Global Navigation Satellite System Enhancement for Tsunami Early Warning Systems

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Agenda and Proceedings of the GTEWS 2017 Workshop

GTEWS Clip:

GEONET Captures the Tohoku-oki Earthquake & Tsunami

Motivation and Support

With little to no warning more than 230,000 lives were lost to the Great Indian Ocean Tsunami of December 26, 2004 (Figure 1). The lack of warning was attributed to several failures including the absence of a proper tsunami

Figure 1: Tourists become aware of the first of six tsunami waves at Hat Rai Lay Beach, near Krabi in southern Thailand, December 26, 2004. ***(GettyImages)***

warning system for the Indian Ocean as well as inadequate sensing technology and analysis systems for large earthquakes and the resulting tsunamis. The devastating loss of life focused the efforts of scientists, engineers and politicians to establish the Indian Ocean Tsunami Warning System and improve the sensor networks for more accurate and rapid estimates of tsunami potential. A combined network of seismic and geodetic sensors quickly emerged as an accurate, efficient, and cost-effective enhancement to tsunami early warning systems for those communities nearest the earthquake epicenter. Geophysicists demonstrated the potential value of the regional network of the Global Positioning System (GPS) receivers of the Global Geodetic Observing System (GGOS) in providing rapid and accurate tsunami warning and tracking. GPS ground displacement could have provided tsunami warning within 15 minutes of the earthquake ***if the GPS network data were available in real-time and proper analysis systems were in place.*** Later work has shown that GPS measurement of the ionospheric disturbance induced by the earthquake could have provided tsunami verification and tracking to provide further warning to the regional coastal communities.

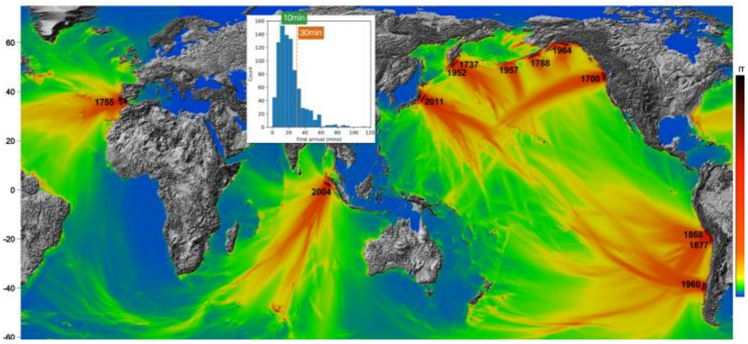
The GPS provides accurate centimeter scale positioning and microsecond timing to surface, air and spaceborne receivers. The GPS has been joined by several other international regional Global Navigation Satellite Systems (GNSS) that share similar capability and provide enhanced regional coverage. The International

Committee on Global Navigation Satellite Systems of the United Nations Office for Outer Space Affairs is working with the GNSS provider nations to promote interoperability through international protocols. The improving reliability, accuracy, and utility of GNSS is accomplished through a global expansion of GNSS receiver networks. The nearly universal adoption of GNSS for positioning and timing supports more reliable and cost-effective receiving equipment and more capable analysis systems. Earth scientists use the GNSS observations to measure millimeter scale deformation due to fault motion, volcanic inflation, and even subsurface water storage. GNSS satellites continuously broadcast at multiple frequencies to measure the delays introduced as the signals pass through the Earth's ionized upper atmosphere from satellite to receiver. Ground networks of GNSS receivers, improve the accuracy of GNSS but they also can resolve the deformation of the Earth's surface as well as the dynamics of the ionosphere in response to solar and Earth surface dynamics on the ionosphere.

The demonstrated capability of GNSS to accurately, rapidly, and cost effectively measure deformation of the Earth's surface and the response of the ionosphere to this deformation is the factual basis for GTEWS 2017 workshop and this report. Figure 2 displays the distribution of significant historical tsunamis. Rapid and accurate tsunami warning is particularly important to those communities nearest to the tsunami source. The accompanying chart in Figure 2 indicates that these communities are inundated within an average of 30 minutes of the causative mega-thrust earthquake. Tsunamis can also be generated by forces other earthquakes such as volcanic eruptions, severe weather changes, landslides or even impacts from extra-terrestrial objects. GNSS can provide some degree of warning during these events as well. The GTEWS 2017 workshop recommends improved international collaboration to enhance existing and planned tsunami warning systems with GNSS technology.

On March 11, 2011, the Tohoku-oki earthquake and tsunami unleashed another terrible tragedy upon the Japanese people that posed great challenges to the Japanese government. The Tohoku-oki earthquake occurred off shore from the world's most advanced GNSS network, the GEONET, designed and operated by The Geospatial Information Authority of Japan (GSI). Several retrospective studies of the Tohoku-oki earthquake captured by the GEONET demonstrated that accurate tsunami inundation predictions could be provided within 5 minutes of the earthquake occurrence. The first waves of the Tohoku-oki tsunami struck nearby shorelines within 30 minutes of the earthquake which is characteristic of most tsunami prone coastal regions. Therefore, GNSS enhancement to tsunami early warning could have provided coastal communities nearest the earthquake epicenter with at least 25 minutes of accurate early warning to find safer ground. GEONET data also demonstrated that GNSS imaging of ionospheric disturbance could verify the generation and propagation of the tsunami.

Figure 2: Distribution of historic global tsunamis and their propagation energy. (Institute of Computational Technologies & Institute of Computational Mathematics and Mathematical Geophysics, Siberian Division, Russian Academy of Sciences). Chart insert portrays the tsunami arrival time for a near field Indo-Pacific mega-thrust earthquakes ([Melgar, 2017](#)).



The GNSS enhancement to Tsunami Early Warning Systems (GTEWS) has been agonizingly slow despite robust scientific advances and demonstrations of its utility. To encourage the adoption of GTEWS, [Resolution #4](#) of the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) called upon its member states, associations and commissions to support the GNSS enhancement of tsunami warning systems. [Resolution #4](#) also recommended that this initiative should be focused upon the Indo-Pacific region that is at greatest risk of tsunami disaster (Figure 2).

The [GNSS Tsunami Early Warning Systems Workshop](#) (**GTEWS 2017**) was held in Sendai, Japan on July 25-27, 2017 and supported by NASA in collaboration with the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG), the Association of Pacific Rim Universities (APRU) Multi-Hazards Hub at Tohoku University in Sendai, and the International Research Institute of Disaster Science (IRIDeS) at Tohoku University. The **GTEWS 2017**workshop seeks to implement the vision articulated by IUGG 2015 [Resolution #4](#) to encourage broader cooperation within the Indo-Pacific community of APEC economies for the adoption of GTEWS. The two-day [GTEWS 2017 Workshop](#) reviews the principles of GNSS positioning, the geophysics of mega-thrust earthquakes, and GTEWS techniques in utilizing GNSS displacement and ionospheric imaging to advance global tsunami warning. Presentations discussed the requirements for effective tsunami warning and the optimal design of GTEWS networks. Representatives of several prototype GTEWS networks described the status of their networks, the challenges to operations and further development of existing networks. The meeting also provided significant opportunities for discussion following each presentation and during special sessions to resolve critical objectives of the workshop. A final plenary session was devoted to reviewing and advancing these discussions.

The GTEWS 2017 Workshop is aligned with the goals and priorities of the **UNISDR [Sendai Framework for Disaster Risk Reduction 2015-2030](#)**. The recommendations of the GTEWS 2017 workshop support the Sendai

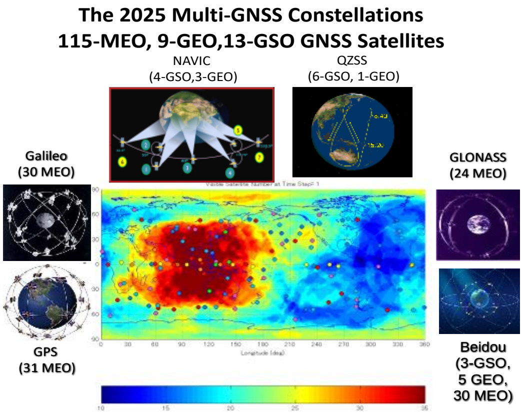
Framework goal to substantially reduce disaster mortality through the application of multi-national investments in GNSS technology to provide an adequate and sustainable multi-hazard early warning system and disaster risk information. The GTEWS 2017 workshop recommendations listed in the final section of this report can be framed within the four action priorities of the Sendai Framework as follows.

1. **Understand disaster risk:** Short term disaster risk will be improved by rapid and accurate tsunami warnings for a clearer understanding of impending disaster risk. More rapid accurate information improves the community response to warnings and will save lives in the medium term. The GTEWS network improvements will provide better long-term estimates of disaster risk through better scientific understanding of the evolving geologic forces.
2. **Strengthen disaster risk governance to manage disaster risk:** The workshop recommends the development of the GNSS Shield Consortium of national GNSS networks to share development strategies and information to better understand and prepare for tsunami disasters. The GNSS Shield Consortium of both research and operational agencies will contribute to the national and regional dialogue on tsunami preparedness.
3. **Invest in disaster risk reduction for resilience:** The workshop recommends public-private agreements to ensure Fourth Generation or better wireless broadband coverage for 100% of tsunami prone territories to enable real-time GNSS network deployment in remote regions to minimize warning latency.
4. **Enhance disaster preparedness for effective response:** Prototype GTEWS networks of the proposed GNSS Shield Consortium will accelerate tsunami warning system development and analysis within the Indo-Pacific region.

GTEWS is enabled by large investments in the development and implementation of the US Global Positioning System (GPS), the Chinese Beidou, the European Galileo, and the Russian GLONASS. The Japanese QuasiZenith Satellite System (QZSS) and the Indian IRNSS/NAVIC regional constellations are especially important to GTEWS because they improve the accuracy and resolution of GNSS measurements for the earthquake and tsunami prone regions of the Indo-Pacific (Figure 3). Nations support the development of these satellite navigation satellite constellations because they ensure national security, spur economic growth, and support scientific advancement.

Commercial enterprise and government agencies are also expanding GNSS ground infrastructure for a wide variety of GNSS based services (Figure 4). GTEWS will benefit from and build upon these broad-based investments. The adoption of GTEWS by the developing economies and island nations of the Indo-Pacific will increase preparedness to tsunami disasters and strengthen economic vitality through improvements to communications, positioning, and timing and the benefits of possible international investments.

