Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_194-1

Symmetric Triaxial Seismometers

Bruce Townsend*
Nanometrics, Inc., Kanata, Ontario, Canada

Synonyms

Galperin configuration seismometer; Homogeneous triaxial seismometer

Introduction

Of the class of seismic instruments measuring ground motion known as triaxial seismometers, most provide three signal outputs that represent mutually orthogonal motions in the East, North, and Vertical (or X, Y, and Z) directions (see entry "► Broadband Seismometers"). Of these, some are designed with three independent internal sensors that are respectively sensitive to motions in the three XYZ directions, and so directly measure the single vertical and two horizontal motion degrees of freedom. Some triaxial seismometers use a different configuration known as a Galperin arrangement (Galperin 1955), also known as a "symmetric triaxial" or "homogeneous" design (Melton and Kirkpatrick 1970). In the Galperin configuration, the sensing elements are also arranged to be mutually orthogonal, but instead of one axis being vertical, all three are inclined upwards from the horizontal at precisely the same angle, as if they were aligned with the edges of a cube balanced on a corner. The operational principles of a design based on the Galperin configuration have many similarities as well as some important differences relative to one based on the conventional XYZ arrangement. The Galperin configuration presents some significant benefits for the users, owners, and manufacturers of seismometers that use this topology, as well as implying some trade-offs users should be aware of.

Benefits of a symmetric triaxial seismometer include being able to more easily distinguish external noise sources from internal ones, that mass centering does not compromise mutual orthogonality of the three axes, assurance of well-matched responses of the three outputs, and ability to achieve higher performance in smaller packages. A trade-off made by the Galperin approach is that unlike conventional XYZ seismometers that can suffer the failure of one axis element while continuing to provide valid output signals for the remaining two directions, all elements in a symmetric triaxial system must function for any of its XYZ outputs to be valid.

The first modern broadband seismometer to be based on a Galperin configuration was the Streckeisen STS-2, an observatory-grade vault instrument introduced in 1990. Nanometrics introduced a symmetric triaxial seismometer with a 240 s lower corner period, the Trillium 240, in 2004. There are now a wide variety of symmetric triaxial seismometers available including models designed for borehole, posthole, ocean bottom, and vault installation and ranging from ultracompact to the large form factors.

---

*Email: BruceTownsend@nanometrics.ca

Principles of Operation

Inertial Sensing Principles

Measuring motion must always be done relative to some frame of reference. Seismometers by definition use an inertial reference; that is, motion is sensed relative to a proof mass that is suspended in such a way that the proof mass tends to remain stationary while the seismometer that is coupled to the earth (or a structure) moves relative to it. The sensing element includes some means of measuring the motion of the sensing frame to its suspended proof mass. The proof mass in most broadband seismometers is a boom hinged at one end and balanced near a null point by a mainspring. A capacitive displacement transducer is often used to sense boom deflection.

A broadband seismometer achieves its wide response and exceptional linearity by means of a force-feedback electronic control loop that includes a forcing coil constantly working to keep the mass at dead center. The electric current required to counteract any deflection of the proof mass is proportional to the acceleration of the frame. In a sense, the forcing coil must at each instant apply exactly the same acceleration to the proof mass as the seismometer is experiencing for the proof mass to “keep up with” (stay stationary relative to) the seismometer. The seismometer output is derived from a signal within the control circuit that is proportional to the time integral of acceleration, providing a signal representative of velocity.

Broadband Axis Essential Elements

A typical arrangement for a broadband seismometer axis is to have a boom hinged at one end with two capacitor plates and a wire-wound coil mounted on it to serve as the displacement transducer and forcing coil, respectively. The mounting frame has one fixed capacitor plate arranged to sit between the two on the boom, and a permanent magnet and yoke fitting into and around the boom’s forcing coil. This arrangement is mounted within the pressure vessel of the seismometer in one attitude for the vertical axis (the boom and capacitor plates horizontal) but in the upright attitude for the horizontal axes (the boom and capacitor plates vertical with the hinge at the bottom). Usually, the electronic feedback circuit together with the power conditioning, output signals, controllers, and related circuitry is on printed circuit boards arranged above the three sensing elements.

Figure 1 shows conceptual mechanical diagrams of a typical broadband axis construction configured to sense vertical motion; both perspective and side views are shown. This and subsequent diagrams are highly simplified for the purpose of illustrating solely the essential functional elements. The hinged boom with its attached forcing coil (shown in cutaway) and two outer capacitor plates have a combined proof mass $\boldsymbol{M}$ and together with the mainspring make a mechanical oscillator. The electric forcing coil attached to the movable boom acts around a permanent magnet fixed to the frame and is driven by force-feedback control loop electronics to maintain the proof mass at its measurement null point, which is where the fixed center capacitor plate is equally centered between the two outer capacitor plates. The boom is pulled down by gravity with force $\boldsymbol{F_g}$ that must be counterbalanced by the mainspring applying torque at the hinge point.

Figure 2 shows the essential construction of a horizontal axis. The principles of the horizontal and vertical designs are evidently the same, but with the horizontal axis oriented so as to be sensitive to sideway acceleration and insensitive to vertical motion. A significant difference between the two designs is that the horizontal axis mainspring only supplies a restoring force when the boom deflects from its rest position and does not counterbalance any gravitational force ($\boldsymbol{F_g} = 0$), whereas the vertical axis mainspring both supplies a restoring force and counterbalances the weight of the boom against gravity ($\boldsymbol{F_g} = \mathbf{Mg}$).

See entry “► Broadband Seismometers” for more information on the operational principles.

DOI 10.1007/978-3-642-36197-5_194-1

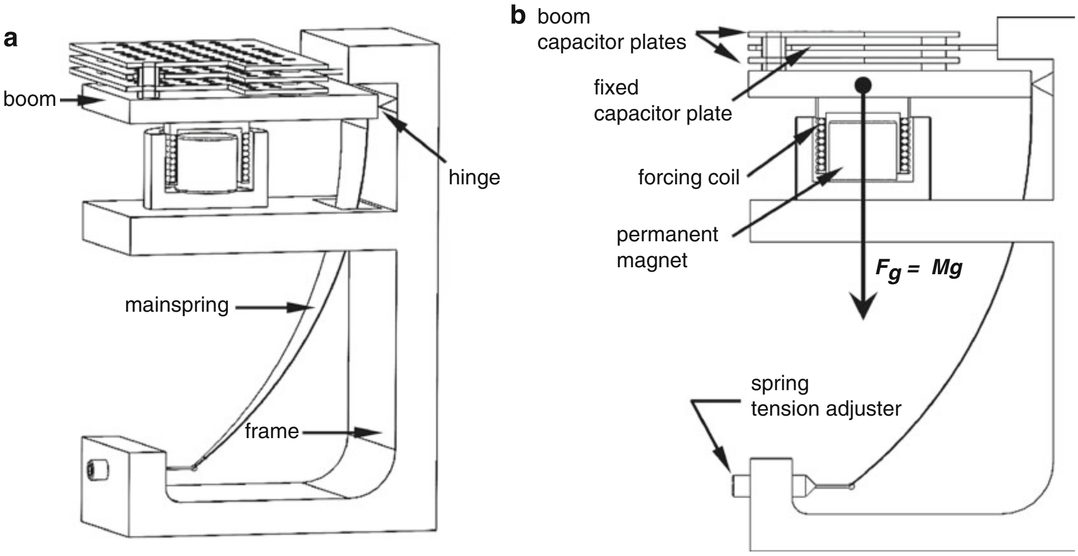

Fig. 1 Force-feedback seismometer vertical axis construction. (**a**) Perspective view. (**b**) Side view (© Nanometrics)

The XYZ Sensor Configuration

The conventional vertical/horizontal or XYZ arrangement within a triaxial seismometer has one sensing element arranged so that it is sensitive to vertical (Z) motion and two sensing elements that are sensitive to horizontal motions in the X and Y directions. This corresponds to the output signals preferred for most seismology purposes; one generally wants to record the vertical, East and North components. However, the design of the vertical sensing element is unavoidably distinct from that of the two horizontal elements. The constant gravitational acceleration of the Earth that acts on (in fact, defines) the up direction and is absent in the horizontal directions means the vertical and horizontal elements must be of different designs.

