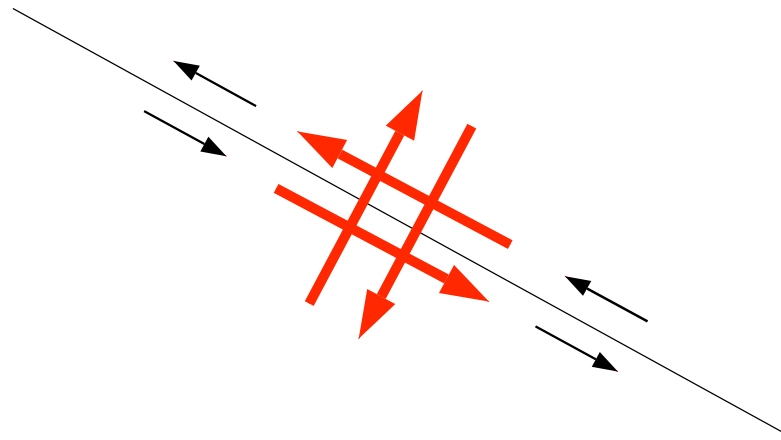


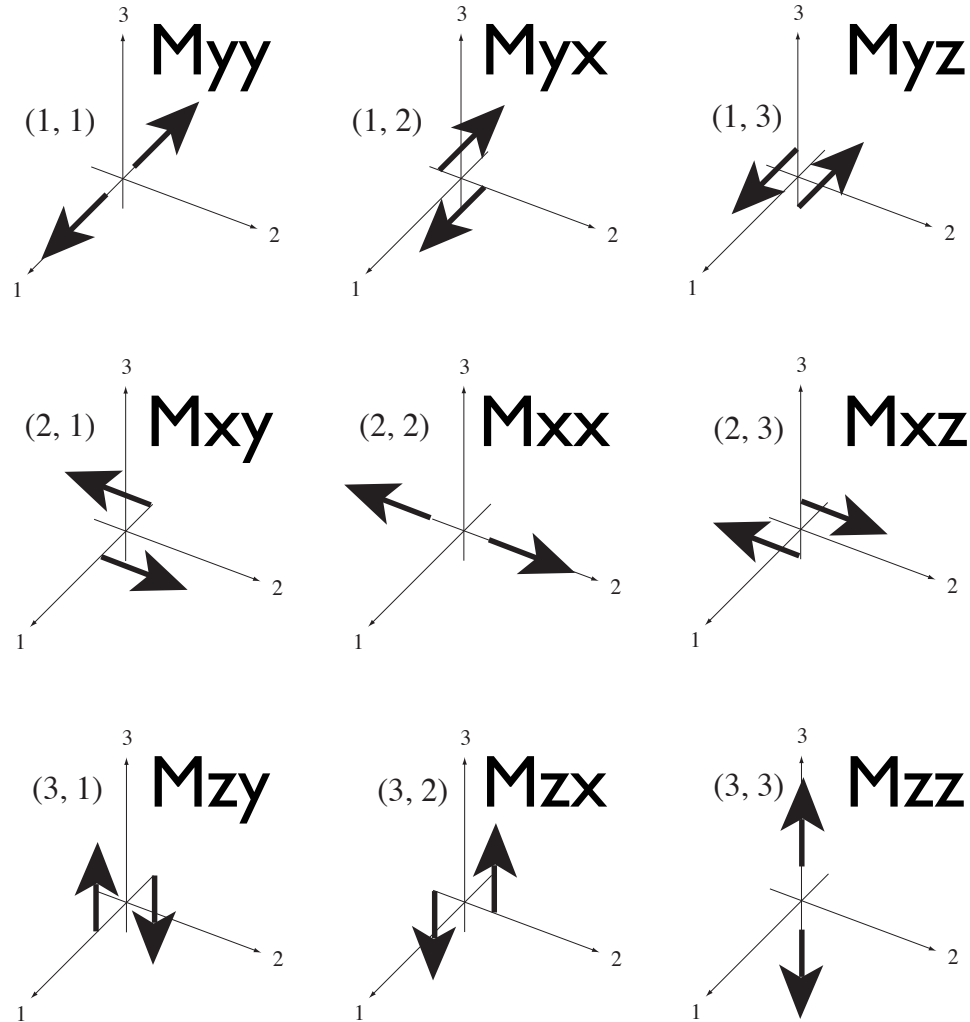
1. Moment-tensor analysis using global data
2. The Global CMT catalog
3. Using calibration information in waveform analysis
4. Data quality control using signals
5. Data quality control using noise
6. Finding interesting things in the noise

Faulting force model



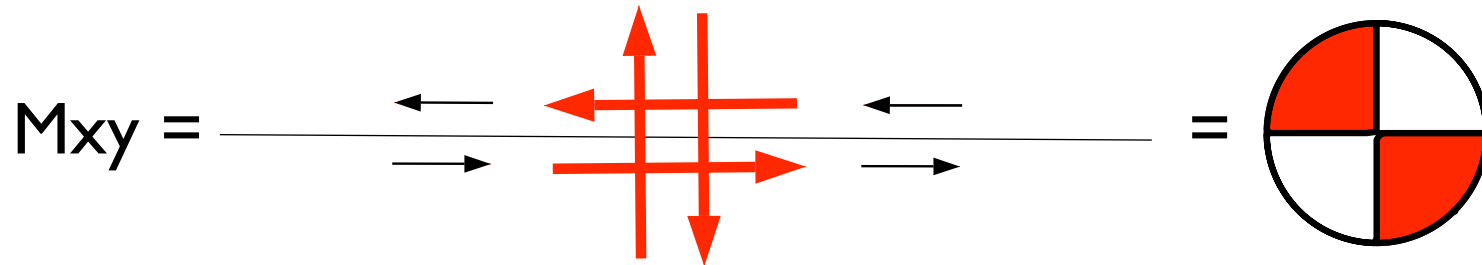
The elastic stress release in an earthquake is described by a double couple of forces

The nine dipoles of the seismic moment tensor



(Aki and Richards, 2002)

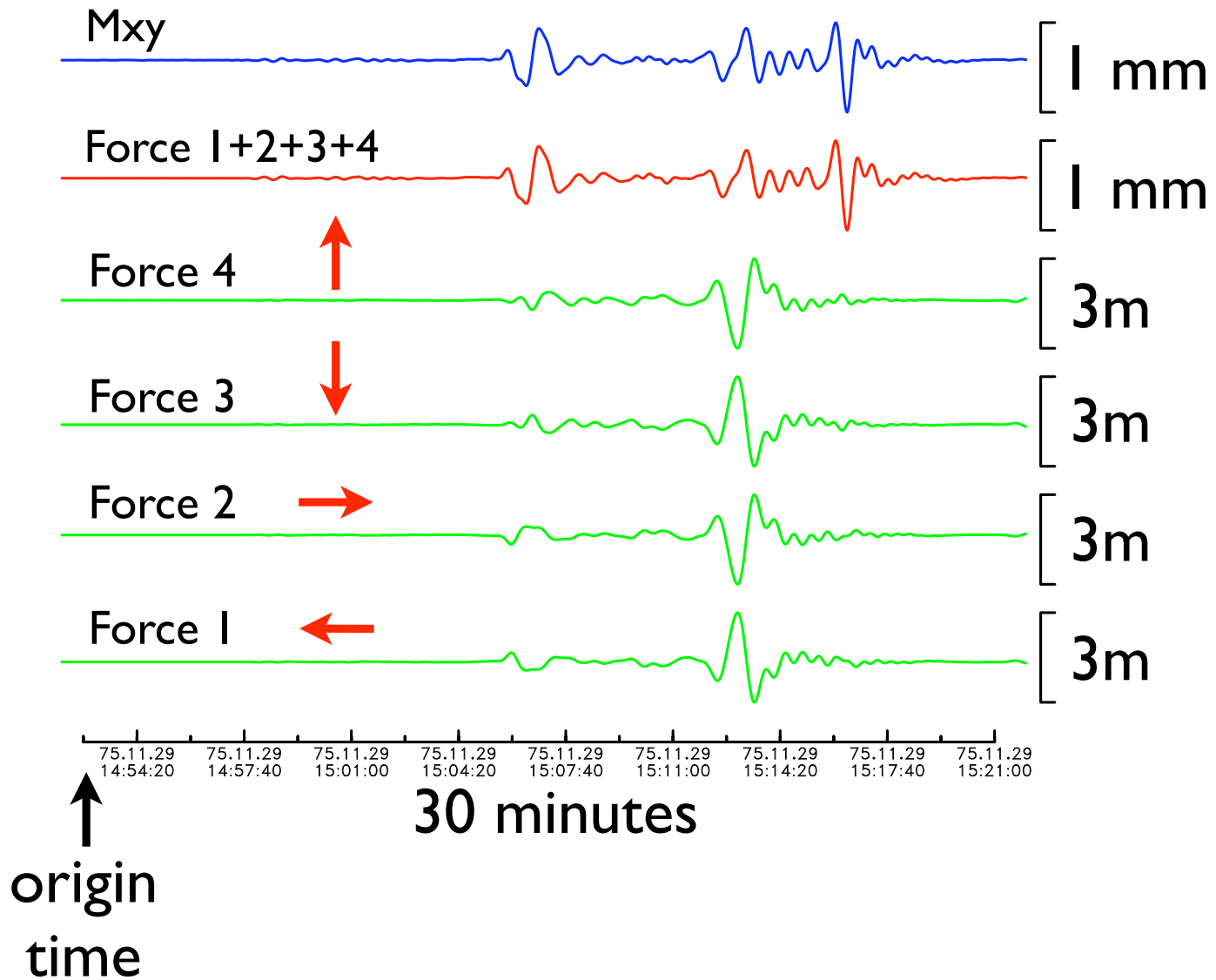
But, $M_{xy}=M_{yx}$, $M_{yz}=M_{zy}$, $M_{xz}=M_{zx}$



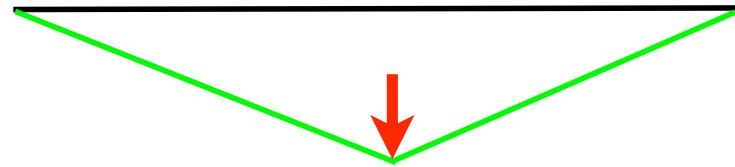
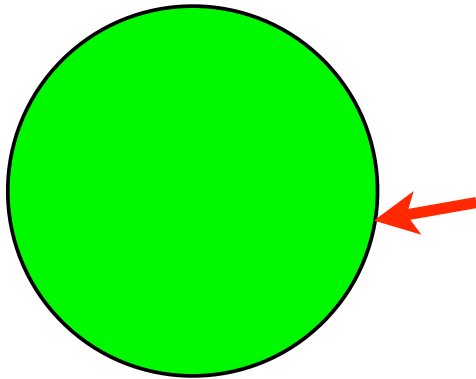
for example,

$$10^{28} \text{ dyne-cm} = 10^{24} \text{ dyne} \times 10000 \text{ cm}$$

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



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

where \mathbf{f} is the force vector and \mathbf{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 $[\text{Observed waveform} - \text{Model waveform}]^2$

with respect to the moment tensor elements.

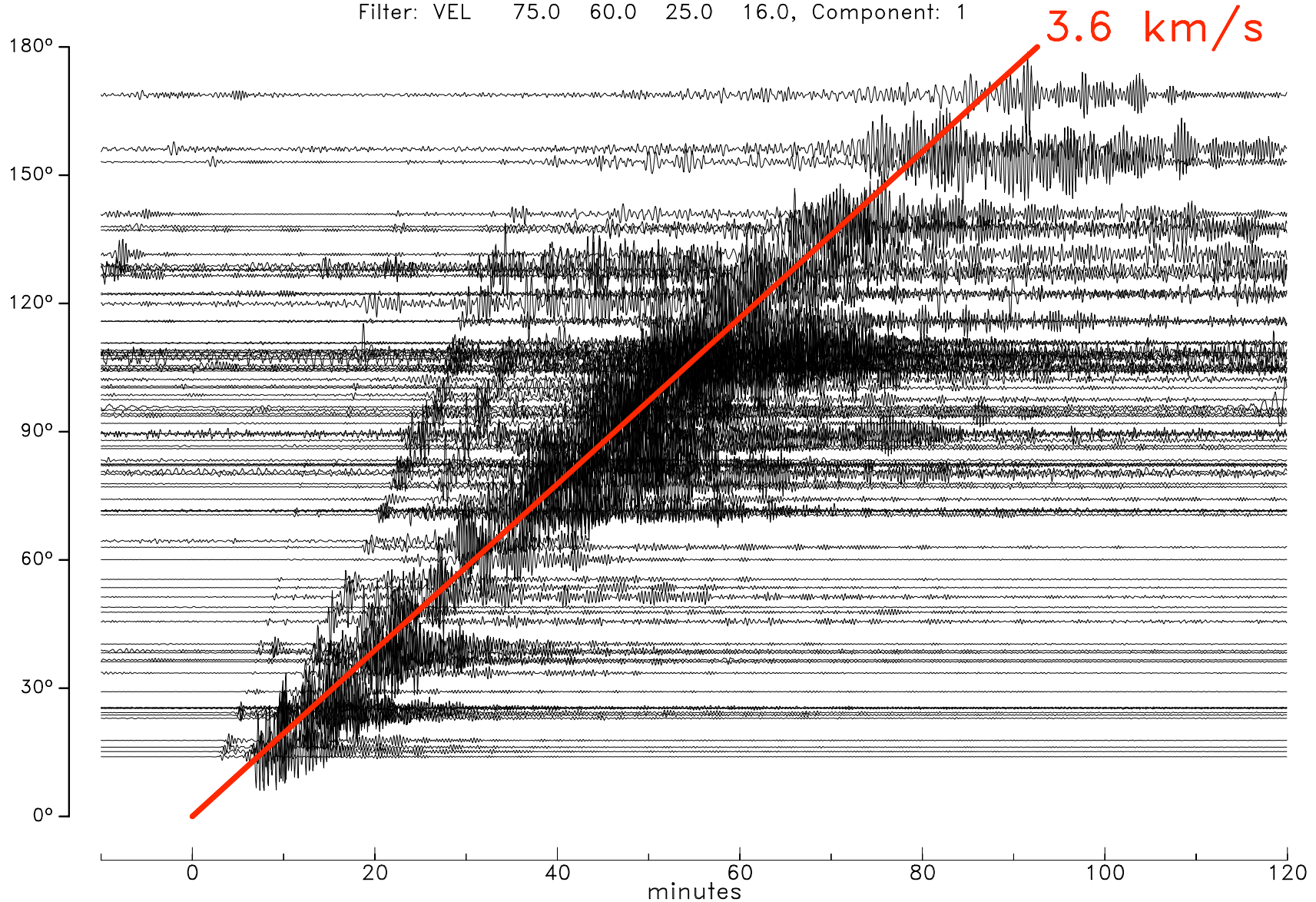
STS-I Seismometer
at Harvard, Mass.



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

E200604040230A

Event: 2006/04/04, 02:30:28.0, OFF COAST OF JALISCO, MEXICO
Hypocenter (PDE): Lat= 18.69, Lon=-107.06, h= 33.9, mb=5.9, MS=5.9
Filter: VEL 75.0 60.0 25.0 16.0, Component: 1



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

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:

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

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

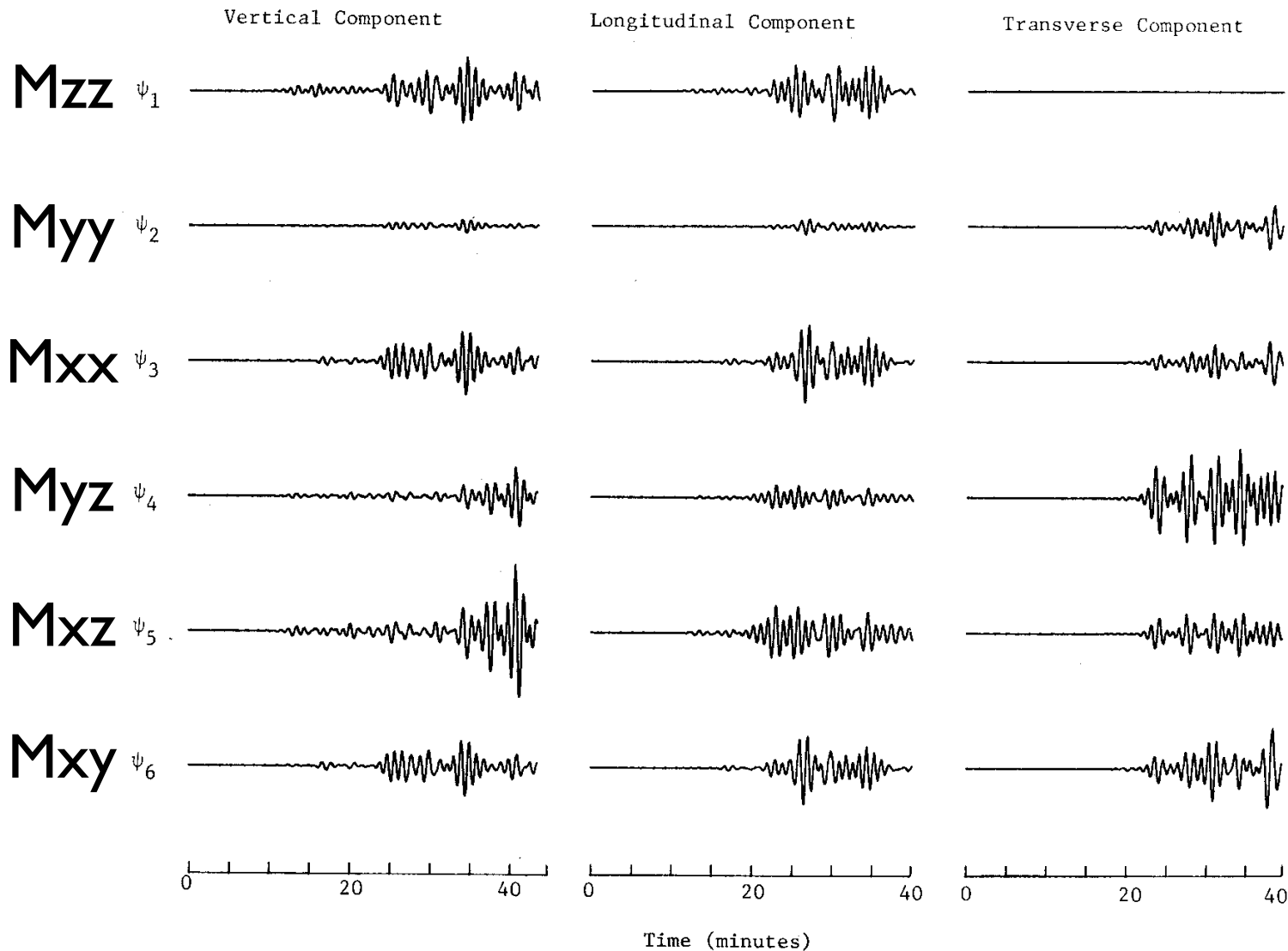
$f_1 = M_{zz}$, $f_2 = M_{yy}$, etc.; $N=6$

