GEOSense BH-1 Corehole Seismometers
Version 5

Sensor Serial Number:

BH-1-20

March, 2004

GEOSense, LLC
409 N. Pacific Coast Hwy., #427
Redondo Beach, CA 90277
310-371-0150
www.geosense.com

Instrument Description

The BH-1 corehole seismometer is a compact, low-power, low-noise, wide bandwidth acceleration and velocity sensor. It utilizes Mark Products L-28B, 4.5 Hz geophones as the raw transducer element. Two horizontal elements (L-28LBH, long travel geophones) and one vertical element (L-28B) are integrated into a small-format sensor package. Proprietary electronic techniques are used to convert ground motion to an acceleration-sensitive signal with wide bandwidth (0.1 to 200 Hz typical). This acceleration signal is further conditioned to convert the accelerometer's signal to a separate velocity-sensitive output. The velocity output has a typical bandwidth of 1 to 200 Hz. The resulting sensor has a response that is comparable to sensors (e.g., triaxial, L-4C geophones) that are an order of magnitude larger. The use of long-travel, 4.5 Hz geophone elements facilitate deployment: the sensors are intrinsically shock-tolerant and they can be deployed at tilts in excess of +/-4^{o}.

These sensors incorporate a significant upgrade in the electronics (version 5). This includes:

Temperature-Compensation: A copper reference impedance is used to compensate for temperature-induced variations of the geophone's coil resistance. This improves the thermal stability of the sensor's transfer function. Over a temperature range of –5C to +40C, the transfer function is nearly independent of temperature. This concept was first implemented in the last version of the sensors (electronics version 4). Its performance has been optimized in version 5.

Increased Bandwidth: The accelerometer bandwidth has been increased over previous versions, using patented feedback compensation techniques. The bandwidth of the latest-generation sensors has been increased by approximately 2X on both the high and low frequency ends.

Increased Full-Scale Acceleration Range: The accelerometer's full-scale range has been increased to 0.04 g, from 0.009 g in the earlier versions (versions 3 and 4). Although, it is rare that such large signals are observed, it is possible that clipping of the accelerometer might be masked by the signal conditioning (integration and high pass filtering) stage that provides the velocity-sensitive output. By reducing the scale factor of the accelerometer, more gain can be placed later in the signal chain. In the earlier versions of the sensors (assuming a nominal velocity scale factor of 3500 V/m/sec), a full-scale output signal would clip first on the (earlier) acceleration-sensitive stage, for frequencies above 12.3 Hz. In the latest version (version 5), this frequency has been increased to approximately 27 Hz. Extensive modeling and test show that this change has not significantly affected the sensor noise equivalent performance. It is still dominated by the front-end amplifier in the electronics (this amplifier has not been changed).

Differential Velocity Output and Single-Supply Operation: The sensors now provide a fully differential velocity output. This has been implemented for use with latest-generation versions of the input amplifiers on the GEOSense LP-1 data logger. The use of differential drive and a differential receiver has shown improved noise immunity. In end-to-end tests of prototype differential sensors, no disk-drive-induced transients (a concern with previous sensors) have been observed in the data records. The scale factors of these two outputs are nominally +1750 V/m/sec and –1750 V/m/sec. The differential signal is the standard 3500 V/m/sec that has been provided by all versions of the sensors. In view of the limited number of pins (8) in the underwater connector, the use of differential drive requires a switch to "single-supply" operation. In this version of the sensors, a local, circuit-ground is generated within the board. Its level is mid-way between the + and – power supply voltages. When used with the LP-1 logger, one should connect the +5V and –5V supplies from the power supply (PS) board to the +S and –S inputs, respectively. In this way, the local circuit ground will be very close to the center of the common mode range of the logger's input amplifiers. ***Remember that the "Ground" connection is now an output (buffered). It should NOT be connected to an active source.*** The differential velocity output signals are referenced to this ground. Keep in mind that one can still use the +Velocity and Ground outputs to provide the usual single-ended signal. If necessary, the electronics can be modified for dual-supply operation, however, this change requires some changes of the component values on the boards. If this is desired, please contact GEOSense.

Single-Ended Acceleration Output: A separate connection is provided for the acceleration-sensitive signal from each sensor axis. Recording of this signal may be useful for higher frequency applications (e.g., above 27 Hz), where the acceleration output is larger than the velocity output. The acceleration signal is also useful during diagnostic step testing of the sensors (described below).

Step Testing: Using a patented electronic architecture, the sensor's frequency response and general state-of-health can be determined through application of a step signal. The resulting step response of either the acceleration or velocity output can be related to the frequency response of the sensor.

Smaller Form, Terminal Block Connectors: The added capabilities of the electronics require a greater number of I/O connection points. We are now using 2.54 mm pitch terminal blocks to provide 13 connections.

To date, a number of shipments of sensors have been made:

March, 2003: BH-1-14, BH-1-15, BH-1-16, BH-1-18
These were completely new sensors

June, 2003: BH-1-8, BH-1-9, BH-1-10, BH-1-17, BH-1-19
Sensors 8, 9, and 10 reuse the existing, long-travel sensor elements and have been upgraded with new electronics boards.
Sensors 17 and 19 utilize new sensor elements. These replace sensors 4 and 6 (older, short-travel) in order to provide a larger operating tilt range.

