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D.34b current situation and know-how on tsunami and EWS

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D.34b current situation and know-how on tsunami and EWS

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1. Introduction

Tsunami are long water waves generated by different mechanisms such as sub-aerial and submarine landslides and volcanic eruptions and meteoric impacts, but the most common and effective mechanism is due to submarine earthquake (Boschi et al, 1997; Bernard et al.,2009). In this case around the seismic source the seafloor is displaced as effect of the earthquake and the water column over the source is affected by the sea bottom motion. In the process of recovering its gravitational equilibrium the displaced water mass causes an abrupt conversion of a large amount of potential energy into kinetic energy, causing the horizontal propagation of a free surface disturbance: the tsunami wave is now generated and can travel long distances with very low attenuation, thanks to its great wavelength. These waves become very dangerous and destructive when they approach the coast where the steep bathymetric gradient causes their shortening in wavelength and their growing in amplitude.

In spite of the great effort dedicated in the last decades to the study of the tsunami generation mechanism, this process is presently still poorly understood. In particular it is still an open question if, after a great submarine earthquake, a destructive tsunami will be generated or not, as shown for instance by the recent submarine earthquakes of Samoa Islands on September 29, 2009 and of Sumatra on the following day. The magnitude of these events were similar (respectively equal to 8,3 and 7.6), but in the first case a destructive tsunami was generated, while in the second case no tsunami occurred.

To cope the tsunami threat the first rudimentary tsunami warning system to alert the community was put in place in Hawaii in the 1920s. More advanced systems were developed after the tsunamis caused by 1946 Aleutinian Islands Earthquake and after 1960 Chile Earthquake that devastated Hilo island. From the eighties of the past century, thanks to the measurement in open ocean of the bottom pressure perturbation caused by the transit of a tsunami wave (Filloux, 1982), a more reliable and effective tsunami warning system (Gonzales, Bernard et al., 2009) began to be developed for the Pacific area. The tsunami warning systems are presently based on the earthquake magnitude and hypocentre depth evaluation (seismic events larger than 7.0 in magnitude and shallower than 60 km are considered potentially tsunamigenic) and take advantage of the different propagation speed of tsunamis and earthquakes, about 220 m/s against 5000 m/s respectively. In turn the epicentre location of the seismic event, its magnitude and the bathymetry of the area threatened by the possible tsunami are used as input parameters by very fast numerical models which compute expected tsunami wave heights and arrival times at coast (cit. MOST, Titov). To avoid too many false alarms, the observed sea level heights in open ocean or at distant tide gauges are used to confirm the actual generation of the tsunami.

In principle, a very dense and properly distributed network of the sensors used for sea level height estimation as bottom pressure recorders, tide gauges and GPS buoy can be used also for the detection of non seismic triggered tsunamis. However, for non seismic triggered tsunami, this network is less effective, reliable and characterized by delayed timein issue the warning with respect to the case of seismic generated tsunamis.

In the case of tsunamis generated by an earthquake, if the coasts to be mitigated by the tsunami impact are not too close to the generation area, the propagation speed mismatch between seismic and tsunami wave can give time enough to allow the evaluation of the earthquake main parameters (through the seismic network and using fast dedicated algorithms), to compute the tsunami forecast and to issue the watches and warnings messages to the population.

In optimal condition, with a wide and advanced tsunami warning system in place and with an extended seismic network with good coverage, the lag between the seismic event and the emission of the first watch and warning bulletin is presently in the order of 15 minutes. The Pacific Tsunami Warning Center/NOAA/NWS was able to release the first warning 16 minutes after the magnitude 8.1 Samoa tsunamigenic seismic event of September 29th, 2009.

Concluding, the present tsunami warning procedure for tsunamis generated by earthquakes can be summarized as follows: after a shallow submarine earthquake exceeding a given magnitude, the seismic signals are used to issue warning messages which are successively confirmed or cleared by the sea level height measurements.

The present methodology, based on two separated steps, one concerning the seismic signal and one the sea level heights, appear to be the very effective and must be used in the tsunami warning procedure: at least, until a reliable model able to quickly predict which earthquakes produce significant tsunamis well be available. Anyway this technique, which requires in its first step a certain amount of time to estimate the earthquake parameters and then a certain amount of time to compute the tsunami heights and arrival times, presently shows an intrinsic weakness in the case of near-shore tsunamigenic seismic sources and in general when the tsunami arrival times are very short (situation which is unfortunately common to all Mediterranean basin and to Japan) or in the case of tsunamis not triggered by seismic events. In these cases , a different approach to the tsunami warning problem must be investigated and eventually undertaken, in addition to the optimization of the algorithms and computing times, This approach, which should complement the present tsunami warning system methodology:, follows two main directions:

1) the identification of the tsunamigenic sources, where possible, and their continuous monitoring with dedicated instruments. In this way it it is possible a very quick evaluation of the source parameters used in tsunami warning and the use of ready made scenarios for issuing the watch and warning bulletins. This strategy has been followed, for instance, by NEAREST for the localization of the potentially tsunamigenic tectonic sources of the Gulf of Cadiz and with the development of a tsunameter able to operate in generation area. A similar approach has been also adopted by the Italian Civil Protection for non tectonic sources, as in the case of the Sciara del Fuoco scar in Stromboli Island: here, the gravitative instability of the volcanic slope, that causes tsunamigenic sub-aerial/submarine landslides, is continuously monitored by SAR sensors (Casagli et al., 2009). In the marine area, bottom pressure recorder and tide gauges have been installed to detect the tsunami.

2) the identification of possible tsunami precursors, which can travel faster than tsunami waves and from which the actual generation of a tsunami may be directly inferred. Various authors have proposed sound waves, propagating in air or in the water, generated by the tsunami or by the earthquake or by the sea bottom motion caused by the earthquake or by the landslide, as possible tsunami precursors (Peltier and Hines, 1976; Okal et al., 2003; Chierici et al., 2010).

The use of tsunami precursors would benefit, for instance in case of near-shore seismic tsunamigenic sources, of shorter time required only for the evaluation of the earthquake epicentral localization, with the actual generation of the tsunami directly inferred from the precursor itself. In fac, the epicentral localization is based on arrival times of the seismic signals at different (and circumstantial few) stations, while much longer times are required to evaluate also the earthquake hypocentre depth and magnitude, as it happens in the present warning procedure. This approach can be very useful also in case of on seismic tsunamis, as for instance the tsunamis generated by submarine landslides, where the tsunami precursor could be detected much earlier than the sea level signals. As we will see later, the hydro-acoustic precursor proposed within NEAREST appears to be very promising.

2. State of the art of the Tsunami Early Warning System

An effective early warning is defined as “the provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response”.

The main goal of any early warning system against natural and human induced hazards is the protection of population, so once a threat has been detected and a warning bulletin has been issued to the Civil Authorities, a number of procedures starts which are not less important and critical of the rapid issuing of the warning bulletins in the purpose of saving lives. These procedures concerns for instance the population preparedness and education, the evacuation plans, the way the warning is transmitted to end users and the means to distribute the warning and many other topics depending also on social factors.

To be effective and complete, an early warning system needs to include four interacting elements:

a) risk knowledge,**b**) monitoring and warning services,**c**) dissemination and communication,**d**) response capability.Each of these elements has deep, direct and reciprocal linkages with the others. The monitoring and warning services, has been the main object of discussion in the introduction, but experience has shown that technically high quality prediction by themselves are insufficient to achieve the desired reduction in losses and impacts (Basher, 2006). The human factor in early warning systems is in fact very significant (Twigg, 2002).In the following, the state of the art of tsunami warning systems, mainly in the sense of monitoring and warning services, will be briefly discussed.

2.1 The Pacific, United States and part of Caribbean Islands areas.

As a consequence of the disastrous tsunamis occurred in Sumatra, on December 26th, 2004 the development of reliable Tsunami Early Warning System (TEWS) received in the last years a strong impulse both from scientific and civil institutions.