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):

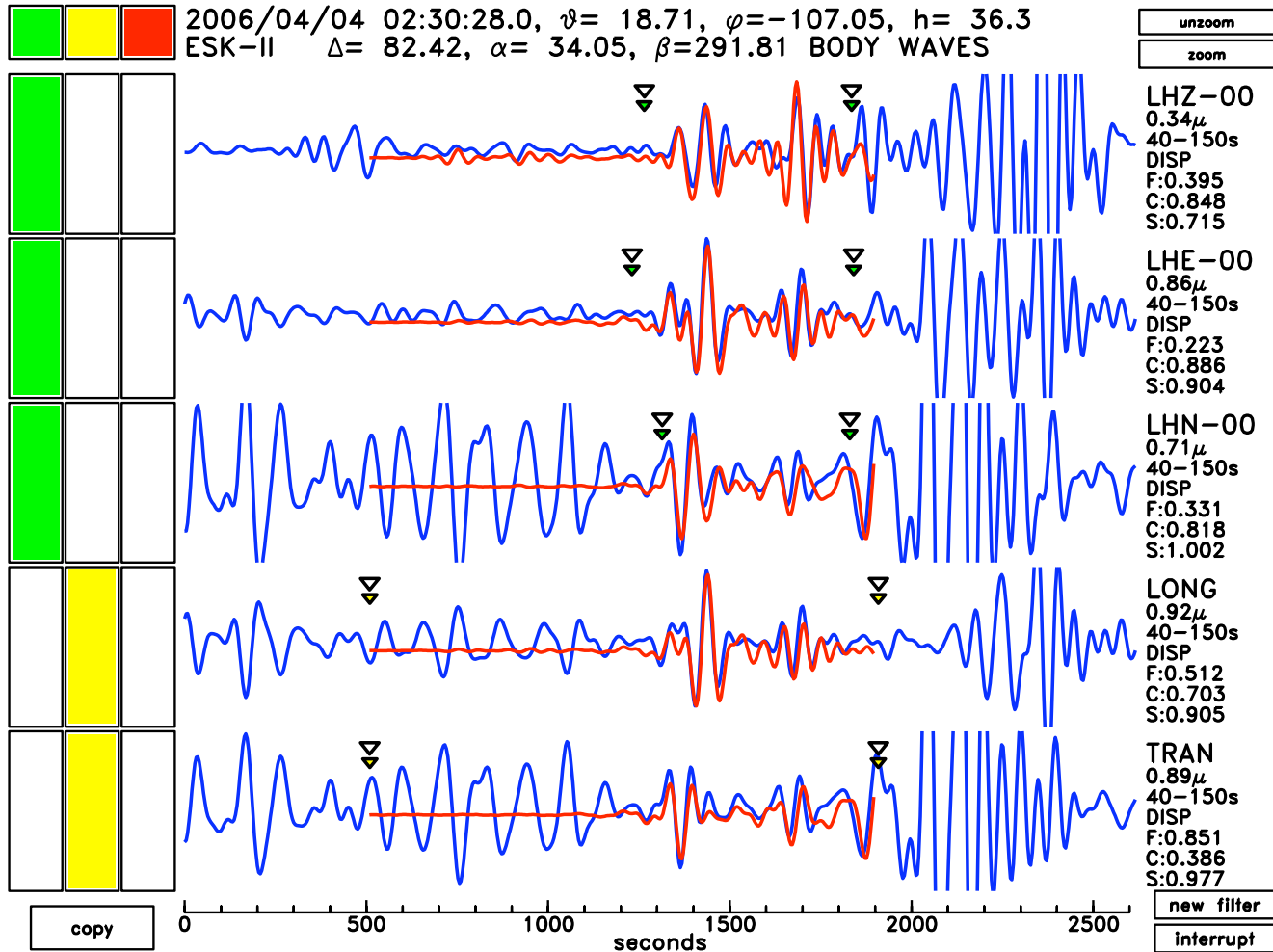
$$u(\mathbf{x}, t) = \sum_k [1 - \exp[-\alpha_k(t - t_s)] \cos \omega_k(t - t_s)] \mathbf{M} : \mathbf{e}^{(k)}(\mathbf{x}_s) \mathbf{s}_k(\mathbf{x})$$

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



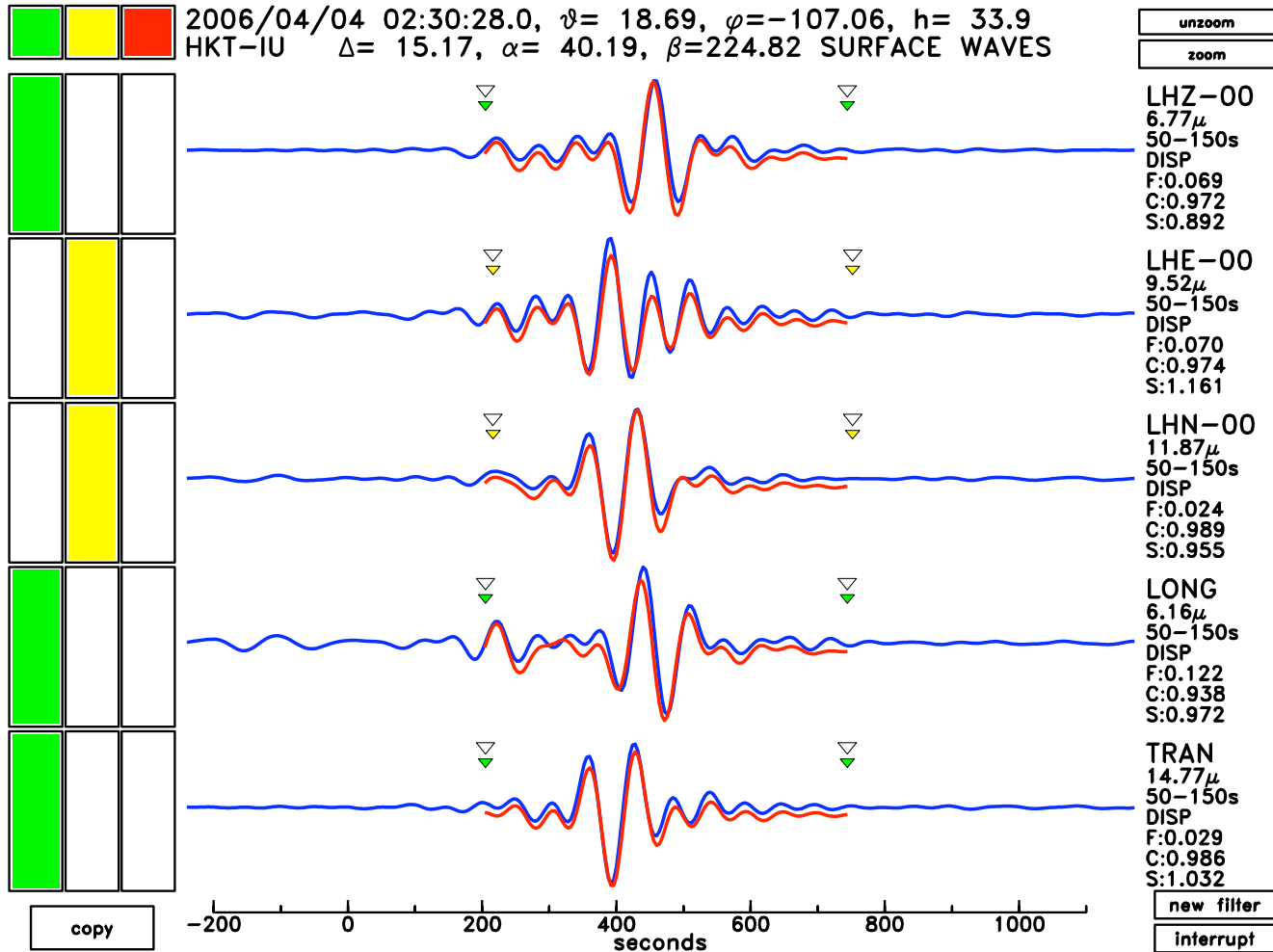
Excitation kernels for deep earthquake (580 km)

Fit to seismograms: Body waves at Eskdalemuir, Scotland



blue - data ; red - model

Fit to seismograms: Surface waves at Hockley, Texas



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:

$$A_{ij} = \sum_k \int_{t_{k1}}^{t_{k2}} \psi_{ik} \psi_{jk} dt ; b_j = \sum_k \int_{t_{k1}}^{t_{k2}} u_k \psi_{jk} dt.$$

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

Solution for the Source Centroid

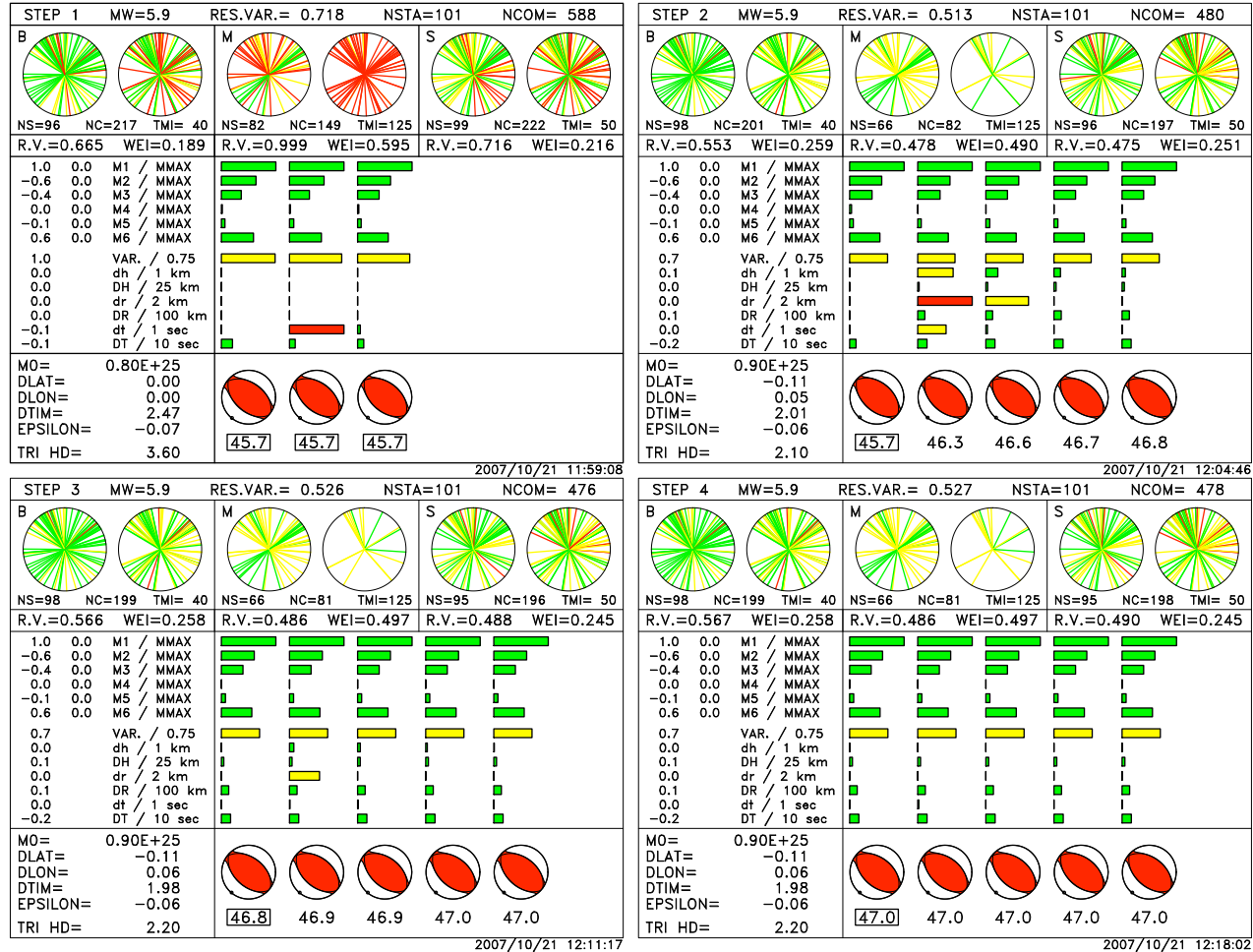
The earthquake centroid can be determined simultaneously with the source model parameters by expansion of the equations of condition to allow for a perturbation in the location of the source (Dziewonski, Chou and Woodhouse, 1981):

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

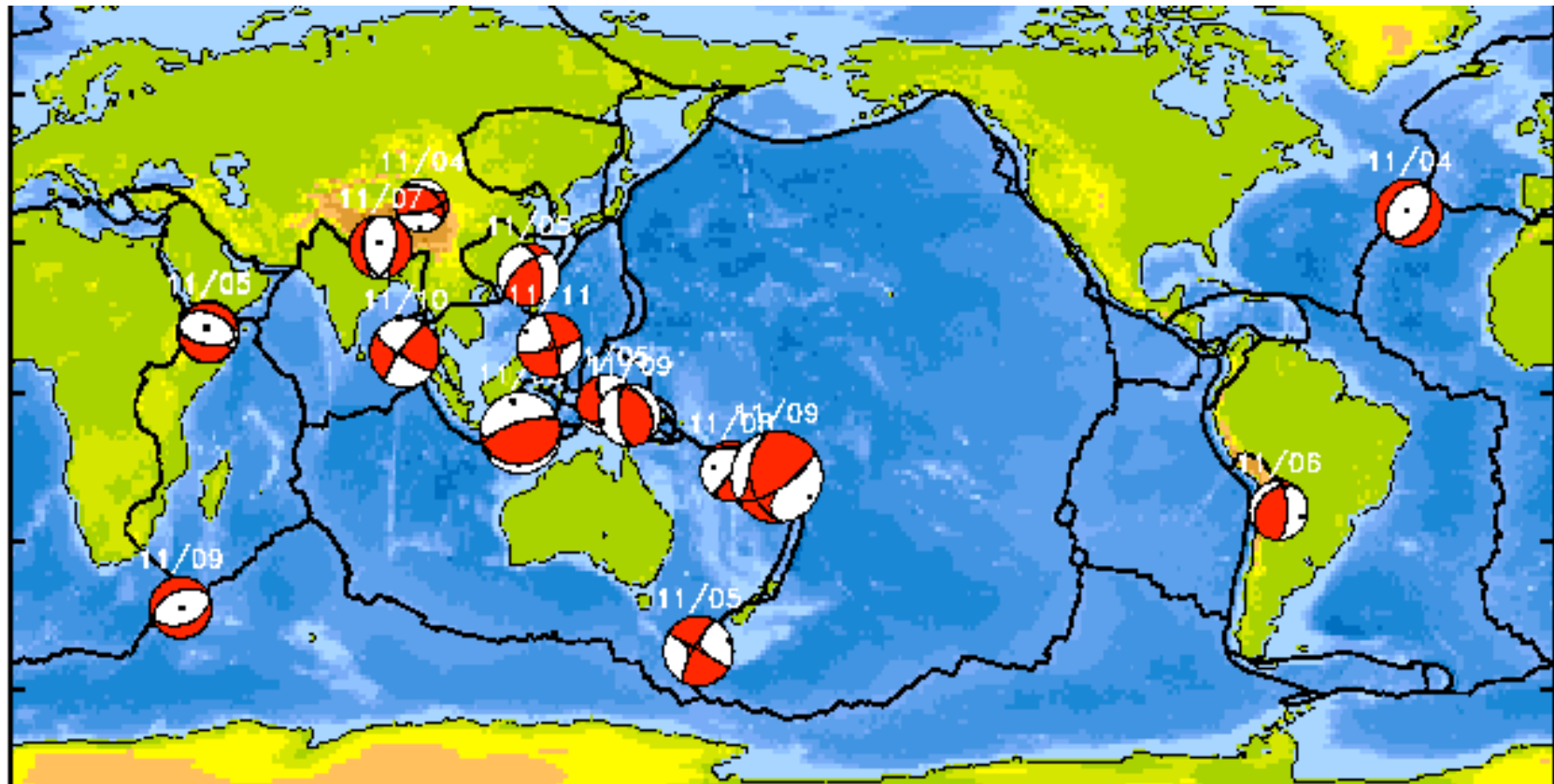
where the superscript (0) indicates parameters determined for the starting location. The problem can then be solved iteratively.

