Engineering Seismology and Seismic Hazard – 2019

Lecture 20

Seismometry

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The Seismometer

A seismometer is an instrument which reacts to the shaking induced by any natural or anthropogenic source of vibration, producing a mechanical of electrical response.

If such instrument has also recording capabilities, it is more generally called seismograph.

Commonly, seismometers are used to study earthquakes, although they can be used to analyze micro vibrations (e.g. ambient noise) and for geophysical prospecting.

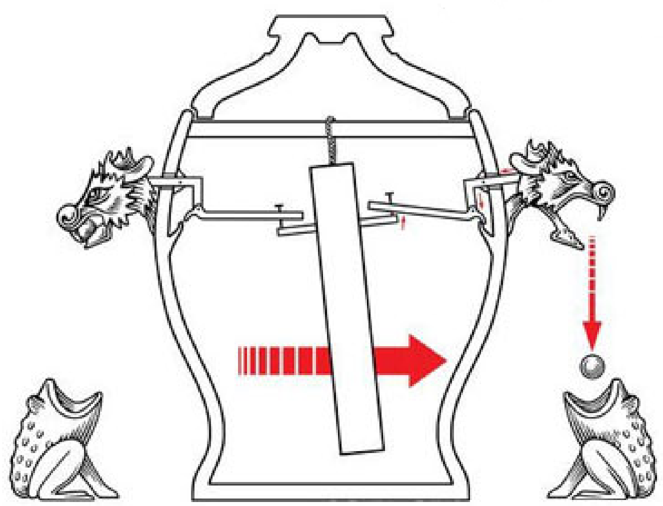
4.5HZ Geophone

Seismometer S13

Trillium 240

Early Origin of Seismometry

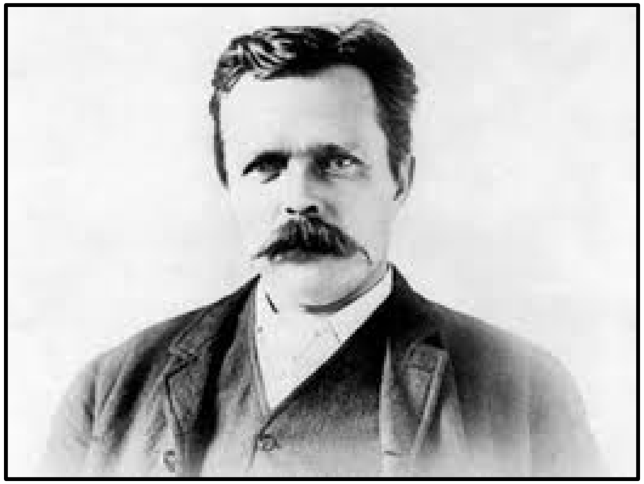
The first instrument considered capable of detecting the occurrence of an earthquake was the Seismoscope, created in China by Zhang Heng (mathematician, astronomer and inventor), about 130 B.C.



The seismoscope could additionally provide useful (although very inaccurate) information about ground shacking direction, for a first-guess earthquake location.

History of Seismometry

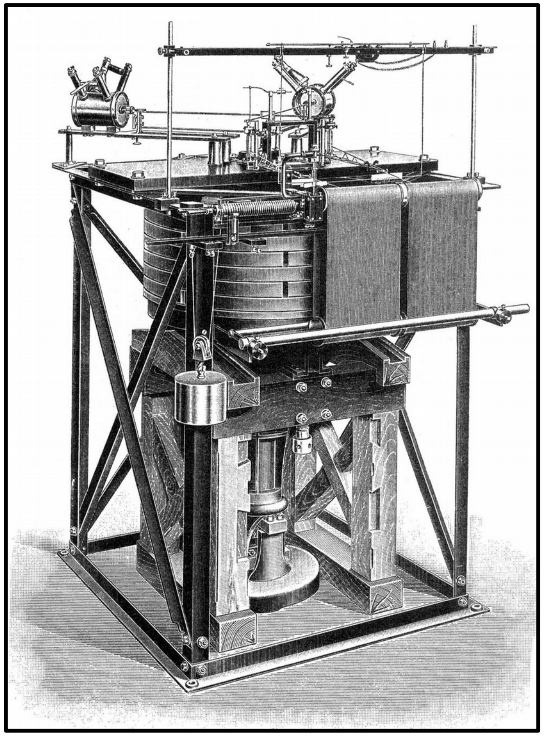
Seismometry has gained scientific recognition only from the beginning of the last century, thanks to the pioneering studies of John Milne, a British geologist collaborating with the Japanese Seismological Society.



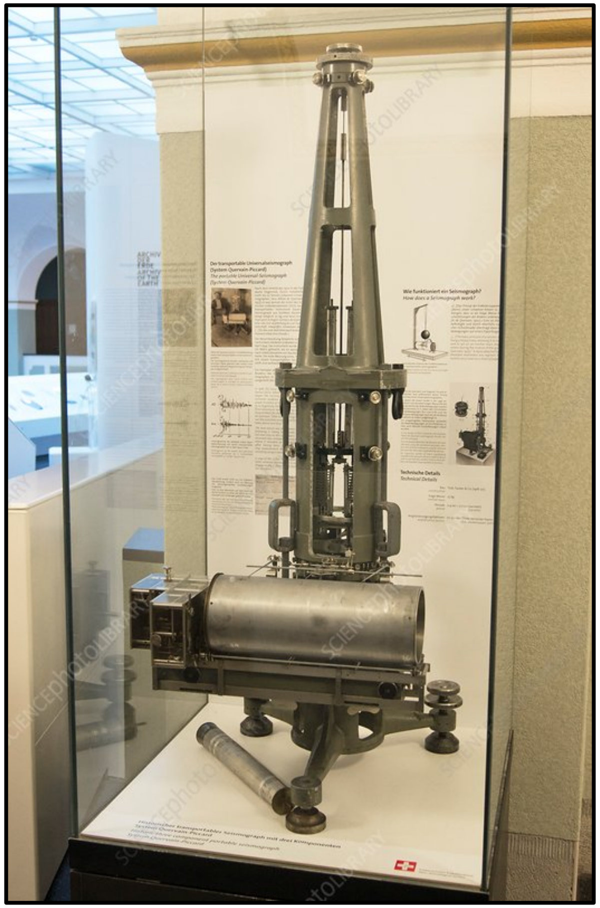
John Milne (and wife) with Russian seismologist Boris Galitzin working on its horizontal pendulum.

History of Seismometry

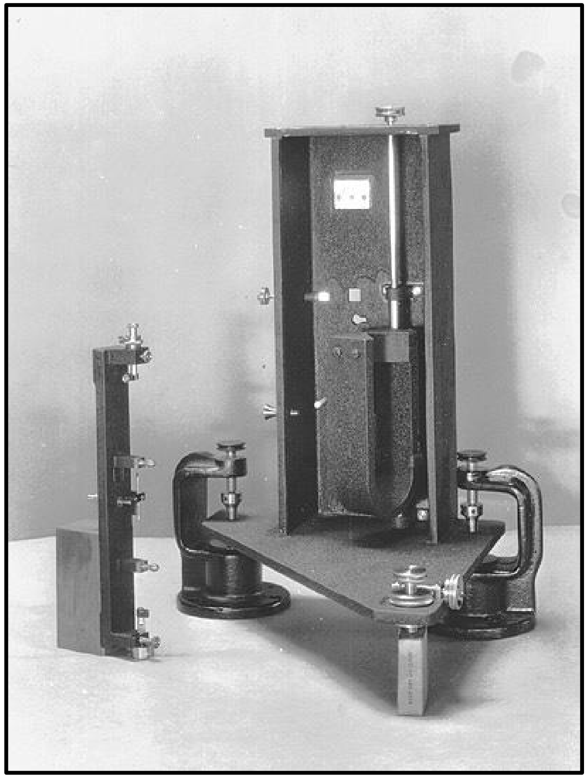
From these early developments, more and more accurate instruments has been proposed, each with a diverse and creative engineering solution.



Short period Weichert seismometer



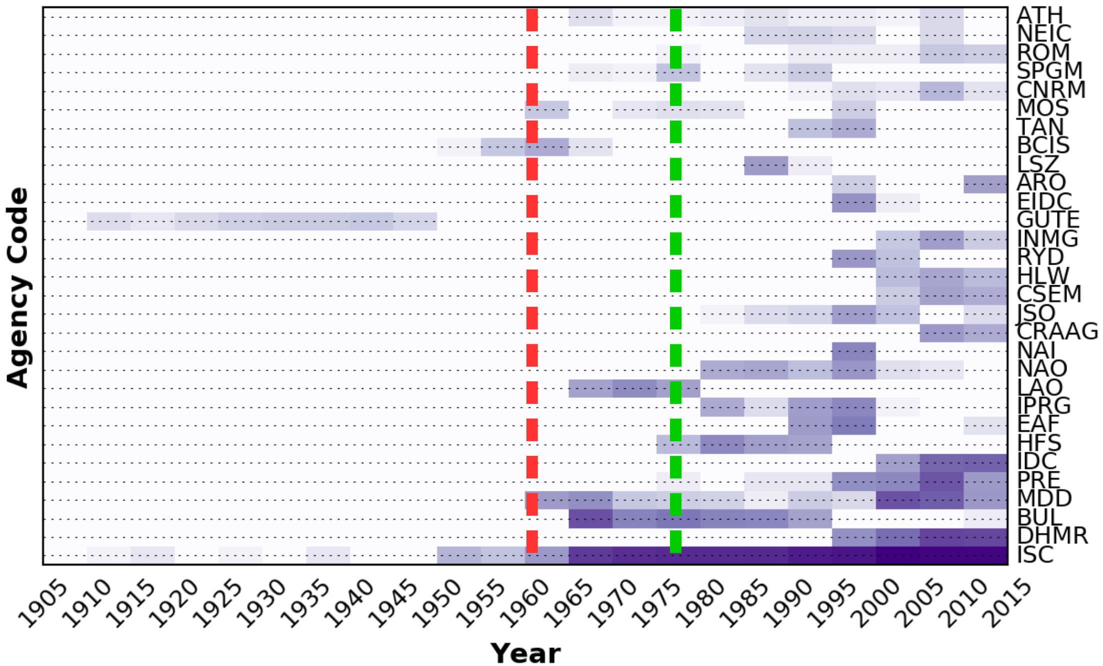
Quervain-Picard portable vertical seismometer

