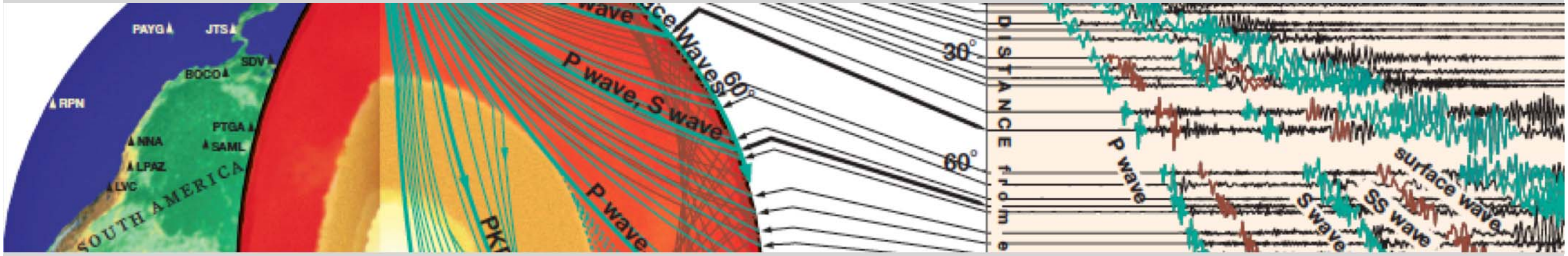


Seismology and Tsunami Warning Center Operations

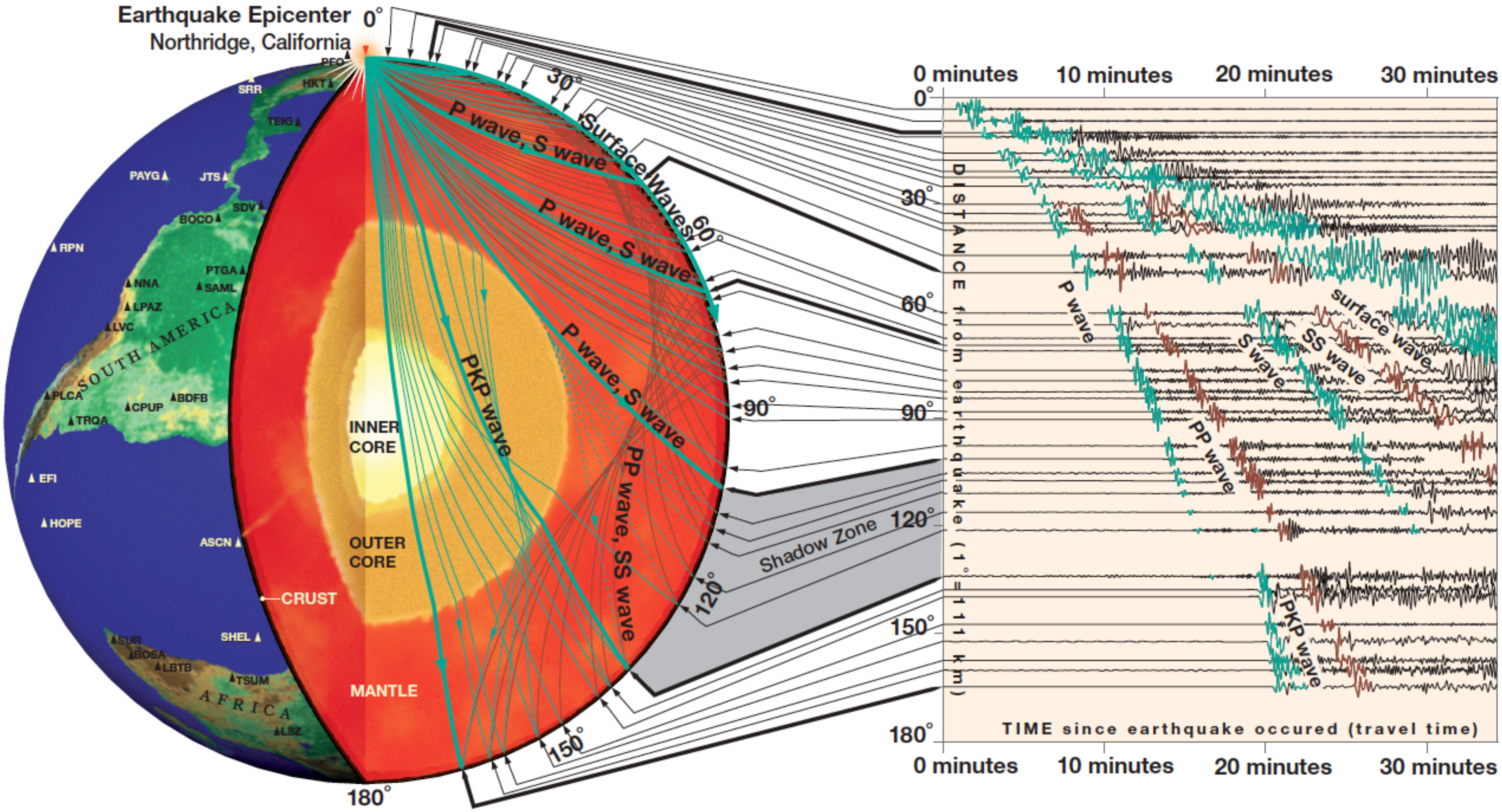
Gerard Fryer
Pacific Tsunami Warning Center

ITIC Training Program Hawaii
August 25, 2014

Earthquake Detection and Characterization

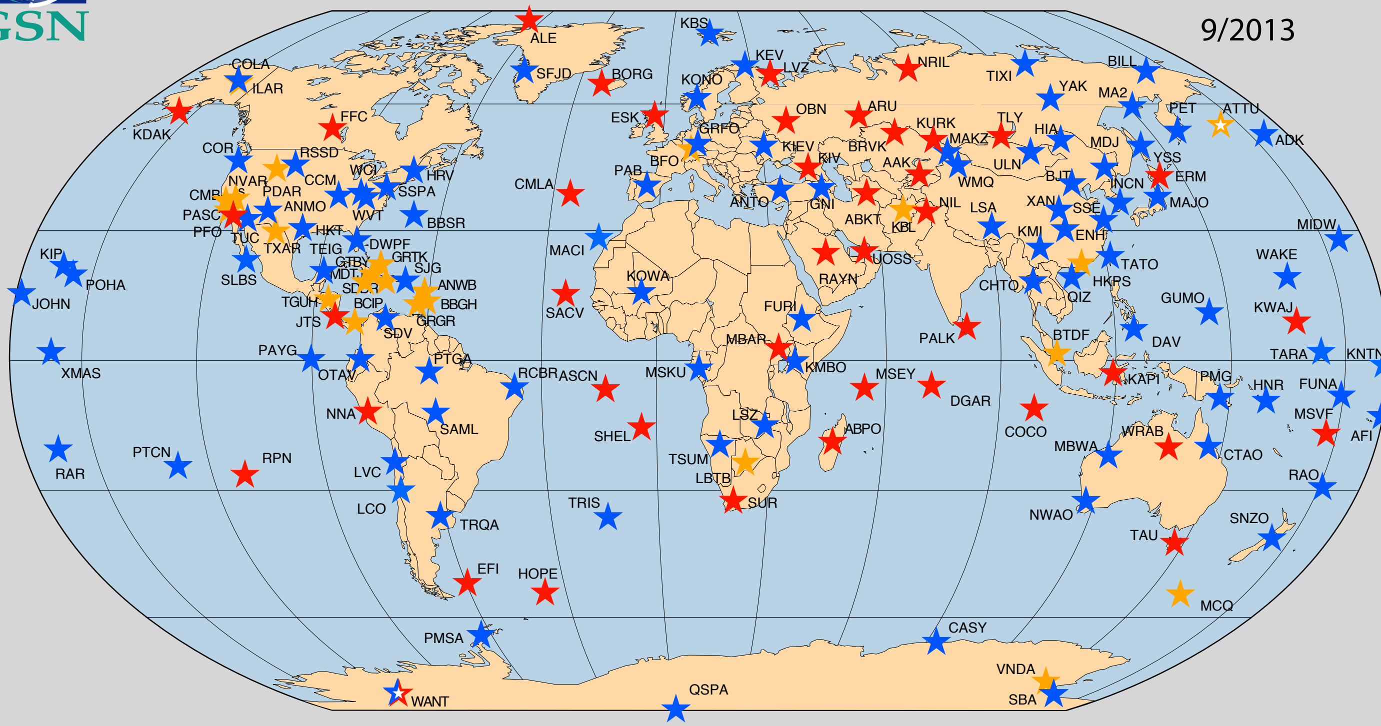
- Motivation: Seismic waves travel roughly 60 times faster than a tsunami, so you can learn a huge amount about an earthquake, including its tsunamigenic potential, before you have any direct information about the tsunami.
- What we solve for now:
  1. Latitude, longitude, depth, origin time (5-7 minutes)
  2. Magnitude (6-8 minutes)
  3. “Fast” or “slow” earthquake? (7-8 minutes)
  4. Mechanism (25 minutes)
- Not yet implemented but high on the wish list:
  1. Magnitude correct to 0.2 within 5 minutes
  2. Rupture direction and extent (finite fault solution)

Seismic travel times



Seismic Networks

GSN GLOBAL SEISMOGRAPHIC NETWORK



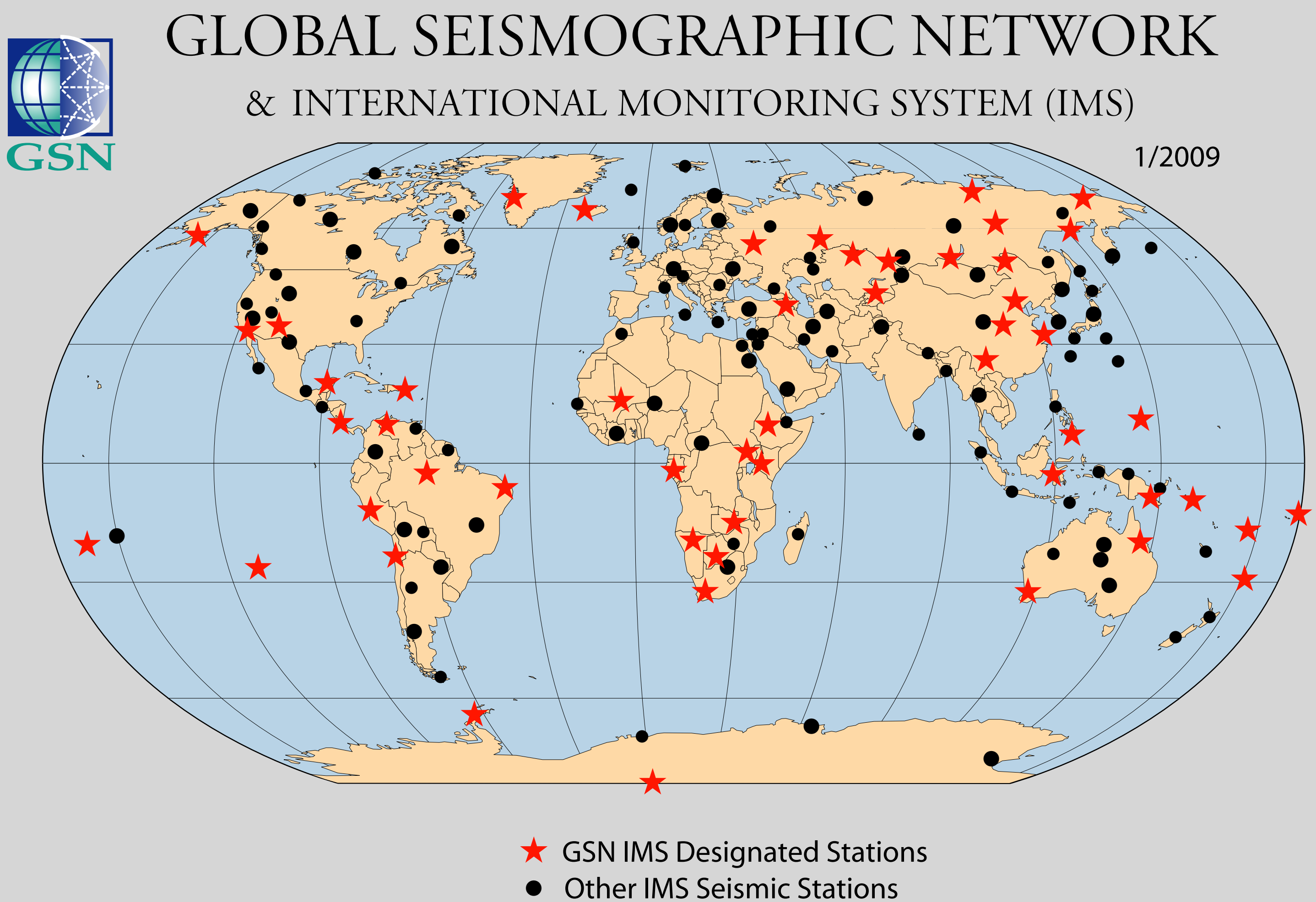
IRIS / IDA Stations

IRIS / USGS Stations

Affiliate Stations

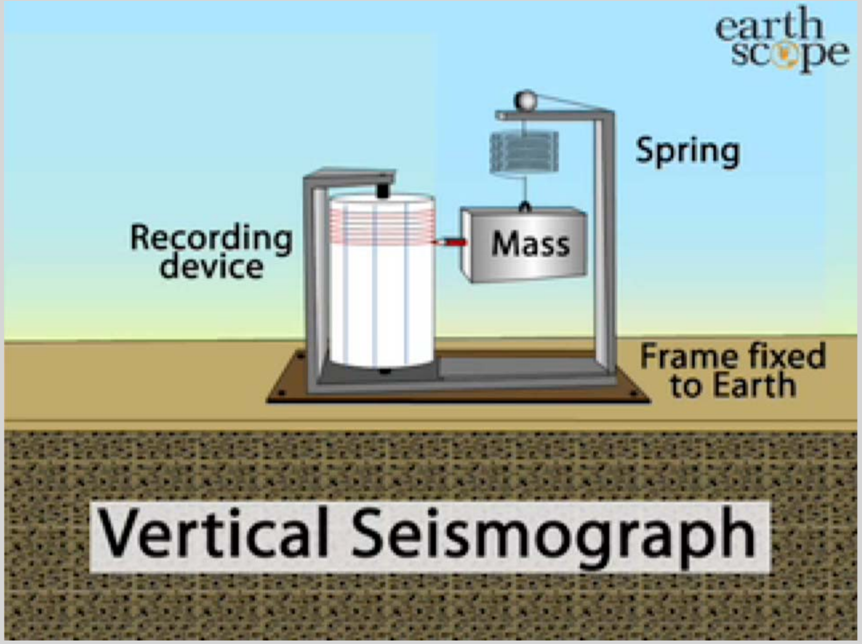
Planned Stations

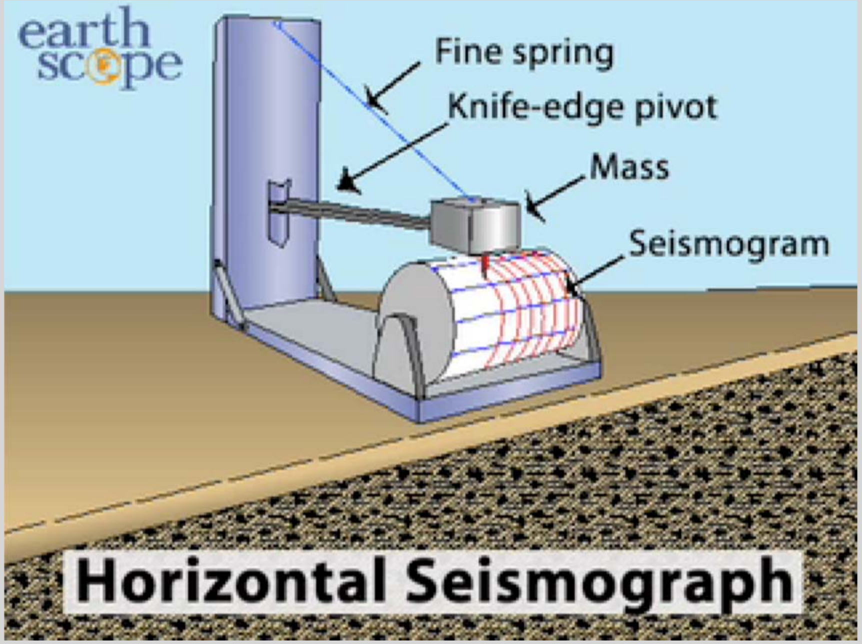
Seismic Networks



Seismometers

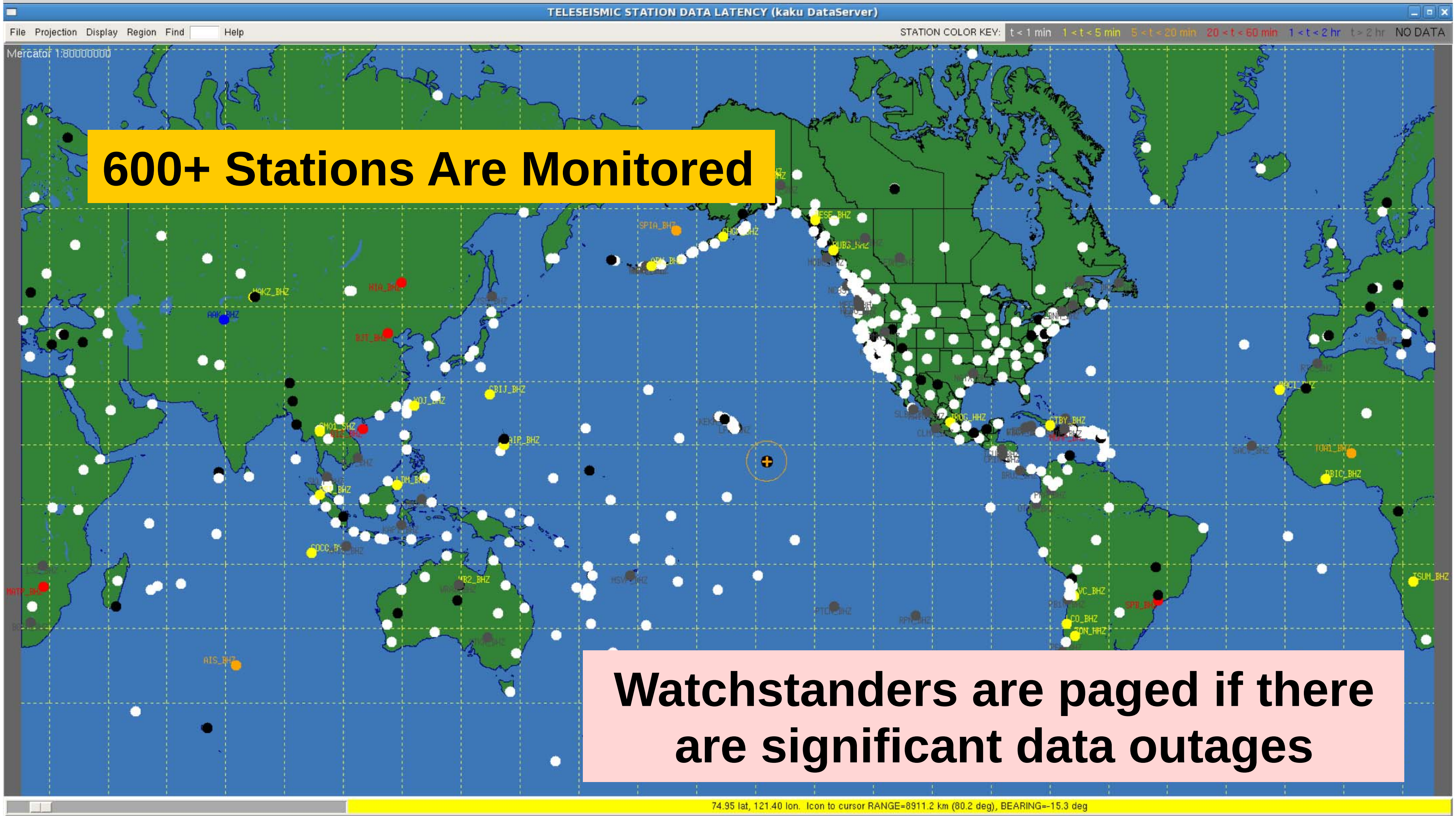
- We get data from about 650 seismometers worldwide in near-real time (latency is typically a few tens of seconds).
- These are ***broadband*** seismometers (i.e., capable of recording energy from 1 to 300 seconds period). It is broadband seismometers that make tsunami warning possible.