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



Two weeks of quick CMTs, November 2009



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

The Global CMT Project

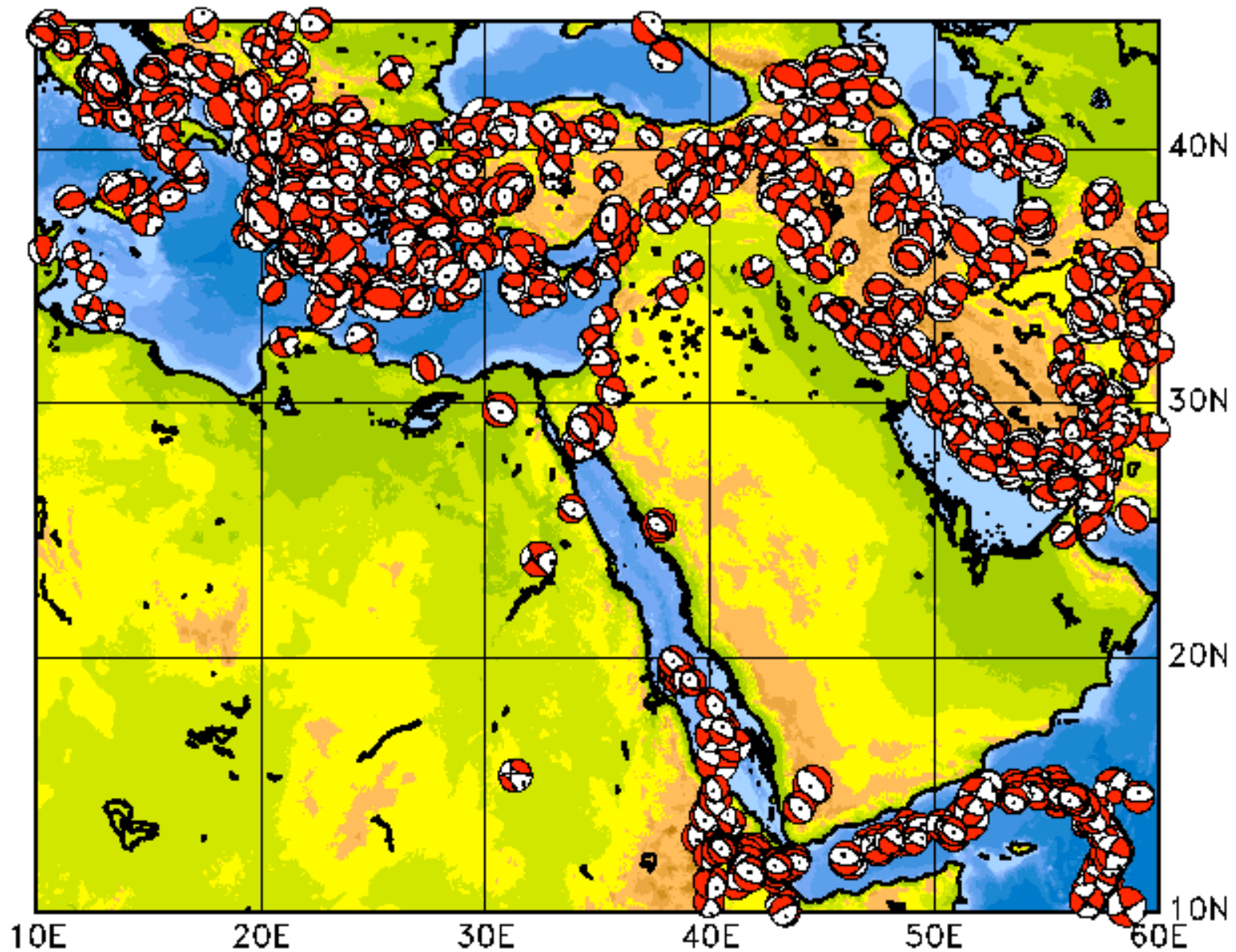
Project started in 1981 (A.M. Dziewonski et al.)

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

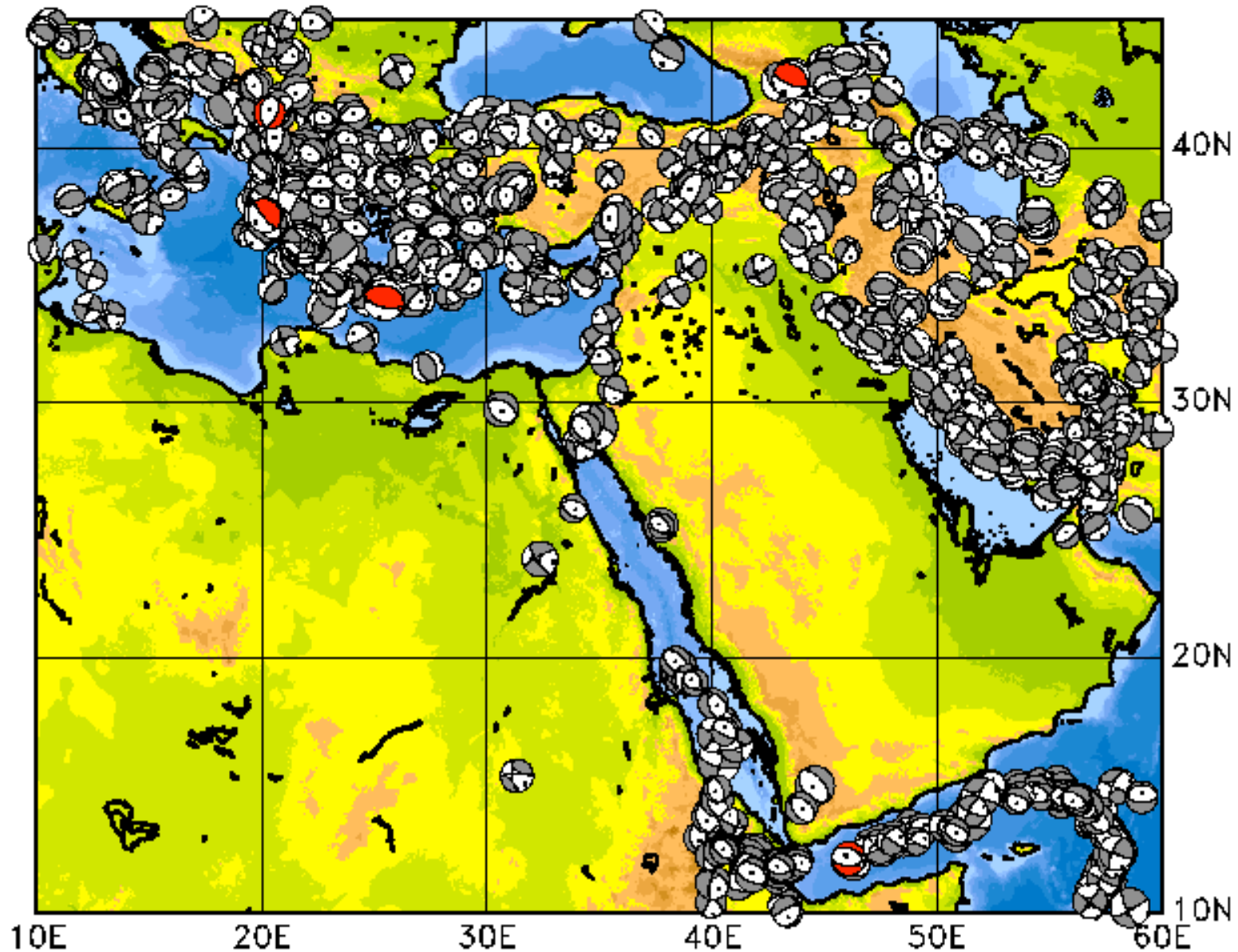
CMT catalog contains ~30,000 moment tensors for the period 1976-2009

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

Shallow earthquakes, 1976-2009

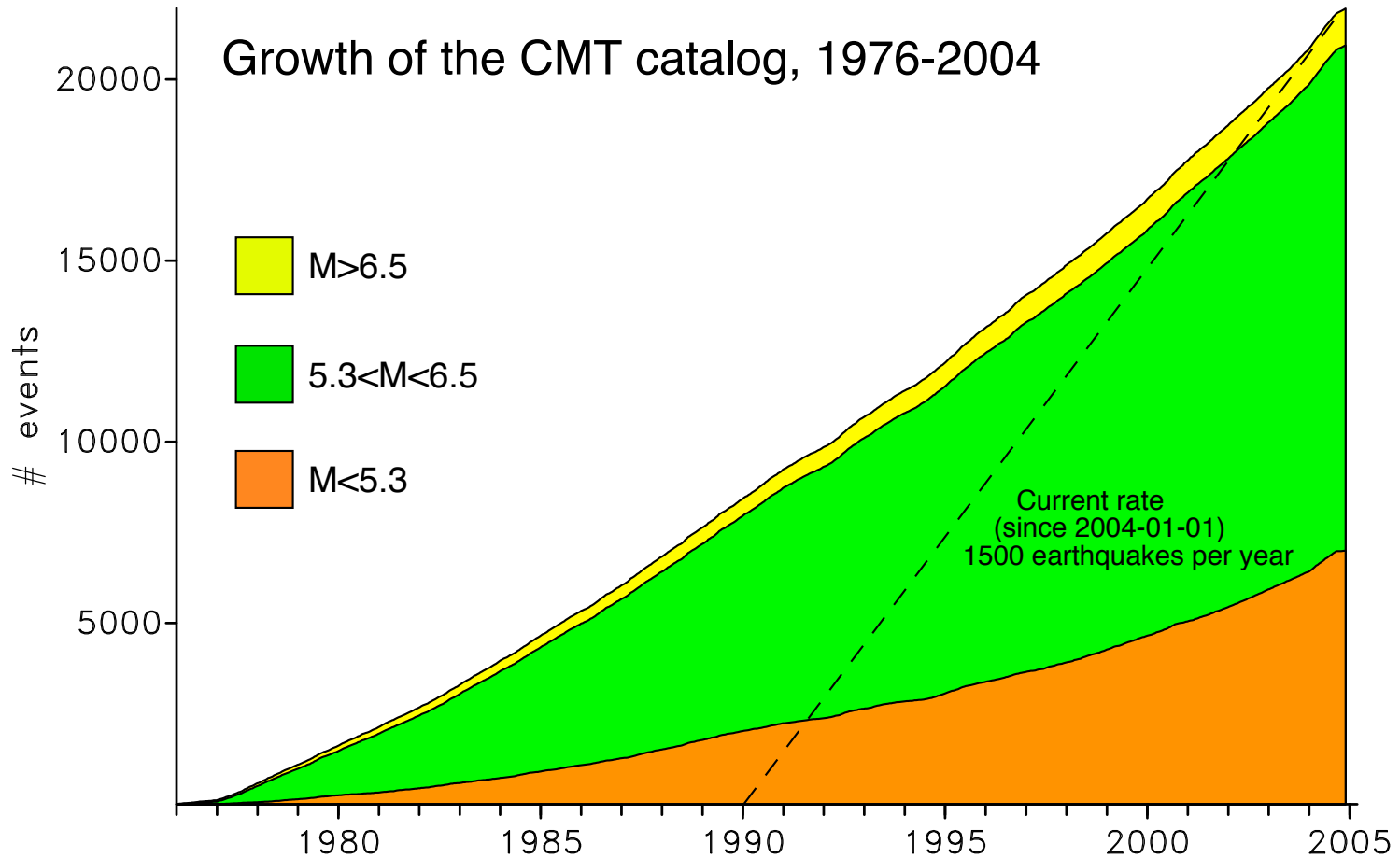


Shallow earthquakes, 1976-2009



red - earthquakes in last three months

We analyze 1500-2000 earthquakes per year



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

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

3. Using calibration information in waveform analysis

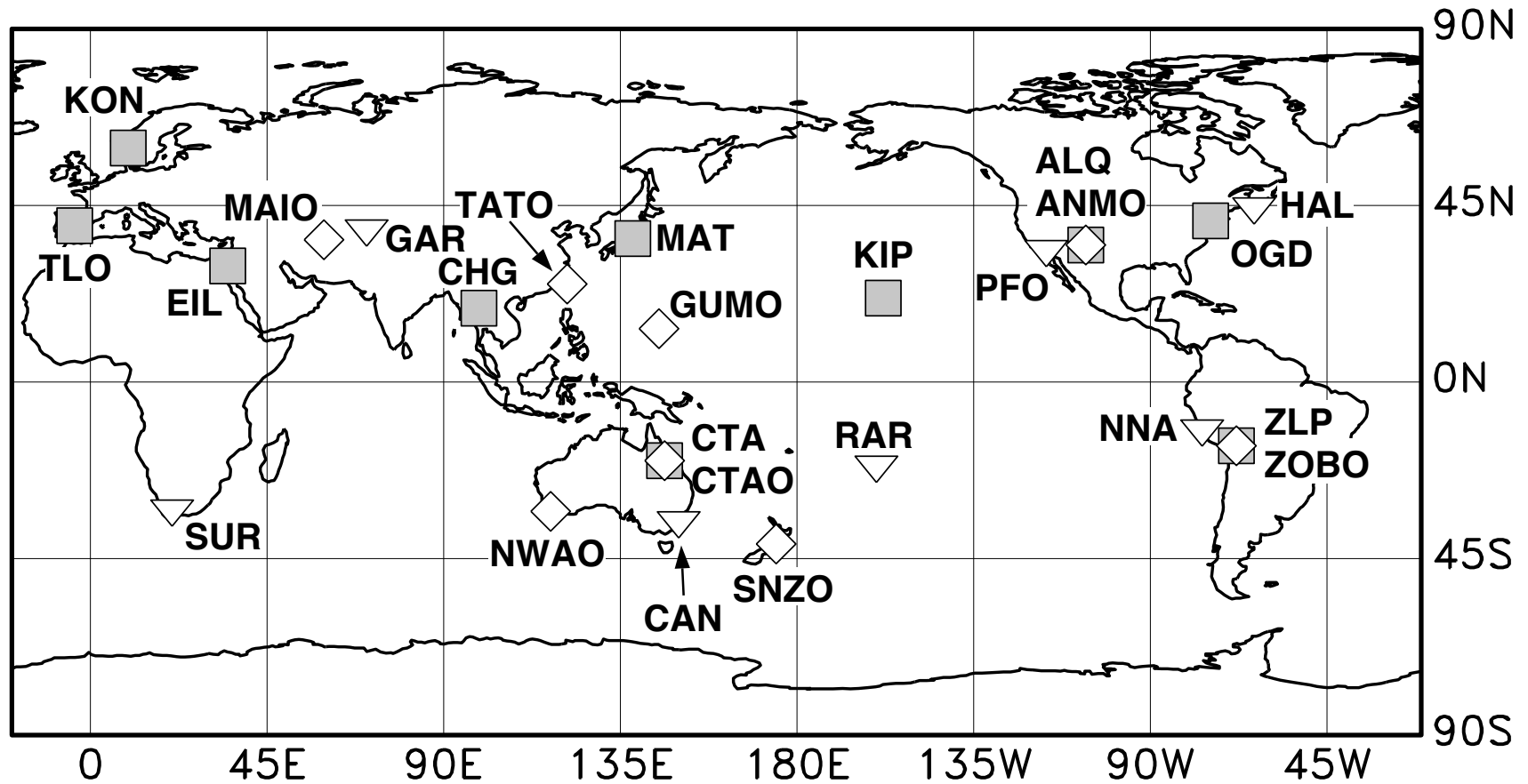
4. Data quality control using signals

5. Data quality control using noise

6. Finding interesting things in the noise

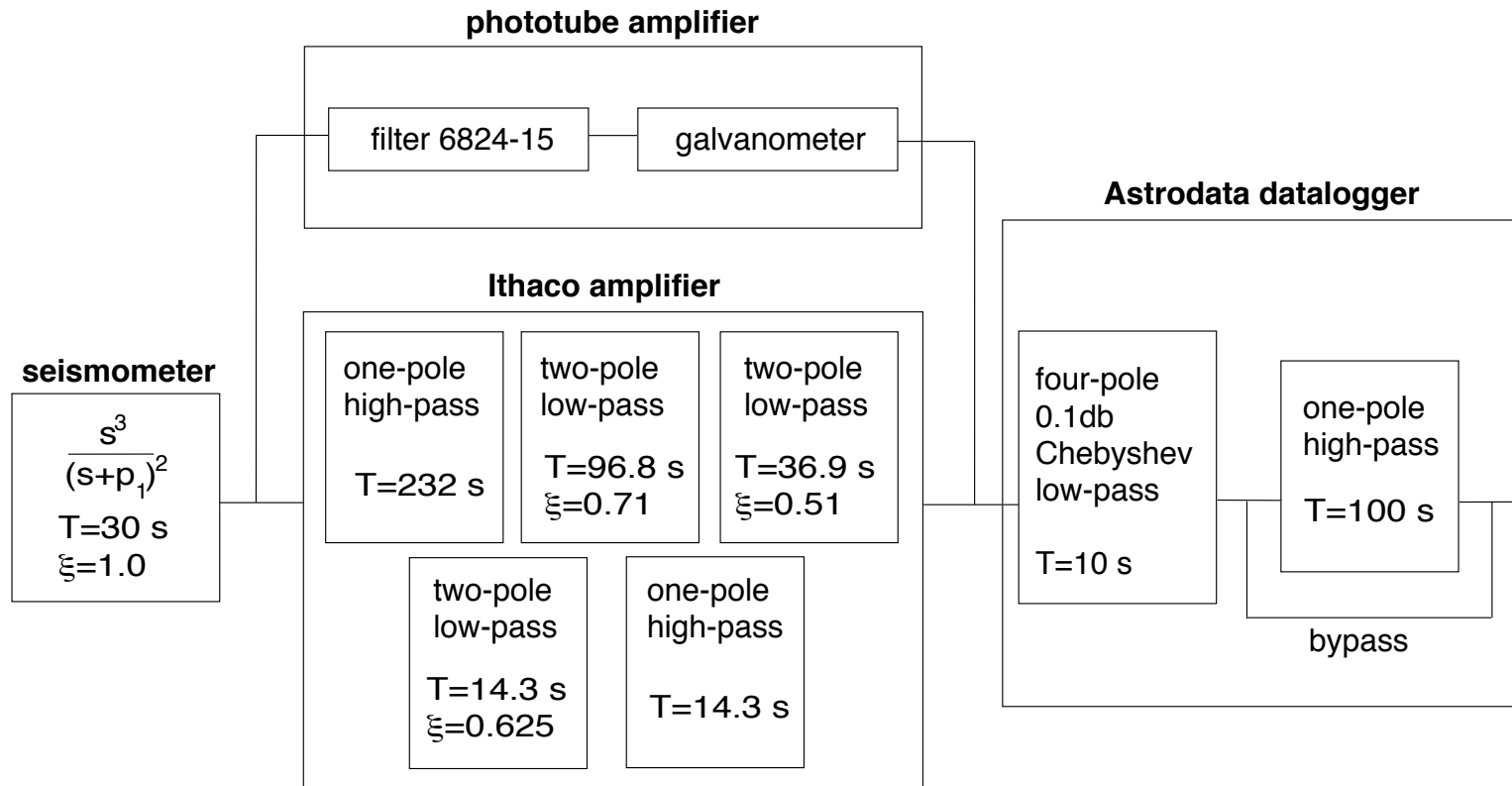
**Quantitative waveform analysis requires
highly accurate instrument response information**