The first reliable Tsunami Early Warning System (TEWS) has been realized by the U.S. National Oceanic and Atmospheric Administration (NOAA) with the installation of the Deep Ocean Assessment and Reporting of Tsunami (DART, Meining, 2005). The Pacific Tsunami Warning System is based on DART buoys and on the American and Pacific regional seismic networks, whosesignals are processed by fast dedicated algorithms:.then, using fast tsunami propagation model (MOST, Titov and Gonzales, 1997) the the warning is issued. The bottom pressure recorders (BPR) are used to monitor the pressure perturbations at depth, including the perturbation generated by the travelling tsunami waves, to confirm or to clear the warning. The data acquired by the BPR are processed by a dedicated tsunami detection algorithm (Mofjeld 2000) on board the deployed instrument in real time. If a parent tsunami signal is detected then a warning message is sent via the one-way acoustic link to a surface buoy and then via satellite link to the land Tsunami Warning Center. The first six DART boys has been deployed in 2001. The development of the system received a strong improvement in the framework of the DART II project in 2005 (Green, 2006). In particular a two-way acoustic link have been installed on the bottom pressure recorder, allowing a re-configuration of the threshold of the pressure signal from land. The network has been progressively extended reaching the number of 39 deployed stations (Fig. 1). This network of bottom pressure recorders is presently protecting a large part of Pacific basin and the Atlantic coasts of United States and some of Caribbean Islands. (DART has been recenctly re-funded with about 40 M$)

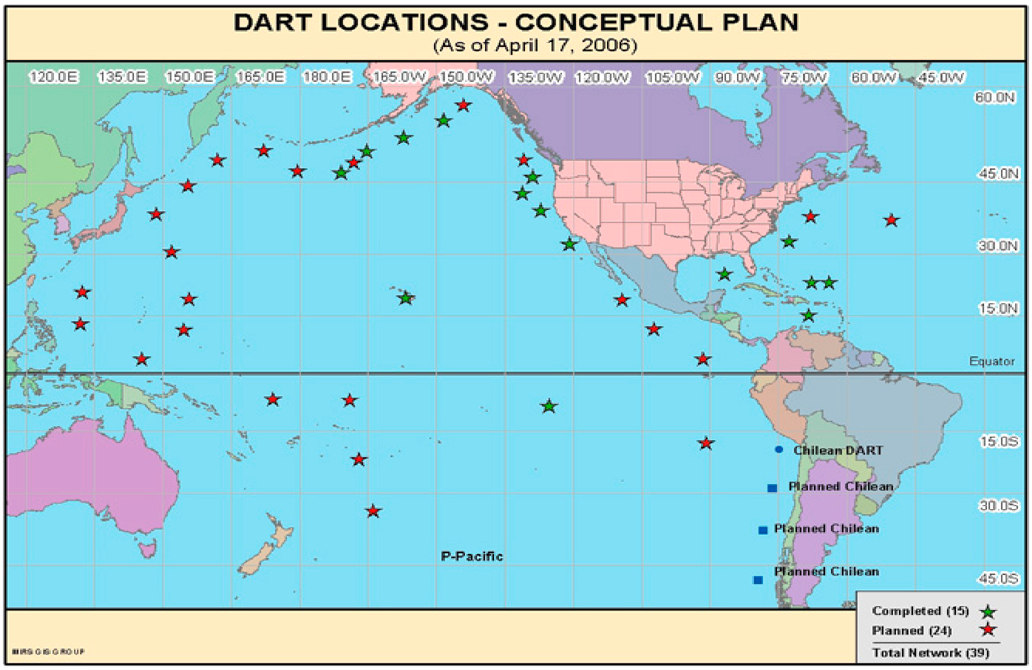


Figure1 - DART buoy distribution: at present all the 39 buoys are deployed.

The DART system is at present the only regional tsunami early warning system completely operational, and it has shown very good reliability and effectiveness during the recent tsunamigenic events of Samoa Islands (Central Pacific), on September 29th 2009 and of Conception (Chile), on February 27th 2010. The tsunami warning was issued by Pacific Tsunami Warning Center / NOAA/ NWS within few minutes after the earthquake (16 minutes and 12 minutes respectively). Unfortunately in both these events, while the majority of the involved population was alerted in time, few localities where reached by the tsunami waves very soon after the earthquake, about 20-30 minutes, as for example happened at Pago Pago in 2009, which was reached by a 1.45 m wave after XX minutes and Talcahuano, during the 2010 event, which was hit by tsunami wave of 2.34 meter height at 6.53z, nineteen minutes after the quake.

In the Pacific area, also Japan is developing its own tsunami early warning system, designed to cope the threat of the vicinity of the tsunamigenic sources to the Japanese coasts. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) developed, in the framework of the Dense Ocean-floor Network System for Earthquakes and Tsunamis (DONET) project, the first submarine cabled real-time seafloor observatory network (Fig. 2) to monitor and detect submarine earthquakes and tsunami waves (DONET has been funded with 35 M$ and it is waiting for 100 M$ more).

- DONET (dense ocean network system for earthquakes and tsunamis)

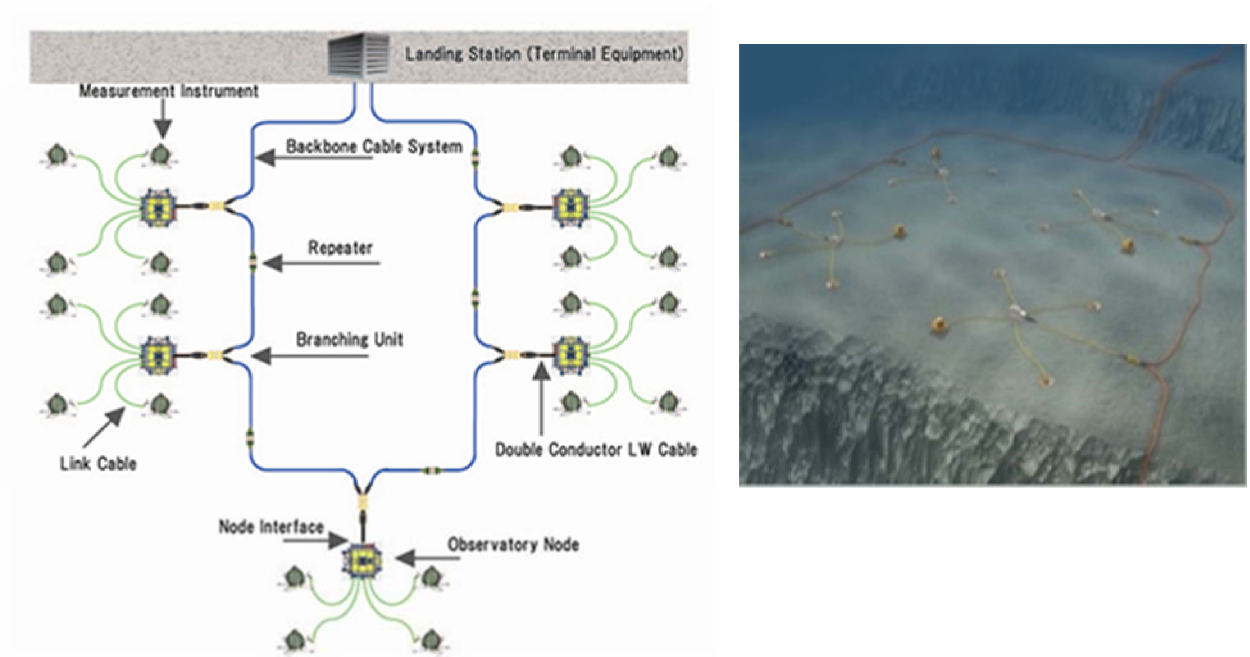


Figure 2 - DONET scheme.

This project started in 2006 with the installation of twenty cabled monitoring observatories in the active seismic zone of To-Nankai (Kawaguchi, 2002) subduction zone. Each observatory is composed of a seismometer and a bottom pressure recorders. The sensors density of the network would provide them immediate detection of the tsunami. The Japan Meteorological Agency's Tsunami Warning System is at present able to issue the first alarm usually down to 5 minutes for the local tsunamis.

The Pacific area is presently the best protected from the tsunami threat, both concerning the development of the warning and monitoring services and the awareness and the preparedness of the population and of the civil authorities and the response capability

2.2 The Indian Ocean area

Few months after the disastrous tsunami of Sumatra, on March 2005 has been started the project “German Indonesian Tsunami Early Warning System” (GITEWS) headed by German Research Centre for Geosciences (GFZ). The tsunami early warning system developed in the framework of this project consists of a network of Ocean Bottom Units (OBU), tide gauges and a GPS buoy. The OBU unit is equipped with seismometer and pressure sensors. The innovative feature, with respect to the DART and DART II system, is represented by the use GPS buoys measurements in order to correct the bottom pressure measurement, that can be biased by the sudden displacement of the seafloor caused by the submarine earthquake (Rudloff, 2009, Nosov et al, 2007). The data from the various sensors are collected and analyzed at the warning center ofthe Meteorological, Climatology and Geophysical Agency of Indonesia (BMKG) ocated in Jakarta. The Officer on Duty, based on simulations and pre-taylored hazard and risk maps of the coastlines, and with the help of a Decision Support System (DDS) software, which analyse all the information, the available data, and the modeling outputs, is enabled to assess, if a tsunami has been generated, where and when it is to be expected and which height might be reached by the wave. GITEWS went into operation at the very end of 2008, when entered its optimization phase. At that time two of the ten planned buoys were installed, and further 4 buoys were waiting for installation.

Through GITEWS project, within the framework of Intergovernmental Oceanographic Commission (IOC) of UNESCO, 9 tide gauge and GPS measuring station have been installed along the coast of the Indian Ocean, to collect reliable sea level data and horizontal and vertical displacement of the ground not only from Indonesian coast but also from neighbouring states.

GITEWS was designed expressly to meet the stringent warning times (about 20 minutes in extreme case) imposed by the Indonesian tectonic setting.In fact, GPS buoys have been added to the bottom pressure recorders to correct the effect generated in bottom pressure signal by the possible displacement of the sea bottom in tsunami generation areas GITEWS uses the software SeisComP3 developed by GFZ which is able to determine the localization and the magnitude of an earthquake within few minutes. The same software is used also by the warning system of the neighbouring states, as for instance the Indian Tsunami warning system.

(GITEWS has been funded with 54 M$ by German governmet plus 8.77M$ by DEWS EUproject in the framework of the VI programme).

