

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?

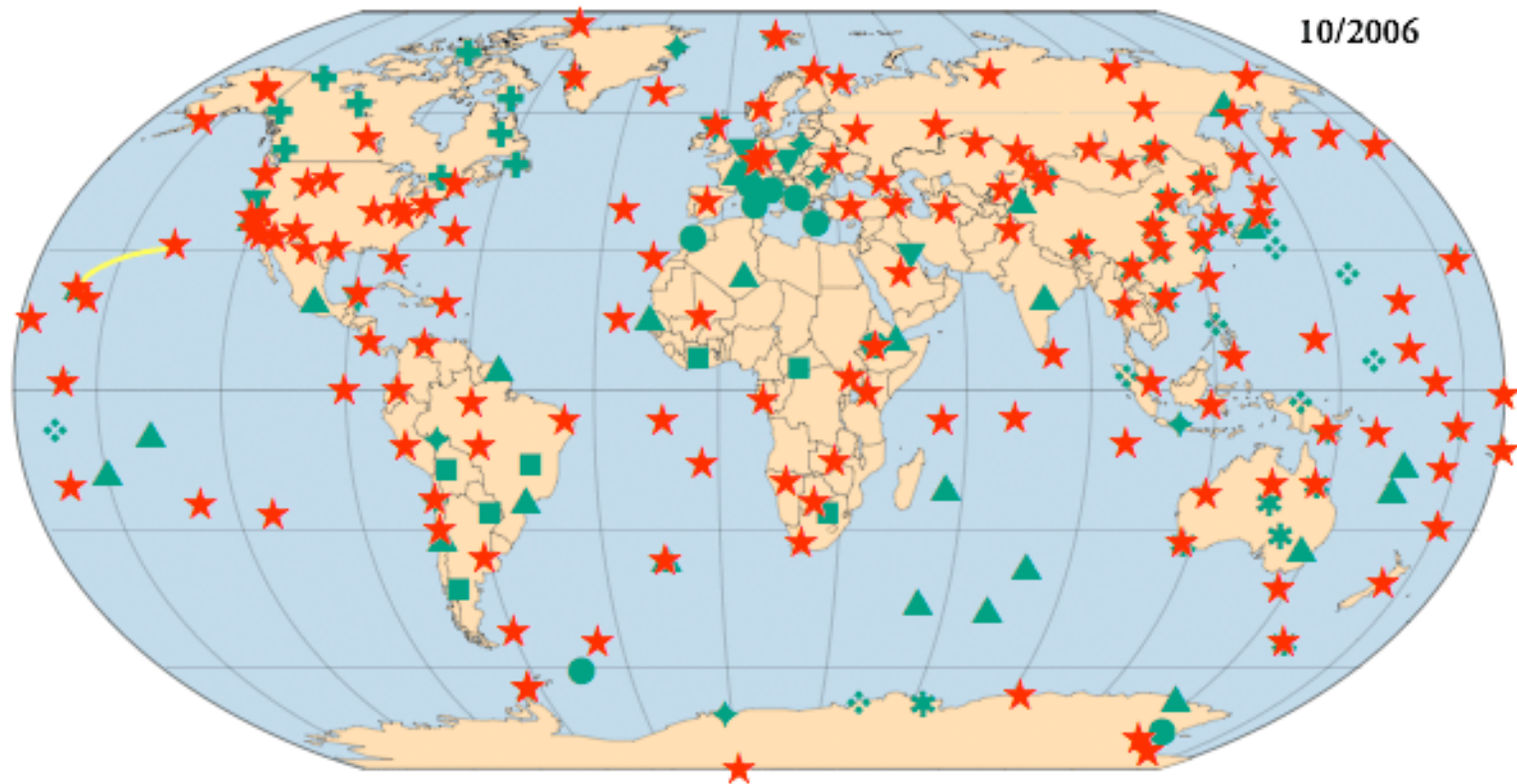
Literature

- 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).
- Shearer, Introduction to Seismology, Cambridge University Press, 1990, 2009 (to appear in July)
- Aki and Richards, Quantitative Seismology, Academic Press, 2002.
- Tarantola, Inverse Problem Theory and Model Parameter Estimation, SIAM, 2005.
- Gubbins, Time series analysis and inverse problems for geophysicists, Cambridge University Press
- Scherbaum, Basic concepts in digital signal processing for seismologists