The Global Digital Network in 1976

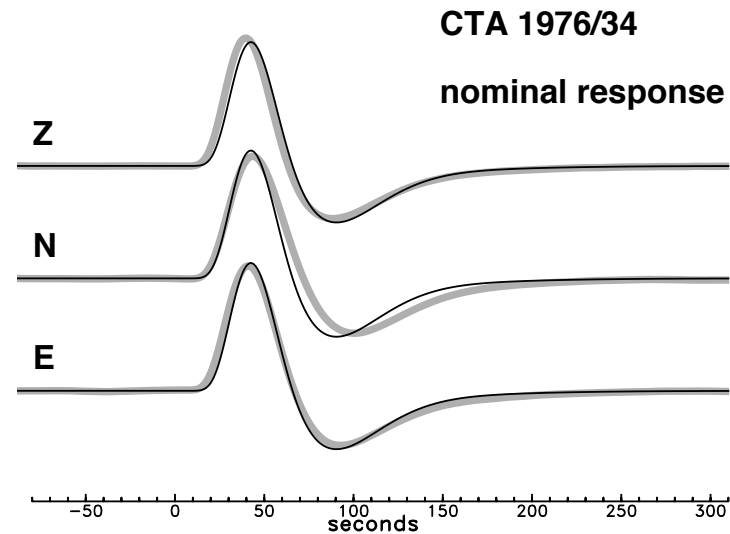


■ High-Gain Long-Period (HGLP) network

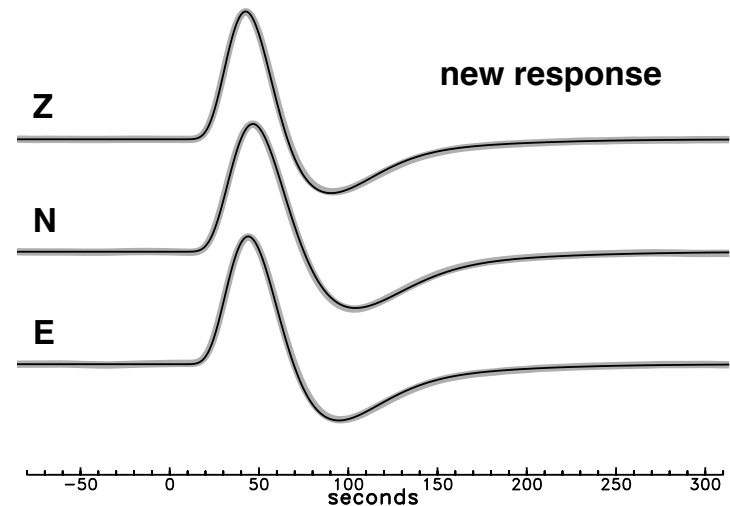
HLGP seismometer and recording system



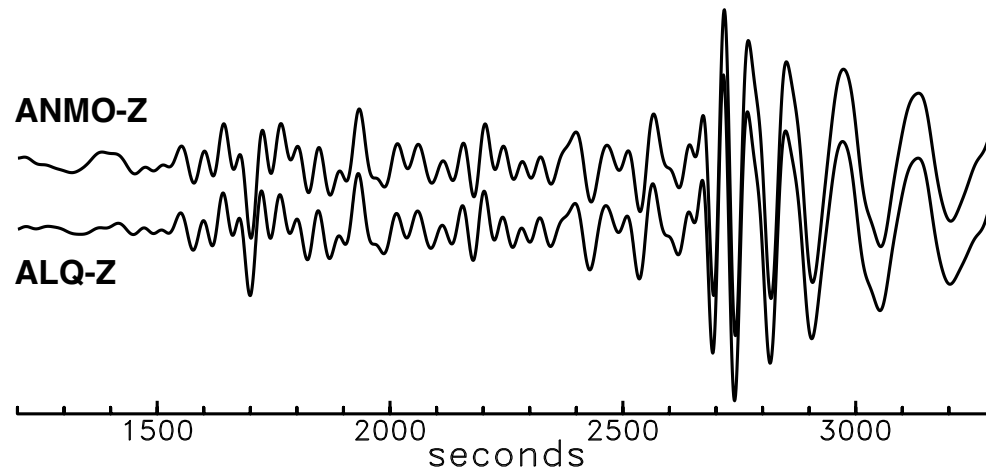
Original calibration
pulses and pulses for
nominal response



Original calibration
pulses and pulses for
new response after
inversion

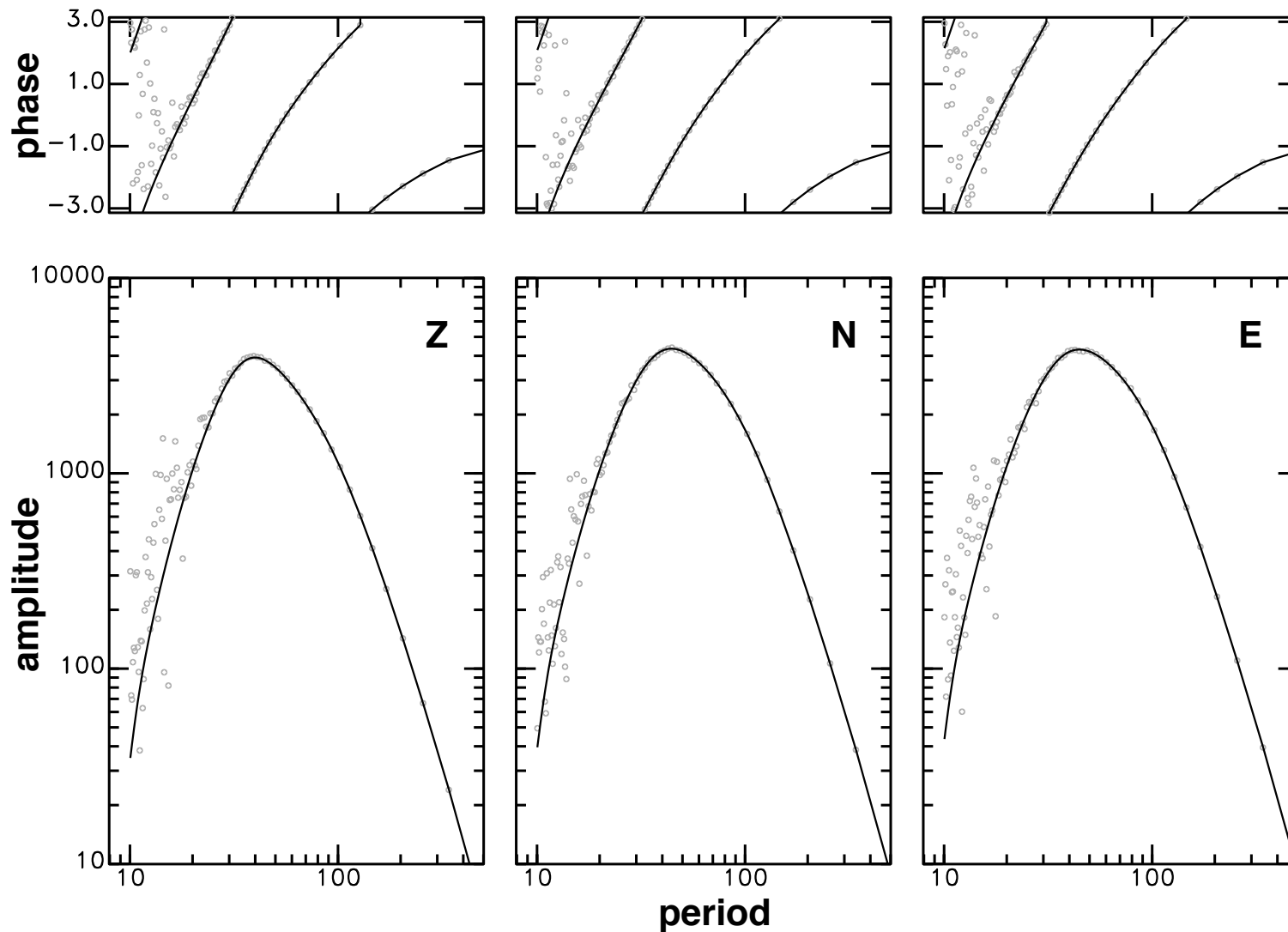


Comparison of waveforms after normalizing responses for two stations in the same location

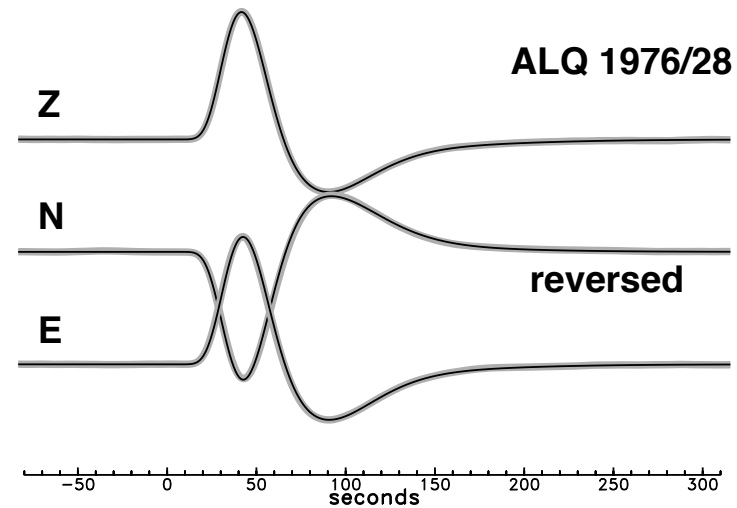


Check of new responses -- sine-wave calibrations

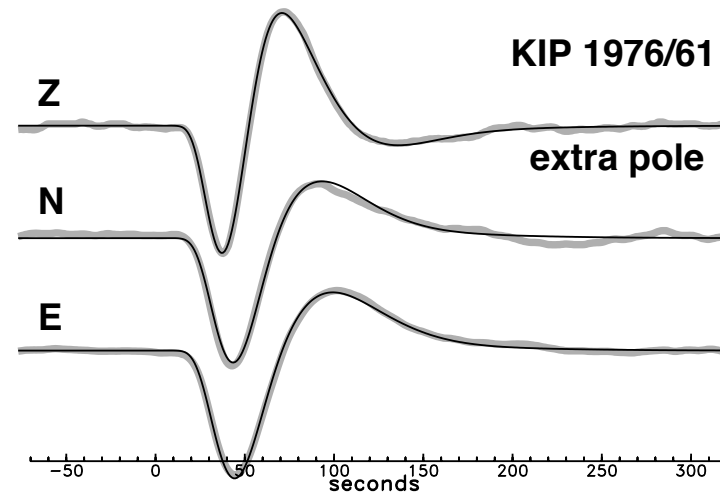
KON 1976/33



Some channels were reversed for some periods of time

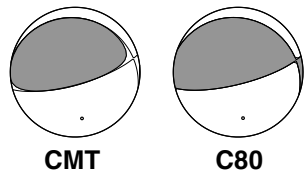


Some channels had extra filters for some periods of time

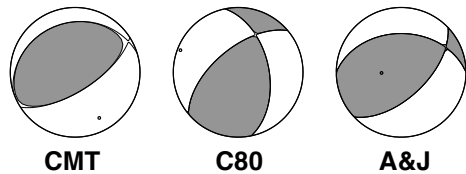


Waveform comparisons (observed and synthetic) after correcting seismograms using new responses: The 1976 Friuli earthquake