From October 200,7 in the Indian Ocean is operative also the Indian Tsunami Warning System, with the tsunami warning centre managed by the Indian National Centre For Ocean Information Services (INCOIS) and located in Hyderabad. The warning centre receives seismic data from the national seismic network of the India Meteorological Department (IMD) and from other international seismic networks. The system is able to detect seismic events of magnitude M> 6 in the Indian Ocean Basin in the less than 12 minutes after the event. The warning centre receive also data via satellite from six ocean buoys equipped with pressure sensors installed by National Institute of Ocean Technology (NIOT), four in the Bay of Bengal and two in Arabian Sea. In addition, Survey Of India (SOI) and NIOT have installed 30 tide gauge to monitor the progress of tsunami waves. INCOIS will share data with Asian Disaster Preparedness Centre in Bangkok (Thailand). Seismic and sea level data are processed using a custom software application generating alerts whenever the prescribed threshold is exceeded. The release of tsunami watches and warning is based on pre-set decision support rules and are disseminated to the concerned authorities following a standard operating procedure. The Centre issues bulletins on a three level scale: watch, alert and warning. The alert is issued to science departments and administration officials and is divided into two sub levels, orange which is not made public and red when public is advised to prepare to evacuate if necessary. The warning level means that actual evacuation begins. Inundation maps have been computed by Integrated Coastal and Marine Area Management (ICMAM) using data from 5 historical earthquakes and the high resolution bathymetry generated by National Remote Sensing Centre (NRSC). The real time Information Technology has been supplied by Tata Consultant Services (TCS): INCOIS has been funded with 27.8 M$

Many other countries facing Indian Ocean are adding their tsunami warning capabilities to the Indian Ocean Tsunami Warning System coordinating each other. Among these countries must be cited in particular Australia, which faces both Pacific and Indian Ocean and, after the 2004 Sumatra event, acquired a national tsunami warning system based on DART II buoys for bottom pressure measurement. The Australian system benefits also of the Pacific Ocean Warning system described in the paragraph above. The first Australian tsunami buoy was deployed , in collaboration with NOAA, in the South East Tasman Sea in the mid of April 2007. North East, South East, East and South East Australian coasts are now protected by DART II buoys and coastal sea level stations. Geoscience Australia (GA), which operates the Australian seismic network, and Emergency Management Australia (EMA) are the governmental agencies in charged to provide the warning to the Bureau of Meteorology and to coordinates the operations of territorial Emergency Management Organisations respectively. The Bureau is in charged to run tsunami forecast model to generate the first estimate, to issue the warning to public and to verify the actual existence of the tsunami using the data from sea level enhanced network. EMA has also the responsibility for improving public awareness and preparedness for tsunami. The Australian Tsunami Warning System (ATWS) supports the international efforts to establish the Indian Ocean Tsunami Warning System (IOTWS) and contributes to the facilitations of tsunami warning for South East pacific. ATWS has been funded with 68.9 M$.

In conclusion Indian Ocean, which was the theatre of the worst tragedy caused by a tsunamis in the last two century, is now protected b a state of the art monitoring and warning service, while the education and preparedness of the involved population is still in progress.

2.3 Mediterranean and Atlantic European Regions

As clearly stated at page 11 of the document "Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and connected Seas, NEAMTWS, Implementation Plan, Version 3.4, October 2009, printed on behald the Intergovernmental Oceanografic Commissio (IOC), Technical Series: "*Among the regions that are covered by the ICGs established by the IOC, the North Eastern Atlantic and Mediterranean region (NEAM) is at present the only one where at least an interim tsunami warning system is not in place, which shows how urgent it is for the ICG/NEAMTWS to make any efforts to establish a first nucleus of this TWS as soon as possible*". This sentence might be enough to conclude the paragraph about the state of the art of tsunami warning in this area where millions of people are prone to tsunami threat as documented by historical tsunamis catalogue (Tinti et al). Notwithstanding the real situation is not so discouraging because in a number of European countries including Israel, some key elements for a Tsunami warning system are presently in place. They are of good technical quality and routinely working, as for instance national seismic networks, communication systems and facilities. The first step, as recommended by NEAMTWS implementation plan, is the integration of the national seismic networks, to achieve and earthquake parameters estimation time within about five minutes. The same integration efforts must be done regarding sea level data collected by national services and scientific institutions. Thanks and to national support and to EU funding some European countries have also developed the technology needed to build up a state of the art tsunami monitoring and early warning services including regional warning centers, ocean bottom pressure recorders networks and near real time data transmission, fast algorithms to detect parent tsunami signals and all the information and knowledge needed to produce inundation maps etc. Presently, some EU project dedicated to the tsunami warning and involving the main European and North African Geophysical and Geological Institution, namely NEAREST in the Gulf of Cadiz, TRANSFER in Mediterranean and, for some aspect, SEAHELLARC in Eastern Mediterranean are in their final phase. The only European country with a running tsunami warning network is Great Britain that has chosen a different approach in tsunami warning by using a network of tide gauges only (Woodworth, 2009). This kind of system can be useful in case of tsunamis generated at long distance from the coasts to be mitigated and it is not suitable in case of near-shore tsunamigenic sources. The National Tidal and Sea Level Facility (NTSLF) project has been developed by the United Kingdom since 2002. The NTSLF is based on a network of 45 tide gauges (the UK National Tide Gauge Network) sites all around the UK coastline complemented by a geodetic networks, to monitor vertical land movements, and by other tide gauges located around the British Dependent Territories of the South Atlantic and Gibraltar (Alcock, 1998).

Few words must be dedicated to Africa which is still unprotected on the Indian Ocean side as well as on the Atlantic Ocean and Mediterranean and Red Sea seas: with the exception of Morocco, Tunisia Algeria and Egypt, which are starting some very initial actions, and the presence of few tide gauges (linked to a satellite) installed by Proudman Oceanographic Laboratory on behalf of UNESCO (Alcock et al., 1998).

3. The contribution of NEAREST

To face the hazard connected to near-shore tectonic tsunamigenic sources, NEAREST proposed an integrated approach consisting in the localization and the characterization of the tsunamigenic sources the development of a new deep water tsunami detection instrument: *the" tsunameter"*, able to operate in generation area, its installation nearby the tsunamigenic source the development of new fast and more accurate tsunami detection algorithms.

NEAREST implemented also, in prototypical form, all the basic parts of a "state of the art regional" tsunami monitoring and warning service, including:

1) the integration of a regional seismic network for the rapid identification of the potentially tsunamigenic earthquakes in the SW Iberian margin (within less than 5 min)

2) the temporary installation (two test missions of about 1 year each) of the tsunameter at 3200 m depth offshore Cabo de S. Vicente and the transmission in near real time of event messages, periodical status messages and bottom pressure data via satellite link to a land station and their automatic distribution to other scientific centers,

3) the installation in the Gulf of Cadiz of a real time network of tide gauges devoted to the tsunami warning,

4) the modeling of the arrival times and wave amplitudes at selected coastal test localities and the production of flooding maps for the same localities

5) the implementation of a simulator for the decision maker authorities.

Moreover in the framework of NEAREST a number of scientific results have been obtained, which can be used for tsunami warning purpose and for the evaluation and mitigation of the tsunami hazard in general and in SW Iberia in particular, namely:

a) the complete identification and the localization of the tectonic potential tsunami sources in the Gulf of Cadiz,

b) the mapping of the sediment instabilities in the same area

c) the definition of the crustal velocity model of the offshore of SW Iberia,

d) the exhaustive recognition of the records of paleo-tsunamis that flooded coastal areas and wetlands of South Portugal, Spain and North Morocco and the location and sampling of the marine records that could be related to paleo-seismic events as submarine slides. NEAREST correlated the occurrence of onshore/offshore tsunami deposits to paleo-seismicity.

e) the development of a theoretical work concerning hydro-acoustic signal and tsunami wave generated by seafloor motion taking into account of a compressible sedimentary layer. The results of this model showed the existence of a possible “hydro-acoustic tsunami precursor” , that could be integrated in a new generation of Tsunami Early Warning System. Below, we give a short description of NEAREST main features concerning the development of a TWES. The results obtaineg by NEAREST concerning the idenfirfication and caracterization of the tectonic sources coupled with the knowledge of the seismicity are discussed in other documents.

3.1 The Virtual Network

NEAREST carried out the integration of the three seismic centres of IM (Portugal), UGR (Spain) and CNRST (Morocco) for real time acquisition, sharing and processing seismic, tide gauges and abyssal station data, point 1, 2 and 3 of the paragraph above. As example, Figure 3 show the seismic station received at UGR node, Figure 4 the coastal tide gauges received by IM. Figure 5 shows an example of tide gauges recording during the 17 Dec. 2009 earthquake occurred in the Gulf of Cadiz.

