# *Development of a GNSS-Enhanced Tsunami Early Warning System*


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**Dr. Tony Song** *Jet Propulsion Laboratory*
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***Plus many many more.***

NOAA
CWU
SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego
NSF
USGS science for a changing world
UNAVCO
University of California Berkeley Seismological Laboratory
NASA
Jet Propulsion Laboratory
California Institute of Technology
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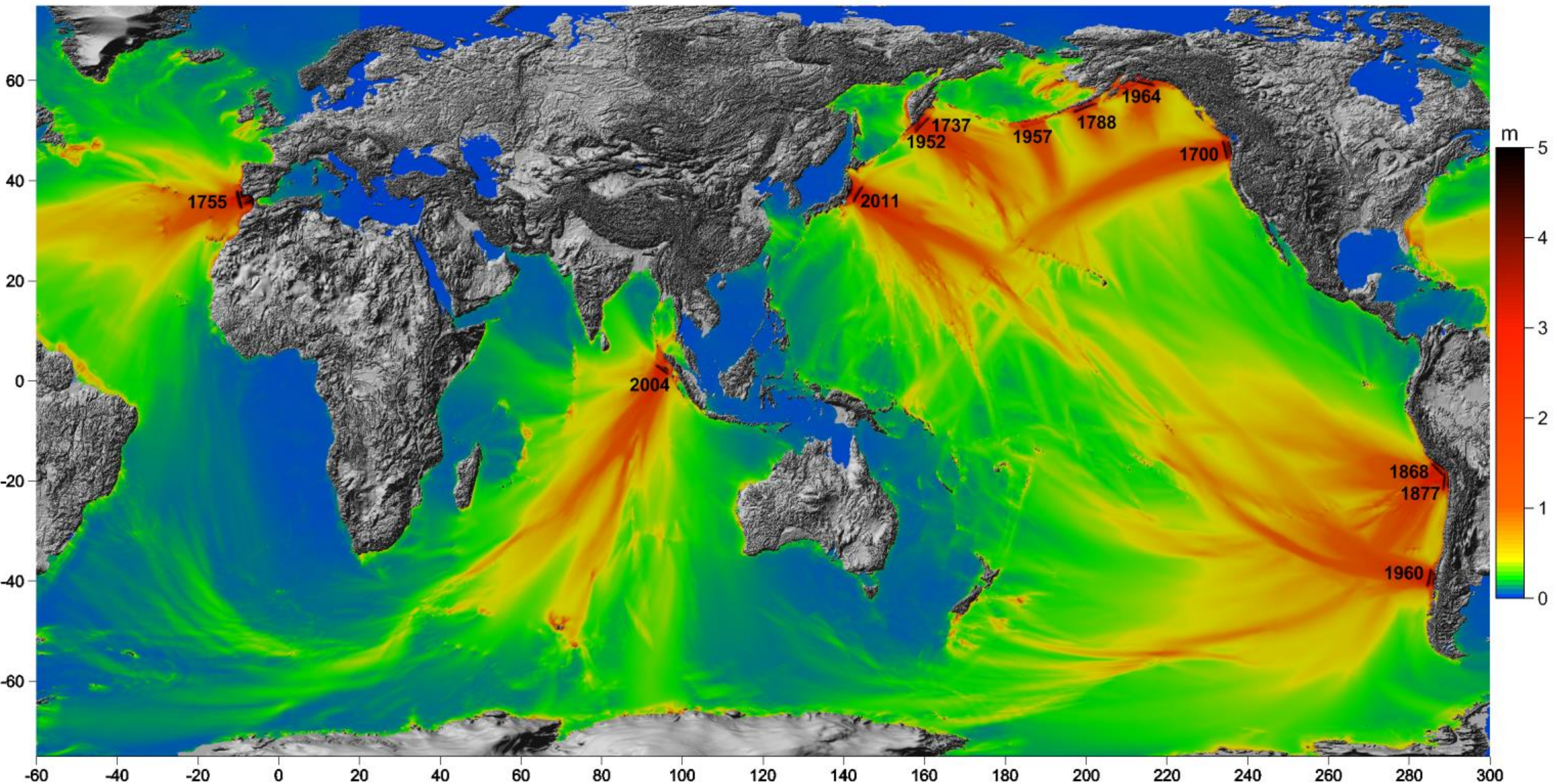
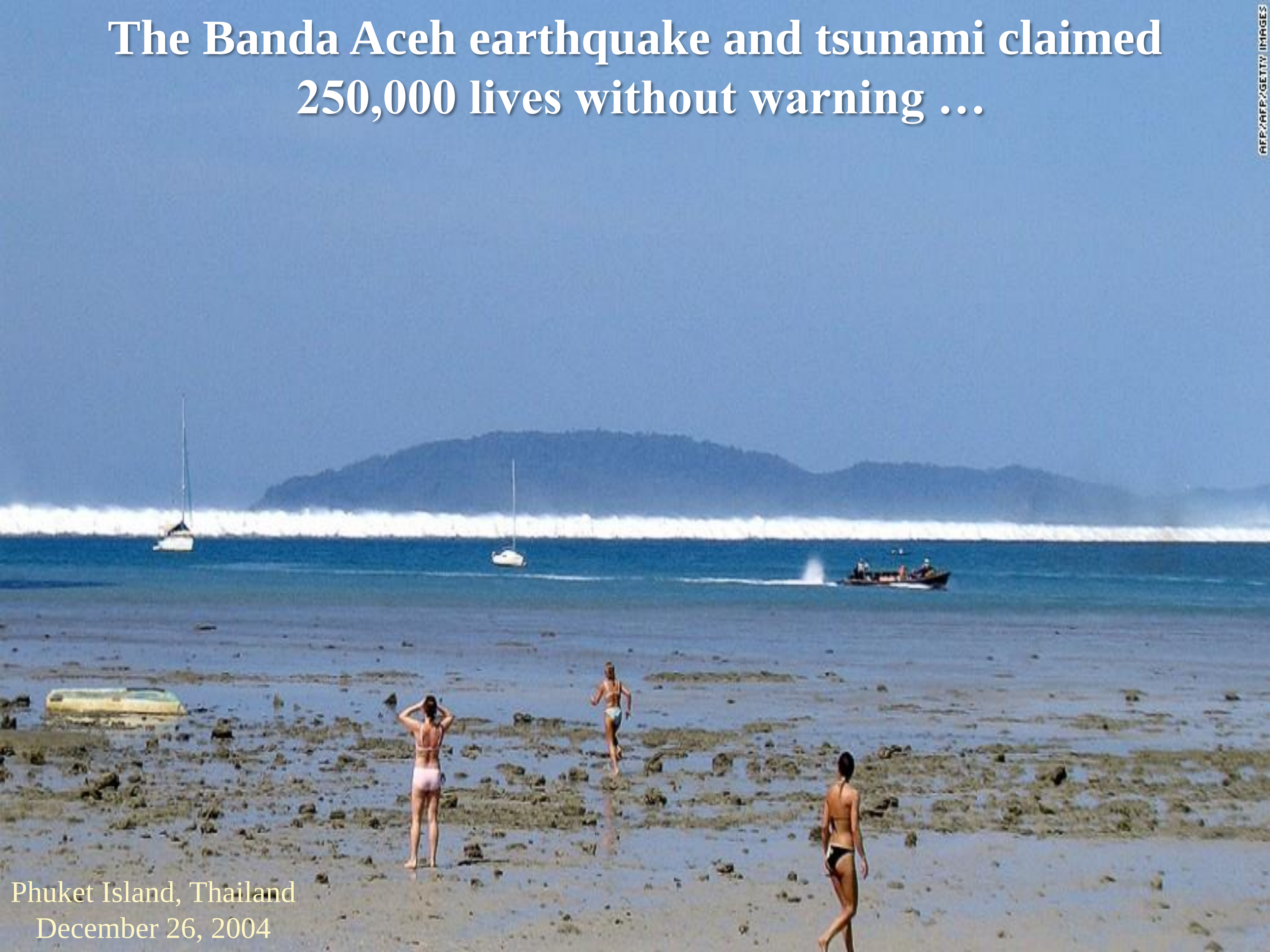
# The Significant Earthquakes Triggered Tsunamis

(https://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1)




**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

# The Banda Aceh earthquake and tsunami claimed 250,000 lives without warning …




Phuket Island, Thailand
December 26, 2004

# What questions are asked when there is an earthquake in tsunami prone regions?

***Where was the earthquake?*** **Lat/Lon/Depth**

***How large was it?*** **Accurate Magnitude**

***Could the earthquake generate a tsunami?***
**Nature of earthquake – thrust, normal, strike-slip, oblique**

***Was there a tsunami?*** **DART buoys, other**

***How much time do communities have before the tsunami makes landfall?*** **Tsunami energy modeling**

***How far will the tsunami come onshore?***

***How deep will the water be?***
**Subsidence measurements and inundation modeling**

# Real-time GNSS can help address many of these questions for most earthquakes



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**Measurement of the land surface deformation**
**Measurement perturbations in the ionosphere**
**Improves latency and accuracy of models**
**Next generation models include coastal subsidence**

} Real-Time GNSS

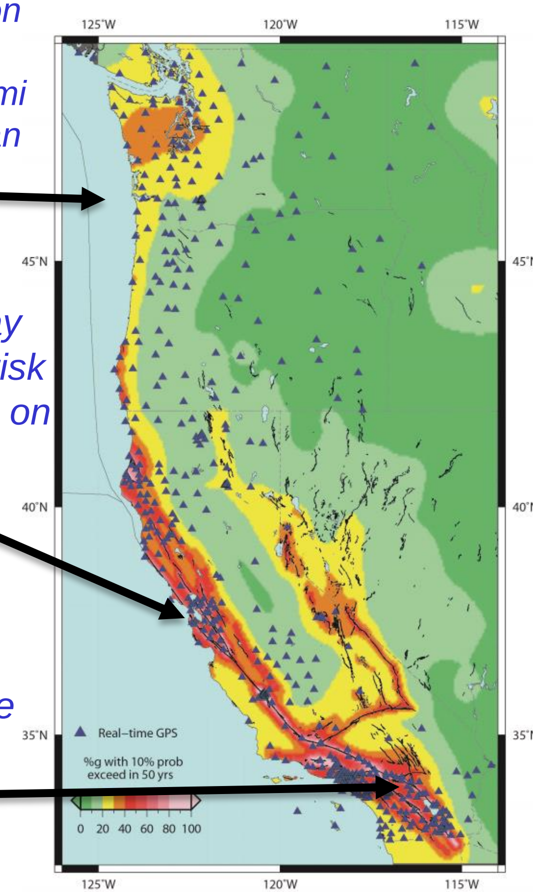
# The READI Working Group

- **R**eal-Time **E**arthquake **A**nalysis for **D**isaster m**I**tigation network (READI): ~750 GPS stations, a NASA driven project
- Super set of GNSS networks maintained by (sorted according to largest to smallest number of stations):
  - UNAVCO/PBO
  - CWU/PANGA
  - USGS/Pasadena-SCIGN & Menlo Park
  - UC Berkeley/BARD
  - Scripps Institution of Oceanography/SCIGN
  - JPL/Caltech

*Cascadia Subduction Zone – Mw 9.0 earthquake & tsunami similar to 2011 Japan events*

