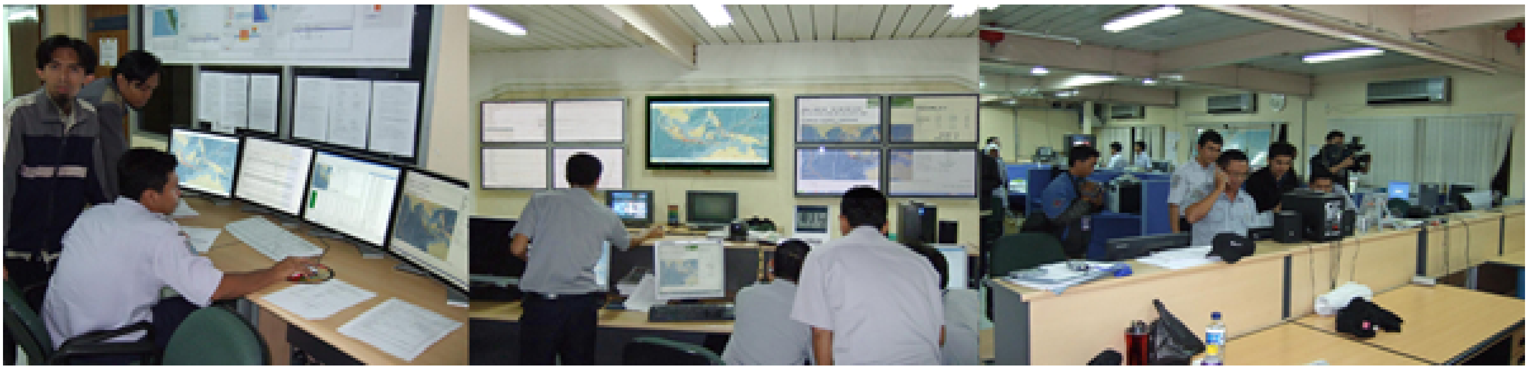
Orfeus Newsletter

Volume 8 - No. 1 June 2008

Timely Regional Tsunami Warning and Rapid Global Earthquake Monitoring

Winfried Hanka, Joachim Saul, Bernd Weber, Jan Becker and GITEWS Team

GeoForschungsZentrum, Potsdam, Germany



The challenge

After the tsunami tragedy following the great Sumatra quake of December 26, 2004 the GEOFON program of GFZ Potsdam was appointed to design and implement the land based seismic component of the German-Indian Ocean Tsunami Warning System (GITEWS), mainly due to its expertise in Internet-based near real-time data acquisition [*Hanka et al.*, 2003], rapid near real-time earthquake alerts (http://www.gfz-potsdam.de/geofon/new/eq_inf.html) and virtual seismic network management [*van Eck et al*., 2004]. The other components of the envisaged innovative tsunami warning system for Indonesia are GPS buoys, ocean bottom pressure sensors, tide gauges, CGPS stations and a tsunami simulation module, a library of pre-calulated tsunami scenarios. Within this concept, the earthquake monitoring system plays a central role [*Hanka et al.,* 2006]. The time available to warn the population in the coastal areas after a tsunami has been generated by a large earthquake in the Sunda trench is extremely short since the expected tsunami travel times are only in the order of 20-40 minutes. Therefore tsunami watch or warning bulletins will have to be issued preferably within 5 minutes in order to be able to initiate timely civil protection measures. Thus, these bulletins will have primarily to be based on rapidly determined earthquake parameters and selected pre-calculated tsunami scenarios which fit the initial seismic parameters. Other sensor data such as buoy and tide gauge data will usually not be available within such short time frame but will be needed later-on to either validate a warning status or to be able to cancel it. Success in tsunami early warning for Indonesia also will benefit the other Indian Ocean rim countries within the planned IOTWS (Indian Ocean Tsunami Warning System, coordinated by UNESCO/IOC). Therefore international cooperation is the key, both for primary data exchange (e.g. seismic data and earthquake parameters) but also for the exchange of warning dossiers. The same is also true for the EuroMed area, where also preparations for the establishment of a tsunami warning system for the NE Atlantic, the Mediterranean and adjacent seas (NEAMTWS) have been initiated. GFZ is trying to bring in here its expertise and achievements from GITEWS. From this project, also GFZ's initial earthquake monitoring task as EMSC key node for the dissemination of rapid global earthquake alerts benefits substantially.

