SW of San Vicent Cape with a magnitude of 6.0ML (Figure 14), was reported, by Email and mobile GSM message, to the Civil Protection Authorities 3m43s after origin time.

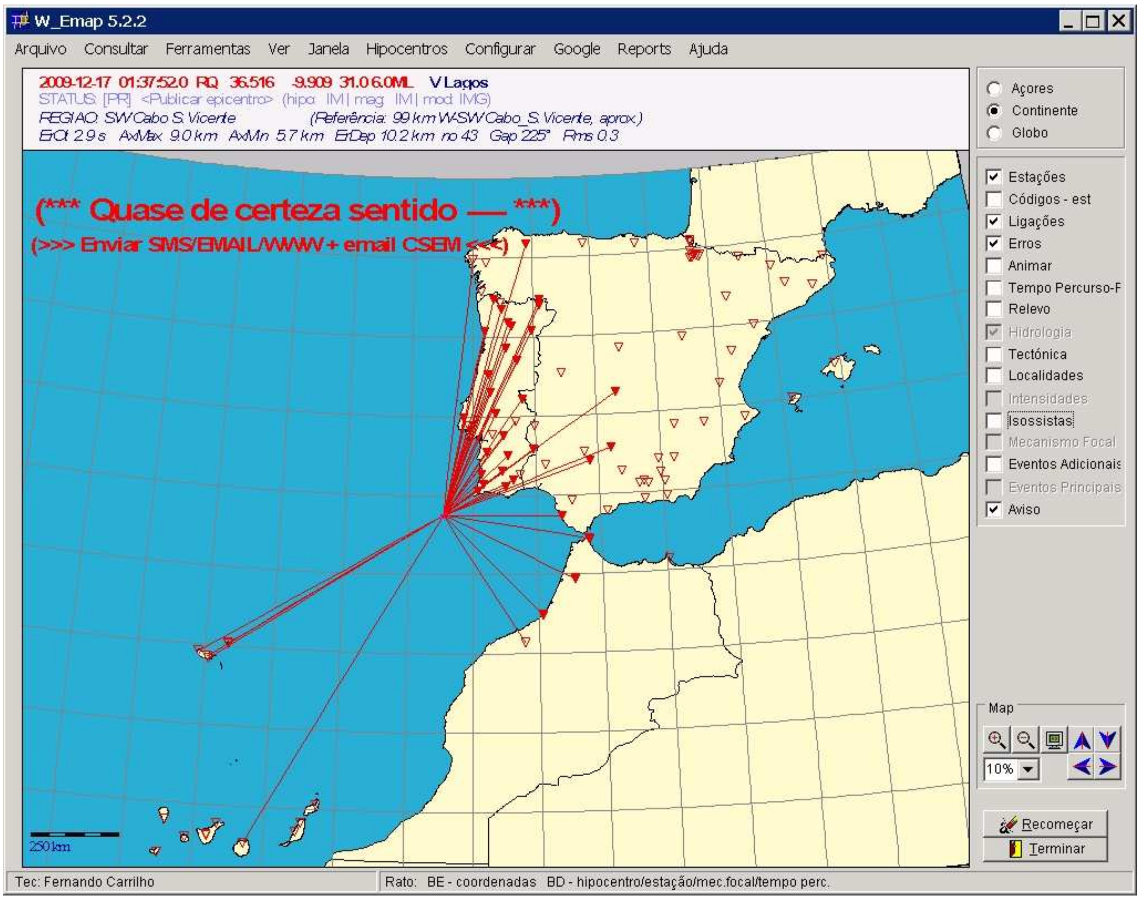


Figure 14. Hypocentral location

However there is a major constrain in this schema, related with magnitude. For regional events only ML is being computed and this formulation can only be used to magnitudes up to 6.5 or 7.0, because it will saturate for larger events. It is required that a fast Mw computation procedure should be implemented on top of SEISAN, in order to be able to properly quickly evaluate the larger earthquakes.

3.3.2. Seiscomp3.0

The main features of SC3 have already be explained in section 3.2.
real time all the seismicity that might occur in this region, particularly the one that might represent a tsunamigenic threat.

