Modern Seismology Lecture Outline

• Seismic networks and data centres
• Mathematical background for time series analysis
• Seismic processing, applications
  – Filtering
  – Correlation
  – Instrument correction, Transfer functions
• Seismic inverse problems
  – Hypocentre location
  – Tomography
Key questions

• What data are relevant in seismology?
• Where are they acquired?
• What observables are there?
• What are acquisition parameters?
• How to process seismic observations?
• How to solve seismic inverse problems?
• What information can we gain?
Literature

• Stein and Wysession, An introduction to seismology, earthquakes and earth structure, Blackwell Scientific (Chapts. 6, 7 and appendix) see also http://epscx.wustl.edu/seismology/book/ (several figures here taken from S+W).


• Gubbins, Time series analysis and inverse problems for geophysicists, Cambridge University Press

• Scherbaum, Basic concepts in digital signal processing for seismologists
Global seismic networks
Regional seismic networks
Local seismic networks
Temporary (campaign) networks

EarthScope Instruments - Updated at 9:18 GMT Wednesday May 6, 2009
Click here to display table for all stations shown on this map

<table>
<thead>
<tr>
<th>Locate Any Seismic Station</th>
<th>Show Data Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic</td>
<td>All Instruments</td>
</tr>
<tr>
<td></td>
<td>National - Continental US</td>
</tr>
<tr>
<td></td>
<td>Since Project Start</td>
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</tbody>
</table>

Legend:
- Instrument

Alaska
Seismic arrays
Seismic arrays
Seismic data centres: NEIC

National Earthquake Information Center (NEIC) mission: 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.

Earthquake Data Available from the NEIC:
- Current Worldwide Earthquake List
- AutoLM
- Data Available Through FTP
- Earthquake Catalog Search
- Earthquake Summary Posters
- Large Earthquakes This Year
- Latest Fast Moment Tensor Solutions
- Latest Energy & Broadband Solutions
- Moment Tensor & Broadband Source Parameter Search
- Earthquakes More than 150 Years Ago
Seismic data centres: ORFEUS

ORFEUS (Observatories and Research Facilities for European Seismology), is the non-profit foundation that aims at co-ordinating and promoting digital, broadband (BB) seismology in the European Mediterranean area.

More information...

News

15-04-2009: ORFEUS booth at EGU 2009
Information about ORFEUS, EMSC, NERIES and EPOS will be available at booth no. 36 at the EGU 2009 in Vienna, Austria (April 20-24, 2009).

The ORFEUS Annual Report 2008 is available at the Documents page.

12-03-2009: ORFEUS Working Group 3 meeting at EGU
There will be an ORFEUS Working Group 3 meeting at the EGU 2009 in Vienna, Austria. The meeting will be held on Tuesday 21st April, from 12:00 to 13:30 hrs, in room SMM (Yellow Level, Ground Floor). The main item for discussion is archiving and access to data from portable instrumentation, and the potential for inclusion in the imminent NERIES proposal. More information on Working Group 3.

21-01-2009: ORFEUS Observatory Coordination Meeting
From May 2 to May 6, 2009, the Annual ORFEUS Observatory Meeting (International
Seismic data centres: IRIS
Seismic data centres: ISC
Seismic data centres: GEOFON

Data Access

Scope

The GEZ Seismological Data Archive holds data from many permanent networks - primarily from the GEOFON network, but also from many GEOFON partner networks, the part of the GEVN - GEOFON Extended Virtual Network, for which GEZ acts as backup archive and data distribution center - as well as from temporary deployments. (Near) real-time data streams from permanent networks are mostly coming in over Internet. It is immediately accessible on request from the archive or continuously by GeoLink real-time data feeds from the open GEOFON GeoLink server. Most of the acquired European networks are members of the Virtual European Broadband Seism Network (VEBNS). Data from recent temporary networks is usually restricted to the project consortium until its data release for public use. Although most data sets are derived from broadband stations, also a substantial amount of short-period data is archived as well as some strong motion and OBS data. All data sets are accessible jointly in a uniform way through a web-based user interface.

The GEZ Seismological Data Archive is linked by GEZ's GeoLink protocol to other partners' data centers in Germany (German Integrated Data Archive - GIDA) and Europe (European Integrated Data Archive - EIDA) where access to all data archives is granted simultaneously.

- the archive for the permanent GEOFON VBB network,
- the archive for the GEOFON partner networks,
- the archive for the passive seismological experiments of the GEZ Geophysical Instrument Pool Potsdam (GIPP),
- the archive for the German Task Force Earthquake (data archival pending),
- the main node in the German Integrated Data Archive (GIDA),
- a major node in the European Integrated Data Archive (EIDA).
EMSC
Seismic data centres: EarthScope

References to EarthScope related data, data products, and tools are provided to further support the scientific community and those with an interest in measurement data from more than one thousand instruments located across North America. The freely available, high precision data can be viewed as the most important legacy of the National Science Foundation’s largest investment in solid-Earth Science.

New EarthScope Data Portal Release

The premier release of the EarthScope Data Portal is now available online. The new portal provides an additional means for students, researchers, and others interested in scientific data to simultaneously explore EarthScope’s various instrument networks, as well as seamlessly download data from multiple stations and instrument types. The intuitive Google Maps-based user interface provides a familiar means to filter stations by geography, data class, or station identifier. Additional temporal and spatial filters give users the ability to further refine their searches as needed.

Developed in cooperation with San Diego Supercomputer Center (SDSC), Incorporated Research Institutions for Seismology (IRIS), University NAVSTAR Consortium (UNAVCO) and International Continental Scientific Drilling Program (ICDP), this release culminates more than a year of dedicated effort from numerous individuals who deserve the gratitude of the scientific community.
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.?
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 Andaman earthquake).

Horizontal 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

*translations - displacements*

Data example: the San Francisco earthquake 1906, recorded in Munich
Seismic observables

translations - velocities

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 \( \mu \text{m/s} \) to \( \text{m/s} \).

\[
v(x, t) = \partial_t u(x, t) = \dot{u}(x, t)
\]
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/s$^2$ (four times gravity, see *Science* 31 October 2008: Vol. 322. no. 5902, pp. 727 – 730)

\[ a(x,t) = \ddot{\partial}_t^2 u(x,t) = \dddot{u}(x,t) \]
Displacement, Velocity, Acceleration

Figure 6.6-14: Relation between displacement, velocity, and acceleration in the time domain.
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?
Seismic observables

Strain components (2-D)

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

\[ \begin{align*}
\begin{pmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{pmatrix}
&= \frac{1}{2} \nabla \times \mathbf{v} = \frac{1}{2} \begin{pmatrix}
\frac{\partial y v_z - \partial z v_y}{\partial x v_y - \partial y v_x} \\
\frac{\partial z v_x - \partial x v_z}{\partial x v_y - \partial y v_x}
\end{pmatrix}
\end{align*} \]

**Rotation rate**

**Rotation sensor**

**Ground velocity**

**Seismometer**
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

_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)
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)
Questions

• How many independent motions are there descriptive of the motion of a measurement point (deformable, undeformable media)?
• Describe measurement principles for the three main observable types!
• What is the role of the time derivative of translational measurements? Domains of application?
• Compare qualitatively displacement, velocity, and acceleration of an earthquake seismogram!
• What is the advantage of having an array of closely spaced seismometers?
• What is the frequency and amplitude range of earthquake-induced seismic observations?