Real-time GNSS for natural hazards: Early warning and monitoring systems

Yehuda Bock

Institute of Geophysics and Planetary Physics

Scripps Institution of Oceanography

&

The READI Working Group

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GORDON AND BETTY MOORE FOUNDATION

USGS science for a changing world

SCEC an NSF+USGS center

University of California Berkeley Seismological Laboratory

southern california earthquake data center

CWU

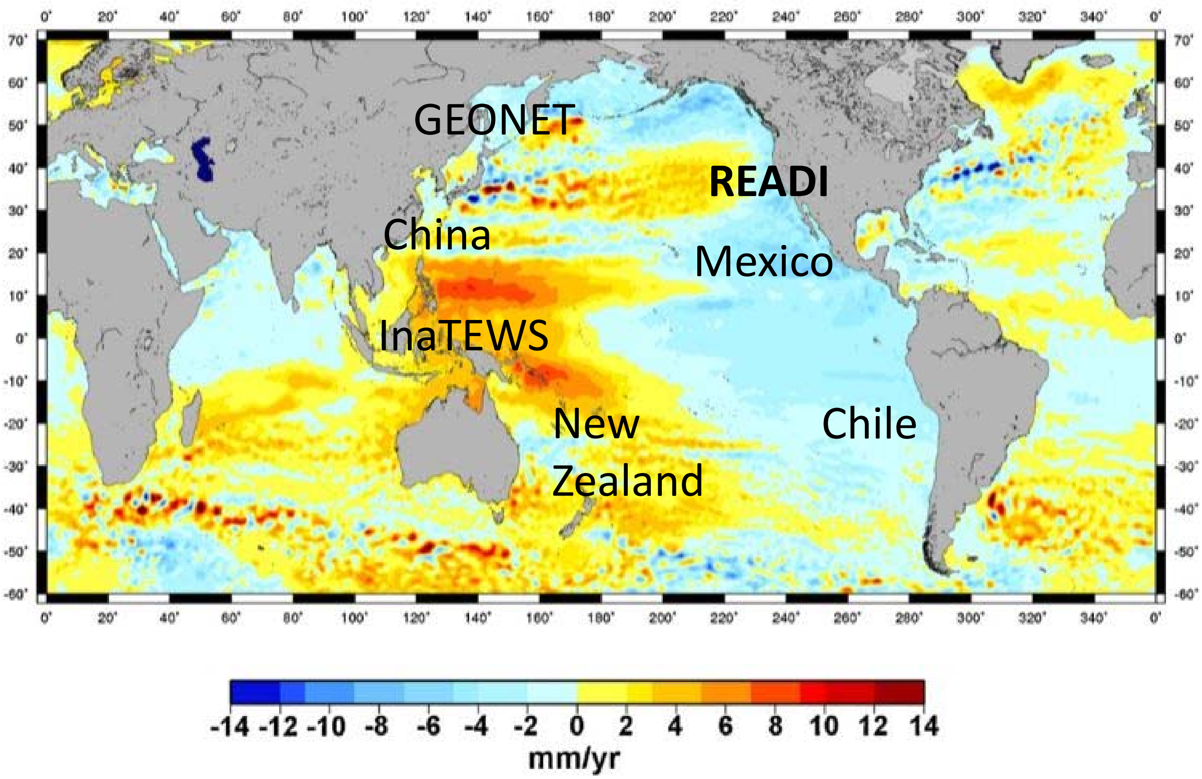
California Institute of Technology 1891

Scripps Institution of Oceanography UC San Diego

Jet Propulsion Laboratory
California Institute of Technology

UNAVCO

READI Working Group Mission



Spatial trend patterns in sea level from satellite altimetry data over 1993–2010, B. Meyssignac, A. Cazenave / Journal of Geodynamics, 58 (2012) 96–109.

Aim: An Indo-Pacific Tsunami Early Warning System that utilizes GNSS real-time displacements and ionospheric measurements along with seismic, near-shore buoys and ocean-bottom pressure sensors to rapidly estimate magnitude and finite fault slip models for large earthquakes, and then predict tsunami source, energy scale, geographic extent, inundation and runup.

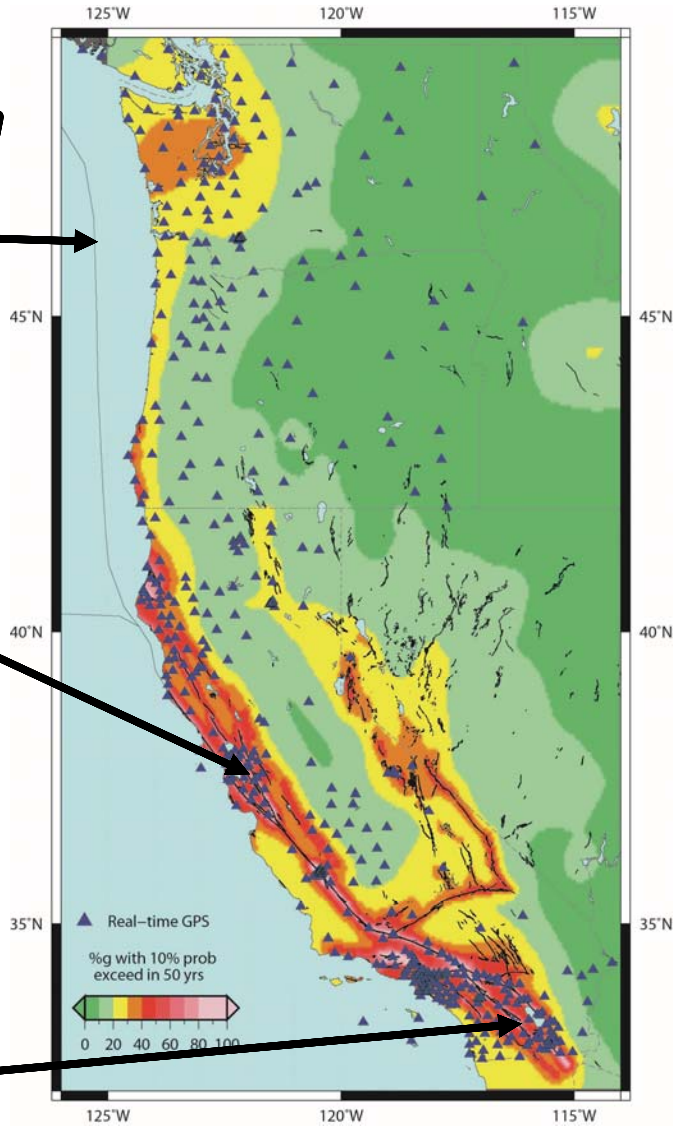
Rapid predictions are critical for those coastal communities that are in the near-source region and may have only minutes of warning time.