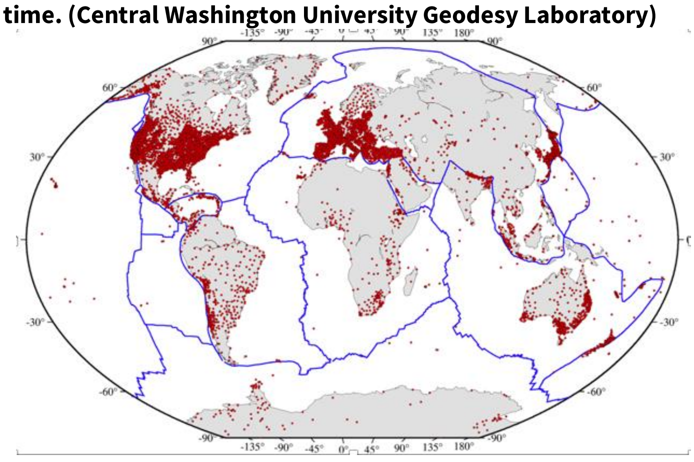
Figure 3: The Western Indo-Pacific will see about 40 GNSS satellites at any one time. (Adapted from S. Kogure)



GTEWS Development History

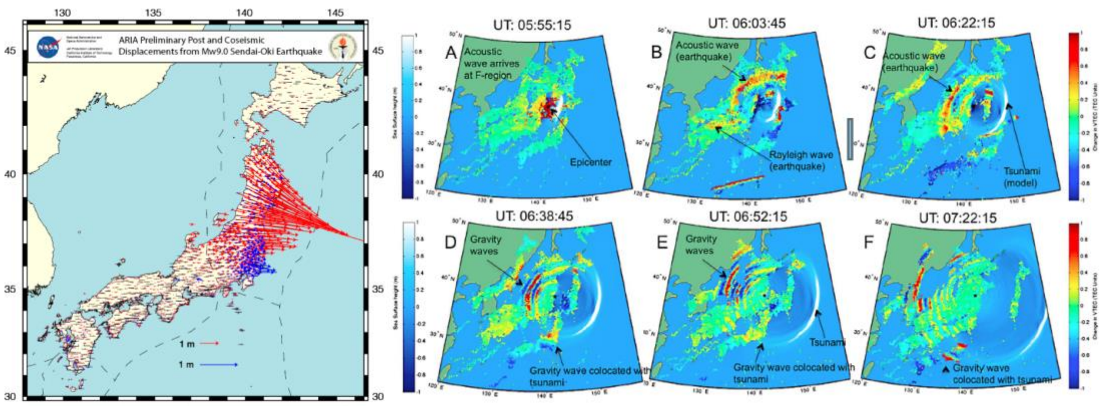
Coastal communities are advised to seek higher ground whenever the earth shakes - but there are areas that do not experience shaking despite an approaching tsunami either because of the nature of the earthquake or the community's distance from the epicenter (Figure 1). There are also many Indo-Pacific earthquakes that do not generate tsunamis. Tsunami warning based upon shaking or earthquake magnitude can be fast but of limited accuracy. False alarms can result because earthquake magnitude is a measure of earthquake energy and is not a reliable measure of the seafloor motion that generates a tsunami. Aside from instrumental vulnerabilities such as instrument saturation due to excessive accelerations, an earthquake of significant magnitude may be too deep or its fault motion may not result in sufficient seafloor displacement to generate a tsunami. False warnings undermine the credibility of future warnings and can impose significant negative economic and societal impact from the diversion of community activity. However, many people do not respond immediately to tsunami warnings because there is a history of false or exaggerated tsunami alarms. The U.S. Government Accountability Office report (GAO, 2006)

Figure 4: More than 16,000 GNSS receivers provide publicly available data though only about 10% are available in real-time. (Central Washington University Geodesy Laboratory)



estimates a Pacific Ocean tsunami false alarm rate of 75%. False alarms may also cause panic with the issuance of

Figure 5: Tohoku-oki earthquake and tsunami GNSS measurements by the GEONET: Left: Static displacement of the main shock (Mw 9.0)-red and the aftershock (Mw 7.9)-blue. (After *Simons et al, 2011*) Right: Sequence of ionospheric imaging shows development and propagation of ionospheric disturbance coupled to the earthquake and tsunami. (After *Galvan et al, 2012*). The Tohoku-oki earthquake occurred at UT 05:46 March 11, 2011.



large-scale tsunami alarms to surrounding countries without certainty of an impending tsunami. Better resolution of seafloor displacement and sea surface displacement will improve tsunami prediction and monitoring.

Tsunami disasters of the last two decades were mostly caused by megathrust earthquakes along the Indo-Pacific convergent plate boundaries known as The Ring of Fire. The 2004 Mw 9.2 Sumatra-Andaman Earthquake and Great Indian Ocean tsunami (Ammon et al, 2005; Ishii et al, 2005; Lay et al, 2005; Stein & Okal, 2005, Subarya et al, 2006) created the greatest loss of life along the Sumatra coastline nearest the earthquake epicenter from tsunami inundation heights of up to 30 m (Paris et al 2009). The Mw 8.8 2010 Maule earthquake in Chile (Lay et al, 2010; Delouis et al 2010) resulted in 124 tsunami related fatalities and wave heights up to 15-30 m along the coast nearest the epicenter (Fritz et al, 2011). The 2011 Mw 9.0 Tohoku-oki earthquake in Japan (Simons et al, 2011; Lay & Kanamori, 2011) generated a tsunami with inundation amplitudes as high as 40 m and left over 15,000 casualties (Mori et al, 2012). The Tohoku-oki, 2011 was the first large tsunami to impinge upon a heavily developed and industrialized coastline in modern times. The tragic loss of life and the economic collapse of nearly 400 km of coastline (Hayashi, 2012) reminds us of the vulnerability of even our most advanced societies.

Reliance upon seismically determined earthquake magnitude for large earthquakes can lead to a severe under-estimation of the earthquake magnitude, source and extent (Hoshiba and Ozaki, 2014; Katsumata et al, 2013; Wright et al, 2012) as demonstrated in both the Sumatra-Andaman earthquake of 2004 and the subsequent Tohoku-oki earthquake of 2011. In 2004 the underestimate led to the hours long delay in a tsunami warning while the tsunami inundated without warning the coastlines of neighbouring countries (Figure 1). In 2011, the underestimate of the Tohoku-oki earthquake magnitude resulted in early tsunami run-up estimates that were too low by tens of meters (Ozaki, 2011). An estimate of Mw7.2 was determined after 30 seconds and revised to Mw 8.0 after 107 seconds (Hoshiba et al, 2011). More accurate Japan Meterological Agency (JMA) and the US Geological Survey (USGS) estimates (Mw 8.9) were available 1-2.5 hours after the earthquake occurrence (Hayes et al, 2011). The USGS released a finite fault model about 7 hours following the earthquake occurrence time (Duputel et al, 2011, Hayes et al, 2011). The subsequent refinement to the earthquake tsunami potential was of little value to communities in the near field when a 40-meter tsunami (Mori et al, 2012) struck the Sanriku coast within 30 minutes of earthquake rupture.

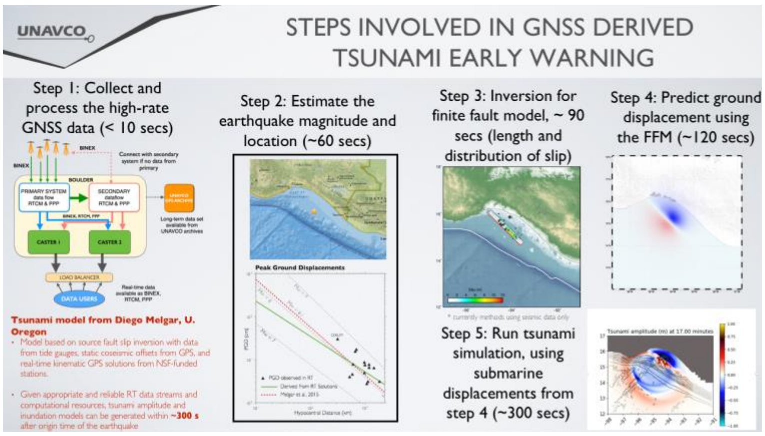
GTEWS: Tsunami Early Warning Technology

Significant GTEWS development efforts were published prior to the Tokoku-oki earthquake of March 11, 2011, many of which will be found in the bibliography of this report. It was the Japanese GEONET, the world's most advanced GNSS ground network of 1300 GPS receivers, that provided a convincing demonstration of the value of GTEWS for enhanced tsunami disaster warning. Figure 5 displays the GEONET measurements of ground displacement and ionospheric imaging during the March 11, 2011 Tokoku-oki Mw9.0 earthquake. These measurements provide a clear example of the role that GNSS measurements can play in the providing rapid, accurate and cost-effective tsunami early warning. The left image displays ground displacement due to fault slip from both the major tsunami inducing fault slip (red) of Mw 9.0 and a subsequent less intense Mw 7.5 earthquake (blue). The red arrow in this diagram display maximum eastward displacement of 5 meters. The right image displays GNSS measurements of ionospheric disturbance occurring 6-10 minutes following the Mw 9.0 earthquake in response to a localized rise in sea level over the earthquake epicenter estimated to be 4 meters. The ground displacement and ionospheric imaging measurements of Figure 5 should demonstrate the simple visual value of these data in the prediction and verification of an impending major tsunami. But most important is that research efforts prior to the Tohoku-oki earthquake laid the ground work for GNSS analysis systems to provide even more precise warning information to the near field communities. Unfortunately, the Japanese GEONET nor most of the Info-Pacific GNSS networks have been equipped with the necessary communications and analysis systems to serve this purpose.

GTEWS: Ground Displacement: GNSS measurements of ground displacement can improve the speed and accuracy of earthquake magnitude estimates. Blewitt et al, 2006; Sobolev et al, 2006; and Song, 2007 demonstrated that real-time access to existing regional GPS measurements could have provided a rapid and accurate estimate of the earthquake's Mw9.2 magnitude and predicted a significant tsunami within 15 minutes of the Sumatra-Andaman earthquake.

GNSS displacement measurements provide both magnitude and direction of the ground motion which is critical information for estimating displacement of the seafloor and its tsunamigenic potential Song, 2007 calculated the tsunami potential and provided a numerical tsunami model from the GNSS displacement measurements. The numerical tsunami model closely resembled the tsunami measured by orbiting ocean altimetry satellites and by coastal communities of the Indo-Pacific. Sobolev et al 2006 demonstrated that an optimum distribution of GPS receivers derived from a geodynamic numerical model of the local geology will significantly improve tsunami inundation predictions. Sobolev el al, 2007 proposed the application of their network design principles to the entire Indo-Pacific Ring of Fire with the proposed "GPS Shield" for tsunami early warning. Unfortunately, these four studies were retrospective analyses and their recommendations were not implemented in time for the 2011 Tohoku-oki earthquake.

