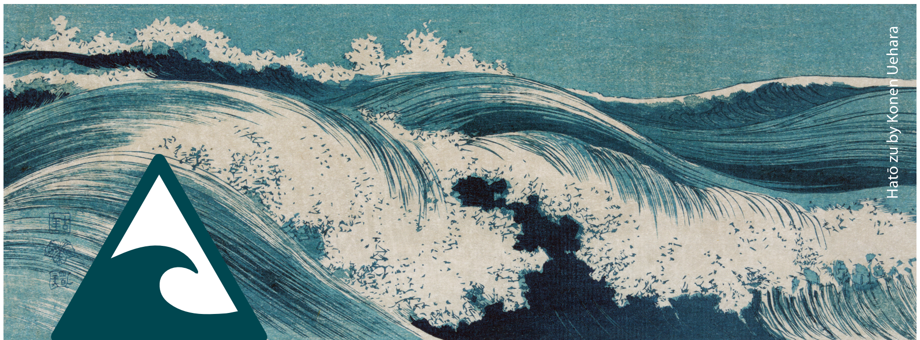

Global Navigation Satellite System to Enhance Tsunami Early Warning Systems

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Content:

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. This devastating loss of life focused the efforts of scientists, engineers and politicians to strengthen tsunami early warning systems beginning with an accurate and rapid estimate 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 at risk communities nearest the earthquake epicenter. In the months following the Great Indian Ocean Tsunami, geophysicists demonstrated that analysis the GPS network of the Global Geodetic Observing System could have provided warning within 15 minutes after the Sumatran earthquake ***if the network data were available in real time.***

Figure 1: Tourists on the beach at Phuket Island, Thailand becoming aware of the approaching Great Indian Ocean tsunami.

On March 11, 2011, the Tohoku-oki earthquake and tsunami unleashed another terrible tragedy upon the Japanese people and posed great challenges to the Japanese government. The Tohoku-oki earthquake occurred off shore from the world's most advanced GPS network, the GEONET, designed and operated by The Geospatial Information Authority of Japan (GSI). The Tohoku-oki earthquake did underscore the potential and extraordinary societal value of **Global Navigation Satellite Systems (GNSS)** to tsunami warning systems. Several retrospective studies of the Tohoku-oki earthquake deformation 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

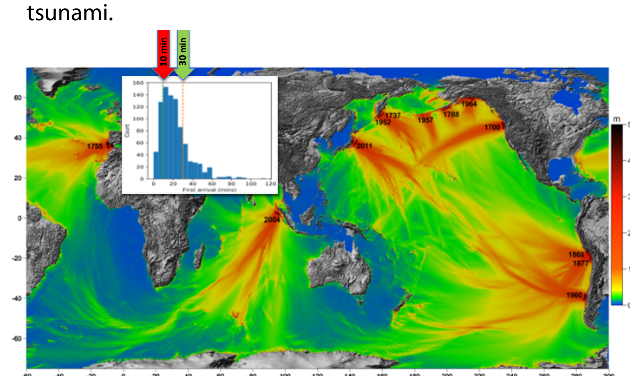

Figure 2: Distribution of historic global tsunamis and their propagation paths. (Gusiakov et al, 2015). Chart portrays distribution of minimum tsunami runup time for Indo-Pacific coasts. (Melgar, 2017).

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 analysis also demonstrated the value of GNSS ionospheric disturbance imaging to verify the generation and propagation of the tsunami.