READI network in Western U.S. – Utilizing 600+ real-time high-rate GPS stations spanning areas of high seismic and tsunami risk

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

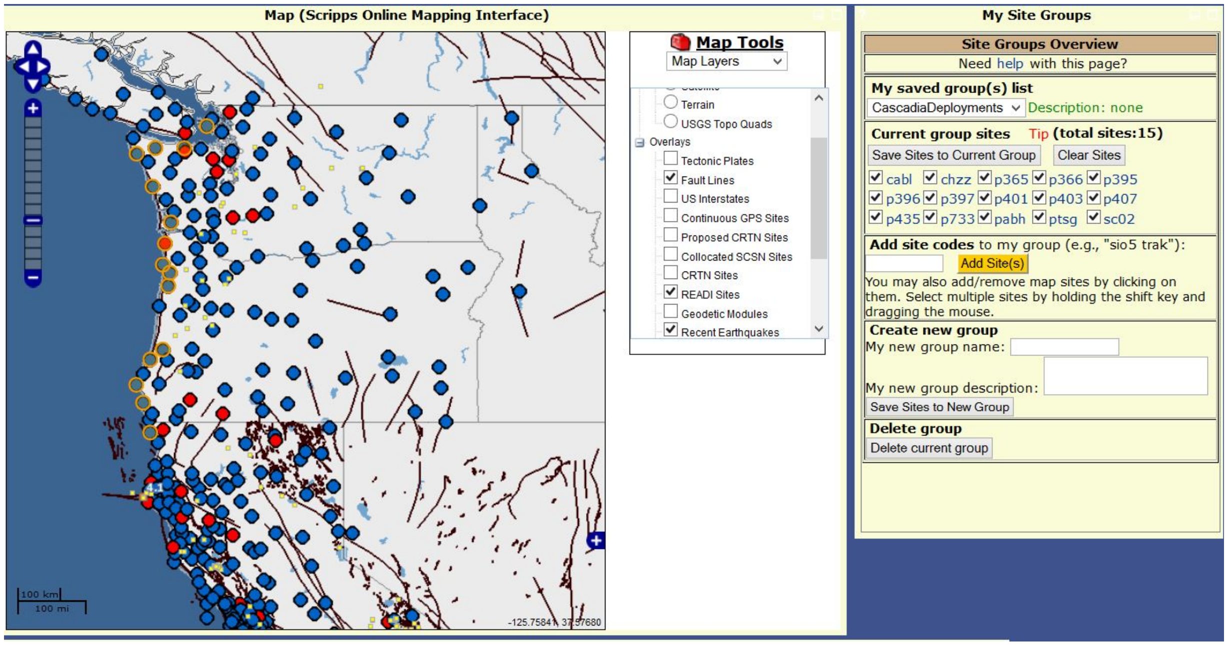
Southern San Andreas fault – overdue for large earthquake

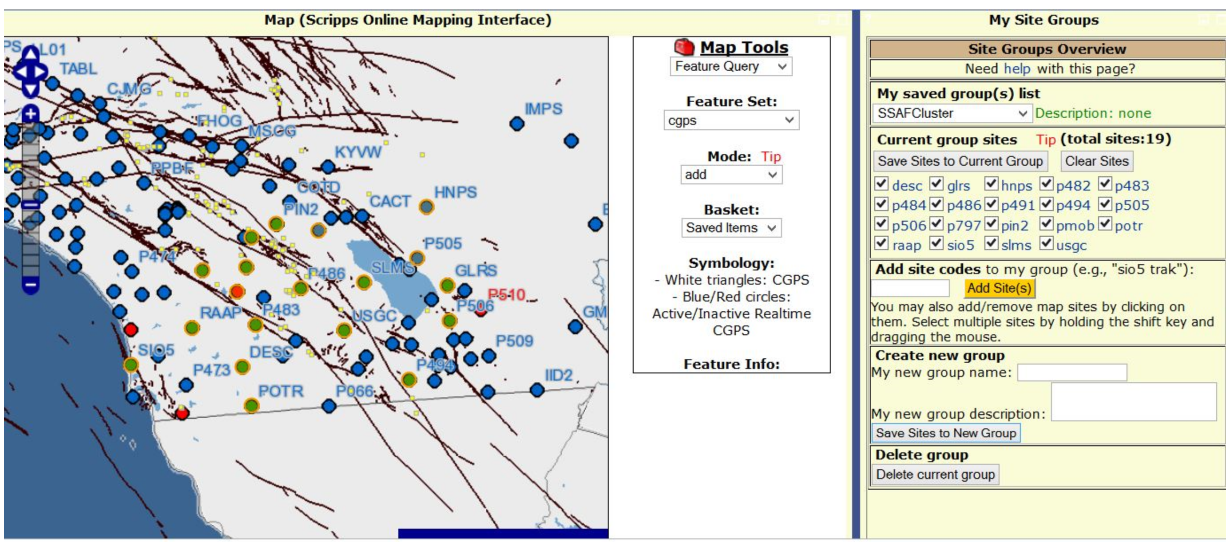


- **R**eal-Time **E**arthquake **A**nalysis for **D**isaster m**I**tigation network (READI): ~600 GPS stations, a NASA driven project
- Super set of GPS networks maintained by (sorted according to largest to smallest number of stations):
  - UNAVCO/PBO
  - CWU/PANGA
  - USGS/Pasadena-SCIGN & Menlo Park
  - UC Berkeley/BARD
  - Scripps Institution of Oceanography/SCIGN
  - California Department of Transportation/CVSRN

http://sopac.ucsd.edu/projects/realtime/READI/

READI Clusters: Cascadia & Southern San Andreas Fault





Cascadia Cluster

Focused on Cascadia event:

15 PBO Stations: SC02, P435, P403, P401, PABH, P397, P407, CHZZ, P396, P395, P366, P365, CABL, P733, PTSG

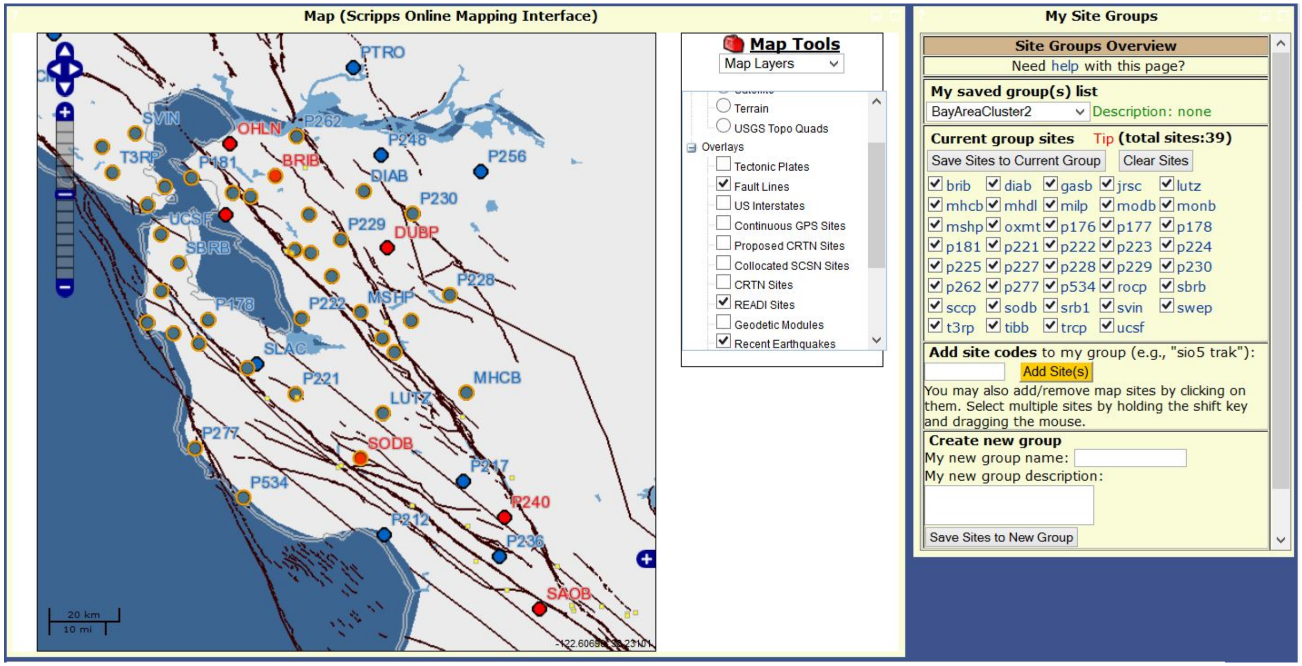
SSAF Cluster

Focused on southern San Andreas fault event:

(*All stations with SIO seismogeodetic upgrade*)

19 Stations (12 PBO, 6 SIO, 1 MWD): DESC, GLRS, HNPS, P482, P483, P484, P486, P491, P494, P505, P506, P797, PIN2, PMOB, POTR, RAAP, SIO5, SLMS, USGC

READI Clusters: San Francisco Bay Area



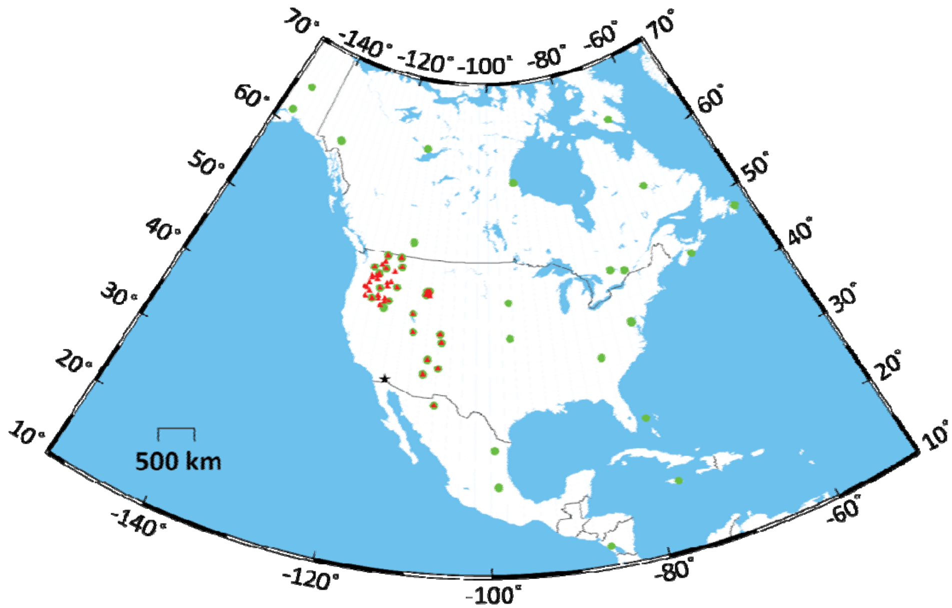
Bay Area Cluster
Focused on Hayward fault event:

39 stations (17 BARD, 16, PBO, 6 USGS):
brib, diab, gasb, jrsc, lutz, mhcb, mhdl, milp, modb, monb, mshp, oxmt, p176, p177, p178, p181, p221, p222, p223, p224, p225, p227, p228, p229, p230, p262, p277, p534, rocp, sbrb, sccp, sodb, srb1, svin, swep, t3rp, tibb, trcp, ucsf

Note: Both CWU and SIO are in the process of building up the infrastructure to process all READI stations, and to perform the real-time combination

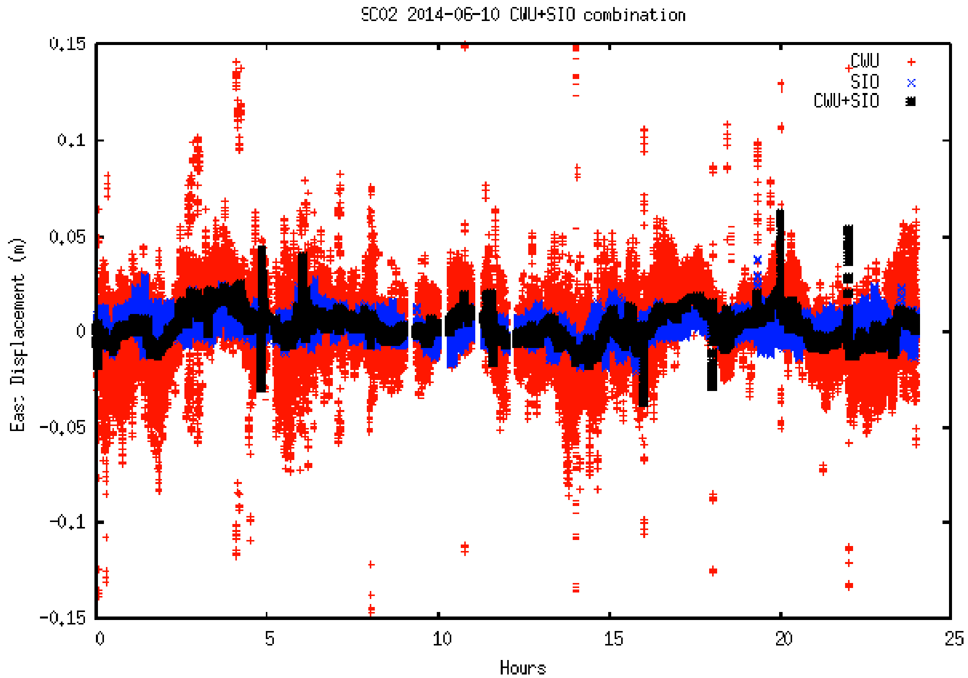
READI Analysis 1 Hz Displacements @ CWU & SIO

- Independently estimate once per second displacements with a latency of 2-3 seconds.
- CWU: precise point positioning (PPP) methodology using a GIPSY engine and global satellite clock estimates from IGS – no ambiguity resolution.
- SIO: precise point position client with ambiguity resolution (PPP-AR) using satellite clock estimates and fractional cycle biases estimated from 1 Hz GPS data from IGS and PBO data in North America and outside the zone of expected strong motion on the West Coast.
- CWU: Adjustment of CWU & SIO 1 Hz displacements using a Kalman filter to estimate a combined solution.
- Main issue (for SIO) is real-time data gaps in the PPP-AR reference network. GNSS should help improve overall PPP robustness.

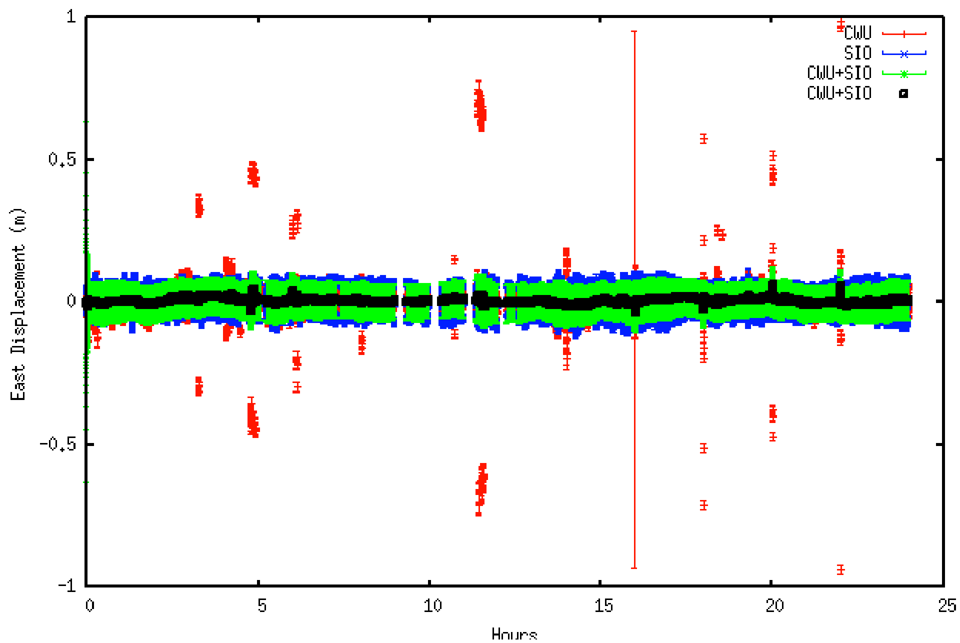


Real-time GPS stations used by SOPAC to estimate satellite clock biases and fractional phase cycle biases for PPP-AR