The essential differences forced on the design by the presence or absence of the constant $\boldsymbol{g_o} \cong \mathbf{9.81\ m/s^2}$ acceleration of gravity are the spring suspending the boom and the mass centering mechanism if there is one. Other design differences may also arise from practical design considerations such as the physical orientation of the vertical axis sensor being different with respect to the seismometer case, common electronics circuit boards, connectors, and the like. The vertical axis will have a hinged boom lying in the horizontal plane needing a strong spring to suspend it against gravity, and will tend to be tall and narrow as in Figure 1. A horizontal axis, having an inverted pendulum oriented in the vertical plane, will tend to be wider and shorter as in Figure 2. This creates challenges for the designer when attempting to fit one vertical and two horizontal axis elements in a single enclosure and can result in larger enclosures and/or further asymmetries between the horizontal and vertical designs to optimize physical fit.

The primary function of the mainspring that suspends the proof mass is to apply a restoring force to the mass in the direction of its center position, so that when the mass is deflected by some acceleration acting on it, the spring acts in the opposite direction to restore the position of the mass. The spring constant (the force the spring applies per unit of deflection) is generally as weak as can be practically achieved, so as to ensure the mass may freely move relative to the frame in which it is suspended. However, the mainspring of a vertical sensor must also balance the suspended proof mass against the acceleration of gravity, whereas the mainspring of a horizontal sensor does not. For example, a proof mass of $\boldsymbol{M} = \mathbf{200\ g}$ in a vertical axis of the type shown in Fig. 1 experiences a downwards force due to gravity of $\boldsymbol{F_g} = \mathbf{Mg} = \mathbf{1.96}\ \boldsymbol{N}$ that applies a torque at the hinge point, and

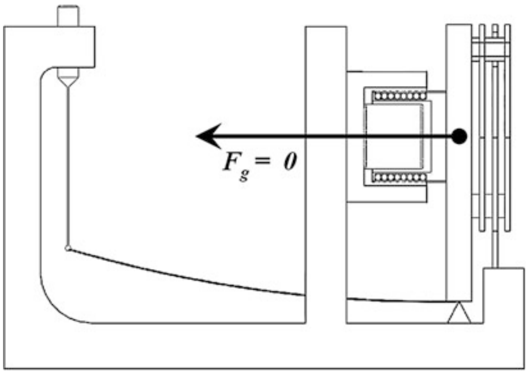

Fig. 2 Force-feedback seismometer horizontal axis construction (© Nanometrics)

the spring must apply the equivalent counteracting torque to keep the mass balanced at the center position.

Adjusting the sensing axis so that the boom is positioned at the center position of the displacement transducer is known as "mass centering." This is a mechanical operation which is done for some seismometers by the operator turning an adjustment screw, and for others by microprocessor-controlled motors within the seismometer making the adjustments automatically, initiated by an external command or signal. On a horizontal axis, this is often done by tilting the axis (e.g., Guralp CMG-3T, Streckeisen STS-1) one way or the other within a range of a few degrees, which allows gravity to act sideways on the axis in proportion to the sine of the tilt angle (which for small angles is directly proportional to the tilt angle). If the mass is decentered either because the spring is applying a decentering force or because the seismometer is tilted off level, applying a small amount of gravity to one side or the other of the axis by tilting it in the opposite direction deflects the mass back to its center position. This method is depicted in Fig. 3, showing a horizontal axis on its internal mounting plate in an off-level situation. In Fig. 3a, gravity has pulled the boom off-center and its two capacitor plates are not centered about the middle capacitor plate that is fixed to the frame. In Fig. 3b, the axis has been tilted mechanically to re-center the boom mass. Note that the direction of sensitivity changes as the axis is tilted.

Tilting a vertical axis to center the mass is not practical because the effect of gravity on the axis is proportional to the cosine of the tilt angle, which for small angles has almost no effect: a vertical axis would have to be tilted by 10.7° to counteract the same deflection as for a 1° tilt of the horizontal axis element. Instead, the mass centering for a vertical axis is done in one of two ways: by adjusting the tension of the main spring to change the force applied to the boom (e.g., Guralp CMG-3T) or by changing the position of the center of gravity of the hinged proof mass by moving an adjustable slug horizontally along the mass relative to the hinge point (Streckeisen STS-1). Figure 4 shows how both methods work in principle. In practice the mechanisms are of course more elaborate and are often motorized. Note that, unlike the method of tilting the axis, the direction of sensitivity does not change as the spring tension is changed or the center of mass of the boom is adjusted.

A non-Galperin three-component broadband seismometer includes two horizontal axes and one vertical axis, usually mounted within a common pressure vessel. Because axis tilting is used for mass centering the horizontal elements but not the vertical element, the mutual orthogonality of the XYZ components is compromised by the degree of tilt applied. This phenomenon is illustrated in Fig. 5, which shows one of the two horizontal axes and the vertical axis side by side on the same tilted base, the two axis elements having been centered by different methods resulting in non-orthogonal directions of sensitivity.

DOI 10.1007/978-3-642-36197-5_194-1

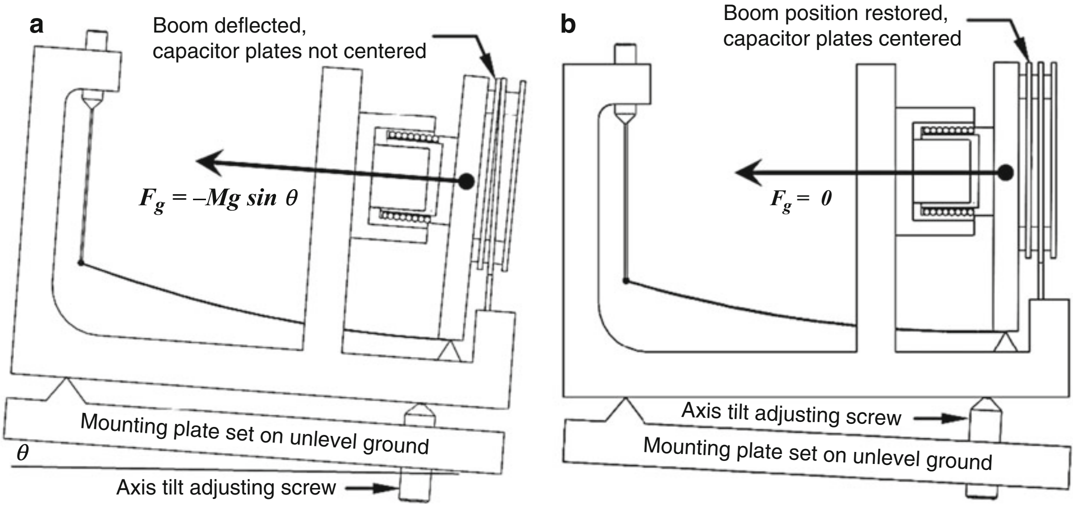

Fig. 3 Mass centering a horizontal axis by tilting. (**a**) Tilted axis on unlevel ground. (**b**) Axis internally tilted to re-center mass (© Nanometrics)

