A GNSS Based Tsunami Warning System Augmentation for the Indo-Pacific Region

John LaBrecque
GGOS Geohazards Monitoring Focus Area
IUGG GeoRisk Commission
Overlook Systems Technologies, Inc

Phuket Island, Thailand
December 26, 2004

International Union of Geodesy and Geophysics (IUGG)

IAG GGOS

USTTI 2015 Course
GPS Applications for Disaster Management
Washington, DC October 13, 2015

A Tsunami Warning System must provide accurate and timely tsunami warnings within the first half hour of mega-thrust earthquakes

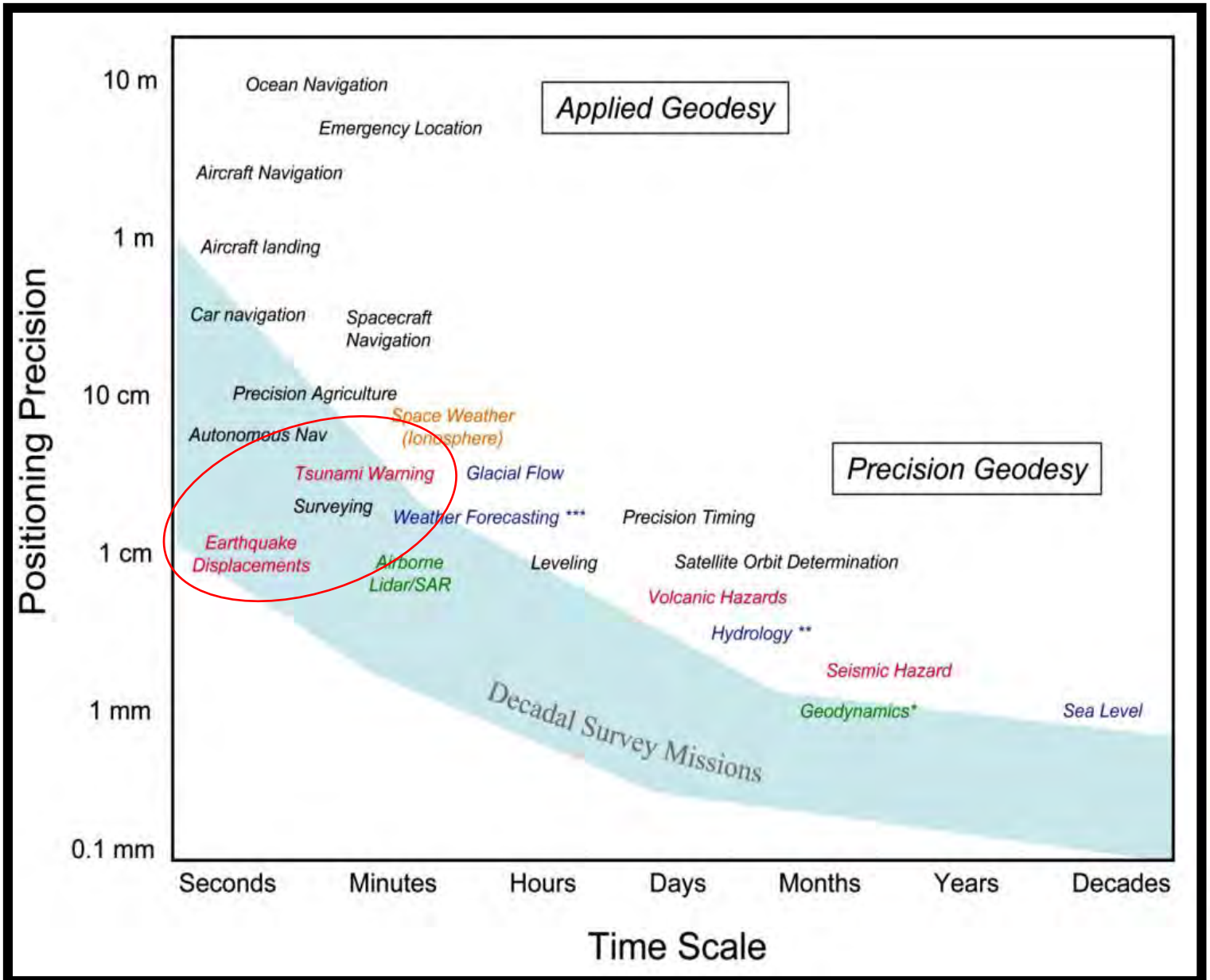
International Union of Geodesy and Geophysics (IUGG)

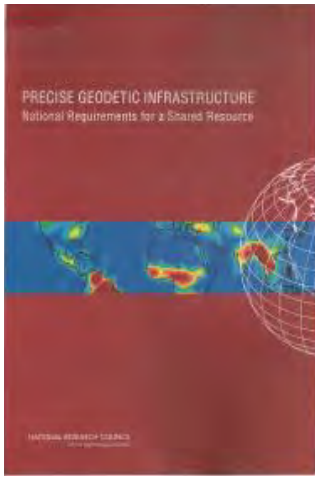
IAG GGOS

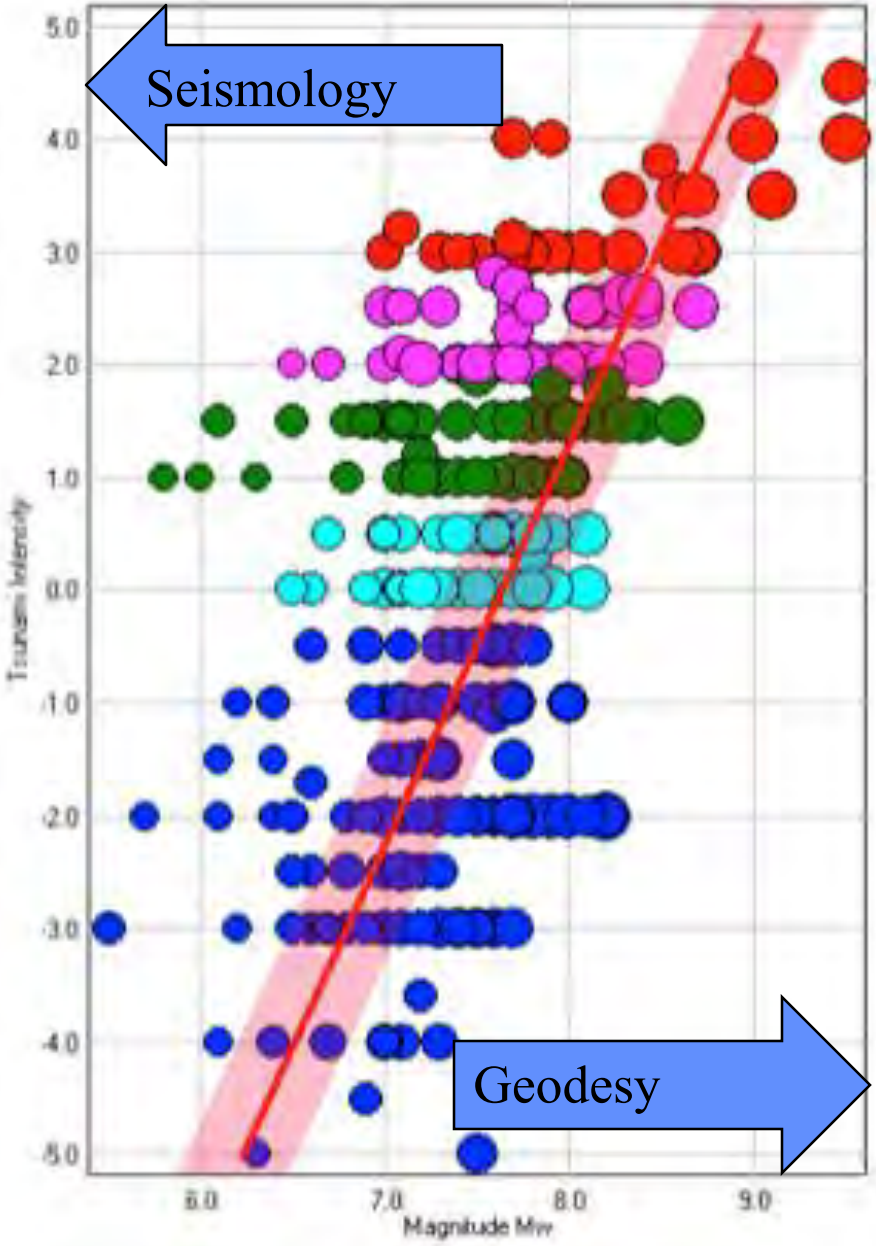
Tohoku March 11, 2011

Fast and Accurate Tsunami Predictions
From Real Time GNSS Analysis

A well distributed Real Time GNSS Ground Network can provide this accurate and timely tsunami warning





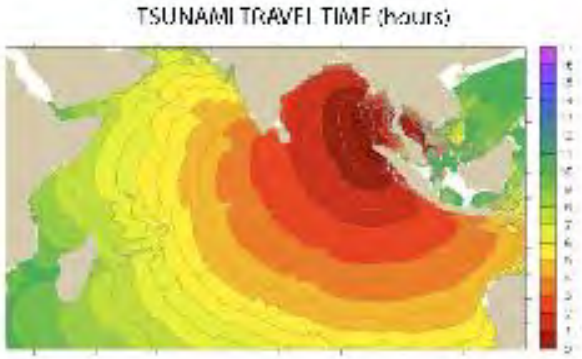


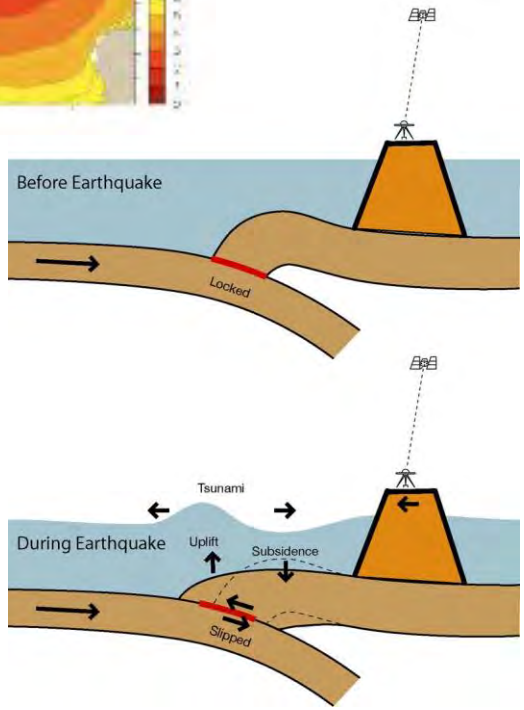
GNSS data can augment seismic data for large earthquakes.

