# SEISMOMETER & SEISMOGRAM

## Definitions

A **seismometer** is an instrument that measures and records motions of the ground, including those of seismic waves generated by earthquakes, nuclear explosions, and other seismic sources.

A **seismogram** is a graph output by a seismograph. It is a record of the ground motion at a measuring station. The energy measured in a seismogram may result from an earthquake or from some other source, such as an explosion.

**Seismograph** is another term used for seismometer, though it is more applicable to the older instruments in which the measuring and recording of ground motion were combined than to modern systems, in which these functions are separated.

## Seismometer

**Seismometers** (in Greek *seismos* = earthquake and *metero* = measure) are instruments that measure and record motions of the ground, including those of seismic waves generated by earthquakes, nuclear explosions, and other seismic sources. Records of seismic waves allow seismologists to map the interior of the Earth, and locate and measure the size of these different sources.

**Seismograph** is another term used for seismometer, though it is more applicable to the older instruments in which the measuring and recording of ground motion were combined than to modern systems, in which these functions are separated. Both types provide a continuous record of ground motion; this distinguishes them from **seismoscopes**, which merely indicate that motion has occurred, perhaps with some simple measure of how large it was.

## Basic principles

Inertial seismometers have:

- A mass, usually called the **inertial mass**, that can move relative to the instrument frame, but is attached to it by a system (such as a spring) that will hold it fixed relative to the frame if there is no motion, and also damp out any motions once the motion of the frame stops.
- A means of recording the motion of the mass relative to the frame, or the force needed to keep it from moving.

Any motion of the ground moves the frame. The mass tends not to move because of its inertia, and by measuring the motion between the frame and the mass the motion of the ground can be determined, even though the mass does move.

Early seismometers used optical levers or mechanical linkages to amplify the small motions involved, recording on soot-covered paper or photographic paper.

Modern instruments use electronics. In some systems, the mass is held nearly motionless relative to the frame by an electronic negative feedback loop. The motion of the mass relative to the frame is measured, and the feedback loop applies a magnetic or electrostatic force to keep the mass nearly motionless. The voltage needed to produce this force is the output of the seismometer, which is recorded digitally. In other systems the mass is allowed to move, and its motion produces a voltage in a coil attached to the mass and moving through the magnetic field of a magnet attached to the frame. This design is often used in the geophones used in seismic surveys for oil and gas.

Professional seismic observatories usually have instruments measuring three axes: north-south, east-west, and up-down. If only one axis can be measured, this is usually the vertical because it is less noisy and gives better records of some seismic waves.

The foundation of a seismic station is critical. A professional station is sometimes mounted on bedrock. The best mountings may be in deep boreholes, which avoid thermal effects, ground noise and tilting from weather and tides. Amateur, or less exotic instruments are often mounted in insulated enclosures on small buried piers of unreinforced concrete. Reinforcing rods and aggregates would distort the pier as the temperature changes. A site should always be surveyed for ground noise with a temporary installation before pouring the pier and laying conduit.

## Zhang Heng's Seismometer

In 132, Zhang Heng of China's Han dynasty invented the first seismometer, called Houfeng Didong Yi (lit. instrument for measuring the seasonal winds and the movements of the Earth). By use of a mechanical chain reaction caused by the earth's heavy vibration during an earthquake, a pendulum mechanism within the copper-framed, urn-shaped seismometer would sway and activate a series of levers. This in turn would ultimately drop a spherical brass ball from an artificial dragon-mouth of the urn's top into an artificial toad-mouth below, signifying the cardinal direction of the earthquake. Use of this device was recorded in the historical text of the Book of Later Han.

## An early example

The principle can be shown by an early special purpose seismometer. This consisted of a large stationary pendulum, with a stylus on the bottom. As the earth starts to move, the heavy mass of the pendulum has the inertia to stay still in the non-earth frame of reference. The result is that the stylus scratches a pattern corresponding with the earth's movement. This type of strong motion seismometer recorded upon a smoked glass (glass with carbon soot). While not sensitive enough to detect distant earthquakes, this instrument could indicate the direction of the initial pressure waves and thus help find the epicenter of a local earthquake — such instruments were useful in the analysis of the 1906 San Francisco earthquake. Further re-analysis was performed in the 1980s using these early recordings, enabling a more precise determination of the initial fault break location in Marin county and its subsequent progression, mostly to the south.

### Early designs

After 1880, most seismometers were descended from those developed by the team of John Milne, James Alfred Ewing and Thomas Gray, who worked together in Japan from 1880-1895. These seismometers used damped horizontal pendulums. Later, after World War II, these were adapted into the widely used Press-Ewing seismometer.

