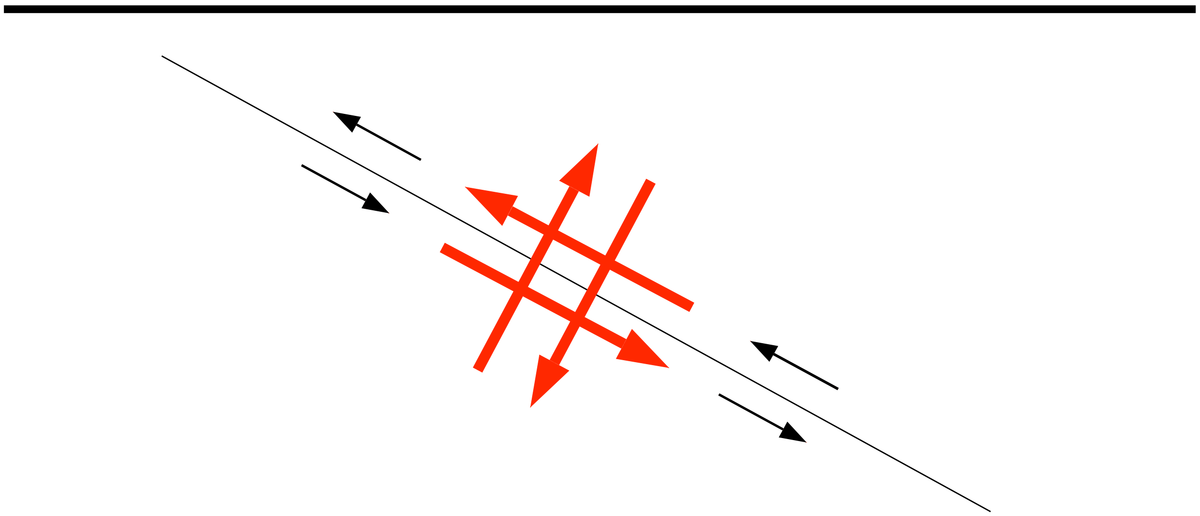
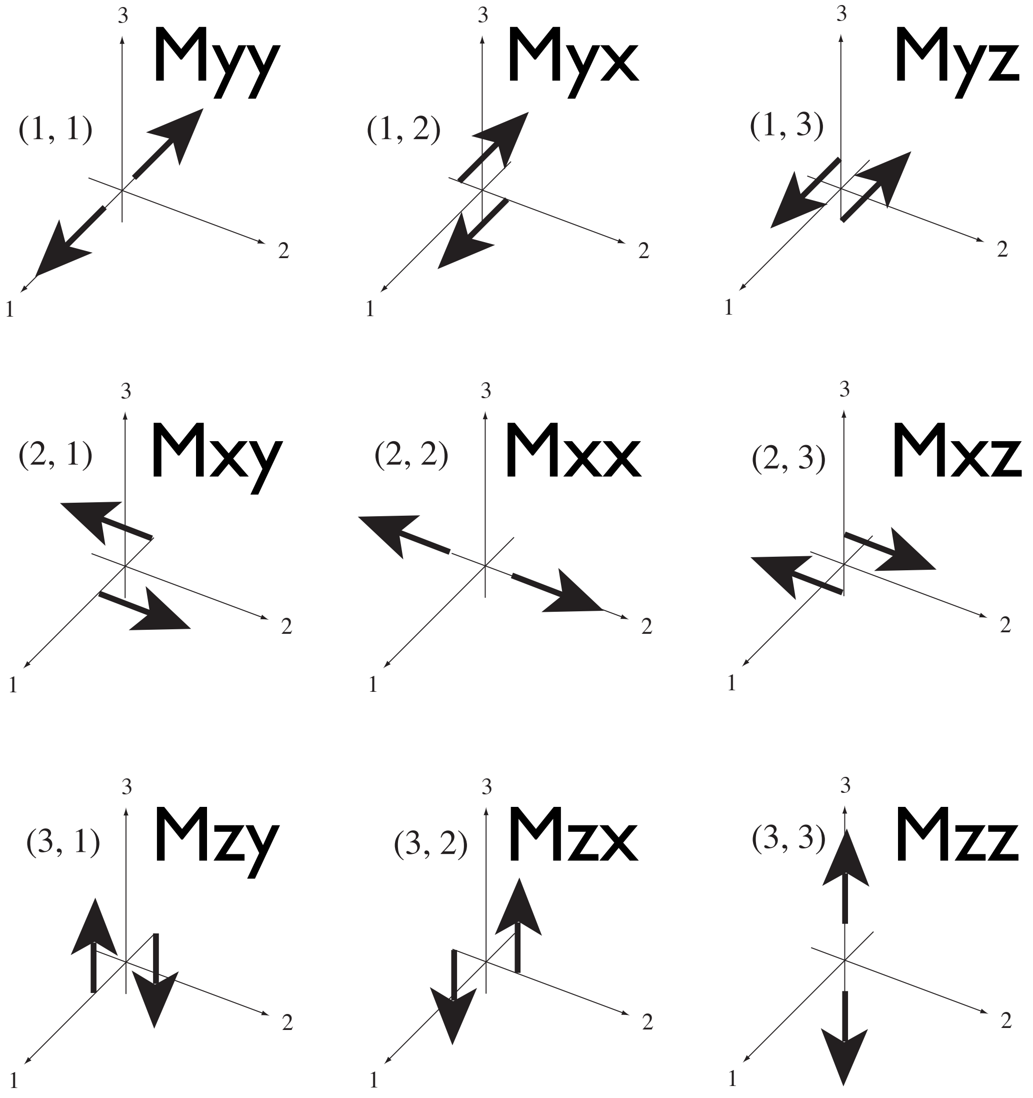
1. Moment-tensor analysis using global data
2. The Global CMT catalog
3. Using calibration information in waveform analysis
4. Data quality control using signals
5. Data quality control using noise
6. Finding interesting things in the noise
7. Using noise for tomography

Faulting force model



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

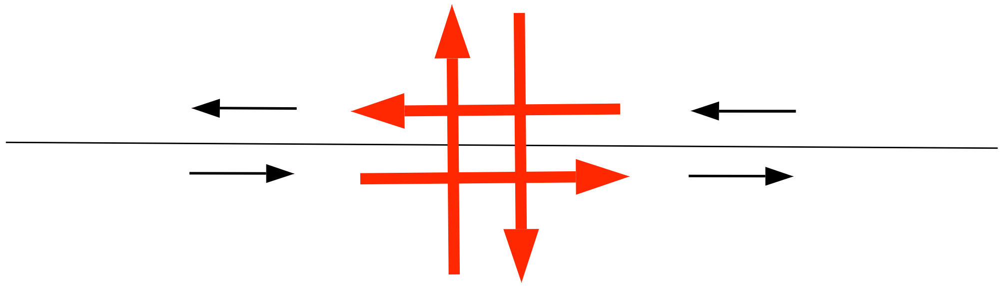
The nine dipoles of the seismic moment tensor



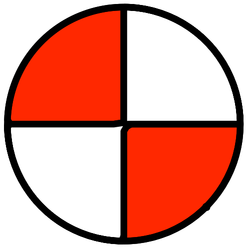
(Aki and Richards, 2002)

But, Mxy=Myx, Myz=Mzy, Mxz=Mzx

Mxy =



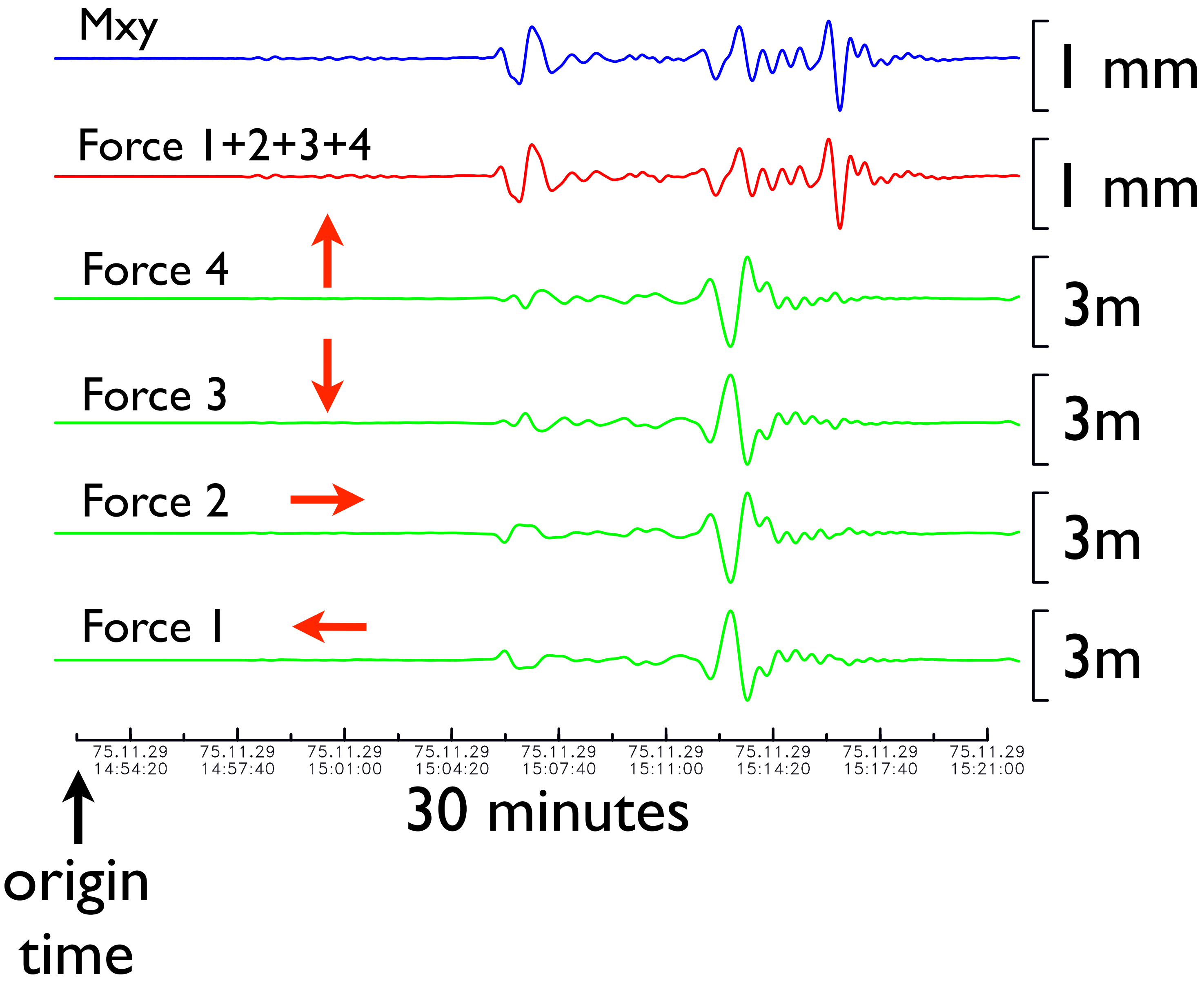
=



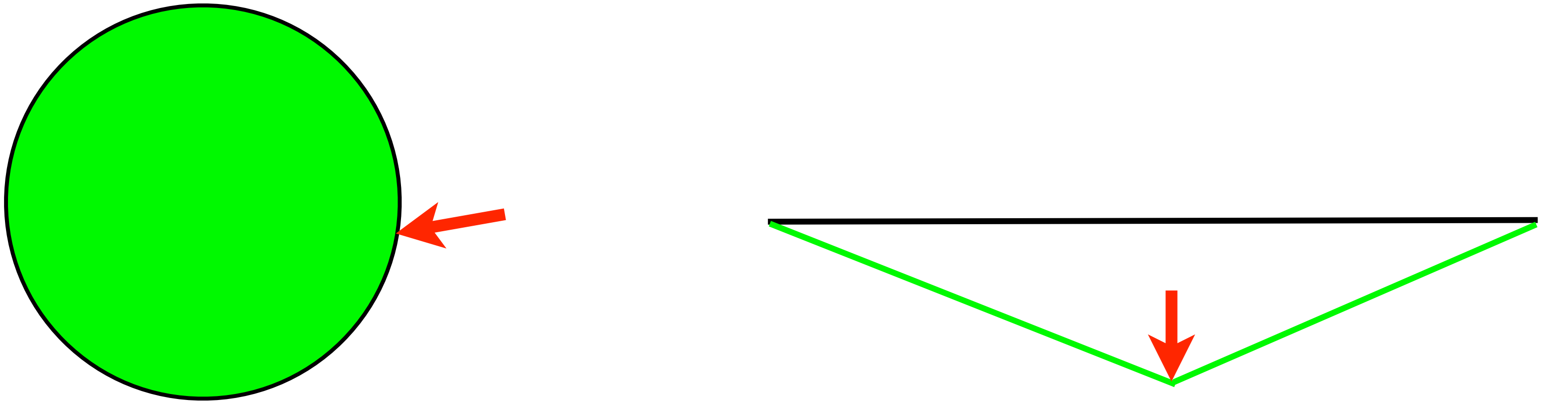
for example,

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

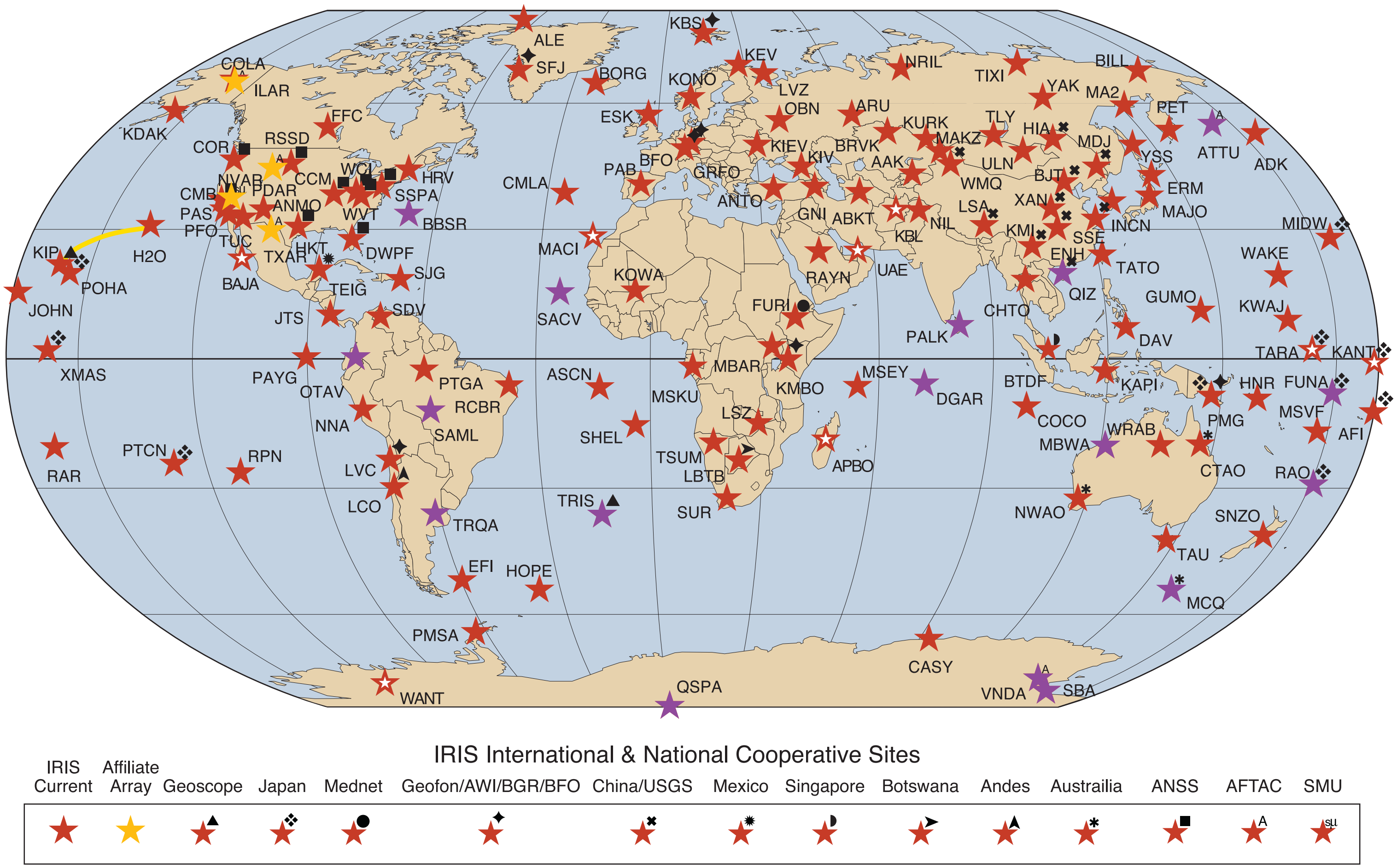
Model waveform depends only on the six elements of the moment tensor,

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

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

with respect to the moment tensor elements.

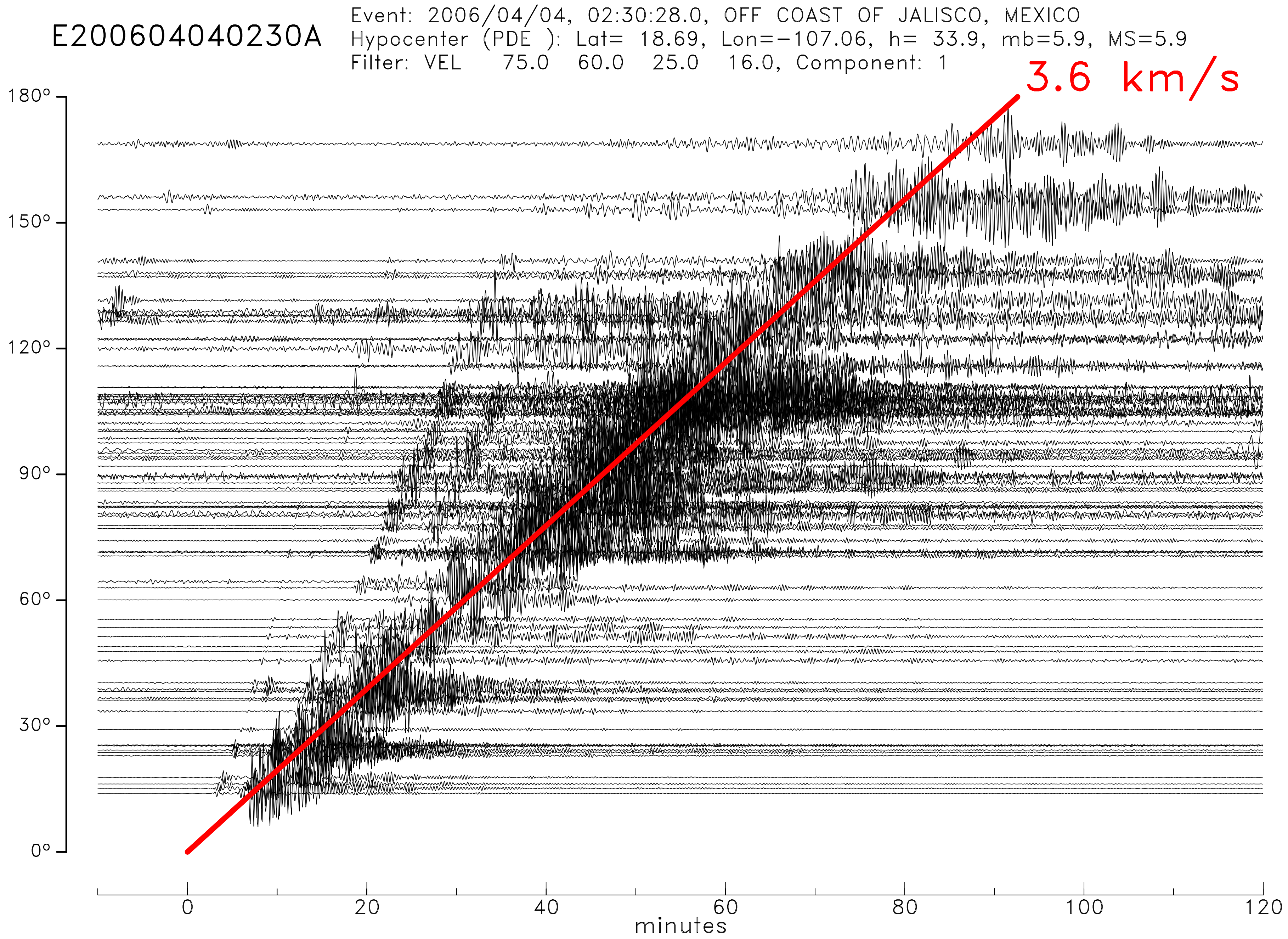
GLOBAL SEISMOGRAPHIC NETWORK



Current GSN station coverage of Earth is shown as of August 2005. Sites added in the past five years are noted in purple (stations) and orange (arrays). Sites planned to be completed are noted with white stars. Cooperative sites are indicated by symbols on the upper right "shoulder" of the stars.