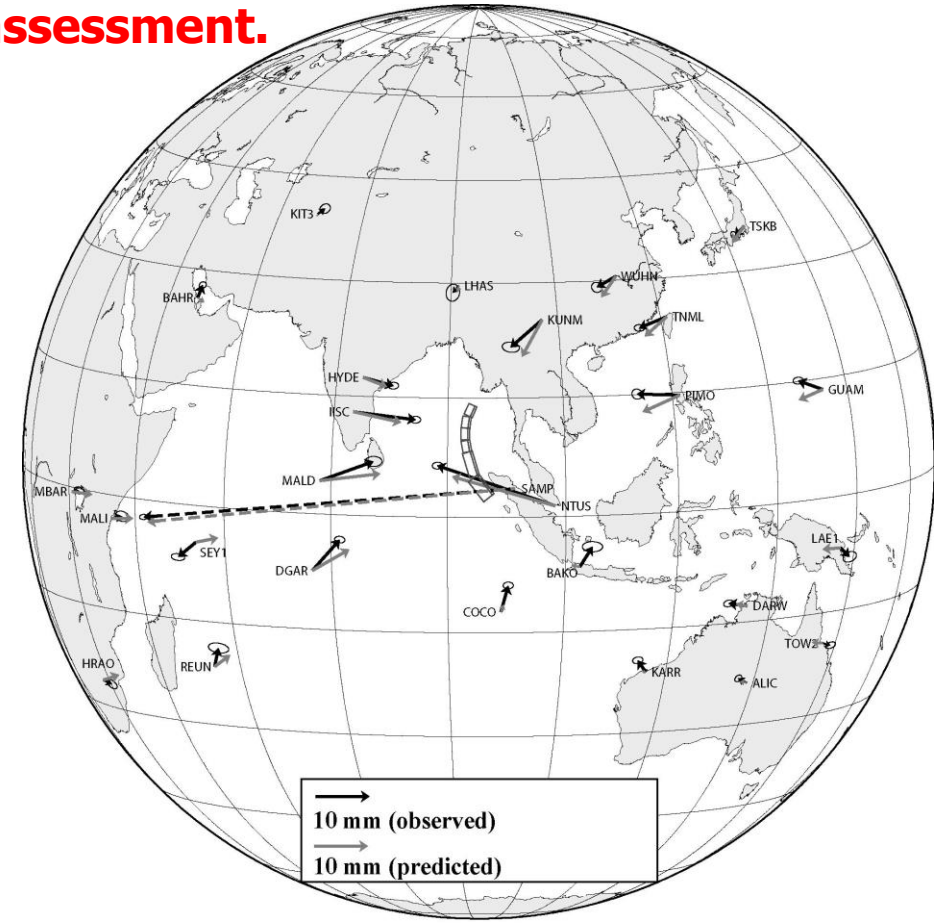
Dependence of tsunami intensity I (on Soloviev-Imamura scale) on Ms magnitude (on the left) and Mw magnitude (on the right) of submarine earthquakes since 1900 in the World Ocean (from-Gusiakov, 2015)

Three Studies of the Regional Geodetic Data Taken December 26, 2004 Recognized 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.

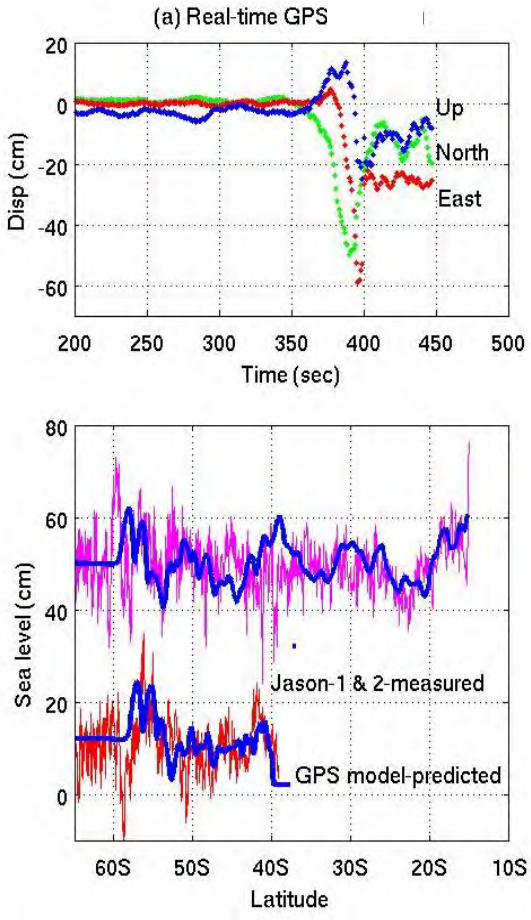


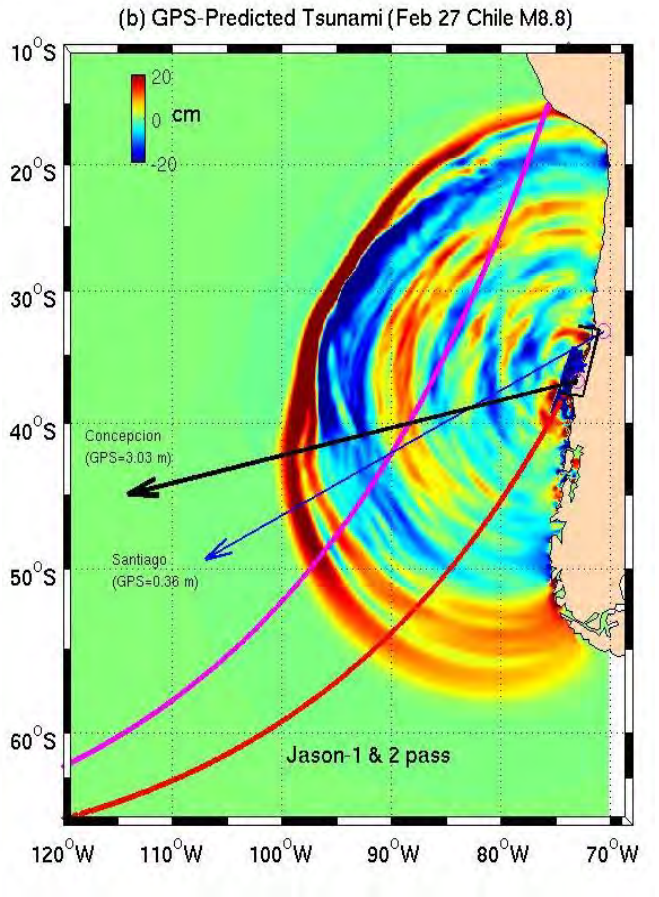




- Blewitt et al. 2006, Rapid determination of earthquake magnitude using GPS for tsunami warning systems
- Sobolev et al, 2007, Tsunami early warning using GPS Shield arrays
- Song et al, 2007, Detecting tsunami genesis and scales directly from coastal GPS stations

February 27, 2010: Chile M8.8 Earthquake Demonstrated First Real Time GPS based Tsunami Prediction





(a): NASA's Global Differential GPS (GDGPS) measured the Chile M8.8 earthquake displacement in real time at Santiago.

(b): JPL GREAT alert team predicted a moderate sized tsunami using the real-time GPS and the Song tsunami generation model.

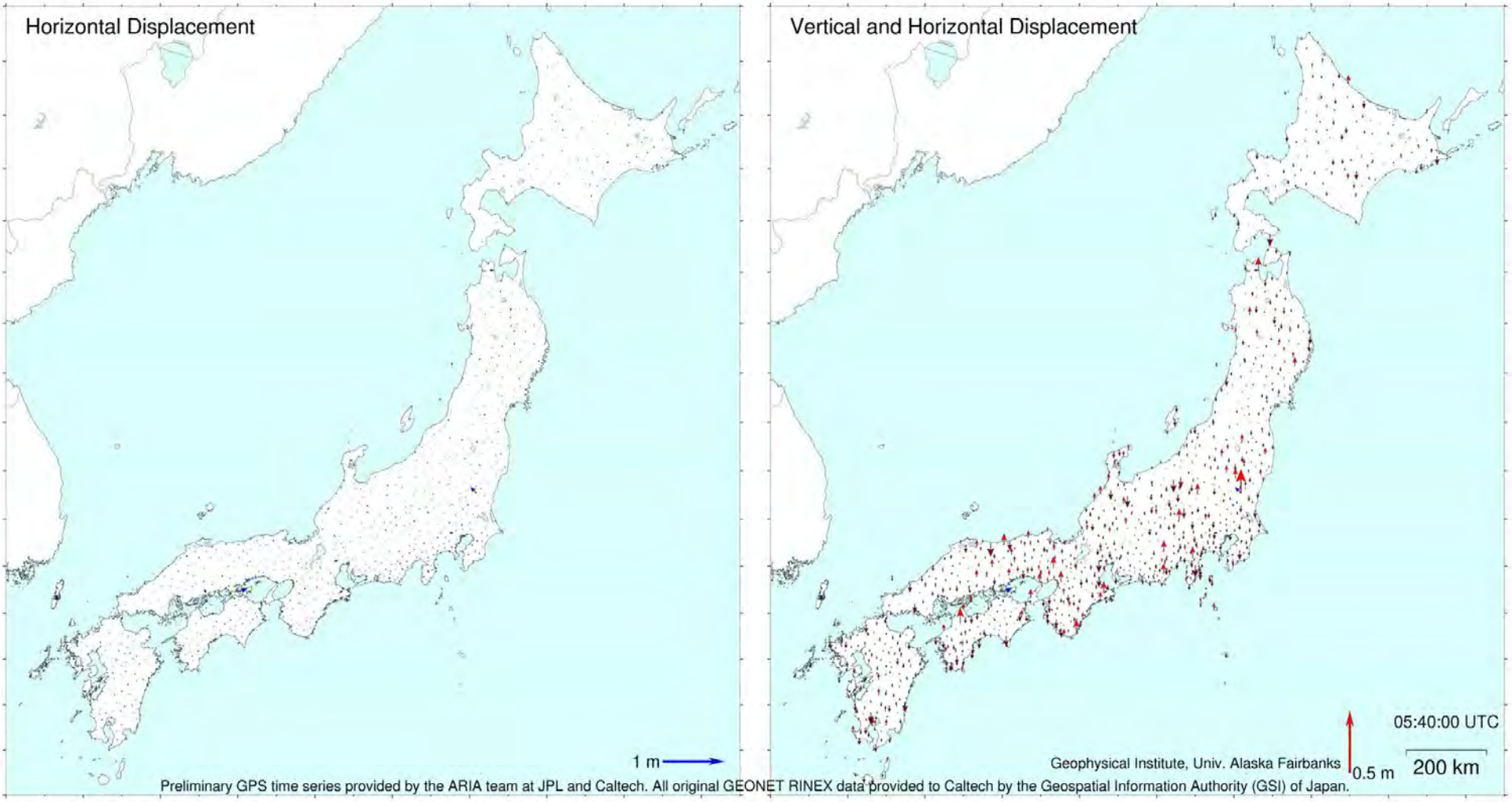
(c): NASA/CNES satellites Jason-1 and Jason-2 confirm the tsunami amplitude prediction of the GPS-based model prediction.

