Development of a GNSS-Enhanced Tsunami Early Warning System

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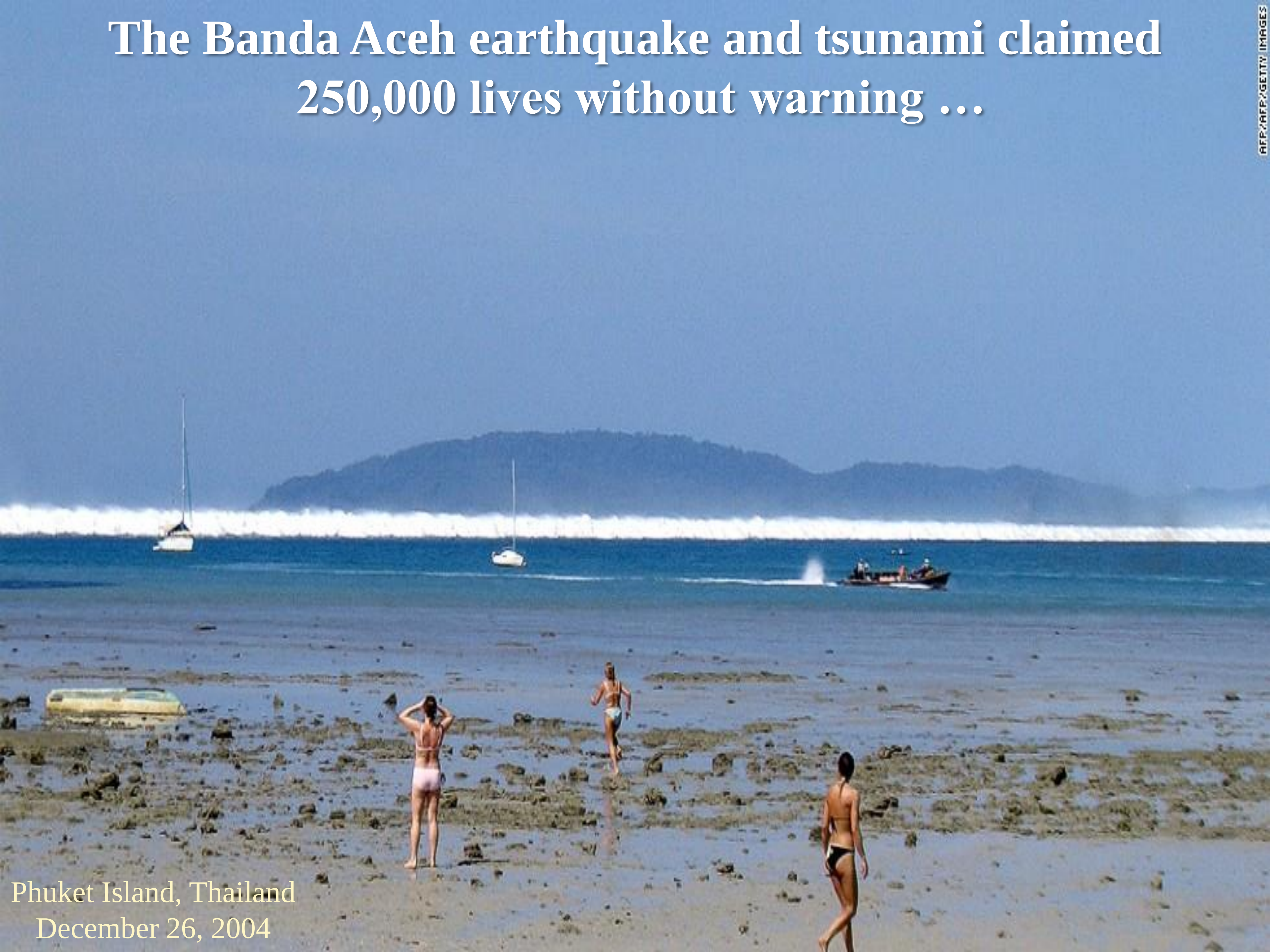
Plus many many more.

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 perturbations in the ionosphere
Improves latency and accuracy of models
Next generation models include coastal subsidence

} Real-Time GNSS

The READI Working Group

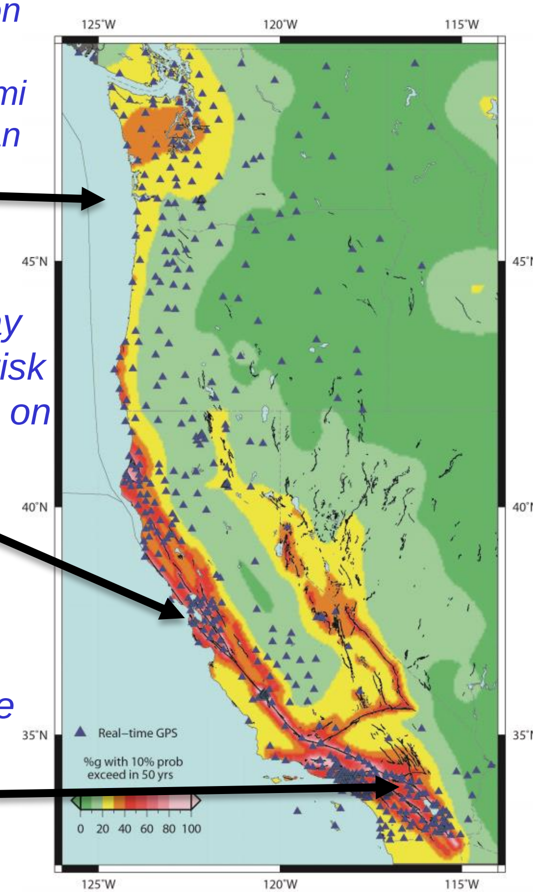
- **R**eal-Time **E**arthquake **A**nalysis for **D**isaster m**I**tigation network (READI): ~750 GPS stations, a NASA driven project
- Super set of GNSS networks maintained by (sorted according to largest to smallest number of stations):
  - UNAVCO/PBO
  - CWU/PANGA
  - USGS/Pasadena-SCIGN & Menlo Park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

NASA NSF NOAA

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

W

California Institute of Technology 1891

CWU

USGS science for a changing world

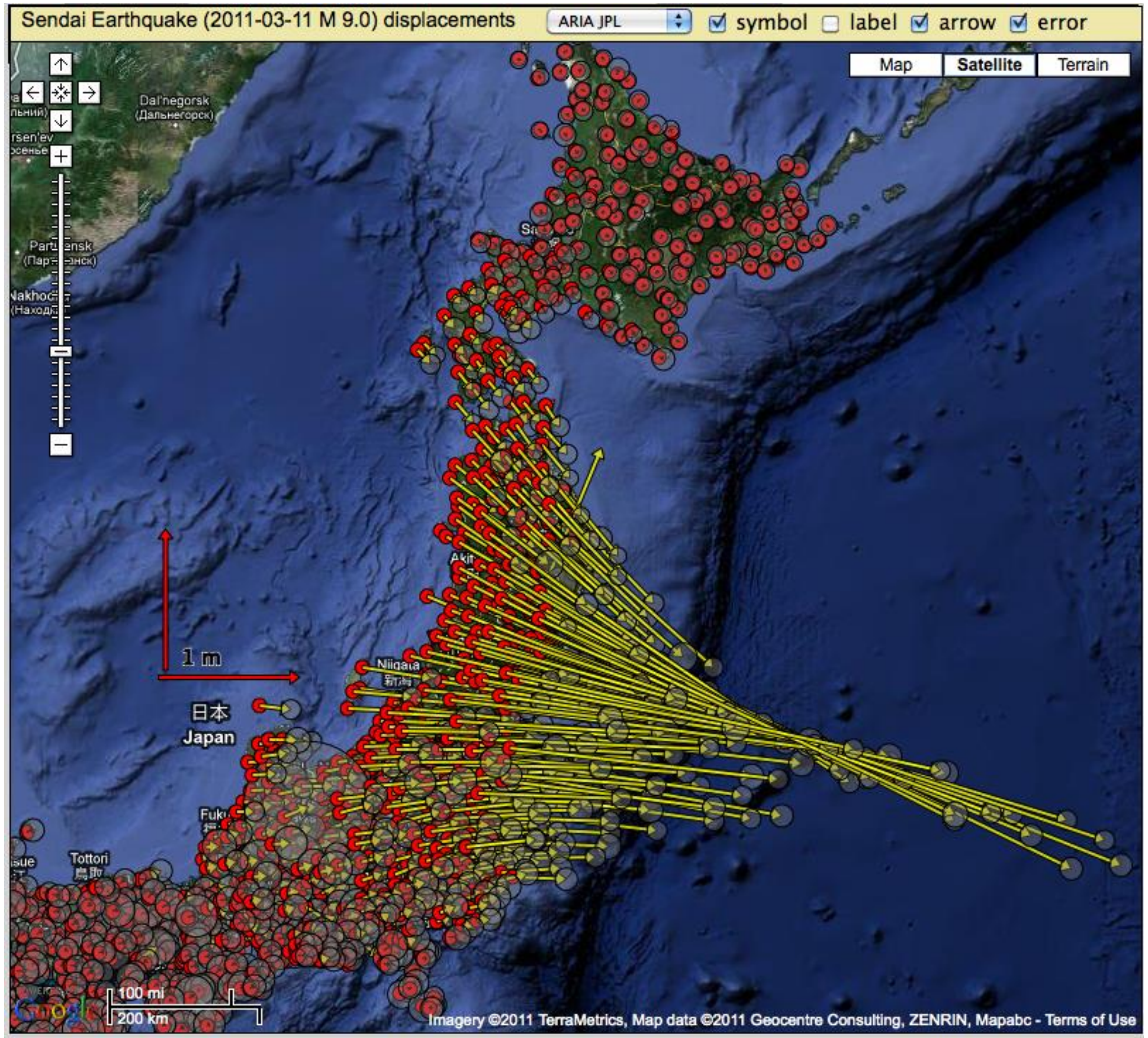
Scripps Institution of Oceanography UC San Diego

