2017 GNSS TEWS Workshop

Developing an international community of scientists in support of GNSS-TEWS could save countless lives, and would enhance many of the existing collaborations on tsunami science and awareness of these potential mega-disasters. It fits well with the recent United Nations UNISDR 2015 Sendai Framework themes to promote solutions for Disaster Risk Reduction around the Pacific Rim and elsewhere (2). These themes include improved building practices, improved response, and research for accelerating disaster science (3). More specifically there has been broad agreement on overall themes including:

- Building sustainable and resilient communities
- Emergency preparedness and disaster management, including activities relating to the efficient movement of capital, goods, services and people.
- Balanced Growth: Macro-economic policy coordination and information-sharing
- Secure Growth: Human security
- Innovative Growth: Science and technology and ICT approaches in disaster preparedness, risk reduction, response and post-disaster recovery and cooperation in search and rescue

More specific goals include:

- Substantially reduce global disaster mortality by 2030, aiming to lower the average per 100,000 global mortality rate in the decade 2020–2030 compared to the period 2005– 2015;
- Substantially enhance international cooperation to developing countries through adequate and sustainable support to complement their national actions for implementation of the present Framework by 2030;
- Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.

Priorities for action within the Sendai Framework across multiple layers of government at the local, national, and global levels include:

- Understanding disaster risk.
- Strengthening disaster risk governance to manage disaster risk.
- Investing in disaster risk reduction for resilience.
- Enhancing disaster preparedness for effective response and to “Build Back Better” in recovery, rehabilitation and reconstruction.

The workshop will be held in Sendai, Japan during July 25-27, 2017 in collaboration with 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 workshop will be co-organized by the US-based GNSS community and READI groups. The science and data are currently available around the circum- and intra- Pacific and Indian Ocean basins to develop and deploy an operational prototype. The initial planning workshop will begin the process of coordinating the science associated with such a system with international partners, and to plan the initiation of necessary activities, specifically involving data needs.

These international partners include the Asia-Pacific Economic Cooperation organization (APEC), and its principal committees, including the Policy Partnership on Science, Technology and Innovation (PPSTI), and the Emergency Preparedness Working Group (EPWG). Other important international partners are the Association of Pacific Rim Universities (APRU) which has a seat on the PPSTI of APEC, and its Multi-Hazards hub co-located at the International Research Institute of Disaster Science (IRIDeS) at Tohoku University in Sendai, Japan, and the APEC Cooperation for Earthquake Simulations (ACES) groups. The Global Geodetic Observing System (GGOS) also has identified this workshop to be the first organizational meeting of its GATEW Working Group on GNSS Augmentation to the Tsunami Early Warning System. The GATEW Working Group is comprised of agencies, institutions and research groups from over sixteen Indo-Pacific and European countries with capabilities and expressed interests in the goals of enhanced tsunami warning (http://kb.igs.org/hc/en-us/articles/218259648-Call-for-Participation-GNSS-Augmentation-to-the-Tsunami-Early-Warning-System) through cooperative data sharing and analysis. Partnership with the other earth observation communities will also be solicited through the International Committee on GNSS (ICG), the International GNSS Service (IGS), the Group on Earth Observations (GEO), and the Committee on Earth Observation Satellites (CEOS).

The rationale for holding the workshop in Sendai, Japan, and for involving these international partners includes the following:

- We are seeking international partners and participation, to bring in their data, capabilities and resources to contribute. Therefore we need to involve APRU and APEC. APEC is the important political and governing body in the region. APRU has a significant presence in the region by virtue of their Multi-hazards hub at Tohoku University, and their membership on the PPSTI standing committee of APEC.
- We plan to have the experimental system in Japan since they will likely have tsunamis during the time of the experiment due to the high level of ongoing seismic activity. In addition, the Japanese have made substantial investments in tsunami-related research.

- The Japanese have indicated they would like to bring Japanese government agencies, including GSI, JMA, and NEID, among others, into the workshop and the forthcoming experiment.

Background and History

Beginning with the M9.3 earthquake and tsunami in Sumatra on December 26, 2004, and continuing to the more recent past with the M8.8 2010 Maule, Chile earthquake, and the March 11, 2011 M9.1 Tohoku-Oki earthquake and tsunami off the coast of north eastern Japan, it has been recognized that great tsunamis represent a significant threat to many regions around the Pacific Rim. In the United States, the M~9 Cascadia earthquake of January 26, 1700 AD is now recognized to have been in this category of great earthquakes and tsunamis that threaten all coastal areas around the Pacific Rim.

