Multi-Country Proposal

Global Mobile Tsunami Warning System using Amazon Web Server— A Life-Saving Platform

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Recently in September of 2018, more than 2,000 lives were lost to the M7.5 Indonesian Palu/Sulawesi tsunami generated by a nearby earthquake. Footage filmed on **mobile phones** showed that people received no warning of the earthquake before the tsunami hit. Clearly, a **mobile alert system** could have provided early warnings to those **phones**. In fact, JPL's Global Real-time Earthquake and Tsunami Alert (GreatAlert) prototype system was running/testing during the M7.5 Palu/Sulawesi Indonesia event. The mobile app was designed to send the first alert to people within 200 km range of a large (M>7) earthquake once the location is detected in minutes. The full results (the second alert) were generated from the prototype system in JPL within several minutes after the earthquake, and forwarded the results from an iPhone (when traveling in Japan) to NOAA's Tsunami Warning Centers (TWCs), as well as NASA-related offices. Unfortunately, the real-time results could not reach the local people and stakeholders as no communication channels existed then, and the results could only publish after the event on the NASA Disasters Program Website [https://disasters.nasa.gov/sulawesi-island-indonesia-earthquake-and-tsunami-2018]. Nevertheless, the real-time test clearly demonstrated that the technology for detecting earthquakes and tsunamis is there, but effective communication to the public is lacking.

Tsunamis—large, rapidly moving ocean waves resulting from disturbances on the ocean floor due to large earthquakes—are among the most devastating of all natural hazards. Since the devastating 2004 Indian Ocean tsunami that killed about 230,000 people, about 30 earthquakes with magnitudes higher than M7 have been recorded, including the disastrous 2011 Japanese tsunami. The following **Table** shows how frequent and destructive tsunamis have occurred recently.

Date	Location	Magnitude	Casualty	Cause / Reference
26 Dec 2004	**Sumatra**	**9.2**	**~230,000**	**No tsunami warning**
28 Mar 2005	**Nias Island**	**8.7**	**~300**	**Panic evacuation [Song 2007]**
3 May 2006	Tonga	8.0	No tsunami	False alarm [Tang et al., 2008]
19 July 2006	**West Java**	**7.7**	**~730**	**No tsunami warning**
1 Apr 2007	Solomon Island	8.0	~54	No tsunami warning
29 Sep 2009	**Samoa Islands**	**8.1**	**~189**	**No tsunami warning**
27 Feb 2010	**Mule, Chile**	**8.8**	**Local tsunami**	**[NASA release 2010]**
25 Oct 2010	Mentawai	7.8	~509	No warning [Hill et al. 2012]
11 Mar 2011	**Tohoku, Japan**	**9.0**	**~19,000**	**Issued warning but too small**
8 Sep 2017	**Mexico Chiapas**	**8.2**	**No tsunami**	**[Chen et al. 2018]**
30 Sep 2018	**Palu, Indonesia**	**7.5**	**~2,000**	**Warning cancelled prematurely**

Modern seismometers are very reliable in detecting an earthquake's location and magnitude within a few minutes after a quake [*Hayes et al.*, 2011]. Because it usually takes 10 to 30 minutes for a deep-ocean tsunami to reach the nearby coast, many lives can be saved if an effective communication channel/device exists to alert people near the earthquake. While it is true that a larger earthquake magnitude usually indicates a greater tsunami potential, the reality expressed in the above table clearly shows that earthquake magnitude is not a good predictor of a resultant tsunami. In fact, an unacceptable 75% false alarm rate has prevailed in the Pacific

Ocean, according to the 2006 U.S. Government Accountability Office report [*GAO-06-519*]. Too many false alarms not only undermine the credibility of government agencies and the existing system, but also have significant negative economic and societal impact. According to the state of Hawaii's most recent estimation, an evacuation due to a false tsunami alarm in 1996 had cost the state $71 million in economic losses in 2006 dollars [*GAO-06-519*].

There are two major problems with current tsunami warning systems. **First**, it is logistically and programmatically difficult for the tsunami research community to access the systems of stakeholders and to implement their technology and data into the system for improvements. Currently, only Japan's JMA (Japanese Meteorology Agency) and NOAA's TWCs (Pacific and National Tsunami Warning Center) and BMKG (Indonesia Meteorology Climatology and Geophysical Agency) operate tsunami warning systems. Operation is the main duty of the warning center personnel. On the other hand, no funding mechanism exists to allow the science community to access their operational systems for improvement. **Second**, many (99%) coastal regions and countries do not have tsunami warning facilities. Even if the warning centers can make a correct prediction, the information can only reach a limited area, usually goes to local government agencies, and then, the effective communication depends the local governments and their facilities.

We believe a mobile tsunami warning system is a better alternative: first, it can reach almost anywhere in the world; second, it can be selective (only for those people at risk without affecting others away from the effective range—a technology that has been developed and tested in our GreatAlert Apple version) without panicking others; and finally, it can be open-source for the science community and stakeholders to use and develop for improvements, which is the main effort of this project.

