Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_172-1

Principles of Broadband Seismometry

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Synonyms

Weak-motion sensor; Very broadband seismometer

Introduction

There are many different types of instruments which can be used to detect ground motion. Broadband seismometers belong to a class of sensors called inertial sensors. In contrast, methods of sensing ground motion such as strainmeters and Global Positioning Systems (GPS) are not considered inertial sensors.

In this entry the principles of operation of broadband seismometers are discussed and contrasted with those of passive seismometers. The criteria for selecting a seismometer are discussed. Particular attention is paid to noise-generating mechanisms, including self-noise generated within the sensor, environmental sensitivities, and installation-related noise.

Applications

Broadband seismometers are very versatile instruments which have many applications in the field of earthquake engineering, including:

- Event detection and location (see ► Seismic Event Detection and ► Earthquake Location)
- Earthquake magnitude and moment-tensor estimation (see ► Earthquake Magnitude Estimation, ► Earthquake Mechanism Description and Inversion and ► Long-Period Moment-Tensor Inversion)
- Volcanic eruption early warning (see ► Long-Period and Very Long-Period Seismicity on Active Volcanoes: Significance and ► Real-Time Forecasting of Volcanic Eruptions and ► Noise-Based Seismic Imaging and Monitoring of Volcanoes)
- Subsurface imaging (see, e.g., ► Passive Seismic Interferometry for Subsurface Imaging)
- Site response (see, e.g., ► Site Response: Comparison Between Theory and Observation and ► Probabilistic Seismic Hazard Assessment: An Overview)
- Restitution of ground displacement (see ► Selection of Ground Motions for Time-History Analyses and ► Seismic Actions due to Near-Fault Ground Motion)

Classes of Inertial Sensors

In the broadest sense, a seismometer is any instrument which responds to ground motion, and a seismograph is any instrument which subsequently makes a recording of that ground motion. In practical usage however, a seismometer refers to a specific subclass of inertial sensors. One way to

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DOI 10.1007/978-3-642-36197-5_172-1

understand where the broadband seismometer is situated relative to the other classes of instruments, which measure ground motion, is to take a tour of the family tree of inertial sensors.

Inertial sensors consist of a frame and a "proof mass" suspended within the frame. Movement of the frame is sensed by sensing differential motion between the frame and the proof mass. The suspension usually constrains the proof mass to have one or more degrees of freedom, which can be either rotational or translational. If these degrees of freedom are purely rotational, the instrument is called a rotational seismometer or a gyroscope (see Lee et al. 2012).

Translational inertial sensors have many subclasses. One way of understanding their classification is to look primarily at the types of motion each is designed to measure: static or dynamic, strong or weak, horizontal or vertical, and long period or short period (these terms are explained in the paragraphs which follow).

Inertial sensors which are configured to detect static accelerations include gravimeters and tiltmeters, which are arranged to detect vertical and horizontal accelerations, respectively. Neither instrument is required to measure the full acceleration due to gravity. A tiltmeter can be leveled to produce zero output when it is installed; the mainspring of a gravimeter is similarly adjusted to cancel a standard acceleration due to gravity. Thus the sensitivity of a gravimeter or a tiltmeter can be quite high because the range of accelerations to be measured is quite small. Finally, since traveling seismic waves are generally not of interest for gravimeters and tiltmeters, these instruments typically have a low-pass characteristic with an upper corner frequency which is relatively low, typically 1 Hz or lower.

An ► accelerometer is another type of inertial sensor which is configured to detect accelerations down to zero frequency. Unlike a gravimeter or a tiltmeter, they are typically configured to read peak accelerations on the order of 1 g or larger without clipping and thus must have relatively low sensitivities. They can be used to detect static accelerations, for the purpose of integrating them to obtain position as in an inertial guidance system, or they can be used to detect strong seismic motions. Like a gravimeter they have a flat response to acceleration down to zero frequency, but the upper corner of their low-pass response will be at a much higher frequency.

A seismometer differs from gravimeters, tiltmeters, and accelerometers in that it is not required to respond to ground motion all the way down to zero frequency; this enables it to have a higher sensitivity and therefore measure much smaller motions than an accelerometer. They typically have transfer functions which are flat to velocity over at least a decade, but many hybrid responses, flat to acceleration over some significant band, are viable alternatives (Wielandt and Streckeisen 1982). "Strong-motion velocity meters" capable of detecting motions as large as those detectable on an accelerometer are also commercially available, but the term seismometer is generally reserved for an instrument which measures weak motion.

Traditionally the basic subgroupings of seismometers were long period or short period, depending on whether the lower corner period is above or below about 7 s period (see section "Ground Motion Spectra" below). Modern broadband seismometers span both frequency bands and have made long-period seismometers obsolete.

Like a short-period seismometer, a geophone is usually a passive seismometer (see ► Historical Seismometers and ► Passive Seismometers), but one with a higher corner frequency and lower sensitivity.

The transfer functions of representative examples from the main classes of inertial sensors are plotted in Fig. 1 for ground motion in units of acceleration and in Fig. 2 for units of velocity. Seismometers have the highest sensitivity of all inertial seismometers, and broadband seismometers have the highest sensitivity of all of these classes at long periods, but not at zero frequency.

DOI 10.1007/978-3-642-36197-5_172-1

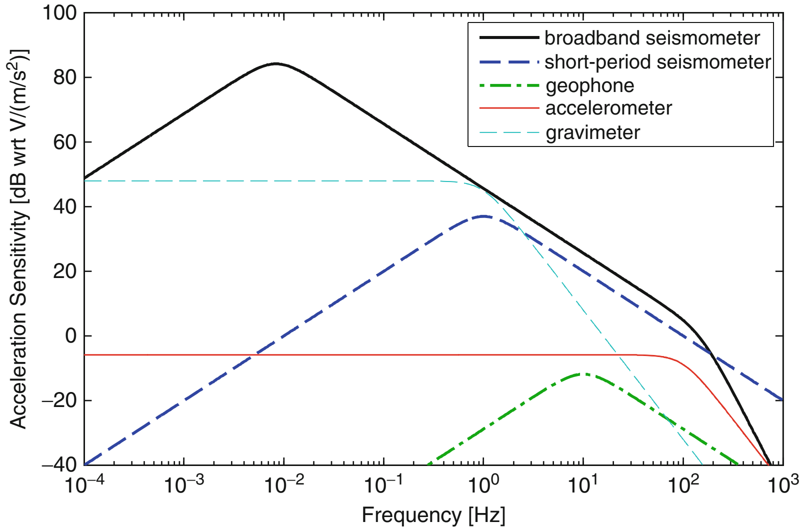

Fig. 1 Response to acceleration of inertial sensors

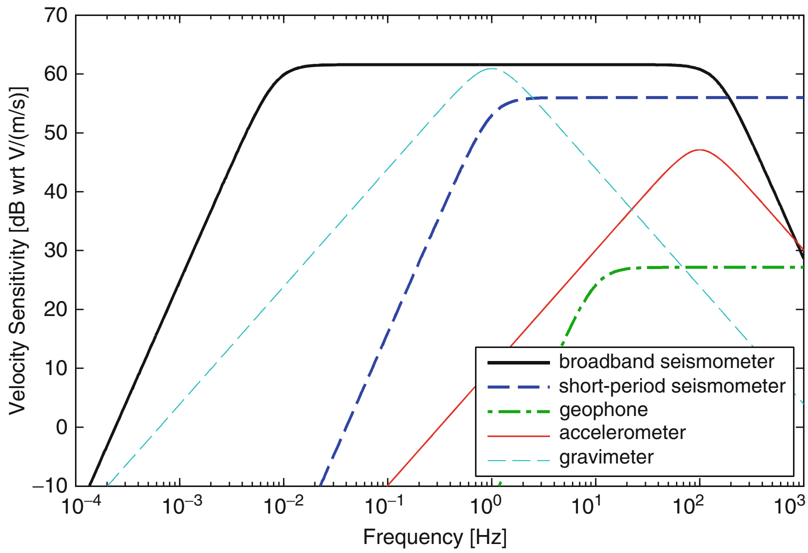

Fig. 2 Response to velocity of inertial sensors

The following sensors were taken as typical of the classes shown in Figs. 1 and 2:

- **Accelerometer**: a class A accelerometer (Working Group on Instrumentation, Siting, Installation, and Site Metadata 2008), e.g., Nanometrics Titan
- **Gravimeter:** based on the CG-5 (Scintrex Limited 2007)
- **Broadband seismometer:** based on the Trillium 120 (Nanometrics, Inc 2009)
- **Short-period seismometer:** based on the S-13 (Geotech Instruments, LLC 2001)
- **Geophone:** based on the SG-10 (Sercel - France 2012)

For more discussion of the importance of the sensitivity of a seismometer to its performance, see section "Response."

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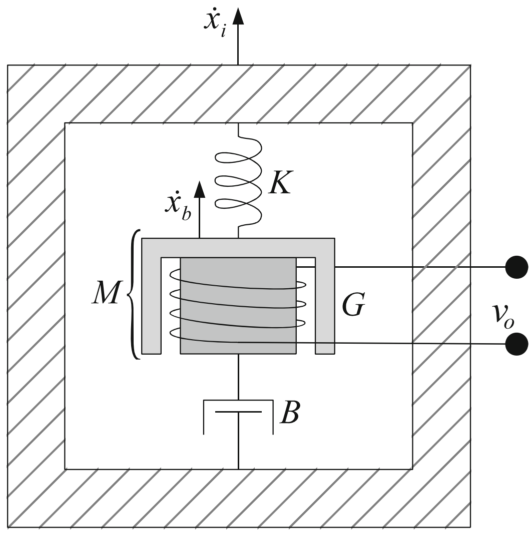

Fig. 3 Mechanical schematic of a passive inertial sensor

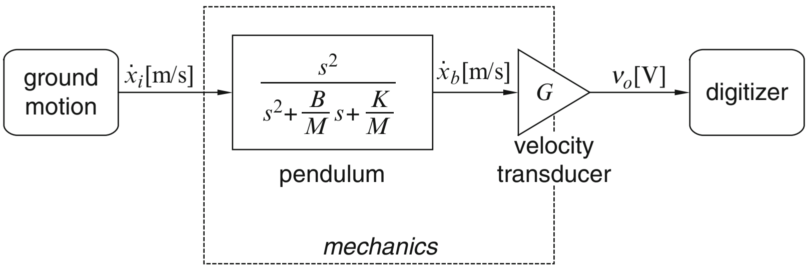

Fig. 4 System block diagram of a passive inertial sensor

Force Feedback

The principles of operation, benefits, and drawbacks of an active inertial sensor are best understood in relation to the operation of a passive inertial sensor, since the latter is effectively a component in the former.

Modern short-period seismometers and geophones are passive inertial sensors which consist of a pendulum with a velocity transducer with sensitivity $\boldsymbol{G}$ in V·s/m mounted so as to measure the relative velocity $\dot{\boldsymbol{x}}_{\boldsymbol{b}}$ of a proof mass $\boldsymbol{M}$ and frame of the sensor, as shown in Fig. 3. The spring constant of the mainspring and suspension combined $\boldsymbol{K}$ and the viscous damping $\boldsymbol{B}$ determine the transfer function of the pendulum, required to relate the output voltage $\boldsymbol{v_o}$ to the input motion of the frame, $\dot{\boldsymbol{x}}_{\boldsymbol{i}}$.

A block diagram of the whole passive seismometer system, from ground motion to the digitizer, is shown in Fig. 4.

The Laplace transform of the transfer function which converts frame velocity to an output voltage is (Aki and Richards 2002; Wielandt 2002)

$$\frac{V_o}{sX_i} = G\frac{\mathrm{s}^2}{\mathrm{s}^2 + \frac{B}{M}s + \frac{K}{M}}\left[\frac{\mathrm{V}\cdot\mathrm{s}}{\mathrm{m}}\right]$$

Here the output voltage V_o and input displacement X_i are written in uppercase to emphasize that this transfer function operates in the frequency domain. It is a property of the Laplace transform that

DOI 10.1007/978-3-642-36197-5_172-1

multiplication by the (complex) frequency s in the frequency domain is equivalent to differentiation in the time domain, so sX_i is the input *velocity*. Another property of the Laplace transform is that to evaluate the (complex) transfer function at a given frequency f in Hz or angular frequency $\omega = 2\pi f$ in rad/s, one makes the substitution $s = j\omega$.

