CMG-3ESP

Operator's Guide

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1 Preliminary Notes

1.1 Proprietary Notice

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1.2 Cautions and Notes

Cautions and notes are displayed and defined as follows:

Caution: A yellow triangle indicates a chance of damage to or failure of the equipment if the caution is not heeded.

Note: A blue circle indicates indicates a procedural or advisory note.

1.3 Manuals and Software

All manuals and software referred to in this document are available from the Güralp Systems website: www.guralp.com unless otherwise stated.

1.4 Conventions

Throughout this manual, examples are given of command-line interactions. In these examples, a fixed-width typeface will be used:

```
Example of the fixed-width typeface used.
```

Commands that you are required to type will be shown in bold:

`Example of the fixed-width, bold typeface.`

Where data that you type may vary depending on your individual configuration, such as parameters to commands, these data are additionally shown in italics:

`Example of the fixed-width, bold, italic typeface.`

Putting these together into a single example:

```
System prompt: user input with variable parameters
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2 Introduction

The CMG-3ESP is a three-axis seismometer consisting of three sensors in a sealed case, which can measure the north/south, east/west and vertical components of ground motion simultaneously. Each sensor is sensitive to ground vibrations in the frequency range 0.003 – 50 Hz, a broadband frequency response made possible by advanced force-balance feedback electronics. Because of this wide response range, the 3ESP can replace many of the instruments conventionally used in a seismic observatory; it also produces true pulse-shape records suitable for modern earthquake mechanism analysis.

The 3ESP is designed for mounting on a hard, near-horizontal surface well coupled to the bedrock. After levelling and orienting the case, you can perform accurate adjustments internally by sending the instrument control signals. These electronics allow it to compensate for a tilt of up to 3 ° from horizontal.

Once levelled and centred, the 3ESP will begin operating automatically. It outputs analogue voltages representing ground velocity on balanced differential lines. These voltages can be recorded using a separate logging device or digitizer. For testing and installation purposes, a hand-held control unit is supplied which can monitor the instrument's output.

The seismometer unit is self-contained apart from its 12 V power supply. Centring can be carried out by sending control signals to the instrument, either through the hand-held control unit or through an attached Güralp digitizer.

Each seismometer is delivered with a detailed calibration sheet showing its serial number, measured frequency response in both the long period and the short period sections of the seismic spectrum, sensor DC calibration levels, and the transfer function in poles/zeros notation.

2.1 Options

2.1.1 Form factors

The CMG-3ESP can be supplied in several forms, besides its standard configuration:

- The CMG-3ESP Compact is internally identical to the standard 3ESP, but has a different arrangement of components allowing it to fit in a smaller casing.
- The 3ESP can also be supplied in a slimline form factor, with vertically-stacked sensors, suitable for installation in post-holes (see Section 3.5, page 17.)
- The 3ESP is also available in borehole form as the CMG-3ESPB.

Any of these can be supplied with integral digitizers and data modules, allowing the 3ESP to form a complete, integrated seismic installation.

2.1.2 Output types

The standard 3ESP has a single 26-pin mil-spec waterproof connector for signals, control and power.

A supplied breakout box connects to the sensor allowing separate connection to a power supply, recording system and hand-held control unit.

As an option the 3ESP can be supplied with other output connector types, *e.g.* standard 26-pin D sockets, to your own pin-out specification.

2.1.3 Sensor response

The 3ESP can be supplied with a response which is flat to velocity from 100 Hz to any of 0.1 Hz (10 s), 0.033 Hz (30 s), 0.016 Hz (60 s), 0.01 Hz (100 s) or 0.0083 Hz (120 s). Alternatively, a *hybrid* response function may be provided. See Section 6.1, page 30, for more details.

If you do not require high-frequency data, a low-pass filter may be installed at a frequency (below 100 Hz) that you specify.

3 Installing the 3ESP

3.1 First encounters

3.1.1 Unpacking

The 3ESP seismometer is delivered in a single transportation case. The packaging is specifically designed for the 3ESP and should be reused whenever you need to transport the sensor. Please note any damage to the packaging when you receive the equipment, and unpack on a safe, clean surface. The package should contain:

- The seismometer
- A breakout box (which provides separate connections for the signal, control and power lines)
- A cable to join the sensor to the breakout box;
- Hand-held Control Unit (HCU) for monitoring sensor outputs and calibration, if ordered;
- 10-pin connector for your power lead
- Calibration and installation sheet.

Assuming all the parts are present, stand the seismometer in the centre of a bench and identify its external features:

- Handle with North indication,
- 26-pin connector for input and output,
- Bubble level,
- Air vent port,
- Three adjustable feet
- Two accurate orientation pins (one brass and one steel).

3.1.1.1 Serial number

The sensor's serial number can be found on the label stuck to the top lid of the sensor. It is also stamped onto the side of the sensor base, next to the N/S indicator, and into the lid itself. You should quote this serial number if you need assistance from Güralp Systems.

3.1.1.2 Handling notes

The 3ESP is a sensitive instrument, and is easily damaged if mishandled. If you are at all unsure about the handling or installation of the device, you should contact Güralp Systems for assistance.

Caution: Do not bump or jolt any part of the sensor when handling or unpacking.

Caution: Do not kink or walk on the data cable (especially on rough surfaces such as gravel), nor allow it to bear the weight of the sensor.

Caution: Do not connect the instrument to power sources except where instructed.

Caution: Do not ground any of the signal lines from the sensor.

Caution: Do not move the instrument whilst the masses are unlocked. You should report any sign of loose components, or any sound of parts moving inside the instrument, to Güralp Systems.

3.1.2 Connections

The instrument has a 26-pin connector which can be joined using the cable provided to a digitizer or breakout box. Individually shielded twisted-pair cabling *must* be used for the sensor outputs, control lines and power supply. If you need to make up a suitable cable, you should confirm the cable type with Güralp Systems.

Connector pin-outs are given in Appendix A on page 38.

3.1.2.1 Using a digitizer