Global seismic networks

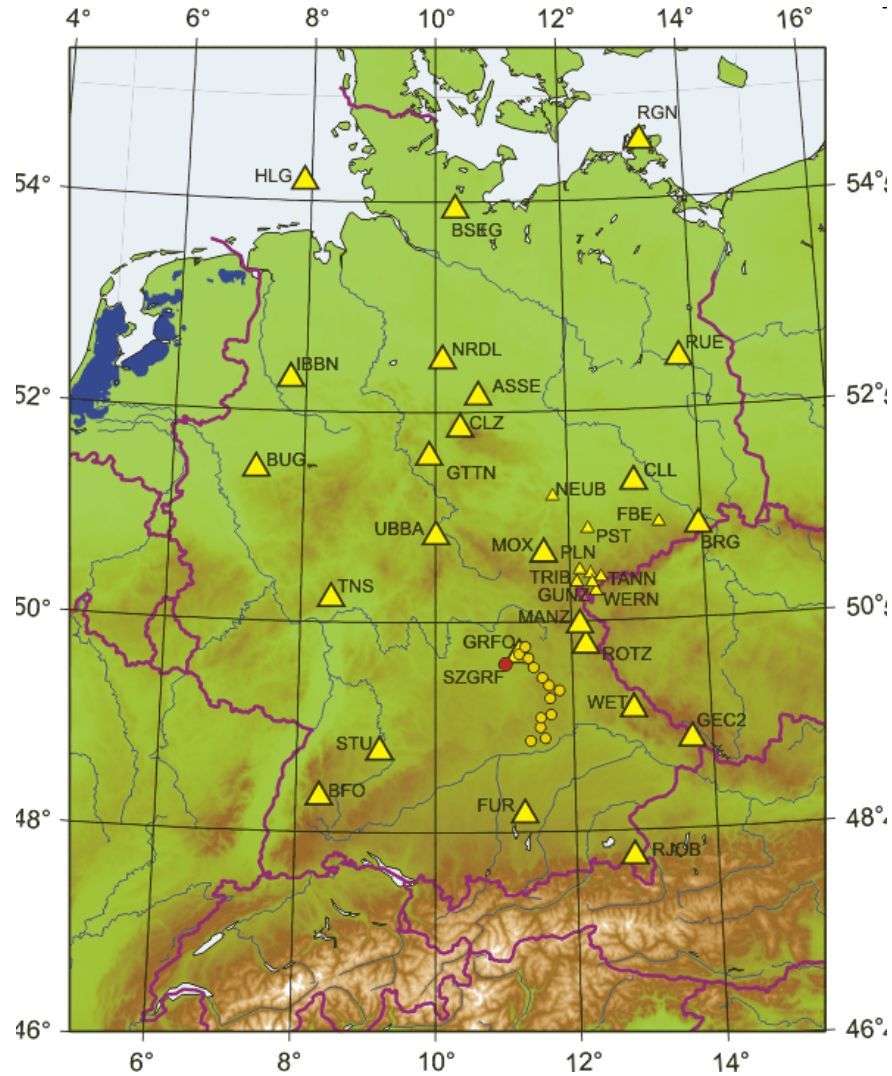


**International Federation of
Digital Seismograph Networks**

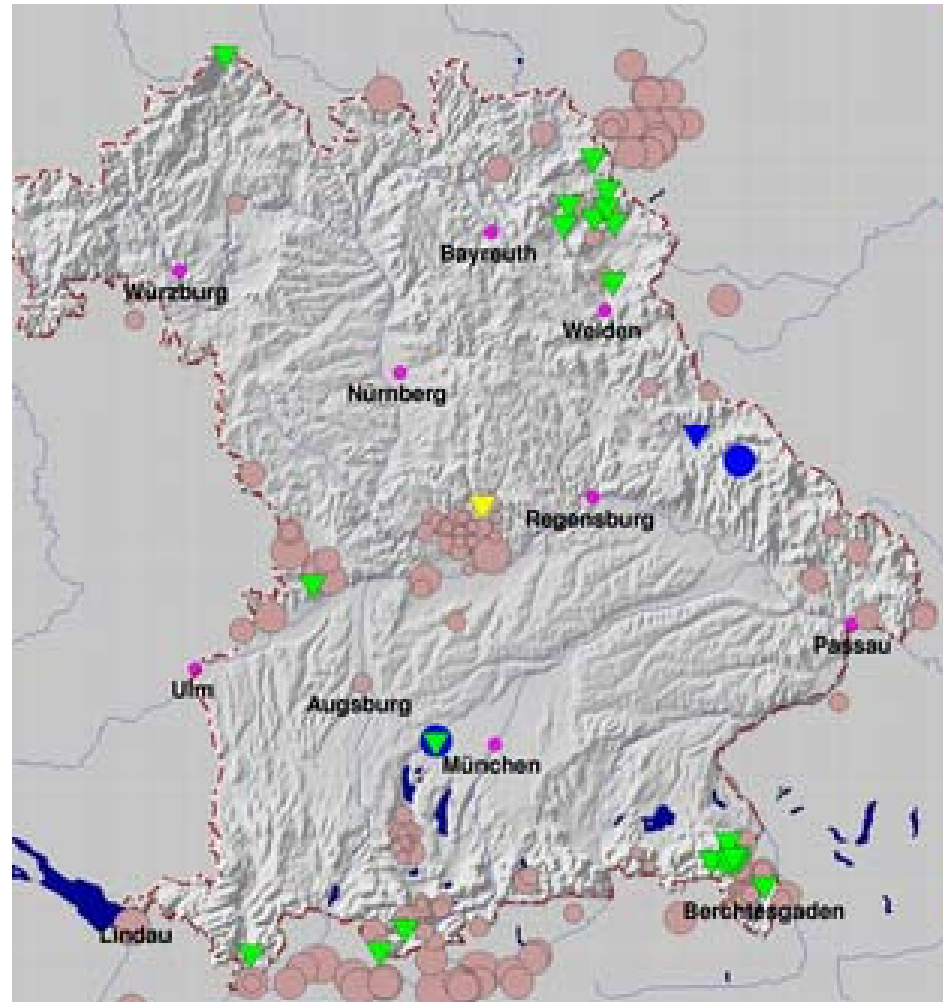


IRIS GSN Australia Canada France Germany Italy Japan U.S. Other
★ ✱ + ▲ ◆ ● ❖ ■ ▼

