Seismic networks, data centres, instruments

Seismic observables and their interrelations

Earthquake service, seismic experiments, seismometer configurations, seismic network design
Earthquake / Noise

12 am

6 am

12 pm

6 pm

Data centres and observables
Seismic observables: Period ranges (order of magnitudes)

- Sound 0.001 – 0.01 s
- Earthquakes 0.01 – 100 s (surface waves, body waves)
- Eigenmodes of the Earth 1000 s
- Coseismic deformation 1 s – 1000 s
- Postseismic deformation +10000s
- Seismic exploration 0.001 - 0.1 s
- Laboratory signals 0.001 s – 0.000001 s

-> What are the consequences for sampling intervals, data volumes, etc.?
Passive vs. active experiments

• Passive
  – Natural sources (earthquakes, noise)
  – Long-term (weeks to decades)
  – Earthquake service
  – Volcano Monitoring
  – Global Tomography

• Active
  – Man made sources (explosions, hammer, piezo, laser)
  – Crustal, near surface tomography
  – Hydrocarbon exploration
  – Reflection, refraction
Passive Experiments
(monitoring, earthquake service)
Local seismic networks
Regional seismic networks
Global seismic networks (FDSN)

- IRIS / IDA Stations
- Planned Stations
- IRIS / USGS Stations
- Affiliate Stations
Seismic data centres: NEIC

The mission of the National Earthquake Information Center (NEIC) is to determine rapidly the location and size of all destructive earthquakes worldwide and to immediately disseminate this information to concerned national and international agencies, scientists, and the general public. The NEIC provides a comprehensive, global seismic database on earthquake parameters and their effects that serves as a solid foundation for basic and applied earth science research. Please visit the World Data Center website to learn more about the WDC system.

Earthquake Data Available from the NEIC

- Current Worldwide Earthquake List
- AutoDRM
- Data Available Through FTP
- Earthquake Catalog Search
- Earthquake Summary Posters
- Recent Earthquakes This Year
- Latest Fast Moment Tensor Solutions
- Latest Energy & Broadband Solutions
- Moment Tensor & Broadband Source Parameter Search
Tasks:

- Determine **origin time** and **location** of earthquake
  - Hypocentre, epicentre
- Determine earthquake **source mechanism**
- Determine **tsunami risk** (where applicable)
- (near real time estimate) of **seismic intensity** (damage)
- Receive damage reports, create **intensity maps**
- Communicate to public, inform agencies
- Expert service (damage)
Was ging so völlig daneben?

Christchurch, Februar 2011
Tohoku-Oki, März 2011
Erdbeben und Tsunamis

• Erdbeben

P-Wellen ca. 6km/s
Oberflächenwellen ca. 3km/s

Transmission von Information zum Datenzentrum mit nahezu Lichtgeschwindigkeit

• Tsunamis

Erzeugung abhängig von Herdmechanismus

Ausbreitungsgeschwindigkeit

\[ c = \sqrt{gh} \]

\( g = 9,81 \text{ m/s}^2 \)
\( h \text{ Meerestiefe (m)} \)
Typische Wellenlängen 100-500km
Passive Experiments
(campaign data, time-limited)
... Die Regenfälle, die im August zum Hochwasser führten, hatten ihren Höhepunkt am Tag 218 ...
Data centres and observables

Modern Seismology – Data processing and inversion

Observations

(Kraft et al., GJI, 2006)
Externer Einfluss auf Erdbeben?
US Array – Big Foot

EarthScope Instruments - Updated at 9:18 GMT Wednesday May 6, 2009

Click [here](#) to display table for all stations shown on this map

<table>
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<tr>
<th>Locate Any Seismic Station</th>
<th>Show Data Latency</th>
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US Array - Observations
Science with US Array

- Fact or fiction?
- Significant geodynamic feature?
- Amplitude correct?
- Spatial scale correct?
- Depth correct?

