Implementation of a Global Navigation Satellite System (GNSS) Augmentation to Tsunami Early Warning Systems

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with generous support from NASA

<u>In Support of IGS 2014 and IUGG 2015 Recommendations</u>: The Global Geodetic Observing has issued a Call for Participation to establish a working group as a catalyst and motivating force for the definition of requirements, identification of resources, and for the encouragement of international cooperation in the establishment, advancement, and utilization of GNSS for a Augmentation to the Tsunami Early Warning Systems.

IGS

IAG GGOS

Recommendation of the IGS 2014 Workshop:

http://kb.igs.org/hc/en-us/articles/204125433-2014-IGS-Workshop-Summary-Recommendations

The IGS encourages and coordinates member organizations to establish protocols and develop a system for establishment of moderate density GNSS network (e.g. in Indo-Pacific), real-time data sharing, analysis centers, and advisory bulletins to the responsible government agencies in accord with the IAG's Global Geodetic Observing System (GGOS) Theme #2 for natural hazards applications.

International Union of Geodesy and Geophysics-2015:

http://www.iugg.org/resolutions/IUGGResolutions2015.pdf

…..Resolves:

•To engage with IUGG member states to promote a GNSS augmentation to the existing tsunami early warning systems.

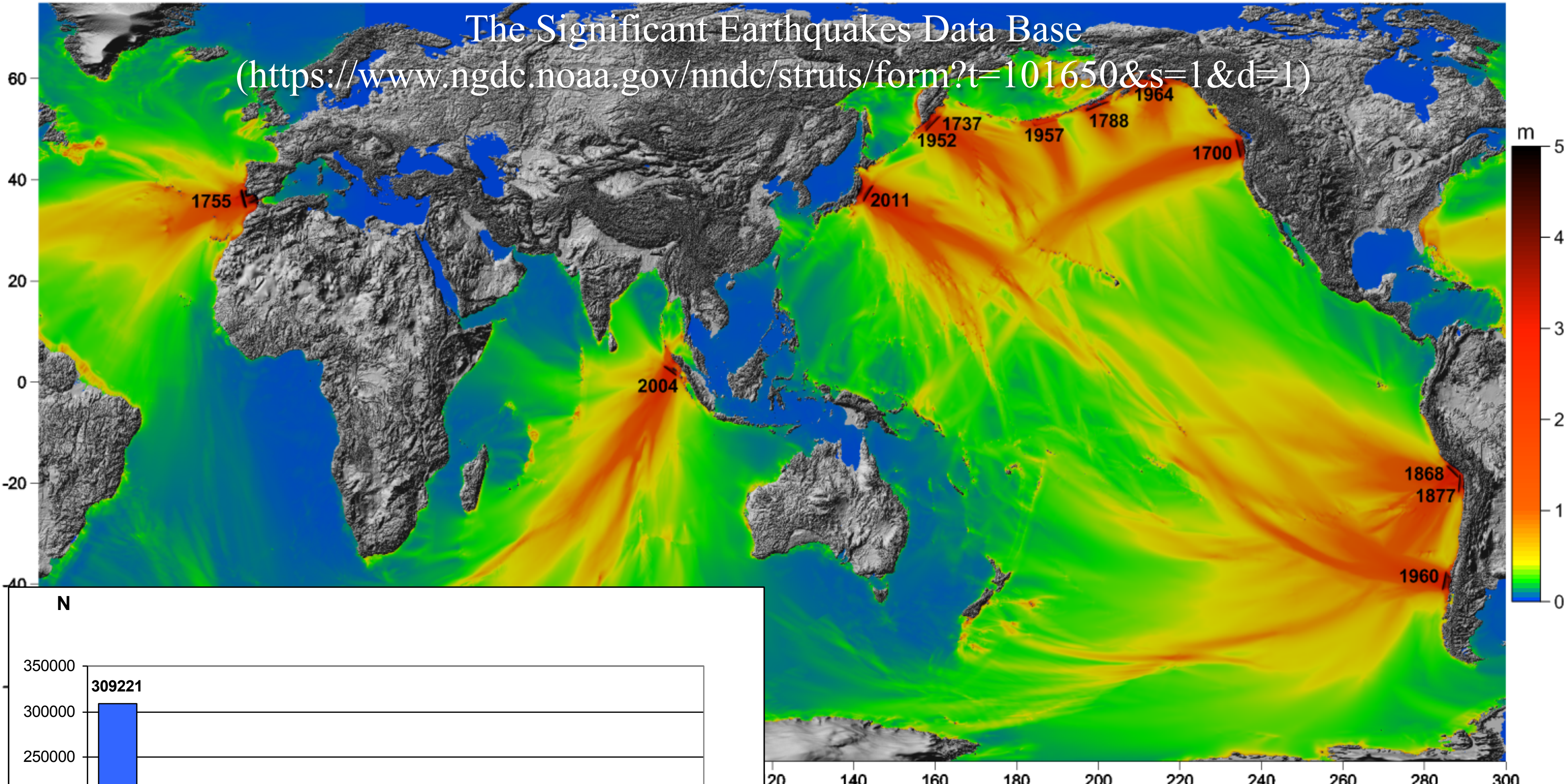
•Initially to focus upon the Pacific region because the high frequency of tsunami events constitutes a large risk to the region's large populations and economies, by developing a prototype system, together with stakeholders, including scientific, operational, and emergency responders.

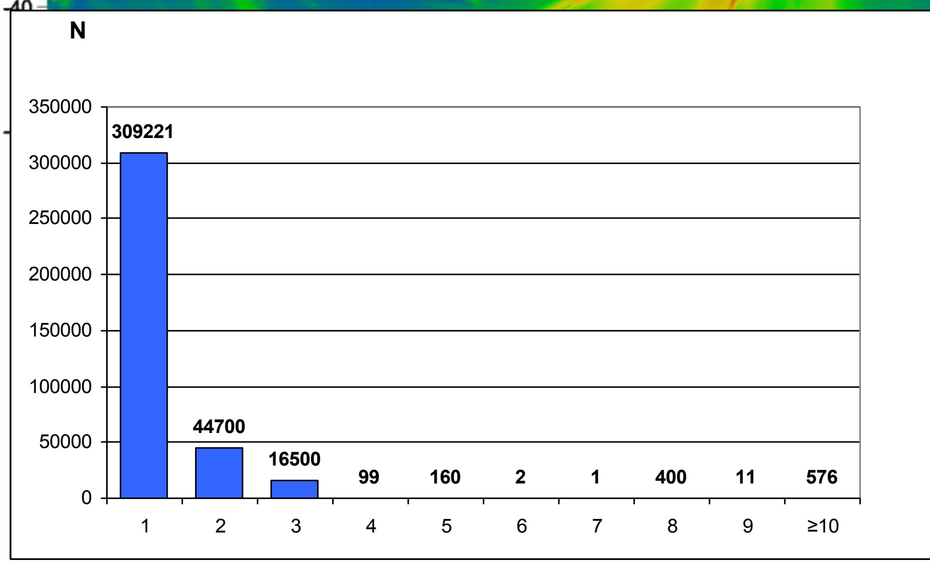
Intergovernmental Coordination Group for the Pacific Tsunami Warning and Mitigation System- Honolulu, 2015

http://www.ioc-tsunami.org/index.php?option=com_oe&task=viewDocumentRecord&docID=15449

Asia-Pacific Space Geodynamics Project- Moscow, 2015

http://agora.guru.ru/display.php?conf=apsg-2015&page=item004&PHPSESSID=ulifq5u9fi4o8retibdl1fu3b3





Energy flux for trans-oceanic mega-tsunamis historically known. Insert figure – distribution of fatalities over the tsunami propagation time (up to 85% fatalities occur during the first hour). Calculations are made in ICT SB RAS by means of MGC numerical package for tsunami modeling (Chubarov, Babailov, Beisel, 2011).

