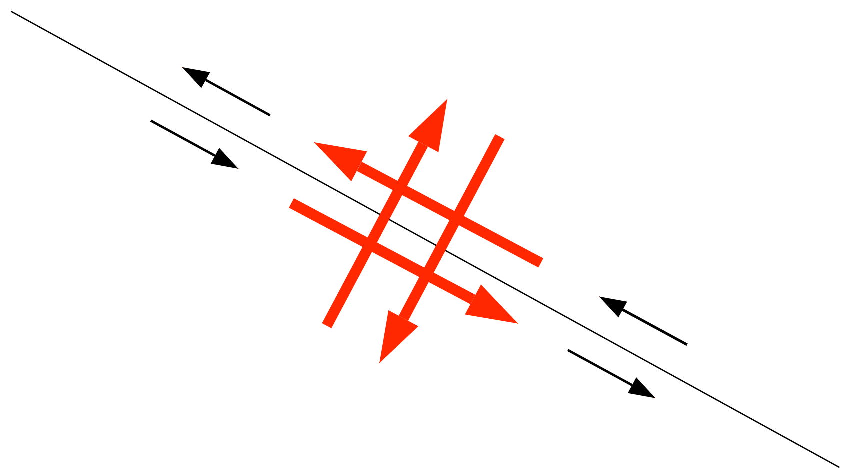
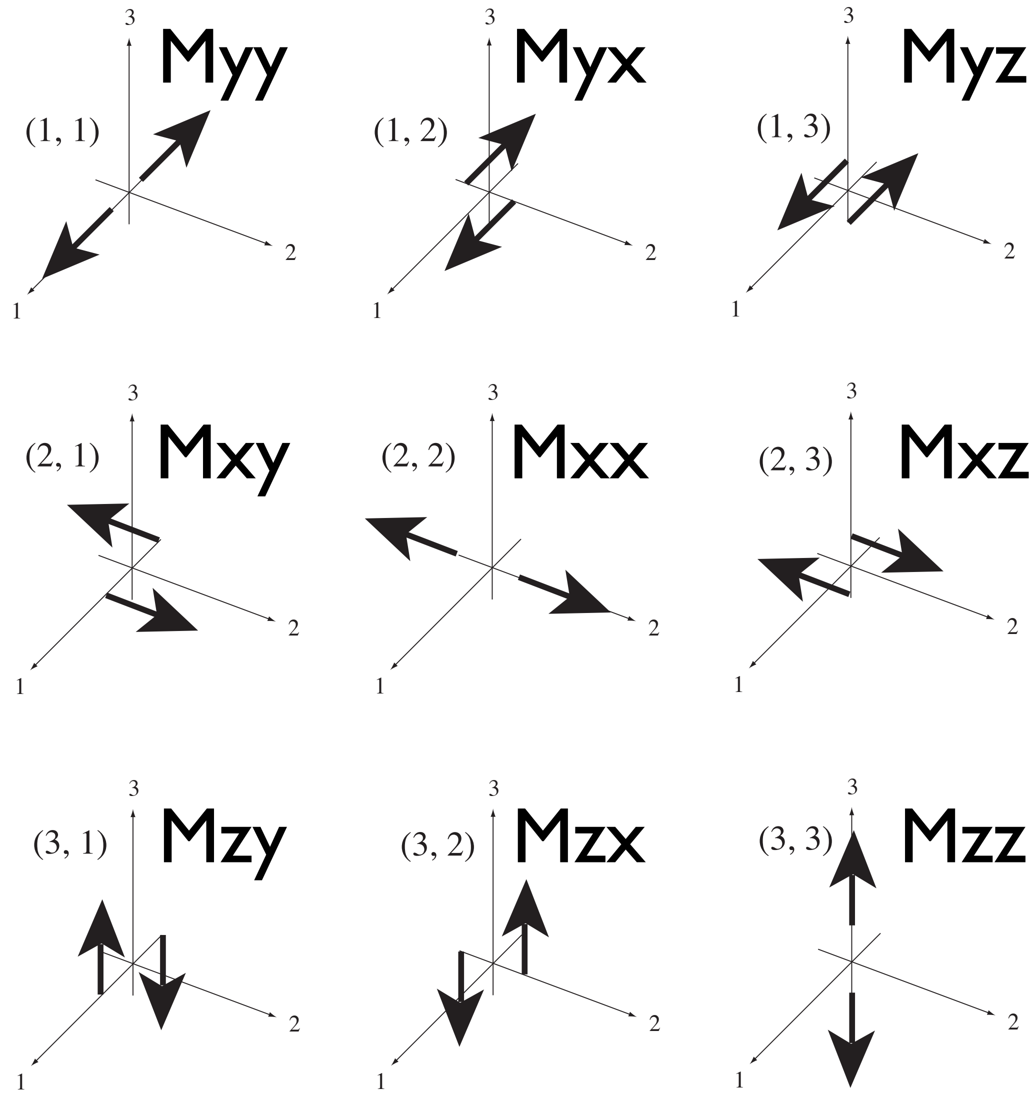
1. Moment-tensor analysis using global data
2. The Global CMT catalog
3. Using calibration information in waveform analysis
4. Data quality control using signals
5. Data quality control using noise
6. Finding interesting things in the noise
7. ~~Using noise for tomography~~

Faulting force model



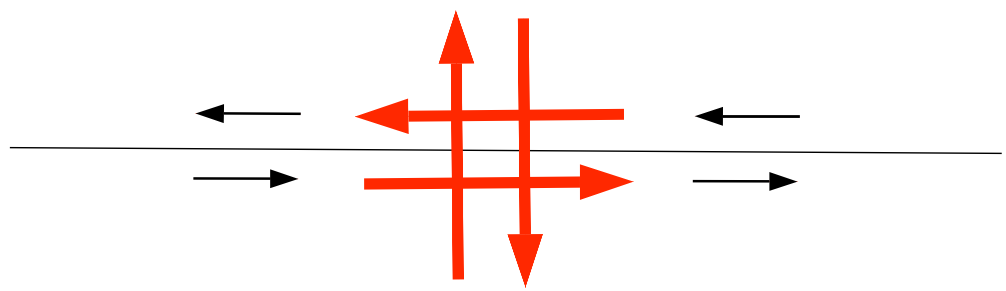
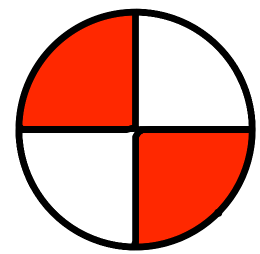
The elastic stress release in an earthquake is described by a double couple of forces

The nine dipoles of the seismic moment tensor



(Aki and Richards, 2002)

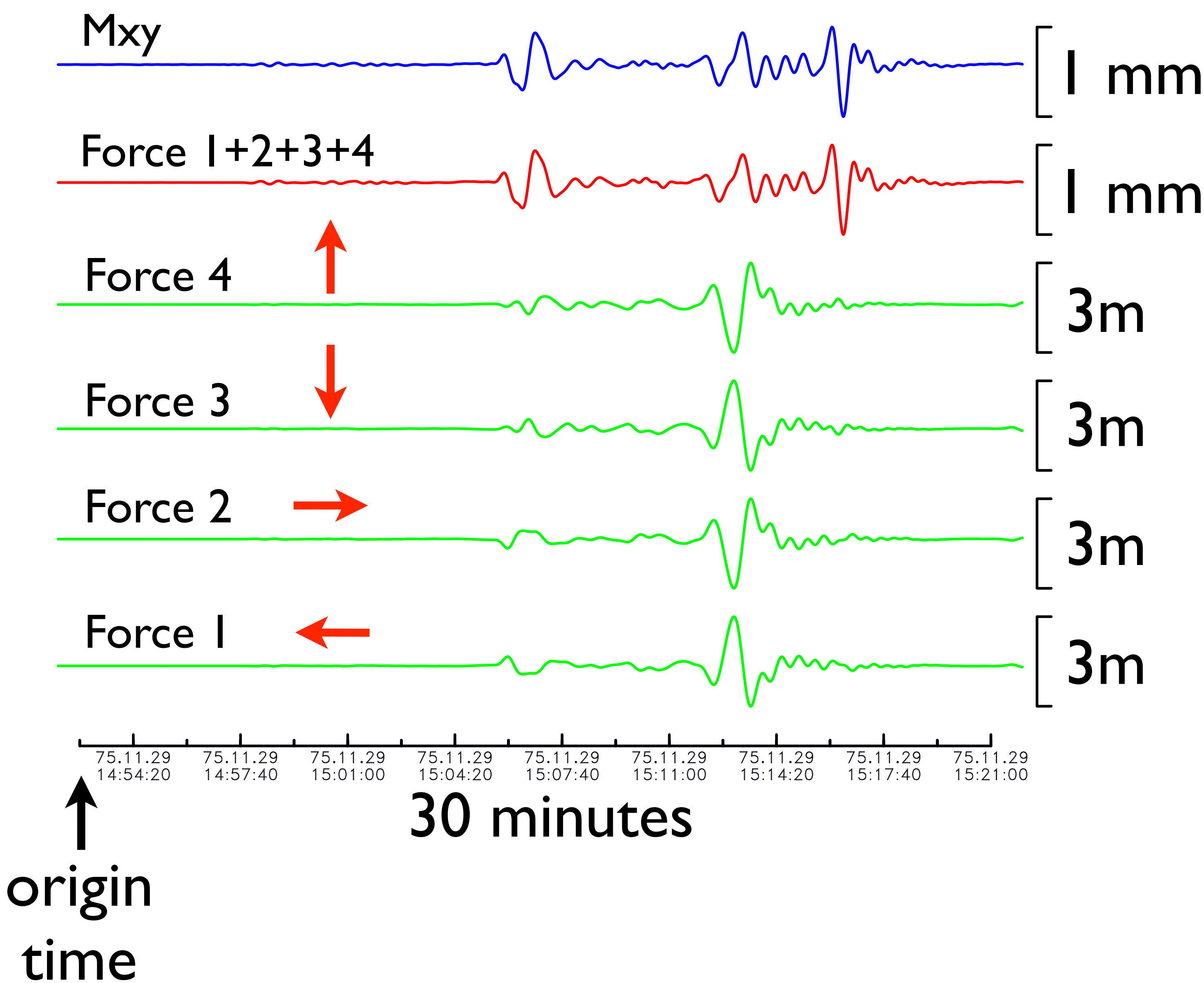
But, $M_{xy}=M_{yx}$, $M_{yz}=M_{zy}$, $M_{xz}=M_{zx}$

M_{xy} =  = 

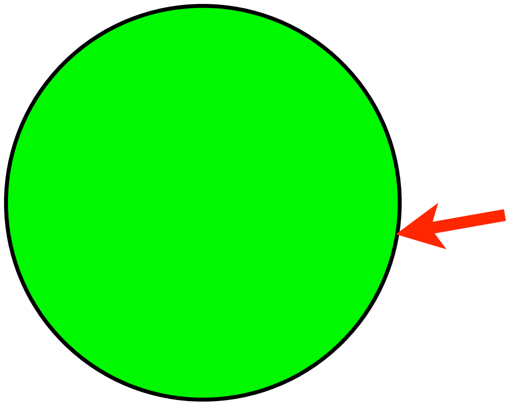
for example,

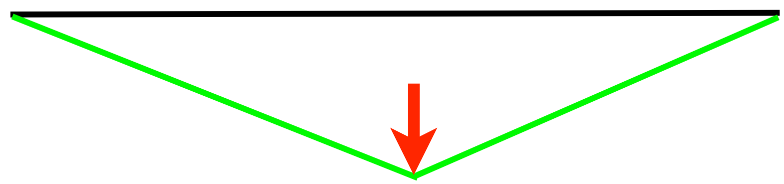
10^{28} dyne-cm = 10^{24} dyne x 10000 cm

Calculated force seismograms (6000 km distance)



The vibrations caused by a force acting on or in the Earth can be modeled by summation of Earth's normal modes





$$u(\boldsymbol{x}, t) = \sum_k \left[1 - \exp\left[-\alpha_k (t - t_s)\right] \cos \omega_k (t - t_s)\right] \boldsymbol{f} \cdot \boldsymbol{w}^{(k)}(\boldsymbol{x}_s) \boldsymbol{s}_k(\boldsymbol{x})$$

where $\boldsymbol{f}$ is the force vector and $\boldsymbol{w}^k$ is the displacement of the k-*th* mode.

Moment-tensor analysis by waveform fitting

(Observed seismogram)/(Instrument response) x Filter = Observed waveform

(Synthetic displacement seismogram) x Filter = Model waveform

Model waveform depends on:
1. Earthquake parameters
2. Earth structure

If the Earth structure and the earthquake location are known, the

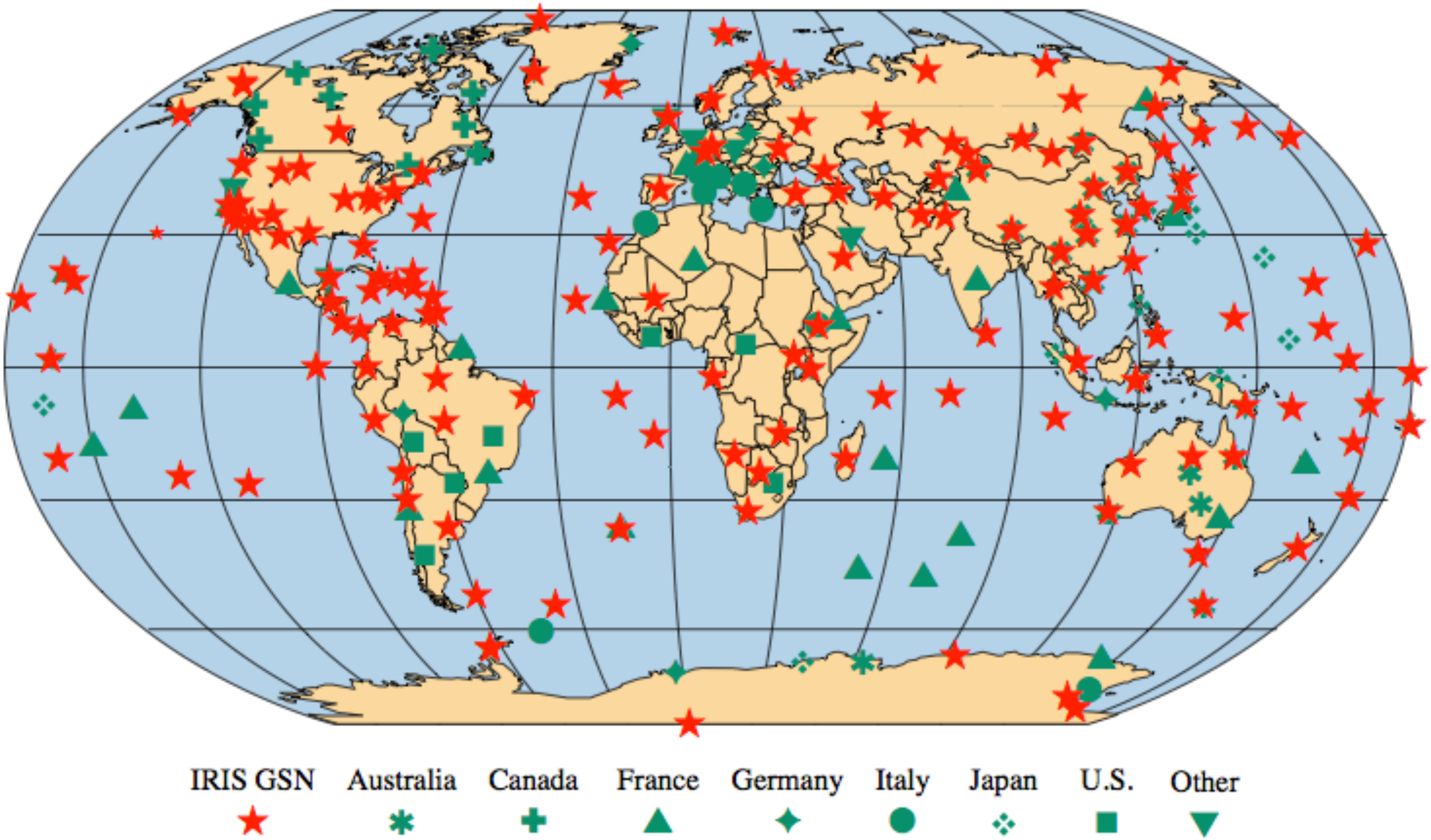
Model waveform depends only on the six elements of the moment tensor,

M_{xx}, M_{yy}, M_{zz}, M_{xy}, M_{xz}, and M_{yz}

Minimize the difference [Observed waveform - Model waveform]^2

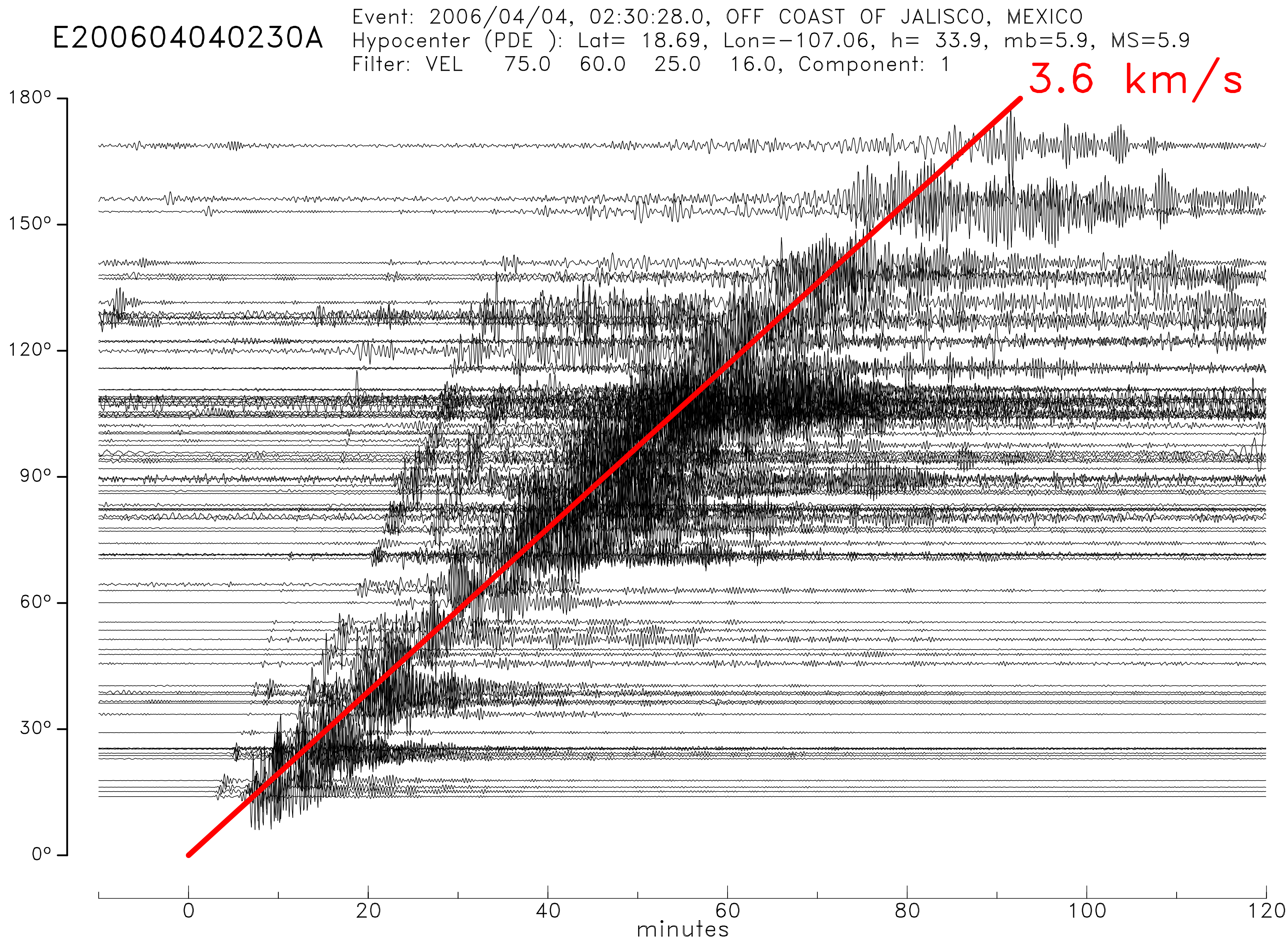
with respect to the moment tensor elements.

International Federation of Digital Seismograph Networks



STS-1 Seismometer
at Harvard, Mass.

Global network record section for an earthquake off the coast of Jalisco, Mexico



Moment-tensor analysis by waveform fitting

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M_{xx}, M_{yy}, M_{zz}, M_{xy}, M_{xz}, and M_{yz}

Minimize the difference $[\text{Observed waveform} - \text{Model waveform}]^2$

with respect to the moment tensor elements.

Seismogram Modeling

The k-*th* seismogram in a data set for a given earthquake can be represented by:

$$u_k(\boldsymbol{r}, t) = \sum_{i=1}^{N} \psi_{ik}(\boldsymbol{r}_0, \boldsymbol{r}, t) f_i$$

where ψ_{ik} are the excitation kernels and f_i are independent parameters of the source model.