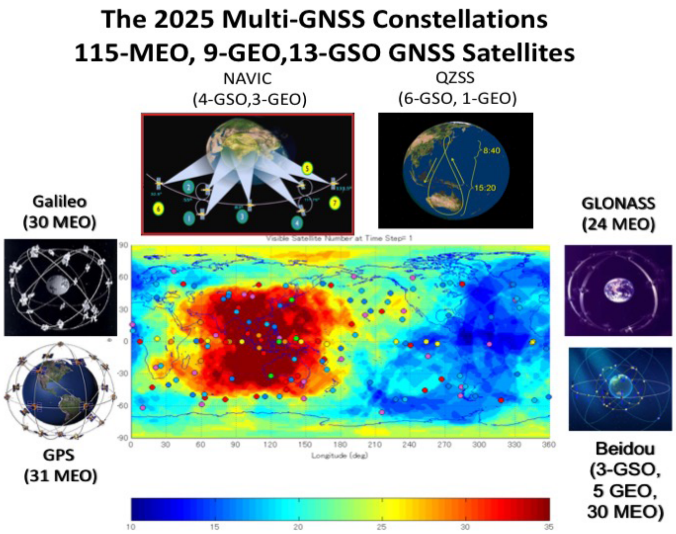

Figure 3: Center illustration displays expected all in view GNSS satellites for the Indo-Pacific. The Red of the Western Indo-Pacific will see about 40 satellites at any time. Courtesy J. Dawson

The adoption of GNSS Tsunami Early Warning (GTEWS) has been agonizingly slow despite robust scientific advances and demonstrations of its utility. Thousands of lives have been lost to tsunami disasters in the 14 or more years since Great Indian Ocean Tsunami of December 26, 2004. To encourage development, 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. The IUGG 2015 *Resolution #4* also recommended that this initiative should be focused upon the Indo-Pacific region that is at greatest risk of tsunami disaster.

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 GTEWS 2017 workshop is aligned with the goals and priorities the **UNISDR Sendai Framework for Disaster Risk Reduction 2015-2030** (*https://www.unisdr.org/we/coordinate/sendai-framework*). The recommendations of 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 are listed in the final section of this report and 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 disaster warnings for a clearer understanding of impending disaster risk. More rapid accurate information will also improve 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 a GNSS Shield consortium that will share development strategies and information to better understand and prepare for tsunami disasters. This GNSS Shield consortium of both research and operation 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 Generation 4 or better broadband coverage for 100% of tsunami prone territories to enable real time GNSS network deployment in remote regions.
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.

GTEWS is enabled by the 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 over the more active earthquake and tsunami source 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 applications (Figure 4). GTEWS benefit from 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 a strengthened economic vitality through the supporting improvements of communications, positioning, and timing as well as being a wonderful way to benefit from international investments.

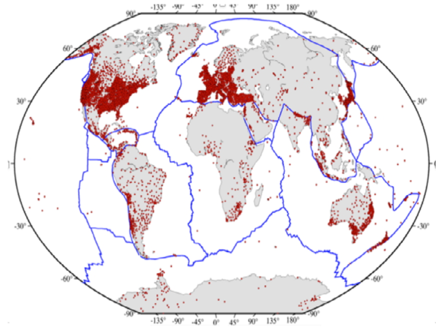

Figure 4: 16,000 GNSS receivers provide publicly available data though only about 10% are available in real time.

GTEWS 2017 Program: The two day GTEWS 2017 workshop included reviews of the geophysics of mega-thrust earthquakes, the principles of GNSS positioning and GTEWS techniques to utilizing GNSS displacement and ionospheric imaging. 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. **Recordings of the GTEWS2017 workshop presentations and discussions are available at** *https://www.dropbox.com/s/e53sksa7q9z8dkl/2017%20GTEWS%20Program.pdf?dl=0*.

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. There are also many Indo-Pacific earthquakes that do not generate tsunamis. Tsunami warning based upon shaking or earthquake magnitude can be fast but its limited accuracy can result in false alarms because earthquake magnitude is a measure of earthquake energy and not a reliable measure of the seafloor motion that generates a tsunami. Aside from instrumental vulnerabilities such as clipping, 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. Better resolution of seafloor displacement and sea surface displacement can 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 also 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) resulted in over 230,000 casualties. The greatest loss of life occurred 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 (Simmons 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 neighboring 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 M 7.2 was determined after 30 seconds and revised to M 8.0 after 107 seconds (Hoshiba et al., 2011). More accurate JMA and 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 refinements to the earthquake tsunami potential were 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.