1.1 Goals and Expected Significance

1.1.1 Goals

The goal is to develop a mobile tsunami warning system based on JPL's mobile Global Real-time Earthquake and Tsunami Alert (GreatAlert) prototype system and to release it as an open-source platform:

- Enabling the scientific community to access NASA data and software for improvements of earthquake and tsunami modeling based on real events,
- Enabling stakeholders, particularly in those developing countries without a TEW system or facility, to have to a TEW system by adding their local data/networks onto the global platform for their regional or national applications, and
- Enabling coastal residents and beach visitors to receive early tsunami alerts or alarms from their mobile phones if they are in the effective range of a coming tsunami (without affecting others who are not in nearby danger).

1.1.2 Expected Significance

Tsunamis have been among the most devastating hazards in recent decades. Directly using NASA's technology and data for societal benefit and saving lives is a game-changer for NASA missions and program goals. Traditionally, NASA data have been used for research and publications. However, advances in information technology enable access to NASA data in real-time. This is the first instance of using a mobile phone as a tsunami warning tool. For the first time, tsunami warnings can reach anywhere in the world, thanks to the mobile phone technology and NASA information and technology programs. This effort benefits the humanity. This project

shows a unique example of how NASA technology (automated software) and data (e.g., the GDGPS data, ocean data, applied science products) with Amazon Web Server can be used and combined with regional networks in real-time for saving lives.

1.2   Perceived Impact to State of Knowledge

Currently, coastal residents and beach visitors can only receive tsunami warnings from existing coastal facilities, such as loudspeakers or sirens. However, many (99%) coastal regions and countries do not have these facilities, which are expensive to install and maintain, and can be easily damaged by earthquakes. Even worse, only a few tsunami warning centers, mainly in Japan and the U.S., operate tsunami early warnings, mainly based on seismic data, which have limitations in predicting tsunami scales for effective early warnings (*Weinstein and Lundgren*, 2008). As a consequence, people going to beaches or living near the ocean still face the dire threat of tsunamis.

Mobile communication is a fast growing technology in this information era. In fact, the ubiquitous mobile devices are the only logical approach to quickly reach as many people as possible in tsunami-prone regions. Our prototype mobile warning system is inexpensive and globally applicable, and can issue alarms in near-real-time. This has been tested within JPL on 30 real-time events (M>6 earthquakes) for last two years (Apple iOS devices only so far).

1.3   Technical Approach and Methodology

This project will deliver a community accessible platform with three innovative components: (i) a plug-in mechanism for real-time streaming and augmenting both regional and global data, (ii) an automated system for earthquake and tsunami modeling, and (iii) a mobile app in both Apple and Android versions for public communications. These three components will allow the scientific community and stakeholders to access NASA real-time data, particularly the GDGPS System for both global and regional enhanced applications. **Figure 1-1** gives an overview of the three components (white, red, green) of the mobile tsunami warning system:
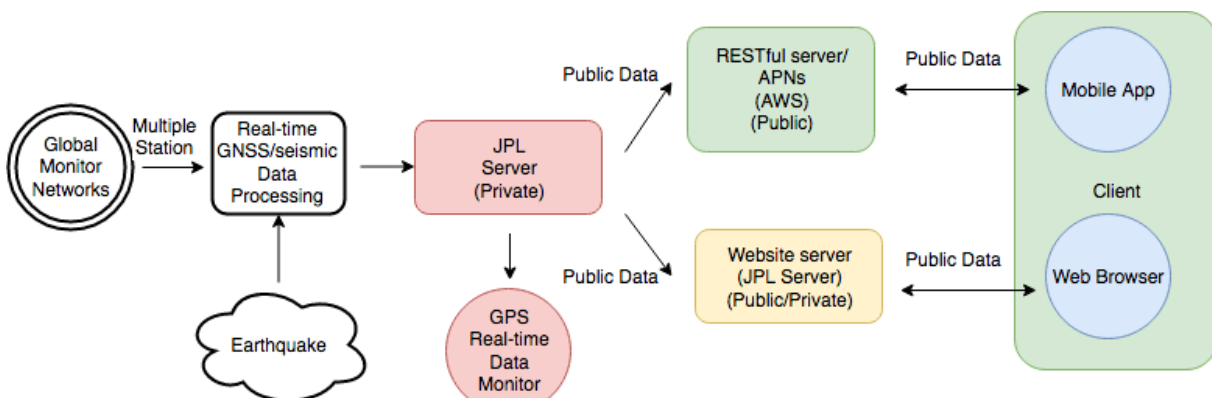

Figure 1-1. The mechanism to generate data that triggers alerts through Amazon Web Server (AWS) to be sent to mobile phones.

It should be noted that NASA funding has been applied for the in-house research and development to mature and improve the Global real-time earthquake and tsunami Alert (GreatAlert) system, including the mobile apps (Apple and Google versions) development. However, NASA is a research agency, does not support operational services to the public. The GEO-AWS credit will be used to support the data communications to the public, as marked by the green components in Figure 1-1.

In the following sub-sections, we identify the remaining challenges and present our solutions to resolve these challenges. Furthermore, we will detail our plans to open source-code of our system to the scientific community, stakeholders, and the general public for real-time applications.