From Sigloch et al.
Current Experiments: AlpArray

Data centres and observables
Goals with regional networks

• Tomography under the Alps
• Understanding alpine tectonics
• Monitoring seismicity
• Investigating time-dependence
  – Deglaciation
  – External forcing (defrosting, rain)
• Ambient noise observations
• Seismic signals of rockfalls – passive monitoring
Objectives

- Imaging upper and lower mantle structures beneath La Réunion hotspot
- Relationships with the south African superplume
- Signature in the transition zone
- Plume-lithosphere interactions, mantle flow, influence of pre-existing structures (ridges, transforms)
- Plume – ridge interaction – role of the Rodrigues ridge
- Plume signature with the surface observables (Bathymetry, gravimetry, magnetism).
Data centres and observables

**RHUM-RUM project**

- **57 OBS RHUM-RUM**
- **12 stations DEPAS**
- Seychelles – Mauritius - Rodrigue
- **25 stations GFZ Madagascar**
- **30 stations US MACOMO**
- **5 stations RHUM Iles Eparses**
- **5 stations RHUM Madagascar**

**Stations AfiricArray**
Lava lake 2007 La Reunion
Marion Dufresne

Data centres and observables
What we needed …
Data centres and observables

... but then ...
Ocean bottom seismometer experiments

- OBS systems are expensive
- Risk of loss during experiment
- Ship time required – expensive
- Very noisy data (poor data quality)
- Special requirements for sensors (low power consumption)
- Timing problems (no GPS access at seafloor)
- National OBS pools available
Passive Experiments
(small scale seismic arrays)
Seismic Arrays

Data centres and observables
Array Data
Estimating wavefield gradients

\[ y(x) = \sin(kx) \]

- station 1
- station 2
- maximum displacement
- difference between two stations
- \( \lambda/4 \) on the x-axis
Benefits of seismic array

• Extract information about propagation direction
• Extract information about phase velocities
• Estimate the wavefield gradients (strain and rotation)
• Estimate incidence angles
• Separate P and S waves (Rayleigh and Love waves)

-> originally designed to improve detection and localization of nuclear tests
- July, 2014 (30 days)
- 150 station points
  (300 geophones, 10 Hz)
Source: Nakata
Beamforming

Speed, angle

Receiver array

Slow
Fast

North slowness

0.5 km/s

East slowness

3-6 Hz

A

B

C

1000 m

0.5 km/s
Seismic Arrays

• ... are becoming and more popular
• AoA (Array of Array experiments are being proposed)
• Seismic sensors are becoming cheaper so large N experiments are the future
• For some areas this is difficult
  – Planets
  – Boreholes
  – Ocean floor
Active Experiments

Explosions
Vibrator trucks
Hammer
Marine Reflexionsseismik

- Vessel under way
- Acoustic source
- Hydrophone array

Sea bed
- Sand layer
- Bedrock
- Buried channel

Data centres and observables
Data centres and observables
Data centres and observables

Transalp
Tiefen Migrationen
Reservoir lifetime monitoring: Valhall

Experiment to be repeated annually:

- 50,000+ shots
- 2300+ OBC [hydrophones]
- O(Tbyte) of Data
- Typical (even small) experimental setup
- Seemingly gigantic simulation/inversion task in 3D (full waveform inversion)

Gestel et al. (2008), TLE
Thue future: full waveform inversion

Sirgue et al. (2010)
Seismic Observables

translation

strain

Rotation (tilt)
Seismic observables: *translations*

**Translational motions** are deformations in the direction of three orthogonal axes. Deformations are usually denoted by $u$ with the appropriate connection to the strain tensor (explained below).

Each of the orthogonal motion components can be measured as displacement $u$, velocity $v$, or acceleration $a$.

The use of these three variations of the same motion type will be explained below.
Seismic observables: *translations - displacements*

Displacements are measured as "differential" motion around a reference point (e.g., a pendulum). The first seismometers were pure (mostly horizontal) displacement sensors. Measureable *co-seismic* displacements range from *microns to dozens of meters* (e.g., Great Andamanan earthquake).

Horiztonal displacement sensor (ca. 1905). Amplitude of ground deformation is mechanically amplified by a factor of 200.

Today displacements are measured using GPS sensors.
Seismic observables: \textit{translations} - \textit{displacements}

Data example: the San Francisco earthquake 1906, recorded in Munich
Most seismometers today record ground velocity. The reason is that seismometers are based on an electro-mechanic principle. An electric current is generated when a coil moves in a magnetic field. The electric current is proportional to ground velocity $v$.