*San Francisco Bay Area – Increasing risk of large earthquake on Hayward fault*

*Southern San Andreas fault – overdue for large earthquake*




University of California Berkeley Seismological Laboratory

USGS science for a changing world

Scripps Institution of Oceanography UC San Diego

Jet Propulsion Laboratory
California Institute of Technology

CWU

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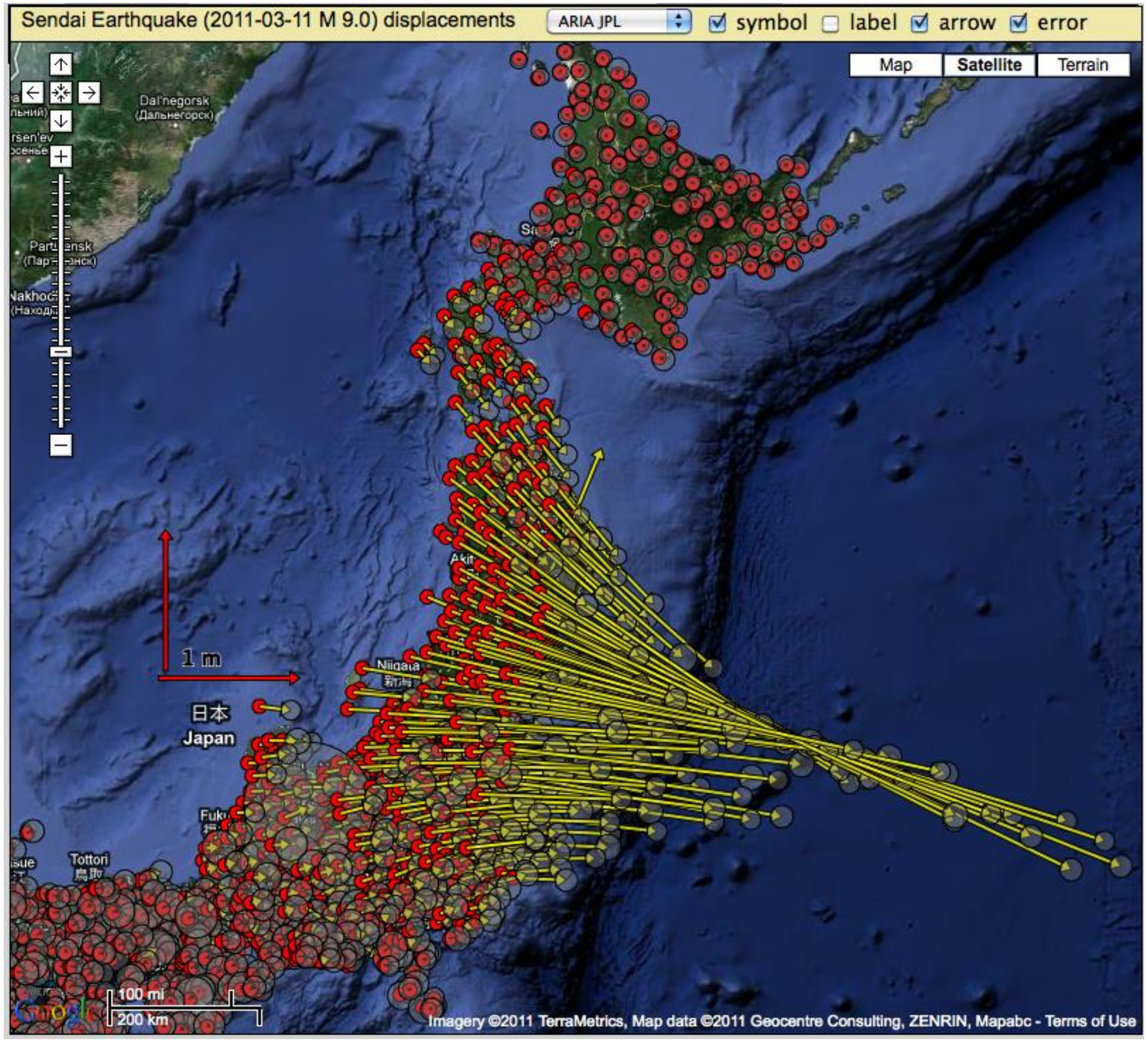
# GNSS Earthquake and Tsunami Early Warning