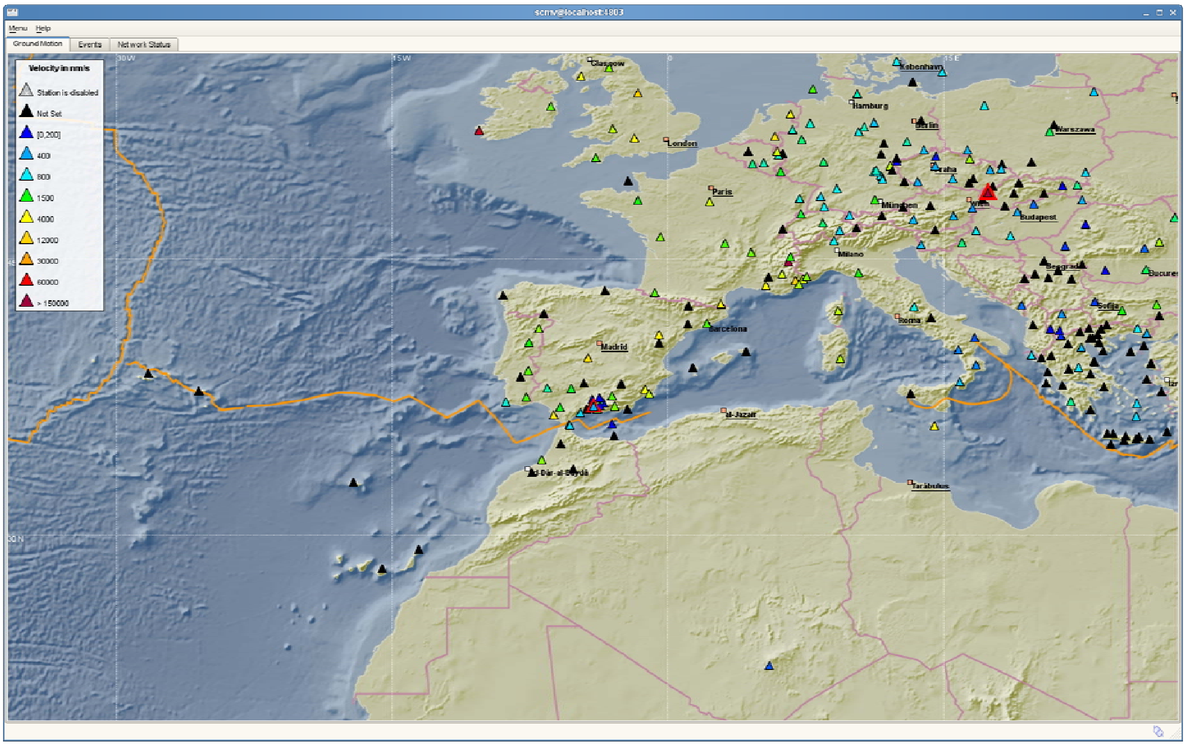


Figure 3 - Geographical distribution of the seismic stations received by SC3 platform at UGR node.

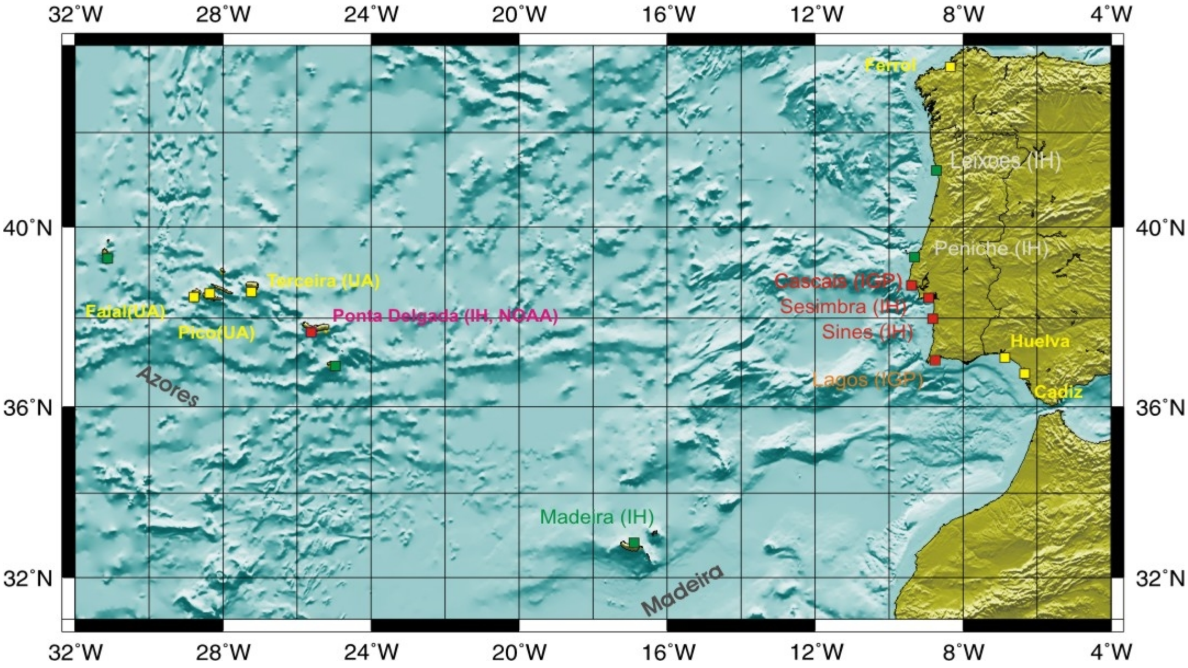


Figure 4 - Current status of the coastal tide gauge collection at IM. Red squares, real-time connection via Seiscomp. Yellow squares, near real-time connection trough Internet and TAT. Green squares, expansion of the network planned for 2010.

This work allowed to define a Virtual Seismic Network for the target region that could be dedicated to a future Tsunami Early Warning in SW Iberia margin and/or to support other possible focal points dedicated to the surveillance in other Regions. The Virtual Seismic Network developed could now locate and estimate the main earthquake parameters in the SW Iberian margin in less than five minutes using SeisComP3 software package developed by GFZ (see in Fig. 6 the flow chart). As matter of fact, the Prototype of the Tsunami Early Warning System (P-TEWS) developed in NEAREST, is currently implemented at NEAREST partner IM (Instituto de Meteorologia, Portugal).

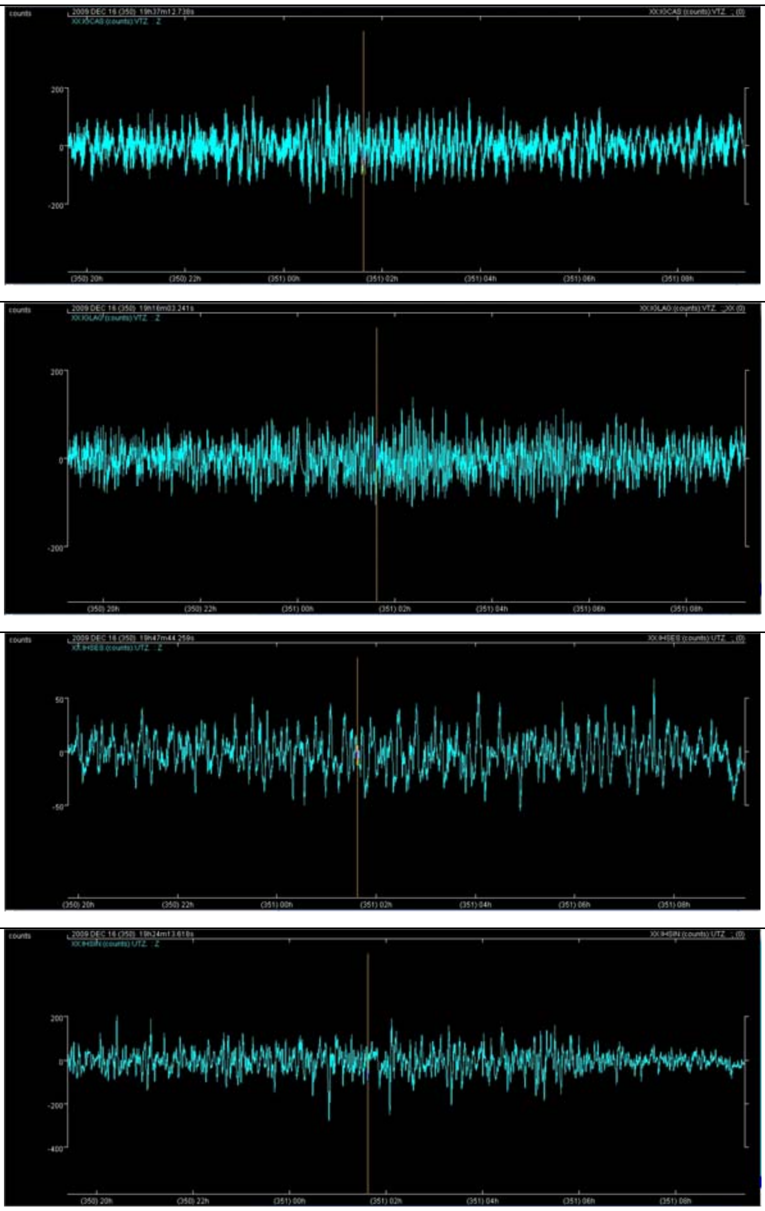


Figure 5 - Tide-gauge recordings from the Cascais, Lagos, Sines and Sesimbra stations the day a magnitude 6.0 earthquake occurred in the Gulf of Cadiz, the 17th December 2009 (origin time marked by yellow line).