1.3.1 Earth observation (GNSS and tele-seismic) networks

<u>**The NASA Global Differential GPS (GDGPS) System**</u> provides the operationally robust and self-sustainable front-end required for a global natural hazard monitoring system (www.gdgps.net). It is a high accuracy, high-reliability, 24/7 Global Navigation Satellite System (GNSS) augmentation system, developed by JPL to support the real-time positioning, timing, and orbit determination requirements of its customers at NASA, the Air Force, and in industry. Its natural hazard monitoring capabilities were developed and refined by NASA's Application Program (through the GREAT Alert Project, 2008-2010, and follow-up funding), and by the Earth Surface and Interior Program, which also sponsors part the GDGPS ground tracking network as part of NASA's geodetic observatory. In addition to GPS, the GDGPS System observes all other available GNSS, including the Russian GLONASS, Chinese BeiDou, European Galileo, and Japanese QZSS. Recognizing that operational reliability is key to real-time processes, including natural hazard decision-making processes, the GDGPS System is based on end-to-end redundant architecture, designed to eliminate single points of failure (**Figure 1-2**).
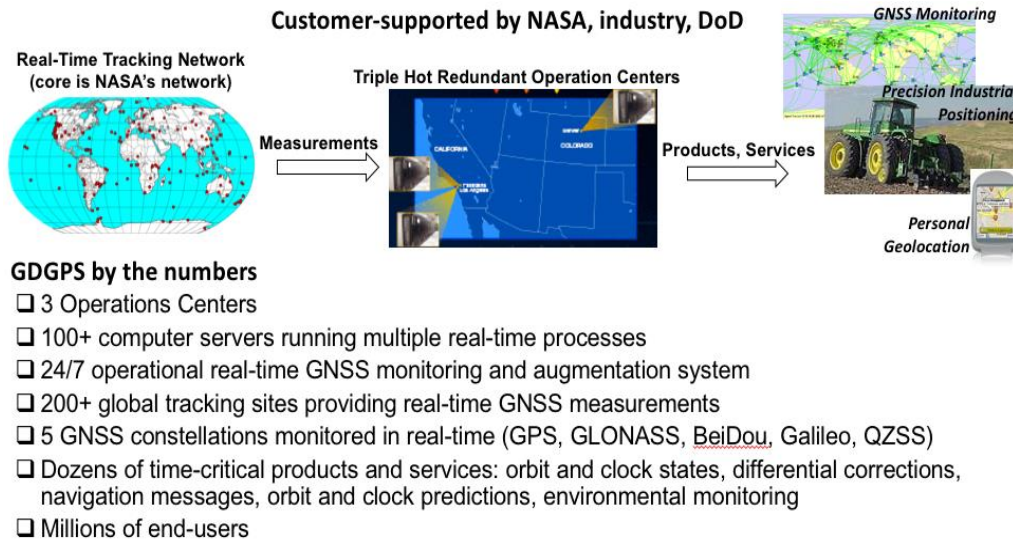

Figure 1-2. Highly redundant architecture has enabled the GDGPS System to provide robust and reliable mission-critical GNSS-positioning services, 24/7, since 2000.

One of the world's largest globally-distributed, centrally-managed real-time GNSS tracking networks, the GDGPS tracking network consists of a core of NASA-owned 80+ globally-distributed tracking sites, and draws real-time data from hundreds of additional tracking sites contributed by a variety of government agencies. These include dense regional networks (such as PBO in the U.S), and many sites along the 'ring-of-fire' in the Pacific, and other earthquake-prone regions on Earth (**Figure 1-2**). More real-time GNSS tracking sites are constantly being added globally by various agencies, local authorities, and our collaborative partnerships. Under the proposed effort, the GDGPS System will seek and identify additional

GNSS real-time tracking sites in seismically active regions, and incorporate them into its real-time positioning operations. It will also continue to focus on these regions for its own investment in tracking infrastructure, targeting the most earthquake-prone, under-monitored locales.

The GDGPS System is producing position solutions for all sites of interest at 1 Hz, with latency of less than 10 seconds. For a well-constructed site, the accuracy of the estimated position is better than 5 cm in each coordinate. Unique among its peers, the GDGPS System is completely self-sufficient, producing its own highly-accurate real-time orbit and clock solutions for all GNSS satellites. Home-grown technology, in the form of the RTGx software, ensures optimal consistency between the real-time orbit and clock solutions and the position solutions [Bar-Sever et al., 2014]. RTGx is JPL's flagship GNSS data analysis software, the navigation software for the next generation GPS control segment (OCX) [Bertiger et al., 2012], and was developed under the high quality standards required of the core navigation software for operational GPS, one of the world's most important infrastructures.