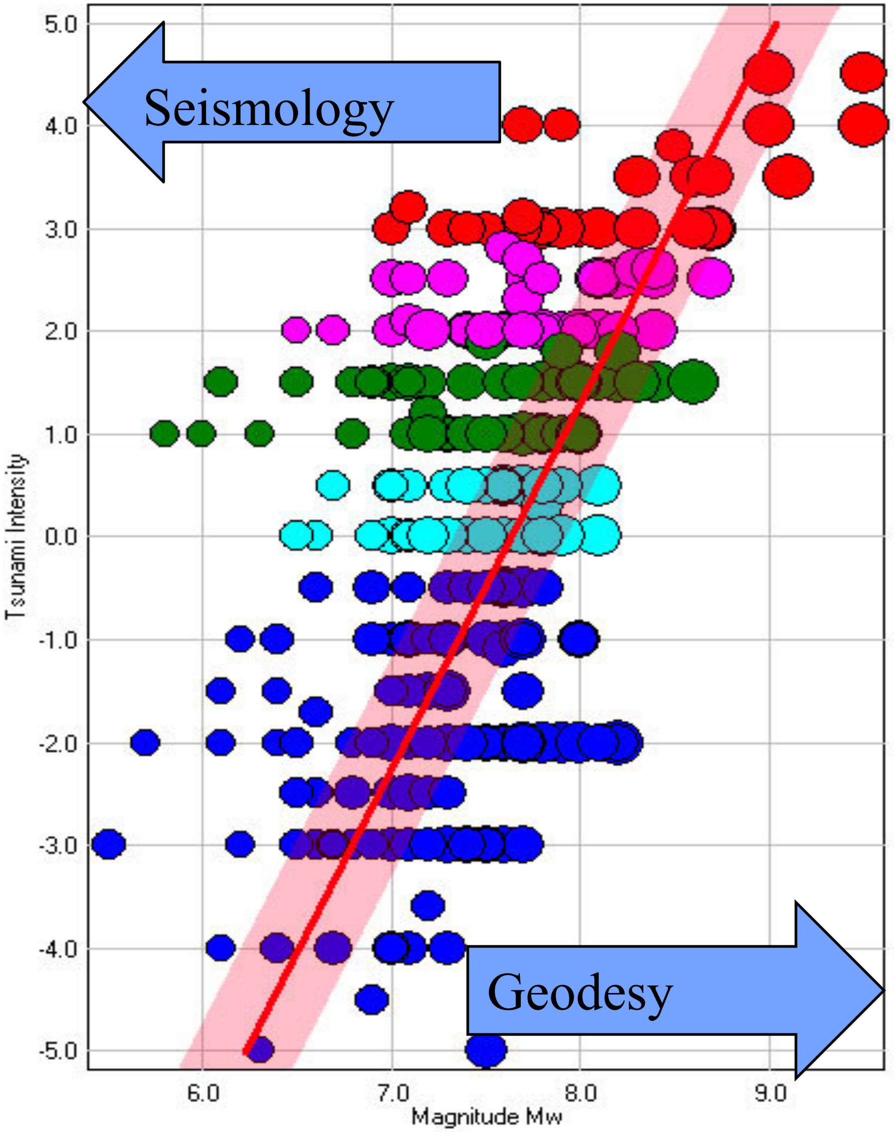
Ref: Gusiakov et al, 2015

Phuket Island, Thailand
December 26, 2004

The Tsunami Warning System must provide accurate tsunami predictions within minutes of mega-thrust earthquakes.

Phuket Island, Thailand
December 26, 2004

Why GNSS Augmentation? Because Minutes Matter!



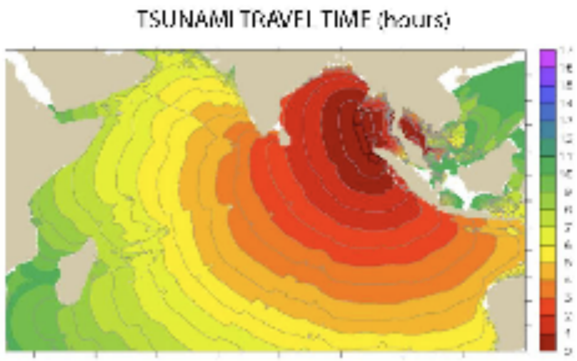
Global Tsunami Magnitude (on Soloviev-Imamura scale) vs Earthquake Moment Magnitude since 1900 (from-Gusiakov et al, 2015)

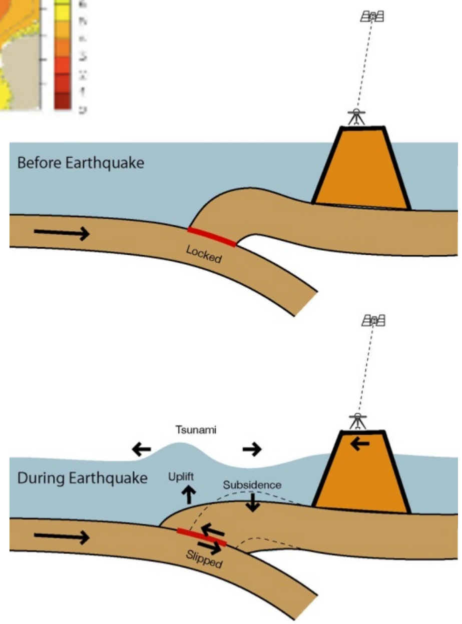
For mega-thrust earthquakes GNSS augmentation can provide accurate and timely input to tsunami warning models for both near and far fields of the epicenter.