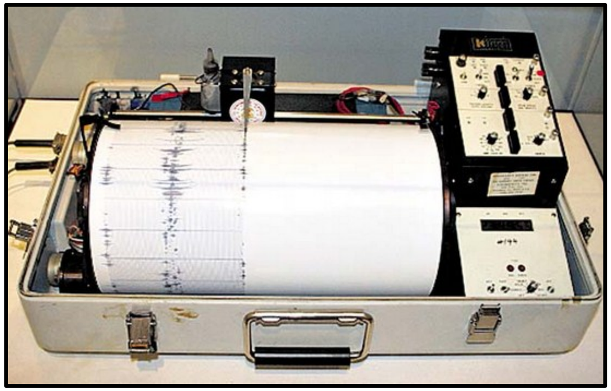


Wood Anderson torsion pendulum

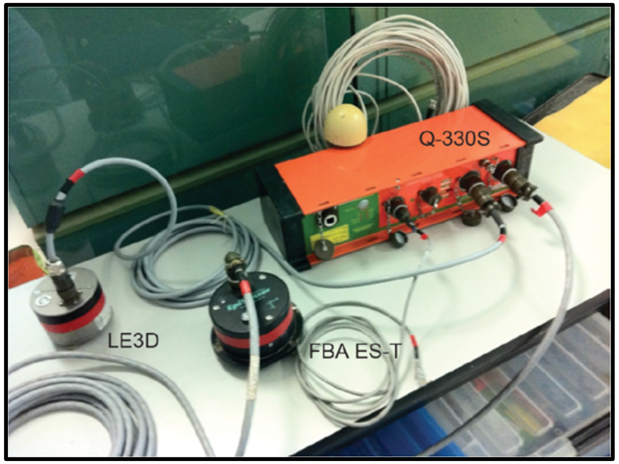
History of Seismometry

Only from the 50s seismometer became a standard observation tool, thanks in particular to the latest developments in electronic, analog first and digital in a subsequent time.





Kinemetric drum seismograph



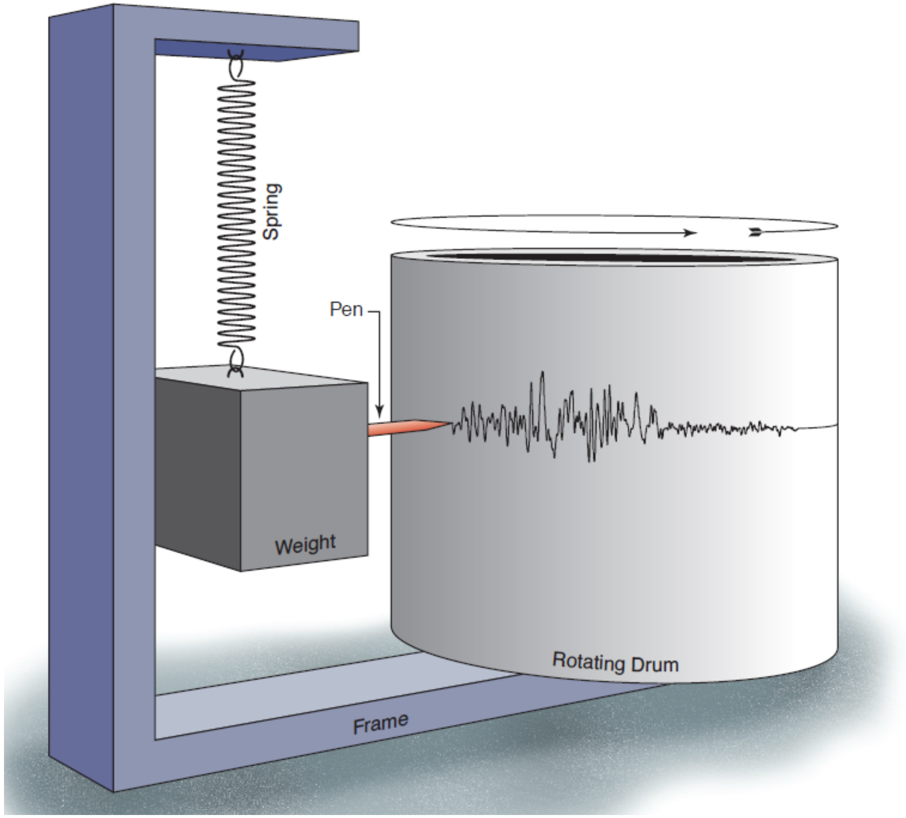
Digital Seismograph Quanterra Q330 with Lennartz 3D velocity sensor and Kinemetrics Episensor accelerometer

Working Principle

A seismometer detects the relative variation of location between a measuring and a reference point.

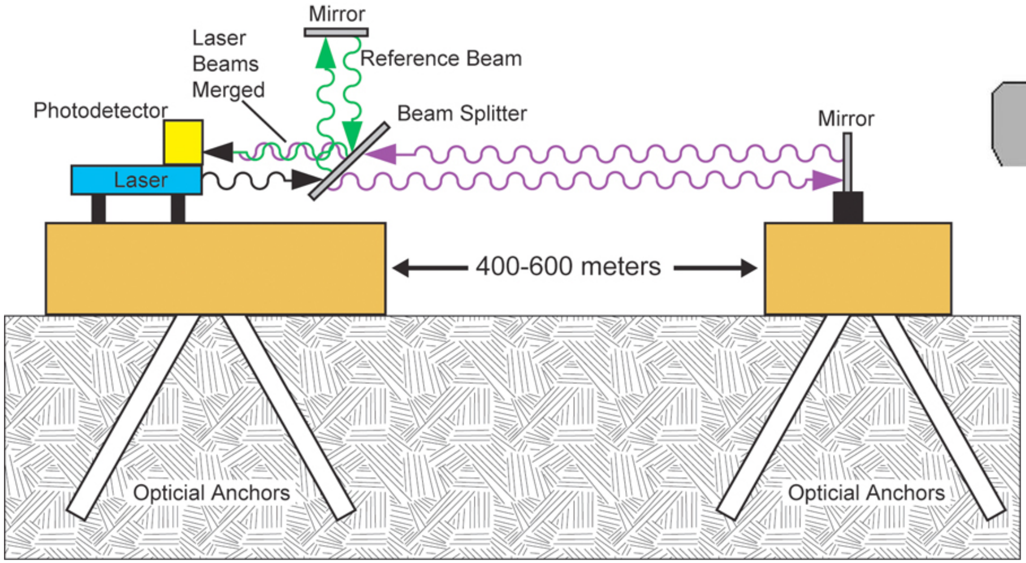
Since it is not possible to use an absolute reference system, a relative inertial reference frame is often used instead.

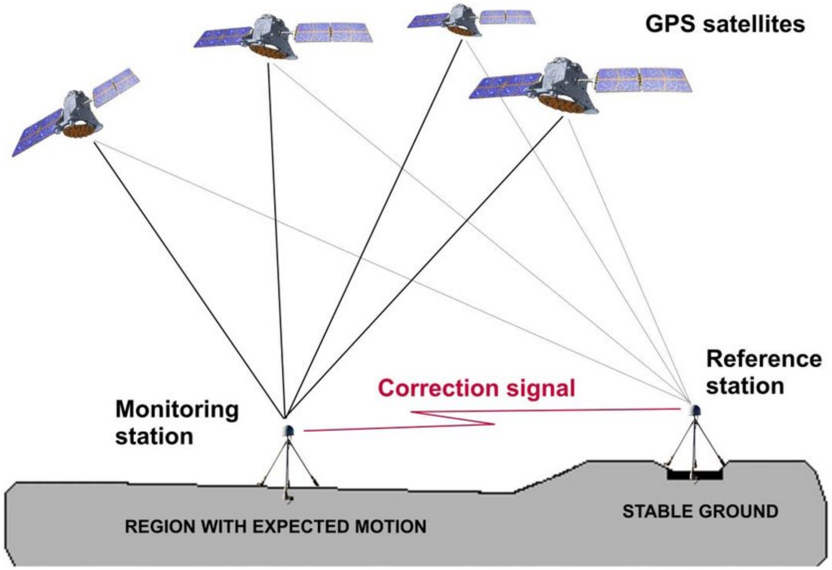
This simply consists in a mass which opposes to the variation of its state (at rest or moving at constant velocity)



Working Principle

Note that any other relative reference frame can be used, local as in **strainmeters** or global as for satellite constellations in **GPS** measurements.





Main Seismometer Types

Seismometers are generally classified based on the following:

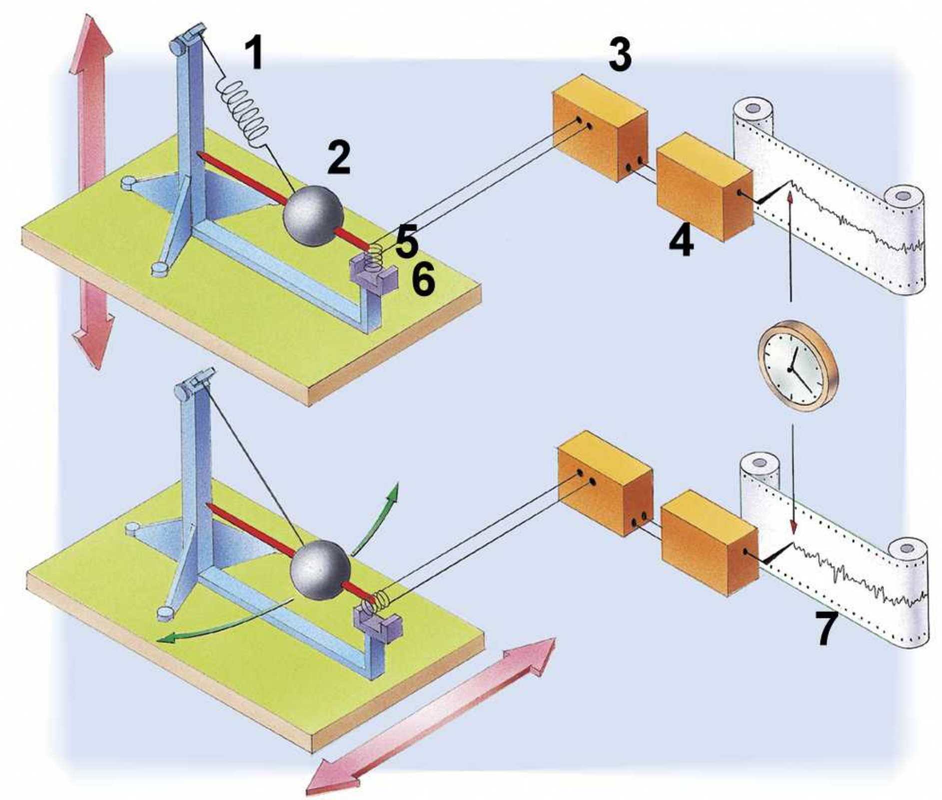
- Measuring direction or component (vertical, horizontal, rotational)
- Measured property (displacement, velocity, acceleration)
- Working principle (mechanical or electro-mechanical, active or passive)
- Frequency band of linear response
- Dynamic range
- Working environment design (ground, water, space...)