For high sensitivity in the passband, the generator constant of the velocity transducer must be large. Typically the velocity transducer is constructed like a voice coil in a speaker: many turns of copper passing through a narrow gap in a magnetic circuit energized by a strong magnet with large diameter are required for a large generator constant. This is shown schematically in Fig. 3.

By comparison with the standard form of a second-order transfer function

$$F(s) = S\frac{s^2}{s^2 + 2\zeta\omega_0 s + {\omega_0}^2}, \tag{1}$$

we can write expressions for the sensitivity S, the natural frequency f_o in Hz, the angular natural frequency $\omega_0 = 2\pi f_o$, and the (dimensionless) damping constant ζ_0 of the pendulum:

$$S = G$$

$$f_o = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

$$\zeta_0 = \frac{1}{2\omega_0}\frac{B}{M} = \frac{B}{2\sqrt{KM}}$$

Below the natural frequency, the sensitivity of passive seismometer drops off rapidly, as shown in Figs. 1 and 2. At the resonant frequency, the degree of "peaking" in the transfer function is controlled by the damping constant ζ_0. Low damping corresponds to a strongly peaked response, something which is generally not desirable, because it means the output will be dominated by signal at that frequency, and because the system has a greater tendency to clip at that frequency.

For high sensitivity at low frequencies, the spring stiffness K [N/m] must be low and the mass M [kg] must be large. For maximum bandwidth while maintaining passband flatness, the viscous damping B [N/(m/s)] is generally set – often with the aid of an external damping resistor not modeled here – so that the dimensionless damping constant ζ_0 is approximately $1/\sqrt{2}$.

Passive seismometers have the obvious advantage of requiring no power to operate. Indeed the device is literally a generator, albeit one which produces very little power. However, modern digital seismology requires that some power be expended on digitization and subsequent telemetry or storage, so the seismograph system as a whole always consumes some power.

The chief disadvantages of passive seismometers for recording ground motion at long periods are:

(a) The suspension system and velocity transducer have nonlinearities as a function of the displacement of the proof mass from equilibrium. These nonlinearities can cause excursions in the output signals which cannot be removed by post-processing.
(b) Large masses and compliant suspensions are required to achieve high sensitivity at long periods, making for an instrument, which is physically large, difficult to construct and susceptible to damage when being transported.
(c) Conflicting damping requirements: As we shall see below, the damping must be as low as possible in order to minimize self-noise, but for a flat transfer function the damping must be set to

DOI 10.1007/978-3-642-36197-5_172-1

a level much higher than the minimum. A transfer function which is strongly peaked will have a corresponding "notch" in its clip level, limiting its ability to record during large or nearby events.

A force-feedback or "active" seismometer solves these problems by taking a mechanical system like that of the passive seismometer, as shown in Fig. 3, and adding a displacement transducer *T*, as shown in Fig. 5. In an active seismometer, the voice coil $\boldsymbol{G}$ is used to produce a force on the proof mass by driving it with a feedback current $\boldsymbol{i_f}$ instead of using it to produce a voltage proportional to the velocity of the proof mass.

It is a remarkable fact that every generator is also a motor. The force transducer in the feedback path of an active seismometer has the same physical configuration as the velocity transducer at the output of a passive seismometer. Moreover the electromotive force generated per unit of velocity or "motor constant" of the former in V/(m/s) is identical to the force generated per unit of current or "generator constant" of the latter in N/A:

$$G = \frac{e}{\dot{x}} = \frac{f}{i} \left[\frac{\mathrm{V{\cdot}s}}{\mathrm{m}} = \frac{\mathrm{N}}{\mathrm{A}}\right]$$

The displacement transducer shown in Fig. 5 is generally one of two types. A linear-variable differential transformer (LVDT) is effectively a transformer where the coupling to the secondary winding(s) is a function of the position of a movable magnetic core. A capacitive displacement transducer (CDT) is a capacitor where the capacitance is varied by changing the spacing or overlapping area of the capacitor plates. In order to reduce nonlinearity and increase sensitivity, transducers of both types are normally implemented as part of a bridge circuit, requiring three windings in the case of an LVDT or three capacitor plates in the case of a CDT. In both cases the displacement transducers operate at a carrier frequency well above the passband of the instrument, and the outputs require demodulation back down to the passband before they are passed on to the compensator, output, and feedback stages.

The feedback loop is closed using feedback electronics which take the displacement transducer output voltage and produce an appropriate feedback current as shown in the block diagram of Fig. 6.

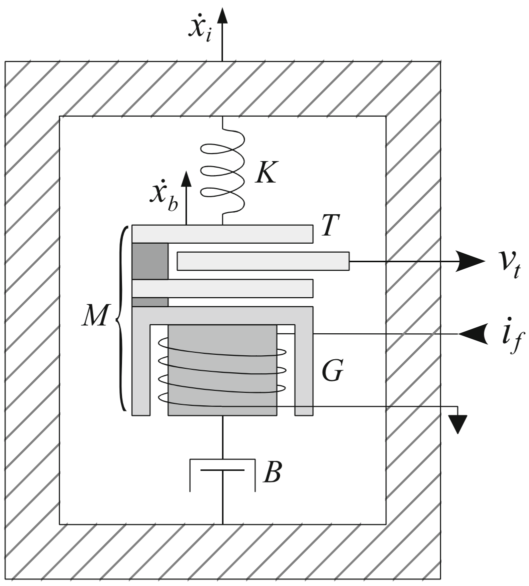

Fig. 5 Mechanical schematic of an active inertial sensor

DOI 10.1007/978-3-642-36197-5_172-1

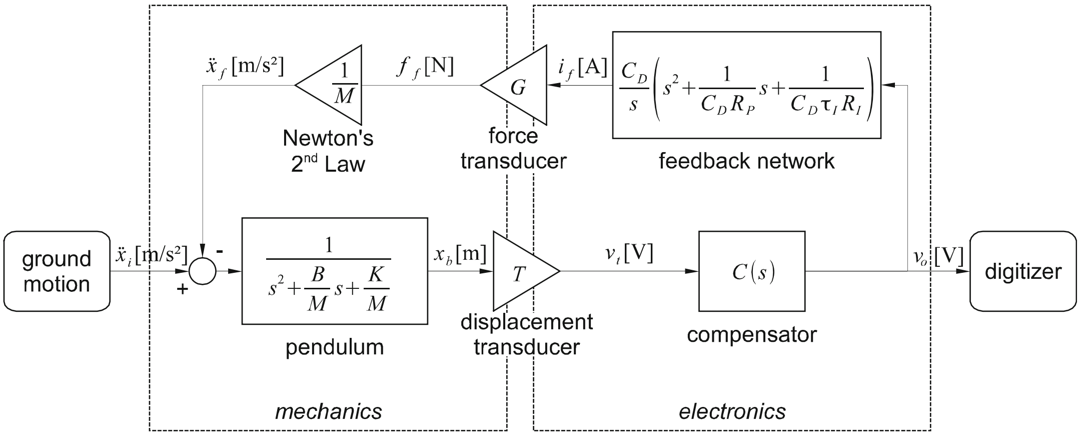

Fig. 6 Block diagram of an active inertial sensor using force feedback

Two main blocks of interest in the feedback electronics are a compensator $C(s)$ in the forward path and the feedback network itself.

Discussions of the components, design, or limitations of the compensator are beyond the scope of this entry, but suffice it to say that the challenge is to simultaneously ensure high loop gain and stability and that the compensator design determines the shape of the roll-off of the closed-loop transfer function at high frequency.

A few of the key components in the feedback network are explicitly indicated in Fig. 6, namely, the "differential" feedback capacitor C_D, a "proportional" feedback resistor R_P, and an "integral" feedback resistor R_I. The integrator time constant τ_I is another key parameter of the feedback circuit.

Feedback control systems have the property that as long as the loop gain is sufficiently high (and the system is stable), the transfer function of the system is the inverse of the feedback transfer function (Phillips and Harbor 1991). In the case of an inertial sensor, this means that the transfer function is determined by electronic components in the feedback network not the physical characteristics of the pendulum. Furthermore this same feedback holds the proof mass substantially at rest with respect to the frame of the sensor, greatly reducing the impact of nonlinearities in the suspension and transducers.

Thus, for high loop gain, a good approximation of the transfer function of the active seismometer of Fig. 6 is

$$\frac{V_o}{sX_i} = \frac{M}{GC_D}\frac{\mathrm{s}^2}{\mathrm{s}^2 + \frac{1}{C_D R_P}s + \frac{1}{C_D \tau_I R_I}}\left[\frac{\mathrm{V\cdot s}}{\mathrm{m}}\right]$$

By comparison with the standard form of a second-order transfer function (1), we can write expressions for the sensitivity, corner frequency, and damping of this force-feedback seismometer:

$$S = \frac{M}{GC_D}$$

$$f_o = \frac{\omega_0}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{C_D \tau_I R_I}}$$

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$$\zeta_0 = \frac{1}{2C_D R_P \omega_0} = \frac{1}{2R_P}\sqrt{\frac{\tau_I R_I}{C_D}}$$

The properties which make an active force-feedback seismometer a good tool for broadband weak-motion seismology become apparent:

(a) The effects of nonlinearities as a function of displacement of the proof mass from its rest position are greatly reduced, using a displacement transducer and high loop gain.
(b) High sensitivity at long periods is achieved by selecting components in the feedback path. In order to achieve a particular natural frequency, the electronic components required in a force-feedback seismometer are much smaller than the mechanical components required in a passive seismometer with the same response.
(c) The damping of the pendulum can be made low without affecting the closed-loop response of the system, since the damping ζ_0 of the closed-loop system is determined entirely by the components in the feedback network.

The power required to operate a force-feedback seismometer must be considered its chief disadvantage relative to a passive seismometer. Although the power consumption can often be kept to a fraction of the rest of the recording system, the fact that power must be provided at all does increase the size and complexity of cables, connectors, and the digitizer itself. The versatility of the broadband seismometer relative to passive alternatives, however, can more than make up for this.

Ground Motion Spectra

The sensing of ground motion due to earthquakes and other phenomena is fundamentally limited by the background motion of the earth. Efforts to define minimum, maximum, and typical ground motion models go back at least as far as the 1950s (Brune and Oliver 1959).

An important current standard consists of the new high- and low-noise models (NHNM and NHNM) (Peterson 1993) which in practice sets limits on the typical background motion at well-constructed vaults. It represented an improvement over the old noise models (OLNM and ONHM) because it included stations with the then-new STS-1 seismometer, the first high-quality very broadband sensor. These four models are plotted in Fig. 7 below.

In the band 0.05–1 Hz all models of ground motion are dominated by a peak called the microseismic peak. This peak is in fact made up of two peaks. The first peak, typically between 10 and 16 s period, corresponds to the natural period of waves generated by storm winds in mid-ocean. This peak is sometimes called the primary microseism. Because the mean pressure at the ocean bottom is proportional to the square of wave height, standing waves at mid-ocean produce a larger, double-frequency peak between 4 and 8 s period (Longuet-Higgins 1950). Ocean micro-seisms dominate recordings made by sensors with sufficiently low self-noise and divide ground motion into two important bands, commonly called short period (above the microseismic peak) and long period (below the microseismic peak).

Peterson dealt with the non-stationarity of the nonetheless random processes underlying the background motion of the earth by simply discarding time segments containing earthquakes or noise bursts. More recent models of ground motion spectra deal with the problem of non-stationarity in a more sophisticated way, using statistical approaches which evaluate the probability distribution of the power spectral density (PSD) as a function of frequency.