NASA

Jet Propulsion Laboratory
California Institute of Technology

UNAVCO

GNSS Earthquake and Tsunami Early Warning



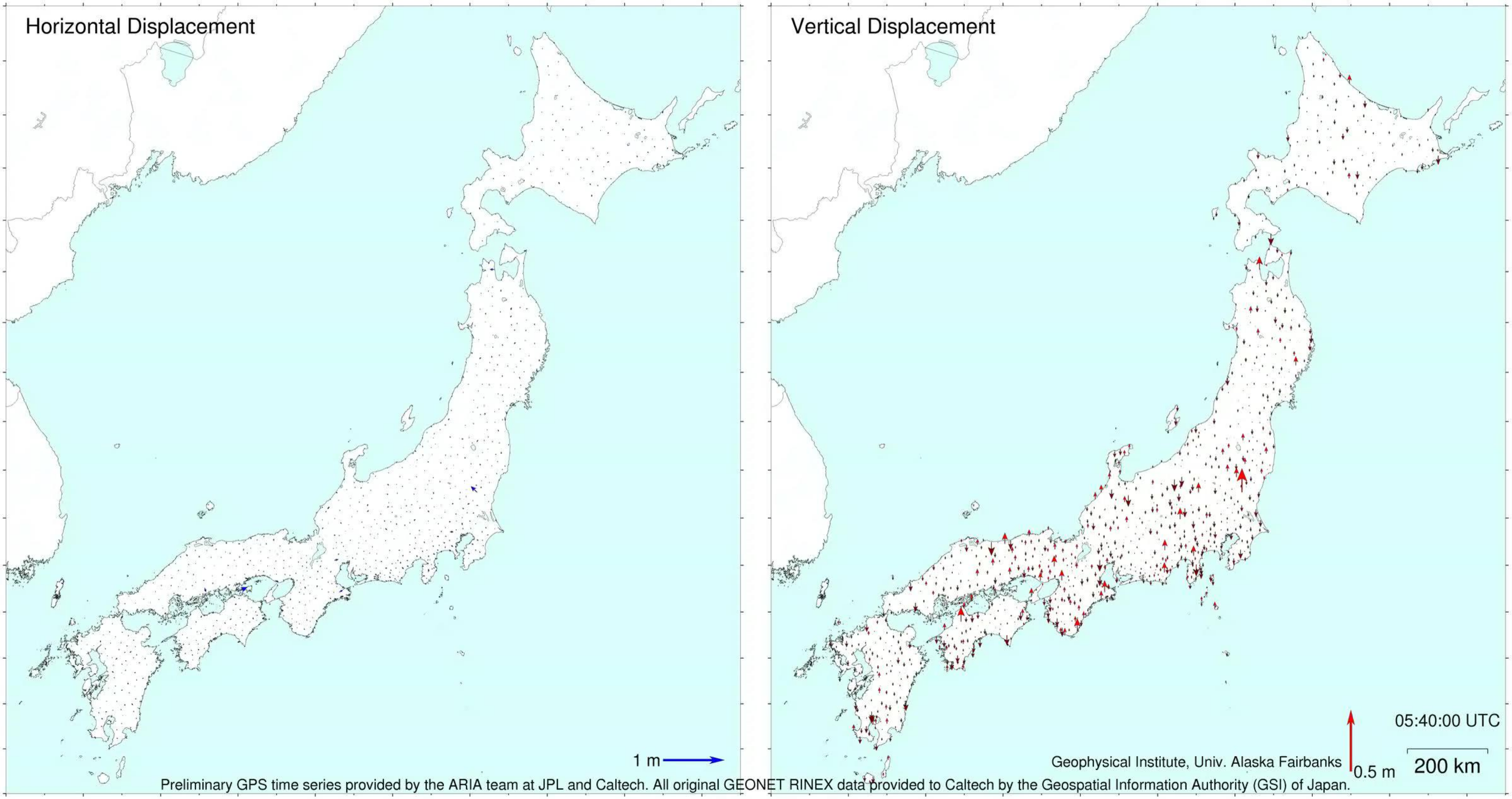
Data courtesy of the Geospatial Information Authority of Japan GSI

GEONET GPS Array

Great East Japan Earthquake and Tsunami

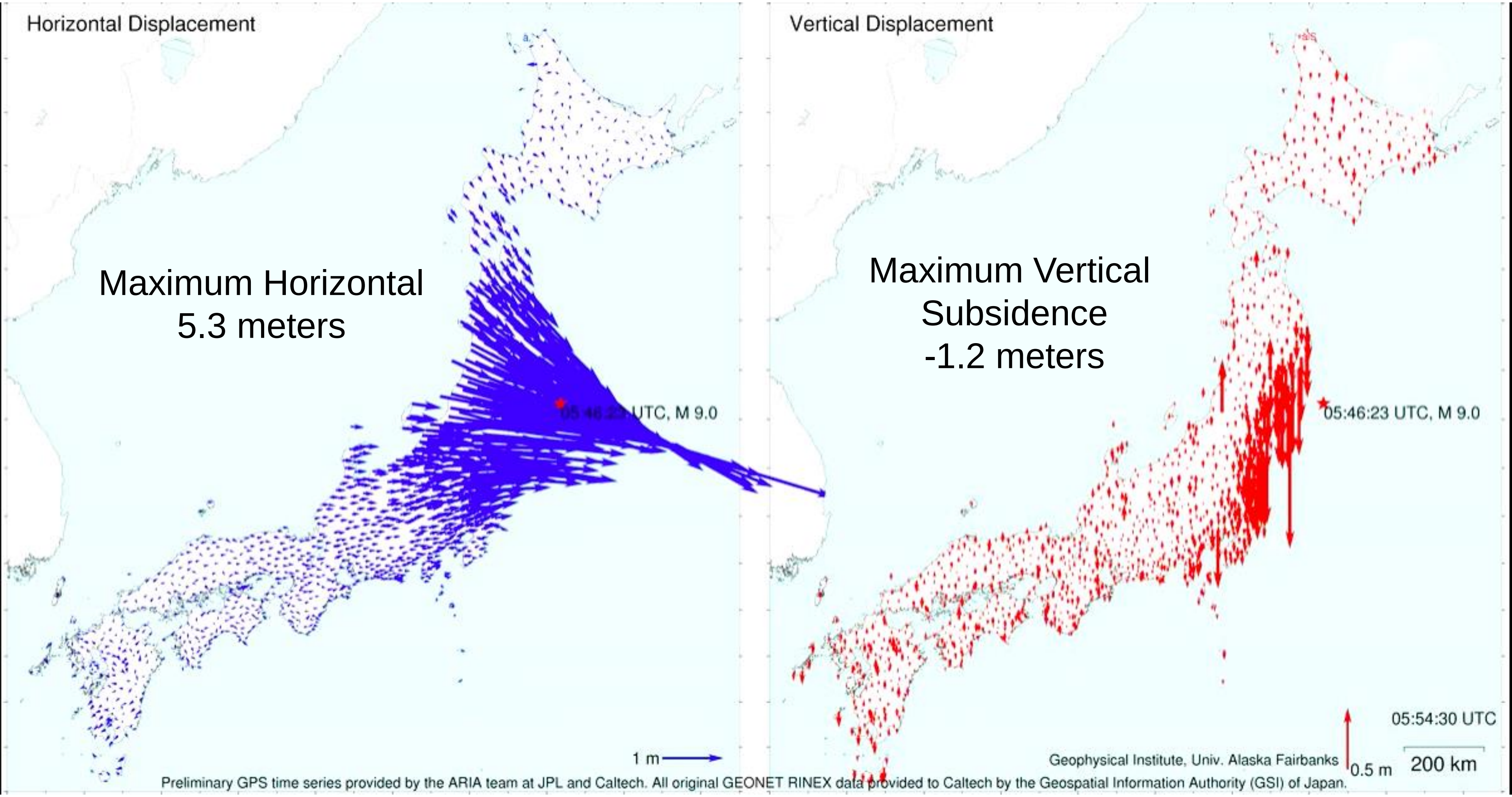
Maximum GPS displacement ~5 meters

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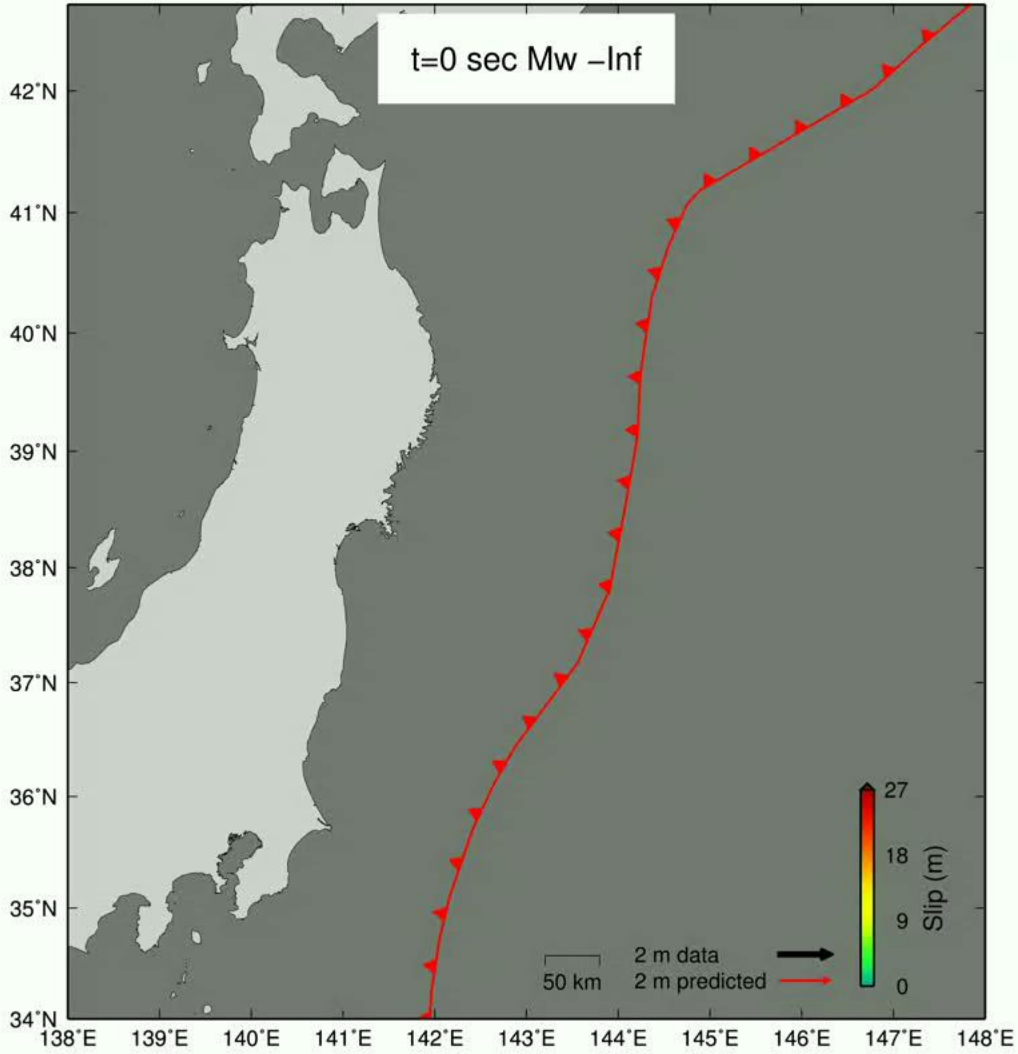
Real-Time GNSS for Rapid Earthquake Magnitude Determination and Fault Slip Distribution



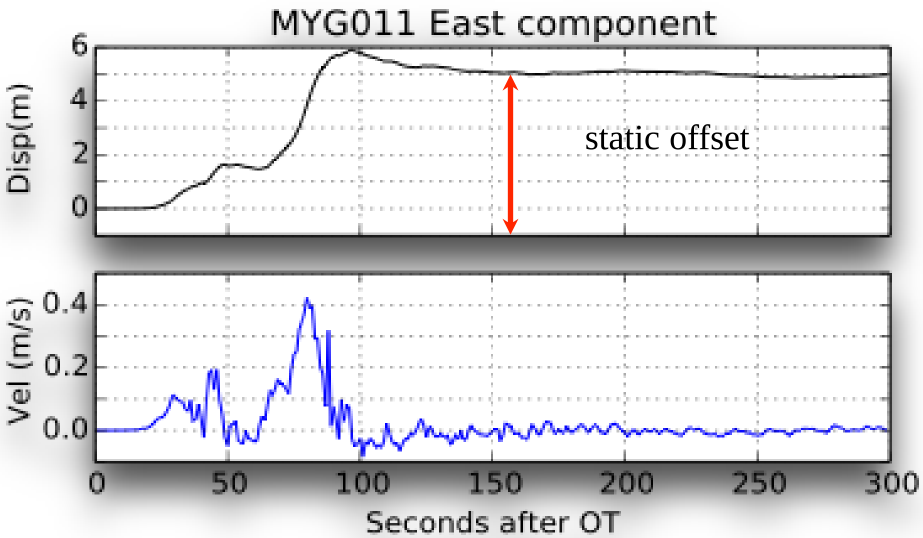
Case 1 – model determines fault location