The 3ESP can be connected directly to any Güralp Systems digitizer using the signal cable provided. This is the simplest way to use a 3ESP instrument. All the instrument's functions are available through the digitizer, including centring, and in instruments equipped with the option, remote locking and unlocking.

We recommend that you keep the digitizer near the instrument if at all possible, to minimize the length of analogue cable required. Once digitized, the signal is robust to degradation by noise or attenuation. Keeping the digitizer in the quiet, stable conditions of a seismic installation also provides it with an optimum environment for the on-board ADCs.

3.1.2.2 The breakout box

This unit separates the lines in the signal cable, so you can connect a power supply, a recording system, and the hand-held control unit:

You can also use the breakout box to centre the sensor masses. If your 3ESP includes the remote locking and unlocking option, you will be supplied with a slightly different breakout box with additional buttons for locking and unlocking the masses.

The standard breakout box is rain resistant but *not* waterproof. If you intend to use a breakout box in your installation, you should site it away from potential flooding. If this is not possible, a larger unit is optionally available which can be immersed in water without damage. (The 3ESP itself is, however, completely waterproof.)

3.1.2.3 Power supply

The sensor requires a 12 V power supply, which it obtains through the socket and breakout box or digitizer. You will need to make up a suitable cable to connect a 12 V power source to the 10-pin connector on the breakout box (spare 10-pin mil-spec connectors are provided for this purpose.) Using a 12 V, 25 Ah sealed heavy-duty lead-acid battery, you should expect the instrument to operate for around a week without recharging.

If you prefer, you can power the 3ESP directly from the connector on the top panel (see Appendix A on page 38).

A power management module can be installed as an option, which allows the 3ESP to operate from a 10 – 15 V supply range. This module also cuts the input power to the sensor electronics if it drops below 10.5 V, to minimize discharge from battery-operated installations.

The 3ESP draws a nominal current of 75 mA from a 12 V supply when in use. During locking and unlocking of the sensor masses, this current rises briefly to 600 mA. It is recommended that you carry a spare 12 V battery when visiting an installation for maintenance, in case the sensor needs to be moved and the on-site batteries no longer have sufficient charge to perform the locking procedure.

3.1.2.4 Signal output

The sensors output voltages representing ground velocity on floating differential lines. The breakout box provides a *RECORDER* connector for attaching to a recording system or digitizer. You can use any multi-channel recording system, provided that it has high-impedance floating differential inputs.

If you are using a Güralp Systems digitizer, you can connect the instrument directly to the digitizer without using the breakout box; power will be supplied through the digitizer, which can also activate the sensor control lines.

The breakout box also provides a *CONTROL* output, which can be connected to the Hand-held Control Unit. This device lets you monitor output signals from the instrument, and perform on-site calibration. For more information, see Section 5.1, page 28.

3.2 Installation notes

The goal of any seismic installation is to ensure that wave-trains arriving at the instrument accurately reflect the internal motion of subsurface rock formations. To achieve this, the seismometer and its emplacement need to be considered as a mechanical system, which will have its own vibrational modes and resonances. These frequencies should be raised as high as possible so that they do not interfere with true ground motion: ideally, beyond the range of the instrument.

In particular, the sensor needs to be protected against environmental factors such as

- Fluctuations in temperature
- Turbulent air flow around walls or trees, or around sharp corners or edges in the immediate vicinity of the sensor
- Vibration caused by equipment in or near the installation, particularly computer equipment
- Vibration caused by heavy machinery (even at a distance), or by overhead power lines

In seismic vaults, instruments are often installed on piers. It is important to ensure that the interface between the pier and the floor does not introduce noise, and that the pier itself does not have resonant frequencies within the passband. Ideally, a seismic pier will be significantly wider than it is high (to minimize flexing) and will form a single piece with the floor, *e.g.* by moulding a poured concrete floor with a wooden frame.

Many situations do not allow for the construction of a seismic vault. For example, you may need to deploy quickly to monitor the activity of a volcano showing signs of rejuvenation, or to study the aftershocks of a major earthquake; or the site itself may be too remote to ship in construction equipment.

Temporary installations can be protected against spurious vibrations by

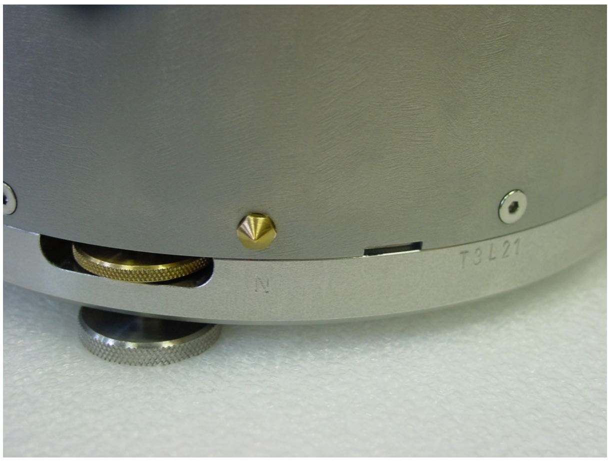
- Selecting a suitable site
- Placing the instrument in a protective enclosure (an open-sided box of 5 cm expanded polystyrene slabs, placed over the instrument and taped down to exclude draughts, makes an excellent thermal shield)
- Standing the sensor on bedrock where possible, or at least deep in well-compacted subsoil
- Clearing the floor of the hole of all loose material
- Using as little extra mass as possible in preparing the chamber

After installation, the instrument case and mounting surface will slowly return to the local temperature, and settle in their positions. This will take around four hours from the time installation is completed. If you require long-period recording, you should re-zero the instrument after this time.

3.3 Installing in vaults

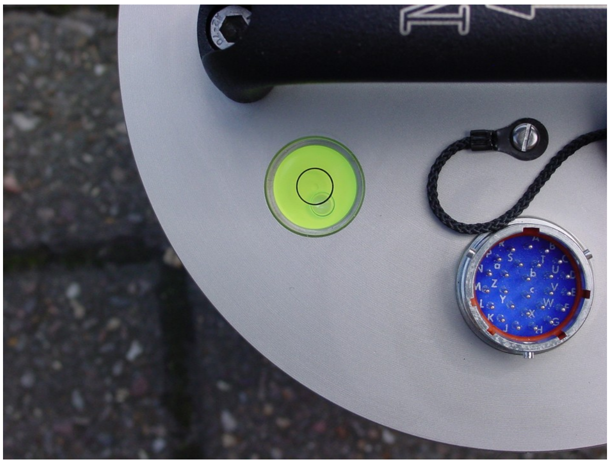
You can install a 3ESP in an existing seismic vault with the following procedure:

1. Unpack the sensors from their container, saving the shipping boxes for later transportation.
2. Prepare the mounting surface, which should be smooth and free of cracks. Remove any loose particles or dust, and any pieces of loose surfacing. This ensures good contact between the instrument's feet and the surface.
3. If it is not already present, inscribe an accurate North-South line on the mounting surface.
4. Place the sensor over the scribed line, so that the brass and steel pointers are aligned with the marked directions, with the brass pointer facing North. This can be done by rotating the base of the sensor whilst observing it from above. The brass pointer can be found next to one of the feet:



5. If you cannot easily see the pointers, you should align the sensor using the north arrow on the handle. However, the alignment of the handle with the sensors inside is less accurate than the metal pointers, so they should be used wherever possible.