(d): Next steps: Strengthen real time GDPS network, automate models.

March 11, 2011:The GSI GEONET GPS Array

Demonstrated

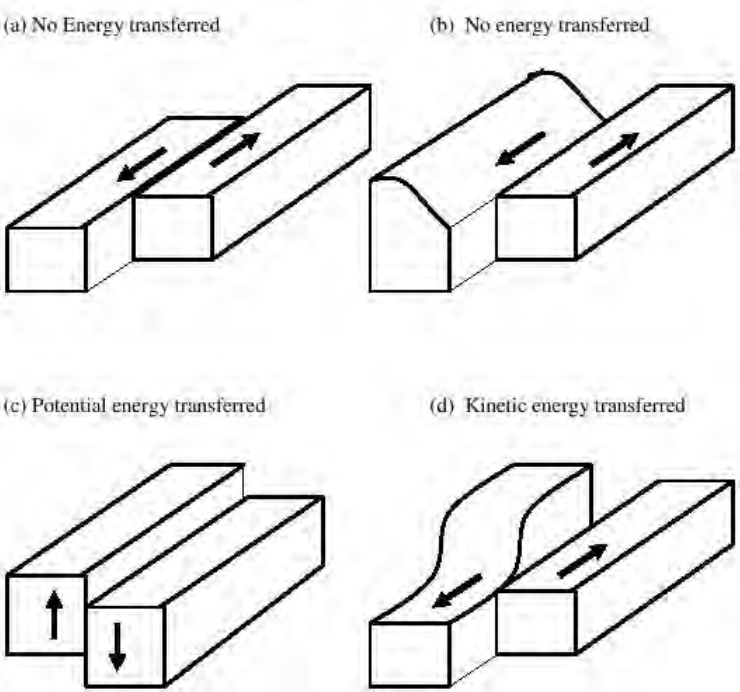
- **Capability to Predict a Tsunami**
- **Observe the Resulting Tsunami**



http://gps.alaska.edu/ronni/sendai2011.html: Ronni Grapenthin

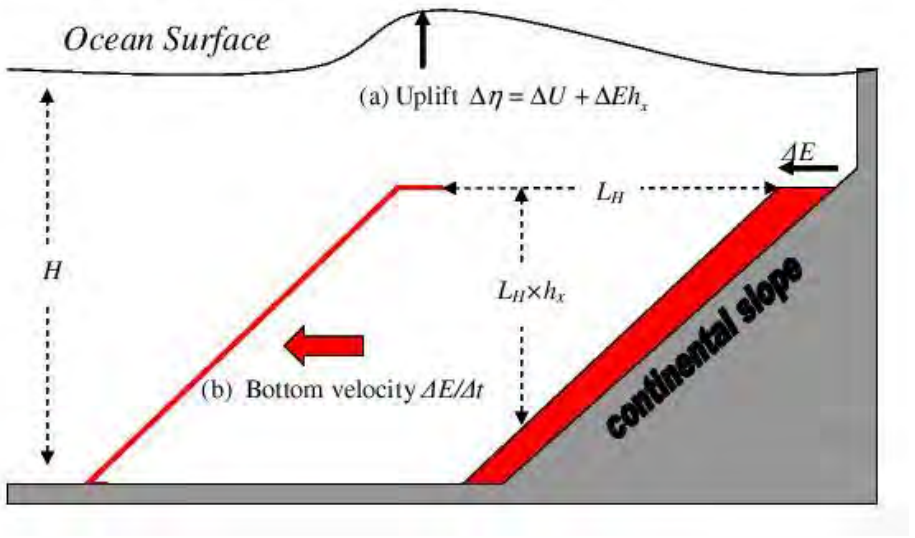
GNSS analysis was shown capable of rapidly describing the total displacement and the momentum transfer from land to ocean needed for an accurate and timely tsunami prediction.

1: Lateral motions of continental slopes transfer the major tsunami energy



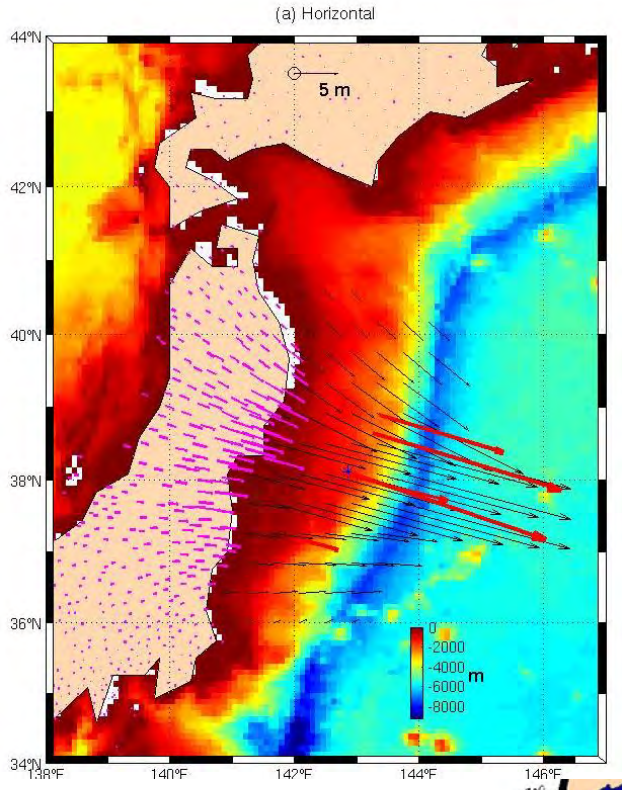
2: To detect tsunamis source energy:

Both PE and KE are needed



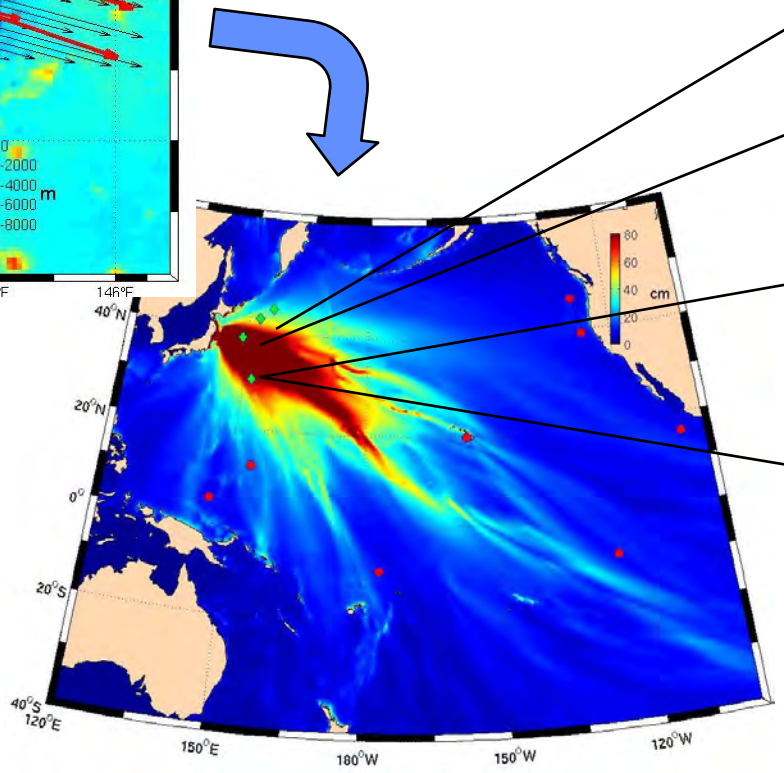
Tony Song, January 2009

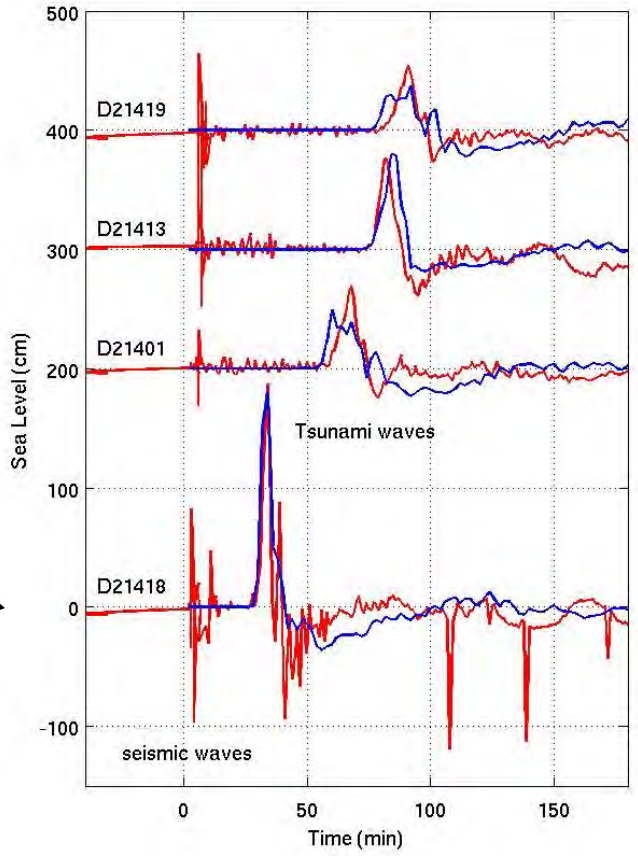
The 2011 Tohoku-Oki Tsunami: Prediction



There are about 1,200 GPS stations (GeoNet) on Japanese Islands. Several hind cast studies demonstrated accurate earthquake magnitude and tsunami predictions within 5 minutes (e.g. Song et al., 2012, Ohta et al., 2012, Melgar et al., 2012)

.