S. E. Minson et al, 2013 JGR

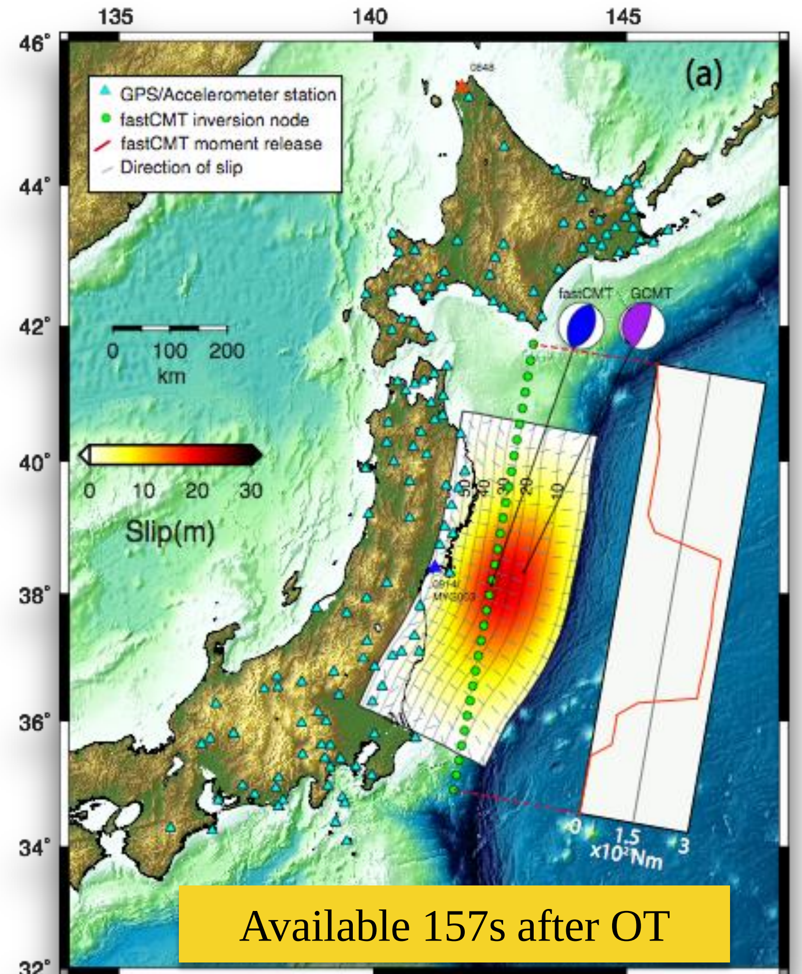
GNSS Static Slip Model 157 seconds

- 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 <u>static</u> field
  - **Static = simple and fast**



2011 Mw 9 Great East Japan Earthquake



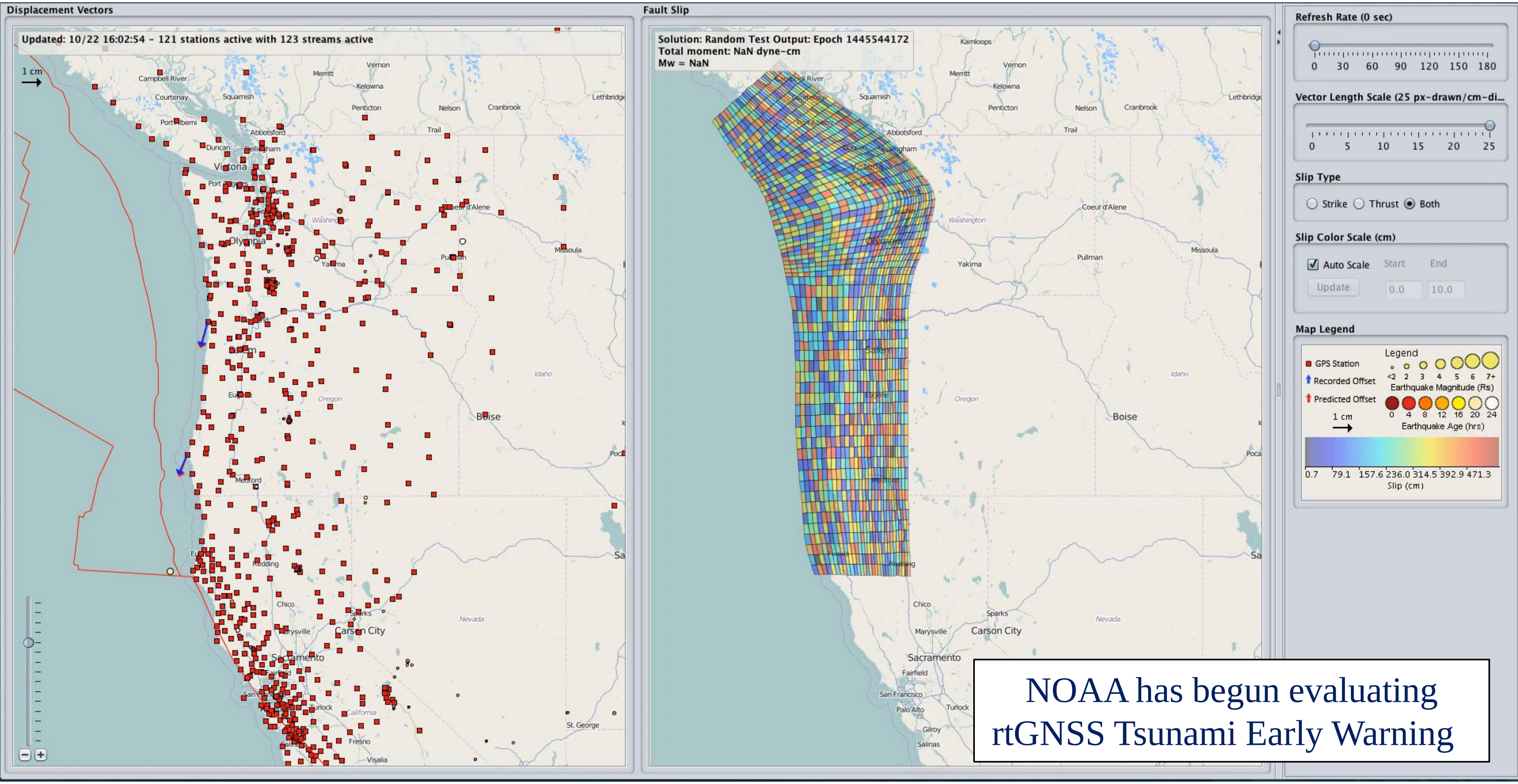
Available 157s after OT

Source: Melgar et al., GRL, 2013

GNSS Earthquake Source Model for a Predefined Fault

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

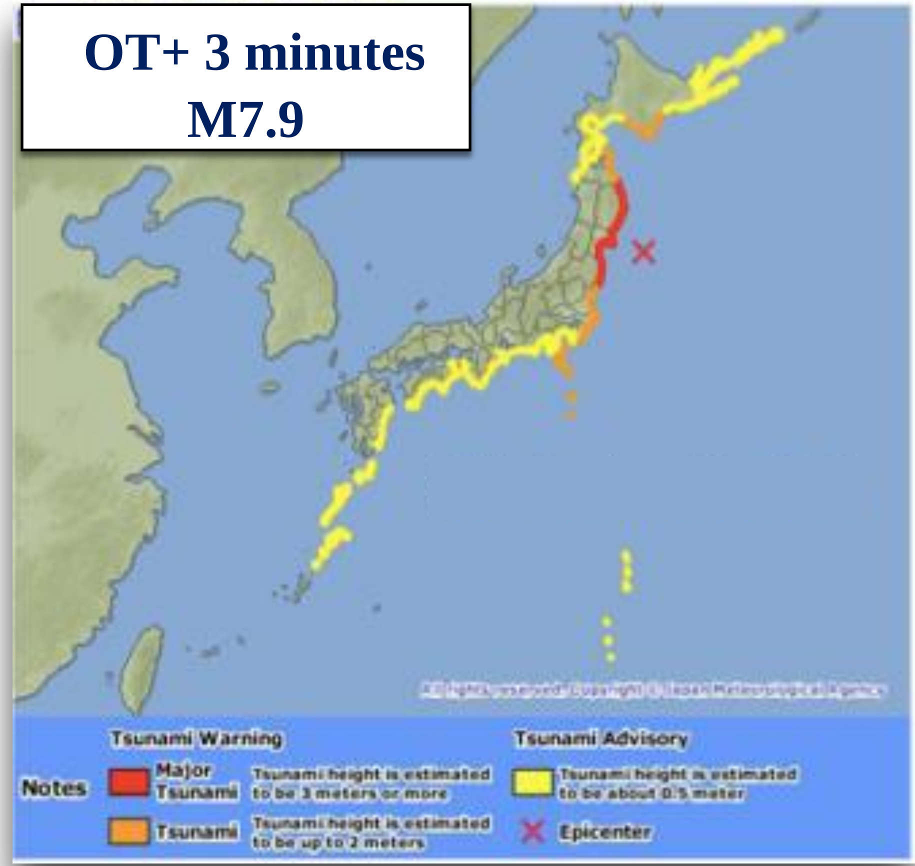
Prototype running in real-time on a fixed fault surface