Global Tele-seismic Network (e.g., GSN) and its combination with GNSS: Real-time GNSS sites are sparse and only constrain the source inversion from the landside. Recently, we have developed an automated joint inversion based on near-field (epicentral distance < 1000 km) GNSS data and mid-range (epicentral distance from 30° to 45°) tele-seismic P waveforms [Chen et al., 2019]. Neither the near-field GNSS nor the mid-range tele-seismic data clip or saturate during large earthquakes, while the fast-traveling P-waves, within 6~8 minutes of the quake, are still essential to constrain the source in regions where very few or no GNSS stations are available.

Near-field broadband seismograms can saturate during strong shaking caused by large earthquakes. Tele-seismic P and S waves are separated at far-field epicentral distance (>=30°) from other large phases and usually used to image earthquake source. Compared with P waves, S waves travel at a relatively slow speed and may delay the system's response. Besides, automated picking of S waves is more challenging. As a result, we only adopt real-time tele-seismic P waveforms from the Global Seismographic Network (GSN) in our system (see station distribution in **Fig. 1-3**). We decimate the raw observations to 1 Hz and bandpass filter them with [0.009 0.4] Hz. We trim the length of P wave windows to 120 s.

Compared with tele-seismic stations, the near field GNSS receivers (< 1000 km) have much less latency and provide higher resolution of slip distribution. Therefore, in our system, we give GNSS data higher priority. If we have more than seven stations (note that the number seven is quite arbitrary, as will be discussed later), we will not use seismic data. Otherwise, we will include seismic data. The joint usage of GNSS and seismic data raises the issue of relative weight. This is an ongoing research topic and no rule of thumb exists yet. However the trial-and-error method that is frequently used is not suitable for real-time implementation. Here, we normalize each data type by its own norm and assign equal weights to them. Based on the global system, our main effort is to enhance its regional applications.

Targeted regional enhancements: Hazards know no borders. Earthquakes and tsunamis are particular examples that can affect many surrounding counties. We have formed a plan to collaborate with regional/national stakeholders to use our prototype system for regional enhanced applications (see attached supporting letters). There are two main rationales for this collaborative plan:

- For all tsunami-prone regions, the methodology of using real-time GNSS and seismic data for tsunami early warning is similar. There is no need to duplicate the effort for each

of the regions. The global platform allows those regional stakeholders without a tsunami warning system or facility to use NASA data and system for their regional applications.

- Each region, however, has its own data system. Some allows to share the local data, while others do not allow. The best strategy is to share the common (global) platform, allowing the local stakeholders to enhance the system for their own applications.

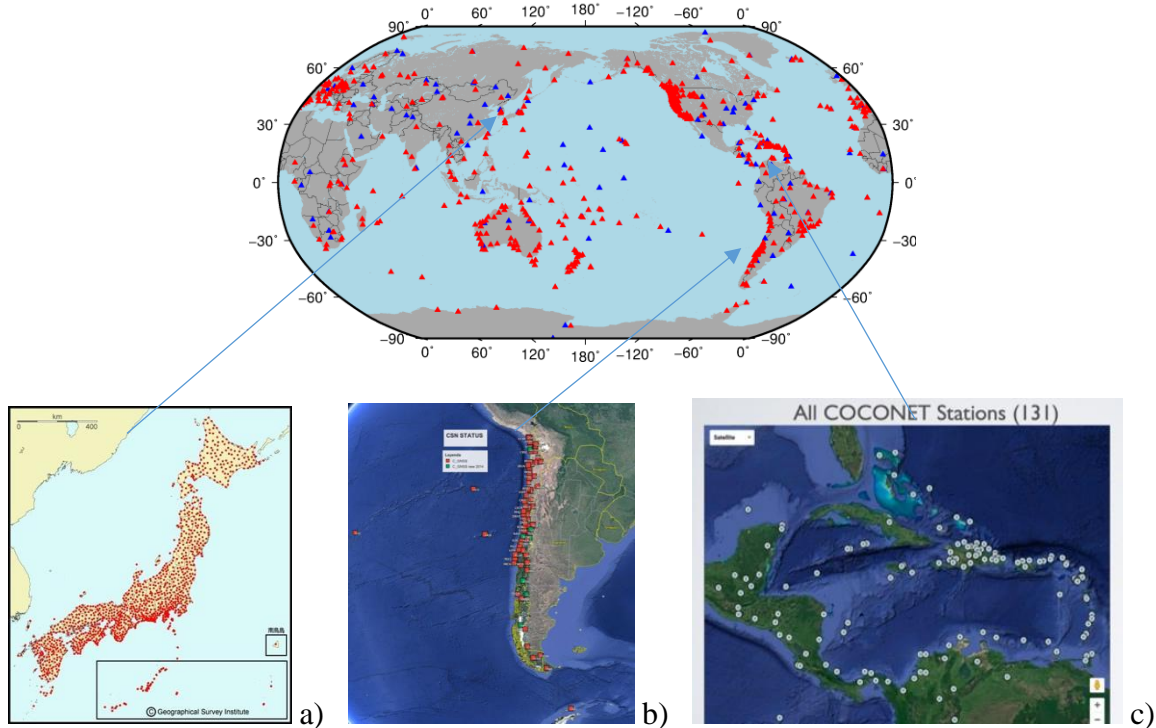**Figure 1-3** illustrates our strategy through collaborations for regional enhancements:

Figure 1-3. Upper panel is the global real-time GNSS (red) and tele-seismic (blue) networks used by NASA GreatAlert system, which will be available to all users. Lower panels are examples of targeted regions through collaboration with the local stakeholders to enhance and to plug-in their local data system as **GreatAlert_Japan, GreatAlert_Chile, or GreatAlert_Caribbean** for their regional or national applications. Images from Prof. Yusaku Ohta of Japan, Prof. Sergio E. Barrientos, and Dr. Patricia Mothes.