Figure 6: GTEWS analysis process to provide accurate tsunami warning within 5 minutes of the earthquake. (Adapted from UNAVCO/Diego Melgar, University of Oregon)



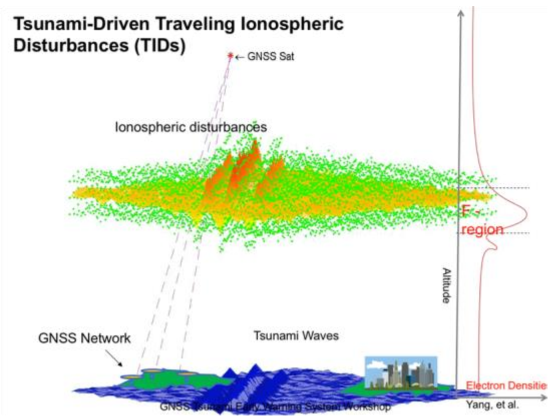
GNSS real time analysis has become a very powerful tool with the development of multiple approaches to the measurement of real time displacement using a variety of techniques both at the receiver and within central processing facilities. Positioning resolution for these systems is at the centimeter level with sampling rates of one sample per one second or better. The techniques in common use are Real Time Kinematic (RTK) (e.g. Ohta et al, 2012) and Precise Point Positioning (PPP) (e.g. Zumberge et al, 1997, Crowell et al, 2012). The combined real time analysis from multiple GNSS constellations also appears to reduce positioning errors as reported in various studies (e.g., Geng et al, 2017).

Retrospective analysis of the GEONET measurements demonstrated that accurate earthquake fault models and tsunami predictions could be issued within five minutes of the earthquake (Ohta et al, 2012, Song et al, 2012, Xu and Song, 2013, Hoechner et al 2013, Melgar and Bock, 2013, Riquelme et al, 2016). Figure 6 displays one of many approaches taken in these studies but the end results are similar. These analyses require data from well distributed real time GNSS networks such as that outlined by Sobolev el al, 2007. Recent studies indicate that analyses can be further improved with the combined analysis of seismogeodetic data derived from nearby GNSS and accelerometer instrumentation (e.g. Melgar et al, 2013b).

The reliability of GTEWS crustal displacement analysis relies upon the accurate and rapid assessment of the time and location of the earthquake. This is best derived from seismic network information. and an effective information system for the dispersal of warnings to the response agencies and the public. GTEWS is termed an enhancement because it enhances and builds upon the accuracy and timeliness of warning systems and does not replace the essential functions of existing warning systems.

GTEWS: Ionospheric Imaging: A tsunami is generated by the rapid displacement of a large volume of water that disturbs of the ocean surface and evolves into long wave length gravity waves given appropriate dimensions for the ocean basin. Atmospheric acoustic and gravity waves couple the ionosphere to this ocean surface displacement signal. Both acoustic and gravity waves are amplified a thousand times or more due to the decrease in atmospheric density with atmospheric altitude. Within the ionosphere, the amplified gravity waves influence the distribution of ionized plasma under the influence of the ambient Earth's magnetic field. The physics of ionospheric-oceanic coupling was described over forty years ago by Peltier and Hines, 1976 who suggested that measurement of the ionospheric perturbations could lead to efficient global tsunami detection and monitoring. Unfortunately, thirty years passed before finding an efficient means to exploit ionospheric imaging for tsunami warning.

Figure 7: GNSS Traveling Ionospheric Disturbance measurement concept. (A. Komjathy)



Artru et al 2005a provided convincing observational evidence that GNSS measurements of Total Electron Content (TEC) could detect ionospheric disturbances generated by a propagating tsunami. GNSS dual frequency receivers estimate the TEC along the ray path as frequency dependent signal delays. The point where the ray path from a GNSS satellite to a ground receiver passes through the region of maximum ionization (about 350 km altitude) is termed an "ionospheric piercing point" and assigned the measured TEC anomaly along the ray path. The geometry of ray paths from ground receiver to GNSS satellites result in piercing points that can be detected well over the horizon and hundreds of kilometers from the receiver's location. A GNSS receiver can therefore monitor the ionosphere for thousands of square kilometers surrounding its position. The GEONET images of Figure 5 (right panel) represent about 6000 piercing points determined by 1300 GEONET receivers and 5 to 8 GPS satellites. It is expected within the next decade that the addition of new GNSS satellites will improve the resolution of ionospheric disturbances by five or more times. Increased piercing point density will provide higher resolution ionospheric images and more reliable warning of the development and propagation of future tsunamis.

GTEWS ionospheric imaging benefits from time dependent 3-D models of the ionospheric response to Earth surface disturbances. These models implement first-principles of atmosphere, ionosphere and thermosphere dynamics (e.g. Ridley et al, 2006, Hickey et al, 2009, Mai and Kiang, 2009, Occhipinti et al, 2008; Rolland et al, 2011, Occhipinti et al, 2013, Vadas and Nicolls, 2012, Kherani et al, 2012, Meng et al 2015, Zettergren and Snively, 2018). Most numerical ionospheric models provide time dependent three-dimensional representation of ionospheric TEC perturbation given a tsunami's wave height, wave period, wavelength, and propagation direction (Figure 7). These models provide for quantitative imagery that is important to communicating risk with emergency managers and affected populations. (e.g. Galvan et al, 2012, Komjathy et al, 2016, Occhipinti et al, 2013, Astafyeva et al, 2011. Astafyeva et al, 2013, Meng et al,2018, Rolland et al, 2010).

Both acoustic pressure waves and gravity waves were generated during the Tokoku-oki earthquake and resulting tsunami (Figure 5). Acoustic pressure waves travel to the ionosphere more rapidly creating a TEC disturbance over the sea level uplift within 10 minutes of the earthquake (Figure 5: UT 05:55). It is believed that the intensity and areal extent of these acoustic wave induced TEC anomalies can provide an estimate of the distribution of vertical displacement of the sea surface, thereby validating the tsunami potential within the first ten minutes of the seismic rupture (Occhipinti et al, 2013, Meng et al, 2018, Zettergren and Snively, 2018). As demonstrated by the Japanese GEONET measurements, a land-based array of GNSS receivers located at a moderate distance about the epicenter could provide independent verification of tsunami predictions derived from seismic and GNSS ground displacement measurements. About one hour later, ionospheric gravity waves linked to the propagating sea surface tsunami waves appear after the initial ocean disturbance resolves itself into propagating tsunami waves (Figure 5: UT 06:38). GNSS ionospheric imaging can track the propagation and estimate the tsunami wave heights to provide accurate warning for far field communities (Komjathy et al, 2016; Rakoto et al, 2018). Rakoto et al, 2018 demonstrated the inversion of these propagating ionospheric waves to estimate wave heights of the associated tsunamis for the 2012 Haida Gwaii, 2006 Kuril Islands, and the 2011 Tohoku tsunamis. The Rakoto et al, 2018 estimates were within 20% of DART buoy measurements.

Finally, real-time ionospheric imaging for tsunami warning has been challenged by receiver and satellite biases and the variable state of the ionosphere that can require significant post processing and delay warnings. The NASA/JPL GDGPS program and the Geodesy and Geomatics Division - University of Rome La Sapienza reported the initiation of real-time GNSS ionospheric disturbance analysis using the VARION **(V**ariometric **A**pproach for **R**eal-Time **ION**osphere Observation) algorithm (Savastano *et al*, 2017). Real-time information from this prototype system is available at https://iono2la.gdgps.net/ .

GTEWS Requirements

Effective GTEWS enhancement of tsunami early warning requires real-time access to an optimally distributed network of GNSS receivers, reliable broadband communications, capable analysis centers, and products that can be rapidly assimilated into the existing tsunami early warning systems. Tsunami warning is a race against time for those coastal communities nearest the earthquake epicenter because a tsunami could arrive in within five to forty minutes of a nearby earthquake.

GTEWS enhancement will build upon tsunami warning systems that currently utilize seismic data for earthquake location, occurrence time, and an effective system for informing the public of tsunami hazard. A GTEWS enhancement would provide more timely and accurate estimates of tsunami potential than a warning based on earthquake magnitude alone (Figure 6).

The GNSS enhanced warning system should utilize ionospheric imaging to provide continuing updates on tsunami potential and arrival times to augment or substitute for ocean bottom pressure networks. Six to ten minutes after a major earthquake, the GTEWS ground network should detect the first ionospheric disturbance at ionospheric piercing points above the epicenter or point of maximum ocean surface inflation. Given a sufficient dense distribution of ionospheric piercing points it should be possible to verify estimates of the initial sea surface displacement and refine tsunami warnings to communities nearest to the earthquake epicenter.

Within an hour of the earthquake occurrence, GNSS ionospheric imaging should begin to detect the propagating tsunami as it spreads from the earthquake epicenter. The ionospheric imaging data will augment and enhance data observations from deep ocean DART buoys and tsunami source models derived from observed or estimated seafloor displacement. The GTEWS enhancement of observations and models will significantly reduce false alarms to coastal communities in the far field.

GNSS Ground Networks: Effective GTEWS requires a well distributed network of GNSS receivers as described by Sobolev et al, 2006, 2007. The optimal design of a GTEWS network must address the regional geology, power, security, communications, financing and regulations. Some savings in network development could come from the upgrade of over 16,000 publicly broadcasting GNSS stations (Figure 4). Public-private cooperation to provide critical communications, support infrastructure, or the sharing of data from private networks may also provide additional resources for GTEWS development.

Data Sharing: Megathrust earthquakes and the resulting tsunamis do not respect national boundaries. The development of an Indo-Pacific GTEWS will require the sharing of data and software and cooperation amongst research agencies and institutions. Unfortunately sharing of real-time GNSS data and its analysis both within and amongst the Asia-Pacific economies is impeded by national policies, agency regulations, commercial managed data systems, poor communications and poorly developed GNSS infrastructure. The UN General Assembly established the Global Geodetic Information Management (UN-GGIM) to address disaster mitigation and other applications through the sharing of geodetic data amongst member states. Some GTEWS 2017 workshop participants spoke of their agency's open data policies that are in accord with the UN-GGIM program for the sharing of geodetic information for natural hazards and scientific research. The International Oceanographic Committee has successfully established collaboration amongst tsunami warning centers. We encourage the IOC to extend this cooperation to GTEWS data sharing.

Real-time Data Streaming: Broadband communications technology and infrastructure is generally sufficient for real-time data exchange amongst GNSS analysis centers. The primary challenge is to provide a reliable path between individual GNSS receivers in remote locations and the GTEWS analysis centers. Each region has its unique challenges to real-time data transmission. Each tsunami prone region will likely require an optimized data distribution plan to provide network observations of analysis centers in real-time. Redundancy of data paths should be included where possible to ensure resilience during a major earthquake. Workshop attendees reported that currently available Fourth Generation cell phone networks are sufficient for GTEWS real-time data transfer. Therefore, GTEWS implementation in developing economies could be a stimulus for improving communications to remote communities.