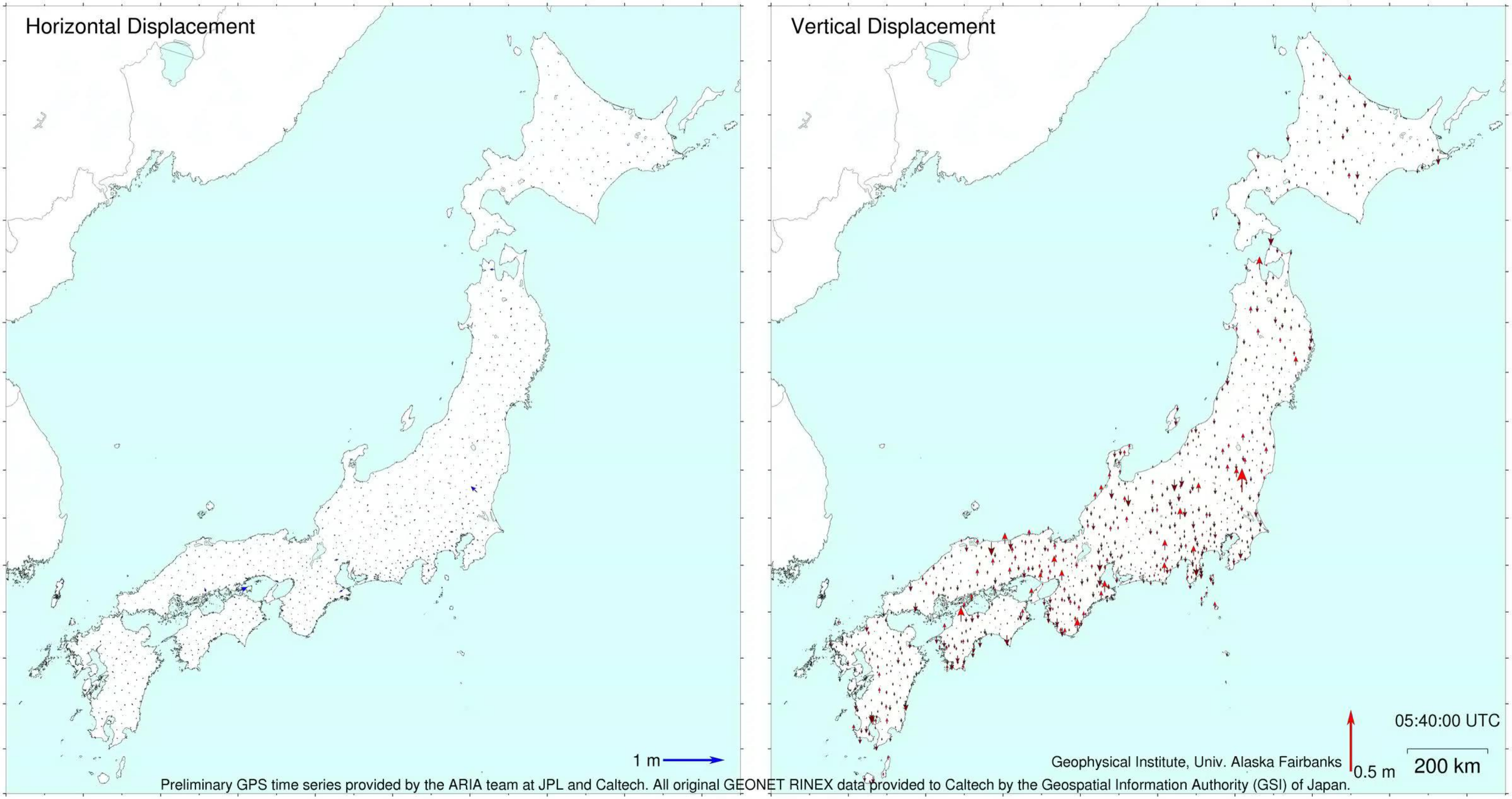

Data courtesy of the Geospatial Information Authority of Japan GSI

GEONET GPS Array

Great East Japan Earthquake and Tsunami

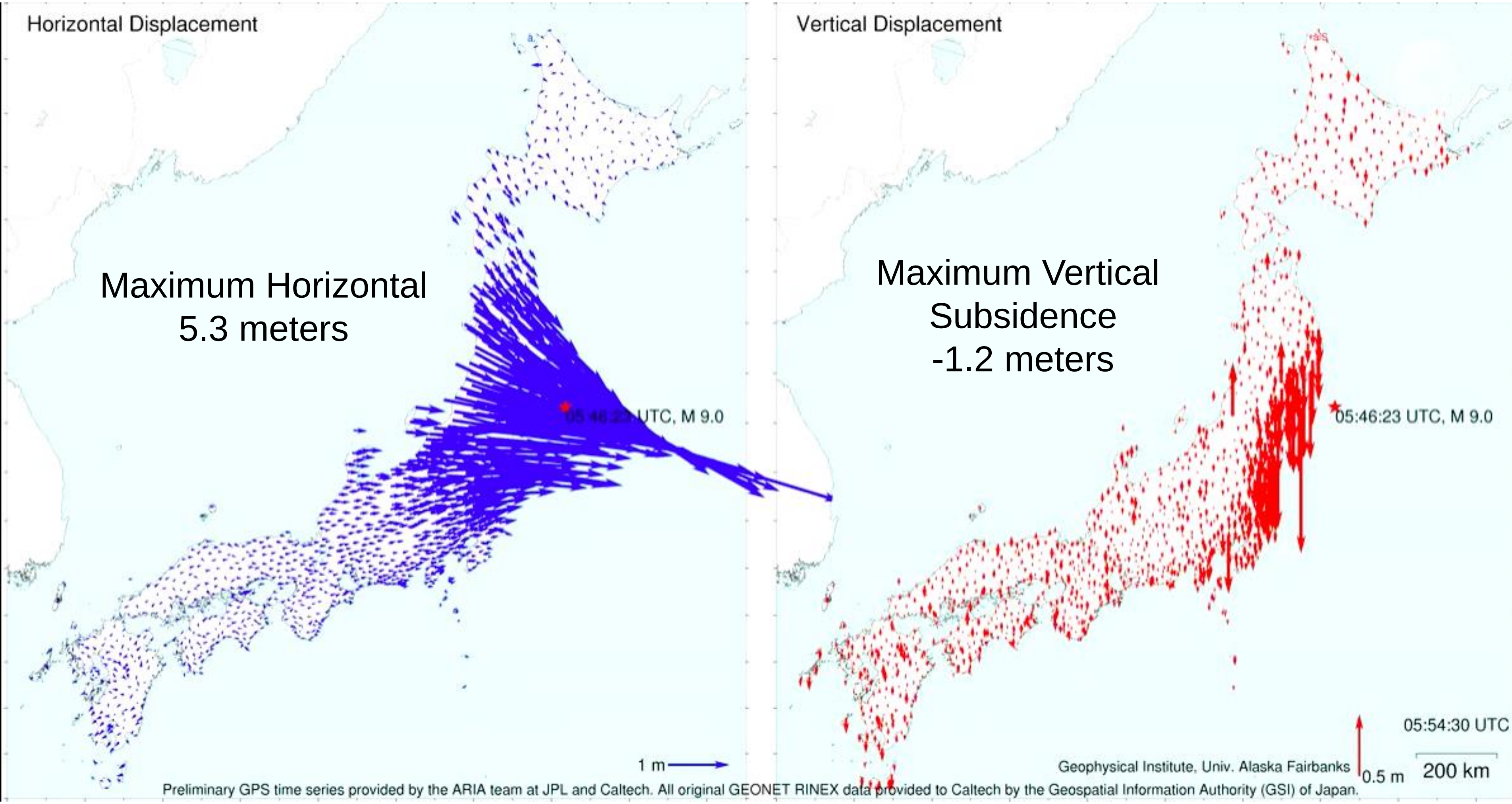
Maximum GPS displacement ~5 meters

# GSI GEONET GPS Array Earthquake Displacement Pattern




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

# GSI GEONET GPS Array Earthquake Displacement Pattern

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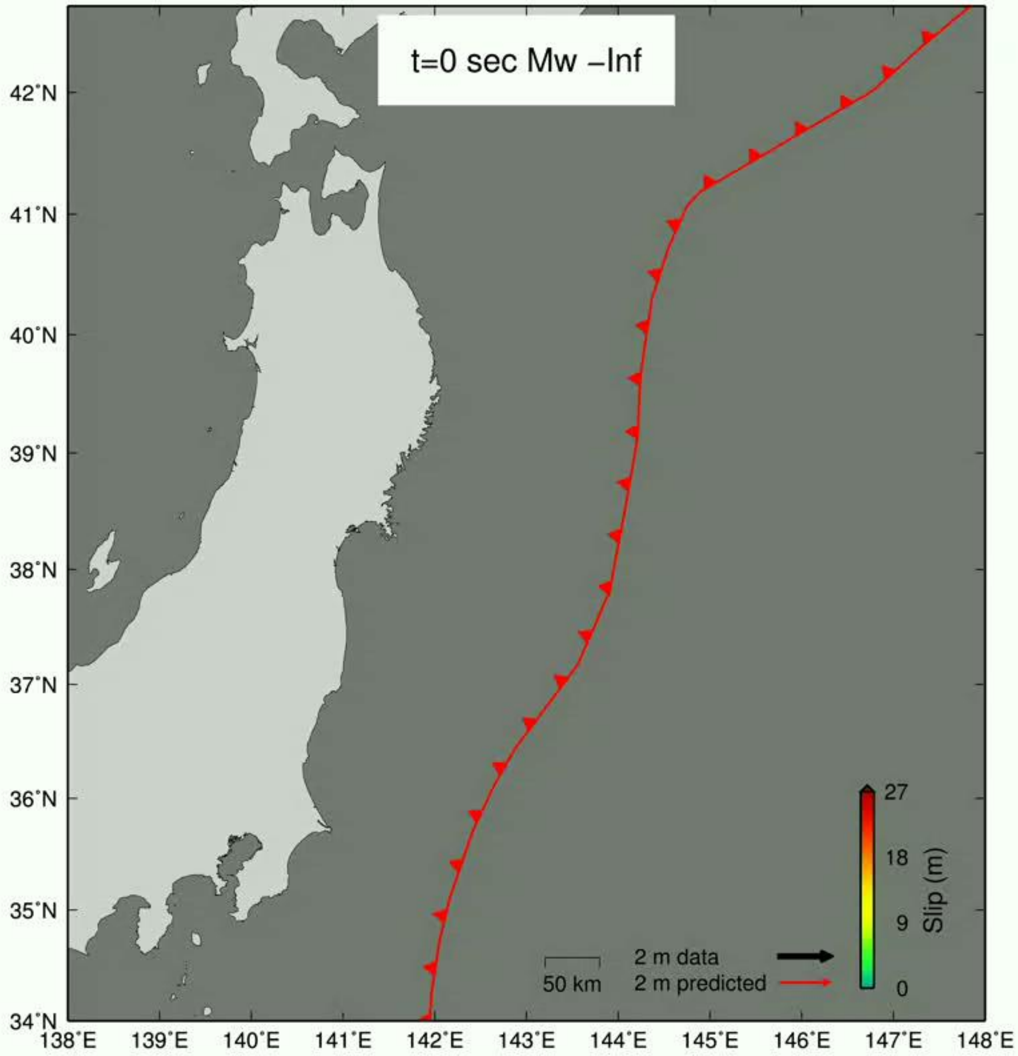
**Two Cases:**

- **Loosely constrained fault model – data resolves the best fault orientation and slip distribution**
- **Predefined fault surface – data resolve best slip distribution – fault complexity and models cells**