The network

The rapid determination of seismic parameters for tsunamogenic earthquakes requires a dense seismic network with many stations as close to the source region as possible. On the other hand, standard seismic equipment will be saturated if too close. Therefore GITEWS and other seismic stations in Indonesia are equipped with normal broadband seismometers as well as with strong motion accelerographs. In total, a network of 160 of such stations is proposed for Indonesia. Most stations (presently 80, planned 100 - unfortunately not many of high quality) are provided by Indonesia, another 15 by Japan and 10 by China, all telemetered by VSAT to Jakarta. Within GITEWS, 22 stations (12 existing) are under constructions in Indonesia and another 15 in other Indian Ocean rim countries (2 already installed on the Maldives). A private VSAT system using an Indonesian satellite is used for the data transfer from the GITEWS stations in Indonesia, Sri Lanka and the Maldives to the warning center at BMG in Jakarta. The stations in the Western Indian Ocean as well as in the Mediterranean (for NEAMTWS) will be collected by 3 different satellites linked to GFZ via a second GITEWS VSAT hub in Austria. In addition, data from other networks (Australia, Malaysia, South Africa, IRIS, GEOSCOPE, more to come) are imported via Internet. Presently, the virtual seismic network for the Indian Ocean available at BMG consists already of about 130 stations, while the global virtual network at GFZ Potsdam (GEOFON Extended Virtual Network, GEVN) is even composed of more than 500 stations (Figure 1).