For example, studies of the Global Seismological Network (GSN) resulted in noise models of vertical (Z) and horizontal (H) ground motion (GSNNMZ and GSNNMH, respectively) (Berger

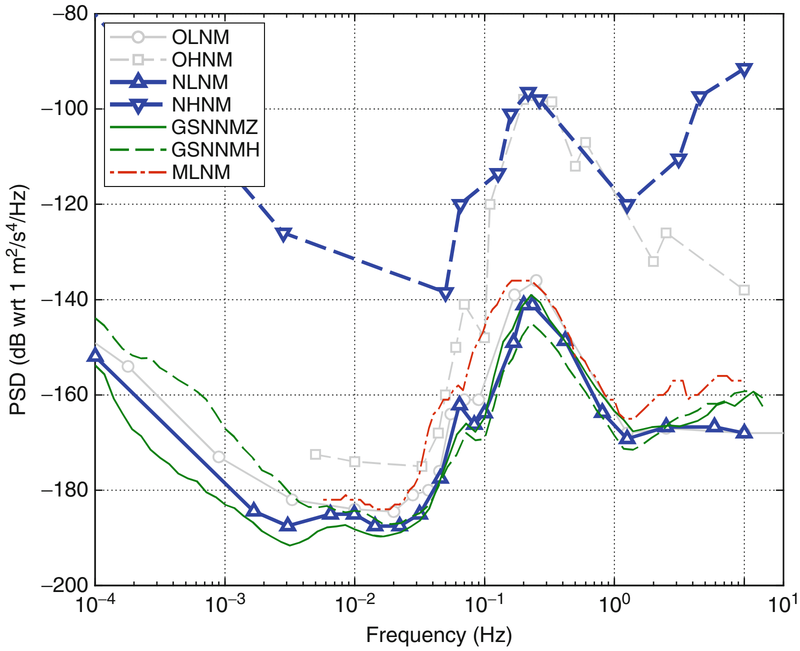

Fig. 7 Models of ground motion spectra

et al. 2004), and a study of the continental United States has produced the mode low-noise model (MLNM) (McNamara and Buland 2004): both studies employ the notion of the PSD probability density function (PDF) to produce estimates of ground motion spectra at quiet sites. Figure 8, reprinted from Figure 8 of McNamara and Buland (2004), shows how transient phenomena (e.g., calibration signal injected into the seismometer) are represented alongside stationary phenomena (e.g., the microseismic peak) using this approach.

The PSD PDF allows a more precise statistical definition of ground motion low-noise models. For example, the MLNM was constructed as the per-frequency minimum of the *modes* of the PDF of a set of broadband seismic stations distributed across the continental United States. Similarly, the GSNNM is the per-frequency minimum of the 1st (quietest) percentile of the PDF of the stations in the GSN. As shown in Fig. 7, the GSNNMZ is lower than the NLNM at very long periods (<0.01 Hz); this new lower limit is likely to still be limited by the performance of the STS-1.

Despite the advance in network performance monitoring that the PSD PDF represents, the NLNM remains the standard by which seismometer self-noise floors are measured, and many of the most common features of background ground motion are represented relative to the NLNM and NHNM.

Some strong generalizations can be made about background motion at long periods:

- Horizontal components are never quieter than vertical components at a given location. See section on "Tilt."
- Sites on alluvium are never quieter than nearby sites on hard rock. See section on "Site Selection."
- Surface sites are never quieter than nearby underground sites. See section "Downhole and Ocean-Bottom."

Indeed, the NHNM at long periods is made up of horizontal ground motion records at surface vaults on alluvium, while the NLNM at long periods is made up of vertical records on hard rock, mainly in subsurface vaults (Peterson 1993).

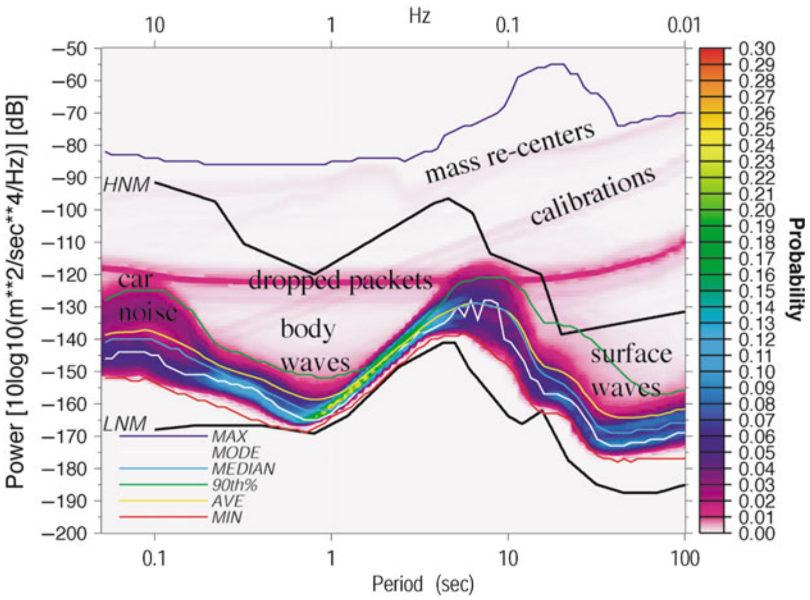

Fig. 8 Typical acceleration power spectral density probability density function

There are fewer features of ground motion at short periods (above the microseismic peak) which can be generalized. As at long periods, surface sites are never quieter at short periods than nearby underground sites, but horizontals and verticals tend to have similar levels. In both bands "cultural noise" such as that due to traffic can be problematic, as can noise due to wind in trees or running water. Finally, there is always a minimum in the ground noise spectrum at or just above 1 Hz.

Although the NLNM was constructed from the records of land-based seismometers, it may also represent a hypothetical quietest site under the sea. Seismic noise surveys on the ocean bottom have not yet been undertaken on the scale that they have been on land. It is clear from the work which has been done so far, however, that the noise levels are generally significantly higher. Most of the ocean floor is covered with sediment which is more compliant than sediment on land, and seismic velocities are lower. Seafloor compliance means that excess site noise due to deformation and tilt can result from both variations in pressure due to waves at the surface and currents traveling along the bottom of the ocean (Webb and Crawford 2010). When precautions are taken to mitigate these effects, site noise can approach the levels observed on land.

In conclusion, although models based on larger or more regionally focused samples of sites exist, and although statistical methods have improved with time, Peterson's NLNM remains the standard by which the noise performance of broadband seismometers and sites are judged. It represents a hypothetical "quietest site on earth" so a good broadband seismometer should be able to resolve it. The NLNM is therefore commonly used as a reference curve on plots of broadband seismometer self-noise. In turn, at the very longest periods, it may be that the NLNM is limited by the available broadband sensor technology.

Ground Motion Unit Conversion

Ground motion can be expressed in the time domain units of displacement [m], velocity [m/s], or acceleration [m/s^2]. In the frequency domain, a ground motion signal can furthermore be represented either as an amplitude spectrum ["per Hz," e.g., m/s^2/Hz] or as a PSD ["per $\sqrt{\text{Hz}}$," e.g., m/s^2/$\sqrt{\text{Hz}}$]. In assessing the performance of a seismograph station, it is essential to be able to convert between various units fluently.

DOI 10.1007/978-3-642-36197-5_172-1

For example, comparison of earthquake spectra (typically a displacement amplitude spectrum or peak band-passed acceleration spectrum) to the clip level of a station (typically a maximum amplitude of acceleration or velocity) allows determination of the maximum earthquake magnitude which can be detected without clipping. Similarly, comparison of the same event spectra to seismograph self-noise or site noise (typically represented as an acceleration PSD) determines the minimum detectible magnitude. Finally, comparison of seismometer clip and self-noise levels as a function of frequency gives the clearest representation of seismometer dynamic range.

Acceleration-Velocity-Displacement

The simplest kind of conversion is integration and differentiation to obtain different time derivatives of ground motion. For example, to convert an acceleration to a velocity or from velocity to displacement at a given frequency f, one simply divides by the amplitude by the angular frequency $\omega = 2\pi f$. This follows straightforwardly from the equivalence of differentiation in the time domain to multiplication in the frequency domain by the Laplace frequency $s = j\omega$. Thus for sinusoidal amplitudes of acceleration $|a|$, velocity $|v|$, and displacement $|d|$ at frequency f, the following relations hold:

$$|a| = 2\pi f|v| \tag{2}$$

$$|v| = 2\pi f|d| \tag{3}$$

These relations have wide applicability in converting amplitude spectra of finite energy signals of earthquakes between acceleration, velocity, and displacement and in converting PSDs of stationary between acceleration, velocity, and displacement.

Another type of conversion is needed for the comparison of finite energy signals and stationary signals. In particular, conversion from a PSD to the equivalent amplitude requires that a minimum of two factors be specified: a bandwidth and a crest factor.

Relative Bandwidth

Parseval's theorem can be used to compute the root-mean-square amplitude a_{RMS} expected given the one-sided power spectral density as a function of frequency $a_{\mathrm{PSD}}(f)$ and lower and upper frequency band limits $f_H > f_L$:

$$a_{\mathrm{RMS}}^2 = \int_{f_L}^{f_H} a_{\mathrm{PSD}}^2(f)df$$

This equation applies equally well to acceleration, velocity, or displacement, but note that if the RMS is in units, then the PSD is in units$/\sqrt{\mathrm{Hz}}$.

For narrowbands the spectrum can be assumed to be constant within the band so that

$$a_{\mathrm{RMS}}^2 = a_{\mathrm{PSD}}^2(f_H - f_L) = a_{\mathrm{PSD}}^2 k_{\mathrm{RBW}} f$$

$$a_{\mathrm{RMS}} = a_{\mathrm{PSD}}\sqrt{k_{\mathrm{RBW}} f} \tag{4}$$

where the "relative bandwidth factor" is defined as

DOI 10.1007/978-3-642-36197-5_172-1

Table 1 Common choices of relative bandwidth

Bandwidth	b	n	k_{RBW}	$k_{\mathrm{RBW}}\vert_{\mathrm{dB}}$
Octave	2	1	0.707	−1.5
1/6 decade	10	6	0.386	−4.1
1/2 octave	2	2	0.348	−4.6
1/3 octave	2	3	0.232	−6.4

$$k_{\mathrm{RBW}} \equiv \frac{f_H}{f} - \frac{f_L}{f}$$

It is common to define bands as a fraction 1/n of either an octave (b, 2) or a decade (b, 10), as follows:

$$\frac{f_H}{f_L} = b^{\frac{1}{n}}$$

and furthermore to dispose the band limits symmetrically (in a logarithmic scale) around the band center, so that

$$\frac{f_H}{f} = \frac{f}{f_L} = b^{\frac{1}{2n}}$$

so that the relative bandwidth factor k_{RBW} for various bandwidths can be evaluated using

$$k_{\mathrm{RBW}} = b^{\frac{1}{2n}} - b^{-\frac{1}{2n}}$$

Some common choices of bandwidth are listed in Table 1. Two which appear commonly in seismometer specifications, 1/2 octave and 1/6 decade, are close enough that they are often considered interchangeable. The octave bandwidth is considered typical of a passive seismometer and has been used in some important studies of typical earthquake spectra (Clinton and Heaton 2002).

The choice of a relative bandwidth thus permits conversion of a power spectral density to an equivalent RMS amplitude.

Crest Factor

The second factor needed when comparing stationary and transient signals is called a “crest factor,” and is defined as the ratio of peak amplitude to RMS amplitude. The correct choice of crest factor depends on the nature of the signal in question. Broadband Gaussian noise will surpass its standard deviation 32 % of the time and twice the standard deviation 5 % of the time, for example. These conditions would correspond to crest factors of 1 and 2, respectively.

The signals which make up background ground motion do often have Gaussian distributions (Peterson 1993), as do the self-noise of seismometers and digitizers. When a Gaussian signal is passed through a narrowband filter, the peak amplitudes of the signal which results have a Rayleigh distribution (Bormann 2002), corresponding to a crest factor:

$$k_{\mathrm{crest}} = \sqrt{\frac{\pi}{2}} \cong 1.25$$

DOI 10.1007/978-3-642-36197-5_172-1

Given a crest factor, the equivalent amplitude can be estimated from a PSD using

$$a_{\mathrm{peak}} = a_{\mathrm{RMS}} k_{\mathrm{crest}} \tag{5}$$

As with the equations accounting for relative bandwidth, this equation applies equally well to acceleration, velocity, or displacement.

Decibels

Ground motions are often expressed in decibels. By convention the reference amplitude for the decibel in this context is the corresponding metric unit. For example, an acceleration PSD is converted to dB using

$$a_{\mathrm{PSD}}\big|_{\mathrm{dB}} = 20\log_{10}\left(\frac{a_{\mathrm{PSD}}}{\frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}}\right)$$

while a velocity amplitude is converted using

$$v_{\mathrm{peak}}\big|_{\mathrm{dB}} = 20\log_{10}\left(\frac{v_{\mathrm{peak}}}{\mathrm{m/s}}\right)$$

Thus, the various unit conversions of Eqs. 2, 3, 4, and 5 become:

$$a\big|_{\mathrm{dB}} = v\big|_{\mathrm{dB}} + 20\log_{10}\left(\frac{2\pi f}{\mathrm{rad}}\right) \tag{6}$$

$$v\big|_{\mathrm{dB}} = d\big|_{\mathrm{dB}} + 20\log_{10}\left(\frac{2\pi f}{\mathrm{rad}}\right) \tag{7}$$

$$a_{\mathrm{RMS}}\big|_{\mathrm{dB}} = a_{\mathrm{PSD}}\big|_{\mathrm{dB}} + 10\log_{10}(k_{\mathrm{RBW}}) + 10\log_{10}\left(\frac{f}{\mathrm{Hz}}\right) \tag{8}$$

$$a_{\mathrm{peak}} = a_{\mathrm{RMS}}\big|_{\mathrm{dB}} + 20\log_{10}(k_{\mathrm{crest}}) \tag{9}$$

These relations can be seen in action Fig. 13 below, where the band-passed peak velocity amplitudes of earthquakes are compared to the clip level and noise floor of a seismometer.