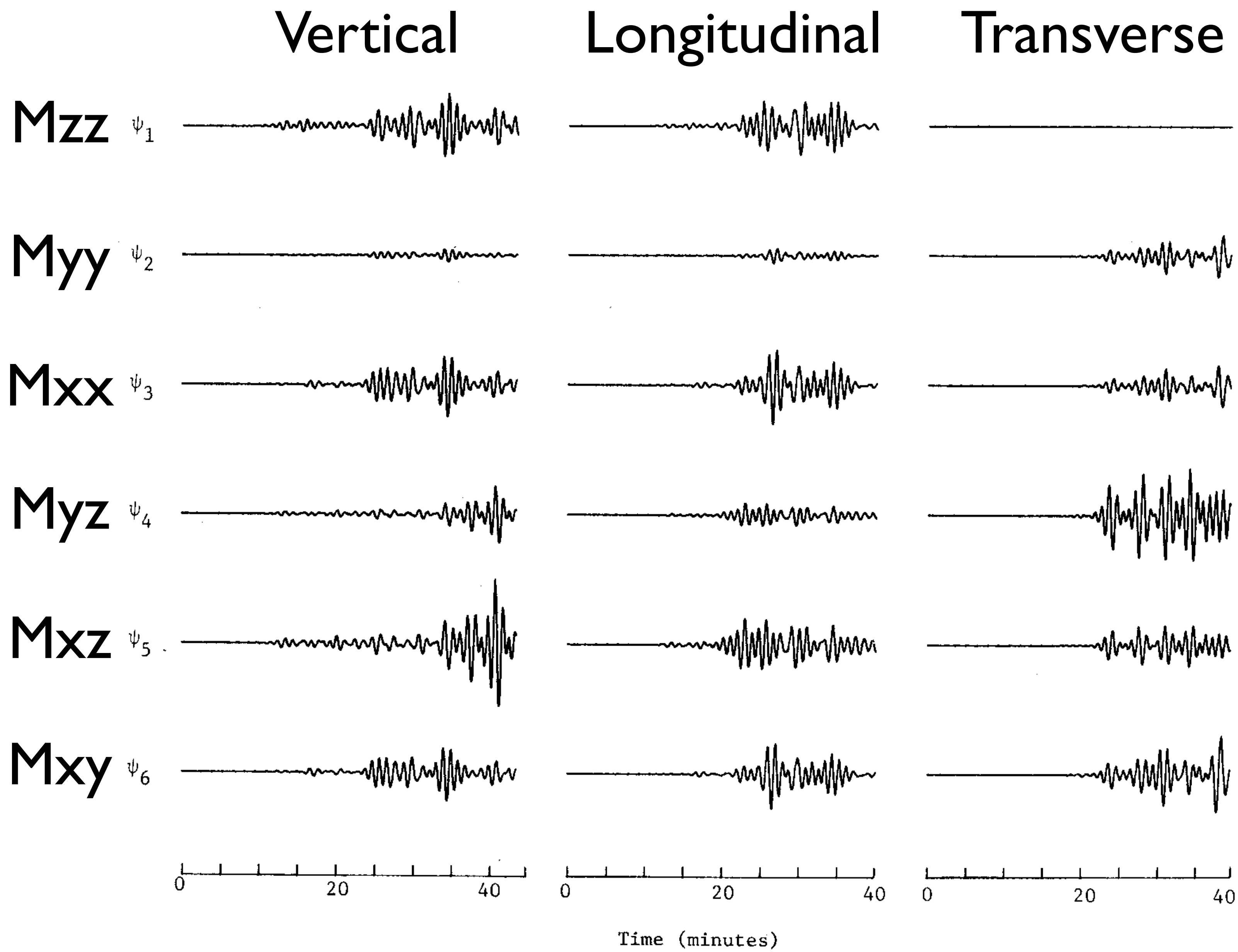
f_1 = Mzz, f_2 =Myy, etc.; N=6

Seismogram Synthesis for a Moment-Tensor Source

The seismic displacement field can be calculated by superposition of the normal modes of the Earth (Gilbert, 1971):

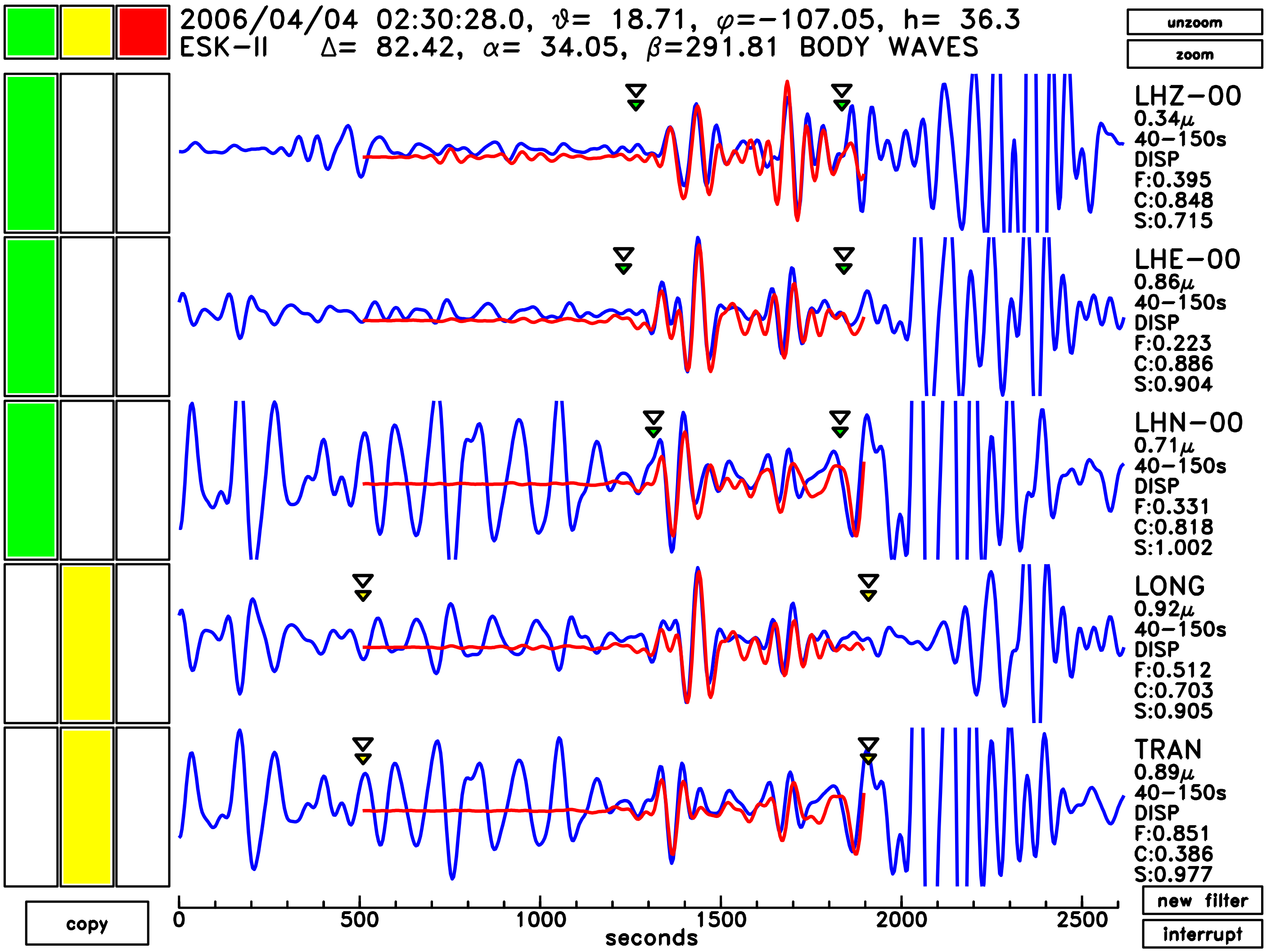
$$u(\boldsymbol{x}, t) = \sum_k \left[1 - \exp\left[-\alpha_k (t - t_s)\right] \cos \omega_k (t - t_s)\right] \boldsymbol{M} : \boldsymbol{e}^{(k)}(\boldsymbol{x}_s) \boldsymbol{s}_k(\boldsymbol{x})$$

where α_k is the decay constant of and $\boldsymbol{e}^k$ is the strain tensor in the k-*th* mode; $\boldsymbol{s}_k$ is the eigenfunction of the k-*th* mode; and $\boldsymbol{M}$ is the seismic moment tensor.



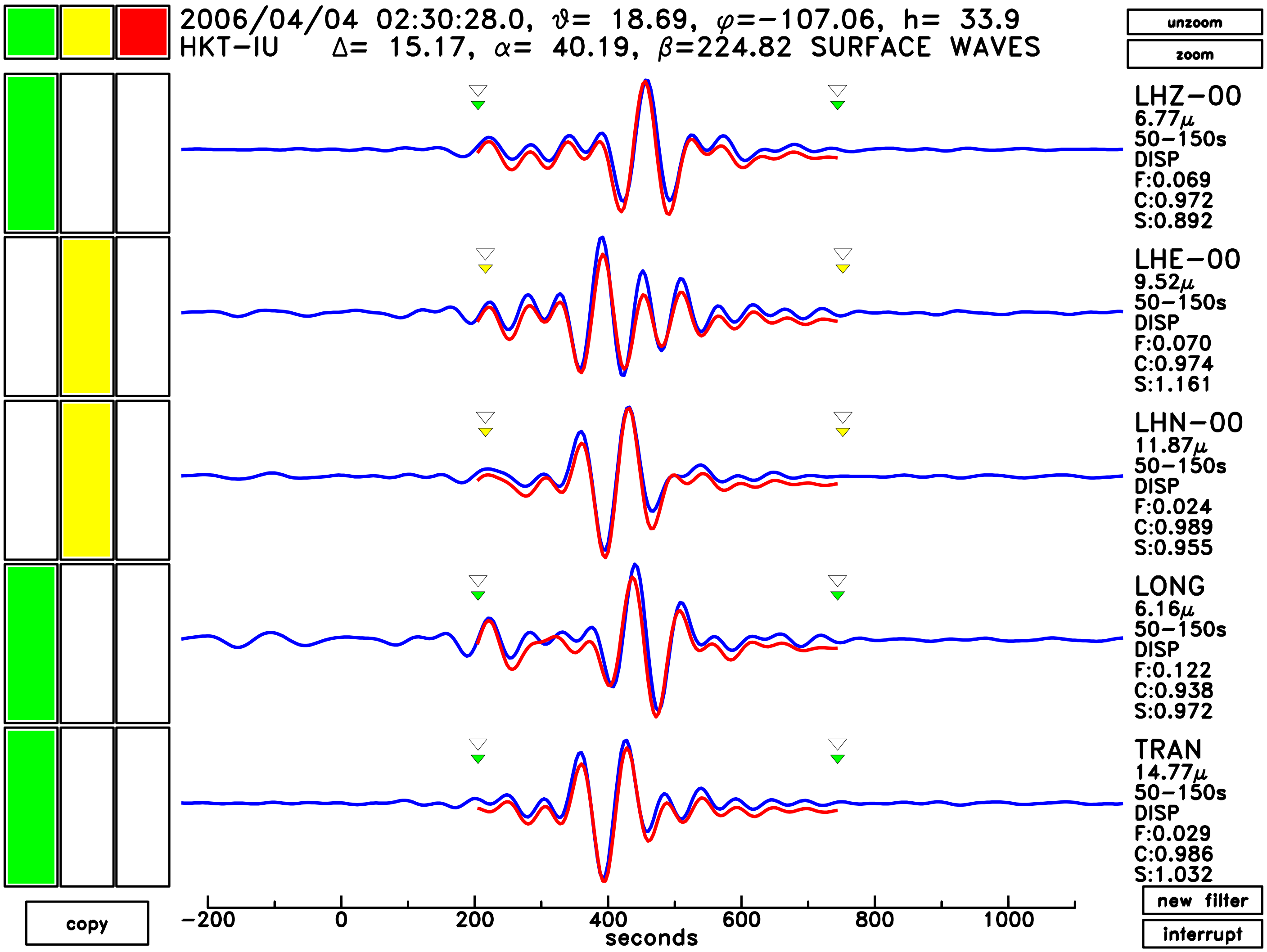
Excitation kernels for deep earthquake (580 km)

Fit to seismograms:
Body waves at Eskdalemuir, Scotland



blue - data ; red - model

Fit to seismograms: Surface waves at Hockley, Texas



blue - data ; red - model

Estimation of the Source Parameters

For a point source, the elements f_i can be estimated by solving $\mathbf{A} \cdot \mathbf{f} = \mathbf{b}$, where:

$$A_{ij} = \sum_k \int_{t_{k_1}}^{t_{k_2}} \psi_{ik} \psi_{jk} dt \; ; \; b_j = \sum_k \int_{t_{k_1}}^{t_{k_2}} u_k \psi_{jk} dt.$$

This procedure requires that the position of the source $(\boldsymbol{r}_0, t_0)$ be known.

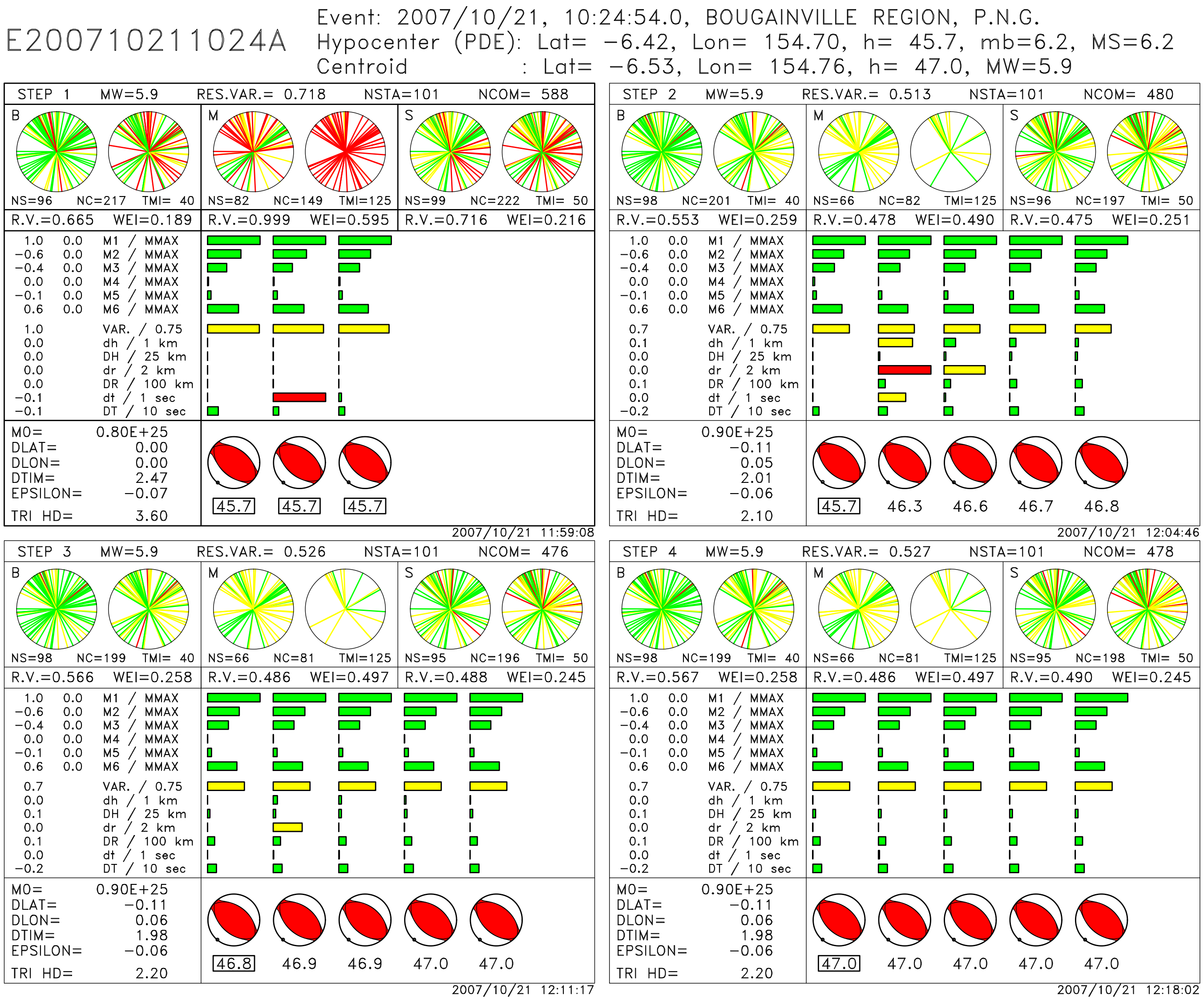
Solution for the Source Centroid

The earthquake centroid can be determined simultaneously with the source model parameters by expansion of the equations of condition to allow for a perturbation in the location of the source (Dziewonski, Chou and Woodhouse, 1981):

$$u_k = u_k^{(0)} + \{\psi_{ki,j}^{(0)} \cdot \delta x_j - \psi_{ki,t}^{(0)} \cdot \delta t_0\} \cdot f_i^{(0)} + \psi_{ki}^{(0)} \cdot \delta f_i \;;$$

where the superscript (0) indicates parameters determined for the starting location. The problem can then be solved iteratively.

Iterative procedure for moment-tensor source converges nicely



From: Global CMT <gcmt@ldeo.columbia.edu>
Subject: quick CMT: 2014/07/29, 10:46:15.2, OAXACA, MEXICO, MW=6.4
Date: July 29, 2014 10:23:07 AM EDT
To: cmtcustomers@ldeo.columbia.edu

Here is the solution for the recent event.