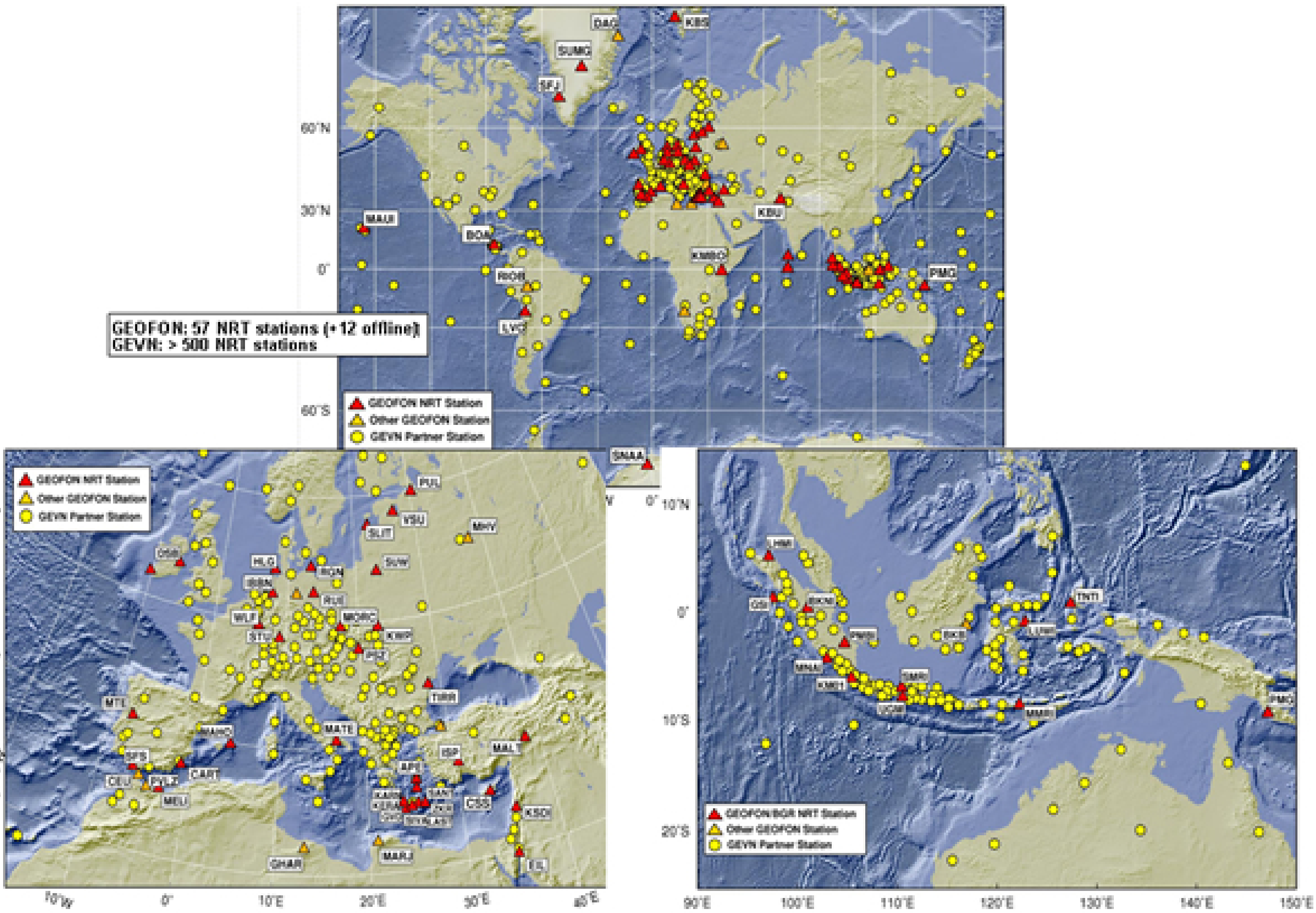


Figure 1. Global and regional virtual seismic networks for EuroMed and Indonesia as acquired at GFZ Potsdam and BMG in Jakarta (Indian Ocean stations only). Red triangles show the GEOFON NRT stations, orange ones the offline stations. The yellow dots ar the GEVN partner stations as provided for earthquake monitoring purposes.

GITEWS and GFZ earthquake monitoring

Even more challenging than the setup of an appropriate seismic network is the design and implementation of efficient acquisition and processing software (see special box below). Unlike the rest of the tsunami warning control center software, an early prototype version of SeisComP 3.0 was already available for installation and testing at BMG (Meteorological and Geophysical Agency in Jakarta, hosting the Indonesian tsunami warning center) in early May 2007. Just before the Bengkulu earthquake sequence an updated version for routine service became available in early September. Since this system processed at this time already the real-time data of quite a big virtual seismic network - about 100 stations within and around Indonesia (Figure 1) - it was possible to achieve already a rather short processing time for the real-time data analysis for these events. E.g. it was possible to obtain for the first and most tsunamogenic quake on September 12 (final moment magnitude 8.4) a first "heads-up" alert after just less than 2 minutes after origin time and a first estimate of location, depth range and magnitude (!) after 2:30 minutes. A stable solution estimating a moment magnitude of 7.9 based on 25 stations was available after 4:20 minutes leading to the first tsunami alert ever issued by BMG below 5 minutes (Figure 2). Also in global context this success represents a remarkable landmark. The pre-IOTWS alerts as presently issued temporarily by PTWC and JMA reached BMG after 14 and 26 minutes, respectively, while the NEIC solution was available after 19 minutes, all listing very similar results.