Data Availability/Latency Monitoring

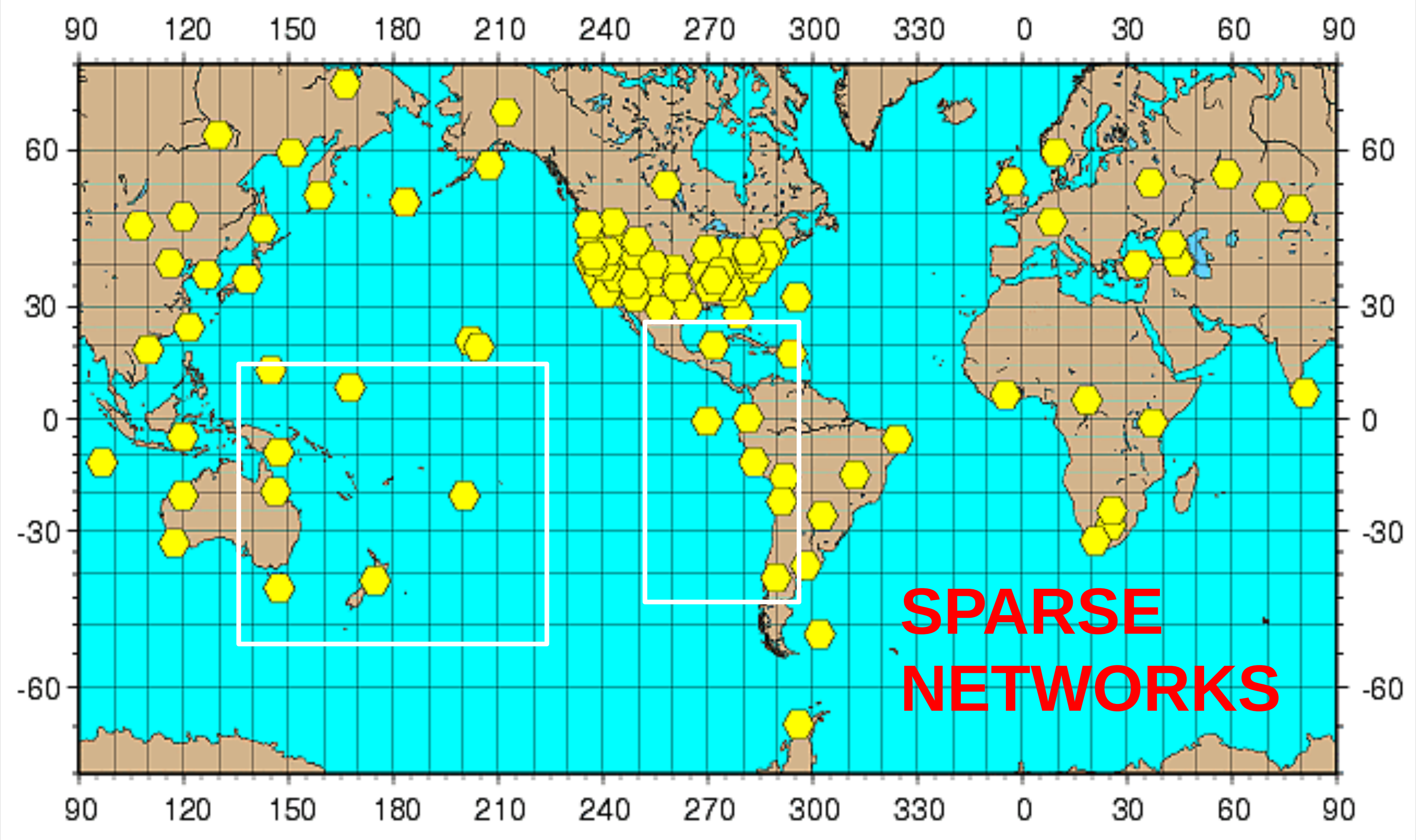
STATION COLOR KEY: t < 1 min | 1 < t < 5 min | 5 < t < 20 min | 20 < t < 60 min | 1 < t < 2 hr | t > 2 hr | NO DATA