# Real-Time GNSS for Rapid Earthquake Magnitude Determination and Fault Slip Distribution

**Case 1 – model determines fault location**

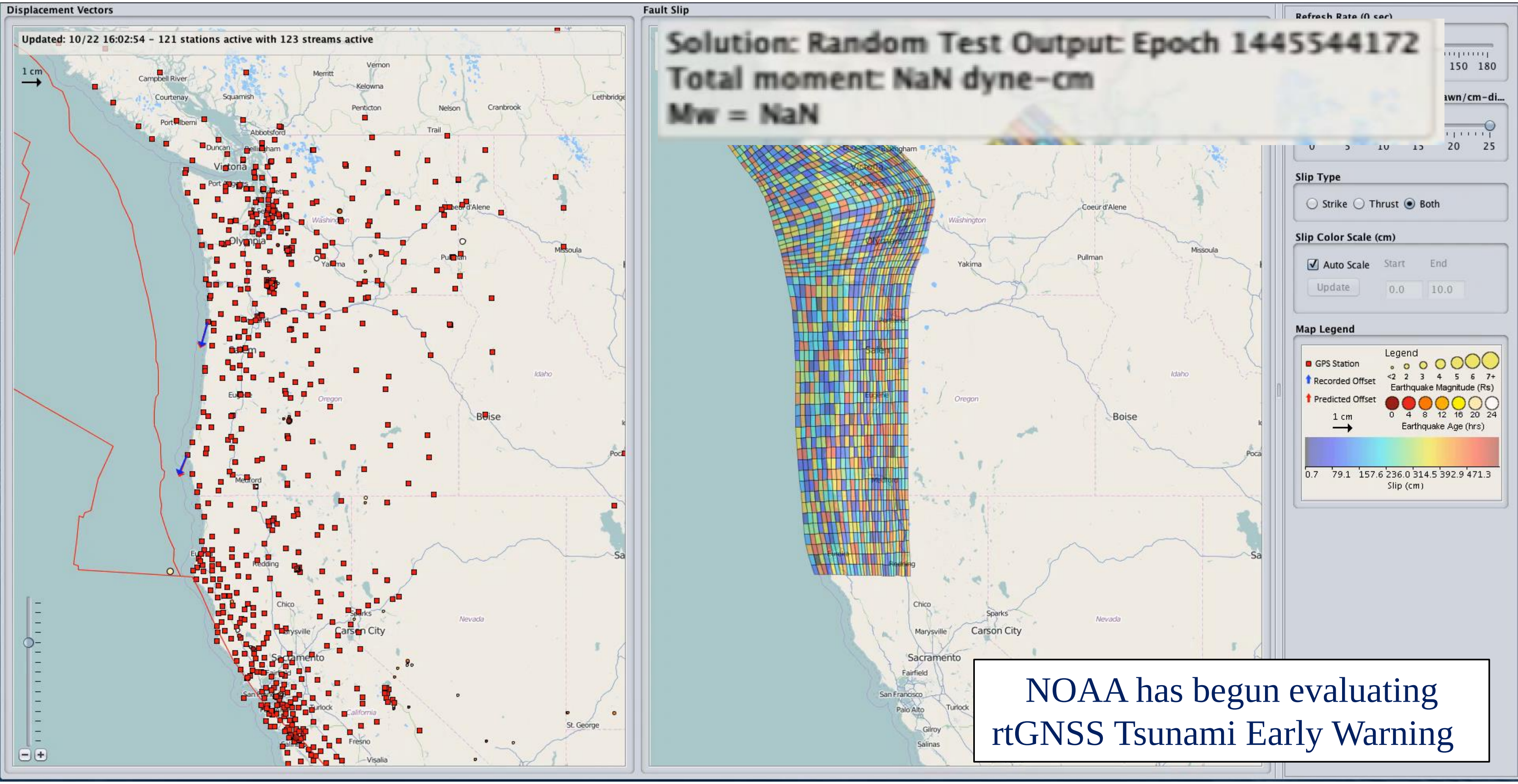



S. E. Minson et al, 2013
JGR

# GNSS Earthquake Source Model for a Predefined Fault

## Case 2 –Real-time displacements on a fixed fault surface

Prototype running in real-time on a fixed fault surface

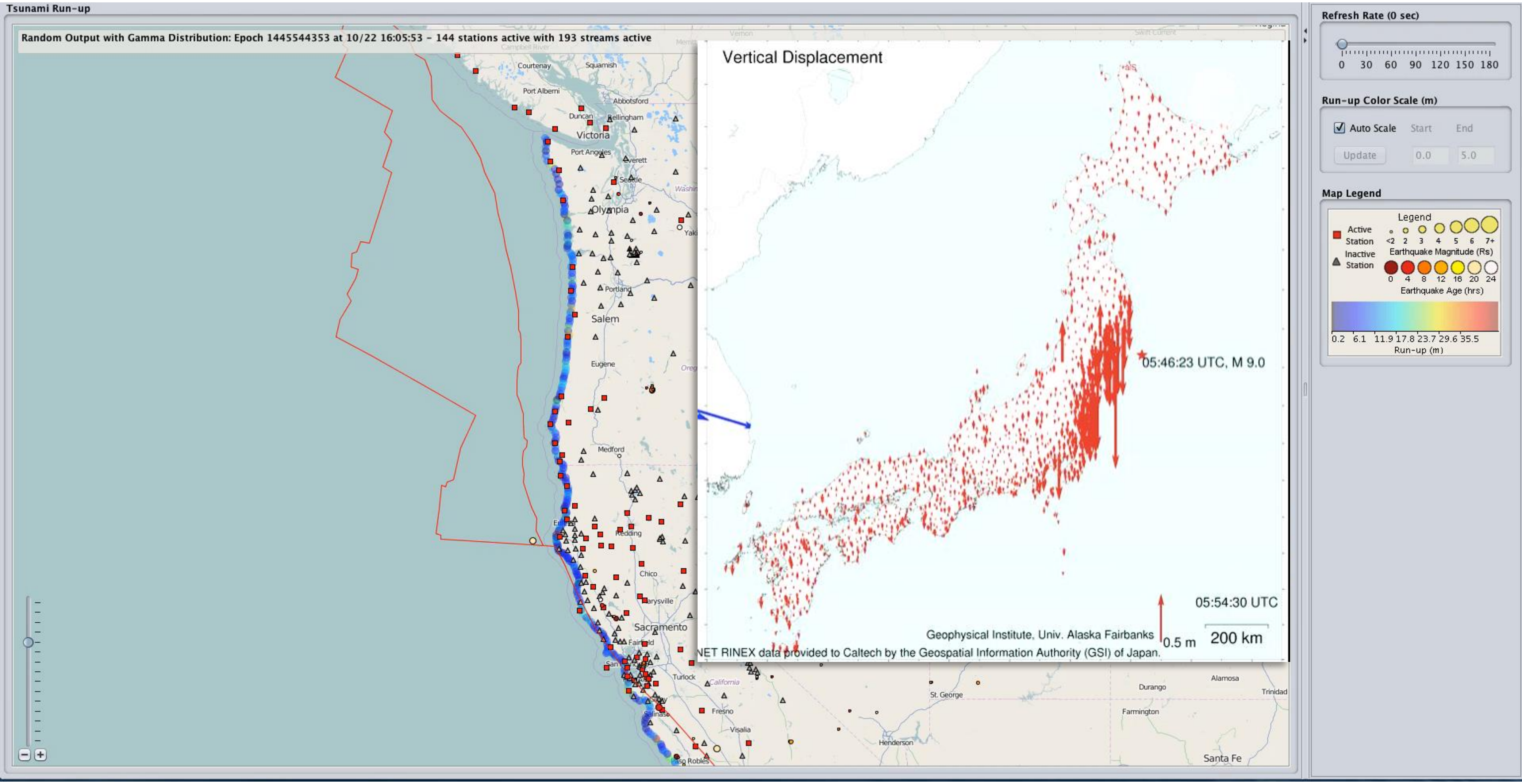



NOAA has begun evaluating rtGNSS Tsunami Early Warning

**Developed by the READI Working Group**

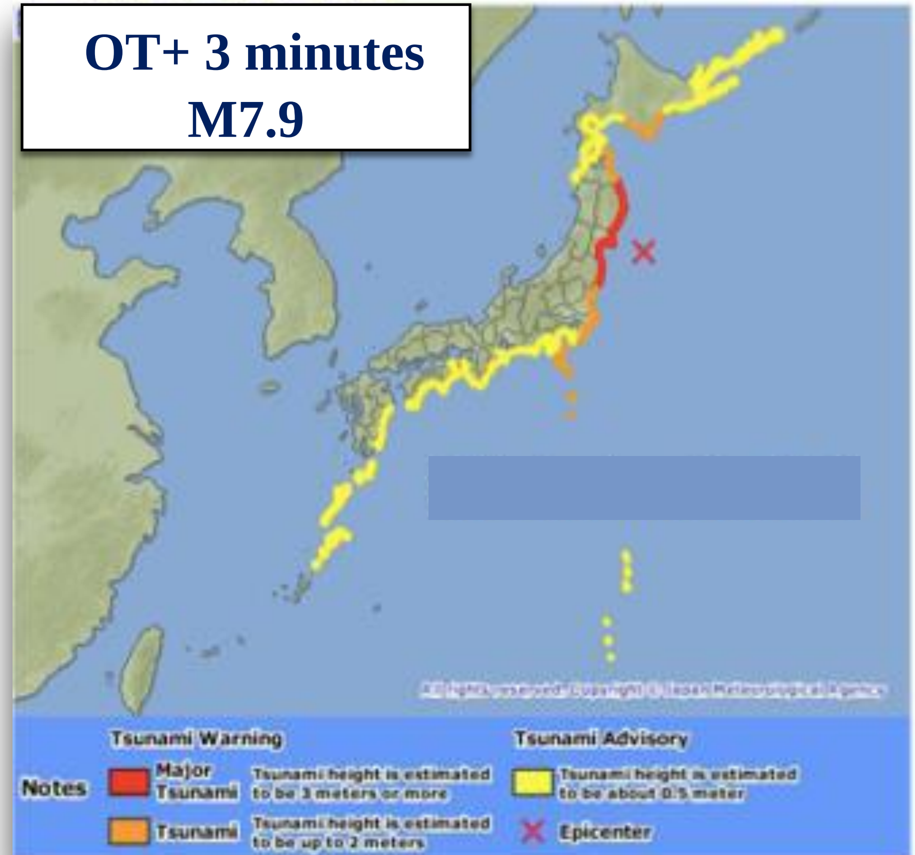
# Projected Tsunami Rise-Up along West Coast

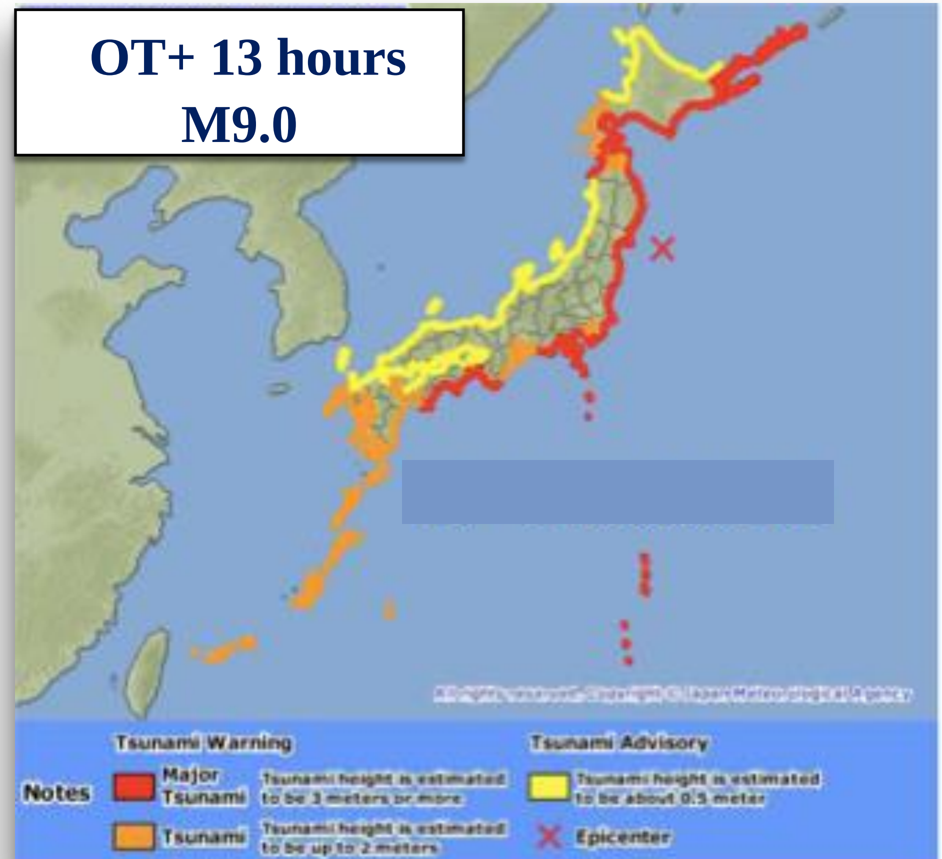
rtGNSS



# Seismic Data Alone Underestimated the Size of the Earthquake

## *Fast and Accurate Magnitude Determination Is Essential*




Japan seismic data =>
magnitude => tsunami impact based on
precomputed database
*Japanese Meteorological Agency*

Japan seismic data & teleseismic data =>
magnitude => tsunami impact based on
precomputed database
*Japanese Meteorological Agency*

Source - Ozaki et al, 2011, EPS

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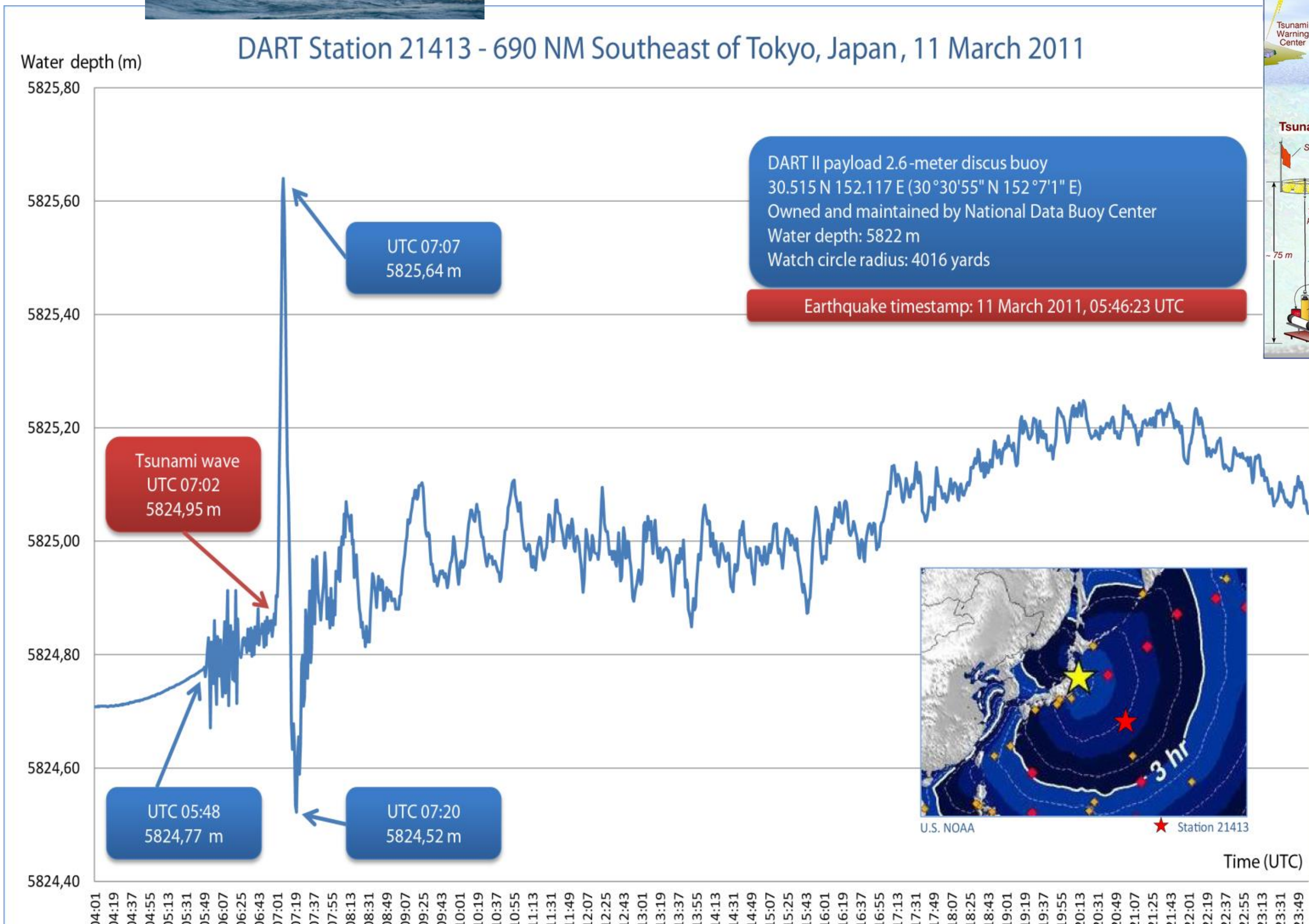
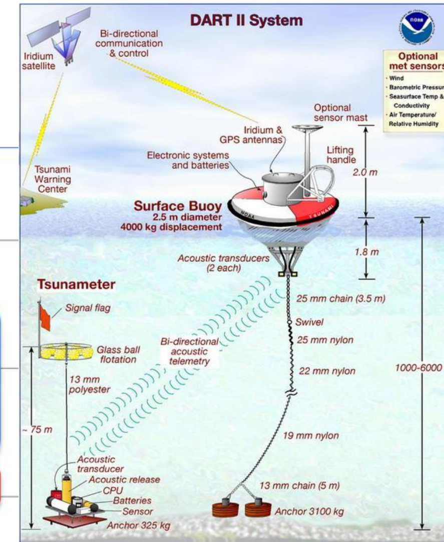
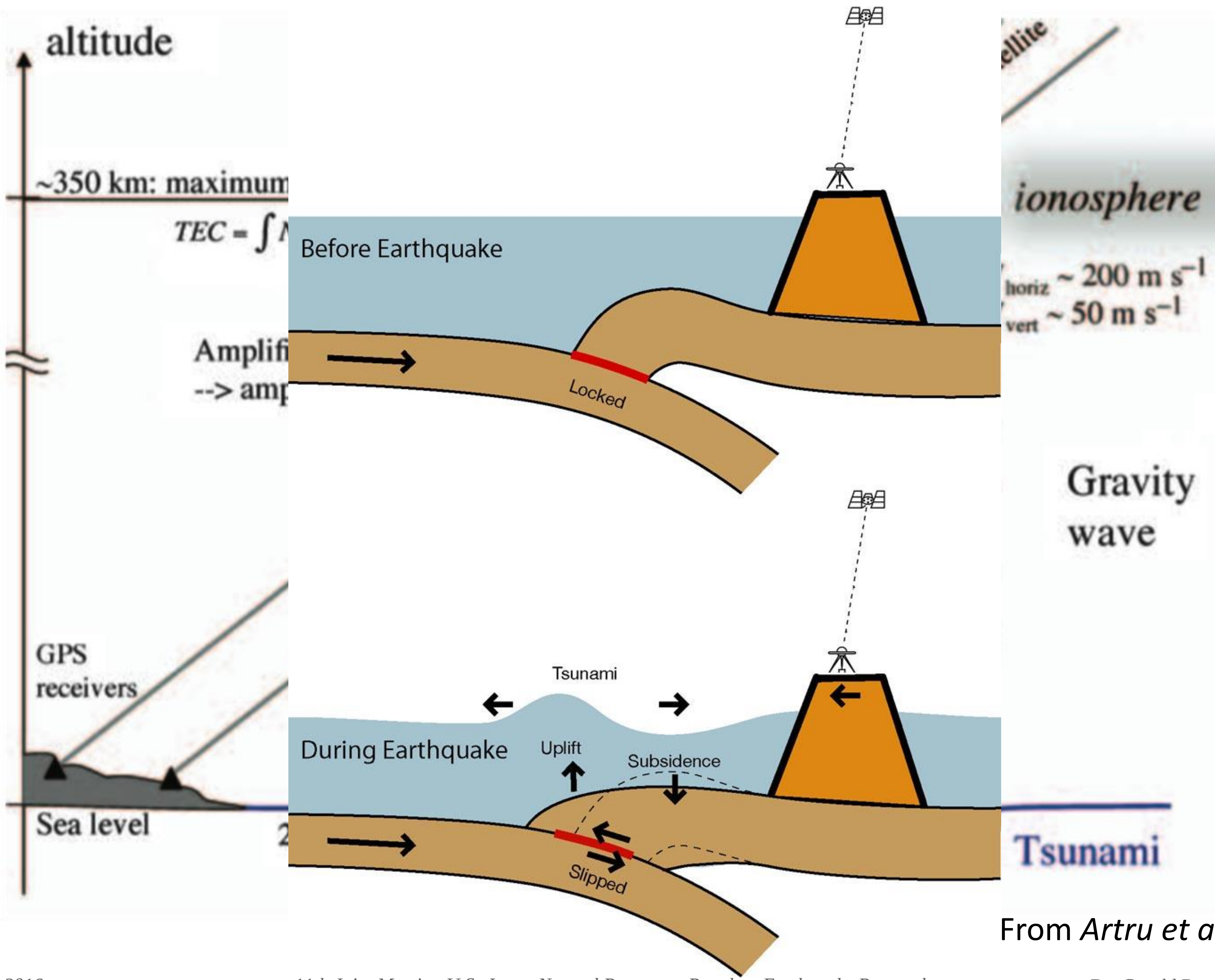
# Currently – DART Buoys are only way to track tsunamis in open ocean