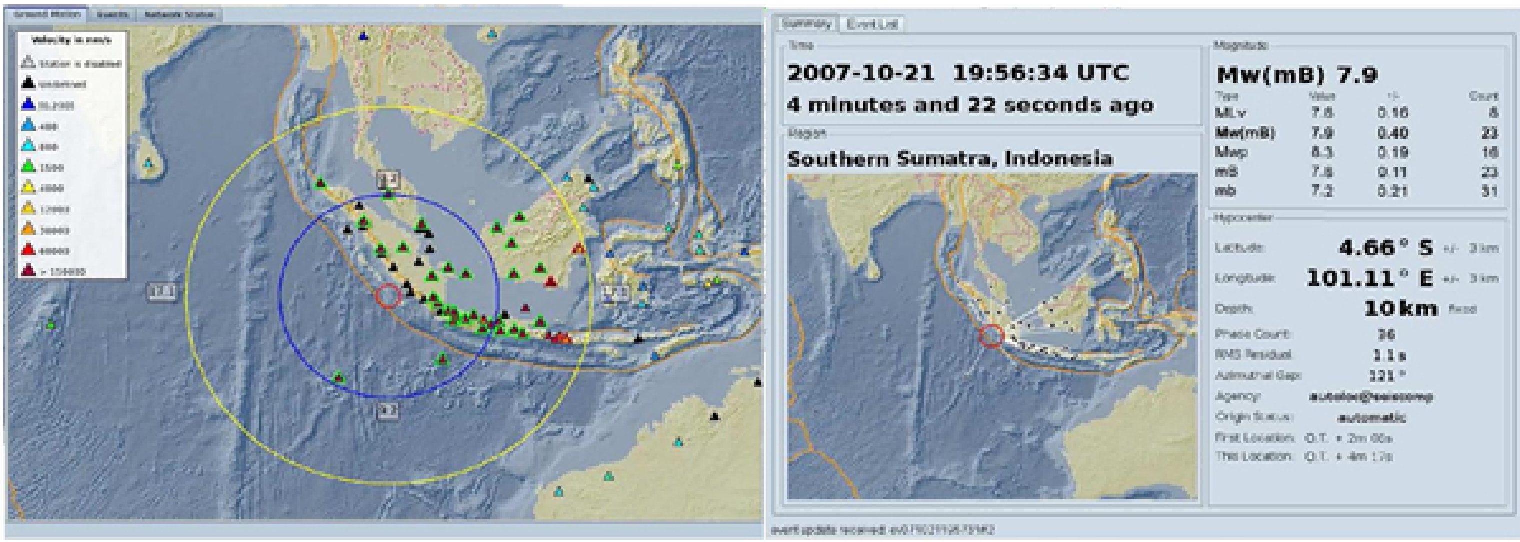


Figure 2. Screenshots of two of the SeisComP 3.0 displays as displayed at the Indonesian Tsunami Warning Center at BMG during the Bengkulu M=8.4 earthquake of September 13, 2007 (from replay). This earthquake generated a local tsunami and BMG was able to issue a tsunami warning within 5 minutes, based on the rapid and fully correct results of the SeisComP 3.0 system.

In parallel to the activities in Indonesia, also at GFZ Potsdam the SC3 prototype system was installed and used to process the data of the GEOFON Extended Virtual Network (GEVN), meanwhile composed of more than 500 stations worldwide. The new system became GFZ's central routine earthquake monitoring system by beginning of August 2007, replacing the old SC2 based purely automatic one. In addition to automatic solutions (from 25 picks onwards), now also manual solutions both for smaller events (between 10 and 24 picks) and the most important larger ones are issued. Due to SC3's sophisticated graphics modules the manual analysis becomes very quick and easy, since the modules can be connected to a central SC3 server either locally - e.g. from a professional local multi-screen analyst work place - or remotely from ordinary laptop or desktop PCs at home or from anywhere on the Internet. Although the extra effort for this manual service is only minimal, so far the manual interaction is done on voluntary basis and GFZ does still not operate a full 24/7 earthquake or even tsunami warning service! The new system and procedures helped also to improve the quality and quantity of the published events substantially with respect to the old system, while the dissemination of the automatic alerts is slightly delayed due to the higher number of picks required (Figure 3).