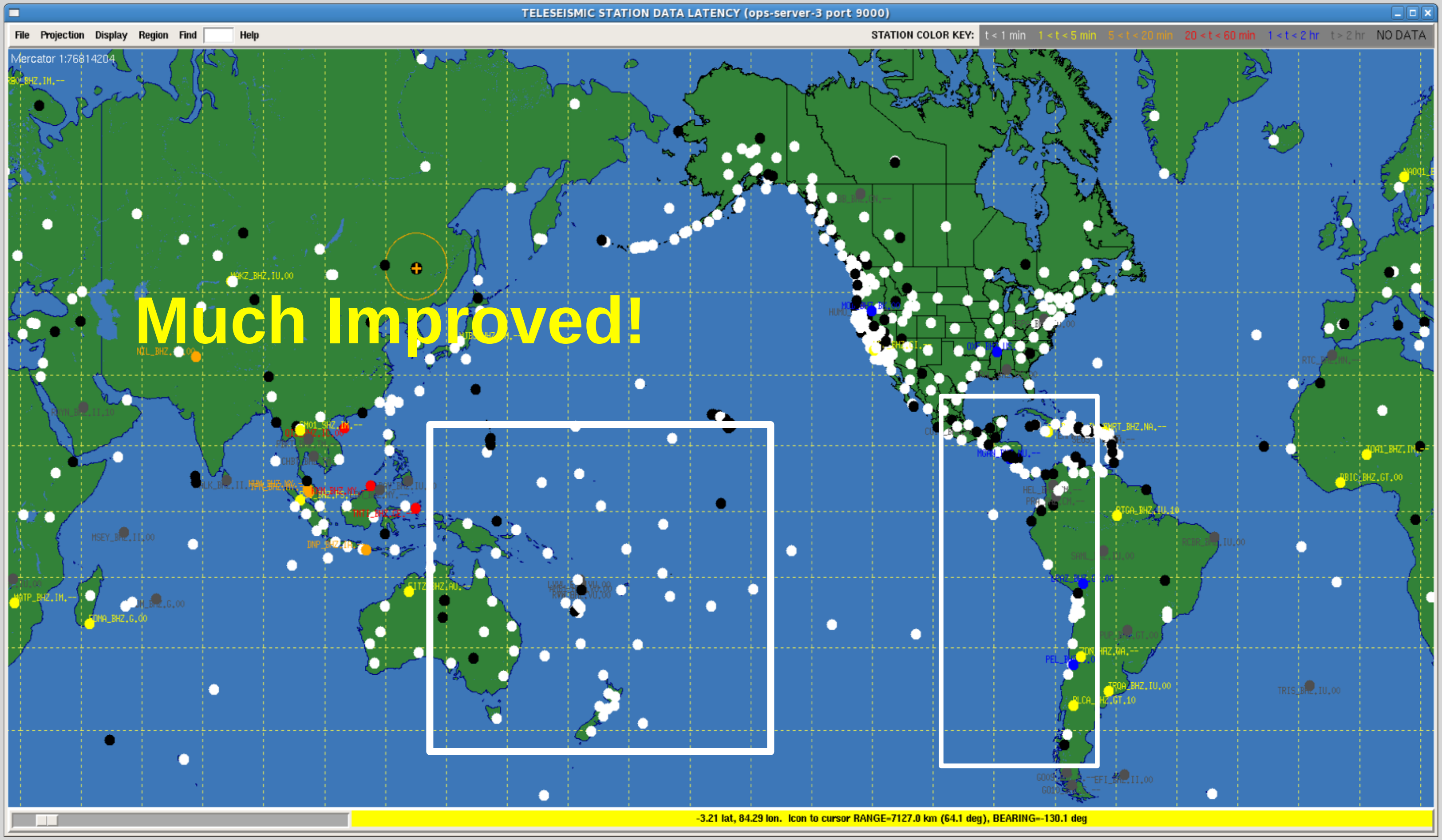
600+ Stations Are Monitored

Watchstanders are paged if there are significant data outages

Broadband Seismometer Distribution Oct. 2007

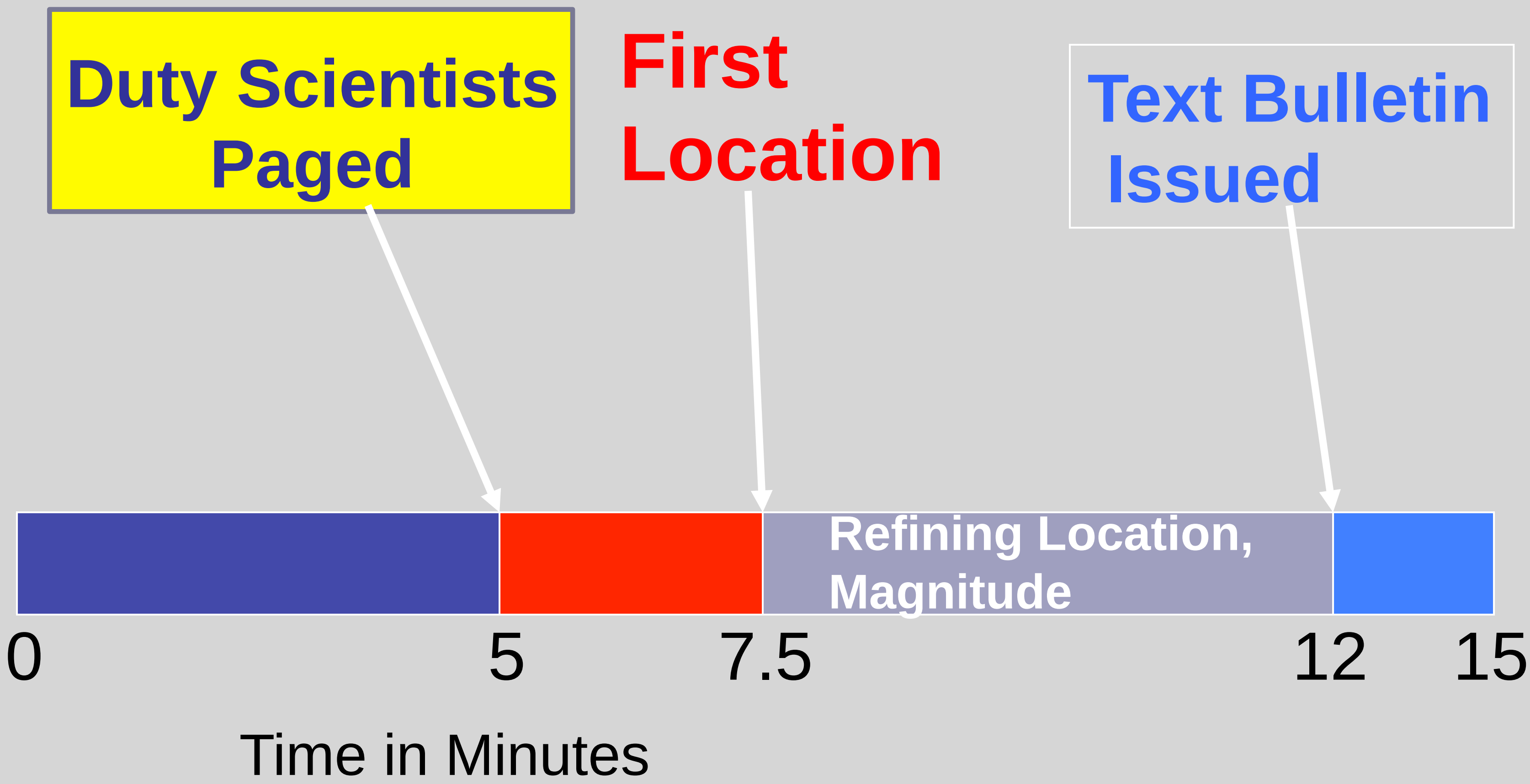


Broadband Seismometer Distribution May 2014



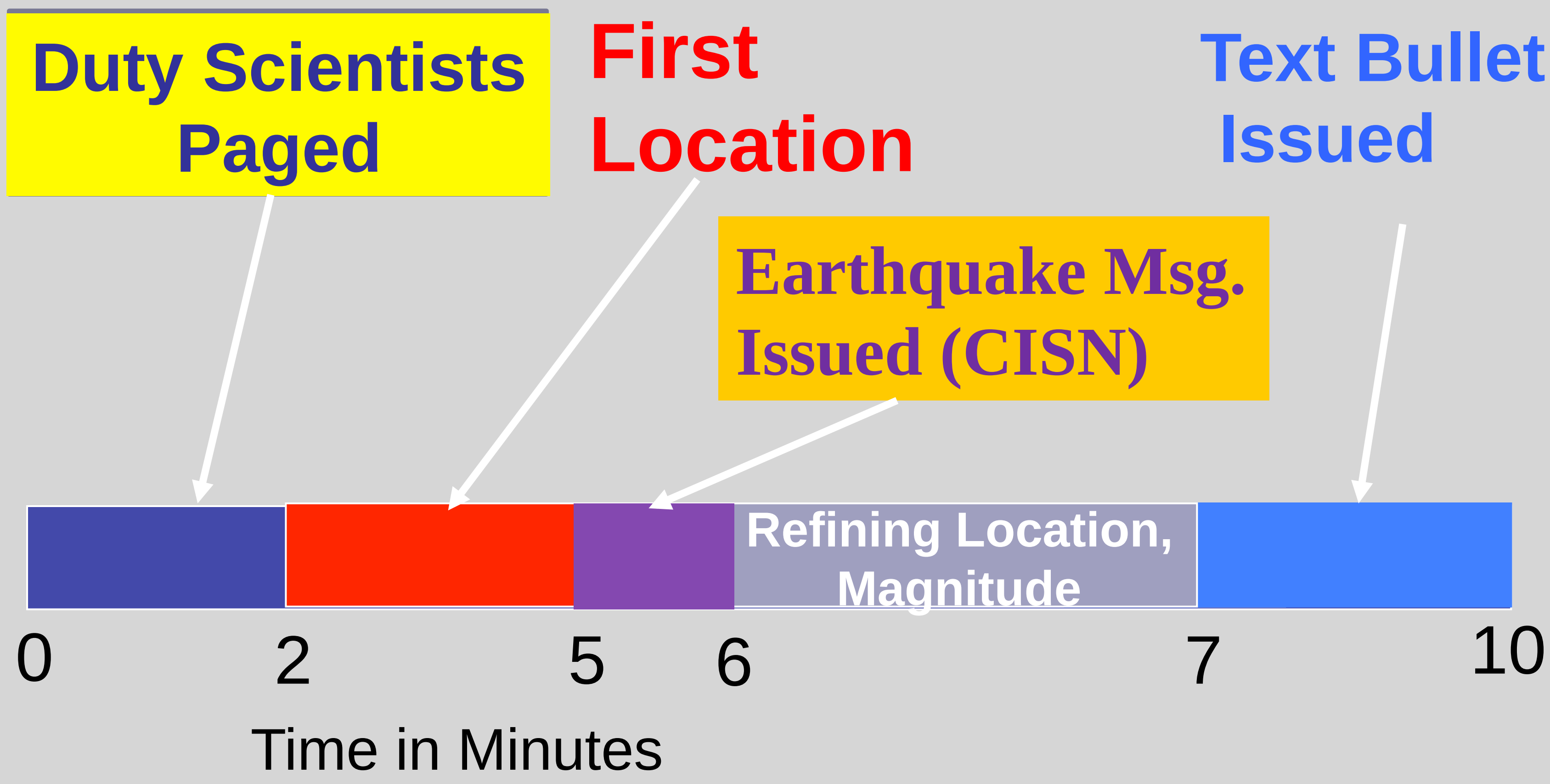
Earthquake Outside Hawaii Region

Timeline to Issue Initial Bulletin 2008



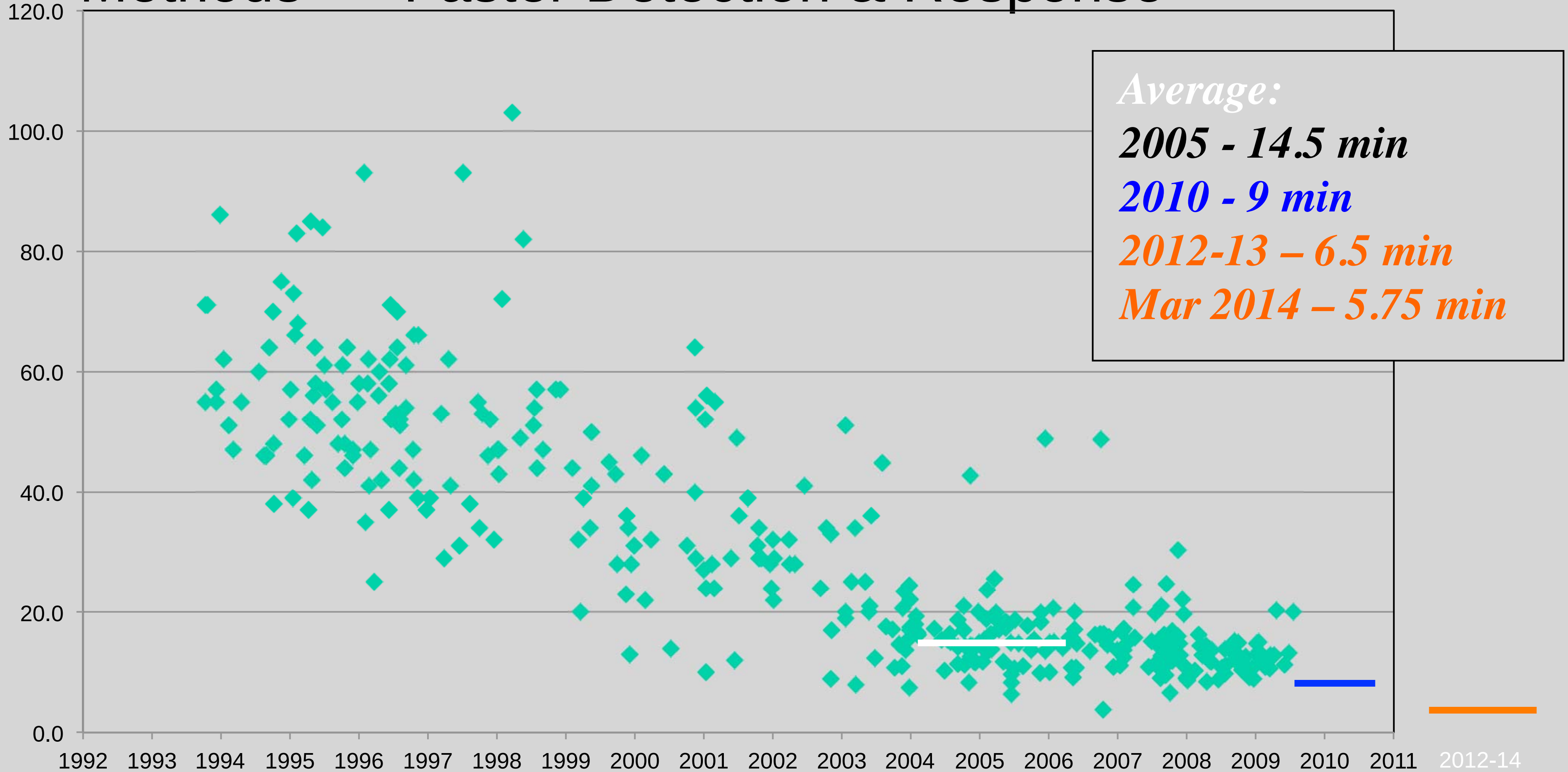
Earthquake Outside Hawaii Region

Timeline to Issue Initial Bulletin 2014



PTWC Elapsed Time to Initial Bulletin

Earthquakes: Denser Networks, Higher Quality Data, Better and Faster Methods => Faster Detection & Response

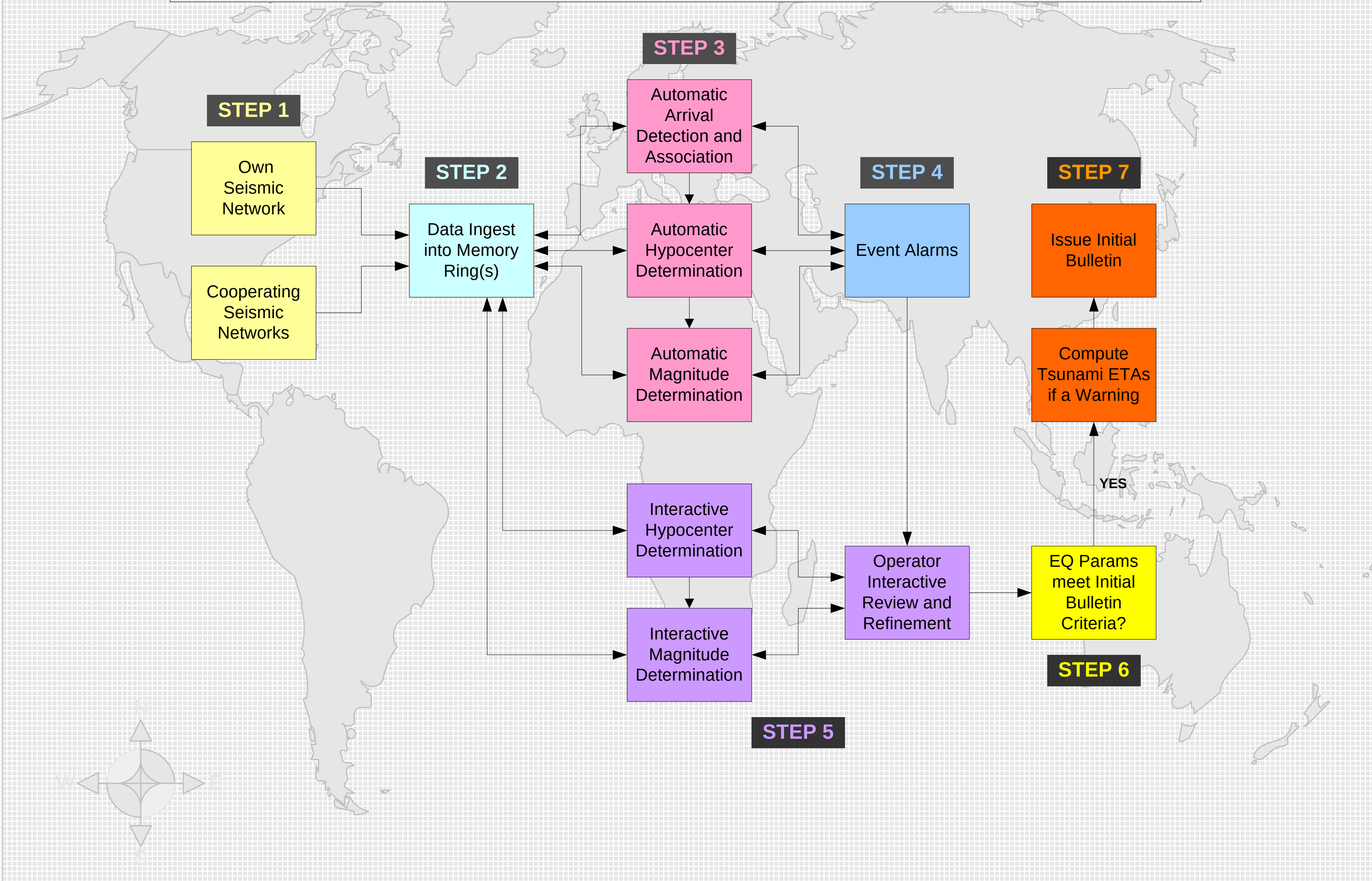


Current PTWC Products

- Text product only
- Product – Countries put in Warning / Watch status. Estimated arrival times provided

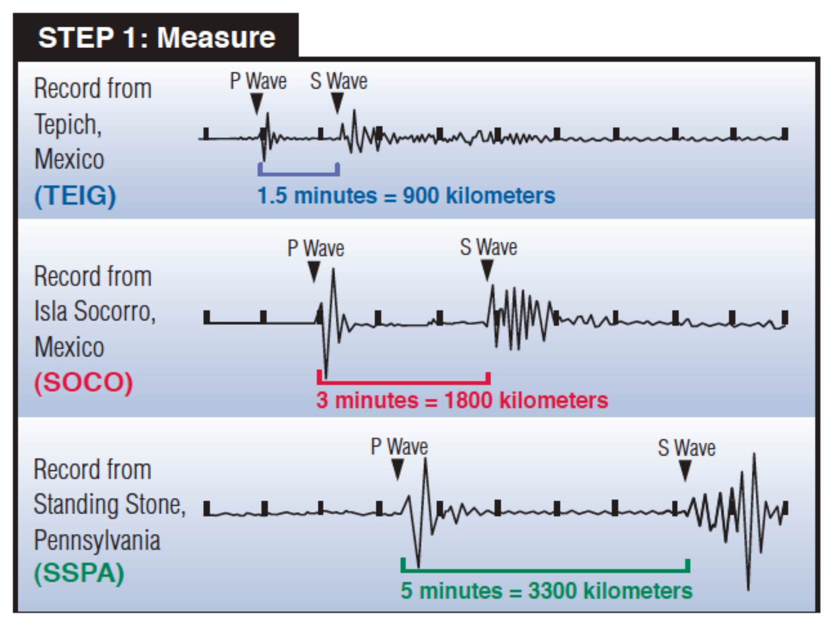
Earthquake	Product Type	Description
Magnitude 6.5-7.5 or >6.5 and >100km depth or far inland	Information Bulletin	No Tsunami Threat or only small Local Tsunami Threat
Magnitude 7.6-7.8 and <100 km depth and under sea or near sea	Regional Warning	Warning to 1000km from epicenter
Magnitude >7.8 and <100km depth and under sea or near sea	Expanding Warning	Warning if < 3 hours to impact, Watch if 3-6 hours to impact
Confirmed major tsunami	Pacific-wide Warning	Confirmed tsunami with widespread destructive threat

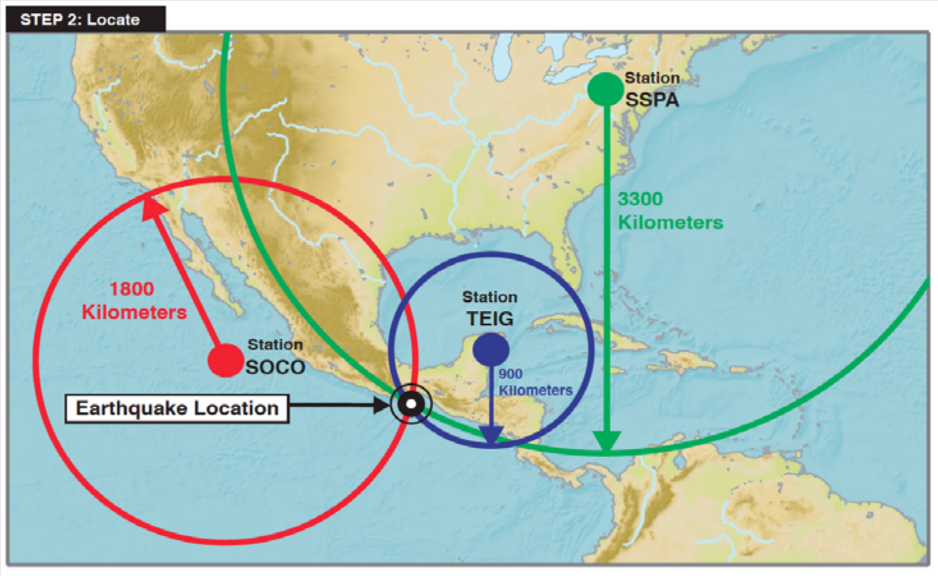
PTWC General Processes and Procedures for Initial Tsunami Bulletins



Locating earthquakes

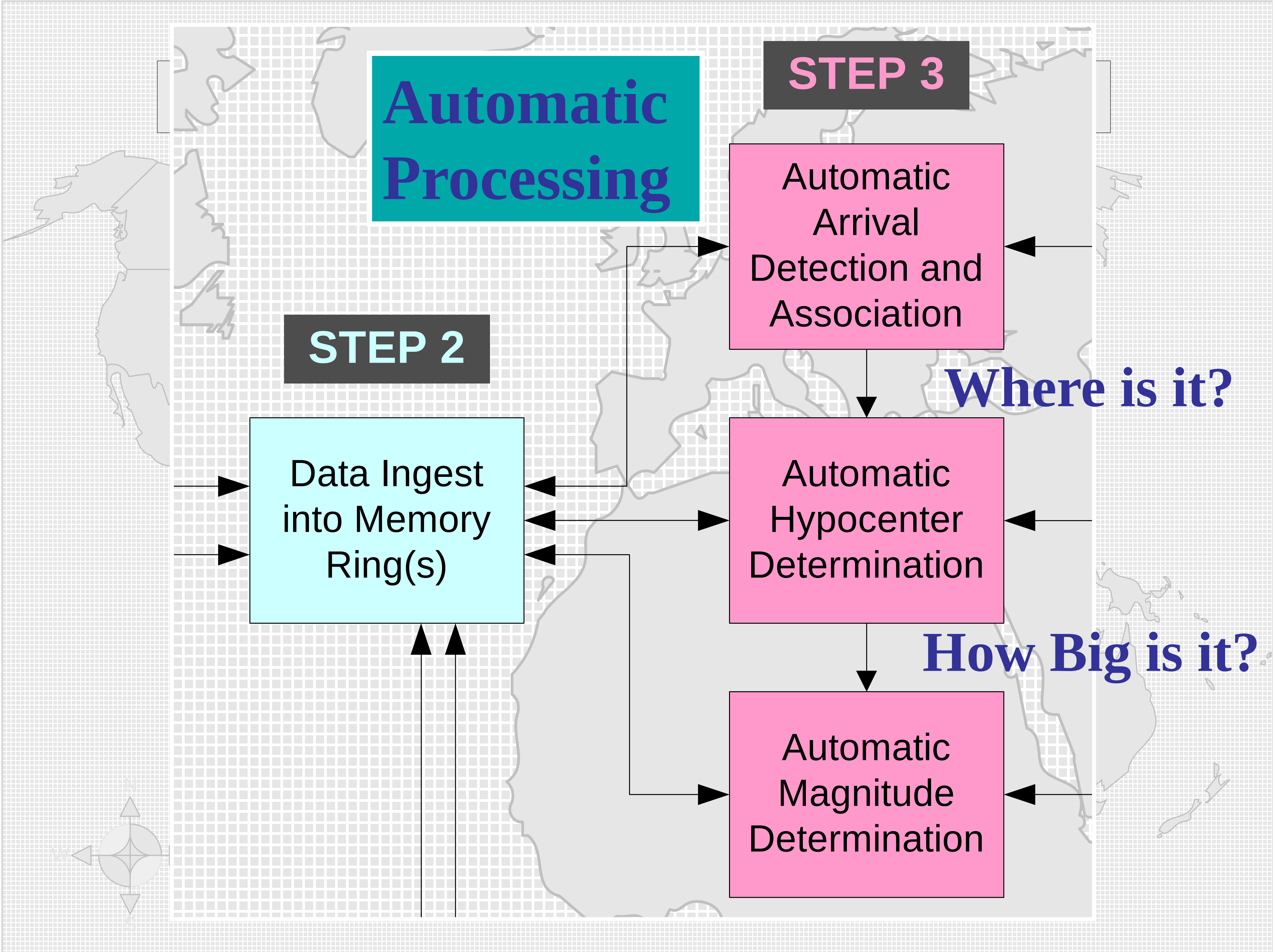
- Four unknowns: lat, long, depth, origin time.
- Need a minimum of four stations. More is better. The stations may not be well located relative to the earthquake, however, so we often have to fix depth.





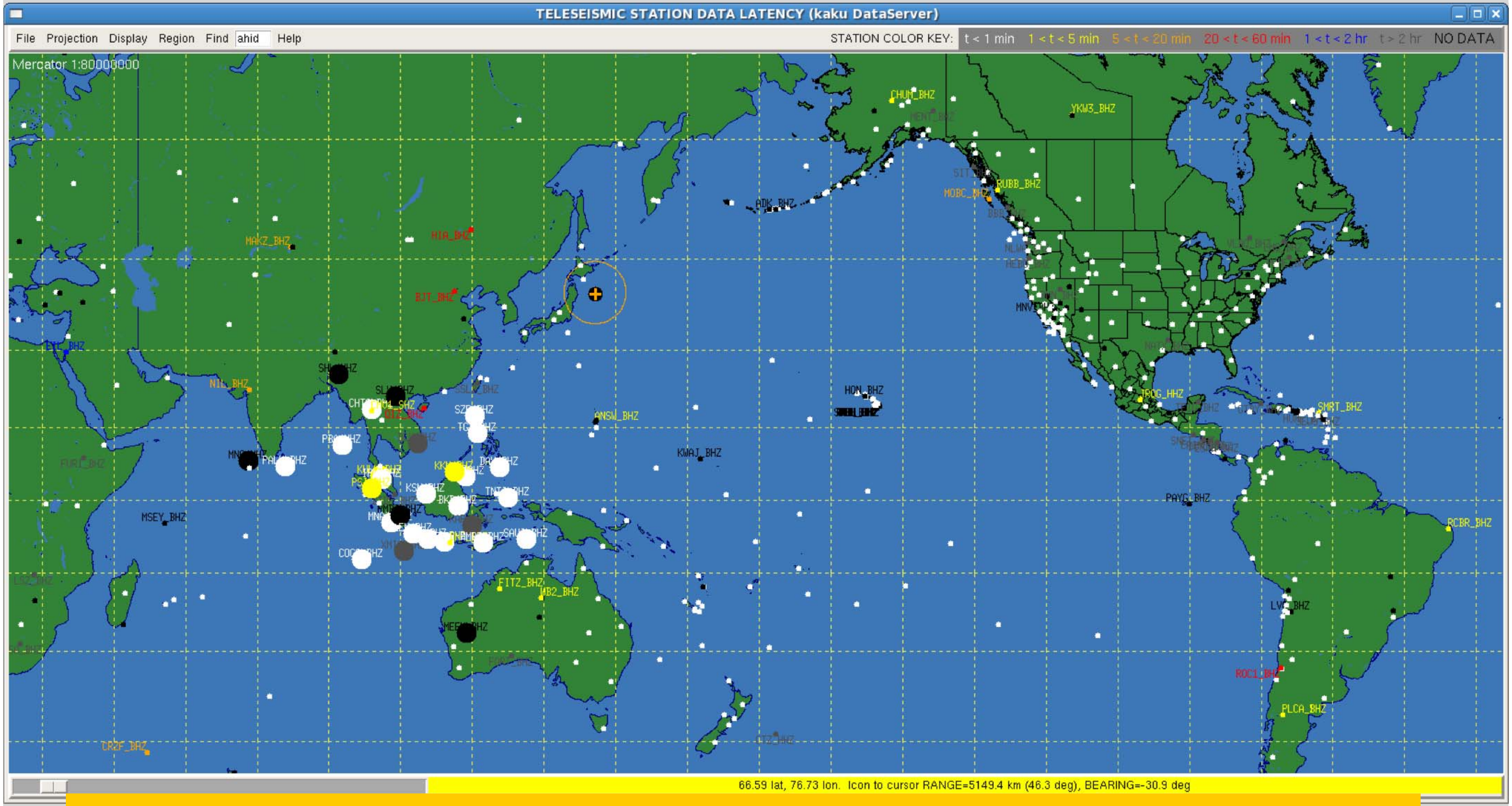
Automation tools

- A *Picker* scans each seismogram and identifies possible seismic arrivals.
- An *Associator* groups picks from different seismograms to try to identify earthquakes.
- If picks are consistent with an earthquake, standard magnitude algorithms compute an automatic magnitude.
- *Paging*:
  - If one seismometer has a pick with a large signal-to-noise ratio, the duty scientist gets a page.
  - If two or more seismometers in a given region have picks within a few minutes of each other, the duty scientist and the standby scientist both get pages.
  - If the automatic magnitude exceeds 5.6, both scientists get pages.



