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

\[
\begin{align*}
M_{yy} & \quad (1, 1) \\
M_{yx} & \quad (1, 2) \\
M_{yz} & \quad (1, 3) \\
M_{xy} & \quad (2, 1) \\
M_{xx} & \quad (2, 2) \\
M_{xz} & \quad (2, 3) \\
M_{zy} & \quad (3, 1) \\
M_{zx} & \quad (3, 2) \\
M_{zz} & \quad (3, 3)
\end{align*}
\]

(Aki and Richards, 2002)
But, $M_{xy}=M_{yx}$, $M_{yz}=M_{zy}$, $M_{xz}=M_{zx}$

For example,

$10^{28}$ dyne-cm $= 10^{24}$ dyne $\times 10000$ cm
Calculated force seismograms (6000 km distance)

- **Mxy**
- Force 1+2+3+4
- Force 4
- Force 3
- Force 2
- Force 1

30 minutes

Origin time

<table>
<thead>
<tr>
<th>75.11.29</th>
<th>14:54:20</th>
<th>14:57:40</th>
<th>15:01:00</th>
<th>15:04:20</th>
<th>15:07:40</th>
<th>15:11:00</th>
<th>15:14:20</th>
<th>15:17:40</th>
<th>15:21:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>3m</td>
<td>1 mm</td>
<td>3m</td>
<td>3m</td>
<td>3m</td>
<td>3m</td>
<td>3m</td>
<td>3m</td>
<td>3m</td>
<td>3m</td>
</tr>
</tbody>
</table>
The vibrations caused by a force acting on or in the Earth can be modeled by summation of Earth's normal modes

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

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-1 Seismometer at Harvard, Mass.
Global network record section for an earthquake off the coast of Jalisco, Mexico

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
Filler: VEL 75.0 60.0 25.0 16.0, Component: 1

3.6 km/s
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,

\[ M_{xx}, M_{yy}, M_{zz}, M_{xy}, M_{xz}, \text{ and } M_{yz} \]

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:

\[ u_k(r, t) = \sum_{i=1}^{N} \psi_{ik}(r_0, r, t)f_i \]

where \(\psi_{ik}\) 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):

\[ u(x, t) = \sum_{k} \left[ 1 - \exp \left( -\alpha_k (t - t_s) \right) \cos \omega_k (t - t_s) \right] M : e^{(k)}(x_s) s_k(x) \]

where \( \alpha_k \) is the decay constant of and \( e^{k} \) is the strain tensor in the \( k \)-th mode; \( s_k \) is the eigenfunction of the \( k \)-th mode; and \( M \) is the seismic moment tensor.
Excitation kernels for deep earthquake (580 km)

<table>
<thead>
<tr>
<th></th>
<th>Vertical</th>
<th>Longitudinal</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{zz}$</td>
<td>$\psi_1$</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>$M_{yy}$</td>
<td>$\psi_2$</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>$M_{xx}$</td>
<td>$\psi_3$</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>$M_{yz}$</td>
<td>$\psi_4$</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>$M_{xz}$</td>
<td>$\psi_5$</td>
<td>--------------</td>
<td>----------</td>
</tr>
<tr>
<td>$M_{xy}$</td>
<td>$\psi_6$</td>
<td>--------------</td>
<td>----------</td>
</tr>
</tbody>
</table>

Time (minutes)
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, $\nu = 18.69$, $\varphi = -107.06$, $h = 33.9$
HKT-IU $\Delta = 15.17$, $\alpha = 40.19$, $\beta = 224.82$ SURFACE WAVES

LHZ-00
6.77$\mu$
50–150s
DISP
F: 0.069
C: 0.972
S: 0.892

LHE-00
9.52$\mu$
50–150s
DISP
F: 0.070
C: 0.974
S: 1.161

LHN-00
11.87$\mu$
50–150s
DISP
F: 0.024
C: 0.989
S: 0.955

LONG
6.16$\mu$
50–150s
DISP
F: 0.122
C: 0.938
S: 0.972

TRAN
14.77$\mu$
50–150s
DISP
F: 0.029
C: 0.986
S: 1.032

blue - data ; red - model
Estimation of the Source Parameters

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

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

This procedure requires that the position of the source $(r_0, t_0)$ be known.
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.
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.COUPL: M0= 4.84*10**25
NP1: STRIKE= 146; DIP= 34; SLIP= -89
NP2: STRIKE= 325; DIP= 56; SLIP= -91

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 $M \geq 8.0$
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