6. The top panel of the 3ESP includes a spirit level:



Level the sensor using each of the adjustable feet of the instrument in turn, until the bubble in the spirit level lies entirely within the inner circle. (The instrument can operate with up to 2 ° of tilt, but with reduced performance).

7. The feet are mounted on screw threads. To adjust the height of a foot, turn the brass locking nut anticlockwise to loosen it, and rotate the foot so that it screws either in or out. When you are happy with the height, tighten the brass locking nut clockwise to secure the foot. When locked, the nut should be at the *bottom* of its travel for optimal noise performance.

8. Connect the sensor to the breakout box or a Güralp digitizer if you are using one.

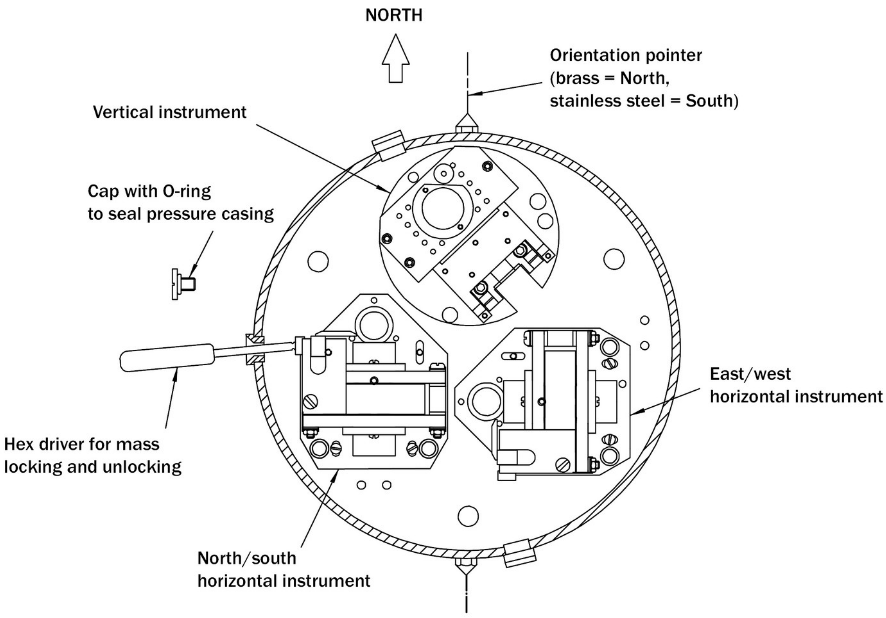
9. Connect a 12 V power supply either directly or through the breakout box or digitizer.

10. *If your 3ESP instrument has the standard, manual mass control system,* three sockets on the casing of the 3ESP allow each mass to be locked and unlocked. Locate the socket corresponding to the vertical sensor mass.

    Otherwise, skip to step 16.

    Remove the pressure cap from the socket.

11. Carefully insert a 3 mm hex driver into the casing, allowing it to be guided into the conical socket on the sensor housing within. The inner sockets are not precisely aligned with the holes in the casing, since their position is determined by the fixed component. Use the diagram below to help you locate the socket.



12. Turn the driver anticlockwise to unscrew it.

    After this point, you should be careful not to tilt the instrument, or you may damage it.

13. Clean the pressure cap and apply a thin layer of molybdenum disulphide grease to the O-ring and mating surfaces.

14. Install the pressure cap. Do not over-tighten.

15. Repeat steps 8 – 13 for the north/south and east/west components.

16. Check the mass position outputs using a digital multimeter, digitizer or the hand-held control units.

    If your instrument has the optional automatic mass control system, unlock the sensor masses by holding the *ENABLE* and *UNLOCK* buttons on the breakout box or hand-held control unit down together for 7 seconds. The *BUSY* LED will start flashing, and then go out. The unlocking process may take a minute or longer.

    Alternatively, if you are using a DM24 digitizer and Scream!, right-click on the digitizer's entry in Scream! and select **Control…**. Click on the **Mass control** tab, followed by **Centre**.

    Alternatively, if you are using a DM24 digitizer and a DCM, navigate to the **Actions → Digitizer Setup → Port *x*** page for the digitizer and click on the **Centre instrument** button at the bottom of the page. (If the *Mass control* tab is unavailable, make sure the correct sensor type is chosen in the *Sensor type* tab, apply, and open a new *Control* window.)

    Otherwise, if your instrument does not have this option, skip this step.

17. Re-centre the masses if required. If you have a breakout box or hand-held control unit, you can do this by holding the *ENABLE* and *CENTRE* buttons on the unit down together for 7 seconds. The *BUSY* LED will start flashing, and then go out.

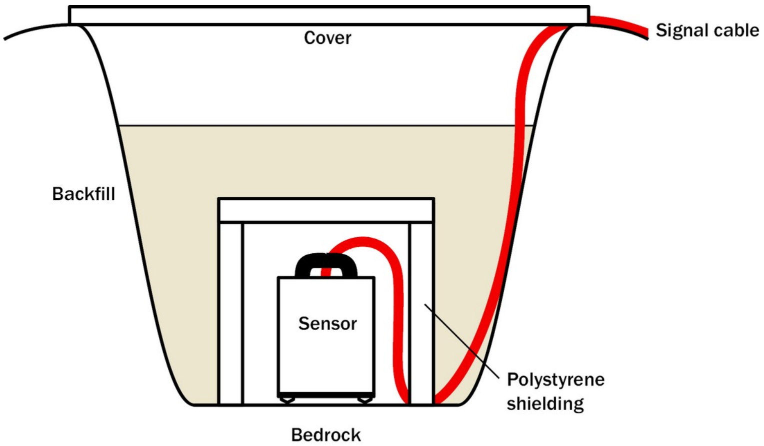
18. If you are using a DM24 digitizer and Scream! or a DCM, you can also access the *CENTRE* function from the **Mass control** or **Digitizer Setup** windows as described above.

19. Cover the instrument with thermal insulation, for example, a 5 cm expanded polystyrene box. This will shield it from thermal fluctuations and convection currents in the vault. It also helps to stratify the air in the seismometer package. Position the thermal insulation carefully so that it does not touch the sensor package.

20. Ensure that the sensor cable is loose and that it exits the seismometer enclosure at the base of the instrument. This will prevent vibrations from being inadvertently transmitted along the cable.

3.4 Installing in pits

For outdoor installations, high-quality results can be obtained by constructing a seismic pit.



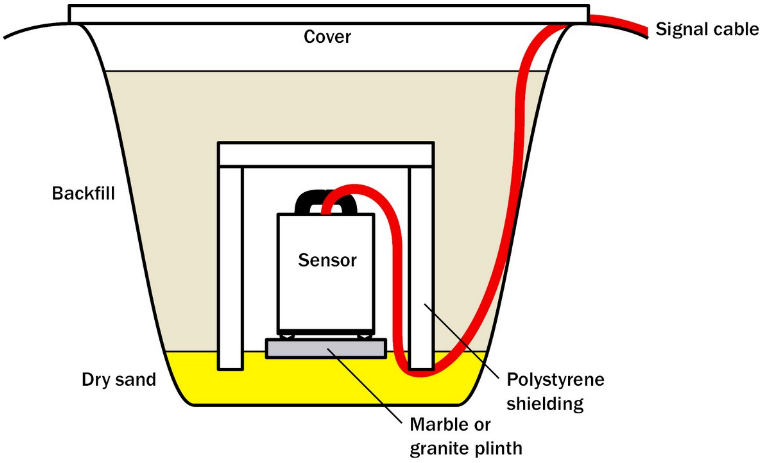
Depending on the time and resources available, this type of installation can suit all kinds of deployment, from rapid temporary installations to medium-term telemetered stations.

Ideally, the sensor should rest directly on the bedrock for maximum coupling to surface movements. However, if bedrock cannot be reached, good results can be obtained by placing the sensor on a granite pier on a bed of dry sand.

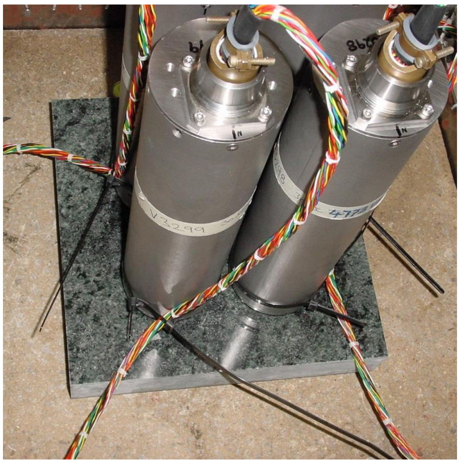
1. Prepare a hole of 60 – 90 cm depth to compacted subsoil, or down to the bedrock if possible.

On granite or other hard bedrock, use an angle grinder to plane off the bedrock at the pit bottom so that it is flat and level. Stand the instrument directly on the bedrock, and go to step 7.

On soft bedrock or subsoil, you should install a pier as depicted below.



2. Pour a layer of loose, fine sand into the pit to cover the base. The type of sand used for children's sand-pits is ideal, since the grains are clean, dry and within a small size range. On top of the sand, place a smooth, flat granite plinth around 20 cm across, and shift it to compact the sand and provide a near-level surface.



3. Placing a granite plinth on a sand layer increases the contact between the ground and the plinth, and improves the performance of the instrument. There is also no need to mix concrete or to wait for it to set, as in step 4.

   Alternatively, if time allows and granite is not available, prepare a concrete mix with sand and fine grit, and pour it into the hole. Agitate ("puddle") it whilst still liquid, to allow it to flow out and form a level surface, then leave to set. Follow on from step 7.

4. Puddled concrete produces a fine-textured, level floor for placing the seismometer. However, once set hard, the concrete does not have the best

possible coupling to the subsoil or bedrock, which has some leeway to shift or settle beneath it.

Alternatively, for the most rapid installation, place loose soil over the bottom of the pit, and compact it with a flat stone. Place the seismometer on top of this stone. This method emulates that in step 3, but can be performed on-site with no additional equipment.

5. Set up the instrument as described in the previous Section.

6. The instrument must now be shielded from air currents and temperature fluctuations. This is best done by covering it with a thermal shield.

7. An open-sided box of 5 cm expanded polystyrene slabs is recommended. If using a seismic plinth on sand (from steps 3–4 or 5), ensure that the box is firmly placed in the sand, without touching the plinth at any point. In other installations, tape the box down to the surface to exclude draughts.

   Alternatively, if a box is not available, cover the instrument with fine sand up to the top.

8. The sand insulates the instrument and protects it from thermal fluctuations, as well as minimizing unwanted vibration.