READI 1 Hz Displacement Combination – SC02 Cascadia station



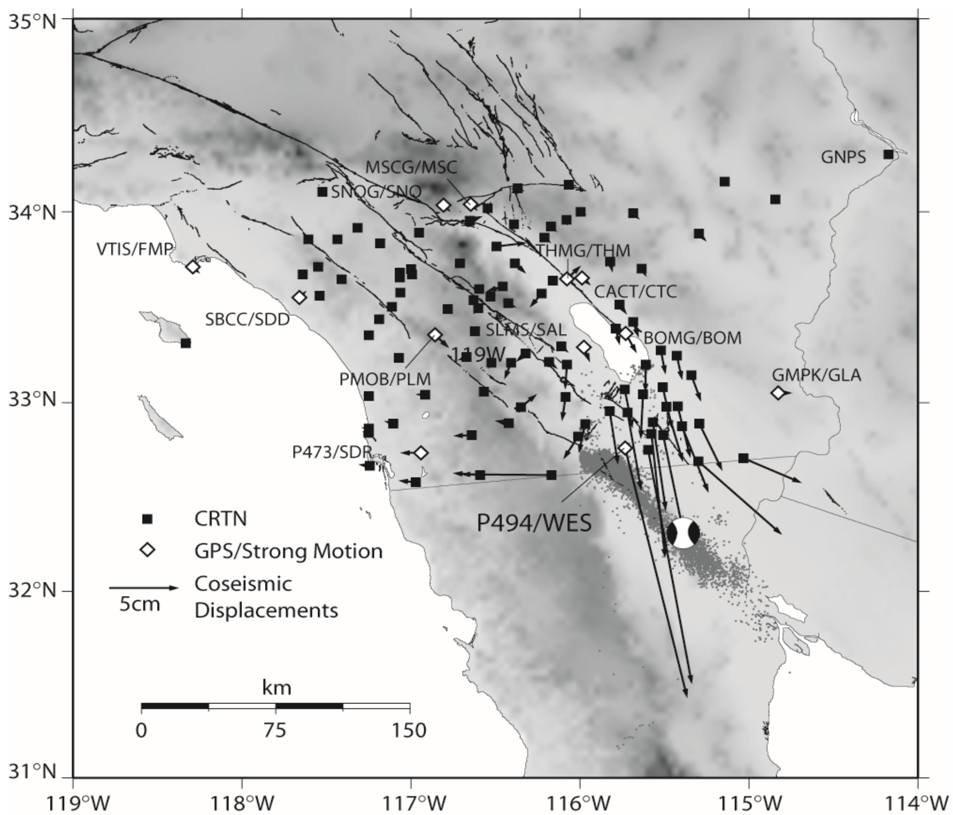
CWU & SIO and combination solution (East component), excluding outliers. The SIO solution is less noisy because phase ambiguities are resolved.



CWU & SIO individual solutions, combination including outliers and one-sigma uncertainty band.

READI Working Group Plans

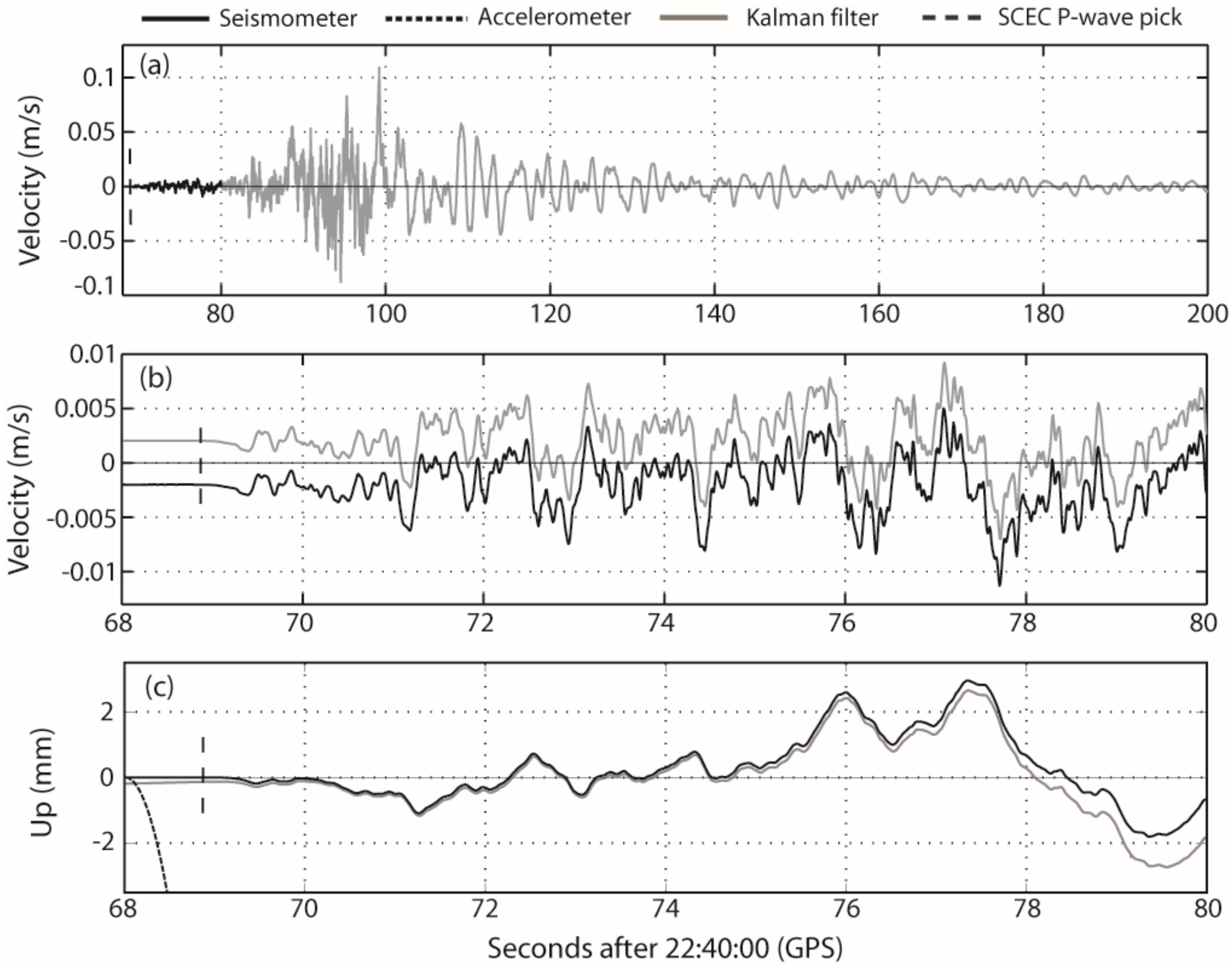
- **Plan** to replay the 2010 Mw 7.2 El Mayor-Cucapah earthquake and other earthquakes to test and improve the combination algorithms, as well as the individual solutions, and to participate in October CalOES exercise of a large earthquake and aftershock on the southern section of the San Andreas fault.
- **Next**, replay the 2011 Mw 9.0 Tohoku-oki earthquake and tsunami, or a Cascadia event based on the Japan earthquake parameters.
- **Help promote** real-time data exchange among Pacific Rim countries for an integrated Indo-Pacific Tsunami Early Warning System.



