The value and role of GNSS in earthquake and tsunami early warning

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The value of GPS in hazards warnings was quickly recognized following the 2004 M9.1 Sumatra earthquake. Since then numerous efforts have arisen to incorporate real time GNSS into both earthquake and tsunami early warning. Here we will synthesize the knowledge gained since then and summarize what the value of GNSS is in regards to both earthquake and tsunami warning. Drawing on examples from the operational system in the western US we will argue that GNSS must be, alongside traditional seismic deployments, a key component of any capable warning system. We will also discuss techniques for routine testing of such systems with synthetic earthquakes and simulated GNSS data.

Keywords: Early warning, GNSS, tsunami

REGARD: GNSS-based rapid finite fault modeling system

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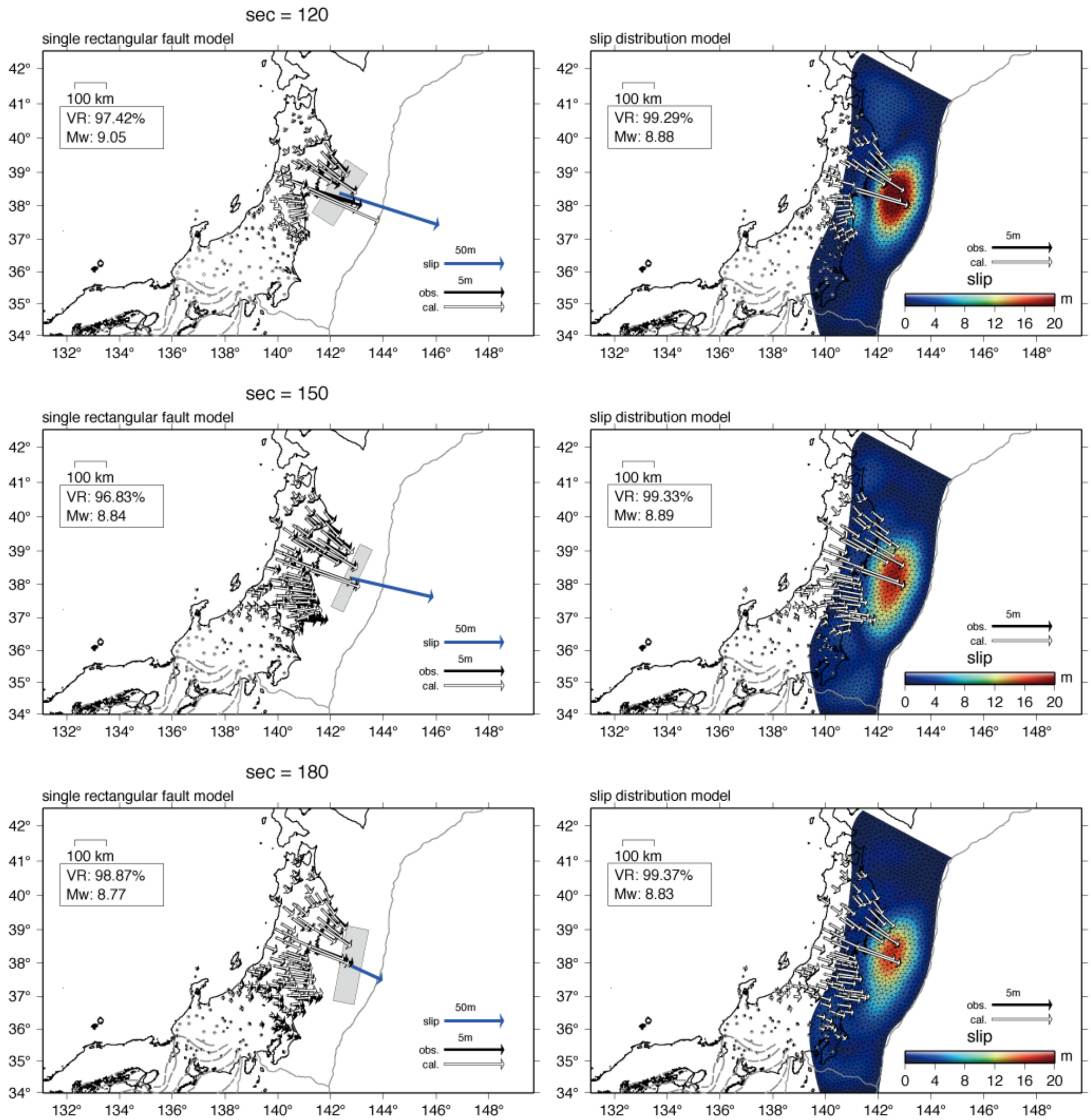
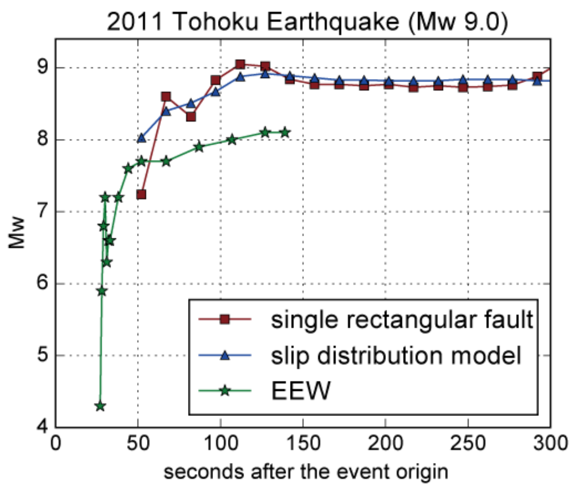
We present a newly developed real-time GNSS system REGARD (the Real-time GEONET Analysis system for Rapid Deformation monitoring), which estimates single rectangular fault and slip distribution models within 3 minutes. The new system is part of the GNSS Earth Observation Network (GEONET) operated by Geospatial Information Authority of Japan, and it was developed in collaboration with Graduate School of Science, Tohoku University.