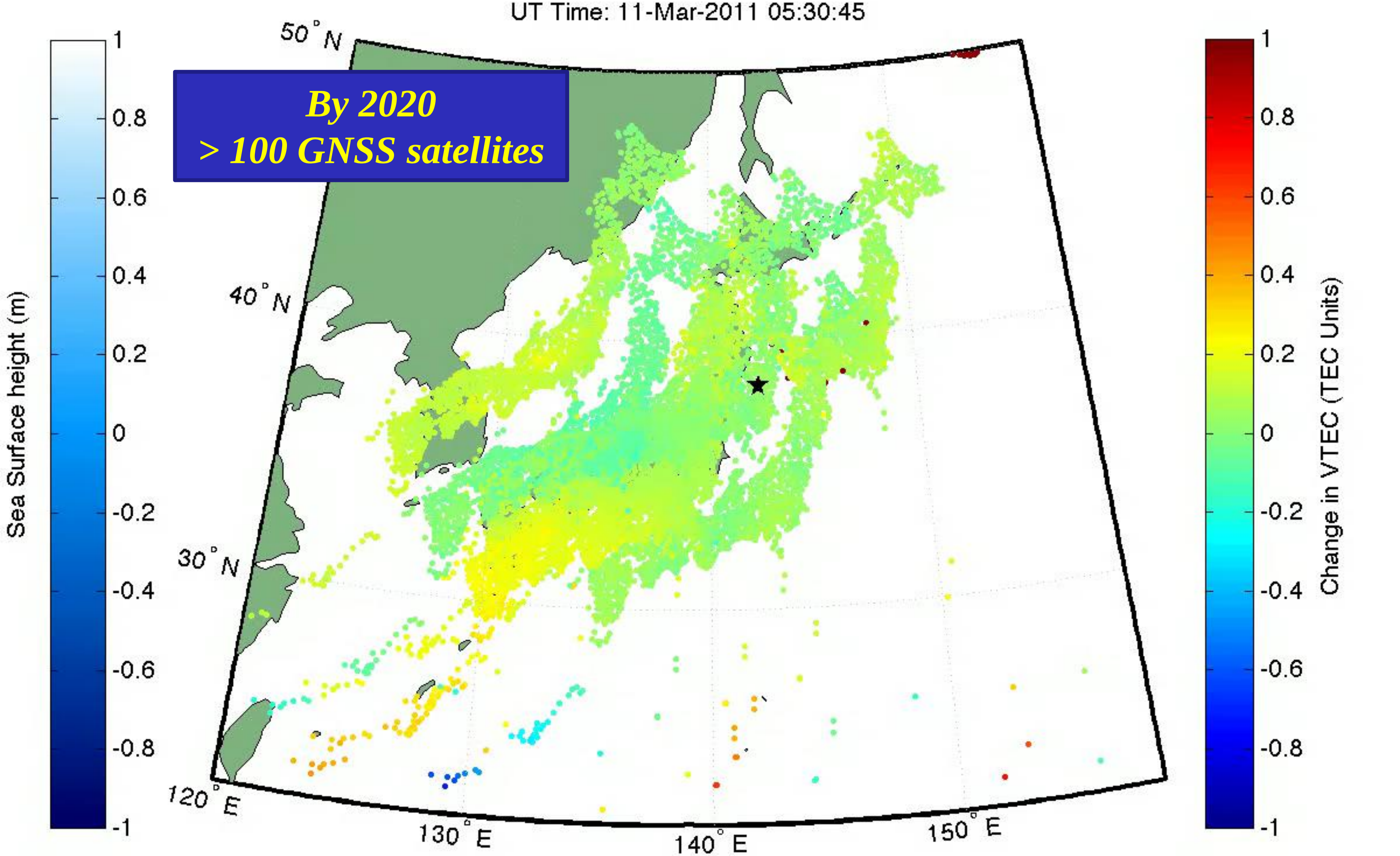



# The Tsunami Generated Displacement of the Ocean Surface Couples to the Ionosphere




From *Artru et al.,* 2005

# GSI's GEONET Captured the Ionospheric Coupled Waves and Imaged the Tsunami Generation and Propagation




**Ionospheric Response to Mw 9.0 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)

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} Real-Time GNSS

# GNSS Earthquake and Tsunami Early Warning

Expanding the earthquake and tsunami early warning globally requires access to **shared *real-time*** GNSS data in areas that are:

- Seismically active – *also in regions with volcanic unrest*
- Coastal communities that may be impacted by a tsunami

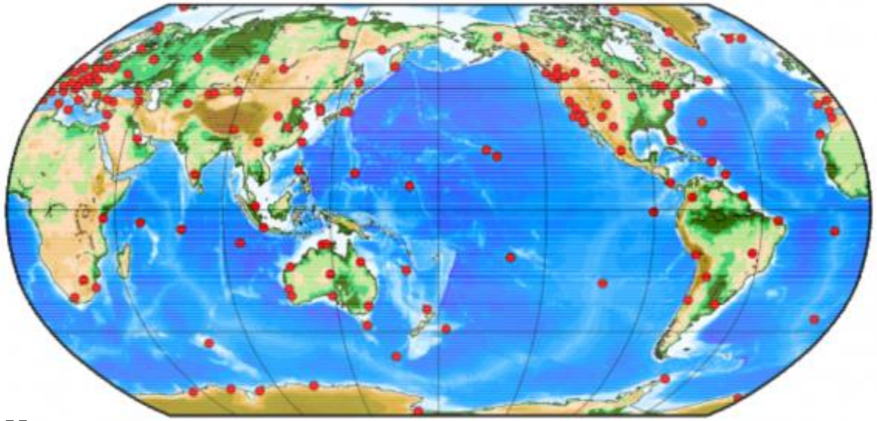
Partnership with regional/national tsunami and earthquake early warning Centers.

- The GNSS Early Warning approach enhances current capabilities

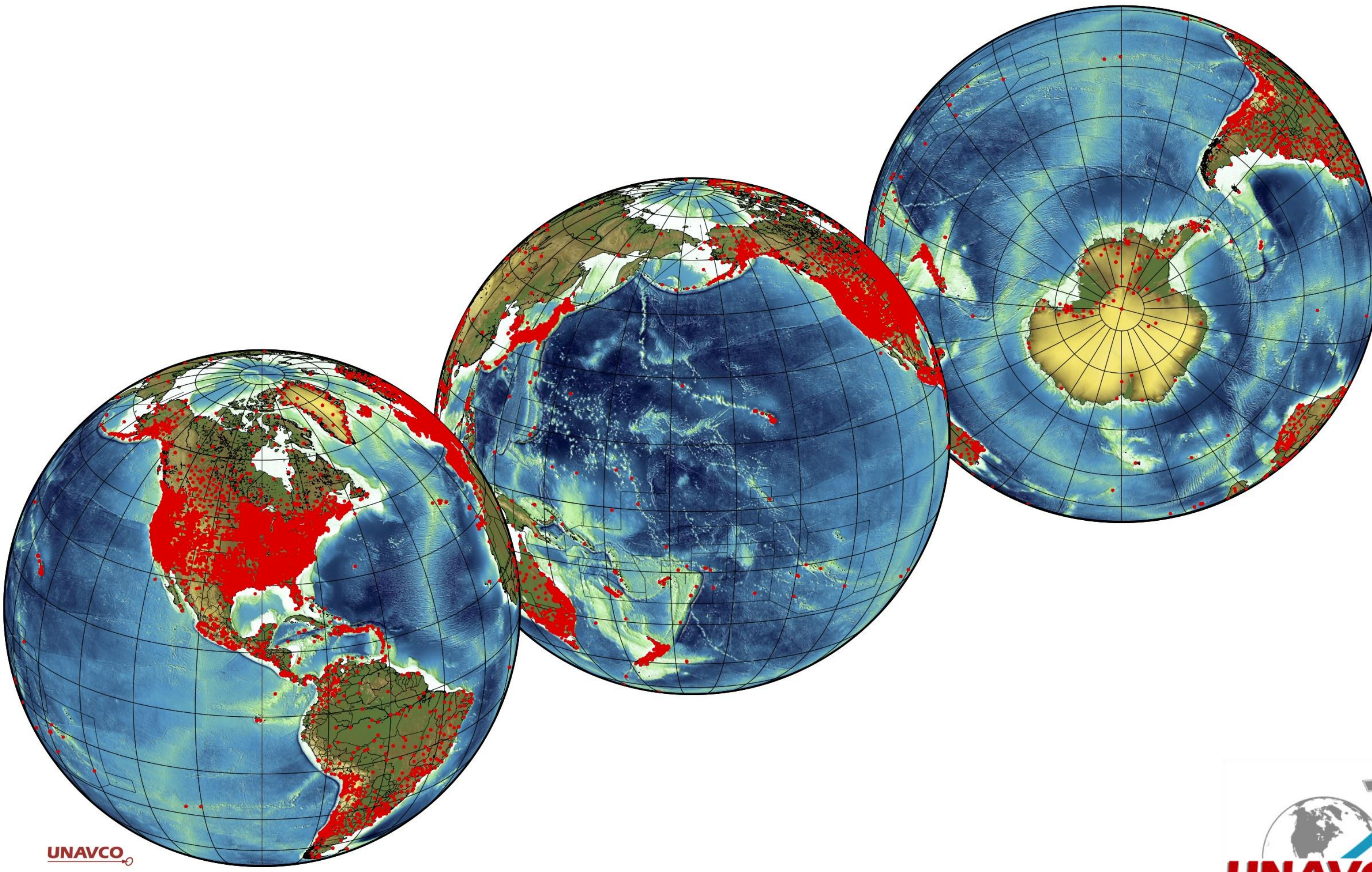
Partnership with the International GNSS and Earth Observation's communities

- ICG – UN International Committee on Global Navigation Satellite Systems + UNOOSA
- IGS – International GNSS Service
- GGOS – Global Geodetic Observing System
- GEO – Group on Earth Observations
- CEOS – Committee on Earth Observation Satellites