Cost is a limiting factor for sustainable GTEWS within some regions of the Indo-Pacific. One recommendation to reduce the cost of communication is to calculate and store displacement information at the GNSS receiver. These data could then be relayed to the analysis center when triggered by a special event such as an earthquake. Agreements with global communications firms may also lead to cost relief for the real-time data transfer from remote receiver locations. It should be recognized that enhanced internet access for developing economies will also address the Sendai Framework goal of fostering economic growth.

Integration of GTEWS and Existing Tsunami Warning Systems: GTEWS program products can be seamlessly incorporated into existing national and international tsunami warning systems. Strong partnerships between GTEWS research organizations and operational agencies must exist for a successful outcome. Some organizations such as GeoScience Australia or the Centro Sismologico Nacional of Chile can achieve the integration without significant interagency effort because the geodetic research and operational warning capability are integrated within the operational agency structures. The Japanese and US agencies have a distinct separation between the research and development institutions and the agencies mandated for emergency response. The incorporation of GTEWS products has been more challenging for these countries because the effort can interfere with agency plans and operations. At the time of this writing the US NOAA and the NASA sponsored READI prototype network are engaged in advanced efforts to integrate GTEWS products within NOAA's Tsunami Warning System. The completion of these initial efforts is expected in 2019.

Prototype GTEWS Networks

The Great Sumatran Earthquake and Tsunami of 2004 stimulated research and investment to improve the prediction of tsunamis. The demonstrated capability of GNSS in support of environmental sensing and disaster risk assessment and operational savings fostered the development of real-time networks in many nations. Among the advances was the development of prototype GNSS Tsunami Early Warning networks. Five prototype, real-time quasi-operational GNSS networks where presented to the workshop. These networks are capable of demonstrating prototype GTEWS activities within the Indo-Pacific region. These prototype GTEWS networks are advancing the acceptance of GTEWS while also advancing GTEWS science and technology. Each prototype system has its own characteristics and algorithms for GNSS based measurement of crustal displacement and can provide ionospheric imaging for the prediction, detection and tracking of tsunamis. The networks also serve as effective building blocks from which we begin the development of an Indo-Pacific network for GNSS Enhanced Tsunami Early Warning.

Figure 8: GITEWS GPS distribution in Indonesia (status Dec 2009); green triangles- reference stations, yellow boxes- GPS at tide gauges. (Source: GFZ German Centre for Geosciences-Potsdam)

German-Indonesian Tsunami Early Warning System (GITEWS). GITEWS was established in 2005 in response to the Indian Ocean Earthquake and Tsunami (http://www.gitews.org/en/status). GITEWS deployed a combination of ocean bottom pressure sensors, tide gauges, seismometers, and GPS receivers. The initial task of the GITEWS GPS receivers was to provide positioning information to the co-located tide gauges. Sobolev et al, 2006, 2007; Hoechner et al, 2008, Babeyko et al, 2010; Behrens et al, 2010; Falck et al, 2010 demonstrated via numerical models the utility of GPS in near-field tsunami early warning for the determination of fault dislocation and tsunami warning. The GITEWS project plans were modified to include near real-time GPS offsets into the operative scenario matching algorithm although the density and latency of the GPS network was sub-optimal for effective tsunami early warning. The GITEWS network has been transferred to sole operation by the Meteorological, Climatological and Geophysical Services (BMKG) in Jakarta, Indonesia.

Sobolev et al (2007) further proposed the establishment of a "GPS Shield" network for Indonesia and the Indo-Pacific with optimally positioned set of GPS receivers along a transect perpendicular to the trench axis. Babeyko, 2017 presentation to the workshop recommended that the GTEWS networks should optimize the effectiveness of tsunami warning based upon numerical models of regional geology and local infrastructure as proposed by Sobolev et al (2007).

Real-time GEONET Analysis for Rapid Deformation Monitoring (REGARD). The REGARD system utilizes over 1200 GEONET real-time GNSS stations to determine ground displacement and fault models. The importance of GEONET in the demonstration of GTEWS capability cannot be understated given that the data are prominently used throughout this report and by the numerous cited studies. Geospatial Information Authority of Japan (GSI), operator of the GEONET, and the Japan Meteorological Agency (JMA), which has the earthquake and tsunami warning mandate, are in discussions to adopt REGARD products in the issuance of tsunami warnings. The Japanese Cabinet Office has adopted REGARD as a model for damage assessment. The Tohoku University's high-performance computing center and REGARD displacement products for rapid tsunami inundation modeling are based on the TUNAMI code (Ohta et al, 2018). Real-time data from the GSI GEONET is available for agreed fees to cover actual costs.

Figure 10: READI Network (*Central Washington University Geodesy Laboratory)*

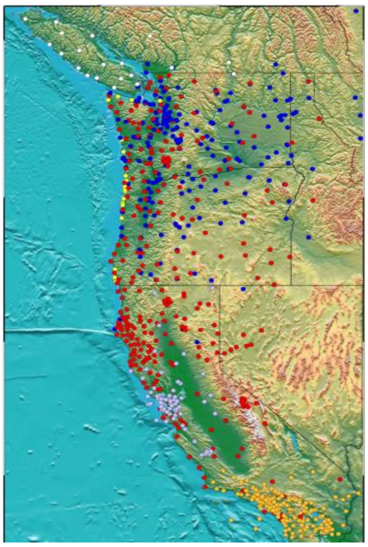
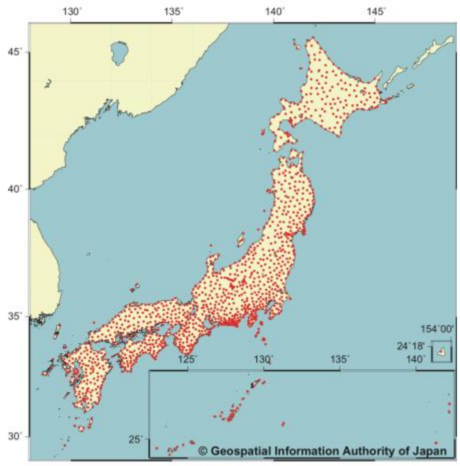


Figure 9: The Japanese GEONET (courtesy Geospatial Information Agency, Japan).



Real-time Earthquake Analysis for Disaster MItigation (READI). READI is a research project that leverages the 550+ station real-time GPS super network in Western North America to prototype an earthquake and tsunami early warning system using GPS (GNSS) technology and GPS/seismic integration (seismo-geodesy). Canadian agencies and the READI program share their real-time network data. The US National Science Foundation supports the operation of the US portion of the READI network, The Geological Survey of Canada of Natural Resources Canada streams data from the Canadian Western Canada Deformation Array (WCDA). NASA funds real-time READI tsunami warning development activities at UCSD's Scripps Institution of Oceanography (SIO), Central Washington University, the Jet Propulsion Laboratory (JPL) of the California Institute of Technology and the University of Nevada Reno. The analysis centers employ different software implementations for comparative analysis and also provide a unified analysis product. The READI research group is collaborating with the Pacific Tsunami Warning Center (PTWC) and the National Tsunami Warning Center (NTWC) in accord with an agreement between NASA and

NOAA. The collaboration seeks to develop and test the integration of real-time GNSS enhancement to NOAA's Tsunami Early Warning system. Emphasis is on the provision of accurate real-time GNSS displacement data compatible with NOAA analysis systems. The collaboration is expected to yield a real-time operational GNSS enhancement to tsunami warning in early 2019. The collaboration may be used as model for the integration of GNSS early warning displacement information into existing tsunami early warning systems.

Chilean National Seismic Network. The network of the Centro Sismologico Nacional (CSN) consists of about 133 stations with collocated GNSS, seismometers and strong motion instruments. Not all GNSS stations are available in real-time due to the challenges of establishing broadband communications to remote areas. CSN provides earthquake warning and interacts with the Chilean Hydrographic Office (SHOA). CSN has applied the W-Phase and Peak Ground Displacement models in joint analysis of seismic and geodetic data (seismo-geodetic) analysis ([Riquelme et al 2016](#)). The high rate of tsunamigenic megathrust earthquakes in the near and long term makes the CSN network a very important contribution in GTEWS development. The CSN has stated that its GPS data are openly available but communications costs and availability in remote locations limits the number of stations available. Communications and network management software remains the primary challenge.

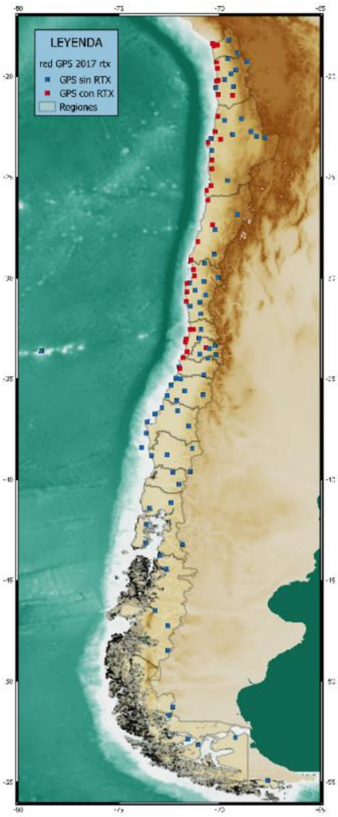
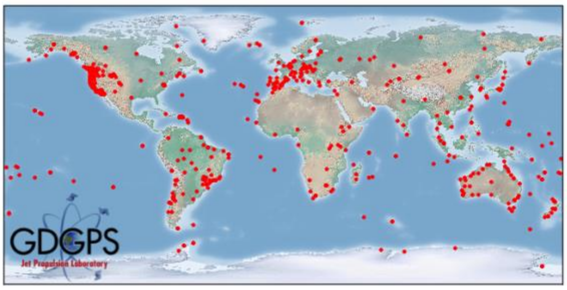


Figure 11: The Chilean CSN network of 133 GNSS receivers. Red squares indicate active real-time GNSS stations. (Courtesy U. Chile)

Global Differential GPS/VARION (GDGPS/VARION). The NASA/JPL GDGPS System [http://www.gdgps.net] processes real-time data from more than 200 globally distributed tracking sites. GDGPS operates about 80 of these sites and ingests data from other real-time tracking sites operated by national and international organizations such as the IGS-RT network. Tracking data from these sites are streamed in real-time to selected real-time analysis centers and to a caster operated by the CDDIS of the NASA Goddard Space Flight Center. These data are used to derive GNSS orbit and clock states, and monitor the motion of each tracking site. Despite the large tracking network, station distribution remains relatively sparse in certain seismically active parts of the world. Nevertheless, GDGPS can detect and measure most major earthquakes in real-time in support of earthquake source analysis and tsunami predictions.