Recording Directions

Although ground displacement is a vector field, seismometers can record a single component of movement a time, typically translational, either vertical or horizontal.

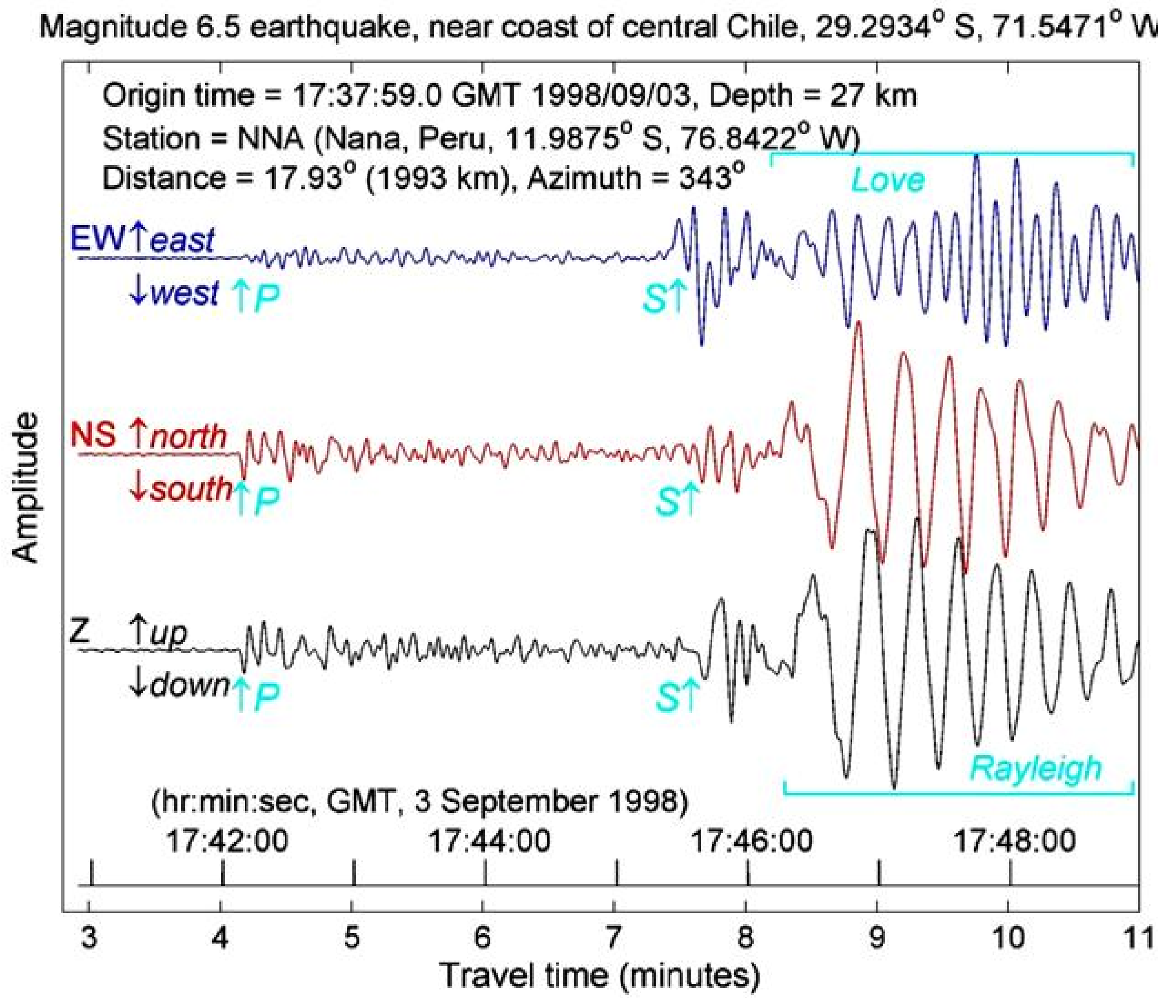
According to the recoding direction, the instrument is designed with different mechanical characteristics.

Three-component seismometers are simply a combination of single-component elements.



Recording Directions

The recording direction strongly depends on the performed study and on the wave type to be analyzed.



Examples:

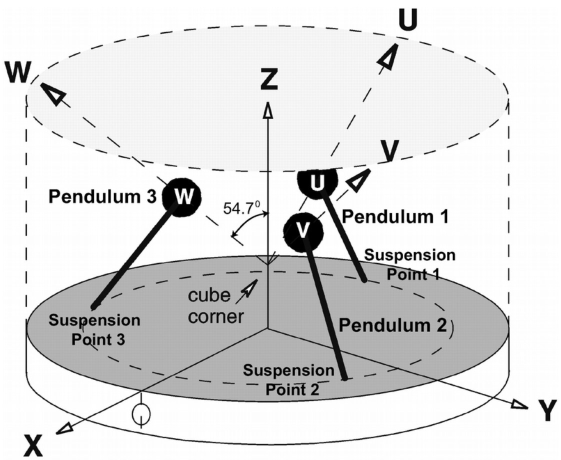
1) Seismic tomography on first arrivals
>> preferentially vertical seismometers

2) Engineering local seismic response
>> typically horizontal seismometers

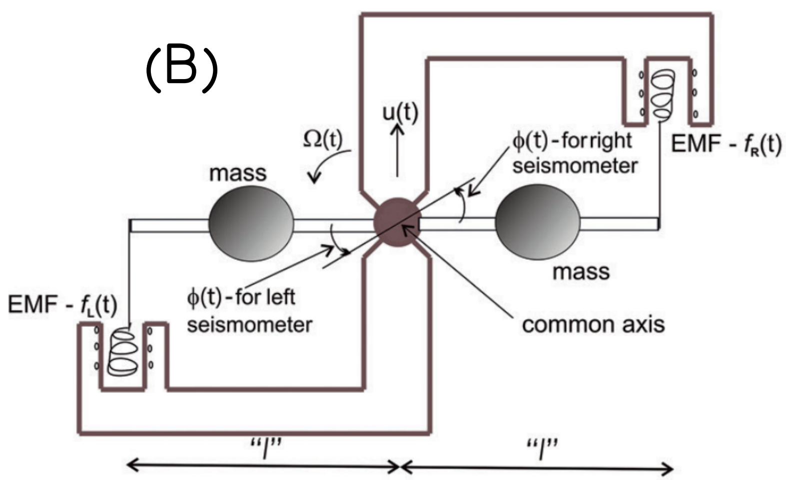
Recording Directions

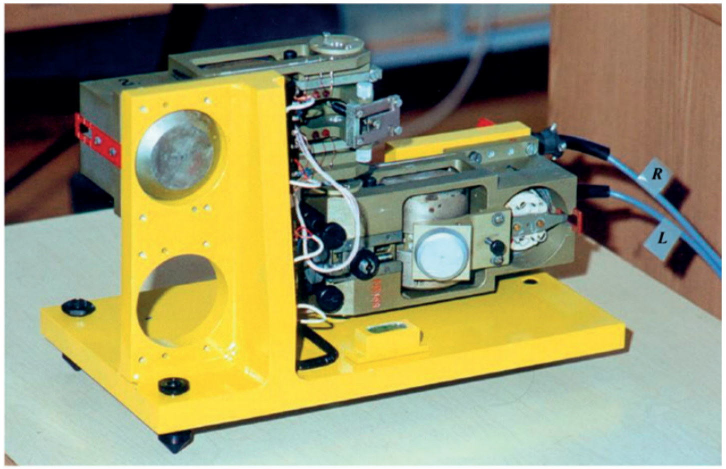
Special seismometers can record oblique translational motion (A) and rigid rotations (B).