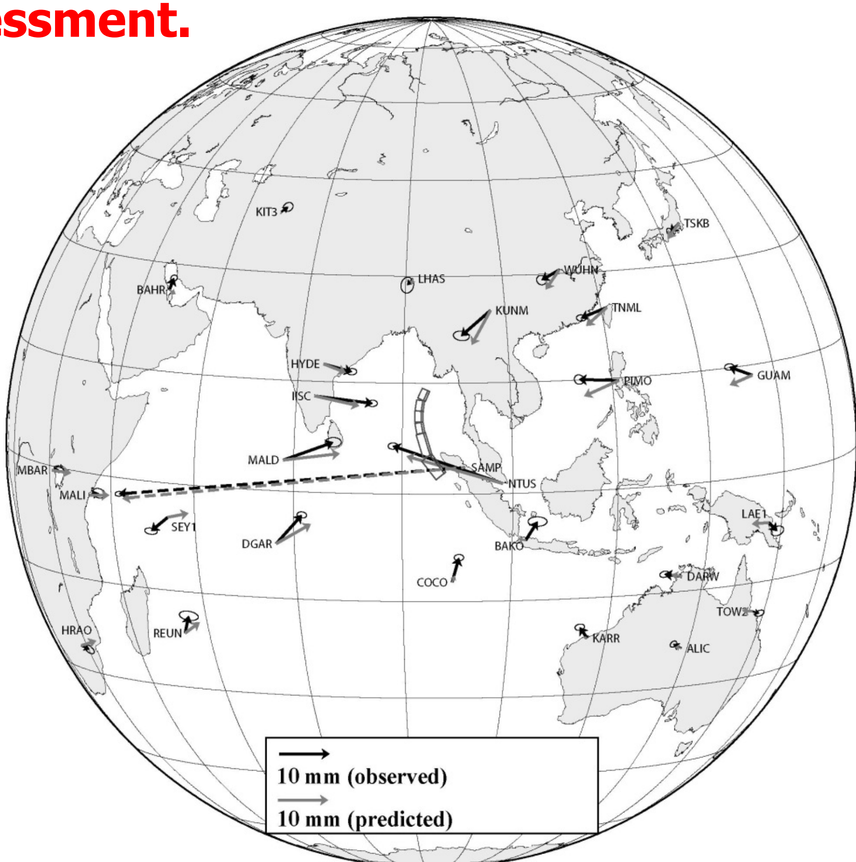
- **GNSS provides accurate position and velocity of ground displacements**
- **Accurate inversions for earthquake moment magnitude can take less than 3 minutes for near field warning**
- **GNSS measurements of ionospheric dynamics (changes in Total Electron Content) can be used to track tsunamis for far field warning.**

Three Studies of the Regional Geodetic Data Taken December 26, 2004 Demonstrated the Value of a Global Regional GNSS Real Time Network

A Dense Global Real Time GPS Network would have warned of the Indian Ocean Tsunami within 15 minutes- days before the broad band seismic analysis-provided an accurate assessment.

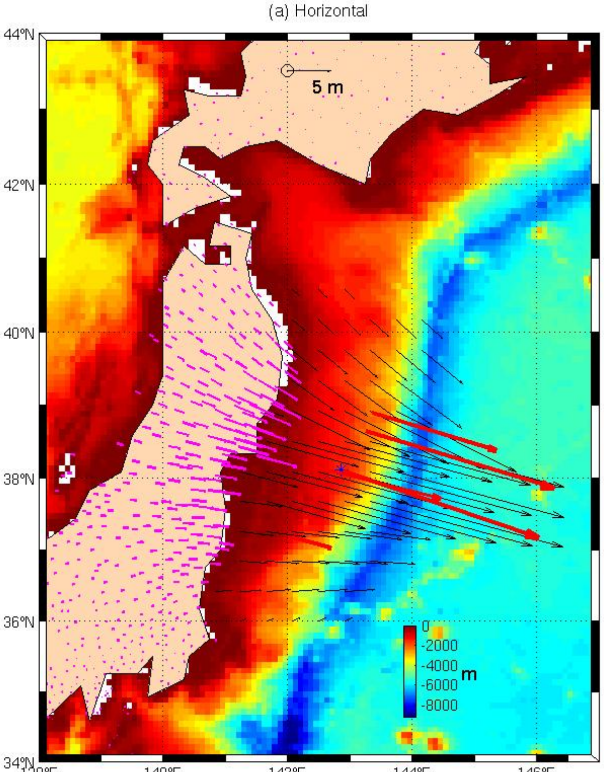






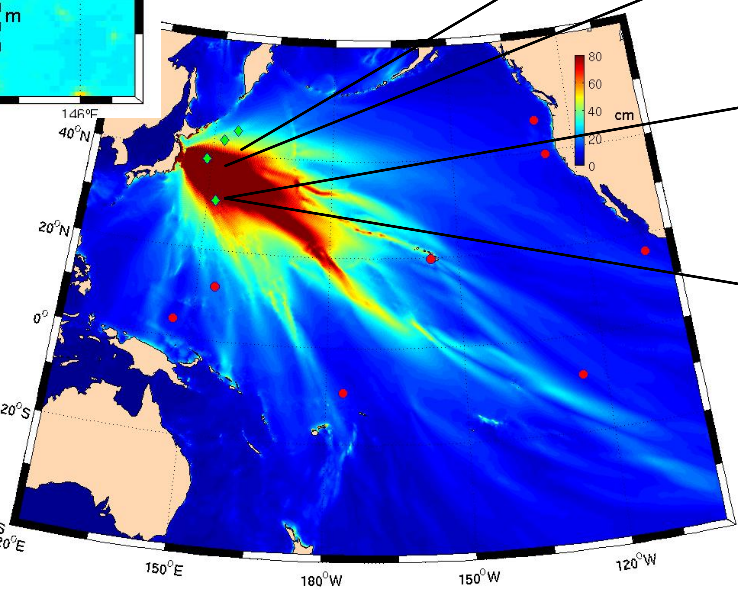
- •Blewitt et al. 2006, Rapid determination of earthquake magnitude using GPS for tsunami warning systems
- •Sobolev et al, 2007, Tsunami early warning using GPS Shield arrays
- •Song et al, 2007, Detecting tsunami genesis and scales directly from coastal GPS stations