The REGARD system consists of real-time GNSS positioning, automatic detection of coseismic displacements by seismic events, and quasi real-time finite fault model inversion. The real-time data from the GEONET stations are processed by the RTKLIB (Takasu, 2013) and GSILIB (GSI, 2015) softwares. Then, the displacement time-series are monitored by RAPiD algorithm (Ohta et al., 2012) to detect earthquake events. If an early earthquake warning with $M > 7$ is issued and/or the displacement more than 10 cm occurred at neighboring 3 stations, the finite fault models are estimated from the coseismic displacement field.

The performance of the automatic inversions of the finite fault models is examined by using real raw GNSS data of the past large earthquakes : the 2003 Tokachi-oki earthquake (moment magnitude (M_w) 8.3), the 2011 Tohoku earthquake (M_w 9.0), and the 2011 off Ibaraki earthquake (M_w 7.7). A simulated 1707 Hoei-type Nankai Trough earthquake (M_w 8.7) is also tested. The Mw estimates with high variance reductions > 90 % were derived for all the earthquakes within 3 minutes. It is noteworthy that the M_w 8.83 was estimated for the 2011 Tohoku earthquake by 3 minutes without saturations. The performance assessment of REGARD confirmed that the real-time GNSS analysis is very powerful to estimate reliable Mw for large earthquakes with $M > 8$ rapidly.

Keywords: GNSS, GEONET, Real-time Kinematic GNSS, Rapid finite fault model, RTK


sec = 120
single rectangular fault model
100 km
VR: 97.42%
Mw: 9.05
slip distribution model
100 km
VR: 99.29%
Mw: 8.88
sec = 150
single rectangular fault model
100 km
VR: 96.83%
Mw: 8.84
slip distribution model
100 km
VR: 99.33%
Mw: 8.89
sec = 180
single rectangular fault model
100 km
VR: 98.87%
Mw: 8.77
slip distribution model
100 km
VR: 99.37%
Mw: 8.83
slip
50m
obs.
cal.
5m
slip
m
0 4 8 12 16 20


2011 Tohoku Earthquake (Mw 9.0)
Mw
seconds after the event origin
single rectangular fault
slip distribution model
EEW

The EarthScope Plate Boundary Observatory and allied networks as a platform for seismo-geodetic integration to support Earthquake and Tsunami Early Warning Systems across the Americas