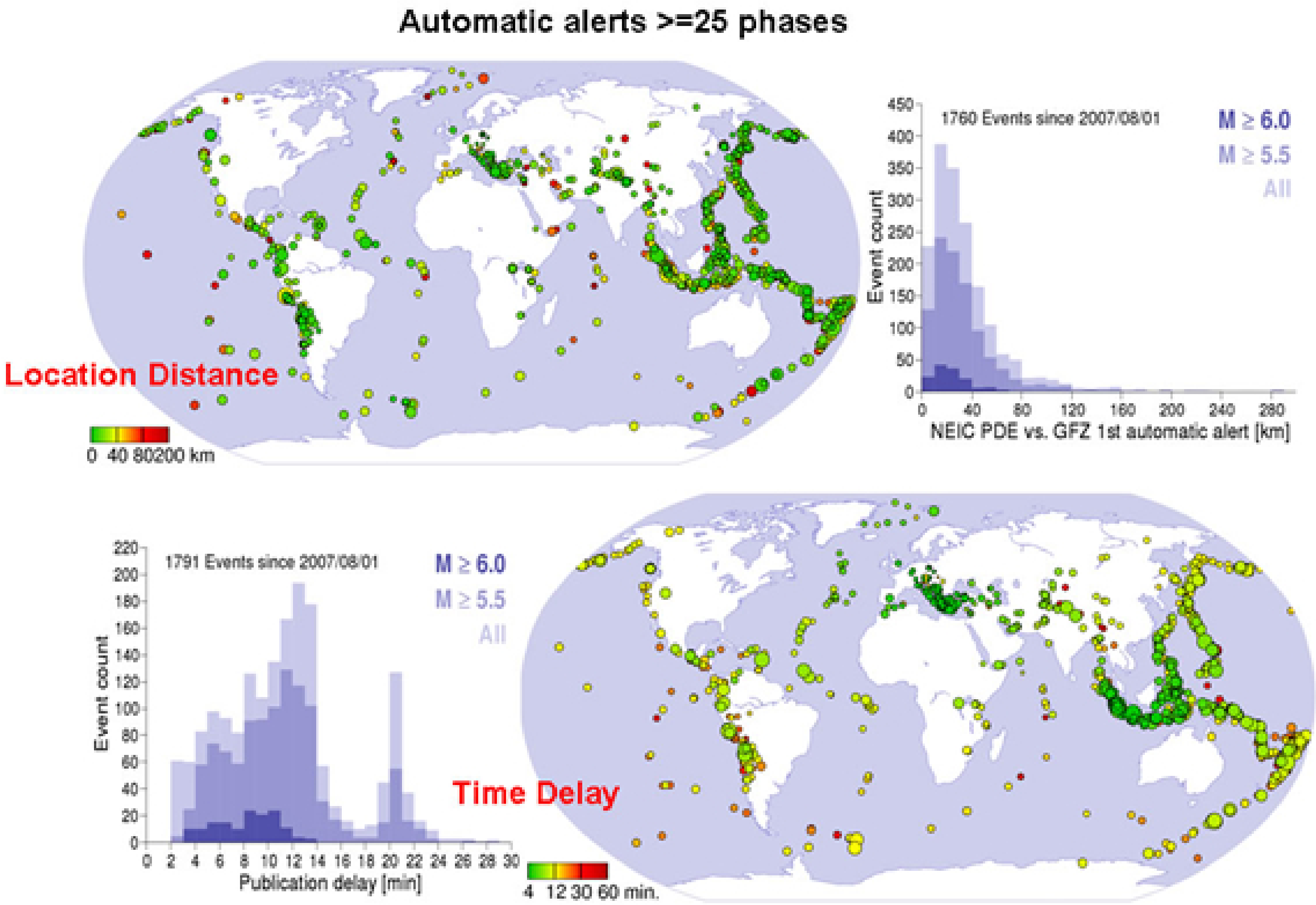


Figure 3. Performance of the global automatic earthquake monitoring system at GFZ. Shown is the location difference of first published GFZ solution compared (usually based on 25 associated picks) to the NEIC manual one and the publishing delay times in respect to origin time. Later solutions (automatic or manual) are expected to be even better.

Besides the professional and highly efficient software design, adequate magnitudes that allow a rapid quantification of very large earthquakes are an essential ingredient to effective tsunami warning. In SC3, we adopted the original Gutenberg & Richter body-wave magnitude mB, which uses the full broadband P wave signal. It therefore does not suffer from the spectral saturation of the more well-known narrow-band mb. A new mB calibration function allows mB estimates starting at distances as low as 5Â° [*Bormann and Saul,* 2008]. In a second step mB is mapped to Mw(mB). This magnitude performs comparably well to other P-wave based Mw estimators like Mwp (which is determined in SC3 as well), but is much simpler to compute and less sensitive to data errors such as (small) gaps, which are common in real-time processing. The use of mB as a proxy for Mw thus allows quick and robust magnitude estimates after as little as 2 minutes and provides the basic tool for earthquake quantification in SC3! An extension of mB to mBc (cumulative mB for giant quakes with M > 8.5) is under development. Other standard (Ml, mb) and non-standard magnitudes (Mjma) are also computed in parallel, others are planned.

Networking SeisComP 3.0 systems

The innovative distributed network approach of SC3 allows also to connect various centers and exchange both waveform data and processing results. This feature is used to connect the primary GITEWS processing centers at GFZ and BMG in Jakarta with each other, but also to link them with other national and regional tsunami warning centers in the Indian Ocean area (IOTWS framework) or in Europe (NEAMTWS framework). In principle any seismic center could be attached, even those without SC3 having installed. There, parameter exchange would be carried out through QuakeML import and export. In the moment, GFZ is serving the tsunami warning centers of the Maldives and India this way, in Europe LDG (France) and IGN (Spain) are connected. Later-on, in the Indian Ocean it is planned to link with the GITEWS partners in Thailand, Malaysia, Sri Lanka, Yemen, Kenya, Tanzania, Madagascar and South Africa (Figure 4). In Europe also the other candidate NEAMTWS regional tsunami watch centers (RTWC) at INGV (Italy), NOA (Greece), KOERI (Turkey) and IMP (Portugal) will be linked to the GFZ SC3 server (Figure 5). More institutions may follow.