(A)



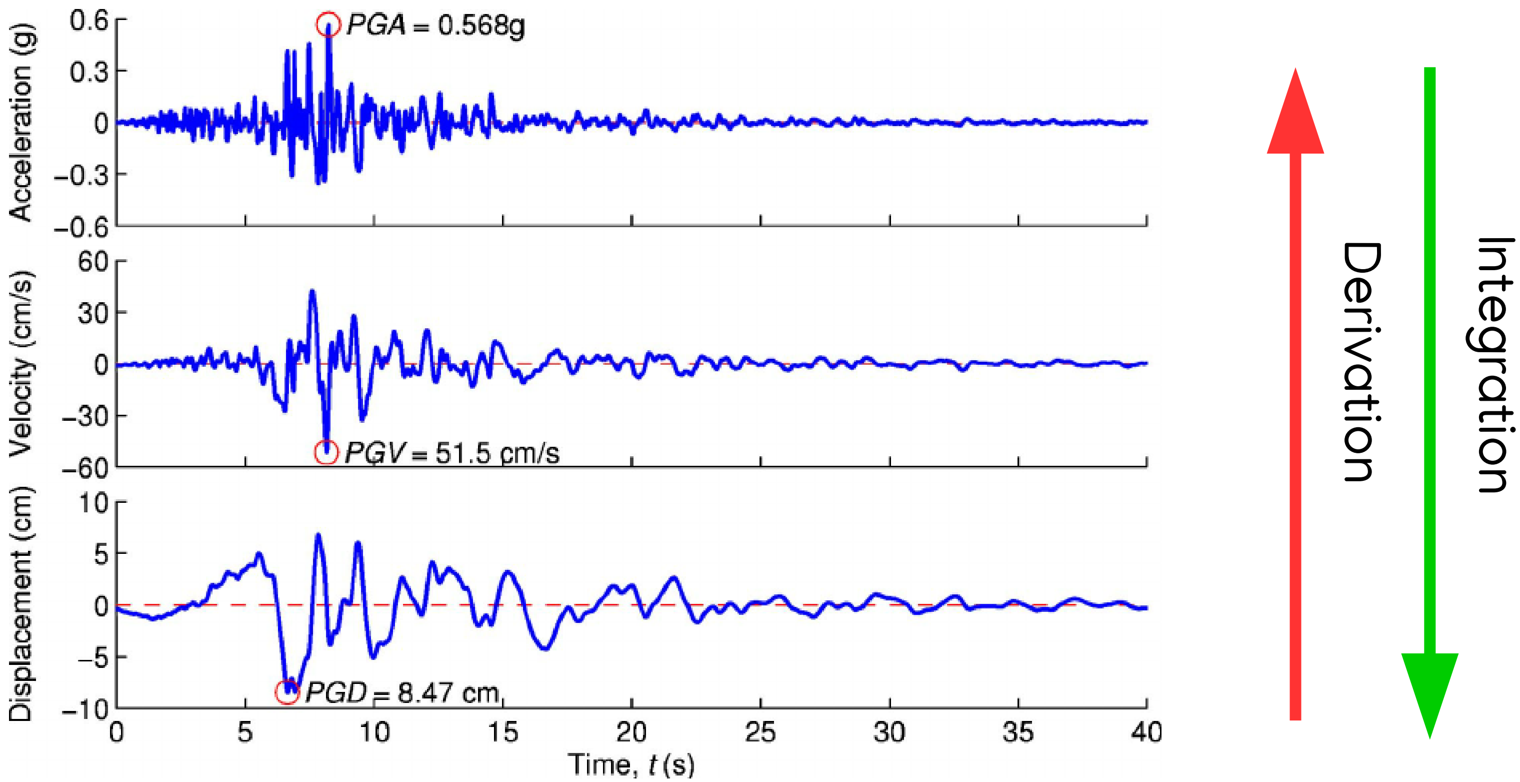
(B)





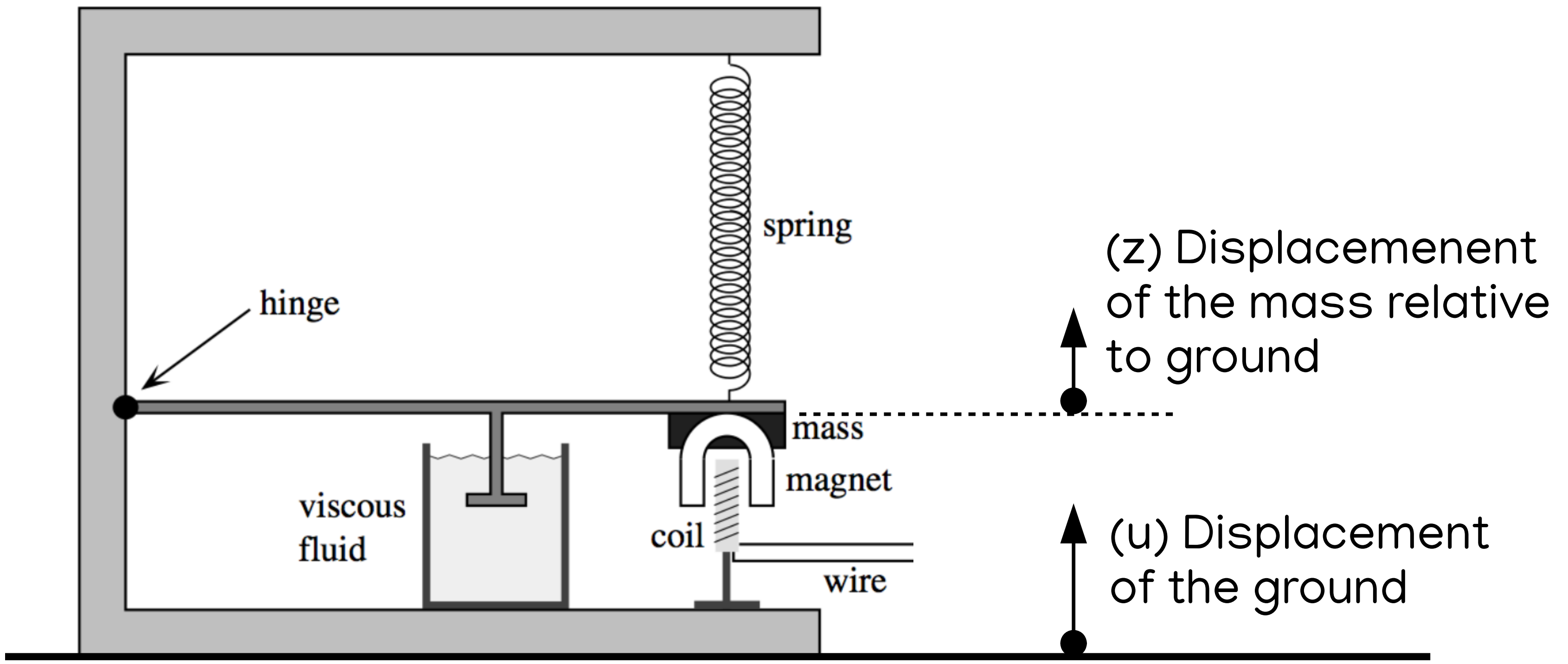
Measured Motion

Depending on the physical quantity that is measured, seismometers are classified as accelerometers, velocimeters and dynamic strainmeters (less frequent).



Working Principle

A standard inertial seismometer (e.g. vertical) is made of:
– a mass free to move in a single direction (through a hinge)
– a spring, supporting the mass
– a damping mechanism (viscous fluid or a reaction coil)



Working Principle

The system response could be analytically defined by balancing the acting forces, according to the first principle of dynamic.

$$F_s = -kz,$$ → Elastic force

$$F_d = -D\frac{dz}{dt},$$ → Damping force

$$-kz(t) - D\frac{dz(t)}{dt} = m\frac{d^2}{dt^2}\left[u(t) + z(t)\right],$$ → External input

$$\ddot{z} + \frac{D}{m}\dot{z} + \frac{k}{m}z = -\ddot{u}.$$

This last could be rewritten as:

$$\omega_0^2 = k/m,$$
$$2\epsilon = D/m.$$

$$\ddot{z} + 2\epsilon\dot{z} + \omega_0^2 z = -\ddot{u}.$$

Working Principle

The balance equation can be solved by assuming an harmonic solutions (in Fourier domain) for the ground displacement (u) and for the mass displacement relative to the ground (z).

$$u(t) = U(\omega)e^{-i\omega t}, \quad z(t) = Z(\omega)e^{-i\omega t}.$$

Therefore, by computing the derivative and substituting it will be:

$$\begin{aligned}
\ddot{u} &= -\omega^2 U(\omega)e^{-i\omega t}, \\
\dot{z} &= -i\omega Z(\omega)e^{-i\omega t}, \\
\ddot{z} &= -\omega^2 Z(\omega)e^{-i\omega t}.
\end{aligned}$$

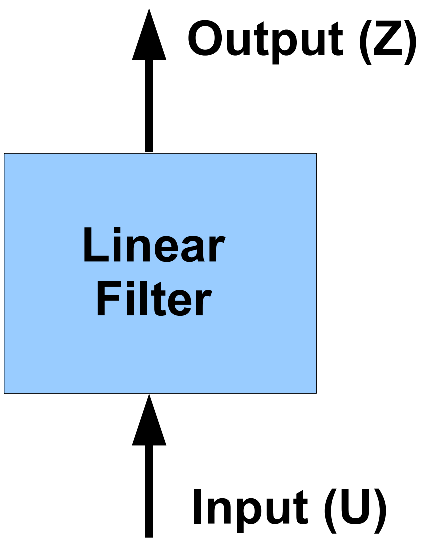
$$-\omega^2 Z(\omega) - 2\epsilon i\omega Z(\omega) + \omega_0^2 Z(\omega) = \omega^2 U(\omega),$$

Instrumental Response

Finally, grouping the common terms:

$$Z(\omega) = \frac{\omega^2}{\omega_0^2 - 2\epsilon i\omega - \omega^2} U(\omega) = \mathcal{Z}(\omega)U(\omega),$$

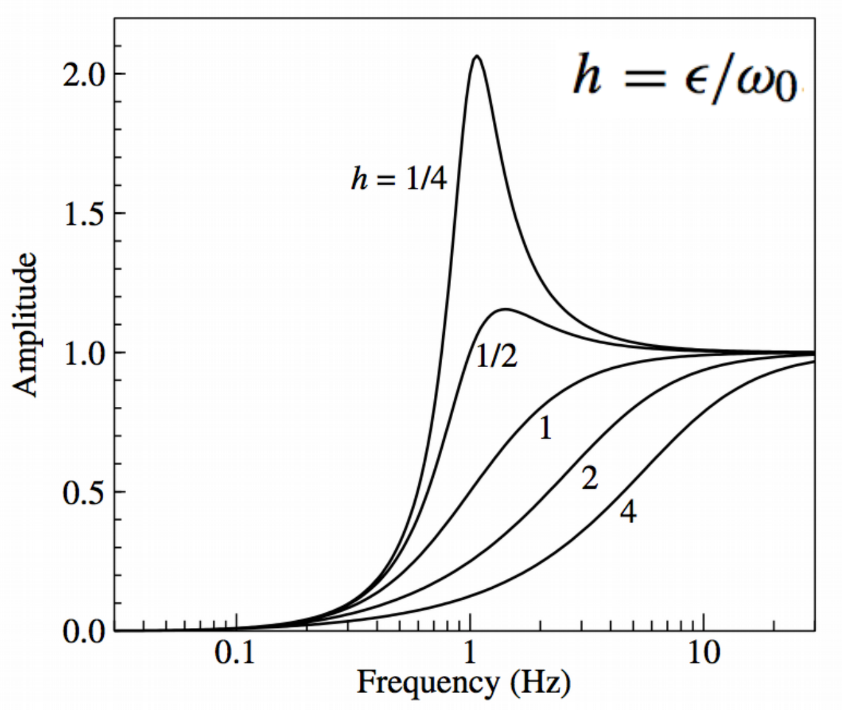
System Transfer Function
(also called impulse response)