July 29, 2014, OAXACA, MEXICO, MW=6.4

Howard Koss

```
CENTROID-MOMENT-TENSOR  SOLUTION
GCMT EVENT:     C201407291046A
DATA: II LD IU G  DK CU MN IC GE
KP
L.P.BODY WAVES:140S, 350C, T= 40
MANTLE WAVES:  110S, 184C, T=125
SURFACE WAVES: 135S, 342C, T= 50
TIMESTAMP:      Q-20140729095630
CENTROID LOCATION:
ORIGIN TIME:      10:46:20.1 0.1
LAT:17.97N 0.01;LON: 95.66W 0.01
DEP:104.6  0.4;TRIANG HDUR:  3.8
MOMENT TENSOR: SCALE 10**25 D-CM
RR=-4.160 0.026; TT= 1.130 0.028
PP= 3.040 0.031; RT= 1.050 0.022
RP=-1.440 0.024; TP=-2.580 0.028
PRINCIPAL AXES:
1.(T) VAL=  5.176;PLG=11;AZM= 55
2.(N)      -0.666;     1;    325
3.(P)      -4.500;    79;    232
BEST DBLE.COUPLE:M0= 4.84*10**25
NP1: STRIKE=146;DIP=34;SLIP= -89
NP2: STRIKE=325;DIP=56;SLIP= -91

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

Quick CMT solution derived from real-time data from the GSN

Oaxaca
July 29, 2014
M=6.4

2. The Global CMT catalog

3. Using calibration information in waveform analysis

4. Data quality control using signals

5. Data quality control using noise

6. Finding interesting things in the noise

7. Using noise for tomography

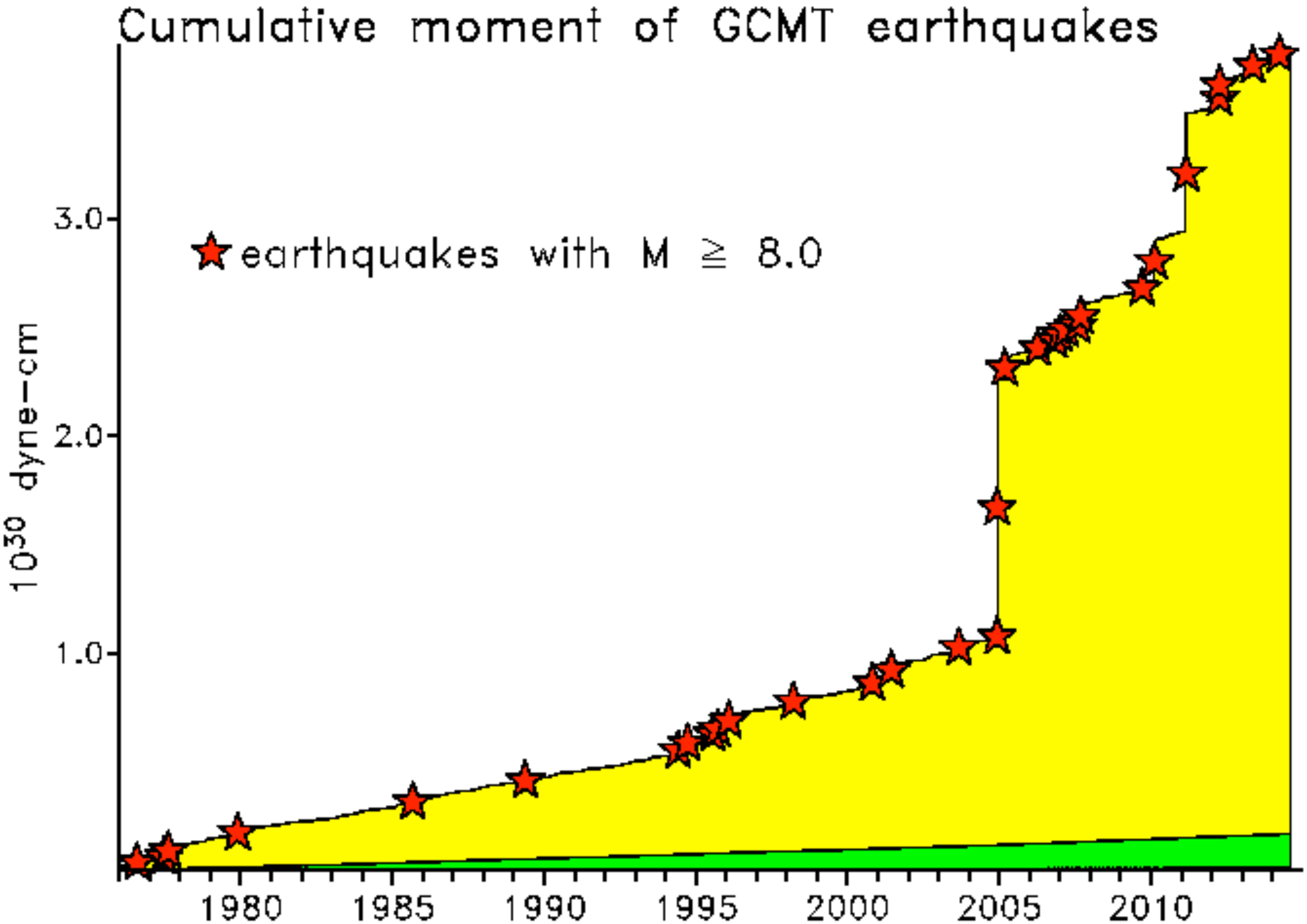
The Global CMT Project

Project started in 1981 (A.M. Dziewonski et al.)

Goal is now to determine source parameters for all earthquakes with M>5 worldwide

CMT catalog contains ~41,000 moment tensors for the period 1976-2014

In 2006 the project moved from Harvard University to Lamont-Doherty Earth Observatory at Columbia University