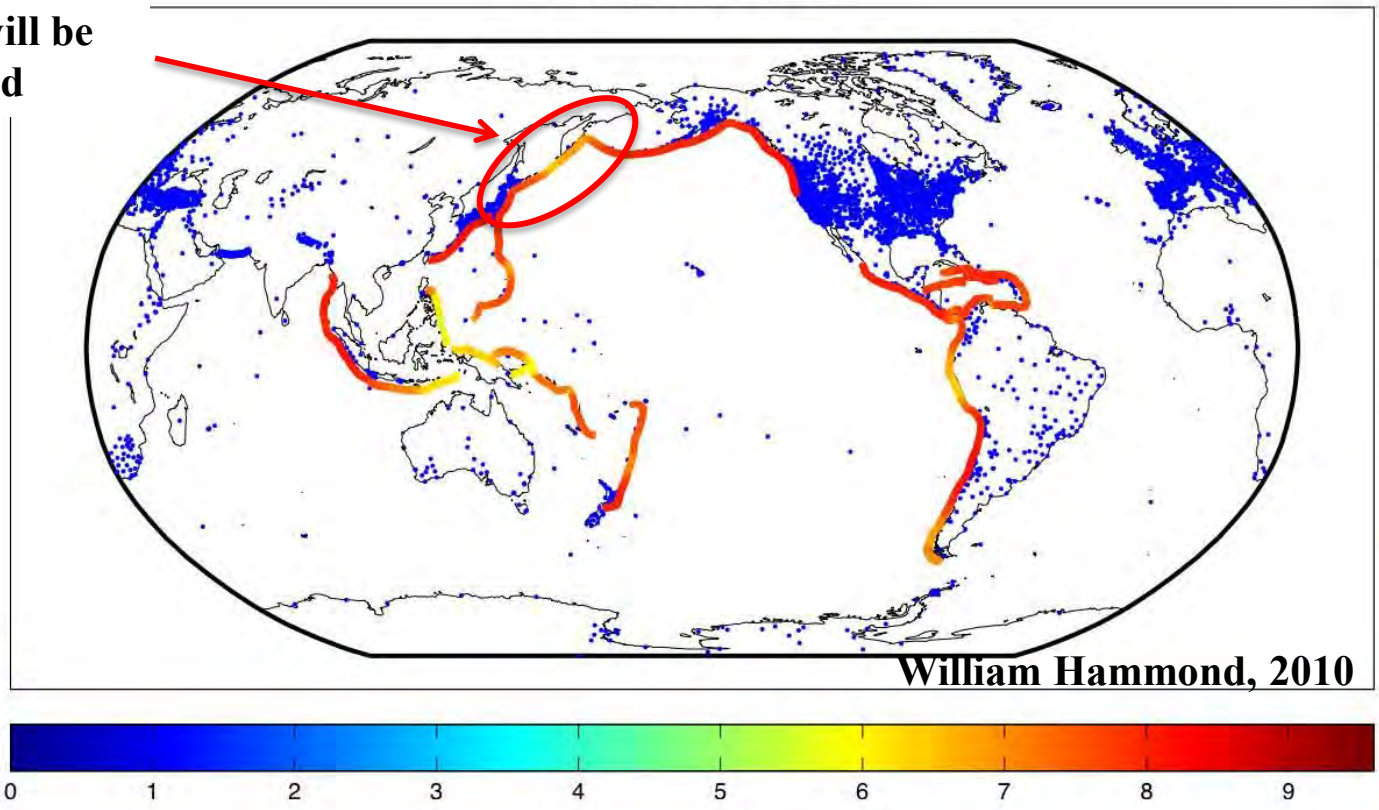


Tsunam

Resolvability of Magnitude of M9 Earthq
NGL Processed GPS Stations ☐

Simulating the ability to resolve a M9 Earthquake along the "Ring of Fire" using available GPS networks

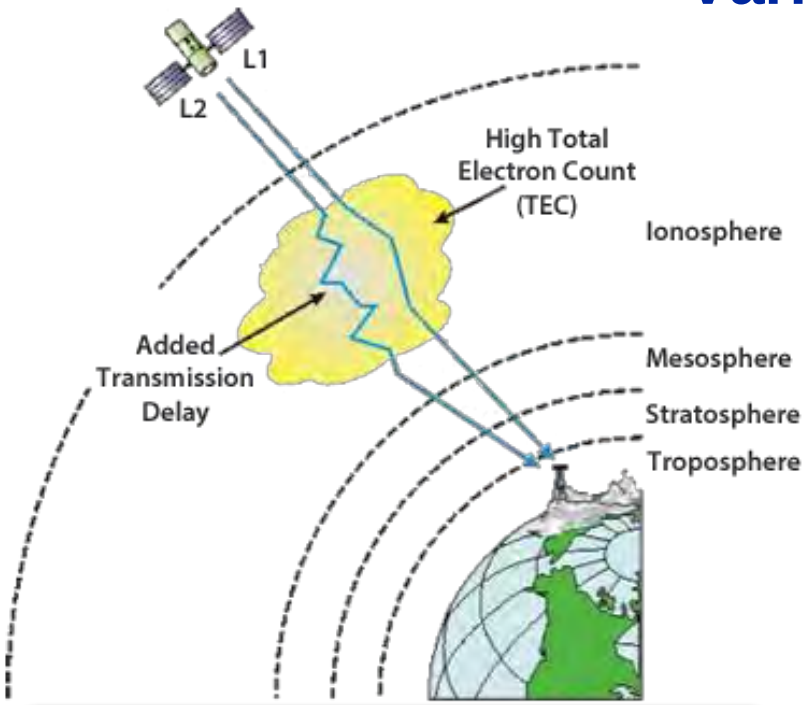
M9 earthquake will be under-resolved



Simulations indicate that the Kamchatka-Kuril region (as well as many other regions along the "ring of fire") is not equipped with sufficient density of GNSS receivers to enable GNSS-based resolution of large earthquakes

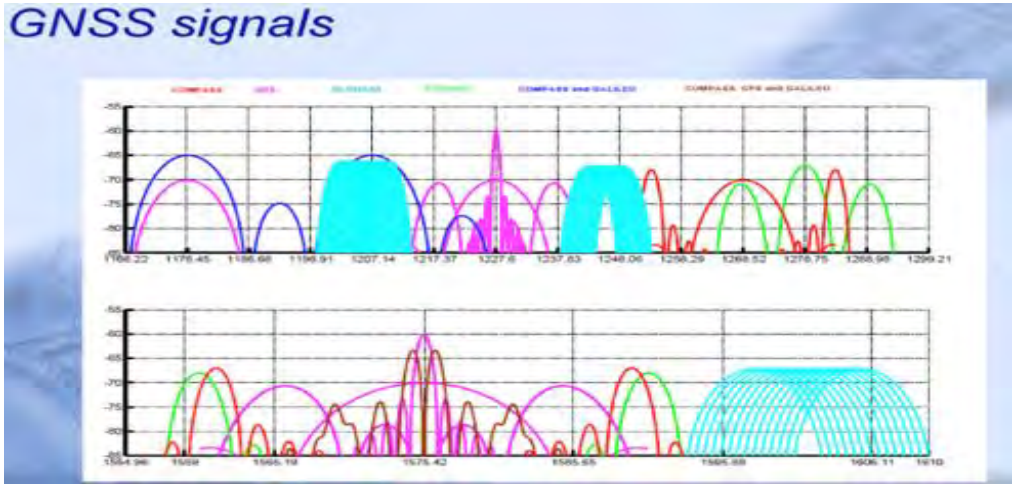
GNSS Ionospheric Measurements Can Track Tsunamis Propagation Across the Indo-Pacific

GNSS Provides a Sensitive Measurement of Ionospheric Variability

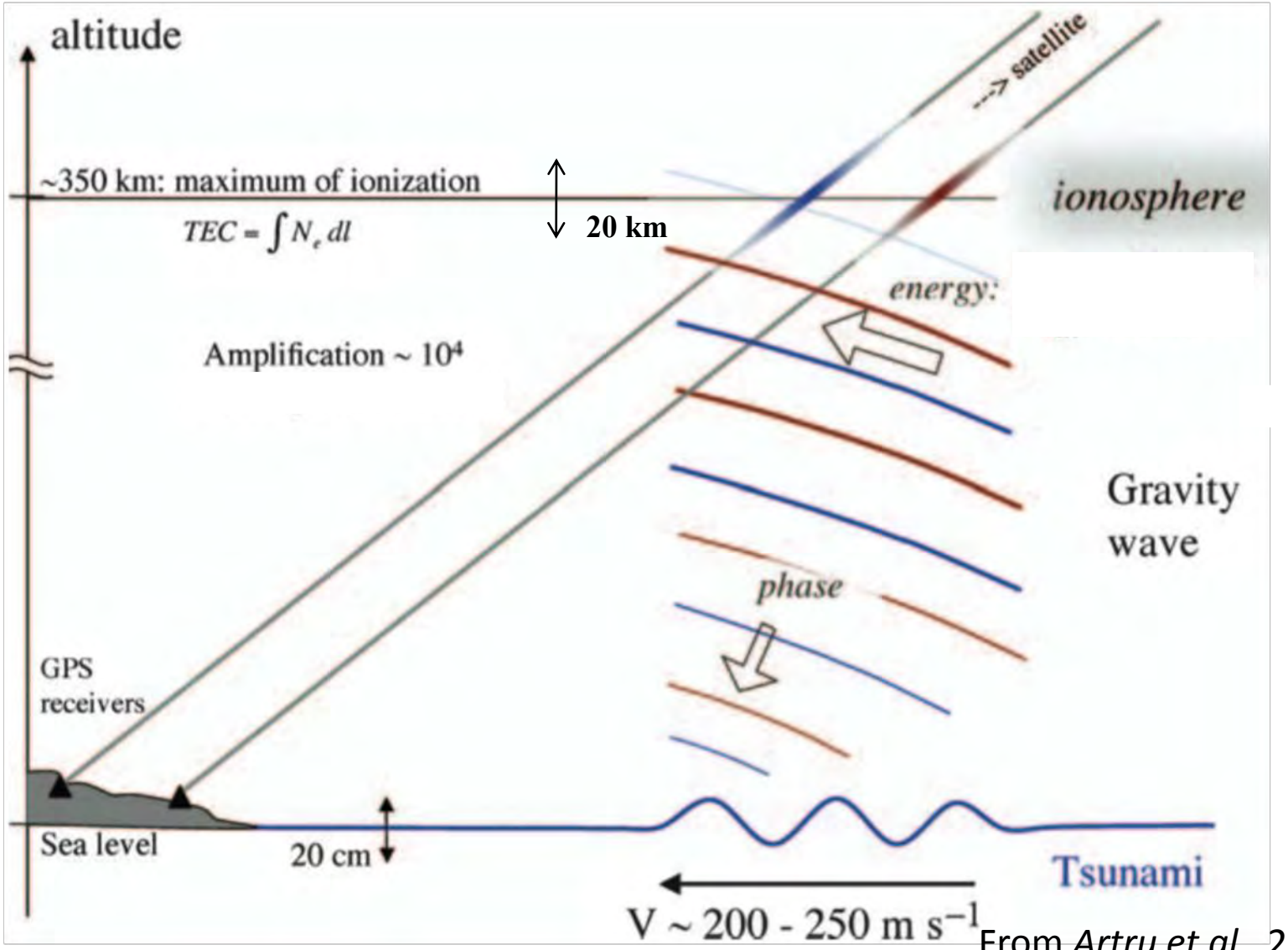


Effect of ionospheric refraction. The GPS signal are affected in different ways, depending on whether it is a question of codes or phases.