9. Ensure that the sensor cable is loose and that it exits the seismometer enclosure at the base of the instrument. This will prevent vibrations from being inadvertently transmitted along the cable.

10. Cover the pit with a wooden lid, and back-fill with fresh turf.

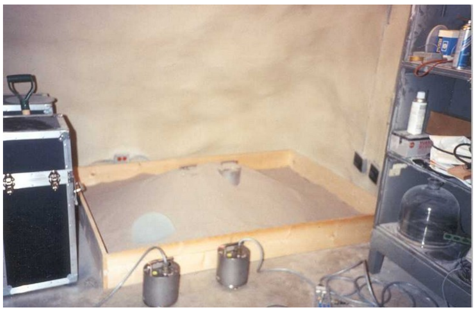
3.4.1 Other installation methods

The recommended installation methods have been extensively tested in a wide range of situations. However, past practice in seismometer installation has varied widely.

Some installations introduce a layer of ceramic tiles between a rock or concrete plinth and the seismometer (left):


However, noise tests show that this method of installation is significantly inferior to the same concrete plinth with the tiles removed (right). Horizontal sensors show shifting due to moisture trapped between the concrete and tiling, whilst the vertical sensors show 'pings' as the tile settles.

Other installations have been attempted with the instrument encased in plaster of Paris, or some other hard-setting compound (left):



Again, this method produces inferior bonding to the instrument, and moisture becomes trapped between the hard surfaces. We recommend the use of fine dry sand (right) contained in a box if necessary, which can also insulate the instrument against convection currents and temperature changes. Sand has the further advantage of being very easy to install, requiring no preparation.

Finally, many pit installations have a large space around the seismometer, covered with a wooden roof. Large air-filled cavities are susceptible to currents which produce lower-frequency vibrations, and sharp edges and corners can give rise to turbulence. We recommend that a wooden box is placed around the sensor to protect it from these currents. Once in the box, the emplacement may be backfilled with fresh turf to insulate it from vibrations at the surface, or simply roofed as before.

By following these guidelines, you will ensure that your seismic installation is ready to produce the highest quality data.

3.5 Installing in post-holes

The 3ESP is suitable for installation in post-holes. In soft subsoil, a hole 2 – 4 m deep and 20 cm wide can be conveniently excavated using a tractor-mounted or hand-operated post-hole auger. To minimize surface effects, you should ensure that the hole is at least 1 m deeper than the length of the instrument, and preferably somewhat more.

Since the hole has no lining, it may occasionally flood. However, most soil types are sufficiently permeable to allow water to soak away, leaving the packing material moist.

To install a 3ESP in a post-hole:

1. Clean the post-hole, making sure there is no loose material around the mouth of the hole or on its base.
2. Prepare the instrument package, making sure the inclinometer is visible, and attach it to a winch or hoist by clamping a light steel cable to the centre of the handle so that the package hangs vertically. Connect the signal cable to the instrument.
3. Add packing material to the hole to about 15 cm depth. Fine crushed rock, with a high proportion of rock flour and fine particles, makes excellent packing material. Alternatively, a mixture of 3 mm grade angular coarse grit with around 30% medium grit gives good results. Moisten the packing material in the hole and ram firm.
4. Lower the instrument to the bottom of the hole, but without slackening the lifting cable.
5. Fill more packing material around the instrument for about 30 cm, moisten, and ram firm.
6. Use the inclinometer to check that the instrument remains within its tilt tolerance (± 2 °).
7. Continue filling, moistening and packing until the instrument is buried, checking that the tilt remains within tolerance.
8. Release the strain on the lifting cable, and allow the packing material to settle for 24 hours.
9. If all is well after the settling period, release the lifting tackle, coil a tail of the lifting wire into the top of the hole and backfill almost to the surface.
10. Ensure that the signal cable is slack, and fix it to a support at the top of the hole.
11. Ram a split wooden bung into the top of the hole, and cover with sandbags.
12. Attach the signal cable to your recording equipment or breakout box. Carry out preliminary tests using a hand-held control unit, if required.

4 Calibrating the 3ESP

4.1 The calibration pack

All Güralp sensors are fully calibrated before they leave the factory. Both absolute and relative calibration calculations are carried out. The results are given in the calibration pack supplied with each instrument:

Works Order : The Güralp factory order number including the instrument, used internally to file details of the sensor's manufacture.

Serial Number : The serial number of the instrument

Date : The date the instrument was tested at the factory.

Tested By : The name of the testing engineer.

There follows a table showing important calibration information for each component of the instrument, *VERTICAL, NORTH/SOUTH,* and *EAST/WEST.* Each row details:

Velocity Output (Differential) : The sensitivity of each component to velocity at 1 Hz, in volts per m/s. Because the 3ESP uses balanced differential outputs, the signal strength as measured between the +ve and –ve lines will be twice the true sensitivity of the instrument. To remind you of this, the sensitivities are given as 2 × (single-ended sensitivity) in each case.

Mass Position Output : The sensitivity of the mass position outputs to acceleration, in volts per m/s². These outputs are single-ended and referenced to signal ground.

Feedback Coil Constant : A constant describing the characteristics of the feedback system. You will need this constant, given in amperes per m/s², if you want to perform your own calibration calculations (see below.)

Power Consumption : The average power consumption of the sensor during testing, given in amperes and assuming a 12 V supply.

Calibration Resistor : The value of the resistor in the calibration circuit. You will need this value if you want to perform your own calibration calculations (see below.)

4.1.1 Poles and zeroes

Most users of seismometers find it convenient to consider the sensor as a “black box”, which produces an output signal V from a measured input x. So long as the relationship between V and x is known, the details of the internal mechanics and electronics can be disregarded. This relationship, given in terms of the Laplace variable s, takes the form:

$(V/x)(s) = G \times A \times H(s)$

In this equation

- *G* is the acceleration output sensitivity (gain constant) of the instrument. This relates the actual output to the desired input over the flat portion of the frequency response.
- *A* is a constant which is evaluated so that $A \times H(s)$ is dimensionless and has a value of 1 over the flat portion of the frequency response. In practice, it is possible to design a system transfer function with a very wide-range flat frequency response.
- The normalising constant *A* is calculated at a normalising frequency value *f*m = 1 Hz, with $s = j\,f$m, where $j = \sqrt{-1}$.