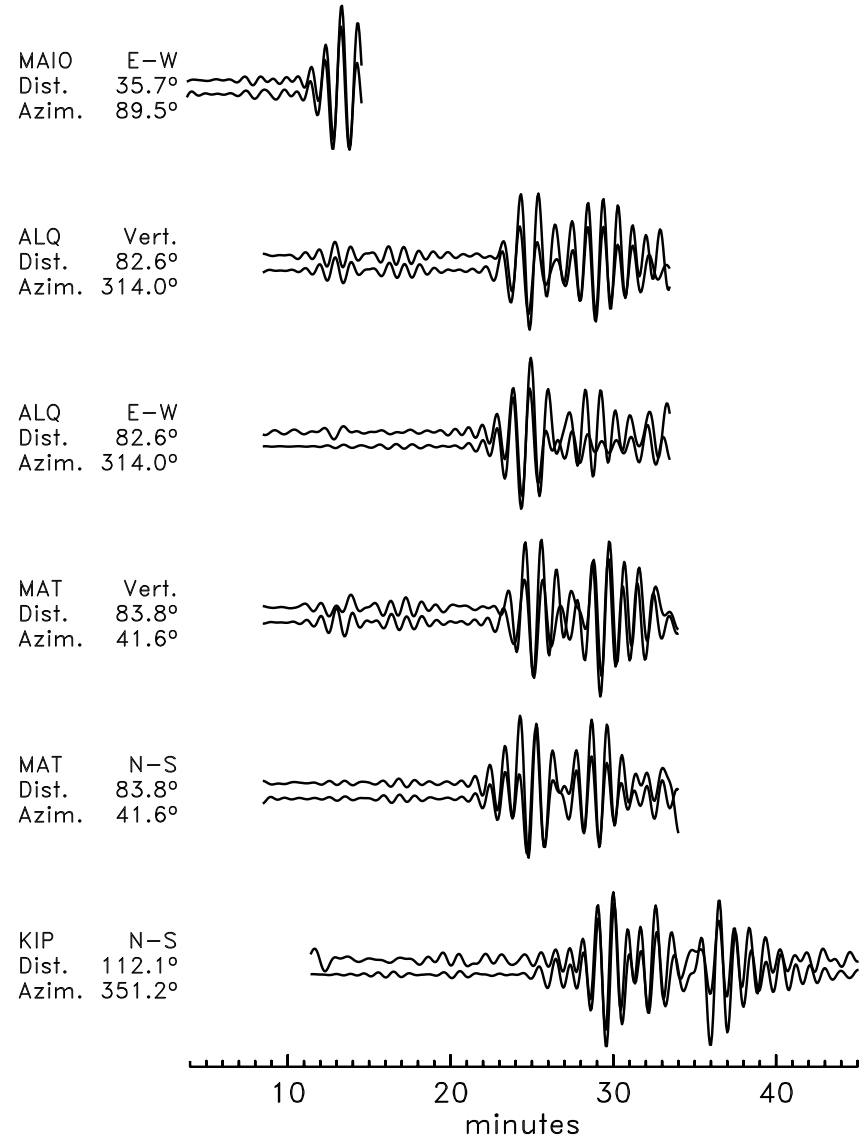
Friuli Events



**Main Shock
6 May 1976**



**Aftershock
15 Sept. 1976**



4. Data quality control using signals

5. Data quality control using noise

6. Finding interesting things in the noise

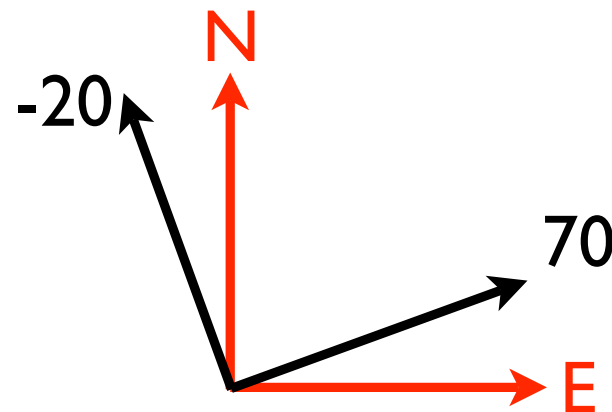
4a. Sensor orientation

4b. Sensor response stability

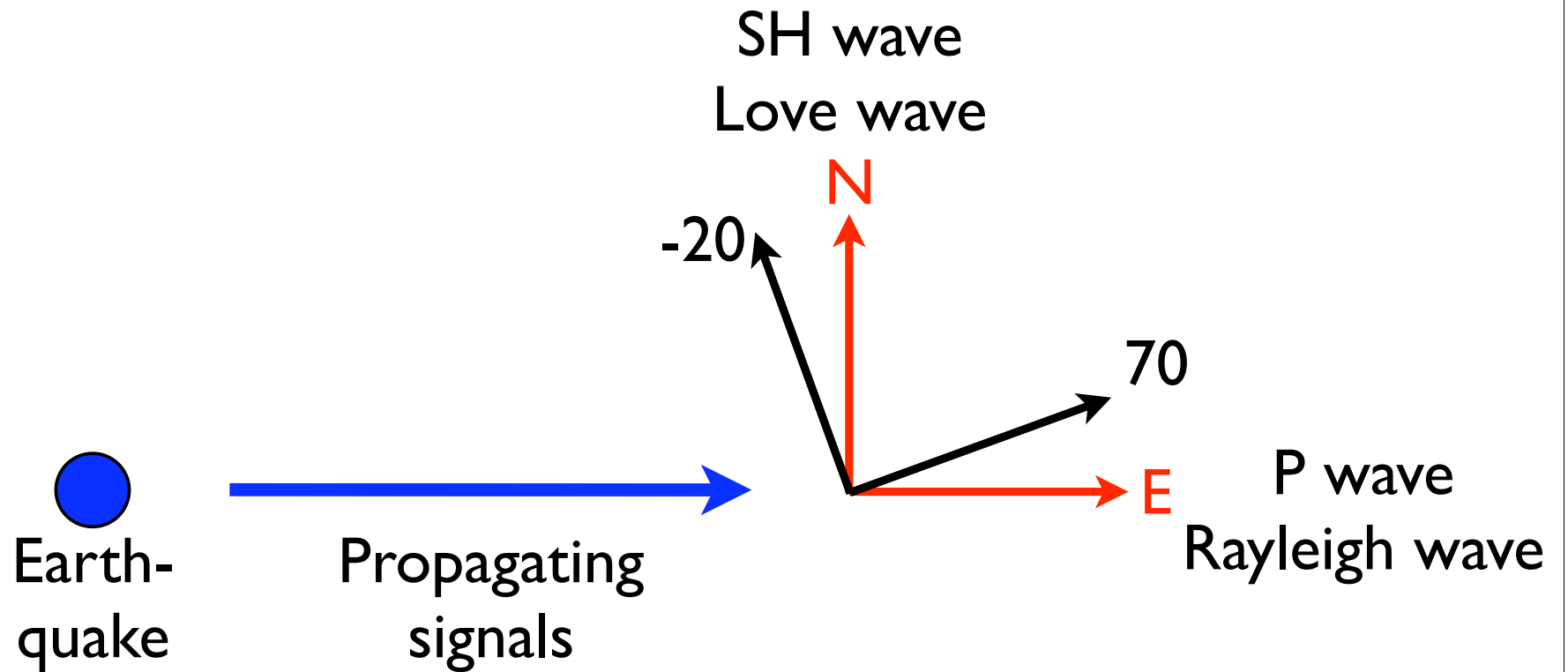
Horizontal Polarization Problems

Desired (assumed) orientation of seismometer

True orientation of seismometer

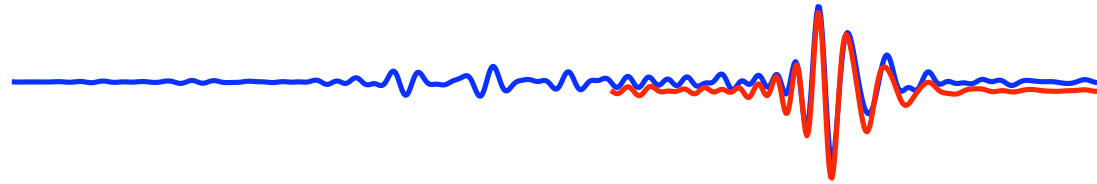


Natural Polarization of Earthquake Signals



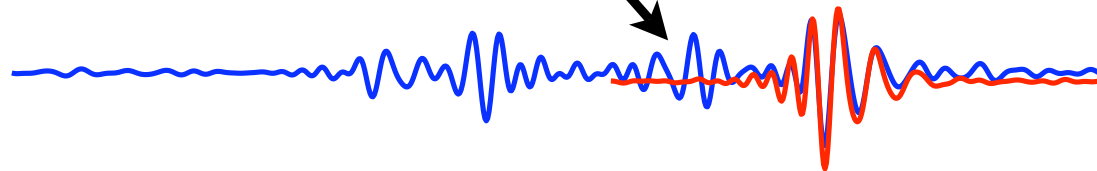
Symptoms of a misoriented sensor

Vertical



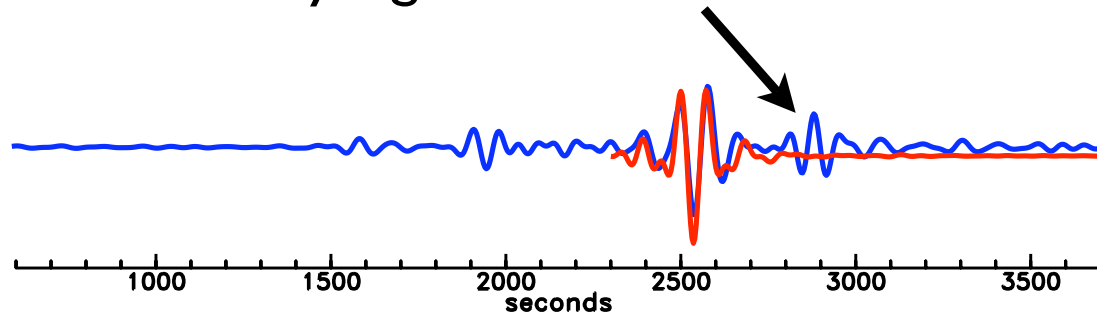
Love wave on longitudinal

Longitudinal



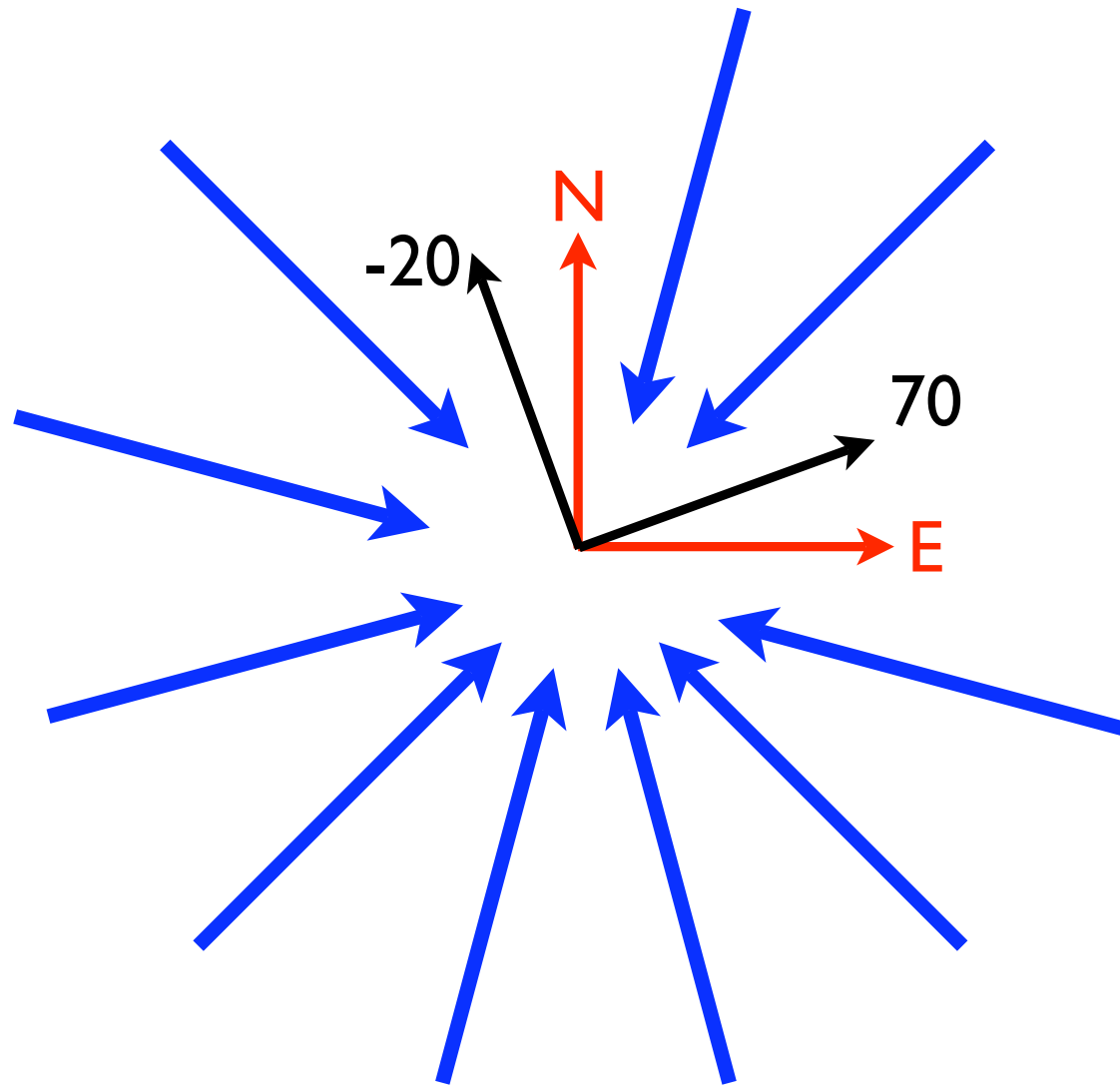
Rayleigh wave on transverse

Transverse

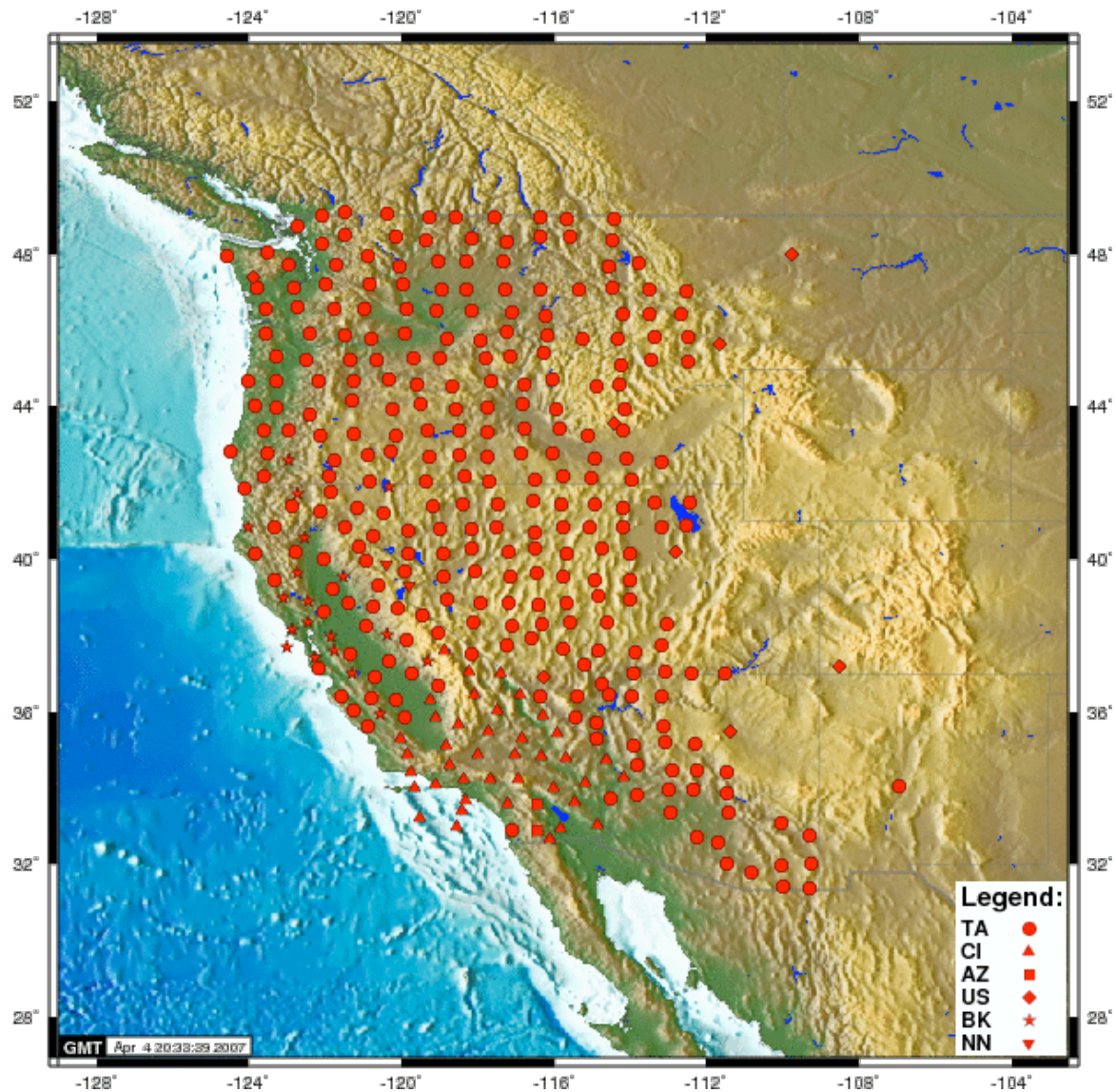


Station D09A, earthquake on 08/20/2007

Many earthquake signals --
invert for orientation of sensor



USArray Transportable Array, April 2007



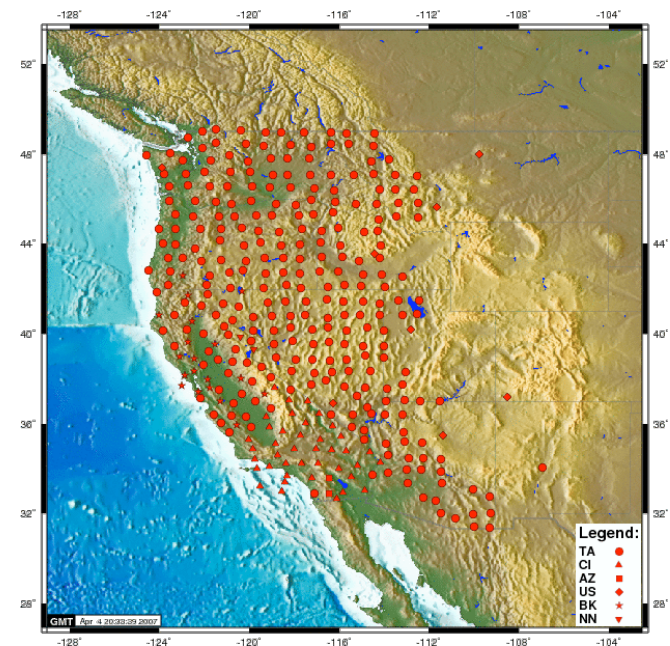
Polarization analysis of USArray data using earthquake signals recorded in 2006-2007

400+ USArray stations

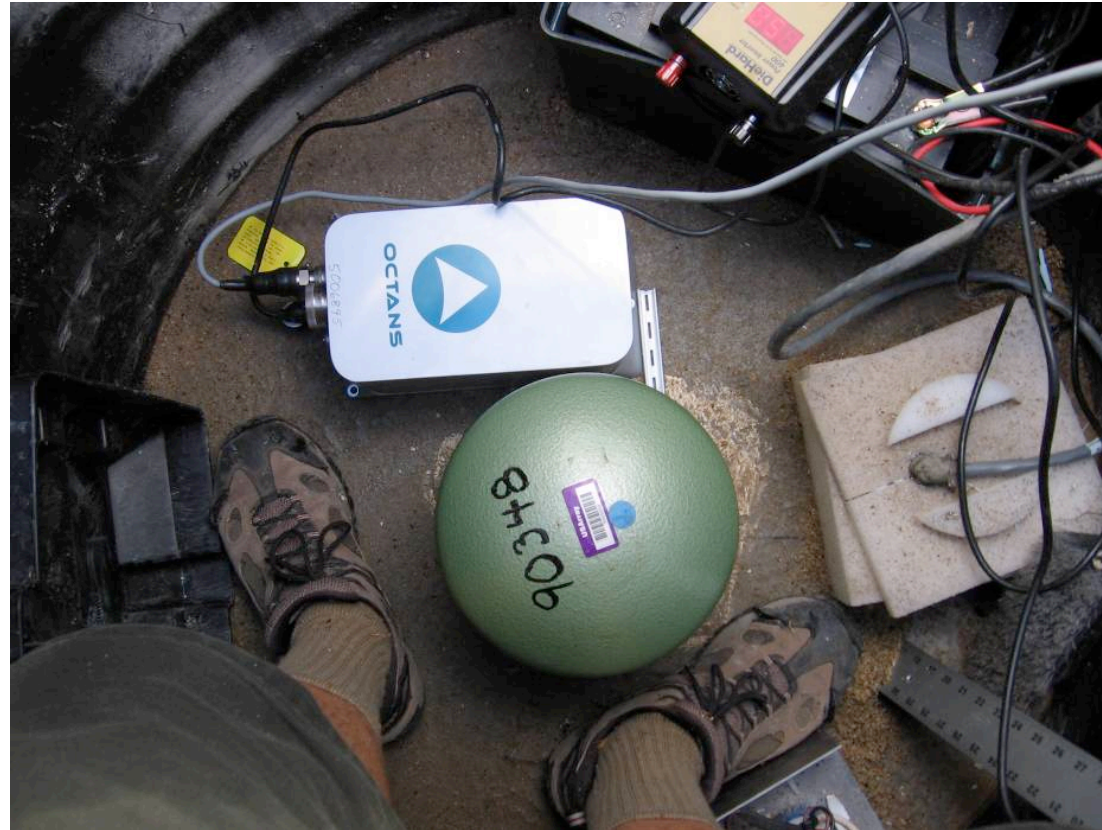
Result:

> 5% misoriented > 10 degrees

> 10 % misoriented > 5 degrees

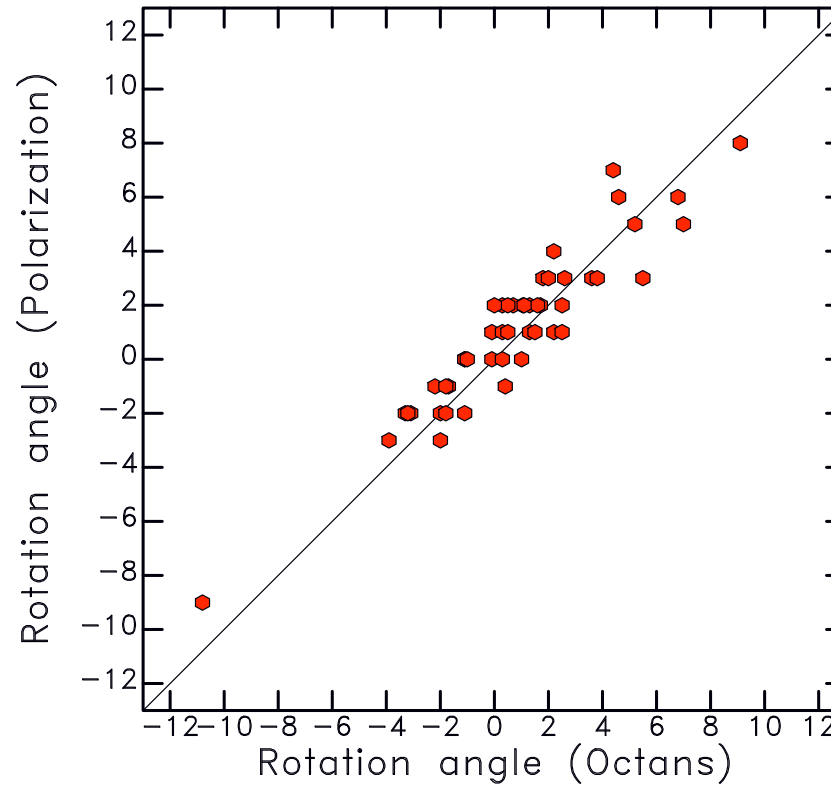


Octans interferometric laser gyro



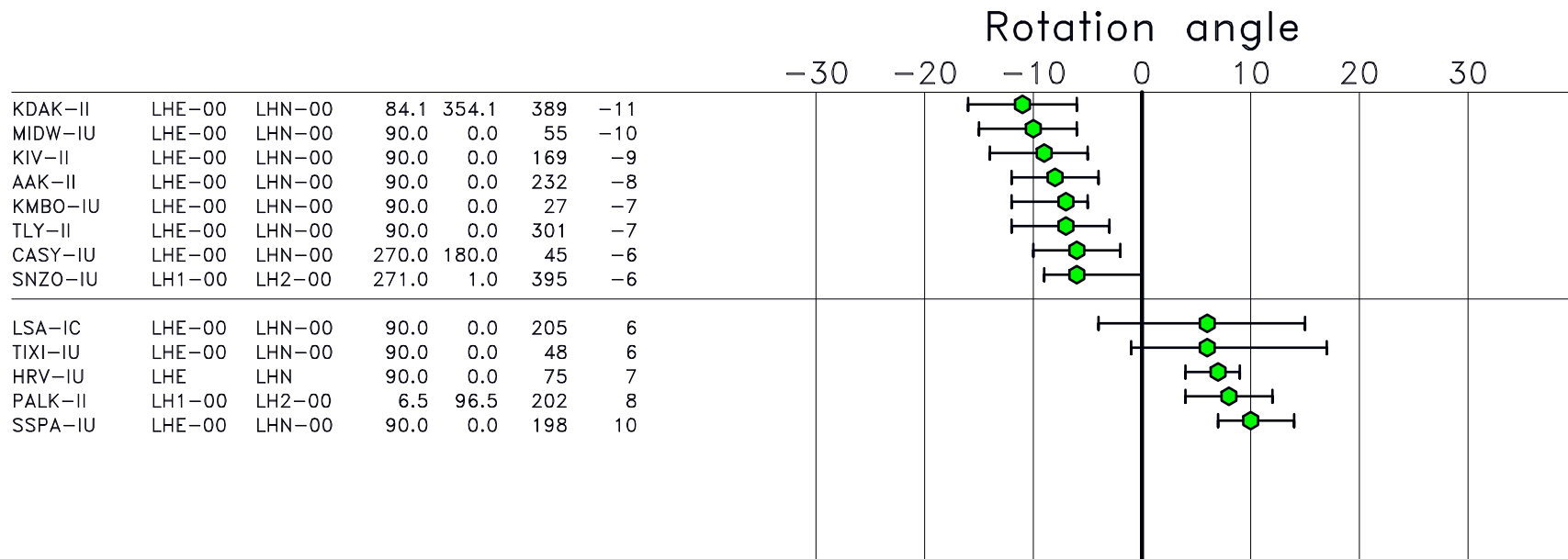
Agreement of field (Octans) and polarization angles

estimated from
seismograms



measured in the field

Outliers (>5 deg) II, IU, IC as of 2009/11/08



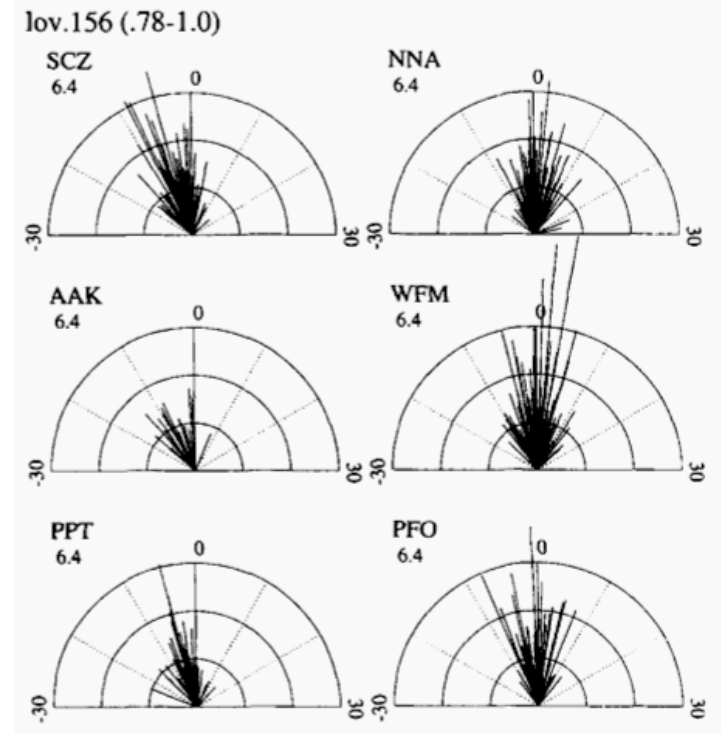
several GSN outliers have been eliminated
in the last year or so by updates to metadata
or (for secondary sensors) re-orientation of
the sensor

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



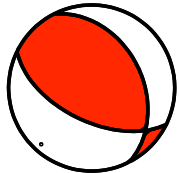
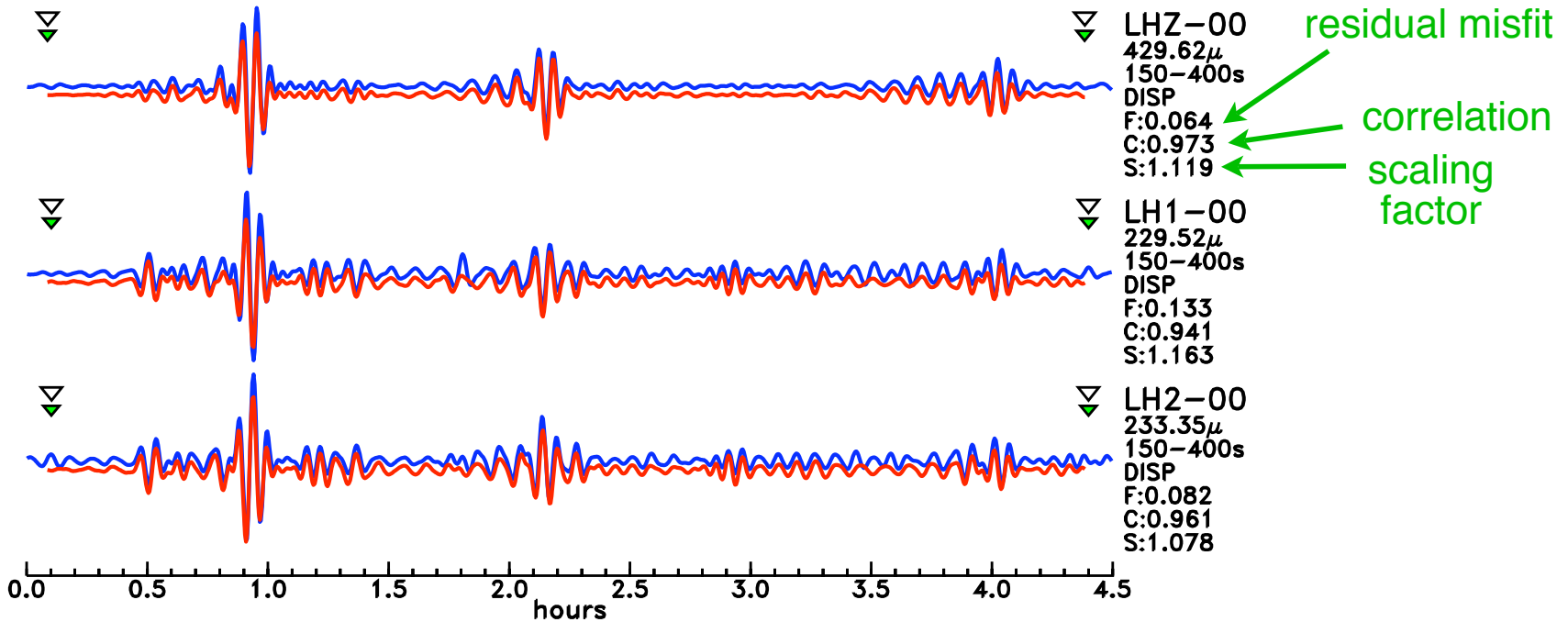
(Laske, 1995)

4b. Sensor response stability

Blue - observed seismograms

Red - synthetic seismograms

2005/10/08 03:50:38.0, $\delta = 34.43$, $\varphi = 73.54$, $h = 10.0$
POHA-IU $\Delta = 108.72$, $\alpha = 48.71$, $\beta = 318.75$ MANTLE WAVES

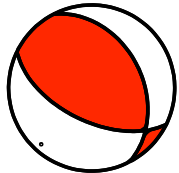
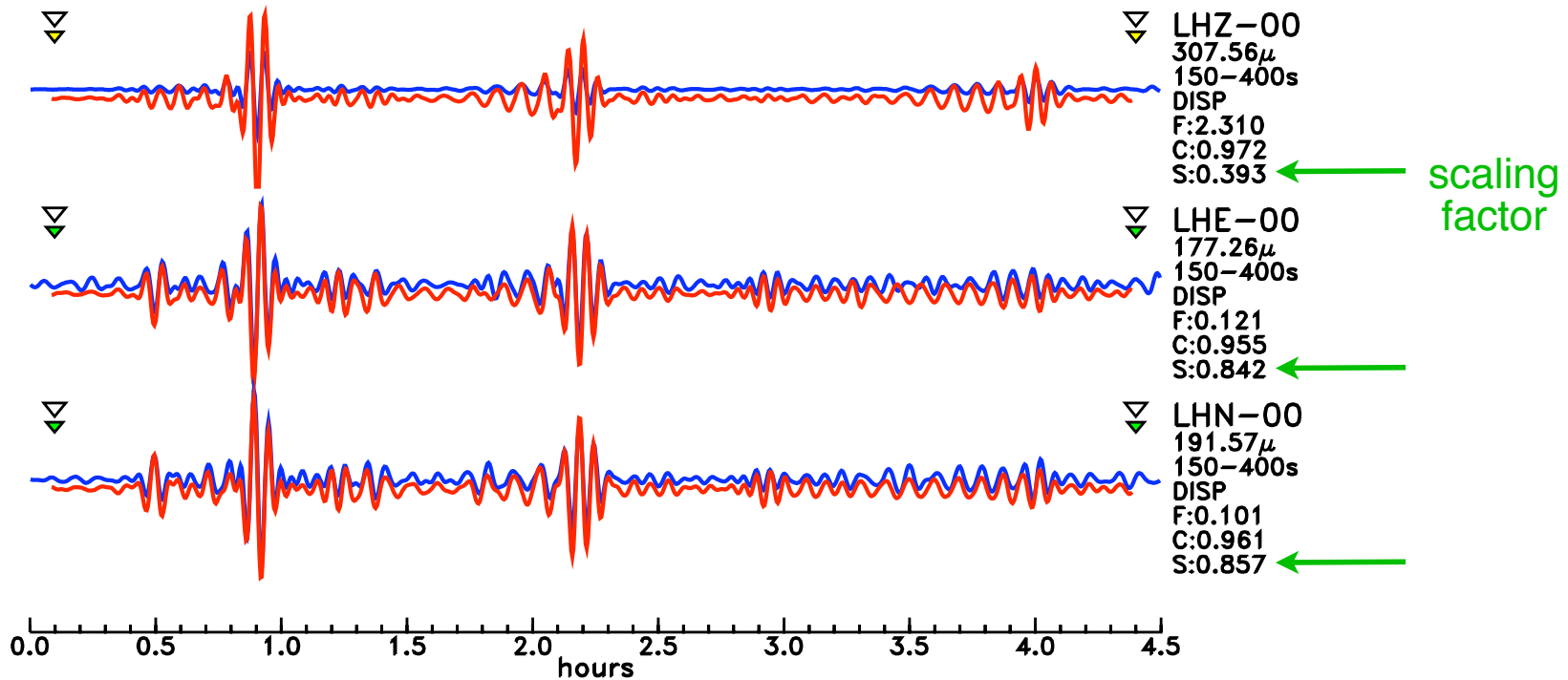


$$S = \frac{\sum_{i=1}^N O_i S_i}{\sum_{i=1}^N S_i^2}$$

Blue - observed seismograms

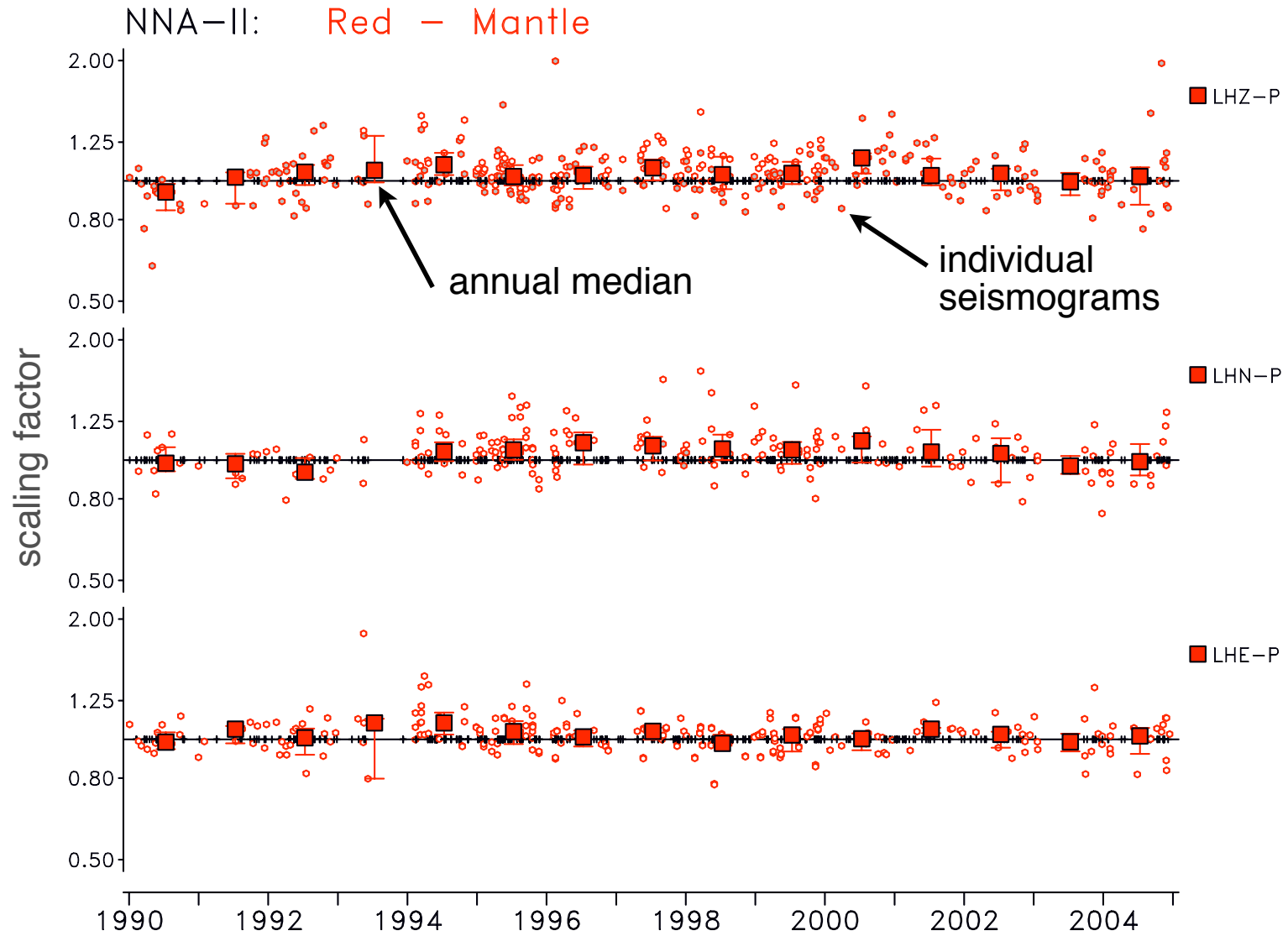
Red - synthetic seismograms

2005/10/08 03:50:38.0, $\vartheta = 34.43$, $\varphi = 73.54$, $h = 10.0$
KIP-IU $\Delta = 105.93$, $\alpha = 49.37$, $\beta = 317.68$ MANTLE WAVES