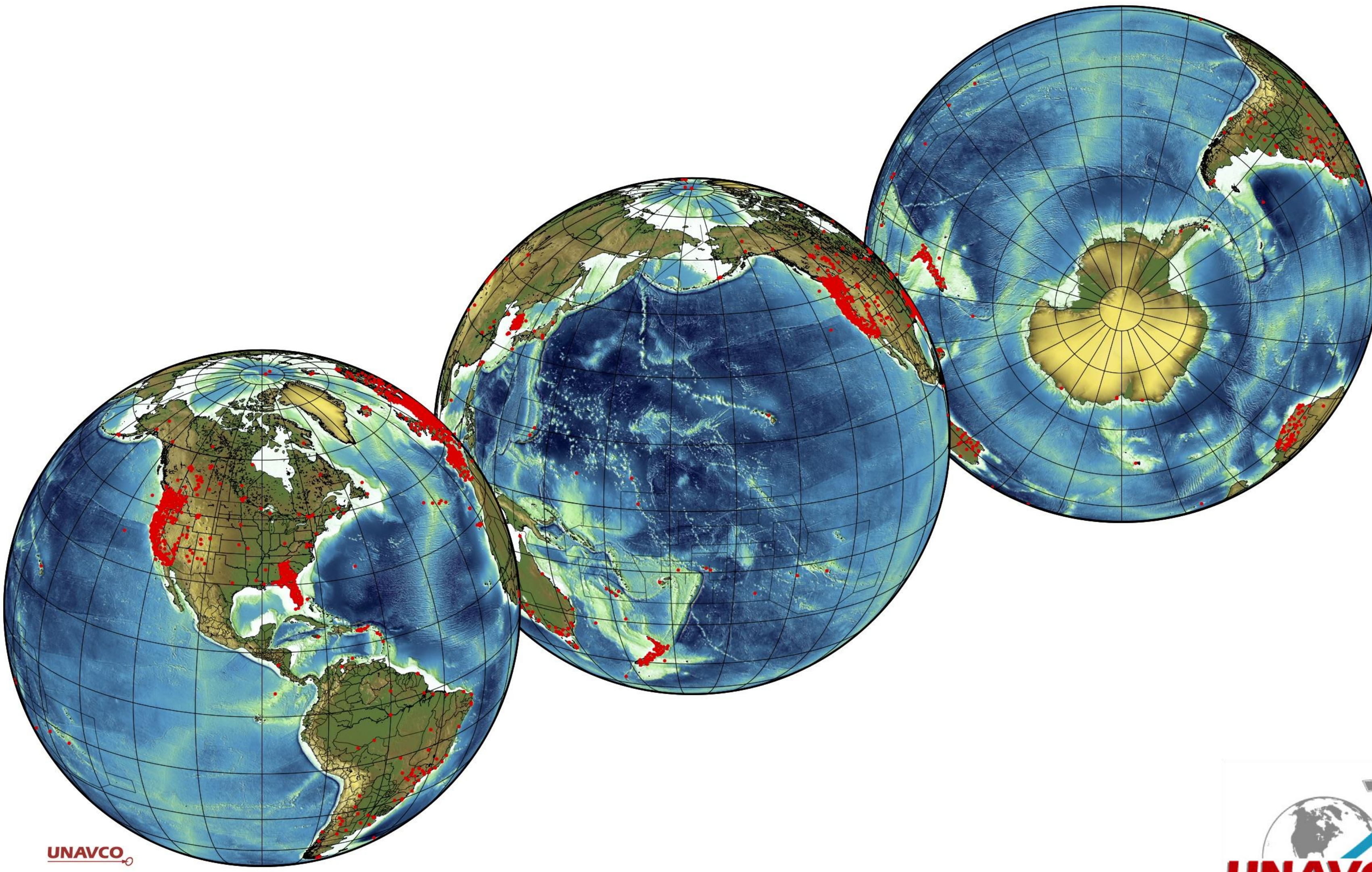
GGOS/IGS Real-TimeNetwork



# Known and Publically Accessible Continuous GNSS sites – 14,667



# Known and Publically Accessible Real-Time GNSS sites – 2,287

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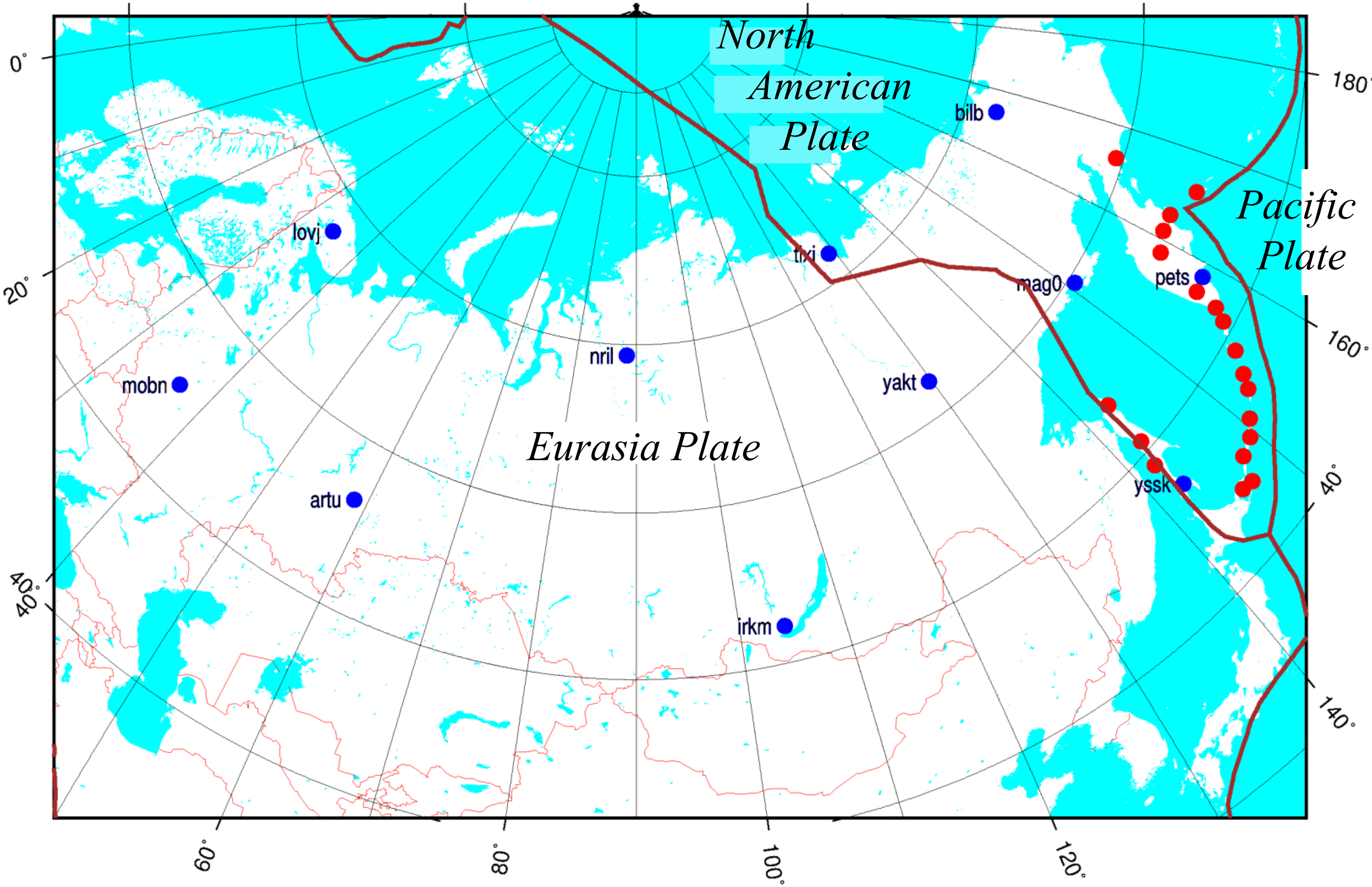
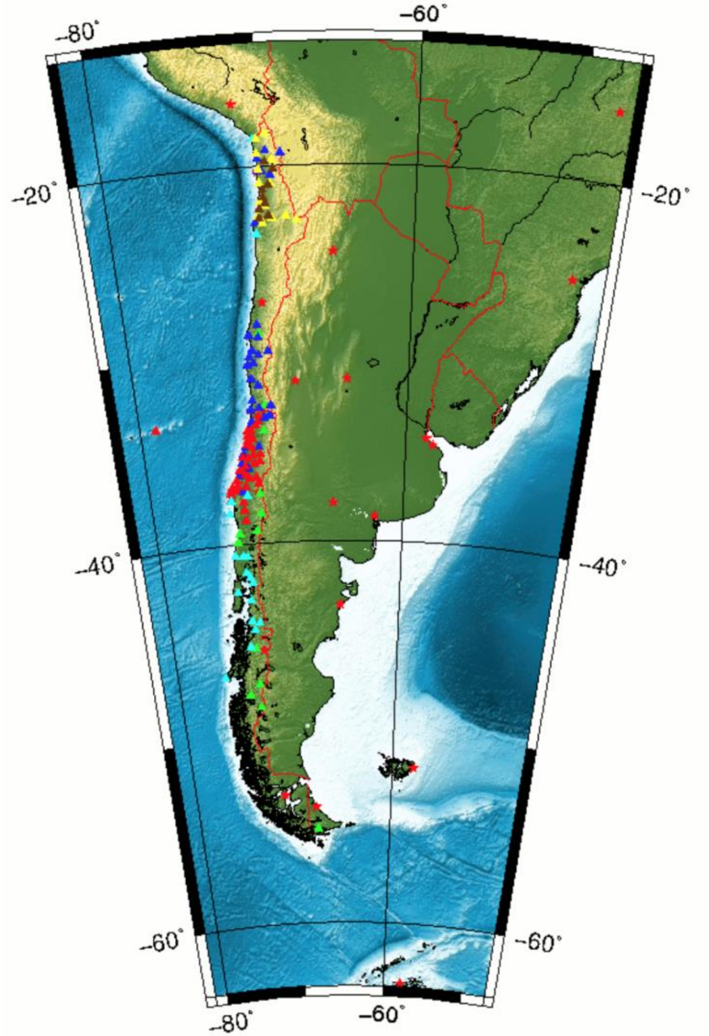
# Continental and regional GNSS networks
# Geophysical Survey Russian Academy of Sciences




- NEDA sites (according to IGS catalog)
- Pacific coastal sites (according to recent published research)

# Chile National Net

## >150 GNSS sites, 40 real-time GNSS sites




CAP/IGM/UDEC stations
UDEC/GFZ/IGM stations
IPGP/DFG stations
CALTECH stations
GFZ/IPGP/DGF stations

More than 151 C-GNSS

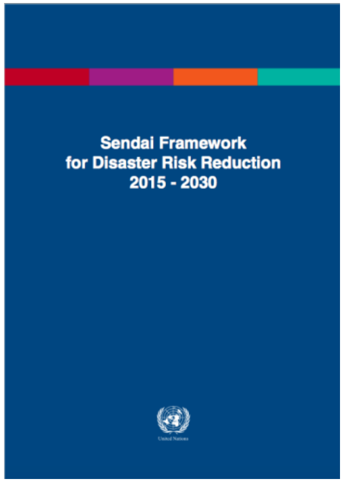
Crustal Dynamics Data Information System

**http://cddis.nasa.gov**

# GNSS Earthquake and Tsunami Early Warning

## SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION

A real-time GNSS network would support a number of goals described the Sendai Framework




*18. **To support the assessment of global progress in achieving the outcome and goal of the present Framework, seven global targets have been agreed.***

*(a) 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;*

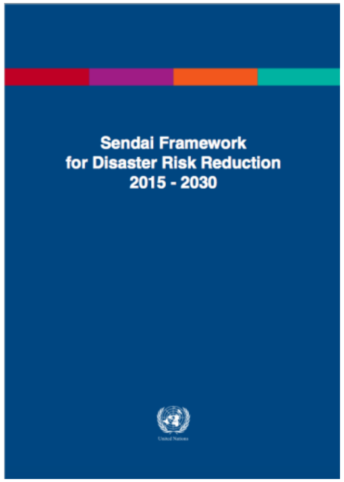
*(f) Substantially **enhance international cooperation** to developing countries through adequate and sustainable support to complement their national actions for implementation of the present Framework by 2030;*