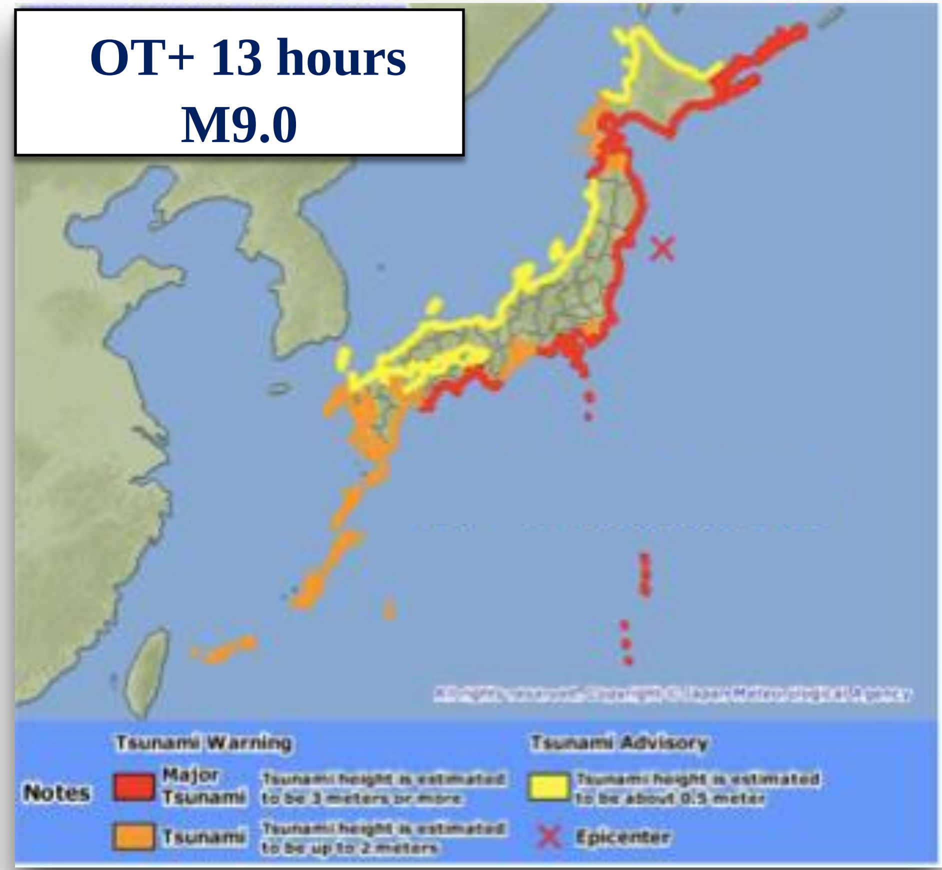


Developed by the READI Working Group

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
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Source - Ozaki et al, 2011, EPS

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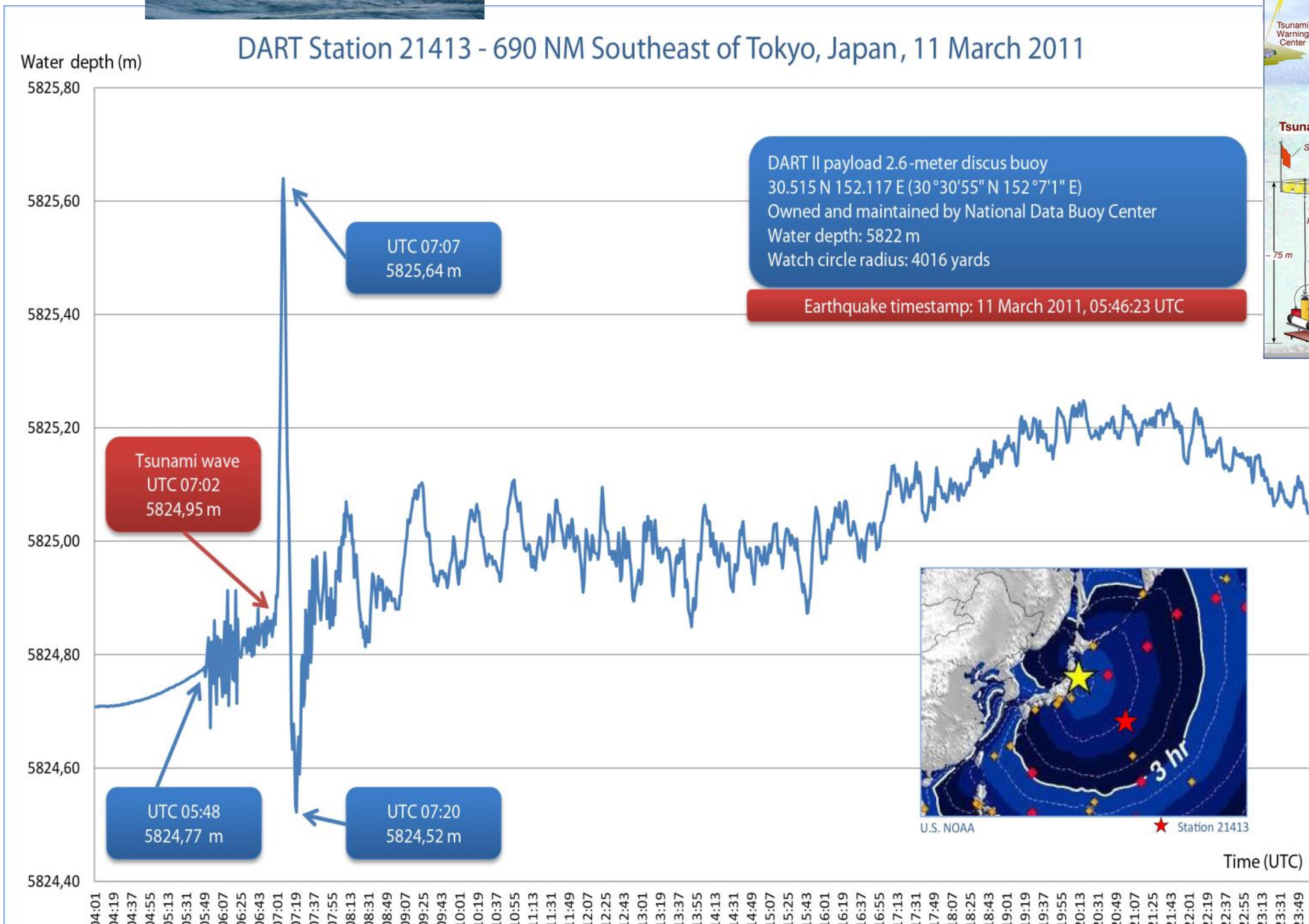
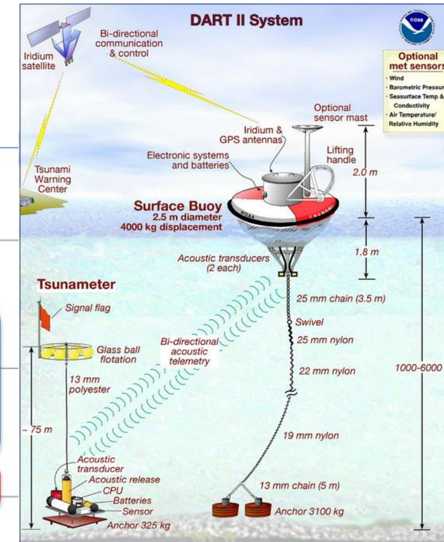
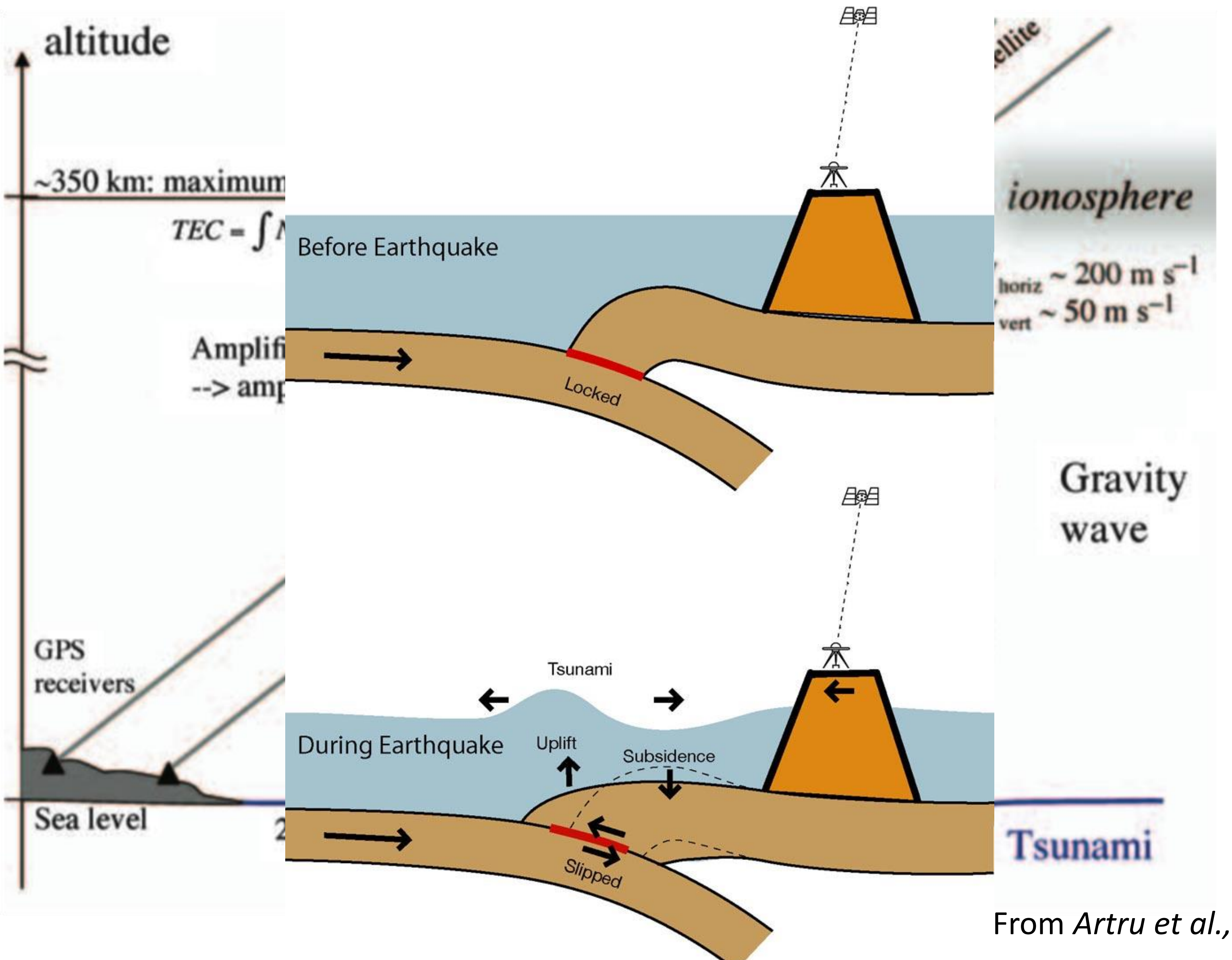
Currently – DART Buoys are only way to track tsunamis in open ocean