- $H(s)$ is the transfer function of the sensor, which can be expressed in factored form:

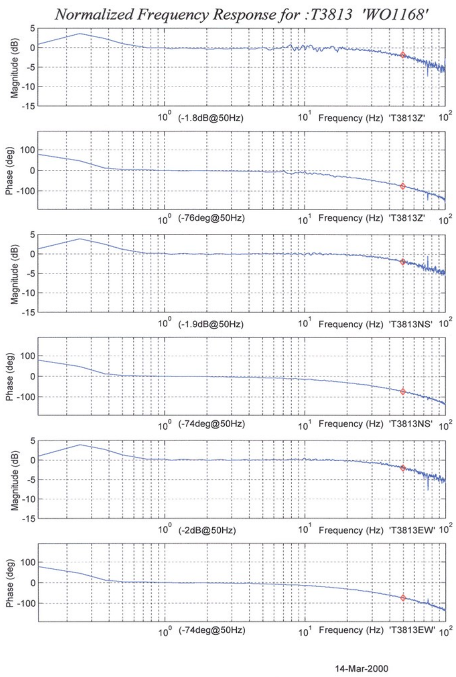
$$H(s) = N \frac{\prod_{i=1,n} s - Z_i}{\prod_{j=1,m} s - P_j}$$

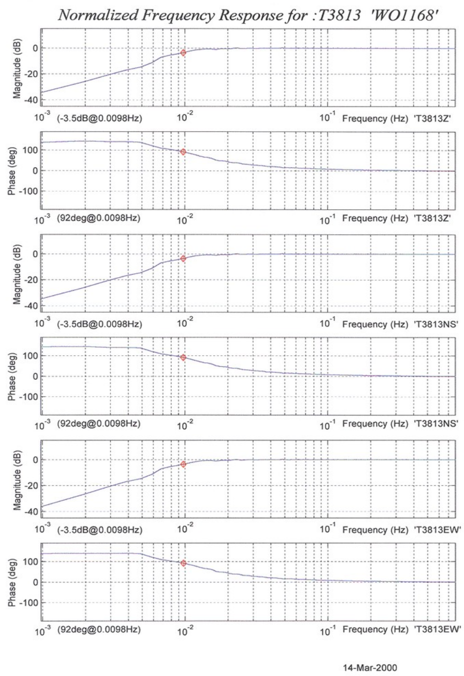
In this equation z_n are the roots of the numerator polynomial, giving the zeros of the transfer function, and p_m are the roots of the denominator polynomial giving the poles of the transfer function.

In the calibration pack, *G* is the sensitivity given for each component on the first page, whilst the roots z_n and p_m, together with the normalising factor *A*, are given in the *Poles and Zeros* table. The poles and zeros given are measured directly at Güralp Systems' factory using a spectrum analyser. Transfer functions for the vertical and horizontal sensors may be provided separately.

4.1.2 Frequency response curves

The frequency response of each component of the 3ESP is described in the normalised amplitude and phase plots provided. The response is measured at low and high frequencies in two separate experiments. Each plot marks the low-frequency and high-frequency cut-off values (also known as –3 dB or half-power points).

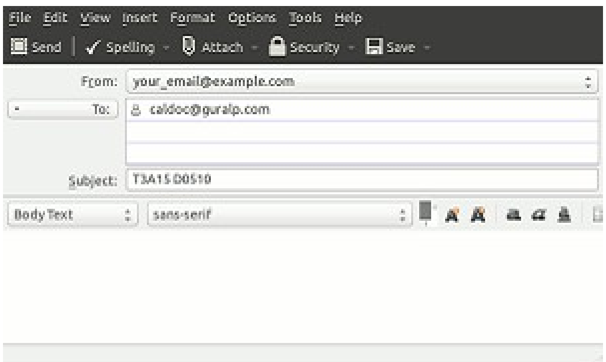




If you want to repeat the calibration to obtain more precise values at a frequency of interest, or to check that a sensor is still functioning correctly, you can inject calibration signals into the system using a Güralp digitizer or your own signal generator, and record the instrument's response.

4.1.3 Obtaining copies of the calibration pack

Our servers keep copies of all calibration data that we send out. In the event that the calibration information becomes separated from the instrument, you can obtain all the information using our free e-mail service. Simply e-mail caldoc@guralp.com with the serial number of the instrument in the subject line, *e.g.*



The server will reply with the calibration documentation in Word format. The body of your e-mail will be ignored.

4.2 Calibration methods

Velocity sensors such as the 3ESP are not sensitive to constant DC levels, either as a result of their design or because of an interposed high-pass filter. Instead, three common calibration techniques are used.

- Injecting a step current allows the system response to be determined in the time domain. The amplitude and phase response can then be calculated using a Fourier transform. Because the input signal has predominantly low-frequency components, this method generally gives poor results. However, it is simple enough to be performed daily.
- Injecting a sinusoidal current of known amplitude and frequency allows the system response to be determined at a spot frequency. However, before the calibration measurement can be made the system must be allowed to reach a steady state; for low frequencies, this may take a long time. In addition, several measurements must be made to determine the response over the full frequency spectrum.
- Injecting white noise into the calibration coil gives the response of the whole system, which can be measured using a spectrum analyser.

You can perform calibration either using a Güralp DM24 digitizer, which can generate step and sinusoidal calibration signals, or by feeding your own signals into the instrument through a hand-held control unit.

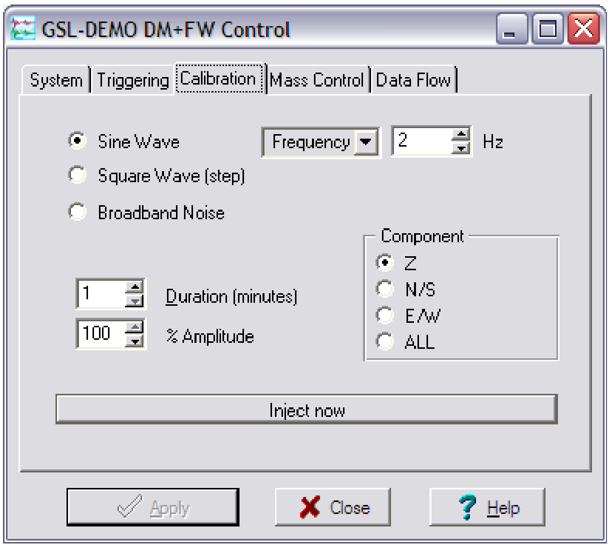
Before you can calibrate the instrument, its calibration relays need to be activated by pulling low the *CAL ENABLE* line on the instrument's connector for the component you wish to calibrate. Once enabled, a calibration signal provided across the *CAL SIGNAL* and *SIGNAL GROUND* lines will be routed through the feedback system. You can then measure the signal's equivalent velocity on the sensor's output lines. Güralp Hand-held Control Units provide a switch for activating the *CAL ENABLE* line.

4.3 Calibration with Scream!

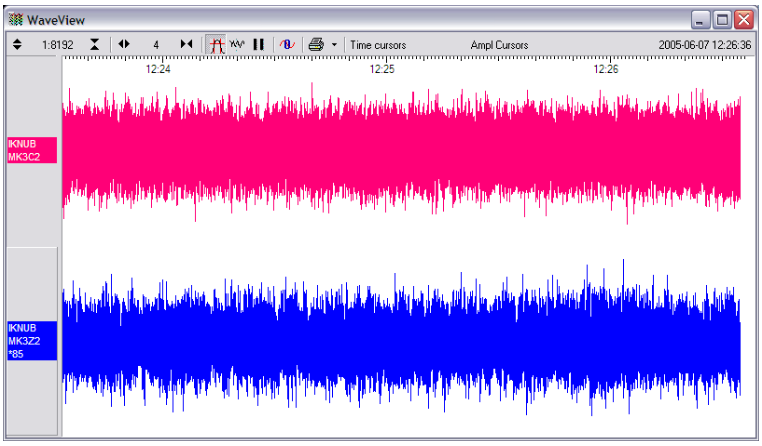
Güralp digitizers provide calibration signal generators to help you set up your sensors. Calibration is most easily done through a PC running Güralp's Scream! software.

Depending on the digitizer type, sine-wave, step and broadband noise signal generators may be available. In this section, broadband noise calibration will be used to determine the complete sensor response in one action. Please refer to the digitizer's manual for information on other calibration methods.

1. In Scream!'s main window, right-click on the digitizer's icon and select **Control...**. Open the *Calibration* pane.



2. Select the calibration channel corresponding to the instrument, and choose **Broadband Noise.** Select the component you wish to calibrate, together with a suitable duration and amplitude, and click **Inject now**. A new data stream, ending `C`*n* (*n* = 0 – 7) or `MB`, should appear in Scream!'s main window containing the returned calibration signal.



3. Open a *Waveview* window on the calibration signal and the returned streams by selecting them and double-clicking. The streams should display the calibration signal combined with the sensors' own measurements. If you cannot see the calibration signal, zoom into the *Waveview* using the scaling icons at the top left of the window or the cursor keys.

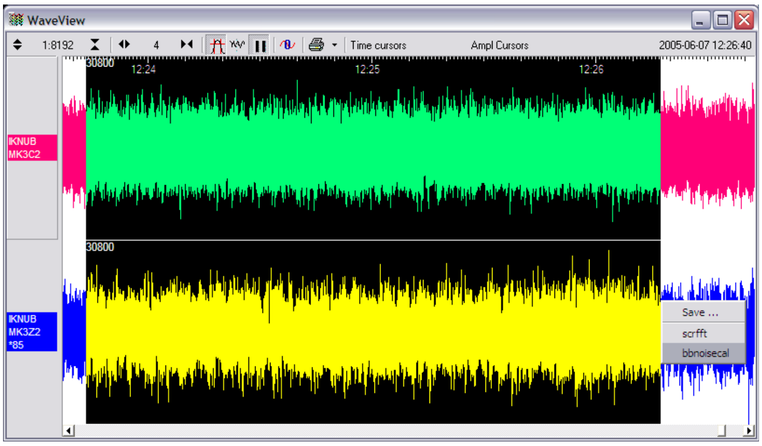
4. Drag the calibration stream `C`*n* across the *Waveview* window, so that it is at the top.

5. If the returning signal is saturated, retry using a calibration signal with lower amplitude, until the entire curve is visible in the *Waveview* window.

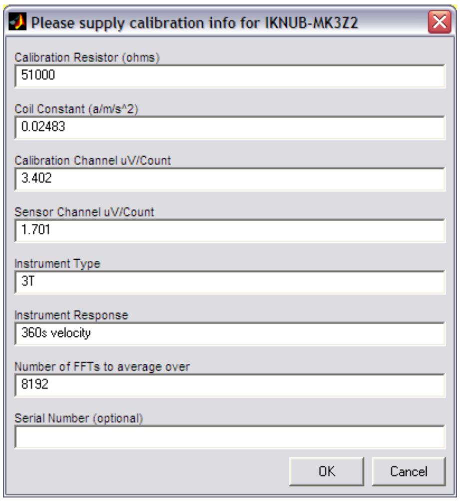
6. If you need to scale one, but not another, of the traces, right-click on the trace and select **Scale...**. You can then type in a suitable scale factor for that trace.

7. Pause the Waveview window by clicking on the  icon.

8. Hold down `SHIFT` and drag across the window to select the calibration signal and the returning component(s). Release the mouse button, keeping `SHIFT` held down. A menu will pop up. Choose **Broadband Noise Calibration.**



9. The script will ask you to fill in sensor calibration parameters for each component you have selected.



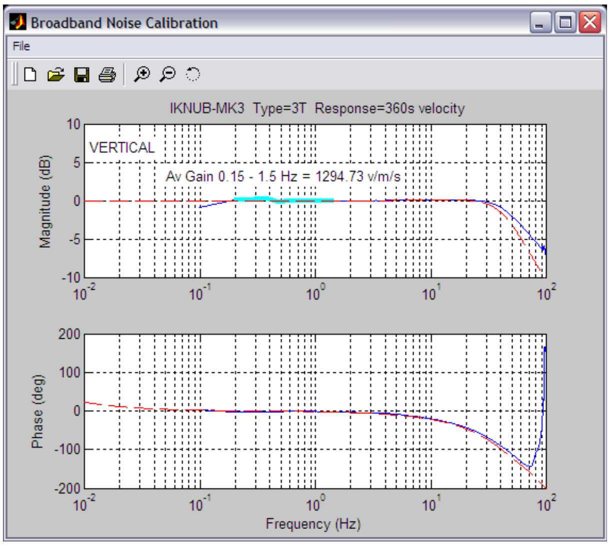
10. Most data can be found on the calibration sheet for your sensor. Under *Instrument response*, you should fill in the sensor response code for your sensor, according to the table below. *Instrument Type* should be set to the model number of the sensor.

11. If the file `calvals.txt` exists in the same directory as Scream!'s executable (`scream.exe`), Scream! will look there for suitable calibration values. A sample `calvals.txt` is supplied with Scream!, which you can edit to your requirements. Each stream has its own section in the file, headed by the line `[`*instrument-id*`]`. The ***instrument-id*** is the string which identifies the digitizer in the left-hand pane, *e.g.* `GURALP-DEMO`. It is always 6 characters (the system identifier) followed by a dash, then 4 characters (the serial number.) For example:

```
[instrument-id]
Serial-Nos=T3X99
VPC=3.153,3.147,3.159
G=1010,1007,1002
COILCONST=0.02575,0.01778,0.01774
CALVPC=3.161
CALRES=51000
TYPE=sensor-type
RESPONSE=response-code
```

12. Click OK. The script will return with a graph showing the response of the sensor in terms of amplitude and phase plots for each component (if appropriate.)

13. The accuracy of the results depends on the amount of data you have selected, and its sample rate. To obtain good-quality results at low frequency, it will save computation time to use data collected at a lower sample rate; although the same information is present in higher-rate streams, they also include a large amount of high-frequency data which may not be relevant to your purposes.



14. The bbnoisecal script automatically performs appropriate averaging to reduce the effects of aliasing and cultural noise.

4.3.1 Sensor response codes

Sensor	Sensor type code	Units (V/A)
CMG-5T or 5TD, DC – 100 Hz response	CMG-5_100HZ	A
CMG-40T-1 or 6T-1, 1 s – 100 Hz response	CMG-40_1HZ_50HZ	V
	CMG-40_1S_100HZ	V
CMG-40T-1 or 6T-1, 2 s – 100 Hz response	CMG-40_2S_100HZ	V

Sensor	Sensor type code	Units (V/A)
CMG-40T-1 or 6T-1, 10 s – 100 Hz response	CMG-40_10S_100HZ	V
CMG-40, 20 s – 50 Hz response	CMG-40_20S_50HZ	V
CMG-40, 30 s – 50 Hz response	CMG-40_30S_50HZ	V
CMG-3T or 3ESP, 30 s – 50 Hz response	CMG-3_30S_50HZ	V
CMG-40, 60 s – 50 Hz response	CMG-40_60S_50HZ	V
CMG-3T or 3ESP, 60 s – 50 Hz response	CMG-3_60S_50HZ	V
CMG-3T or 3ESP, 100 s – 50 Hz response	CMG-3_100S_50HZ	V
CMG-3T or 3ESP, 120 s – 50 Hz response	CMG-3_120S_50HZ	V
CMG-3T, 360 s – 50 Hz response	CMG-3_360S_50HZ	V
CMG-3TB or 3V / 3ESP borehole, 30 s – 50 Hz response	CMG-3B_30S_50HZ	V
CMG-3TB or 3V / 3ESP borehole, 100 s – 50 Hz response	CMG-3B_100S_50HZ	V
CMG-3TB or 3V / 3ESP borehole, 120 s – 50 Hz response	CMG-3B_120S_50HZ	V

4.4 Calibration with a hand-held control unit

If you prefer, you can inject your own calibration signals into the system through a hand-held control unit. The unit includes a switch which activates the calibration relay in the seismometer, and 4 mm banana sockets for an external signal source. As above, the equivalent input velocity for a sinusoidal calibration signal is given by

$$v = V / 2\pi f R K$$

where V is the peak-to-peak voltage of the calibration signal, f is the signal frequency, R is the magnitude of the calibration resistor and K is the feedback coil constant. R and K are both given on the calibration sheet supplied with the 3ESP.

The calibration resistor is placed in series with the transducer. Depending on the calibration signal source, and the sensitivity of your recording equipment, you may need to increase R by adding further resistors to the circuit.

4.5 The coil constant

The feedback coil constant K is measured at the time of manufacture, and printed on the calibration sheet. Using this value will give good results at the time of installation. However, it may change over time.

The coil constant can be determined by tilting the instrument and measuring its response to gravity. To do this, you will need apparatus for measuring tilt angles accurately.

1. Measure the acceleration due to gravity, g, at your location.
2. Tilt the instrument slightly, and measure its attitude and the gain of the *mass position* output for the component you wish to calibrate.
3. Repeat this measurement for several tilt angles.
4. For the vertical sensor, the input acceleration is given by $a = g \sin \varphi$, whilst for the horizontal sensor, it is $a = g\,(1 - \cos \varphi)$.
5. Calculate the input acceleration for each of the tilt angles used, and plot a graph of mass position output against input acceleration.
6. The gradient of the line obtained gives the sensitivity of the coil (in $V/m/s^2$, if g was measured in m/s^2 and the mass position in V.)
7. The coil constant K is equal to this sensitivity divided by the value of the displacement feedback resistor, given on the calibration sheet.

5 Accessories

5.1 The hand-held control unit

This portable control unit provides easy access to the seismometer's control commands, as well as displaying the output velocity and mass position (*i.e.* acceleration) on an analogue meter. It takes input from the 26-pin connector at the bottom, and repeats it at the connector on the side for connection to further equipment.

The hand-held control unit can be sited up to 50 m from the breakout box.

5.1.1 The meter

The meter at the top of the unit allows you to monitor the voltage outputs of the instrument. Using the knob below, you can select either the mass position output or the velocity output, for each of the three components. There is also a *RANGE* switch allowing you to alter the sensitivity of the meter.

5.1.2 Calibration

The hand-held control unit can be used to calibrate the 3ESP. To activate the calibration relays, turn the knob to the component you wish to calibrate, and introduce a calibration signal on the *CAL SIG* banana sockets.

5.1.3 Control commands

You can use the hand-held control unit to centre the sensor masses. If your 3ESP includes the remote locking and unlocking option, you can also lock and unlock the masses through the hand-held control unit as described below; otherwise, you will need to lock and unlock the masses manually (see Section 3.3, page 10.)

- To unlock the sensor masses on a sensor with automatic mass control, press the *ENABLE* switch down, and the *LOCK/UNLOCK* switch up simultaneously for 7 seconds. The *BUSY* LED will light. All three masses are unlocked, each in turn. The sensor then automatically moves on to centre the masses, during which time the *BUSY* LED will flash. When the *BUSY* LED goes out, the instrument is ready for use.
- You should not attempt to move the instrument without re-locking the masses.
- To lock the sensor masses on a sensor with automatic mass control, press the *ENABLE* and *LOCK/UNLOCK* switches down simultaneously for 7 seconds. When the *BUSY* LED goes out, the instrument is ready for transportation.
- To re-centre the sensor masses on any 3ESP instrument, press down the *ENABLE* and *CENTRE* switches simultaneously for 7 seconds. When the *BUSY* LED stops flashing, the centring process has finished. You may need to initiate several rounds of centring before the instrument is ready; when no more centring is required, pressing the *ENABLE* and *CENTRE* buttons has no effect.

5.1.4 Outputs

The remaining banana sockets provide easy access to the output voltages of the instrument. For each component (vertical, N/S and E/W):

- the left-hand two sockets expose the balanced differential outputs representing ground velocity, and
- the right-hand socket exposes the mass position (acceleration) output.

Ground references for each of these voltages are provided at the bottom of the unit. Ensure that you do not connect either side of a differential output to ground.

6 Inside the 3ESP

6.1 The sensors

The horizontal and vertical sensors are similar in design. The inertial mass in both cases consists of a transducer coil and a leaf-spring suspended boom which swings on a frictionless hinge. A triangular spring supports the weight of the mass; in the vertical sensor this spring is pre-stressed, with a natural period around 0.5 s, whilst the horizontal sensor has an unstressed flat spring with a natural period around 1 s. CMG-3ESP sensors have no spurious resonances below 140 Hz, and weigh around 180 g. The small boom size and stiff springs allow three independent instruments to be mounted within the casing, together with all the associated feedback electronics.

The 3ESP functions by monitoring the position of each mass with a capacitative position sensor. The three sensors are identical. Signals from the sensors are fed into an electronic processing unit, which is mounted in a screened compartment above the mechanical components (see below for details on the feedback circuitry.)