To deal with this problem, very significant work has been done in the development of cost effective and efficient GNSS-based data systems to quickly estimate a number of vital earthquake parameters that are necessary to predict the likelihood of resulting tsunami and to track tsunami waves for communities nearest the earthquake's epicenter and as they propagate to distant coastlines around the world.

Published results using retrospective real-time analysis of GNSS networks has shown that the moments and slip displacement patterns of large magnitude earthquakes can be calculated within 3-5 minutes. Furthermore, algorithms now exist to use these earthquake source models to assess the likelihood of tsunamis and to predict the extent, inundation and run-up of tsunami waves.

A complementary approach is to use the GNSS networks to track the tsunamis using disturbances in the ionosphere. It has also been shown that augmenting these GNSS stations with relatively inexpensive accelerometers will improve the accuracy and timeliness of our ability to determine if an earthquake will produce a tsunami. Studies have also shown the benefit of supplemented the land- and atmosphere-based data with ocean surface and ocean bottom sensors. In short, we can now demonstrate that the existence of a real time GNSS network of stations in the Pacific could have provided sufficient early warning of tsunamis to save tens of thousands of lives.

Technical Details

For the great earthquakes and tsunamis mentioned above, the hardest hit were those closest to the earthquake source, a scenario for which there exists no adequate early warning system available today.

Most notably the 2004 Mw 9.2 Sumatra-Andaman event (Ammon et al., 2005; Ishii et al., 2005; Lay et al., 2005; Stein & Okal, 2005, Subarya et al., 2006) resulted in over 250,000 casualties, the majority of them on the nearby Sumatra mainland, with inundation heights of up to 30 m (Paris et al. 2007). 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 in the near-source coast (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 resulting in over 15,000 casualties (Mori et al., 2012) and was the first case of a large tsunami impinging upon a heavily developed and industrialized coastline in modern times. In addition to the tragic loss of life the economic collapse of the near-source coastline, which spans nearly 400 km, was almost complete (Hayashi, 2012).

Japan operates a system designed to provide near-source tsunami warnings (Tatehata, 1997; Ozaki, 2011) by utilizing rapidly determined hypocenters and magnitudes from the Japanese Meteorological Agency (JMA) to perform a database query of pre-computed scenarios. These scenarios, computed on-line and well in advance of the event, include intensity estimates at predetermined locations along the coast. When the earthquake strikes these parameters seed the database query and the resulting model guides the warnings issued to the public. However, this approach has severe limitations. During the 2011 Mw 9 Tohoku-oki event, a strict reliance on seismic data parameters led to a severe underestimation of magnitude earthquake source extent (Hoshiba and Ozaki, 2014; Katsumata et al., 2013; Wright et al., 2012). This led to underestimates of the extent and intensity of the tsunami power/scale which were not revised until many hours after the event.

Early estimates of earthquake magnitude from JMA were too low by 1-2 orders of magnitude; an estimate of M 7.2 was determined after 30 seconds and revised to M 8.0 by 107 seconds (Hoshiba et al., 2011), and an accurate estimate (Mw 8.9) was unavailable until after 2.5 hours (Hayes et al., 2011) It took 20 minutes for a better estimate of magnitude to be made teleseismically through the W phase method (Duputel et al., 2011, Hayes et al., 2011). However, maximum tsunami amplitudes of ~40 m (Mori et al., 2012) were reached in the Sanriku coast within only 30 minutes of rupture initiation. The underestimate of the earthquake magnitude led to early run-up estimates that were too low by up to tens of meters (Ozaki, 2011).

Retrospective analysis in simulated real-time mode of high-rate (1 Hz) GNSS (primarily GPS) data collected during the 2011 Tohoku-oki event on the Japanese mainland from a network of more than 1000 stations convincingly demonstrated that tsunami warnings in coastal regions immediately adjacent to large events could be effectively issued without regard for magnitude or faulting type (Melgar et al., 2013b; Song et al., 2012; Xu and Song, 2013). Similar GPS-enhanced approaches have also demonstrated using the 2004 Sumatra earthquake-related GPS data (Blewitt et al., 2006; Song, 2007) and during the

2010 Chilean tsunami (NASA release). The reason for this is that GNSS directly estimated near-source ground displacements without clipping. The static field obtained from GNSS is the longest period information that is measurable from an earthquake, effectively nullifying any saturation concerns.

Using the static displacement field it is then possible to construct source inversion models that range from point source (Melgar et al., 2012) to line moment tensors (Melgar et al., 2013b) and heterogeneous slip inversions (Crowell et al., 2012; Melgar et al., 2013b; Minson et al., 2014). As demonstrated for the 2011 Tohoku-Oki earthquake, it would have been possible to obtain a reliable magnitude and produce a static finite-fault slip model within 2-3 minutes of earthquake origin time strictly from the onshore GPS static displacements (Ohta et al., 2012; Melgar et al., 2013b). That information could then have been used to model the seafloor displacement as input to reliable tsunami prediction models of extent, inundation and run-up, well before the first tsunami waves started arriving (Melgar and Bock, 2013). This GNSS-TEW approach for the Tohoku-oki event could have effectively added 15 to 20 more minutes of early warning guidance and response time for communities at highest risk.