Automatic Processing
STEP 2
STEP 3
Data Ingest into Memory Ring(s)
Automatic Arrival Detection and Association
Where is it?
Automatic Hypocenter Determination
How Big is it?
Automatic Magnitude Determination

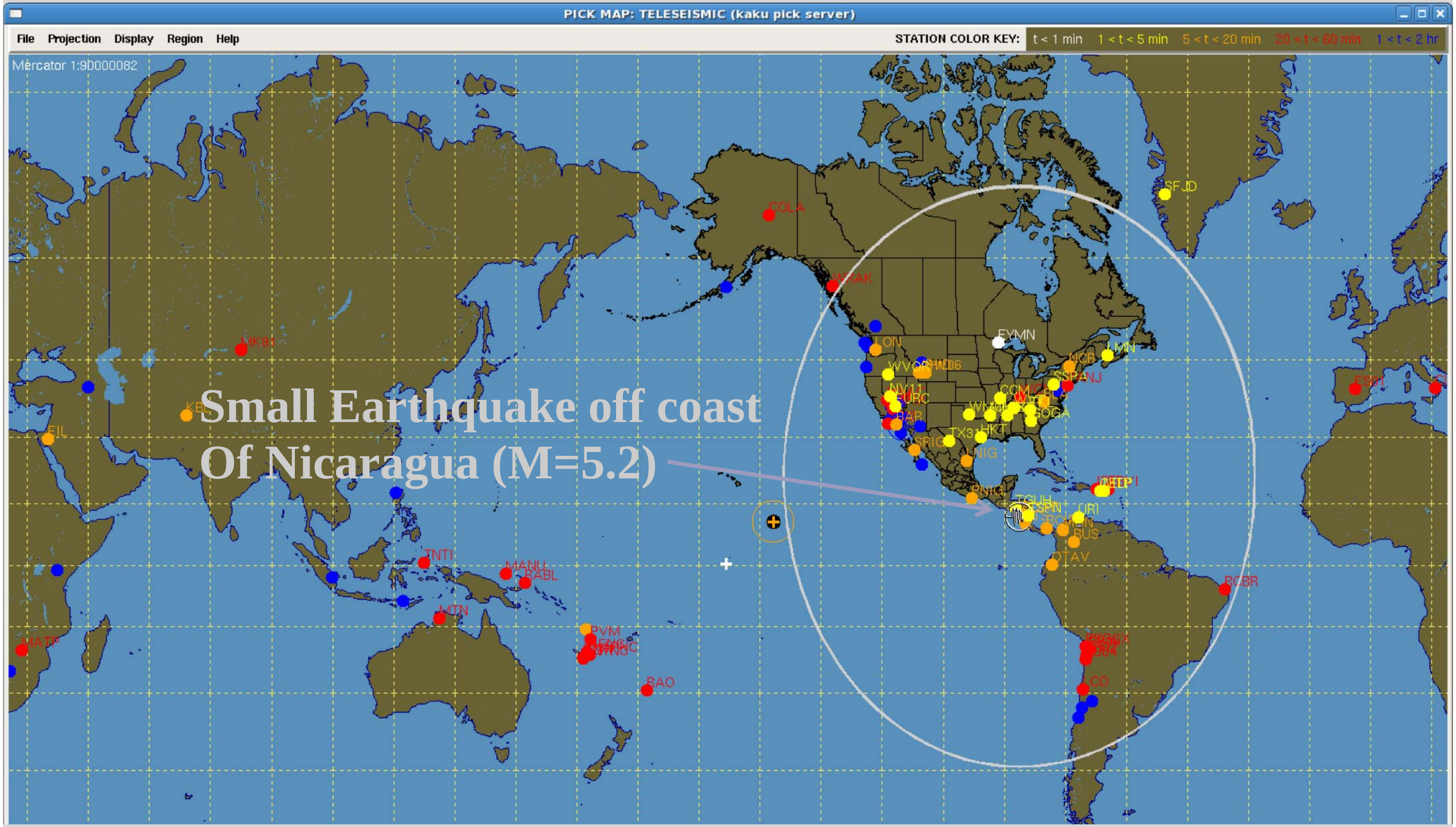
Broadband Seismometer Distribution



The large dots are the stations involved in the East Indian Ocean Alarm region. PTWC has 14 such alarm regions. PTWC alarms will be triggered by any earthquake with M > 5.5, and often triggered by much smaller earthquakes.

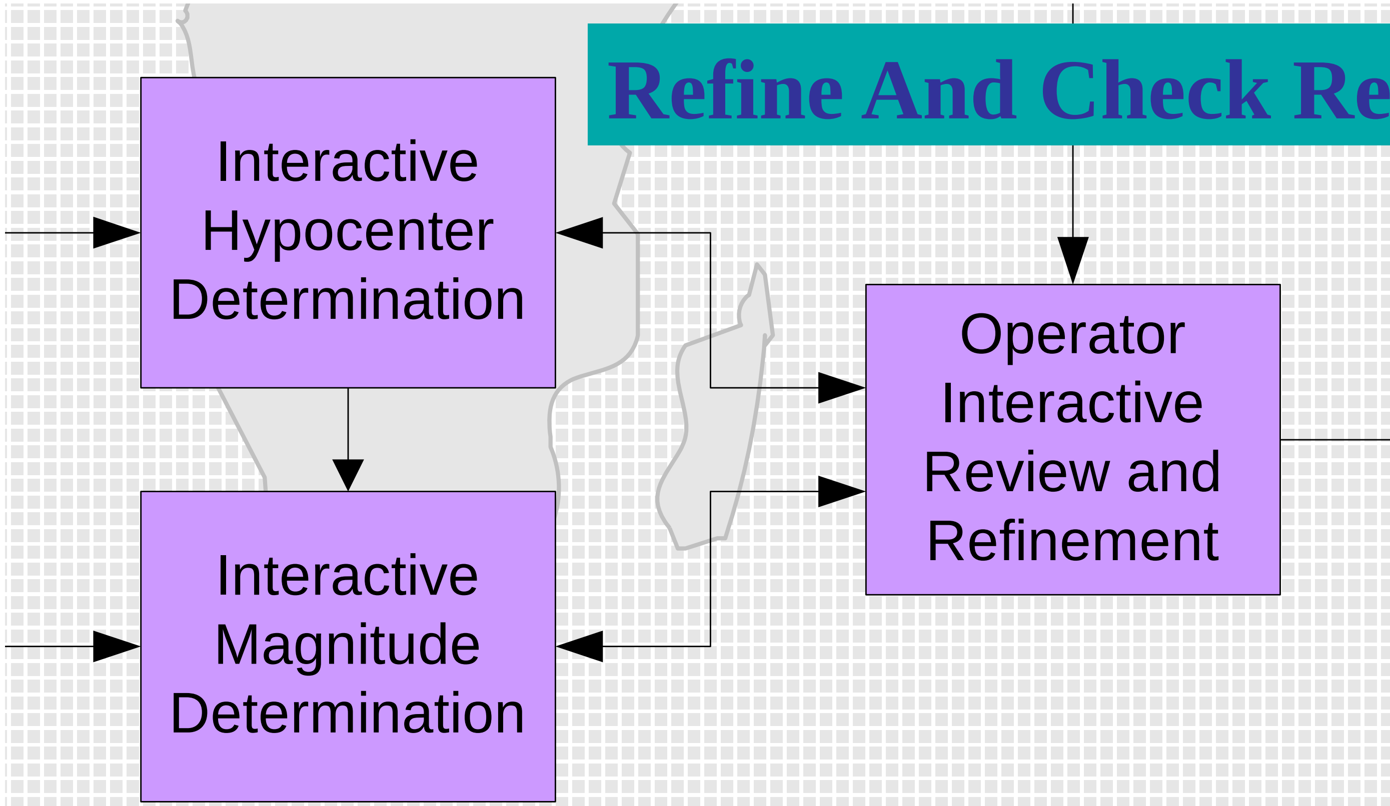
Seismic Detection Monitor

STATION COLOR KEY: t < 1 min 1 < t < 5 min 5 < t < 20 min 20 < t < 60 min 1 < t < 2 hr



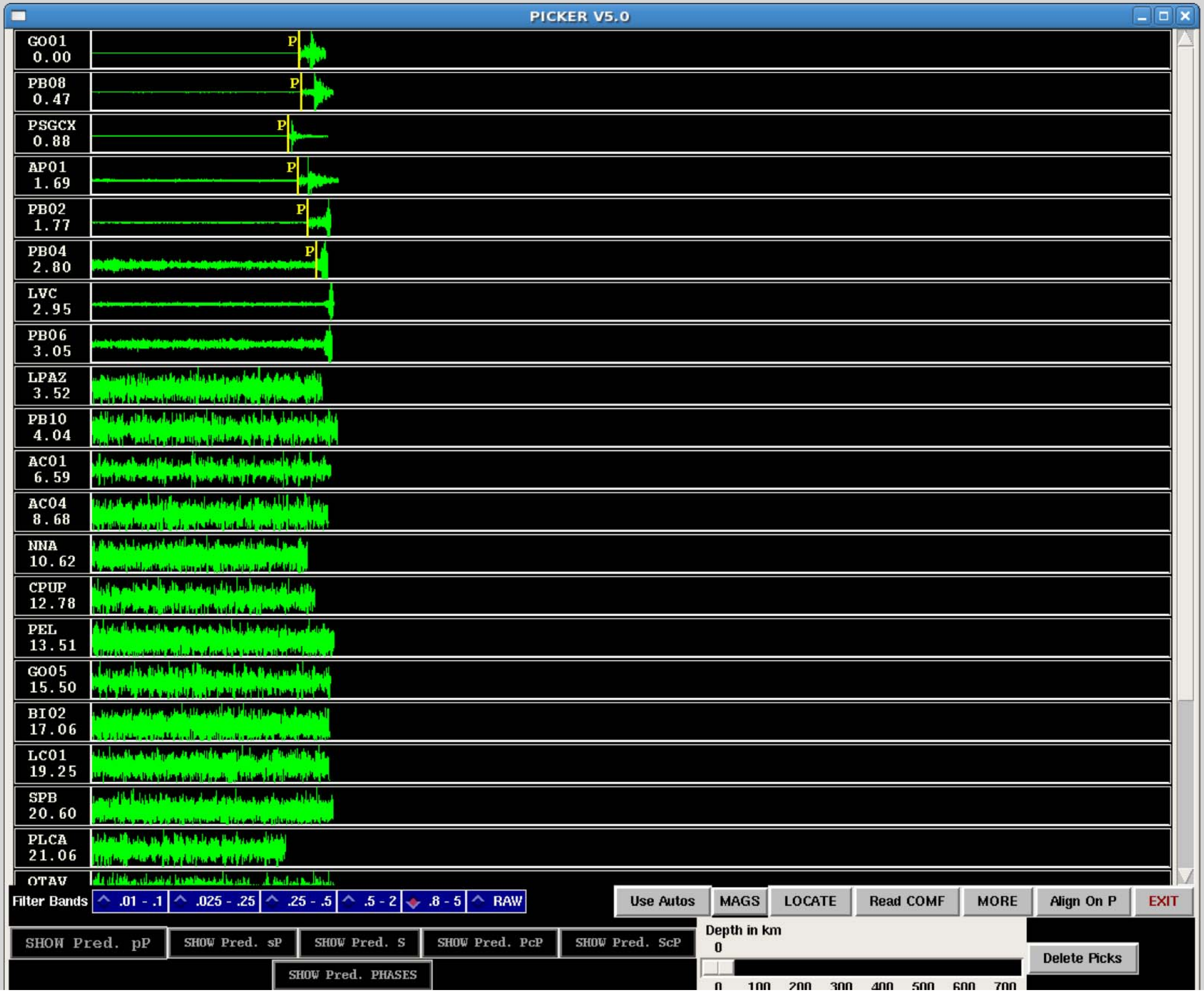
PTWC General Processes and Procedures for Initial Tsunami Bulletins

