Seismic instruments

ErSE390 Seismic waves

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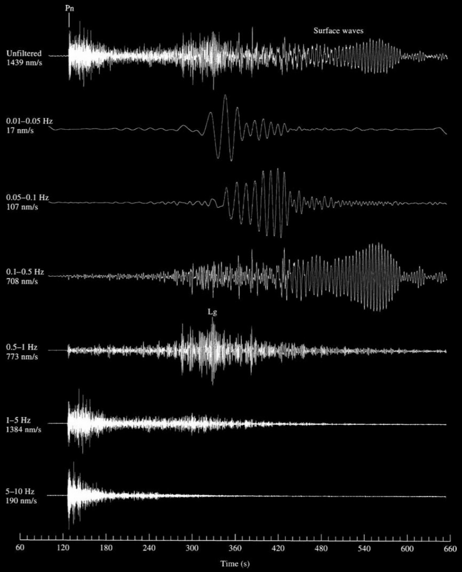
Primer

We will look into the basic principles of how ground motions can be recorded, the various types of recording instruments, and how we find the "true" ground displacement given some digital output of a seismometer.

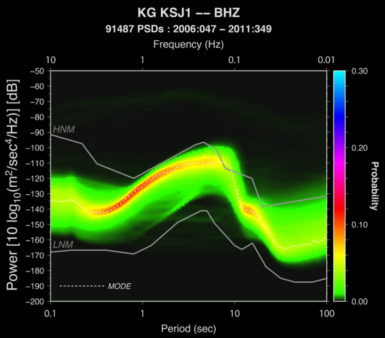
Basic instrumentation

Traditional instruments I



Seismic waveforms can dramatically change when filtered in different frequency bands (we have seen this already when looking at diffuse wavefields). It is clear that instruments recording ground motion must therefore cover a wide range of frequencies (and amplitudes), i.e., have a wide dynamic range, to capture all information.

Traditional instruments II



Recognizing the strong oceanic noise between periods of 2-8 seconds at any recording site, traditional instruments were built to being sensitive to either motions below or above this noise peak. This led to the development of short-period (SP) and long-period (LP) seismometers. Short-period stations were important to measure arrival times of body waves (periods < 2 s), and long-period stations to capture surface waves (periods > 13s).

Digital seismometers took over in the 1960s. Newer seismometers, called broadband seismometers, took over by the 1970s. Broadband seismometers are now capable to cover the whole period range, replacing the need for separate short/long-period ones. They are now the standard instrumentation for national, regional and global seismic networks like the Global Seismographic Network (GSN).

Basic measurements

Ground motions can be separated into

translational ground motion

(horizontal & vertical) displacement/velocity/acceleration at a site (including gravitational acceleration)

measured by pendulum seismometers (broadband seismometers, short/long-period seismometers, geophones),..

strain motion

length deformation between 2 separate measurement points

measured by strainmeters, distributed acoustic sensing (DAS) systems, LIGO (laser interferometer gravitational-wave observatory),..

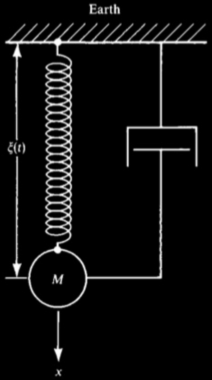
rotational motion

rotational motion caused by Earth's rotation, plate tectonics, S-wavefield motions

measured by rotation seismometers, ring lasers, (fibre-optic) gyroscopes, ..

Seismometry principle

In the following, we will focus on the measurement of the oscillatory ground motions (displacement/velocity/acceleration) by a pendulum seismometer. This can be achieved by a basic inertial sensor consisting of a mass attached to a spring and damping mechanism.



An inertial sensor can be described by a single-degree-of-freedom (SDOF) damped oscillator:

$$\ddot{\xi}(t) + 2\epsilon\omega_s\dot{\xi}(t) + \omega_s^2\,\xi(t) = -\ddot{u}(t)$$

with $\omega_s = \sqrt{\frac{k}{M}}$ and $\epsilon = \frac{c}{2M\omega_s}$, driven by the ground motion $\ddot{u}(t) = \frac{d^2u(t)}{dt^2}$. We can measure the position ξ of the mass, and thus obtain a measurement for the ground motion acceleration $\ddot{u}$.

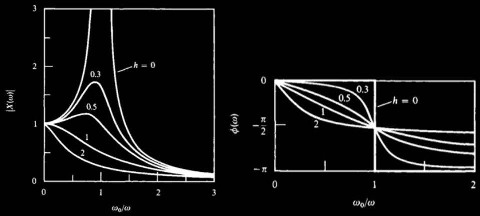
Frequency-response function

To translate the measurement of the inertia sensor to ground displacement, we have to know the response of the instrument at any frequency ω:

$$\xi(\omega) = u(\omega)X(\omega)$$

with $X(\omega)$ being the frequency-response function. It is determined by the SDOF equation:

$$X(\omega) = \frac{-\omega^2}{\omega^2 + 2i\epsilon\omega - \omega_s^2}$$



The amplitude response is given by $|X(\omega)|$ and the phase response $\phi(\omega)$ such that $X(\omega) = |X(\omega)|\, e^{i\,\phi(\omega)}$.
The best damping of the instrument is usually achieved at the critical damping value such that $h = \frac{\epsilon}{\omega_s} = 1$.