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

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.

Vertical Longitudinal Transverse

Mzz

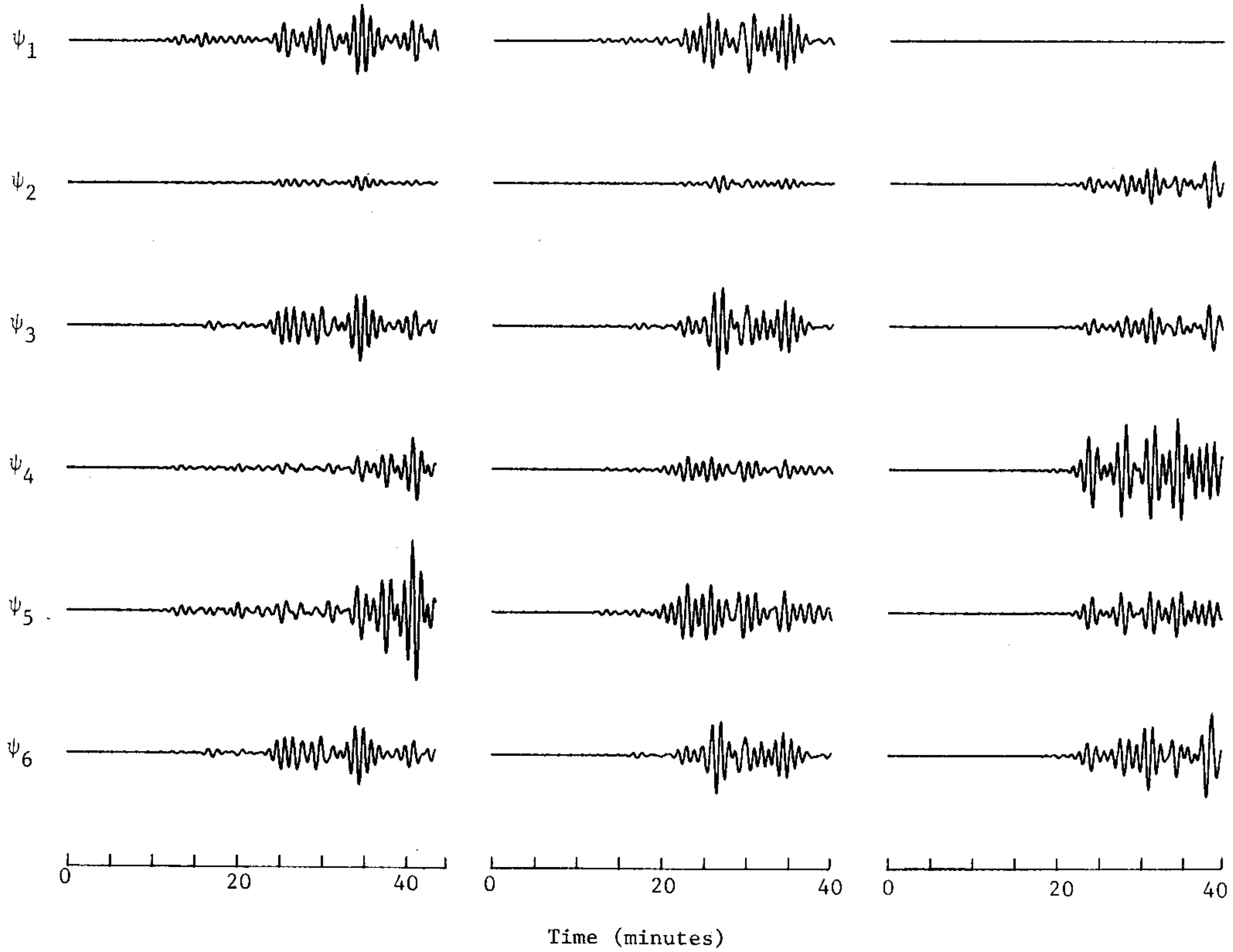
Myy

Mxx

Myz

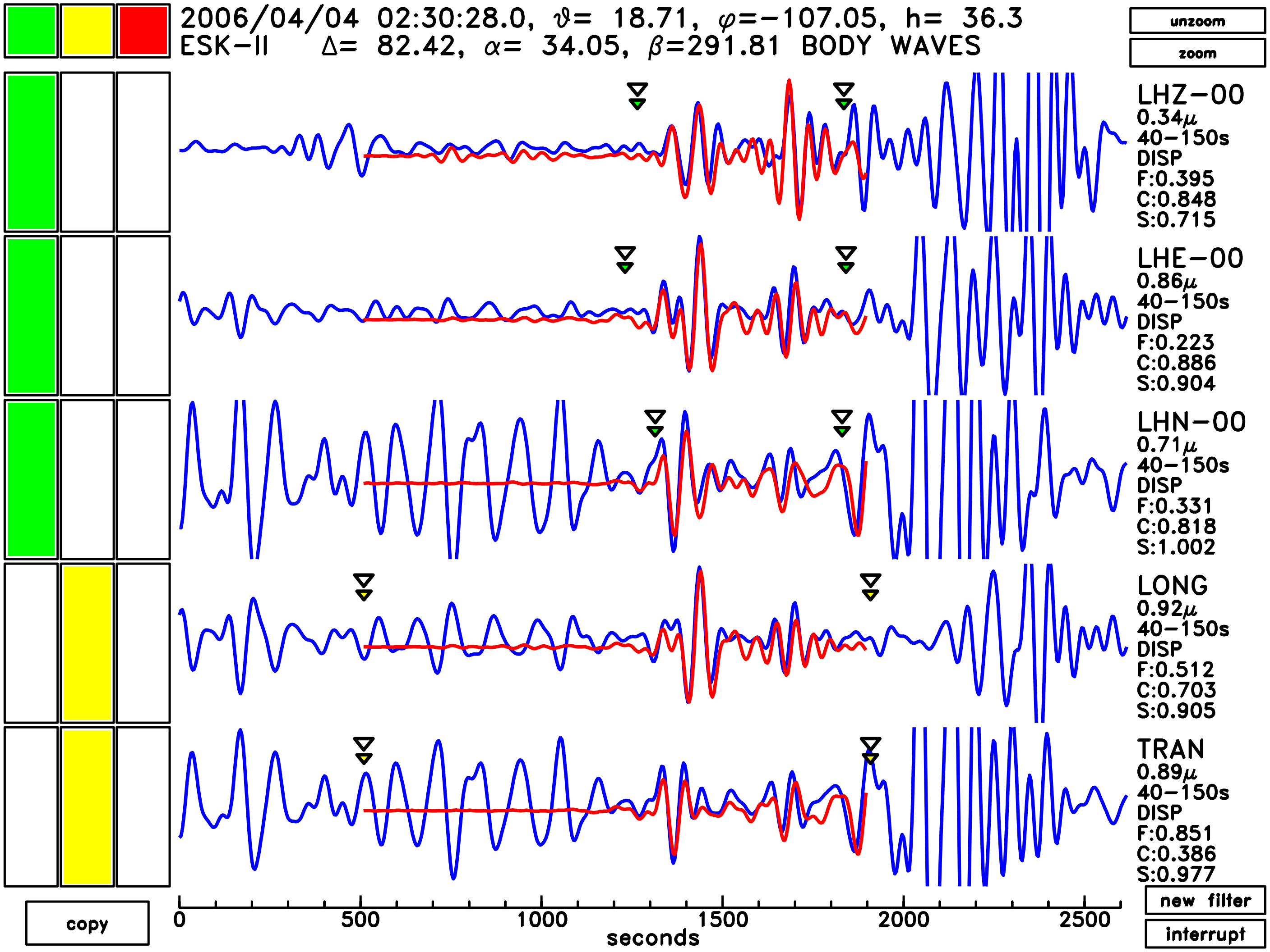
Mxz

Mxy



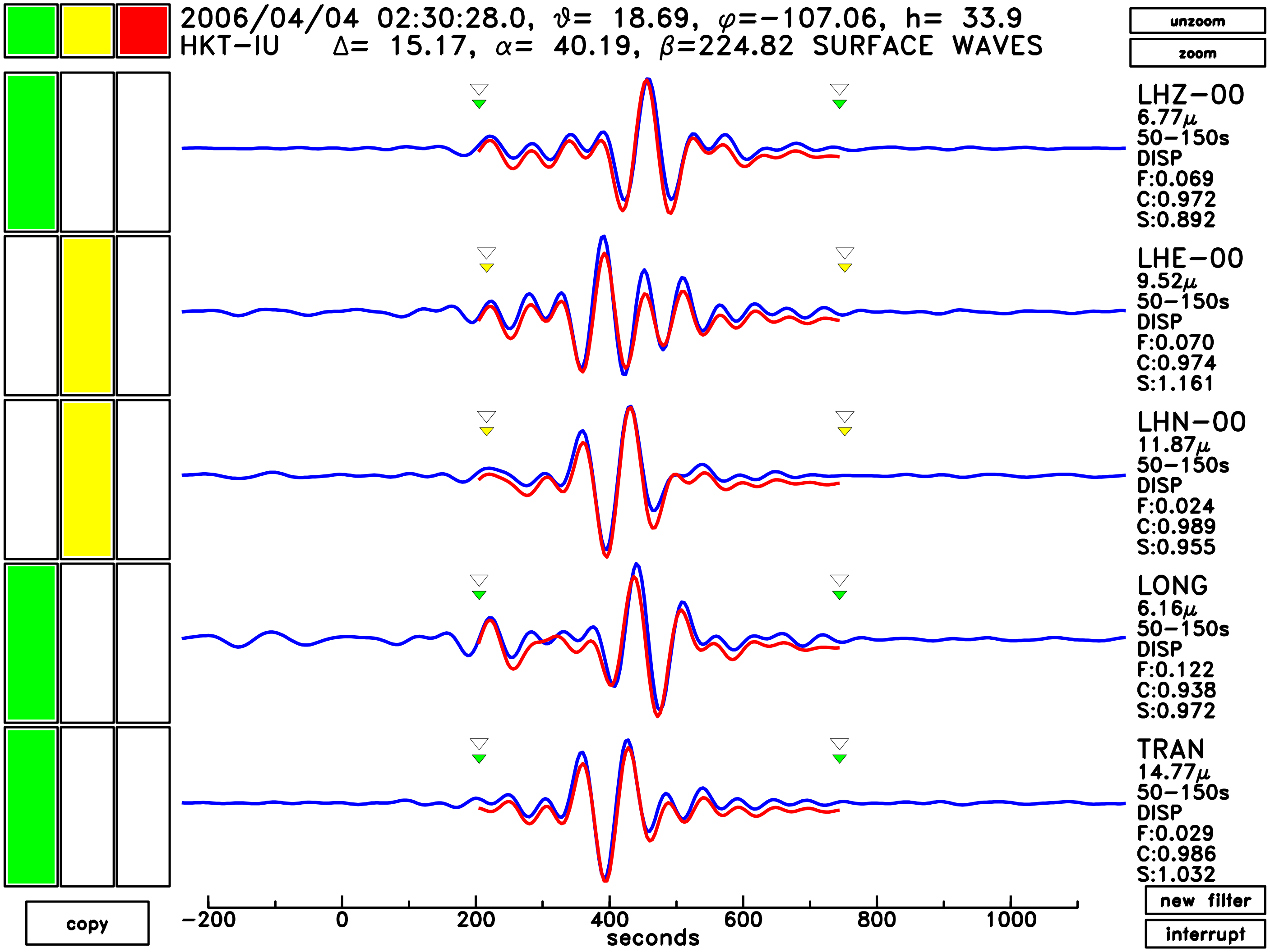
Excitation kernels for deep earthquake (580 km)

Fit to seismograms:
Body waves at Eskdalemuir, Scotland



blue - data ; red - model

Fit to seismograms:
Surface waves at Hockley, Texas



```
2006/04/04 02:30:28.0, ϑ= 18.69, φ=-107.06, h= 33.9
HKT-IU    Δ= 15.17, α= 40.19, β=224.82 SURFACE WAVES
```

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.