- **Japan's Real-time GEONET Analysis for Rapid Deformation Monitoring (REGARD):** The REGARD utilizes over 1200 GEONET real time GNSS stations to determine ground displacement and fault models. The Geospatial Information Agency 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. Prof. Yusuku Ohta is leading a group at Tohoku University in developing the REGARD and tFISH algorithms for JMA. We will collaborate with Prof. Ohta to compare and validate each other.

- **Caribbean and Adjacent Regions:** 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 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-centric mitigation activities will help to build tsunami resiliency. There are 131 COCONET receivers, of which 48 operate in real time. However, many of the real-time receivers in Northwest South America region have not been released (per. Com. Pat Mothes). We planned to collaborate with Patricia Mothes of Instituto Geofísico, Escuela Politécnica Nacional, Quito-Ecuador to process those receivers for enhancing the Caribbean and Adjacent regions.

- **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 warnings and interacts with the Chilean Hydrographic Office (SHOA). The high rate of tsunamigenic megathrust earthquakes in the near and long term makes the CSN network a very important contribution to the regional tsunami warning system. The CSN has stated that its GPS data is 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. Dr. Sergio Barrientos is the director of CSN. We will collaborate with his team to resolve the communication issues by installing the GreatAlert prototype system in the local center for their applications.

1.3.2 Automated earthquake and tsunami modeling system

<u>**Earthquake models:**</u> Rapid and reliable earthquake source estimation is crucial for tsunami energy-scale determination and effective tsunami early warnings. Finite source inversion overcomes the oversimplification of point-source approximation for large earthquakes, thus providing a more accurate estimation of earthquake displacements leading to tsunami hazards. We have developed an innovative Fast-Joint-Inversion algorithm combining near-field (<1000 km) GPS/GNSS with far-field (between 3000 ~ 4500 km) seismic P-waves. Neither the near-field GPS/GNSS, nor the far-field seismic data, clip or saturate, while the fast-traveling P-waves in the far-fields, within 6~8 minutes of the quake, are still useful for constraining the source in regions where near-field GPS data is not dense enough.

We have developed an earthquake fault slip inversion framework for large seismic events (M ≥ 7) using real-time GNSS, strong motion, and tele-seismic data [Chen et al. 2018c]. The system utilizes the complementary strength of GNSS and seismic data and can perform and complete automatic source inversion within 10 minutes of the earthquake. Near field real-time GNSS record co-seismic displacements without saturation thus provide direct constraint to finite fault slip. But RT GNSS observations are not always available because of non-uniform GNSS distribution on a global scale, limiting its use in resolving earthquake source. In comparison, teleseismic data is always available thanks to the global seismic network (e.g., GSN) but with longer latency due to seismic wave propagation to desirable epicentral distance (~30º). Combination of the two ensures a robust estimation of earthquake finite source at all times. Moreover, the system also has implemented near real-time integration of co-located GPS and strong motion data to produce more accurate seismogeodetic waveforms for fault slip inversion [Chen et al., 2018a]. Our rapid earthquake source inversion is triggered by earthquake broadcast

information (origin time, hypocenter location, and magnitude) from TWCs and/or USGS, typically available 1-2 minutes after the earthquake.