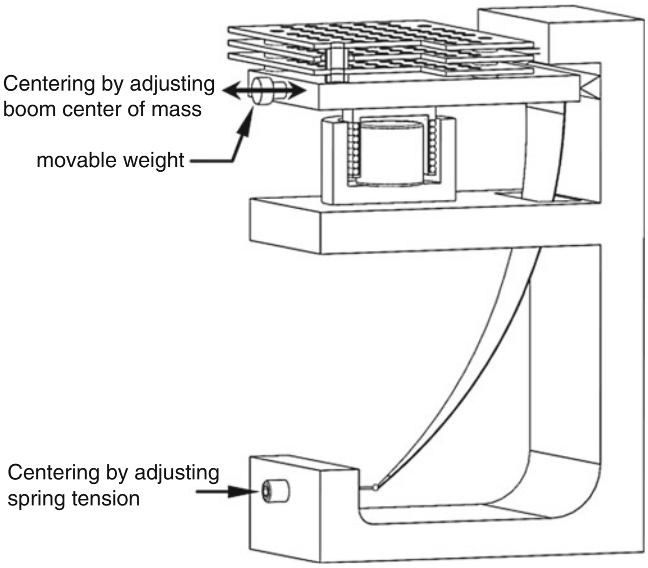

Fig. 4 Two methods for mass centering a vertical axis (© Nanometrics)

Practical design considerations also tend to encourage differences in implementation between the vertical and horizontal sensors. Asymmetries between the vertical and horizontal sensor elements arise for several practical reasons, despite the principles of operation being much the same. Besides the mainspring designs that must be different (one counters gravity, the other does not) and the significantly different mass centering mechanisms, the physical orientation and aspect height/width ratio of the two types of axis are asymmetrical. As the two horizontal axes and one vertical axis mount side by side on a common base plate (or are stacked vertically for a borehole configuration), such practical details, such as mounting features, wiring harness, and circuit board connectorization, fit, and placement within the enclosure and other considerations generally lead to substantive design differences between the vertical and horizontal elements.

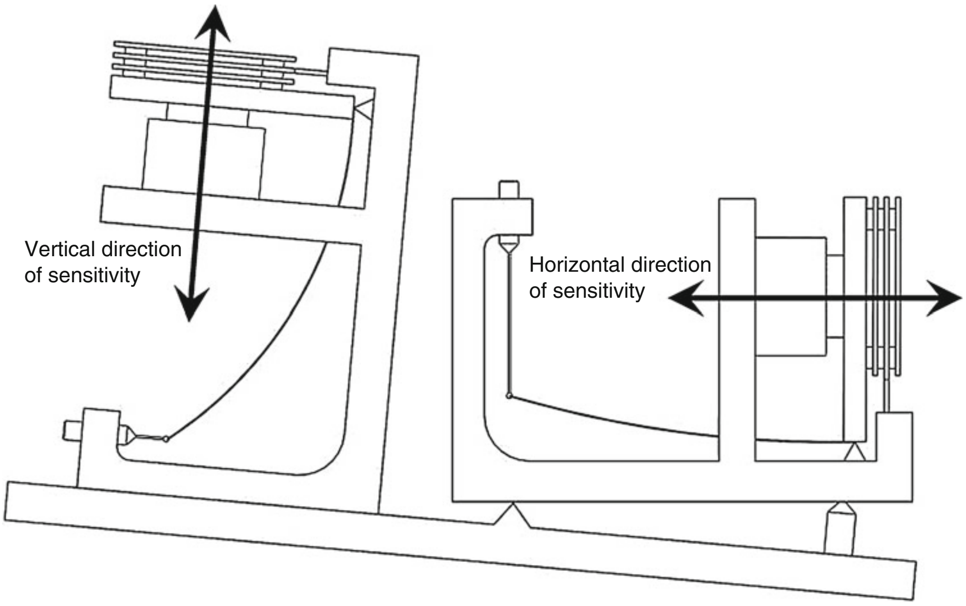

Fig. 5 Vertical and horizontal component non-orthogonality (© Nanometrics)

The Galperin Sensor Configuration

An alternative configuration to the conventional XYZ horizontal/vertical arrangement was proposed by Galperin, in which the three sensing elements of a triaxial seismometer are arranged in such a way that permits them to be identical in every respect. This is achieved by rotating the orthogonal sensing axes from the XYZ frame of reference to an orientation where each of the three (still mutually orthogonal) axes is inclined up from the horizontal plane at the same angle.

Figure 6 illustrates a symmetric triaxial arrangement. The directions of sensitivity of the new U, V, and W axes are shown overlaid on the XYW coordinate system. In this orientation, the edges (or directions of sensitivity, or axes) are often given the designations U, V, and W (Wielandt 2002), creating a new "UVW" coordinate system. The projections downwards of the three UVW axes onto the horizontal plane are lines radiating from the center equally spaced 120° apart. This arrangement is called symmetrical because each axis "sees" the same proportion of gravitational acceleration and this allows the axes to be constructed identically. It is possible to choose any upwards inclination angle θ for the three axes for this arrangement to be symmetrical (such as 45°), but setting $\theta = \tan^{-1}\left(\frac{1}{\sqrt{2}}\right) \cong 35.26^\circ$ also makes the UVW axes mutually orthogonal.

The UVW system is then a simple rotation from the XYZ. This can be visualized by thinking of the XYZ directions of sensitivity as the three edges of a cube radiating from one of its eight corners, where the cube is resting on a horizontal surface. The X and Y directions are along two perpendicular edges of the cube's bottom face, and the Z direction is the vertical edge of the cube that joins the same corner where the X and Y edges meet. Now visualize the cube being tilted upwards with only the common corner resting on the flat surface, and balance it so that the topmost corner of the cube is directly above its bottom corner. The edges that meet at the bottom corner are still of course mutually orthogonal but now form the same angle upwards with respect to the flat surface base.

The trigonometry of this "balanced cube" arrangement results in the angle formed between any of the UVW axes and the horizontal plane being $\theta = \tan^{-1}\left(\frac{1}{\sqrt{2}}\right) \cong 35.26^\circ$. The complementary angle with respect to the vertical is then $\theta_0 = 90^\circ - \theta \cong 54.74^\circ$.

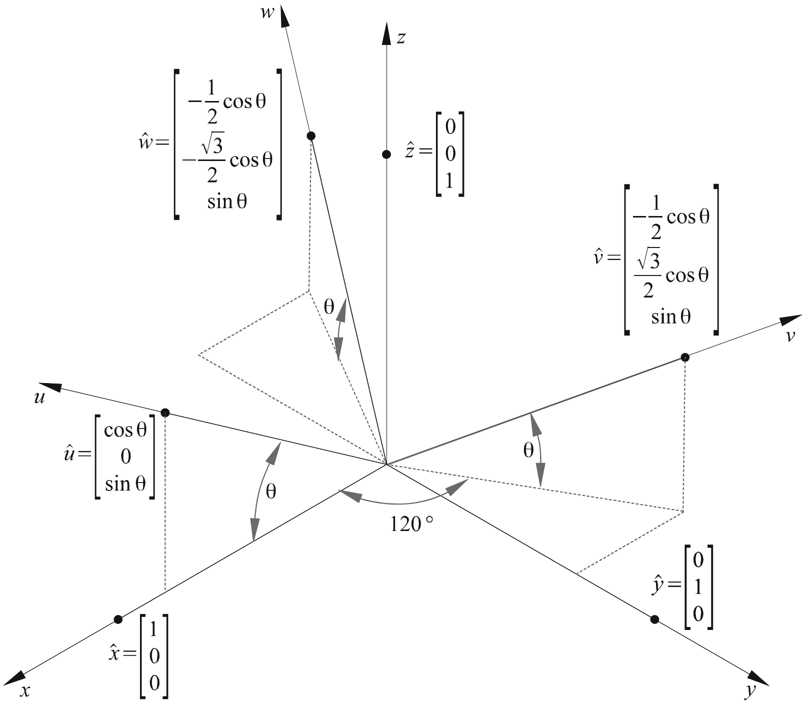

Fig. 6 Isometric view of UVW and XYZ coordinate systems (© Nanometrics)

Figure 6 employs the convention used in Nanometrics Trillium seismometers whereby the projection of U in the XY plane points in the X direction, and the UVW system is right-handed like the XYZ coordinate system (Nanometrics Inc. 2013). The convention for Streckeisen seismometers is that the projection of U in the XY plane is antiparallel to X and that the UVW coordinate system is left-handed (Streckeisen and Messgeräte 1995).