***(g) Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.***

# GNSS Earthquake and Tsunami Early Warning

## SENDAI FRAMEWORK FOR DISASTER RISK REDUCTION

A real-time GNSS network would support a number of goals described Sendai Framework




### IV. Priorities for action

***20. Taking into account the experience gained through the implementation of the Hyogo Framework for Action, and in pursuance of the expected outcome and goal, there is a need for focused action within and across sectors by States at local, national, regional and global levels in the following four priority areas****:*

***Priority 1: Understanding disaster risk.***

**GNSS 99.99% of the time**
**Scientific Research**

*Priority 2: Strengthening disaster risk governance to manage disaster risk.*

*Priority 3: Investing in disaster risk reduction for resilience.*

*Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.*


**Save the date**

**Real-Time GNSS Tsunami Early Warning Workshop**

**July 25-27, 2017 — Sendai, Japan**

**Gerald Bawden**

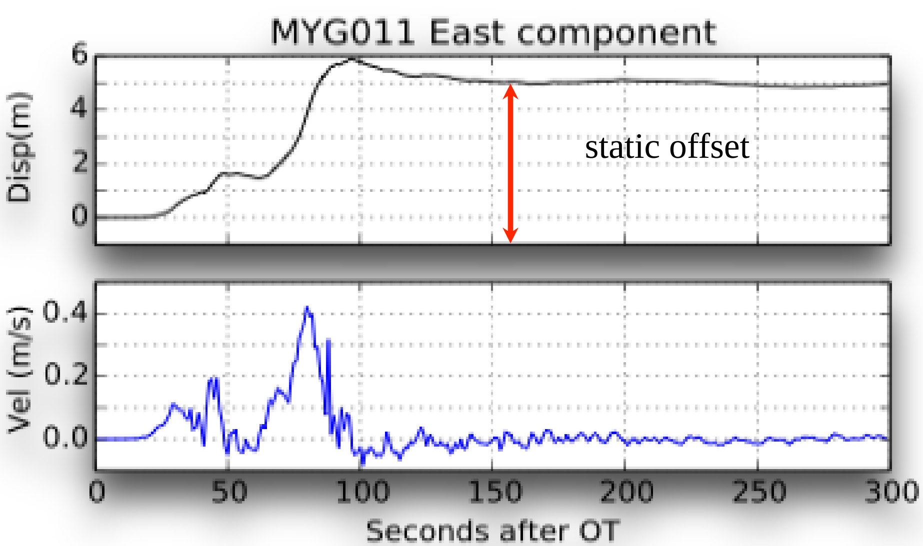
**Gerald.W.Bawden@NASA.gov**

# Backup Slides

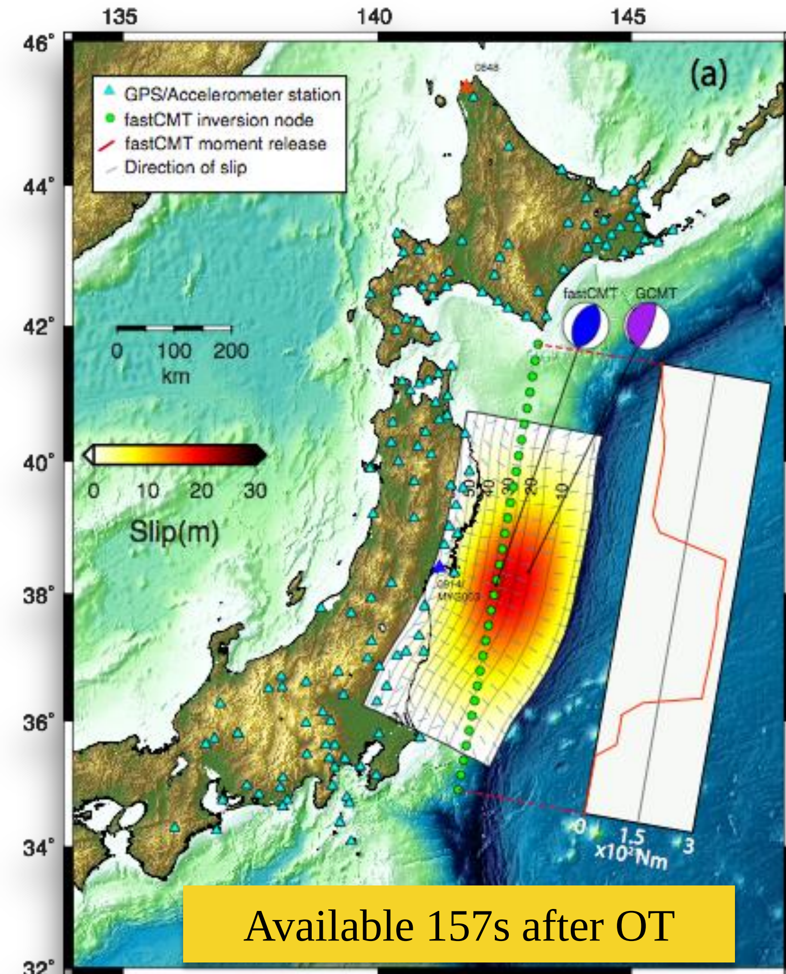
# GNSS Static Slip Model 157 seconds

- Magnitude estimates from seismic data-only tend to saturate for large events.
- Regional seismic data are band limited, they cannot adequately capture long periods in real-time.

- Create rapid models with the GNSS static field
    - **Static = simple and fast**

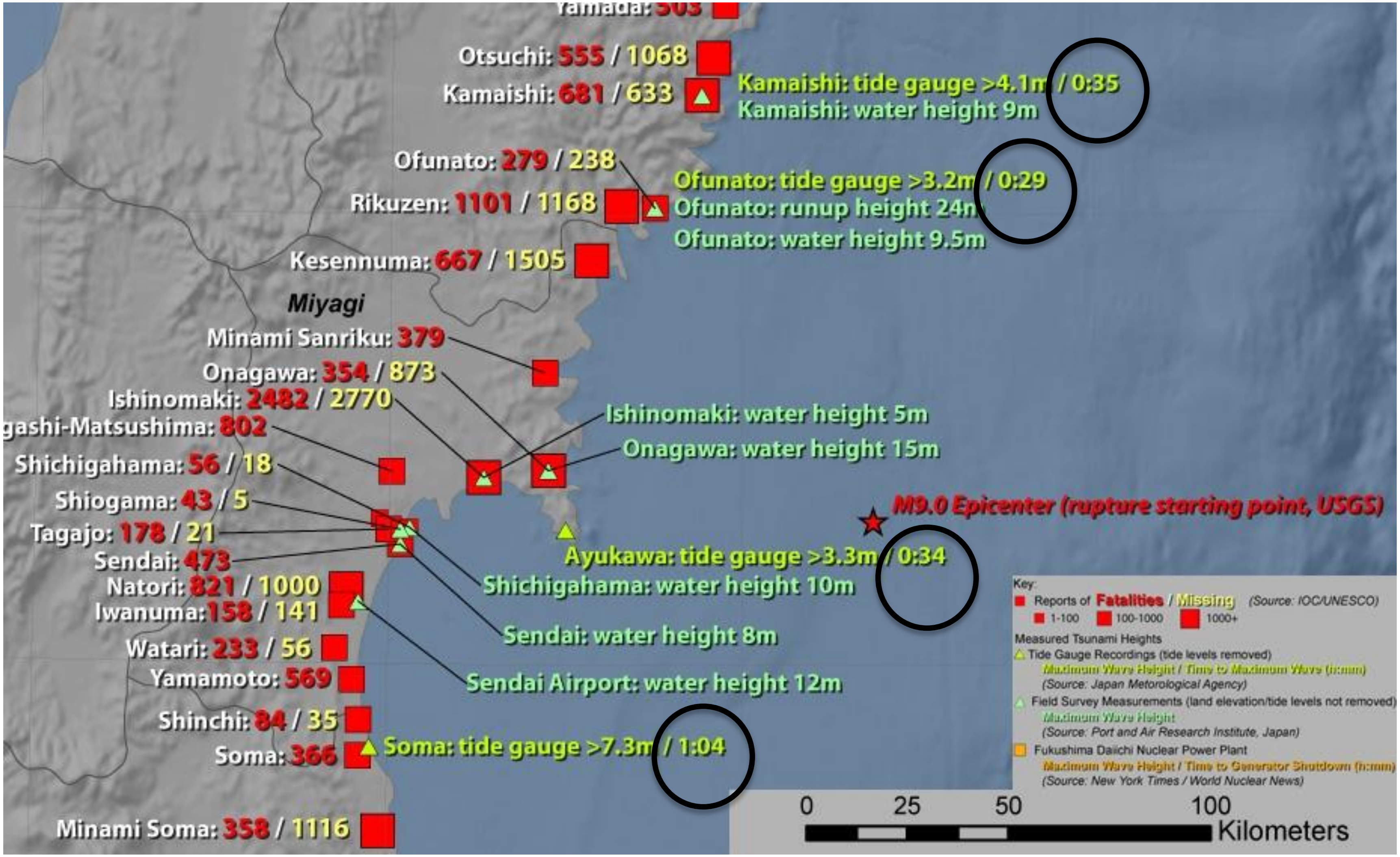



2011 Mw 9 Great East Japan Earthquake




Source: Melgar et al., GRL, 2013

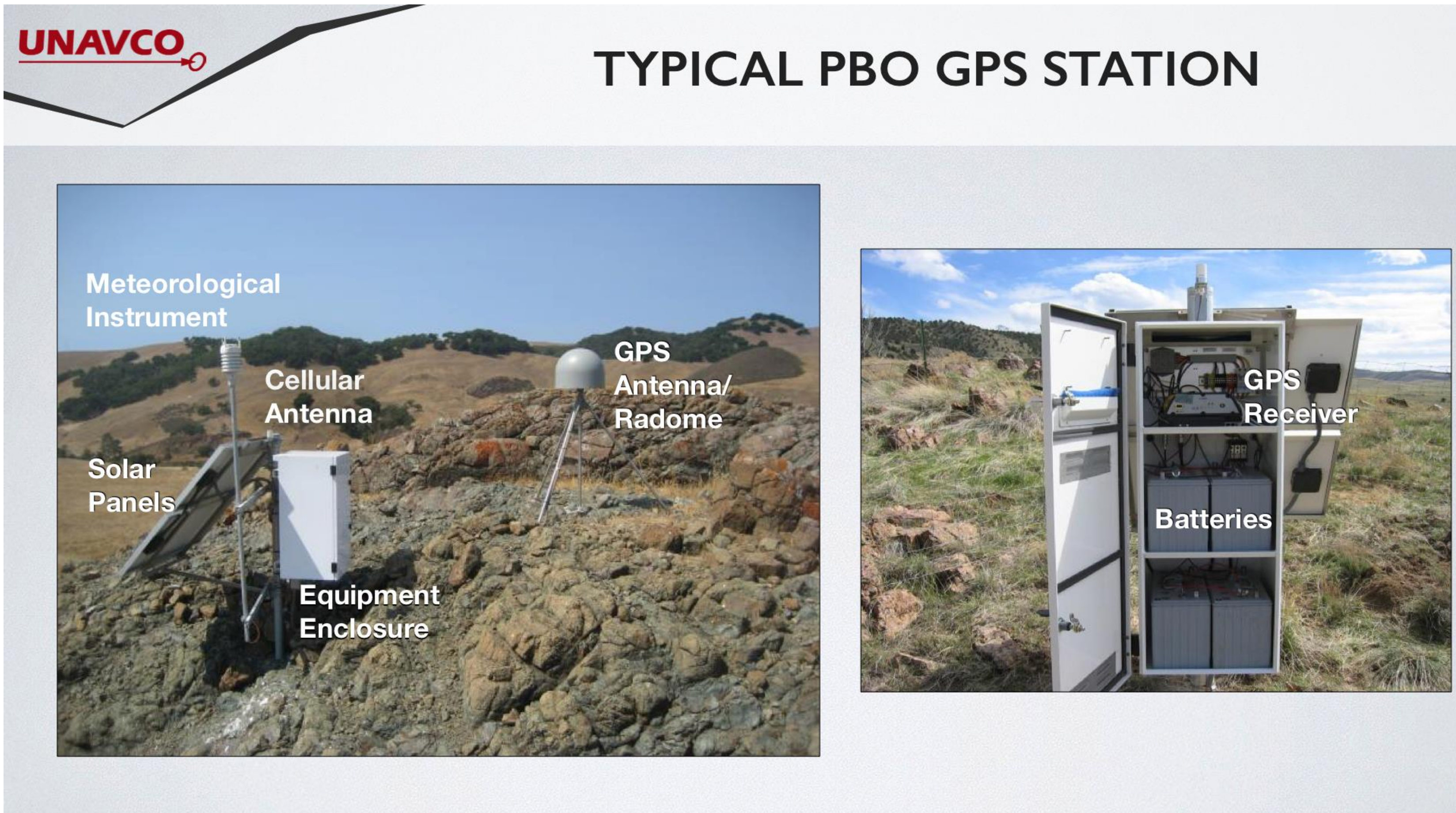
# Tsunami travel times for 2011 Mw 9.0 Tohoku-oki earthquake