Cumulative moment of GCMT earthquakes
earthquakes with M ≧ 8.0
10^30 dyne-cm
1.0
2.0
3.0
1980
1985
1990
1995
2000
2005
2010

The CMT catalog can be accessed at
www.globalcmt.org

To receive Quick CMT solutions by email,
send me an email at
ekstrom@ldeo.columbia.edu

3. Using calibration information in waveform analysis

4. Data quality control using signals

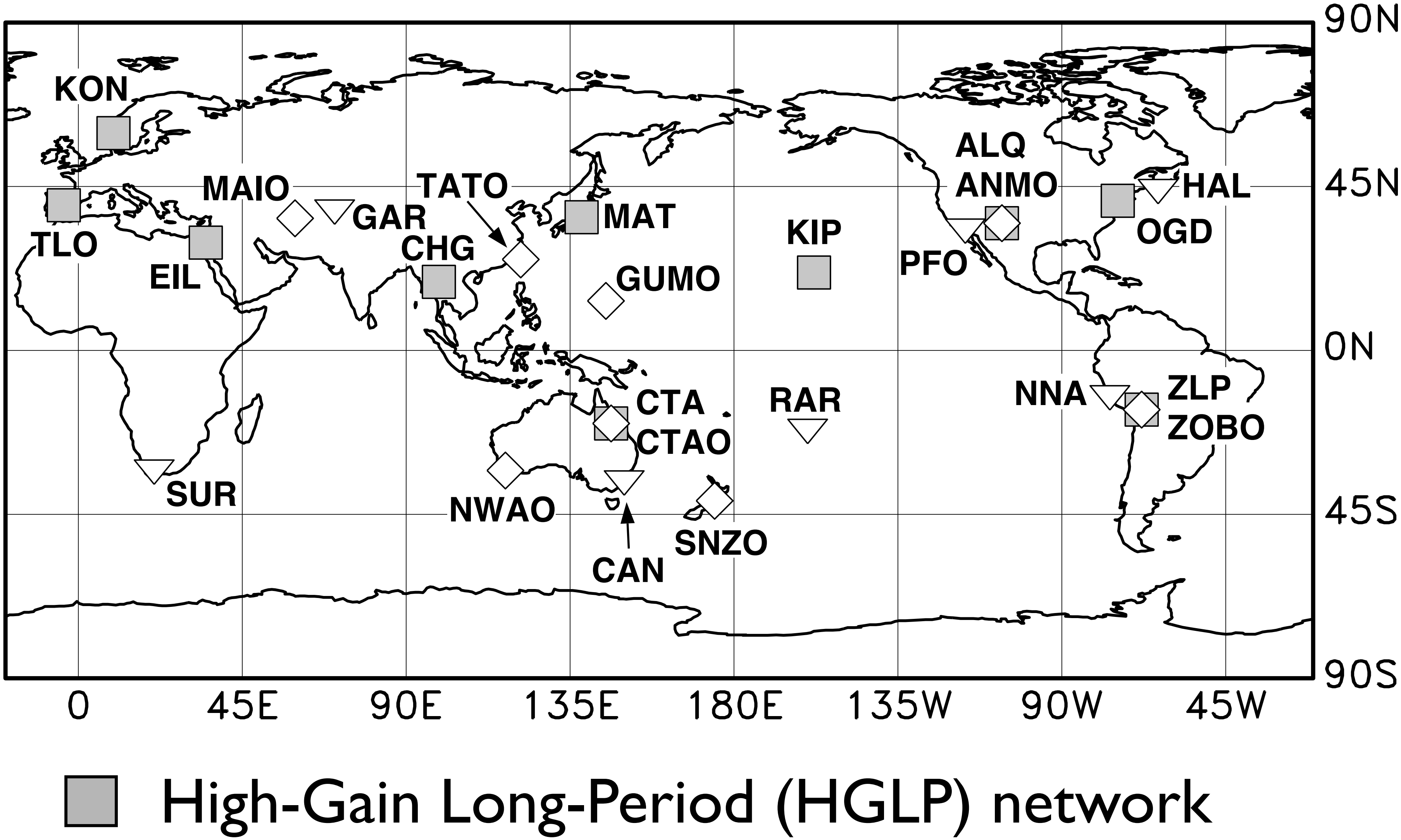
5. Data quality control using noise

6. Finding interesting things in the noise

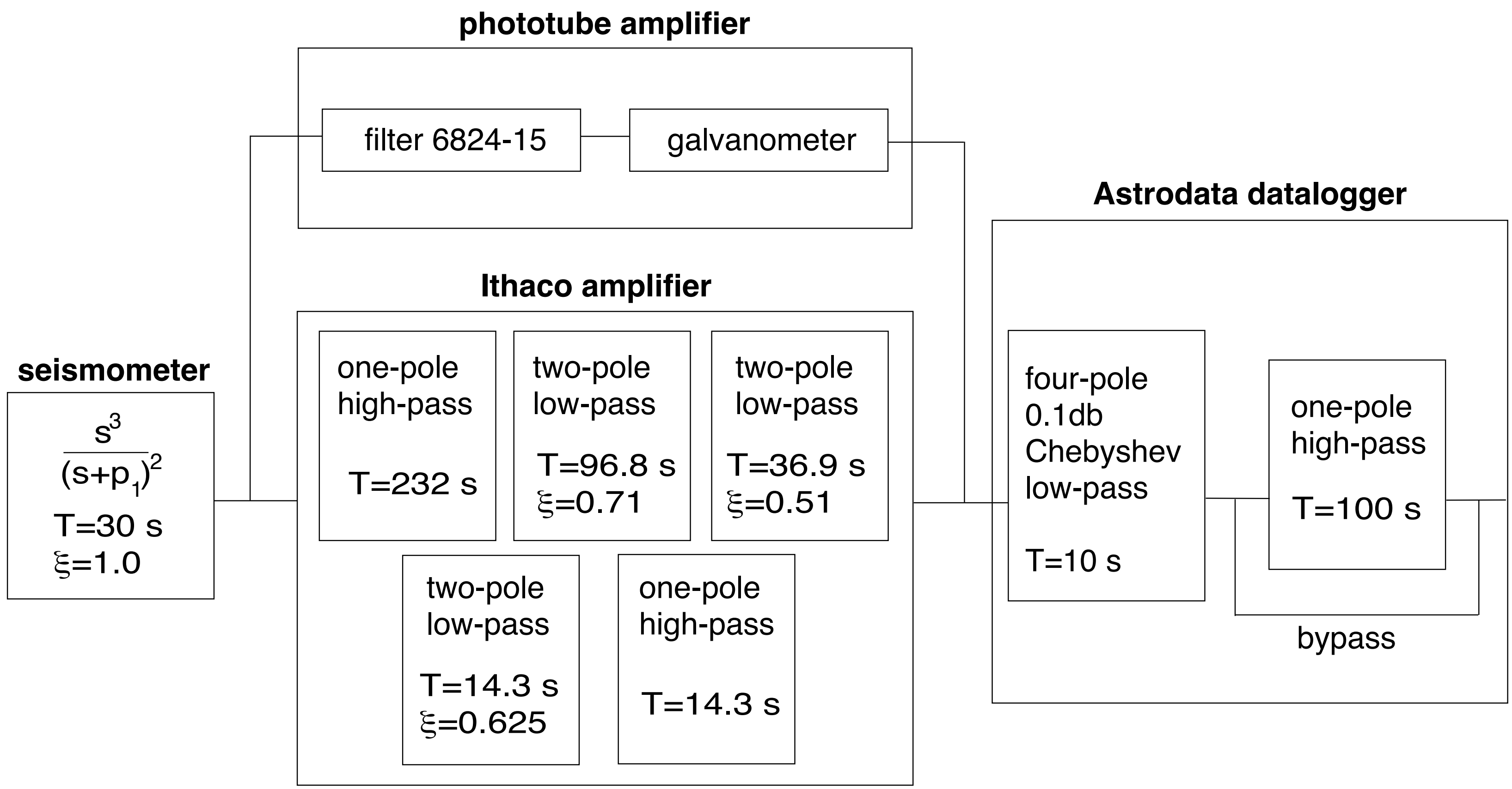
7. Using noise for tomography

Quantitative waveform analysis requires
highly accurate instrument response information

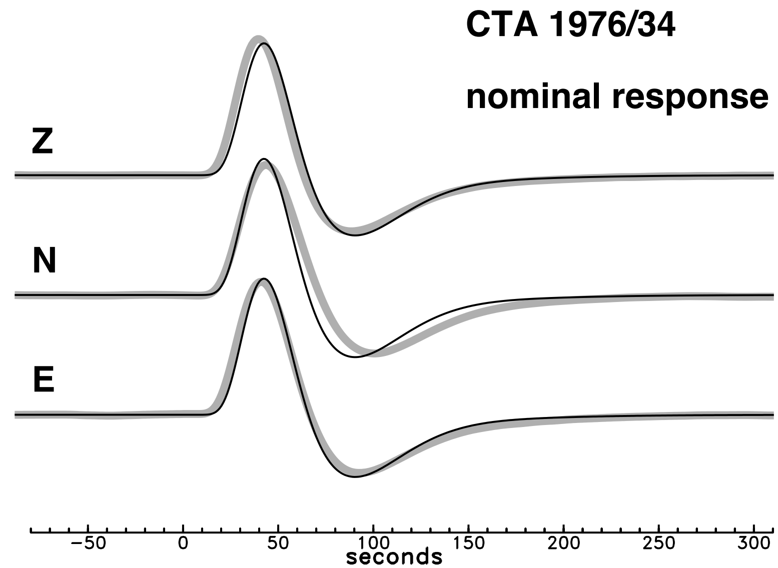
The Global Digital Network in 1976



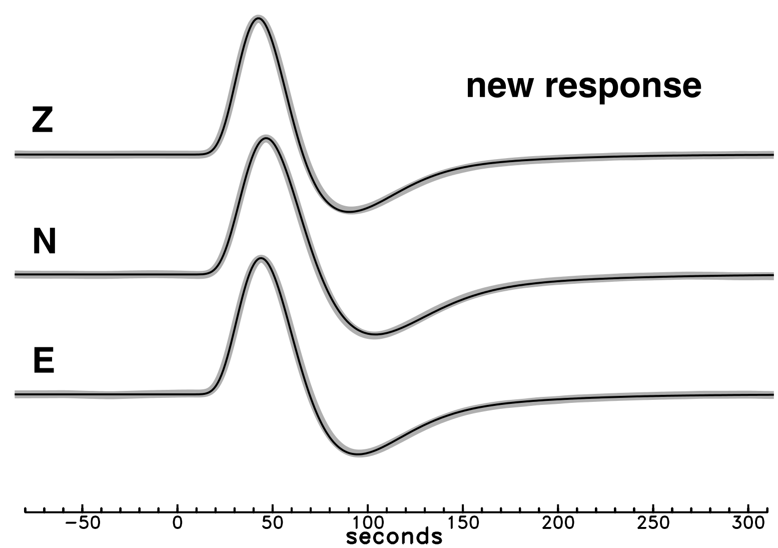
HGLP seismometer and recording system



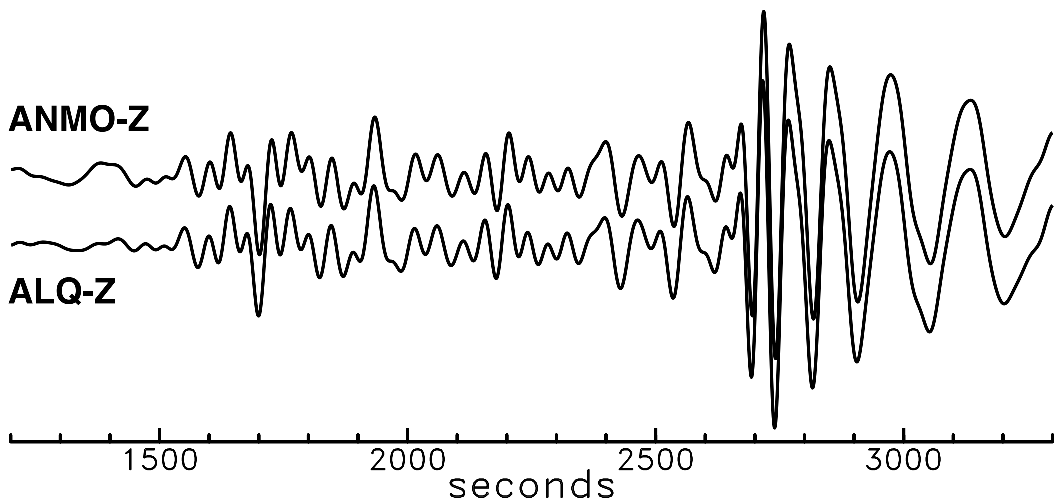
Original calibration pulses and pulses for nominal response



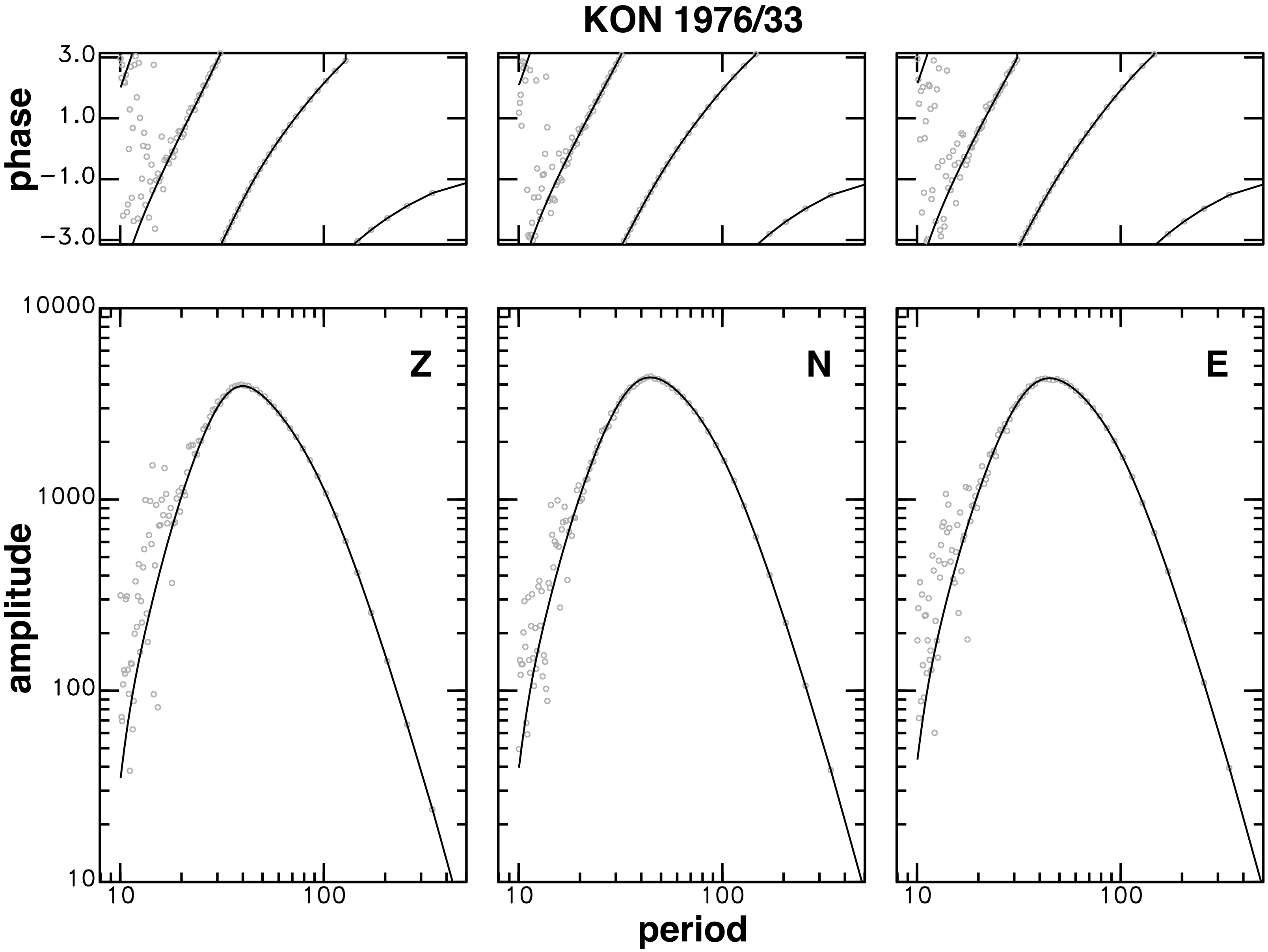
Original calibration pulses and pulses for new response after inversion



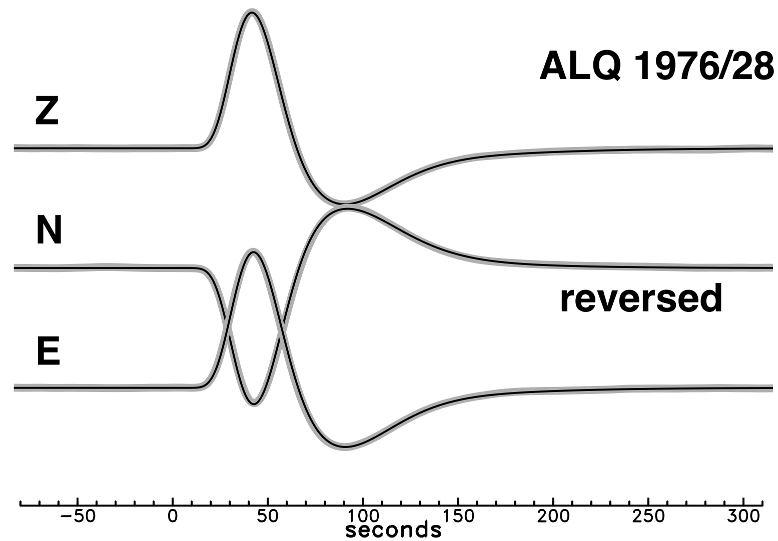
Comparison of waveforms after normalizing responses for two stations in the same location



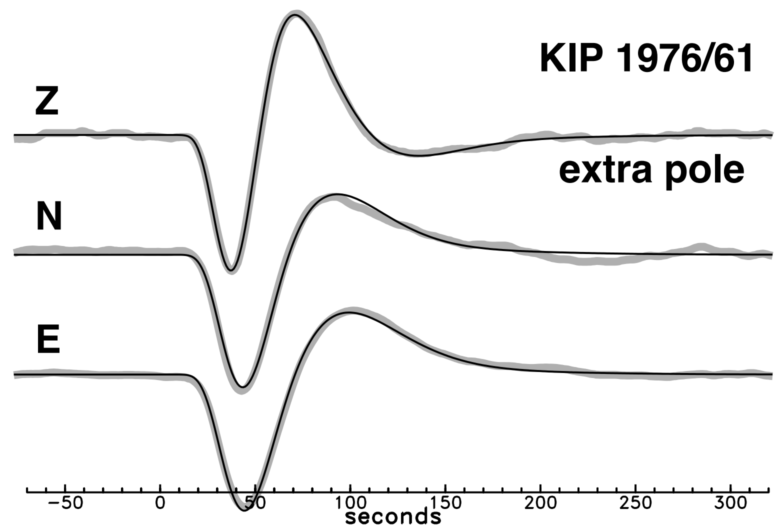
Check of new responses -- sine-wave calibrations



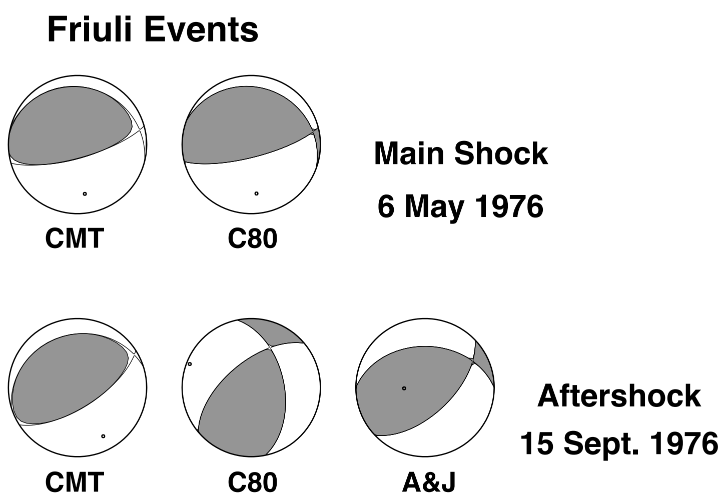
Some channels were reversed for some periods of time

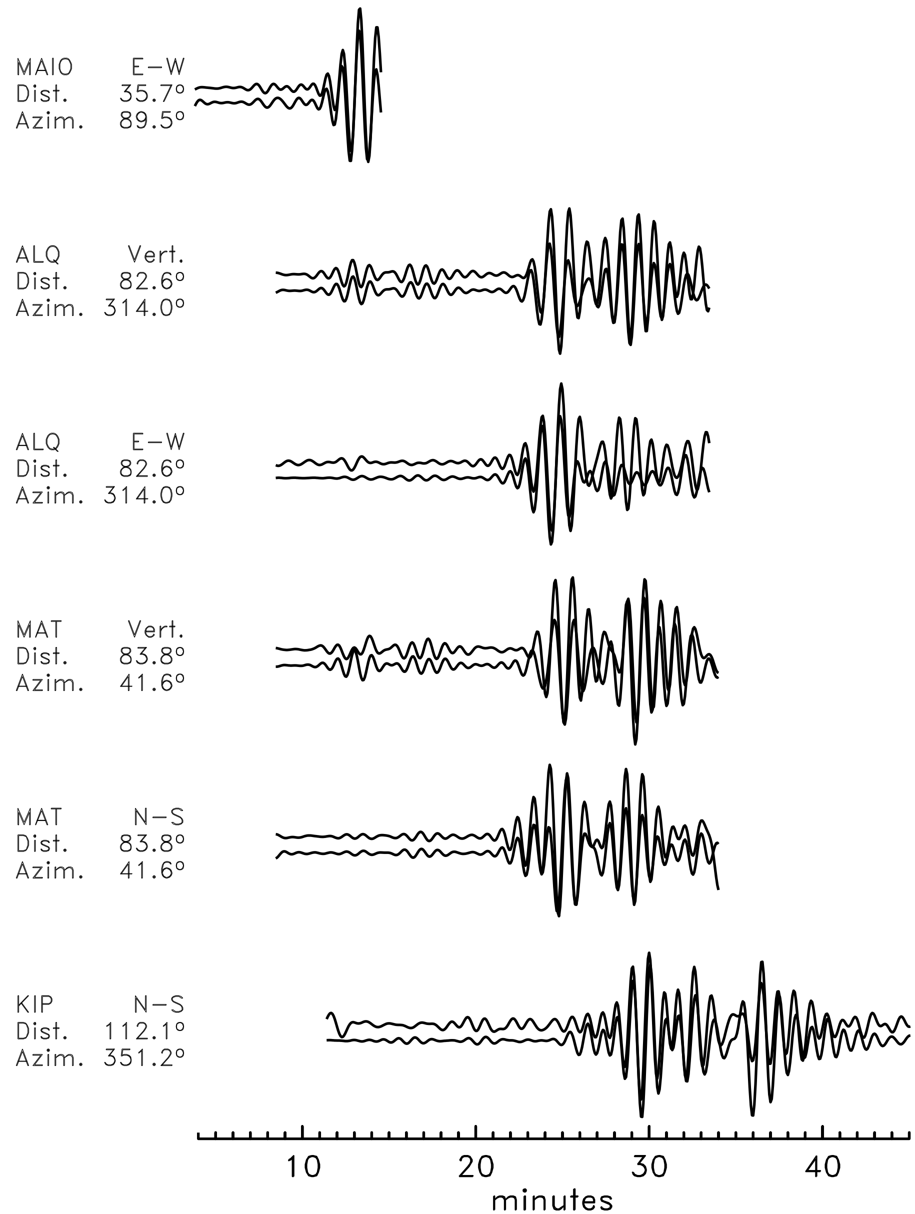


Some channels had extra filters for some periods of time