Note that the term "symmetric triaxial" is not in itself sufficiently specific to fully define the Galperin configuration, as any triaxial orientation with horizontal projections spaced 120° apart and where each axis of sensitivity forms the same angle with respect to vertical (say, e.g., 45° instead of 54.74°) is a symmetric arrangement. Each axis still experiences gravity equally and they are arranged symmetrically with respect to each other, but they no longer meet at right angles as the edges of a cube. The Galperin topology requires the three axes to be mutually orthogonal as well as having the same angle with respect to the vertical direction, which then fully constrains their mutual orientation. Nevertheless, the "symmetric triaxial" designation is usually assumed to refer to the more specific Galperin topology.

Figure 7 shows conceptual mechanical diagrams of the structure of an axis suitable for a symmetric triaxial seismometer, showing the boom set at an oblique angle, but otherwise based on the same principle as a vertical axis, with the mainspring suspending the weight of the boom against gravity ($F_g = \mathrm{Mg}\sin\theta$). For the specific case of a Galperin axis set at a $\theta \cong 35.26°$ angle, $\sin\theta = \frac{1}{\sqrt{3}}$. Because each axis experiences the same static acceleration due to gravity, $\frac{1}{\sqrt{3}}g_0$, the mainspring counterbalancing gravity is identical on all three axes. Because the direction of sensitivity of each axis is inclined by the same angle $\theta_0 = 90 - \theta$ with respect to the vertical, the physical design of the axis can be made identical for all three UVW component directions.

The directions of sensitivity with respect to the X or East direction are of course different for each axis – they are equally spaced 120° apart as shown in Fig. 6 – but that is achieved by arranging the three identical sensing elements next to each other on the same horizontal base and pointing them in

DOI 10.1007/978-3-642-36197-5_194-1

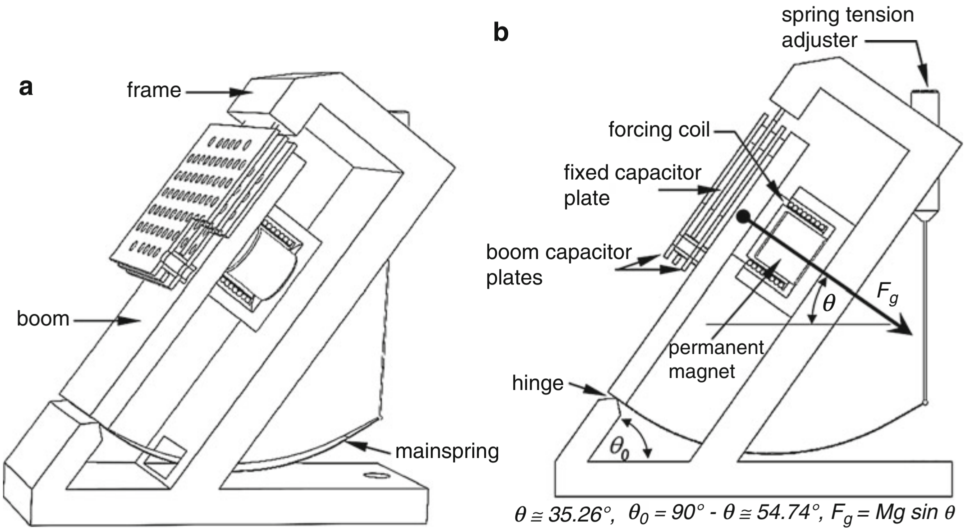

Fig. 7 Oblique axis construction suitable for a symmetric triaxial seismometer. (**a**) Perspective view. (**b**) Side view (© Nanometrics)

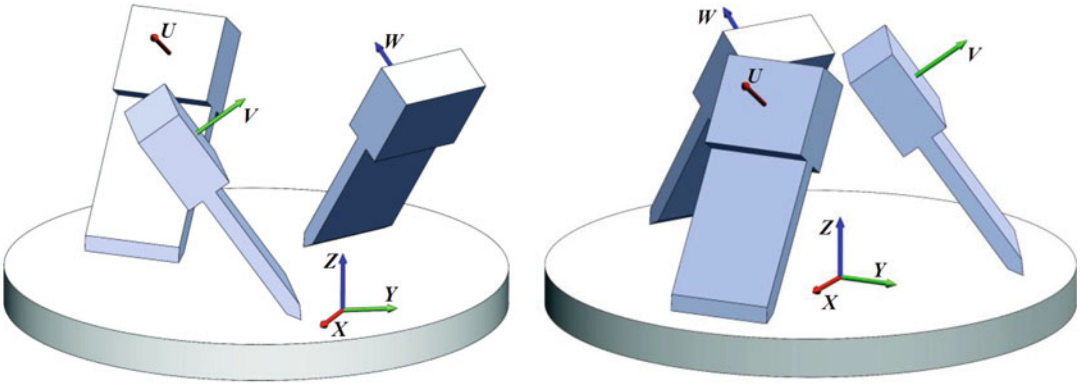

Fig. 8 Two Galperin-type axis arrangements for a vault instrument (© Nanometrics)

different but equally spaced directions as shown in Fig. 8. This is typically how vault seismometers are configured internally. Seismometers for borehole or posthole installations usually have the three axis elements stacked in a vertical column, one above the other pointing in different directions, but the principle is the same. The diagrams in Fig. 8 illustrate that there is more than one suitable way to dispose the three Galperin axis elements within a seismometer. Note that the relative directions of X, Y, Z, U, V, and W are the same in both arrangements; the three axis elements have just been translated to different positions on the base. The leftmost arrangement of axis elements is employed in the Nanometrics Trillium 120P vault instrument, for example, while the Streckeisen STS-2 vault instrument employs an arrangement similar to the one shown on the right.

Mass centering of a Galperin-type axis may be achieved by any of the methods used with horizontal or vertical axes: tilting the axis, adjusting the mainspring, or manipulating the center of gravity of the boom. Examples of each method used on Galperin-type instruments are the Streckeisen STS-2 vault instrument that moves a slug on the boom, the various models of Nanometrics Trillium observatory-grade seismometers that adjust the tension on the mainspring, and the Geotech KS54000 borehole seismometer that tilts each axis in its vertical stack.

DOI 10.1007/978-3-642-36197-5_194-1

Mutually orthogonality UVW (and therefore XYZ) directions of sensitivity are maintained because the masses of all three axes are centered using the same technique, taking advantage of the symmetry of the design. Unlike in Fig. 5 that shows how a vertical and horizontal axis can become mutually non-orthogonal, the Galperin designs do not adjust one axis using a different technique than the others. For example, the direction of sensitivity of the Galperin axis depicted in Fig. 7 is fixed by its geometry to be at 90° to the face of the boom. Adjusting the tension of the spring to re-center a deflected mass does not alter the direction of sensitivity, and because the three axes are permanently fixed to a common mounting plate as in Fig. 8, the three UVW directions remain mutually orthogonal.