When the instrument is being transported, the masses are locked securely in their frames so as to relieve strain on the support hinges. This locking is performed by a small motor-driven clamp in response to a signal from the surface controller unit.

Before using the instrument, the boom of the vertical sensor must be levelled and the bases of the horizontal sensors tilted, so that the masses are centred in their equilibrium positions. These adjustments are made by small DC motors controlled remotely.

The signal voltages output by the 3ESP are proportional to ground velocity, and are transmitted from the instrument on balanced differential lines. In addition, mass position signals are sent as single-ended circuits referred to analogue ground on the output plug. The 3ESP also receives control signals, which are used to clamp and unclamp the masses, and to run the motors which level and centre the instrument once in position. Finally, a line is provided for you to apply a calibrating voltage to the force transducers, thereby measuring the deflection sensitivity.

6.2 Locking and unlocking

6.2.1 Manual control

The mass clamps in the 3ESP push each mass into precisely-machined cavities, so that they are unable to move in any direction. The force required to disengage the masses is more than 15 times the weight of the mass, allowing you to transport the instrument safely.

The mass clamps will *not* secure the masses against hard knocks and jolts. The 3ESP should always be transported with at least 15 cm of foam padding. You will have received suitable packing material with the instrument.

6.2.2 Automatic control

The 3ESP contains a control microprocessor which drives the centring adjustment motors when its input line is grounded for 0.2 – 7 seconds. As an option, this microprocessor can also be programmed to drive clamping motors, allowing you to lock and unlock the masses remotely by grounding two further input lines. These input lines can be controlled from the breakout box or Hand-held Control Unit.

Each command acts on the vertical, N/S and E/W masses in turn. The microprocessor prevents the system from attempting incompatible actions (*e.g.* centring when the masses are clamped.)

While a command is taking place, if you are using a Hand-held Control Unit, its *BUSY* LED will flash; you can use this for diagnostic purposes. See the description of each command for full details.

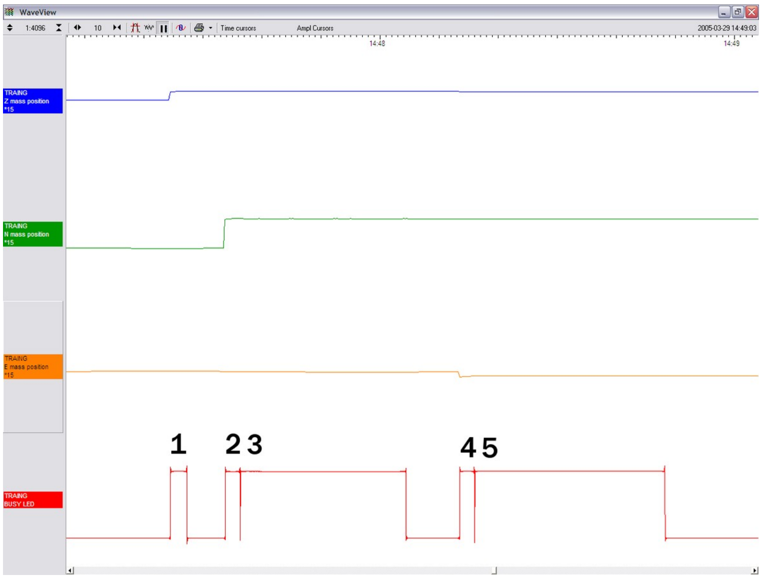
When no command is active, *i.e.* all three lines are high, the control microprocessor goes into a power-saving mode. In routine operation, the lines are controlled from the breakout box, Hand-held Control Unit or digitizer. If you send control signals to the 3ESP manually, you must ensure that the lines are pulled high after sending the signal, or the equipment may be damaged. A "biased-OFF" type switch can be used for this purpose.

6.2.2.1 *LOCK* (remote control option)

This command locks the masses and clamps the horizontal sensors by tilting them up to their end stops.

If *LOCK* is activated when the masses are already locked, the processor will unlock them and attempt to lock again. This is useful if you suspect that the locking procedure has failed.

In detail, the process acts as shown in the following graph. The top three streams are the *mass position* outputs of each component (Z, N/S and E/W, respectively), whilst the bottom one represents the state of the *BUSY* LED (up = on).



In the five-stage process, each mass in turn is locked with a motorised micrometer (stages 1, 2, 4), and the *N/S* and *E/W* sensor bases are tilted to their end stops (stages 3 and 5). At some point during each tilting stage, the position of the relevant mass will flip to one or other side.

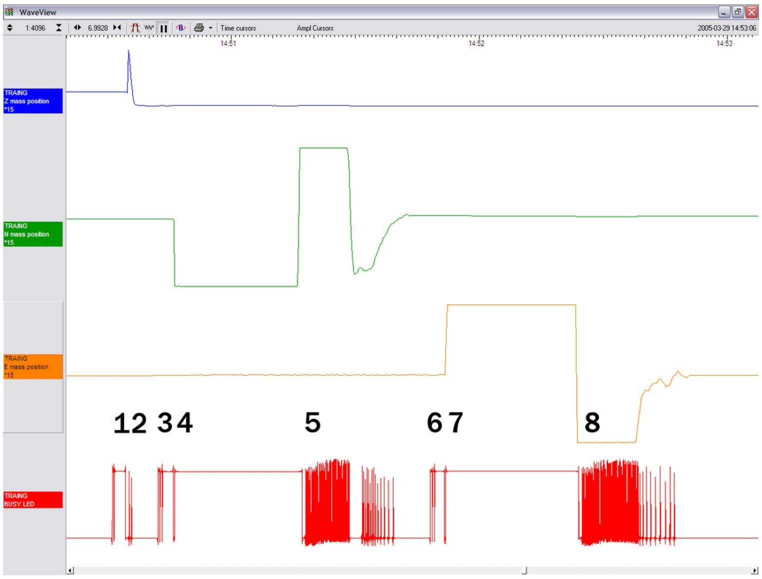
The *BUSY* LED is lit during each stage, but goes out briefly between stages, allowing you to follow the progress of the lock.

6.2.2.2 *UNLOCK* (remote control option)

This command unlocks the sensor masses and prepares the instrument to begin operating.

If *UNLOCK* is activated when the masses are already unlocked, the processor will lock them and attempt to unlock again. This is useful if you suspect that the locking procedure has failed.

During the *UNLOCK* procedure, the instrument automatically performs a round of centring for each component.



Again, you can use the *BUSY* LED to monitor the progress of unlocking.

1. The instrument checks to see whether the vertical mass is locked, and unlocks it if necessary.

2. The vertical mass is centred by applying pulses to the motor. This stage is often very short, since the vertical mass is locked near its central position.

3. The instrument checks the N/S sensor and base, and unlocks the sensor.

4. The N/S sensor base is tilted to its level position. This process takes rather longer. At some point during this stage, the mass may flip to the other side (as seen in the green trace.)

5. The N/S sensor mass is centred by applying pulses to the motor. This stage will take longer than stage 2, since it must move the mass all the way from its end stop. As the mass nears the centre, the control circuit spaces out the pulses.

6. The E/W component is checked and unlocked.

7. The E/W sensor base is tilted to its level position as in step 4.

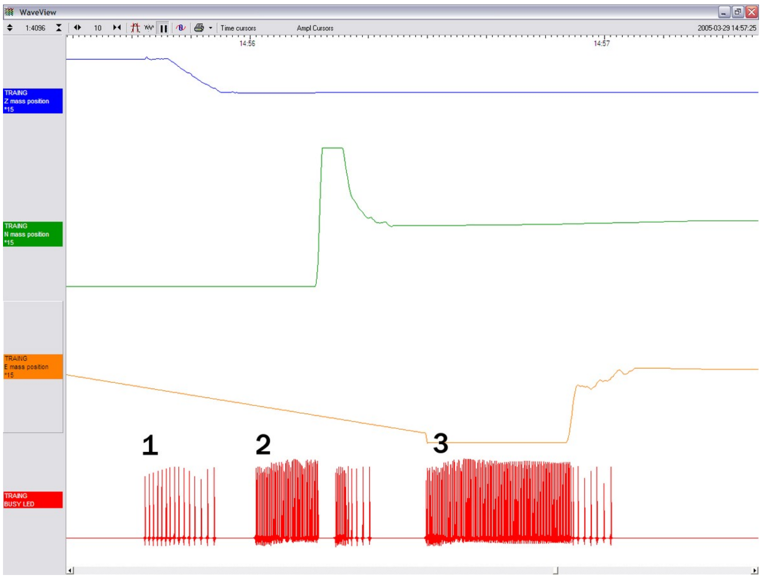
8. The E/W sensor mass is centred as in step 5.

After unlocking, the instrument automatically performs a round of centring (see below).

6.2.2.3 CENTRE (all instruments)

This command re-centres the masses. If the masses are clamped, or if the sensor mass positions do not exceed ± 1.2 V, the *CENTRE* command does nothing. Otherwise, it attempts to zero the output of the vertical, N/S and E/W sensors in sequence by exerting small extra forces on the boom. For the vertical sensor, a motor-driven adjuster presses a small spring lever against the boom until the mass position sensor indicates an offset close to zero. In the case of the horizontal sensors, the sensor frame is tilted on its base plate. Again, the controller monitors the mass position sensor and stops the centring process once it reaches its lowest offset.

This graph shows a typical centring process:



The *BUSY* LED pulses to indicate that it is centring the Z component. Each pulse corresponds to a small force on the mass. The pulses become more spaced out as this goes on, until a pulse is missed, signifying that no corrective impulse is needed.

The N/S component follows in the same way. The mass position output does not change for a while, as the true mass position is outside the range of the output. In this case, the pulses cause the mass to overshoot the central position, and a second group of pulses in the opposite direction is applied to bring it into line.

The E/W component follows in the same way. All three masses are now centred and the process completes.

After the sensor unlocks the masses, the first round of centring has to move the N/S and E/W components all the way from their end stops, whilst the *Z* component is often closer to the proper position. Because of this, the first Z centring operation takes much less time than the others, and you may not notice it.

After successful centring, the mass position outputs should be in the range 0.1 – 0.8 V. If the centring process leaves the mass position outputs above ±1.1 V, you should start another centring cycle by activating the *CENTRE* command again. You will probably need to initiate the centring process several times before the masses are adequately centred.

6.3 The feedback system

The output from a modern broadband seismometer does not depend on the natural characteristics of the instrument. Instead, the period and damping of the sensor is completely determined by a feedback loop which applies a force to the sensor mass opposing any motion. The force required to *restrain* the movement of the mass can then be used to measure the inertial force which it exerts as a result of ground motion.