It should be pointed out that the available real-time GPS/GNSS sites are not uniformly distributed, and are unfortunately not dense enough to compute the most simple fault geometry or central moment tensor (CMT) for most of the regions. Unfortunately, it does not work in most of the cases because very few regions have the concentrated GPS sites of the Japan region. To resolve this issue, we have developed an innovative approach by using the historical CMT focal mechanisms (hisCMT) (**Figure 1-4**) as the initial starts and real-time iteration to derive final fault geometry and earthquake slip in the automated iteration system [Chen et al., 2017 and 2018c]. Note that this approach is mostly useful in the regions where no predefined fault database is available, providing complementary strength to our fast finite source inversion.
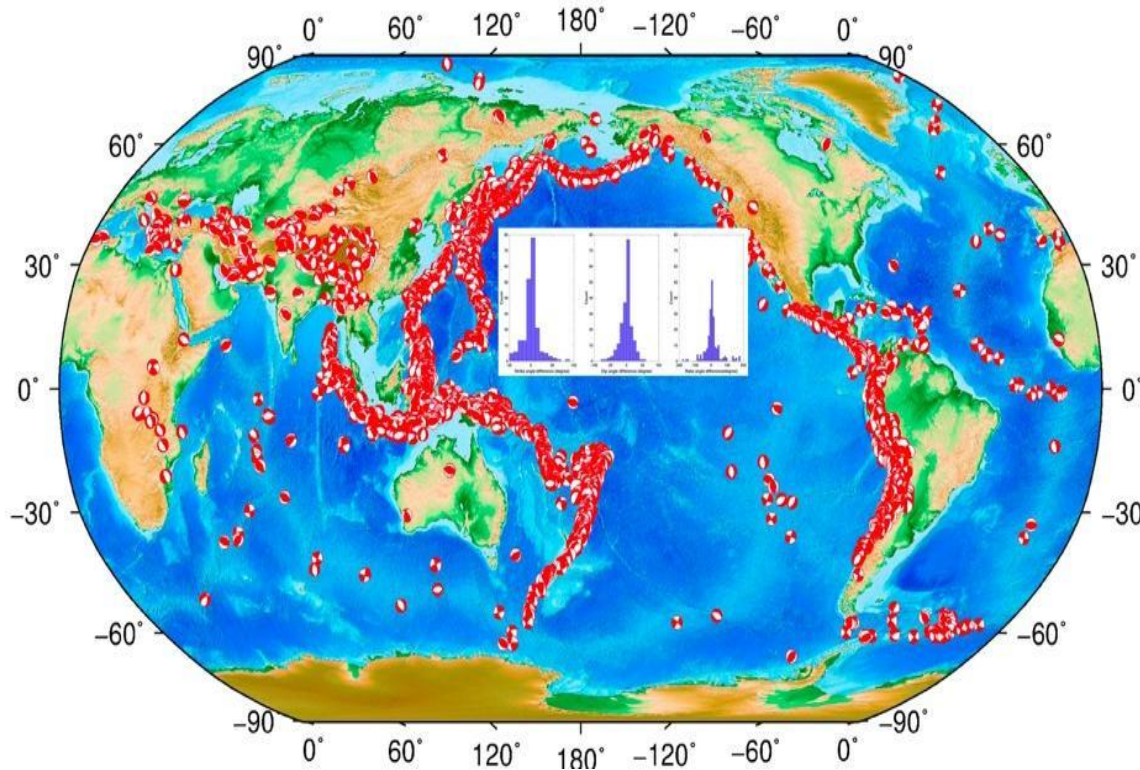

Figure 1-4. Focal mechanisms of historical events (http://www.globalcmt.org). Insert figures are the histogram for the dip, strike and rake angles, respectively. The statistics show that 91% of strike angle agree with each other within 40°, clearly showing that the mean statistics of the past events provides the best informed initial estimates of fault geometry [Chen et al., 2019b].

In our prototype system, the modules and algorithms have been automated to access three real-time Earth observation networks: (1) the locally dense and globally distributed GNSS network, (2) the global broadband seismic network (including seismo-geodetic sensors), and (3) the global Deep-ocean Assessment and Reporting of Tsunami (DART) network, as shown in **Figure 1-5**.

Tsunami models: Our tsunami source and initial conditions are calculated from both vertical and horizontal displacements of the seafloor. Large or great subduction earthquakes near the continental slope involving both significant horizontal and vertical displacements of faulting

often cause strong tsunamis. Besides the vertical acceleration of water caused by seafloor deformation which raises the ocean's potential energy, the horizontal displacement of a slope can accelerate water into horizontal directions (i.e., transfer momentum from moving slopes to oceanic water), therefore providing the ocean with kinetic energy (KE). The accelerated three-dimensional velocity of water particles in the vicinity of moving slopes has been formulated by Song et al. [2008]:

$$u_b(z) = \begin{cases} E/\tau & if \quad -h \le z \le -R_x = \min\{h, L_H \mid h_x \mid\} \\ 0 & othewise \end{cases} \tag{1}$$

$$v_b(z) = \begin{cases} N/\tau & if \quad -h \le z \le -R_y = \min\{h, L_H \mid h_y \mid\} \\ 0 & othewise \end{cases} \tag{2}$$

$$w_b(z) = (U + E \cdot h_x + N \cdot h_y)/\tau \qquad -h \le z < 0 \tag{3}$$

where τ is the rise-time of faulting, L_H is the effective scale of the horizontal motion, z is the vertical coordinate at the undisturbed ocean surface, and $u_b(z)$ and $v_b(z)$ are the bottom-water velocity within the range of R_x and R_y, respectively; meanwhile, $w_b(z)$ is the vertical velocity due to the seafloor uplift and is limited by the water depth h. The effective range of the horizontal acceleration L_H is limited by the characteristic boundary-layer thickness ($L_H|h_x| <200$ m). If the slope height is zero or the slip direction is parallel to the slope, it generates no force to the ocean, except the negligible bottom-friction force. Note that the total co-seismic displacement (E,N,U) is the sum of all the subfault displacements ($\Delta E,\ \Delta N,\ \Delta U$) in equations (1-3) or the predicted values from the inversion modeling. This three-dimensional forcing mechanism will be implemented into our automated system to transfer the GPS-derived seafloor motions into tsunami initials (i.e., sea surface perturbation and bottom-layer velocity).