Coseismic displacements for 2010 Mw 7.2 El Mayor-Cucapah, Mexico earthquake

Seismogeodesy & Earthquake Early Warning @ SIO

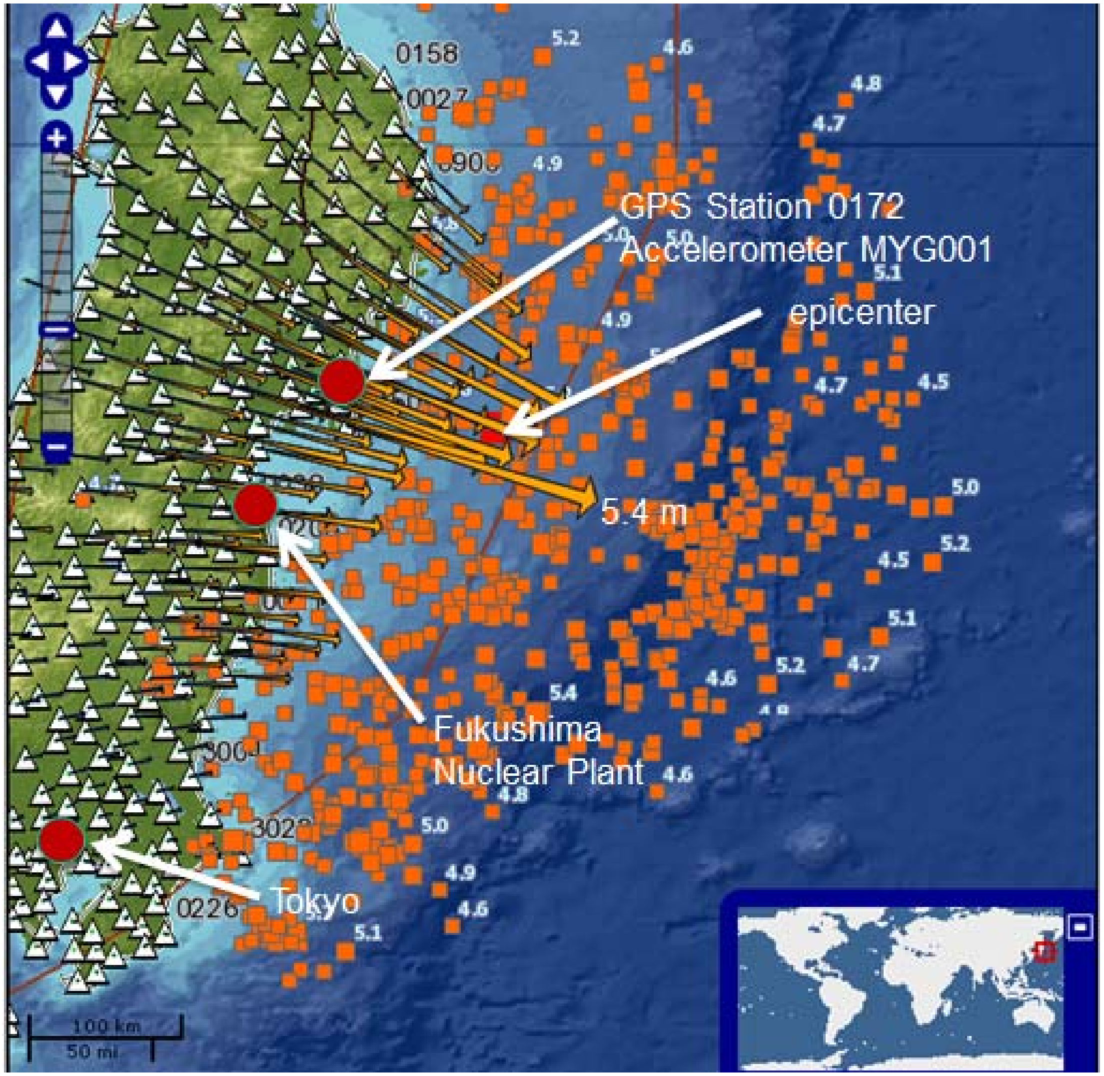
2010 Mw 7.2 El Mayor-Cucapah Earthquake, Site P494/WES



- **Optimal combination of GPS and strong motion accelerometer data using Kalman filter**
- **Distinct advantages over seismic data during large earthquakes and for near source / fault monitoring where early warning is critical**

Source: Bock et al., 2011, BSSA

Seismogeodetic analysis: 2011 Mw 9.0 Tohoku-oki,Japan earthquake



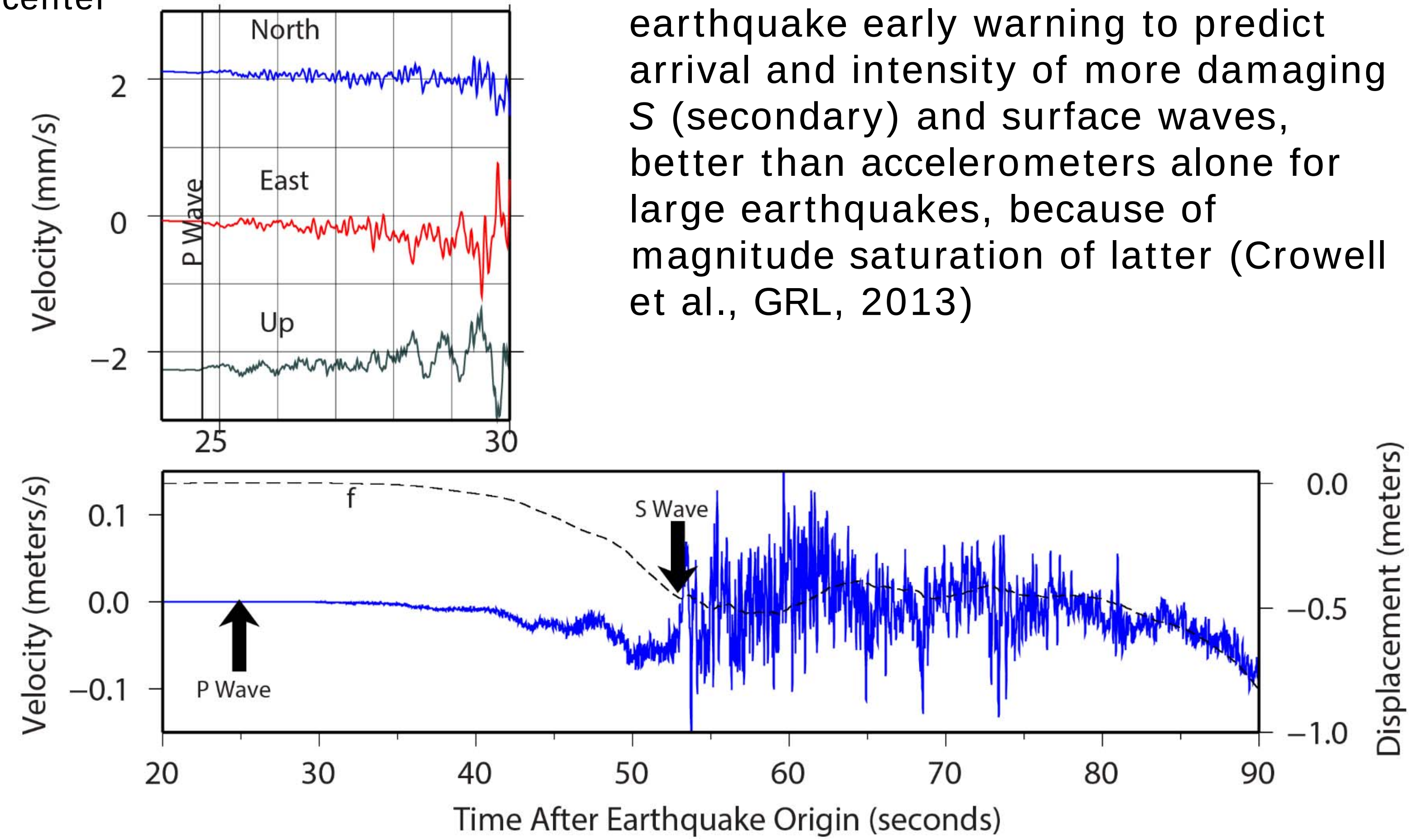
Coseismic displacements for 2011 Mw 9.0 Tohoku-oki earthquake computed from Japan's 1200+ station CGPS Network (GEONET). Maximum surface displacement on land was 5.24 meters at station 0550 on coast about 100 km from epicenter