Components of Station Noise

The noise power at a seismic station is the sum of the noise powers of the seismograph and the background motion at the site:

$$\left\langle \left|\ddot{x}_{\mathrm{station}}\right|^2 \right\rangle = \left\langle \left|\ddot{x}_{\mathrm{seismograph}}\right|^2 \right\rangle + \left\langle \left|\ddot{x}_{\mathrm{site}}\right|^2 \right\rangle$$

It is important that the station noise be low enough to not obscure the signals of interest when they arrive. This is shown in cartoon form in Fig. 9.

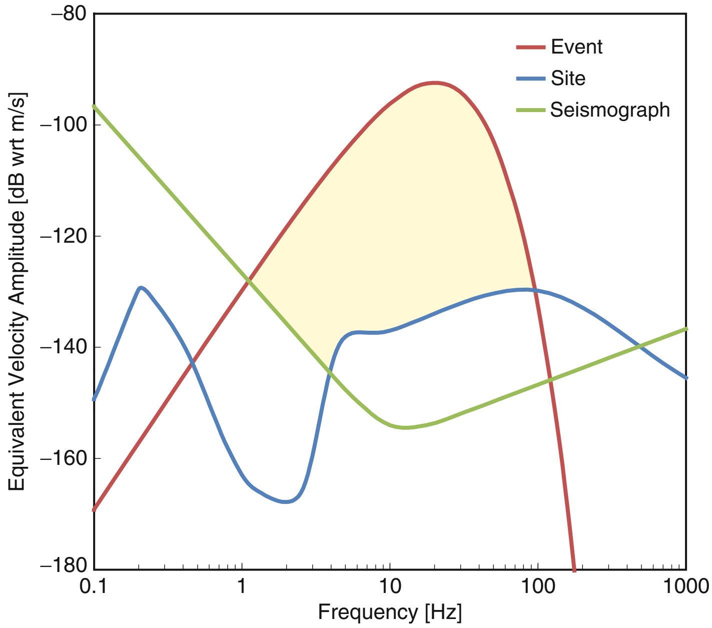

Fig. 9 Representative station (noise) and small event (signal) spectra

A modern seismograph station consists, in turn, of a seismometer and a digitizer, as shown schematically in Fig. 10. Both elements must be considered in determining the performance of the station as a whole.

Similarly the clip level of a seismograph station is a combination of the clip level of the seismometer and of the digitizer. A difference is that whereas noise powers are summed, the clip level of a system is the minimum of the clip level of all of the components, when referred to common units.

The importance of the sensitivity of a digitizer is now apparent. The sensitivity must be high enough to minimize the digitizer's contribution to the station noise, but at the same time it must be low enough that the clip level of the digitizer does not degrade the station clip level so much that events of interest will be clipped. Note that a system incorporating a seismometer which achieves a high sensitivity to ground motion using a high-gain output stage is equivalent to a system in which the digitizer subsystem includes a preamp with the same gain.

The self-noise of seismometers can be divided roughly into those that are stationary, in the sense that the probability distribution does not change with time, and those that are nonstationary.

Of the sources of stationary noise in a seismometer, there are two main subcategories, called "white" noise and "flicker" noise sources. White noise sources have the same amount of noise power per unit of (absolute) bandwidth in frequency; flicker noise sources have the same amount of noise power per fractional (relative) bandwidth, for example, per octave or per decade. The PSD of a white noise source is independent of frequency; the PSD of a flicker noise source varies as the inverse of frequency (Motchenbacher and Connelly 1993), i.e., proportional to $f^{-\alpha}$ where typically α is close to 1 but can be as high as 1.5.

In the process of referring the noise at various points in the feedback loop to the input of a seismometer, each source must be referred to the sensor input. This is similar to converting ground motion units from velocity to displacement and from displacement to velocity. Thus in principle various components of the noise floor of a seismometer can be proportional to f^n (or equivalently a slope of $10n$ dB/decade) where n is any positive or negative number, usually an integer.

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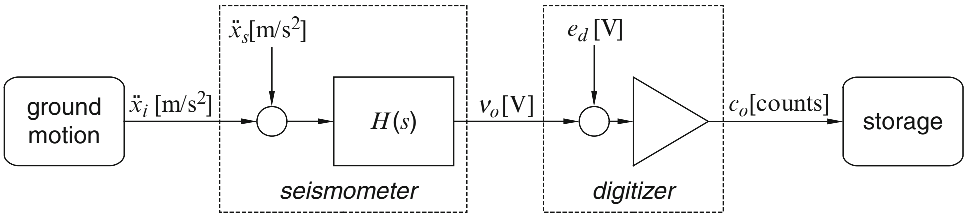

Fig. 10 Components of a seismograph station

In practice, in a well-designed force-feedback seismometer, the equivalent acceleration PSD of the self-noise will be proportional to f^{-3} (-30 dB/decade) at low frequencies and proportional to f^4 (40 dB/decade) at high frequencies (Hutt and Ringler 2011).

For example, the displacement transducer in a feedback seismometer results in a white noise proportional to displacement, but to determine the equivalent acceleration, a double integration is required, so the slope of the acceleration PSD is f^4, and this tends to dominate the self-noise of the sensor at high frequencies. Similarly the digitizer white noise component, when converted from velocity to acceleration PSD, has a f^2 (20 dB/decade) characteristic and will tend to dominate the station noise near 10 Hz.

Two noise sources common to all seismometers, active and passive, are Johnson and Brownian noise. Johnson noise is a noise source due to thermal agitation of the electrons that make up the current flow in a resistor. For a resistance R [Ω] at temperature T [K], the expectation value of the voltage PSD across its terminals will be:

$$\left\langle |e_n|^2 \right\rangle = 4k_bTR$$

where $k_b = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant. For low noise, resistors must have small values, but this generally results in greater power consumption.

Brownian noise is similar to resistor noise, both in terms of the statistical mechanics which explain it, and in the white noise spectrum which results. In particular, the Brownian motion of the boom of a pendulum results in an equivalent acceleration PSD of the frame of that pendulum equal to:

$$\left\langle |\ddot{x}_n|^2 \right\rangle = \frac{4k_bTB}{M^2}$$

Thus it is clear that for low noise, the proof mass must be large while the viscous damping must be small. All known voice-coil and capacitive transducers require narrow gaps for high sensitivity; this is a source of viscous damping and can only be avoided by pumping the pendulum enclosure down to a hard vacuum, something quite difficult in practice. The downside of large proof masses is increased size and fragility; many broadband seismometers required masses to be locked during transportation.

Nonstationary noise sources are also very important to the overall performance of a seismometer. A common example of nonstationary noise is what is sometimes referred to colloquially as a "pop." The characteristic waveform is a randomly occurring disturbance having the shape of the impulse response of the seismometer. When such a signal is referred to the input of the seismometer, it turns out to correspond to a sudden step change in acceleration at the input to the seismometer, equivalent to a sudden step change in tilt of the instrument. Because "pops" occur at random times, they contribute a f^{-2} characteristic to the acceleration PSD noise spectrum.

"Pops" are often associated with temperature transients associated with initial installation and power-on. However, some sensors, which are poorly designed or have been insufficiently tested or damaged during handling, will exhibit an unusual susceptibility to pops after initial installation, and the excess "pop" noise will subsequently never die down to an immeasurable level. "Pop" noise is a low-frequency phenomenon which happens intermittently on a very long time scale. This is why, during testing of broadband seismometers, it is imperative to test sensors for a relatively long period of time, on the order of days or weeks, and include all data collected on a statistical basis, giving the median and maximum noise levels as much attention as the minimum noise level.

The PSD PDF (see section "Ground Motion Spectra") is a particularly useful tool in performing this type of analysis. Figure 8 shows how the PSD PDF represents rare, transient events such as mass-centering operations are captured in the maximum of this distribution, while the typical behavior is captured in the mode. This allows the whole available record to be analyzed, without "window-shopping." This is as it should be: single-occurrence "pops" can be as much of a problem in interpreting seismograms as stationary noise sources and should therefore be considered just as much a part of the overall self-noise performance. See ► Seismometer Self-Noise and Measuring Methods.

Selection Criteria

Many factors need to be taken into consideration in choosing a broadband seismometer. Self-noise, clip level, and transfer function are the basic performance criteria, while power and size can crucially determine the cost of the overall installation. These factors and others are treated in this section.

Sensor Self-Noise

Broadband seismometers are required to have a self-noise less than the NLNM, a hypothetical "quietest site on Earth," at least over some wide band. The self-noise cannot be measured deploying the sensor where there is no ground motion: the NLNM shows that there is no such place on Earth. Modern methods require at least three sensors be installed side by side on a rigid pier and a coherence-based analysis technique (Sleeman et al. 2006; Evans et al. 2010). Careful management of thermal, magnetic, and pressure shielding is required (see section on "Installation Procedures"), particularly to observe the performance of the best sensors at very long periods.

One comprehensive self-noise study (Ringler and Hutt 2010) includes all the important broadband seismometers as of its writing. Figures 11 and 12, reprinted from Figures 13 and 14 of that study, show the lowest 5th percentile and median noise of each sensor, respectively.

The abbreviations used in Figs. 11 and 12 are the same as those used in Table 2 below with the following exceptions: T-120, T-240, and T-Compact are the Nanometrics Trillium 120, Trillium 240, and Trillium Compact, respectively, and the 151–120 was the predecessor of the Geotech 151B-120. It is also worth noting that the STS-2 performance shown in these figures is that of a model with higher gain at 20,000 V·s/m and a correspondingly lower clip level, and that the CMG-3TB tested was a borehole variant of the standard CMG-3T.

The median self-noise was for some sensors close to the 5th percentile, while for others it was significantly higher. This can be taken as an indicator of the uniformity and/or the temporal stability of the sensors. The peak in the noise floors directly under the microseismic peak is not a feature of the sensor noise floor, but an artifact of imperfect misalignment correction.