Waveform comparisons (observed and synthetic) after correcting seismograms using new responses: The 1976 Friuli earthquake





Main Point:

Quantitative waveform analysis requires
highly accurate instrument response information

4. Data quality control using signals
5. Data quality control using noise
6. Finding interesting things in the noise
7. Using noise for tomography

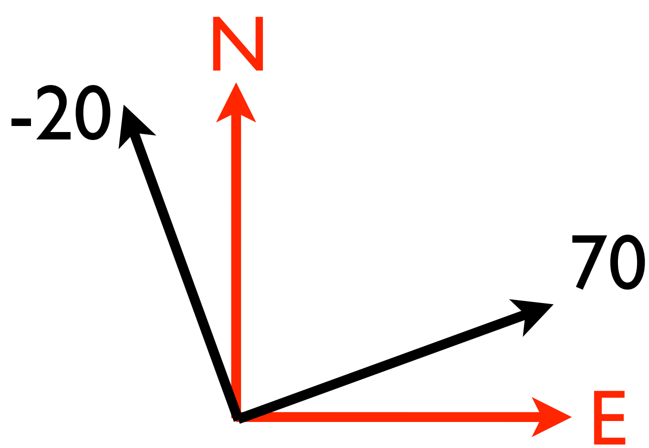
4a. Sensor orientation

4b. Sensor response stability

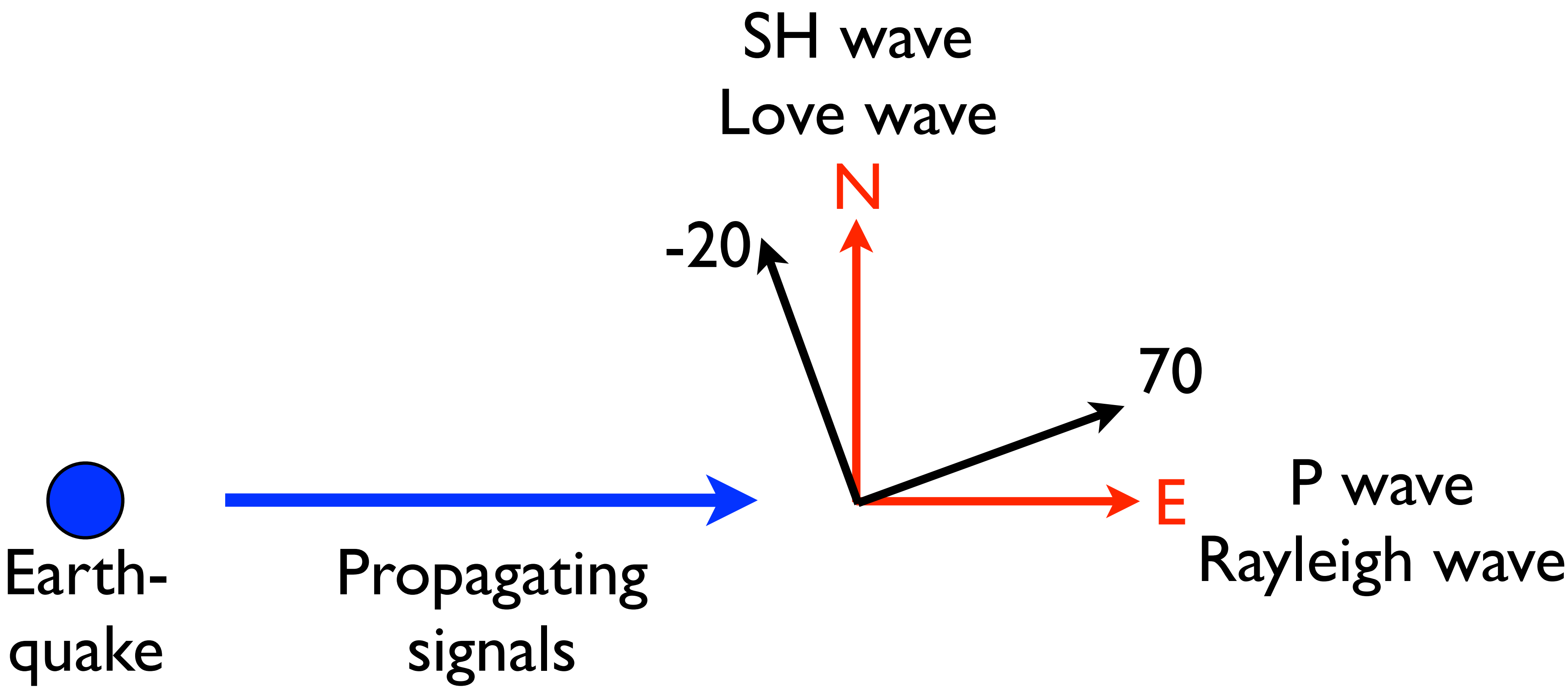
Horizontal Polarization Problems

Desired (assumed) orientation of seismometer

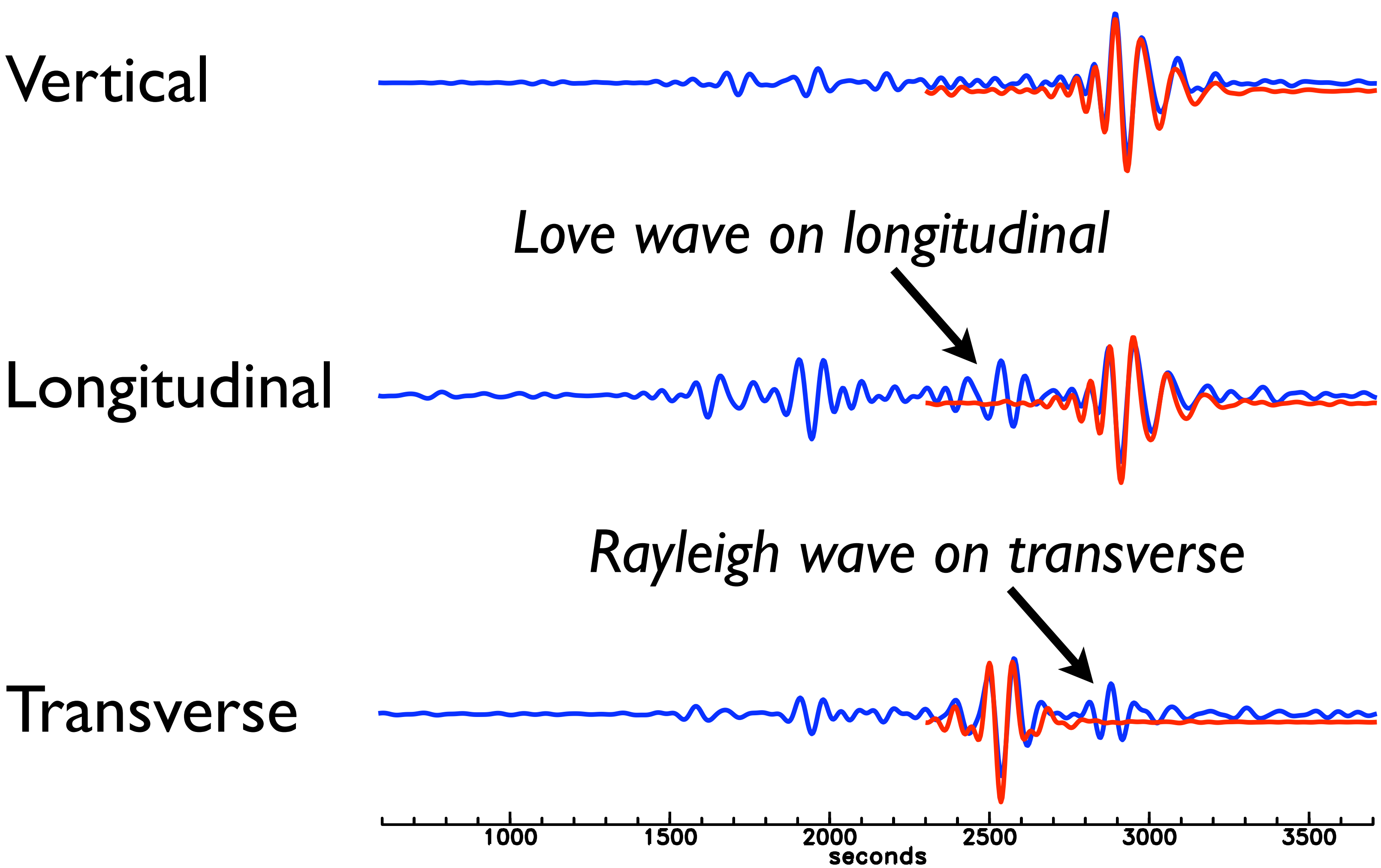
True orientation of seismometer



Natural Polarization of Earthquake Signals

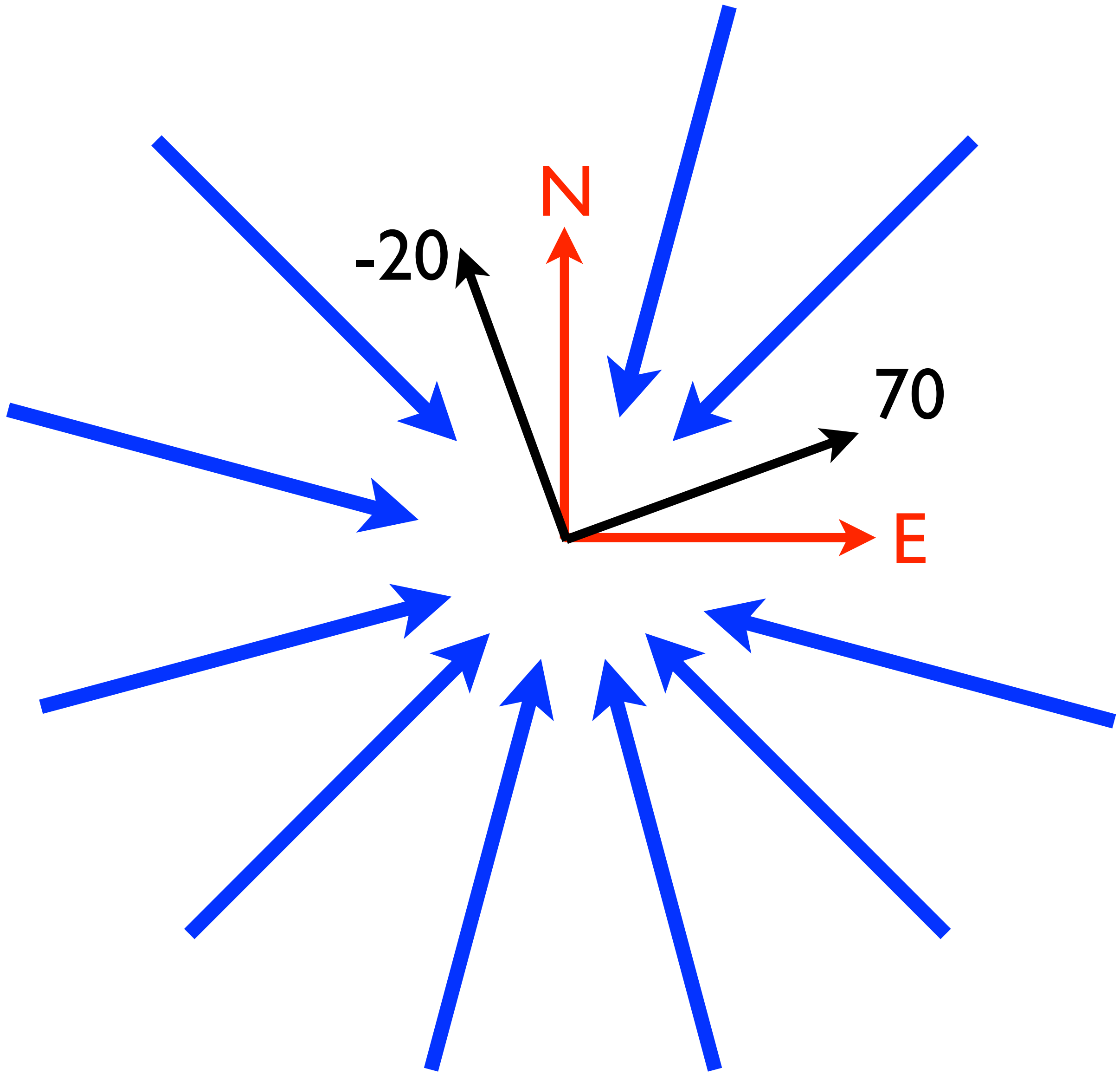


Symptoms of a misoriented sensor

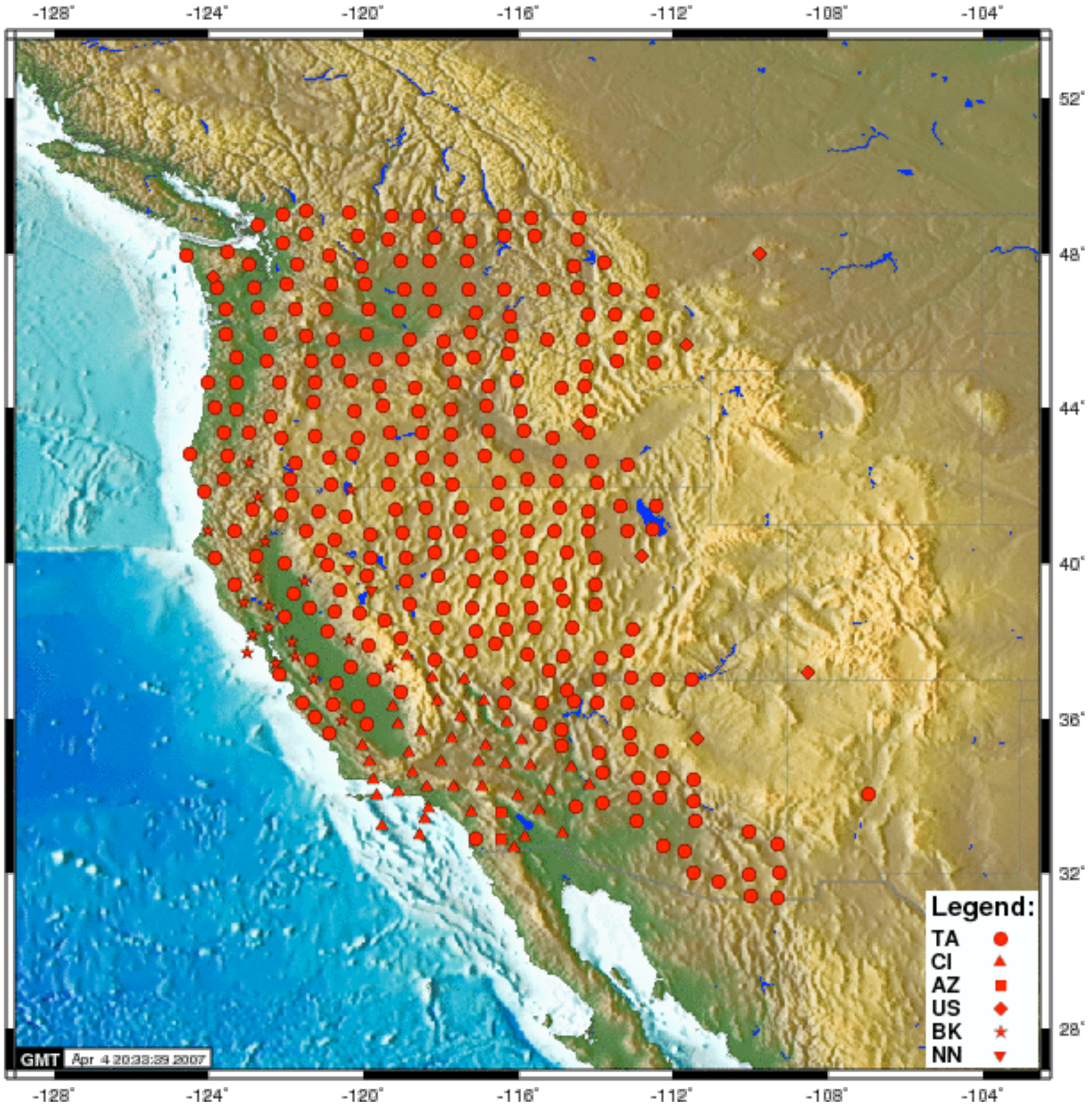


Station D09A, earthquake on 08/20/2007

Many earthquake signals --
invert for orientation of sensor



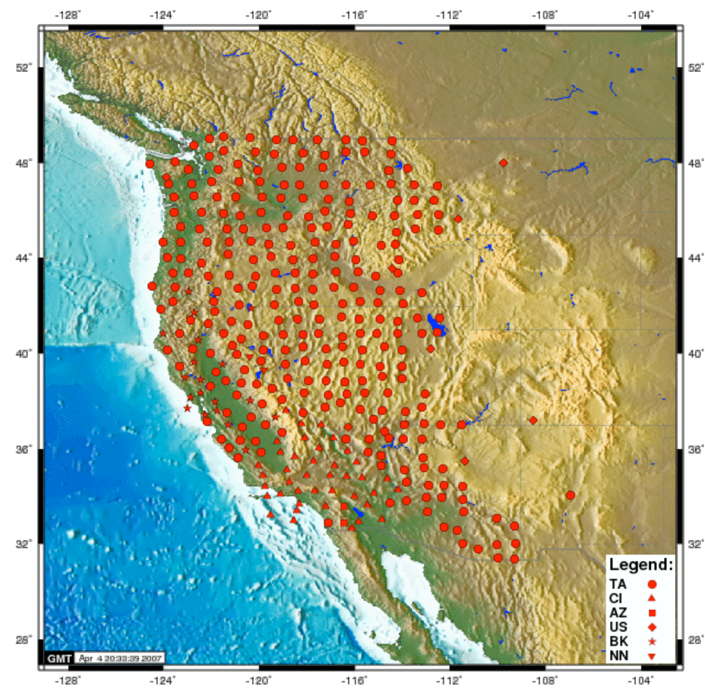
USArray Transportable Array, April 2007



Polarization analysis of USArray data using earthquake signals

400+ USArray stations

Result:
> 5% misoriented > 10 degrees
> 10 % misoriented > 5 degrees

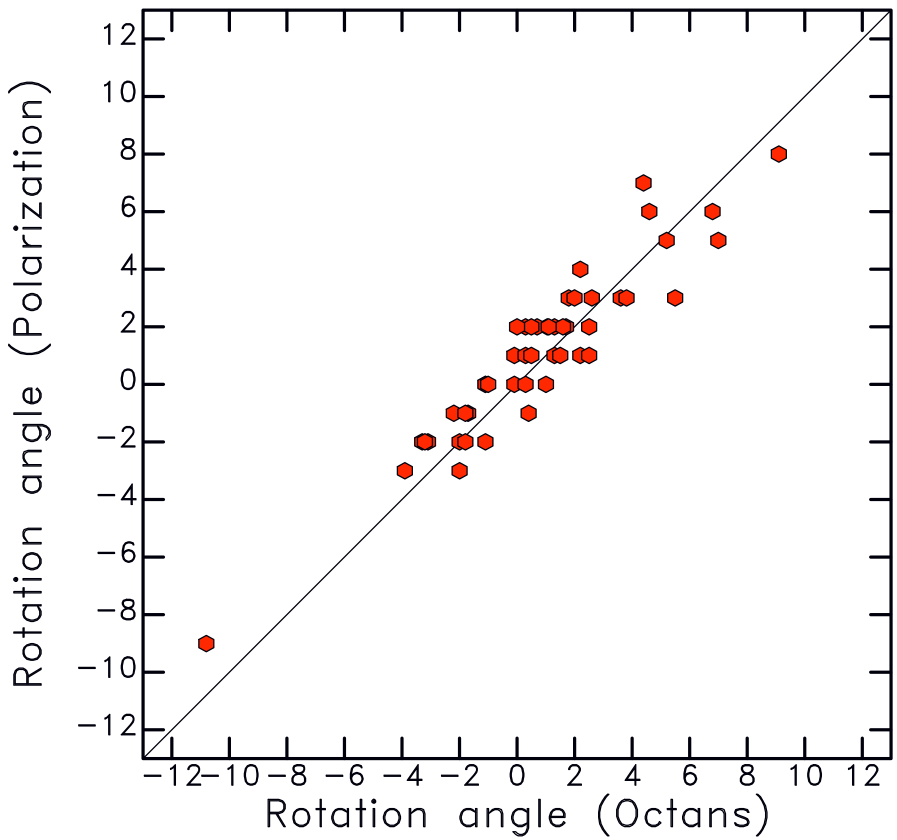


This is a common problem in many networks!

Octans interferometric laser gyro

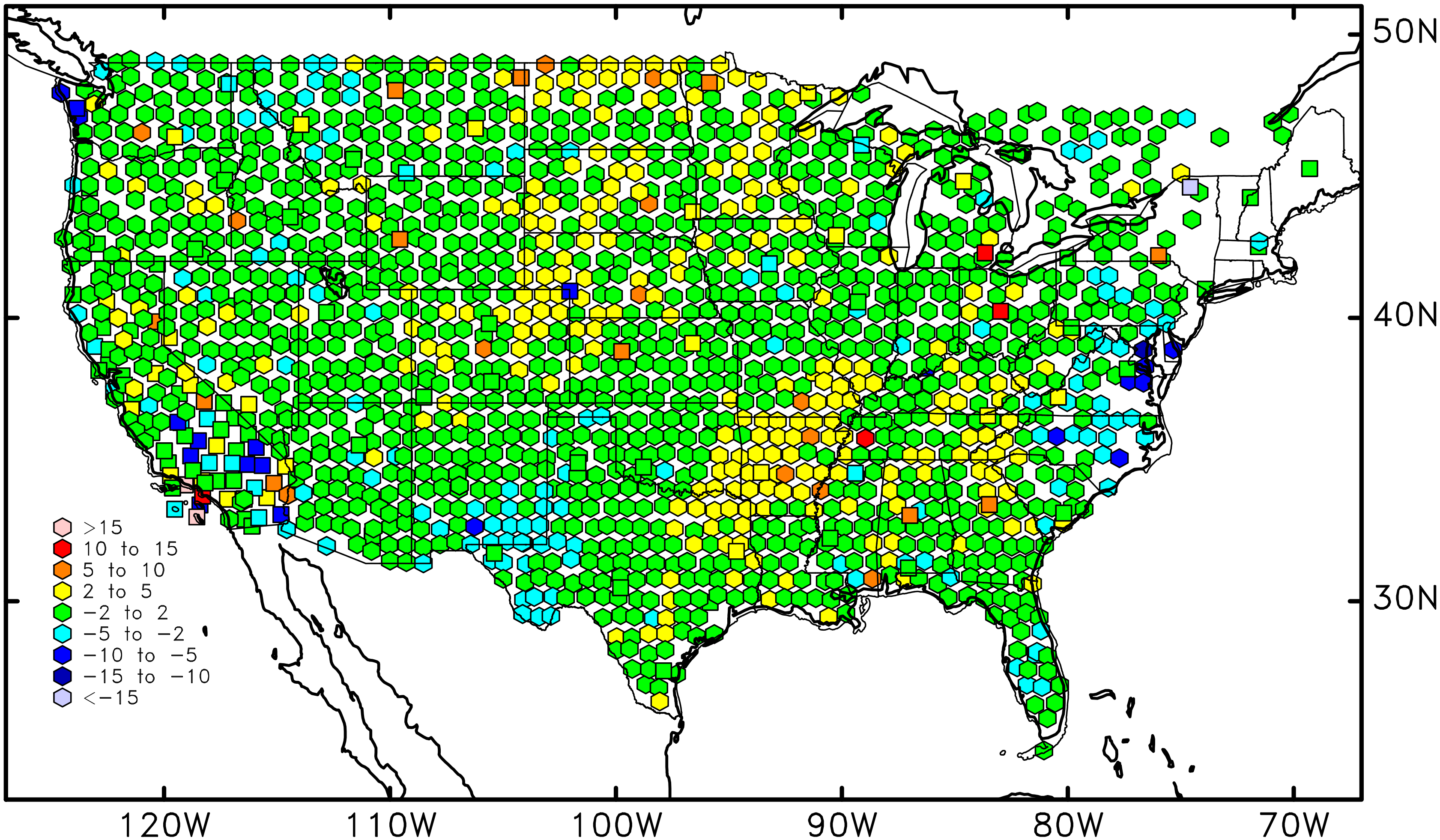
Agreement of field (Octans) and polarization angles

estimated from seismograms



measured in the field

Station polarization anomalies



Intermediate-period surface waves