Figure 12: Global Differential GPS (GDGPS) network. (http://www.gdgps.net)



GDGPS provides real-time tsunami warning information to NOAA's Pacific Tsunami Warning System. GDGPS also hosts the VARION prototype real-time TEC measurement system for tsunami verification and monitoring (Savastano et al, 2017). Results of VARION analysis are published in real-time on the VARION GDGPS website (https://iono2la.gdgps.net/

The Asia-Pacific Reference Frame Networks: We chose this regional network because the network is striving to develop and maintain a permanent continuously operating network comprised of many national networks. The New Zealand GeoNet and Australian AuScope networks discussed by Dawson, 2017 and D'Anastasio, 2017 are the primary components of this network that provide data in real-time for open distribution. Real-time data access to the numerous other networks is challenging but efforts are underway to address these challenges. The UN Global Geodetic Information Management for the Asia Pacific (UN-GGIM-AP) is working to encourage more development of GNSS networks and the sharing of data from those networks. The primary purpose of this network is maintenance of the reference frame but if data are available in real-time- GTEWS algorithms could be applied to these data for tsunami warning.

Figure 13: APREF network comprises of several Asia-Pacific national and privately-operated networks. (Geoscience Australia)

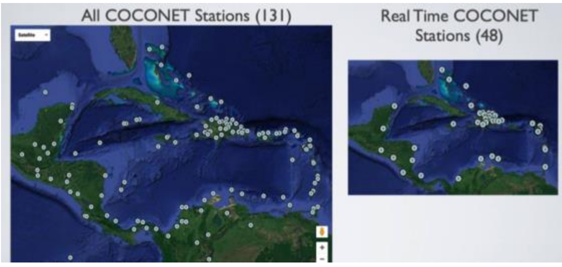
The New Zealand networks consist of 51 real-time multi-GNSS receivers of the GeoNet and PositionNZ networks. These data are available for open distribution. These data are not currently processed for tsunami warning purposes, but streamed real-time data are freely available to subscribed users. The proximity of the Hikurangi subduction interface to New Zealand coasts and of the Kermadec Trench earthquakes places a requirement upon accurate estimates of local and regional tsunami formation in the Southwest Pacific. A challenge to New Zealand as well as to the development of an Indo-Pacific GTEWS is the availability of Southwest Pacific

Islands real-time GNSS observations. Several stations are currently installed in the region but real-time access has proved difficult largely due to a lack of funding for local station operators and broadband communications.

The Australian government in response to the Great Sumatran Earthquake and Tsunami, established the Joint Australian Tsunami Warning Centre (JATWC) operated by the Bureau of Meteorology (Bureau) and Geoscience Australia (GA). The JATWC does not currently process GNSS for tsunami warning purposes but it does operate about 200 real-time GNSS stations in the AuScope network. These data are available as streamed real-time data to subscribers.

COCONet Contribution to Caribbean GTEWS. The US National Science Foundation funds the Continuously Operating Caribbean GPS Observational Network (COCONet) as part of the newly recognized Network of the Americas (NOTA) operated by UNAVCO and providing a foundation for the implementation of GTEWS within the Caribbean. Over the past 500 years more than 75 tsunamis have killed 4484 people in the Caribbean Basin. The Intergovernmental Coordination Group for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE EWS) coordinates international tsunami warning and mitigation activities, including the issuance of timely and understandable tsunami bulletins in the Caribbean. Comprehensive tsunami mitigation programs require complementary and sustained activities in tsunami hazard risk assessment, tsunami warning and emergency response, and preparedness. Stakeholder involvement and coordination is essential, and community-based, people-centered mitigation activities will help to build tsunami resiliency. The Caribbean Tsunami Warning Program (CTWP) is supported with the tsunami early warning information by The Pacific Tsunami Warning Center operated by NOAA. Furthermore, the CTWP has indicated a strong interest in developing a program to enhance its tsunami warning activities with GNSS data that could be advanced by the NOAA-NASA cooperation on the implementation of READI prototype systems.

Figure 14: COCONET (UNAVCO)



INCOIS: Prototype GTEWS network: During the final manuscript preparation, the Editors were informed of the ongoing development of the Indian National Centre for Ocean Information Services (INCOIS) GTEWS network at 36 Andaman and Nicobar Island locations specifically for the purpose of tsunami early warning. Unfortunately, a more complete understanding of the INCOIS GTEWS prototype network was not available to the workshop participants.

Workshop Findings and Recommendations

Findings: The GTEWS 2017 workshop findings are drawn from recorded discussions that followed individual presentations and breakout sessions captured in the workshop video and audio archives.

- GTEWS will improve the accuracy, response time, economics and sustainability of tsunami early warning.
- Development of GTEWS will directly support the Sendai Framework by increasing community resilience and economic growth particularly for developing and small island nations where tsunami early warning infrastructure is poorly developed. Economic growth will be enhanced with improved GNSS infrastructure and broadband availability.
- GTEWS can be implemented using currently available technology and measurement systems. GTEWS benefits are based upon currently available GNSS signals, commercial GNSS receivers, and analysis algorithms, broadband communications capability such as Fourth Generation wireless networks.
- Development of effective GTEWS enhancement for the Indo-Pacific requires:
    - optimization of real-time GNSS receiver networks;
    - international agreements for the distribution of GNSS real-time data;
    - cooperation of disaster response agencies.

Recommendations: The Editors reviewed recordings of the GTEWS 2017 presentations and discussions. Test bed development programs and GNSS deployment strategies similar to GPS Shield concept (Sobolev et al (2007) were echoed and updated in several workshop discussions and presentations. Cooperation currently exists amongst the GTEWS prototype networks and several network operators have expressed support for open data exchange. The prototype networks are encouraged to establish the **GNSS Shield C**onsortium to begin GTEWS development the Indo-Pacific region. The consortium should work on data and product compatibility, data sharing, the identification of data analysis capabilities, and the incorporation of GTEWS data products within existing tsunami warning systems. **GNSS Shield** data measurements should include crustal displacement for accurate tsunami predictions and ionospheric imaging for the validation the tsunami development and propagation. A successful development of the **GNSS Shield** will increase our understanding of geodynamics, improve our response to natural disasters while also contributing to the economic development of the nations that it serves. The recommendations expressed here are not a full accounting of all cogent recommendations made during the workshop. We recommend readers to view the workshop recordings for a more complete understanding of the presentations and discussions.

1. **The GGOS/IUGG, APRU and the UN-GGIM are encouraged coordinate efforts to develop a GNSS Shield Consortium for the Indo-Pacific.** The workshop discussed several approaches to increasing the level of support for GTEWS. The GTEWS 2017 workshop brought these organizations together because their independent programs where aligned with the workshop's vision. The GNSS Shield Consortium will influence the development of ministerial level support and acceptance GTEWS by the Asia-Pacific economies while also accelerating the development of GTEWS prototype networks. Some discussion suggested that the IUGG/IAG provide organizational leadership for the GNSS Shield Consortium through an office of the GGOS and the International GNSS Service. Others recommended a more government level management with the APEC providing an organizational framework. Perhaps a hybrid approach to leadership through a cooperative agreement between the IUGG/IAG/APEC organizations would provide maximum opportunity for the development of government policy, research and development.
2. **The GNSS Shield Consortium should work to encourage software, data exchange, and continued improvement of network design and performance.** GNSS enhancement to tsunami early warning has progressed through international exchanges of research results and measurements fostered by the International GNSS Service and the Global Geodetic Observing System. The call for action by the IUGG 2015 Resolution #4 requires strong working relationships between the research community and those government agencies tasked with the national mandate for the issuance of warnings. The GNSS Shield Consortium will develop protocols for the exchange of real-time GNSS tsunami warning data, the sharing of research results, and the development of support agreements.

   A portable analysis system capable of applying consortium software to individual network data will provide a means to develop data protocols and compare algorithms more rapidly than waiting for data exchange agreements. Two realizations were proposed for this portable analysis system: (1) a cloud-based analysis capability (2) a portable computer system to be installed alongside existing analysis systems for the prototype network.

3. **Strengthen broadband communication to underserved regions of the GNSS Shield.** Portions of the prototype GTEWS networks are not connected through real-time communications between receiver and analysis centers. Broadband communications can bring security and economic activity to under-served

regions. The GNSS Shield Consortium should begin immediate discussions with broadband suppliers to reduce the cost and improve the quality of broadband service to challenging portions of the Indo-Pacific. Real-time GTEWS communications requirements can be met with current Fourth Generation wireless technology. Care must be taken however because cell phone networks are under greatest pressure during regional disasters and real-time GTEWS communications will be less secure during those periods when their access is most needed. Communications security should be of paramount importance to GNSS Shield. These wireless networks can also be employed for the effective communication of tsunami threat and other hazard warnings.

4. **Work with national organizations including those mandated for natural hazards mitigation to develop agreements for inclusion of their GNSS receivers within the GNSS Shield.** National or agency level restrictions for access to real-time GNSS data is the greatest challenge to the establishment of an effective GTEWS system. Generally, the nations of the eastern Pacific are open to the sharing of real-time GNSS data. The western Pacific and eastern Indian Ocean have adopted more restricted access to existing GNSS network data. GNSS Shield Consortium should begin negotiations to allow exchange of real-time data for Indo-Pacific regional analysis. It may be possible to achieve access to real-time data by accepting restrictions on the use of the released data or perhaps a sub-selection of the national network stations.
5. **Design an optimal GNSS Shield network for both crustal displacement and high-resolution TEC monitoring.** Sobolev et al 2007 and this workshop recommended a numerical analysis that includes local geology, seismicity and communications infrastructure. Use existing GNSS sites wherever possible. Several nations are installing or operating GNSS networks to improve their understanding of crustal dynamics, weather, or to provide for commercial or governmental activities that may be candidates for inclusion in a GTEWS.
6. **Understand the operational requirements of existing tsunami warning systems and determine the steps required to interface these tsunami warning systems.** GTEWS is an observational and analysis capability that must be integrated with public advisory and warning capability. Therefore, a recommended action is to establish working contacts with existing tsunami warning systems and strengthen existing interactions in order to promote GNSS-solutions and to devise paths for their

implementation. The rapid and successful implementation of GTEWS will rely upon fluid interactions amongst national agencies.

The incorporation of GNSS GTEWS products into existing tsunami warning systems may require substantial engineering of data flows and products. For developing nations and small island nations, a stand-alone real-time GTEWS system will likely be the best approach if there is little existing tsunami warning infrastructure. A stand-alone GTEWS system might include supporting instrumentation such as integrated MEMS seismometers, and an analysis system with a recognized and approved public capability.

Bibliography

Ammon, C. J., C. Ji, H.-K. Thio, D. Robinson, S. Ni, V. Hjorleifsdottir, H. Kanamori, T. Lay, S. Das and D. Helmberger (2005). "Rupture process of the 2004 Sumatra-Andaman earthquake." Science 308(5725): 1133-1139.