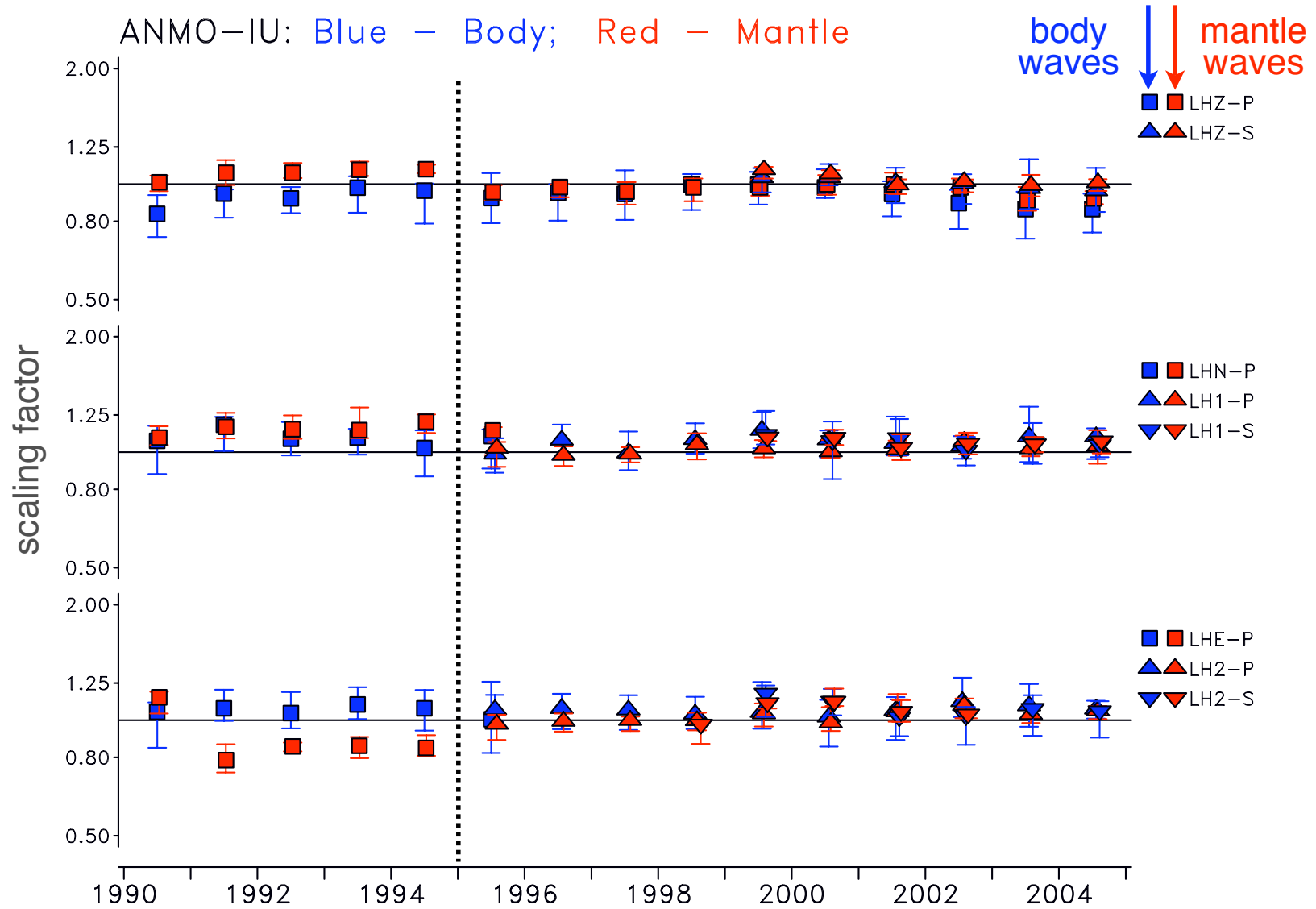


$$S = \frac{\sum_{i=1}^N O_i S_i}{\sum_{i=1}^N S_i^2}$$

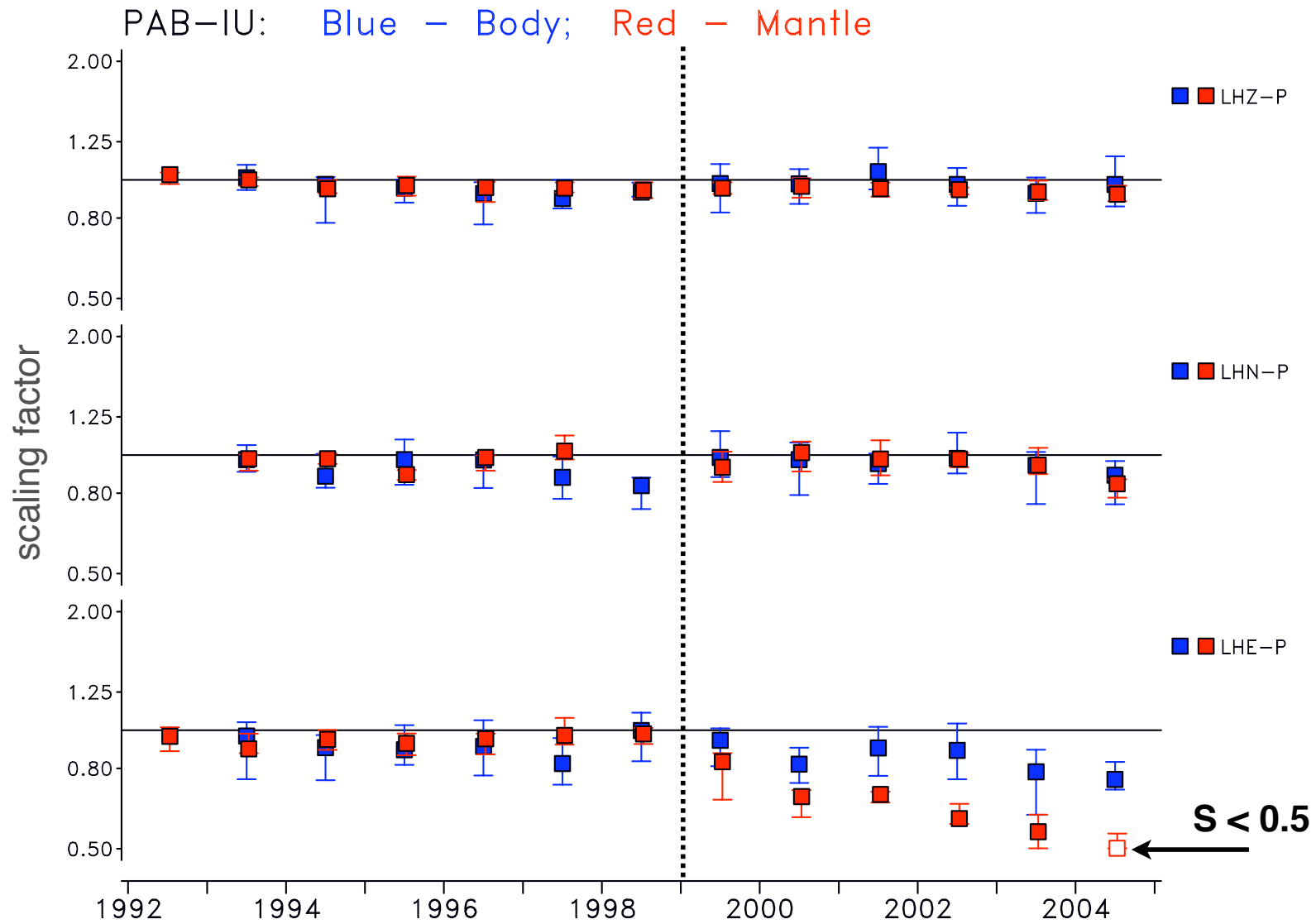
Scaling factors at NNA-II, 1990-2004



Scaling factors at ANMO-IU, 1990-2004

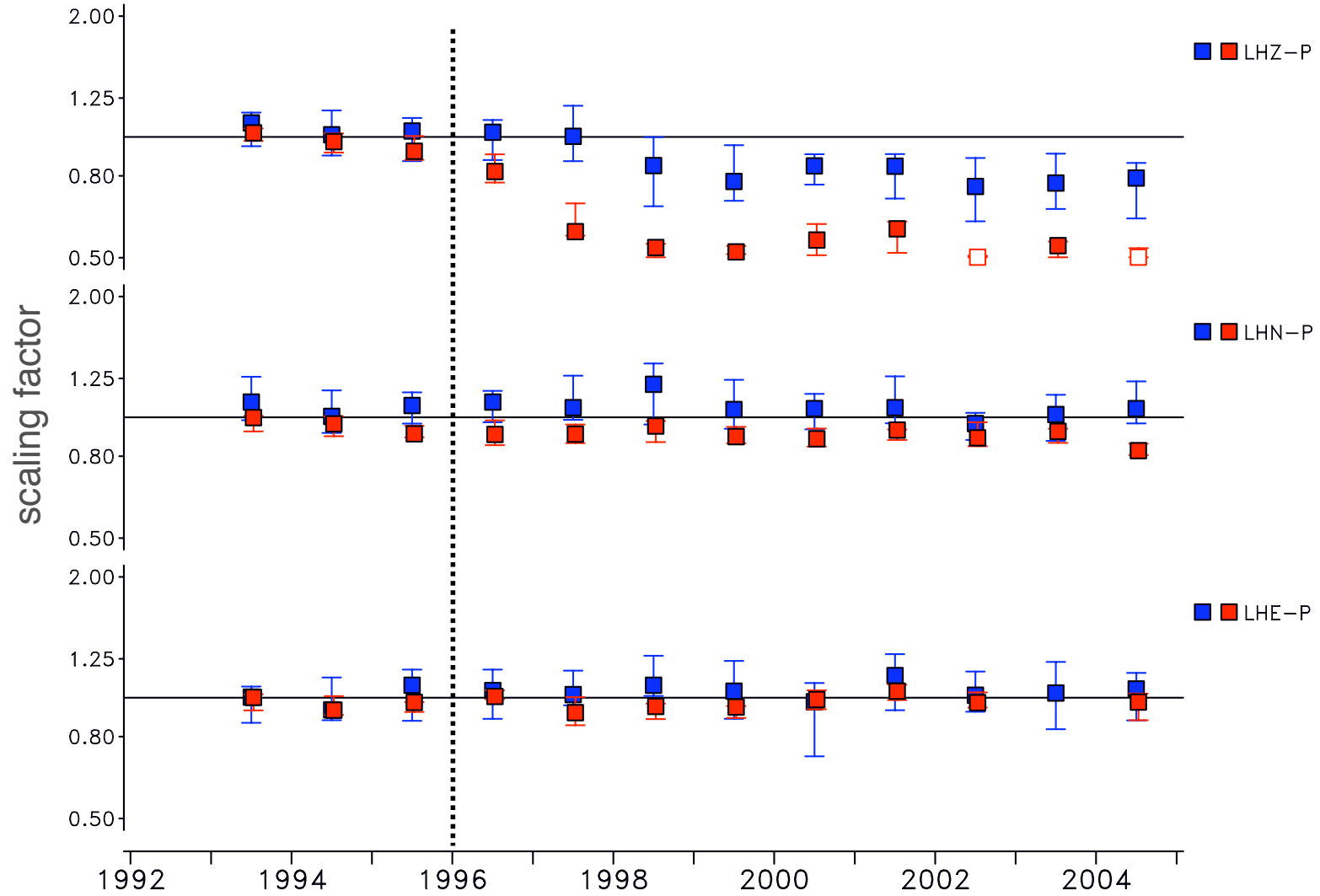


Scaling factors at PAB-IU, 1992-2004

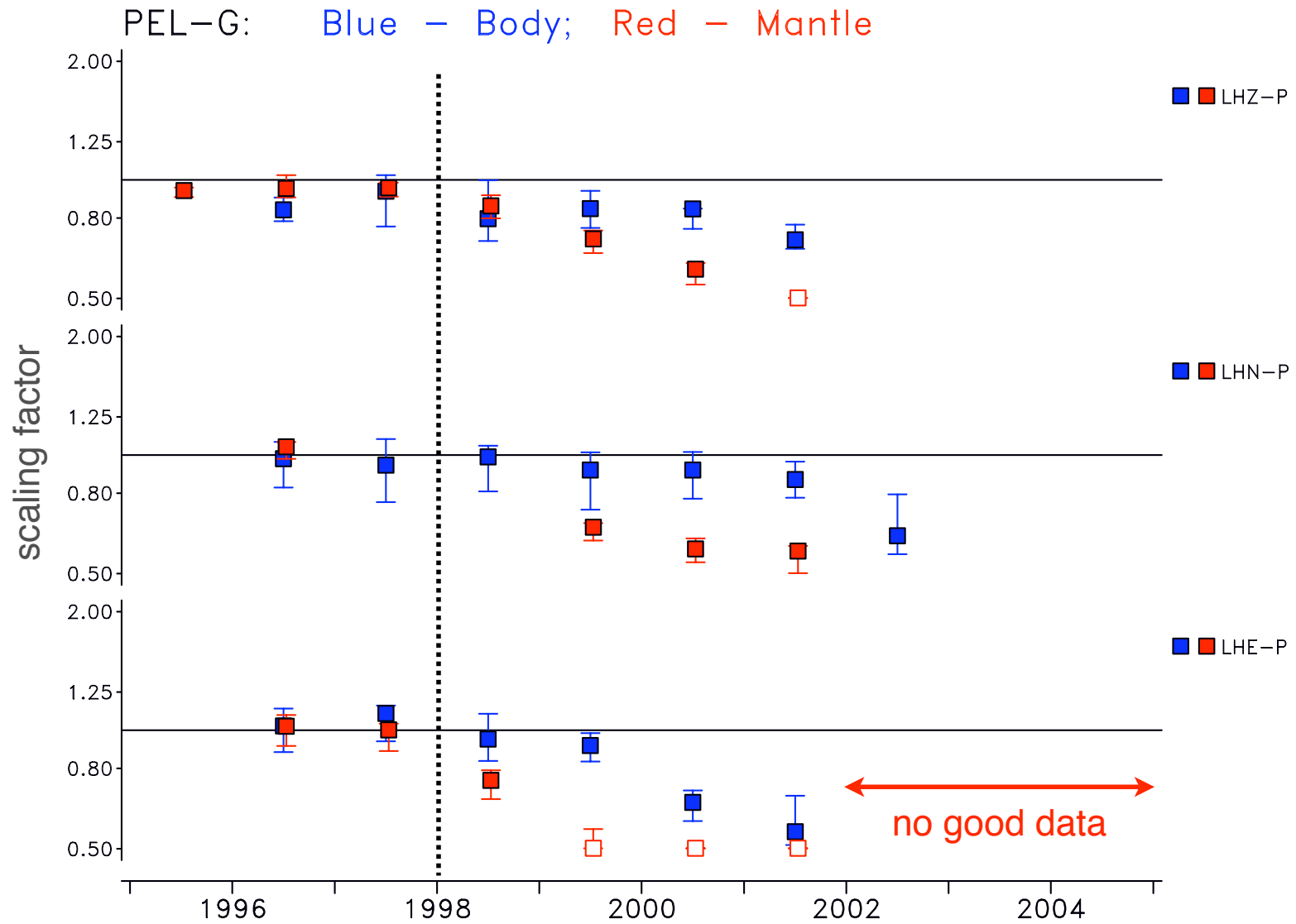


Scaling factors at LVZ-II, 1993-2004

LVZ-II: Blue - Body; Red - Mantle



Scaling factors at PEL-G, 1996-2002

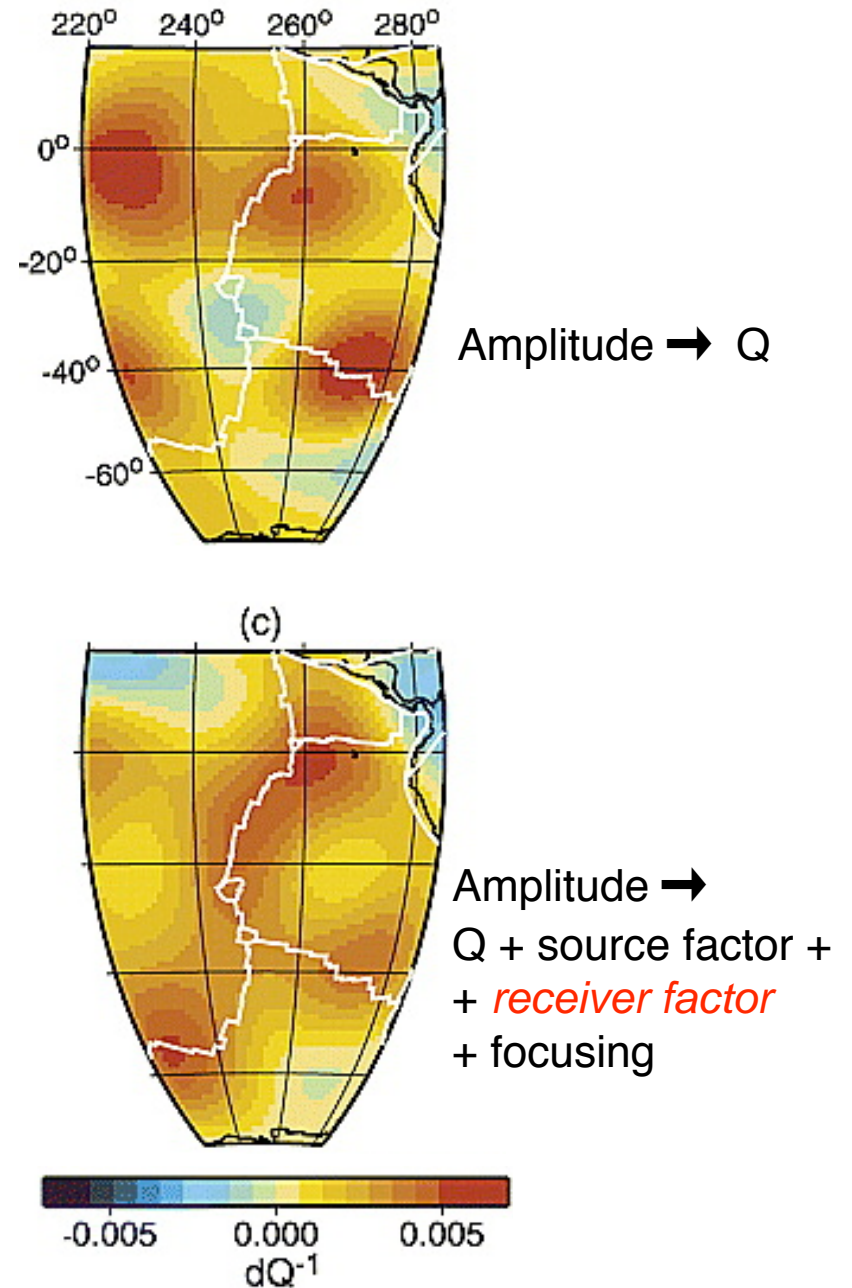


Summary

- All results are available at: www.ldeo.columbia.edu/~ekstrom/Projects/WQC/SCALING
 - Most stations show no, or small, deviations from the reported response
 - A few stations (e.g., GTSN) show constant offsets in gain of 10-20%
 - *Approximately 15% of stations equipped with STS-1 seismometers show a time- and frequency-dependent deterioration of the true gain*
- ➡ Cause of problem?
- ▶ How to fix instruments?
 - ▶ How to fix response information retroactively?
- ➡ Recommend regular instrument calibration

Why does it matter?