(squares are non-TA)

Statistics of absolute polarization anomalies

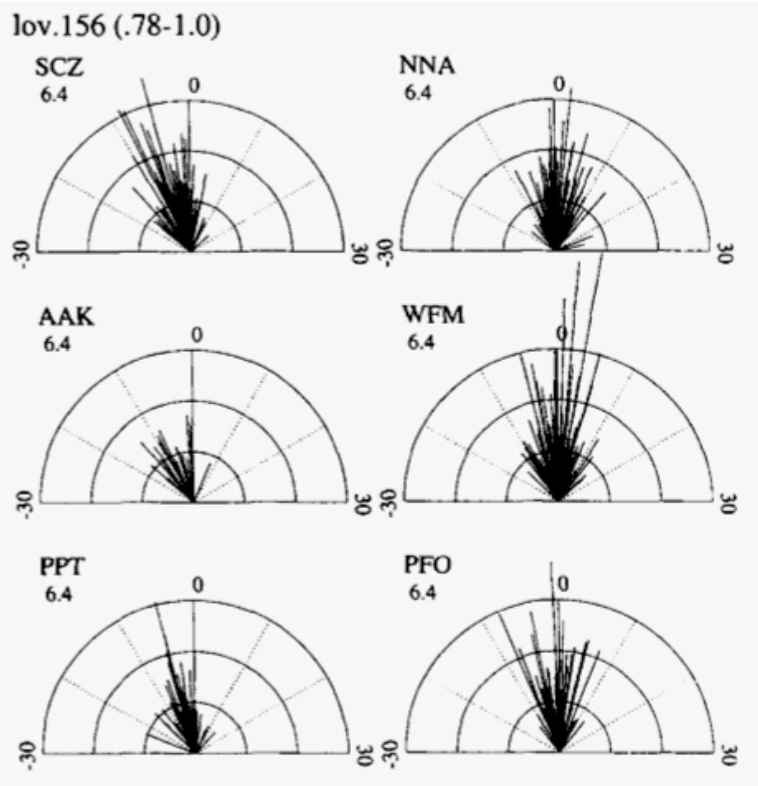
network	≤3 deg.	≤6 deg.	#epochs
TA	92.2%	98.9%	1829
US	69.6%	90.5%	158
BK	82.1%	100.0%	28
CI	58.2%	77.1%	122
II+IU	76.6%	91.1%	726
G	85.7%	98.7%	77

Sensor orientation

Most GSN and USArray TA stations are well oriented, but not all.

Why does it matter?

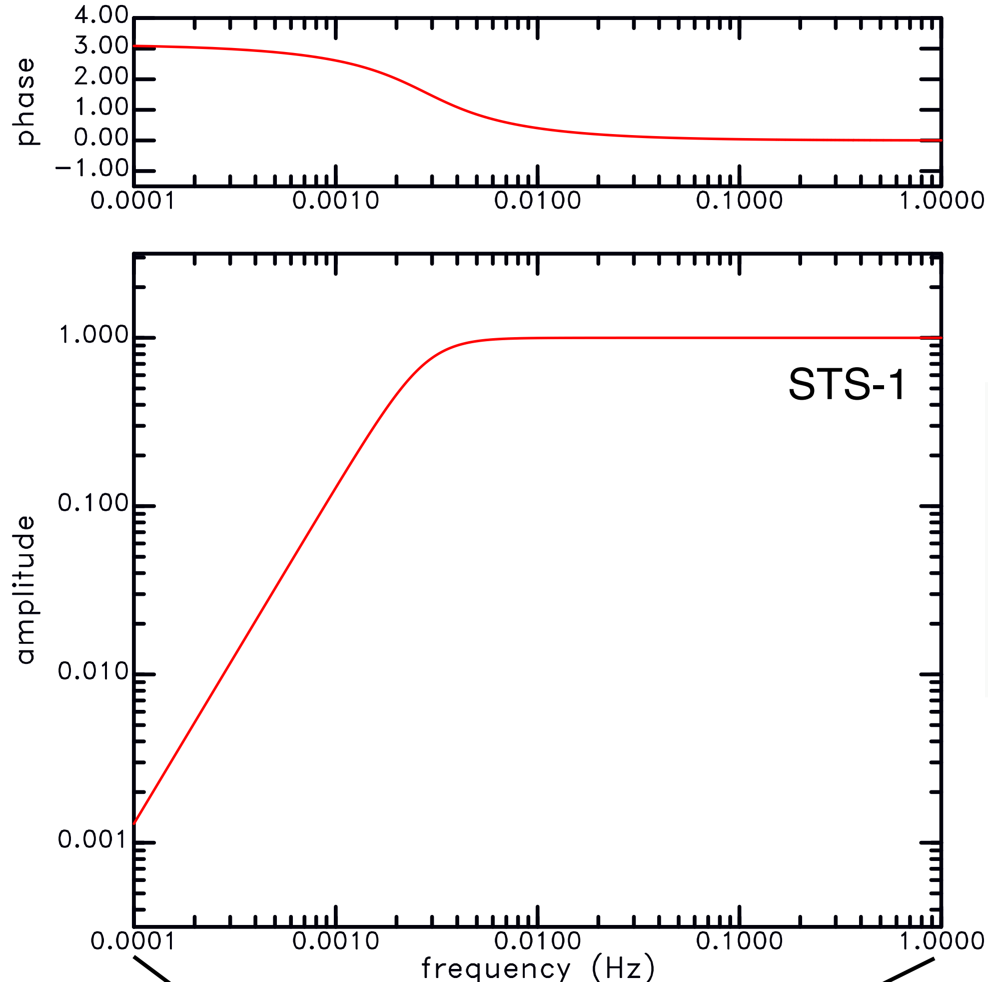
- Modeling of earthquake sources
- Measurement of Love wave / toroidal mode parameters
- Estimates of anisotropy
- Estimates of off-great-circle arrival angle, for both elastic and anelastic structure (tomography)



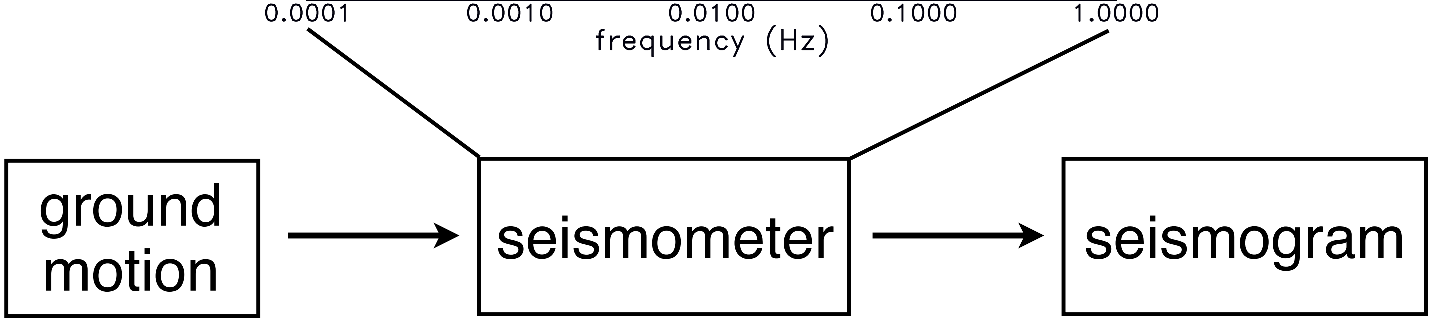
(Laske, 1995)

4b. Sensor response stability

Seismometer frequency response

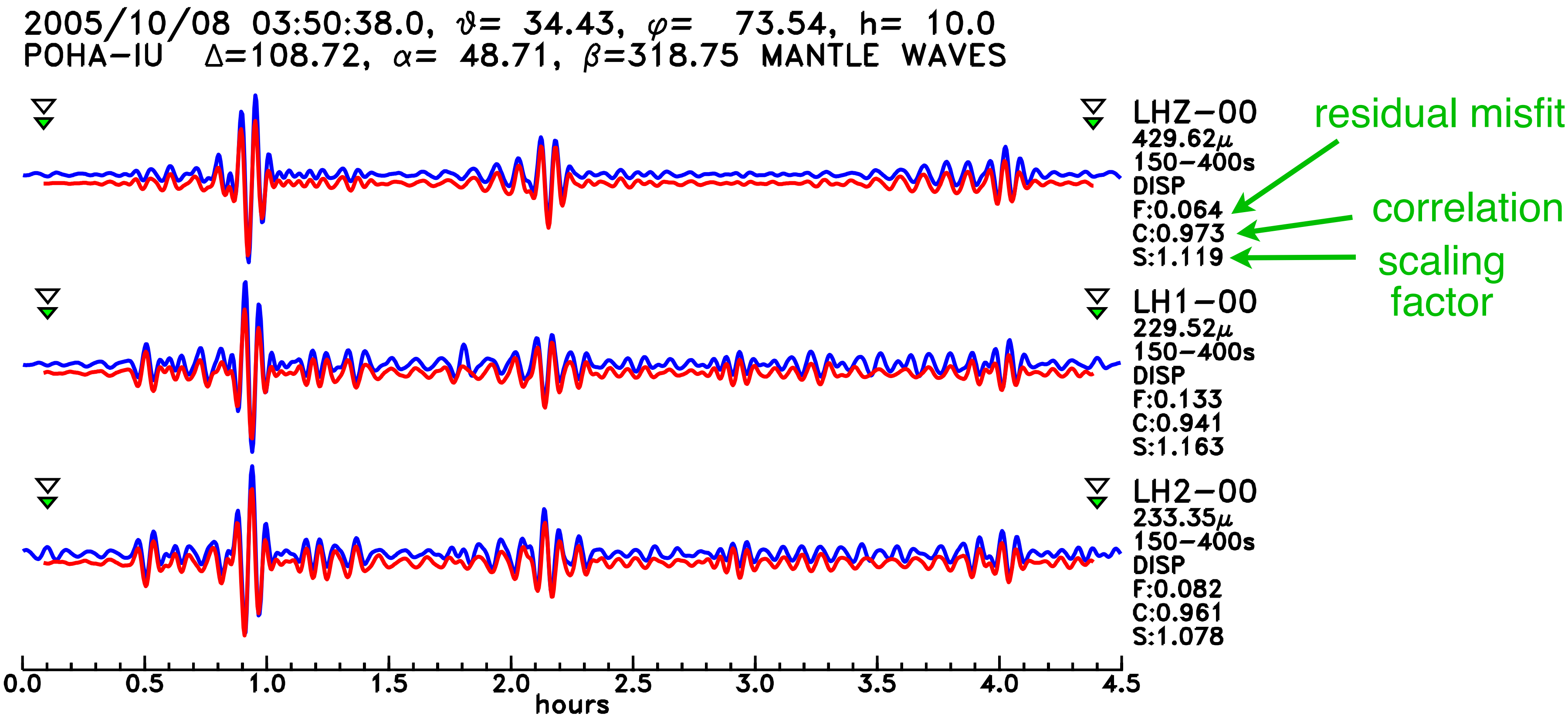


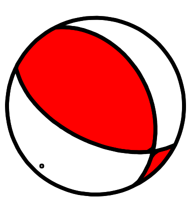
$$T(s) = K \frac{\prod_{i=1}^{N} (s - z_i)}{\prod_{j=1}^{M} (s - p_j)}$$



Blue - observed seismograms

Red - synthetic seismograms

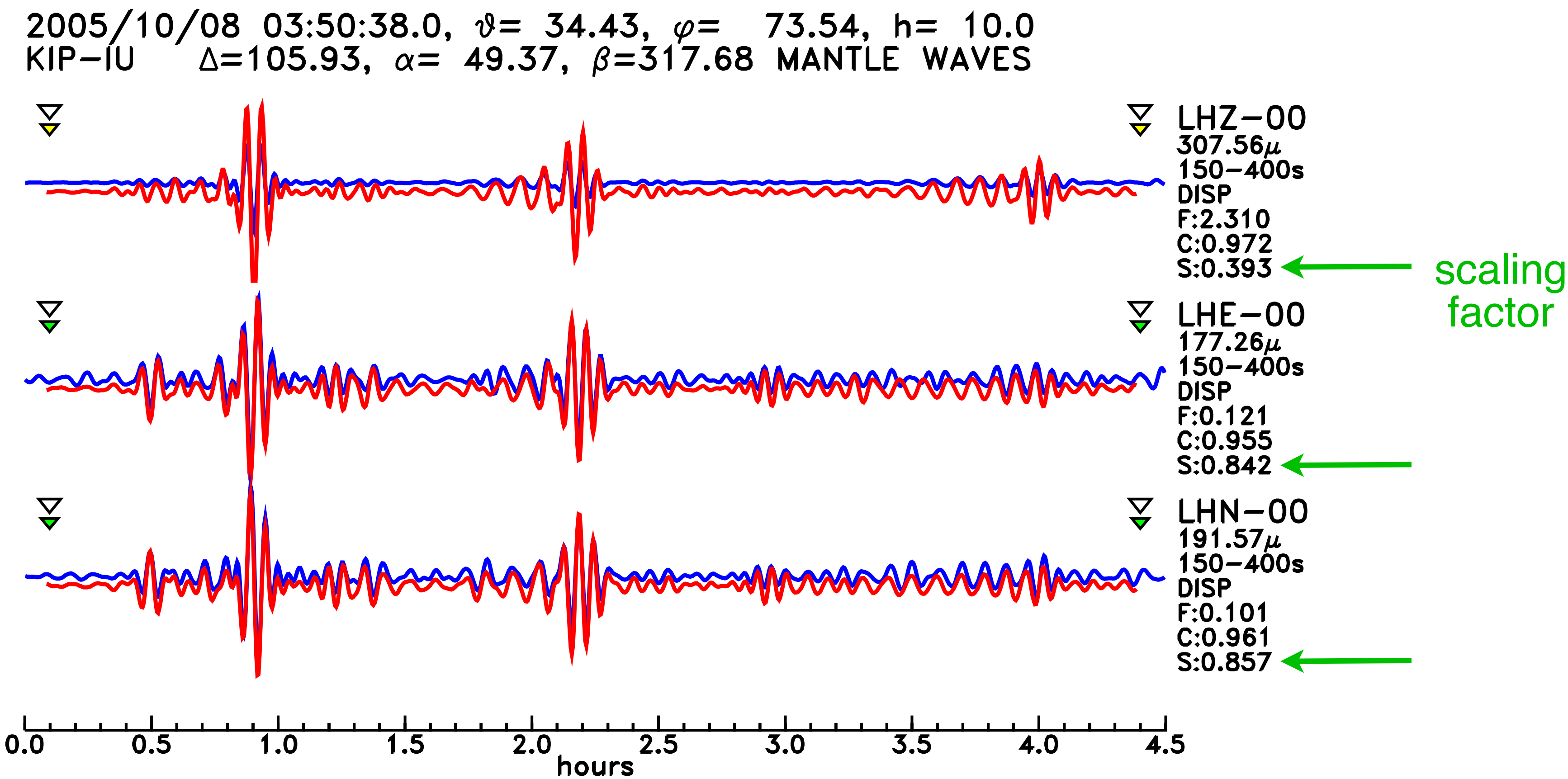


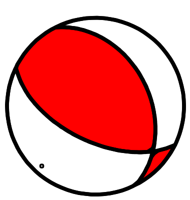


$$S = \frac{\sum_{i=1}^{N} o_i s_i}{\sum_{i=1}^{N} s_i^2}$$

Blue - observed seismograms

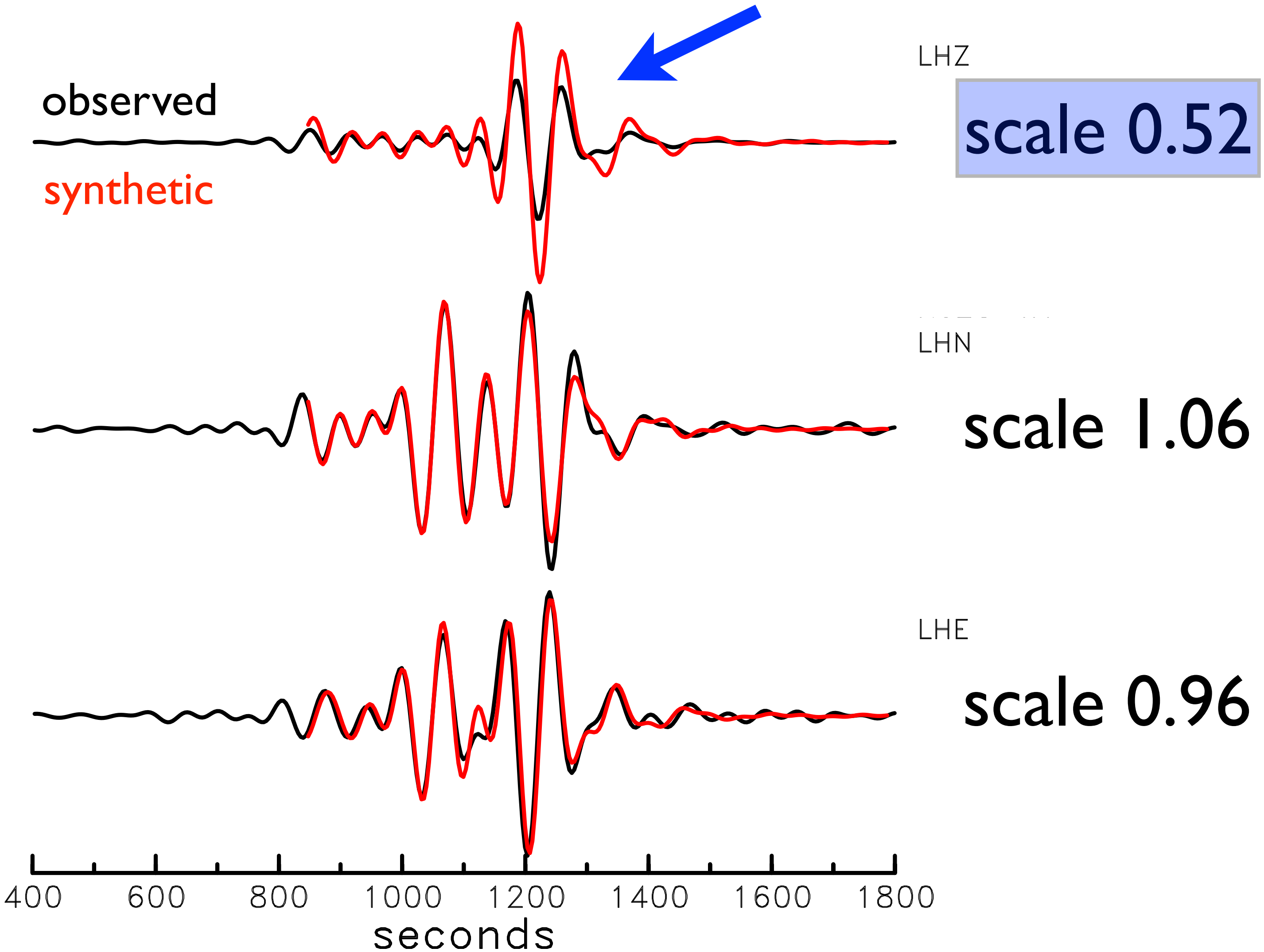
Red - synthetic seismograms





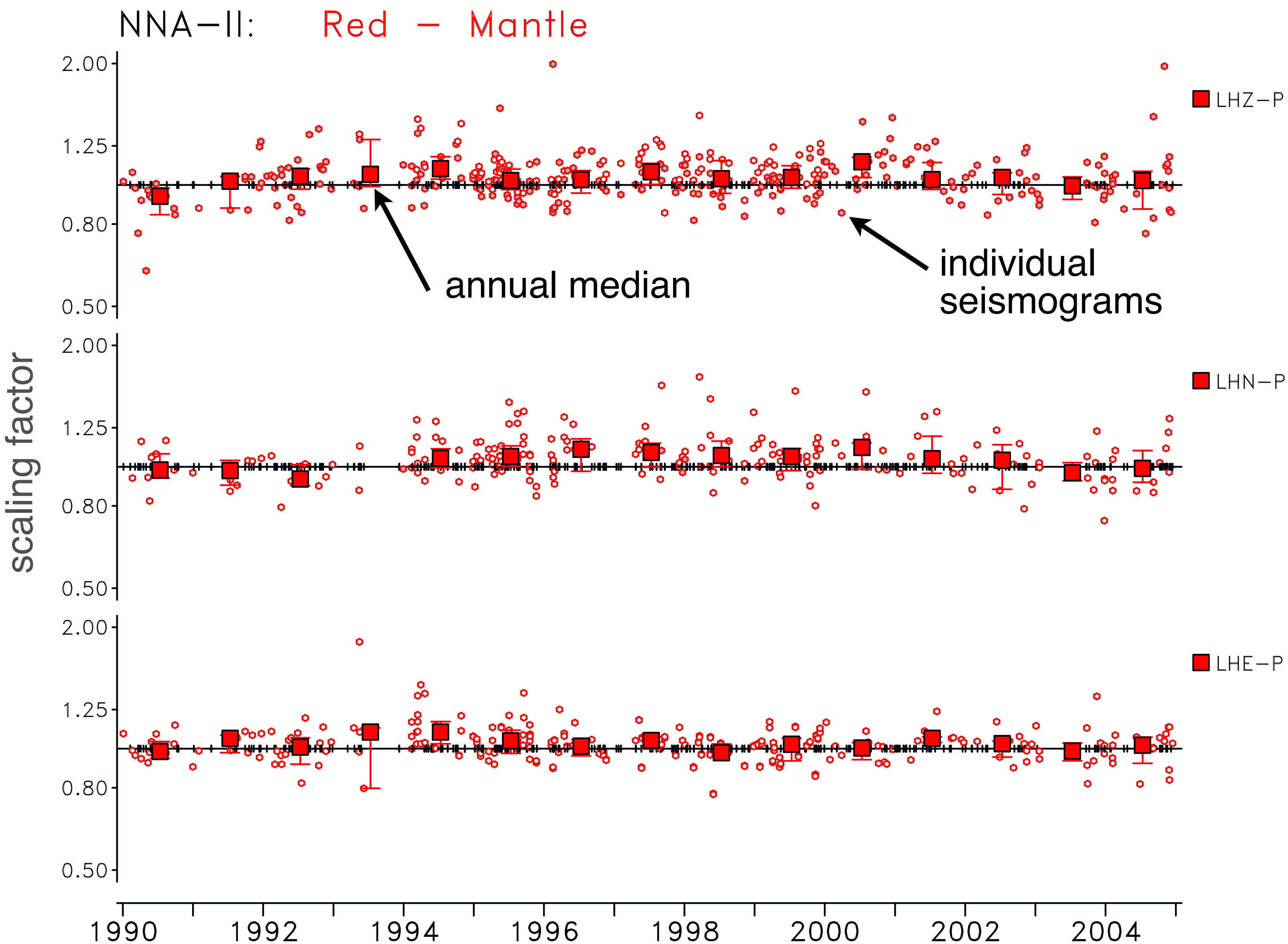
$$S = \frac{\sum_{i=1}^{N} o_i s_i}{\sum_{i=1}^{N} s_i^2}$$

Symptoms of a seismometer with wrong gain

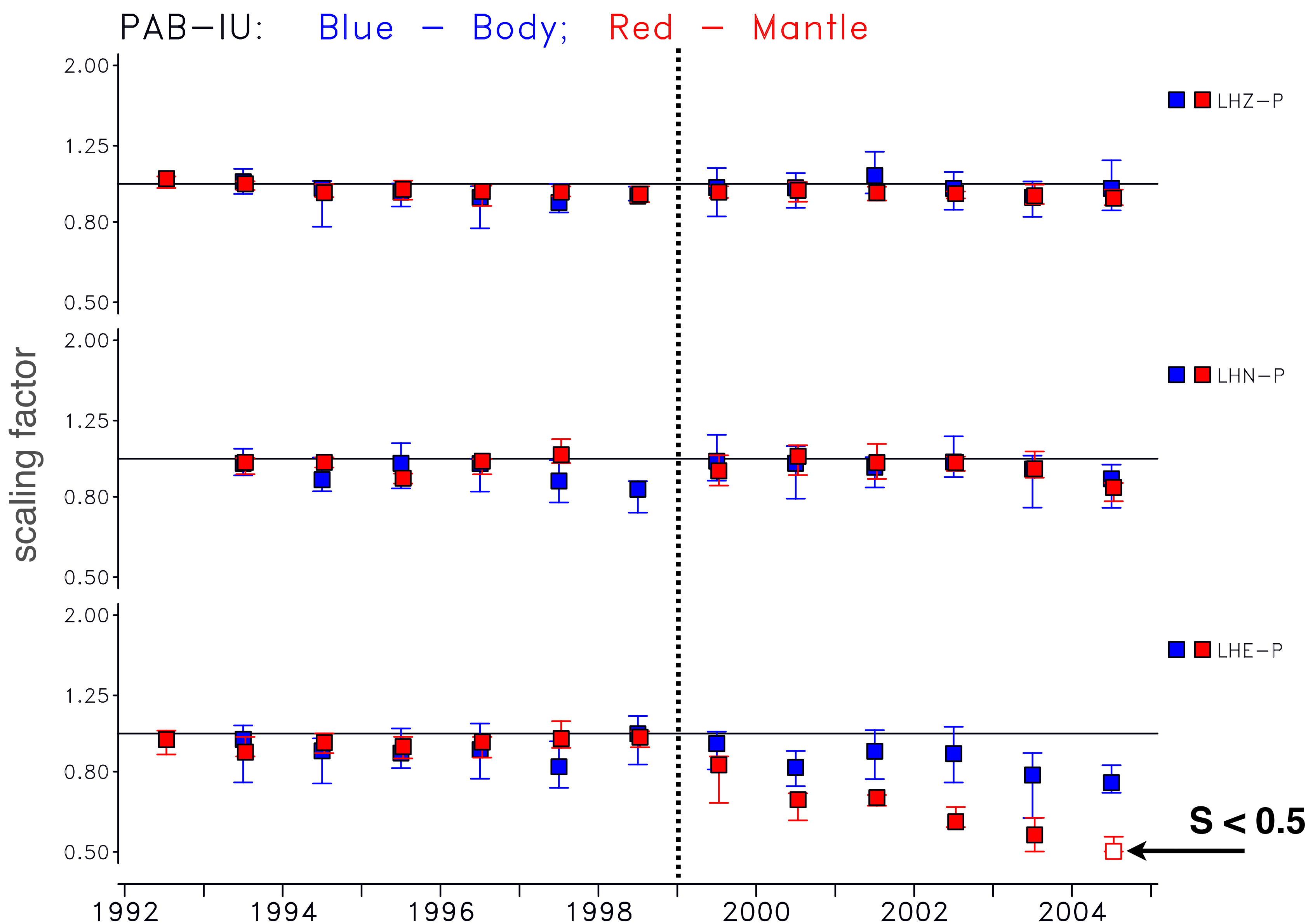


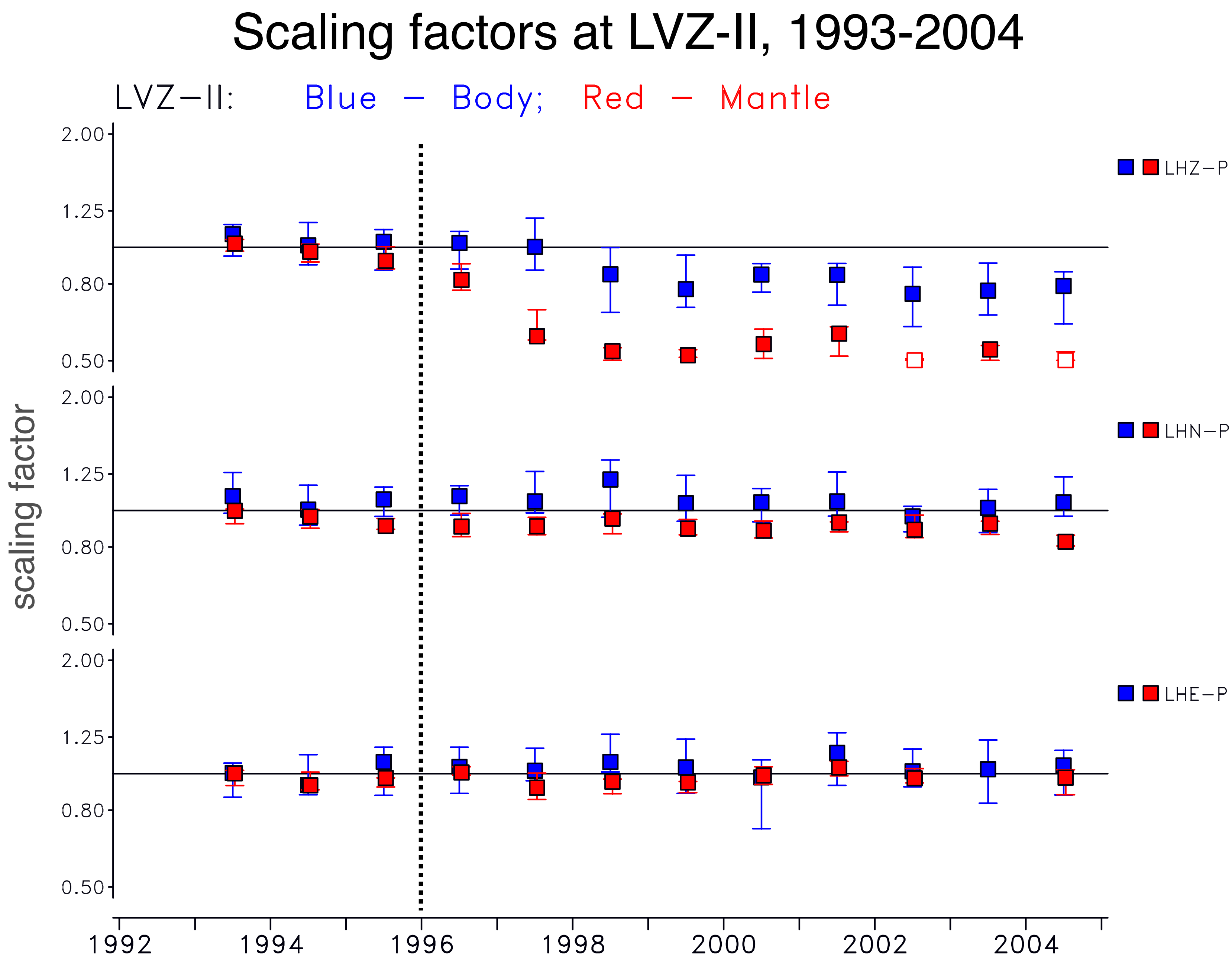
Station N02C, earthquake on 06/14/2006