GNSS measurements of ground displacement will 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 predicted the generation of a significant tsunami within 15 minutes of the Sumatra-Andaman earthquake. Blewitt et al. 2006 demonstrated that the ground displacement measured by the Asia-Pacific component of the Global Geodetic Observing System's GPS network could provide a rapid and accurate estimate of the earthquake's Mw9.2 magnitude.

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 numerical model from the observed displacement from these GPS observations near to the epicenter that closely resembled the tsunami measured by 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 the measurement accuracy of crustal displacement and the potential tsunami inundation. 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.

The Japanese GEONET, the world's most advanced GNSS ground network of 1200 GPS receivers, provided valuable observations of crustal and ionospheric disturbances resulting from the Tohoku-oki mega-thrust earthquake (Figure 5). Retrospective analysis of the GEONET measurements demonstrated that accurate earthquake fault models and tsunami predictions (Ohta et al., 2012; Song et al., 2012; Melgar et al., 2013b; Xu and Song, 2013; Hoechner et al. 2013, Melgar and Bock, 2013) could be issued within five minutes of the earthquake (Figure 6).

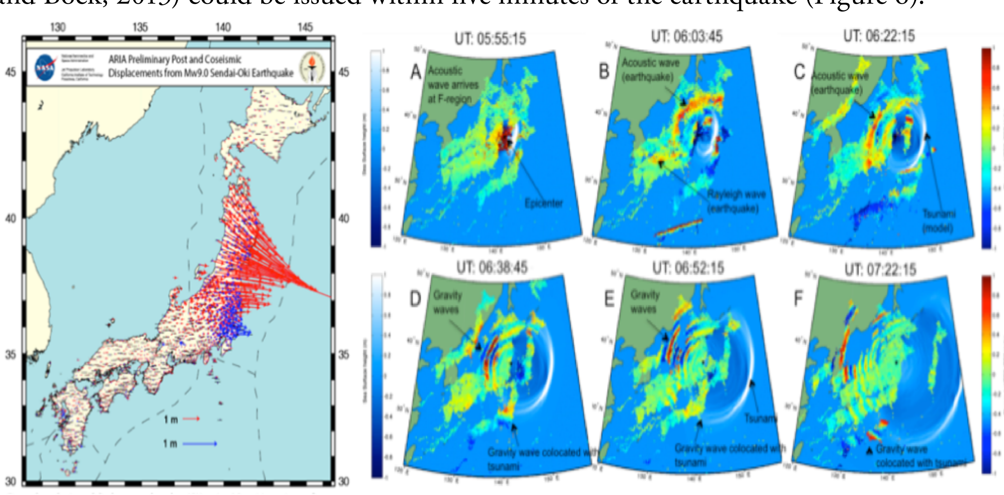

Figure 5: GTEWS Measurements by GEONET: Left: Static displacement of the main shock (Mw 9.0)-red and the aftershock (Mw 7.9)-blue. Right: Sequence of ionospheric imaging shows development and propagation of ionospheric TIDs. Note that the first ionospheric disturbance appears within 9 minutes of the main earthquake.

Tsunami Detection and Monitoring

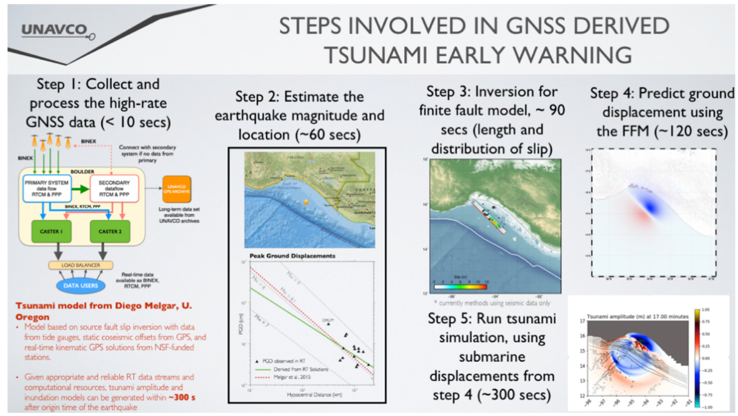

Figure 6: GTEWS analysis process to provide accurate tsunami warning in less than 5 minutes from earthquake occurrence.