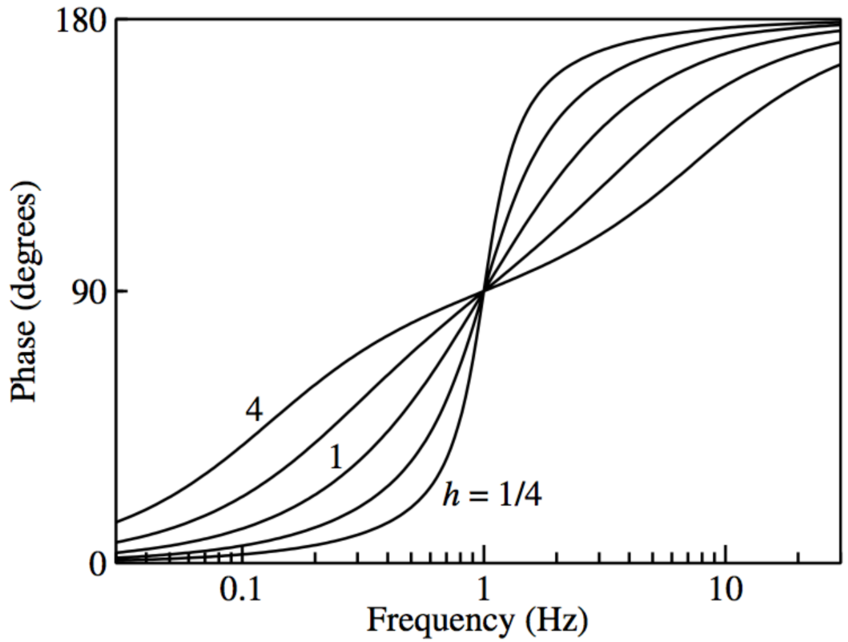


The transfer function can be seen as the linear relation between input (U) and output (Z) of the system → convolution!

Instrumental Response

The transfer function is complex, therefore it is possible to show separately its **amplitude** and **phase** information as function of the angular frequency.

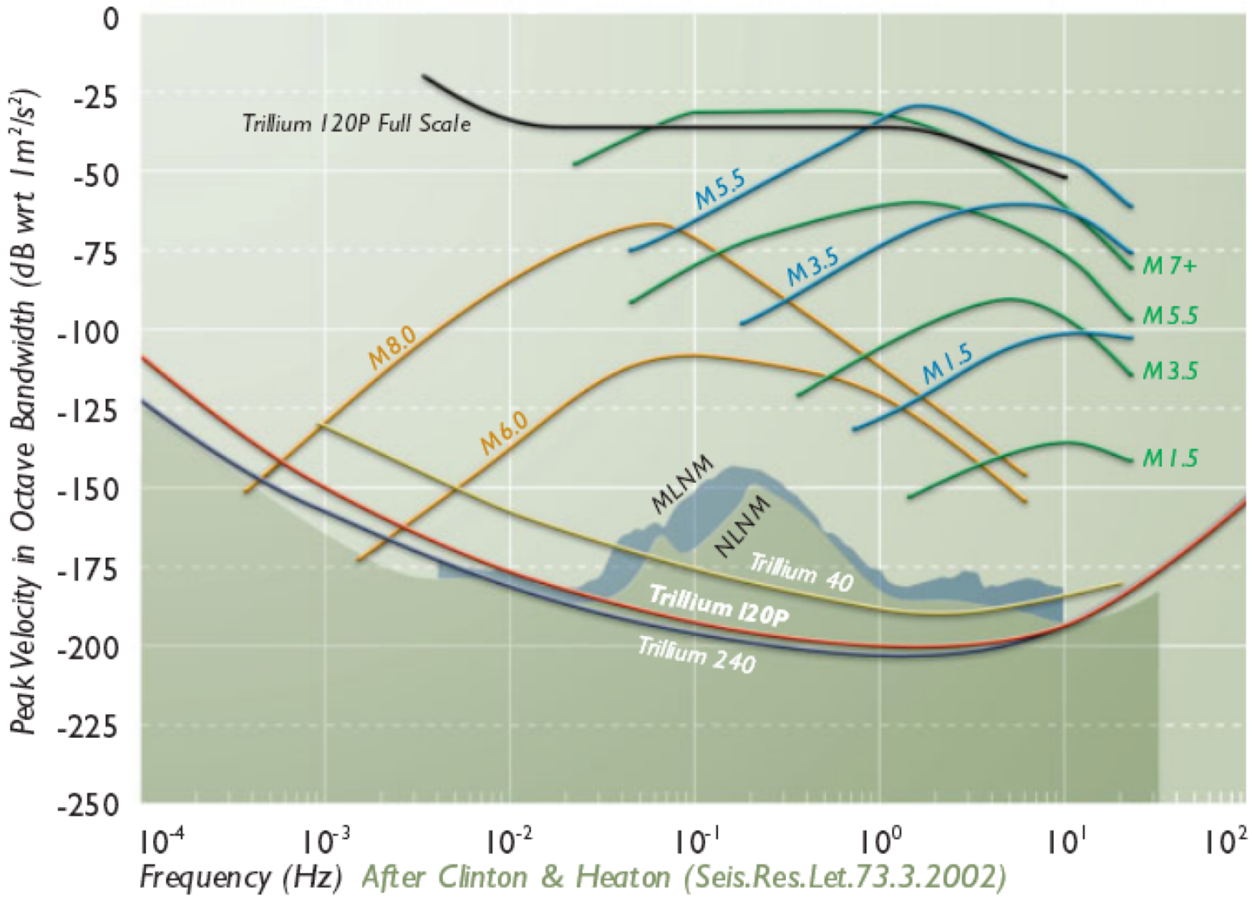




Depending on the balancing effect of elastic parameters and of damping, the system will produce amplification or deamplification in particular frequency ranges.

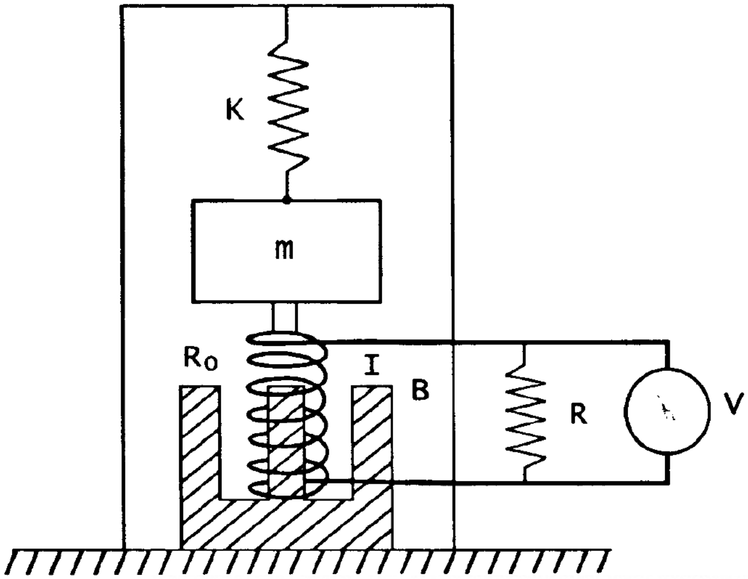
Physical Limits

The instrumental response of purely mechanical systems is limited. How to extend to those low frequencies of seismological interest?



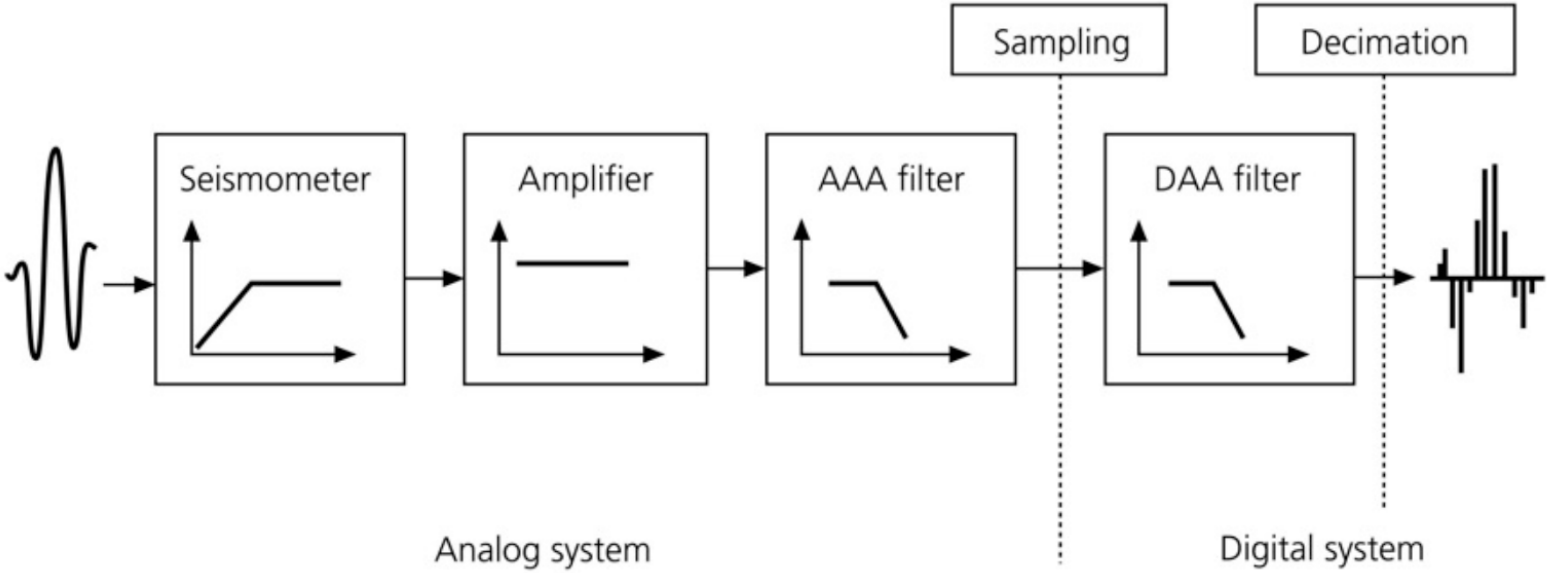
Sismometro Quervain Picard
(1000kg)

Electromagnetic Transducers



In modern instruments, the mechanical reaction to ground displacement is converted into an electric signal.