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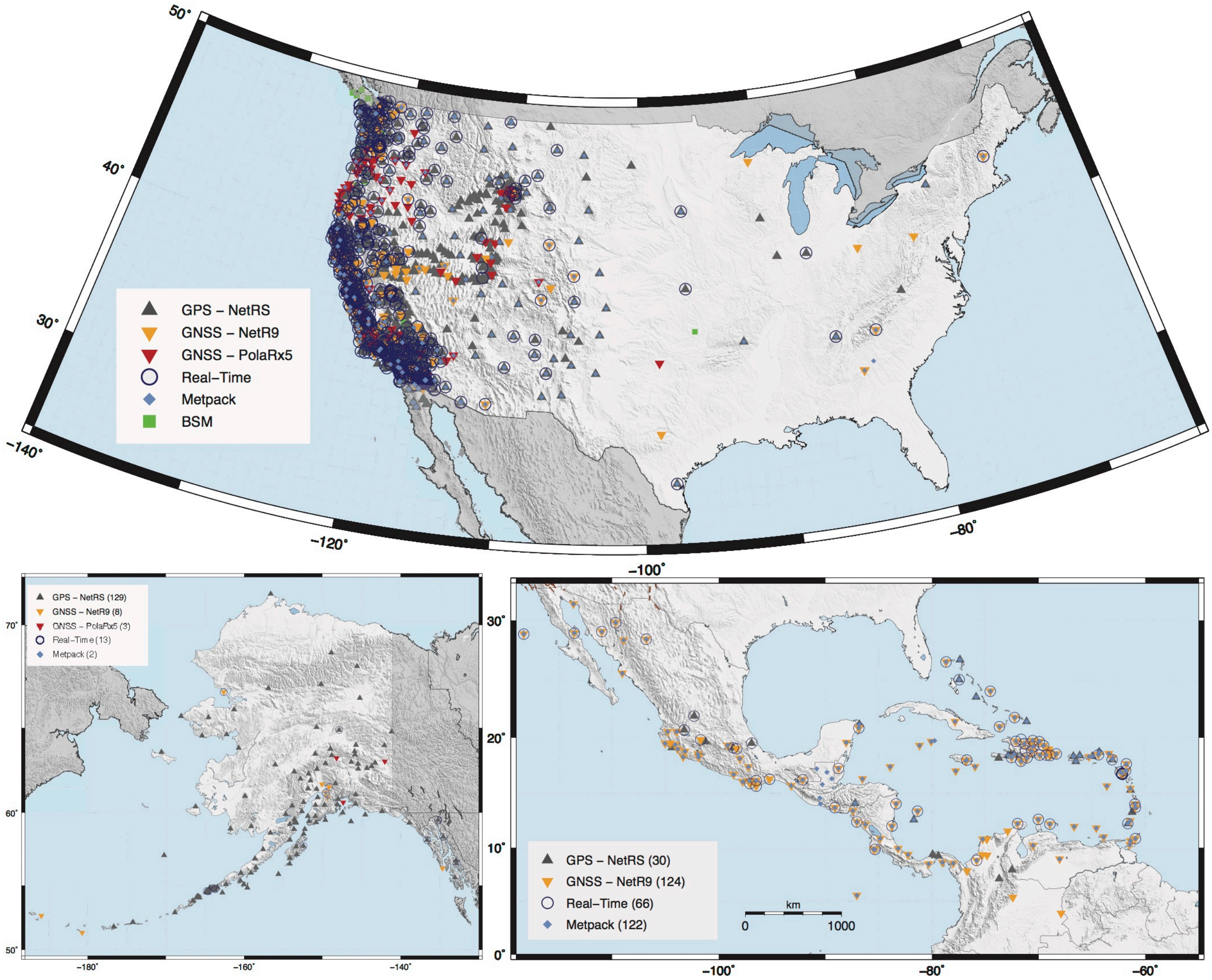
The NSF-funded GAGE Facility, managed by UNAVCO, operates approximately ~1300 continuous GNSS stations distributed across North America, northern South America, and spanning the circum-Caribbean. Based on community input from several workshops and associated reports starting in 2011, UNAVCO has been exploring ways to increase the capability and utility of geodetic resources under its management to improve our understanding in diverse areas of geophysics including properties of seismic, volcanic, magmatic and tsunami deformation sources. Networks operated by UNAVCO for the NSF have the potential to profoundly transform our ability to rapidly characterize geophysical events, provide early warning, as well as improve hazard mitigation and response. Specific applications currently under development include earthquake early warning, tsunami early warning, and tropospheric modeling with university, commercial, non-profit and government partners on national and international scales. In the case of tsunami early warning, for example, an RT-GNSS network can provide multiple inputs in an operational system starting with rapid assessment of earthquake sources and associated deformation, which leads to the initial model of ocean forcing and tsunami generation. In addition, terrestrial GNSS can provide direct measurements of a tsunami through the associated traveling ionospheric disturbance from several hundreds of km away as they approach the shoreline, which can be used to refine tsunami inundation models. Any operational system like this has multiple communities that rely on a pan-Pacific real-time open data set. Other scientific and operational applications for high-rate GNSS include glacier and ice sheet motions, tropospheric modeling, and better constraints on the dynamics of space weather.