Refine And Check Results

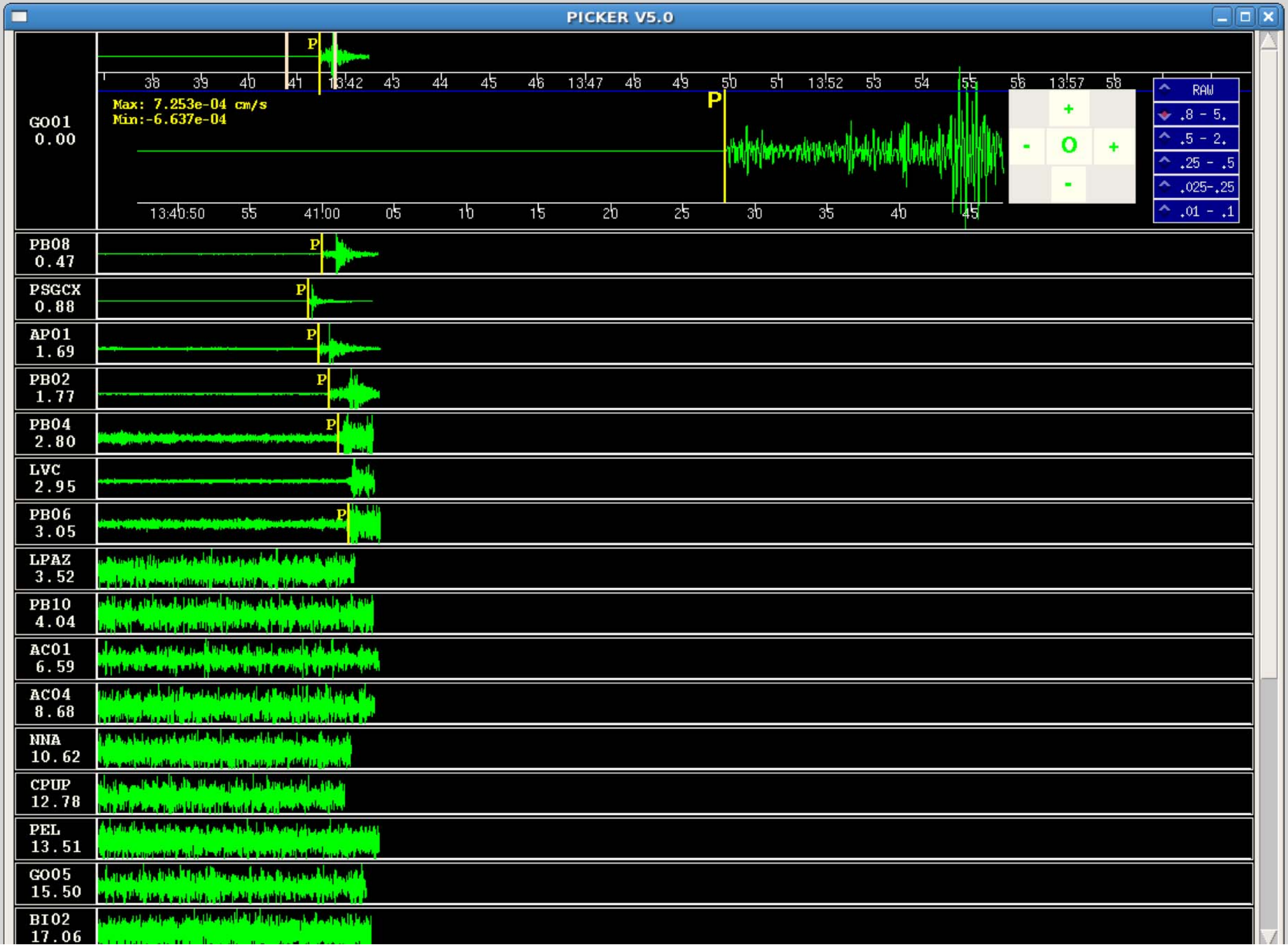


STEP 5

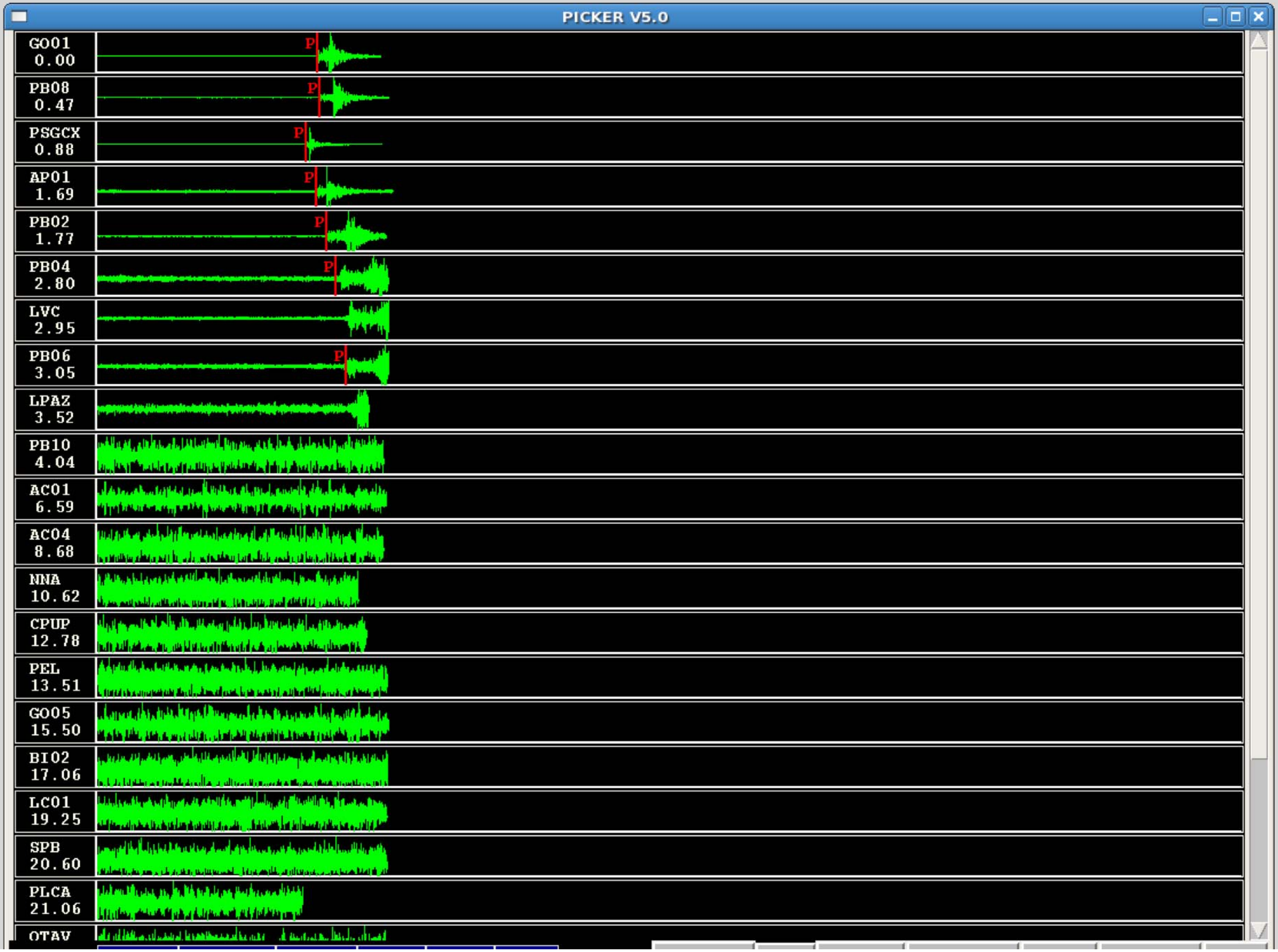
A small earthquake in Chile last night: yellow lines are auto picks



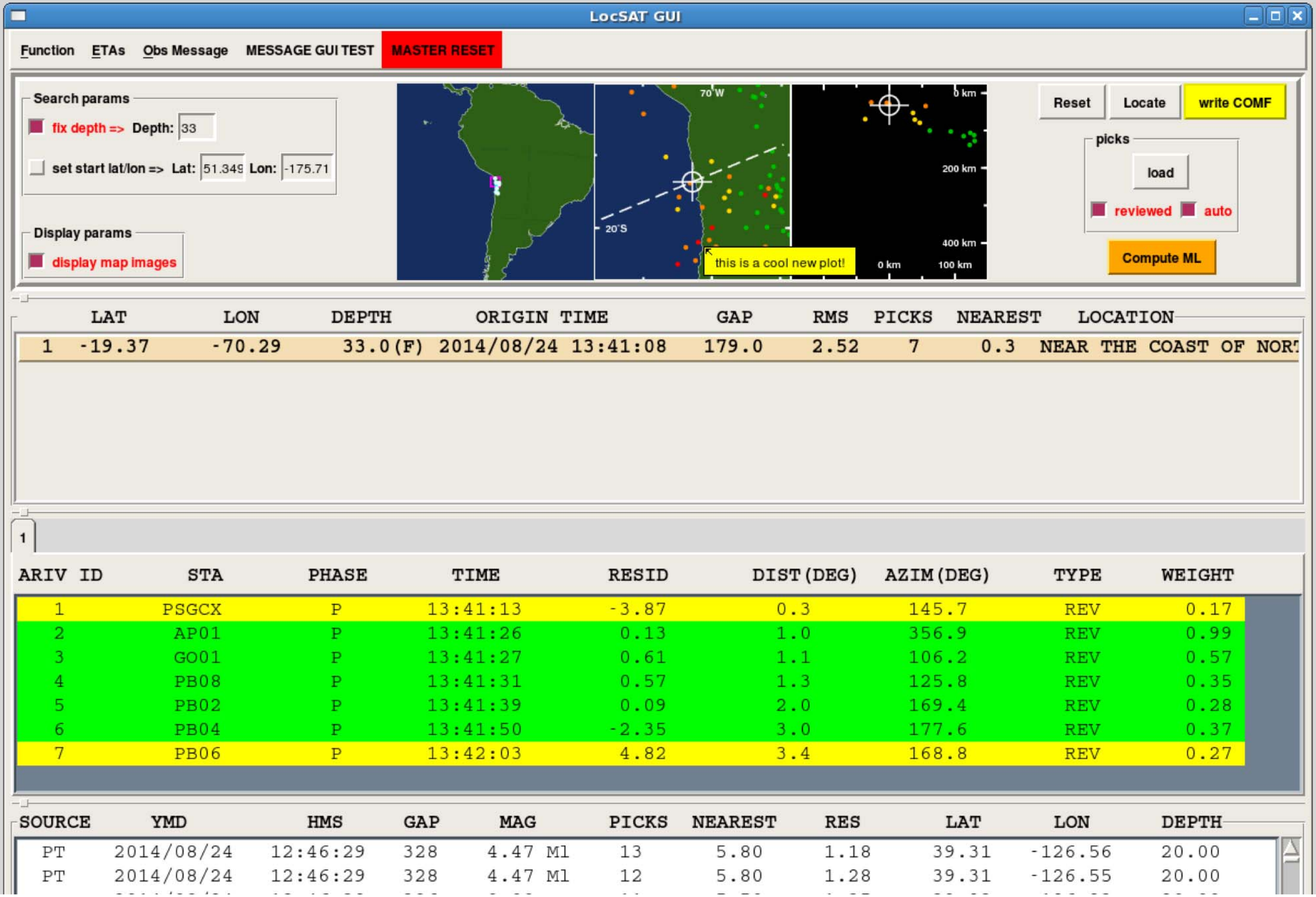
Here I'm reviewing a pick



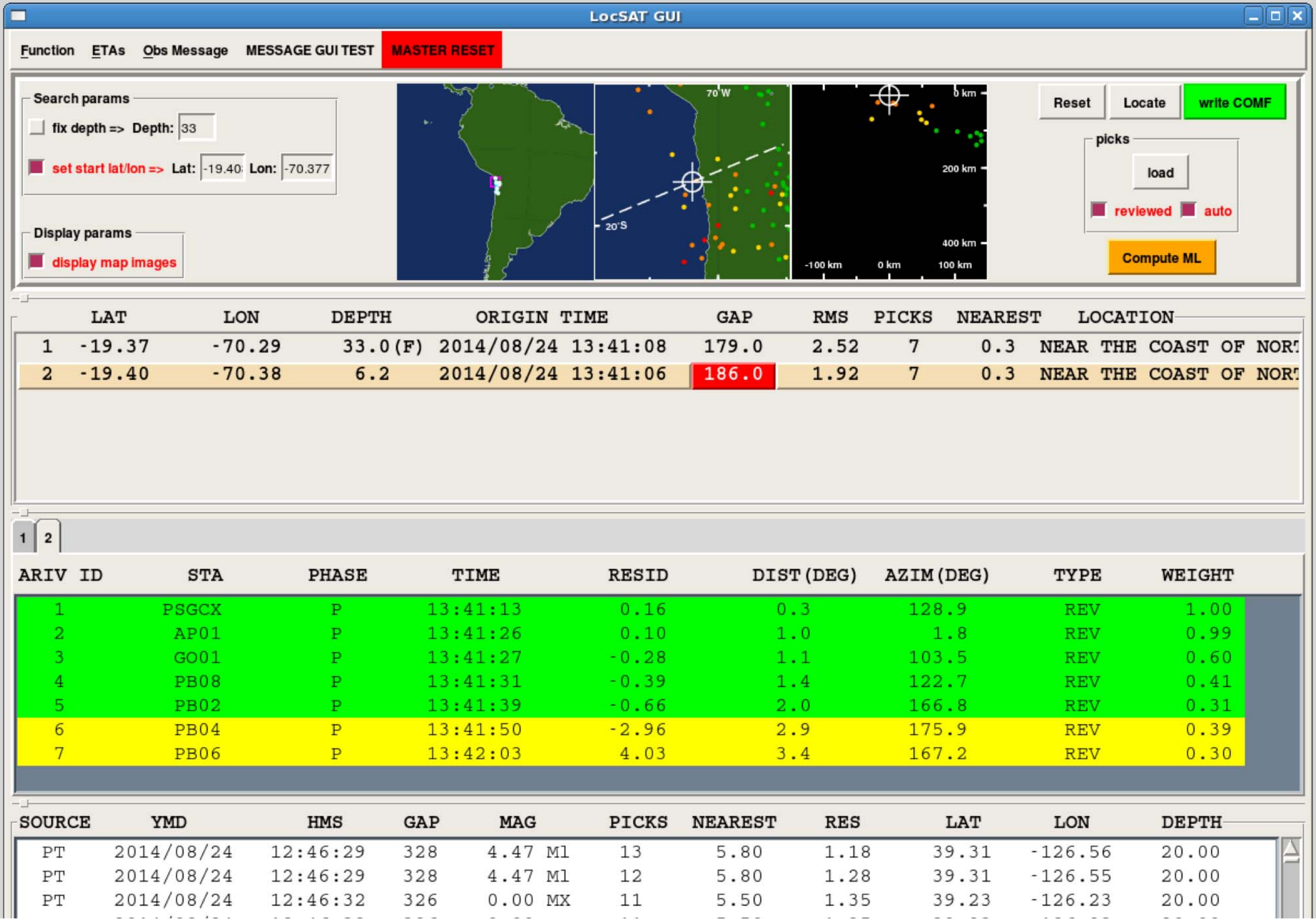
Reviewed picks (red lines)



Picks are passed to the location program (Locsat)
Initially I try a fixed depth (33 km)



Then I allow depth to float to get an improved solution



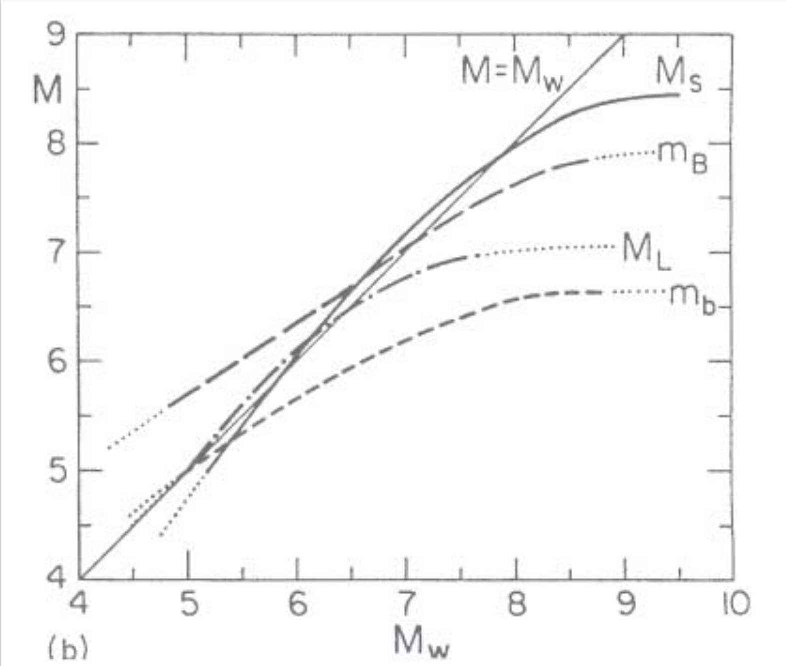
Magnitude

- Once you have the earthquake location you can figure out the magnitude.
- Traditional magnitude measures (Richter magnitude, surface-wave magnitude) are made at too high a frequency to sample the energy from great earthquakes, so those scales saturate. We use broadband magnitude measures (all lumped under the label of “moment magnitude” or M_w) for which the problem of saturation is much reduced.
- I’ll talk about two techniques: M_{wp} (moment magnitude from *P*-wave), and the *W*-phase determination of moment magnitude.

Understanding moment magnitude
...or what bumped the Richter scale?

Saturation

- Traditional magnitude measures (mb, Ml, Ms) suffer from saturation.
- Occurs for 2 reasons:
  - The magnitude is calculated for a time window that is less than the duration of the rupture (particularly effects mb)
  - The wavelength of the wave is too short to “see” all of the rupture (effects mb, Ml, and Ms)



Kanamori 1983

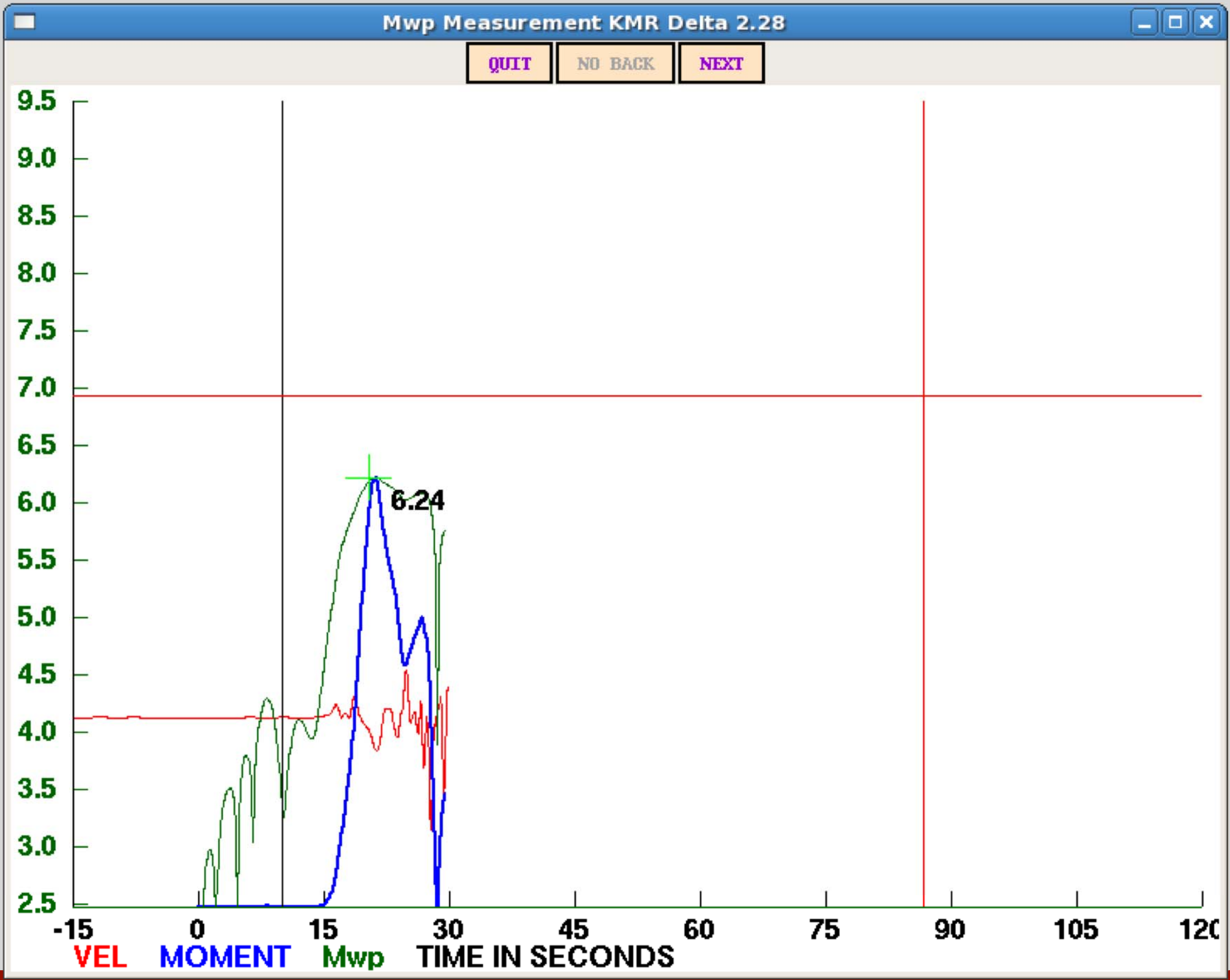
M_{wp} (first proposed by Tsuboi, *et al*., 1995)

- Problem: Traditional magnitude measurements, while reasonably fast, severely underestimate the size of great earthquakes. Centroid Moment Tensor solutions get the magnitude right, but can take hours—too slow for tsunami warning.
- Suggestion: The displacement record of the first-arriving P waves is a good approximation to the source-time function of the earthquake (i.e., the slip on the fault as a function of time). So integrate the *P*-wave portion of a broadband seismogram from velocity to displacement, integrate again to get seismic moment M_0. Moment magnitude, M_w, is then simply obtained from the standard experssion