Artru, J., V. Ducic, H. Kanamori, P. Lognonné, and M. Murakami (2005a), Ionospheric detection of gravity waves induced by tsunamis, Geophys. J. Int., 160, 840–848, doi:10.1111/j.1365-246X.2005.02552. x.

Artru, J., P. Lognonné, G. Occhipinti, F. Crespon, R. Garcia, E. Jeansou, and M. Murakami (2005b), Tsunami detection in the ionosphere, Space Res. Today, 163, 23–27.

Astafyeva, E., P. Lognonné, and L. Rolland (2011), First ionosphere images for the seismic slip of the Tohoku-oki earthquake, Geophys. Res. Lett., doi:10.1029/2011GL049623.

Astafyeva, E., L. Rolland, P. Lognonne, K. Khelfi, and T. Yahagi (2013), Parameters of seismic source as deduced from 1 Hz ionospheric GPS data: Case study of the 2011 Tohokuoki event, J. Geophys. Res. Space Physics, 118, doi:10.1002/jgra.50556.

Babeyko, A. Y., Hoechner, A., and Sobolev, S. V. (2010), Source modeling and inversion with near real-time GPS: a GITEWS perspective for Indonesia, Nat. Hazards Earth Syst. Sci. 10, 1617-1627, doi: 10.5194/nhess-10-1617-2010.

Babeyko, A.Y., (2017), GTEWS 2017 Workshop presentation, https://www.dropbox.com/s/a05koes8q747s9g/2C-GTEWS2017Babeyko.pptx?dl=0

Behrens, J., Androsov, A., Babeyko, A. Y., Harig, S., Klaschka, F., Mentrup, L. (2010), A new multi-sensor approach to simulation assisted tsunami early warning, Nat. Hazards Earth Syst. Sci. 10, 1085-1100, doi:10.5194/nhess-10-1085-2010.

Benedetti, E., Branzanti, M., Biagi, L., Colosimo, G., Mazzoni, A., Crespi M. (2014). Global navigation satellite systems seismology for the 2012 Mw 6.1 Emilia earthquake: Exploiting the VADASE algorithm, Seismological Research Letters, Volume 85, Issue 3, May-June 2014, Pages 649-656, doi:10.1785/0220130094.

Blewitt, G., C. Kreemer, W. C. Hammond, H.-P. Plag, S. Stein, and E. Okal, Rapid determination of earthquake magnitude using GPS for tsunami warning systems (2006), Geophys. Res. Lett., 33, L11309, doi:10.1029/ 2006GL026145.

Blewitt, G., W. C. Hammond, C. Kreemer, H. P. Plag, S. Stein, and E. Okal (2009), GPS for real-time earthquake source determination and tsunami warning systems, J. Geod., 83, 335–343, doi:10.1007/ s00190-008-0262-5.

Bock, Y., D. Melgar, B. W. Crowell (2011), Real-Time Strong-Motion Broadband Displacements from Collocated GPS and Accelerometers, Bull. Seismol. Soc. Am., 101, 2904-2925, doi: 10.1785/0120110007.

Branzanti, M., G. Colosimo, M. Crespi, and A. Mazzoni (2013). GPS near-real-time coseismic displacements for the great Tohoku-oki earthquake, IEEE Geosci. Remote Sens. Lett. 10, 372376, doi:10.1109/LGRS.2012.2207704.

Calais, E., and J.B. Minster (1995), GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, Geophys. Res. Lett., 22, 1045-1048, 10.1029/95GL00168.

Colosimo, G., M. Crespi, and A. Mazzoni (2011), Real-time GPS seismology with a stand-alone receiver: A preliminary feasibility demonstration, J. Geophys. Res, 116, B11302, doi: 10.1029/2010jB007941.

Crowell, B. W, Y. Bock, D. Melgar, (2012), Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment, Geophys. Res. Lett., 39, L09305.

Crowell B. W., D. Melgar, Y. Bock, J. S. Haase, and J. Geng (2013), Earthquake magnitude scaling using seismogeodetic data, Geophys. Res. Lett., 40, 1-6. doi:10.1022/2003GL058391.

D'Anastasio E., (2017), GTEWS 2017, https://www.dropbox.com/s/bjhjqth269frqcb/6A-GTEWS%202017%20D%27Anastasio.mp4?dl=0

Dawson, J., (2017), GTEWS 2017, https://www.dropbox.com/s/ygmhno43rvwvw70/6B-GTEWS2017%20Dawson.mp4?dl=0

Delouis, B., et al (2010), Slip distribution of the February 27, 2010 Mw= 8.8 Maule earthquake, central Chile, from static and high-rate GPS, InSAR, and broadband teleseismic data, Geophysical Research Letters 37(17).

Duputel, Z., L. Rivera, H. Kanamori, G. Hayes, B. Hirschhorn, S. Weinstein (2011). "Real-time W phase inversion during the 2011 off the Pacific coast of Tohoku Earthquake." Earth, Planets and Space 63(7): 535-539.

Falck, C., Ramatschi, M., Subarya, C., Bartsch, M., Merx, A., Hoeberechts, J., and Schmidt, G. (2010). Near real-time GPS applications for tsunami early warning systems, Nat. Hazards Earth Syst. Sci., 10, 181–189, doi:10.5194/nhess-10-181-2010.

Fratarcangeli F. M. Ravanelli, A. Mazzoni, G. Colosimo, E. Benedetti, M. Branzanti, G. Savastano, O. Verkhoglyadova, A. Komjathy, M. Crespi (2018). The variometric approach to real-time high-frequency geodesy. Rendiconti Lincei Scienze Fisiche e Naturali https://doi.org/10.1007/s12210-018-0708-5.

Fritz, H. M., C. Petroff, P. Catala, R, Cienfuegos, P. Winckler, N. Kalligeris, R. Weiss, S. Barrientos, G. Meneses, C. Valderas-Bermejo, C. Ebeling, A. Papadopoulos, M. Contreras, R. Almar, J.C. Dominquez, C. Synolakisi (2011). "Field survey of the 27 February 2010 Chile tsunami." Pure and applied Geophysics 168(11): 1989-2010.

Galvan, D. A., A. Komjathy, M. P. Hickey, and A. J. Mannucci (2011), "The 2009 Samoa and 2010 Chile tsunamis as observed in the ionosphere using GPS total electron content." J. of Geophys. Res. Space Physics, (116). A06,318, 10.1029/2010JA016204.

Galvan, D. A., A. Komjathy, M. Hickey, P. Stephens, J. B. Snively, T. Song, M. Butala, and A. J. Mannucci (2012), Ionospheric signatures of Tohoku-Oki Tsunami of March 11, 2011: Model comparisons near the epicenter, Radio Science, 47(RS4003).

Geng, J., D. Melgar, Y. Bock, E. Pantoli, and J. Restrepo (2013a), Recovering coseismic point ground tilts from collocated high-rate GPS and accelerometers, Geophys. Res. Lett., 40. doi:10.1002/grl.51001

Geng, J., Y. Bock, D. Melgar, B. W. Crowell, and J. S. Haase (2013b), A seismogeodetic approach applied to GPS and accelerometer observations of the 2012 Brawley seismic swarm: Implications for earthquake early warning, Geochem. Geophys. Geosyst., 14. doi:10.1002/ggge.20144

Geng J, Jiang P, Liu J (2017) Integrating GPS with GLONASS for high rate seismogeodesy. *Geophys. Res. Lett.* **44**, 3139-3146. doi:10.1002/2017GL072808

Geng J, Pan Y, Li X, Guo J, Liu J, Chen X, Zhang Y (2018) Noise characteristics of high-rate multi-GNSS for subdaily crustal deformation monitoring. *J. Geophys. Res.* 123, doi:10.1002/2018JB015527.

GAO (2006), GAO-06-519 U.S. Tsunami preparedness, United States Government Accountability Office report, June

(2006).

Gusiakov, V., P. Dunbar, L. Kong, 2015, Historical Mega-Tsunamis in the World Ocean and Their Implication for Coastal Hazard Assessment, IUGG General Assembly, Prague.

Hammond, W. C., B. A. Brooks, R. Bürgmann, T. Heaton, M. Jackson, A. R. Lowry and S. Anandakrishnan (2011), Scientific Value of Real-Time Global Positioning System Data, Eos, Transactions American Geophysical Union, Volume 92, Issue 15, pages 125–126, 12 April (http://onlinelibrary.wiley.com/doi/10.1029/2011EO150001/abstract

Hayashi, T. (2012). "Japan's Post-Disaster Economic Reconstruction: From Kobe to Tohoku." Asian Economic Journal 26(3): 189-210.

Hayes, G. P., P.S. Earle, H.M. Benz, D.J. Wald, R.W. Briggs (2011). "88 Hours: The US Geological Survey National Earthquake Information Center Response to the 11 March 2011 Mw 9.0 Tohoku Earthquake." Seismological Research Letters 82(4): 481-493.

Hickey, M. P., G. Schubert, and R. L. Walterscheid (2009), Propagation of tsunami-driven gravity waves into the thermosphere and ionosphere, J. Geophys. Res., 114, A08304, doi:10.1029/2009JA014105.

Hoechner, A., Babeyko, A.Y. and Sobolev, S.V. (2008). Enhanced GPS inversion technique applied to the 2004 Sumatra earthquake and tsunami. Geophys. Res. Lett. 35, L08310, doi:10.1029/2007GL033133.

Hoechner, A., Ge, M., Babeyko, A. Y., and Sobolev, S. V. (2013). Instant tsunami early warning based on real-time GPS – Tohoku 2011 case study, Nat. Hazards Earth Syst. Sci. 13, 1285-1292, doi: 10.5194/nhess-13-1285-2013.

Hoshiba, M., Kamigaichi, O., Saito, O., Tsukada, S. and Hamada, N. (2008). Earthquake early warning starts nationwide in Japan, *EOS Trans*, *AGU*, **89**, 73-74.

Hoshiba, M., Ohtake, K., Iwakiri, K., Aketagawa, T., Nakamura, H. and Yamamoto, S. (2010). How precisely can we anticipate seismic intensities? A study of uncertainty of anticipated seismic intensities for the Earthquake Early Warning method in Japan, *Earth Planets Space*, **62**, 611-620.

Hoshiba, M., Iwakiri, K., Hayashimoto, N., Shimoyama, T., Hirano, K., Yamada, Y., Ishigaki, Y. and Kikuta H. (2011). Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_W 9.0) —Earthquake Early Warning and observed seismic intensity—, *Earth Plants Spaces*, **63**, 547-551.

Hoshiba, M. and Ozaki, T. (2012). Earthquake Early Warning and Tsunami warning of JMA of the 2011 off the Pacific coast of Tohoku Earthquake (in Japanese), *Zisin 2*. **64**, 155-168.