Identified 142 "collocated" NIED stations with triggered 100 Hz KiK-net and K-Net accelerometer data (e.g., 0914/*MYG003*) and estimated 100 Hz displacements and velocities using a Kalman filter

Coseismic displacements by ARIA group at Caltech/JPL provided by Susan Owen

Seismogeodetic Earthquake Early Warning @ SIO

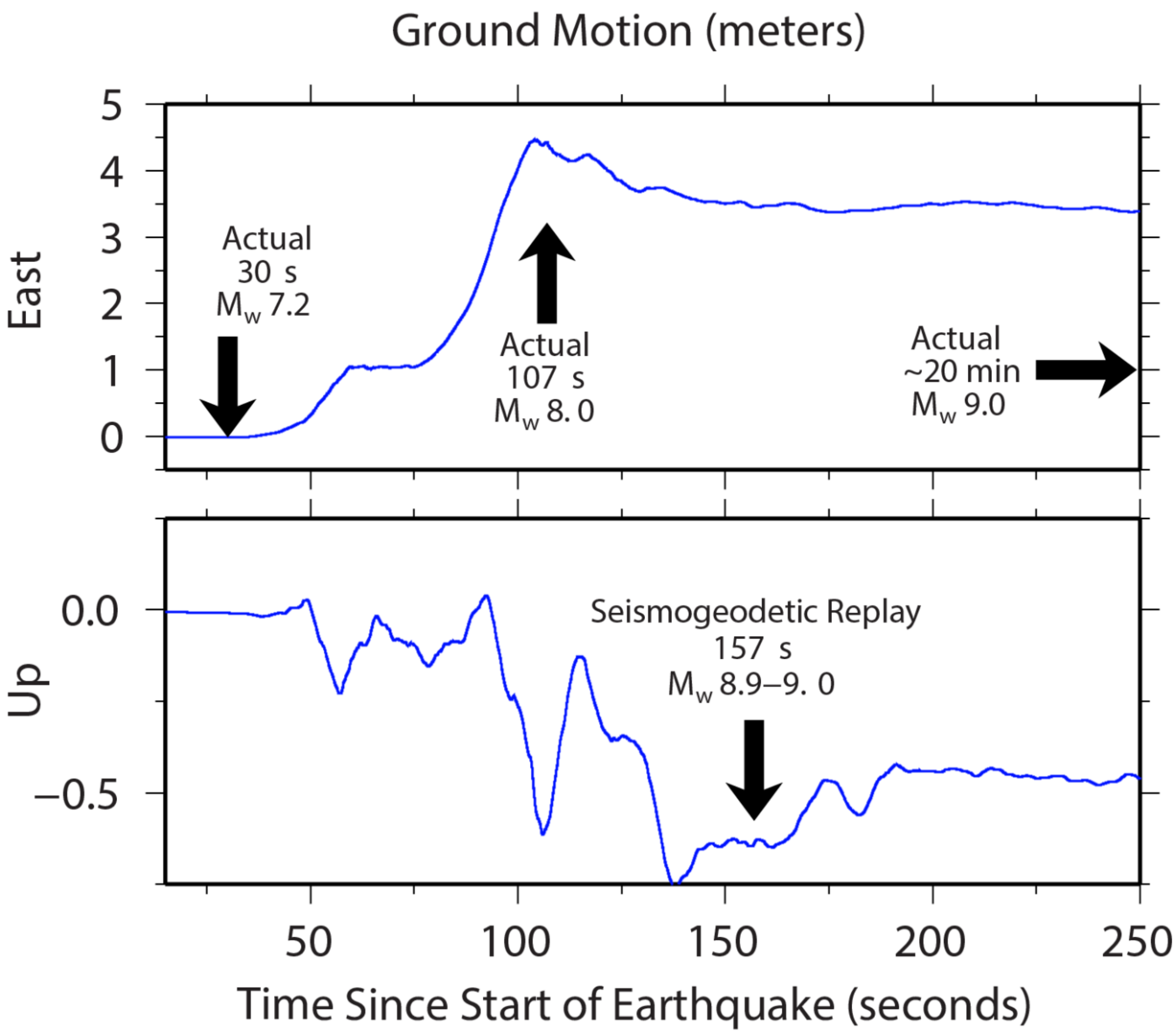
2011 Tohoku-oki earthquake GEONET GPS station 0914 and K-NET accelerometer MYG003, 155 km from the JMA hypocenter



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

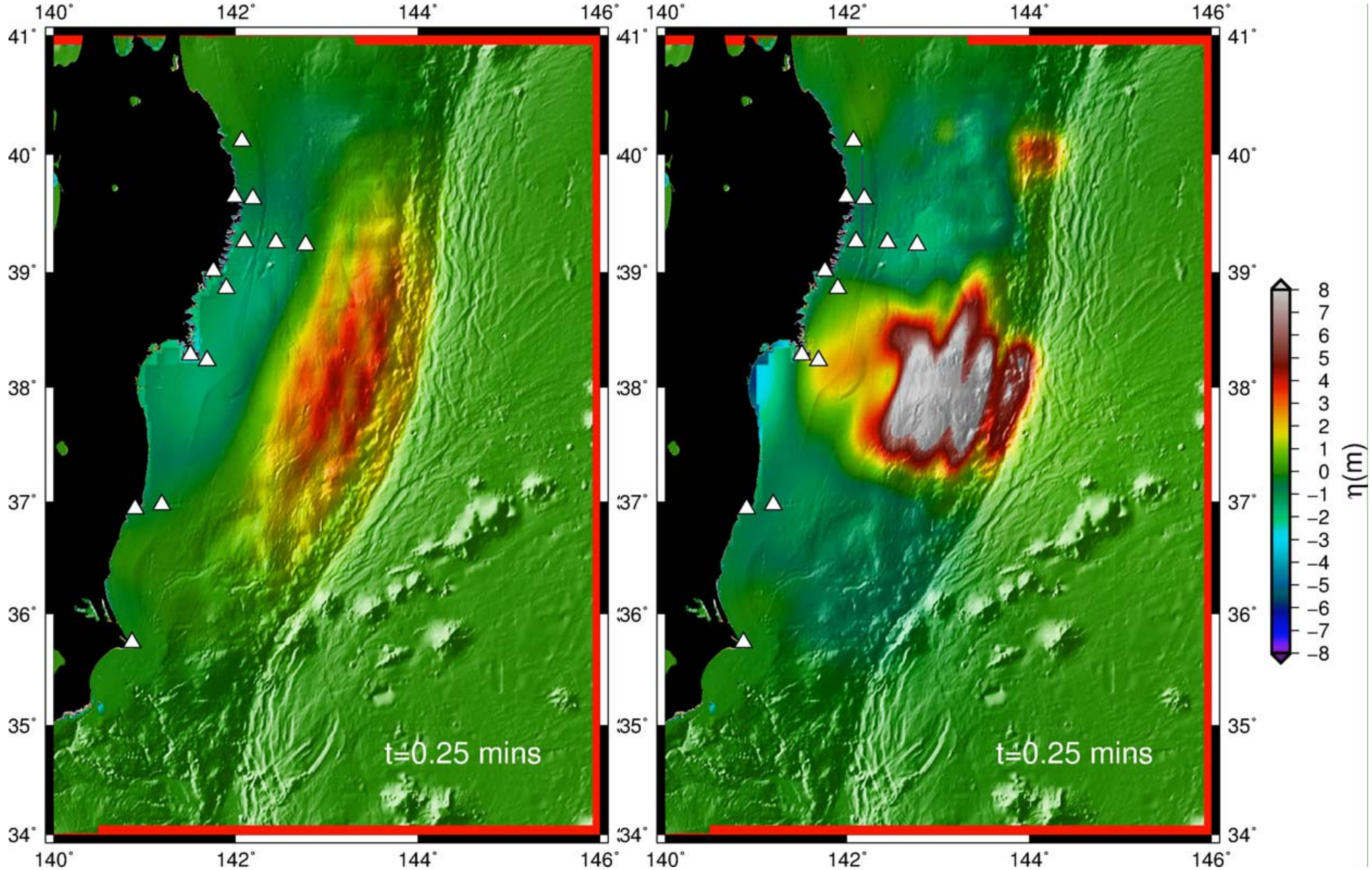
Seismogeodetic Displacements and Magnitude Estimation