GNSS measurements of ionospheric disturbance can also be used to verify the development and monitor the propagation of tsunamis away from the earthquake epicenter. GNSS measures the dispersion of its multifrequency signals to estimate Total Election Content (TEC) along the ray path from receiver to satellite to improve positioning accuracy. Low frequency variations in the TEC can arise from gravity waves known as Traveling Ionospheric Disturbance (TID) that propagate through the ionosphere away from the source. TIDs generated by acoustic pressure waves from long wave length ocean surface disturbances and measured by GNSS TEC imaging can provide both detection and tracking information to tsunami warning systems.

Acoustic coupling between ocean and ionosphere was described nearly fifty years ago by Peltier and Hines (1976). During those fifty years three-dimensional (3-D) time-dependent numerical models (Occhipinti et al., 2006, 2008, 2011; Vadas and Nicolls, 2012; Mai and Kiang, 2009) and a spectral full-wave model (Hickey et al., 2009) have been developed to better understand TIDs caused by tsunamis. The JPL Wave Perturbation – Global Ionosphere Thermosphere Model (WP-GITM) (Ridley et al., 2006, Meng et al. 2015) is a 3-D tsunami-ionosphere coupling model that implemented tsunami-induced gravity waves into the first-principles of the ionosphere and thermosphere dynamic models. WP-GITM will provide three dimensional representation of ionospheric TID in response to tsunami wave height, wave period, wavelength, and propagation direction. Artru et al. 2005a,2005b Yuen et al., 1969; Kelley et al., 1985; Calais and Minster, 1995; Komjathy et al., 2012; Liu et al.,2011, Savastano et al., 2017, Galvan et al., 2011, 2012; Komjathy et al., 2013, 2015 confirmed the utility of GNSS TID analysis for environmental monitoring including the detection of tsunamis.

GNSS ionospheric TID imaging can capture the effect of long wavelength ocean dynamics enabling a practical and cost effective means to verify tsunami generation and monitor tsunami propagation (Figure 7). The ray path from receiver to GNSS satellite pierces the region of maximum ionosphere ionization at about 350 km altitude referred to as an "ionospheric piercing point". The TEC measured along the ray path is assigned to the respective piercing point. In a sense, each piercing point could be viewed as a single pixel of an ionospheric disturbance. Each piercing point records the dynamics of the ocean surface directly beneath. Increasing the piercing point density provides a better image of the ionospheric disturbance and therefore the causative ocean surface disturbance. Furthermore, as the GNSS receiver receives signals from a satellite descending to lower elevations, the respective piercing point is responding to ocean dynamics hundreds of kilometers away from the receiver. Therefore, a GNSS receiver measuring tsunami generated TIDs can monitor a propagating tsunami hundreds of kilometers away.

Figure 5 (right panel) illustrates the imaging of TIDs generated by the Tohoku earthquake using the data measured by the GSI GEONET network. These GEONET images represent about 6000 piercing points for 1200 GEONET receivers and 5 GPS satellites (up to 8 satellites) at any one time. In the coming decade, 30 to 45 satellites will be in view for locations within the Indo-Pacific. The density of piercing points over the Japanese GEONET will increase to 36000 to 54000 broadly distributed piercing points. This enhanced piercing point density will provide a more uniform and higher resolution image of the development and propagation of future tsunamis.