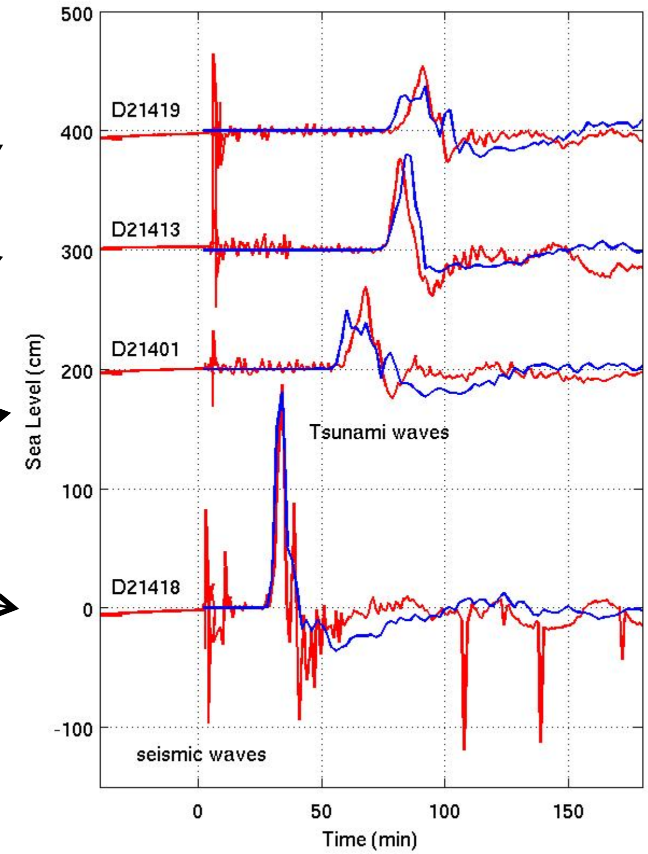
Predicting the 2011 Tohoku-oki Tsunami



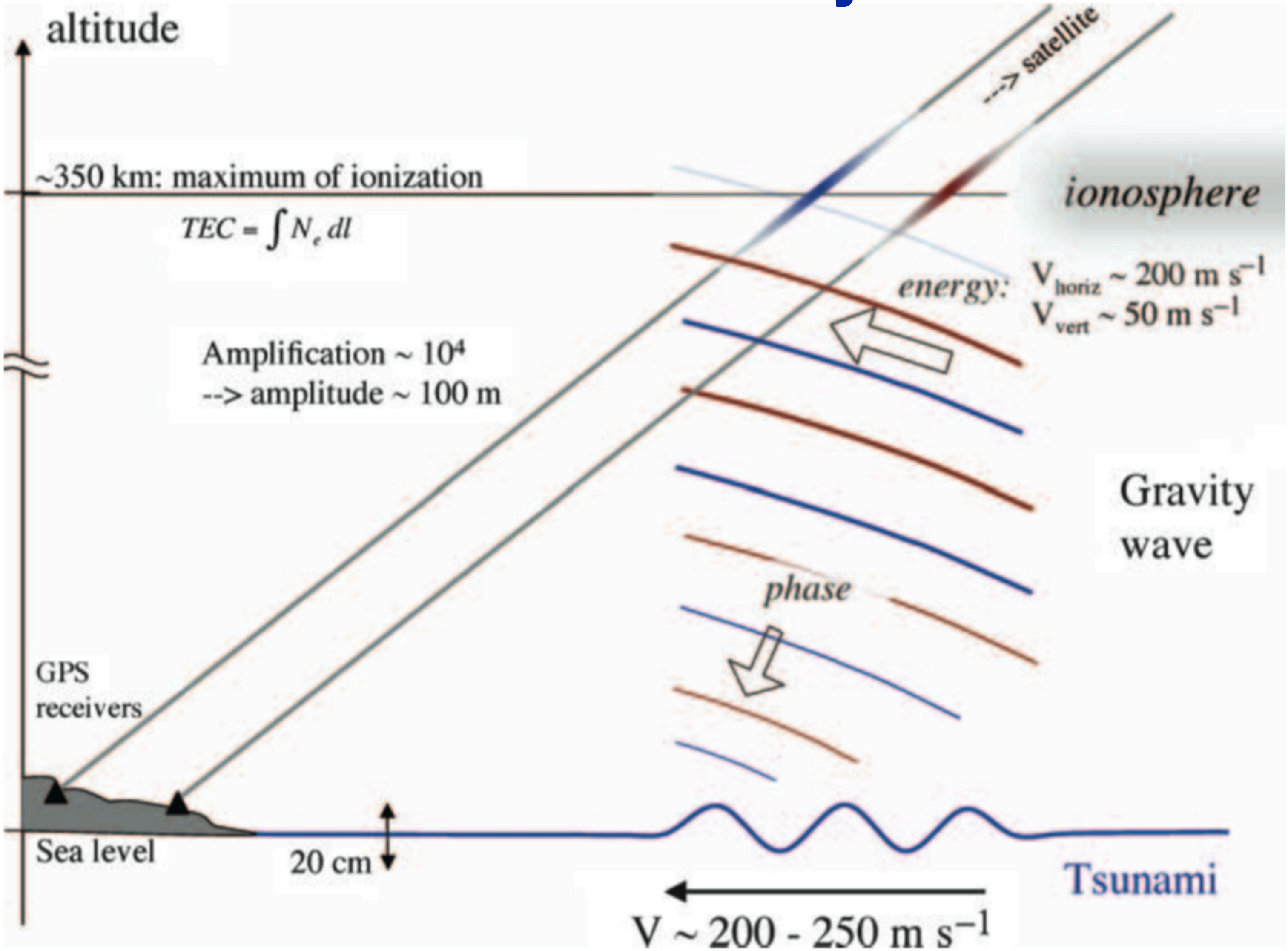
Using a small subset of the 1,200 GPS stations (GeoNet) on the Japanese Islands, hind cast studies using different approaches demonstrated accurate earthquake magnitude and tsunami predictions within 5 minutes (e.g. Song et al., 2012, Ohta et al., 2012, Melgar et al,, 2012).