Hoshiba, M. and T. Ozaki (2014). Earthquake Early Warning and Tsunami Warning of the Japan Meteorological Agency, and Their Performance in the 2011 off the Pacific Coast of Tohoku Earthquake (Mw 9.0). Early Warning for Geological Disasters, Springer: 1-28.

Huai Z., Y. Shi, D. A. Yuen, Z. Yan, X, Yuan, C. Zhang, 2008. Modeling and Visualization of Tsunamis, Pure and Applied Geophysics, 165, 475–496, DOI 10.1007/s00024-008-0324-x

IGSMAIL-6358 (2011). Magnitude 8.8 earthquake offshore of Japan - Preliminary computation of GPS displacement waveforms at MIZU and USUD, https://lists.igs.org/pipermail/igsmail/2011/000192.html

Ishii, M., P.M. Shearer, H. Houston, J.E. Vidale, (2005), Extent, duration and speed of the 2004 Sumatra–Andaman earthquake imaged by the Hi-Net array, Nature 435(7044): 933-936.

Kanamori, H., L. Riviera, 2008, Source inversion of W phase: speeding up seismic tsunami warning, Geophys.Jour. Int., V.175, n .1, pp 222-23 8, https://doi.org/10.1111/j.1365-246X.2008.03887.x .

Katsumata, A., Ueno, H., Aoki, S., Yasushiro, Y and S. Barrientos, Rapid magnitude determination from peak amplitudes at local stations, Earth. Planets Space, 65, 843-853 (2013).

Kelley, M. C., R. Livingston, and M. McCready (1985), Large amplitude thermospheric oscillations induced by an earthquake, Geophys. Res. Lett., 12, 577–580, 10.1029/GL012i009p00577.

Kherani, E.A., P. Lognonné, H. Hébert, L. Rolland, E. Astafyeva, G. Occhipinti, P. Coïsson, D. Walwer, E. R. de Paula, 2012, Modelling of the total electronic content and magnetic field anomalies generated by the 2011 Tohoku-Oki tsunami and associated acoustic-gravity waves, *Geophysical Journal International*, Volume 191, Issue 3, 1 December 2012, Pages 1049–1066,https://doi.org/10.1111/j.1365-246X.2012.05617.x

Komjathy, A., R.B. Langley, and F. Vejrazka (1996). "Assessment of Two Methods to Provide Ionospheric Range Error Corrections for Single-frequency GPS Users." In GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications, the Proceedings of International Association of Geodesy Symposium, No. 115, Boulder, CO, 3-4 July 1995, Springer-Verlag, New York, pp. 253-257.

Komjathy, A., D.A. Galvan, P. Stephens, M.D. Butala, V. Akopian, B.D. Wilson, O. Verkhoglyadova, A.J. Mannucci, and M. Hickey (2012). "Detecting Ionospheric TEC Perturbations Caused by Natural Hazards Using a Global Network of GPS Receivers: the Tohoku Case Study." Earth, Planets and Space, Special Issue on "The 2011 Tohoku Earthquake" Vol. 64, pp. 1287–1294, 2012, doi:10.5047/eps.2012.08.003.

Komjathy, A., T. Song, and A. Buis (2013), "Drop in the Ocean: Data from the Global Differential GPS network can predict the size of tsunami." Meteorological Technology International, pp. 20-21. April 2013.

Komjathy, A., Y-M Yang, X. Meng, O. Verkhoglyadova, A.J. Mannucci and R.B. Langley (2015). "Recent Developments in Understanding Natural-Hazards-Generated TEC Perturbations: Measurements and Modeling Results." In the Proceedings of the 2015 Ionospheric Effects Symposium, Alexandria, VA, May 12-14 (Best Paper Award).

Komjathy, A., Y.-M. Yang, X. Meng, O. Verkhoglyadova, A. J. Mannucci, and R. B. Langley (2016), Review and perspectives: Understanding natural-hazards-generated ionospheric perturbations using GPS measurements and coupled modeling, Radio Sci., 51, doi:10.1002/2015RS005910.

Lay, T., H. Kanamori, C. Ammon, M. Nettles, S. Ward, R. Aster, S. Beck, S. Bilek, M. Brudzinski, R. Butler, H.R. DeShon, G. Ekstrom, K. Satake, S. Sipkin (2005). "The great Sumatra-Andaman earthquake of 26 December 2004." Science 308(5725): 1127-1133.

Lay, T., C. Ammon, H. Kanamori, K. Koper, O. Sufri and A. Hutko (2010). "Teleseismic inversion for rupture process of the 27 February 2010 Chile (Mw 8.8) earthquake." Geophysical Research Letters 37(13).

Lay, T. and H. Kanamori (2011). "Japan earthquake." Phys. Today 64(12): 33.

Liu, J. Y., C. H. Chen, C. H. Lin, H. F. Tsai, C. H. Chen and M. Kamogawa, M. (2011), Ionospheric disturbances triggered by the 11 March 2011 M9.0 Tohoku earthquake, J. Geophys. Res., 116, A06319, doi:10.1029/2011JA016761.

Mai, C. L., and J.F. Kiang (2009), Modeling of ionospheric perturbation by 2004 Sumatra tsunami, Radio Sci., 44, RS3011, doi:10.1029/2008RS004060.

Melgar, D., Y. Bock and B. Crowell (2012), Real-time centroid moment tensor determination for large earthquakes from local and regional displacement records, Geophys. J. Int. doi: 10.1111/j.1365-246X.2011. 05297.x

Melgar, D and Y Bock, 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, 1-17.

Melgar, D., Y. Bock, D. Sanchez and B. W. Crowell (2013a), On robust and reliable automated baseline corrections for strong motion seismology, J. Geophys. Res., 118, 1–11. doi:10.1002/jgrb.50135

Melgar, D., B. W. Crowell, Y. Bock, and J. S. Haase (2013b), Rapid modeling of the 2011 Mw 9.0 Tohoku-oki earthquake with seismogeodesy, Geophys. Res. Lett., 40, 1-6. doi:10.1002/grl.50590

Melgar, D. and Y. Bock (2015), Kinematic earthquake source inversion and tsunami inundation prediction with regional geophysical data, J. Geophys. Res.-Solid Earth, 120:3324-3349. 10.1002/2014jb011832

Melgar, D., R.M Allen, S. Riquelme, J.H. Geng, F. Bravo, J.C. Baez, H. Parra, S. Barrientos, P. Fang, Y. Bock, M. Bevis, D.J. Caccamise, C. Vigny, M. Moreno, R. Smalley (2016), Local tsunami warnings: Perspectives from recent large events, Geophys. Res. Lett., 43, doi:10.1002/2015GL067100.

Melgar, D. 2017, GTEWS 2017, https://www.dropbox.com/s/pwl5frckqujhg7d/3E-GTEWS2017%20Melgar.mp4?dl=0

Meng, X., A. Komjathy, O. P. Verkhoglyadova, Y.-M. Yang, Y. Deng, and A. J. Mannucci (2015), A new physics-based modeling approach for tsunami-ionosphere coupling, Geophys. Res. Lett., 42, doi:10.1002/2015GL064610.

Meng, X., Verkhoglyadova, O. P., Komjathy, A., Savastano, G., & Mannucci, A. J. (2018). Physics-based modeling of earthquake-induced ionospheric disturbances. Journal of Geophysical Research: Space Physics, 123, 8021–8038. https://doi.org/ 10.1029/2018JA025253

Minson, S., J. Murray, J.O. Langbein, J.S. Gomberg, (2014), Real-time inversions for finite fault slip models and rupture geometry based on high-rate GPS data, Journal of Geophysical Research: Solid Earth 119(4): 3201-3231.

Mori, N., T. Takahashi, The 2011 Tohoku Earthquake Tsunami Joint Survey Group (2012), Nationwide post event survey and analysis of the 2011 Tohoku earthquake tsunami, Coastal Engineering Journal 54(01) https://doi.org/10.1142/S0578563412500015

Mungov, G., et al (2012), DART® Tsunameter Retrospective and Real-Time Data: A Reflection on 10 Years of Processing in Support of Tsunami Research and Operations, Pure and applied Geophysics: 1-16.

NASA release (2010), http://www.nasa.gov/topics/earth/features/tsunami_prediction.html

Occhipinti, G., P. Lognonné, E. A. Kherani, and H. Hebert (2006), Three-dimensional waveform modeling of ionospheric signature induced by the 2004 Sumatra tsunami, Geophys. Res. Lett., 33, L20104, doi:10.1029/2006GL026865.

Occhipinti, G., E. A. Kherani, and P. Lognonné (2008), Geomagnetic dependence of ionospheric disturbances induced by tsunamigenic internal gravity waves, Geophys. J. Int., 173, 753–765, doi:10.1111/j.1365-246X.2008.03760. x.

Occhipinti, G., P. Coisson, J. Makela, S. Allgeyer, A. Kherani, H. Hebert, and P. Lognonné (2011), Three-dimensional numerical modeling of tsunami-related internal gravity waves in the Hawaiian atmosphere, Earth Planets Space, 63(7), 847–851, doi:10.5047/eps.2011.06.051.

Occhipinti, G., L. Rolland, P. Lognonné, S. Watada, From Sumatra 2004 to Tohoku-Oki 2011: The systematic GPS detection of the ionospheric signature induced by tsunamigenic earthquakes, 2013, J. Geophys. Res., 118, doi:10.1002/jgra.50322.

Occhipinti, G., The Seismology of the Planet Mongo: The 2015 Ionospheric Seismology Review, AGU Books, Subduction Dynamics: From Mantle to Mega Disasters, 2015. Editors: G. Morra, D. A. Yuen, S. King, S. M. Lee, S. Stein, ISBN 978-1-118-88885-8.

Ohta, Y., T. Kobayashi, H. Tsushima, S. Miura, R. Hino, T. Takasu, H. Fujimoto, T. Inuma, K. Tachibana, T. Demachi, T. Sato, M. Ohzono, N. Umino, (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., doi:10.1029/ 2011JB008750.

Ohta Y., T. Inoue, S. Koshimura, S. Kawamoto, and R. Hino, Role of real-time GNSS in near-field tsunami forecasting (2018), J. Disaster Res.,13, No.3.

Ozaki, T. (2011). "Outline of the 2011 off the Pacific coast of Tohoku Earthquake (Mw9.0)-Tsunami warnings/advisories and observations." Earth, planets and space 63(7): 827-830.

Paris, R., P. Wassmer, J. Sartohadi, F. Lavigne, B. Barthomeuf, E. Desgages, D. Grancher, P. Baumert, F. Vautier, D. Brunstein, C, Gomez (2009). "Tsunamis as geomorphic crises: lessons from the December 26, 2004 tsunami in Lhok Nga, west Banda Aceh (Sumatra, Indonesia)." Geomorphology 104(1): 59-72.

