Progress in GTEWS Ground Displacement Measurements and Tsunami Warning

Marcelo C. Santos

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

M. C. Santos (✉)
Department of Geodesy and Geomatics Engineering, University
of New Brunswick, Fredericton, NB, Canada
e-mail: msantos@unb.ca

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 tsunamigenic 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)

Fig. 3 Network of the Americas (NOTA)

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 Sismológico 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 con-

tiguous 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

Fig. 6 COCONet—Continuously Operating Caribbean GPS Observational Network

Fig. 7 GNSS-Aided Tsunami Early Detection System (GATED)

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 on-line 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.

Acknowledgements The author would like to acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada. He also thanks the very useful critique from both anonymous reviewers.

References

- ABC, Boxing Day tsunami (2014) How the disaster unfolded 10 years ago. Australian Broadcasting Corporation, The Internet, 23 Dec 2014
- Asia-Pacific Reference Frame (APREF) (2019) Retrieved July 5, 2019 from <http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame>
- Babeyko A (2017) GITEWS - lessons learned, GNSS tsunami early warning system workshop, July 25–27, Sendai, Japan, 2017
- Benedetti E, Branzanti M, Biagi L, Colosimo G, Mazzoni A, Crespi M (2014) Global navigation satellite systems seismology for the 2012mw6.1 emilia earthquake: Exploiting the VADASE algorithm. *Seismol Res Lett* 85(3):649–656. <https://doi.org/10.1785/0220130094>
- Blewitt G, Kreemer C, Hammond WC, Plag H-P, Stein S, Okal E (2006) Rapid determination of earthquake magnitude using GPS for tsunami warning systems. *Geophys Res Lett* 33:L11309. <https://doi.org/10.1029/2006GL026145>
- Fortunato M, Sonnessa A, Ravanelli R, Mazzoni A, Crespi M (2019) Validation of GNSS variometric web engine: a new tool for GNSS community. IUGG general assembly, 8–17 July, 2019
- Geng J, Melgar D, Bock Y, Pantoli E, Restrepo J (2013a) Recovering coseismic point ground tilts from collocated high-rate GPS and accelerometers. *Geophys Res Lett* 40:5095–5100. <https://doi.org/10.1002/grl.51001>
- Geng J, Bock Y, Melgar D, Crowell BW, Haase JS (2013b) A seismo-geodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning. *Geochem Geophys Geosyst* 14(7):2124–2142. <https://doi.org/10.1002/ggge.20144>
- Harig S, Immerz A, Griffin WJ, Weber B, Babeyko A, Rakowsky N, Hartanto D, Nurokhim A, Handayani T, Weber R (2019) The tsunami scenario database of the Indonesia Tsunami Early Warning System (InaTEWS): Evolution of the coverage and the involved modeling approaches. *Pure Appl Geophys* 177:1379–1401. <https://doi.org/10.1007/s00024-019-02305-1>