< 300 sec



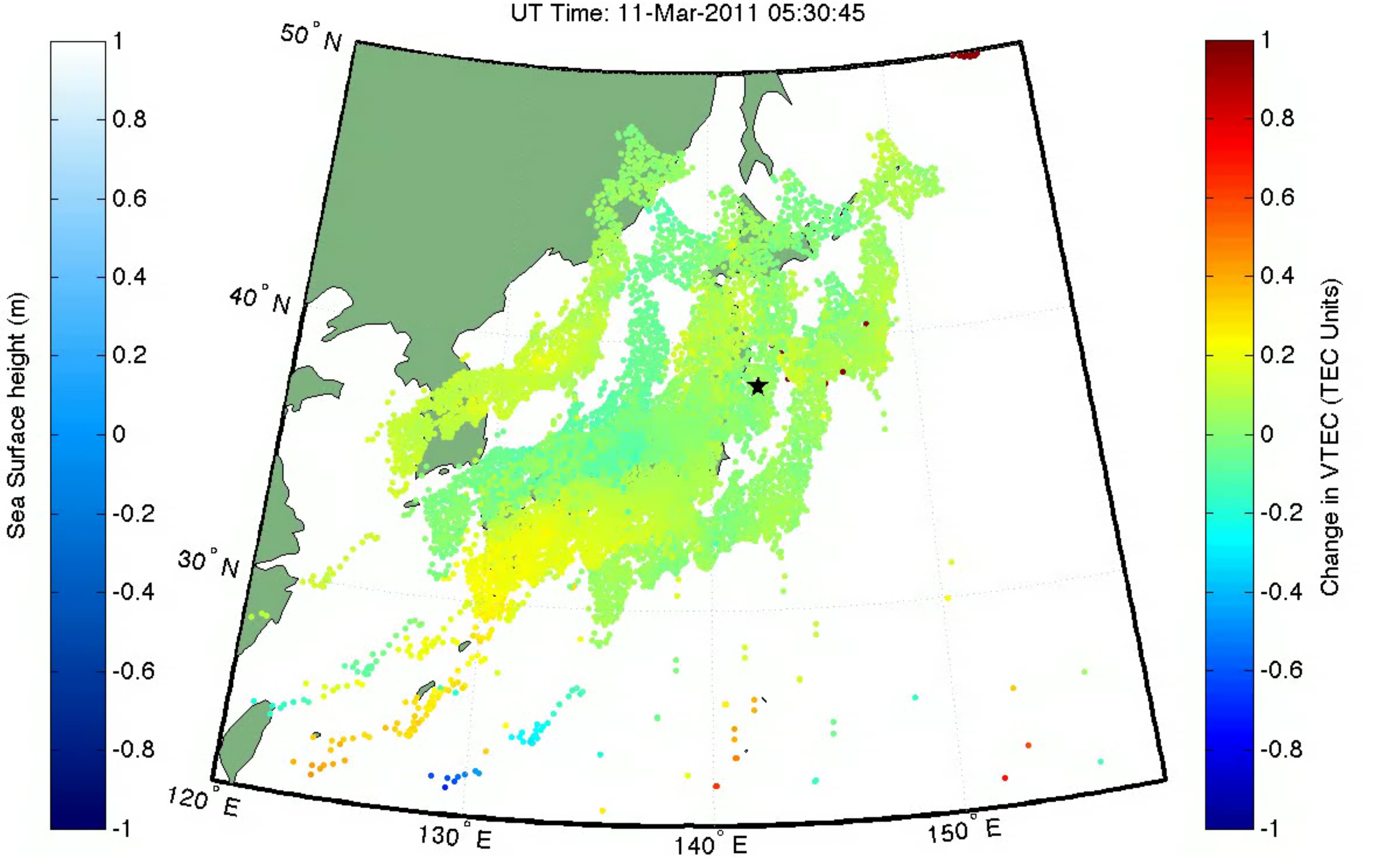


GNSS Can Detect Coupled Ionospheric Gravity Waves More Than 1300 km beyond the Horizon



From *Artru et al.*, 2005

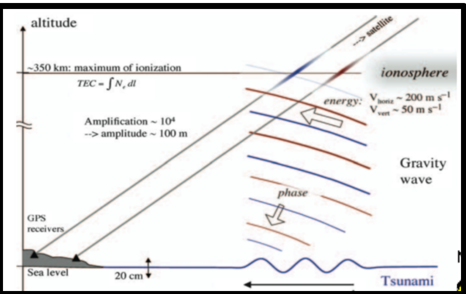
GSI's GEONET Also Captured the Ionospheric Coupled Waves and Imaged the Tsunami Generation and Propagation-For the First Time

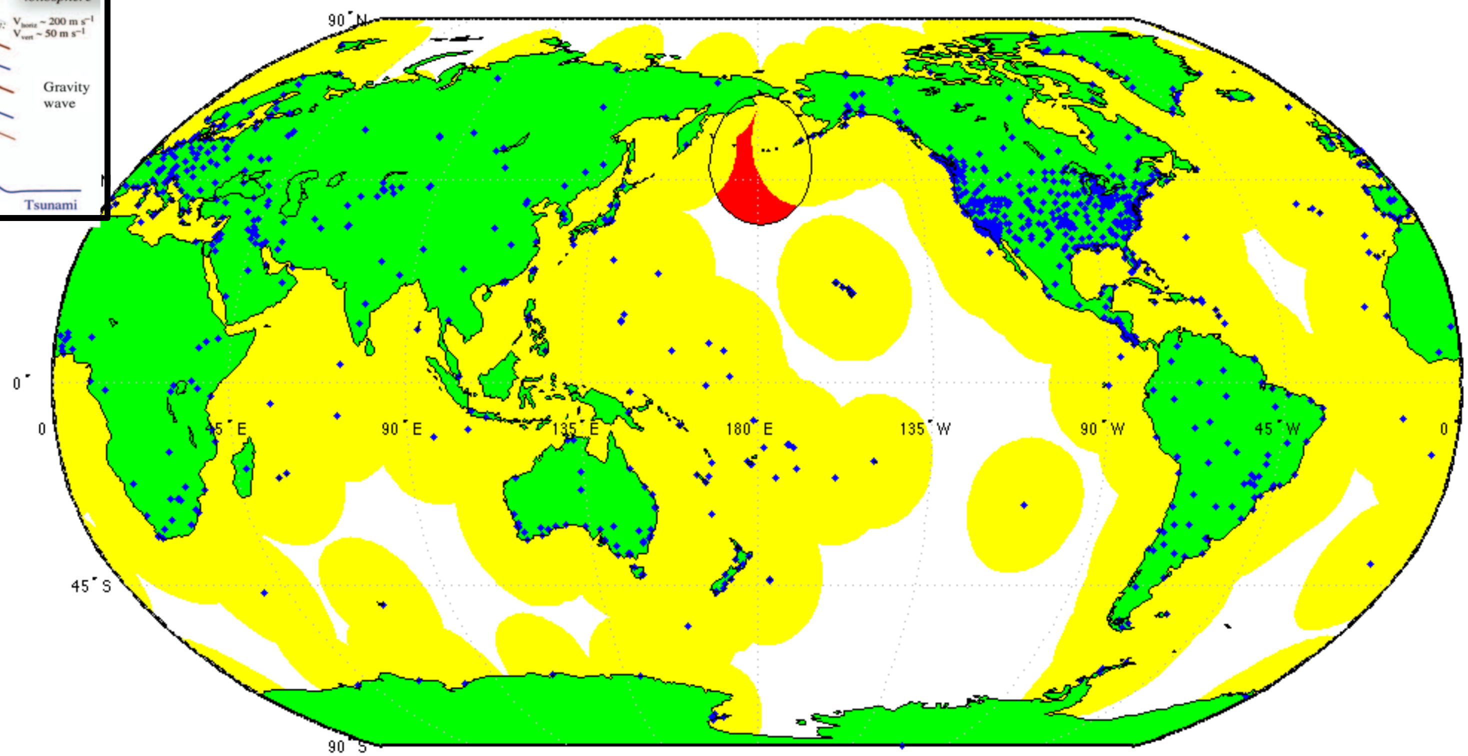


Ionospheric Response to Mw9.0 Tohoku Earthquake and Tsunami in Japan on March 11, 2011, A.Komjathy, D.A.Galvan, M.P Hickey, P.Stephens, Mark Butala, and A.Mannucci, (http://visibleearth.nasa.gov/view.php?id=77377)

Tsunami Tracking Capability of Current Network

Yellow zones indicate region of ionospheric piercing point detection from existing GNSS receiver network. Assumes 10 degree elevation and the Ionospheric shell at 450 km