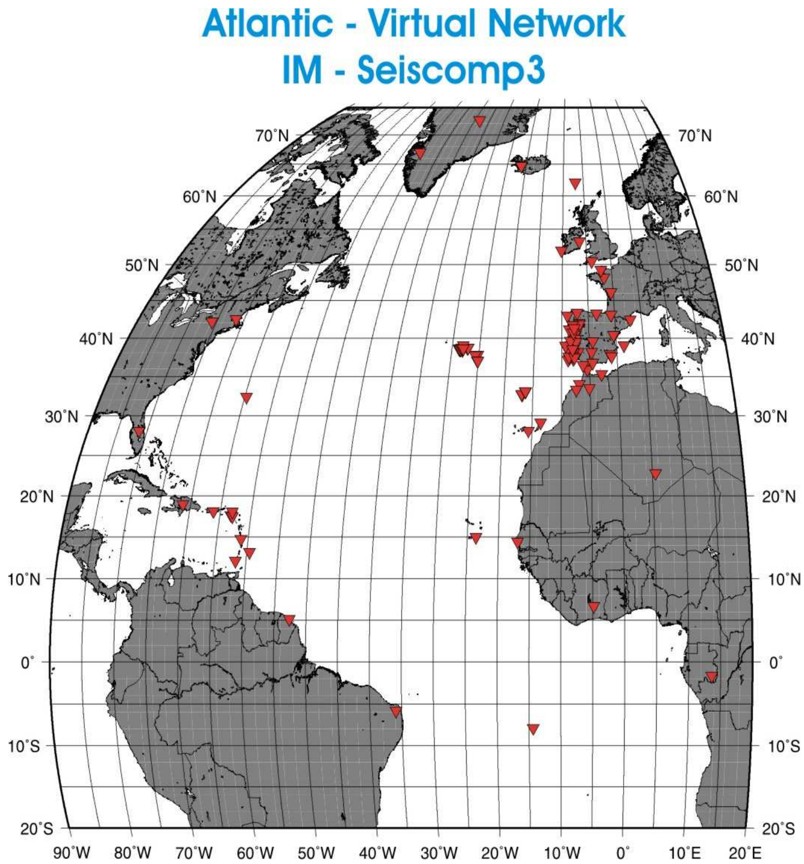


Figure 15. Atlantic "Virtual" Seismic Network controlled by Seiscomp3.0 platform at IM

One of the most interesting features is the capability to quickly estimate hypocenter parameters as well as magnitude, particularly the possibility to compute fast MW (Critical for tsunami potential assessment). However there are still some constrains which comes from the previous AutoLoc versions (Seiscomp 2.6), namely the difficulty to properly compute travel times using more suitable regional velocity models than the global IASP91, no S arrivals are automatically detected, as well as potentially unsuitable magnitude evaluation for regional smaller events (measurements are performed on velocity traces; its not possible to include proper ML regional attenuation parameters and station corrections).

The already mentioned 2009.12.17 earthquake was also automatically analysed by the SC3 installed on rtwc.meteo.pt (Figure 16). According to the final solution from IM, revised manually, the earthquake was located aprox 100 km at SW of San Vincent Cape, with an focal depth of 34 km and a magnitude of 6.0ML (Harvard CMT has evaluated magnitude as 5.6Mw).

The first solution was computed by SC3 1m43s after origin time, using only 4 stations. The first stable solution was obtained 2 minutes after origin time, with an epicentral difference of ~12km to IM final results and pratically the same depth. As expected the epicentral differences became smaller as number of stations increases but this was true only during the first 4 minutes, because after that the epicentral differences becomes slightly larger (~15km) as more distant stations were integrated into the computations. This last fact can be attributed to the mix of regional and teleseismic information in the location process.