- Hodgkinson K, Mencin MD, Sievers C, Dittman T, Feaux K, Austin KE, Walls CP, Mattioli GS (2018) A real-time GNSS network of the Americas. In: American geophysical union fall meeting, abstract IN42B-04, 2018
- Hoehner A, Ge M, Babeyko AY (2013) Sobolev SV Instant tsunami early warning based on real time GPS – Tohoku 2011 case study. *Nat Hazards Earth Syst Sci* 13:1285–1292. <https://doi.org/10.5194/nhess-13-1285-2013>
- IUGG, Resolution 4 (2015) International union of geodesy and geophysics general assembly, 22 June – 2 July, 2015, Prague, Czech Republic
- Kawamoto S, Ohta Y, Hiyama Y, Todoriki M, Nishimura T, Furuya T, Sato Y, Yahagi T, Miyagawa K, (2017) REGARD: a new GNSS-based real-time finite fault modeling system for GEONET. *J Geophys Res* 122:1324–1349. <https://doi.org/10.1002/2016JB013485>
- Melgar D, Bock Y (2013) Near-field tsunami models with rapid earthquake source inversions from land and ocean-based observations: The potential for forecast and warning. *J Geophys Res* 118:5939–5955. <https://doi.org/10.1002/2013JB010506>
- Melgar D, Crowell BW, Bock Y, Haase JS (2013) Rapid modeling of the 2011 Mw 9.0 Tohoku-oki earthquake with seismogeodesy. *Geophys Res Lett* 40:2963–2968. <https://doi.org/10.1002/grl.50590>
- Melgar D, Crowell BW, Geng J, Allen RM, Bock Y, Riquelme S, Hill EM, Protti M, Ganas A (2015) Earthquake magnitude calculation without saturation from the scaling of peak ground displacement. *Geophys Res Lett* 42:5197–5205. <https://doi.org/10.1002/2015GL064278>
- Mungov G, Eblé M, Bouchard R (2013) DART® tsunameter retrospective and real-time data: A reflection on 10 years of processing in support of tsunami research and operations. *Pure Appl Geophys* 170(9–10):1369–1384. <https://doi.org/10.1007/s00024-012-0477-5>
- Ohta Y, Kobayashi T, Tsushima H, Miura S, Hino R, Takasu T, Fujimoto H, Inuma T, Tachibana K, Demachi T, Sato T, Ohzono M, Umino N (2012) Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (Mw 9.0). *J Geophys Res.* <https://doi.org/10.1029/2011JB008750>
- Riquelme S, Bravo F, Melgar D, Benavente R, Geng J, Barrientos S, Campos J (2016) W-phase source inversion using high-rate regional GPS data for large earthquakes. *Geophys Res Lett* 43:3178–3185. <https://doi.org/10.1002/2016GL068302>
- Sobolev SV, Babeyko AY, Wang R, Galas R, Rothacher M, Stein D, Schröter J, Lauterjung J, Subarya C (2006) Towards real-time tsunami amplitude prediction, EOS, AGU, 87/37, 374. <https://doi.org/10.1029/2006EO370003>
- Sobolev S, Babeyko A, Wang AR, Hoehner A, Galas R, Rothacher M, Sein DV, Schroter J, Lauterjung J, Subarya C (2007) Tsunami early warning using GPS-shield arrays. *J Geophys Res* 112:B08415. <https://doi.org/10.1029/2006JB004640>
- Song YT (2007) Detecting tsunami genesis and scales directly from coastal GPS stations. *Geophys Res Lett* 34:L19602. <https://doi.org/10.1029/2007GL031681>
- Song TY (2019) NASA GNSS tsunami early detection system and its performance in real time. IUGG general assembly, 8–17 July, 2019
- Song TY, Fukimori I, Shum CK, Yi Y (2012) Merging tsunamis of the 2011 Tohoku-Oki earthquake detected over the open ocean. *Geophys Res Lett* 39:L05606. <https://doi.org/10.1029/2011GL050767>
- Song YT, Mothat A, Yim S (2017) New insights on tsunami genesis and energy source. *J Geophys Res Oceans* 122:4238–4256. <http://dx.doi.org/10.1002/2016JC012556>
- Song TY, Chen K, Liu Z (2018) Developing GNSS-aided tsunami early detection system. 10th ACES international workshop, Awaji Island, September 25–28, 2018
- Titov V, Song T, Tang L, Bernard EN, Bar-Sever Y, Wei Y (2016) Consistent estimates of tsunami energy show promise for improved early warning. *Pure Appl Geophys* 173(12):3863–3880. <https://doi.org/10.1007/s00024-016-1312-1>
- UNISDR (2015) Sendai framework for disaster risk reduction 2015–2030, UN office for disaster risk reduction, Geneva, Switzerland, 2015
- von Hillebrandt-Andrade CG (2016) Caribbean tsunami warning system, National tsunami hazard mitigation program annual meeting, February 3–5, Boulder, Colorado, US, 2016
- Xu Z, Song YT (2013) Combining the all-source Green's functions and the GPS-derived source for fast tsunami prediction – illustrated by the March 2011 Japan tsunami. *J Atmos Ocean Technol* 30:1542–1554. <http://dx.doi.org/10.1175/JTECH-D-12-00201.1>

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.