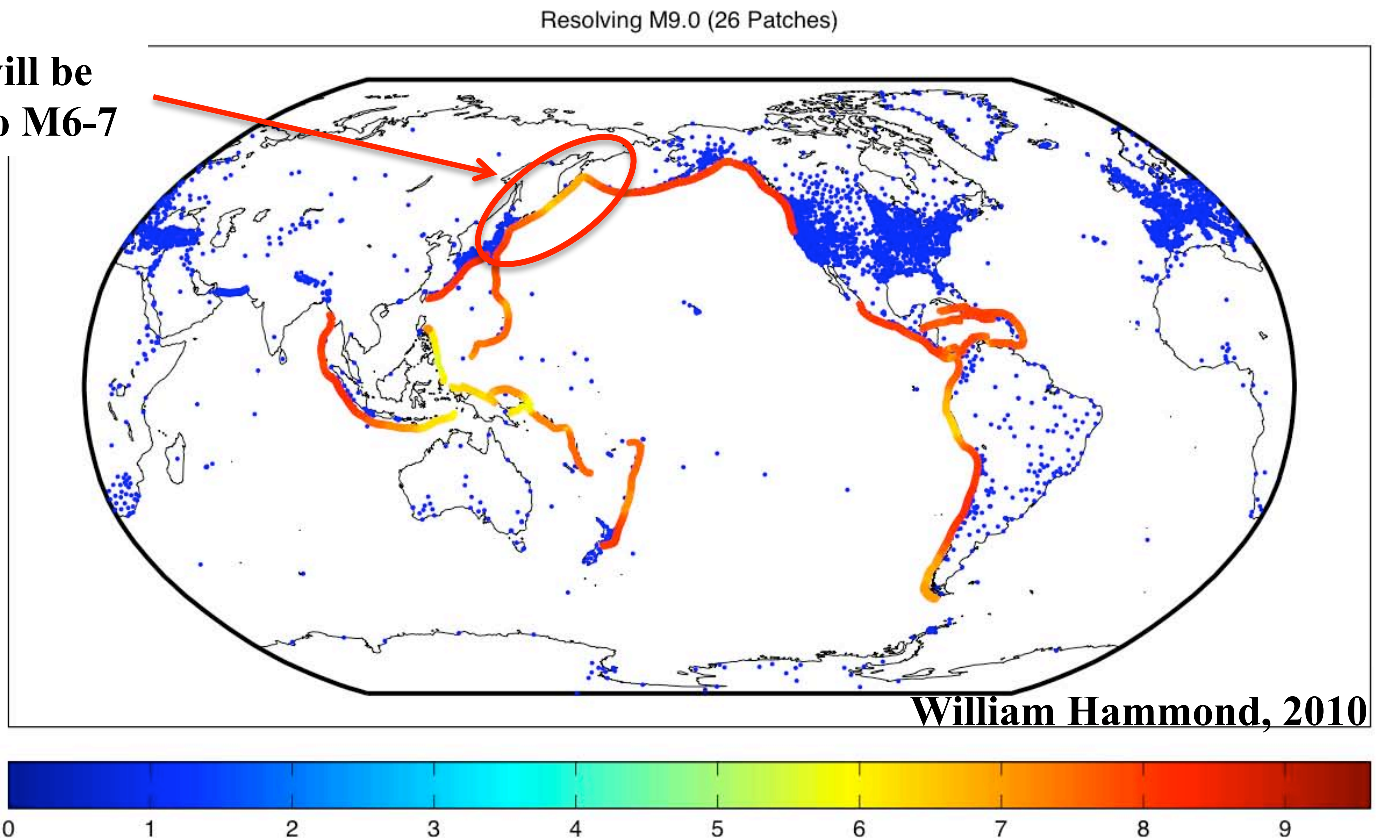


Red zone is only circum-Pacific gap in coverage assuming all stations are upgraded to real time operation.

Tsunami Prediction Capability of the Current Network

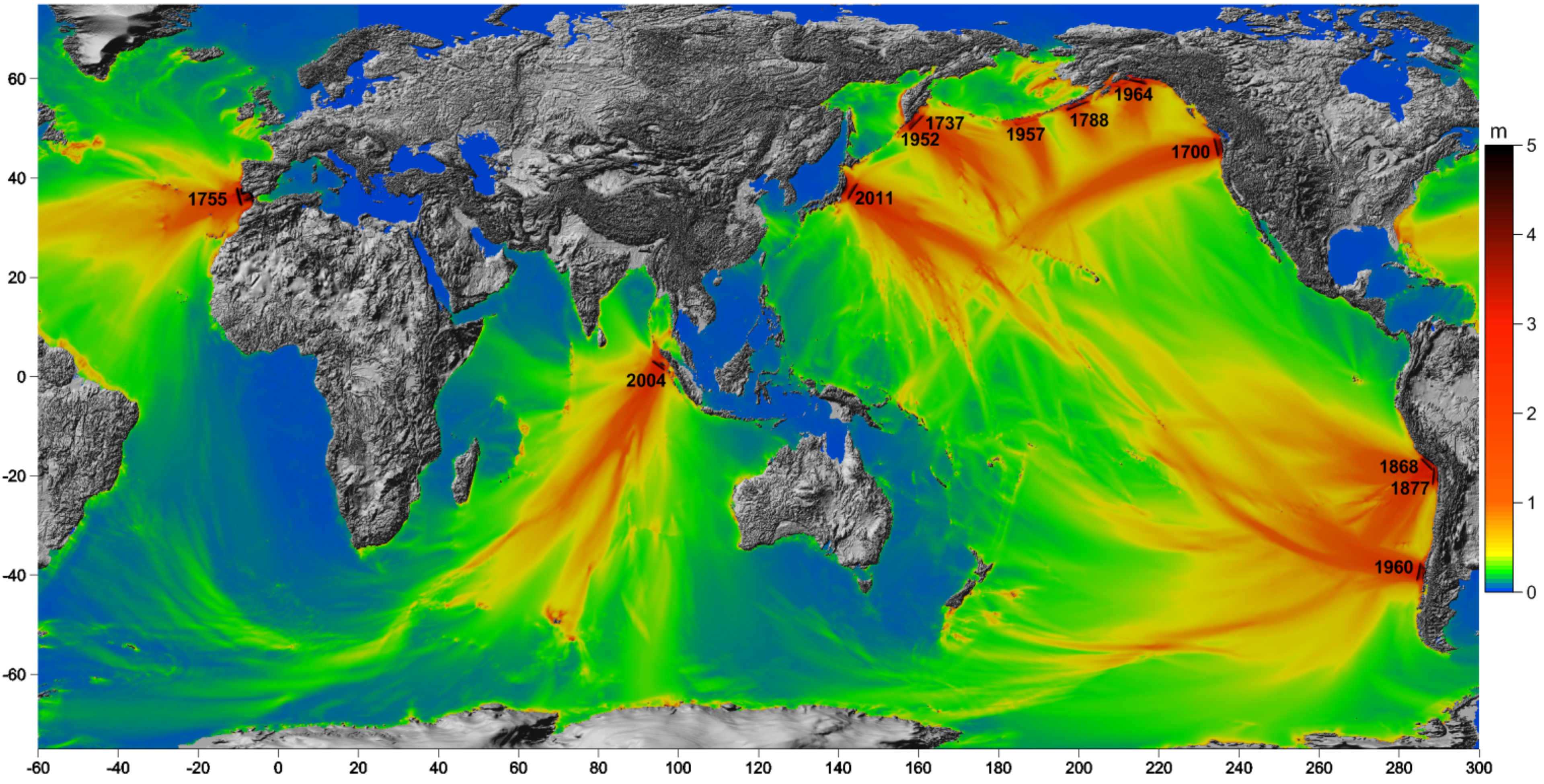
Simulations indicate that the Kamchatka-Kuril region and many other regions along the "ring of fire" are not equipped with a sufficient density of GNSS receivers to enable GNSS-based resolution of large earthquakes.