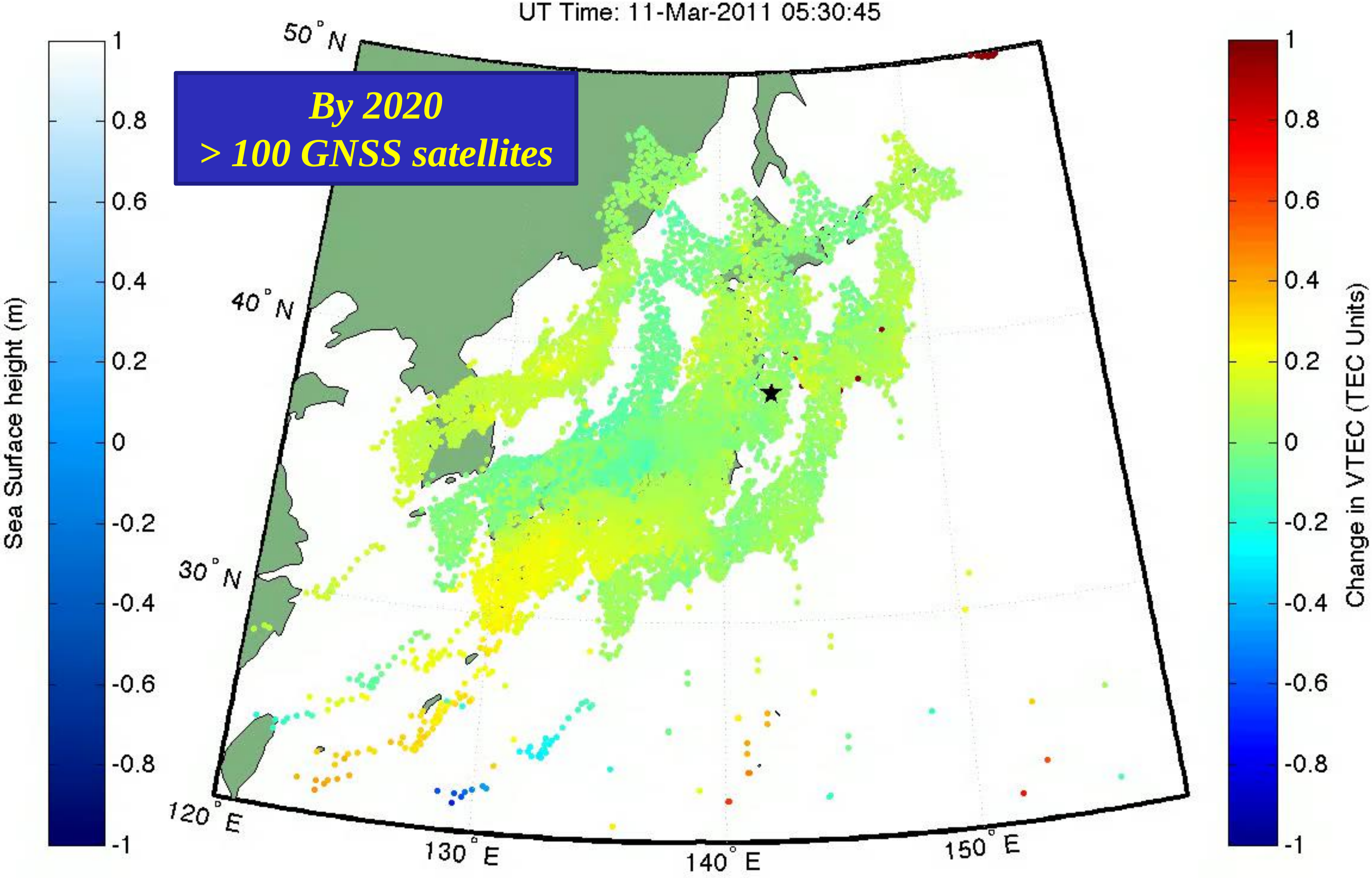
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

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)

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

AFP/AFP/GETTY IMAGES

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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:

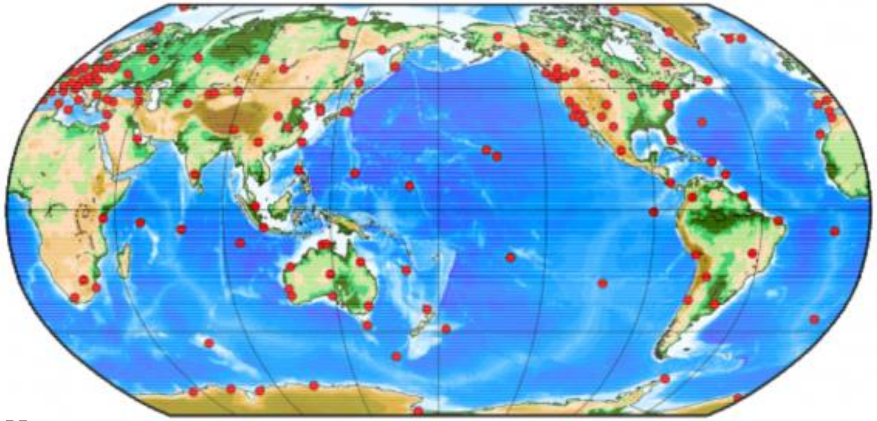
- Seismically active
- Coastal communities that may be impacted by a tsunami

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

- The GNSS Early Warning approach enhances current capabilities

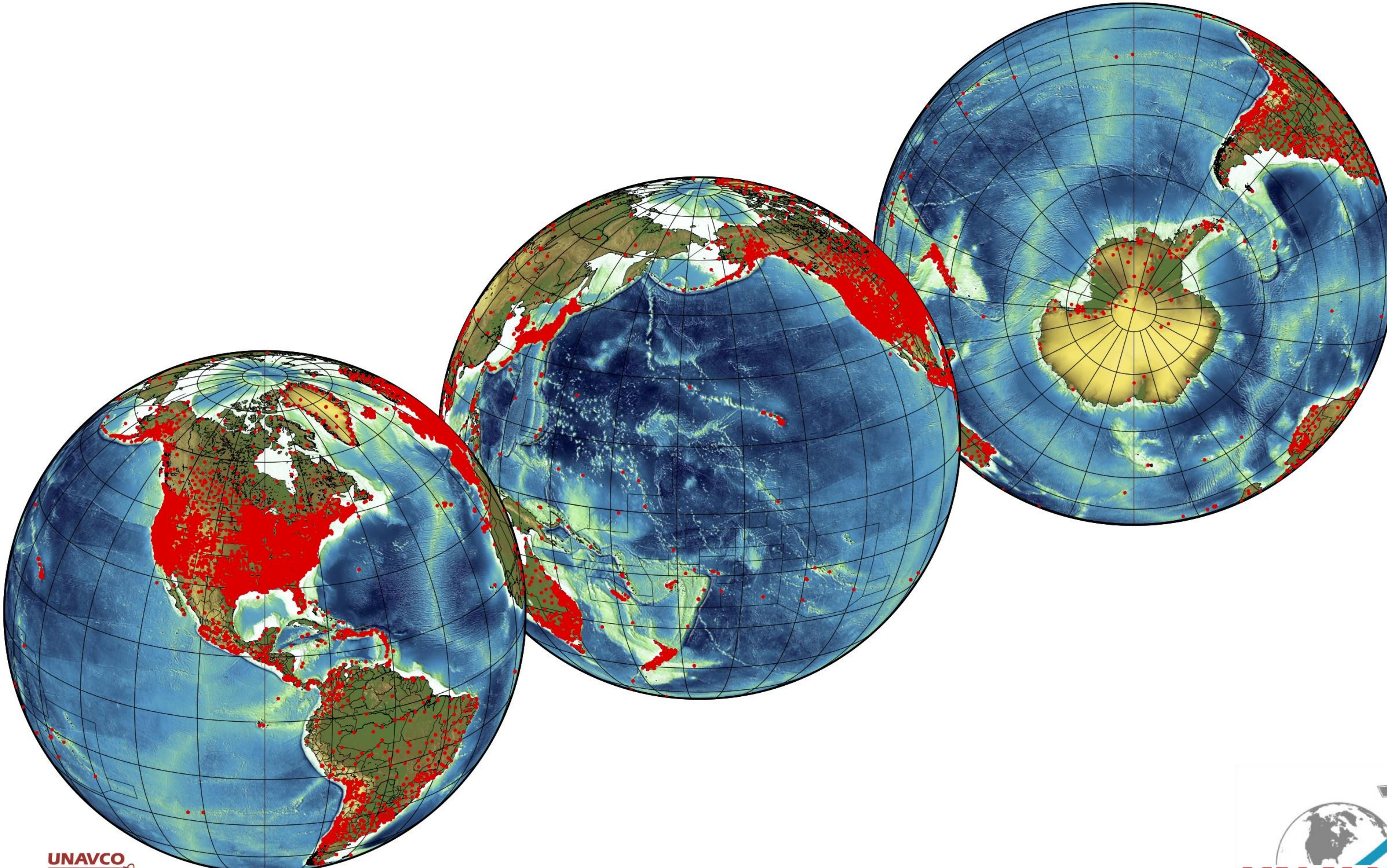
Partnership with the International GNSS and Earth Observation's communities

GGOS/IGS Real-TimeNetwork

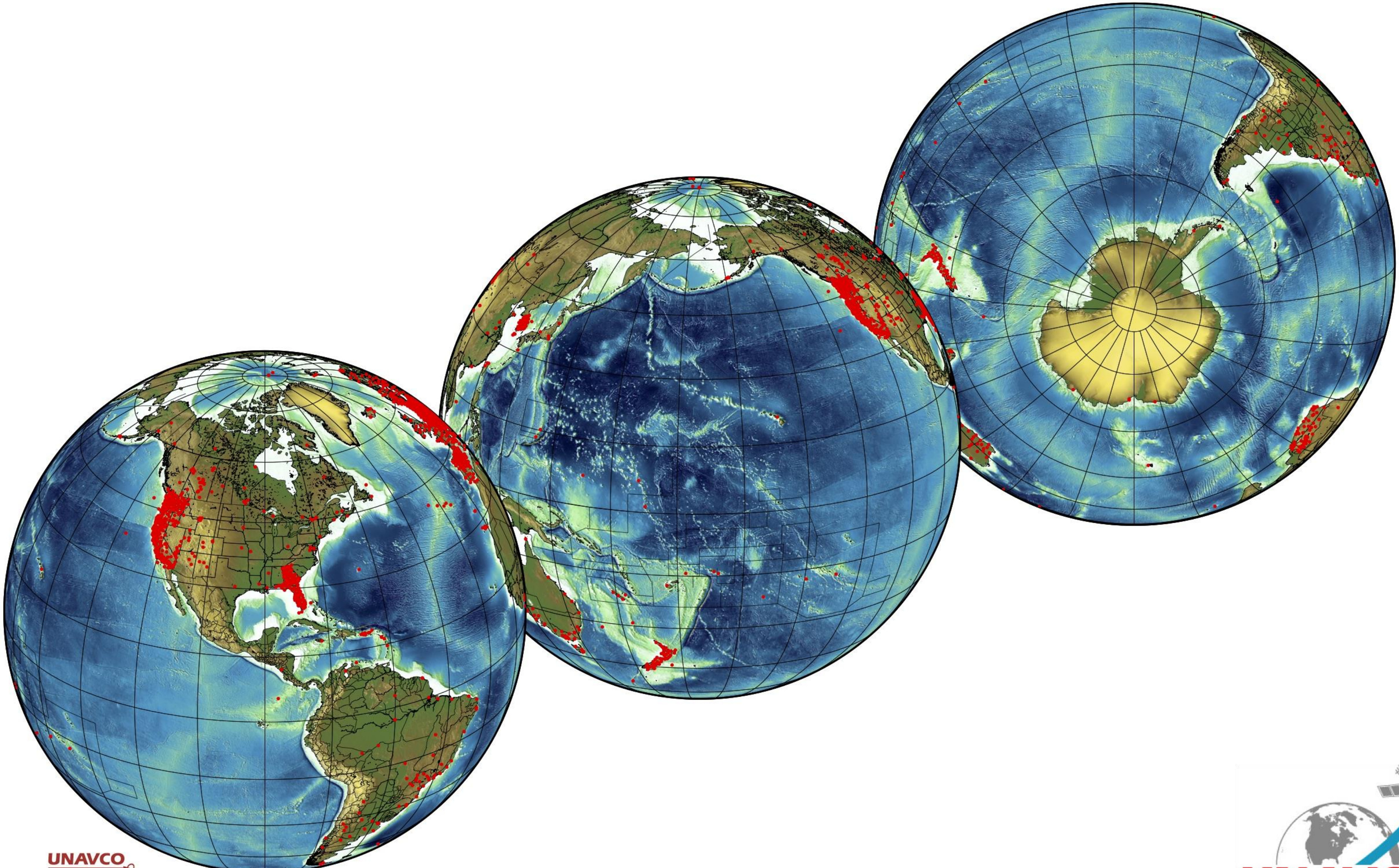


- ICG – UN International Committee on Global Navigation Satellite Systems + UNOOSA
- IGS – International GNSS Service
- GGOS – Global Geodetic Observing System
- GEO – Group on Earth Observations
- CEOS – Committee on Earth Observation Satellites