The commonly desired XYZ horizontal/vertical signals are readily derived from the UVW signals using a vector algebraic transformation:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{\sqrt{6}} \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

The inverse transformation derives UVW from XYZ:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\sqrt{6}} \begin{bmatrix} 2 & 0 & \sqrt{2} \\ -1 & \sqrt{3} & \sqrt{2} \\ -1 & -\sqrt{3} & \sqrt{2} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

The transformation to the conventional XYZ frame of reference may be done at any point, such as by seismic analysis processing software just before the signals are plotted or used as input to seismic analysis algorithms that assume the XYZ reference frame. However, as a convenience to the operators of seismic signal data centers and the users of the seismic data, most Galperin-type seismometers effect the signal transforms within the instrument by summing the UVW signals in the required proportions using a precision analog mixing circuit. Some seismometers (e.g., Nanometrics Trillium models) allow the operator to optionally configure the instrument to output raw UVW instead of the mixed XYZ if desired, though this is primarily used for instrument troubleshooting rather than for routine recording of seismic data.

Benefits and Drawbacks of the Galperin Configuration

The choice between a Galperin and a conventional configuration is usually regarded as a secondary consideration in specifying an instrument, as the internal topology of the seismometer does not of itself dictate the performance or reliability of an instrument. However, while either configuration is capable of achieving reliable high performance, the symmetric triaxial configuration does offer some significant benefits to users. The two topologies have distinct characteristics that are useful to consider when selecting, installing, operating, or troubleshooting a broadband seismometer.

Commonly Cited Trade-Offs

Response Matching

Because the designs of a horizontal axis and a vertical axis differ significantly, it requires special effort in design and diligence in manufacture to match the transfer functions of the two different constructions, if they are to provide the same response to ground motion in terms of passband sensitivity, lower corner frequency/phase response, and the upper corner response. Indeed, there is no constraint other than designer or user preference that requires the response of the vertical to match the response of the horizontal component; the two could be markedly different with the manufacturer providing the specifications for each component by giving, for each axis, a frequency/phase response plot or a set of poles and zeros and passband sensitivity. In contrast, because the Galperin configuration requires its cardinal XYZ outputs to be derived as weighted sums of all the UVW components, the design and the manufacturing must ensure that all three components are very closely matched; otherwise the transfer functions of the XYZ outputs become complicated. The symmetrical nature of the Galperin topology helps produce matched responses because the three axes are constructed identically. Manufacturers of Galperin seismometers supplement this advantage with precision machining, trimming of electronics values, and other calibration measures to precisely match axis responses. The precision matching of U, V, and W components in a Galperin design provides assurance to the user that the X, Y, and Z transfer functions are likely to be consistent and the same as any of the U, V, or W transfer functions.

Response matching is easily tested on a Galperin instrument by providing a vertical signal on a high-quality vertical shake table or by injecting the same calibration signal into all three UVW components simultaneously (which is equivalent to providing a calibration input in the vertical direction). The output should be pure vertical; the extent to which signal is present on the X and Y outputs is a measure of response difference between the UVW elements. By sweeping the frequency of the input and recording the vertical and horizontal outputs, the quality of the response matching can be measured across the frequency band.

In contrast, subjecting a conventional XYZ design seismometer to a pure vertical stimulus tests only the vertical axis and does not provide any insight into how well the responses of the three axis components are matched.

Manufacturing Trade-Offs

Some aspects of the design and manufacture of Galperin instruments are simplified or facilitated, while others are made more complex. Obvious advantages to the manufacturer derive from having only one electromechanical axis design within a seismometer. That means there are fewer unique part types to manage, only one style of axis to build and test, and the identical axes can be readily swapped for troubleshooting or repair purposes. On the other hand, a symmetric triaxial seismometer requires a UVW-to-XYZ analog electronic mixing circuit that is not needed in an XYZ design, adding somewhat to the cost of manufacture.

Because the vertical output signal of a symmetric triaxial design is an equally weighted sum of the UVW components, a clean vertical signal provides complete assurance that all three components are well behaved. As the horizontal signals at most surface sites are usually noisier than the vertical due to tilt effects, especially at long periods, it is often feasible to test and qualify the vertical channel but more difficult to do so for the horizontals. This permits the manufacturers of Galperin designs to reliably test the performance of all three sensor elements by qualifying the vertical signal, providing assurance to the users that all three outputs meet the published specifications. In contrast, the X and Y components of a conventional design cannot be assessed by examining the vertical channel signal.

Reliability Trade-Offs

An often-cited drawback relating to the Galperin configuration is that all three UVW components must be functional and well behaved for any of the XYZ outputs to work (Graizer 2009). It is held that this contrasts with a conventional seismometer where any one of the three components could fail without compromising the other two. This can be seen as a corollary of the fact that a good vertical output from a Galperin configuration provides assurance that all three sensor elements are good.

The spontaneous catastrophic failure of just an individual axis element within an operating seismometer is relatively uncommon. It is more likely for catastrophic failure to occur or be evident at installation time (in which case most operators would choose not to deploy even if there was a good vertical still operating) or for a failure to occur in a way that affects the entire system, such as an electronics fault.

Many seismometers with Galperin configurations provide the ability to remotely choose between UVW and XYZ outputs. In this case, if a failed axis is detected and a site visit is not feasible, high-quality biaxial data can still be recorded after the flip of a switch.

It is possible for an element to develop noise spontaneously, and in this case the conventional design has the advantage: a Galperin design would mix the noisy channel into its vertical output (where it is most easily detected), whereas the conventional XYZ design would only manifest the noise on the output associated with one degraded axis.

A manufacturer can minimize the likelihood of excessive channel noise by ensuring the seismometer self-noise is tested before leaving the factory and by designing the instrument for long-term operation to ensure performance is maintained through the instrument’s operating life.

Other Benefits of a Symmetric Triaxial Design

Using the UVW Orientations to Discriminate Noise Sources

The symmetric triaxial configuration makes it possible to distinguish phenomena that occur within one axis element from those that occur independently of one axis element. The operator can use this to advantage, helping diagnose and resolve problems associated with the environment, installation, ancillary equipment, or the seismometer itself. This is discussed in greater detail in the section “Using the Galperin Topology to Help Discriminate Noise Sources” below.

Assuring the Mutual Orthogonality of Component Signals

The three identical and symmetrically arranged sensor elements of the Galperin configuration are fixed to be mutually orthogonal during manufacture. A mass centering operation, whether moving a slug to shift the boom center of gravity or adjusting mainspring tension to return the boom to center, does not alter the mutual orthogonality of the directions of sensitivity. In the first case the sensitivity direction of each axis is shifted by the same amount and so they remain mutually orthogonal. In the latter case, the tension of the main spring does not alter direction of sensitivity and so orthogonality is also preserved. However, a conventional XYZ design tilts the horizontal axes but adjusts the mainspring tension for the vertical, causing the horizontal directions of sensitivity to change relative to the Z axis. This causes the horizontal components to shift relative to the vertical by an angle equivalent to the tilt of the seismometer housing itself. Effectively, the vertical of an XYZ design remains aligned to the housing while the horizontals remain perpendicular to gravity.

Using the Galperin Topology to Help Discriminate Noise Sources

Using a seismometer that has a Galperin design can facilitate identifying noise sources by showing whether they are specific to one axis element or not. This section discusses noise sources and some methods for troubleshooting noise artifacts that use the characteristics of the symmetric triaxial configuration to advantage.

Noise Sources

A noise artifact is usually apparent only once it is in the seismic record. This record is furthermore the sum of all effects applied by the entire system including the environment, site, seismometer mount, the seismometer itself, cables and connectors, the digitizer, and signal transmission and post-processing. [In this context the "seismometer mount" is a general term that refers to the structure the seismometer is mechanically coupled to. That may be a concrete pier, a gimbal mount such as for an ocean bottom system, surrounding granular substrate as in the case of a buried instrument, a metal bracket affixed to a building structure, and others.] All these components of the end-to-end system must be considered when investigating noise or other signal impairments.

Noise may be generated by processes within the seismometer or by external processes acting on the seismometer. Some noise is expected or unavoidable, such as the manufacturer's characterized self-noise, or may be indicative of instrument defects such as persistent spurious transient noise event ("pops") or installation deficiencies such as thermally driven noise or the seismometer shifting or tilting. It is first useful to review some typical sources of internal and external noise.

