Progress in GTEWS Ground Displacement Measurements and Tsunami Warning

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Abstract
Since its early days, GNSS has been employed for the monitoring of sudden ground movements, such as earthquakes. Its use as a tool to enhance tsunami detection was boosted after analysis of data following the December 2004 Great Ocean Indian Tsunami. The contribution of GNSS towards tsunami warning systems is possible due to several factors, such as advances in the measurement of crustal displacement, developments in GNSS methodology, the growing availability of real-time data streams and advances in processing power and communication means. The paper focuses on the progress of Global Navigation Satellite System Tsunami Early Warning Systems (GTEWS) identifying current implementations and future directions and challenges. The discussion leads to the conclusion that the GNSS technology already satisfies requirements of tsunami early warning systems and that the major hurdles are with other aspects, such as optimal network configuration, real-time flow of data, communication infrastructure, and national and international collaboration. The paper ends highlighting the important role that the Global Geodetic Observing System (GGOS) can play to help overcoming those hurdles.

Keywords
Early warning systems · Geohazards monitoring · GGOS · GNSS · Ground-based GNSS · Tsunami

1 Introduction

GTEWS, GNSS Tsunami Early Warning Systems, is a GNSS-based tsunami early warning system, which offers new observables highly complementary to existing ones. We can consider that it came as a response to a massive tragedy, the Great Indian Ocean Tsunami of December 26, 2004 (because of the date, commonly known as Boxing Day tsunami), which claimed more than 230,000 lives across 14 countries (ABC, Boxing Day tsunami 2014). The tragedy was partially blamed on the lack of a tsunami warning system in the Indian Ocean. Early warning would not have avoided material loss but it would have helped to decrease human loss. It was also recognized that global seismology failed to accurately diagnose the magnitude of this event in time. It became clear there was a need to strengthen tsunami early warning systems and need to an accurate and rapid estimation of tsunami potential. GNSS emerged as a complementary observation platform.

Until then, tsunami early warning relied on seismically determined earthquake magnitude, source and extent of the earthquake. Even with modern seismometers that can provide earthquake information online a few minutes after the earthquake, the inversion of seismographs for complex models is time consuming, delaying the estimate (Song 2007) even though there exists faster ways to compute metrics of an earthquake source. The main aspect though is that seismic methods cannot accurately sense long period energy, the...
larger the magnitude of the earthquake is, something that GNSS can without any concern of saturation (Melgar et al. 2015).

The potential of GNSS was proved with the several post-mission analysis following the 2004 event, when it became evident that 15-min warning was possible if GNSS data were available in real time (Blewitt et al. 2006; Sobolev et al. 2006; Song 2007). For example, Blewitt et al. (2006) demonstrated the use of GPS real-time displacement data would have allowed estimating the moment of the earthquake hours before seismograph estimate was available, therefore, predicting the likelihood of the tsunami and potentially saving thousands of lives. Later, the Tohoku-oki event of 2011, in Japan, was also used to demonstrate that a 25-min accurate early warning was possible (Ohta et al. 2012; Song et al. 2012; Xu and Song 2013; Melgar et al. 2013; Hoechner et al. 2013; Melgar and Bock 2013).

This paper identifies current implementations and future directions of ground-based GNSS tsunami early warning systems, under the light of the IUGG 2015 Resolution 4 (IUGG, Resolution 4 2015) and the UN Sendai Framework for Disaster Risk Reduction (UNISDR 2015). Section 2 overviews the contributions GNSS can provide and the requirements that need to be satisfied for that, Sect. 3 goes over some of the existing and proposed networks, while Sect. 4 indicates GNSS-aided models. Section 5 looks at the recommendations and Sect. 6 ends the paper with a discussion on the status of GNSS for tsunami early detection.

## 2 The Contribution of GNSS

As mentioned before, there are limitations with seismically determined earthquake magnitude for large earthquakes particularly for tsunami early detection due to possible underestimation of earthquake’s magnitude, source and extent. The positive contribution brought by GNSS displacement measurements is to provide both magnitude and direction of ground motion, a critical information for estimating seafloor displacement and its tsunamiogenic potential (Song 2007; Sobolev et al. 2006). Quoting from Song (2007):

> Coastal GPS stations are able to detect continental slope displacements of faulting due to big earthquakes, and that the detected seafloor displacements are able to determine tsunami source energy and scales instantaneously.