Parker, J., C. Norton and G Lyzenga, Parallel GeoFEST for faulted deformation, Concurrency Comp., 22, 1604-1625 (2010)

Peltier, W. R., and C. O. Hines (1976), On the possible detection of tsunamis by a monitoring of the ionosphere, J. Geophys. Res., 81(12), 1995–2000, doi:10.1029/JC081i012p01995.

Pollitz, F. F., (2012) ViscoSim earthquake simulator, Seismol. Res. Lett. 83, 979–982

Rakoto, V., P. Lognonné, L. Roland, P. Coisson, 2018, Tsunami Wave Height Estimation from GPS-Derived Ionospheric Data, Jour. Geophys. Res., pp. 4329-4348, doi:10.1002/2017JA024654

Richards-Dinger, K., and J. H. Dieterich, (2012). RSQSim earthquake simulator, Seismol. Res. Lett. 83, 983–990.

Ridley, A. J., Y. Deng, and G. Toth (2006), The global ionosphere-thermosphere model, J. Atmos. Sol.-Terr. Phys., 68, 839–864, doi: 10.1016/j.jastp.2006.01.008.

Riquelme, S., F. Bravo, D. Melgar, R. Benavente, J. Geng, S. Barrientos, and J. Campos (2016), W-phase source inversion using high-rate regional GPS data for large earthquakes, Geophys. Res.Lett., 43, 3178-3185, doi:10.1002/2016GL068302

Rolland, L., G. Occhipinti, P. Lognonné, and A. Loevenbruck, (2010), The 29 September 2009 Samoan tsunami in the ionosphere detected offshore Hawaii, Geophys. Res. Lett., 37, L17191 doi: 10.1029/2010GL044479.

Rolland, L. M., P. Lognonné, E. Astafyeva, E. A Kherani, N. Kobayashi, M. Mann, and H. Munekane (2011), The resonant response of the ionosphere imaged after the 2011 off the Pacific coast of Tohoku Earthquake, Earth Planets Space, 63, 853–857.

Rundle, J.B., A physical model for earthquakes: 2. Application to southern California, (1988), J. Geophys. Res., 93, 6255 - 6274.

Rundle, PB, JB Rundle, KF Tiampo, J.S. S. Martins, S. McGinnis, W. Klein, (2001) Nonlinear network dynamics on earthquake fault systems, Phys. Rev. Lett., 87, 148501.

Rundle, JB, PB Rundle, W Klein, J Martins, KF Tiampo, A Donnellan and LH Kellogg, (2002) GEM plate boundary simulations for the Plate Boundary Observatory: Understanding the physics of earthquakes on complex fault systems, PAGEOPH, 159, 2357-2381

Rundle, PB, J.B. Rundle, K.F. Tiampo, A. Donnellan and D.L. Turcotte, Virtual California: Fault model, frictional parameters, applications, PAGEOPH, 163, 1819-1846 (2006) doi 10.1007/s00024-006-0099-x.

Sachs, M. K., M. B. Yikilmaz, E. M. Heien, J. B. Rundle, D. L. Turcotte, and L. H. Kellogg, (2012), Virtual California earthquake simulator, Seismol. Res. Lett., 83, 973–978

Satake, K and Y Tanioka, (1995) Tsunami generation of the 1993 Hokkaido-Nansei-Oki earthquake, Pure Appl. Geophys., 145, 803-821

Savastano, G., Komjathy, A., Verkhoglyadova O., Mazzoni A., Crespi M., Wei Y., Mannucci A. (2017). Real-Time Detection of Tsunami Ionospheric Disturbances with a Stand-Alone GNSS Receiver: A Preliminary Feasibility Demonstration, Scientific Reports 7, Article number: 46607, doi:10.1038/srep46607.

Simons, M., S. Minson, A. Sladen, F Ortega, J. Jiang, S. Owen, L. Meng, J-P. Ampuero, S. Wei, R. Chu, D. Helmberger, K. Kanamori, E. Hetland, A.W. Moore, F. Webb (2011). "The 2011 magnitude 9.0 Tohoku-Oki earthquake: Mosaicking the megathrust from seconds to centuries." Science 332(6036): 1421-1425.

Sobolev, S. V., Babeyko, A. Y., 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.

Sobolev, S., A. Babeyko, A., R. Wang, A. Hoechner, R. Galas, M. Rothacher, D. V. Sein, J. Schroter, J. Lauterjung, C. Subarya, (2007), Tsunami early warning using GPS-Shield arrays, *Jour. Geophys. Res*., v. 112, B08415, doi:10.1029/2006JB004640.

Song, Y. T., C. Ji, L.-L. Fu, V. Zlotnicki, C.K. Shum, Y. Yi, and V. Hjorleifsdottir (2005), The 26 December 2004 Tsunami Source Estimated from Satellite Radar Altimetry and Seismic Waves, *Geophys. Res. Lett.*, **23**, doi:10.1029/2005GL023683.

Song, Y. T. (2007), Detecting tsunami genesis and scales directly from coastal GPS stations, Geophys. Res. Lett., 34, L19602, doi:10.1029/2007GL031681.

Song, Y. T., I. Fukumori, C. K. Shum, and Y. Yi (2012), Merging tsunamis of the 2011 Tohoku-Oki earthquake detected over the open ocean, Geophys. Res. Lett., doi:10.1029/2011GL050767 (Nature Highlights, March 8, 2012).

Stein, S. and E. A. Okal (2005). "Seismology: Speed and size of the Sumatra earthquake." Nature 434(7033): 581-582.

Subarya, C., L. Prawirodirdio, J-P. Avouac, Y. Bock, K. Sieh, A.J. Meltzner, D.H. Natawidjaja, R. McCaffrey (2006).

"Plate-boundary deformation associated with the great Sumatra–Andaman earthquake." Nature 440(7080): 46-51.

Tanioka, Y. and K. Satake, 1996, Tsunami generation by horizontal displacement of ocean bottom, Geophys. Res. Letts., Volume 23, Issue 8 https://doi.org/10.1029/96GL00736

Tatehata, H, (1997), In Perspectives on Tsunami Hazard Reduction, volume 9 of Advances in Natural and Technological Hazards Research, pages 175–188. Springer Netherlands, ISBN 978-90-481-4938-4.

Tatehata, H. (1997). “The new tsunami warning system of the Japan Meteorological Agency.” Perspectives on Tsunami Hazard Reduction, Springer: 175-188.

Thomas J. and R. Hughes and Englewood Cliffs, (1987) The finite element method: linear static and dynamic finite element analysis, NJ: Prentice-Hall, (1987).

Titov, V.V. and F.I. Gonzalez, (1997) Implementation and Testing of the Method of Splitting Tsunami (MOST) Model, NOAA Tech. Mem. ERL PMEL-12.

Titov, V., Y. T. Song, L. Tang, E. N. Bernard, Y. Bar-Sever, and Y. Wei (2016), Consistent estimates of tsunami energy show promise for improved early warning, Pur Appl. Geophs., DOI: 10.1007/s00024-016-1312-1.

Vadas, S. L., and M. J. Nicolls (2012), The phases and amplitudes of gravity waves propagating and dissipating in the thermosphere: Theory, J. Geophys. Res., 117, A05322, doi:10.1029/2011JA017426.

Van Aalsburg, J., L. B. Grant, G Yakovlev, P. B. Rundle, J. B. Rundle, D.L. Turcotte and Andrea Donnellan, (2007), A feasibility study of data assimilation in numerical simulations of earthquake fault systems, Phys. Earth. Planet. Int., 163, 149-162

Wang, J, Steven N. Ward, and Lili Xiao. (2015a) Numerical simulation of the December 4, 2007 landslide- generated tsunami in Chehalis lake, Canada. Geophysical Journal International, 201(1):372–376, DOI: 10.1093/gji/ggv026.

Wang, J, Steven N. Ward, and Lili Xiao. (2015b), Numerical modelling of rapid, flow-like landslides across 3-d terrains: a tsunami squares approach to el picacho landslide, El Salvador, September 19, 1982. Geophysical Journal International, 201(3):1534–1544, DOI: 10.1093/gji/ggv095.

Ward, S. N., (2012) ALLCAL earthquake simulator, Seismol. Res. Lett. 83, 964–972

Williamson, A. L., A. V. Newman, P. R. Cummins (2017), Reconstruction of coseismic slip from the 2015 Illapel earthquake using combined geodetic and tsunami waveform data, J. Geophys. Res. Solid Earth, 122, JGRB51991, 2119-2130, doi: 10.1002/2016JB013883.

Williamson, A. L., and A. V. Newman (2018), Suitability of Open-Ocean Instrumentation for use in near-field tsunami early warning along seismically active subduction zones, Pure Appl. Geophys., 1-16, doi:10.1007/s00024-018-1898-6.

Wright, T.J., Houlie, N., Hildyard, M and T. Iwabuchi, (2012) Real-time, reliable magnitudes for large earthquakes from 1 Hz GPS precise point positioning: The 2011 Tohoku-Oki (Japan) earthquake, Geophys. Res. Lett., 39, L12302, dui: 10.1029/2012/GL051894.

Xiao, L, Steven N. Ward, and Jiajia Wang, (2015) Tsunami squares approach to landslide-generated waves: Application to Gongjiafang landslide, Three Gorges Reservoir, China. Pure and Applied Geophysics, 172(12):3639–3654. doi: 10.1007/s00024-015-1045-6.

Xu, Z. and Y. T. Song, (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. Oceanic Tech., http://dx.doi.org/10.1175/JTECH-D-12-00201.1.

Yikilmaz, MB, DL Turcotte, G. Yakovlev, JB Rundle and LH Kellogg, (2010). Virtual California earthquake simulations: Simple models and their application to an observed sequence of earthquakes, Geophys. J. Int., 180, 734-742 DOI: 10.1111/j.1365-246X.2009. 04435.x

Yuen, P. C., P. F. Weaver, and R. K. Suzuki (1969), Continuous, traveling coupling between seismic waves and the ionosphere evident in May 1968 Japan earthquake data, J. Geophys. Res., 74, 2256– 2264.

Zettergren, M.D., J.B. Snively, (2018), Latitude and Longitude Dependence of Ionospheric TEC and Magnetic Perturbations from Infrasonic-Acoustic Waves Generated by Strong Seismic Events, Geophys. Res., V. 46, pp:1121-1888, **https://doi.org/10.1029/2018GL081569**

Zumberge, J.F., M. B. Heflin, D.C. Jefferson, M. M. Watkins, and F. H. Webb, (1997), Precise point positioning for the efficient and robust analysis of GPS data from large networks, Geophys. Res., V. 102, n. B3, pp. 5005-5017.

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