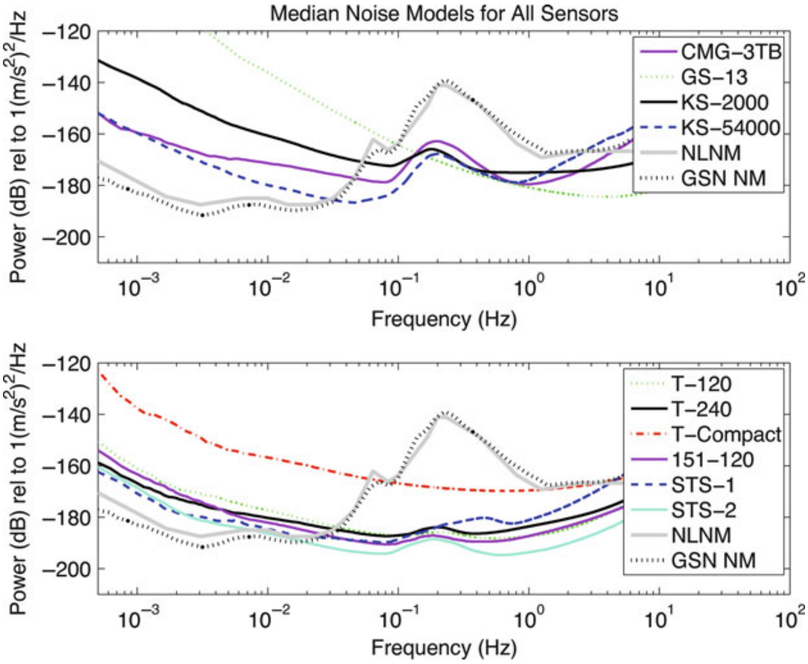

Fig. 11 Median self-noise models of weak-motion seismometers

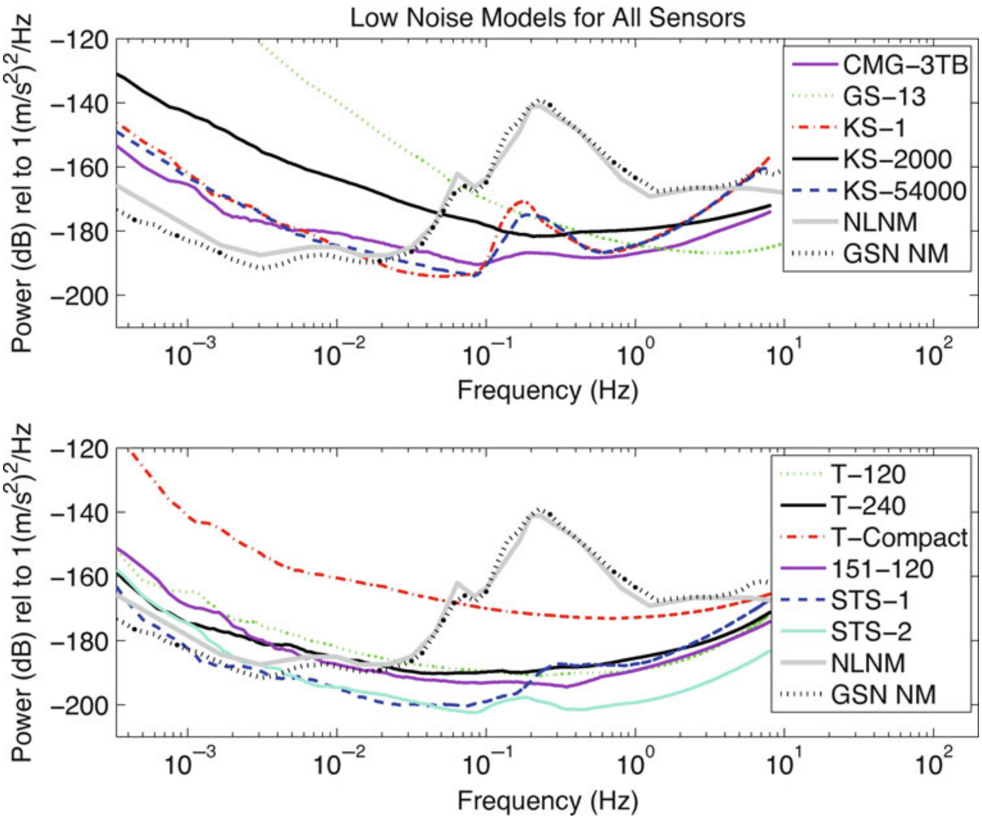

Fig. 12 Low self-noise models of weak-motion seismometers

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DOI 10.1007/978-3-642-36197-5_172-1

Table 2 Specifications of broadband seismometers

Manufacturer	Model	Sensitivity [V·s/m]	Clip [mm /s]	Period [s]	Upper corner [Hz]	Power [W]	Weight [kg]	Sensor volume [L]	Shield volume [L]
Geotech	KS-1	2,400	8	360	5	2.4	43	28	–
Streckeisen	STS-1	2,400	8	360	10	10.5	15	14	450
Nanometrics	Trillium 240	1,200	16	240	200	0.65	14	14	60
Nanometrics	Trillium 120	1,200	16	120	175	0.62	7.2	7.2	32
Guralp	CMG-3 T	1,500	13	120	50	0.75	14	8.4	–
Streckeisen	STS-2	1,500	13	120	50	0.8	13	11	72
Geotech	KS-2000	2,000	10	120	50	0.9	11	8.1	–
REF TEK	151B-120	2,000	10	120	50	1.1	12	12	–
Geodevice	BBVS-120	2,000	10	120	50	1.4	14	8.3	–
Nanometrics	Trillium Compact	750	26	120	100	0.16	1.2	0.8	7.8
Guralp	CMG-3ESP	2,000	10	60	50	0.6	9.5	4.7	–
Guralp	CMG-40 T	800	25	30	50	0.46	2.5	3.9	–

Volumes are for three components and are derived from footprint area and height alone

Given the importance of the NLNM in setting the target performance of broadband seismometers, it is understandable that self-noise requirements are often specified in terms such as "below the NLNM from 30 s to 30 Hz." Although the intention is clear, this is unfortunately a poor choice of wording. In some bands the NLNM is very steep – which is to say that the typical background acceleration PSD at a quiet site is also very steep – and so a great reduction in self-noise may not result in much improvement in the frequencies at which the self-noise crosses the NLNM. Conversely, where the slope of the NLNM is quite similar to that of the self-noise of a seismometer, a small improvement in self-noise will produce an exaggerated improvement in the NLNM-crossing frequency. Finally, care must be taken at high frequencies because the NLNM is simply not defined above 10 Hz (similarly the MLNM does not extend above 10 Hz and the GSNNM does not extend above 13 Hz).

A better way to set a specification on seismometer self-noise is to pick two key frequencies near the edges of the band of interest and set limits in dB at those frequencies. For example, to require the "median self-noise below −185 dB at 0.01 Hz and below −168 dB at 10 Hz" is equivalent to being "below the NLNM from 100 s to 10 Hz," but for the purposes of comparing one seismometer to another, it is more instructive to compare their median performance in dB at specified frequencies than in the NLNM-crossing frequencies in Hz.

Clip Level

The largest measured ground motions resulting from earthquakes have approached peak accelerations of 40 m/s^2 and peak velocities of 3 m/s, although these limits tend to increase with the densification of networks and the passage of time (Strasser and Bommer 2009). No seismograph can measure both the largest and the smallest ground motions. The dynamic range of the current state of the art in analog-to-digital converters is insufficient to cover the >170 dB range required. Although weak-motion seismometers focus on measuring the smallest motions, they are still

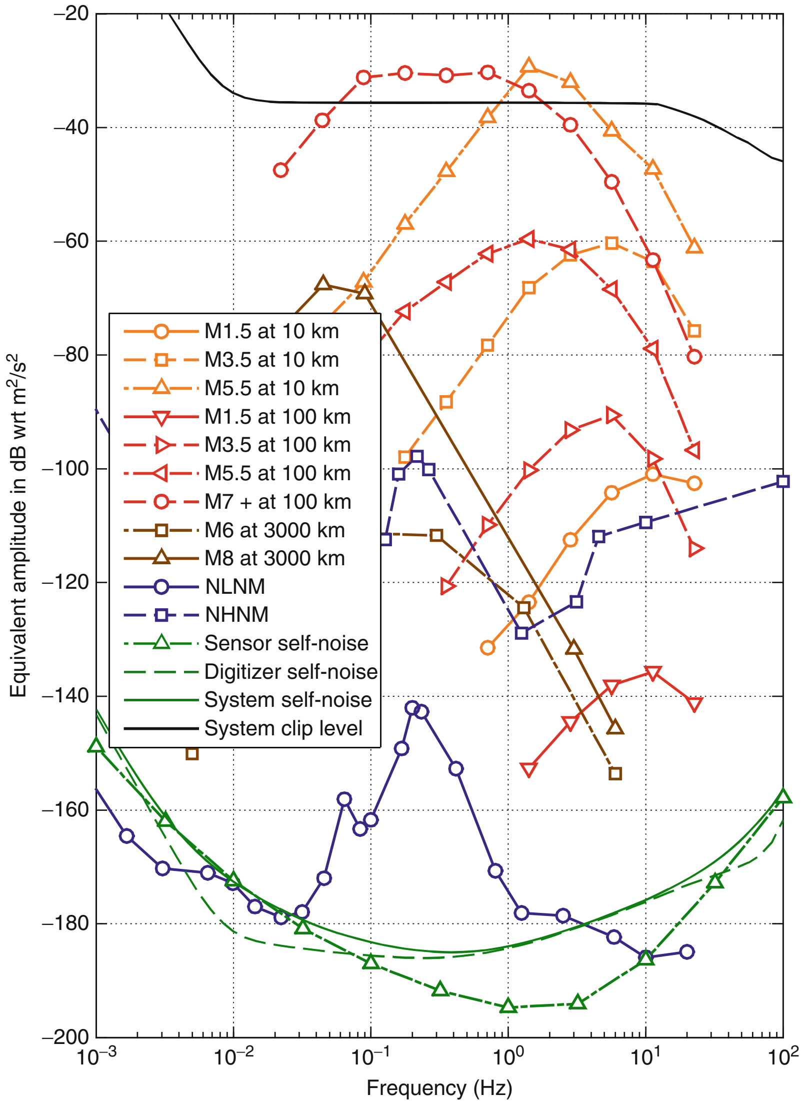

Fig. 13 Earthquake ground motions and seismograph clip levels and noise floors

expected to measure relatively large motions without clipping, so that weak-motion studies are not "interrupted" by strong motion.

Whether the clip level of a particular seismometer is adequate depends on the expected levels of ground motion at the site of deployment. The ground motion resulting from an earthquake varies with the magnitude but also with the distance from the event.

The ground motion resulting from earthquakes is a function of frequency. Figure 13 shows the typical ground motions for large and small earthquakes at local (10 km), regional (100 km) and teleseismic (3,000 km) distances (Clinton and Heaton 2002).

These event spectra are plotted for comparison against the noise floor and clip level of a representative broadband seismograph. It can be seen that the digitizer noise floor is limiting the performance of the seismograph system for frequencies above the microseismic peak. The station operator could choose to increase the digitizer preamp gain or equivalently install a high-gain version of the seismometer. This would result in a reduction of the contribution of the digitizer to the

DOI 10.1007/978-3-642-36197-5_172-1

system noise and therefore make it possible to see smaller events, but it would also reduce the clip level of the system, so that large events would be more likely to clip.

The clip level of a seismometer in the middle of its passband depends solely on the output clip level in volts and its sensitivity. Notwithstanding a hypothetical seismometer which runs from very high voltage rails, a requirement for high clip level is low sensitivity, and vice versa. The sensitivity and clip levels of some representative broadband seismometers are given in Table 2, along with other critical performance criteria.

Broadband seismometers generally use displacement transducers to measure the relative displacement of the proof mass and the frame. The proof mass and its suspension together make a pendulum which has a response which is flat to acceleration and independent of its natural frequency above the natural frequency.

There is usually a critical frequency above which the clip level of a broadband seismometer becomes more or less flat to acceleration. For the seismometer depicted in Fig. 6, the acceleration clip level is 0.17 g and the velocity clip level is 16 mm/s, so this critical frequency is near 16 Hz. If this critical frequency is significantly higher than the peak frequency of the spectra of events of interest, it will not affect clipping behavior for real seismic signals.

Response

It is crucial to understand the transfer function of a broadband seismometer when converting a recording in counts or volts back to appropriate units of ground motion. It is a common mistake to think that the signals at frequencies below the lower −3 dB corner or above the upper −3 dB corner are not useful. In fact the only thing which determines whether or not useful signal is present is signal-to-noise ratio, as illustrated by Figs. 9 and 13. With careful application of the inverse response, useful estimates of ground motion can be obtained well outside the −3 dB band.

Seismometers are sometimes available with different options for lower or upper corner frequency and for the mid-band sensitivity. Note that the term “sensitivity” in the context of seismometers is interchangeable with “generator constant” and will have units of voltage per unit of velocity. When selecting a seismometer, it is important to have in mind the largest signal which is likely to be observed, given the seismicity of the nearest seismogenic zone. Seismic risk maps are invaluable for determining the probability of recurrence of a given peak ground acceleration or velocity, which can then be directly compared to the configured seismograph system clip level. High sensitivity means the contribution of the digitizer to the station noise floor is reduced, but it also means the system clip level is reduced. Some users will prefer to use a low-gain seismometer and a digitizer with a built-in variable-gain preamp, so that they can “dial in” the correct station sensitivity after installation.

One feature of a seismometer not normally represented in its nominal transfer functions is the phenomenon of parasitic resonances. Well-characterized seismometers will have a specification for the lowest mechanical resonance; it is important to make sure that this frequency is above the range of frequencies of interest in a particular study.

Power

There are two advantages to low power. The first is that lower power means a physically smaller footprint and a less costly installation for stations which must be located far from main power systems. Such stations are common because the best seismic sites are generally located away from roads and cities and human activity in general, so-called sources of cultural noise. For a temporary deployment, lower power means fewer batteries are needed for a given length of time. For a permanent deployment at a remote site, lower power means less on-site power generation (e.g.,

DOI 10.1007/978-3-642-36197-5_172-1

fewer solar panels) is needed. A smaller footprint for power generation furthermore generally means less wind-induced seismic noise.