Later, professional suites of instruments for the world-wide standard seismographic network had one set of instruments tuned to oscillate at fifteen seconds, and the other at ninety seconds, each set measuring in three directions. Amateurs or observatories with limited means tuned their smaller, less sensitive instruments to ten seconds.

The basic damped horizontal pendulum seismometer swings like the gate of a fence. A heavy weight is mounted on the point of a long (from 10 cm to several meters) triangle, hinged at its vertical edge. As the ground moves, the weight stays unmoving, swinging the "gate" on the hinge.

The advantage of a horizontal pendulum is that it achieves very low frequencies of oscillation in a compact instrument. The "gate" is slightly tilted, so the weight tends to slowly return to a central position. The pendulum is adjusted (before the damping is installed) to oscillate once per three seconds, or once per thirty seconds. The general-purpose instruments of small stations or amateurs usually oscillate once per ten seconds. A pan of oil is placed under the arm, and a small sheet of metal mounted on the underside of the arm drags in the oil to damp oscillations. The level of oil, position on the arm, and angle and size of sheet is adjusted until the damping is "critical," that is, almost having oscillation. The hinge is very low friction, often torsion wires, so the only friction is the internal friction of the wire. Small seismographs with low proof masses are placed in a vacuum to reduce disturbances from air currents.

Zollner described torsionally-suspended horizontal pendulums as early as 1869, but developed them for gravimetry rather than seismometry.

Early seismometers had an arrangement of levers on jeweled bearings, to scratch smoked glass or paper. Later, mirrors reflected a light beam to a direct-recording plate or roll of photographic paper. Briefly, some designs returned to mechanical movements to save money. In mid-twentieth-century systems, the light was reflected to a pair of differential electronic photosensors called a photomultiplier. The voltage generated in the photomultiplier was used to drive galvanometers which had a small mirror mounted on the axis. The moving reflected light beam would strike the surface of the turning drum, which was covered with photo-sensitive paper. The expense of developing photo sensitive paper caused many seismic observatories to switch to ink or thermal-sensitive paper.

## Modern instruments

Modern instruments use electronic sensors, amplifiers, and recording instruments. Most are broadband, covering a wide range of frequencies: some seismometers can measure motions with frequencies from 30 Hz (0.03 seconds per cycle) to 1/850 Hz (850 seconds per cycle). The mechanical suspension for horizontal instruments remains the garden-gate described above. Vertical instruments use some kind of constant-force suspension, such as the LaCoste suspension that uses a zero-length spring to provide a long period (high sensitivity).

Seismometers unavoidably introduce some distortion into the signals they measure, but professionally-designed systems have carefully-characterized frequency transforms.

Modern sensitivities come in three broad ranges: geophones, 50 to 750 V/m; local geologic seismographs, about 1,500 V/m; and teleseismographs, used for world survey, about 20,000 V/m. Instruments come in three main varieties: short period, long period and broad-band. The short and long period measure velocity and are very sensitive, however they 'clip' or go off-scale for ground motion that is strong enough to be felt by people. A 24-bit analog-to-digital conversion channel is commonplace. Practical devices are linear to roughly a part per million.

Delivered seismogmeters come with two styles of output: analog and digital. Analog seismographs require analog recording equipment, possibly including an analog-to-digital converter. Digital seismographs simply plug in to computers. They present the data in standard digital forms (often "SE2" over ethernet).

## Teleseismometers

The modern broad-band seismograph can record a very broad range of frequencies. It consists of a small 'proof mass', confined by electrical forces, driven by sophisticated electronics. As the earth moves, the electronics attempt to hold the mass steady through a feedback circuit. The amount of force necessary to achieve this is then recorded.

In most designs the electronics holds a mass motionless relative to the frame. This device is called a "Force Balance Accelerometer". It measures acceleration instead of velocity of ground movement. Basically, the distance between the mass and some part of the frame is measured very precisely, by a linear variable differential transformer. Some instruments use a linear variable differential capacitor).

That measurement is then amplified by electronic amplifiers attached to parts of an electronic negative feedback loop. One of the amplified currents from the negative feedback loop drives a coil very like a loudspeaker, except that the coil is attached to the mass, and the magnet is mounted on the frame.

The result is that the mass stays nearly motionless.

Most instruments directly measure the ground motion using the distance sensor.

The voltage generated in a sense coil on the mass by the magnet directly measures the instantaneous velocity of the ground.

The current to the drive coil provides a sensitive, accurate measurement of the force between the mass and frame, thus directly measuring the ground's acceleration (using F=MA of basic physics).

One of the continuing problems with sensitive vertical seismographs is the buoyancy of their masses. The uneven changes in pressure caused by wind blowing on an open window can easily change the density of air in a room enough to cause a vertical seismograph to show spurious signals. Therefore, most professional seismographs are sealed in rigid gas-tight enclosures. For example, this is why a common

Streckheisen model has a thick glass base that must be glued to its pier without bubbles in the glue.