Group Delay=
Total electron content*40.3/f**2

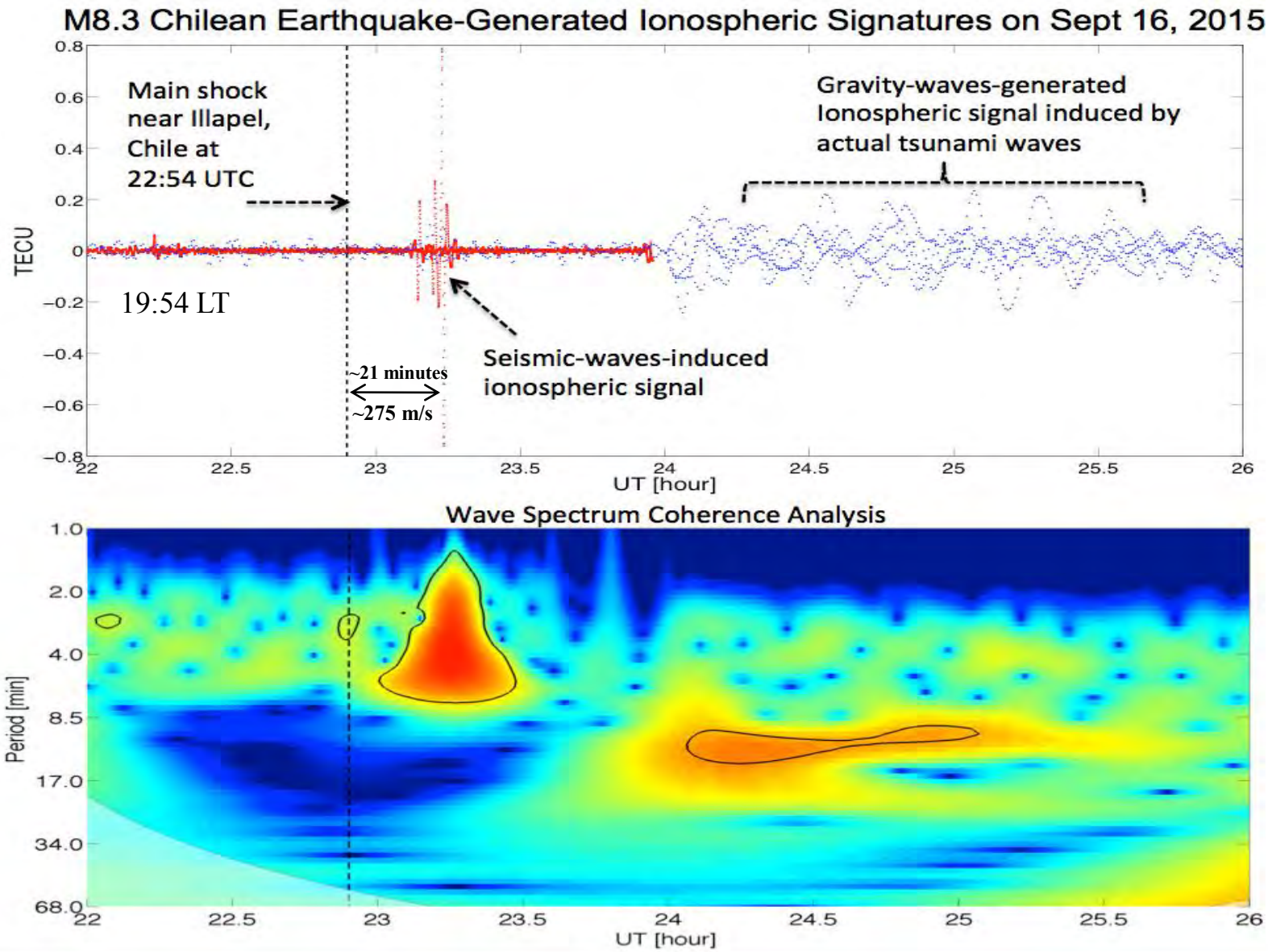


The Tsunami Generated Displacement of the Ocean Surface Couples to the Ionosphere

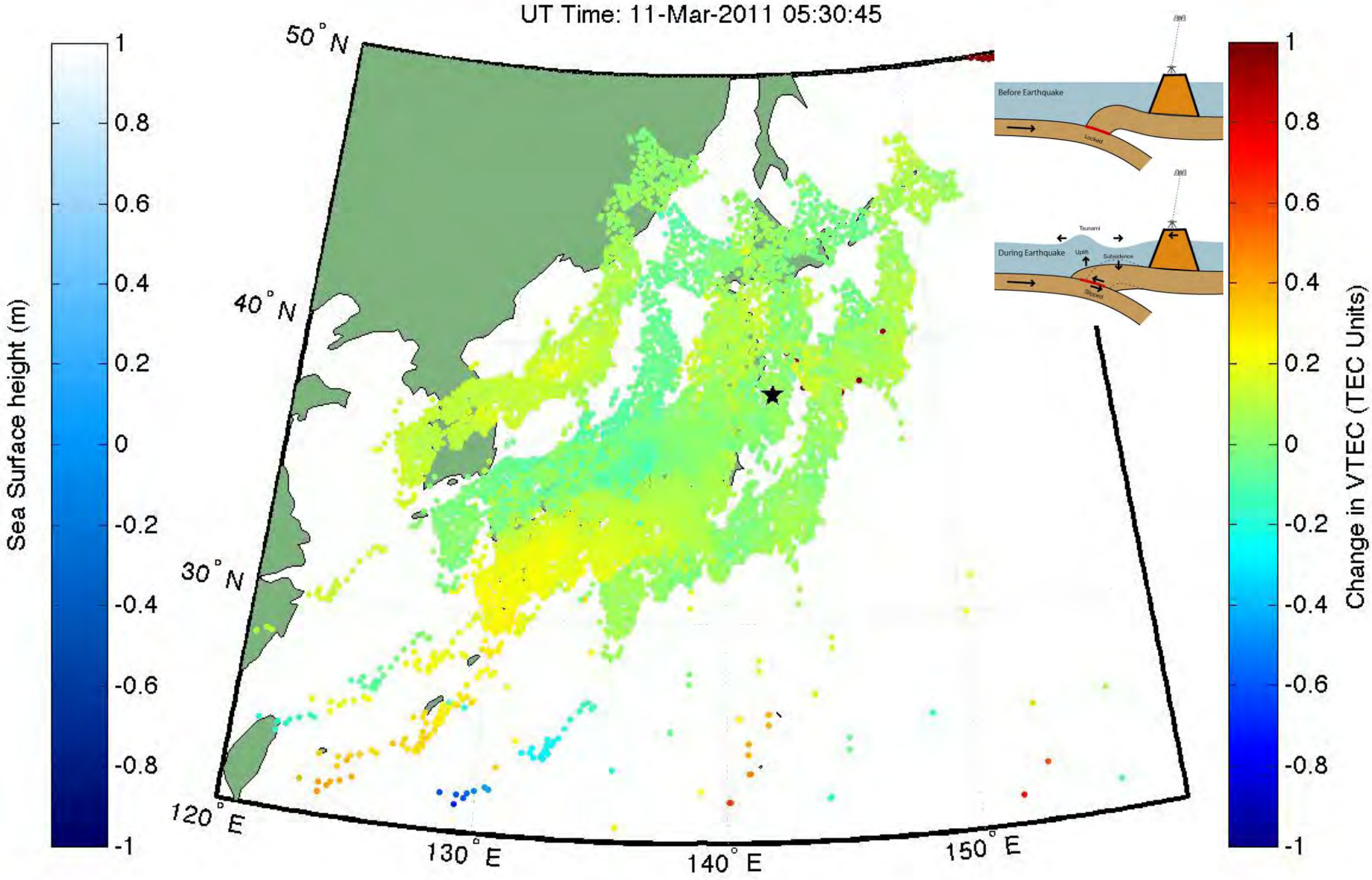


From *Artru et al.*, 2005

Coupled Acoustic Wave Time Delay
Illapel, Chile 9/16/2015 Mw8.3
Pers com: Attila Komjathy, JPL