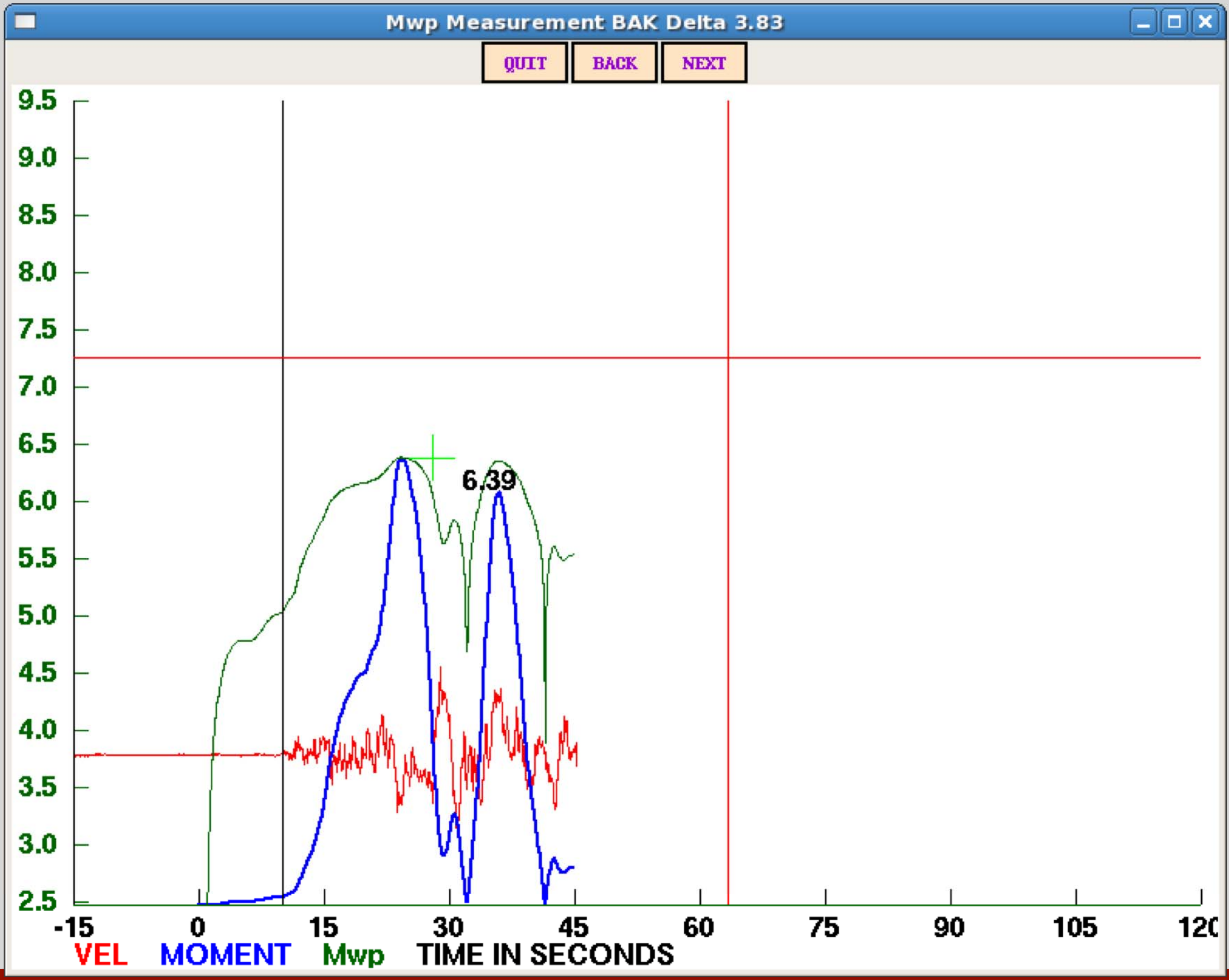
$$M_w = 2/3 \log(M_0) - 10.7$$

- In practice, the operation is performed on the first 120 seconds of the *P*-wave, or as much as is available before *S*-waves arrive.