A second advantage to lower power relates specifically to performance at very long periods in vault-type installations. Power dissipation inside the sensor and digitizer means heat generation. This heat causes convection within the vault, and the resulting airflow tends to be turbulent and chaotic, heating and cooling various surfaces around the vault, in particular the floor, causing small but measurable tilts. Thus, for sensors which consume more power, it becomes more difficult to properly thermally shield well enough to drive the resulting apparent horizontal accelerations down below the NLNM at very long periods.

The power consumption of some broadband seismometers is listed in Table 2.

Size and Weight

The physical size of a seismometer has a multiplying effect on the size and thus the cost of deployment of a seismic station. For vault installations, a larger sensor requires a larger volume to be reserved for thermal shielding. Since a good broadband vault must generally be built below ground level, a larger sensor means the minimum volume which must be dug out for the vault is larger.

For temporary deployments, the size and weight of a sensor can significantly affect ease of deployment. When it is a matter of driving to a remote location and hand-carrying the equipment even further away from the road, it can mean that significantly fewer stations can be set up per day, if the sensor is large and heavy.

Aside from the trouble it causes in a temporary deployment, a heavy sensor has an advantage over a light one, in that the associated thermal mass means better temperature stability.

The volume and weight of some broadband seismometers are listed in Table 2.

Enclosure, Leveling, and Topology

The choice of enclosure for broadband seismometers is an important one. Some common options are vault, borehole, posthole, and ocean bottom.

Enclosures designed for deployment in vaults need to be dust- and watertight, but are generally not designed for submersion to significant depths or durations (i.e., ingress protection ratings of IP66 or IP67 are common, but not IP68). There is no particular restriction on the overall diameter of a vault enclosure, but it should be designed for ease of leveling, orientation, and thermal isolation. For example, the connector should be oriented to allow cables to exit the enclosure horizontally near the surface of the pier. This makes it easy to strain-relieve the cable, minimizing the possibility of cable-induced noise, and to place an insulating cover over top of it. The design of broadband seismometer vaults is described in "Installation Procedures" below.

Enclosures designed for deployment in cased boreholes generally need to have smaller diameters and a mechanism to lock the sensor in the hole. Drilling of boreholes is always more economical for smaller diameters than larger ones; a common casing diameter for broadband seismometers is 15 cm. The connector will generally exit at the top of the sensor and the whole assembly should be rated for continuous submersion to a significant depth (i.e., IP 68 to 100 m or more), since flooding of boreholes is common. Boreholes stray from verticality as they are dug deeper; a remote leveling range of up to $\pm 4°$ is thus typically required. See ▶ Downhole Seismometers for a more detailed discussion.

Enclosures designed for deployment in shallow uncased holes called postholes do not need hole locks. Sensors are generally emplaced in backfilled soil or sand and are simply pulled out or dug out at the end of the deployment. As with borehole sensors, the connector should generally exit at the top

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DOI 10.1007/978-3-642-36197-5_172-1

and must be rated for submersion. There is less control of sensor leveling with deeper holes, and a remote leveling range of ±10° may be required. See ► Downhole Seismometers for a more detailed discussion.

Enclosures designed for ocean-bottom deployment have several requirements which other sensor types do not. Most of the ocean bottom is near 5 km depth, so in order to be deployable over most of the ocean bottom, a sensor would typically have a continuous submersion rating of 6 km. Most ocean-bottom deployments are done by releasing the sensor at the surface and without controlling exactly where it will come to rest on the ocean floor. The sensors are designed to level themselves, typically at a predetermined time after release, and since the exact resting place is not known in advance, a self-leveling range of ±45° or more is required. Prevention of corrosion and biofouling is additional crucial requirement for ocean-bottom enclosures. See ► Ocean-Bottom Seismometers for more information.

When an underground vault in bedrock is available, for example, in an inactive mine or in the basement of a building, then a vault-type enclosure is of course the best choice. When there is some significant overburden, so that to reach bedrock a borehole must be dug and cased, then a borehole-type enclosure is required. And of course ocean-bottom deployments require an ocean-bottom enclosure.

It is not uncommon however that a sensor must be deployed in a location where no preexisting vault or borehole is available. In such situations a posthole installation can give performance as good or better than a vault built according to best practices, at significantly less cost for the overall installation.

If leveling motors are included in the sensor, a remote leveling process is initiated via an external electrical signal or at a configurable time after power-on; otherwise manual leveling by adjustment of set screws is sometimes needed. All enclosure types except vault enclosures require remote leveling capability.

Sensor axis topology is a final consideration. Some studies may require only a single axis of seismic sensing, usually vertical. For triaxial seismic sensing, the sensor outputs should be horizontal (X, Y) and vertical (Z). However certain kinds of installation troubleshooting are easier to do if the internal sensing axes are not aligned to horizontal and vertical. See ► Symmetric Triaxial Seismometers for more information.

Environmental Sensitivities

Spurious signals due to environmental sensitivities are not normally considered part of the self-noise of a seismometer, but they can deleteriously affect the output signal in many of the same ways. Broadband seismometers are particularly sensitive to changing tilt, temperature, pressure, and magnetic fields.

To understand why, consider that in order to have self-noise just equal to the NLNM at 100 s period, you need to be able to discriminate ground motion from all other effects at a level of

$$a_{\mathrm{PSD}} = 10^{\frac{-185}{20}} \frac{\mathrm{m}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}} = 0.56 \frac{\mathrm{nm}}{\mathrm{s}^2\sqrt{\mathrm{Hz}}}$$

And since the self-noise of a seismometer is typically proportional to 1/f in this band, the noise in the decade around $f_{\mathrm{PSD}} = 0.01$ Hz will be

DOI 10.1007/978-3-642-36197-5_172-1

$$a_{\mathrm{NLNM}} = a_{\mathrm{PSD}}\sqrt{f_{\mathrm{PSD}}\ln(10)}\,\frac{\mathrm{nm}}{\mathrm{s}^2} = 0.08\,\frac{\mathrm{nm}}{\mathrm{s}^2}$$

This tiny acceleration, measurable by very broadband seismometers (i.e., a weak-motion inertial sensor with a wide dynamic range over a very broadband), can be overwhelmed by spurious environmental sensitivities, as discussed below.

Tilt

Sensitivity to tilt is an inevitable consequence of inertial sensing, because gravitational equivalence principle tells us that gravity is indistinguishable from accelerations. An inertial sensor tilted from vertical by an angle θ measured in radians experiences an apparent horizontal acceleration of

$$\ddot{x} = g_0 \sin\theta$$

where $g_0 \cong 9.8$ m/s^2 is the standard acceleration due to gravity near the surface of the Earth. For small tilt angles sin $\theta \cong \theta$, so all inertial seismometers have the same tilt sensitivity α_T, that is, the same apparent horizontal acceleration in response to tilt:

$$\alpha_T \equiv \frac{\ddot{x}}{\theta} = g_0 \cong 9.8\,\frac{\mathrm{m/s}^2}{\mathrm{rad}} \cong 0.17\ \frac{\mathrm{m/s}^2}{\circ}$$

Some tilt and rotation is to be expected to accompany the translational motion of a traveling seismic wave, but locally generated non-seismic tilt can prevent critical observations from being made. It is because of their extreme sensitivity to tilt that all inertial translational sensors, including broadband seismometers, record higher levels of apparent horizontal motion than vertical motion at long periods.

In order to resolve the NLNM at 100 s, tilts in the decade band around that frequency would have to be kept smaller than

$$\Delta\theta = \frac{a_{\mathrm{NLNM}}}{g_0} = 5 \times 10^{-10\,\circ}$$

This is an extremely small angle. It corresponds to lifting one side of a 10 m wide structure pier by just 1 Å, the order of magnitude of atomic radii.

Fortunately, locally generated “excess” tilt is not spontaneous but driven by some other environmental factor and can be greatly reduced with careful vault design. For example, it is common for such tilts to be driven by temperature or pressure sensitivity of the seismic vault or nearby subsurface geology. Tilts can also be driven by changes in insulation or water table, vehicular traffic or other cultural activity, or wind loading on nearby structures. Mitigating these sorts of effects is an overriding concern in designing a seismic vault, as described in the section “Installation Procedures.”

Another, more subtle tilt-related effect is that a static tilt will increase off-axis coupling of horizontal motion into vertical. See ▶ Symmetric Triaxial Seismometers for more information. Other than this effect, the actual static tilt of a seismometer is generally not a problem, as long as it is within the operating range of the seismometer.

Most broadband seismometers have an integrator in the feedback circuit, and the operating range of this part of the circuit determines the tilt range of the seismometer. For the lowest possible noise at very long periods, the integrator output resistor must be large, and this restricts the tilt range of the

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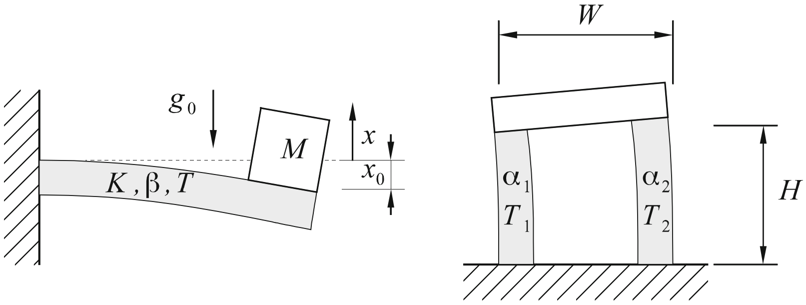

Fig. 14 Schematic representation of vertical (*left*) and horizontal (*right*) temperature sensitivity

seismometer. Thus very broadband seismometers are typically equipped with centering motors or leveling platforms to extend this tilt range. See ► Downhole Seismometers for more information.

Temperature

The operating temperature range of a seismometer is determined by the temperature coefficient of the mechanics and components in the force-feedback circuit. A vertical seismometer involves balancing the acceleration due to the effect of gravity on the proof mass against forces supplied by a suspension. The temperature coefficient relates changes in deflection of the proof mass with temperature and so can be expressed in units of ppm (with respect to g_0 the acceleration due to gravity) per °C. A temperature-compensated axis assembly is one in which changes in forces due to thermoelastic coefficients in the suspension cancel deflections due to coefficients of thermal expansion in the rest of the components (Wielandt 2002), such that a displacement transducer would register no movement of the proof mass.

Some broadband seismometers have very wide temperature ranges, encompassing the full range of possible deployment temperatures. Many of the broadband seismometers with the lowest self-noise, however, have operating temperature ranges of ±10 °C or less. These seismometers are equipped with a re-centering mechanism which must be activated after the seismometer has been installed in a new vault, ideally after its temperature has stabilized. Just as horizontal sensitivity to tilt determines the tilt range, vertical sensitivity to temperature determines the temperature range.

Even for a sensor operating well within its temperature range, spurious horizontal or vertical output signals can result from tiny changes in temperature. The temperature sensitivity is typically a direct proportionality of equivalent input acceleration to change in temperature.

For a seismometer which is not temperature compensated, the temperature sensitivity is typically dominated by the thermoelastic coefficient of the mainspring, as shown in Fig. 14 (left). The cantilever balances the mass M against the force of gravity g_0 but as the temperature T changes the stiffness of the beam, represented as a spring constant K changes, and the apparent vertical acceleration $\ddot{x}$ changes.

Summing the forces on the mass M in Fig. 14 (left), we find

$$\sum F = -Kx + Mg_0 = M\ddot{x}$$

And the temperature sensitivity can be modeled as

$$K = K(\Delta T) = K_0(1 + \beta\Delta T)$$

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DOI 10.1007/978-3-642-36197-5_172-1

So if the instrument is designed so that at $T = 0$, there is no apparent acceleration $\ddot{x} = 0$ and the deflection is static at x_0:

$$x_0 = \frac{Mg_0}{K_0}$$

Now if we allow $T \neq 0$, the apparent acceleration is

$$\ddot{x} = g_0 - \frac{x_0}{M}K_0(1 + \beta\Delta T) = g_0 - g_0(1 + \beta\Delta T) = g_0\beta\Delta T$$

Most copper alloys and steels have a thermoelastic coefficient on the order of β = -300 ppm/°C, the minus sign indicating that the mainspring relaxes with an increase in temperature.