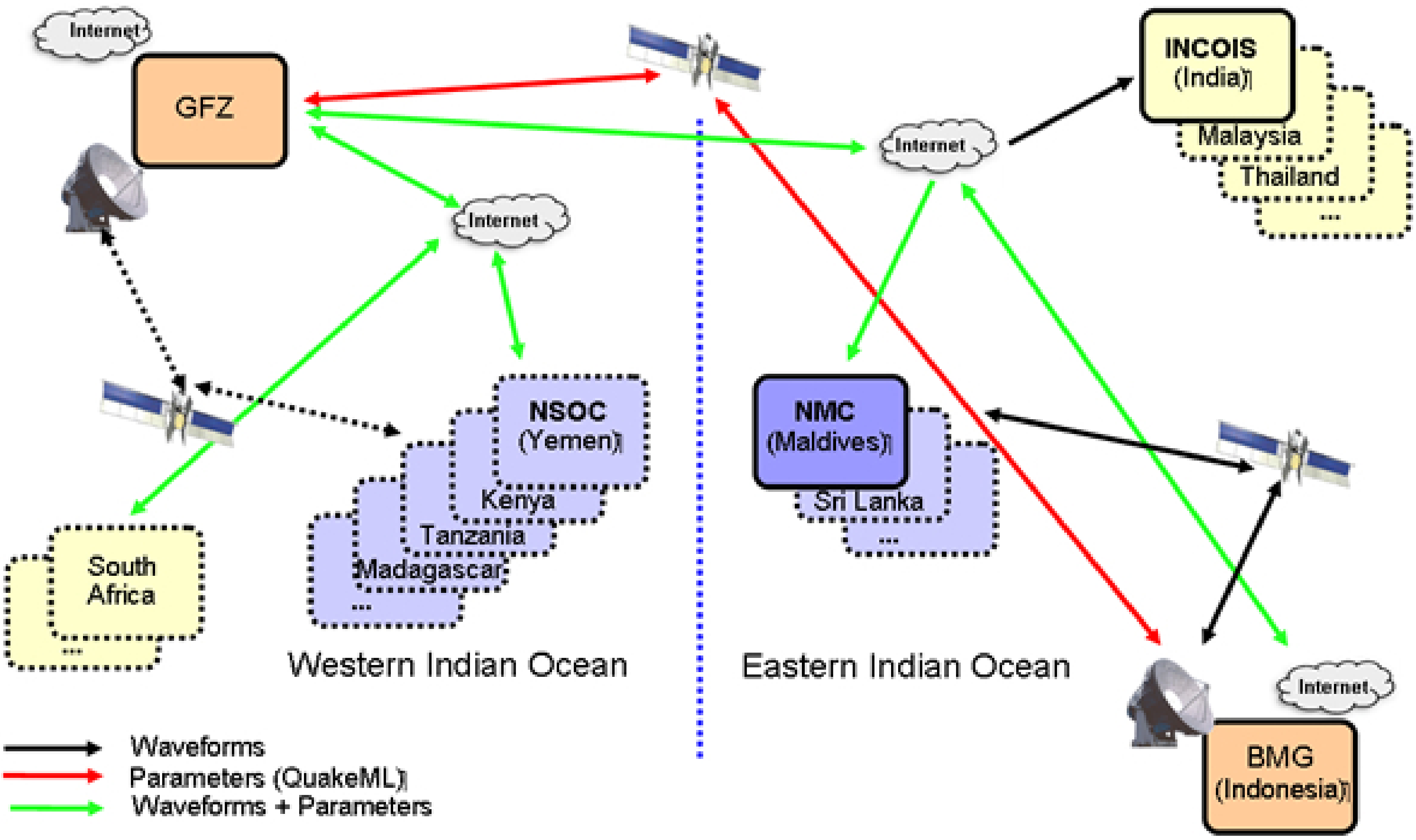


Figure 4. SC3 network as in preparation for the Indian Ocean area, RT data from the Eastern part arrive at BMG in Jakarta, from the Western part in GFZ at Potsdam. Processing results are shared between the two basic centers and with the other GITEWS partners.