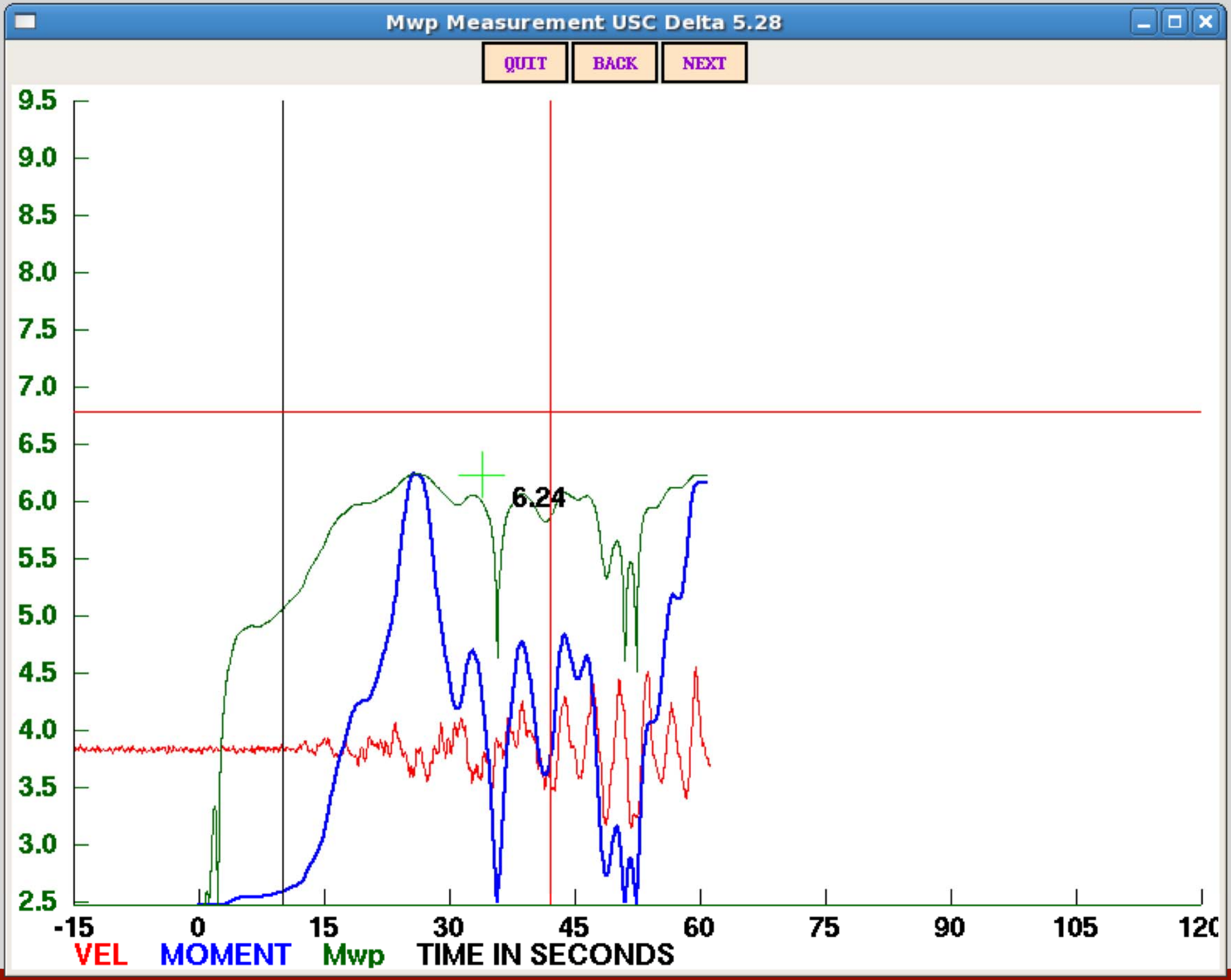
Example: Yesterday's Napa Earthquake



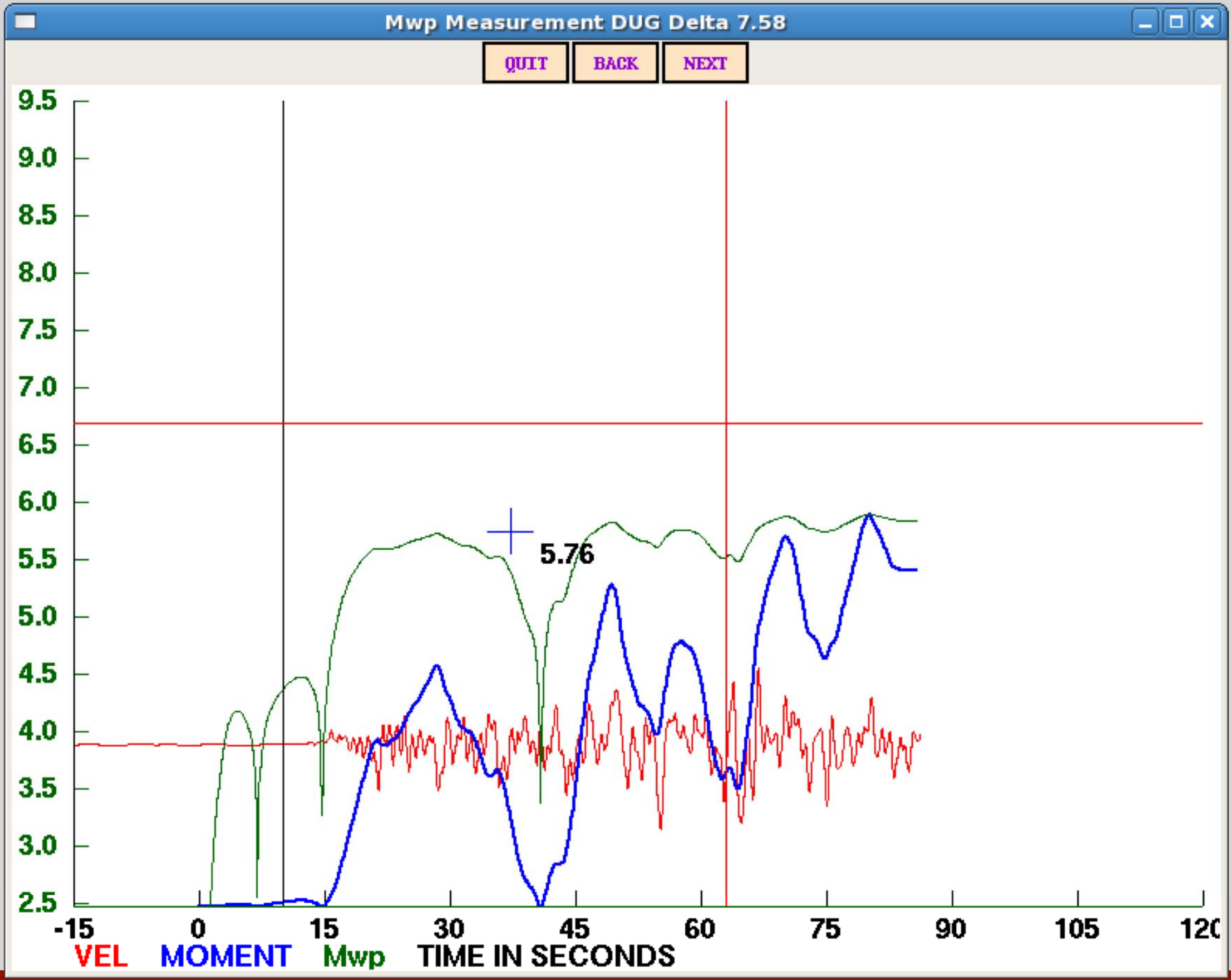
Example: Yesterday's Napa Earthquake



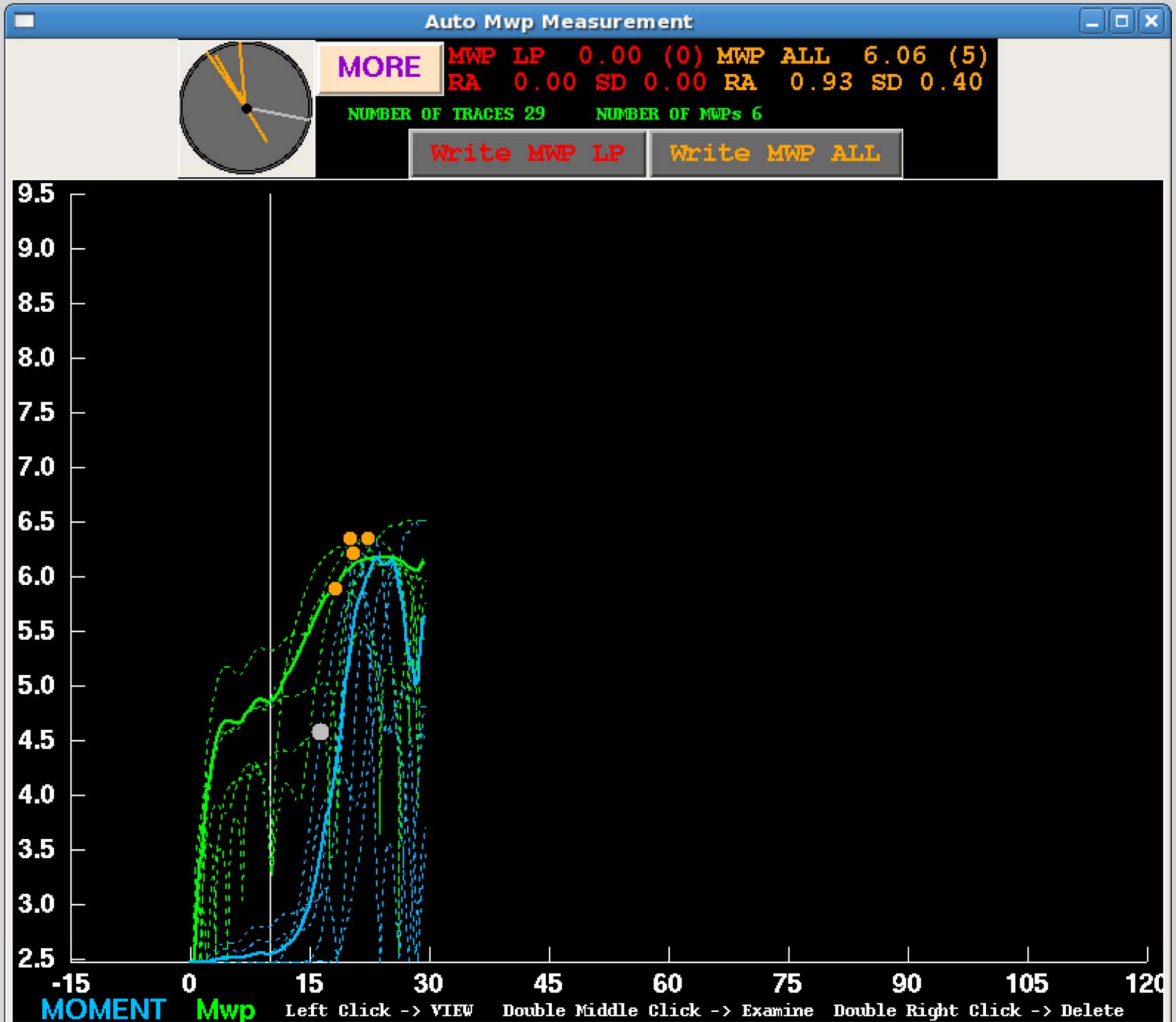
Example: Yesterday's Napa Earthquake



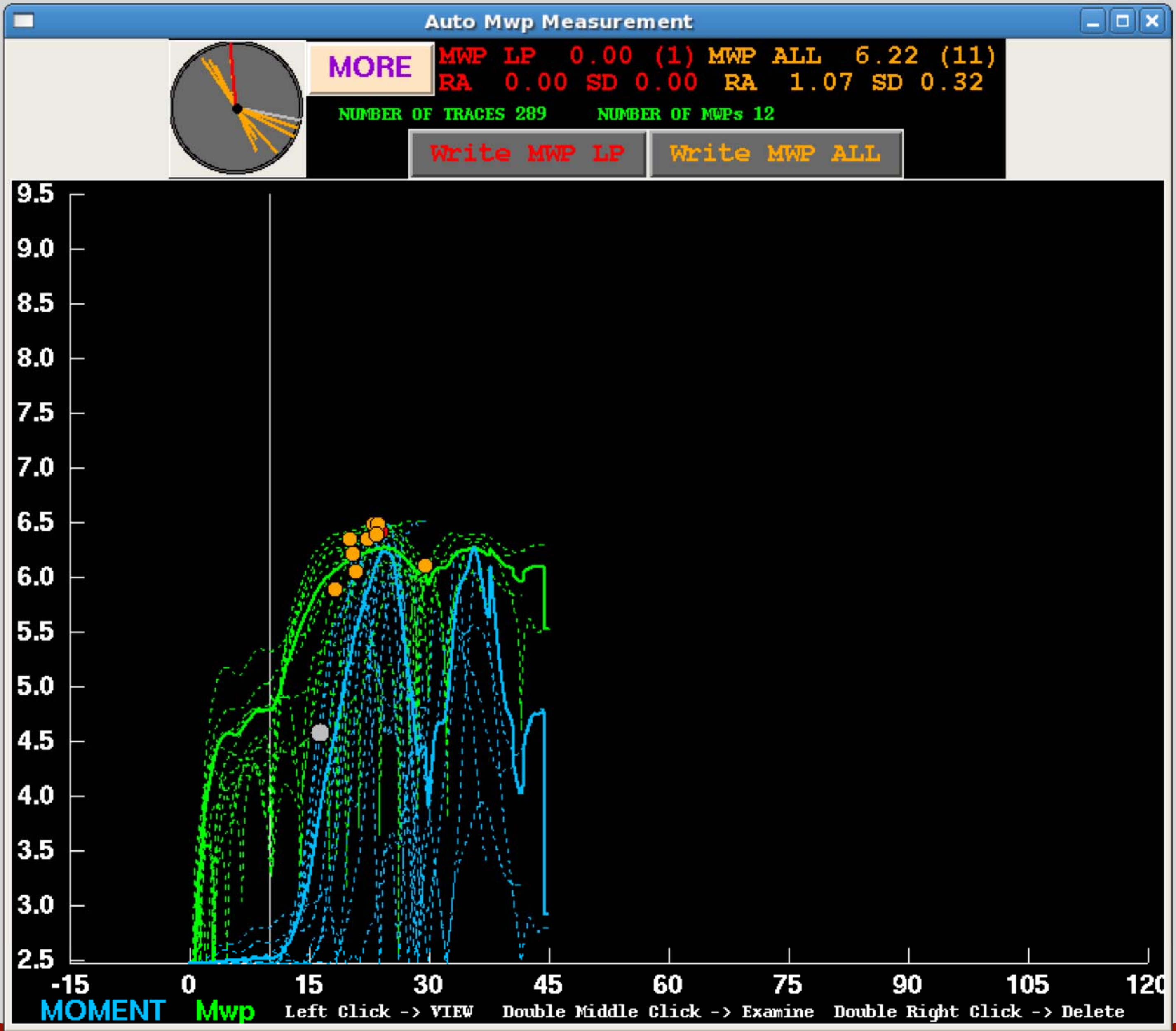
Example: Yesterday's Napa Earthquake



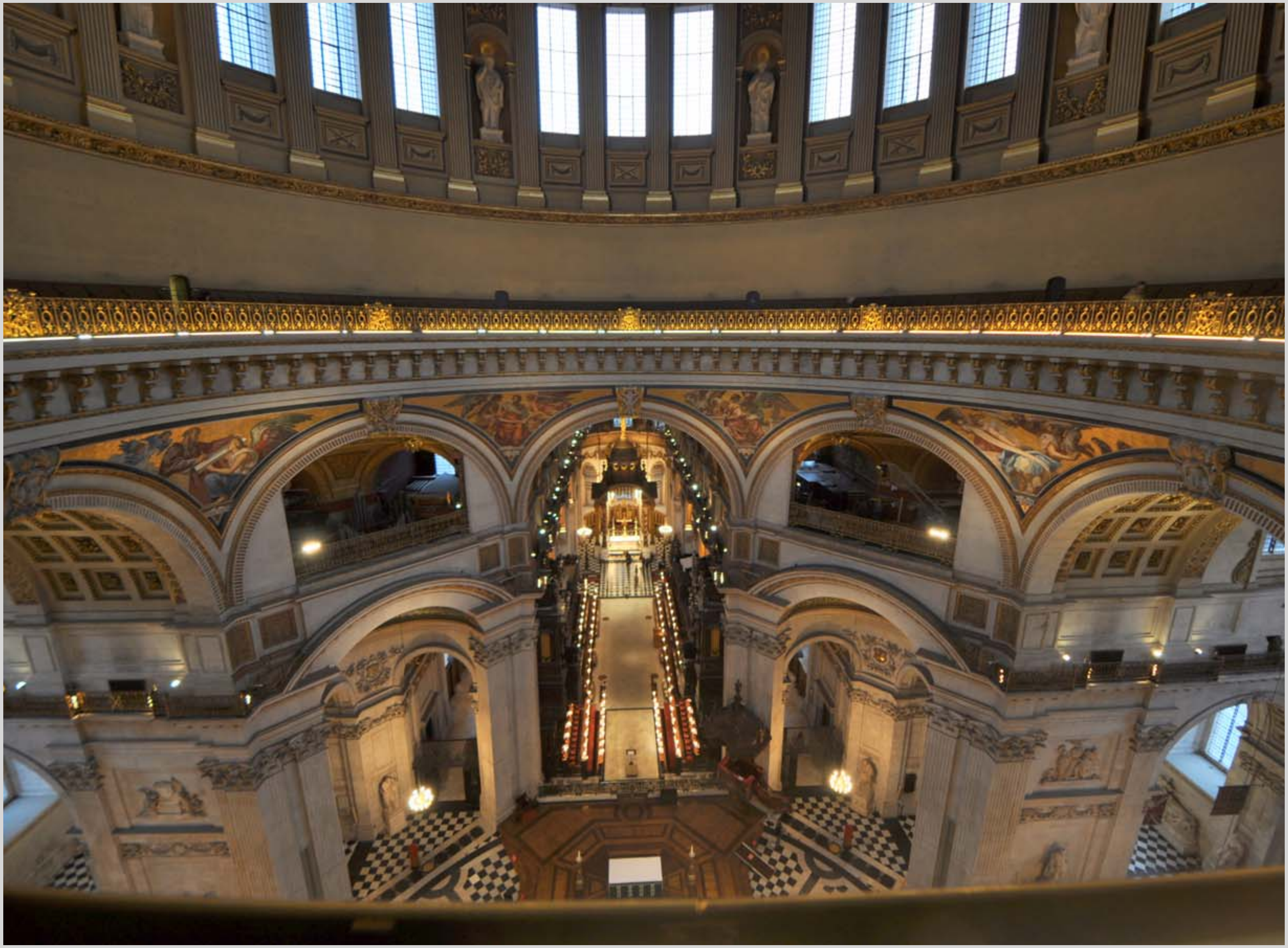
We usually let the M_{wp} alogorithm run automatically



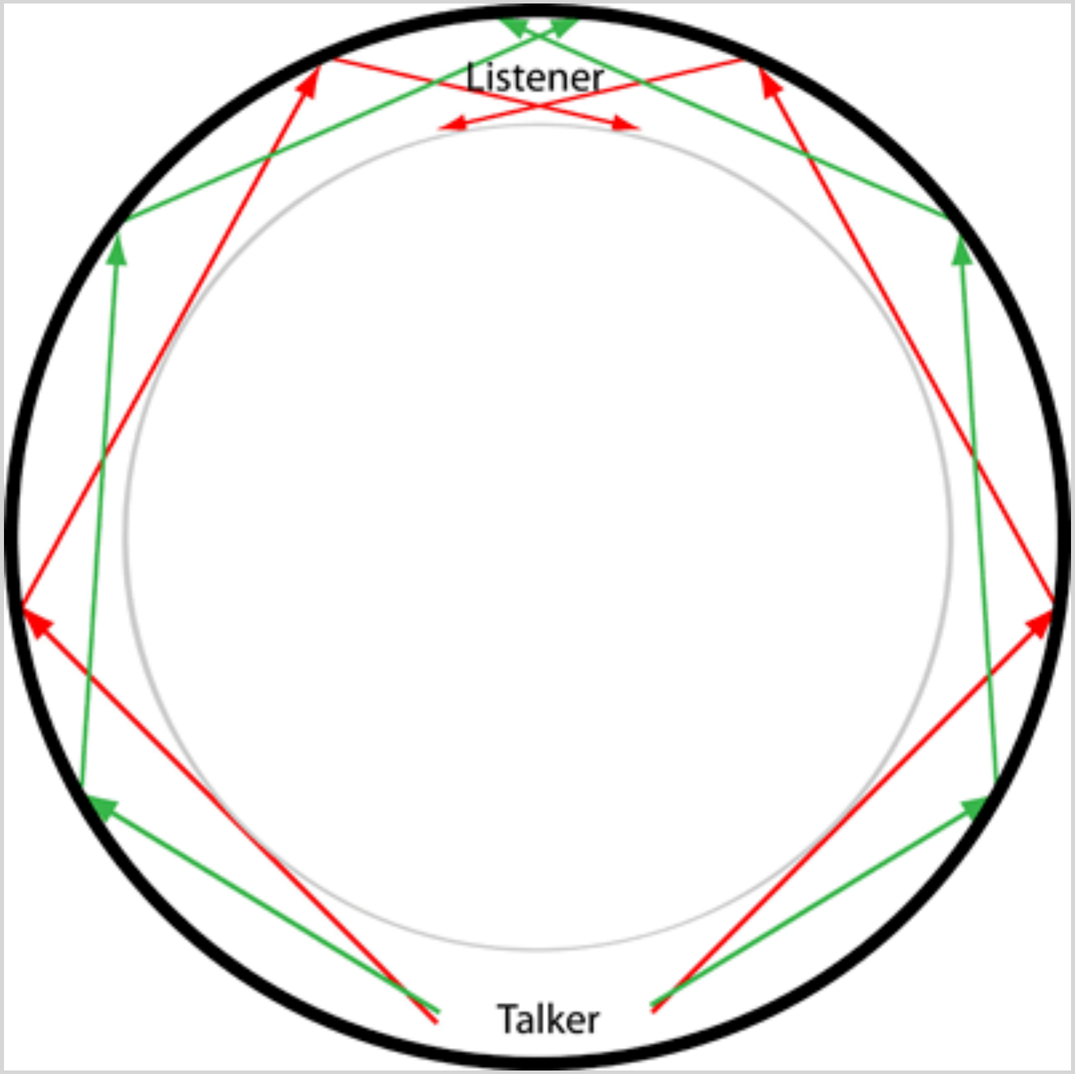
We usually let the M_{wp} alogorithm run automatically



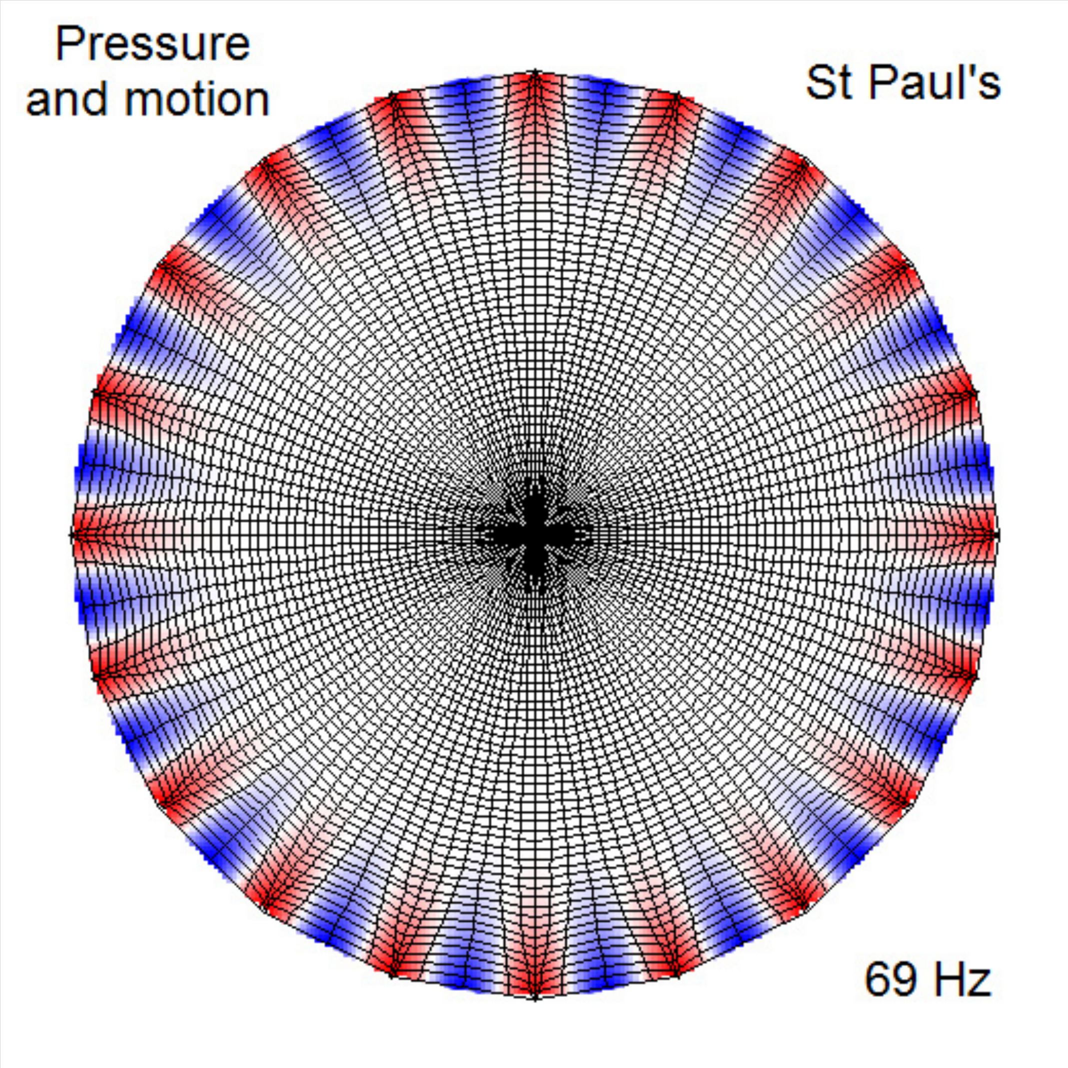
A diversion: whispering galleries



A diversion: whispering galleries

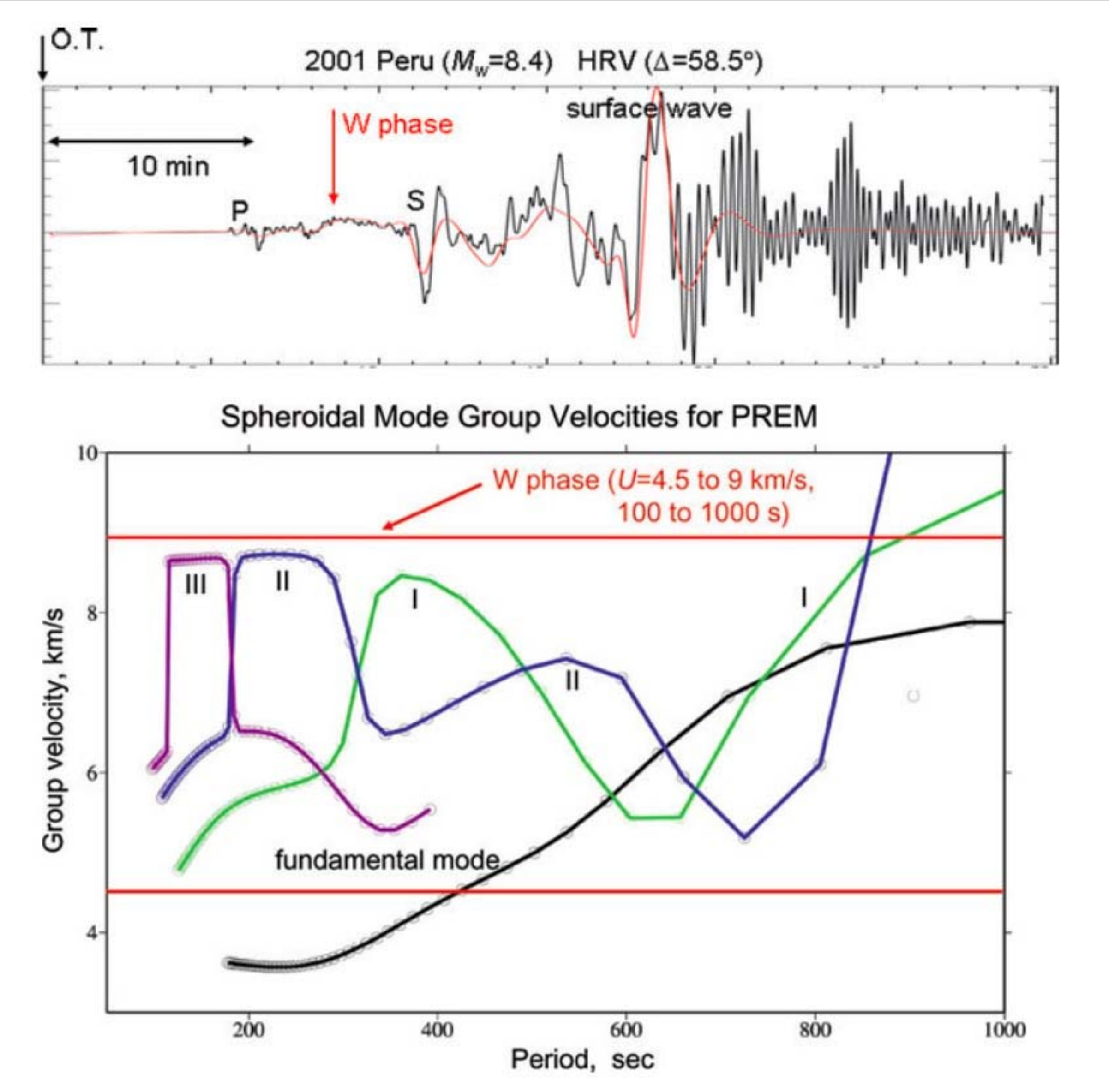


A diversion: whispering galleries

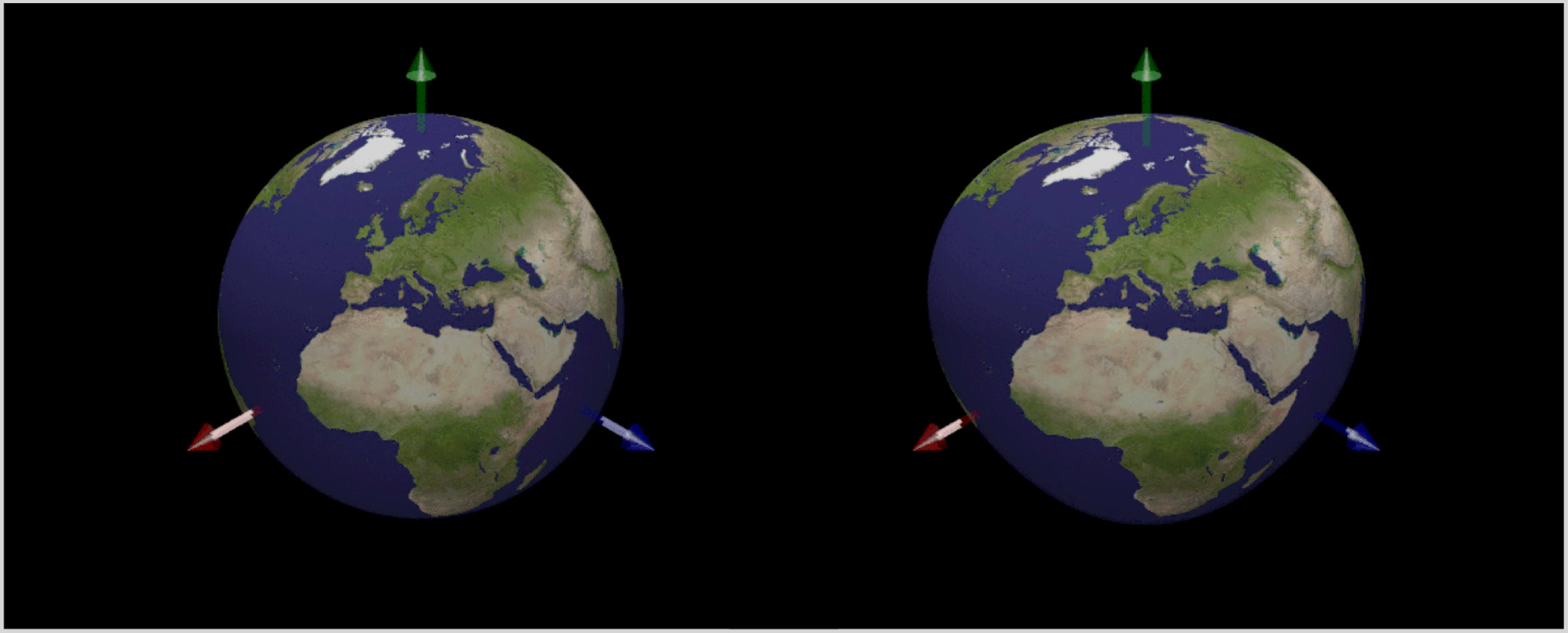


W-phase

- Ramplike long-period phase between *P* and *S* on displacement seismograms.
- Combination of *P*, *PP*, *PS*, *SP*, *PPP*, etc: whispering gallery phases.
- Combination of spheroidal modes.
- *W*-phase assessment of magnitude currently takes 25 min.