Regional seismic networks



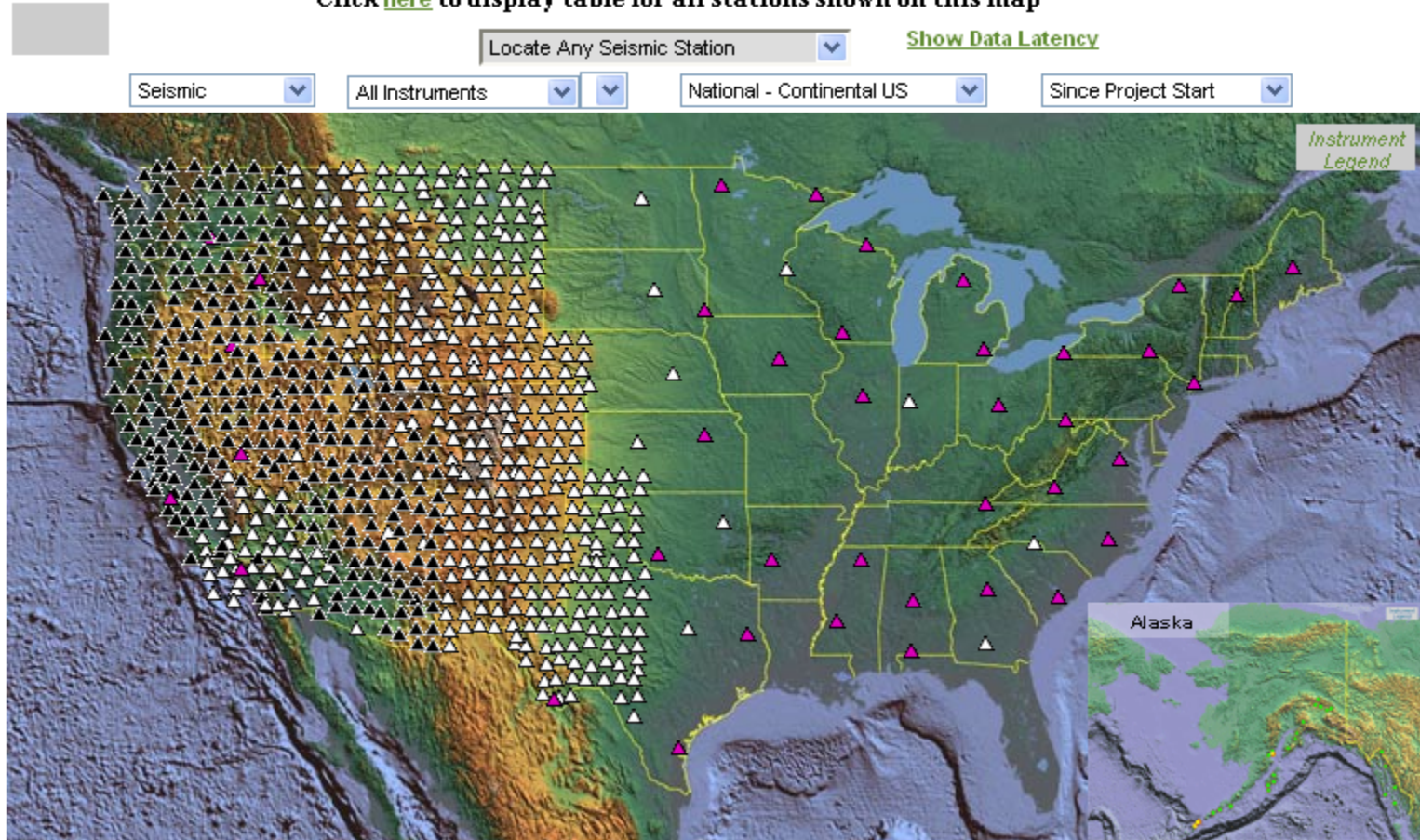
Local seismic networks



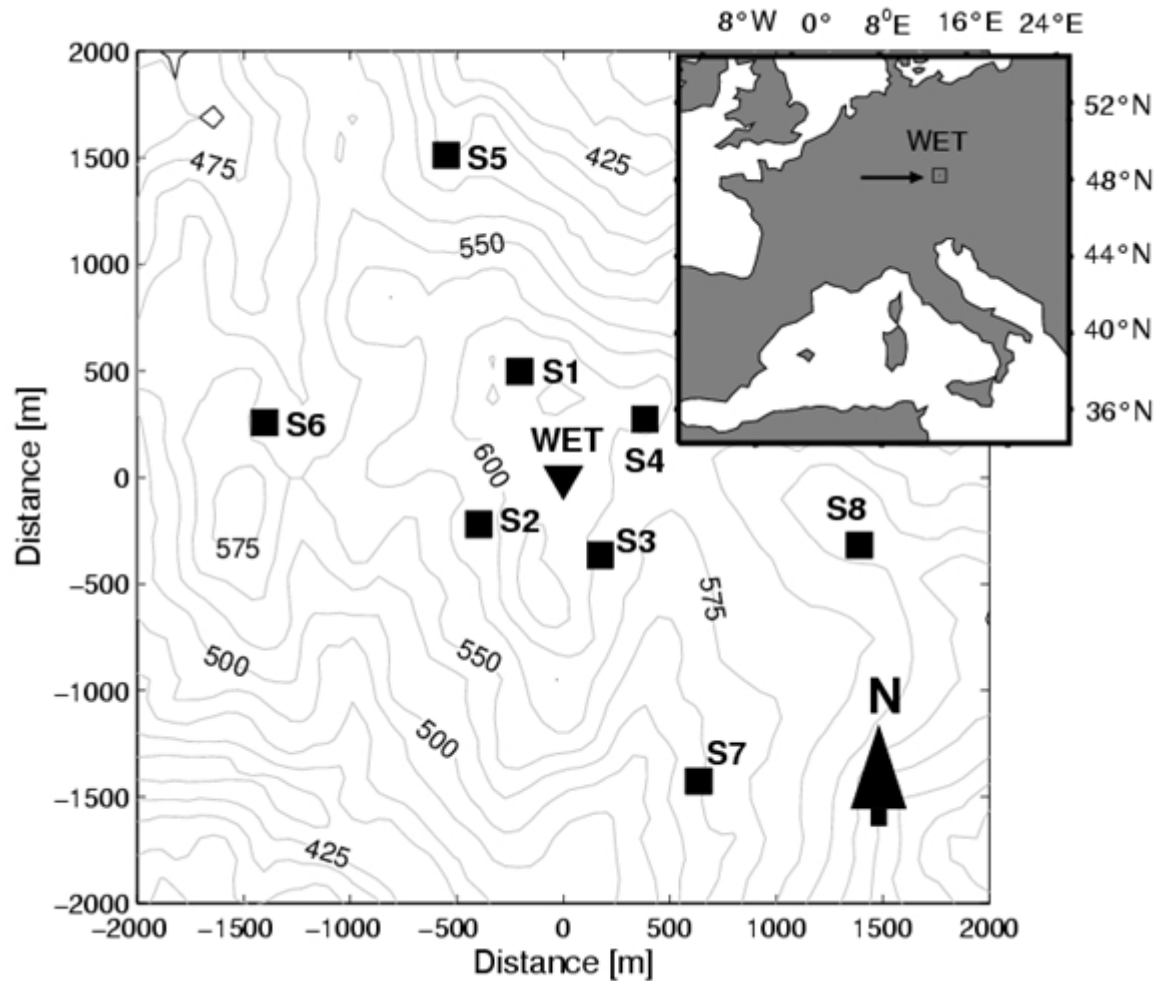
Temporary (campaign) networks

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

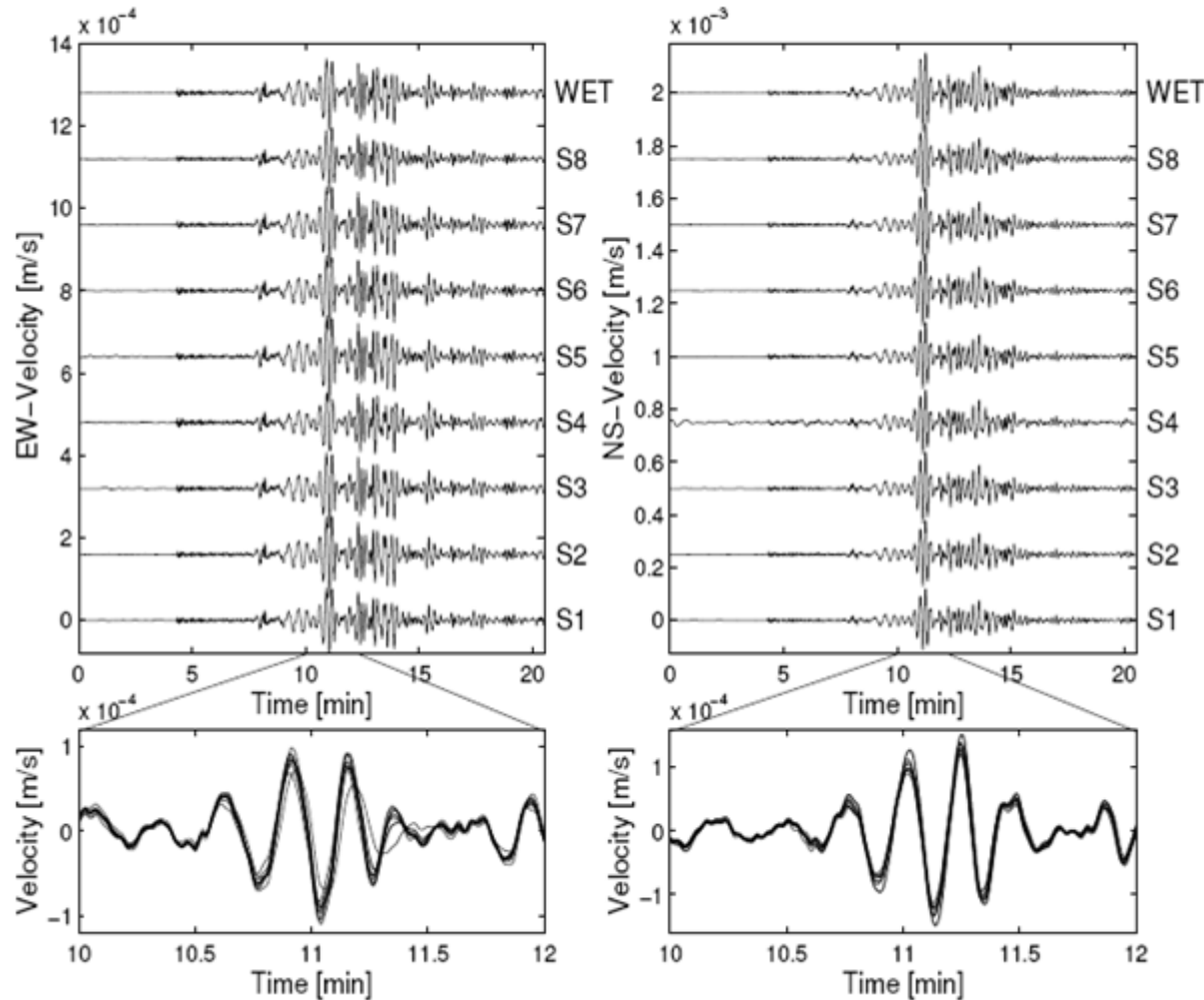
Click [here](#) to display table for all stations shown on this map



Seismic arrays



Seismic arrays



Seismic data centres: NEIC

The screenshot shows a Mozilla Firefox browser window displaying the National Earthquake Information Center (NEIC) website. The address bar shows the URL <http://earthquake.usgs.gov/regional/neic/>. The page features the USGS logo with the tagline "science for a changing world" and a green seismic waveform. Navigation links include "USGS Home", "Contact USGS", and "Search USGS". The main heading is "Earthquake Hazards Program", with sub-links for "Home", "Earthquake Center", "Regional Information", "About Earthquakes", "Research & Monitoring", and "Other Resources". A breadcrumb trail reads "You are here: Home » Regional Information » NEIC".

NEIC Home

- Earthquake Catalogs & Bulletins
- International Registry of Seismograph Stations
- Routine U.S. Mining Seismicity
- Tour Information
- Who We Are
- Contact Us

National Earthquake Information Center - 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/WDC for Seismology compiles and maintains an extensive, 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](#) web site 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](#)
- [Large Earthquakes This Year](#)
- [Latest Fast Moment Tensor Solutions](#)
- [Latest Energy & Broadband Solutions](#)
- [Moment Tensor & Broadband Source Parameter Search](#)
- [Seismicity Maps of the World](#)

A photograph showing a man in a dark shirt and light-colored pants standing next to a large, ornate globe on a stand. He is pointing towards the globe. The background shows a wall with a circular display and other museum-like elements.