M9 earthquake will be under-resolved into M6-7



William Hammond, 2010

Toward the Realization of a GNSS Augmentation to the Tsunami Early Warning System



Toward the Realization of a GNSS Augmentation to the Tsunami Early Warning System

The Working Group will define the fundamental requirements for GNSS augmentation and develop a work plan to achieve these requirements such as:

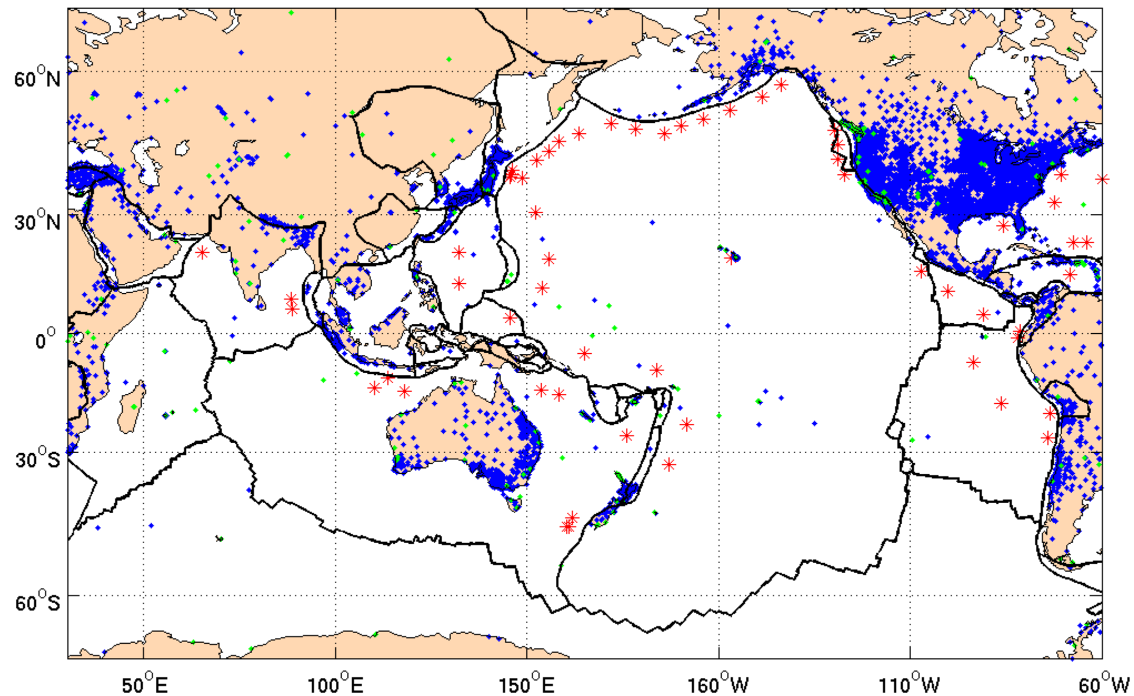
- The GNSS network of sufficient near field real-time stations to capture the permanent displacement signal and provide a rapid and accurate estimate of earthquake magnitude- simulations and real time network expansion may be required;
- The GNSS network must have sufficient far field stations to provide a reference frame and to provide for ionospheric tracking of propagating tsunamis;
- GNSS analysis systems must handle near real-time data with the precise estimation of GNSS orbits and surface displacements;
- The broad regional distribution of Indo-Pacific mega-thrust earthquakes and the regional impact of resulting tsunamis requires the sharing of GNSS capabilities and data;
- As recommended by the IUGG, the working group should strive to insure that the project is integrated as an augmentation to existing tsunami warning systems that include seismometers, ocean bottom pressure sensors, tide gauges, and ocean buoys in order to optimize warning accuracy and timeliness..

Toward the Realization of a GNSS Augmentation to the Tsunami Early Warning System

•The Pacific Region is well populated with GNSS CORS Networks - many that stream data in real-time though some regions need to be densified.

•Several research groups have worked to advance GNSS-aided rapid earthquake magnitude assessment and tsunami prediction.

•Several international teams have recommended the establishment of a GNSS-aided tsunami warning network.

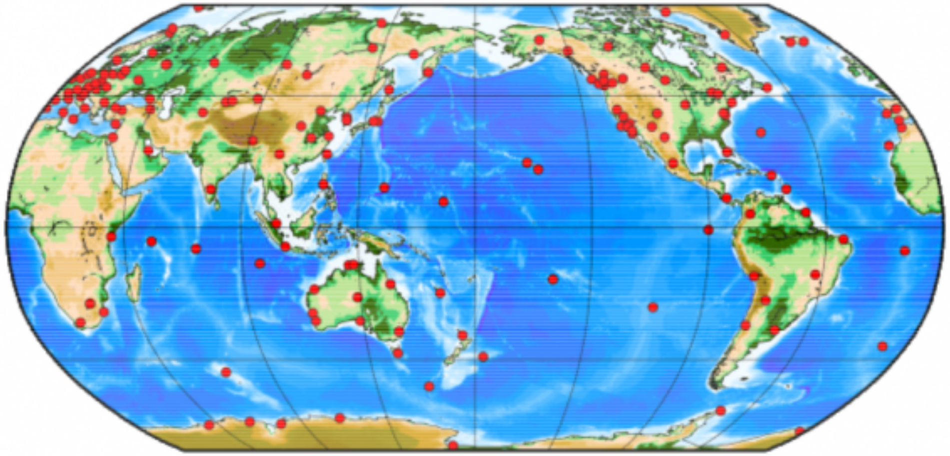


Multi-use GNSS receivers, if streamed and analysed in real-time will begin to provide:

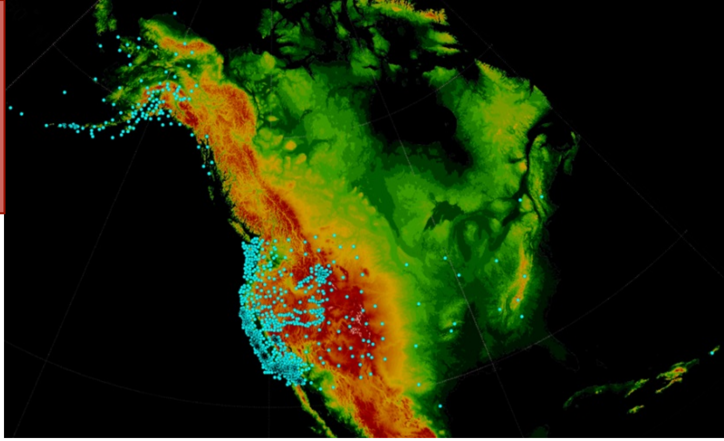
• Rapid accurate assessment of earthquake magnitudes > Mw8; and

• Ionospheric detection of propagating tsunamis.