The sources of noise (defined as any type of additive unwanted signal) in a seismic record include inherent instrument noise (self-noise), environmental effects, excessive instrument noise, installation-driven noise, and ancillary equipment noise. A seismometer's self-noise is usually specified by the manufacturer, typically as a power spectral density (PSD) plot, and this establishes a performance baseline for an installation. Good installation practice will include mitigating sources of environmental noise as much as is practical. Excessive instrument noise is defined as noise originating within the seismometer in addition to its published self-noise characteristic and may represent variability in the manufacturing, defects, or failures. Installation-driven noise is defined as a non-seismic signal that originates from poor or defective installation practices. Lastly, noise may also be added by downstream ancillary equipment such as the digitizer.

Environmental and Installation-Driven Sources of Noise

Seismometers respond in varying degrees to many stimuli besides seismic motion, and while seismometer designers try to maximize the immunity or insensitivity of the instrument to everything except translation ground motion, this is difficult to achieve. The installation must also be designed to maximize the effectiveness of the seismometer. An inadequate installation of even the highest performance seismometers can yield very poor results, showing high noise levels and susceptibility to non-seismic environmental inputs. There is therefore significant benefit in tools and techniques that help diagnose installation deficiencies and distinguish them from instrument problems.

Environmental influences on a seismometer that may cause unwanted output signal (noise) include temperature changes, seismic wave-induced tilt, Earth's magnetic field or fields generated from local equipment, wind-induced ground motion, atmospheric pressure changes, electrical interference induced on the output signal, and other effects. Many environmental influences can be mitigated, such as by providing a temperature stable vault and locating the installation far from vertical structures such as trees that conduct wind noise into the ground. Some are more difficult or even impossible to eliminate, such as apparent vertical accelerations induced by changes in atmospheric pressure, because the apparent acceleration due to gravitation cannot be distinguished from other kinds of acceleration and is relatively insensitive to the depth of the site (Zürn and Wielandt 2007).

Installation-driven noise sources are those that induce motion on the seismometer due to defects in the installation itself. A common example is poor mechanical coupling of the instrument to the ground, which may allow the seismometer to move relative to the structure being monitored. This can be due to poor mounting, inadequate substrate, poor coupling to the ground, improperly locked

DOI 10.1007/978-3-642-36197-5_194-1

mounting feet, or cables applying strain on the seismometer. Such problems most commonly produce tilt noise, but vertical noise is also possible, such as for a seismometer "bouncing" up and down on adjustable feet that have not been tightly locked. Another example is convection-driven air currents within a vault inducing low-frequency horizontal tilt noise. Such noise is produced by slow-moving air currents acting on the seismometer to expand or shrink the sides of its case unevenly and thus tilting it.

A seismometer exhibiting excessive response to environmental stimuli may be indicative of an instrument defect. For example, a leak in the pressure vessel that allows atmospheric air pressure changes to pump air in or out of the seismometer will manifest as a non-seismic vertical signal as the buoyancy of the proof masses responds to internal air density changes. This is most commonly seen in instruments that have access ports that an operator may open, such as to insert a screwdriver for manual mass centering, and that may not be properly closed or where the seals may have degraded.

Sources of Internally Generated Seismometer Noise

All seismometers generate noise internally, that is, they would produce a signal even if the ground was not moving at all. This inherent noise is characteristic of the design and is usually specified in some detail by the manufacturer, although in the case of passive seismometers, the manufacturer will instead usually provide a few parameters from which the self-noise can be estimated. Noise is inherent in electronics circuits due to a multitude of phenomena in conductors and semiconductors, such as thermal noise and flicker noise. The suspended mass and spring has inherent noise due to the Brownian motion of air molecules buffeting the mass, air damping the boom motion, as well as other energy-loss mechanisms. The summation of these effects produces a stationary noise spectrum that is commonly referred to as the seismometer's "self-noise," often represented as a PSD graph and commonly shown together with the New Low Noise Model (NLNM) and New High Noise Model (NHNM) (Peterson 1993). Reputable manufacturers provide this information for each model and produce instruments with performance consistent with their published specifications.

Excessive instrument noise is internally generated noise that exceeds the self-noise specification of the seismometer. There are three broad classes of excessive internal noise:

1. Stationary broadband noise that significantly exceeds the instrument's published self-noise specification
2. Nonstationary transient noise events, such as pops or spikes
3. Stationary narrowband noise, such as tones or oscillations

A common technique for measuring noise is frequency domain analysis, such as plotting the acceleration power spectral density (PSD) of the seismic data over some time period. While tones are readily distinguishable from broadband noise, nonstationary events such as pops have a broadband spectral characteristic (typically proportional to $^{1}/_{f^2}$) that can mislead the troubleshooter. However, small pops may not be readily identified by examining the time-domain time-series data as they may have amplitudes too small to be distinguished from the background seismic activity.

The Galperin Topology and Noise Source Identification

Being able to demonstrate that a noise phenomenon is peculiar to one particular axis element and not the other two, or conversely that a noise is registered by more than one axis, can be a powerful technique to help isolate and identify noise sources and causes. The Galperin topology facilitates this because its sensor reference coordinate system (UVW) is rotated from the vertical/horizontal (XYZ)

Table 1 Channel characteristics of some possible noise sources (© Nanometrics)

	Potential noise sources						
Channels showing non-seismic noise	**Axis mechanics or electronics**	**Tilt motion**	**XY oriented seismometer mount (e.g.,gimbal)**	**UVW-XYZ conversion electronics, cable, digitizer**	**Varying temperature or pressure leaks**	**Varying magnetic fields**	**Power supply, electrical/magnetic interference**
U, V or W only	Probable						
X or Y only		Possible	Possible	Possible			
Z only				Possible	Possible		
X and Y in some proportion but not Z		Probable					
Equally on all X/Y/Z channels				Possible			Possible
Unequally on X/Y/Z channels						Possible	Possible

coordinate system, providing a powerful way to distinguish instrument noise sources from environmental or installation phenomena. Many external noise phenomena have a characteristic direction – often horizontal or vertical – and in any case are unlikely to align with one of the U, V, or W directions. Likewise, noise that is associated with a U, V, or W direction provides a clear indication that the noise source is internal and associated with that axis.

Table 1 provides general guidelines for narrowing down the sources of an observed noise signal and provides a starting point for troubleshooting. This presumes the operator is able to perform the essential basics of signal analysis: conversion from XYZ to UVW domains, plotting time series and frequency domain plots such as a PSD, removing instrument frequency response, and the like. Table 1 also presumes the seismometer has a Galperin topology.

Once a noise artifact is recognized and classified (e.g., stationary broadband, nonstationary transient, or stationary narrowband) and characterized as much as possible, the next step is to determine whether it consistently manifests on a specific X, Y, Z, U, V or W channel or a particularly suggestive combination of these channels. This is equivalent to asking which direction the signal represents. Signals specific to X, Y, or Z suggest East/West, North/South, and up/down motions or phenomena that mimic these. Signals specific to U, V, or W suggest motions in those axis directions or, more likely, phenomena within the axis mimicking this direction. A signal that manifests on X and Y but not (or very little) on Z represents motion in a horizontal direction that is not East/West or North/South, or a phenomena such as tilt that mimics that. A signal that is equal on X, Y, and Z is more likely to be a common-mode electronics noise problem than a real motion in the direction represented.

Because it is unusual to have real seismic motion act exactly along any of these X, Y, Z, U, V, or W directions, signal artifacts with these characteristic directions are more likely to be of non-seismic origin. An exception could be a site expected to have motions exactly along a specific direction, such as a seismometer located near the top of a swaying structure, oriented so that its X channel (say) is aligned with the direction of sway.