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



(Dalton and Ekström, 2006)

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

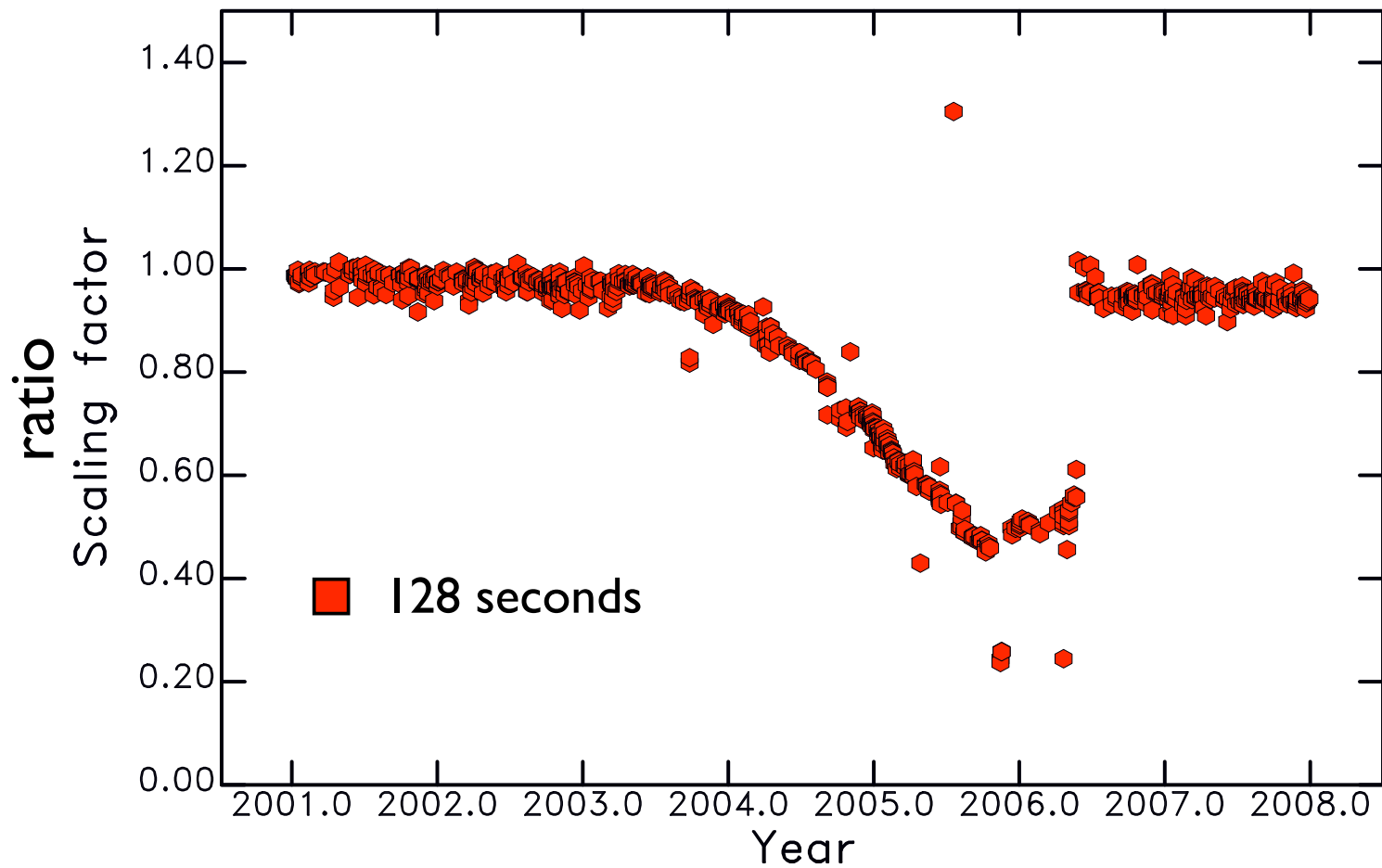
calculate ratio of displacements at some period during times of high signal coherence

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

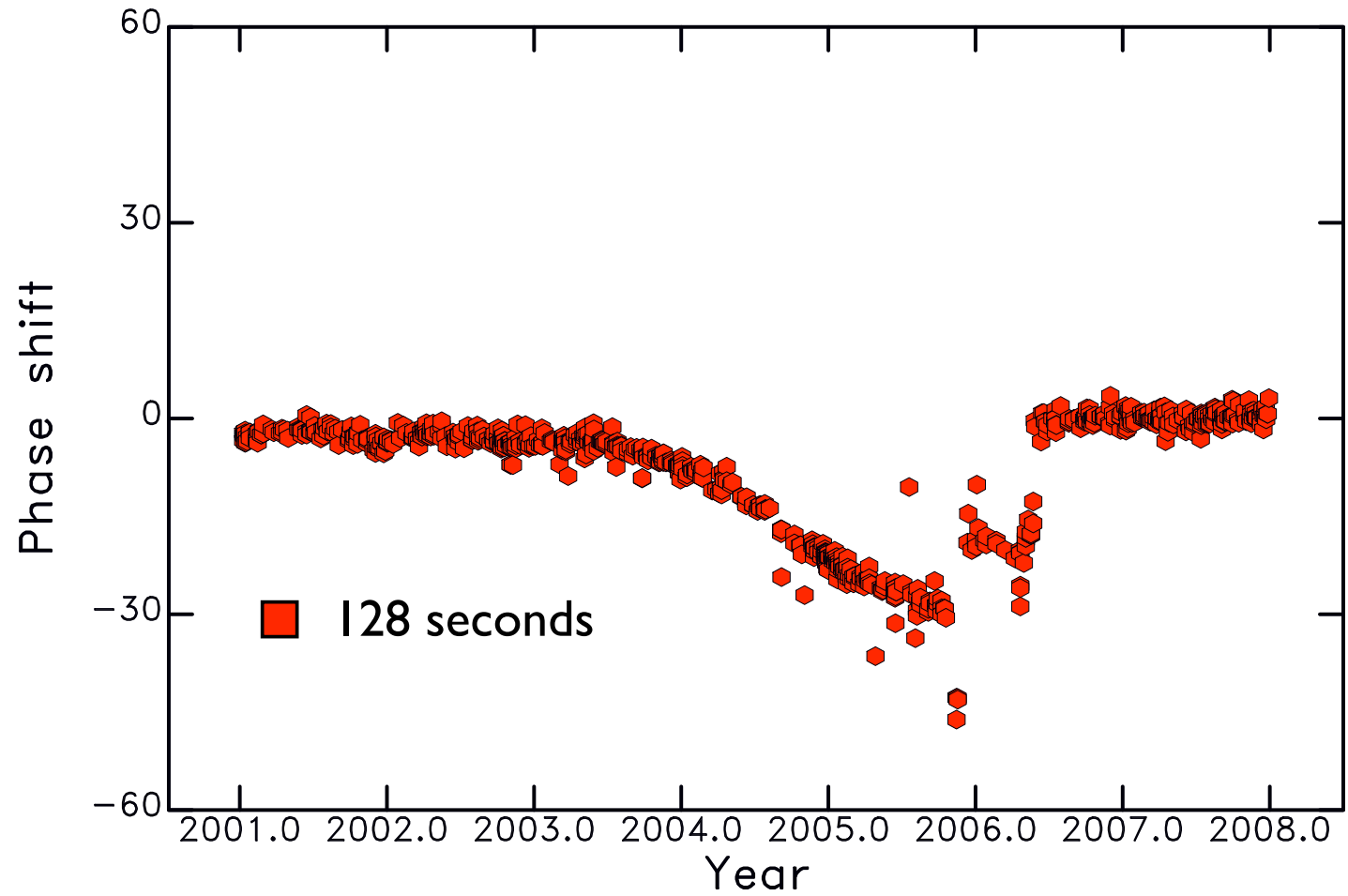
$$\frac{\text{signal B}}{\text{response B}} = \text{displacement B} \quad (\text{deconvolution})$$

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

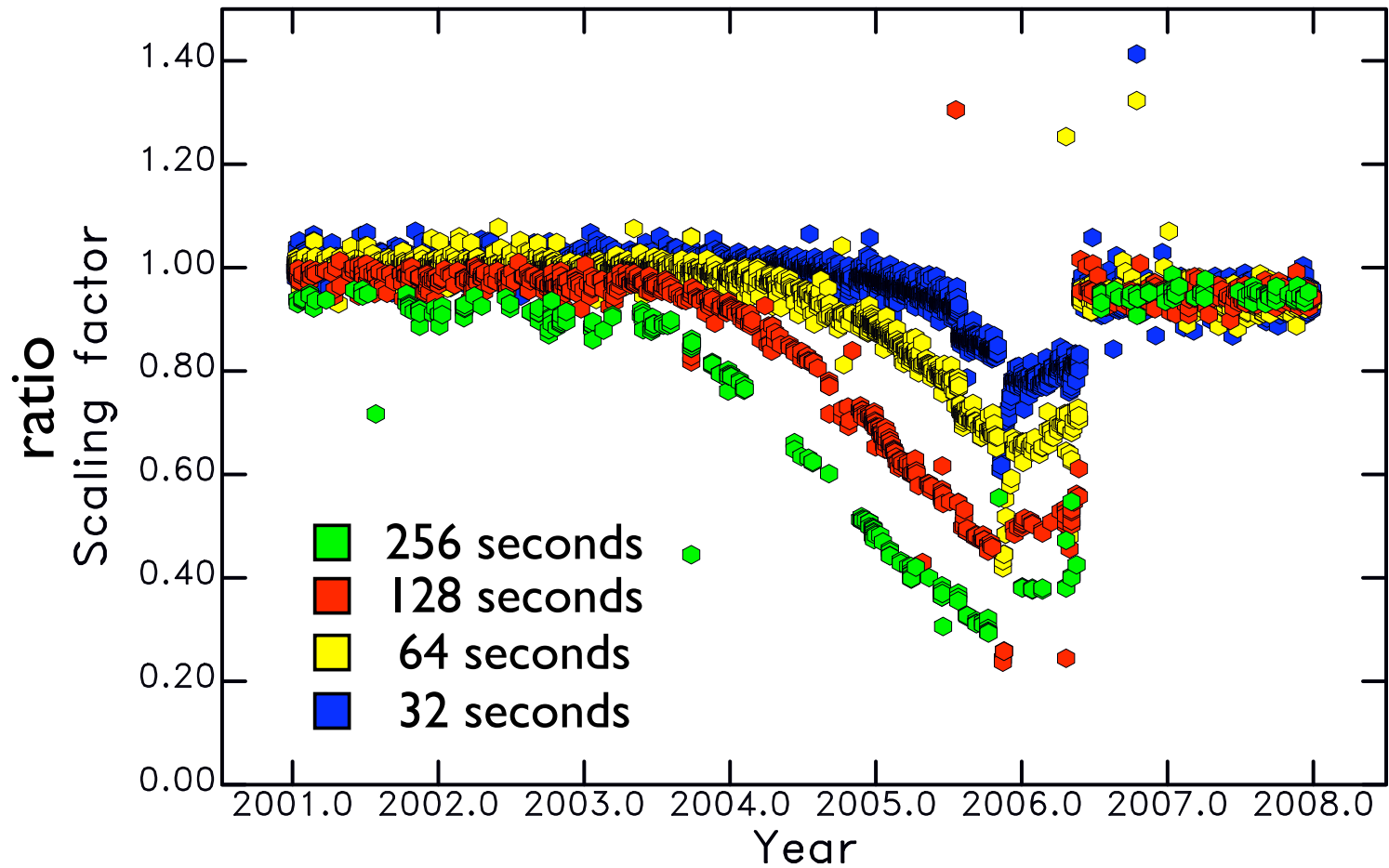
Scaling of STS-1 to STS-2 displacement at station KIP



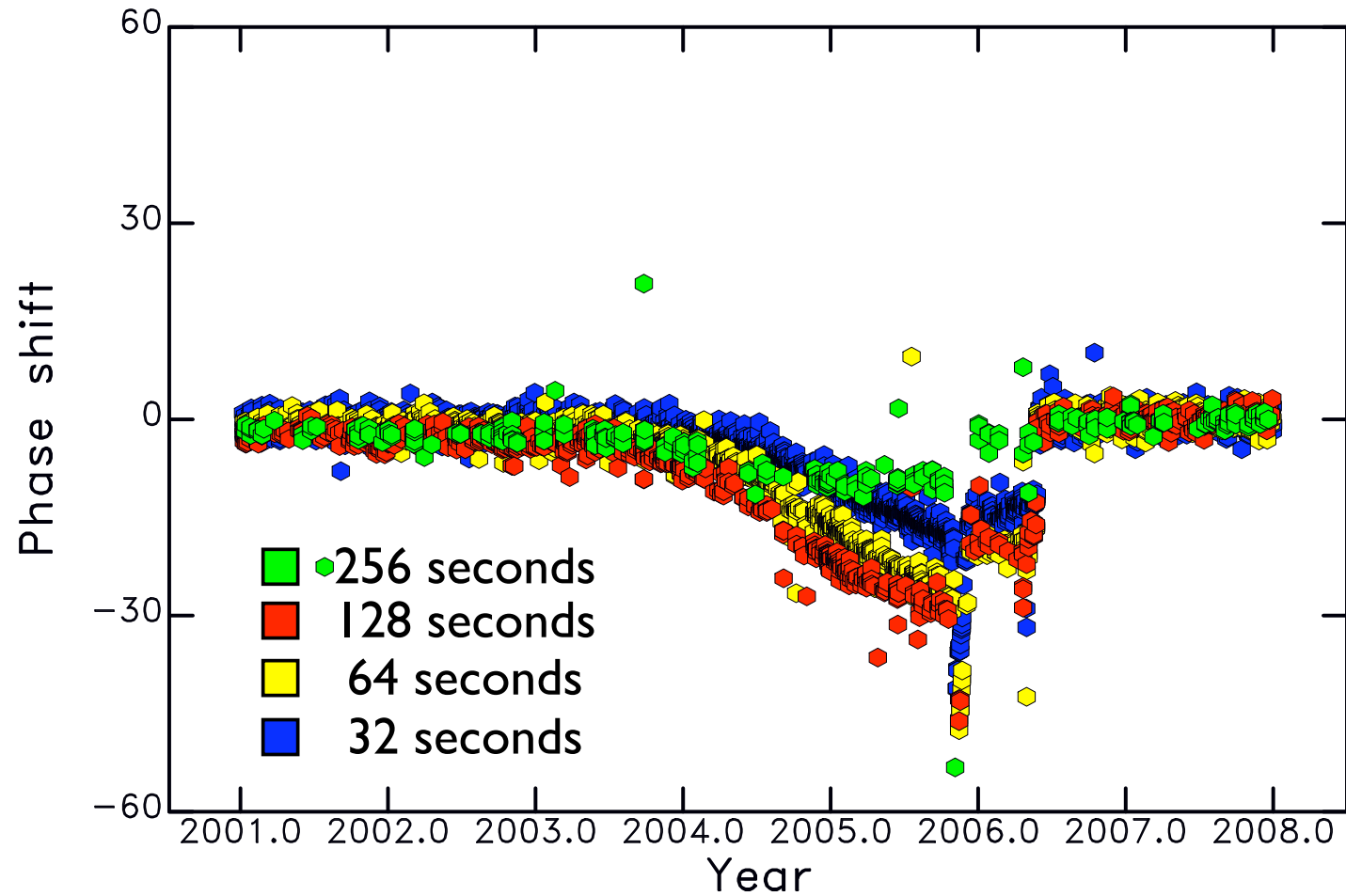
Phase shift of STS-1 to STS-2 displacement at station KIP



Scaling of STS-1 to STS-2 displacement at station KIP



Phase shift of STS-1 to STS-2 displacement at station KIP



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!