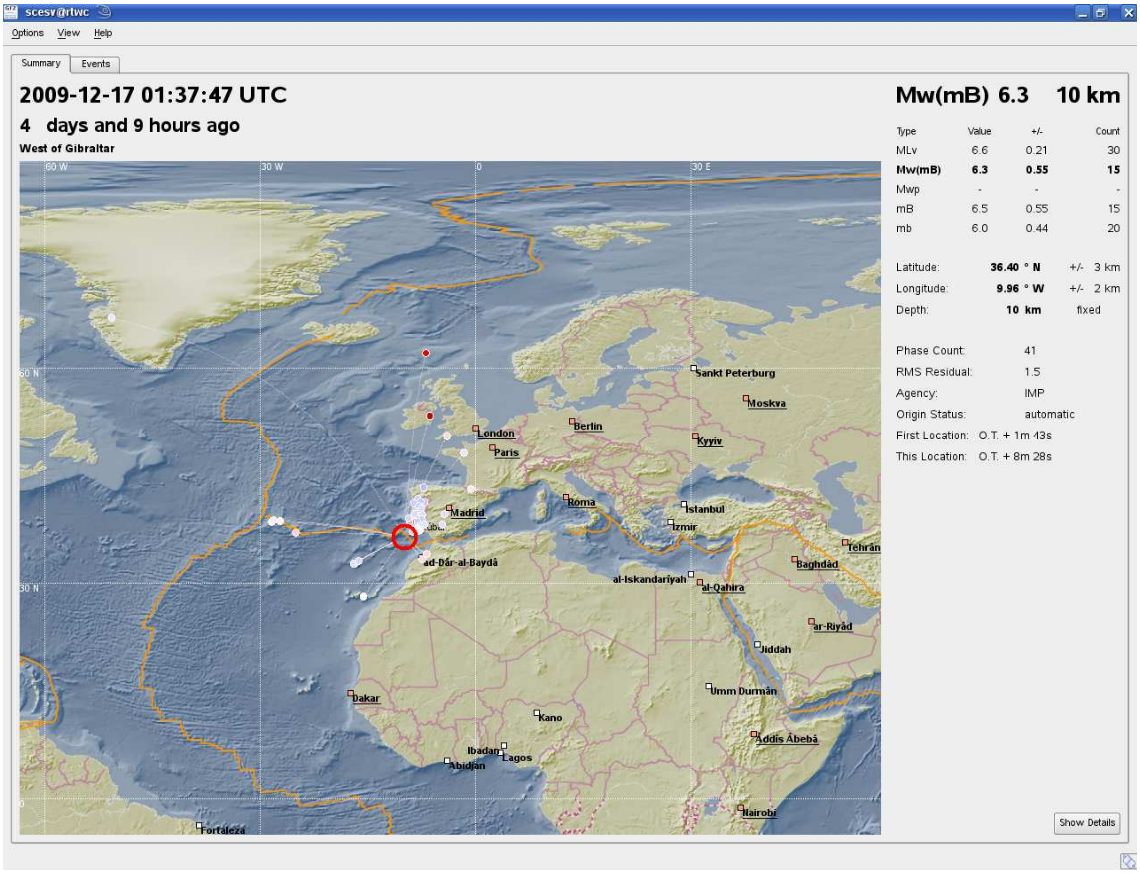
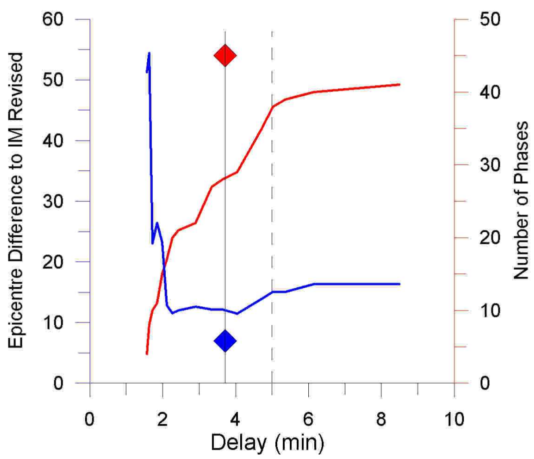


Figure 16. EventSummary graphic module of the SC3 running at IM, showing the information related with magnitude and location parameters of the Saint Vincent Cape of December 17th, 2009 earthquake with Mw(mB)6.3 and Mb6.0.

The location solution communicated by IM to the Portuguese Civil Protection Authorities (IMSOL), computed according to the schema presented in 3.3.1, was released 3m43s after origin time, and it was 6 km away from the final epicentre and 3 km different in depth (31km was the computed), slightly better than the one made available by SC3.0 at the same time. The smaller differences in epicentral location between SC3 and IMSOL can be considered non significative for tsunami early warning purposes. However this is not exactly the same when dealing with the depth parameter. At the 5 min mark, we have an SC3 depth solution evaluated closer to the surface and after 6 min the SC3 location program opted to fix the depth at 10km.

Another important issue is the magnitude. SC3 computed several magnitude values: MLv, mB, mb and Mw(mB). The IMSOL1 plafform, using a calibrated procedure (Carrilho&Vales, 2009), issued a value of 6.0ML. The SC3 also computed a local magnitude, MLv, but the result is very much higher (6.6), which is easily explained by the unproper attenuation coefficents within SC3, as well as the non consideration of stations corrections due to site effects. The preferred solution for SC3 was the Mw(mB) for which a value of 6.3 was assigned. As already mentioned, the moment magnitude issued by CMT (Harvard) was 5.6, much lower then the Mw(mB), and the Mw(mB) computed by SC3 installed at UGR, with a different set of stations, was 5.3 (see section 3.2.1). So, for tsunami early warning and considering this single example, we might be in trouble with the fast magnitude estimation techniques.