Seismogeodesy improves on traditional seismic monitoring by accurately determining magnitude of large (> M 7) earthquakes and by estimating both ground motions and permanent displacements

Source: Melgar et al., GRL, 2013

Model of 2011 Japan Tsunami: Movies

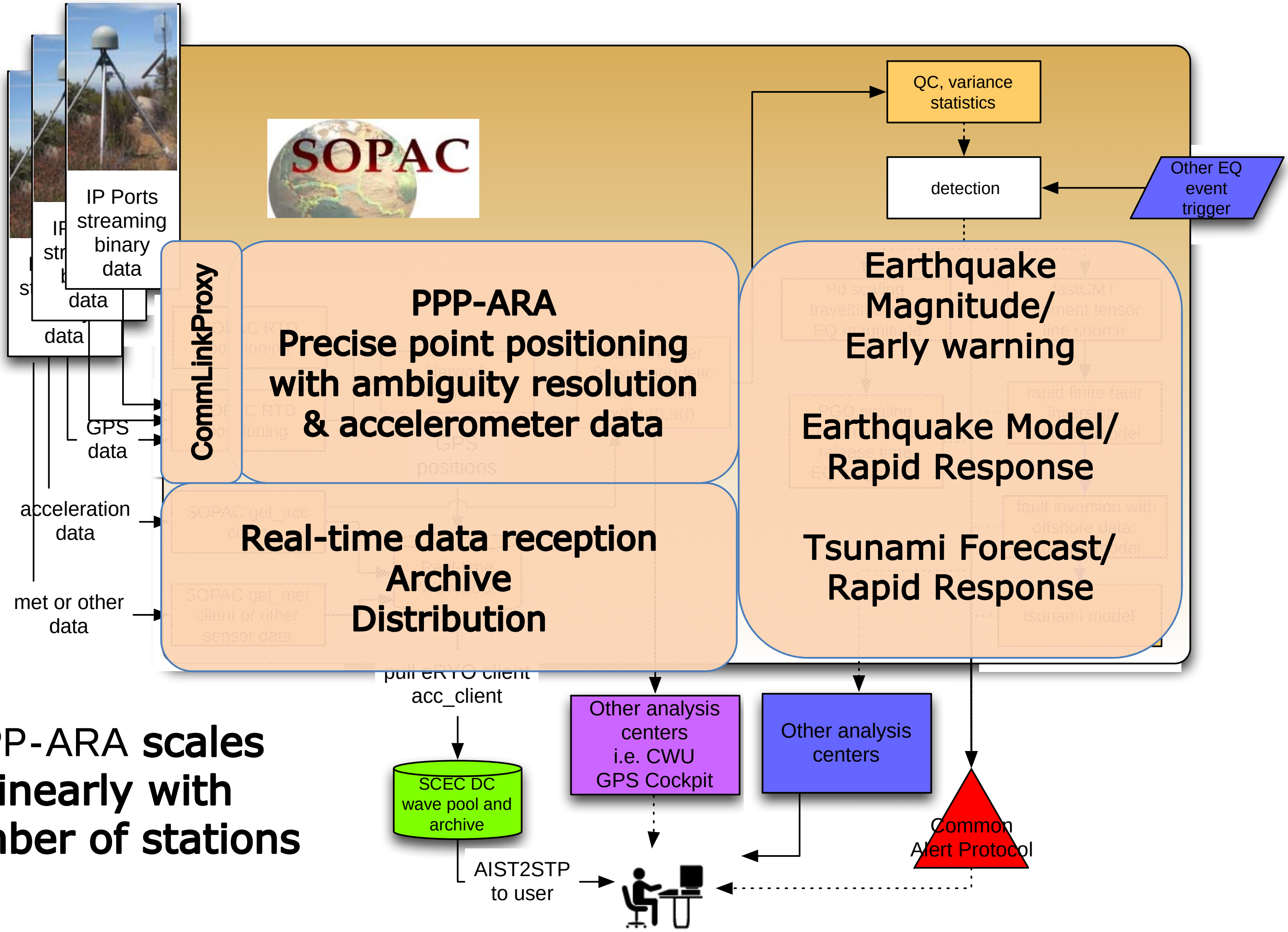


Use GPS data available in 157 seconds after earthquake origin time

Use GPS and near-shore ocean buoys available after 20 minutes

Source: Melgar & Bock, GRL, 2013

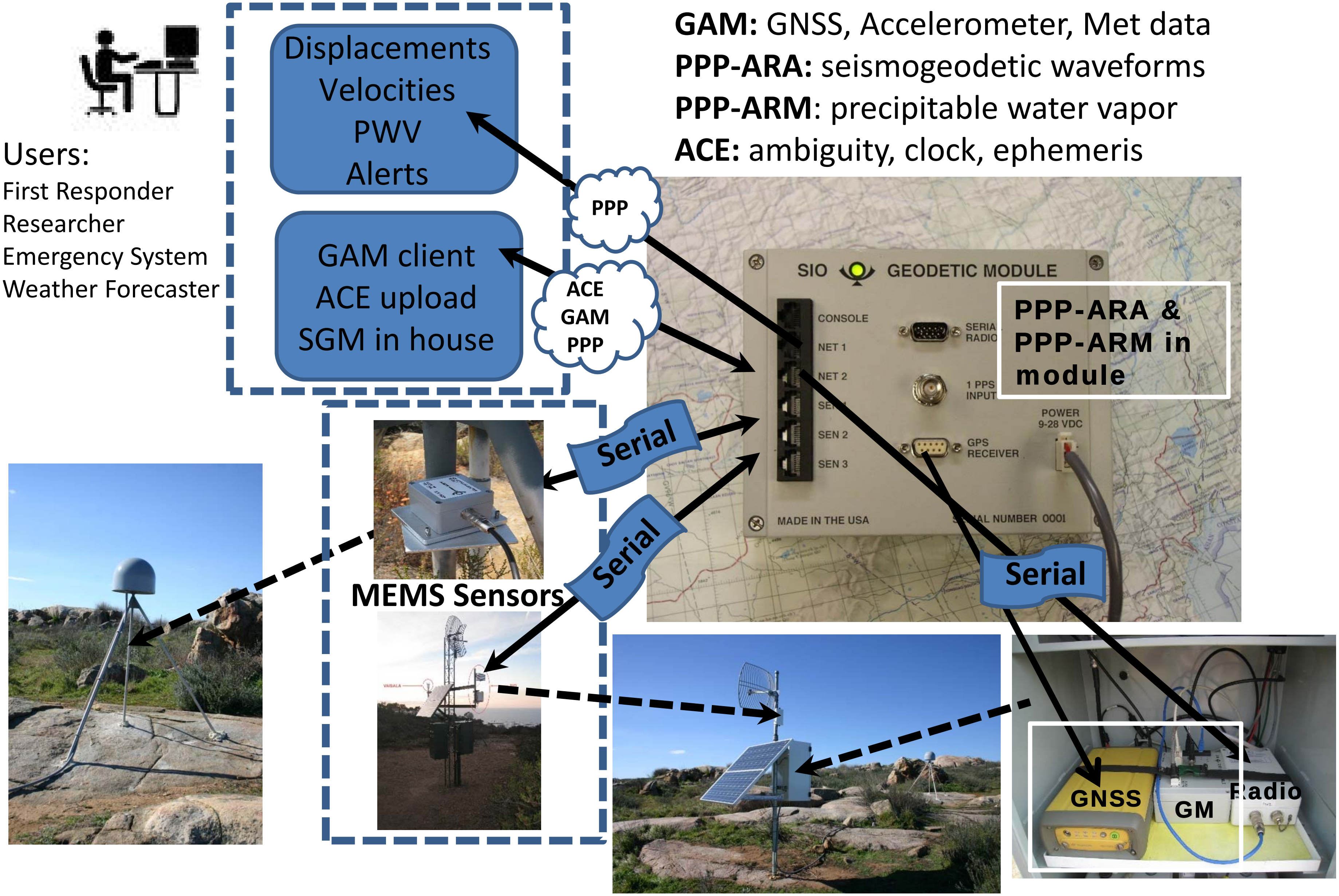
Seismogeodetic Monitoring System @ SOPAC



PPP-ARA **scales linearly with number of stations**

Development and deployment of SIO MEMS accelerometers

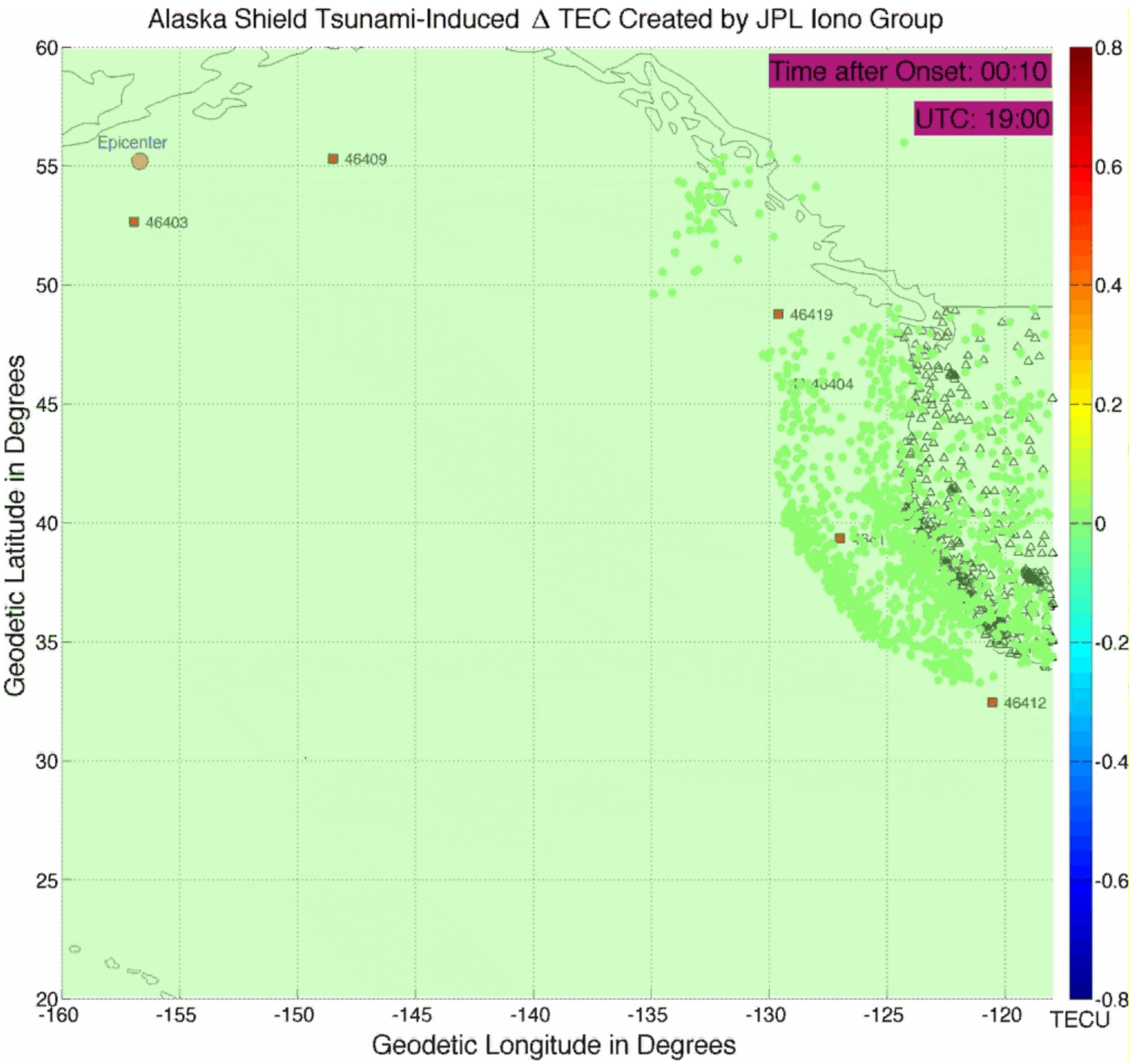
GAM: GNSS, Accelerometer, Met data
PPP-ARA: seismogeodetic waveforms
PPP-ARM: precipitable water vapor
ACE: ambiguity, clock, ephemeris



Work funded by NASA

Alaska Shield Exercise: Tsunami Early Warning Using Real-Time GPS Ionospheric Data

JPL Ionosphere Group for Natural Hazard Detection
Attila Komjathy, Oscar Yang, Xing Meng & Olga Verkhoglyadov



- Earthquakes and tsunamis generate atmospheric gravity waves that disturb ionosphere.
- Disturbance to ionosphere is detectable using raw GPS data-derived total electron content (TEC).
- TEC can be used to detect tsunami, estimate tsunami arrival times, wave heights and uncertainties.
- Movie is from the Alaska Shield Exercise (replay of 1964 Mw 9.2 Alaska earthquake).
- The color-coded simulated data points indicate TEC perturbations at each IPP location based on data from READI stations.

Source: Attila Komjathy, JPL

READI Working Group Recommendation to IGS and GGOS

The WG recommends that the IGS encourage and coordinate member organizations to establish protocols and develop a system for an Indo-Pacific moderate density GNSS network, 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.