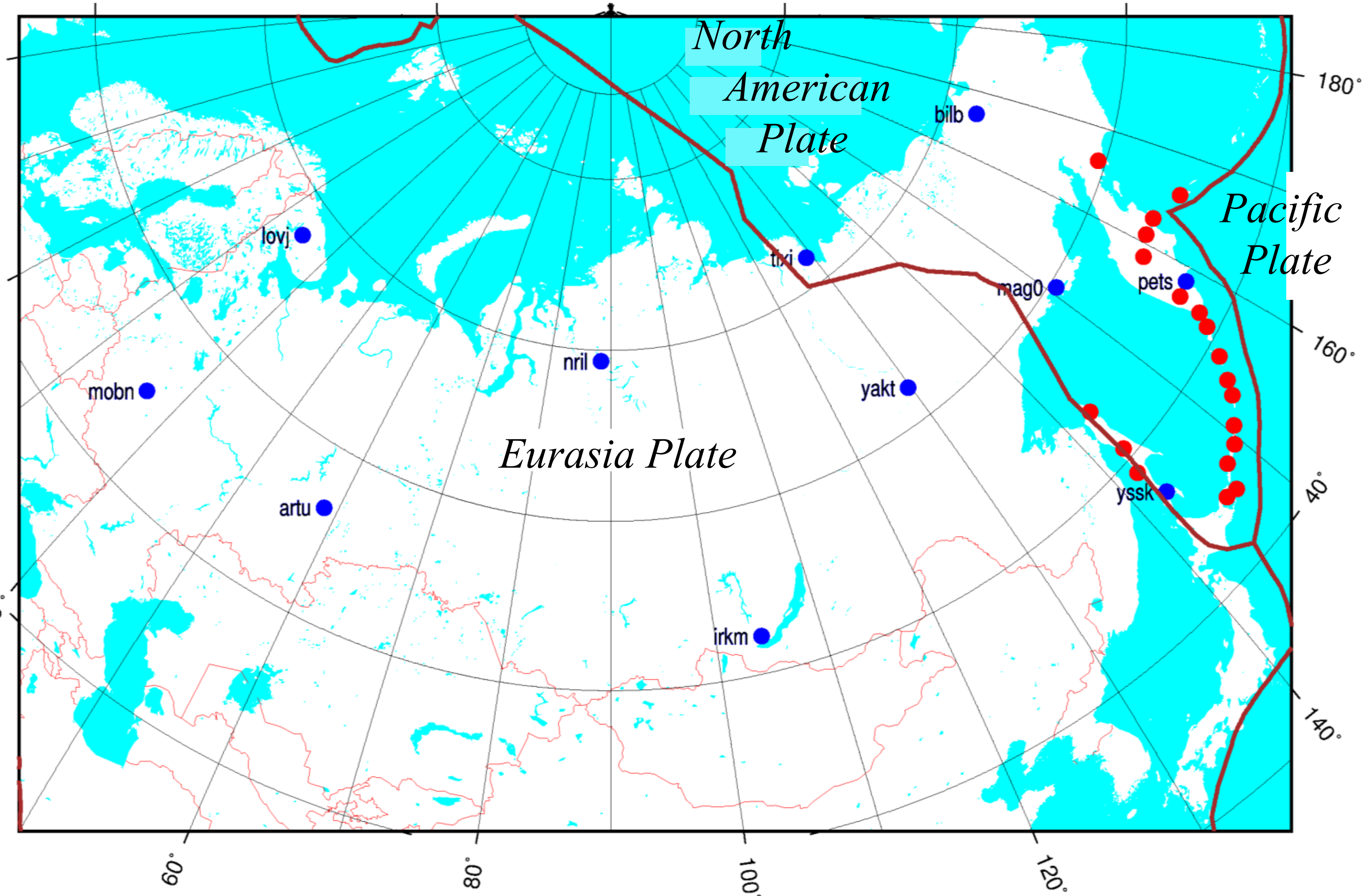
Known and Publically Accessible Continuous GNSS sites – 14,667



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



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)

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.

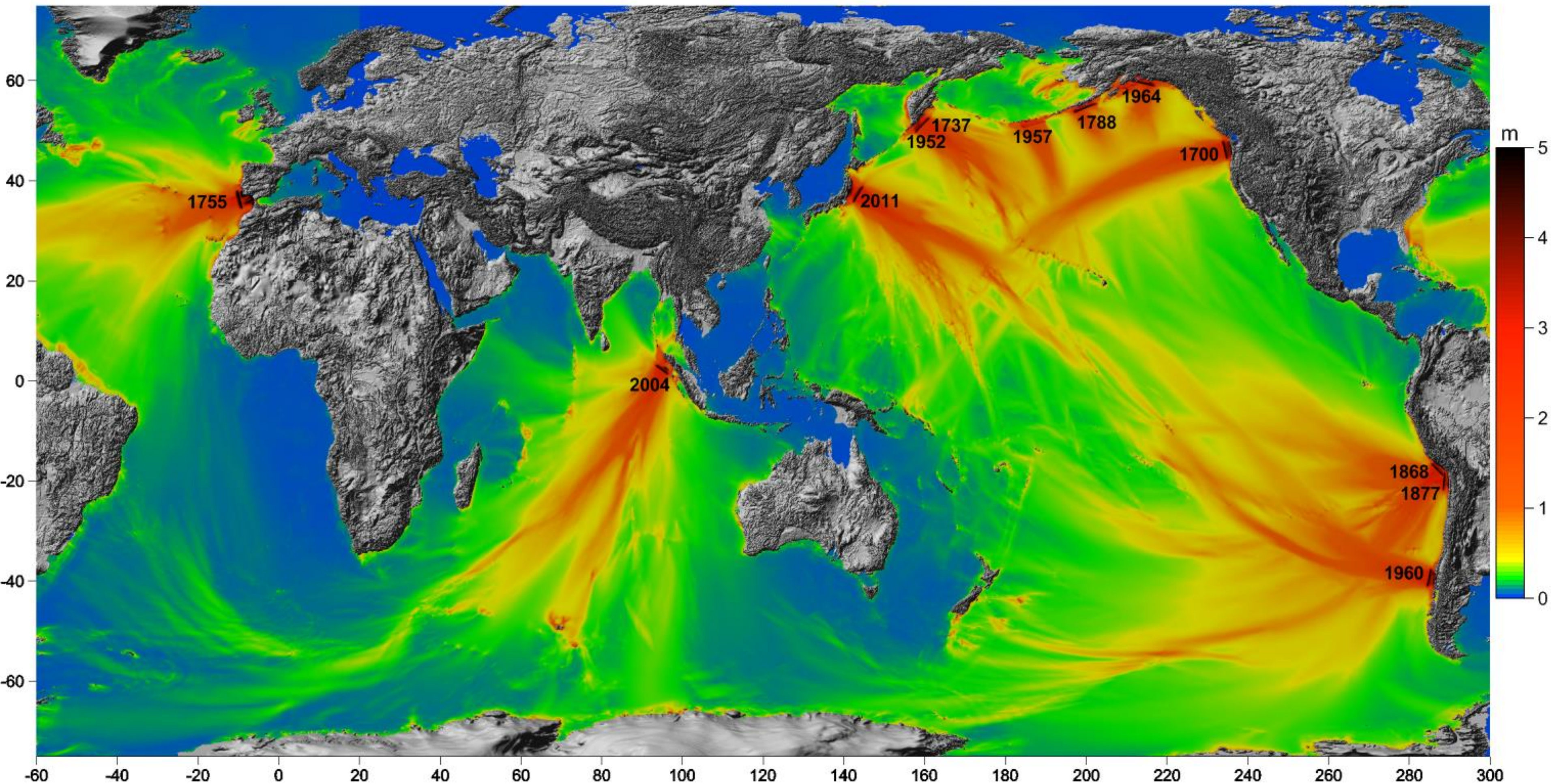
Priority 4: Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.


Save the date
Real-Time GNSS Tsunami Early Warning Workshop
May 29-31, 2017 — Sendai, Japan
NASA
Gerald Bawden
Gerald.W.Bawden@NASA.gov
Kyodo/WENN.com