Poles and zeros

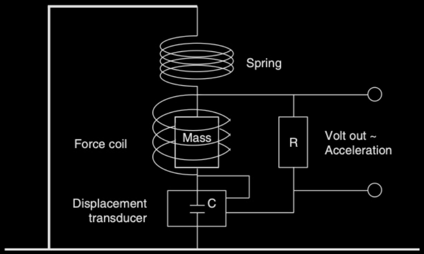
The frequency-response function $X(t)$ can be seen as an instrument filter that will be convolved with ground motion $\xi(t) = u(t) * X(t)$. A convenient way to characterize this filter is through a Laplace transform:

$$X(s) = \frac{\xi(s)}{u(s)} = \frac{\alpha \prod_{i=1}^{m}(s - z_i)}{\beta \prod_{j=1}^{n}(s - p_j)}$$

with (complex valued) z_i called zeros, p_j called poles, and constants α,β given by the instrument.

Traditional seismographs have 3 zeros and 4 poles, typical IRIS broadband instruments are characterized by 5 zeros and 14 poles. To obtain the ground displacement given an instrument record, we have to deconvolve the instrument response from the recording: $u(t) = \xi(t) * X^{-1}(t)$

Digital recording

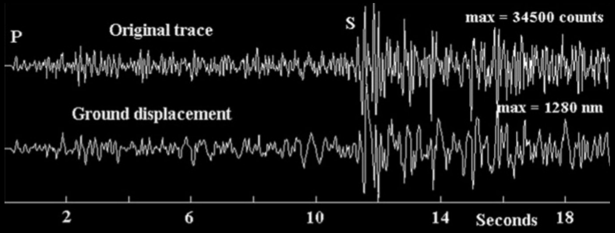


To measure the position of the mass by an electrical system, a coil attached to the sensor mass moving through a magnetic field can be used. The movement of the coil will induce an electrical current through magnetic induction. The voltage can get measured by a transducer and digitizer to a 24-bit signal and recorded in digital counts.

Depending on the transducer either the position (displacement), velocity or acceleration of the mass becomes proportional to the ground motion displacement, velocity or acceleration. Each has its advantages and disadvantage and thus different sensors are available, with broadband instruments mostly proportional to velocity, and strong-motion instruments to acceleration.

Digital recording - force balance

To increase sensitivity to small displacements, broadband instruments now use a force balanced system, where the mass is kept at (almost) fixed position by a feedback coil exerting a force equal and opposite to the inertia force. The voltage required to fix the mass becomes then the sensor output.



With current 24-bit digitizers, a single digital count can usually resolve 100 nV and provide a dynamic range of $\pm 2^{22}$.

Instruments

Seismic sensors I

A vast variety of seismic instruments are in operation for ground motion recordings, most typical ones being:

- *Broadband seismometers*: sensors like the STS-2 by Streckeisen, CMG-3T by Güralp, and Trillium 120 by Nanometrics are popularly used in seismic networks.
- *Accelerometers*: strong-motion sensors like the FBA-2 episensor from Kinemetrics or Titan EA from Nanometrics, measure large amplitude, high-frequency seismic accelerations, and are typically placed in buildings and critical infrastructures; Micro-electro-mechanical systems (MEMS) sensors are used in portable devices.
- *Geophones*: typically single component sensors used in shallow surface and reflection seismology, often sensitive in a frequency range > 2 Hz.

Seismic sensors II

More specialized ones:

- *Distributed acoustic sensing (DAS)*: fibre-optic strain sensors, deploy laser pulses and measure phase changes in Rayleigh backscattered light, are recently used in many geophysical applications.
- *Ocean bottom seismometers*: similar to broadband stations with the additional pressure robustness and low-power requirement needed for employment in deep oceans.
- *MERMAID system*: autonomous floating seismometers by Osean includes acoustic data recording for seismic studies.
- *Community-driven sensors*: seismographs like the Raspberry Shake are low-cost, easy to use seismographs enabling a Do-It-Yourself (DIY) approach and building up a community to monitor earthquakes and other exciting events.

Trends in seismic instrumentation

The development of seismic instruments constantly evolves and improves over time. New devices can become more sensitive, accurate, smaller or cheaper, often driven by market needs.

For example, fibre-optic techniques have made substantial progress in DAS systems and rotational gyroscopes. Micro-electro-mechanical systems (MEMS) are drastically reducing size and become more and more sensitive to measure acceleration in mobile devices such as your mobile phone. Electro-chemical devices have made much improvements over the last decade, further improving mechanical & orientiational issues with seismic instruments. And autonomous systems, such as for example Mermaids, can further help to get measurements in remote areas to improve data coverage.

Stay tuned - more to come in future...

More details and excellent explanations on seismometry can be found for example in these books:

- Aki, K. and Richards, P. G. (2002).
  ***Quantitative Seismology*.**
  University Science Books, second edition edition.
- Havskov, J. and Alguacil, G. (2016).
  ***Instrumentation in Earthquake Seismology*.**
  Springer.
- Lay, T. and Wallace, T. C. (1995).
  ***Modern Global Seismology*.**
  Academic Press.

Shearer, P. (1999).
***Introduction to Seismology*.**
Cambridge University Press.

Stein, S. and Wysession, M. (2003).
***An Introduction to Seismology, Earthquakes, and Earth Structure*.**
Blackwell Publishing.