Spheroidal Normal Modes



$_0S_0$ $_0S_3$

W-phase

- Robust magnitude determination: the moment magnitude M_w from our automatic *W*-phase code is always correct to within 0.2.
- The algorithm works by solving for the Centroid Moment Tensor of the earthquake, so as a bonus, we get the earthquake mechanism.

Earthquake Focal Mechanisms

These describe the direction of slip in an earthquake & the orientation of the fault on which it occurs.

W-phase solutions from the last few days

```
Best Double Couple: M0=6.63E+25
dyn.cm Mw =  6.48
NP1: Strike=  7 ; Dip=20.3579 ;
Slip=101
NP2: Strike=176 ; Dip=70.0154 ;
Slip= 86

            ########-
        -----##########--
     --------############---
   ----------##############---
  -----------###############---
 -----------#################---
------------#################----
-------------########   #######----
---   -------######## T #######----
--- P -------########   #######----
---   --------#################----
--------------#################----
-------------################----
 ------------###############----
  ------------#############----
   -----------############----
     ----------#########----
        -------#######---
            ########-
```

```
Best Double Couple: M0=2.58E+26
dyn.cm Mw =  6.87
NP1: Strike=195 ; Dip=44.4631 ;
Slip=-68
NP2: Strike=346 ; Dip=49.4481 ;
Slip=-110

            ---------
        #################
     ##########--###########
   ##########-------##########
  #########----------##########
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T ######------------------#########
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        ###-----------###
            #-------#
```
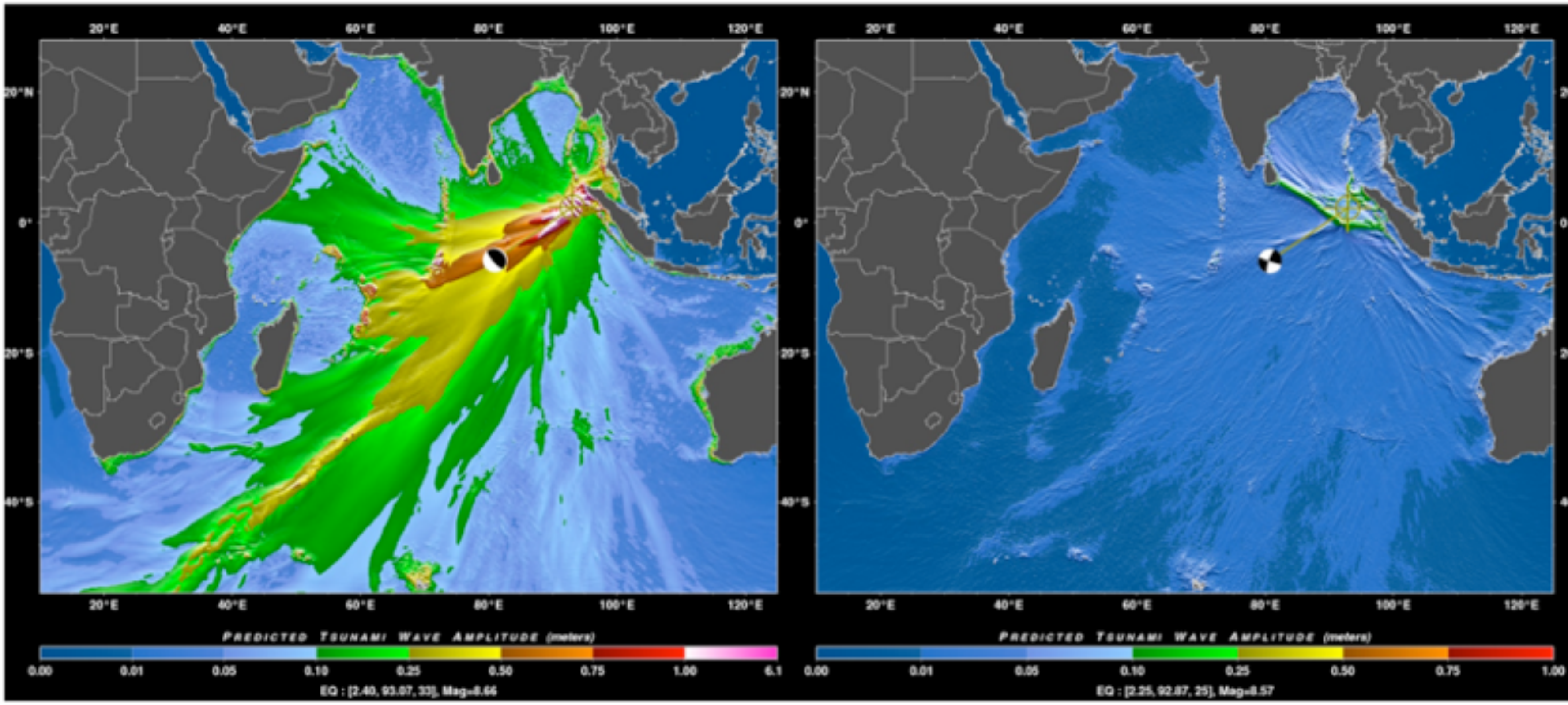

The mechanism matters

PTWC Real Time Forecast of Tsunamis (RIFT)

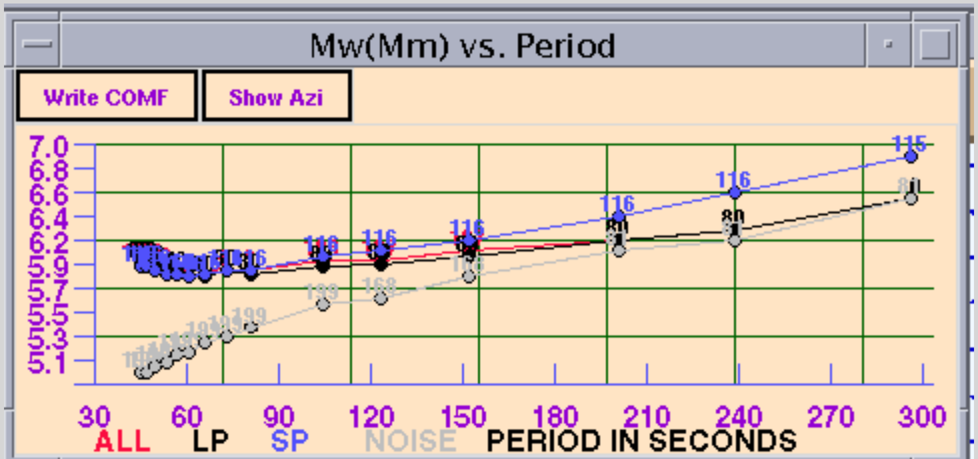


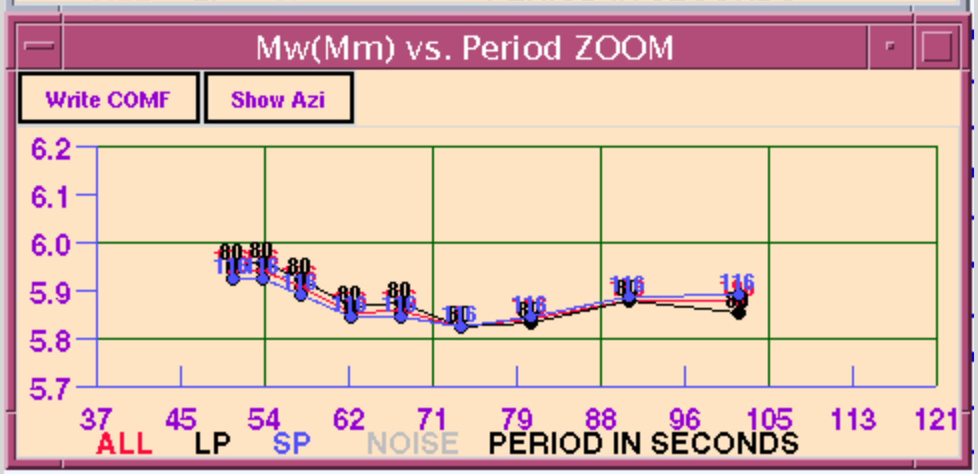
Based on shallow thrust assumption
Mwp=8.66 (initial PTWC Magnitude)

USGS (Gavin Hayes)
Wphase CMT: Mw=8.57 (Strike-slip)

The initial PTWC magnitude is larger than that of the USGS CMT magnitude, but the major difference between the two runs are focal mechanisms: thrust vs. strike-slip.

Mantle magnitude M_m
Largely supplanted by W-phase





Mantle Magnitude

EXIT 13:11:59 01/10

CTAO	DONE	------	6.37	6.85
RCBR	DONE	------	4.76	5.78
GUMO	DONE	------	6.09	6.66
WAKE	DONE	------	6.10	6.67
KAPI	TIME	NA	------	------
MBWA	GAP	NA	------	------
TAU	DONE	------	6.31	6.80
SNZO	DONE	------	4.39	5.53
TATO	DONE	------	6.04	6.62
MIDW	DONE	------	6.42	6.88
NWAO	DONE	------	5.88	6.52
MAJO	DONE	------	5.90	6.53
INCN	PEND	00:00	------	------
YSS	PEND	00:00	------	------
KIP	DONE	------	6.32	6.81
POHA	DONE	------	6.47	6.91
COCO	PEND	00:00	------	------
BJT	PEND	00:00	------	------
PET	DONE	------	6.19	6.73
SMY	PEND	00:00	------	------
HIA	PEND	00:00	------	------
ADK	DONE	------	6.31	6.81
MA2	DONE	------	6.05	6.63
ULN	DONE	------	6.04	6.63
UNV	DONE	------	6.99	7.26
YAK	PEND	00:00	------	------
TLY	DONE	------	6.24	6.76
CCM	DONE	------	6.07	6.64
VNDA	PEND	00:00	------	------
SBA	DONE	------	6.10	6.67

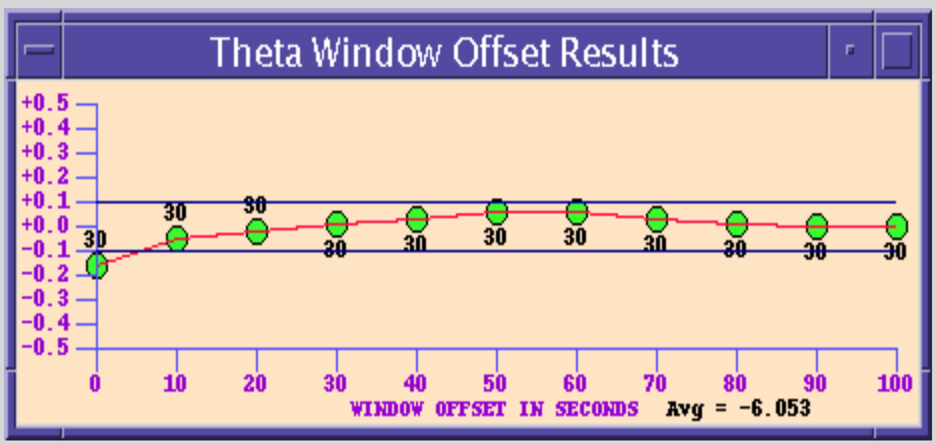
SLEEPING 08 | Mean Mm is: 6.12(24) Mw is: 6.68 | PRINT

SLOW EARTHQUAKES

Theta = $\log_{10}$ (Er / M_o)

E_r is energy carried by high frequency P-waves and Mo is seismic Moment.

Ratio of energy contained by high frequency P-waves to energy released by EQ.



Slow, or tsunami earthquake!

Energy Discriminant

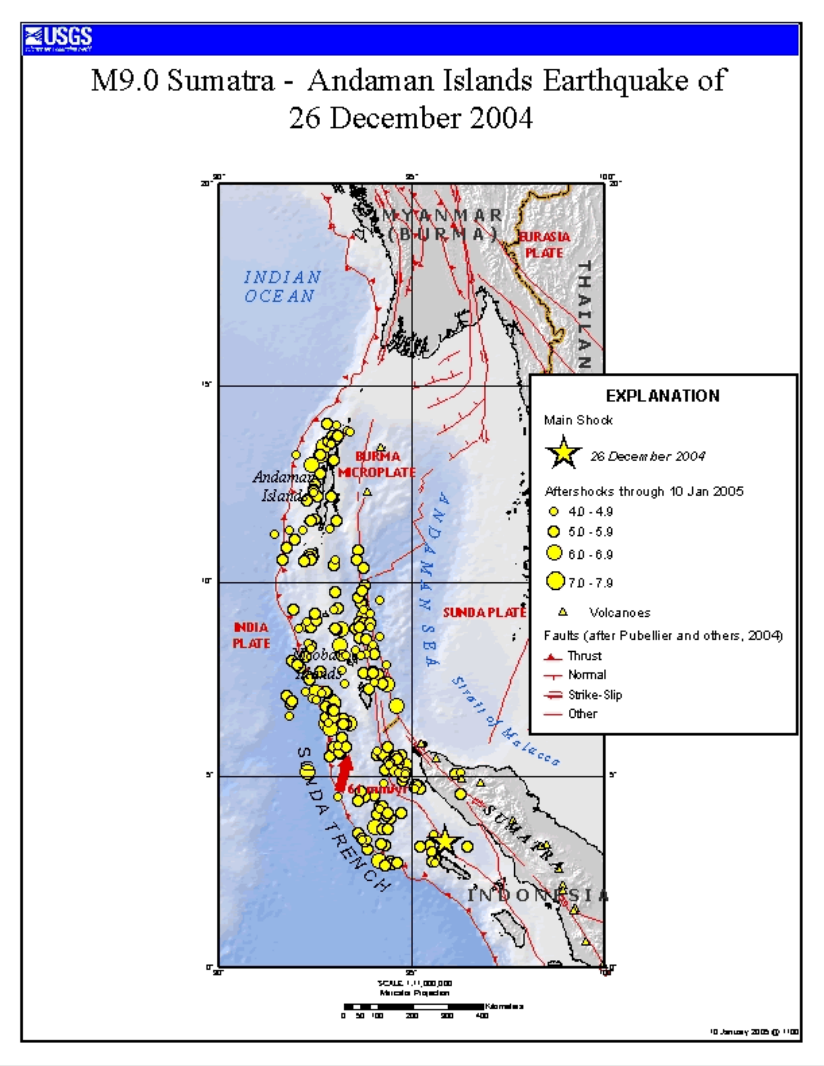
EXIT 01:05:19 09/02 Mw: 7.20

STA	STATUS	ETA	THETA
HIA	PEND	00:00	-----
KDAK	DONE	-----	-6.23
YAK	DONE	-----	-5.32
ULN	DONE	-----	-5.37
TNA	DONE	-----	-6.37
BILL	PEND	00:00	-----
RPN	PEND	00:00	-----
PMR	DONE	-----	-5.81
EYAK	DONE	-----	-5.86
DIV	PEND	00:00	-----
MCK	DONE	-----	-5.86
LSA	PEND	00:00	-----
JCC	DONE	-----	-5.94
SAO	DONE	-----	-6.06
SIT	DONE	-----	-6.14
COLA	DONE	-----	-5.74
SNCC	PEND	00:00	-----
PKD	DONE	-----	-6.03
CRAG	DONE	-----	-6.06
WDC	DONE	-----	-6.00
YBH	DONE	-----	-6.10
ORV	DONE	-----	-6.30
CMB	DONE	-----	-6.18
OSI	PEND	00:00	-----
COR	DONE	-----	-5.94
PAF	GAP	NA	-----
SKAG	DONE	-----	-6.09
PAS	PEND	00:00	-----
KCC	DONE	-----	REM
ISA	PEND	00:00	-----

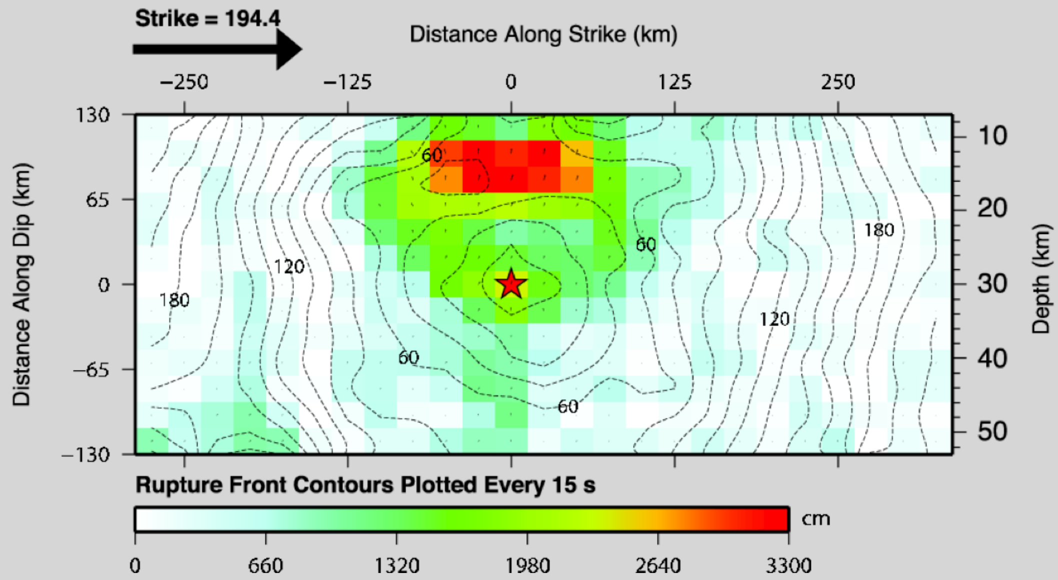
FINISHED | Mean Theta is: –5.83(43) | PRINT

Weaknesses we know about

- Where did the earthquake go? We can deduce epicenter and magnitude in a few minutes, but what happened to the rupture? Fortunately, all post-2004 great earthquakes have had bilateral rupture.
- Fault extent. We need a rapid finite fault procedure (i.e, a description of how rupture is distributed over the fault plane).
- We are not really equipped to handle non-earthquake sources.



Our seismological future



- Fast (crude) finite fault analysis.
- Faster *W*-phase and other automatic techniques (Rivera, Kanamori, Duputel, Lomax, etc.)
- High-rate GPS for rapid source determination.
- We should be able to get M_w and mechanism within 10 minutes.

Mahalo