Backup Slides

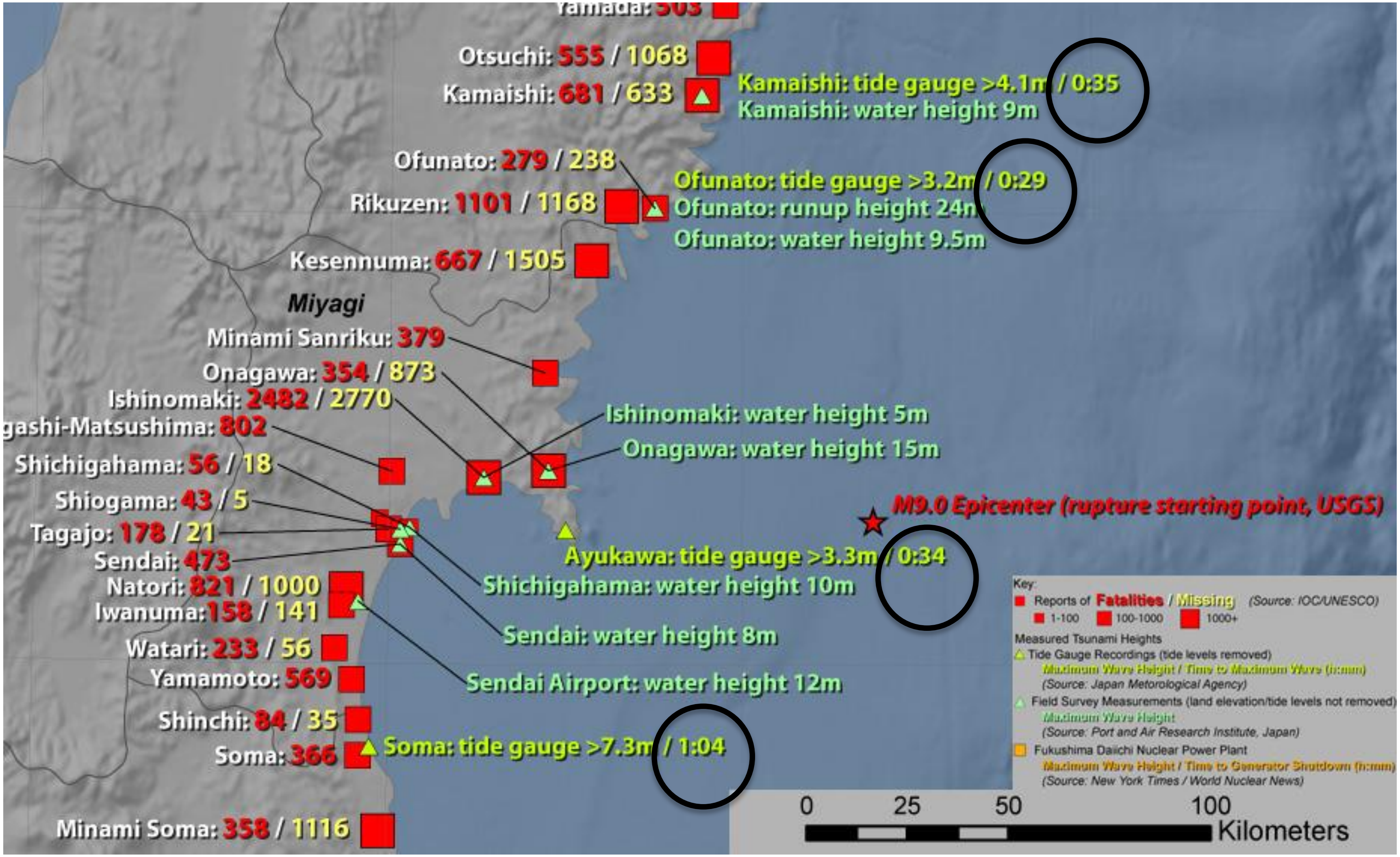
The Significant Earthquakes Data Base

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

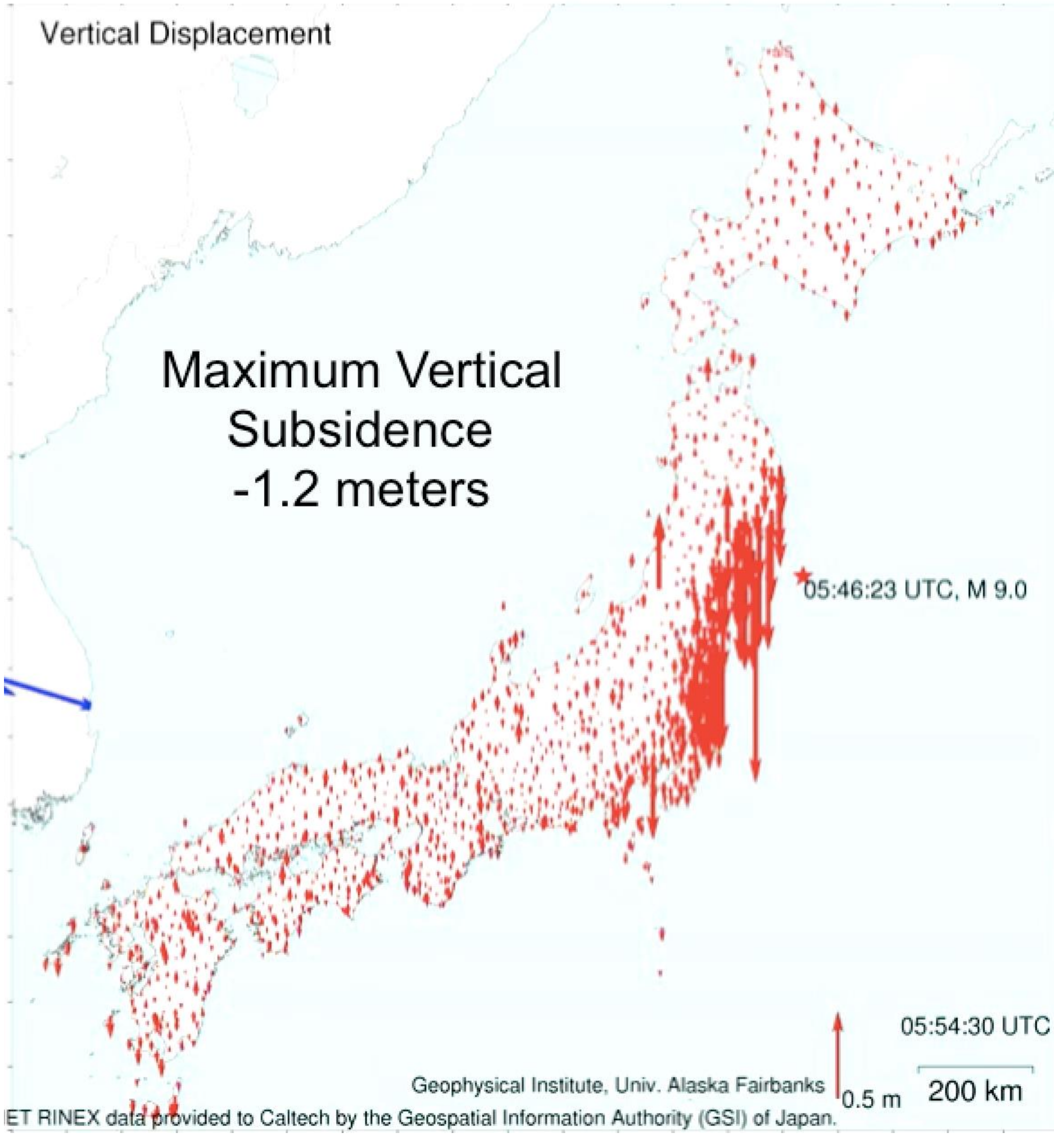


Energy flux for trans-oceanic mega-tsunamis historically known. Insert figure – distribution of fatalities over the tsunami propagation time (up to 85% fatalities occur during the first hour). Calculations are made in ICT SB RAS by means of MGC numerical package for tsunami modeling (Chubarov, Babailov, Beisel, 2011). Ref: Gusiakov et al, 2015

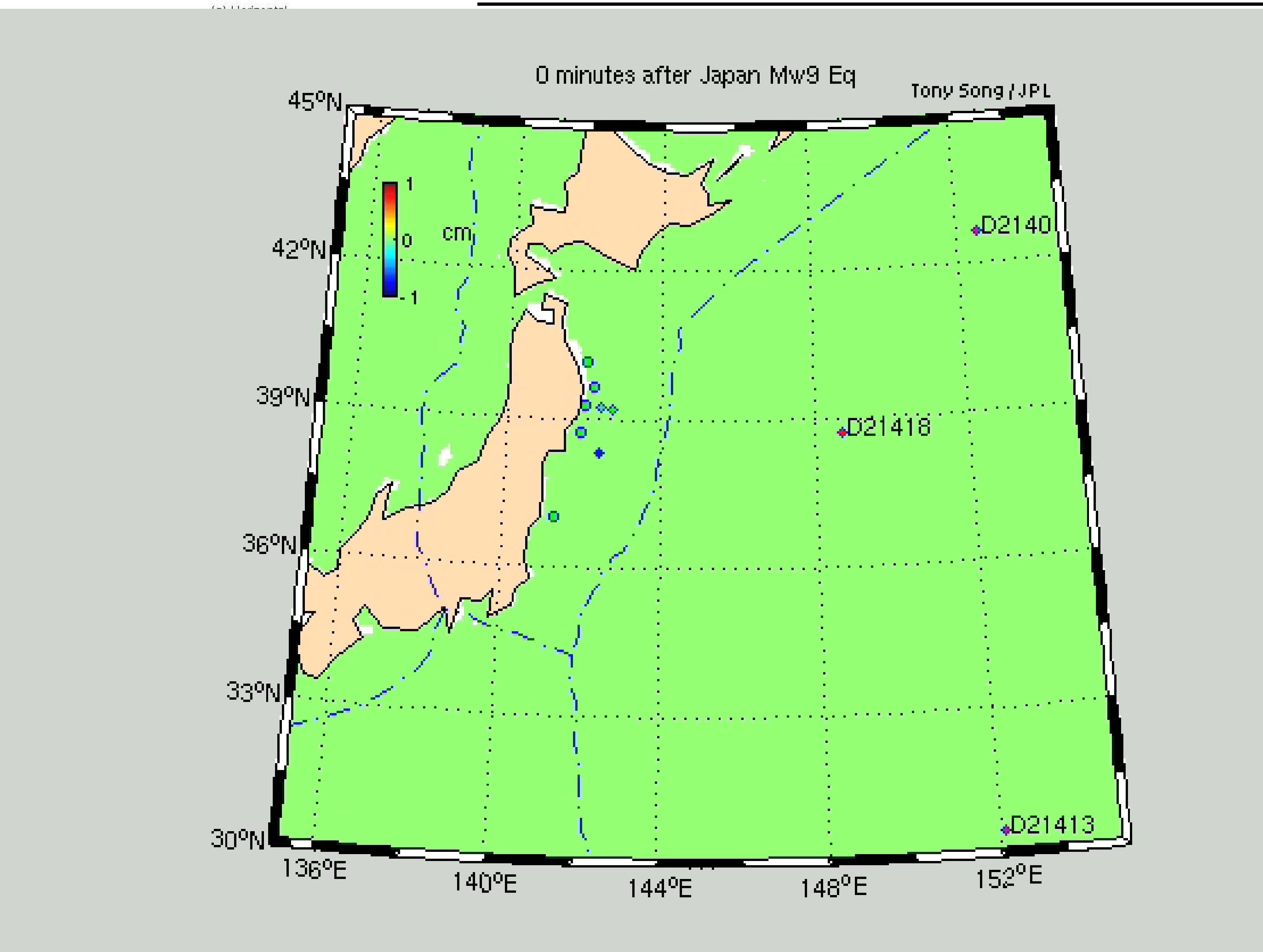
Tsunami travel times for 2011 Mw 9.0 Tohoku-oki earthquake