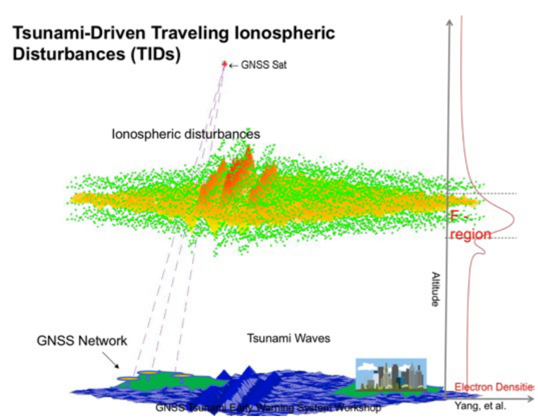

Figure 7: GNSS Traveling Ionospheric Disturbance (TID) measurement concept.

Inversion of TEC anomalies for a quantitative estimate of the sea-surface uplift forcing function could provide a valuable observation for the verification of tsunami generation following a large earthquake. Of special interest would be the first hour of the TEC disturbance because of its unique capability of providing near source tsunami warning. The ultimate goal is the quantitative estimation of tsunami wave height and initial water displacement to accurately predict tsunami runup. Accurate TEC inversion for tsunami wave height is very challenging because of the many variables that determine ionospheric response to the upward welling atmospheric pressure waves. Rakoto et al, 2018 recently reported that the inversion of ionospheric TIDs related to the 2012 Haida Gwaii, 2006 Kuril Islands, and 2011 Tohoku tsunami estimated wave heights to within 20% when compared to DART buoy measurements with poorest results from the Tohoku-oki tsunami due an ongoing space weather event. A TEC anomaly developed over the Tohoku-oki epicenter within 9 minutes of the earthquake occurrence time. A key question is whether these initial ionospheric disturbances can yield quantitative estimates of sea surface uplift resulting in the application of GNSS to tsunami verification and estimate. It is envisioned that the combination of ground-based GNSS and spaceborne ionospheric radio occultation measurements will provide us with high precision sea surface uplift estimates (Komjathy et al., 2016).

Until recently, real time Imaging of TID's was very challenging because the analysis must account for numerous uncertainties including receiver and satellite frequency related biases. A prototype real time TID imaging system was announced at the GTEWS 2017 workshop. The NASA/JPL GDGPS program and the Geodesy and Geomatics Division - University of Rome La Sapienza reported the initiation of real time GNSS ionospheric TID analysis using the VARION (**V**ariometric **A**pproach for **R**eal-Time **ION**osphere Observation) algorithm (Savastano et al., 2017). Real time TID monitoring information from this prototype system is available at *https://iono2la.gdgps.net/*.

GTEWS Requirements

Effective GTEWS enhancement to 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 communities nearest the earthquake epicenter. Depending upon the epicenter location, earthquake fault displacement and the bathymetry of the surrounding seafloor, a tsunami could arrive in within five to forty minutes of a nearby earthquake. A tsunami alert is issued if the earthquake epicenter is in the coastal zone and the estimated earthquake magnitude exceeds a set level (e.g. Mw7.5). We learned that seismic determination of earthquake magnitude is not a very reliable indicator of tsunami potential. GTEWS can be effectively integrated into a tsunami warning system by providing a more rapid and accurate estimate of earthquake magnitude through peak ground displacement and a rapid estimate of seafloor displacement critical to accurate estimates of tsunami wave height and arrival times.