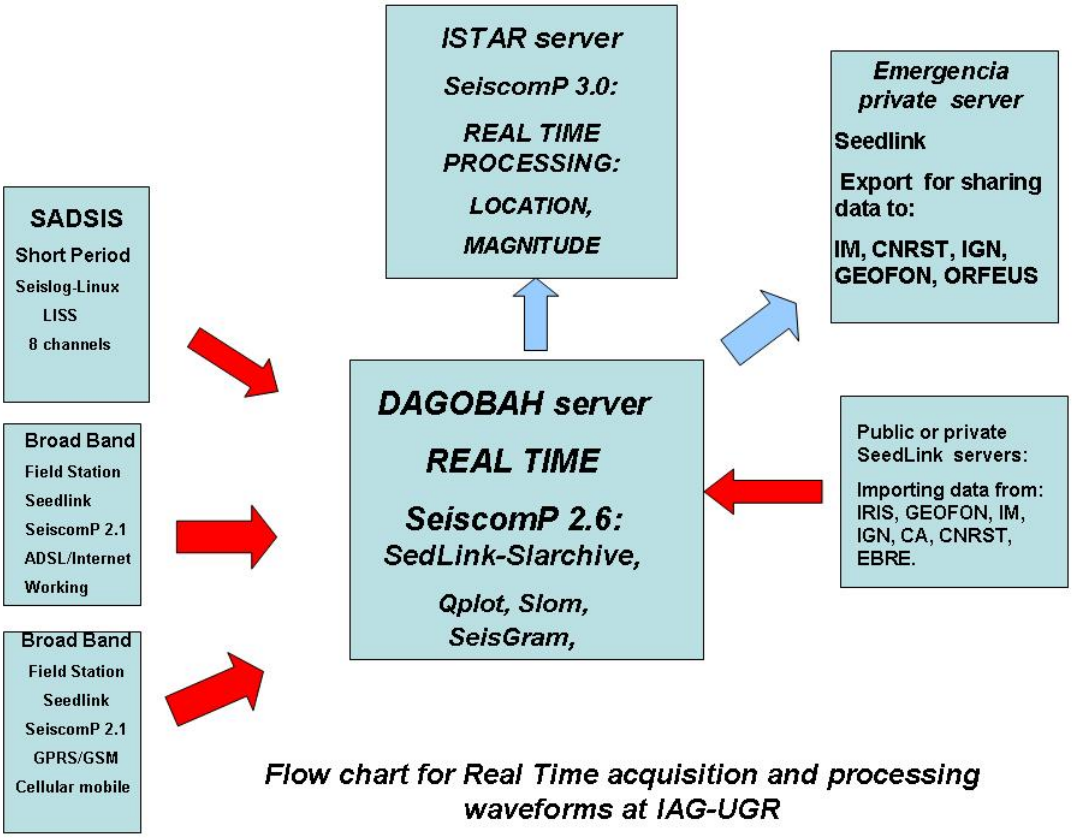


Figure 6 - In this figure is shown the new Real Time acquisition and data processing scheme at IAG-UGR. Red arrow indicate import data in real time from SeedLink servers and blue indicate export to SeedLink server for sharing data with another organisms. Dagobah server is the responsible to receive real time data of from both, the IAG-UGR seismic network (broad band and short period) as from other public or private servers that share data. The second server (Istar) performs the real time processing of the waveforms in order to identify, locate and assess the magnitude of earthquakes and the third (Emergencia) is responsible for exporting data to other agencies that can receive data belonging to our network.

3.2 The tsunami warning decision support sysytem (DSS)

The Prototype of the Tsunami warning System implemented at the Instituto de Meteorologia (IM-Portugal) is based on the Tsunami Analysis Tool (TAT) developed by Alessandro Annunziato and the Joint Research Centre in Ispra (Italy). The basics of the software developed by JRC are explained in Annunziato and Best (2005), Annunziato 2007a and Annunziato 2007b. The status of the current Portuguese Tsunami Warning System was published in the paper by Annunziato et the NEAREST Partners F.Carrilho, L. Matias, M.A. Baptista and R. Omira l. (2009). Fig, XX sketched the data flow within the system.

Through the TAT the Prototype for the Portuguese Tsunami Warning System carries out: .

i) the continuous checkof the seismic signalto provide earthquake parametric data. When a certain number of criteria is met, then software automatically goes to step (ii)

ii) Given a tsunamigenic earthquake, the closest pre-computed scenario is automatically selected. The operator can revise this choice and can also decide if an amplitude factor should be applied to account, for example, to source depth.

iii) The operator validates the scenario that includes estimates for the arrival time of the tsunami to the coastal forecast points and also an estimate of the wave amplitude. A colour code is attributed to each level of amplitude.

iv) Based solely on earthquake information a message is generated and can be distributed to the Emergency Management Agencies.

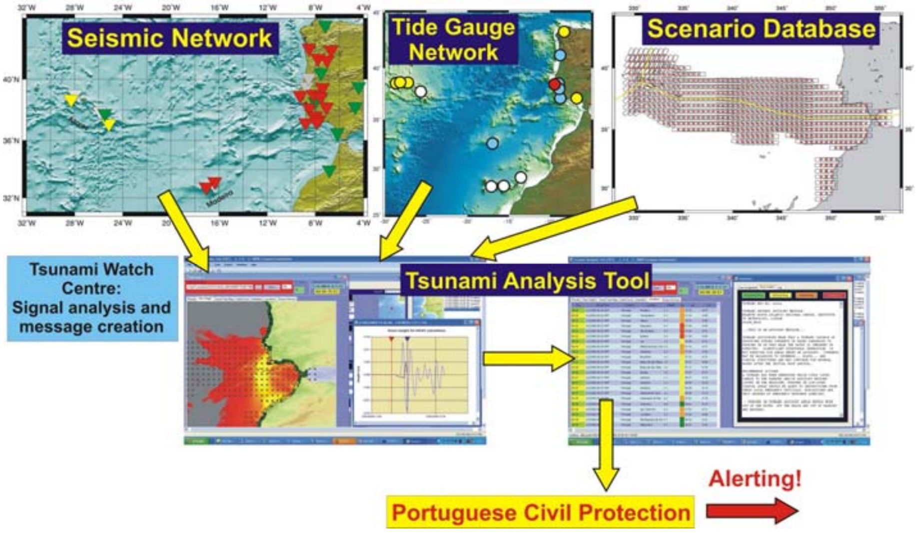


Figure 7 - The Prototype for the Portuguese Tsunami Warning System (Annunziato et al., 2009).

To confirm or cancel the first tsunami message, the operator begins collection in real time the sea level information provided by tide-gauges, and compares the measurements with the models.

Following a Standard Operational Procedure (to be defined) the operator decides on the follow-up messages to be issued and TAT generates the adequate formatted messages.

3.3 The Tsunameter

In the framework of NEAREST, a prototype of a new instrument, called “tsunameter”, has been specifically designed to operate in tsunami generation areas and it has been developed and installed above a major tsunamigenic structure, off the Gulf of Cadiz, at water depth of 3200m (Fig.8).

All the underwater systems and the sensors forming the tsunameter have been hosted onboard the pre existing abyssal station GEOSTAR (Geophysical and Oceanographic Station for Abyssal Research) developed by INGV through previous EU funding, which acts like a carrier (Fig.9) and supplyies the power and the acoustic communication with the surface buoy (Fig.10). The tsunameter is made by a set of devices, some of which are installed at depth, namely: a bottom pressure sensor, accelerometers, seismometer connected to a processing unit. The tsunameter is in charge of the data processing and of the identification of the tsunami wave, if present, and it is able to take into account the possible dynamical and kinematical effects due to the sea floor motion biasing the tsunami signal measurements and identification.

The tsunameter communicates through a dual acoustic link with the surface buoy, which is part of the stand alone configuration of GEOSTAR, hosting the surface devices of the tsunameter, namely: GPS, tilt meter, meteo station, and satellite dual link communication system connected with the control land station. Figure 11 shows the tsunameter communication scheme.

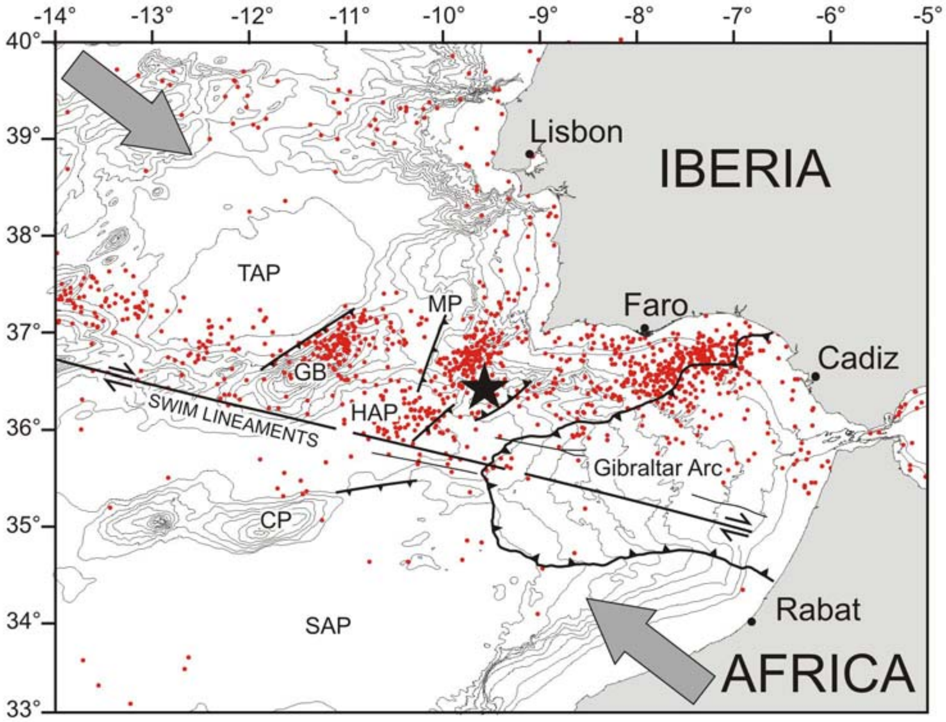


Figure 8 - Gulf of Cadiz tectonic map with GEOSTAR deployment site (Black star). Contour line every 500m. Grey arrows: relative movement direction between Africa and Iberia plates. TAP: Tagus Abyssal Plain; HAP: Horseshoe Abyssal Plain; SAP: Seine Abyssal plain; GB: Gorringe Bank; MP: Marques de Pombal Structure; Swim Lineaments representing the probable modern plate boundary between Africa and Iberia; black line with triangles: major thrust fault present in the area. Red dots are earthquake epicentres distribution in the last ten years (from USGS database).