We then use the tsunami source or initial conditions to calculate the tsunami source energy [*Song et al., 2008*]. The calculation of tsunami energy is based on estimating the volume of water vertically displaced by the faulting (potential energy), and how fast it is displaced horizontally (kinetic energy). Once the total tsunami energy is derived, the tsunami power (scales) can be determined. Based on the linear wave theory in deep oceans (the square root of wave energy is proportional to the wave amplitude), we introduce the following formula to quantify the tsunami scales:

$$S_T \equiv \log_{10} E_T - 10 \tag{4}$$

Here, E_T is the total tsunami-source energy and S_T is the tsunami scale (between 1 to 10 and any value greater than 10 is set to 10). The tsunami source energy scales determined from GPS offsets have been validated for the historical events by tsunami observations from DART buoys [Titov et al., 2016].

DART Validation Modules: To avoid possible bias from GPS-based derivation of the earthquake, nearby ocean-based DART measurements of tsunami height will be assimilated into our system based on the recently proposed all-source Green's function (ASGF) approach of Xu and Song [2013]. The combination of these two existing real-time systems (NASA and NOAA) offers the best solution for early detection and early cancelation. The approach is comprised of a real-time GPS-derived tsunami-source function, followed by the rapid transfer of that source function to time series of tsunami arrivals at one or more points of interest, which are the DART (Deep-ocean Assessment and Reporting of Tsunamis) stations for this particular application. The rapid transfer of the source function to the arrival time series is realized by using the all-source Green's function, which is pre-calculated for the destination point of interest. The ASGF focuses

on a point of interest as a receiver point and allows *all* the model grid points to be potential source points. This new approach is verified by the 2011 Tohoku tsunami using data measured from the DART buoy array. **Figure 1-5** depicts how the DART buoys are used to validate the predicted tsunami by the ASGF approach to tsunami models.
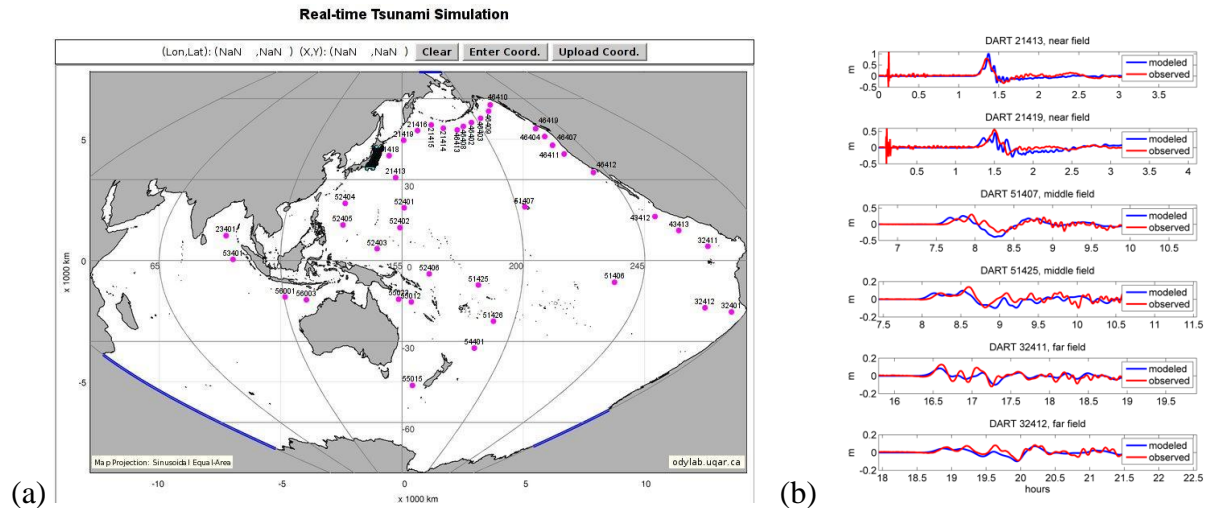

Figure 1-5. (a) global real-time DART observations will be used to validate our system, and (b) example of using DART observations to validate our tsunami models.

1.3.3 *Mobile Apps and cloud environment (AWS)*

As mentioned before, many countries and regions do not have tsunami warning facilities. Mobile communication is the only logical approach to quickly reach as many people as possible in tsunami-prone regions. The GreatAlert app is currently an Apple iOS version only, so we will need to develop an Android version, which is more popular in developing countries. Statistically, there are now more than **700 million iPhones** currently in use worldwide, according to an estimate from BMO Capital Markets analyst; meanwhile, Google has estimated that there are now more than **two billion** monthly active Android devices in use around the world. Our mobile tsunami warning system has the potential to impact people's lives across the globe. The mobile app has three functionalities:

1. **For real-time communication:** During a tsunami emergency, responsible agencies can send alerts/alarms to those people at risk without affecting others. The app is designed such that individual phones calculate their own locations internally from the received alert information of earthquake centers and tsunami-travel-time map (**Figure 1-6a: the first alert**).