This translates to a requirement for temperature stability of

$$\Delta T_z = \frac{a_{\text{NLNM}}}{|\beta|g_0} \cong 7 \times 10^{-9}\ ^\circ\text{C}$$

A related problem is to measure ground motion on the order of the NLNM in the presence of temperature-generated tilts. This problem is significant both at the level of the seismometer and its subassemblies and at the level of the seismic vault and related superstructures. One way to model this effect is to visualize the sensor as a platform with legs which either have different temperature coefficients or which are at different temperatures, as shown in Fig. 14 (right). For such a structure, small differentials produce small tilts:

$$\Delta a = \Delta\theta g_0 = (\alpha_1 T_1 - \alpha_2 T_2)\frac{H}{W}g_0$$

For an enclosure made out of a single material, all that matters is the difference in temperature across the structure. For an enclosure made out of steel or aluminum, the thermal coefficient of expansion is on the order of α = +20 ppm/°C, with the positive sign indicating that the material expands with an increase in temperature. For the resulting equivalent horizontal acceleration to be less than the NLNM at a 100 s period, if the height is the same as the width, the temperature difference across the enclosure must be less than

$$\Delta T_x = \frac{a_{\text{NLNM}}}{\alpha g_0} \cong 1 \times 10^{-7}\ ^\circ\text{C}$$

Obviously the actual dimensions of the structure can result in this effect being significantly amplified or attenuated, as can the geometry and relative stiffness of the members. Furthermore, it is important to note in both cases that static temperatures are not a problem because the seismometer does not respond to static acceleration. What matters is temperature variation with time, in the band of interest, in this case near 100 s period. Although this model is extremely simplistic, the point is that mechanisms for the conversion of changes in temperature into tilt abound, both inside a seismometer and outside.

There is a subtle difference between the vertical temperature sensitivity and the horizontal temperature sensitivity of a seismometer. The vertical output of a seismometer is only sensitive to bulk temperature changes; the horizontal outputs are sensitive to differences in temperature across

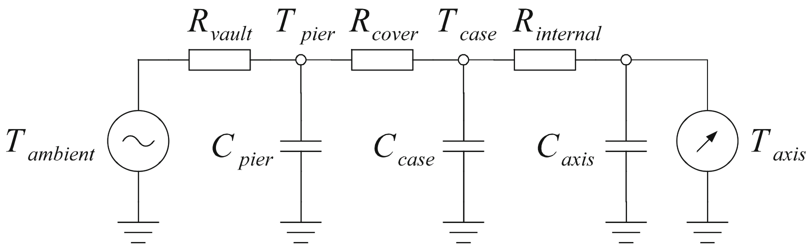

Fig. 15 Thermal/electrical filter analogy

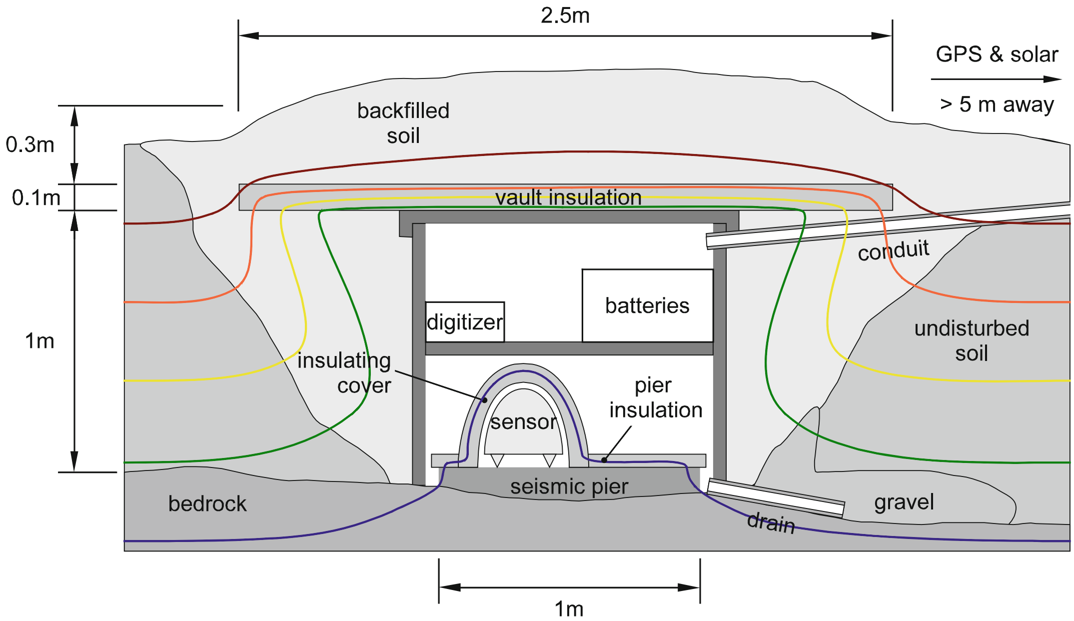

Fig. 16 Idealized broadband vault

the surface of some part of the enclosure or differences in coefficient of thermal expansion combined with bulk changes in temperature.

The design of a thermal shield against bulk temperature changes is relatively straightforward and can be conceptualized by analogy with electronic circuits as designing a series of cascaded single-time-constant thermal low-pass filters. The design of bulk thermal isolation structures requires a series of concentric shells of thermally resistive elements and thermally massive elements.

In Fig. 15 the first layer of thermal insulation R_{vault} shields the thermal mass C_{pier} of the pier, the sensor insulating cover R_{cover} shields the thermal mass C_{sensor} of the sensor, and the internal insulation of the sensor R_{internal}, if any, shields the thermal mass C_{pier} of the individual axes of the sensor. It is important when designing thermal shields to avoid accidentally including any thermal short circuits which decrease the effectiveness of the shielding. A thermal short circuit or thermal bridge is any path which crosses a thermal insulator and has high thermal conductivity. For example, if the electrical conduit in Fig. 16 was made of metal and therefore thermally conductive, it will act as a thermal short circuit and degrade the performance of the vault insulation. This could be visualized in the electrical analogy of Fig. 15 as a low-value resistance in parallel with R_{vault}. A seismometer which includes some thermal insulation measures within its pressure vessel will require less external thermal shielding.

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DOI 10.1007/978-3-642-36197-5_172-1

Bulk thermal isolation of the type described thus far primarily addresses the thermal sensitivity of the vertical output of a seismometer. Inhibiting thermally generated noise on the horizontal outputs of a seismometer is a different problem.

First, a vault must be free of drafts. At the same time, a fully sealed vault can make the vault respond to pressure with tilt, particularly if the vault is not installed on competent rock. The solution in some cases is to design the vault to have a single point at which it vents, so that the internal and external air pressures are equalized without generating drafts across the floor of the vault.

Second, air convection within the vault must be inhibited. This is done by reducing the power dissipated within the vault, by filling airspace within the vault with some material which inhibits airflow. The design of bulk thermal insulation is subtly different from the design of a shield intended to stop convective airflow. See the section on "Installation Procedures" below for more detail.

Pressure

A seismometer not contained within a pressure vessel will exhibit strong pressure sensitivity on the vertical output due to buoyancy of the proof mass. Consider a proof mass with a density $\rho_{\text{proof}} = 8$ g/cm^3 at a temperature $T_{\text{air}} = 293$ K in dry air with a specific gas constant of $R_{\text{air}} = 287$ J/kg · K in standard gravity g_0. For such a seismometer, the vertical sensitivity to air pressure changes due to buoyancy is (Zürn and Wielandt 2007)

$$\alpha_B = \frac{g_0}{\mathrm{P_{air}}} \frac{\rho_{\text{air}}}{\rho_{\text{proof}}} = \frac{g_0}{R_{\text{air}} T_{\text{air}} \rho_{\text{proof}}} = 15 \ \frac{\text{nm}}{\text{s}^2 \bullet \text{Pa}}$$

In order to be able to measure motions on the order of the NLNM at 100 s period, we need to keep variation in pressure under

$$\Delta P_B = \frac{a_{\text{NLNM}}}{g_0} R_{\text{air}} T_{\text{air}} \rho_{\text{proof}} = 0.006 \text{ mPa}$$

This requirement is stringent enough that if the pressure vessel of a seismometer is compromised, the vertical output will be dominated by this buoyancy effect.

A pressure vessel must be well designed in order to ensure that changes in atmospheric pressure do not produce equivalent horizontal or vertical outputs. Three critical specifications, then, are pressure attenuation of the pressure vessel and the pressure sensitivities of the vertical and horizontal outputs.

For the vertical channel of a seismometer in a pressure vessel, the limiting pressure effect is that due to atmospheric gravitation. Using the Bouguer plate model, in which the atmosphere above a station is modeled as a cylindrical plate having constant density, the gravitational pressure sensitivity due to atmospheric gravitation is (Zürn and Wielandt 2007)

$$\alpha_G = 2\pi \frac{G_0}{g_0} = 0.043 \ \frac{\text{nm}}{\text{s}^2 \cdot \text{Pa}}$$

Where the universal gravitation constant is $G_0 = 6.67 \times 10^{-11}$ N·m^2/kg^2. This, then, places a design constraint on a pressure vessel for a broadband seismometer: the pressure vessel will deform in response to changes in atmospheric pressure and result in a corresponding vertical acceleration, but the resulting pressure sensitivity should be less than α_G.

DOI 10.1007/978-3-642-36197-5_172-1

With this number in hand, we can reconsider the effect of buoyancy on the pressure vessel. An increase in atmospheric pressure will cause the volume of air inside the pressure vessel to become smaller; the rigidity of the vessel determines how much smaller. In order for the buoyancy effect to be much smaller than that due to the unavoidable effect of atmospheric gravitation, the pressure vessel must attenuate pressure changes by a factor much greater than

$$k_P = \frac{\alpha_B}{\alpha_G} = 340$$

For the horizontal channels of a seismometer, pressure sensitivity arises because atmospheric loading deforms the ground near the seismometer and produces measurable tilts. The level of sensitivity depends on geology and on depth, with shallow installations on unconsolidated sediment having the greatest sensitivity. At the Black Forest Observatory, the vault is 150–170 m below the surface in hard rock, and the measured admittance is typically (Zürn et al. 2007)

$$\alpha_T = 0.3\ \frac{\text{nm}}{\text{s}^2{\cdot}\text{Pa}}$$

Thus we can set a reasonable limit on the required horizontal pressure sensitivity of a broadband seismometer. When the pressure vessel deforms in response to pressure and causes the horizontal outputs to tilt and exhibit an apparent horizontal acceleration, the resulting pressure sensitivity should be less than α_T.

With both horizontal and vertical pressure sensitivities, a coherence analysis can be used to find a least-squares best-fit to the relative transfer function. This best-fit pressure sensitivity can then be used to correct seismic records for pressure, if a sufficiently sensitive microbarometer is colocated with the seismometer and recorded.

Magnetic

Temperature-compensated materials suitable for mainsprings tend to be magnetic, so inertial sensors tend to be susceptible to magnetic fields. The susceptibility takes the form of direct proportionality of equivalent output acceleration to magnetic field strength.

The magnetic sensitivity of a very broadband seismometer can vary between 0.05 and 1.4 m/s^2/T (Forbriger et al. 2010). In order for the magnetic sensitivity of a seismometer to not interfere with measurement of ground motion down to the NLNM at 100 s during a magnetically quiet period, the vertical magnetic sensitivity must be less than

$$\alpha_M = 0.7\ \frac{\text{nm}}{\text{s}^2{\cdot}\text{T}}$$

For installations which must produce quiet records even during geomagnetic storms, a magnetic shield can be used. Such shields are typically constructed of a high-permeability metal such as permalloy or mu metal.

Geomagnetic storms are not the only source of low-frequency magnetic fields. Hard drives and solar chargers are two examples of common equipment at seismograph stations which tend to generate interfering signals, and should therefore be located as far as away from the seismometer as is practicable.

As with pressure sensitivity, a best-fit magnetic sensitivity can then be used to correct seismic records for pressure, if a sufficiently sensitive magnetometer is colocated with the seismometer and recorded.

DOI 10.1007/978-3-642-36197-5_172-1

Table 3 Classification of rock for site selection

Site quality		S-wave velocity (m/s)	
Grade	Type of sediments/rocks	Min	Max
1	Unconsolidated (alluvial) sediments (clays, sands, mud)	100	600
2	Consolidated clastic sediments (sandstone, marls); schist	500	2,100
3	Less compact carbonatic rocks (limestone, dolomite) Less compact metamorphic rocks; conglomerates, breccia, ophiolite	1,800	3,800
4	Compact metamorphic rocks and carbonatic rocks	2,100	3,800
5	Magmatic rocks (granites, basalts); marble, quartzite	2,500	4,000

Site Selection

There is no substitute for a geological survey when it comes to site selection.