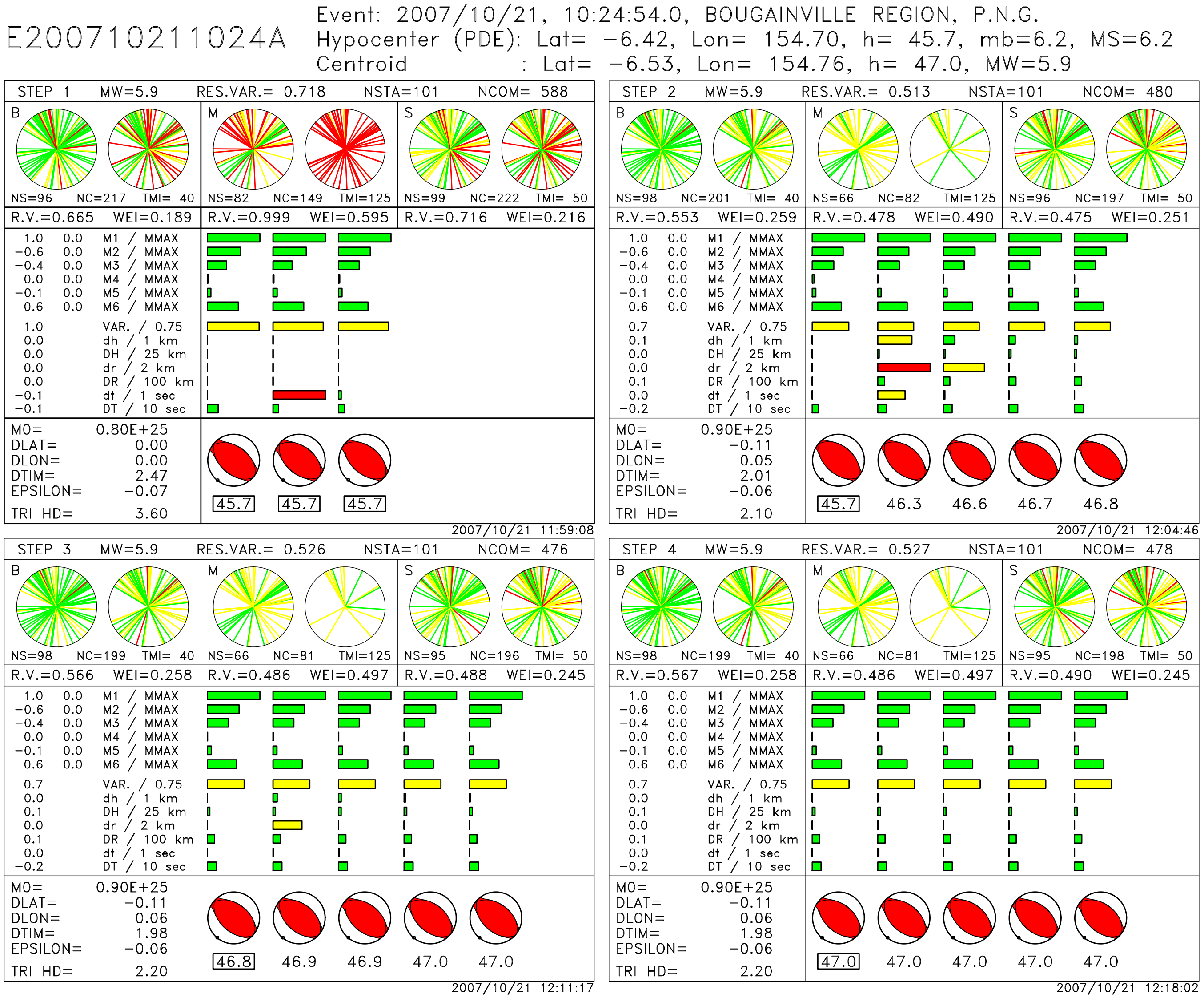
Solution for the Source Centroid

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



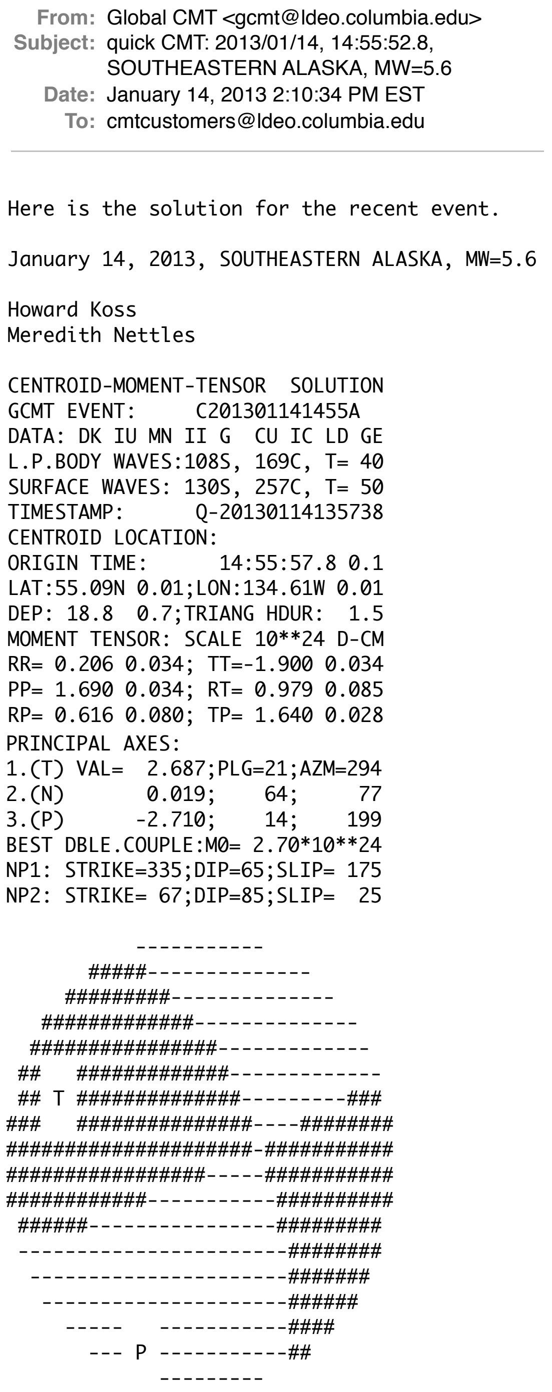
```
                 Event:  2007/10/21, 10:24:54.0, BOUGAINVILLE REGION, P.N.G.
E200710211024A   Hypocenter (PDE):  Lat= -6.42, Lon= 154.70, h= 45.7, mb=6.2, MS=6.2
                 Centroid         :  Lat= -6.53, Lon= 154.76, h= 47.0, MW=5.9
```

```
STEP 1   MW=5.9   RES.VAR.= 0.718   NSTA=101   NCOM= 588
B                          M                          S
NS=96  NC=217  TMI= 40     NS=82  NC=149  TMI=125     NS=99  NC=222  TMI= 50
R.V.=0.665  WEI=0.189      R.V.=0.999  WEI=0.595      R.V.=0.716  WEI=0.216
 1.0   0.0   M1 / MMAX
-0.6   0.0   M2 / MMAX
-0.4   0.0   M3 / MMAX
 0.0   0.0   M4 / MMAX
-0.1   0.0   M5 / MMAX
 0.6   0.0   M6 / MMAX
 1.0         VAR. / 0.75
 0.0         dh / 1 km
 0.0         DH / 25 km
 0.0         dr / 2 km
 0.0         DR / 100 km
-0.1         dt / 1 sec
-0.1         DT / 10 sec
M0=        0.80E+25
DLAT=          0.00
DLON=          0.00
DTIM=          2.47
EPSILON=      -0.07        45.7   45.7   45.7
TRI  HD=       3.60
                                              2007/10/21  11:59:08
```

```
STEP 2   MW=5.9   RES.VAR.= 0.513   NSTA=101   NCOM= 480
B                          M                          S
NS=98  NC=201  TMI= 40     NS=66  NC=82   TMI=125     NS=96  NC=197  TMI= 50
R.V.=0.553  WEI=0.259      R.V.=0.478  WEI=0.490      R.V.=0.475  WEI=0.251
 1.0   0.0   M1 / MMAX
-0.6   0.0   M2 / MMAX
-0.4   0.0   M3 / MMAX
 0.0   0.0   M4 / MMAX
-0.1   0.0   M5 / MMAX
 0.6   0.0   M6 / MMAX
 0.7         VAR. / 0.75
 0.1         dh / 1 km
 0.0         DH / 25 km
 0.0         dr / 2 km
 0.1         DR / 100 km
 0.0         dt / 1 sec
-0.2         DT / 10 sec
M0=        0.90E+25
DLAT=         -0.11
DLON=          0.05
DTIM=          2.01
EPSILON=      -0.06        45.7   46.3   46.6   46.7   46.8
TRI  HD=       2.10
                                              2007/10/21  12:04:46
```

```
STEP 3   MW=5.9   RES.VAR.= 0.526   NSTA=101   NCOM= 476
B                          M                          S
NS=98  NC=199  TMI= 40     NS=66  NC=81   TMI=125     NS=95  NC=196  TMI= 50
R.V.=0.566  WEI=0.258      R.V.=0.486  WEI=0.497      R.V.=0.488  WEI=0.245
 1.0   0.0   M1 / MMAX
-0.6   0.0   M2 / MMAX
-0.4   0.0   M3 / MMAX
 0.0   0.0   M4 / MMAX
-0.1   0.0   M5 / MMAX
 0.6   0.0   M6 / MMAX
 0.7         VAR. / 0.75
 0.0         dh / 1 km
 0.1         DH / 25 km
 0.0         dr / 2 km
 0.1         DR / 100 km
 0.0         dt / 1 sec
-0.2         DT / 10 sec
M0=        0.90E+25
DLAT=         -0.11
DLON=          0.06
DTIM=          1.98
EPSILON=      -0.06        46.8   46.9   46.9   47.0   47.0
TRI  HD=       2.20
                                              2007/10/21  12:11:17
```

```
STEP 4   MW=5.9   RES.VAR.= 0.527   NSTA=101   NCOM= 478
B                          M                          S
NS=98  NC=199  TMI= 40     NS=66  NC=81   TMI=125     NS=95  NC=198  TMI= 50
R.V.=0.567  WEI=0.258      R.V.=0.486  WEI=0.497      R.V.=0.490  WEI=0.245
 1.0   0.0   M1 / MMAX
-0.6   0.0   M2 / MMAX
-0.4   0.0   M3 / MMAX
 0.0   0.0   M4 / MMAX
-0.1   0.0   M5 / MMAX
 0.6   0.0   M6 / MMAX
 0.7         VAR. / 0.75
 0.0         dh / 1 km
 0.1         DH / 25 km
 0.0         dr / 2 km
 0.1         DR / 100 km
 0.0         dt / 1 sec
-0.2         DT / 10 sec
M0=        0.90E+25
DLAT=         -0.11
DLON=          0.06
DTIM=          1.98
EPSILON=      -0.06        47.0   47.0   47.0   47.0   47.0
TRI  HD=       2.20
                                              2007/10/21  12:18:02
```