Seismic data centres: ORFEUS

The screenshot shows a Mozilla Firefox browser window displaying the ORFEUS website. The browser's address bar shows the URL <http://www.orfeus-eu.org/>. The website header features the ORFEUS logo and a navigation menu with links for Organization, Data, Earthquakes, Working Groups, Software, Links, and Home. A Google Custom Search box is also present.

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).
- 06-04-2009: ORFEUS Annual Report 2008**
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 SM4 (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 NERIES2 proposal. [More information on Working Group 3..](#)
- 21-01-2009: ORFEUS Observatory Coordination Meeting**
From May 2 to May 8, 2009, the Annual ORFEUS Observatory Meeting (International

News

- ORFEUS Annual Report 2008
- ORFEUS Observatory Meeting
- ORFEUS Workshop 'Seismic Tomography'
- Last issue ORFEUS newsletter

Announcements

- Jobs
- Workshops/meetings
- Funding

Get Data

- Direct access
- On request

Earthquakes

- Recent earthquakes
- Earthquake monitors

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Seismic data centres: IRIS

The screenshot shows the IRIS website in a Mozilla Firefox browser window. The browser's address bar displays the URL <http://www.iris.edu/hq/>. The website header includes the IRIS logo, the text "Incorporated Research Institutions for Seismology", and a description: "A university consortium sponsored by the National Science Foundation dedicated to exploring the Earth and enhancing awareness of seismology through the collection and distribution of geophysical data and development of educational programs and materials." The NSF logo is also present. A navigation menu contains buttons for Home, About IRIS, Data, Software, Instrumentation, and Publications. A search bar is located in the top right corner.

On the left side, there is a sidebar with a "Quick Links" section containing a dropdown menu and a "Calendar" section with two upcoming events:

- 5/4/09 to 5/5/09: [IRIS Board of Directors Meeting - St. Louis, MO](#)
- 5/13/09 to 5/15/09: [EarthScope National Meeting - Boise, ID](#)

The main content area features a "Seismic Monitor" section with a world map showing seismic activity. Below this, a section titled "Mouse over an IRIS Program for more information:" displays five program thumbnails: DMS, Education & Outreach, GSN, PASSCAL, and USArray.

At the bottom, there are two sections: "IRIS Notices" with a link to [Report Released from the Long Range Science](#), and "PASSCAL Experiments" with a link to [Map of PASSCAL Experiments](#).

Seismic data centres: ISC

The screenshot shows the website of the International Seismological Centre (ISC) in a Mozilla Firefox browser window. The browser's address bar shows the URL <http://www.isc.ac.uk/>. The website features a header with the ISC name in multiple languages: International Seismological Centre, Centre Sismologique International, Международный Сейсмологический Центр, 国際地震センター, 国际地震中心, Internationales Seismologisches Zentrum, and المركز الدولي للبحوث الزلزالية. A "Site Map" icon is visible in the top right corner.

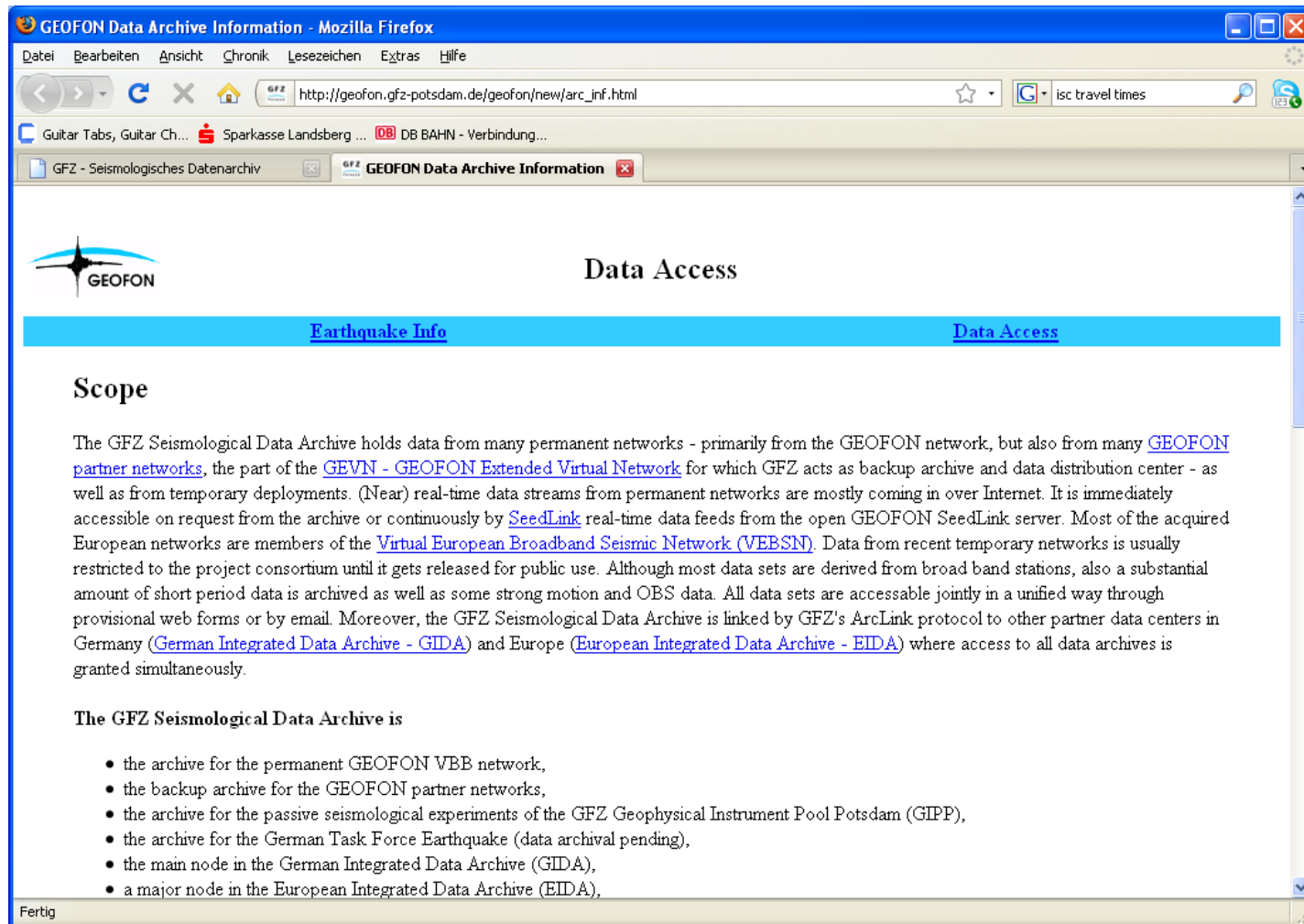
The main content area includes a "Welcome" message, a list of navigation links: "ISC Bulletin", "Registries", "Documents", "Analysis", "Products", "Services", "IASPEI GT", and "EHB Bulletin". A large graphic of a seismic wave is overlaid on the text "International Seismological Centre".