High-Gain Long-Period (HGLP) network
HGLP seismometer and recording system

seismometer
\[ \frac{s^3}{(s+p_1)^2} \]
\[ T=30 \text{ s} \]
\[ \xi=1.0 \]

Ithaco amplifier
- one-pole high-pass
  \[ T=232 \text{ s} \]
  \[ \xi=0.71 \]
- two-pole low-pass
  \[ T=96.8 \text{ s} \]
  \[ \xi=0.51 \]
- two-pole low-pass
  \[ T=36.9 \text{ s} \]
  \[ \xi=0.625 \]

Astrodata datalogger
- four-pole 0.1db Chebyshev low-pass
  \[ T=10 \text{ s} \]
- one-pole high-pass
  \[ T=100 \text{ s} \]

phototube amplifier
- filter 6824-15
- galvanometer

bypass

filter 6824-15
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

![Waveform Comparison](image)
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

Friuli Events

Main Shock
6 May 1976

Aftershock
15 Sept. 1976
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

- Earthquake
- Propagating signals
- SH wave
- Love wave
- P wave
- Rayleigh wave
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
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

<table>
<thead>
<tr>
<th>network</th>
<th>≤3 deg.</th>
<th>≤6 deg.</th>
<th>#epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>TA</td>
<td>92.2%</td>
<td>98.9%</td>
<td>1829</td>
</tr>
<tr>
<td>US</td>
<td>69.6%</td>
<td>90.5%</td>
<td>158</td>
</tr>
<tr>
<td>BK</td>
<td>82.1%</td>
<td>100.0%</td>
<td>28</td>
</tr>
<tr>
<td>CI</td>
<td>58.2%</td>
<td>77.1%</td>
<td>122</td>
</tr>
<tr>
<td>II+IU</td>
<td>76.6%</td>
<td>91.1%</td>
<td>726</td>
</tr>
<tr>
<td>G</td>
<td>85.7%</td>
<td>98.7%</td>
<td>77</td>
</tr>
</tbody>
</table>
Sensor orientation
Most GSN and USAArray 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 \rightarrow \text{seismometer} \rightarrow \text{seismogram}
Blue - observed seismograms
Red - synthetic seismograms

2005/10/08 03:50:38.0, ϑ = 34.43, φ = 73.54, h = 10.0
POHA–IU  Δ=108.72, α = 48.71, β=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, ϕ = 34.43, ω = 73.54, h = 10.0
KIP-1U Δ=105.93, α = 49.37, β=317.68 MANTLE WAVES

\[ S = \frac{\sum_{i=1}^{N} O_i S_i}{\sum_{i=1}^{N} S_i^2} \]
Symptoms of a seismometer with wrong gain

Station N02C, earthquake on 06/14/2006
Scaling factors at NNA-II, 1990-2004

NNA-II: Red — Mantle

Annual median

Individual seismograms
Scaling factors at PAB-IU, 1992-2004

PAB-IU: Blue – Body; Red – Mantle

scaling factor


S < 0.5
Scaling factors at LVZ-II, 1993-2004

LVZ-II: Blue — Body; Red — Mantle

scaling factor


LHZ-P
LHN-P
LHE-P
Scaling factors at PEL-G, 1996-2002

PEL-G: Blue — Body; Red — Mantle

Scaling factor vs. Year

no good data
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

(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*

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

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

\[
\text{ratio} = \frac{\text{displacement} \ A}{\text{displacement} \ B} \quad \text{should be 1.0000!}
\]
Intersensor coherence, ALE-II LHZ, 2003-2009

ALE-II/LHZ–00 vs. ALE-II/LHZ–10: scaling and phase shift, c>0.999

- Scaling factor
  - 256 sec: green circles
  - 128 sec: red circles
  - 64 sec: yellow circles
  - 32 sec: blue circles

- Phase shift (degrees)
  - 256 sec: green circles
  - 128 sec: red circles
  - 64 sec: yellow circles
  - 32 sec: blue circles

Year:
- 2004
- 2005
- 2006
- 2007
- 2008
- 2009
- 2010
Intersensor coherence, DGAR-II LHZ, 2003-2009

DGAR-II.LHZ-00 vs. DGAR-II.LHZ-10: scaling and phase shift, c > 0.999

~5% gain error
Intersensor coherence, KIP-IU LHZ, 1999-2009

~5% gain error
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)

Phase

Amplitude

Frequency (Hz)

mantle waves

h=0.707
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

~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!
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