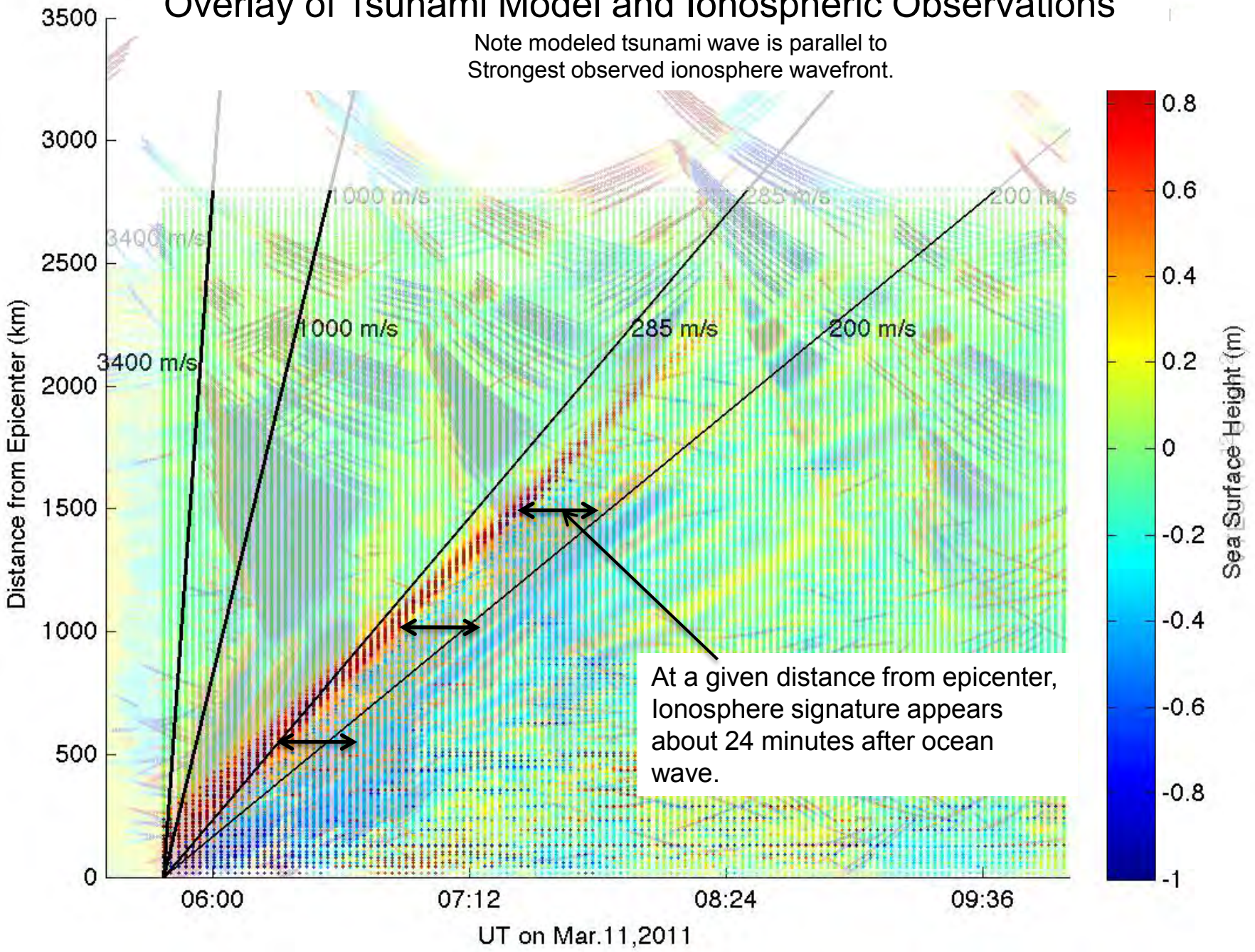
GSI's GEONET Also Captured the Ionospheric Coupled Waves and Imaged the Tsunami Generation and Propagation-For the First Time



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)

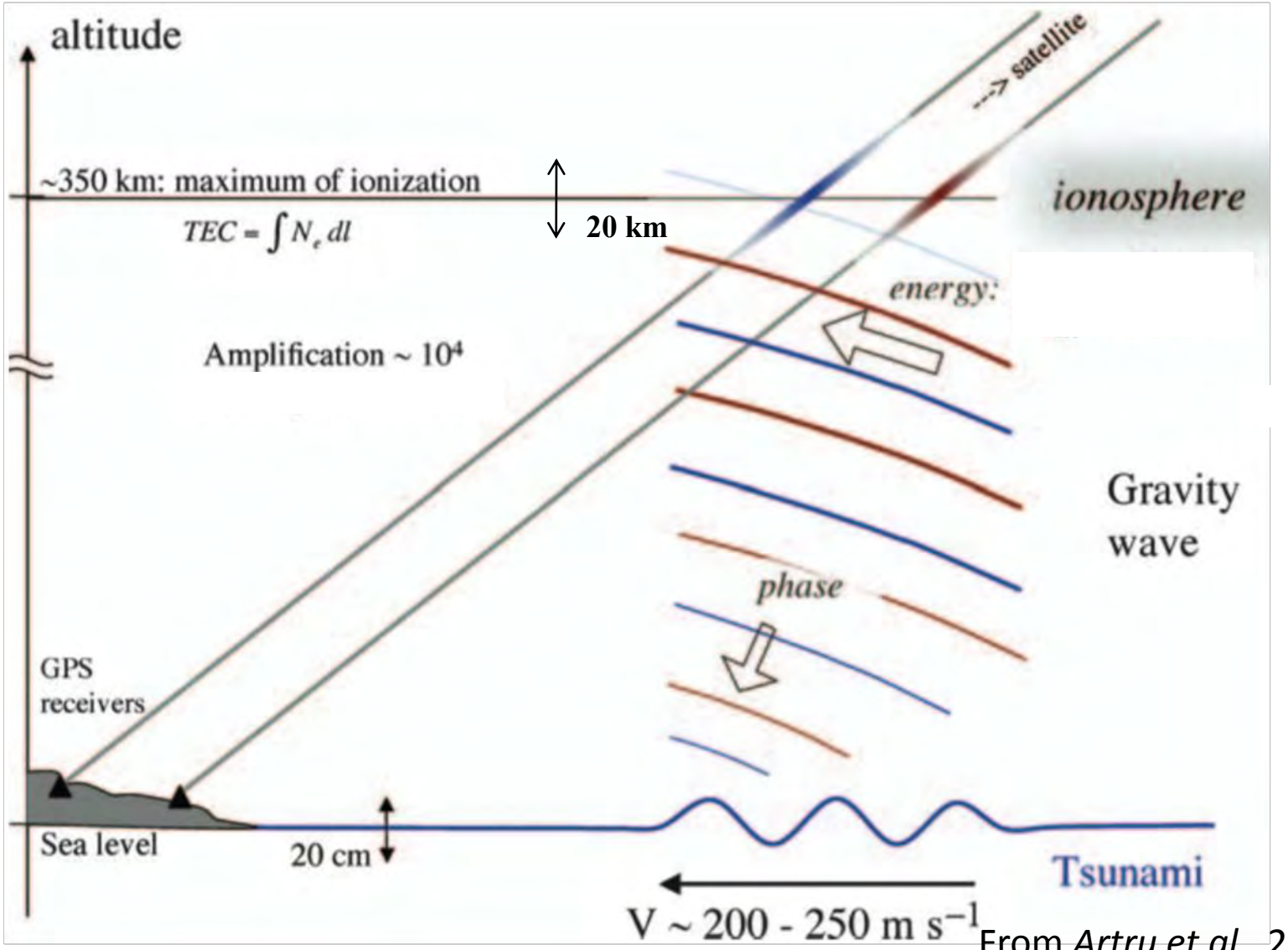
Overlay of Tsunami Model and Ionospheric Observations

Note modeled tsunami wave is parallel to
Strongest observed ionosphere wavefront.



From the work of Song, Galvan, Komjathy, JPL

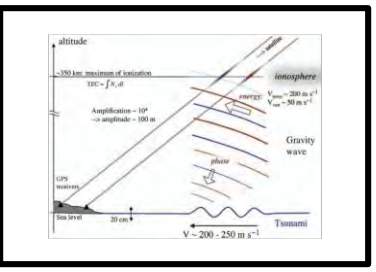
The Tsunami Generated Displacement of the Ocean Surface Couples to the Ionosphere