On the left side, there is a "What's New" section with a red border, containing the following items:

- ISC Interactive Search
- Newsletter Oct - Dec 2008
- ISS station data 1960-1963
- IASPEI Reference Event List

At the bottom right, there are sections for "MEMBERS" and "SPONSORS:" with a small logo next to it. The browser's status bar at the bottom left shows the word "Fertig".

Seismic data centres: GEOFON



The screenshot shows a Mozilla Firefox browser window displaying the GEOFON Data Archive Information page. The address bar shows the URL http://geofon.gfz-potsdam.de/geofon/new/arc_inf.html. The page features the GEOFON logo on the left and the title "Data Access" in the center. Below the title, there are two navigation links: "Earthquake Info" and "Data Access". The main content area is titled "Scope" and contains a paragraph of text describing the archive's holdings and access policies. Below this, a section titled "The GFZ Seismological Data Archive is" lists several key features and roles of the archive.

Data Access

[Earthquake Info](#) [Data Access](#)

Scope

The GFZ 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 GFZ 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 [SeedLink](#) real-time data feeds from the open GEOFON SeedLink server. Most of the acquired European networks are members of the [Virtual European Broadband Seismic Network \(VEBSN\)](#). Data from recent temporary networks is usually restricted to the project consortium until it gets released for public use. Although most data sets are derived from broad band 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 unified way through provisional web forms or by email. Moreover, the GFZ Seismological Data Archive is linked by GFZ's ArcLink protocol to other partner 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 GFZ Seismological Data Archive is

- the archive for the permanent GEOFON VBB network,
- the backup archive for the GEOFON partner networks,
- the archive for the passive seismological experiments of the GFZ 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),

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EMSC

EMSC - European-Mediterranean Seismological Centre - Mozilla Firefox

http://www.emsc-csem.org/index.php?page=home

csem
emsc

Centre Sismologique Euro-Méditerranéen
European-Mediterranean Seismological Centre

Google™ Custom Search Search EMSC

Current time: 2009-05-11 15:44:34 UTC

Member access
Name:
Pwd:
Sign in

Earthquake information Euro-Med seismicity How it works Database & Documents News Projects About EMSC

Euro-Med earthquakes Worldwide earthquakes with M4.0+

Last 24h Last 48h Last week Last 2 weeks

Earthquake news & highlights

- » **Mw 6.3 Central Italy (06/04/2009)**
- » Mw 5.4 Northern Italy (23/12/2008)

See full list

News

- » **EMSC Newsletter (April 2009)**
- » ORFEUS Workshop (July, 2-3 2009)
- » Postdam (GFZ) Training Course
- » SEISM CARE:2009, June 22-24 Martinique Island (France)

All news

Information Services

- » **Earthquake Notification Service**
Get notification by email or SMS
- » **Real Time on Phone & PDA**
- » **RSS Feeds**
- » **Seismicity on Google Earth**

http://www.emsc-csem.org/index.php?page=home#

Seismic data centres: EarthScope

EarthScope Data - Mozilla Firefox

http://www.earthscope.org/data

EarthScope Science Observatories Instrumentation **Data Access** Publications Education & Outreach News About Us

EarthScope Home > Data Access

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 Institution 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.

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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.?

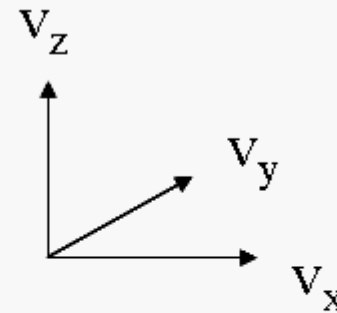
Seismic observables

translations

Translational motions are deformations in the direction of three orthogonal axes. Deformations are usually denoted by \mathbf{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.



Ground velocity
Seismometer

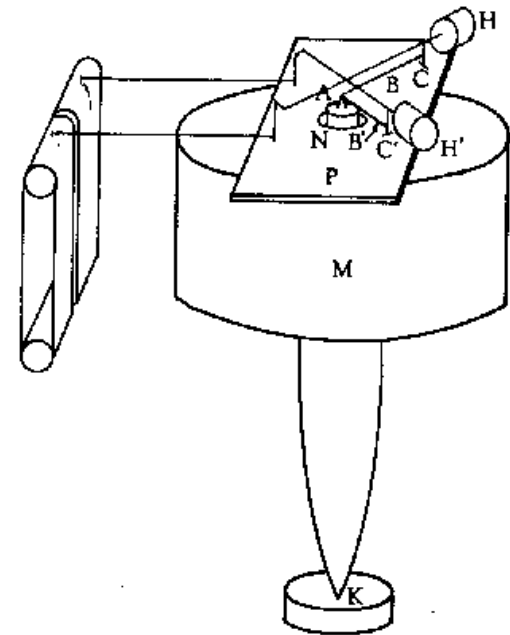
Seismic observables

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.