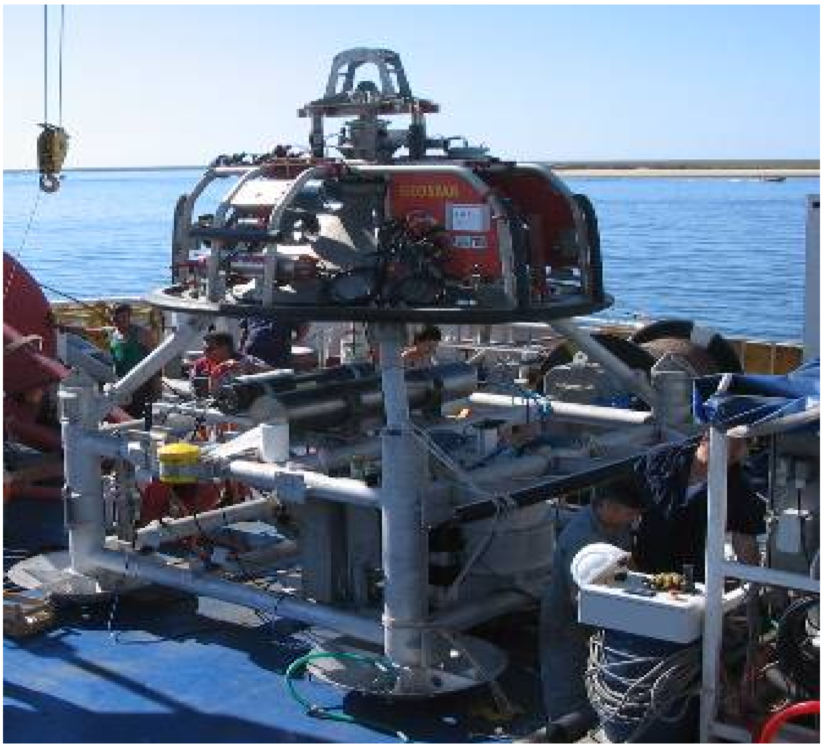


Figure 9 - The GEOSTAR abyssal station equipped with the tsunameter sensors

Figure 10 - The GEOSTAR pre exintet buoy which host the surface devices of the Tsunameter.

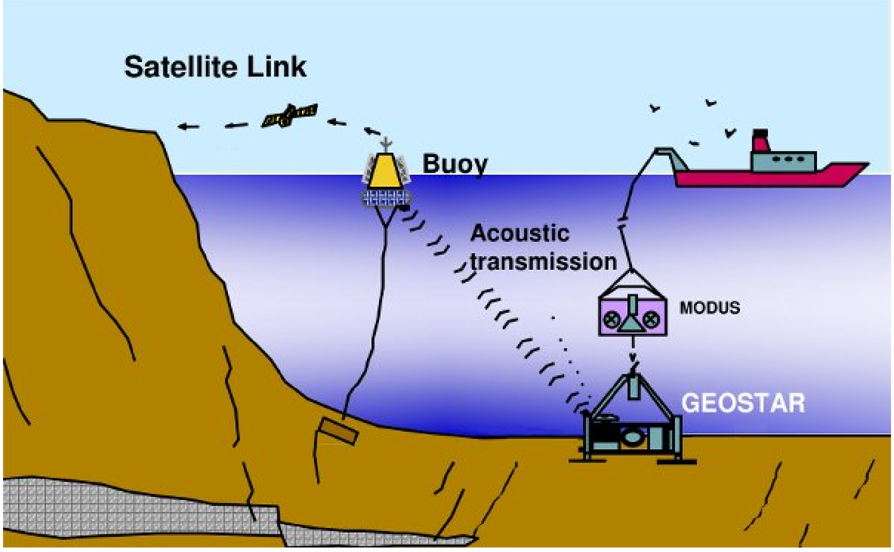


Figure 11 - The tsunameter communication scheme.

The seafloor station is designed to operate in three different ways:

1) Mission mode: two periodic messages are sent to the surface buoy every 6 hours containing, respectively, the sensors status and sampled pressure, accelerometric, gravimetric, correntometric, conductiovity and temperature, data.

2) Event mode: it is triggered by a seismic or pressure event, the data relevant for the warning purpose are sent to the surface buoy.

3) Idle mode: a power saving mode during which the station can be reconfigured and restarted.

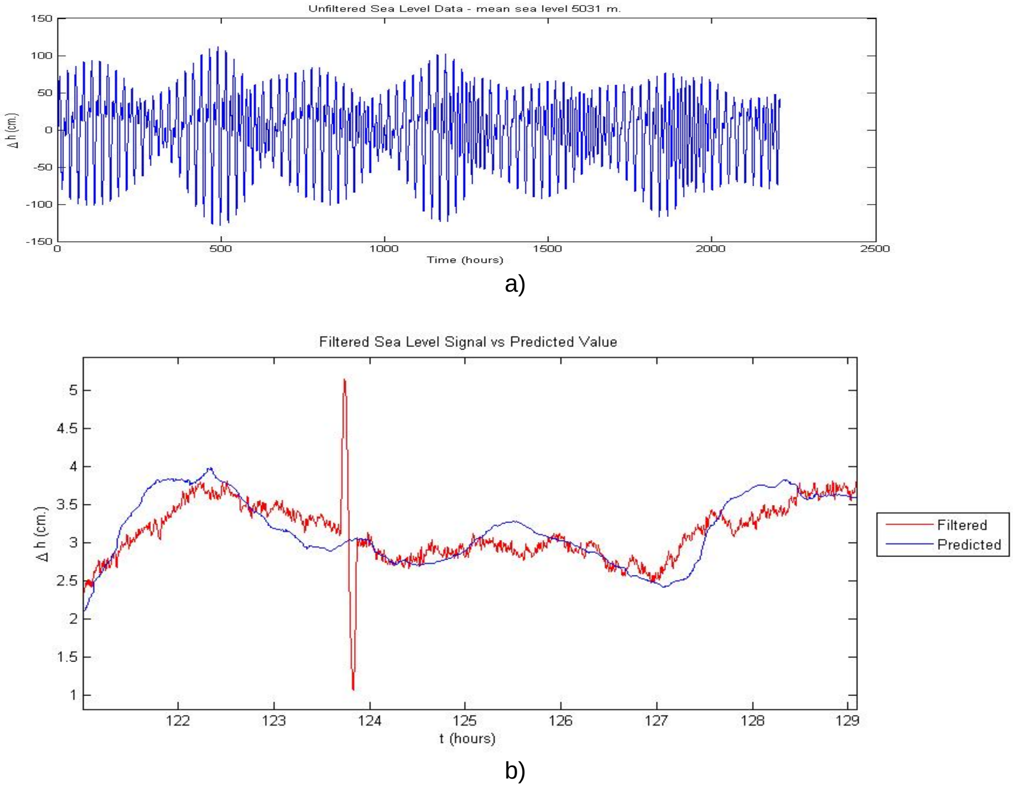
The data acquired by the tsunameter are processed in real-time at the sea-floor by dedicated algorithms and are cross-checked in order to send a tsunami warning message. In particular the tsunami detection procedure is based on a double check on both pressure and seismic events. The seismic data are processed using a Short Term Average over Long Term Average (STA/LTA) algorithm.