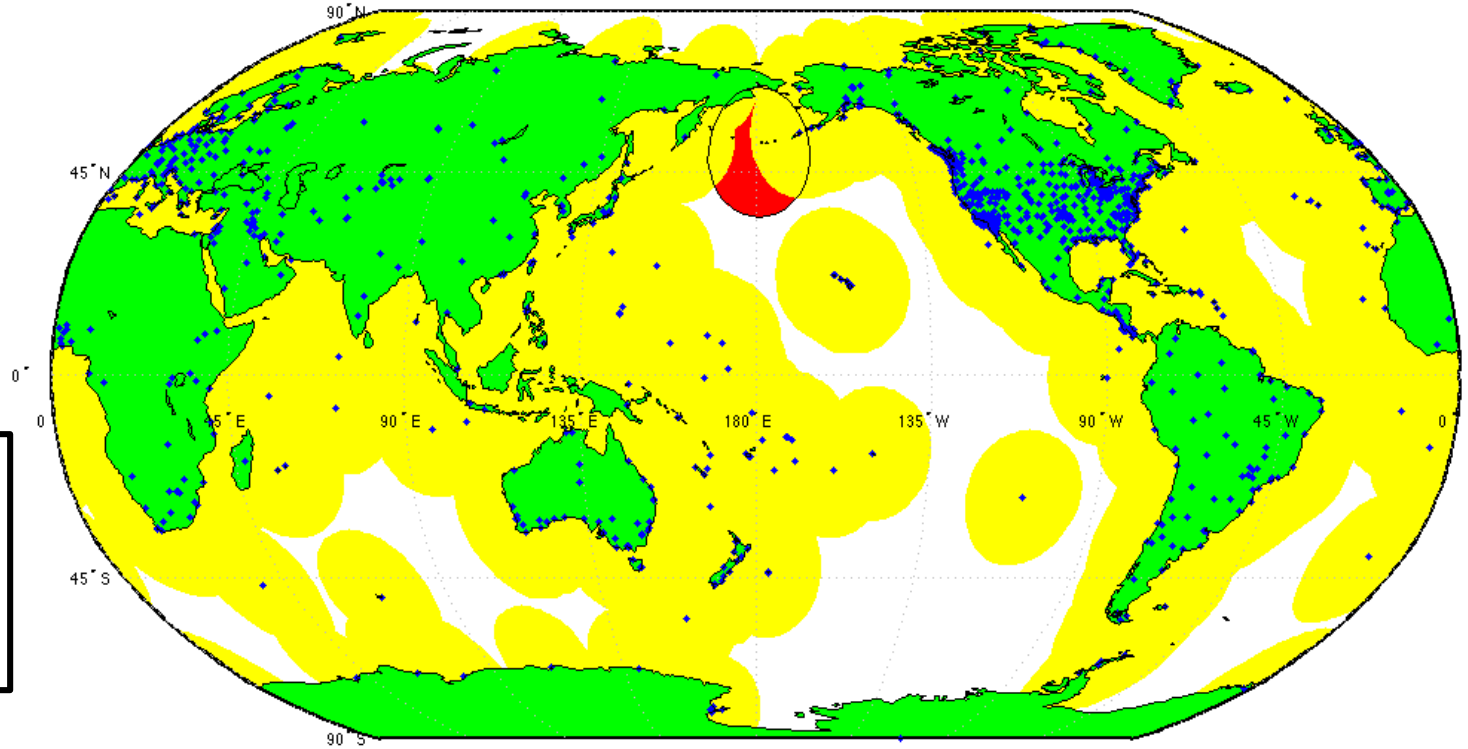


From *Artru et al.*, 2005

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

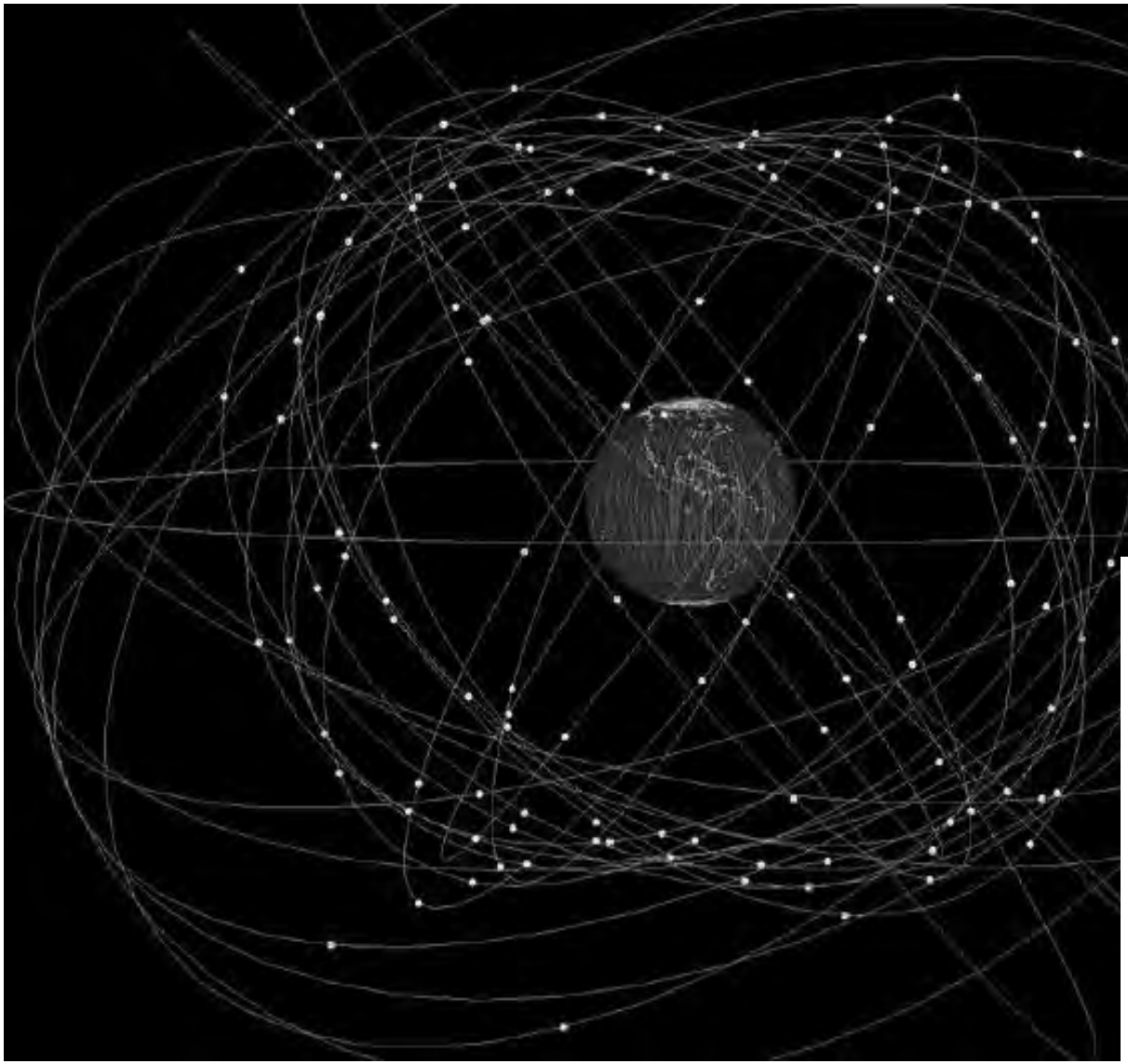




Red zone is only circum-Pacific gap in coverage assuming all stations are upgraded to real time operation.

GNSS Constellations and Ground Infrastructure Are Being Strengthened to Better Serve Society

GNSS Constellations Will Increase Satellites and Signals Over 400% in This Decade

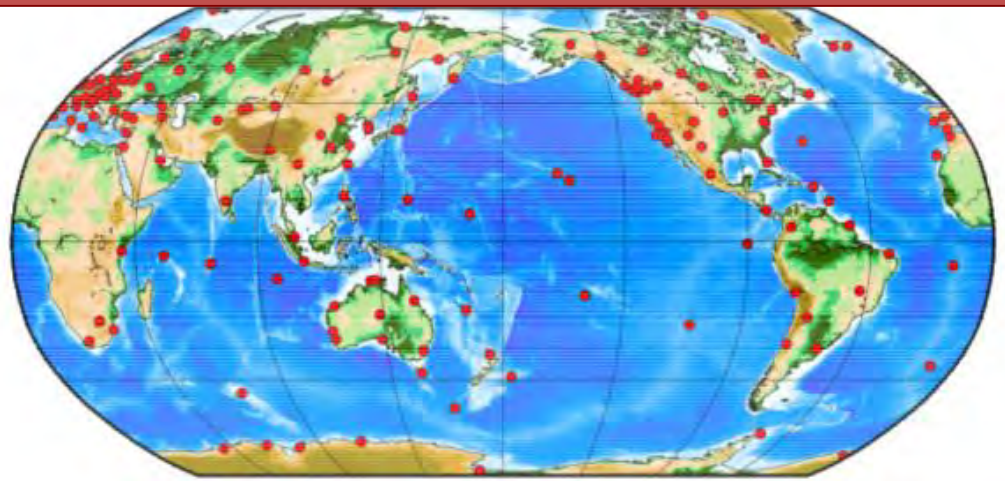


Future (~2020)	
GPS	30
SBAS	14
GLO	24
BDS	35
GAL	30
QZS	4
IRNSS	7
	144

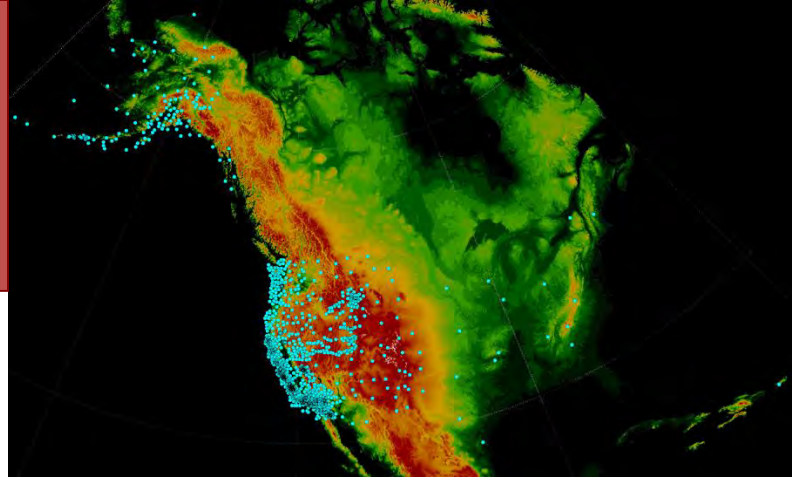
Benefits of > 4X GNSS Signals

- Positioning Accuracy (~2X)
- ITRF accuracy (~2X)
- Reliability (~4X)
- Ionospheric Resolution (~4X)
- Tsunami Predicts (2X-4X)
- Better Earthquake Solutions (?)

Share Real Time Data from the 3,000 Pacific Basin GNSS Stations

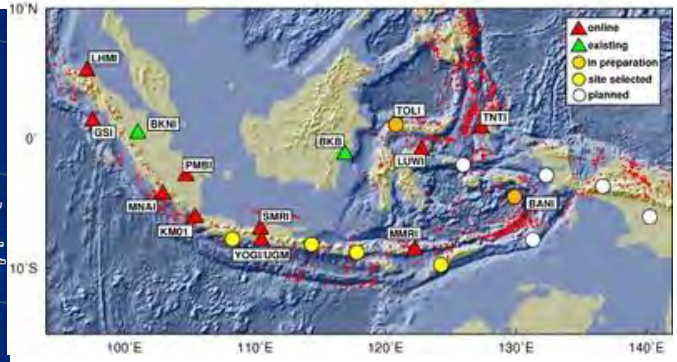


GGOS/IGS Real-Time Network

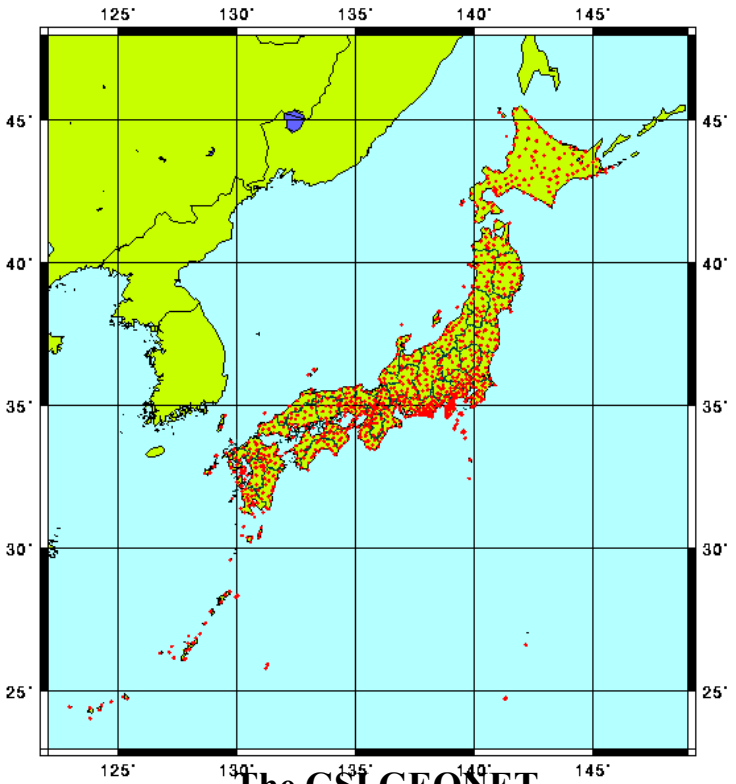


Earthscope Plate Boundary Observatory

Australian Real-Time Network



German-Indonesian Tsunami Early Warning (GITEWS)