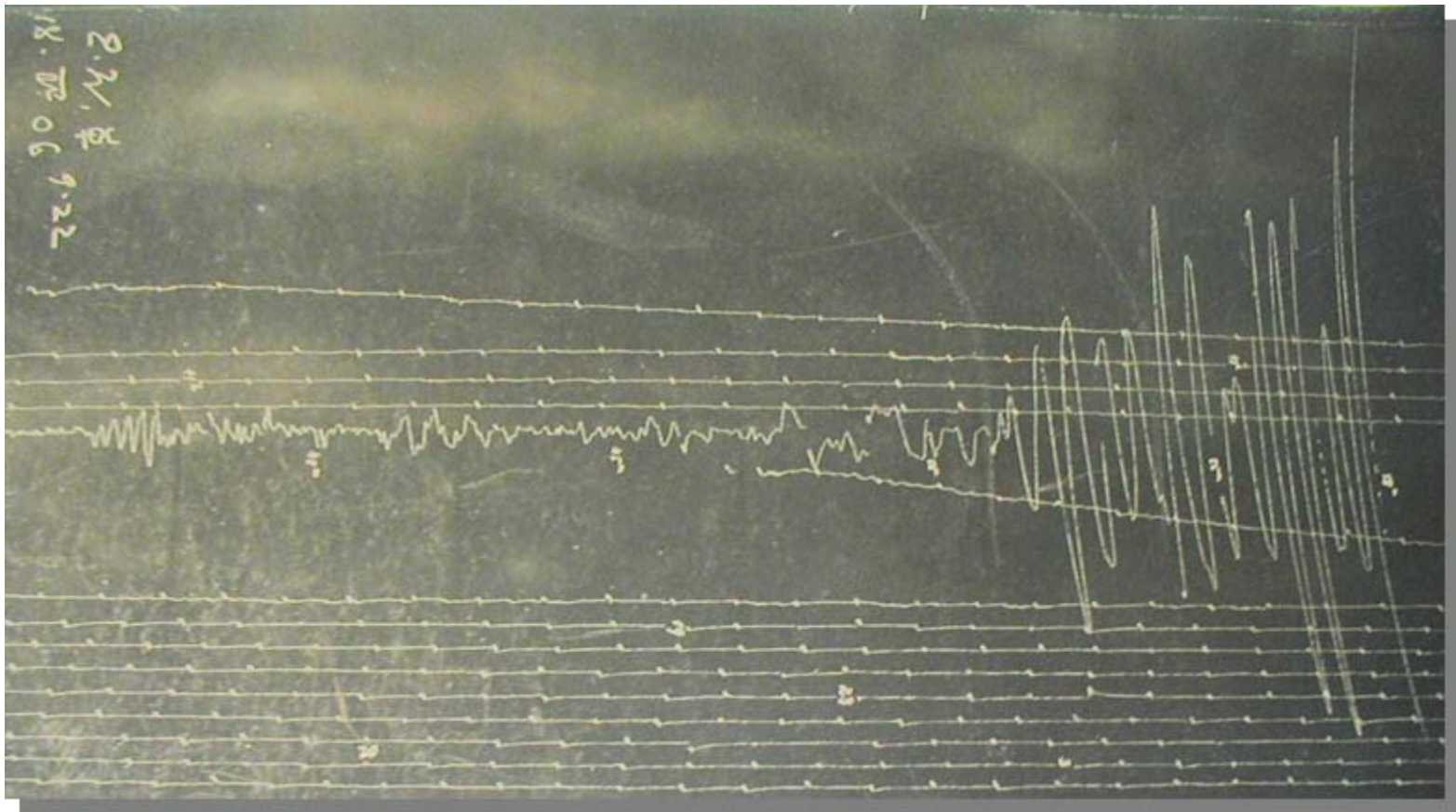
Today displacements are measured using GPS sensors.



Seismic observables

translations - displacements

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



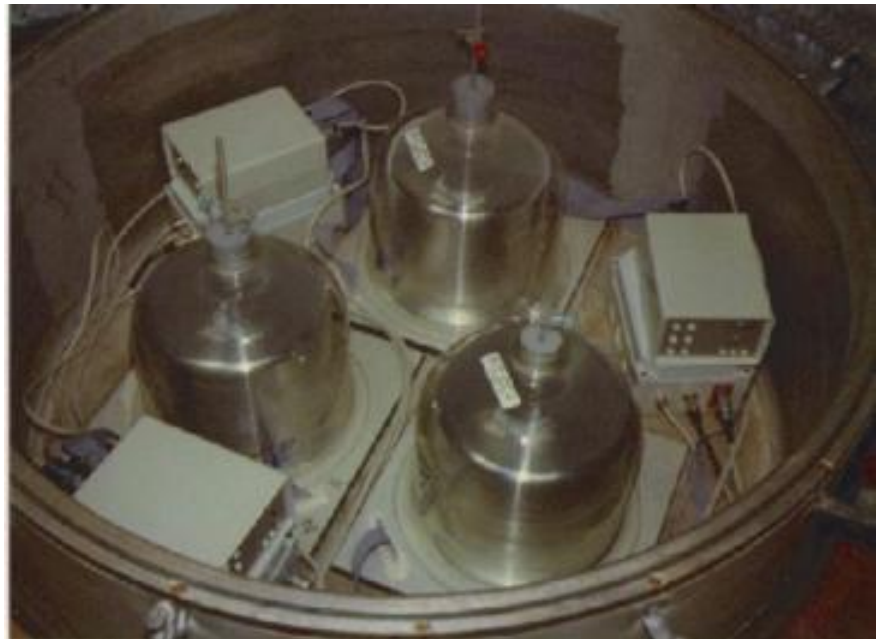
Seismic observables

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 m/s .