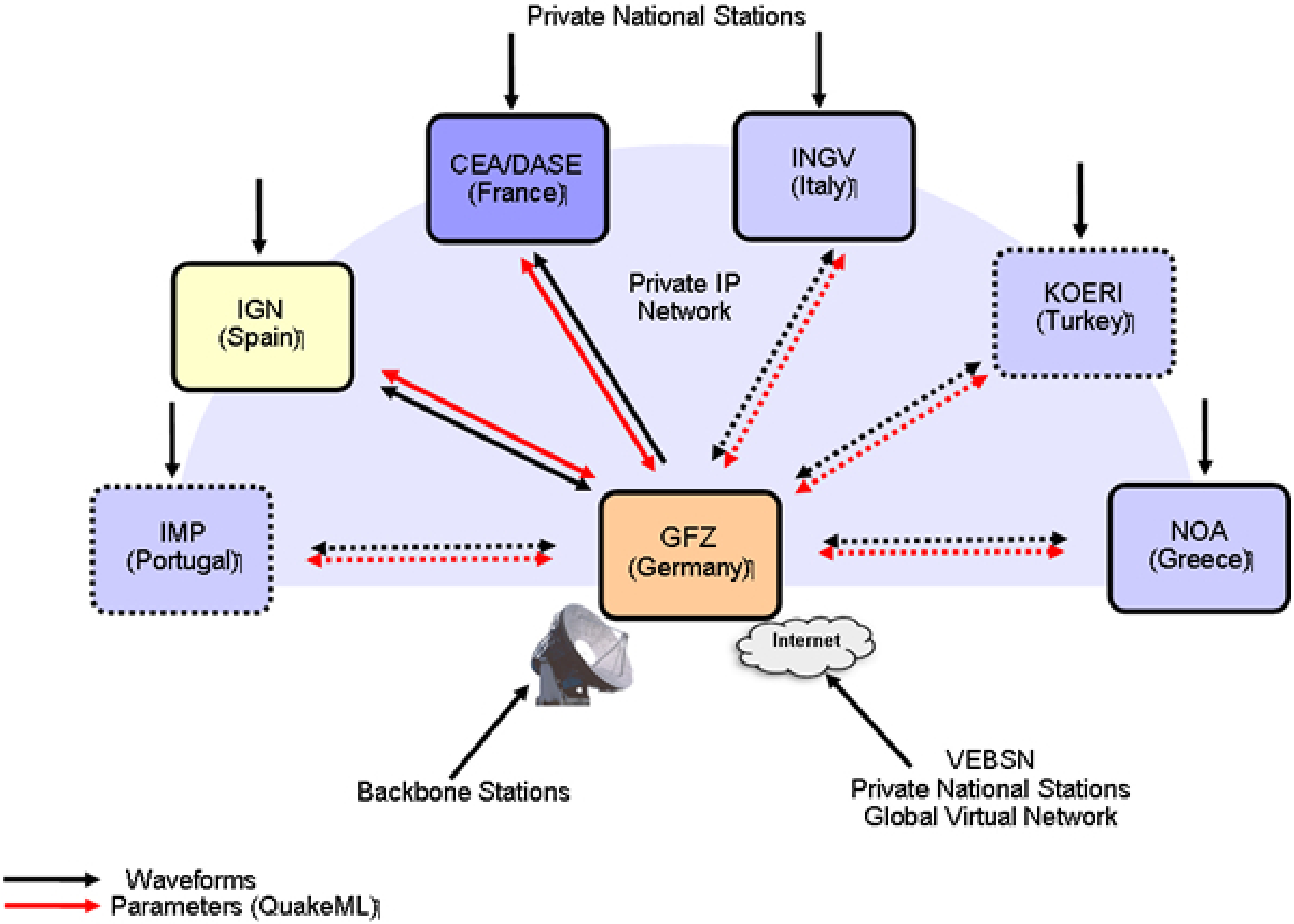


Figure 5. SC3 network as proposed for NEAMTWS. GFZ serves as central background data center for real-time data feeds from VEBSN, additional private stations and the VSAT backbone network. The 24/7 RTWCs obtain selected RT data feeds and automatic processing results for verification and dissemination.

What can Europe gain from GITEWS?

Meanwhile also in EuroMed area preparations for the establishment of the NEAMTWS have been initiated. Due to partly extremely short expected tsunami travel times, the situation at least for the Mediterranean, the Marmara and Black Sea is maybe even more challenging than for Indonesia. Although local tsunami warning is a national task rather than the responsibility of NEAMTWS, it is proposed to assist the planned VSAT based NEAMTWS seismic backbone network (~ 90 stations) by an Internet based extended VEBSN network (VEBSN plus selected non-public stations) to speed-up the earthquake monitoring. Presently an experimental NEAMTWS earthquake monitoring system is under construction on basis of SC3 with several 24/7 RTWCs being responsible for specific coastal regions connected with GFZ as background data center serving both selected real-time data feeds from the EVEBSN and backbone network and automatic processing results to the RTWCs for visual verification, manual interaction and dissemination.

Conclusions

Although the task of issuing reliable earthquake parameters for tsunamogenic earthquakes is rather challenging, the project is on good track. One year of application in 24/7 seismic and tsunami service and continuous improvements has proven that the seismological component of the GITEWS will work! The expertise gained by GITEWS in the Indian Ocean in terms of station design, VSAT communication and software development is also beneficial for Europe, both for the NEATWS process and the general seismological community. Namely SeisComP 3.0 is a major step forward towards a common modern extendable tool for seismic real-time data processing and data mining both for earthquake monitoring and research applications. However, a long way is still to go until the end of the project in 2010.

Acknowlegements

This is publication no. 21 of the GITEWS project. The project is carried by GFZ Potsdam and other institutions in Germany and Indonesia and by other international partners. Funding is provided by the German Federal Ministry for Education and Research (BMBF), Grant 03TSU01.