The GSI GEONET

Development of an Indo-Pacific GNSS Augmentation to the Tsunami Early Warning Network

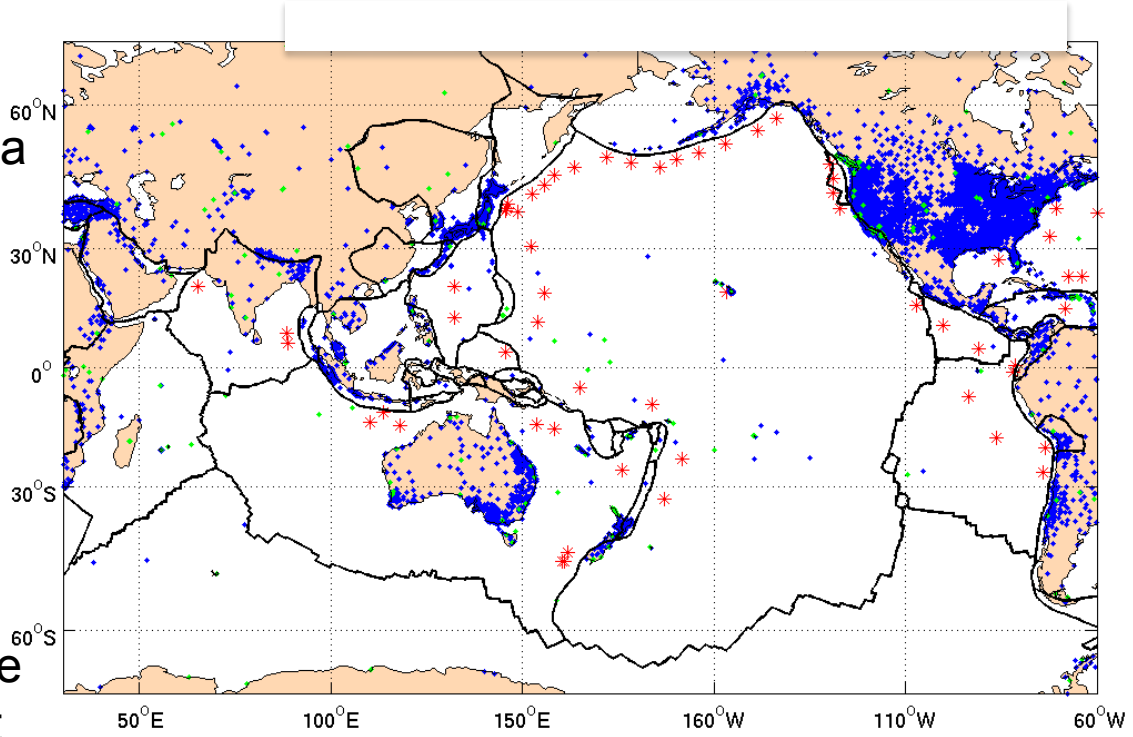
A GNSS Augmentation to the Tsunami Early Warning System Requires International Cooperation and Data Sharing

•The Pacific Region is well populated with GNSS CORS Networks - many that stream data in real-time

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

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

•The UN General Assembly, IUGG, IGS have issued resolutions for the sharing of geodetic data to mitigate Natural Hazards.



Existing GNSS stations if streamed and analysed in real-time will provide:

- Rapid and more accurate tsunami warnings
- Basin wide tracking of propagating tsunamis

Recommendation of the IGS 2014 Workshop, Pasadena, CA:

"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."*

The UN General Assembly

A Global Geodetic Reference Frame for Sustainable Development

February *26, 2015*

Recognizing the importance of international cooperation, as no one country can do this alone, to realize the global geodetic reference frame and services to underpin Global Navigation Satellite Systems technology and provide the framework for all geospatial activity, as a key enabler of spatial data interoperability, disaster mitigation and sustainable development,

Urges Member States to implement open sharing of geodetic data, standards and conventions, on a voluntary basis, to contribute to the global reference frame and regional densifications through relevant national mechanisms and intergovernmental cooperation, and in coordination with the International Association of Geodesy

International Union of Geodesy and Geophysics:

Resolution 4: July 2015

Considering:

•That large populations may be impacted by tsunamis generated by megathrust earthquakes

• Among existing global real-time observational infrastructure, the Global Navigation Satellite Systems (GNSS) can enhance the existing tsunami early warning systems;

Urges:

•Operational agencies to exploit fully the real time GNSS capability to augment and improve the accuracy and timeliness of their early warning systems,

•That the GNSS real-time infrastructure be strengthened,

•That appropriate agreements be established for the sharing of real-time GNSS data within the tsunami early warning systems,

•Continued support for analysis and production of operational warning products,

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.

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

We recommend that APSG in cooperation with the International Oceanographic Commission, Association of Pacific Rim Universities, the IUGG Commissions and Associations and the relevant Indo-Pacific governmental agencies work to advance a GNSS Augmentation to the Tsunami Early Warning Network via an

Initial workshop in 2016 to define the requirements and next steps to establish a GNSS Augmentation to the Tsunami Early Warning System based upon the principles of shared resources and with the goal of establishing designs, agreements, and support to encourage cooperative improvements to infrastructure, algorithms, and data sharing.

International Union of Geodesy and Geophysics (IUGG)

IAG GGOS

References

- Blewitt, G., C. Kreemer, W. C. Hammond, H.-P. Plag, S. Stein, and E. Okal, Rapid determination of earthquake magnitude using GPS for tsunami warning systems, Geophys. Res. Lett., 33, L11309, doi:10.1029/ 2006GL026145, 2006.
- Blewitt, G., C. Kreemer, W. C. Hammond, H.-P. Plag, S. Stein, and E. Okal, GPS for real time earthquake source determination and tsunami warning systems, J Geod 83:335–343, DOI 10.1007/s00190-008-0262-5, 2009.
- Crowell, Bock, Melgar, Real time inversion of GPS data for finite fault modeling and rapid hazard assessment, GRL, VOL. 39, L09305, doi:10.1029/2012GL051318, 2012.
- Galvan,D.A., A. Komjathy, M. P. Hickey, P. Stephens, J. Snively, Y. T. Song, M. D. Butala, and A. J. Mannucci, Ionospheric signatures of Tohoku-Oki tsunami of March 11, 2011: Model comparisons near the epicenter, Radio Science, V. 47, RS4003, doi:10.1029/2012RS005023, 2012 .
- Hoshiba,M. and T. Ozaki, Earthquake Early Warning and Tsunami Warning of the Japan Meterological Agency, and their Performance in the 2011 off the Pacific Coast of Tohoku earthquake (Mw9.0)-Chapter 1, in Early Warning for Geological Disasters; Scientific Methods and Current Practice, F. Wenzel and J. Zschau ed. Springer, pp. 1-28.
- Heki, K., and J. Ping (2005), Directivity and apparent velocity of the coseismic ionospheric disturbances observed with a dense GPS array, Earth Planet. Sci. Lett., 236, 845–855, doi:10.1016/j.epsl.2005.06.010, 2005.
- Heki, K., Y. Otsuka, N. Choosakul, N. Hemmakorn, T. Komolmis, and T. Maruyama, Detection of ruptures of Andaman fault segments in the 2004 great Sumatra earthquake with coseismic ionospheric distur- bances, J. Geophys. Res., 111, B09313, doi:10.1029/2005JB004202, 2006.
- Lauterjung, J., A. Rudloff, U. Munch,D. J. Acksel, The Earthquake and Tsunami Early Warning System for the Indian Ocean (GITEWS)- Chapter 9, in Early Warning for Geological Disasters; Scientific Methods and Current Practice, F. Wenzel and J. Zschau ed. Springer, pp. 165-178. 2014.
- Liu, J.Y., C.H. Chen, C.H. Lin, H.F. Tsai, C.H. Chen, and M. Kamogawa, Ionospheric disturbances triggered by the 11 March 2011 M9.0 Tohoku earthquake, J. Geophys. Res., 116, A06319, doi:10.1029/2011JA016761, 2011.
- Melgar, D., B. W. Crowell, Y. Bock, and J. S. Haase, Rapid modeling of the 2011 Mw 9.0 Tohoku-Oki Earthquake with Seismogeodesy, Geophys. Res. Lett., 40, 1-6. doi:10.1002/grl.50590, 2013.
- Occhipinti, G. P. Dorey, T. Farges, P. Lognonne, Nostradamus: The radar that wanted to be a seismometer, GRL, V. 37, L18104, doi:10.1029/2010GL044009, 2010.
- Ohta, Y., et al. (2012), Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (Mw 9.0), J. Geophys. Res., doi:10.1029/ 2011JB008750.
- Rolland, L. M., G. Occhipinti, P. Lognonné, and A. Loevenbruck, Ionospheric gravity waves detected offshore Hawaii after tsunamis, Geophys. Res. Lett., 37, L17101, doi:10.1029/2010GL044479, 2010.
- Sobolev, S.V., A. Y. Babeyko, R. Wang, A. Hoechner, R. Galas, M. Rothacher, D. V. Sein, J. Schroter,J. Lauterjung,C. Subarya, Tsunami early warning using GPS Shield arrays, JGR, V. 112, B08415, doi:10.1029/2006JB004640, 2007.
- Song, Y. T., C. Ji, L.-L. Fu, V. Zlotnicki, C.K. Shum, Y. Yi, and V. Hjorleifsdottir,The 26 December 2004 Tsunami Source Estimated from Satellite Radar Altimetry and Seismic Waves, *Geophys. Res. Lett.,* 23, doi:10.1029/2005GL023683, 2008.
- Song, Y. Tony, Detecting tsunami genesis and scales directly from coastal GPS stations, Geophys. Res. Lett., 34, L19602, doi:10.1029/2007GL031681, 2007.
- Stein, S., and E. A. Okal, Speed and size of the Sumatra earthquake, Nature, 434, 581–582, 2005.
- Xu, Z. and **Y. T. Song**, Combining the all-source Green's functions and the GPS-derived source for fast tsunami prediction – illustrated by the March 2011 Japan tsunami, *J. Atmos. Oceanic Te*ch., http://dx.doi.org/10.1175/JTECH-D-12-00201.1, 2013.