There are increasing numbers of dense GNSS networks with hundreds of stations that can and do provide real-time data in coastal regions that have a history of great tsunamigenic earthquakes, including the Cascadia subduction zone, the Japanese archipelago, and the Southern American trench. This represents an untapped new valuable data source for tsunami and earthquake early warning. Furthermore, by 2020, there will be over 160 GNSS satellites including those of GPS, European Galileo, Russian GLONASS, Chinese BeiDou, Japanese QZSS, Indian IRNSS and other satellite constellation broadcasting over 400 signals across the L-band, nearly double the number today at any location. The expanded GNSS constellation will improve the accuracy of the GNSS-TEW system and will likely provide future advancements in early warning capabilities.

Seismic and Geodetic analysis analysis techniques have advanced significantly in the five years since the Tohoku-oki event (e.g. Riquelme et al. 2016 and Melgar et al., 2016). These advances allow for more rapid and accurate models for the near field tsunami run-up through the combined analysis of both data types. The challenge posed to this workshop is to identify sensor distributions, data systems, and algorithms to integrate the increasing capabilities of GNSS and seismic networks for an accurate, efficient and effective tsunami early warning system in the near and far fields. It is clear that these run-up predictions can be significantly improved with more detailed surface deformation beyond the estimates provided by Centroid Moment Tensors derived from seismic data alone.

In summary, the identification and augmentation of existing monitoring networks with real-time GNSS would enable more accurate and timely determination of the magnitude for large earthquakes (> ~M8). In addition, characterization of the location, geometry, and extent of fault rupture and the orientation of ground displacement can be input to improved tsunami prediction models. Increased access and use of real-time GNSS data from existing and modernized networks would avoid or minimize underestimating the likelihood of devastating tsunamis. As demonstrated for the 2011 Mw 9.0 Tohoku-oki event this could add effectively 15 to 20 more minutes of early warning guidance and response time for communities at highest risk to take actions that reduce loss of life and damage to infrastructure.

Need for Workshop

The basic purpose of the proposed workshop is to assemble a group of international experts who can contribute to the development of a plan to proceed with the feasibility experiment. To proceed, we need to identify the barriers to development of the system, and then consider the best route to removing these barriers. Initially, we need to consider how the GNSS data will be acquired, shared, and processed. In later stages, we need to construct software and models to analyze and automate the workflow. Specifically, the proposed workshop will focus primarily on the data constraints, and how improved data accessibility flows into the models and automated workflow.

Among the problem areas that we will discuss, are the following:

- How to enable sharing of existing (current) GNSS real-time data in the region. We will need to assemble the key scientists and engineers to obtain agreement on this point.
- Development of cooperative activities for the evaluation of algorithms for standalone geodetic and seismogeodetic tsunami warning systems.
- Development of cooperative activities for the evaluation of ionospheric tracking networks and algorithms for tsunami tracking in the far field.
- How to identify new sites and networks in other Pacific Rim countries that can contribute. Examples in the US include Plate Boundary Observatory in the USA (PBO), the Pacific Northwest Geodetic Array (PANGA), Chilean, Mexican, Australia, New Zealand, Indonesia, and others.
- How to fill gaps in coverage by promoting the installation of new GNSS sites in tsunami-prone regions so that the geodetic and ionospheric coverage is optimized
- How to develop a regional awareness of the program and its potential capability – begin reaching out to the early warning agencies.

Outcomes

The primary product of the workshop will be a report to guide future activities. The report will craft a strategy to develop a Pacific-wide activity involving APEC and non-APEC members (example: Costa Rica has tsunamis but is not a member of APEC), and will describe a plan to develop a real-time partnership for tsunami and earthquake early warning.

Important questions to address in developing the strategy are:

- Where are the current real-time sites?
- Are there NGO sites that could be used?
- Where are the gaps in GNSS site distribution or data quality?
- Are there issues that would make it more difficult to resolve large earthquakes, tsunamis or ionospheric disturbances?
- If there are gaps, what is needed to fill the data gaps with new sites or telemetry?
- What protocols are needed for sharing real time data?
- How should the data be shared, what agencies should be involved?
- Who needs to be involved in GNSS tsunami early warning?
- What are the next steps and timeline?

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http://www.aces.org.au.

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