All CMG-3 series units are based on these general principles. The capacitative position sensor for each mass produces a voltage proportional to the displacement of the mass from its equilibrium position. After amplification, this voltage generates a current in the force transducer coil which tends to force the mass back toward equilibrium. The feedback loop has a sufficiently high gain to cancel the motion of the mass. Since the mass is not moving, the forces acting on it must be balanced; the feedback voltage then directly measures the force, and hence the acceleration, which is being applied to the mass. The feedback loop introduces a phase shift, which must be carefully controlled if the instrument is to remain stable over its entire frequency range. This is achieved using compensation components in the forward and feedback paths.

Force feedback seismometers of this type rely on the assumption that the force transducer produces a field of constant strength. The magnetic circuit and magnet/pole assembly in the 3ESP are designed so that the field strength from the feedback transducer is constant over large deflections and current levels.

In a feedback seismometer with a displacement transducer, it is essential to monitor the acceleration output. This provides the position of the displacement transducer and therefore also the mass position, as the displacement transducer is attached to the sensor inertial mass. The sensor should always be operated with the displacement transducer centred or nulled, so that the response to input acceleration is linear.

There are two types of feedback system which can be used in a 3ESP instrument, known as *hybrid* and *conventional-response* feedback.

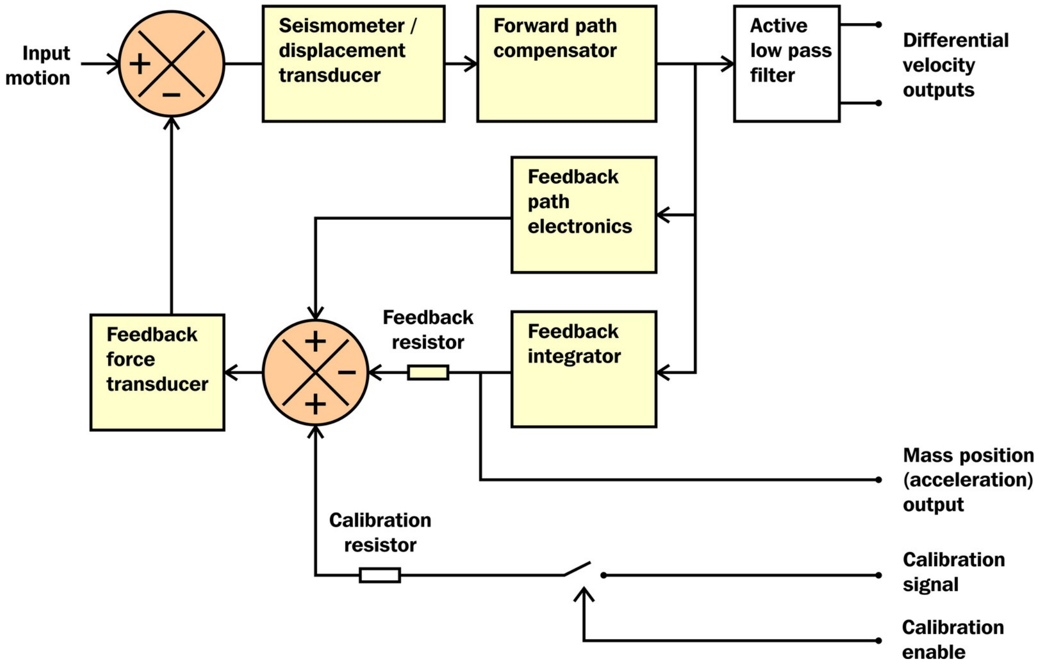
6.3.1 Hybrid feedback

The *hybrid* feedback circuit contains a single capacitor in parallel with a resistor, resulting in a single dominant pole at 0.033 Hz (30 s). Below this frequency, the response of the seismometer is flat to ground acceleration; above it, the response is flat to velocity. (Other values for the acceleration-velocity corner can be provided upon request.) Hybrid-feedback systems provide a stable response, particularly for portable systems, with a high saturation level at high frequencies and a high dynamic range at long periods.

An active low-pass filter provides a high-frequency cut-off point at a frequency you specify. Without the filter, the velocity response is flat up to 100 Hz. Outside the feedback loop there is an active high-pass filter with a corner frequency of 0.01 Hz (100 s) or 0.005 Hz (200 s), which serves to remove any DC offsets.

6.3.2 Conventional-response feedback

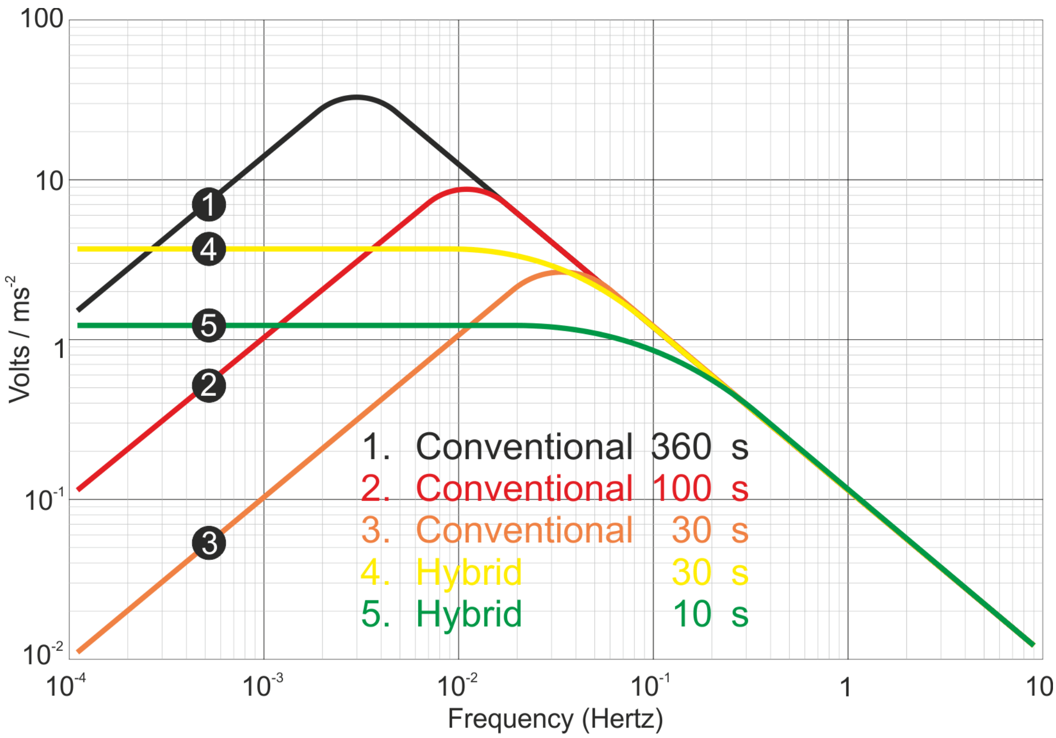
The *conventional-response* feedback system has an additional parallel feedback circuit, consisting of a non-inverting integrator in series with a resistor. This arrangement results in two poles at specified frequencies. The velocity response of a conventional-response system is defined by a transfer function identical to that of a conventional long-period sensor with a damping constant ζ of 0.707 (1/√2).

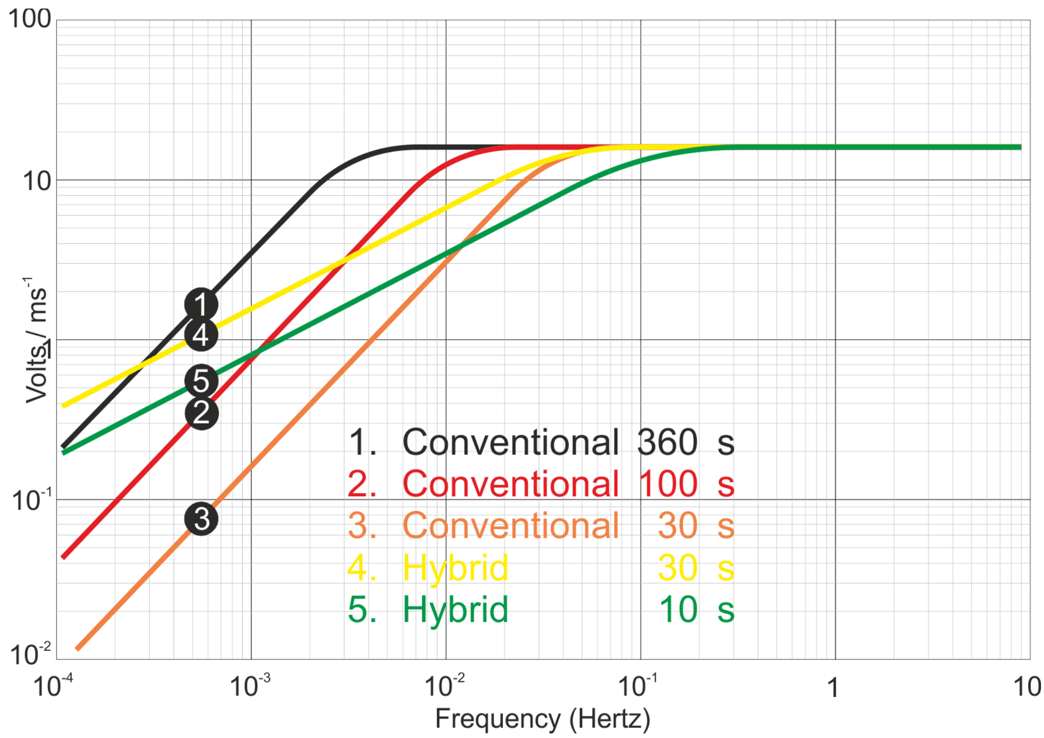


The seismometer can be supplied with an equivalent resonant frequency of 0.033 Hz (30 s), 0.01 Hz (100 s) or 0.0083 Hz (120 s) as required. An active low-pass filter provides a high-frequency cut-off point at a frequency you specify.

6.3.3 Comparisons

The figures below plot the comparative response of a conventional velocity output broadband sensor and a hybrid output broadband sensor. The upper graph shows the response in terms of output against input acceleration in units of V/ms^{-2}, whilst the lower graph is plotted in terms of output against input velocity, in V/ms^{-1}.


100
10
1
10^{-1}
10^{-2}
Volts / ms^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
Frequency (Hertz)
1. Conventional 360 s
2. Conventional 100 s
3. Conventional 30 s
4. Hybrid 30 s
5. Hybrid 10 s


100
10
1
10^{-1}
10^{-2}
Volts / ms^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
Frequency (Hertz)
1. Conventional 360 s
2. Conventional 100 s
3. Conventional 30 s
4. Hybrid 30 s
5. Hybrid 10 s

7 Appendices

7.1 Appendix A - Connector pin-outs

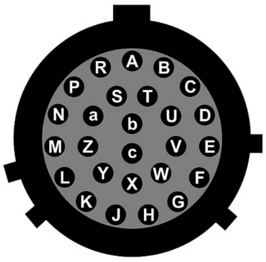
7.1.1 Sensor and control unit output

This is a standard 26-pin “mil-spec” plug, conforming to MIL-DTL-26482 (formerly MIL-C-26482). A typical part-number is ***-16-26P where the '***' is defined by the manufacturer.

Suitable mating connectors have part-numbers like ***-16-26S.

The 26-pin connectors on the breakout box have identical pin-outs.

Pin	Function	Pin	Function
A	Velocity +ve, vertical channel	P	Calibration signal (all channels)
B	Velocity −ve, vertical channel	R	Calibration enable, Z channel
C	Velocity +ve, N/S channel	S	Calibration enable, N/S channel
D	Velocity −ve, N/S channel	T	Calibration enable, E/W channel
E	Velocity +ve, E/W channel	U	Centre
F	Velocity −ve, E/W channel	V	*not connected*
G	Mass position, vertical channel	W	Unlock
H	*not connected*	X	Lock
J	Mass position, N/S channel	Y	Logic ground
K	*BUSY* LED	Z	*not connected*
L	Mass position, E/W channel	a	*not connected*
M	Power −ve (split supply option)	b	Power ground
N	Analogue ground	c	Power +ve



Wiring details for the compatible socket, ***-16-26S, as seen from the cable end (*i.e.* when assembling).

7.1.2 Breakout box DC power connector

This is a standard 10-pin "mil-spec" plug, conforming to MIL-DTL-26482 (formerly MIL-C-26482). A typical part-number is ***-12-10P where the '***' is defined by the manufacturer.

Suitable mating connectors have part-numbers like ***-12-10S.

Pin	Function
A	0 V
B	+12 V DC supply
C	*not connected*
D	*not connected*
E	*not connected*
F	*not connected*
G	*not connected*
H	−12 V DC supply (not used in sensors with internal DC-DC converters)
J	*not connected*
K	*not connected*

Wiring details for the compatible socket, ***-12-10S, as seen from the cable end (*i.e.* when assembling).

7.2 Appendix B - Specifications

Parameter	Specification
Hybrid sensors	0.1 – 50 Hz
Velocity output bandwidth	
High pass filter output flat to acceleration	0.01 Hz – *spec**
High pass filter output flat to velocity	*spec* – 50 Hz*
Mass position output	DC – 0.1 Hz
Velocity sensitivity	1400 V/m/s
Acceleration sensitivity	2000 V/m/s^2
Velocity sensors	
Velocity output bandwidth	*spec* – 50 Hz*
Mass position output	DC – *spec* Hz*
Velocity sensitivity	2 × 750 V/m/s
Mass position sensitivity	1000 V/m/s^2
Mass locking and unlocking	manual; optional remote operation
Mass centring	automatic, MPU controlled
Sensors	3 orthogonal, each 0.180 kg
Lowest spurious resonance	above 140 Hz
Total weight	11 kg
Sensor transducer type	capacitive displacement
Feedback transducer type	magnet/coil
Connector	pressure tight
Temperature range with masses locked	–35 to +75 °C
Operational temperature range	–20 to +65 °C**
Input voltage	10 – 36 V
Current at 12 V DC	75 mA†
Current at 12 V DC during calibration	100 mA†
Current at 12 V DC during centring	330 mA†
Current at 12 V DC during locking and unlocking	490 mA†

**spec* refers to the quoted frequency response value, *e.g.*, for a “30 s” sensor, the value of *spec* would be 30 s = 0.033 Hz.

**Temperatures below –20 °C may be accommodated with additional care. Please consult Güralp Systems for advice.

†Because centring, locking, and unlocking consume varying amounts of power, it is recommended that you use a power supply capable of delivering 1 A at 12 V.

7.3 Appendix C - Revision history

2000-04-28	A	New document
2006-02-21	C	Updates; added revision history
2006-11-15	D	Redrawn diagrams
2011-03-18	E	Changes to vault procedures, formatting updates
2011-08-23	F	Corrections to connector pin-out
2016-02-18	G	Corrections to connector pin-out