Dynamic Coastal Inundation Maps
rtGNSS + Tsunami Rise-Up models



The 2011 Tohoku-Oki Tsunami



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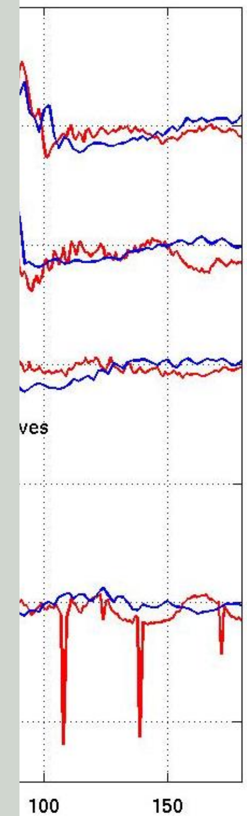
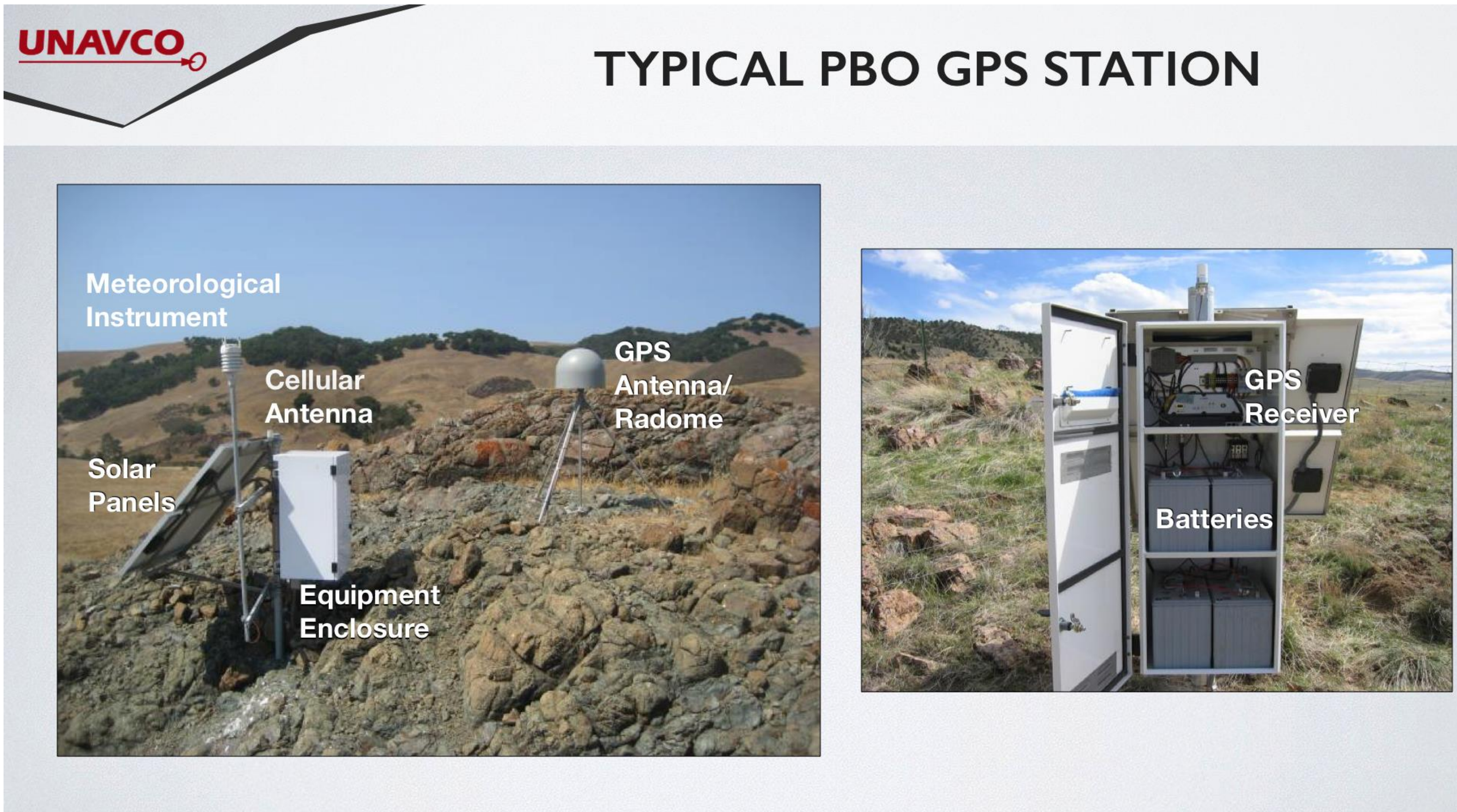


GNSS Site Installation Costs

Costs to build a PBO-quality station:

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



GNSS Site Yearly Costs

UNAVCO

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)

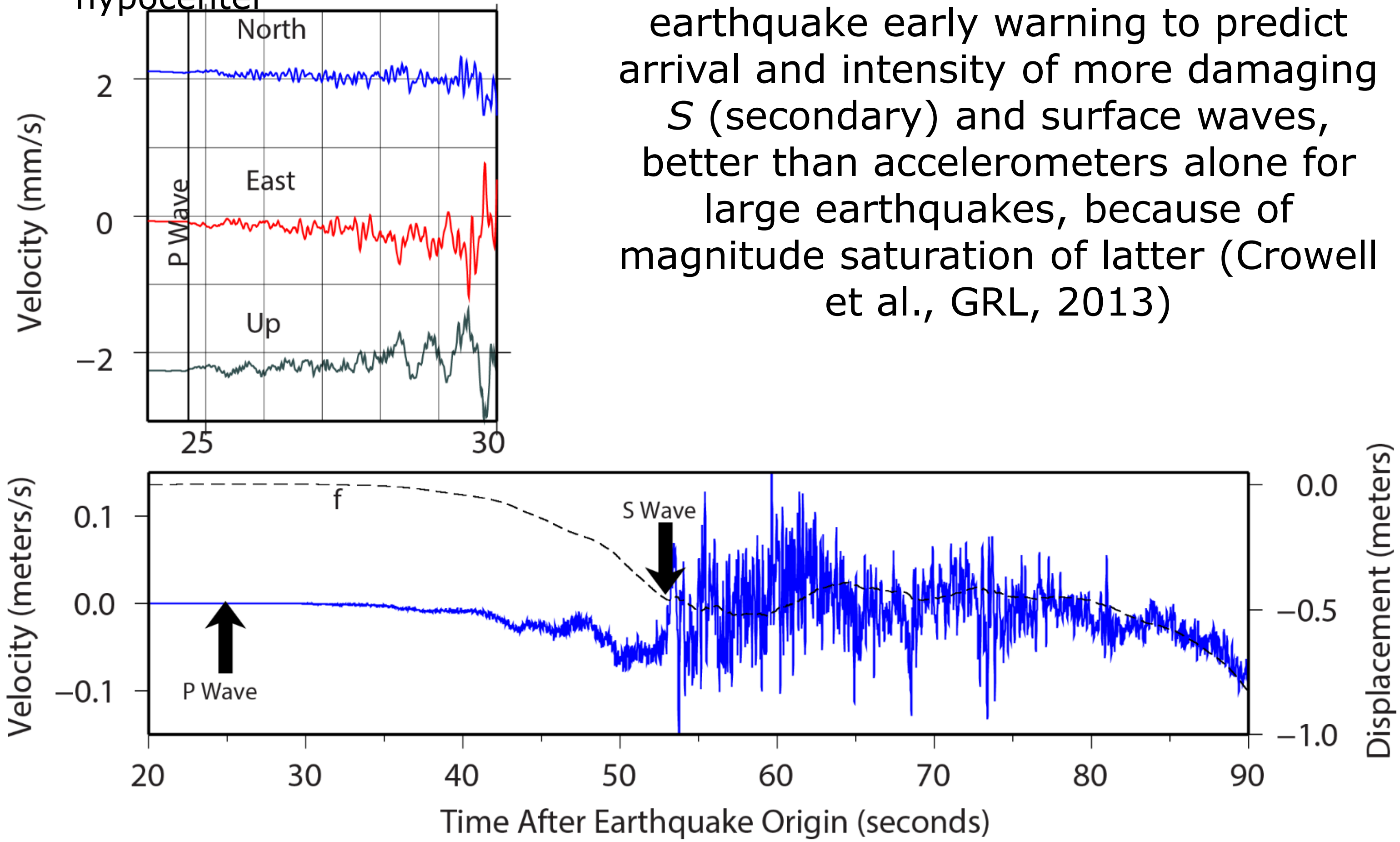
	Mean Cost Per PBO Station Per Year
Field Operations Fixed Costs (Facilities, Storage, Shipping)	$255
Sub-Award Data Processing	$365
Archiving and Data Operations (staff, servers, software, etc)	$899
Realtime Data Handling	$305
Field Travel	$626
Labor (with fringe)	$1,267
Materials/Supplies/Equipment	$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

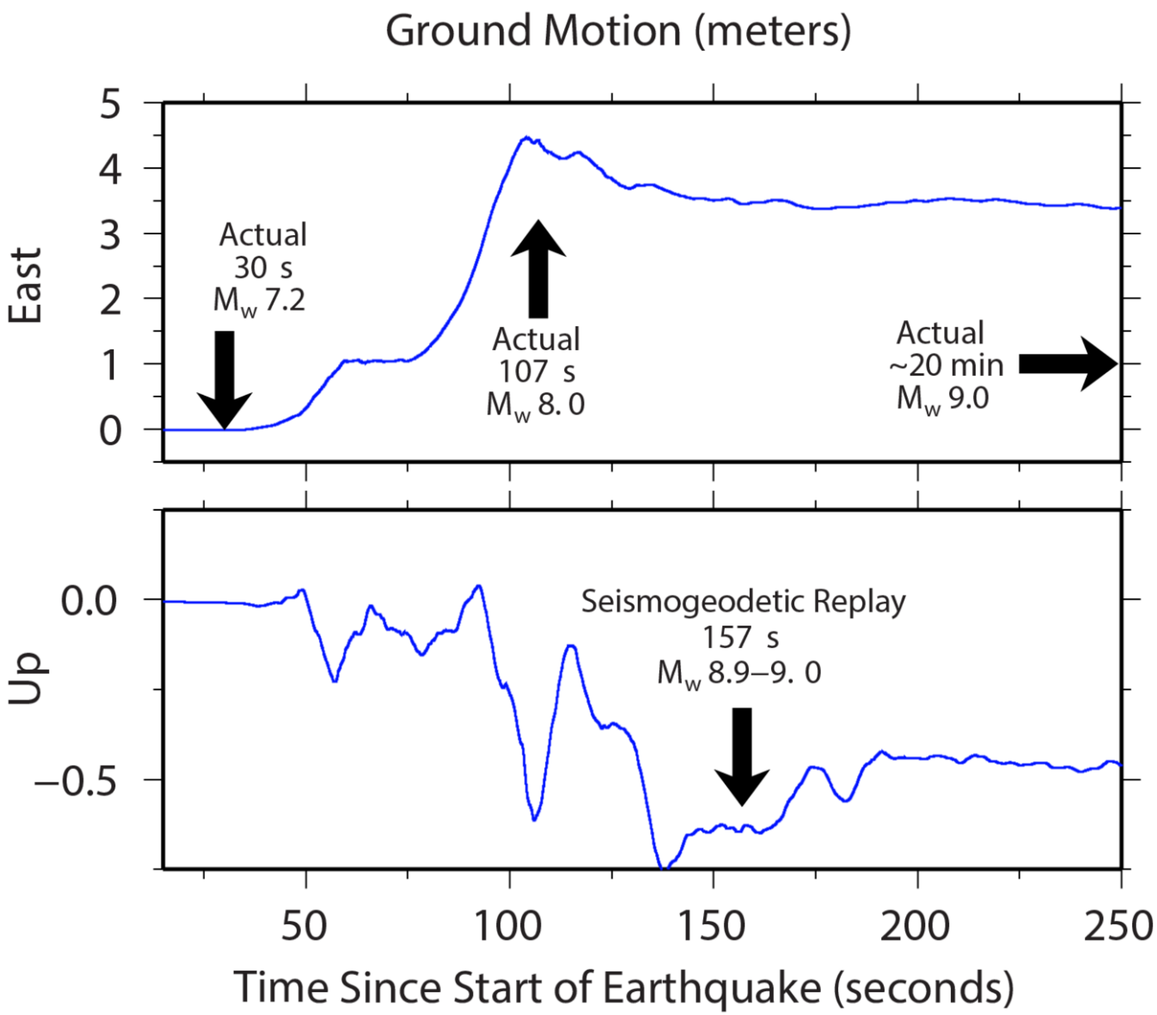
2011 Tohoku-oki earthquake GEONET GPS station 0914 and K-NET accelerometer MYG003, 155 km from the JMA hypocenter

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