The tsunameter hosted on board the GEOSTAR abyssal station has been installed in the Gulf of Cadiz from July 2007 to august 2008, and successively re-deployed in November 2009 for another one- year test mission. During these missions all the part of the tsunameter have been successfully tested in severe real environment condition. The use of the on board accelometers allows the correction of the pressure effects due to the sea bottom displacement and due to the possible pressure sensor motion which may affect the pressure record during seismic events in generation

3.4 The real time Tsunami detection algorithm

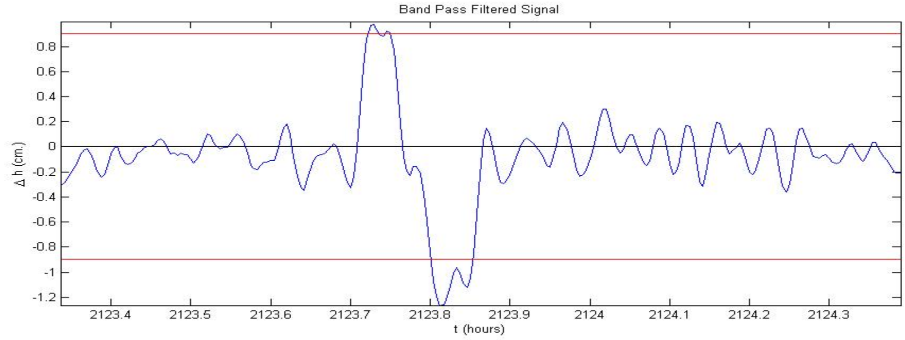
The bottom pressure data acquired by the pressure sensor and the accelerometers data are analysed using the new tsunami detection algorithm developed within NEAREST and composed by a chain of different filters. Each filter can be included or excluded in real time by the processing procedure. The application of this filtering cascade to the bottom pressure time series reduces the dynamical range of the sea level perturbations. In particular, this algorithm is able to take into account also basin effects, reducing the dynamical range of the bottom pressure time series from about 3 meters of equivalent water to few centimetres, obtaining tsunami detection sensibility better than 1cm (Fig.12). Finally, the filtered bottom pressure data are matched against an appropriate tsunami amplitude threshold. Once exceeded, the warning message is issued.

A modified version of the detection algorithm can be applied also to the data set acquired by a tide gauge: in this case the sea level time series is characterised by a wider dynamical range (which can reach also 5 or more meters) with respect open sea, mainly due to tide basin components. To face this problem a new procedure has been developed and added to the filter cascade (Pignagnoli et al., 2010).



a)

b)



c)

Figure 12 - Examples of the new tsunami detection algorithm performances two different filtering configuration are shown. a) The time series dynamical range about 2 m is strongly reduced and a small parent tsunami signal of about 2cm amplitudeb) and 1cm c) respectively are clearly recognizable. Inset c) shows the detection of 1 cm tsunami signal with a warning threshold set to 0.9 cm (red line).

3.5 Tsunami Modeling, Inundation Map and Tsunami event simulation

Tsunami hydrodynamic modeling (Fig.13) was made with a slightly modified version of COMCOT code (Omira et al., 2009a; 2009b). Nested grids have resolutions of 800 m, 200 m and 50 m respectively, in order to assure a good description of bathymetric and topographic features in the area.

Inundation maps were coputed for a test area located in the Algarve (South Portugal), along the Lagos and Sagres coastal areas based on very high-resolution bathymetric data which were, in part, acquired by the project partners (Figs.14, 15). For run-up and inundation computation, a moving boundary scheme to track the moving shoreline (Liu et al. 1995) has been adopted.

In addition a true feasibility study of Early Warning System was performed by simulating a seismic and tsunami event. This was accomplished by developing two simulators.

One simulator that creates synthetic data flows representing seismic information and water level data computed from realistic scenarios to be fed into the monitoring system and test its outcomes. The other simulator that evaluates the consequences of an event seismic and tsunami, being able to figure its environmental impacts to provide the Civil Protection authorities an operational add-to-decision tool in case of a simulated or true crisis.

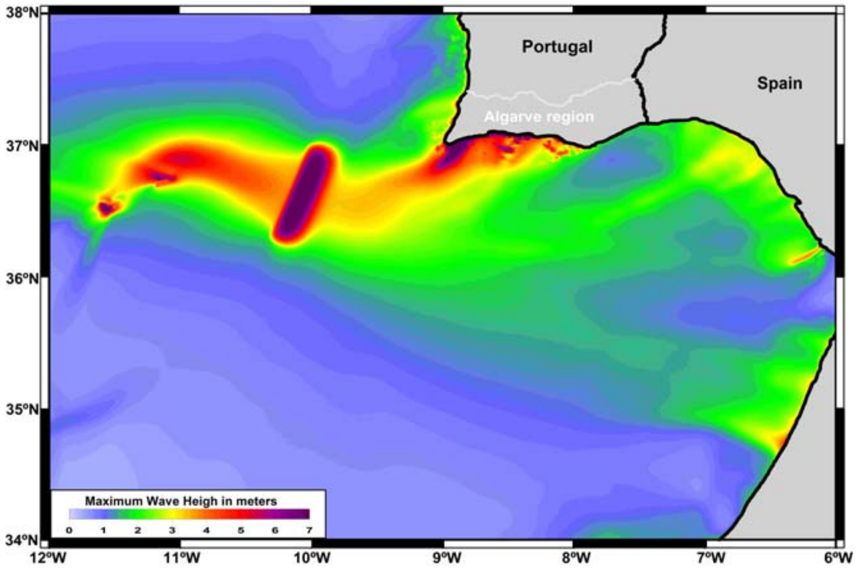


Figure 13 Results of the propagation modeling for the Marques de Pombal scenario.

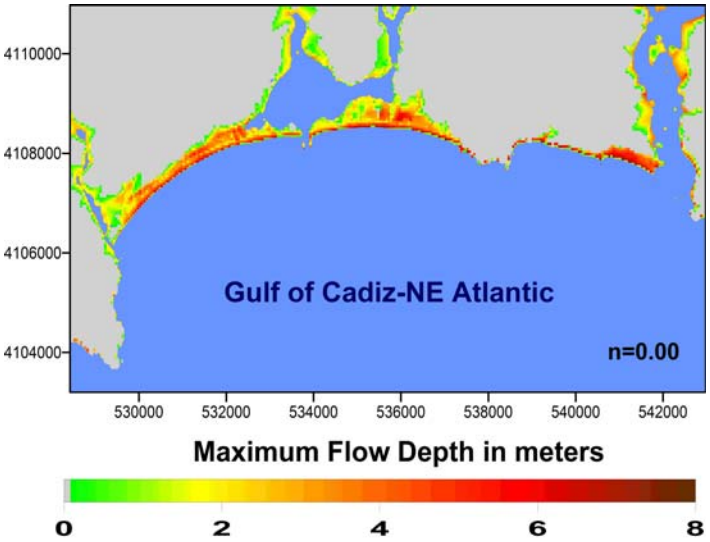


Figure 14 - Inundation Map – Lagos –Portimão area; Marques de Pombal scenario; Manning Coefficient 0.00

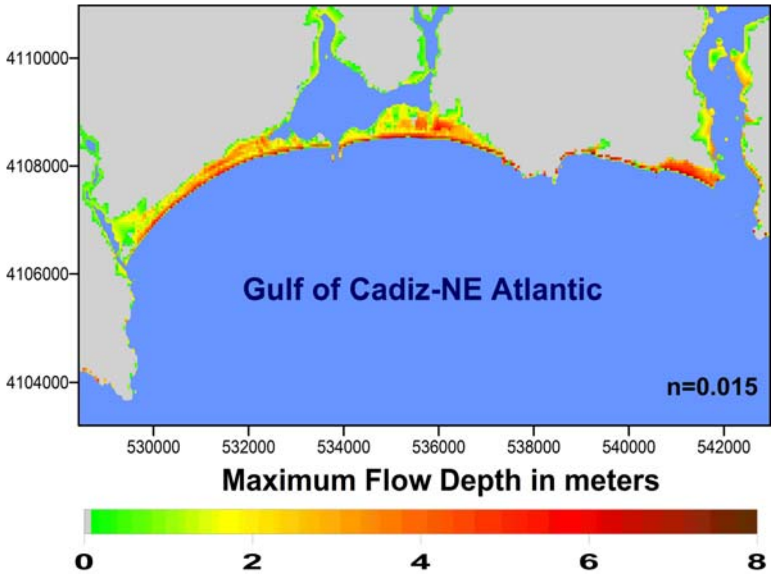


Figure 15 - Inundation Map – Lagos –Portimão area; Marques de Pombal scenario; Manning Coefficient 0.15

3.6 Some scientific results obtained in the framework of NEAREST which can be useful for present and future tsunami warning system

3.6.1 identification and characterisation of the potential large tsunami sources in the Gulf of Cadiz and in SW Portugal*.*

The large amount of geological and geophysical investigation off SW Iberia available to NEAREST partners allowed the recognition and the mapping of the active tectonic structures plus the mapping of the sediment instabilities that may trigger and/or enhance tsunamis.

NEAREST reviewed more than 20,700 km multi-channel seismic lines, and 180,000 km^2 of multi-beam bathymetry and reflectivity data of the Gulf of Cadiz. The main outcome of this work, coordinated by FFCUL, was the production of a tectonic map of the study area and the estimation of the maximum magnitude earthquake of each one of the mapped active faults (fig. 16).