Velocity is the time derivative of displacement. They are in the range of $\mu$m/s to m/s.

$$v(x,t) = \partial_t u(x,t) = \dot{u}(x,t)$$
Seismic observables: *translations* - *accelerations*

Strong motions (those getting close to or exceeding Earth’s gravitational acceleration) can only be measured with accelerometers. Accelerometers are used in earthquake engineering, near earthquake studies, airplanes, laptops, ipods, etc. The largest acceleration ever measured for an earthquake induced ground motion was 40 m/s² (four times gravity, see *Science* 31 October 2008: Vol. 322. no. 5902, pp. 727 – 730).

\[ a(x,t) = \partial_t^2 u(x,t) = \ddot{u}(x,t) \]
Figure 6.6-14: Relation between displacement, velocity, and acceleration in the time domain.
Translational Measurements

• Displacement (m)
  – Old seismometers
  – GPS sensors

• Velocity (m/s)
  – Almost all weak-motion sensors today
  – Geophones in Exploration

• Acceleration (m/s²)
  – Strong motion (close to earthquakes)
  – Engineering, navigation
  – Laptops, smartphones
Seismic observables: *strain*

Strain is a tensor that contains 6 independent linear combinations of the spatial derivatives of the displacement field. Strain is a purely geometrical quantity and has no dimensions.

Measurement of differential deformations involves a spatial scale (the length of the measurement tube).

What is the meaning of the various elements of the strain tensor?

\[
\varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
\]
Seismic observables: \textit{strain}

Strain components (2-D)

\[
\varepsilon_{ij} = \begin{bmatrix}
\frac{\partial u_x}{\partial x} & \frac{1}{2} \left( \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) & \frac{\partial u_y}{\partial y} \\
\frac{1}{2} \left( \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) & \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} & \frac{\partial u_y}{\partial y}
\end{bmatrix}
\]
Seismic observables: \textit{rotations}

\[
\begin{pmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{pmatrix} = \frac{1}{2} \nabla \times \mathbf{v} = \frac{1}{2} \begin{pmatrix}
\partial_y v_z - \partial_z v_y \\
\partial_z v_x - \partial_x v_z \\
\partial_x v_y - \partial_y v_x
\end{pmatrix}
\]

Rotation rate \textit{Rotation sensor} \quad \text{Ground velocity} \textit{Seismometer}
LIGO – strainmeter
Seismic observables: \textit{rotations}

- Rotation is a vectorial quantity with three independent components
- At the Earth's surface rotation and tilt are the same
- Rotational motion amplitudes are expected in the range of $10^{-9}$ – $10^{-3}$ rad/s
- Rotations are only now being recorded
- Rotations are likely to contribute to structural damage
Seismic observables: \textit{tilt}

Tilt is the angle of the surface normal to the local vertical. In other words, it is rotation around two horizontal axes. Any P, SV or Rayleigh wave type in layered isotropic media leads to tilt at the Earth’s free surface. In 3-D anisotropic media all parts of the seismic wave field may produce tilts.

Other causes of tilt:

- Earth tides
- Atmospheric pressure changes
- Soil deformation (water content)
- Temperature effects
- Mass movements (lawn mower, trucks, land slides)

\[ \Theta(x, t) = \hat{\partial}_x u_z \]
Tilt cycle (solid line) and seismicity (dots) on Montserrat, West Indies. The tilt signal goes through an inflection point (maximum/minimum of tilt derivative w.r.t. time, dotted line) as soon as seismicity starts, and again when seismicity ceases, indicating that part of the shear stress that causes the tilt is reduced by seismic slip at the conduit wall during magma ascent. (Source: J. Neuberg)
Summary: Observables

- **Translations** are the most fundamental and most widely observed quantity (standard seismometers)
- Translation sensors are sensitive to rotations!
- **Tilt** measurements are sensitive to translations!
- Really we should be measuring all 12 quantities at each point (cool things can be done with collocated observations of translation, strains and rotations)