2. **For research improvement:** The open-source system allows both scientists and stakeholders to access and review the results simultaneously in real events and to improve the system effectively. The mobile app will record and report the real-time results. The performance can be evaluated and documented immediately after the event (**Figure 1-6b & c: the second alert**).

3. **For better decision-making:** With the mobile app, operational experts would see the data and analyze the results instantly, no matter where they are. A group of experts can reach a consensus for better decision making in response to the crisis. This would be a great help to improve decision making processes (**Figure 1-6d: validation**).

Figure 1-6. NASA GreatAlert app structure: (a) The app icon, (b) First page gives earthquake and tsunami information, (c) earthquake model results, (d) tsunami results.

Furthermore, coastal warning facilities and power lines can be damaged by near-by earthquakes, mainly by the seismic S-waves, which create difficulties for the local governments to reach people at the effective range. To avoid such instances, the mobile warning system uses the fast-traveling P-waves in our system for early warnings, which arrive before the damaging S-waves. The similar technology has been used by the ShakeAlertLA for earthquake early warning (@USGS_ShakeAlert). For earthquake early warning, the useful early-time is only seconds. Fortunately for tsunami early warning, the useful early-time can be tens of minute because tsunami waves travel much slower than seismic waves, usually take 10~30 minutes to reach the coast.

So far, the prototype mobile warning system is based on the Apple iOS version. The GreatAlert app will be available from Apple Store (pending release: search "GreatAlert" from App Store). Beta version has been available to about 50 JPLers for feedbacks (contact Tony Song of JPL for the developer or beta version: http://science.jpl.nasa.gov/people/Song). The data products will be available to the public through the web site (https://gated.jpl.nasa.gov).

We envision that the mobile tsunami warning system will serve as a "weather channel" for earthquakes and tsunamis, providing:
- **A mobile tsunami warning system:** Many countries and regions do not have a tsunami warning facility. The mobile system is a better alternative. For regions with a warning facility, the mobile system can serve as back-up plan.
- **A common platform for research:** Earthquake and tsunami disasters can strike many areas of the world. The open-source system serves as a global platform to provide NASA technologies and data, and to enable researchers and stakeholders to add their data for their own enhancements and applications.
- **A training tool for education:** Earthquake and tsunami knowledge saves lives. Our app is designed to provide information and maps on how to evacuate from a tsunami danger zone into a tsunami safe zone with GPS guidance. Events can serve as safety drills, so people know what to do during a real tsunami.

1.4   Multi-country Collaboration and Consortium of GreatAlert

Collaborating with international partners who are working in the same field is the key to improving the tsunami early warning system by sharing data and experience, as well as lessons. As mentioned above, GreatAlert system (data and algorithms) is **global** in nature; therefore, it makes sense to collaborate with our international peers to allow them to add their regional/national data-network to the global platform for their own regional/national applications. One the other hand, regional applications would certainly improve the global system and pave a way toward a data-sharing environment for the common purpose of hazards mitigation, which follows *the Sendai Framework for Disaster Risk Reduction, the Paris Agreement and the United Nations Sustainable Development Goals.*

We have formed a plan to collaborate with regional/national stakeholders to use NASA global system and satellite data producrts for regional enhanced applications. Our plan has two folds:

A. For regions with tsunami warning systems, like Japan and the U.S., we will transfer useful algorithm modules or data to their systems to enhancements. For example, some of our GNSS modules have been delivered to NOAA's TWCs for applications in our previous efforts. The mobile system can serve as a backup plan.

B. For regions without an operational tsunami warning system, we will collaborate with them to install our system into their stakeholders' systems for their regional applications (with their local data added if available).

1.5   Work Plan

We will deliver a community accessible platform with three innovative components: (i) a plug-in mechanism for real-time streaming and analyzing data from regional networks, (ii) an automated system for earthquake and tsunami modeling, and (iii) a mobile app in both Apple and Android versions for public communication. Software licenses and document review have been approved for the IOS prototype system (Unlimited Release #: URS281108).

Our current work plan consists of three categories of technical tasks (funded by NASA): develop algorithm/modules, app development, and test/validate the global and regional systems in real events (e.g., M>6 earthquakes). These technical tasks are detailed as the follows.

Task 1: Develop a plug-in mechanism allowing scientists and stakeholders to add their regional data system (GNSS receivers, seismometers, and tsunami sensors) into the global platform for their regional or national applications.

Task 2: Collaborate with target countries (Indonesia, Chile, and Ecuador) to implement and test the system for their local applications. We have target regional systems as GreatAlert_Japan, GreatAlert_Chile, or GreatAlert_Caribbean. We will collaborate with our regional representatives as mentioned in the proposal to plug-in their models and data, and to test and validate the system in real-events.

Task 3: Develop the Android version of the app. As mentioned above, Android phones are much more popular around the world, particularly in developing countries such as Indonesia, Chile, and those in the Caribbean.

We will use AWS as the platform to deliver tsunami alert products to the public users and to communicate within the multi-country consortium of GreatAlert (GEO-AWS credit). We will use the Amazon Web Server (AWS) as our base for the development, which is globally applicable and more reliable than an institutional server.

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Further information can be provided upon request.