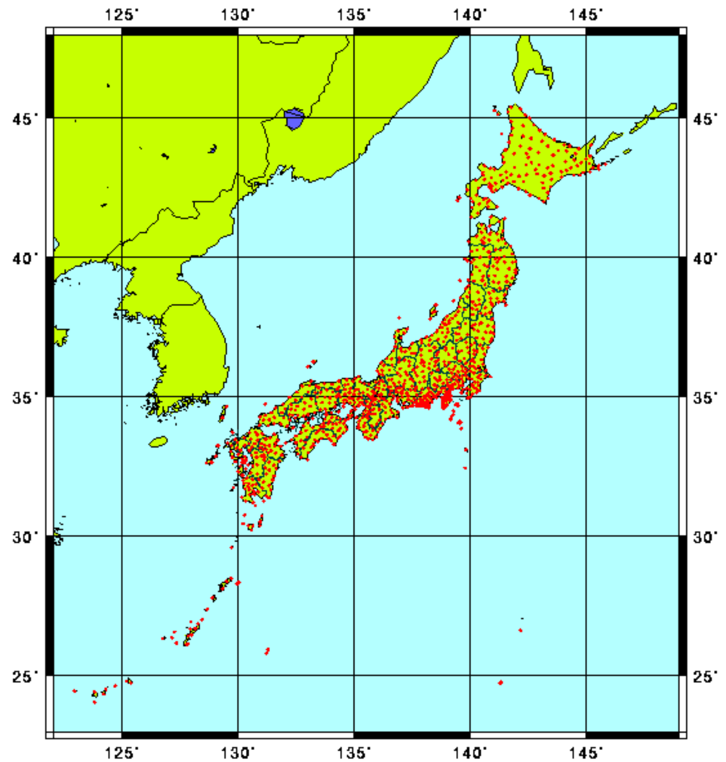
The GGOS Call for Participation seeks encourage partnerships for a robust Tsunami Early Warning Network



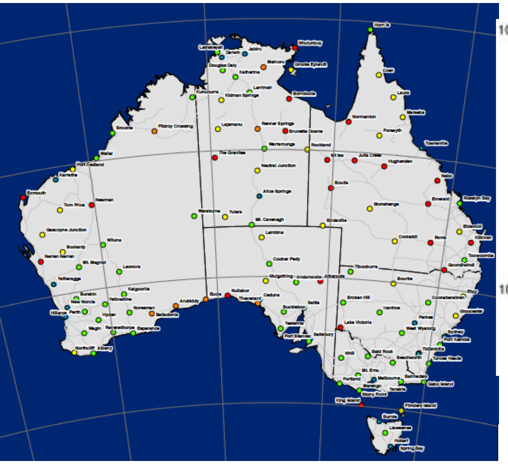
GGOS/IGS Real-Time Network



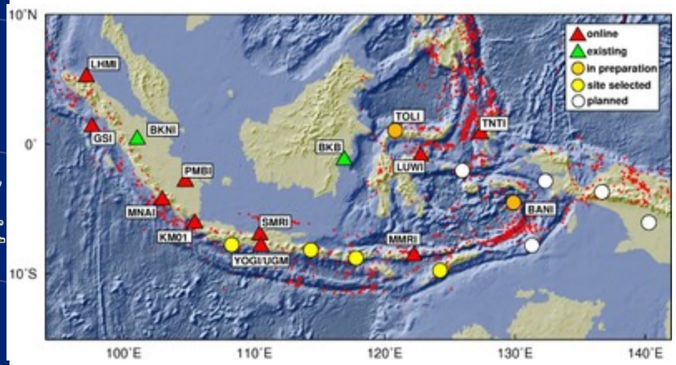
Earthscope Plate Boundary Observatory



The GSI GEONET



Australian AUScope



German-Indonesian Tsunami Early Warning (GITEWS)

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Backup viewgraphs

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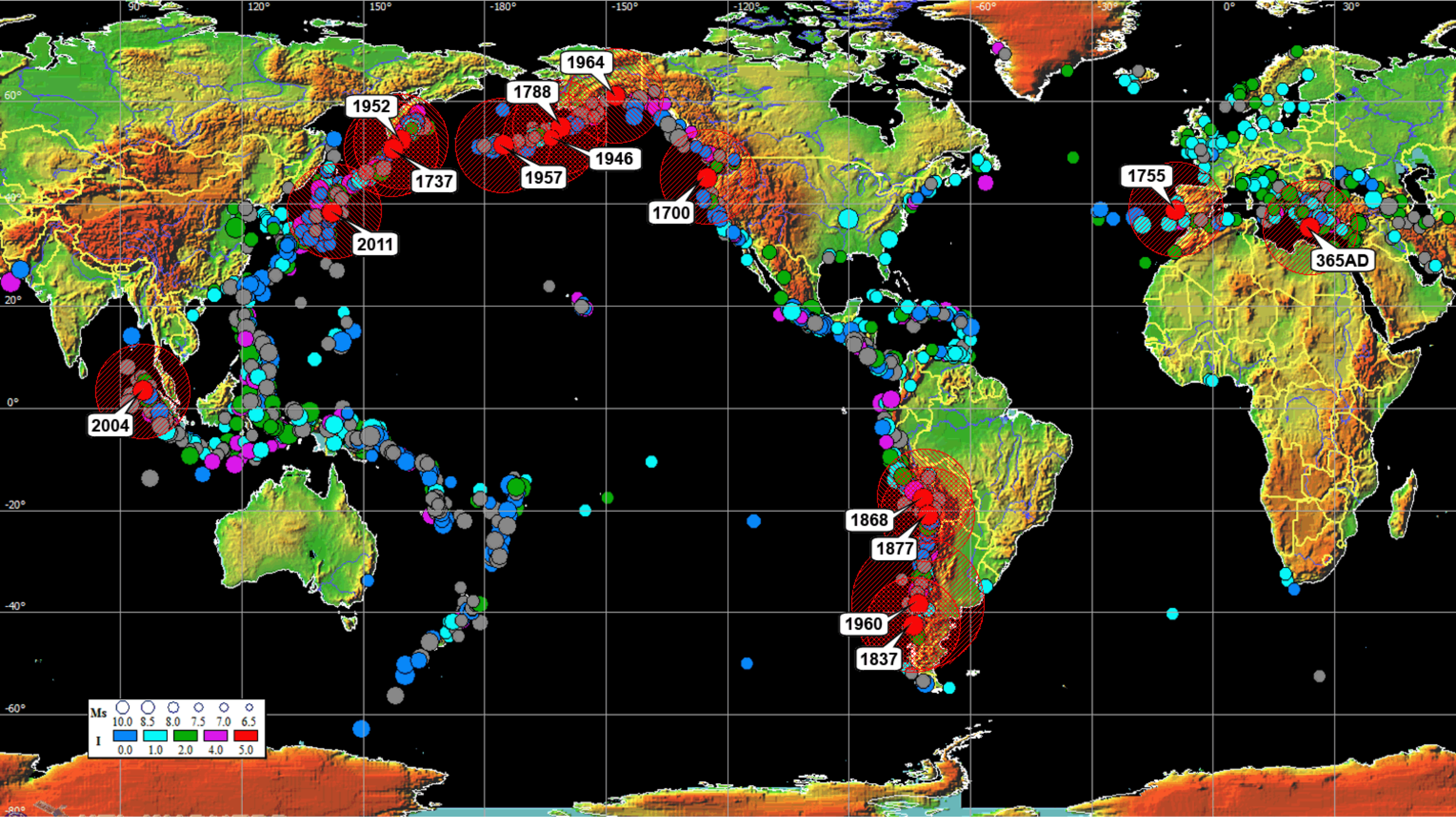

Map of historical tsunamigenic events in the World Ocean. Sources of 2250 events occurred from 2000 BC to 2012 are shown. Color represent the tsunami intensity on Soloviev-Imamura scale. Large red circles highlight the M9 class mega-events resulted in trans-oceanic tsunamis

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