From: Global CMT <gcmt@ldeo.columbia.edu>
Subject: quick CMT: 2013/01/14, 14:55:52.8, SOUTHEASTERN ALASKA, MW=5.6
Date: January 14, 2013 2:10:34 PM EST
To: cmtcustomers@ldeo.columbia.edu

```
Here is the solution for the recent event.

January 14, 2013, SOUTHEASTERN ALASKA, MW=5.6

Howard Koss
Meredith Nettles

CENTROID-MOMENT-TENSOR  SOLUTION
GCMT EVENT:     C201301141455A
DATA: DK IU MN II G  CU IC LD GE
L.P.BODY WAVES:108S, 169C, T= 40
SURFACE WAVES: 130S, 257C, T= 50
TIMESTAMP:      Q-20130114135738
CENTROID LOCATION:
ORIGIN TIME:      14:55:57.8 0.1
LAT:55.09N 0.01;LON:134.61W 0.01
DEP: 18.8  0.7;TRIANG HDUR:  1.5
MOMENT TENSOR: SCALE 10**24 D-CM
RR= 0.206 0.034; TT=-1.900 0.034
PP= 1.690 0.034; RT= 0.979 0.085
RP= 0.616 0.080; TP= 1.640 0.028
PRINCIPAL AXES:
1.(T) VAL=  2.687;PLG=21;AZM=294
2.(N)       0.019;    64;     77
3.(P)      -2.710;    14;    199
BEST DBLE.COUPLE:M0= 2.70*10**24
NP1: STRIKE=335;DIP=65;SLIP= 175
NP2: STRIKE= 67;DIP=85;SLIP=  25

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

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

Southeastern Alaska
January 14, 2013
M=5.6

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

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
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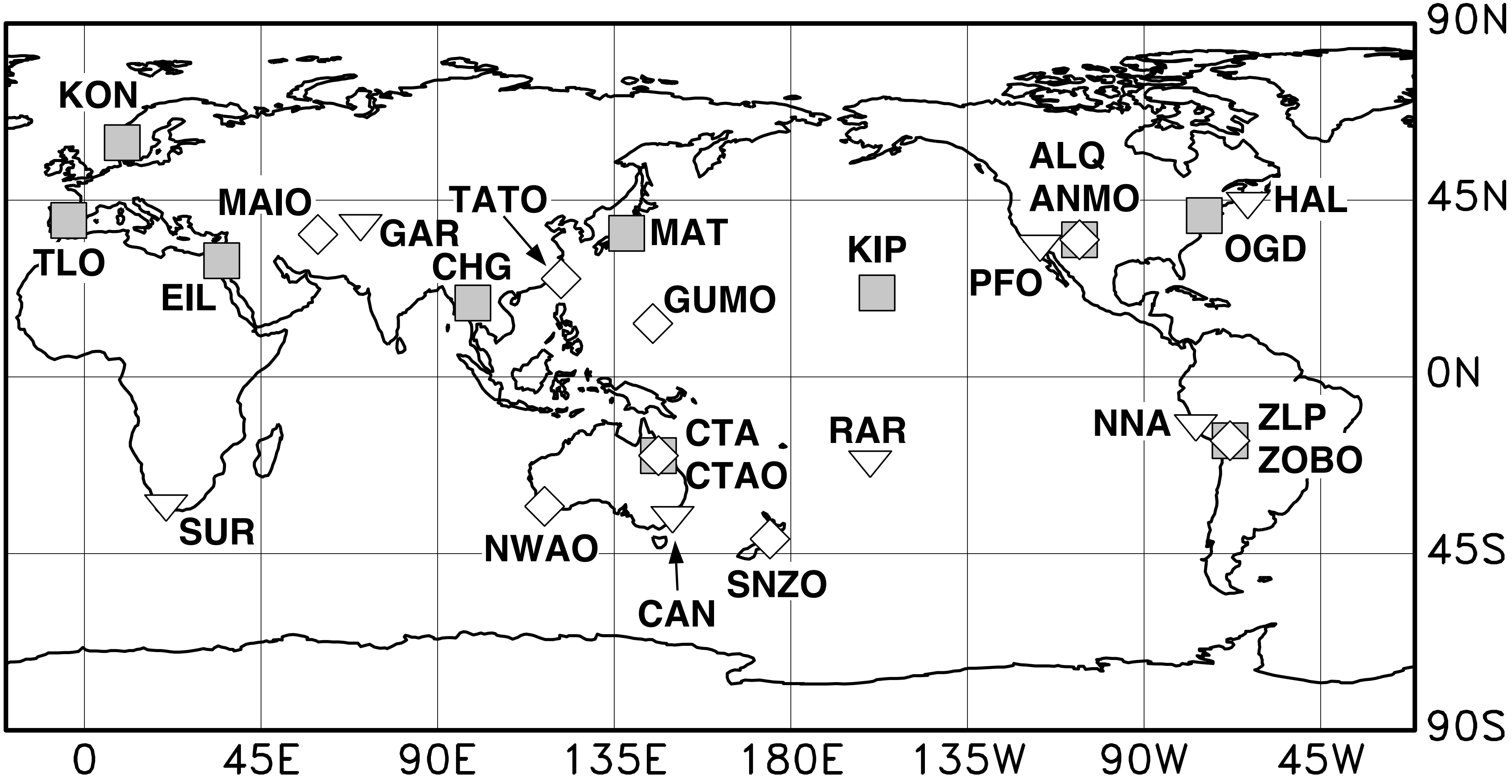
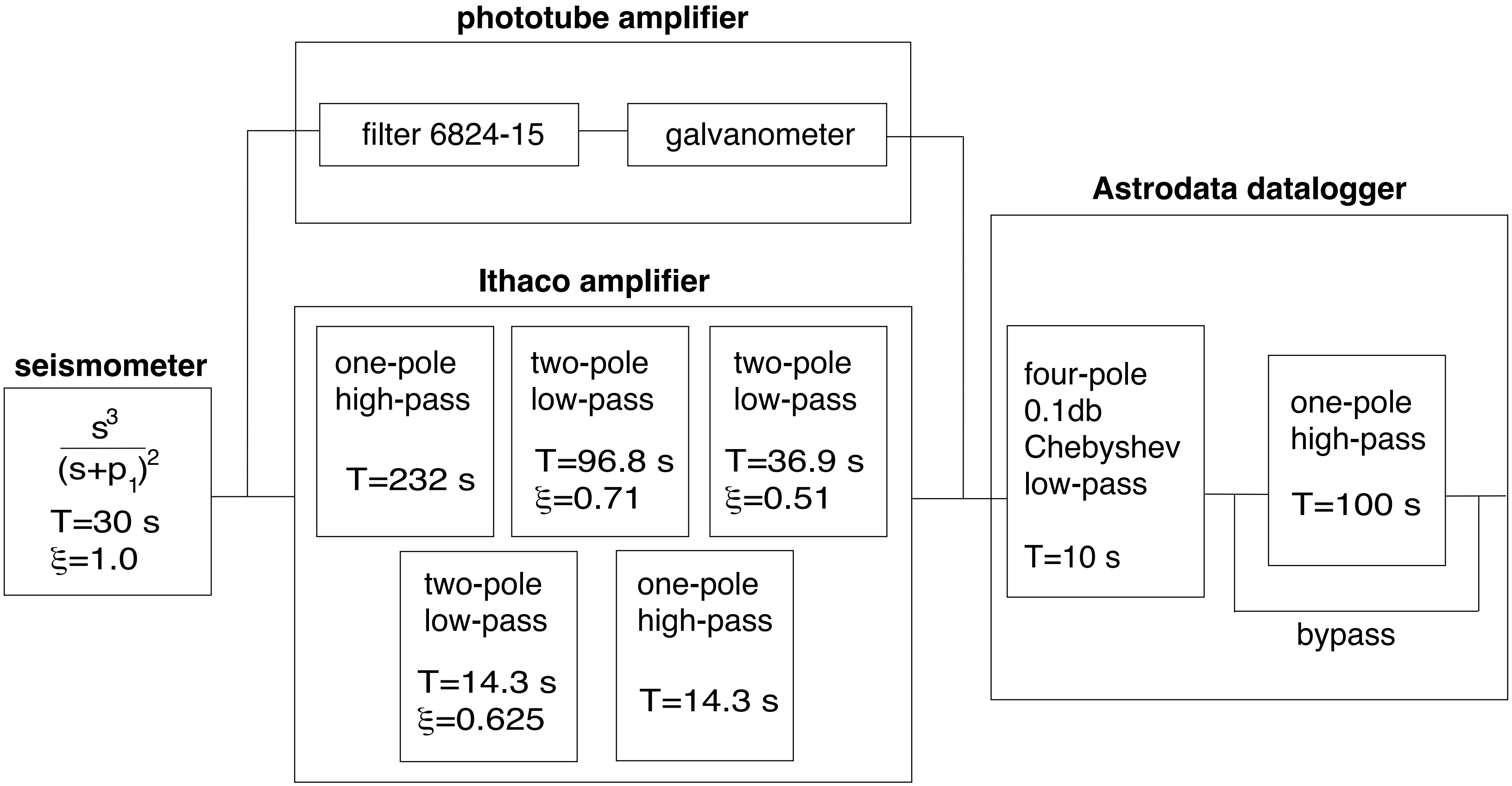