GTEWS enhancement relies upon and augments the analysis systems that currently utilize seismic data for earthquake location, occurrence time and magnitude based upon data obtained from a network of broadband and strong motion seismometers. Tsunami warning systems refine their tsunami warnings with a database of pre-calculated responses to guide the issuance of public warnings including tsunami intensity estimates at predetermined locations along the coast. The systems constantly update their situational awareness and modify the choice of pre-conceived responses based upon additional seismic information, ocean bottom pressure sensors and tide gauges. The same procedures would be in place with GTEWS enhancement but the initial estimate of tsunami potential would be more accurate and detailed than a warning based on earthquake magnitude only. As more GNSS data becomes available within the few minutes of the earthquake finite fault displacement to estimate sea floor displacement, estimates of seafloor displacement derived from finite fault models will be used by tsunami models to estimate timing and tsunami wave heights. The enhanced system could utilize ionospheric imaging to provide continuing updates on tsunami potential and arrival times if an ocean bottom pressure network is not available.

Six to eight minutes after a major earthquake, the GTEWS ground network should detect the first ionospheric disturbance as TEC anomalies at piercing points. If there are a number of adjacent GNSS receivers over an area of 200-500 km, it should be possible to locate the earthquake epicenter and perhaps estimate the size of the initial sea surface displacement from the anomalous TEC values at the imaged piercing points. The TEC information can be used to verify the generation of a tsunami and refine tsunami warnings for communities nearest to the earthquake epicenter.

Thirty to fifty minutes following the earthquake occurrence the TID ionospheric imaging should begin to detect the propagating tsunami as it spreads from the earthquake epicenter. GNSS stations throughout the basin will detect and stimulate preparations for the approaching tsunami. The propagating tsunami will also be predicted based upon a projected travel time from ocean bottom pressure buoys (DART) and tsunami source models derived from observed or estimated seafloor displacement. The combined observations of GNSS and observations by DART buoys will significantly reduce false alarms for coastal communities in the far field from a major event.

- **GNSS Ground Networks:** GTEWS performance 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, lagging communications and associated 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 sufficient for the international exchange of amongst GNSS analysis centers via the global internet infrastructure. 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 Generation 4 cell phone networks are sufficient for GTEWS real time data transfer. Therefore, GTEWS implementation in developing economies could be a stimulus for extending 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 programs products should 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 Chilean National Seismic Network can achieve the integration without significant interagency effort because the geodetic capability 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 to issue public warnings. The incorporation of GTEWS products has been more challenging because the effort will interfere with agency 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 initial efforts is expected in early 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 were 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 for the imaging of TIDS for the prediction, detection and tracking of tsunamis. The networks also serve as effective building blocks from which we can begin the development of an Indo-Pacific network for GNSS Enhanced Tsunami Early Warning.

- **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.

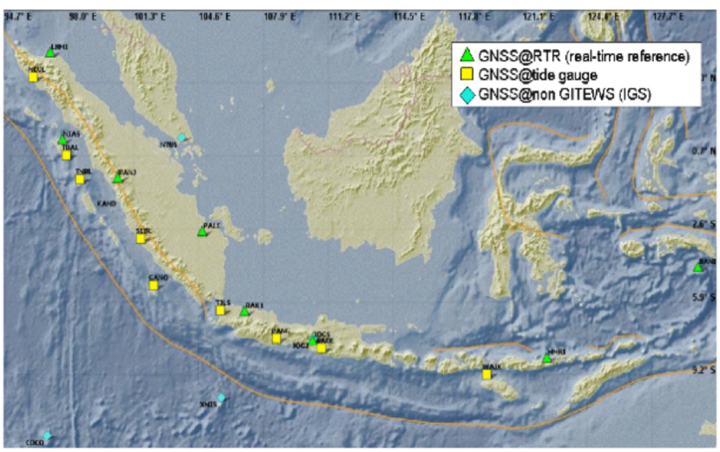

Figure 8: German-Indonesian Tsunami Early Warning System (GITEWS)

Sobolev et al. (2007) further proposed the establishment of a "GPS Shield" network for Indonesia and the Indo-Pacific with optimally positioned sets of GPS receivers along a transect perpendicular to the trench axis. The Babeyko, 2017 presentation to the workshop recommended that the GTEWS networks should optimize 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

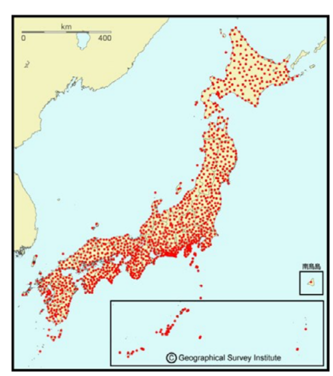

Figure 9: The Japanese GEONET

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. A limited number of GNSS stations are being streamed to select users such as GDGPS.