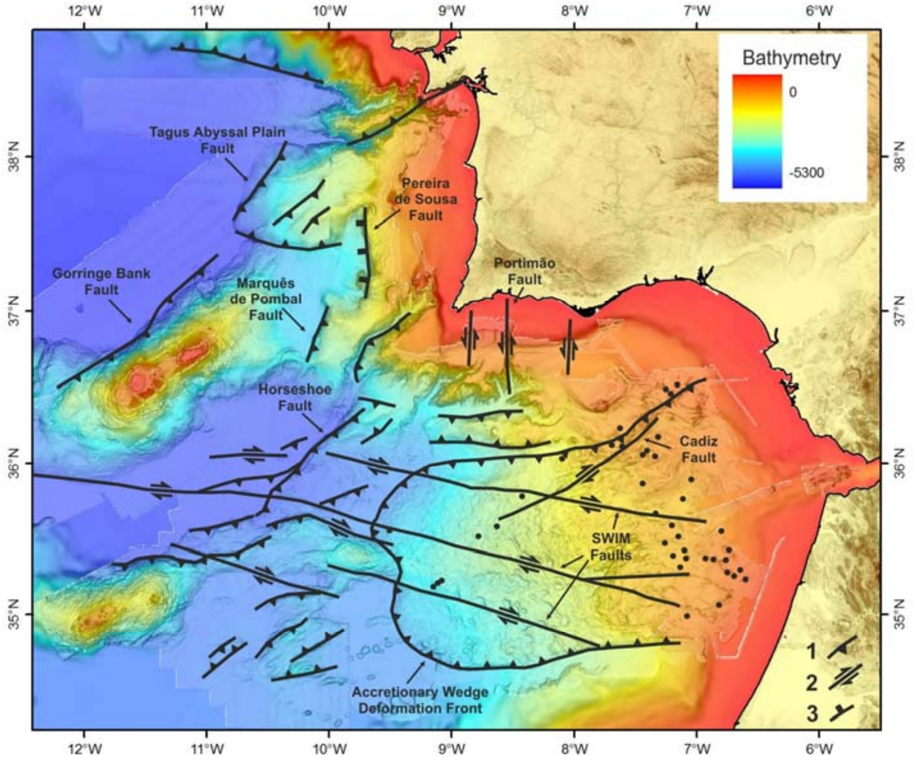


Figure 16 – Tectonic map of SW Iberia resulting form this study.

A major result was the discovery of a set of regional active, possibly dextral, transcurrent faults, WNW-ESE oriented and distributed over a band 600 Km long termed “SWIM Faults”. This major results was summarized on a scientific paper (Zitellini et al., 2009)

Notwithstanding this level of knowledge, to achieve the full comprehension of the source region, NEAREST proceeded one step further by looking for the possible existence of common decollement faults between the various tsunamigenic structures and to correlate the earthquake activity with ruptures and faults. To reach this stage of knowledge, NEAREST carried out one-year monitoring of the natural seismicity in the offshore of SW Iberia using 24 Ocean Bottom Seismometers along with a refraction experiment to define the crustal velocity of the offshore of SW Iberia.

3.6 2 Hydro-acoustic Tsunami Precursor

NEAREST developed a theoretical work concerning hydro-acoustic signal and tsunami wave generated by seafloor motion. The results of this model showed the existence of a possible “hydro-acoustic tsunami precursor” (Fig.17). In particular Chierici et al. (2010) showed that modulated hydro-acoustic waves are generated in the water layer by the sea-floor motion. The presence of the porous sediment acts as a “natural” low pass filter and allows the hydro-acoustic waves to propagate up-slope and outside the generation area with low attenuation. The main and surprising feature of these waves is their modulation which carries information about the seafloor motion and the source main parameters.

The existence of these waves was firstly observed during the Tokachi-Oki 2003 event (Nosov, 2007), when two pressure sensors, located within the generation area, detected an hydro-acoustic signal generated by the seafloor motion induced by the earthquake. For the first time, the model of Chierici et al. is able to correctly reproduce the measured frequency and amplitude of the signal.

These acoustic waves travel with speed much greater than the tsunami waves well preceding their arrival. Information about the source parameters, for instance the sea floor motion velocity, the source extension and the source displacement may be extracted from the very first pulses of the modulation. Thanks to these results the modulation of these acoustic waves may act as a "hydro-acoustic tsunami precursor" and could be integrated in a new generation of Tsunami Early Warning System.

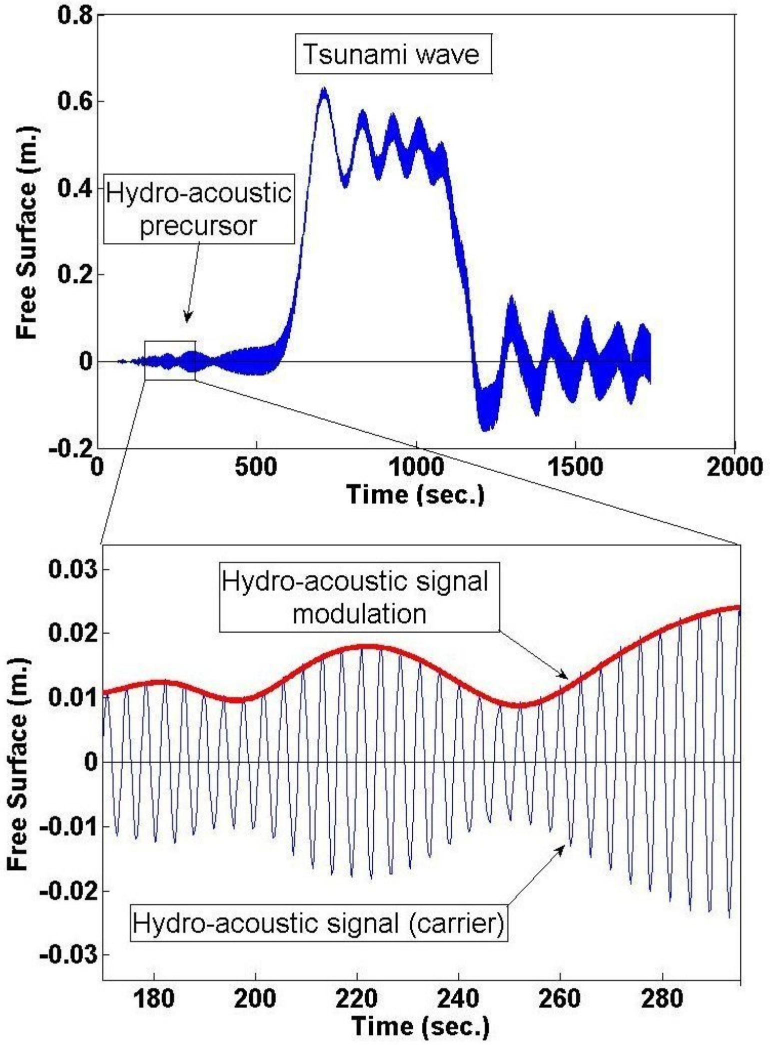


Figure 17 - shows an example of this hydro-acoustic signal, obtained using the model developed by Chierici et al., 2009. The upper inset represents the water surface disturbance for a fixed observation point at 100 km distance from the source. The lower inset shows the hydro-acoustic precursors and its modulation characterised by its pulses Figure Inset a) represents the free-surface plots at fixed observation point located at 100km from the source, while inset b) is the zoom of the first part of the acoustic signal with its modulation.

Conclusion

In conclusion NEAREST has established and tested all the basic parts for the real implementation of a state of the art tsunami early warning service able to operate in tsunami generation areas and in all the situations where very short tsunami warning times are required.

A regional consortium of Istitutions, comprising of Moroccan institutions, possessing the scientific and technological skills and know how to develop, implement and manage aTsunami Warning System and and having the national relevance and istitutial mission to operate it continuosly and routinely has been established. The intergration of the seismic networks of Morocco (CNRST), Portugal (IM) and Spain (UGR) for the real time acquisition, sharing and processing of seismic, tide gauges and ocean bottom pressure data has implemented, tested and well established: this virtual seismic network is presently able to locate and evaluate the magnitude of an earthquake in the Gulf of Cadiz area within less than 5 min.

A regional center, connetting the virtual seismic network to other international warning centers and able to evaluate if a regional tsunami warning should be issued has been implemented and tested.

A new open ocean tsunami detection device, the tsunameter, able to operate in tsunami generation areas and performing a double check on both bottom pressure and seismic signal has been developed, demontrated and tested. Some technological solutions developed and adopted for the realization of the tsunameter, as for instance the real time accelerometers correction to the bottom pressure recorders measurement and the tsunami detection algorithm developed are a step forward the best present technological solution adopted in the current tsunami warning systems. To become an operative instrument the tsunameter must be detached by the hosting station and buoy GEOSTAR and the structural mechanical frame and buoy must be re engineered and down sized.

The theoretical result obtained, concerning the existence of a hydroacoustic tsunami precursor which carry information on source extension, displacement and bottom motion velocity, may allow the new scientifical and technical development on tsunami early warning.

In synthesis, the tools so far developed in the world to face the tsunami menace are not completely effective with respect the tsunamigenic source located near the shore. NEAREST tried to fill this gap developing a prototype of regional TEWS able to account for near-to-shore sources with a response time of 5 minutes. The NEAREST is then a parallel approach to the Japan system DONET which, given its very high cost, appear not applicable, at the moment, to the Mediterranean area. NEAREST Consortium reached this result with a funding not comparable to the ones made available to other countries as schematically showed in the following table:

Funding Country	**TEWS**	**Funding in Milion** $
U.S.A.	**DARTT II**	**40.0**
Japan	**DONET**	**35.0 + 100.0**
German	**GITEWS**	**54.0**
EU	**DEWS**	**8.77**
EU	**NEAREST**	**4.05**
India	**INCOIS**	**27.8**

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