Quantitative waveform analysis requires highly accurate instrument response information

The Global Digital Network in 1976



▨ High-Gain Long-Period (HGLP) network

HGLP seismometer and recording system



seismometer

$\frac{s^3}{(s+p_1)^2}$

T=30 s

ξ=1.0

phototube amplifier

filter 6824-15

galvanometer

Ithaco amplifier

one-pole high-pass
T=232 s

two-pole low-pass
T=96.8 s
ξ=0.71

two-pole low-pass
T=36.9 s
ξ=0.51

two-pole low-pass
T=14.3 s
ξ=0.625

one-pole high-pass
T=14.3 s

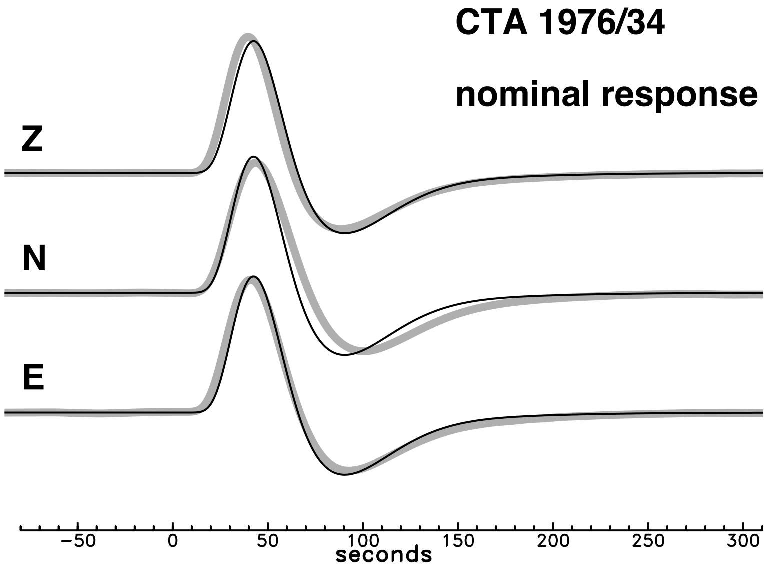
Astrodata datalogger

four-pole 0.1db Chebyshev low-pass
T=10 s

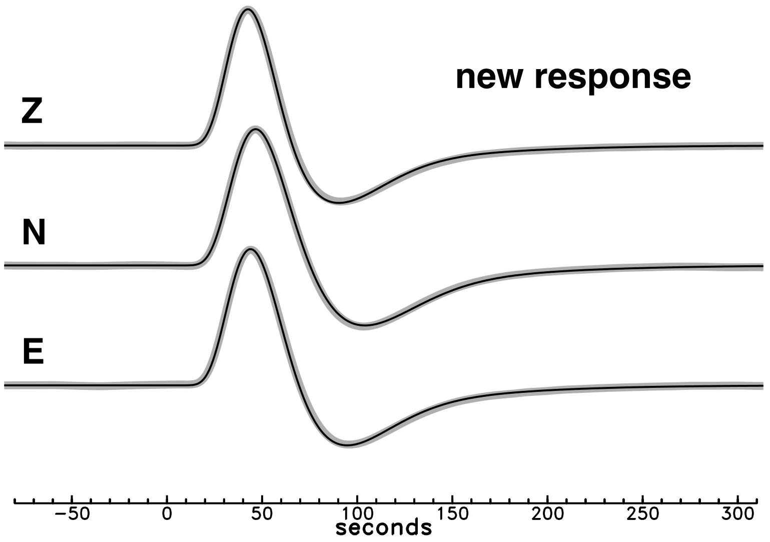
one-pole high-pass
T=100 s

bypass

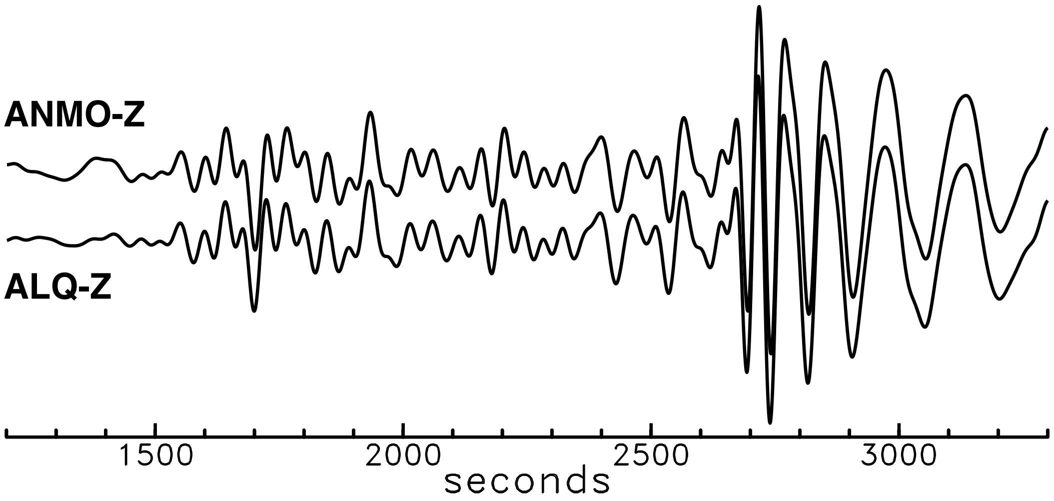
Original calibration pulses and pulses for nominal response



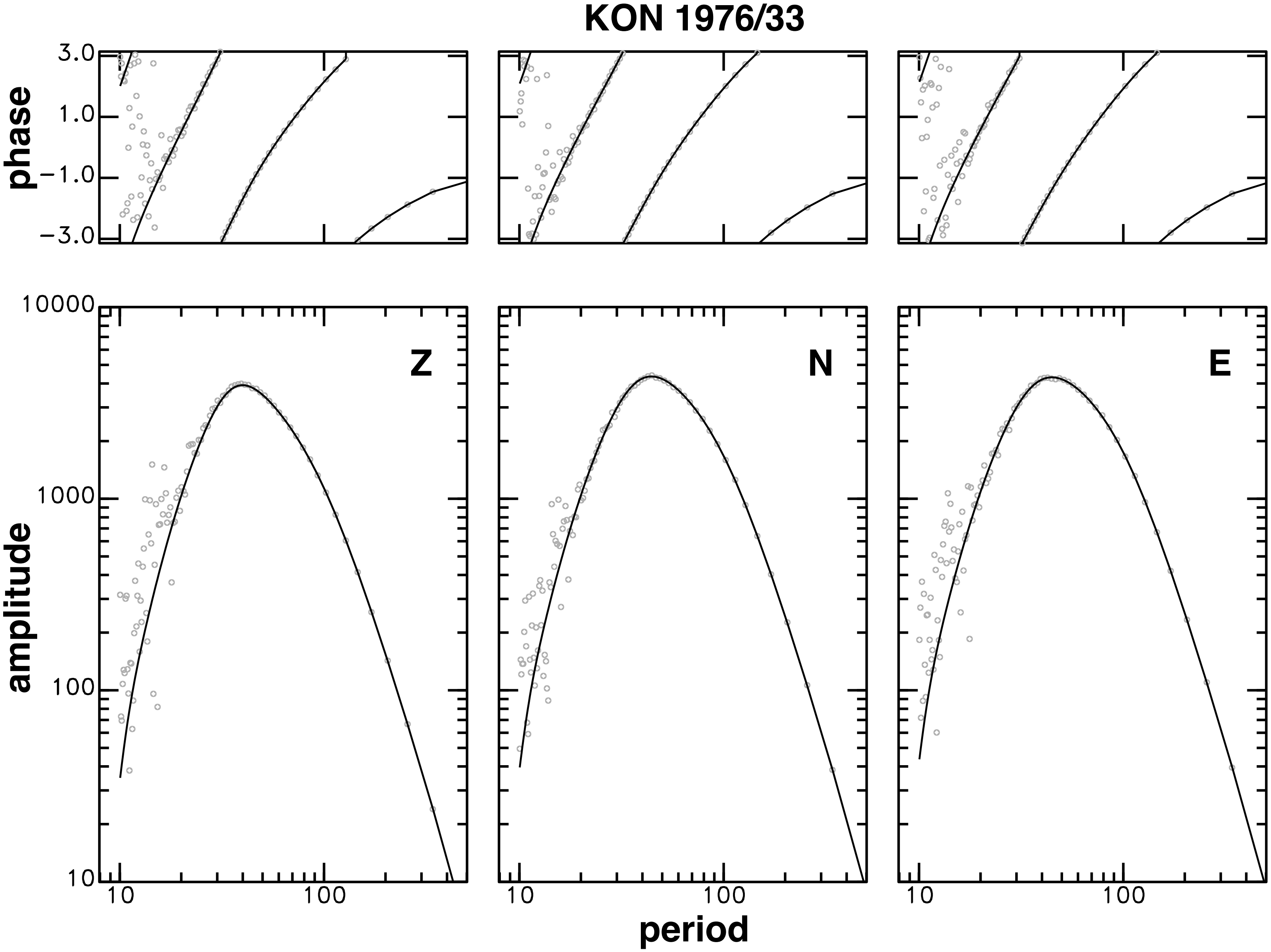
Original calibration pulses and pulses for new response after inversion



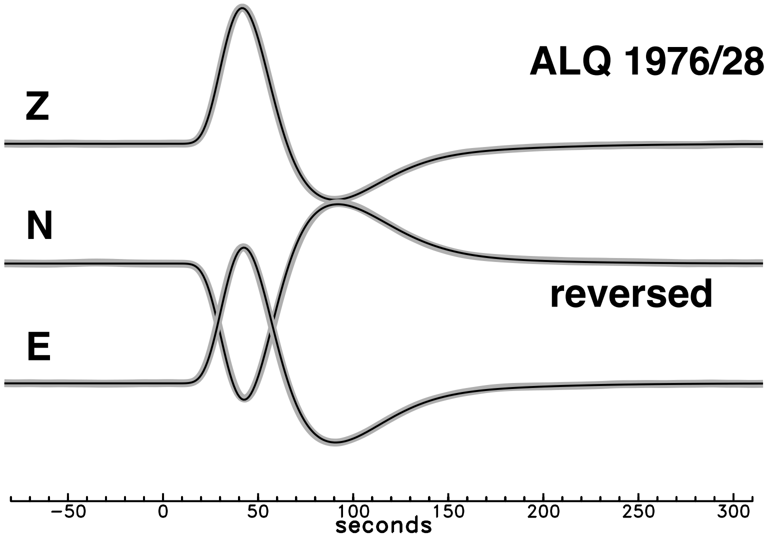
Comparison of waveforms after normalizing responses for two stations in the same location



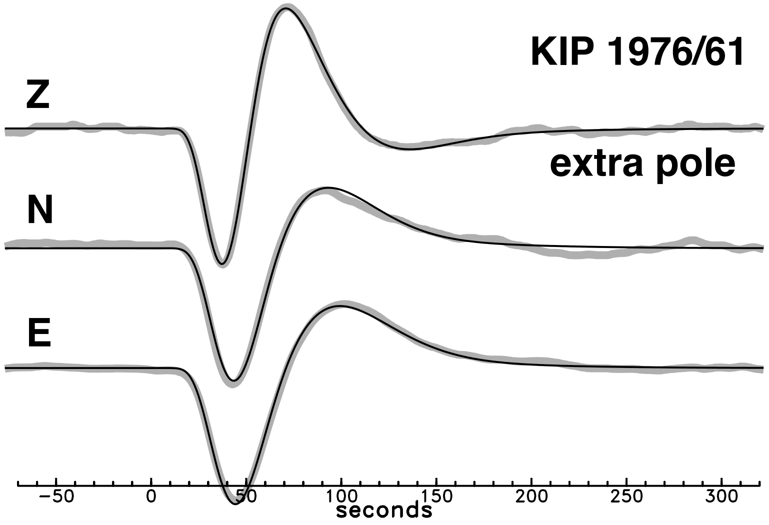
Check of new responses -- sine-wave calibrations



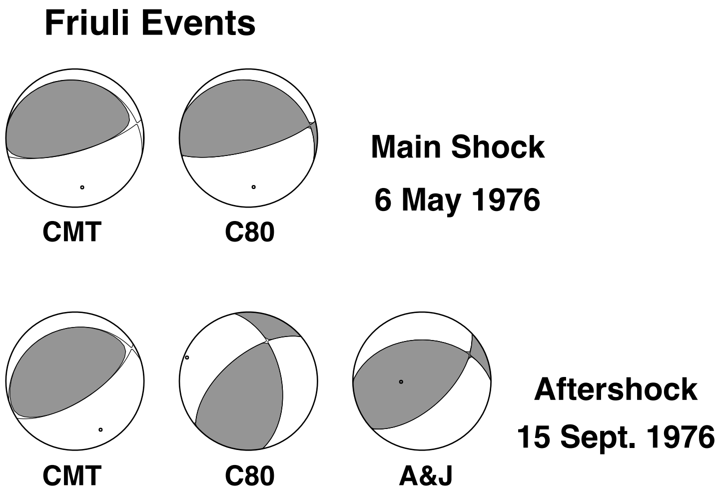
Some channels were reversed for some periods of time

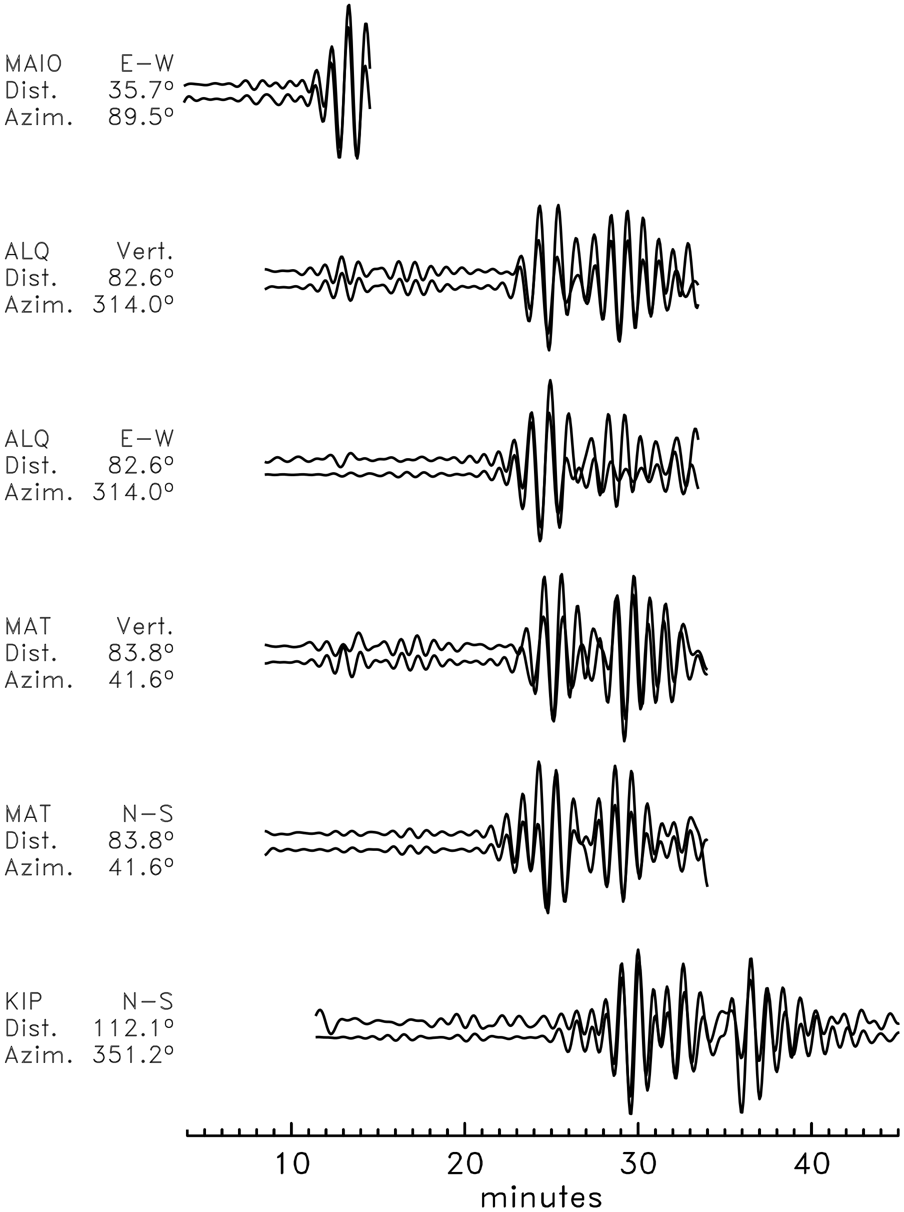


Some channels had extra filters for some periods of time



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