Having narrowed the potential sources, it is usually possible to make further deductions from the character of the signal artifact observed. The next sections discuss typical phenomena and their classifications according to possible sources listed in Table 1.

Axis Mechanics or Electronics: UVW Channel Noise

Noise artifacts apparent on one U, V, or W channel and not on the others point squarely to a noise source associated with that axis. Of course this can only be recognized by transforming the seismic data into the UVW domain to observe that a noise previously apparent on all XYZ channels is suddenly associated with just a single one of the Galperin axis elements. Noise that is vertical (Z only) or horizontal (some combination of X and Y) cannot have a source within a Galperin-type axis.

A noise event commonly attributed to highly sensitive broadband seismometers is that of pops, otherwise known as spikes or steps. These are sudden sharp excursions in the seismic waveform that appear as if there had been a sudden step in acceleration. This can be the result of spontaneous movements at a microscopic level within the axis mechanism or sudden shifting of the seismometer itself due to installation or mounting problems. If a pop is evident only on one U, V, or W axis, it is due to spontaneous movement within the axis, such as some mechanical stress or strain suddenly relaxing. Inadequate design, assembly flaws, component defects, or rough handling can give rise to excessive rate of pops in an axis. One indication of excessive axis pops is when the PSD is plotted for the U, V, and W signals and there is a well-defined $^1\!/_{f^2}$ spectrum in the lowest frequency band of one of the axes. It is well known that seismometers are more prone to pop noise when first manufactured, installed in a new location, or acclimating to a new environment as stresses are relieved.

Excessive broadband axis noise (specific to a U, V, or W axis) can be due to electronics noise, for example, excessive current noise due to components not meeting specification.

Excessive axis-specific narrow band noise is less common, but can occur if there is excessive loop gain or insufficient phase margin in the control loop of one axis. This would generally suggest a manufacturing or design defect and could also be the consequence of component failure or rough handling.

A signal impairment specific to one U, V, or W axis such as zero signal or railed signal suggests an axis failure, such as failure to center, or a failure of the electronic circuitry associated with that axis.

Likewise, a non-seismic noise or other impairment (such as zero signal or railed signal) that is not limited to a U, V, or W channel but manifests as a horizontal or vertical signal cannot be an axis problem but must have some other origin, as indicated in Table 1. The following sections discuss these other potential noise origins.

Tilt Effects: XY Channel Noise

The most common sources of noise are installation deficiencies and environmental stimuli, often where inadequate installation fails to counter environmental drivers such as temperature changes or air currents. Some of these effects are quite subtle but can create significant noise artifacts. It is quite common to see horizontal noise levels for a seismic station be significantly greater than the vertical noise floor (Hanka 2002). While horizontal noise could be ascribed to noisier horizontal components in a conventional XYZ design, with a Galperin topology with identical UVW elements, noisier horizontal data can definitively be attributed to a process external to the seismometer.

Because tilt mixes gravitational acceleration into the horizontal channels in direct proportion to the tilt, and because gravity is significant compared with the small accelerations due to background seismicity, even sudden tilts of less than a millionth of a degree will be registered by broadband seismometers and appear as noise artifacts. The effect is far less significant for vertical because gravity mixes to the vertical in proportion to the cosine of the tilt angle, which is a near-zero effect for small angles.

Seismic waves traveling on the surface of the Earth that produce vertical translation motion (like a cork bobbing on the waves of an ocean) also cause tilt: one can visualize a raft on the same ocean that tilts one way as it rises up one side of the wave and then tilts the other way as it falls. The rise/fall is vertical motion the seismometer will faithfully record, but the tilt induces a small varying sideway component of gravity producing a noise signal on the horizontal channels in addition to the real horizontal motion. Because tilt motion is inherent in seismic motion at the Earth's surface, horizontal tilt noise cannot always be mitigated. However, excessive tilt noise and in particular sudden discrete tilt events are usually indicative of installation problems that should be addressed.

Noise artifacts that appear on X and/or Y but not Z are horizontal and often represent the seismometer tilting in some manner. There are many potential causes and sources of tilt, and so it is useful to further characterize the noise. Sudden isolated transitions are suggestive of rapid discrete tilt events, oscillations can indicate rocking behavior, and broadband horizontal noise may indicate continual random tilting. Steps that occur with a consistent polarity suggest a series of tilts in the same direction, as may happen if the seismometer is slumping in discrete steps to one side. Steps that alternate polarity may indicate a back-and-forth tipping action. The direction of the tilt is indicated by the proportion of X-to-Y noise, and some combination of X and Y (with very little Z) noise is a further confirmation of probable tilt action.

Atmospheric pressure changes acting on a sealed vessel such as a seismometer will deform the vessel to some extent, and because tilts much less than 10^{-6} of a degree can generate noise, even miniscule deformations can matter. Seismometer designers generally take great care to ensure those deformations do not act to tilt the internal sensing elements; otherwise horizontal noise driven by weather changes would be inherent in the instrument (Widmer-Schnidrig and Kurrle 2006). In a well-designed instrument, pressure-driven tilt should not be evident. It is also difficult for a manufacturing or component defect to give rise to pressure-tilt sensitivity; the design either has sufficient pressure immunity or it does not. The inherent symmetry of a Galperin-type topology also provides more opportunity to the designer to optimize pressure vessels with highly symmetric internal mounting arrangements that attenuate pressure vessel deformation effects.

XY-Oriented Seismometer Mount: X or Y Noise

For Galperin-type seismometers, tilt that is aligned strictly with either the X (East) or Y (North) direction is of special interest: while it is possible for tilt to coincide with the X or Y, there may be a specific reason for tilt to occur in a well-defined and aligned orientation. For example, an unlocked foot that is positioned in line with East or North could be suspected, or the seismometer may be mounted on some structure that may tend to tilt in a particular direction. With a conventional XYZ seismometer, X- or Y-aligned noise could either be related to the internal X or Y axes or be due to external tilting. A symmetric triaxial construction experiencing such noise clearly points to an external cause, and when the tilt direction is highly aligned with X or Y, or in some other specific direction in line with a particular mounting feature such as a foot, it provides a useful indication of the likely trouble spot.

A special instance of this is when a Galperin-type seismometer is mounted within a moveable platform, such as a leveling gimbal for ocean bottom deployment. If tilt events are clear in the data and strictly oriented in line with the potential movement of the platform, it is suggestive of gimbal platform movement.

Output Stage Electronics, Cable, and Digitizer: X, Y, Z, or XYZ Noise

Single X, Y, or Z Channel Noise

The only electronics internal to a typical symmetric triaxial seismometer which are specific to a single X, Y, or Z output channel are the UVW-to-XYZ coordinate-conversion circuits that combine the UVW signals to produce XYZ outputs, the signal output drivers, internal cabling, and external connector. It is rare to see noise problems originate from these areas, but it is possible for the failure

DOI 10.1007/978-3-642-36197-5_194-1

of an electronic component to cause a failure of one output channel (or one side of a differential output channel that then would manifest itself as a half-amplitude signal on one channel).

Because the signal is in the XYZ domain from the seismometer onwards, the cable and digitizer must be suspected when troubleshooting. Because the output stage electronics are relatively simple and usually reliable, it is more common for the cause of single-channel or common-mode XYZ failures or noise to be associated with the downstream digitizer or the cable connecting the seismometer to the digitizer.

It is useful to determine if noise apparent on a single output channel is predominantly or exclusively evident on that channel. If there is no attenuated version of that noise on the other channels, it is likely to represent a failure or deficiency of hardware associated with that channel, such as a connector pin or digitizer channel problem. Noise appearing predominantly on one output channel but also on the others in an attenuated form points to an effect predominantly aligned with that channel but not exclusive to it, such as tilt along the X direction.