- **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). The READI program is supported by NASA while the network stations are supported by a number of US and Canadian agencies, states and commercial interests. Canadian agencies and the READI program share their real time network data. NASA funds real-time GPS analyses at UCSD's Scripps Institution of Oceanography (SIO), Central Washington University, ltech's Jet Propulsion Laboratory, California Institute of Technology and University of Nevada Reno. NSF's EarthScope project and Earth Sciences Infrastructure and Facilities supported seismo-geodetic upgrades of GPS stations by SIO and UNAVCO/PBO.

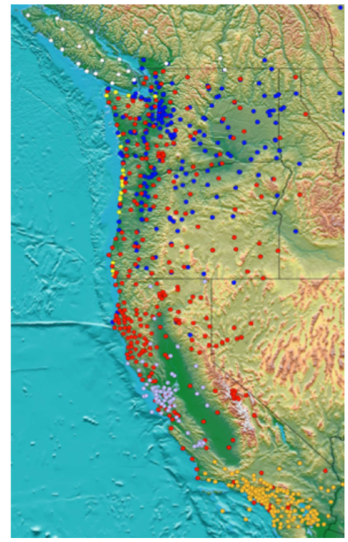

Figure 10: READI Network

  Upgrades of PBO and SCIGN/SIO stations include deployment of SIO Geodetic Modules and MEMS accelerometer packages at existing real-time GPS stations in southern California. READI employs three analysis centers to provide independent analysis of the displacement information and enhance robustness of the product. The centers employ MIT's GAMIT and NASA/JPL's GIPSY-OASIS software, using Precise Point Positioning and ambiguity resolution. The three centers also provide a unified analysis product. SOPAC computes real-time GPS satellite clocks and fractional-cycle biases for use in precise point positioning with ambiguity resolution using real-time data from GPS stations in North America (outside the zone of active tectonic deformation in the Western U.S. and British Columbia). JPL estimates GNSS orbit and clock parameters for its PPP calculation from the NASA/JPL GDGPS network. UCW utilizes orbit and clock parameter provided by the GFZ of Germany.

  The READI research group made considerable progress in a collaboration with the Pacific Tsunami Warning Center (PTWC) and the National Tsunami Warning Center (NTWC), encouraged by 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. The Canadian Western Canada Deformation Array (WCDA) shares its data with the US READI network.

- **Chilean National Seismic Network**. The network of the Centro Sismologico Nacional (CSN) consists of about 150 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.