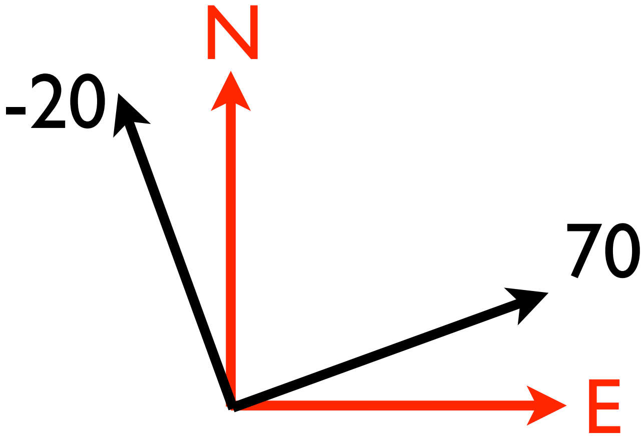
4a. Sensor orientation

4b. Sensor response stability

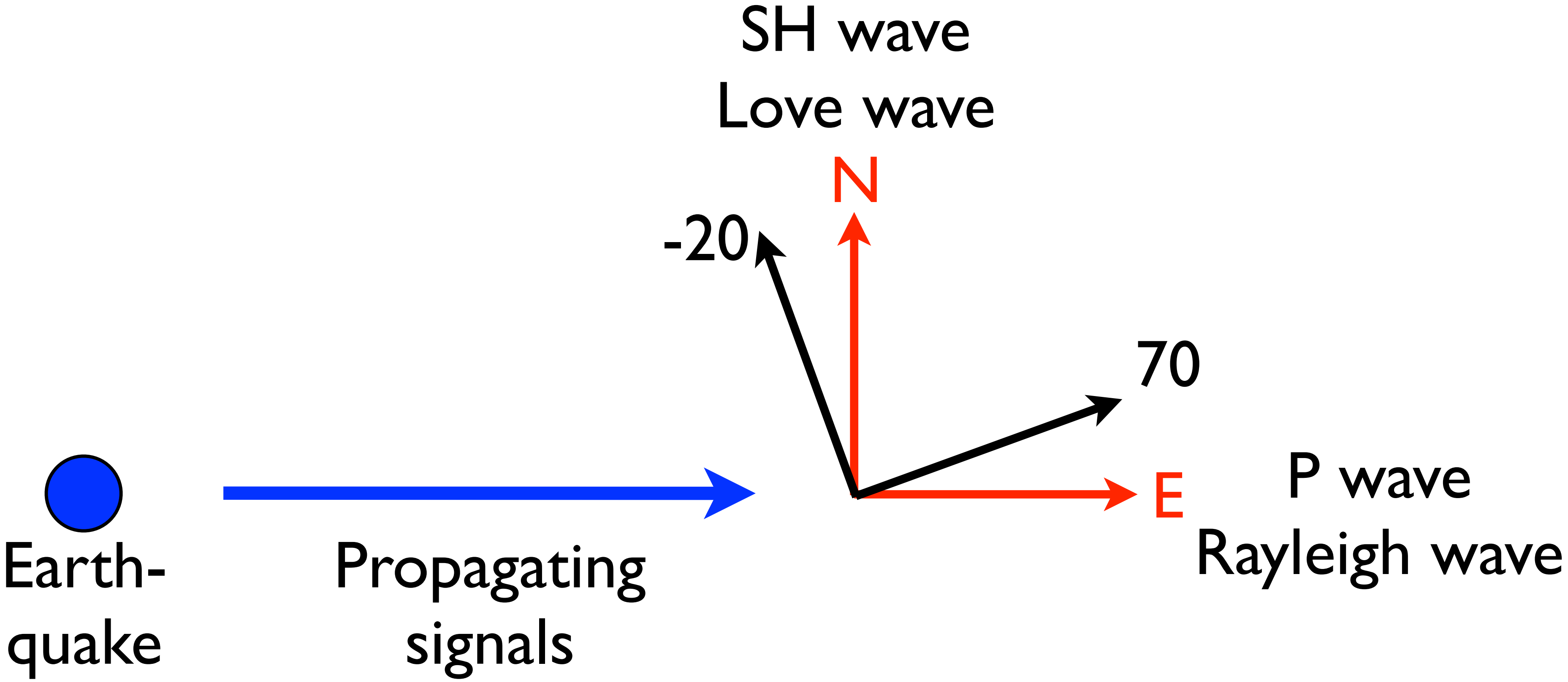
Horizontal Polarization Problems

Desired (assumed) orientation of seismometer

True orientation of seismometer



Natural Polarization of Earthquake Signals



SH wave
Love wave

N

-20

70

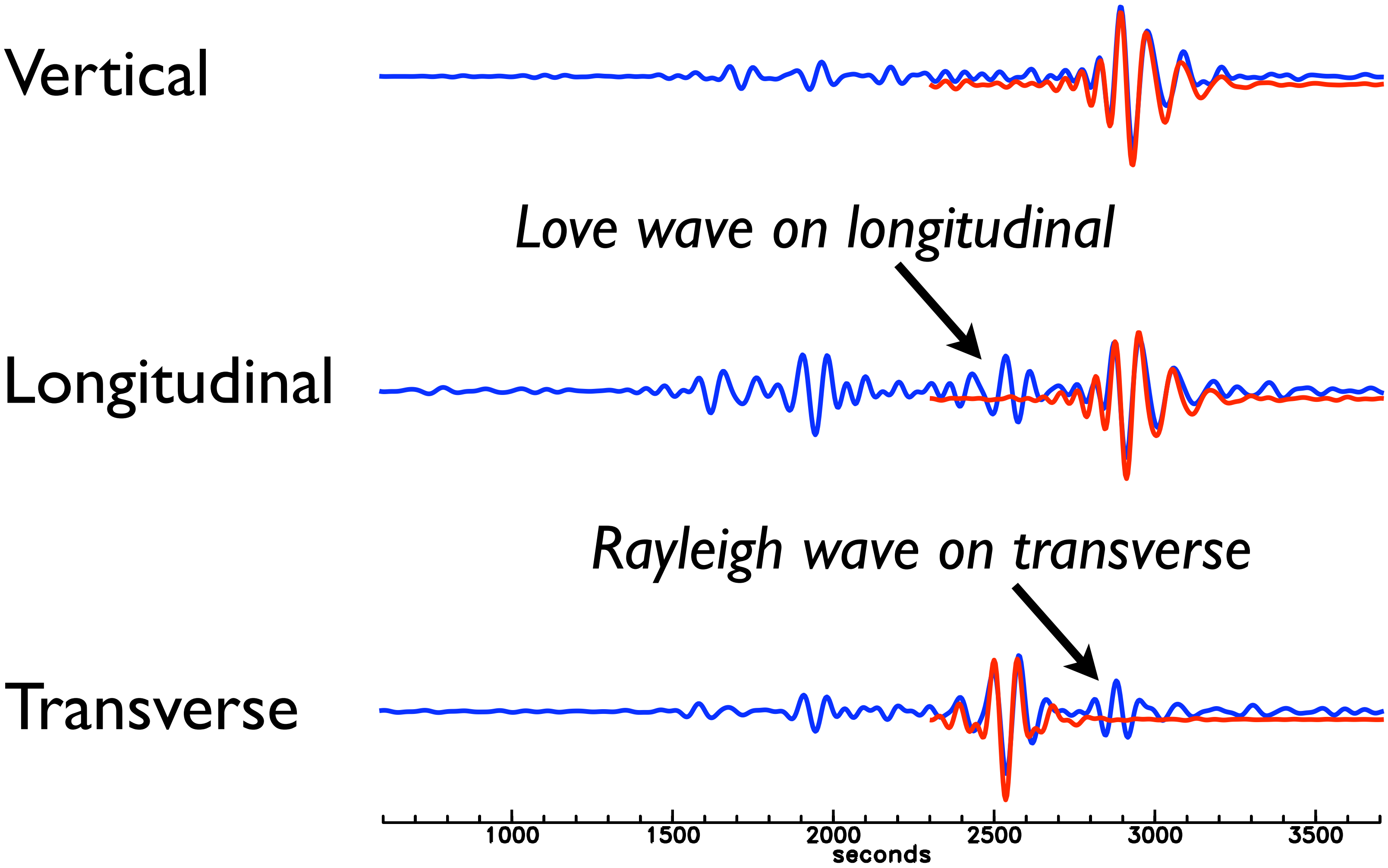
E

P wave
Rayleigh wave

Earth-
quake

Propagating
signals

Symptoms of a misoriented sensor



Vertical

Love wave on longitudinal

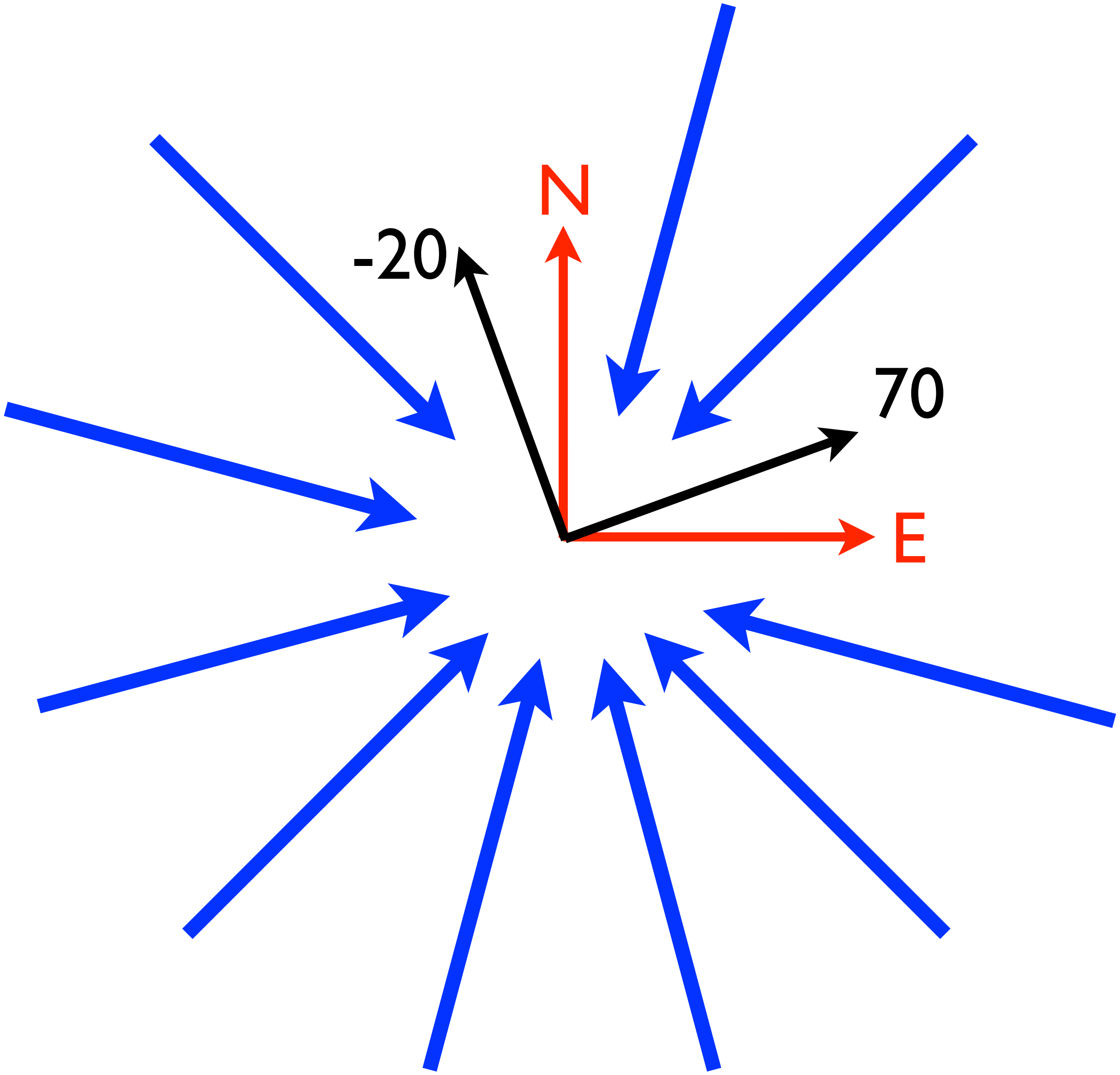
Longitudinal

Rayleigh wave on transverse

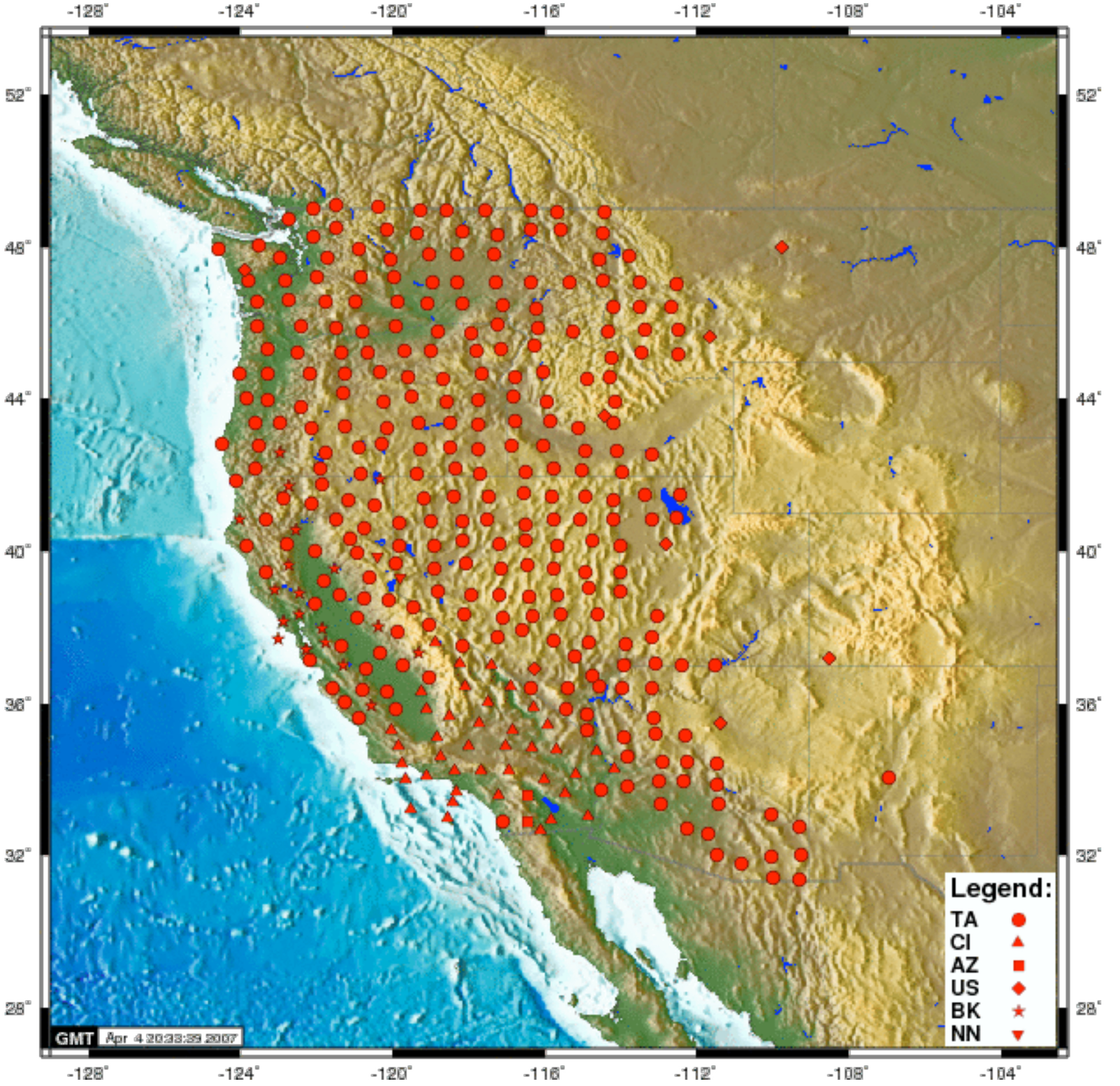
Transverse

Station D09A, earthquake on 08/20/2007

Many earthquake signals -- invert for orientation of sensor



USArray Transportable Array, April 2007



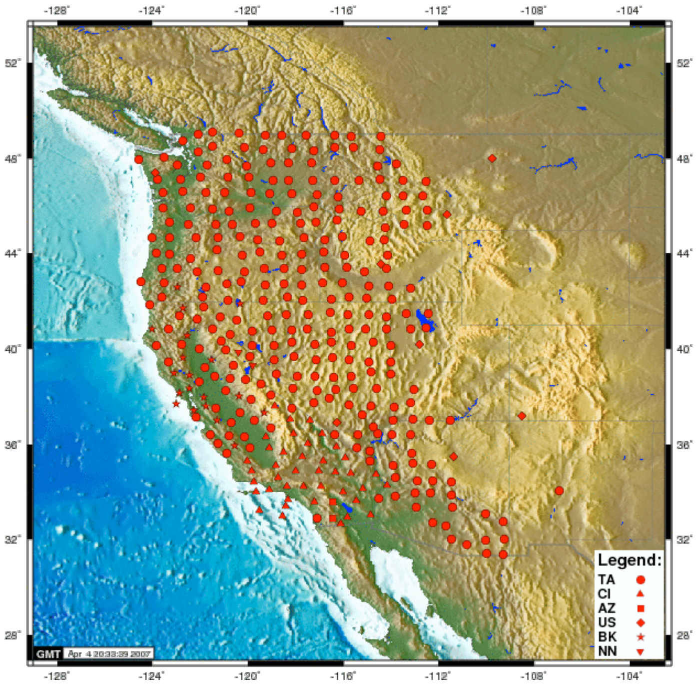
Polarization analysis of USArray data using earthquake signals

400+ USArray stations

Result:

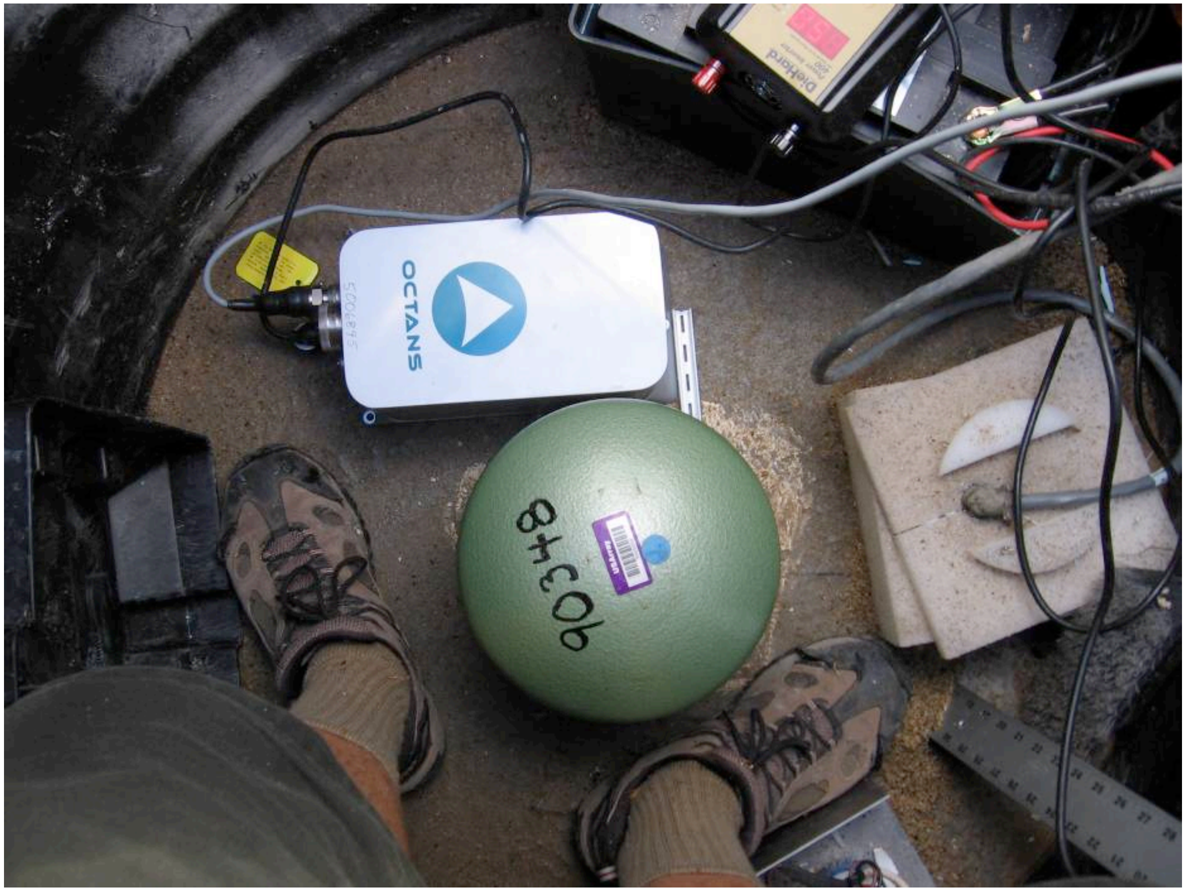
> 5% misoriented > 10 degrees

> 10 % misoriented > 5 degrees



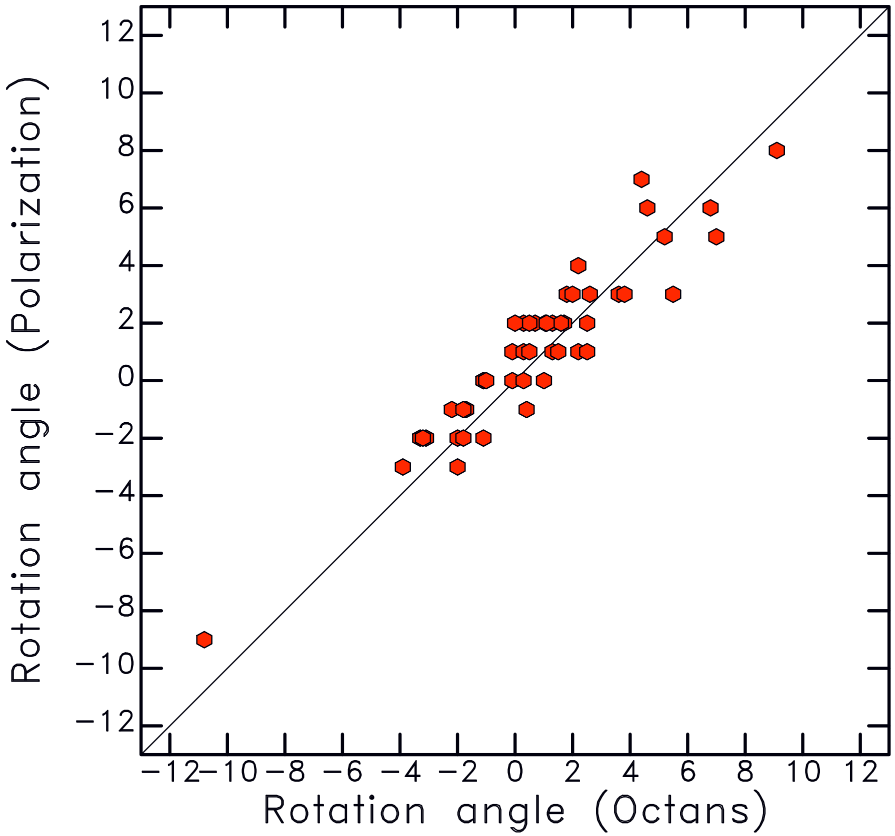
This is a common problem in many networks!

Octans interferometric laser gyro



Agreement of field (Octans) and polarization angles

estimated from
seismograms



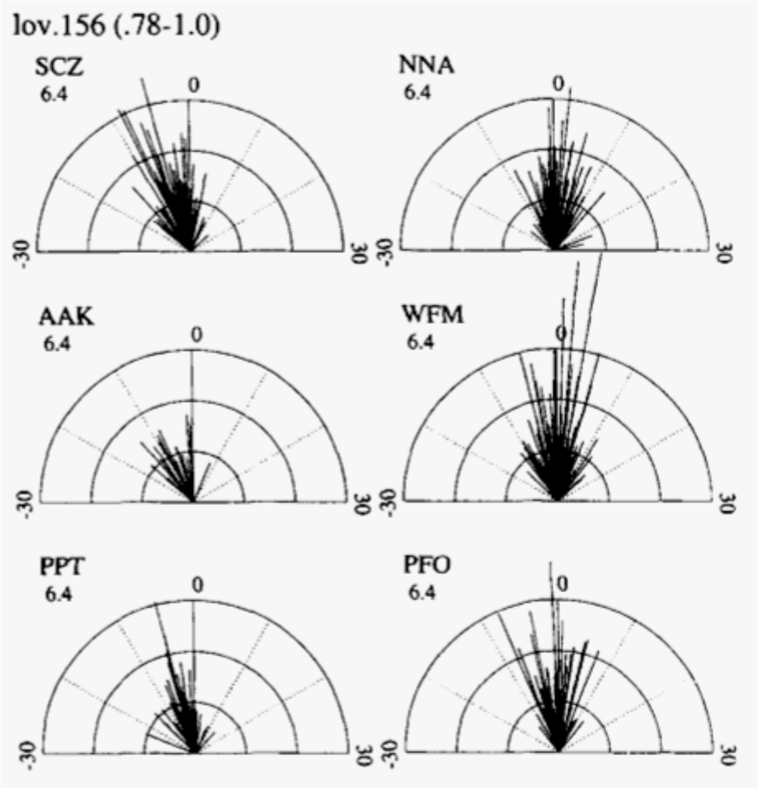
measured in the field

Sensor orientation

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