In 2007, Sobolev et al. (2007) introduced the idea of the **GNSS Shield**, a near-field GNSS array capable of predictions within 10 min after the occurrence of an earthquake. Such array would follow an optimum distribution derived from a geodynamic numerical model of the local geology, significantly improving the measurement accuracy of crustal displacement and the potential tsunami impact. The GNSS shield could be formed for specific zones or around the Indo-Pacific Ring of Fire for tsunami early warning.

These early studies proved that GNSS is indeed capable of providing fundamental information for early detection of tsunami, alleviating the chances of false alarm. More recent studies have corroborated and advanced those initial findings.

To fulfill its full potential, GNSS enhancement to tsunami early warning requires:

- real time access to an optimally distributed network of GNSS receivers,
- reliable broadband communications,
- a good number of capable analysis centers,
- and products that can be rapidly assimilated into the existing tsunami early warning systems

The bottleneck is not the GNSS capabilities (including models and processes) but how to make sure there is GNSS-derived information available as soon as possible.

## 3 GTEWS Networks

What follows is a brief review of GNSS networks used in tsunami early warning systems.

**Indonesian Tsunami Early Warning System for the Indian Ocean (InaTEWS)** InaTEWS is a nice example of international cooperation between nations, which followed in the aftermath of the 2004 Boxing Day Tsunami (Fig. 1). Initially called German-Indonesian Tsunami Early Warning System for the Indian Ocean (GITNEWS), it started in 2005 and is run by Indonesian Meteorological, Climatological and Geophysical Services (BMKG) since 2014. Babeyko (2017), Harig et al. (2019).

**Real-Time GEONET Analysis for Rapid Deformation Monitoring ( REGARD)** GEONET is a network under the Geospatial Information Authority of Japan (GSI) and Japan’s Meteorological Agency (JMA) early warning mandate. GEONET may very well be the world’s densest GNSS ground network, with 1200 GPS receivers, providing valuable observations of crustal deformation (Kawamoto et al. 2017). I have been informed that GEONET data may not be generally available (Fig. 2).

**Network of the Americas (NOTA)** NOTA is a federated network that incorporates three existing major networks: the EarthScope Plate Boundary Observatory (PBO)—a set of 1,100 stations spanning Alaska, the continental US and Puerto Rico; TLALOCNet—40 stations in Mexico; and COCONet—85 stations spanning the Caribbean. NOTA forms a hemispherical-size network with the goal to support a wide range of scientific applications and stakeholders. The intention is to offer high-rate (1 Hz or higher), low-latency (1 s or less) GNSS data, with 25% of the stations
Fig. 1  Indonesian Tsunami Early Warning System for the Indian Ocean

Fig. 2  Real-time GEONET Analysis for Rapid Deformation Monitoring (REGARD)
being upgraded to full multi-constellation. A number of GNSS stations have MEMS accelerometers, being called seismogeodetic stations (Fig. 3). GNSS data is being used by NOAA US National Tsunami Warning System and by many other institutions such as CWU, JPL and SIO (Geng et al. 2013a,b; Hodgkinson et al. 2018).

**Chilean National Seismic Network** The network is composed of nearly 150 stations, operating GNSS, seismometers and strong motion instruments. It is run under the auspices of Chile’s Centro Sismologico Nacional (CSN). It applies precise point positioning and ambiguity resolution in the treatment of GNSS data (Geng et al. 2013b), and, according to Riquelme et al. (2016), applies W-phase and peak ground displacement models for the analysis of seismogeodetic data (Fig. 4).

**Asia-Pacific Reference Frame Network** It is a GNSS network of participating countries, with a Central Bureau, coordinated by Geoscience Australia, to maintain an accurate geodetic framework serving all types of geospatial applications (Fig. 5). Even though not designed for the purpose of a GTEWS, the availability of real-time data and its geographical coverage, near several important trenches and subduction zones, some of the data collected by this network are appealing to be used for tsunami detection (Asia-Pacific Reference Frame 2019).

**Caribbean GTEWS** COCONet, the Continuously Operating Caribbean GPS Observational Network, has become part of the federated Network of the Americas (NOTA), which also includes networks spanning Alaska, the contiguous U.S., and Mexico. COCONet GNSS data could be used by the Caribbean Tsunami Warning Program (CTWP) (von Hillebrandt-Andrade 2016), which plans to enhance its tsunami warning activities with GNSS data (Fig. 6).