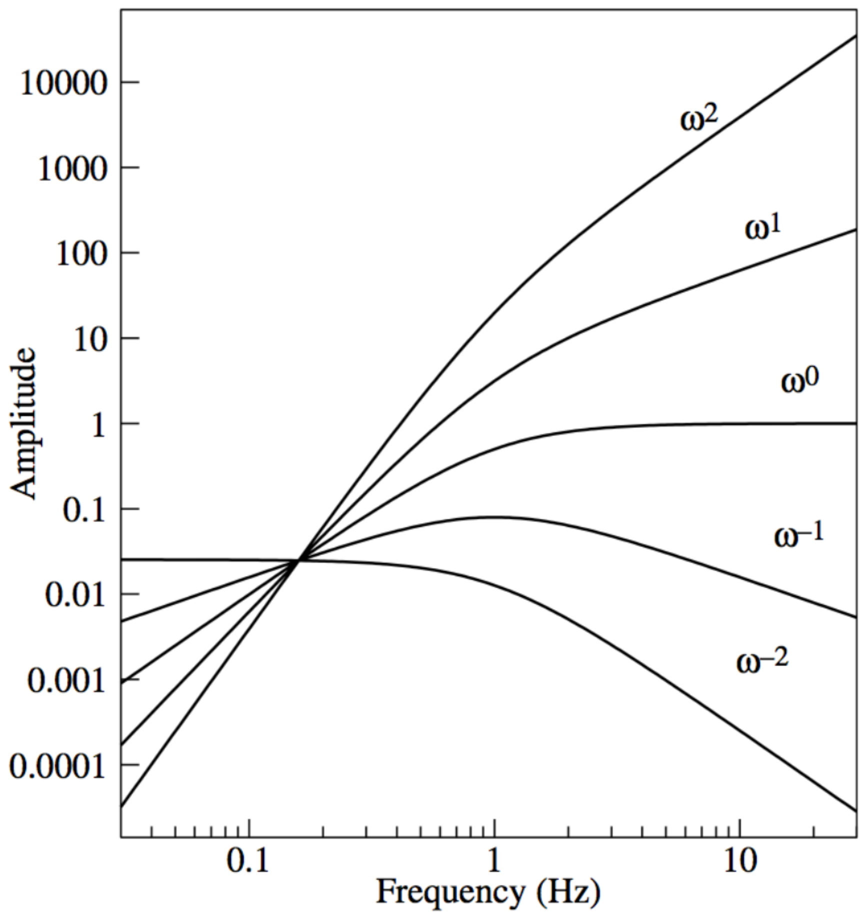
Such signal could be electronically conditioned (filtered or amplified) and stored in digital format.

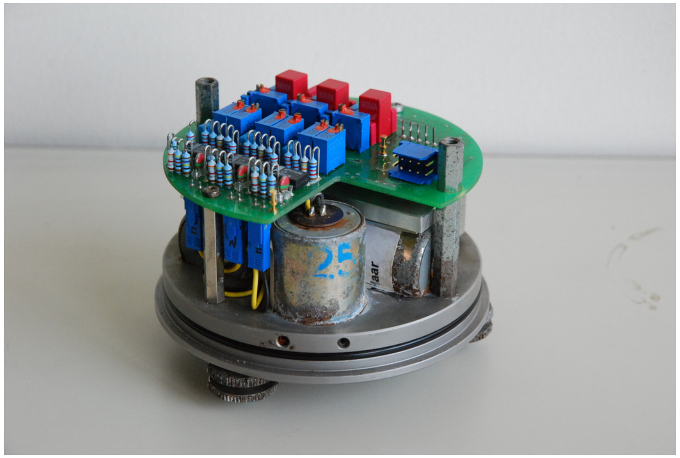


Signal Conditioning

It is possible to modify the output electric signal from a seismometer to improve its low frequency response, extending therefore its usability range.

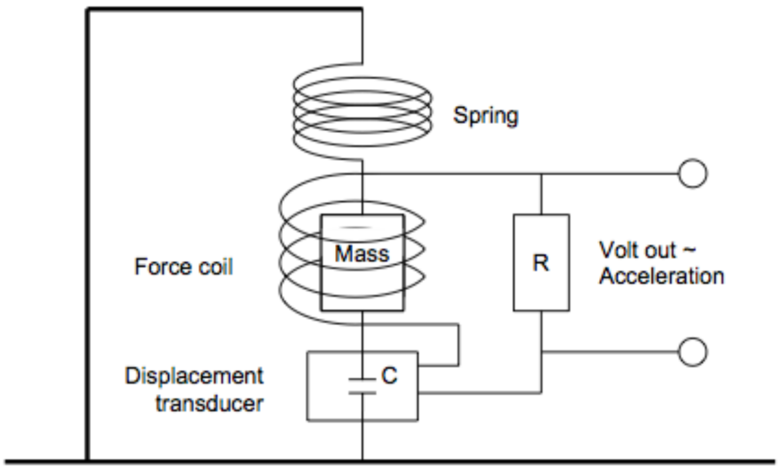
This operation is done before the digital sampling, using ad-hoc analog filter and amplifiers.