Scaling factors at NNA-II, 1990-2004

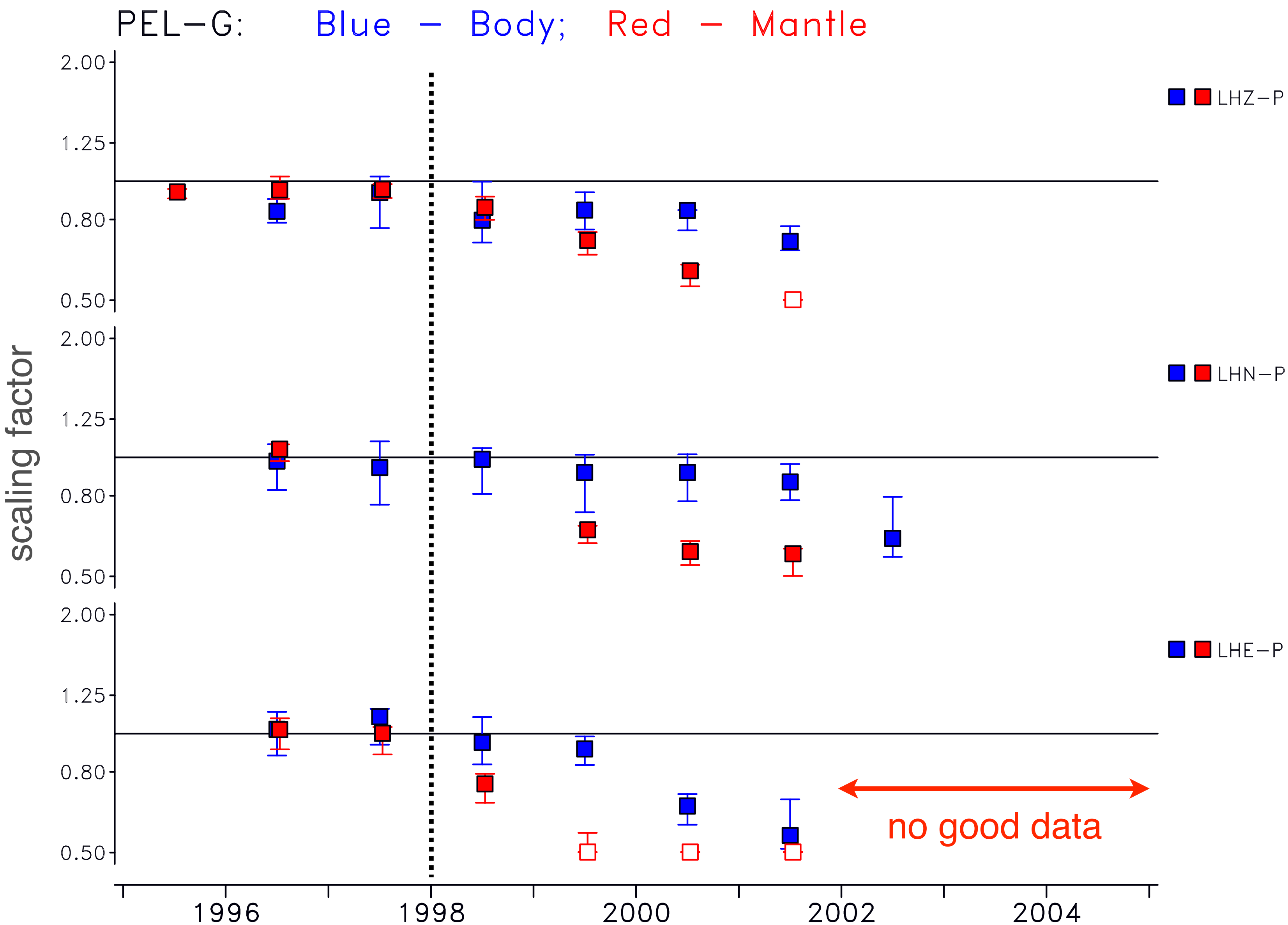


Scaling factors at PAB-IU, 1992-2004



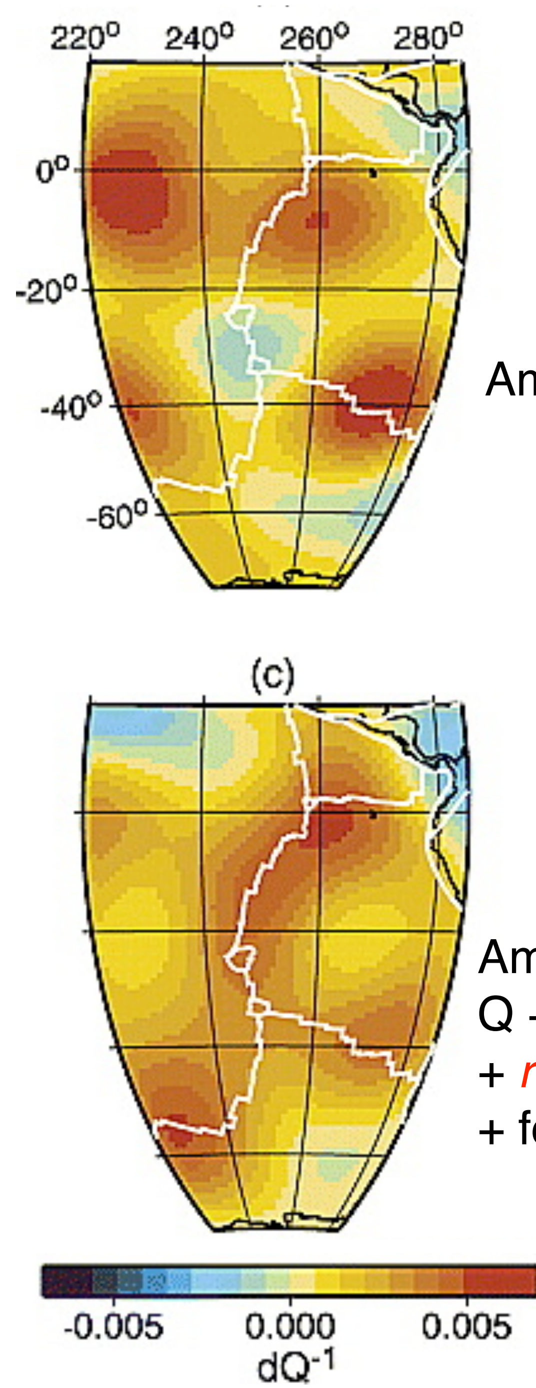

Scaling factors at LVZ-II, 1993-2004
LVZ–II: Blue – Body; Red – Mantle
LHZ–P
LHN–P
LHE–P
scaling factor
2.00
1.25
0.80
0.50
1992
1994
1996
1998
2000
2002
2004

Scaling factors at PEL-G, 1996-2002



Why does it matter?

- Amplitudes carry critical information for improving models of elastic and inelastic (Q) structure
- Also important for improvements in earthquake source modeling



Amplitude → Q

Amplitude →
Q + source factor +
+ *receiver factor*
+ focusing

(Dalton and Ekström, 2006)

A simpler way to do this - if you have two instruments (A and B) in the same location:

calculate ratio of displacements at some period during times of high signal coherence

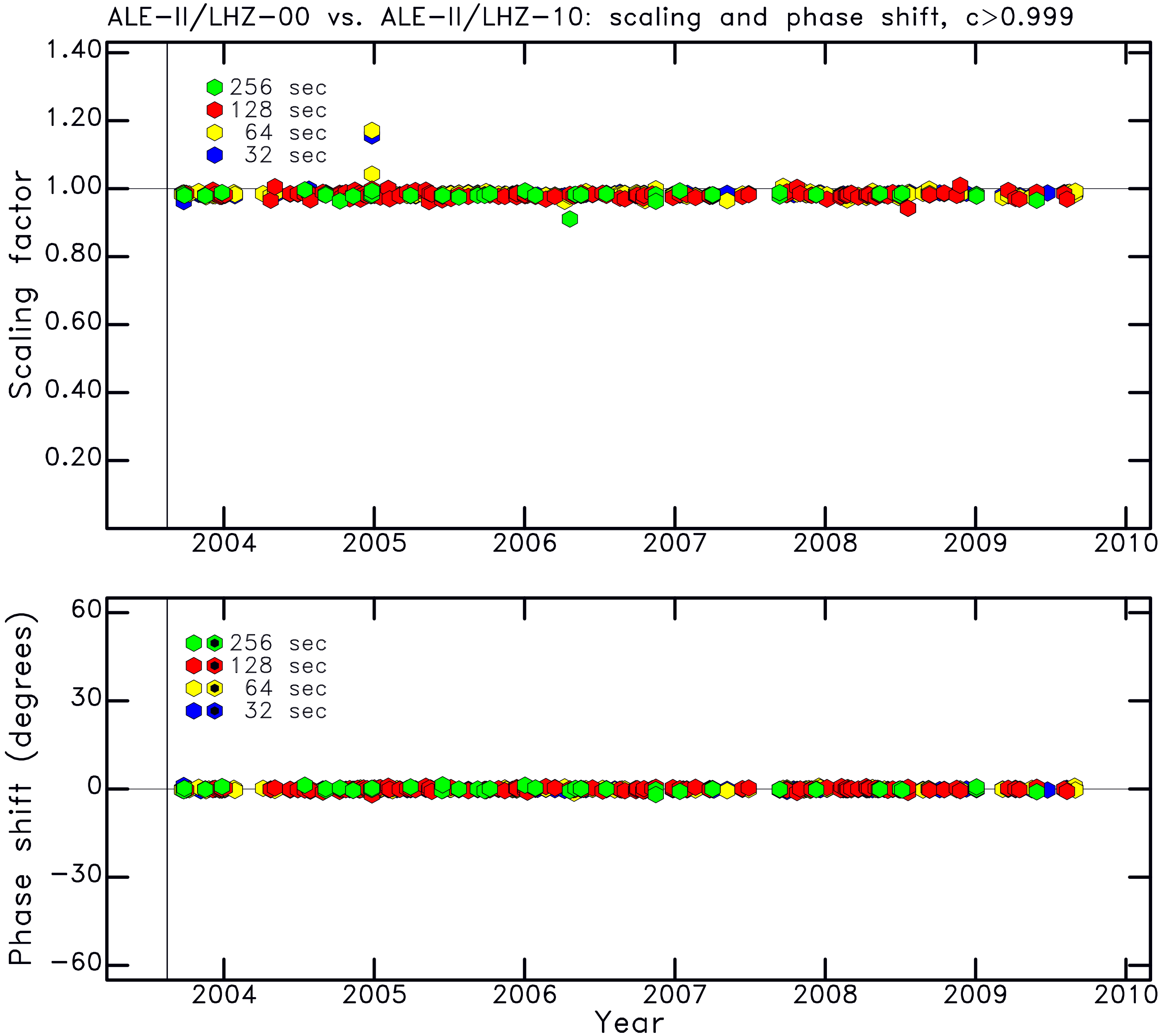
$$\frac{\text{signal A}}{\text{response A}} = \text{displacement A} \qquad \text{(deconvolution)}$$

$$\frac{\text{signal B}}{\text{response B}} = \text{displacement B} \qquad \text{(deconvolution)}$$

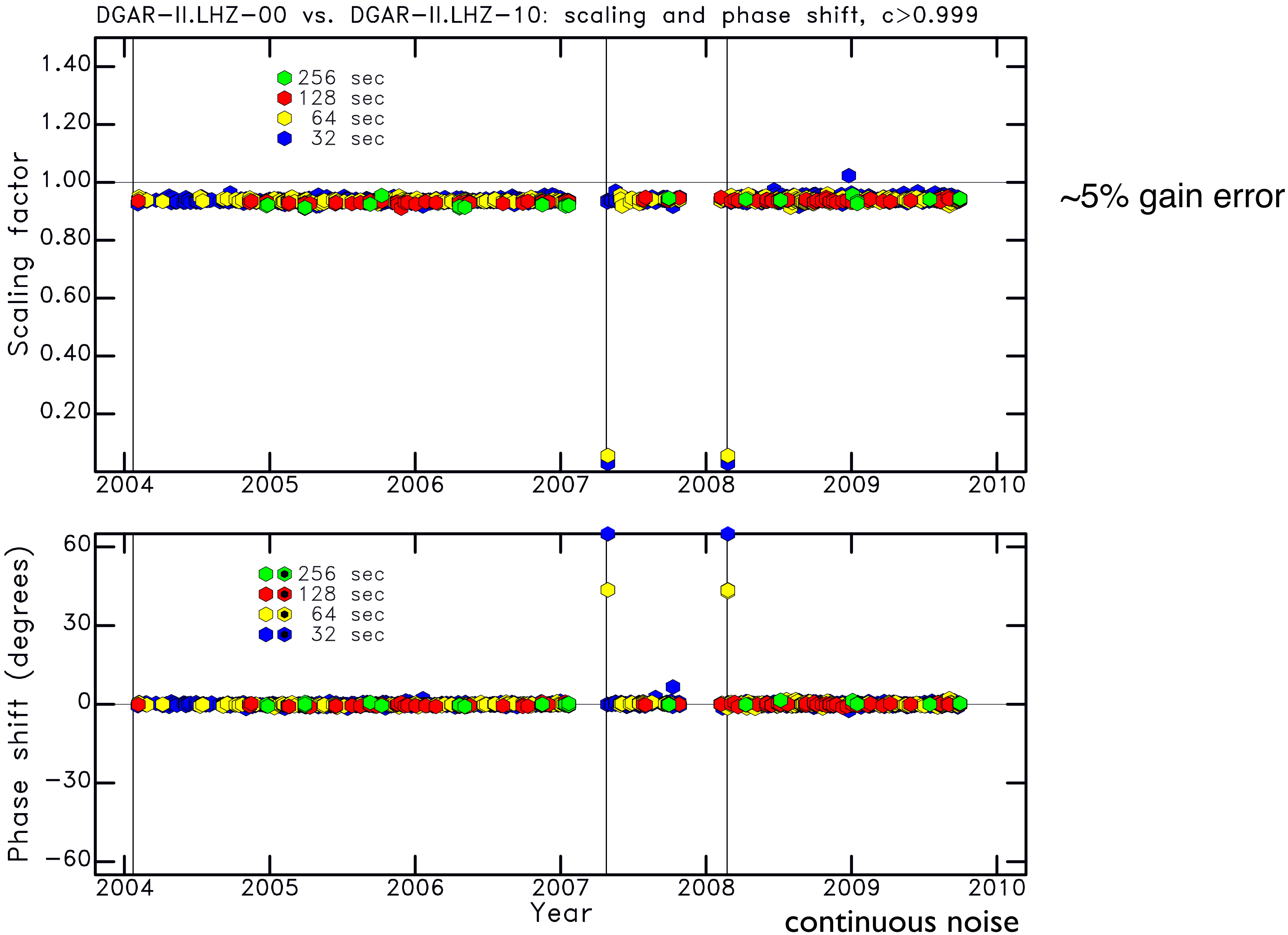
$$\text{ratio} = \frac{\text{displacement A}}{\text{displacement B}}$$

should be 1.0000!

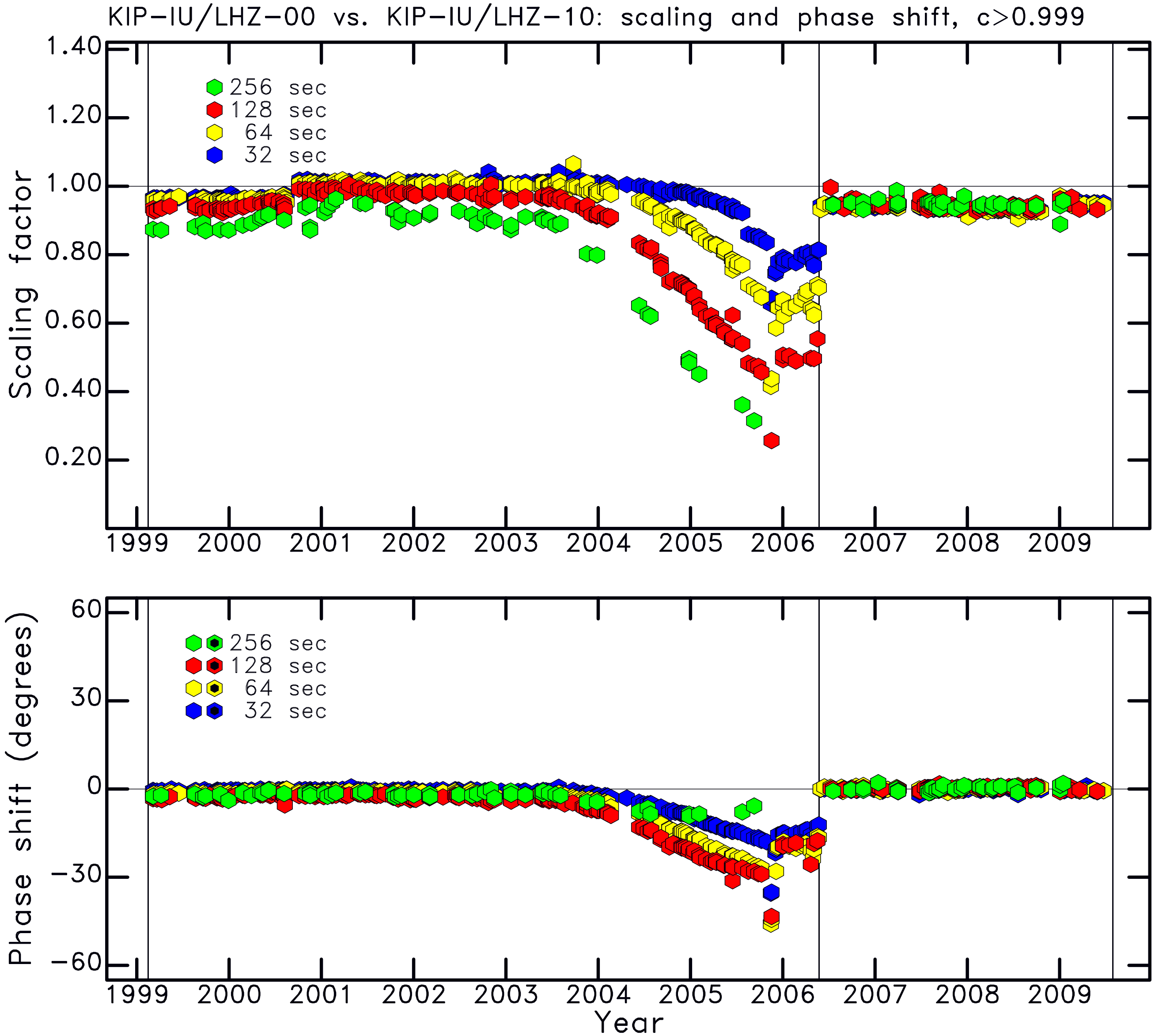
Intersensor coherence, ALE-II LHZ, 2003-2009



Intersensor coherence, DGAR-II LHZ, 2003-2009



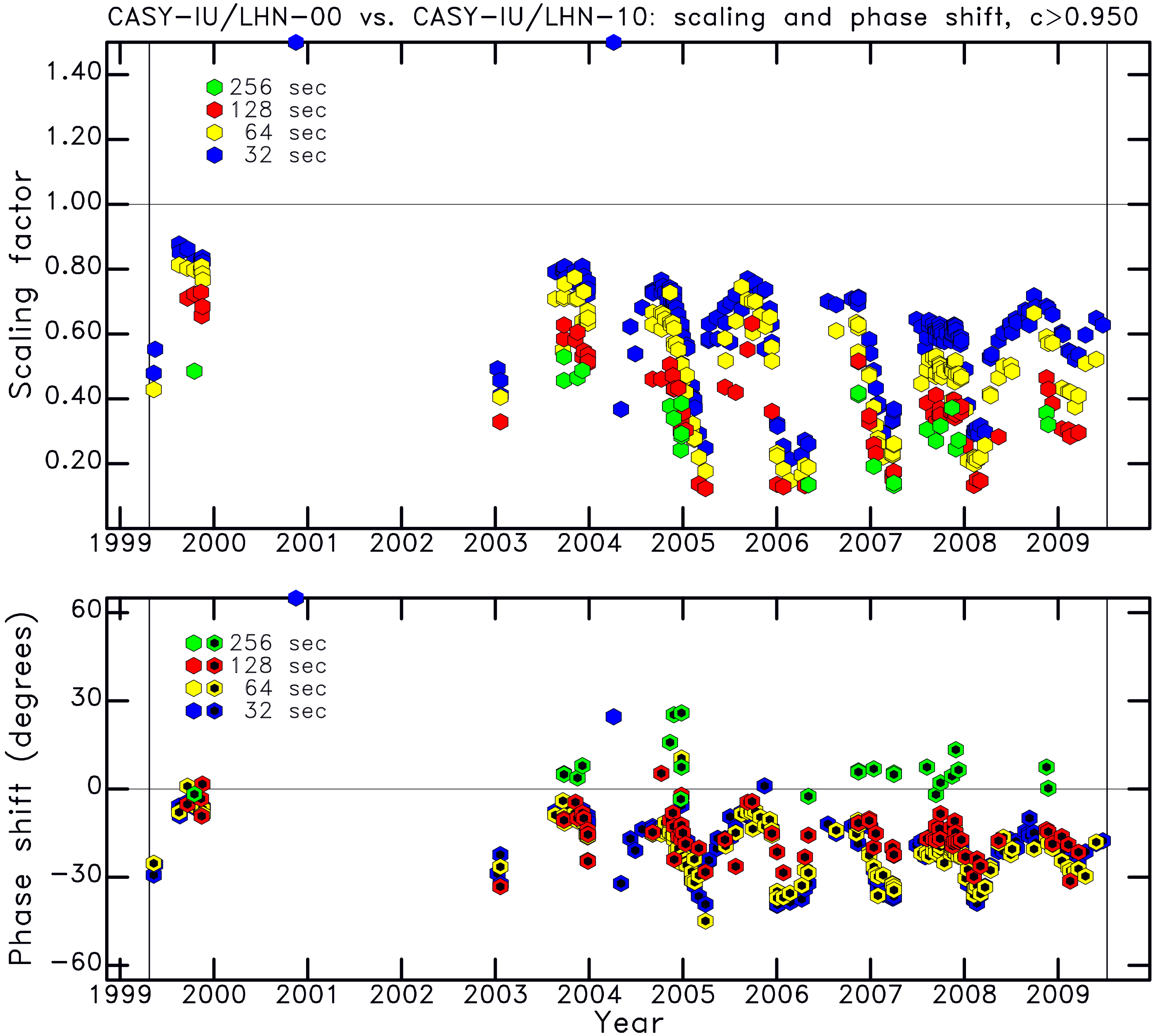
Intersensor coherence, KIP-IU LHZ, 1999-2009



~5% gain error

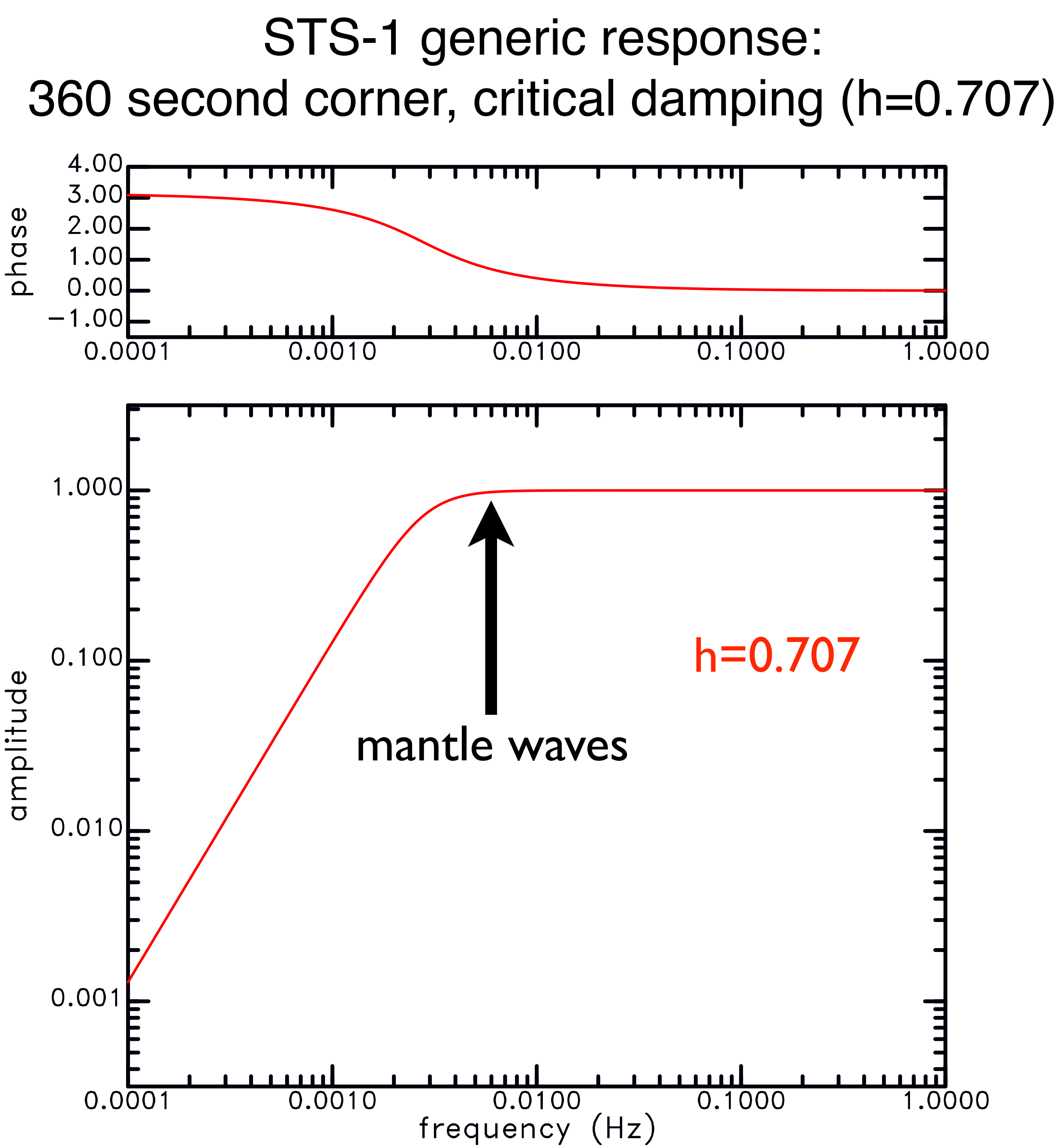
STS-1 decay pattern