**GNSS-Aided Tsunami Early Detection System** Taking advantage of all its infrastructure and availability of GNSS real-time data, NASA started the GNSS-Aided Tsunami Early Detection System (GATED) project (Song et al. 2018), which also takes advantages of NOAA’s DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys (Fig. 7). The advantage of incorporating these latter data will be mentioned in the next section. More about DART in Mungov et al. (2013).

### 4 GNSS-Aided Models

The development of several models have allowed GNSS to offer a fundamental contribution to early tsunami detection. A summary follows.

**Blewitt (2006) Model** Blewitt (2006) model showed that the correct magnitude of the 2004 Boxing Day earthquake could have been determined in real time by complementing the seismic data with measurements from relatively few GPS tracking sites (Blewitt et al. 2006).

**Song (2007) Model** Song (2007) model estimates the energy an undersea earthquake transfers to the ocean to generate a tsunami by using data from coastal GPS stations near the epicenter. With these data, ocean floor displacements
Fig. 4 Chilean National Seismic Network

Fig. 5 Asia-Pacific Reference Frame Networks
caused by the earthquake can be inferred. Tsunamis typically originate at undersea boundaries of tectonic plates near the edges of continents (Song et al. 2017).

**Sobolev (2007) Model** Sobolev (2007) model incorporates numerical models of regional geology and local infrastructure to derive the deployment of an optimal GNSS network (Sobolev et al. 2007).

**Melgar (2013) Model** Melgar (2013) model combines GNSS and accelerometer data to estimate seismogeodetic displacement waveforms, providing mm-level 3-D accuracy and improved estimation of coseismic deformation compared to GNSS-only methods (Melgar et al. 2013).

**Titov (2016) Model** Titov (2016) model combines GNSS data with DART data determining real-time tsunami source
energy improving forecast accuracy and early cancellations, decreasing the chance of false alarm (Titov et al. 2016).

**Going Mobile** During his oral presentation at the IUGG General Assembly, in 2019, Dr. T. Song discussed the development of an App that would provide tsunami warning via the cell phone, derived from the GATED infra-structure (Song 2019). Imagine swimmers accessing that while enjoying the beach! That reminded me of an existing online application called VADASE, the Variometric Approach for Displacements Analysis Standalone Engine, algorithm (Benedetti et al. 2014). VADASE was successfully applied to estimate in a real-time scenario the ground velocities and displacements induced by several earthquakes, and is available on line (Fortunato et al. 2019). It does not offer tsunami warning though.

### 5 A Look into Recommendations

To further our discussion, let us look at the two documents of interest. In a nutshell, the IUGG Resolution 4 (focus on technology) (IUGG, Resolution 4 2015):

- supports the enhancement of Tsunami Early Warning Systems with GNSS real time technology.

The UN Sendai Framework is a very large document, but here we will summarize their concern with human impact and networking. In a nutshell, it suggests actions to UNISDR (2015):

- decrease the impacts, being human, economic and on infrastructure and disruption of basic services, enhance international collaboration, and increase the availability of and access to multi-hazard early warning systems.

### 6 Discussion

As it stands, GNSS technology seems to be capable to provide tremendous contribution to early warning systems. Tests showed that tsunami detection (without the risk of false alarms) is possible just a few minutes after the earthquake, provided the array of GNSS receivers are located within a certain range from the epicenter. As said by Babeyko (2017):

- each particular geographical region needs its own strategy for optimal GNSS-based early warning.

Today, there are capable analysis centers and a growing experience with the handling of GNSS data in real time. There is also a growing availability of high-quality real-time products. And it is reasonable to say that further developments are expected as far as geodetic science is concerned.

Things look bright from the perspective of GNSS. The problem is how to deliver the technology, in terms of:

- optimal network configuration (possible network configuration),
- real-time flow of data,
- communication infrastructure, and
- national and international collaboration (including funding).

All those challenges do not depend on the GNSS technology. The fundamental challenge might be more of coordination rather than with GNSS technology itself.

We conclude the paper emphasizing the important role that GGOS can play helping with coordination and with bringing the multiples organizations and nations together, not just for the optimal use of GNSS technology, but also to help overcome the bottlenecks that prevent the GNSS technology to be used in all its plenitude.

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