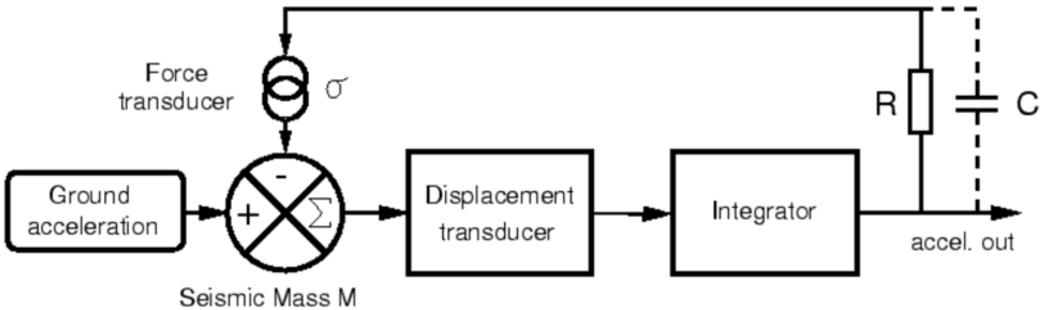
Lennartz 3D 1s

Feedback Seismometers

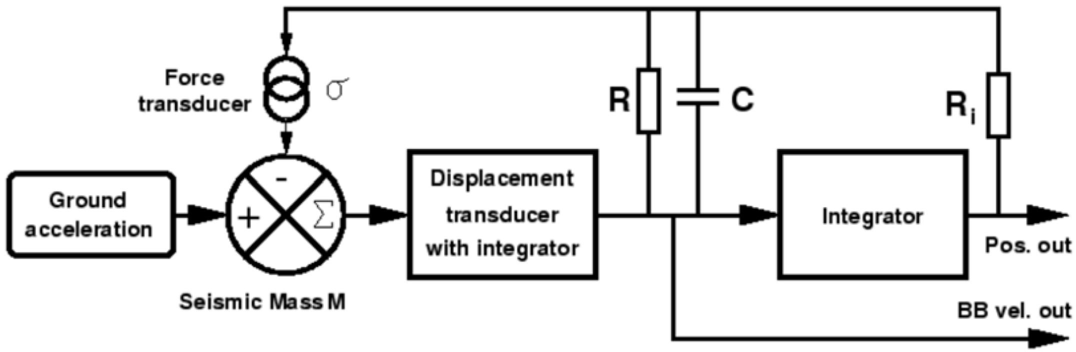


Kinematrics
Episensor

Force-Balance Accelerometer



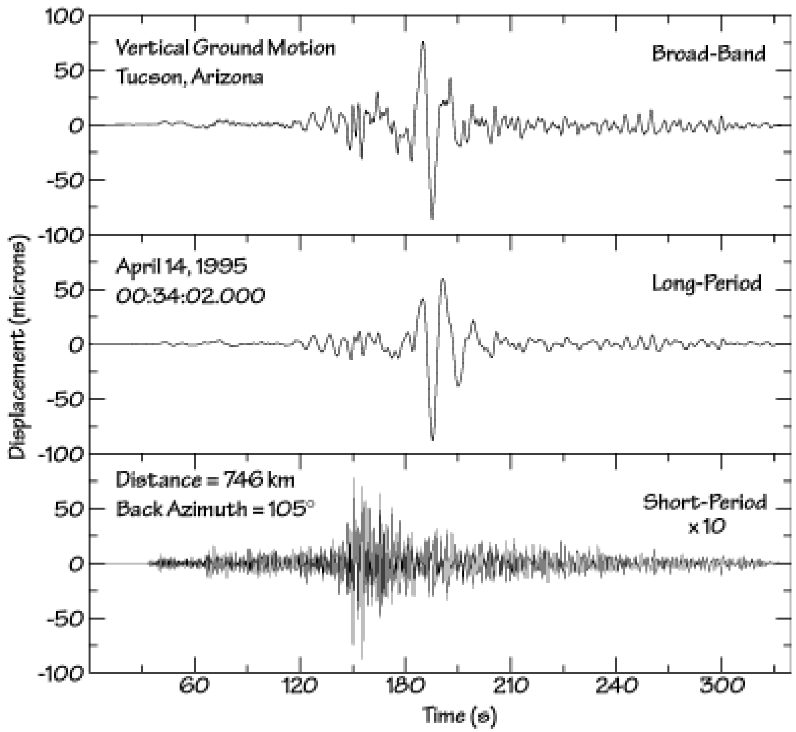
Broad-Band Velocimeter

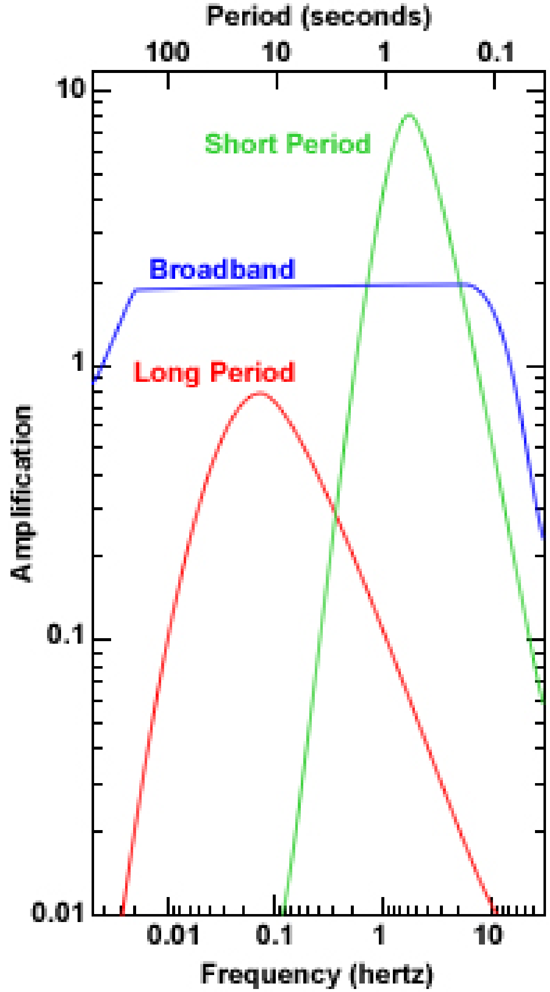


Streckeisen
STS-2

Long-Period Seismometers

Frequency (Hz)	Type of measurements
0.00001-0.0001	Earth tides
0.0001-0.001	Earth free oscillations, earthquakes
0.001-0.01	Surface waves, earthquakes
0.01-0.1	Surface waves, P and S waves, earthquakes with M > 6
0.1-10	P and S waves, earthquakes with M> 2
10-1000	P and S waves, earthquakes, M< 2

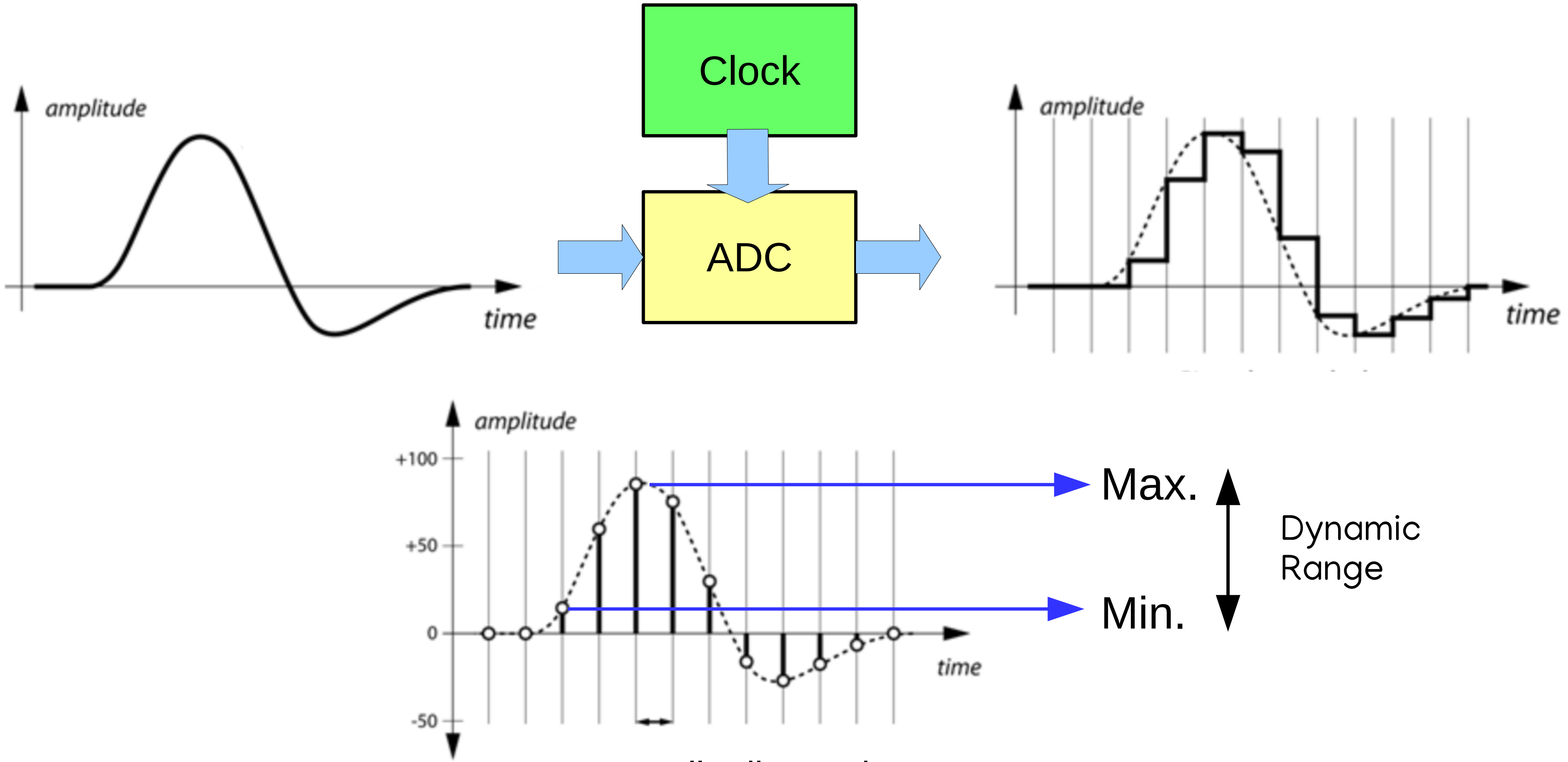




©The COMET Program

Digitization and Dynamic Range

The analog signal is sampled (digitized) by a analog-to-digital converted (ADC) and translated into a numerical sequence that could be stored on digital supports or further elaborated.

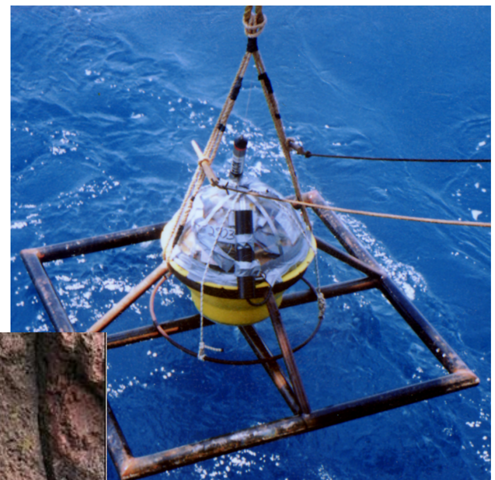


Intervallo di campionamento

Exotic Seismometers

There are highly specialized seismometers which are designed to detect signals in very special conditions.

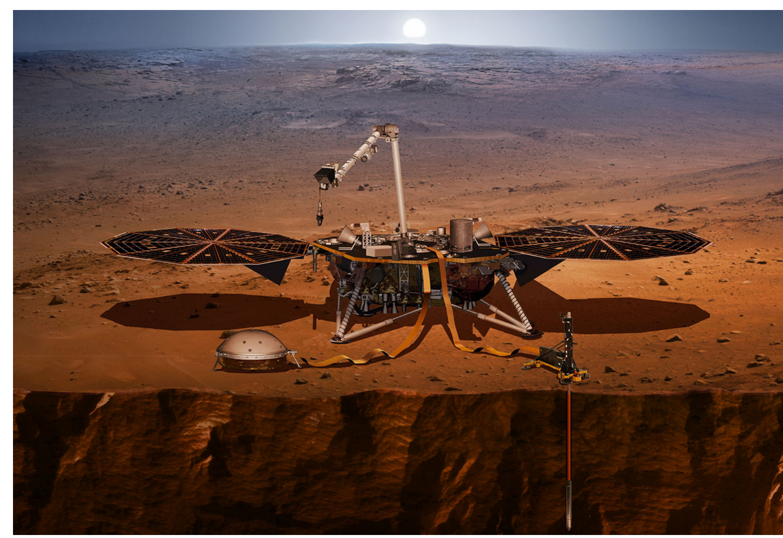
Ocean Bottom Seismometer (OBS)



Hydrophones

Borehole Seismometer (OBS)

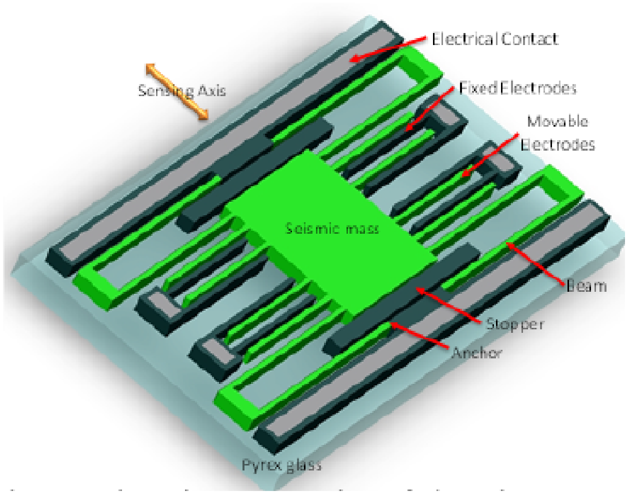
Exoplanetary seismometer (InSight mission)



Future Developments

Current trend is the development of seismometers of progressively reduced size and energy consumption, while keeping their dynamic response substantially unaffected.