# GNSS Site Installation Costs

Costs to build a PBO-quality station:

- Deep Drilled-Braced Monument ~$50K/station
- Shallow Drilled-Braced Monument ~$25K/station



# GNSS Site Yearly Costs

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## COST PER STATION PER YEAR

| | Mean | Median | Min | Max | number of stations (n) |
|---|---|---|---|---|---|
| All Stations | $5.8k | $5.5k | $3.9k | $13.7k | 1100 |
| Critical Stations | $6.1k | $5.5k | $4.0k | $13.7k | 331 |
| Volcanic Targets | $7.9k | $6.7k | $4.1k | $13.7k | 102 |
| Alaska Stations | $8.6k | $7.5k | $4.9k | $13.7k | 140 |
| Low Strain Targets | $5.2k | $5.2k | $4.0k | $8.4k | 260 |
| High Strain Targets | $5.5k | $5.4k | $4.0k | $9.8k | 628 |
| Stable North America | $5.0k | $5.0k | $3.9k | $7.2k | 28 |
| Snow/Soil Moisture Targets | $5.7k | $5.4k | $4.0k | $13.2k | 149 |

# GNSS Site Yearly Costs

UNAVCO

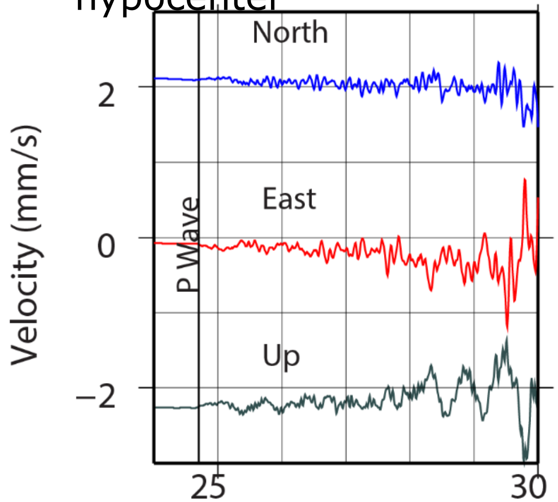
## MEAN COST PER STATION (1100 STATIONS)

| | Mean Cost Per PBO Station Per Year |
|---|---|
| Field Operations Fixed Costs (Facilities, Storage, Shipping) | $255 |
| Sub-Award Data Processing | $365 |
| Archiving and Data Operations (staff, servers, software, etc) | $899 |
| Realtime Data Handling | $305 |
| Field Travel | $626 |
| Labor (with fringe) | $1,267 |
| Materials/Supplies/Equipment | $471 |
| Station Permitting | $469 |
| Data Communications | $386 |
| Indirect Rate (15.79%) | $796 |
| **TOTAL** | **$5.8k** |

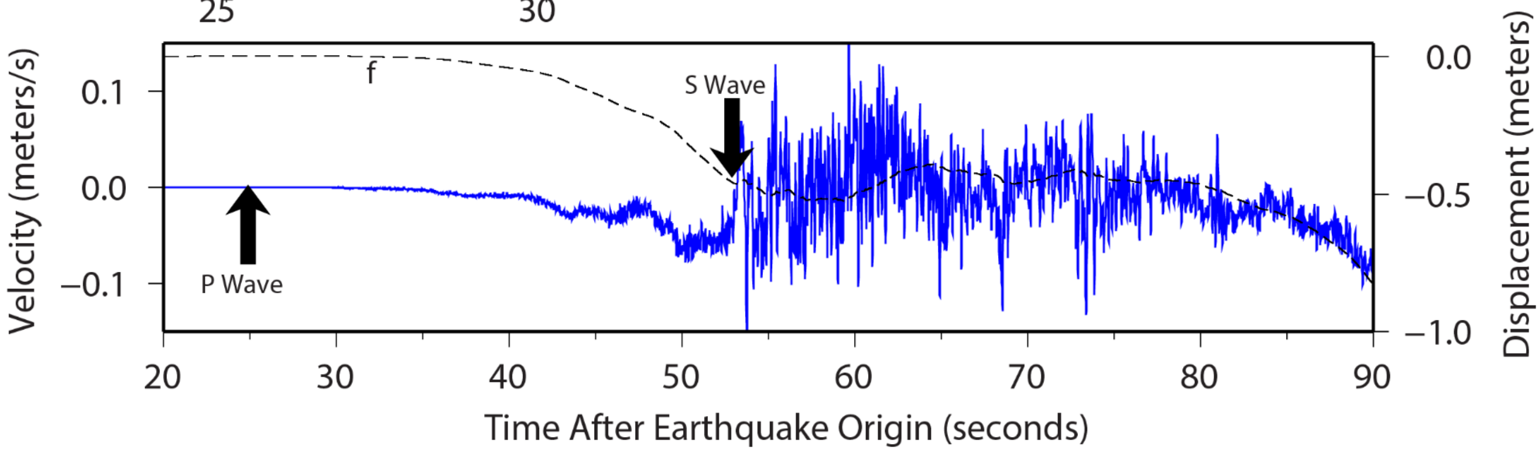
# Next Generation of GNSS will Include Accelerometers

## Seismogeodetic Earthquake Early Warning at Scripps Institute of Oceanography

2011 Tohoku-oki earthquake GEONET GPS station 0914 and K-NET accelerometer MYG003, 155 km from the JMA hypocenter

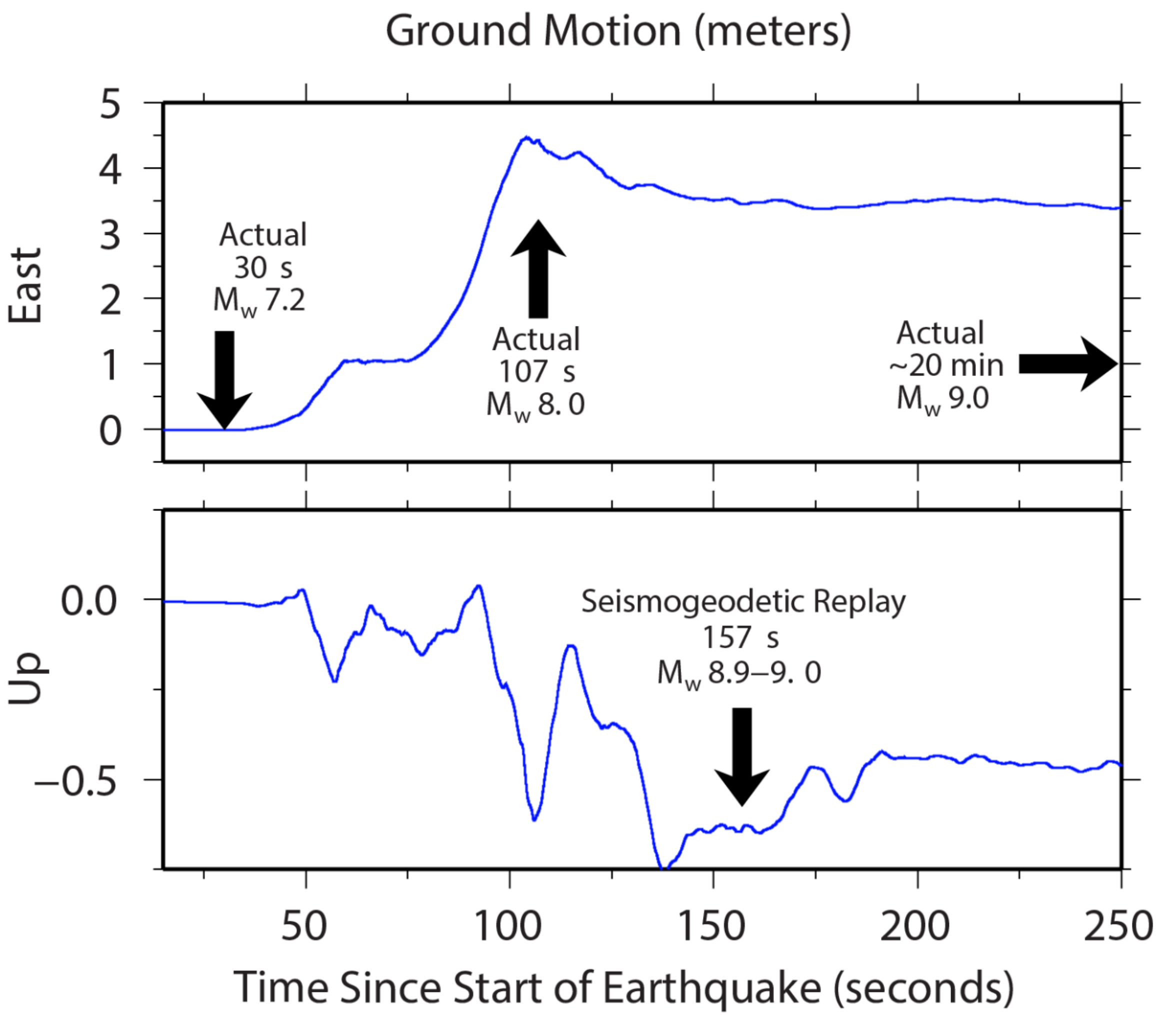



Seismogeodesy detects arrival of seismic *P* (primary) waves used in earthquake early warning to predict arrival and intensity of more damaging *S* (secondary) and surface waves, better than accelerometers alone for large earthquakes, because of magnitude saturation of latter (Crowell et al., GRL, 2013)




**Source: Melgar et al., GRL, 2013**

# Seismogeodetic Displacements and Magnitude Estimation




2011 Tohoku-oki earthquake
GEONET GPS station 0914 and K-NET accelerometer MYG003, 155 km from the JMA hypocenter

Seismogeodesy improves on traditional seismic monitoring by accurately determining magnitude of large (> M 7) earthquakes without saturation and by estimating both ground motions and permanent displacements

**Source: Melgar et al., GRL, 2013**

# Components of a Real-Rime GNSS Tsunami Early Warning System

- **GNSS sites located in seismogenic region *streaming* phase and range in real-time**
- Precise Point Positioning (PPP) estimates calculated and accessible in real-time
- Dynamic change detection algorithms – in real-time
- Earthquake source modeling – in real-time
- Tsunami source modeling – in real-time
  - Continued iterations as new GNSS data are available
  - Continued iterations as other data become available
- Integration of the rtGNSS derived source model into warning assessment and protocols
  - Initial rtGNSS solution
  - Iterative rtGNSS solutions
- Tsunami run-up modeling
  - Including GNSS vertical deformation measurements
- Ionosphere-tsunami linkage – wave propagation