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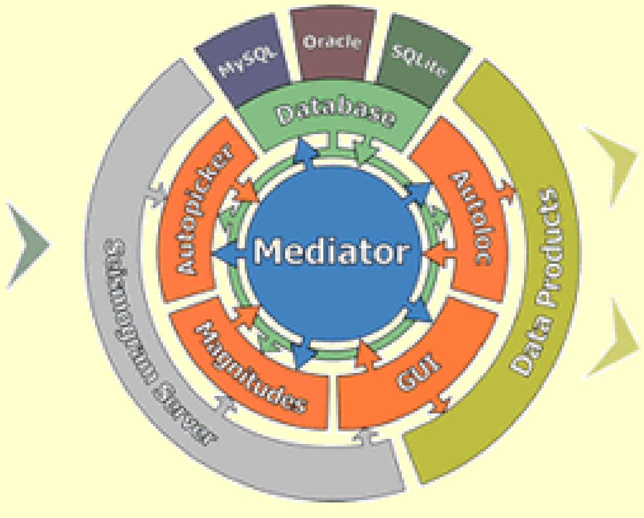
SeisComP 3.0

Although based on a new innovative software architecture and consisting of mostly newly written codes, the SeisComP 3.0 (SC3) software package can be regarded as an extension of the well established SeisComP 1 and 2 versions [*Hanka et al.*, 2003] (*http://www.gfz-potsdam.de/geofon/new /scp.html*).



It combines generalized data acquisition, data quality control, real-time data transfer protocol, automatic procedures to determine location, depth, magnitudes and rupture parameters and sophisticated alert and visualization tools. Although 24/7 operation is mandatory at tsunami warning centers, the basic parameter calculation is at first carried out fully automatic, but visu- al supervision is provided at each stage. Acoustic and optical alert tools are implemented to guarantee the attention of the seismic experts in the warning center. They can interfere any time

and correct automatic results and can also accelerate the automatic processing if desired. The well accepted data acquisition and transfer package SeedLink and the data archive access tool ArcLink remained basically unchanged while the automatic picker and location python moduls of SC2 were re-written in C++ for better integration and performance reasons.

SC3 has a highly modular design and provides several new developed modules for automatic and interactive data processing. A basic automatic system of SC3 consists of modules dealing with quality control, picking, locating, amplitude calculation, magnitude calculation, waveform quality determination and event parameter management. All are stand-alone programs connected through messaging and a central database. The architecture makes it possible to replace a module at any point of the processing chain. The interactive part of the system provides graphical user interfaces for showing the overall situation regarding earthquakes and stations in a map, real time traces and event summary. As SC3 is designed for a fast interactive analysis, it provides a toolkit for analyzing the earthquake parameters as location, depth and magnitudes. The included manual picker is optimized for rapid verification of pre-calculated picks from strong earthquake signals providing e.g. automatic loading of arriving real-time, automatic amplitude scaling and trace alignment. But it allows also conventional offline analysis of small and moderate earthquakes.

A TCP/IP messaging system is used to to distribute the processing results. Using TCP/IP makes it possible to operate the individual modules at different computers connected via LAN or WAN. The messaging system is based on the open source toolkit "Spread". The central component of the messaging system is the "MASTER" handling the dissemination of metadata object messages to their target groups. Target groups are for example PICK, LOCATION. The modules connect to these groups and send their results to other groups. For example the automatic location program receives picks from the PICK group and sends the resulting origins to the LOCATION group. The data model of SeisComP3 is based on QuakeML, a proposed new XML standard for the representation of seismological parameters (https://quake.ethz.ch/quakeml). Beside pure object messages, "Notifier" messages includes also instructions about what to do with the contained object. The "MASTER" uses a database plug-in which interprets these instructions and adds for example an object to a database. SC3 supports SQL based databases such as presently MYSQL and POSTGRESQL, ORACLE support is planned. Normally the modules have only read-access to the database. Beside the "Notifier" message also "Service" and "System" messages exist. They are used to administrate or configure the modules even from remote systems.

For waveform service, SC3 uses its own protocols, SeedLinkfor (near) real-time data feeds and ArcLink for data from online archives. Both became a de-facto standard meanwhile. A more sophisticated special waveform server may be added later-on.

SC3 is written in C++. Also Python is support by using special wrappers. SC3 provides substantial development support for custom modules, namely C++ libraries to ease the development of fully integrated new SC3 modules and wrappers for more loosely coupled modules in other languages. Common tasks like waveform and database access, message communication, math operations etc are already implemented and can be re-used by custom modules.

Seiscomp3 development team: Jan Becker, Bernd Weber, Joachim Saul, Henrik Thoms, Andres Heinloo, Mathias Hoffmann, Steffen Loos, Doreen Pahlke.

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