$$v(x, t) = \partial_t u(x, t) = \dot{u}(x, t)$$



Seismic observables *translations - accelerations*

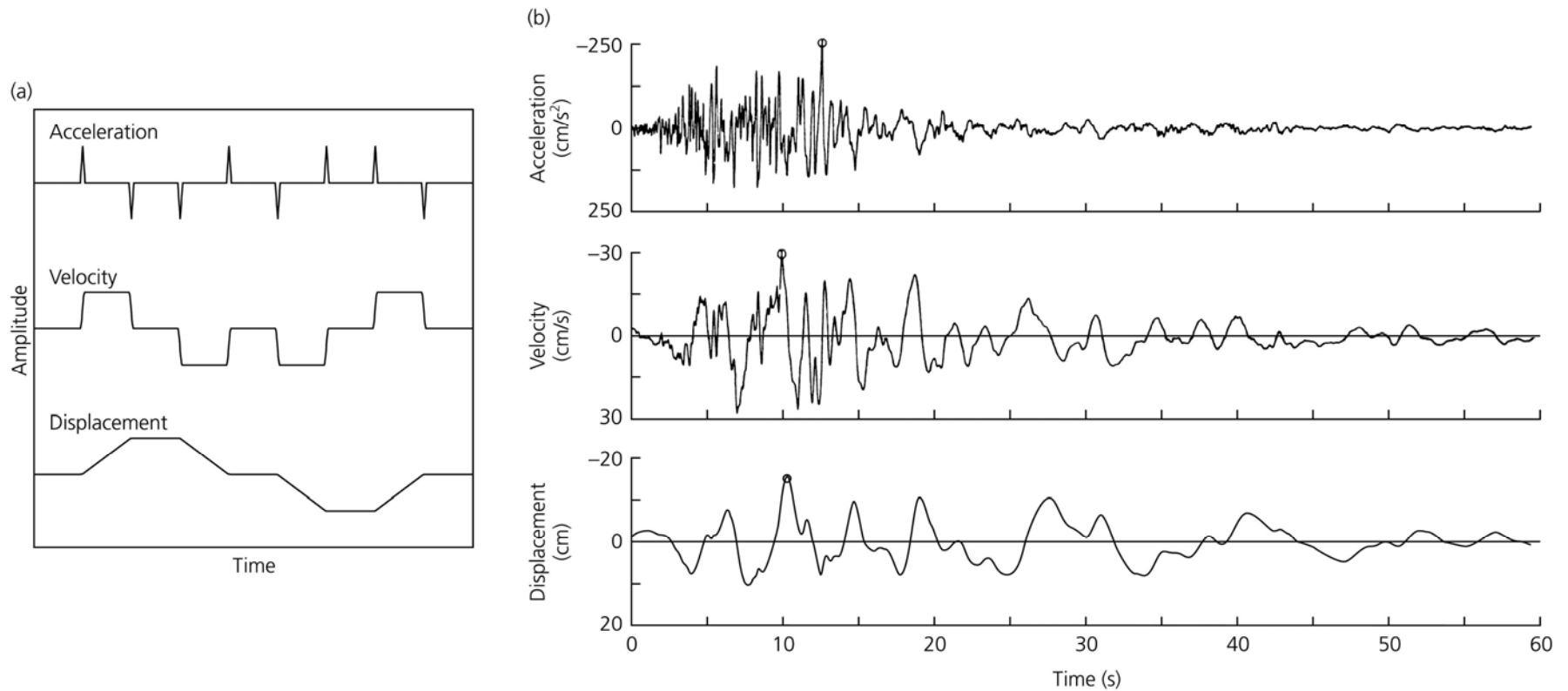
Strong motions (those getting close to or exceeding Earth's gravitational acceleration) can only be measured with accelerometers. Accelerometers are used in earthquake engineering, near earthquake studies, airplanes, laptops, ipods, etc. The largest acceleration ever measured for an earthquake induced ground motion was 40 m/s^2 (four times gravity, see *Science* 31 October 2008: Vol. 322. no. 5902, pp. 727 – 730)

$$a(x, t) = \partial_t^2 u(x, t) = \ddot{u}(x, t)$$



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.

$$\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

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

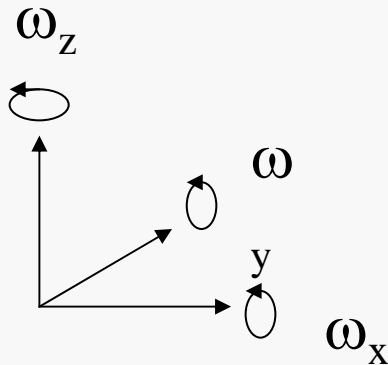
Strain components (2-D)

$$\boldsymbol{\varepsilon}_{ij} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2} \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) \\ \frac{1}{2} \left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \right) & \frac{\partial u_y}{\partial y} \end{bmatrix}$$

Seismic observables

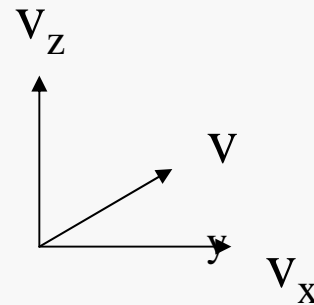
rotations

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



Rotation rate

Rotation sensor



Ground velocity

Seismometer

Seismic observables

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)

$$\Theta(x, t) = \hat{\partial}_x u_z$$

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 colocated 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?