Predominant But Not Exclusive Z Channel Noise

A special case of single-channel noise is Z channel noise. That is because the Z (vertical) channel is produced by an equally weighted sum of the UVW axis signals, and so any phenomena that affects all axis elements equally will manifest predominately on the Z channel. Therefore, Z channel noise could originate from within the seismometer due to a common-mode effect acting on all axis elements or from an external fault on the Z channel in the cable or digitizer. One can usually determine which by the nature of the noise or impairment and also by determining if the noise or impairment is exclusively or just predominately on the Z channel. A common-mode effect acting on all axis elements will predominately manifest on the Z channel, but usually there are slight differences in sensitivity to these effects from axis to axis, so some attenuated version of that noise on the X and Y channels may be present. If the impairment is external, such as a noisy digitizer Z channel, it is much less likely to leak into the X and Y channels.

Common-Mode XYZ Channel Noise

A noise source or impairment that affects all output channels more or less equally (known as a common-mode characteristic) could be associated with the seismometer electronics that serve common functions such as power conversion and control circuits, but is more likely an external common-mode effect, such as noise induced on all input channels to the digitizer by electrical interference. Common-mode XYZ cannot be problems with any or all of the internal Galperin axis elements, because these would manifest in the U, V, W, or Z directions, respectively, never in the direction corresponding to equal XYZ signals.

Temperature Changes and Pressure Leaks: Z Channel Noise

The most common sources of predominately Z channel broadband noise are environmental effects acting on the seismometer, such as varying temperature or pressure leaks. Seismometers respond to temperature changes in part because thermoelastic effects act on the spring that suspends the proof mass against gravity, causing apparent changes in acceleration. These are slow effects and therefore affect low-frequency noise performance. The three axis elements will usually have a similar but not exactly equal sensitivity to temperature changes, manifesting as predominately Z channel noise with much smaller effects on X and Y.

A leak in the pressure vessel of the seismometer would allow air to pump in or out driven by atmospheric pressure changes, and this would cause the proof masses to rise or fall buoyed by changing air density inside the vessel. This creates a very pronounced noise that is strongly vertical.

DOI 10.1007/978-3-642-36197-5_194-1

Pressure leaks mostly arise in seismometers that provide service access ports such as for manual mass centering that may not have been properly closed or where the seals have deteriorated.

Magnetic Field Effects: Unequal XYZ Noise

Broadband seismometers are designed to be as insensitive as possible to changes in external magnetic fields, but some sensitivity is almost inevitable (Forbriger et al. 2010). Springs designed to be relatively insensitive to temperature changes are often fabricated from magnetic materials and so have small but measurable forces applied by the Earth's magnetic field. These can manifest as low-amplitude noise at long periods. Each axis will be sensitive to the direction as well as the strength of the geomagnetic field. Because the direction of the Earth's magnetic field differs depending on location, the effect of changing magnetic fields is not equal on all axis elements, nor are the relative proportions among axis elements consistent or predictable. These are typically small effects and usually only of concern for very high-quality low-noise sites with very low-noise seismometers. Mitigation strategies can include augmenting magnetic shielding.

Electronic Interference: Equal or Unequal XYZ Noise

Noise that appears on all channels may arise from interference of nearby electrical equipment. A common-mode noise appearing equally (or nearly equally) on all channels could indicate a conducted or radiated noise source from a power source such as a battery charger cycling, a nearby motor, or similar problem. The interference is unlikely to be affecting the seismometer itself, as noise induced into the three Galperin axis elements manifests as predominately vertical (Z) channel signals. Induced noise affecting all channels is likely to suggest a cable or digitizer vulnerability or issue of some sort. Mitigation typically includes determining the source if possible, improving shielding or grounding, and changing cables, digitizers, or power sources if faults are suspected.

Summary

A seismometer that is designed using a Galperin arrangement has three identical sensing elements with their directions of sensitivity arranged to be mutually orthogonal, and inclined up from the horizontal plane at an angle of $\theta_0 \cong 35.26°$. This is a subclass of the more general "symmetric triaxial" configuration in which three axis elements are identical and symmetrically arranged with respect to each other. The signals from the three sensors, designated U, V, and W, are usually remixed by analog circuitry within the seismometer to provide a vertical and two horizontal outputs equivalent to a conventional XYZ seismometer. The benefits of the symmetric triaxial approach pertain to site and instrument troubleshooting, channel response matching, ease of manufacturing and testing, reliability, and channel orthogonality. The most frequently cited drawback is that all three axis elements must be functional for any of the three XYZ seismic signal outputs to be valid. The high reliability of the best seismometer designs largely mitigates this concern, and it is furthermore avoided by choosing a seismometer which allows the user to remotely select UVW signals to be output in place of the mixed XYZ in the event of a single axis failure. The second cited drawback inherent in the symmetric triaxial configuration is the requirement for an internal analog electronic mixing circuit to convert UVW to XYZ, although in a well-designed seismometer, this is invisible to the user.

A primary benefit of the Galperin approach is that, because the UVW coordinate systems are different from the XYZ horizontal/vertical reference system, noise sources and faults within an axis are distinguishable from problems that manifest in primarily vertical or horizontal directions. A corollary to this is that a properly functioning vertical channel on a Galperin instrument is a reliable indication that all three UVW elements are good, since the vertical is an equal sum of the three Galperin axes. Response matching is necessary for Galperin instruments to enable proper remixing to XYZ outputs, providing assurance of consistent response independent of the direction of motion. Galperin designs also generally assure rigid orthogonality of the XYZ outputs, whereas the tilting of the horizontal elements in the mass centering operation of conventional designs can produce deviations in X and Y orientation relative to the fixed vertical axis. Manufacturing benefits include having one rather than two axis designs to build and improved ability to test and troubleshoot.

A review of noise sources and characteristics and how their directions align relative to the separate Galperin and horizontal/vertical coordinate systems demonstrates the powerful utility of using a symmetric triaxial configuration to help discriminate and diagnose potential noise problems with the site, installation, or seismometer.

In summary, the Galperin geometry has proven to offer significant benefits to seismometer users and manufacturers and through use and experience has proven to have significant additional benefits in terms of remotely troubleshooting station noise.

References

Forbriger T, Widmer-Schnidrig R, Wielandt E, Hayman M, Ackerley N (2010) Magnetic field background variations can limit the resolution of seismic broad-band sensors. Geophys J Int 183(1):303–312

Galperin EI (1955) Azimuthal method of seismic observations (in Russian). Gostoptechizdat 80

Graizer V (2009) The response to complex ground motions of seismometers with galperin sensor configuration. Bull Seismol Soc Am 99(2B):1366–1377

Hanka W (2002) Parameters which influence the very long-period performance of a seismological station: examples from the GEOFON Network, Section 7.4.4. In: Bormann P (ed) New manual of seismological observatory practice, vol 1. GeoForschungsZentrum, Potsdam, pp 64–74

Melton BS, Kirkpatrick BM (1970) The symmetric triaxial seismometer – its design for application to long-period seismometry. Bull Seismol Soc Am 60(3):717–739

Nanometrics Inc. (2013) Trillium posthole user guide. (17217R5). Nanometrics, Inc., Kanata

Peterson J (1993) Observations and modeling of seismic background noise. Open-file report 93–322, U. S. Geological Survey, Albuquerque

Streckeisen G, Messgeräte AG (1995) Portable very-broad-band tri-axial seismometer STS-2 manual, 50

Widmer-Schnidrig R, Kurrle D (2006) Evaluation of installation methods for Streckeisen STS-2 seismometers. http://www.geophys.uni-stuttgart.de/~widmer/ge2.pdf. Retrieved 25 Oct 2013.

Wielandt E (2002) Seismic sensors and their calibration, Chapter 5. In: Bormann P (ed) New manual of seismological observatory practice, vol 1. GeoForschungsZentrum, Potsdam

Zürn W, Wielandt E (2007) On the minimum of vertical seismic noise near 3 mHz. Geophys J Int 168:647–658