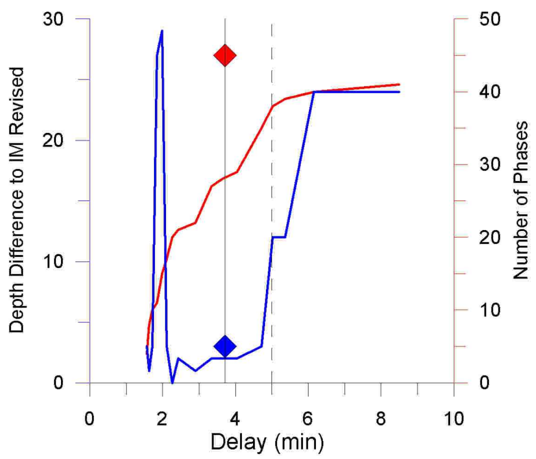


Figure 17. Figure 17.Evolution of differences between the automatic hypocentral solutions, computed by SC3, and the manually revised one. Left: epicentral difference to the manually revised epicentre by IM (blue line), together with number of phases (red); Right: depth difference to the manually revised hypocenter by IM (blue line), together with number of phases (red); diammonds represents the automatic solution validated by the on duty analyst (IMSOL)

4. Conclusions.

The experience in using the Antelope software by the CNRST has shown that this software is highly performing and allows reliable automatic detections and processing. This software allows further to send warning messages within few (5 to 6) minutes by SMS and by email. The Antelope software is moreover user friendly for simple operations such as locating earthquakes. This software requires however, extensive training and familiarity for advanced applications.

This software allows the computing of M_L, m_b and M_s magnitudes in real time, as it receives the different waveform packets. The moment magnitude is not yet integrated within it.

Thus, for tsunami warning purposes, this software is quite performing, except may be for magnitudes, where for very strong events, the types of magnitudes used may saturate and thus, cause an underestimation of the real magnitude. The Antelope software allows though, the integration of new scripts. This means that within the near future, the Morocco tsunami warning center should integrate scripts for new magnitudes estimation, such as $M_w(m_b)$.

From the IAG-UGR experiences, the use of the Seiscomp3.0 platform has been a clear forward step in the management of the fast information (location and size of the earthquakes) related with the regional and global seismic activity. The robustness and speed of the system in obtaining magnitude and hypocentral parameters have been found up improving gradually, parallel to the increased in the number of seismic stations (regional and global) included in the real time processing. The advantage of the platform SC3 platform allows successive improvements and updates as for example the implementation of a more realistic regional Earth model and attenuation parameters. Also the lessons learned in the GITEW could be implemented in the SC3 for a best administration of the data and results in term of a faster and stable location and size evaluation of the seismic source of a future tsunamigenic earthquake in the Gulf of Cadiz.

IM found SC3 software as a possible future tool for the National and Regional Tsunami Warning Centers. Despite some constrains, particularly related with travel time models, magnitudes and non-existing automatic S wave detection, the system shows great capability to quickly compute the basic source parameters, particularly the fast Mw procedures implemented, which, however, must be more deeply investigated. However, IMSOL solution will be kept operational and probably might be enhanced in the future, particularly with the implementation of an Mw algorithm.

5. Recommendations for a future Early Warning System in the Gulf of Cadiz.

The main recommendation comes from facilitating the exchange of seismic data of between the national and regional networks operating in the region, fundamentally with seismic networks in north of Africa. To provide a rapid response by Civil Protection is necessary to supply a faster and stable location and magnitude which is basically related with the maximum number of seismic stations that may be being received in real time, overall in the epicentral area of the expected large earthquake. Fortunately, the different agencies monitoring the region have carried out a strong investment and the numbers of seismic stations, mainly broad band high resolution instruments, deployed in the last years have increased very significantly. Now, it is possible to use protocols as SeedLink or Liss that allow the real time reception and the share between several agencies, which facilitate configuring an *ad hoc* Real Time Virtual Seismic Network dedicated to the surveillance and monitoring of the earthquake activity not only in the Gulf of Cadiz but also in surrounding areas.