While progress has been made toward more open and free data access across national borders and toward more cooperation among cognizant government sanctioned "early warning" agencies, some impediments remain making a truly operational system a work in progress. Combining existing data sets and user communities, for example seismic and tide gauge observations with GNSS and meteorological data products, has proven complicated because of issues related to metadata, appropriate data formats, data quality assessment in real-time and other issues related to using these products operational forecasting.

UNAVCO has embarked on significant improvements to the original infrastructure and scope of our networks. We anticipate that the Plate Boundary Observatory (PBO) and related networks will form a backbone for these efforts with high quality, low latency raw and processed GNSS data as well as providing a platform for integration with other sensors, including broadband and strong motion seismometers. Low-cost MEMS accelerometers already have been deployed at 22 PBO stations in two clusters in California. Other additional and substantial upgrades are required across these networks, however, starting with upgrading the GNSS receiver, through robust data collection, archiving and open distribution mechanisms, to efficient data-processing strategies. UNAVCO is currently in a partnership with the stakeholders to define, develop, and deploy all segments of this improved geodetic network. We present the overarching goals together with current and planned future state of this international resource.

Keywords: Seismogeodesy, EarthScope, Plate Boundary Observatory, Earthquake Early Warning, Tsunami Early Warning



Improvement of Offshore Earthquake Location in Earthquake Early Warning System

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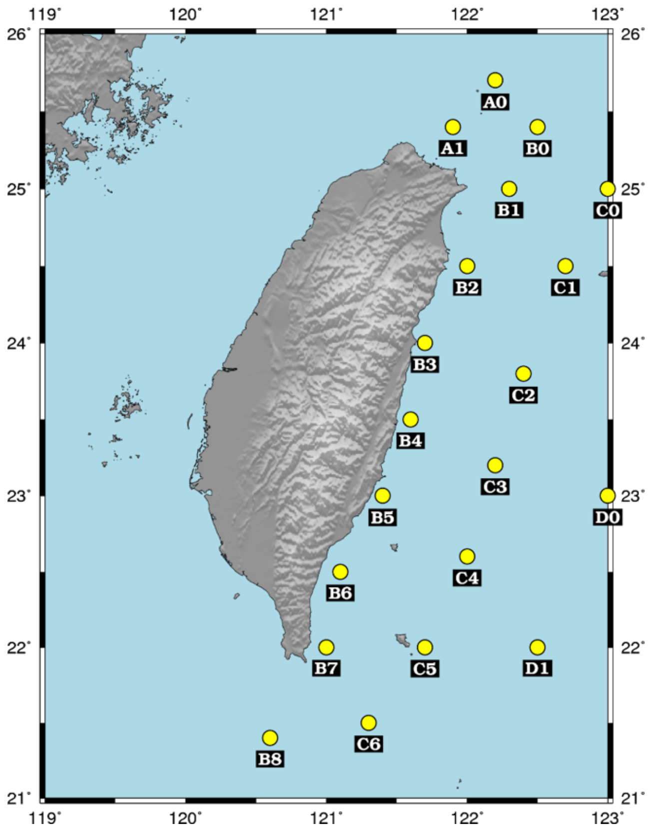
We propose a simple method to improve the accuracy of location estimations for offshore earthquakes in the earthquake early warning (EEW) system. In the Geiger method for earthquake location (Geiger, 1910), a trial epicenter, depth and origin time are required in the location procedure. Usually the trial epicenter is given by the centroid of all triggered stations. The given centroid may far away from the actual epicenter for offshore events. As a result, the Geiger method may lead to a local minimum and the estimated earthquake location may be wrong. Instead of choosing the centroid as trial epicenter, we predefined 20 locations on the offshore area as trial epicenters and concurrently implemented those programs running Geiger method with the predefined ones separately. We assume the best estimation of earthquake location is given by the most timesaving program. The online EEW system has been tested from June of 2016 to January of 2017, detecting 155 earthquakes with magnitude range from 3.1 to 6.0. The results show that using predefined locations as trial epicenters in the Geiger method is able to not only improve the accurate of offshore earthquakes but also reduce the processing time.

Keywords: earthquake early warning, earthquake location, Geiger method

Predefined Locations



Online Test in the EEW system