It might seem logical to make the heavy magnet serve as a mass, but that subjects the seismograph to errors when the Earth's magnetic field moves. This is also why seismograph's moving parts are constructed from a material that minimally interacts with magnetic fields.

A seismograph is also sensitive to changes in temperature, and many instruments are constructed from low expansion materials such as nonmagnetic invar.

The hinges on a seismograph are usually patented, and by the time the patent has expired, the art has improved. The most successful public domain designs use thin foil hinges in a clamp.

Another issue is that the transfer function of a seismograph must be accurately characterized, so that its frequency response is known. This is often the crucial difference between professional and amateur instruments. Most instruments are characterized on a variable frequency shaking table.

## Strong-motion seismometers

Another type of seismometer is a digital strong-motion seismometer, or accelerograph. This data is essential to understand how an earthquake affects human structures.

A strong-motion seismometer measures acceleration. This can be mathematically integrated later to give velocity and position. Strong-motion seismometers are not as sensitive to ground motions as teleseismic instruments but they stay on scale during the strongest seismic shaking.

## Other forms

Accelerographs and geophones are often heavy cylindrical magnets with a spring-mounted coil inside. As case moves, the coil tends to stay stationary, so the magnetic field cuts the wires, inducing current in the output wires. They receive frequencies from several hundred hertz down to 4.5 Hz (cheap) to as low as 1 Hz (pretty expensive). Some have electronic damping, a low-budget way to get some of the performance of the closed-loop wide-band geologic seismographs.

Strain-beam accelerometers constructed as integrated circuits are too insensitive for geologic seismographs (2002), but are widely used in geophones.

Some other sensitive designs measure the current generated by the flow of a non-corrosive ionic fluid through an electret sponge or a conductive fluid through a magnetic field.

## Modern recording

Today, the most common recorder is a computer with an analog-to-digital converter, a disk drive and an internet connection. Many observatories now use computers. For amateurs, a PC with a sound card and software is adequate, and saves a lot of paper.

An algorithm often used to eliminate insignificant observations uses a short-term average and a long term average. When the short term average is statistically significant compared to the long term average, the event is worth recording.

### Interconnected seismometers

Seismometers spaced in an array can also be used to precisely locate, in three dimensions, the source of an earthquake, using the time it takes for seismic waves to propagate away from the hypocenter, the initiating point of fault rupture. Interconnected seismometers are also used to detect underground nuclear test explosions.

In reflection seismology, an array of seismometers images sub-surface features. The data are reduced to images using algorithms similar to tomography. The data reduction methods resemble those of computer-aided tomographic medical imaging X-ray machines (CAT-scans), or imaging sonars.

A world-wide array of seismometers can actually image the interior of the Earth in wave-speed and transmissivity. This type of system uses events such as earthquakes, impact events or nuclear explosions as wave sources. The first efforts at this method used manual data reduction from paper seismograph charts. Modern digital seismograph records are better adapted to direct computer use. With inexpensive seismometer designs and internet access, amateurs and small institutions have even formed a "public seimograph network."

Seismographic systems used for petroleum or other mineral exploration historically used an explosive and a wireline of geophones unrolled behind a truck. Now most short-range systems use "thumpers" that hit the ground, and some small commercial systems have such good digital signal processing that a few sledgehammer strikes provide enough signal for short-distance refractive surveys. Exotic cross or two-dimensional arrays of geophones are sometimes used to perform three-dimensional reflective imaging of subsurface features. Basic linear refractive geomapping software (once a black art) is available off-the-shelf, running on laptop computers, using strings as small as three geophones. Some systems now come in an 18" (0.5 m) plastic field case with a computer, display and printer in the cover!

Small seismic imaging systems are now sufficiently inexpensive to be used by civil engineers to survey foundation sites, locate bedrock, and find subsurface water.

# Seismogram

A '**seismogram'** is a graph output by a seismograph. It is a record of the ground motion at a measuring station. The energy measured in a seismogram may result from an earthquake or from some other source, such as an explosion.

Because P-waves travel through the earth faster than other types of waves, the P-wave is the first arrival of energy from an earthquake or other seismic source to be recorded. The next direct arrivals are the S-waves, and, finally, surface waves. Many reflected and refracted arrivals are typically recorded as well.

Historically, seismograms were recorded on paper attached to rotating drums. Some used pens on ordinary paper, while others used light beams to expose photosensitive paper. Today, practically all seismograms are recorded digitally to make analysis by computer easier. Some drum seismometers are still found, though, especially when used for public display.

Source : http://www.juliantrubin.com/encyclopedia/electronics/seismometer.html