Intersensor coherence, CASY-IU LHN, 1999-2009



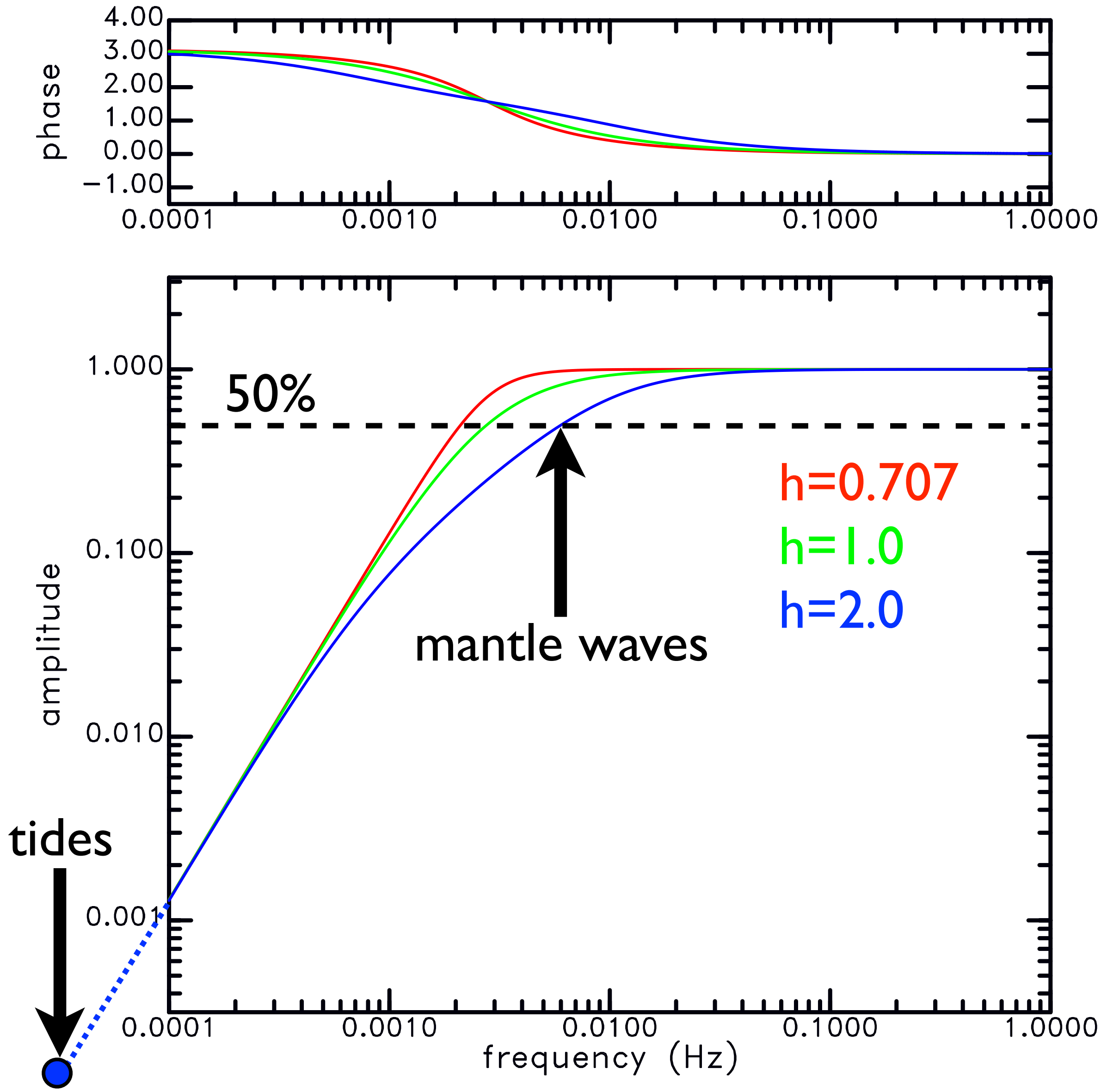
severe time- and frequency-dependent response error

STS-1 response decay



STS-1 response decay

STS-1 typical corrupted response: 360 second corner, overdamped

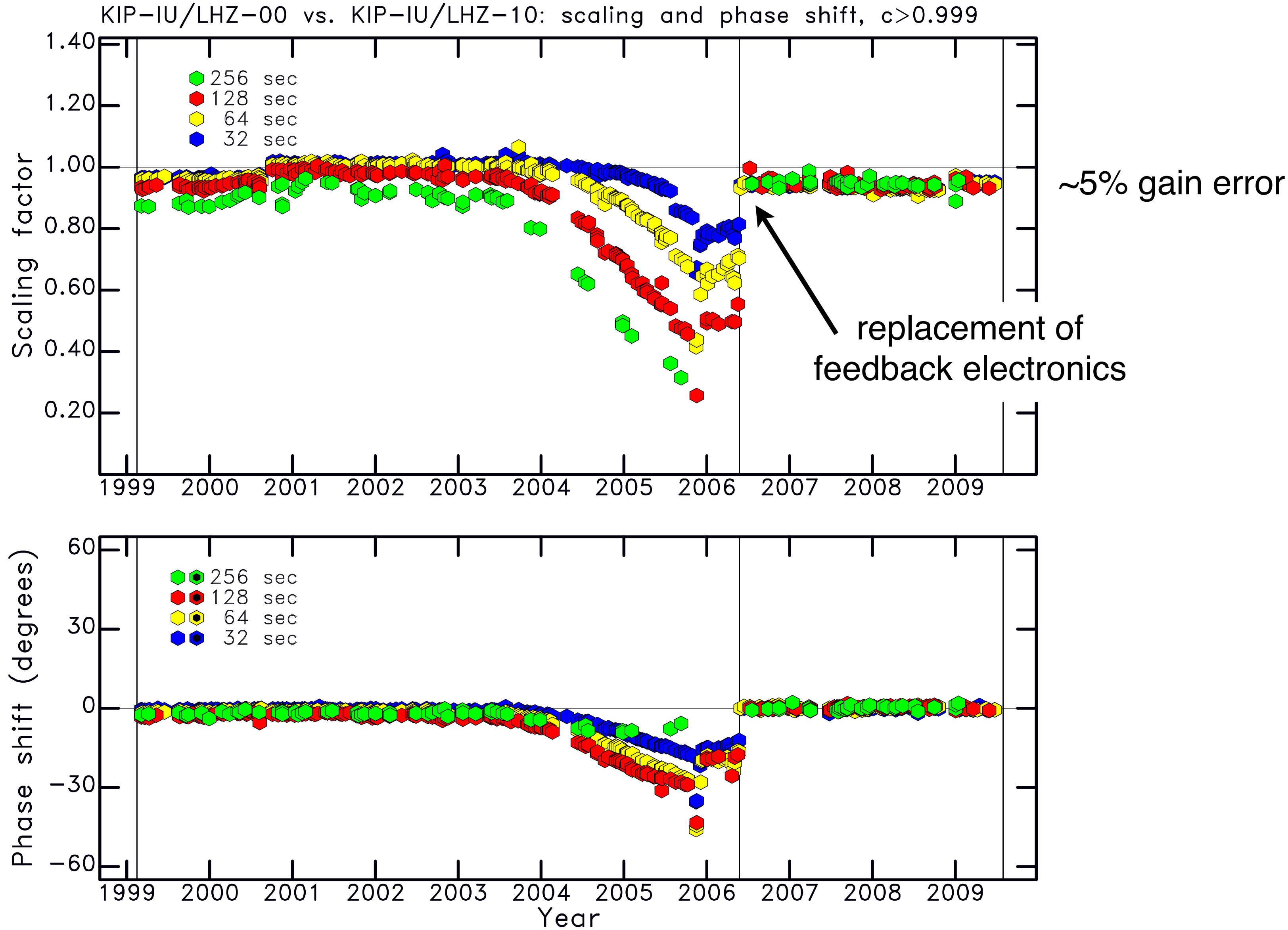


Hutt & Ringler: moisture in FBEs

Yuki & Ishihara: moisture in cable connectors

Hutt & Steim: too-short mechanical free period

Intersensor coherence, KIP-IU LHZ, 1999-2009



STS-1 decay pattern

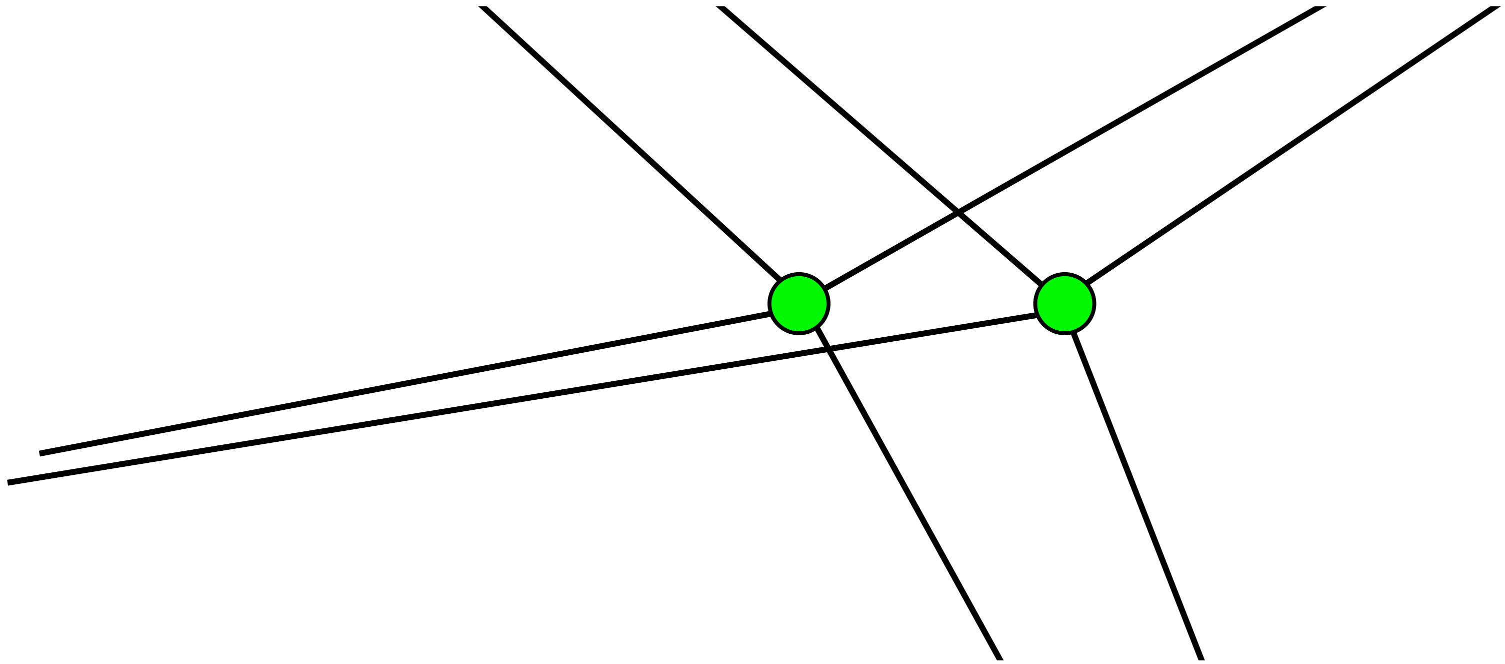
Main points

1. The data can tell you a lot about your stations
2. Things change (calibrate!)
3. All networks can be improved

timing
orientation
response
noise level

All are important!

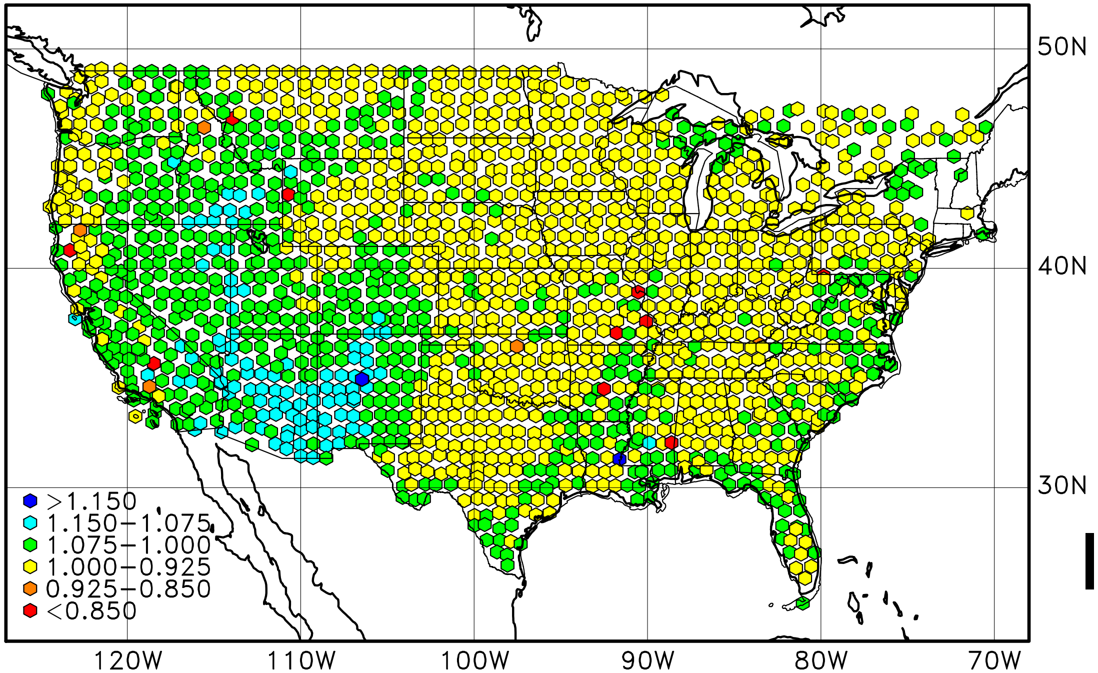
In-depth analysis of Rayleigh wave amplitudes:



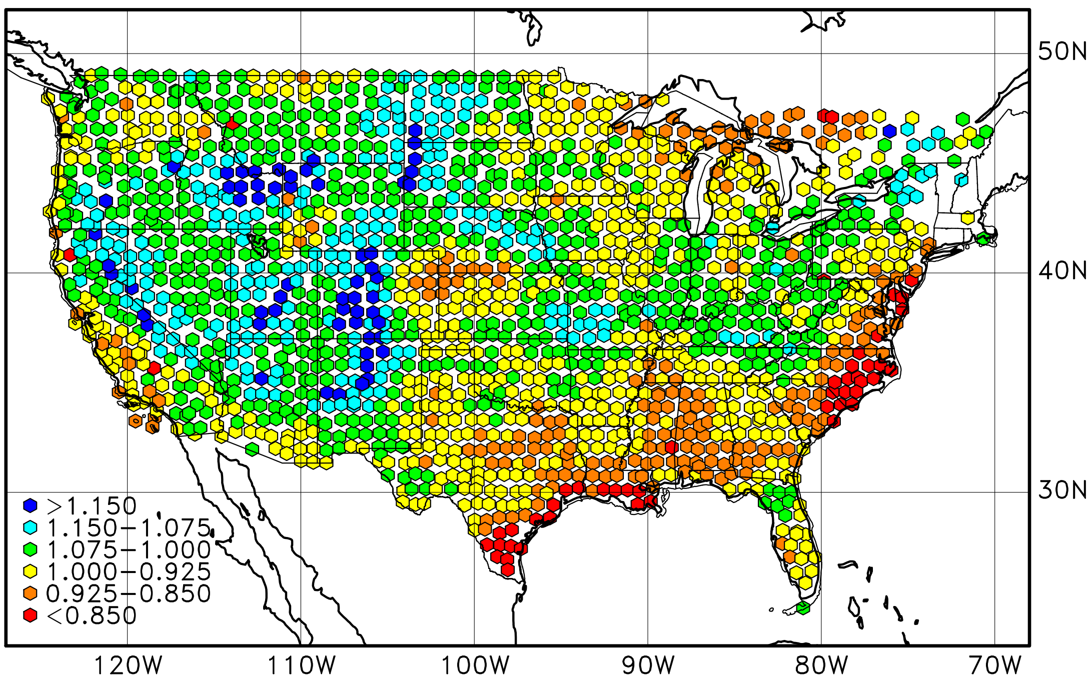
1. Measure Rayleigh wave amplitudes for many sources
2. Form amplitude ratios for adjacent stations
3. Average ratios over all events
4. Link all station pairs to determine amplitude factors across the entire array

Eddy & Ekström, 2013

Observed local Rayleigh wave amplitude factors

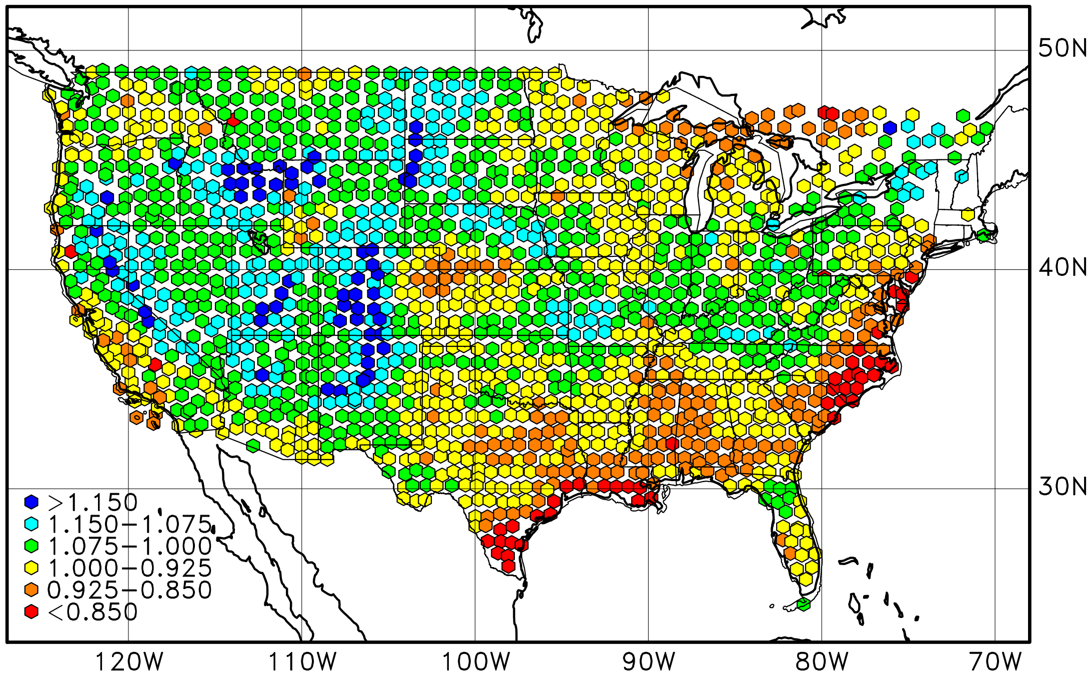


125 sec



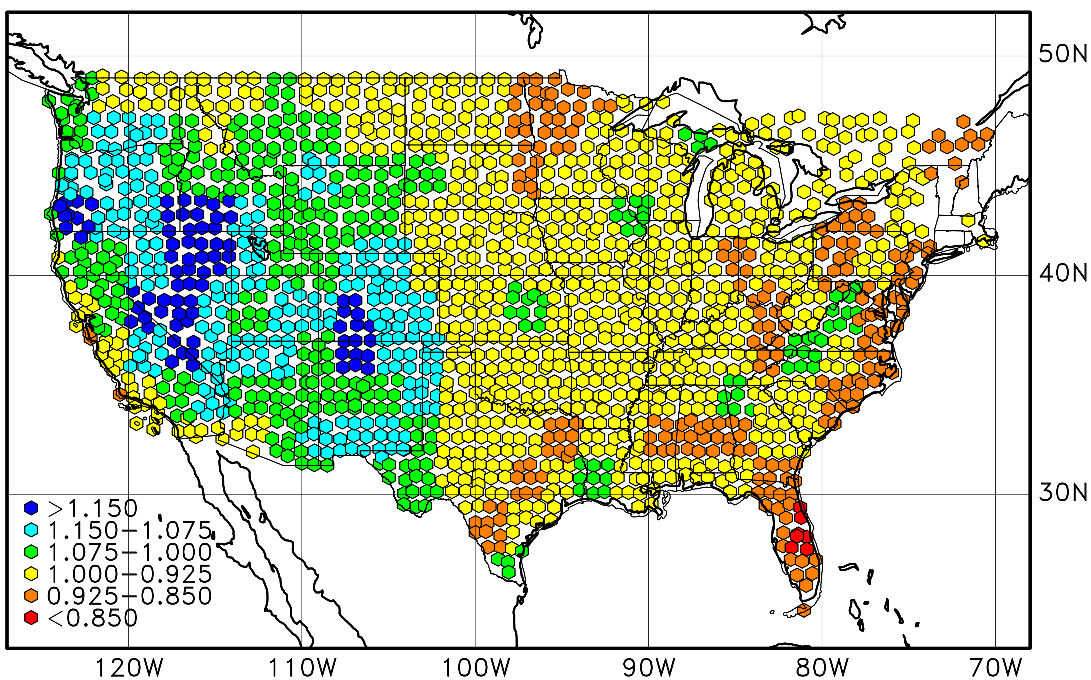
50 sec

Eddy & Ekström, 2013



Rayleigh wave local amplification at 50 sec. at each USArray station

observed



predicted

Predictions from ND08 mantle model (Nettles and Dziewonski, 2008) and CRUST2.0 (Bassin et al., 2000)

Eddy & Ekström, 2013