A site survey provides knowledge of the structures over which the seismometer will be installed. Where possible, seismometers should be installed on bedrock and as far away as possible from sources of cultural noise such as roads, dwellings, and tall structures.

The most important factor to consider in terms of geology is the composition of the uppermost stratum. For example, when the boundary of the uppermost layer is clearly defined as roughly horizontal, the S-wave velocity and thickness of that layer will determine the fundamental resonant frequency at that site. Lower velocities and larger drift thicknesses produce greater site amplification at lower frequencies.

Table 3, reprinted with permission from Trnkoczy (2002), grades site quality according to types of sediments or rocks and gives a sense of how the quality of a site relates to the S-wave velocity.

Low porosity is furthermore important as water seepage through the rock can cause tilts which overwhelm the seismic signal at long periods. Clay soils and, to a lesser extent, sand, are especially bad in this sense.

Installation Procedures

The question of how to get the best performance out of a seismometer is a very involved topic. In this section the focus will be on broadband seismometers in vault enclosures, and in particular the edges of the usual band of interest, near 100 s period and 10 Hz frequency.

Underground Vaults

The STS-1 defined the limits of ground motion measurement at long periods after it was developed, around 1980. Each component of motion, vertical and horizontals, was detected by a mechanical assembly and controlled by a set of feedback electronics in a separate enclosure.

The advent of the STS-1 was accompanied by the development of systems used to maximize its performance (Holcomb and Hutt 1990). For vertical components, pressure and magnetic shielding was provided for vertical components using a glass bell jar and a permalloy shield, respectively.

Specially designed, so-called “warpless” baseplates prevented pressure-generated tilt noise from contaminating horizontal components. The electronics are housed in a separate enclosure which is not sealed and which can require regular replacement of desiccant to avoid anomalous response characteristics (Hutt and Ringler 2011).

DOI 10.1007/978-3-642-36197-5_172-1

The installation of an STS-1 is a delicate procedure; most of the innovations in the field of broadband seismometry since then have aimed at simplifying this procedure as well as reducing power and overall footprint.

To justify the performance of an STS-1, it is usually necessary to have an underground site in hard rock, something which is expensive to construct and unnecessary for earthquake engineering applications.

Shallow Broadband Vault

An idealized broadband vault design is shown in Fig. 16.

One practical procedure for constructing such a site is as follows. A hole is dug using a backhoe in which a large-diameter plastic tube is placed. A concrete slab is poured at the bottom to serve as a pier for the sensors to rest on. Thermal insulation is added around the sensors, and the digitizer is located in a separate compartment above the sensor. A cover is placed over the tube, and the earth which was dug out to make the hole is backfilled around the tube and tamped down up to the level of the lid. A layer of rigid foam insulation is placed across the lid before piling on the rest of the soil removed in digging the hole for the vault.

This same basic procedure can be tailored to the demands of temporary installations. The seismic vault designed for the "transportable array" of the USArray project (EarthScope 2013), for example, features most of the design elements shown in Fig. 16.

Thermal Insulation

Different thermal insulation components in a broadband vault serve different purposes. The sensor insulating cover serves as bulk insulation and as a breeze cover, and by restricting the airspace around the sensor, it stops convection around the sensor. An insulating layer laid on top of the seismic pier prevents convection-driven air currents from causing the pier to distort as they pass over its surface.

The thick layer of insulation over top of the vault serves to bring the vault closer in temperature to a deeper stratum of the ground. Otherwise, a low thermal-resistance path from the vault to the surface would exist, and much of the benefit of burying a sensor in terms of thermal stability would be lost. Surface air temperature variation does not penetrate very deep into the ground; the effect of the insulation is to drive isotherms of temperature variation deeper into the ground, as shown approximately in Fig. 16. A rule of thumb for good-quality rigid Styrofoam insulation is that 2.5 cm of insulation provides the same thermal insulation as 30 cm of soil.

Pier Construction

The vault is drawn in Fig. 16 to accommodate a seismic pier which is significantly wider than a typical broadband seismometer plus its insulating cover. The reason for this is that some room must be left for the operator to stand beside the sensor and bend over it to orient the sensor to north, level it, and lock its feet. Vaults can be made significantly smaller if the seismometer is self-leveling, such as a ► Downhole Seismometer, but of course the problem of sensor orientation still needs to be addressed.

The drain shown schematically in Fig. 16 will only be effective if the water table is at or below the depth of the seismic pier. Broadband vaults such as this one are prone to flooding; the surest remedy to this problem is to make use of a seismometer that is designed for submersion (e.g., ► Downhole Seismometers).

Because of the sensitivity of a broadband seismometer to tilt, the seismic pier should be physically decoupled from the vault wall. The soil at the surface will be constantly shifting due to wind and

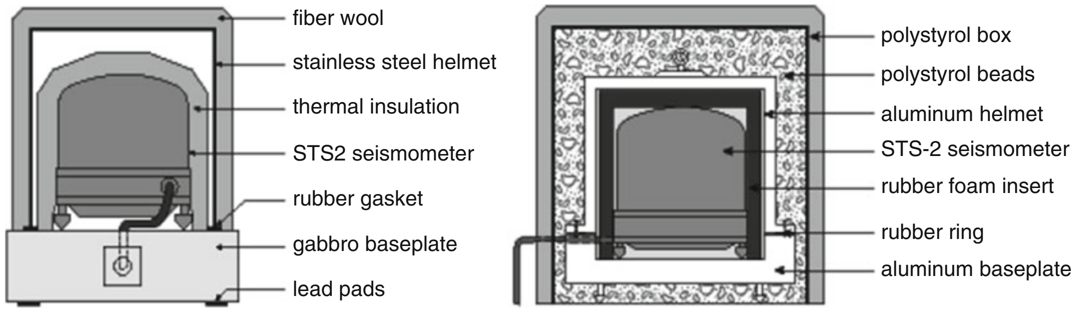

Fig. 17 Thermal and pressure shielding for STS-2 (*left*: GRSN, *right*: GEOFON)

changes in water content or frost heave. Leaving a gap between the vault wall and the pier prevents such soil motion from being transmitted through the vault wall to the pier and producing measurable tilts.

The concrete for the pier should be made from 50 % Portland cement, 50 % sieved sand, and no aggregate. It should be vibrated to eliminate voids and allowed 24 h to harden before use. The pier must not be reinforced with steel; additional strength is not needed, and the different temperature coefficients would result in detectible tilts and cracking with temperature.

All classes of seismometer benefit from being sited on competent rock because levels of high-frequency (>1 Hz) noise of all kinds are lowest when the seismic wave velocities are highest. Broadband seismometers additionally benefit because hard rock sites are less susceptible to tilt, whether driven by pressure, cultural activity, or other phenomena, and horizontal site noise levels will be dominated by tilt at long periods (<0.1 Hz).

Broadband seismometers often must be sited, however, in areas where bedrock does not come near the surface. In these cases the vault design depicted in Fig. 16 is still useful; instead of pouring concrete, it may be convenient to place a stone block on tamped gravel and use that as a seismic pier.

Thermal Shielding

Seismometer insulation is often implemented on a more or less ad hoc basis. Rigid Styrofoam insulation can be glued or taped together to make flat-faced shaped; large-diameter cardboard tubes lined with fiber wool can also be made.

The “Stuttgart shielding” method used in the German Regional Seismic Network (GRSN) is a much more systematic approach, as shown in Fig. 17, reprinted with permission from Hanka (2002). It includes a thick gabbro baseplate, polished on one side, combined with a large stainless steel cooking pot, which provides pressure shielding to improve on the native pressure sensitivity of the STS-2. Both the outside of the pot and the outer surface of the sensor are wrapped with fiber wool to provide thermal insulation. Sometimes the whole assembly is further wrapped in a thermally reflective “space blanket” to provide additional thermal shielding.

A simplified setup was introduced for the GEOFON program. An aluminum enclosure including a “warpless” baseplate provides the needed additional pressure shielding. Thermal shielding is provided by a foam rubber insert inside the aluminum enclosure and polystyrol beads outside the enclosure.

Some manufacturers provide thermal shields as accessories to seismometers. The thermal shield for a Trillium 240 is shown in Fig. 18. This cover is made of rigid molded plastic filled with insulating foam. The cover is formfitting – without quite touching the sensor – so that it greatly restricts convective airflow around the sensor, without allowing forces to be transferred to the sensor body through the insulation. It includes a race for a turn of the sensor cable, which minimizes heat

DOI 10.1007/978-3-642-36197-5_172-1

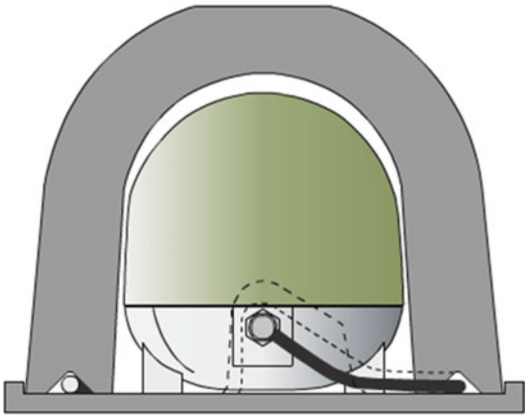

Fig. 18 Thermal shield for Trillium 240

conduction through the cable. The shield includes a foam base gasket which raises the cover up off the pier and allows the cable to exit the shield, and provides a layer of insulation between the sensor and the surface of the seismic pier. Such shielding systems are rugged and easy to transport and provide excellent shielding performance and repeatability.

Other Installation Details

Many precautions which must be taken in installing a broadband seismometer should go without saying but must be stated anyway:

- Surface of pier must be clear of debris.
- Pier should be free of cracks, particularly beneath sensor.
- Insulating cover must be close to sensor but must not touch it.
- Adjustable feet must be firmly locked.
- Connectors must not touch insulating cover.
- Cable must be strain-relieved close to the sensor.
- Cable must not touch any other structure between connector and strain relief.

Cabling is an underrated source of excess long-period horizontal noise in vault-type installations. It is recommended to "strain-relieve" the cable to the pier, sometimes by placing a heavy weight on it close to the sensor. If this is not done, thermal expansion or other motion induced in the cable can be transferred to the seismometer, generating tilt. Sensitivity to cable-induced noise is particularly acute with stiff cables; cables designed for flexibility make the whole job much easier.

It is always important to follow the manufacturer's instructions for sensor installation. Each sensor, for example, will provide different features for physical alignment of the sensor to north.

Downhole and Ocean Bottom

It is well known that site noise decreases with depth. This is the primary motivation for installations in deep, cased boreholes. Two newer techniques, which offer reduced installation costs and an even smaller surface footprint, are posthole and direct-burial installations (Nanometrics 2013). The design of such installations is however beyond the scope of this entry (see ▶ Downhole Seismometers).

The ocean bottom, in contrast, is an important environment for seismometer deployment not because of reduced levels of site noise, but because most of the earth is covered by ocean. It is

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DOI 10.1007/978-3-642-36197-5_172-1

similarly beyond the scope of this entry to treat the relevant installation techniques in detail, except to note some parallels with those used on land. Accurate leveling mitigates coupling of horizontal ground motion into the vertical output. Shallow burial can provide significant shielding from the effects of ocean-bottom currents. Colocated pressure sensors can be used to correct excess noise due to infragravity waves on the vertical. See ► Ocean-Bottom Seismometers.

Summary

A seismometer is a kind of inertial sensor which can detect the smallest ground motions in some frequency band. Broadband seismometers are those which can detect motions which are as small as the background motion at a hypothetical quiet site (as represented by a model such as the NLNM) over a frequency band which extends both above and below the microseismic peak.

A broadband seismometer has much better performance than a passive seismometer of the same physical size. The use of displacement transducers and force feedback results in an instrument with better linearity, lower self-noise, and higher sensitivity at long periods.

A broadband seismometer must be installed in a carefully designed vault to ensure that spurious signals due to tilt driven by temperature and other environmental factors are minimized. A broadband seismometer capable of resolving the NLNM at 100 s should have a vertical pressure sensitivity less than $\alpha_G = 0.04$ nm/s^2/Pa, a horizontal pressure sensitivity less than $\alpha_T = 0.7$ nm/s^2/Pa, and a magnetic sensitivity less than $\alpha_M = 0.7$ nm/s^2/T.

The construction of an effective broadband seismic vault is described in some detail. Several different kinds of thermal insulation, serving different functions, are required for optimal performance at long periods.

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