After the experiences with SC3, seems that this automatic platform could be really interesting to be adopted by the different organisms and agencies involved monitoring and surveillance of the seismic activity in the SW of Iberia region and surrounding areas independently of which will be the future focal point for the surveillance for a TEWS. An important and crucial goal to take in mind and where an important effort has to done is in the deployment of buoys and OBS's because there is an important gap of information (seismic data) in the Gulf of Cadiz. Until now, only inland seismic stations are include in the real time processing.

6. References

Blewitt, G., C. Kreemer, W. Hammond, H.-P. Plag, S. Stein, and E. Okal (2006), Rapid determination of earthquake magnitude using GPS for tsunami warning systems. *Geophys. Res. Lett.,* ***L11309****, doi:10.1029/2006GL026145.*

Bormann, P., and K. Wylegalla (2005), Quick estimator of the size of great earthquakes, Eos Trans. AGU, **86***(46), doi:10.1029/2005EO460005.*

Bormann, P. and J. Saul (2008) The new IASPEI standard broadband magnitude m_B *Seismological Research Letters*; September/October 2008; v. 79; no. 5; p. 698-705; doi: 10.1785/gssrl.79.5.698

Bormann, P. and J. Saul (2009) A fast, non-saturating Magnitude Estimator for Great earthquakes. *Seismological Research Letters*; September/October 2009; v. 80; no. 5; p. 808-816; doi: 10.1785/gssrl.80.5.8

Carrilho, F., and D.Vales (2009). Calibration of Magnitude ML for Portugal Mainland and Adjacent Area. *Book of papers, 6º Simpósio de Meteorologia e Geofísica*, Costa de Caparica. (in press)

Krüger F., and M. Ohrnberger (2005) Tracking the rupture of the M_w = 9.3 Sumatra earthquake over 1,150 km at teleseismic distance. *Nature* ***435****, 937-939 doi:10.1038/nature03696*

Hanka, W., J. Saul, B. Weber, J. Becker and GITEWS Team (2008). Timely regional tsunami warning and rapid global earthquake monitoring. *ORFEUS Electronic Newsletter****, Vol. 8****, No 1, (*http://www.orfeus-eu.org*).*

Lomax, A. and A. Michelini (2005)**,** Rapid Determination of Earthquake Size for Hazard Warning**.** *EOS Trans. AGU,* ***86****, 19, 185-189.*

Lomax, A., (2005), Rapid estimation of rupture extent for large earthquakes: application to the 2004, M9 Sumatra-Andaman mega-thrust**.** *Geophys. Res. Lett.*, **32**, L10314, doi:10.1029/2005GL022437.

Lomax, A. and A. Michelini (2009a), Mwpd: A Duration-Amplitude procedure for rapid determination of earthquake magnitude and tsunamigenic potential from P waveforms. *Geophys. J. Int.*,**176**, 200-214.

Lomax, A. and A. Michelini (2009b), Tsunami early warning using earthquake rupture duration, *Geophys. Res. Lett.,* ***36****, L09306, doi:10.1029/2009GL037223.*

Menke M., and V. Levin (2005) A strategy to rapidly determine the magnitude of great earthquakes. *EOS Trans. AGU,* ***86****, 19, 10*

Ottemöller, L. and J. Havskov (1999). SeisNet: A General Purpose Virtual Seismic Network. *Seismological Research Letters, 70, 5.*

Saul, J.; Bormann, P. (2006): Automated computation of the cumulative broadband body-wave magnitude mBc, ***AGU 2006*** *Fall Meeting (San Francisco, USA 2006).*

Saul, J., J. Becker, B. Weber, A. Heinloo and W. Hanka (2008). Advances in SeisComp 3 development. *In ORFEUS Coordination Meeting & SeisComP 3 Workshop. Barcelona, May 5-7, 2008*

Stein, S. and E. A. Okal, (2005) Speed and size of the Sumatra earthquake, *Nature,* ***434****, 581-582*.

Tsuboi, S., K. Abe, K. Takano, and Y. Yamanaka (1995) Rapid determination of Mw from broadband P waveforms, *Bull. Seism. Soc. Am.*, **83**, 606–613.

Whitmore, P. M., S. Tsuboi, B. Hirshorn, and T. J. Sokolowski (2002) Magnitude-dependent correction for Mwp, *Science of Tsunami Hazards*, **20,4**, 187–192.