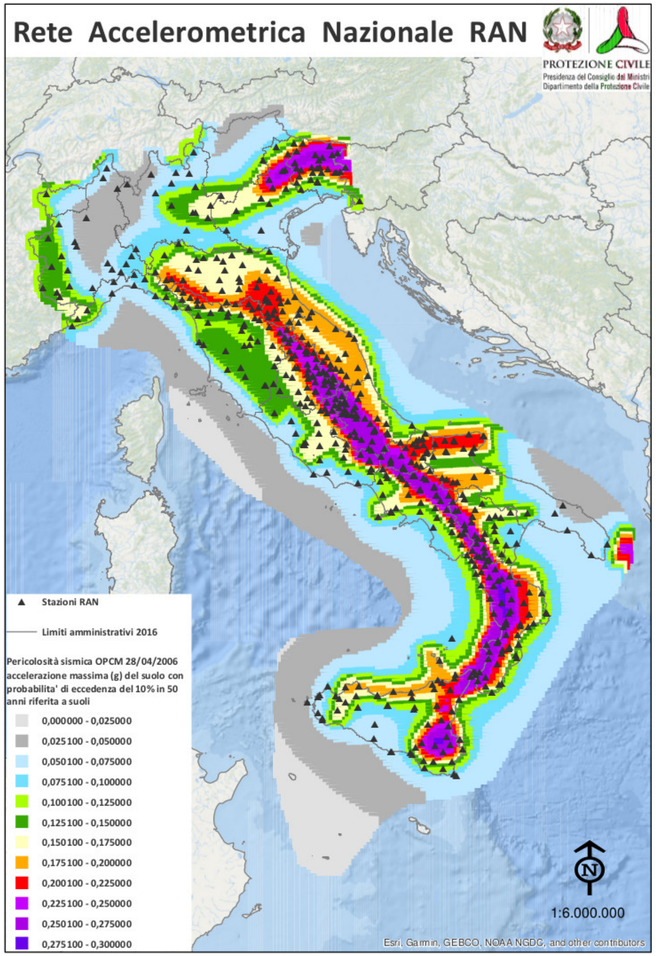
Although not yet performing as "standard seismometers", MEMS (Micro Electro Mechanical Systems) sensors have large potentials. Their performance improved year by year.



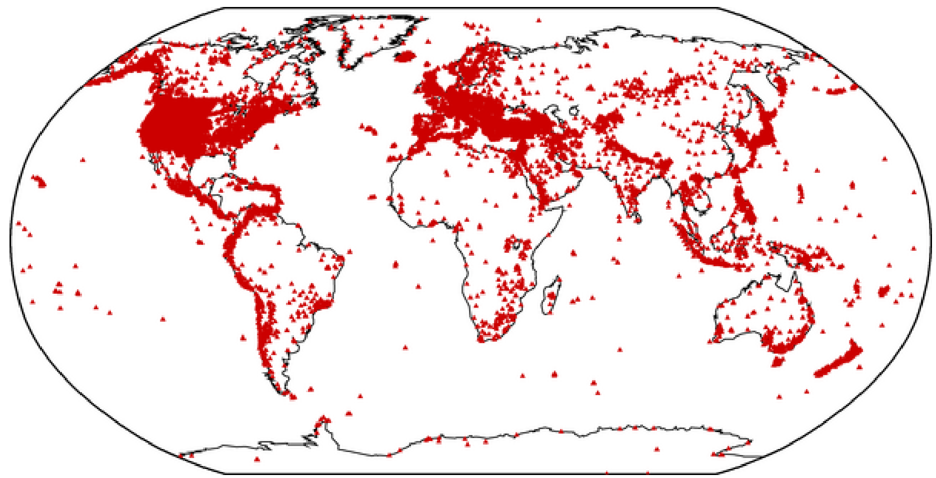
Colibry three-component
MEMS geophone

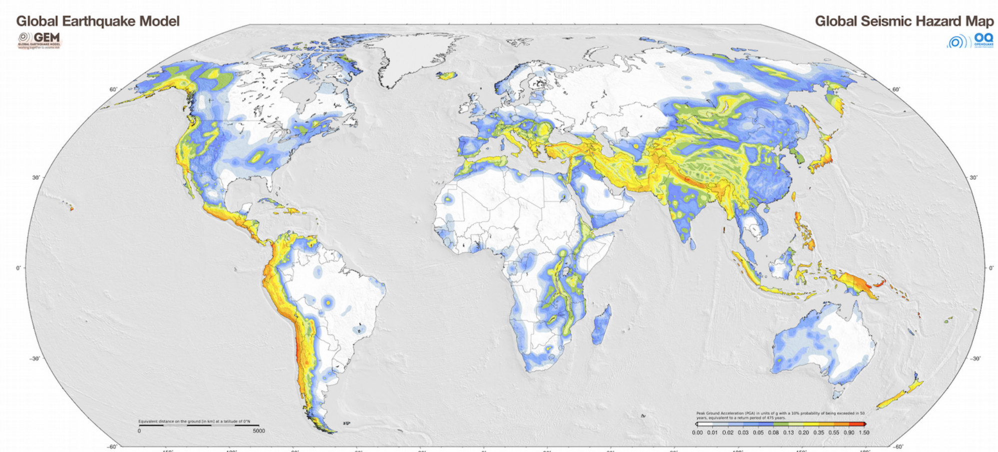
National and Global Networks

Seismic networks are usually denser in high risk regions...

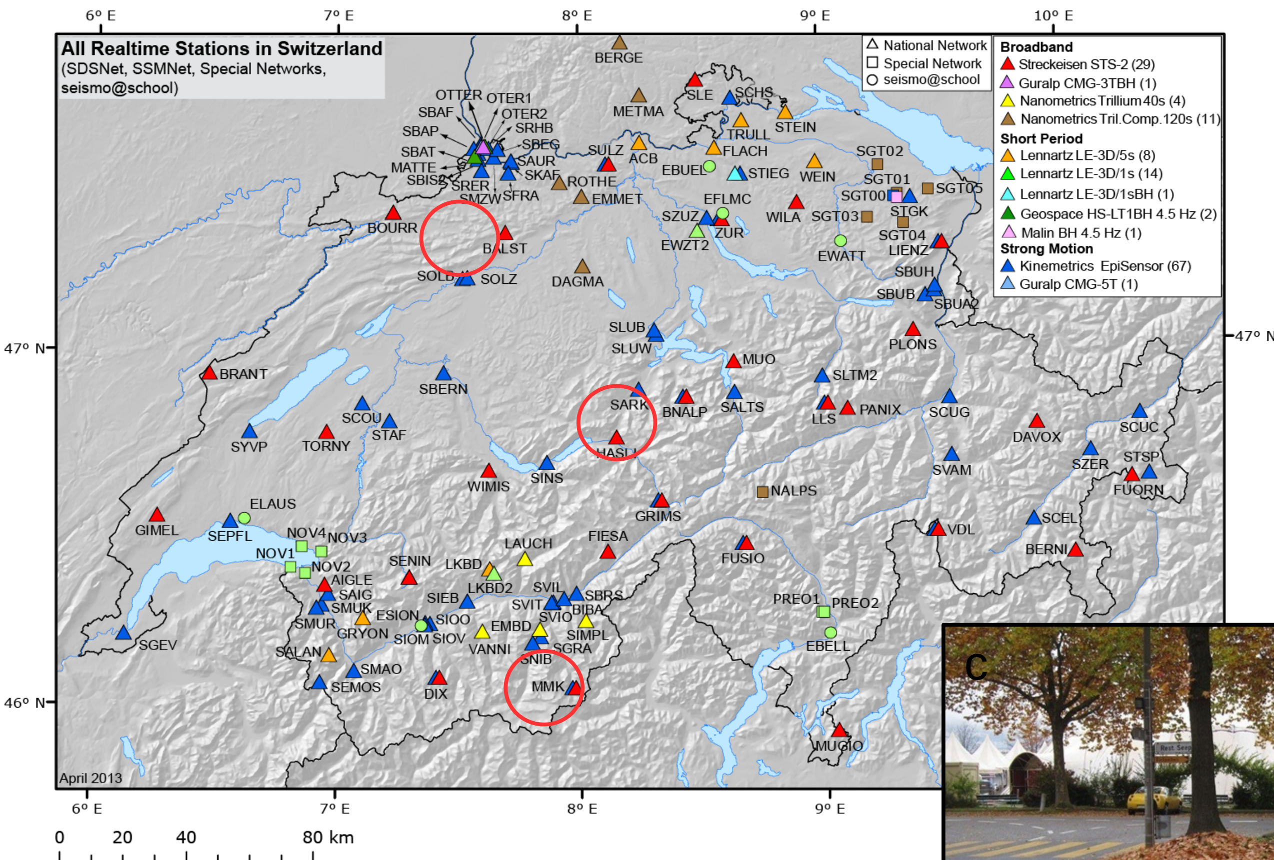


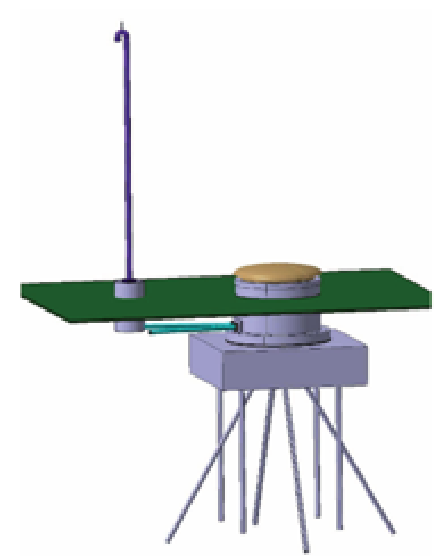
International Registry of Seismograph Stations (IR)





Network Setup





- Strategic significance
- Accessibility
- Optimal site conditions
- Infrastructure logistic

Early Warning Networks