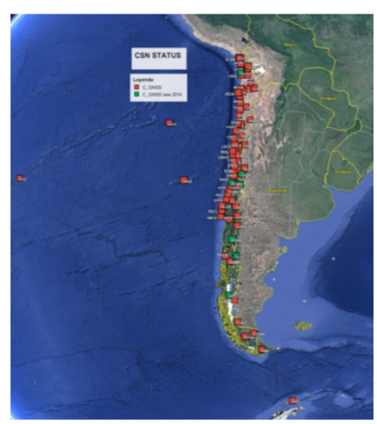

Figure 11: Chilean CSN

- **Global Differential GPS/VARION (GDGPS/VARION)**. The NASA/JPL GDGPS System (*http://www.gdgps.net*) operates some 80 globally distributed tracking sites, but also ingests data from other real-time tracking sites provided by a number of national and international agencies and organizations, including data of the IGS-RT network. It routinely processes real-time data for more than 200 global sites to derive GNSS orbit and clock states, and monitor the motion of each tracking site. Tracking data from the GDGPS networks are streamed in real time to selected real time analysis centers and to a center operated by the CDDIS of the NASA Goddard Space Flight Center. 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. GDGPS provided real time tsunami warning information to NOAA's Pacific Tsunami Warning System following Chile's 2010 Maule earthquake. GDGPS is hosting the VARION prototype real time TEC measurement system for tsunami verification and monitoring. Results of VARION TID analysis are published in real time on the VARION GDGPS website (*https://iono2la.gdgps.net*).

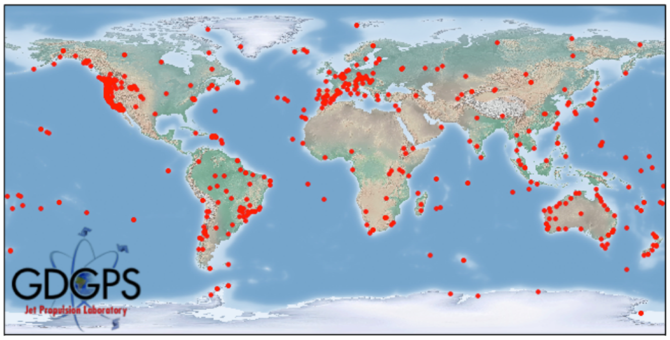

Figure 12: Global Differential GPS (GDGPS)

- **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 and the data is available 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.

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 and 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.

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

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.

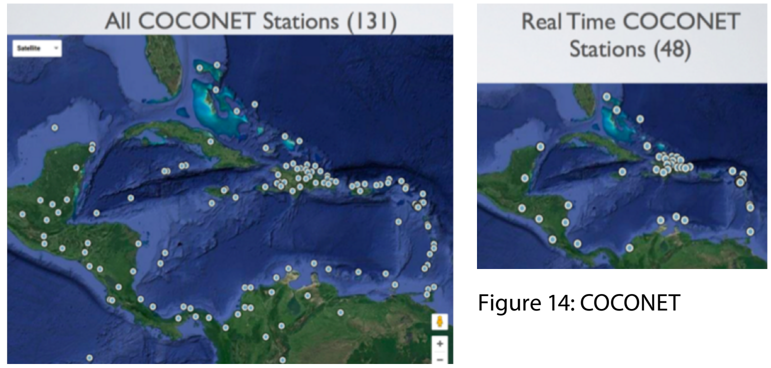

Figure 14: COCONET

- **COCONET Contribution to Caribbean GTEWS.** 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. The US National Science Foundation funded the development of the COCONet GNSS array through its contracts with UNAVCO. Furthermore, the CTWP has indicated a strong interest in developing a program to enhance its tsunami warning activities with GNSS data. This interest could be advanced by NOAA's Pacific Tsunami Warning Center (PTWC), which is currently integrating GNSS into its warning system in cooperation with the NASA supported READI program. The US Plate Boundary Observatory and associated networks in the Caribbean (COCONet) and Mexico (TLALOCNET) are available from UNAVCO. These networks are referred to as the NOTA network (Network Of The Americas). Fifteen of the 40 TLALOCNET stations are available in real time. Of the 1100 PBO stations, 777 are available in real time and 195 of those are multi-GNSS. PBO stations in the Cascadia subduction zone are almost all real-time, but almost none of the stations in Alaska are real-time. There are 131 COCONET receivers of which 48 operate in real time. The GDGPS network real time data are generally available via the CDDIS of the IGS. One concern expressed by UNAVCO is the lack of a defined standard for the archiving of real time data. The conversion of the remaining stations to real time GNSS in the North American network will require significant new funding.

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 Generation 4 cell phone 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** consortium to begin GTEWS development in 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 TID 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 of 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 underserved 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 Generation 4 cell phone technology. Unfortunately 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.
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.

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