Why does it matter?

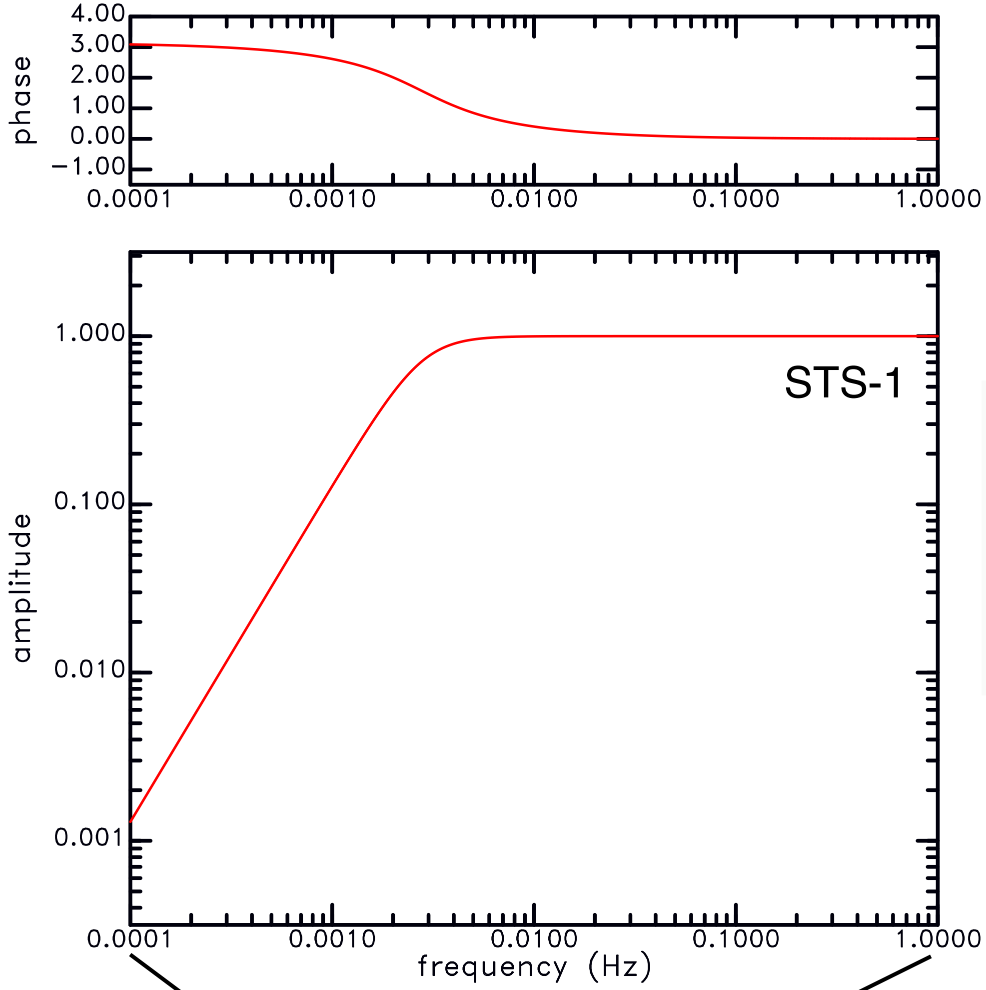
- Modeling of earthquake sources
- Measurement of Love wave / toroidal mode parameters
- Estimates of anisotropy
- Estimates of off-great-circle arrival angle, for both elastic and anelastic structure (tomography)



(Laske, 1995)

4b. Sensor response stability

Seismometer frequency response

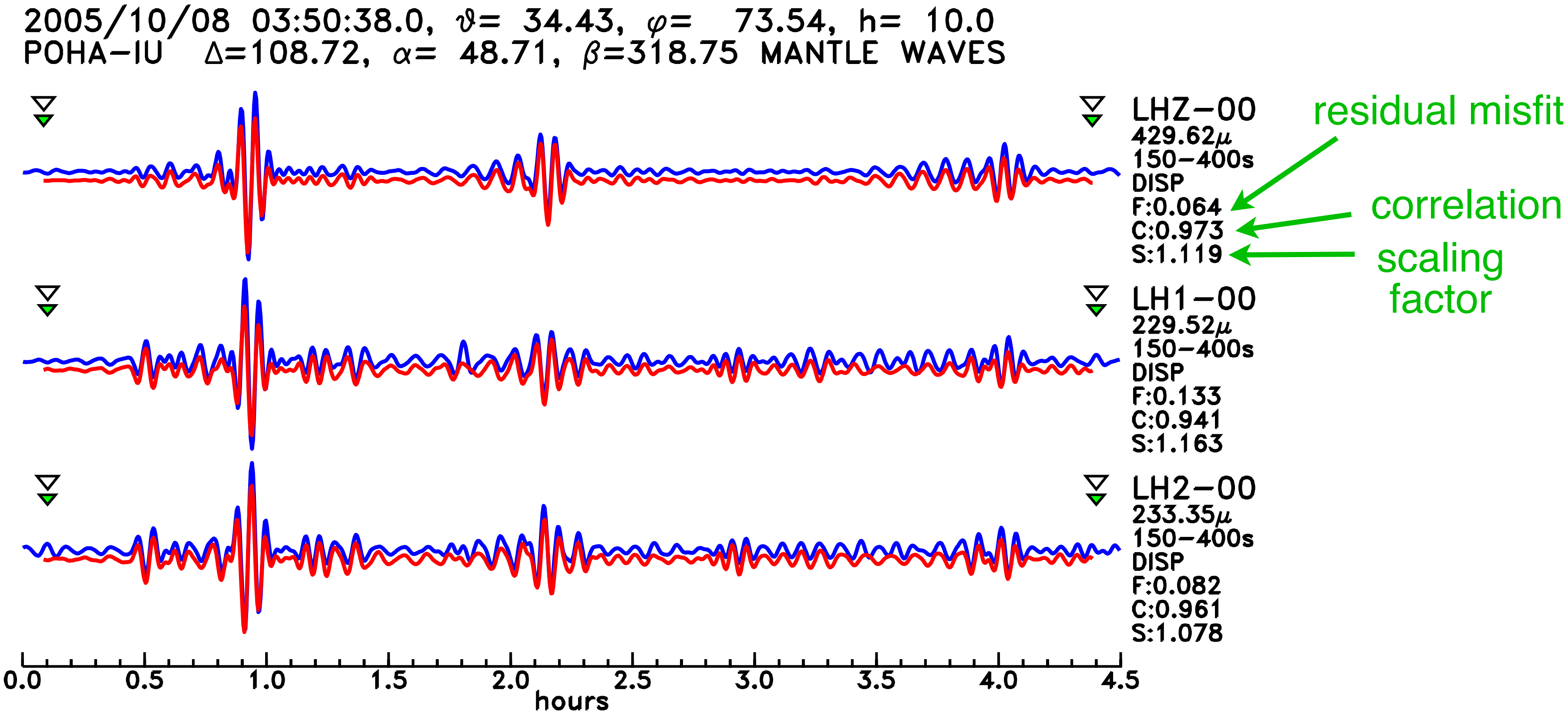


$$T(s) = K \frac{\prod_{i=1}^{N} (s - z_i)}{\prod_{j=1}^{M} (s - p_j)}$$

ground motion → seismometer → seismogram

Blue - observed seismograms

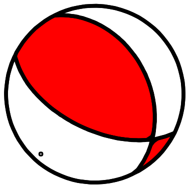
Red - synthetic seismograms



residual misfit

correlation

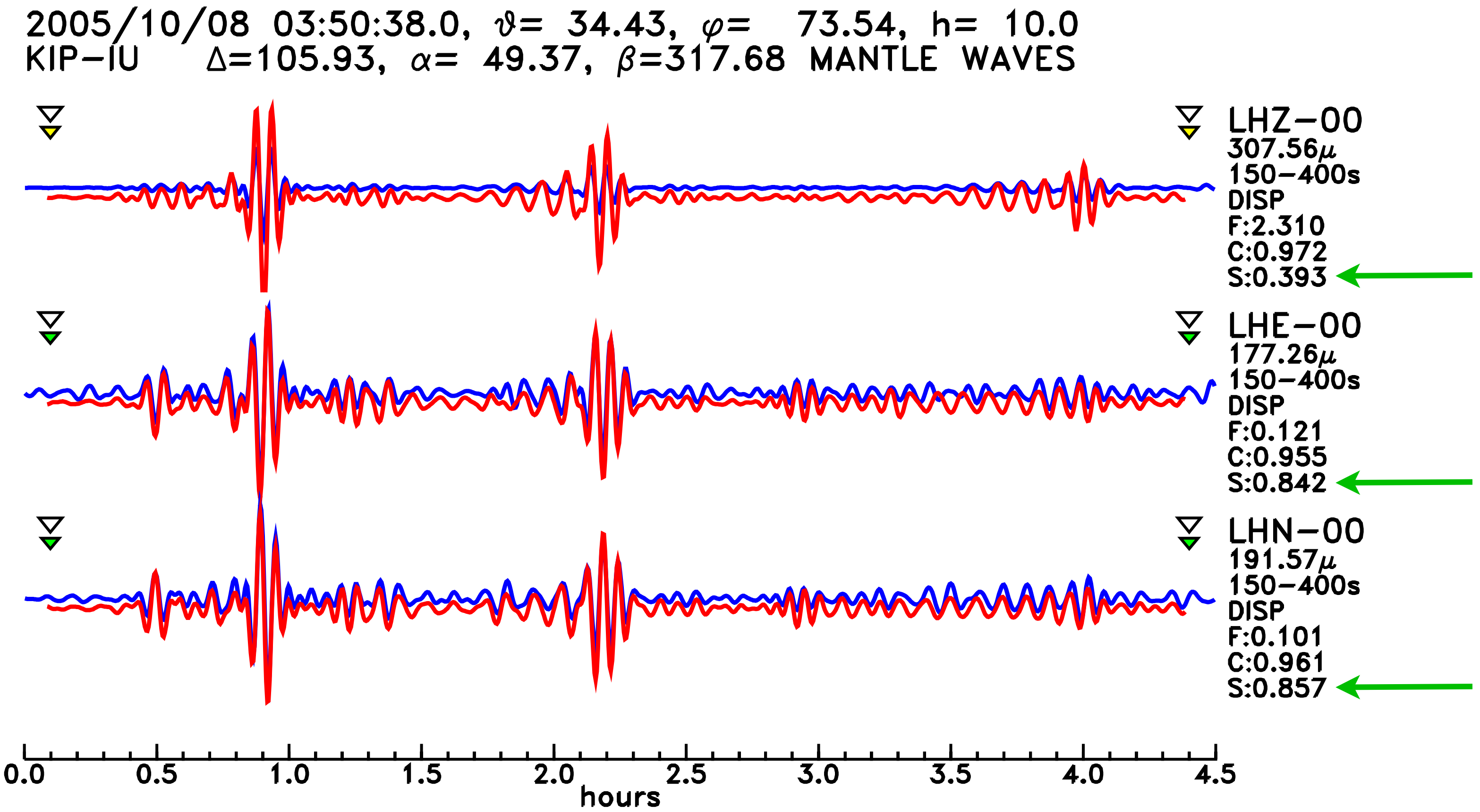
scaling factor



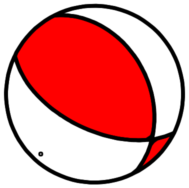
$$S = \frac{\sum_{i=1}^{N} o_i s_i}{\sum_{i=1}^{N} s_i^2}$$

Blue - observed seismograms

Red - synthetic seismograms

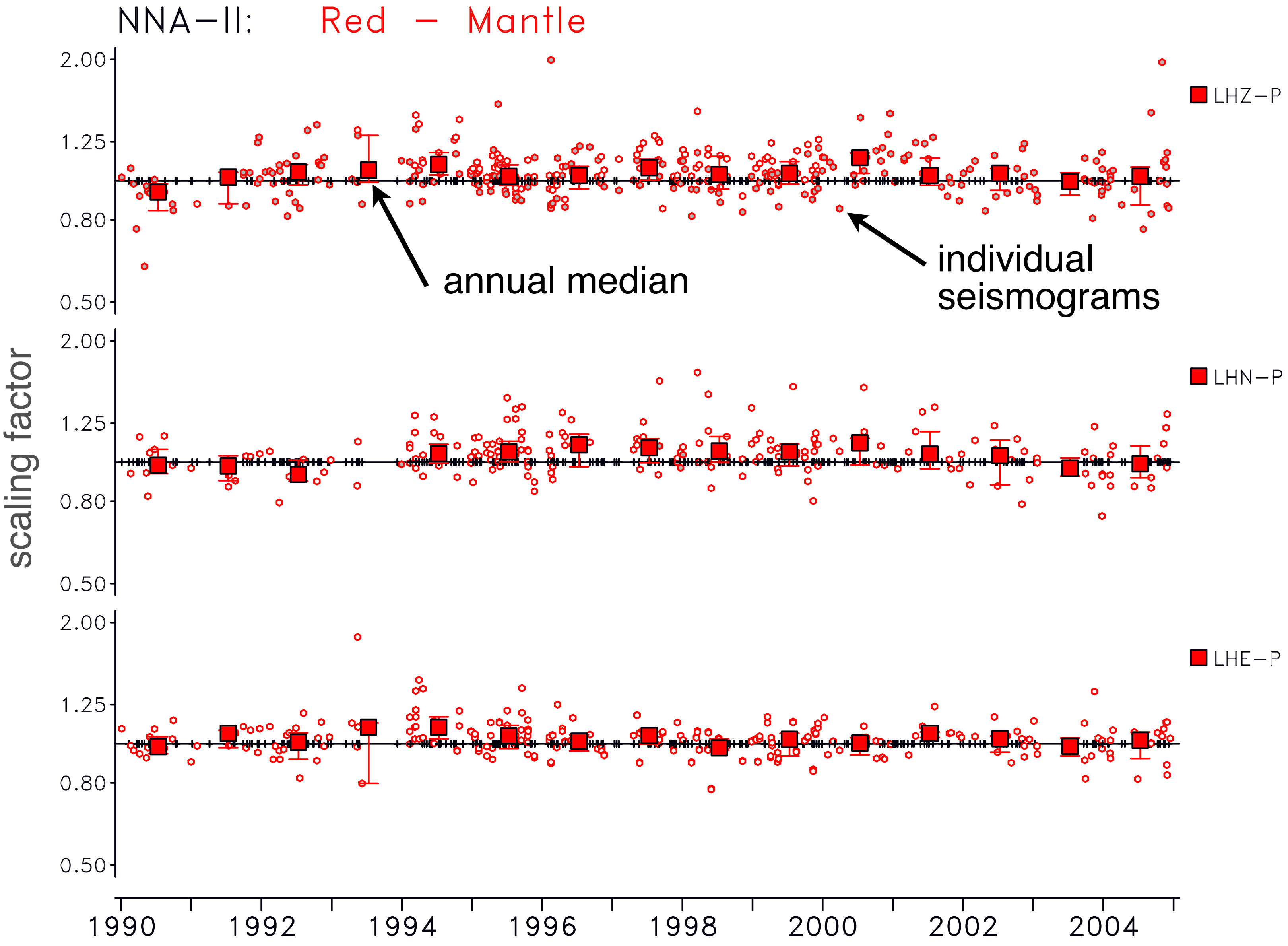


scaling factor



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

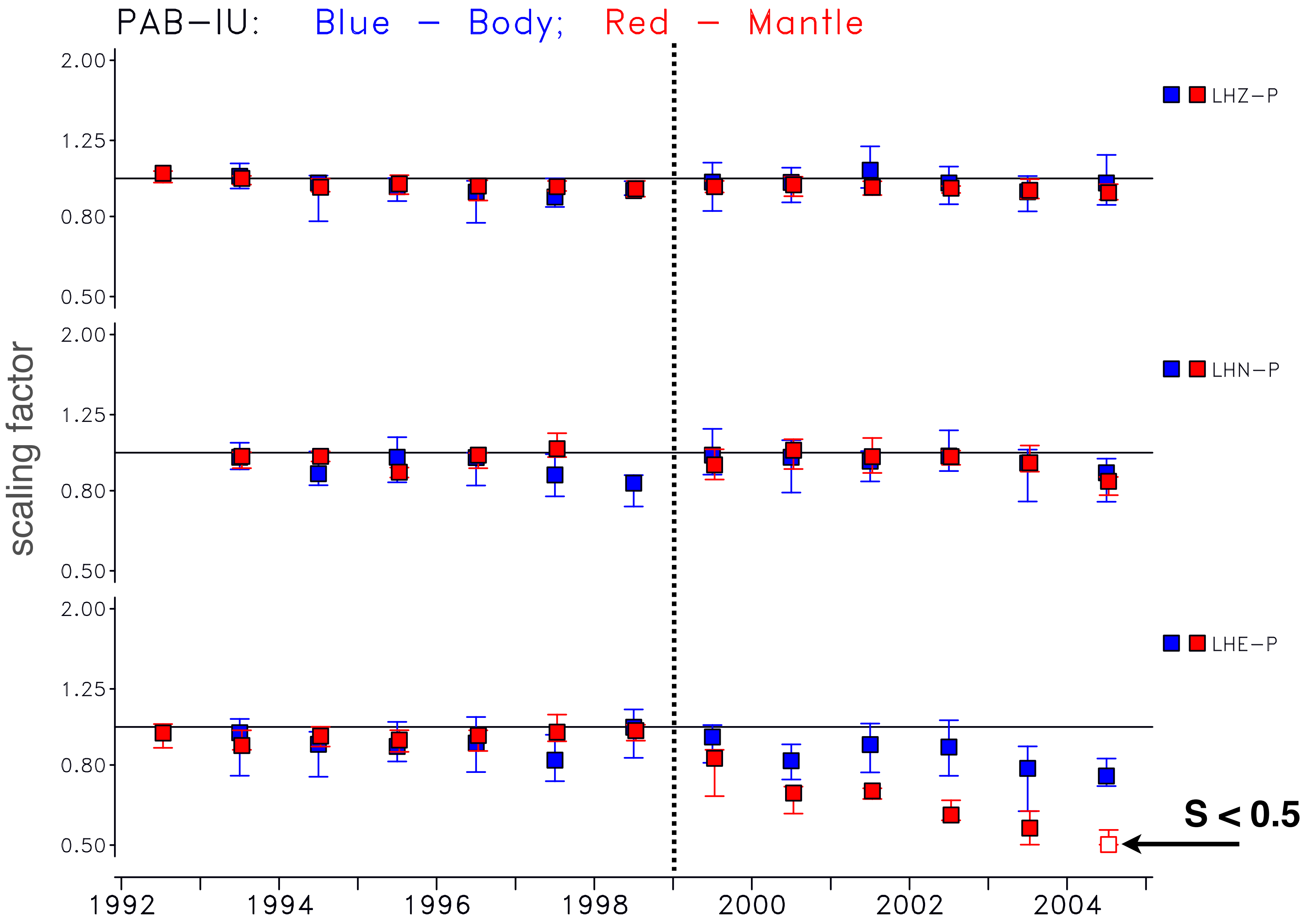
Scaling factors at NNA-II, 1990-2004



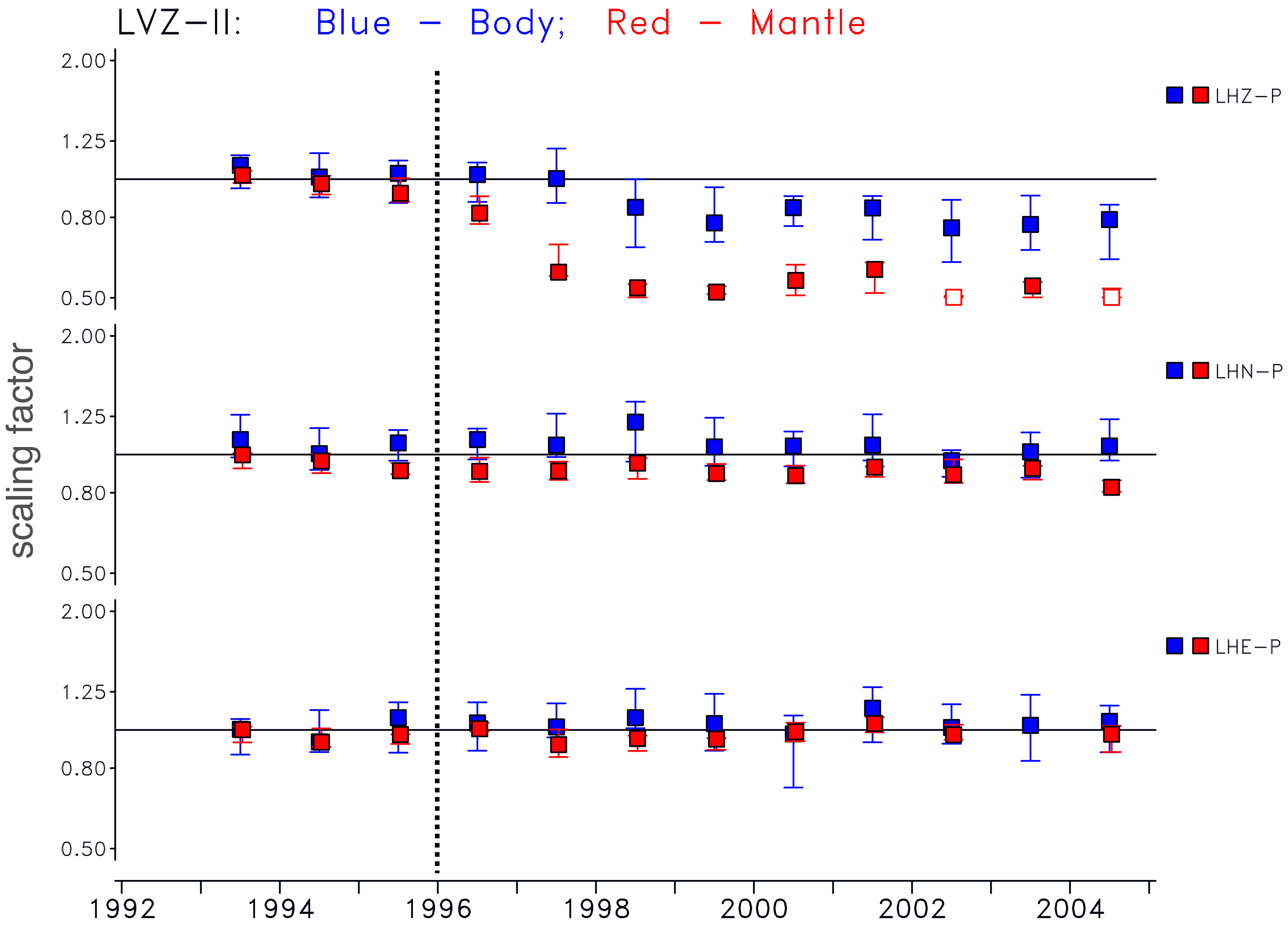
annual median

individual seismograms

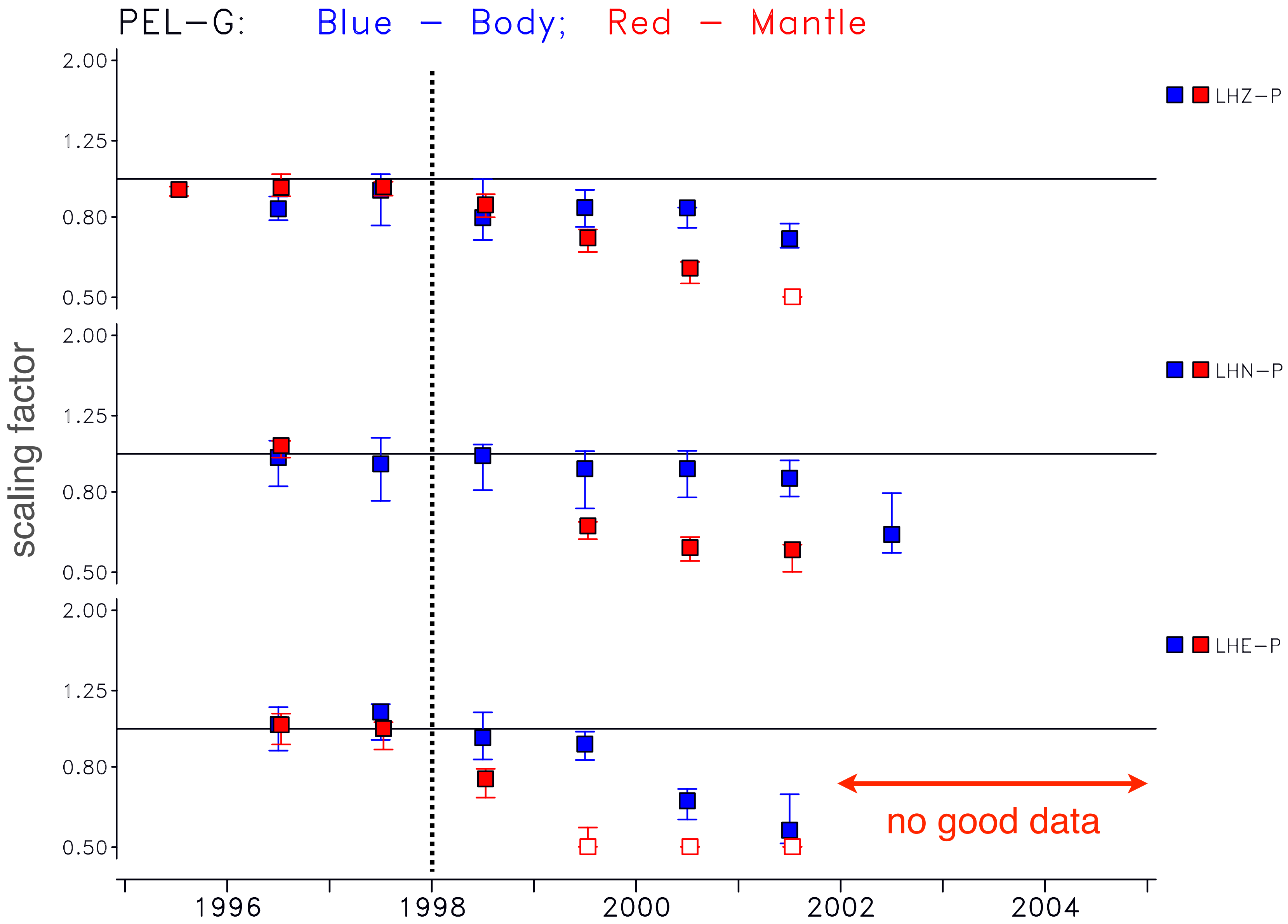
Scaling factors at PAB-IU, 1992-2004



Scaling factors at LVZ-II, 1993-2004

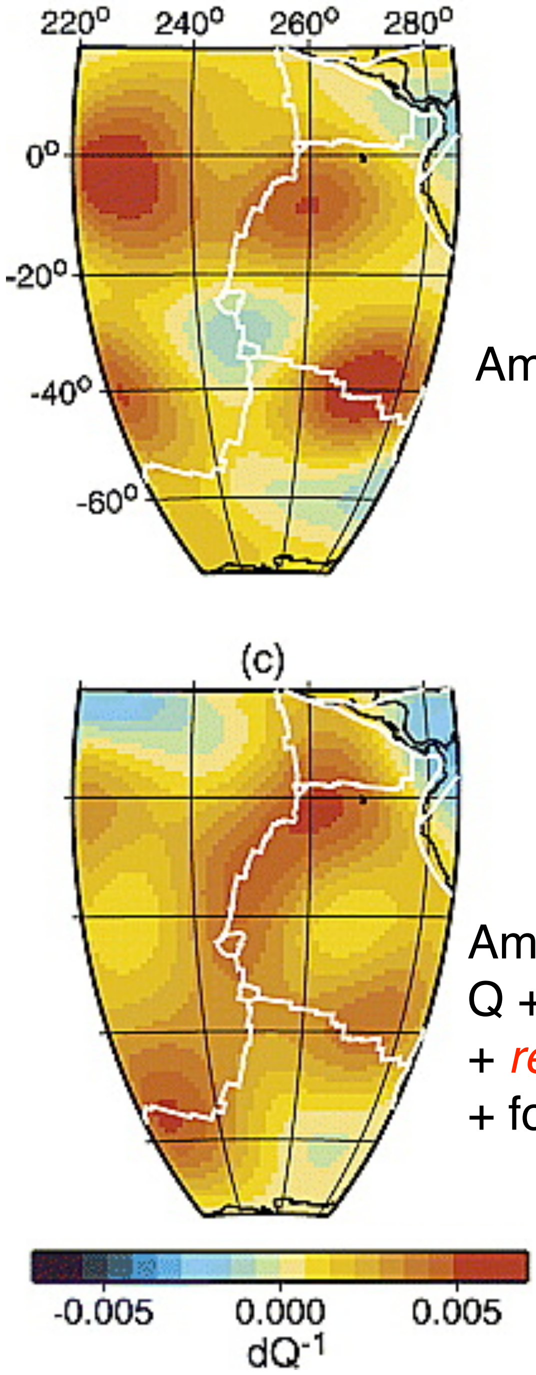


Scaling factors at PEL-G, 1996-2002



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:

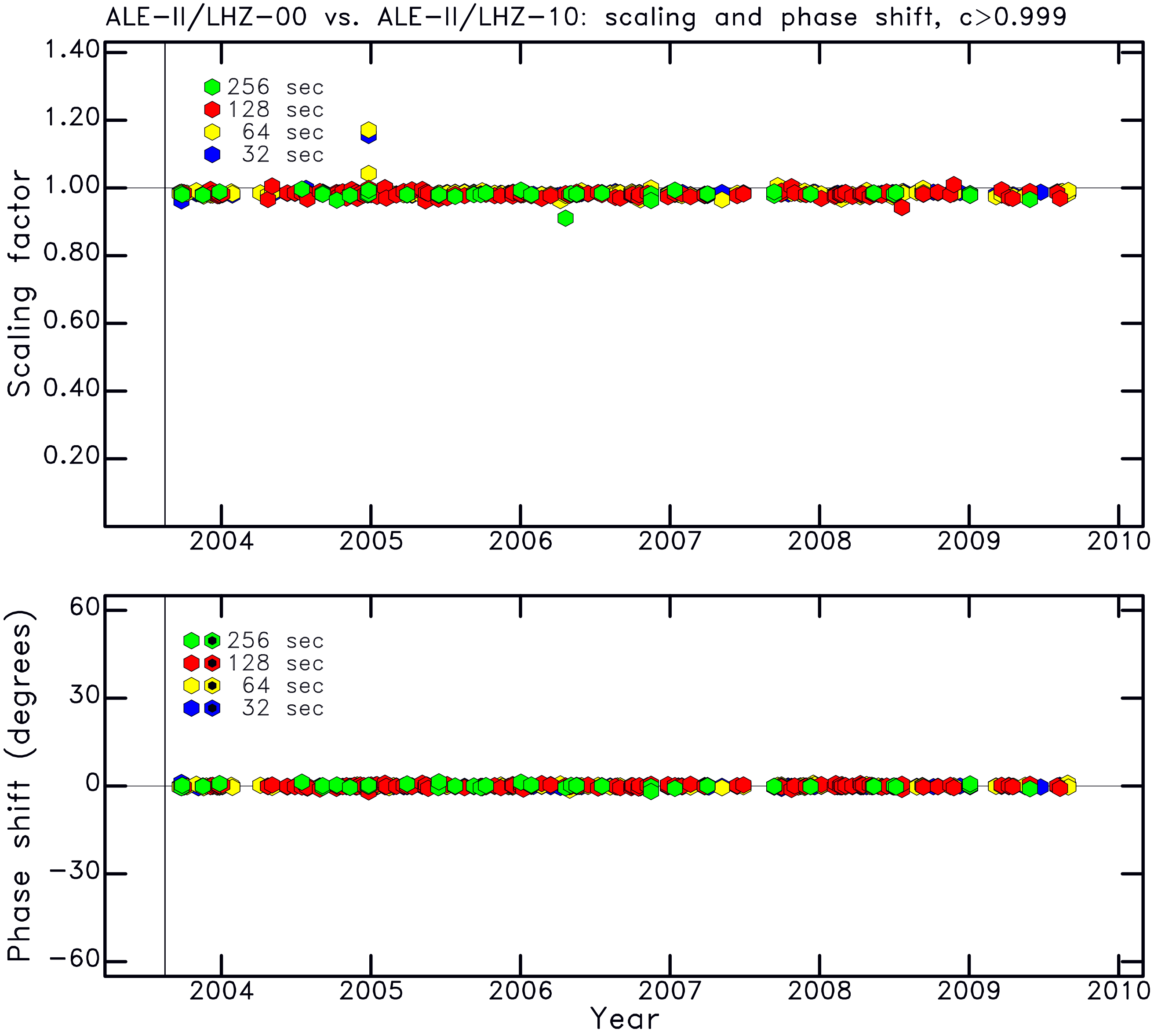
calculate ratio of displacements at some period during times of high signal coherence

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

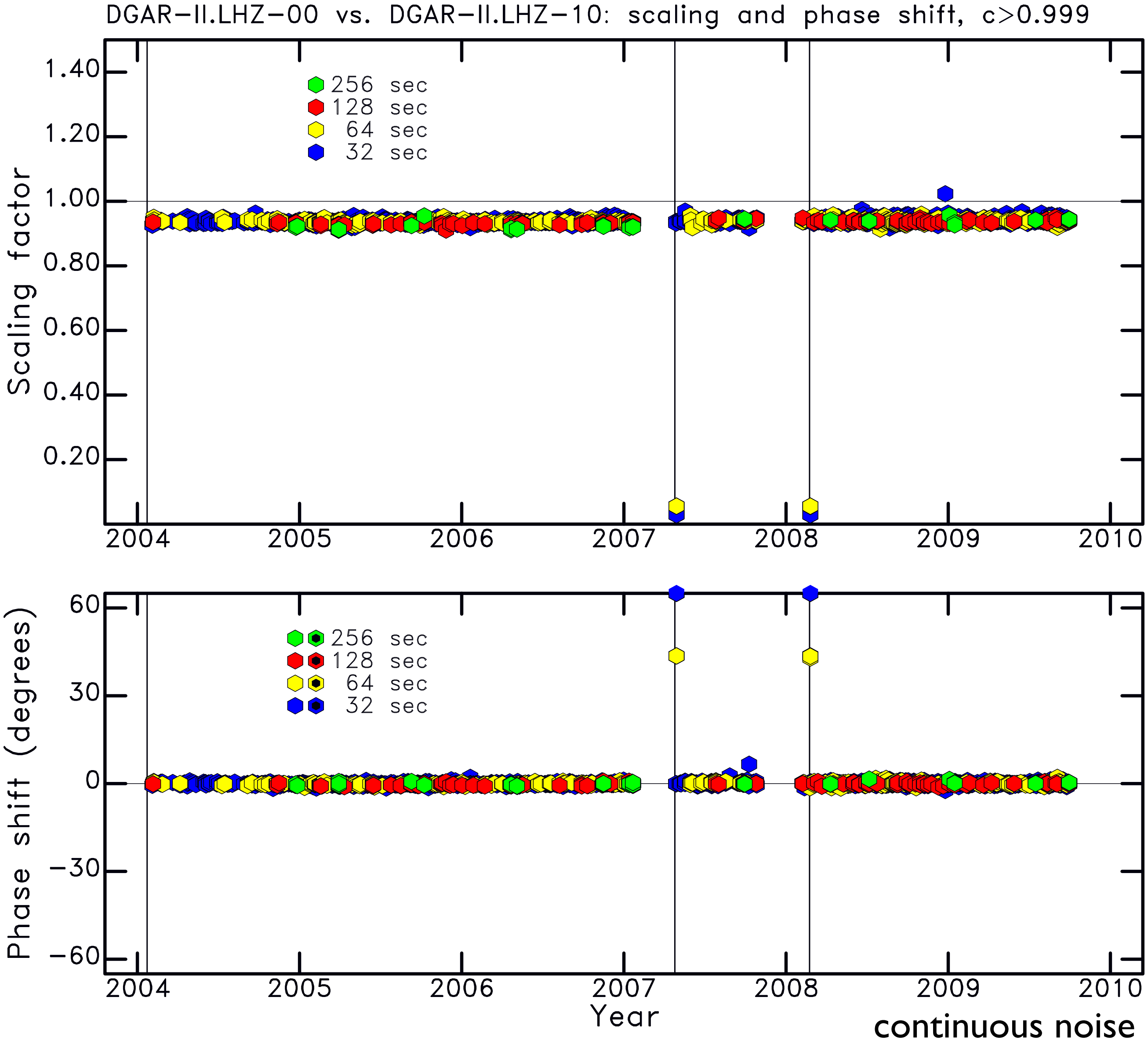
$$\frac{\text{signal B}}{\text{response B}} = \text{displacement B} \qquad \text{(deconvolution)}$$

$$\boxed{\text{ratio} = \frac{\text{displacement A}}{\text{displacement B}} \qquad \text{should be 1.0000!}}$$

Intersensor coherence, ALE-II LHZ, 2003-2009



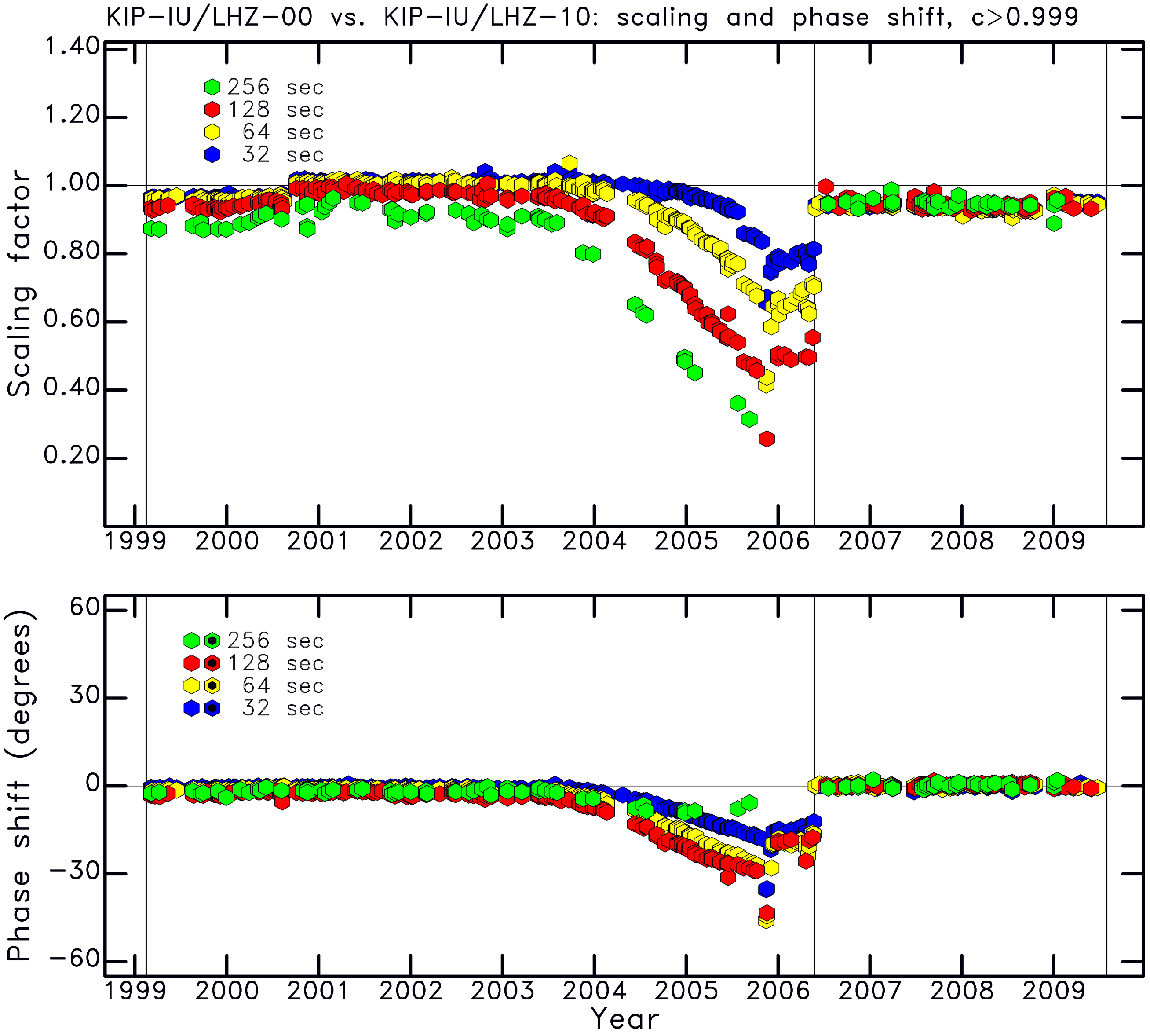
Intersensor coherence, DGAR-II LHZ, 2003-2009



~5% gain error

continuous noise

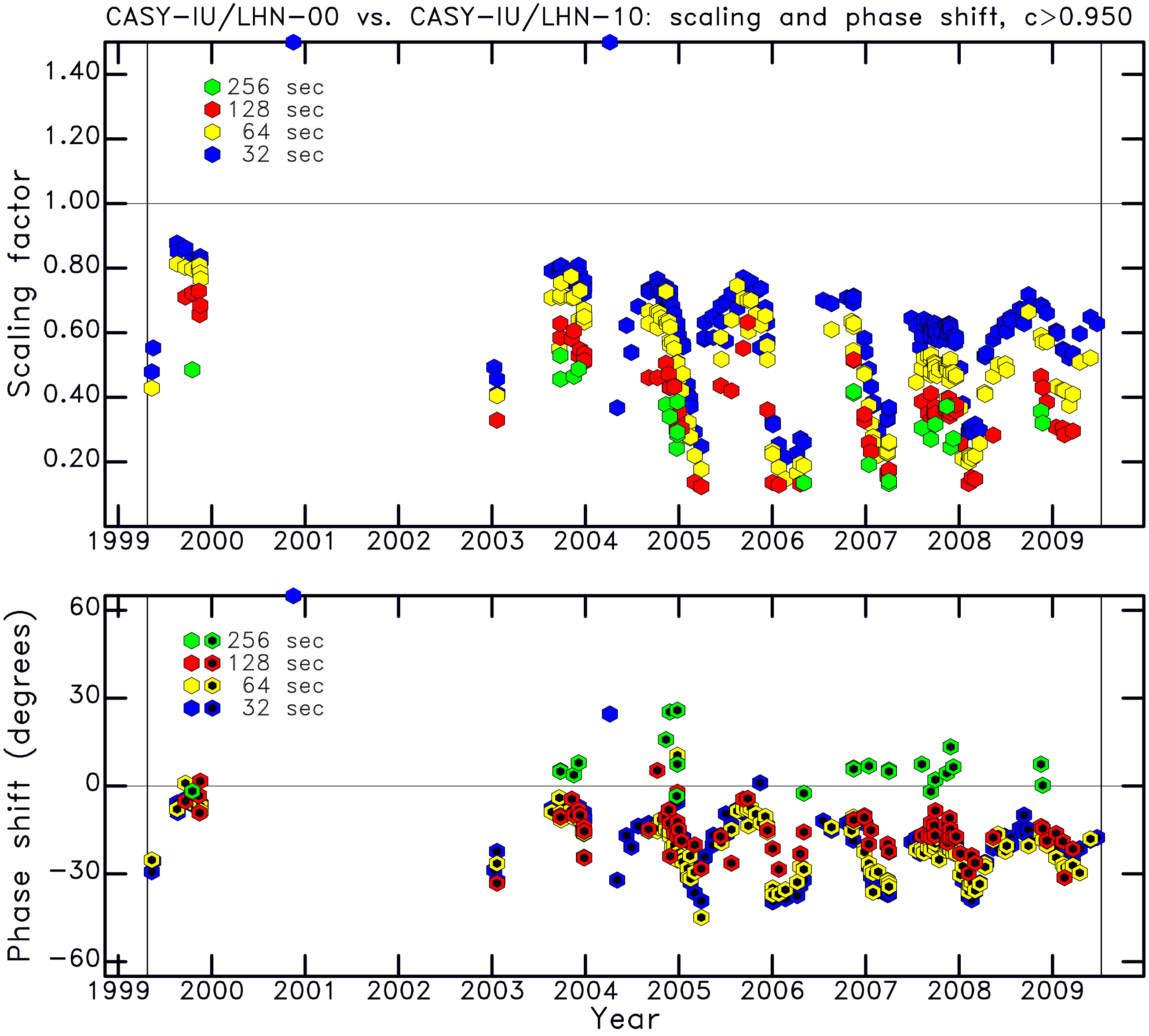
Intersensor coherence, KIP-IU LHZ, 1999-2009



~5% gain error

STS-1 decay pattern

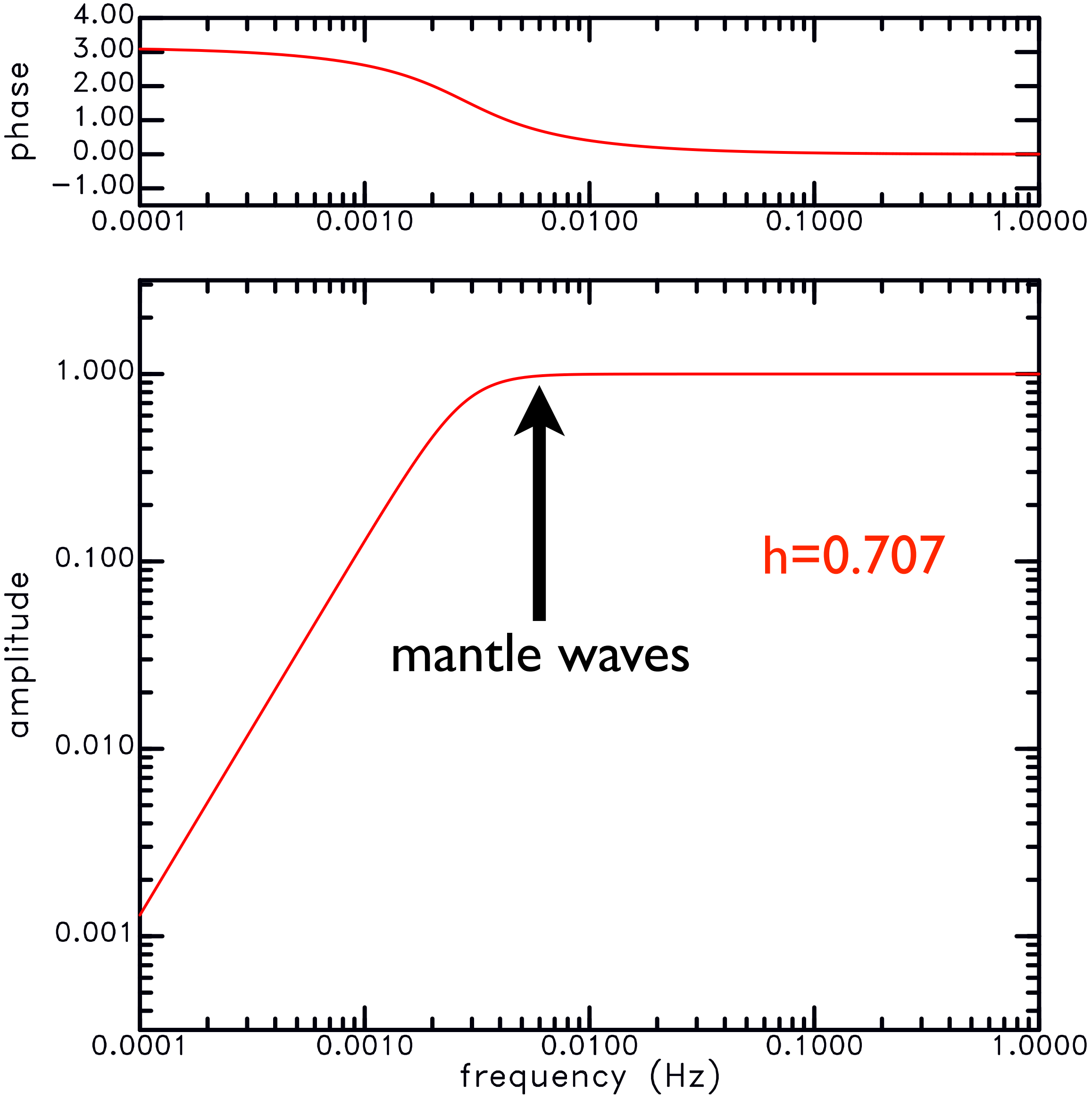
Intersensor coherence, CASY-IU LHN, 1999-2009



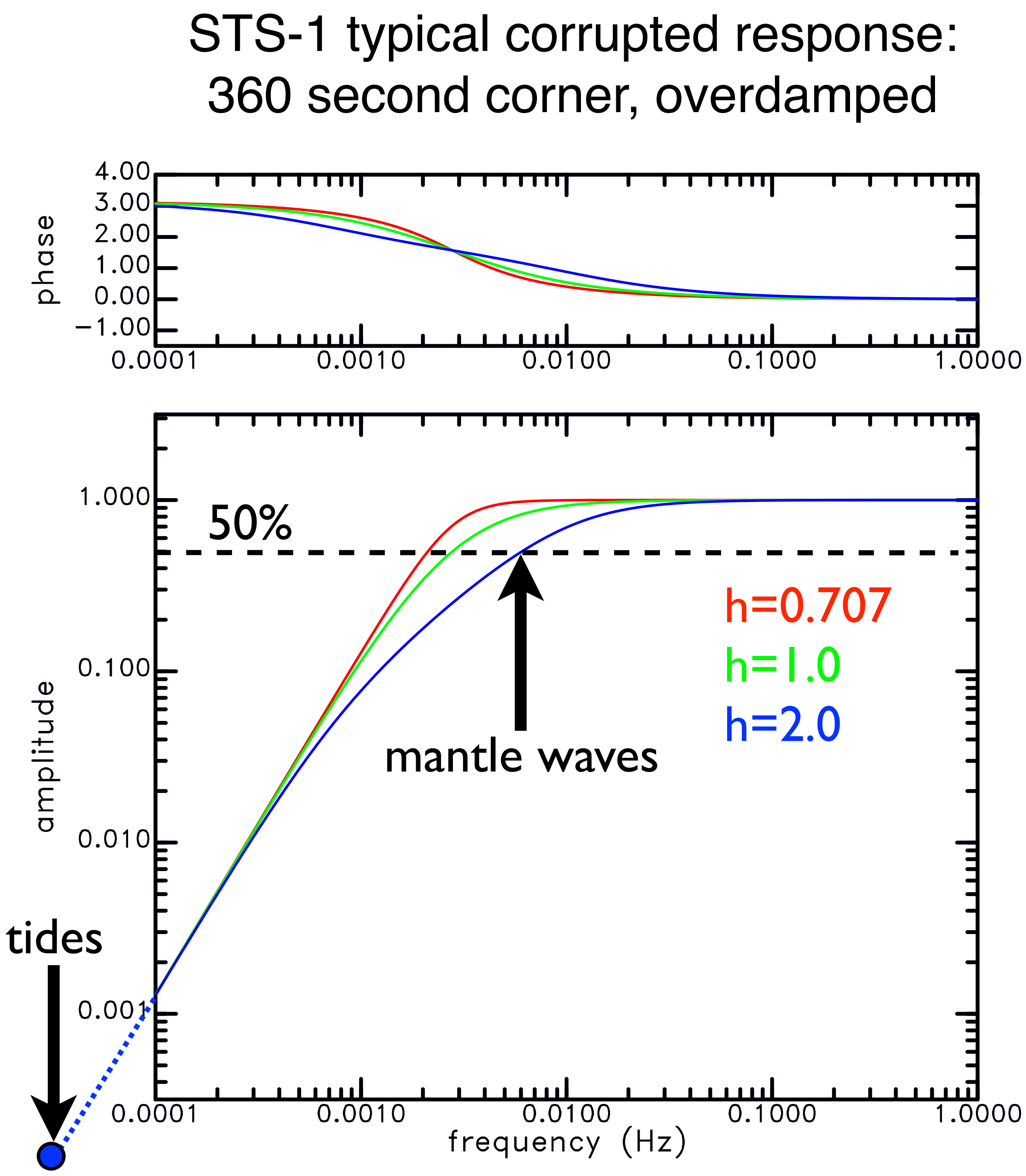
severe time- and frequency-dependent response error

STS-1 response decay

STS-1 generic response:
360 second corner, critical damping (h=0.707)



STS-1 response decay

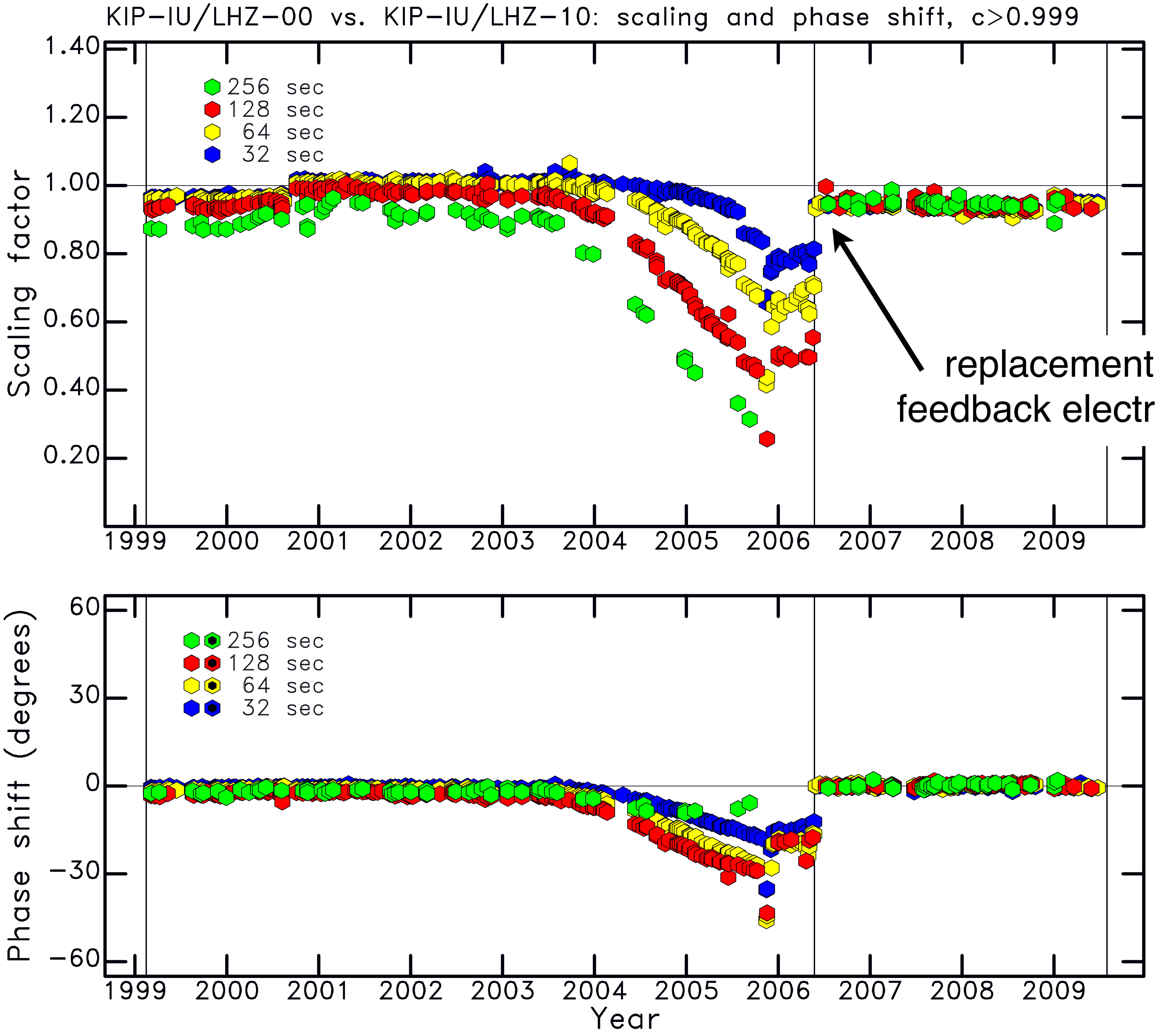


Hutt & Ringler:
moisture in FBEs

Yuki & Ishihara:
moisture in cable
connectors

Hutt & Steim:
too-short mechanical
free period

Intersensor coherence, KIP-IU LHZ, 1999-2009



~5% gain error

replacement of
feedback electronics

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!