March 2004: BH-1-20
This utilizes new sensor elements. It replaces sensor 5 (older, short-travel) in order to provide a larger operating tilt range.

BH-1 Specifications

Responsivity:	Acceleration Output: 10.2 V/m/sec^2, nominal Differential Velocity: 3500 V/m/sec, nominal
Bandwidth:	1 Hz (-6 dB Point, +90 Degree Phase Point) to 200 Hz (-90 degree Phase Point), Nominal
Full-Scale Signals:	+/- 4.0 V minimum voltage from accelerometer outputs Corresponding to +/- 0.04 g input acceleration +/- 8.0 V minimum differential voltage from velocity outputs Corresponding to +/- 2.3 x 10^{-3} m/sec input velocity *Note that for frequencies above 27.1 Hz, the full-scale input velocity is less, owing to clipping of the accelerometer stage of the sensor.*
Noise Equivalent Velocity:	
	~ 1 x 10^{-9} m/sec-rtHz for $f \geq 4$ Hz ~ 5 x 10^{-9} m/sec-rtHz at f = 2 Hz ~2 x 10^{-8} m/sec-rtHz at f = 1 Hz
Power:	+/- 5 V, 0.9 mA, nominal **Absolute maximum input voltage is +/- 7.5V**
Dimensions:	2.0" diameter x 6.25" long See Figure 1
Mounting:	4 of 8-32 mounting holes on 1.50" diameter bolt circle See Figure 1
Axes Orientation:	Unchanged from earlier versions. See Figure 1. The sensitive axes form a right-handed (RH) coordinate system with +Z up. A positive output voltage is obtained for acceleration/velocity along the +axes
Required Alignment of Axes with Local Gravity:	
	X, Y Axes within +/- 4^o of horizontal Z Axis within +/- 8^o of vertical

Terminal Block Connections(Right-to-Left):
See Figure 2.

+S	Positive Power Supply (Input)
-S	Negative Power Supply (Input)
G	Circuit Ground (Output)
+X	X-Axis Positive Velocity (Output)
-X	X-Axis Negative Velocity (Output)
+Y	Y-Axis Positive Velocity (Output)
-Y	Y-Axis Negative Velocity (Output
+Z	Z-Axis Positive Velocity (Output)
-Z	Z-Axis Negative Velocity (Output)
XA	X-Axis Acceleration (Output)
YA	Y-Axis Acceleration (Output)
ZA	Z-Axis Acceleration (Output)
STP	Step Control (Input)

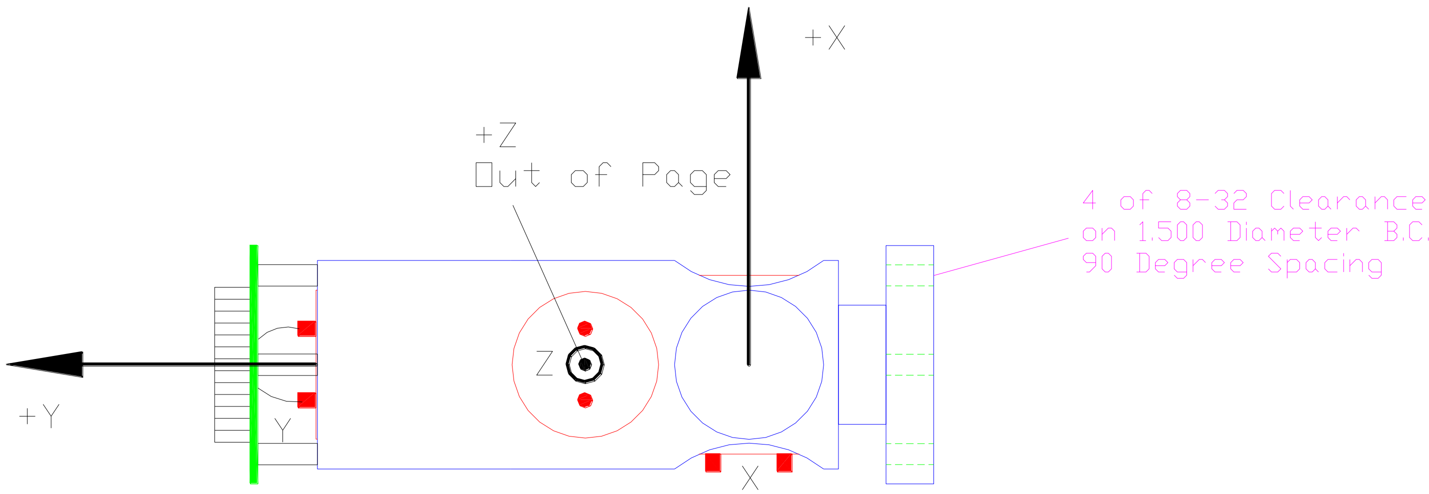


Figure 1. Orientation of sensor axes. During deployment, the Z-sensor (facing out of page) should be oriented with the geophone pins facing upwards. The X and Y sensors (in the plane of the page), should be aligned with the horizontal. The axes (+X, +Y, and +Z) form a right-handed (RH) coordinate system. A sensor velocity in the positive coordinate direction will cause a positive output voltage (on both the acceleration and differential velocity outputs).

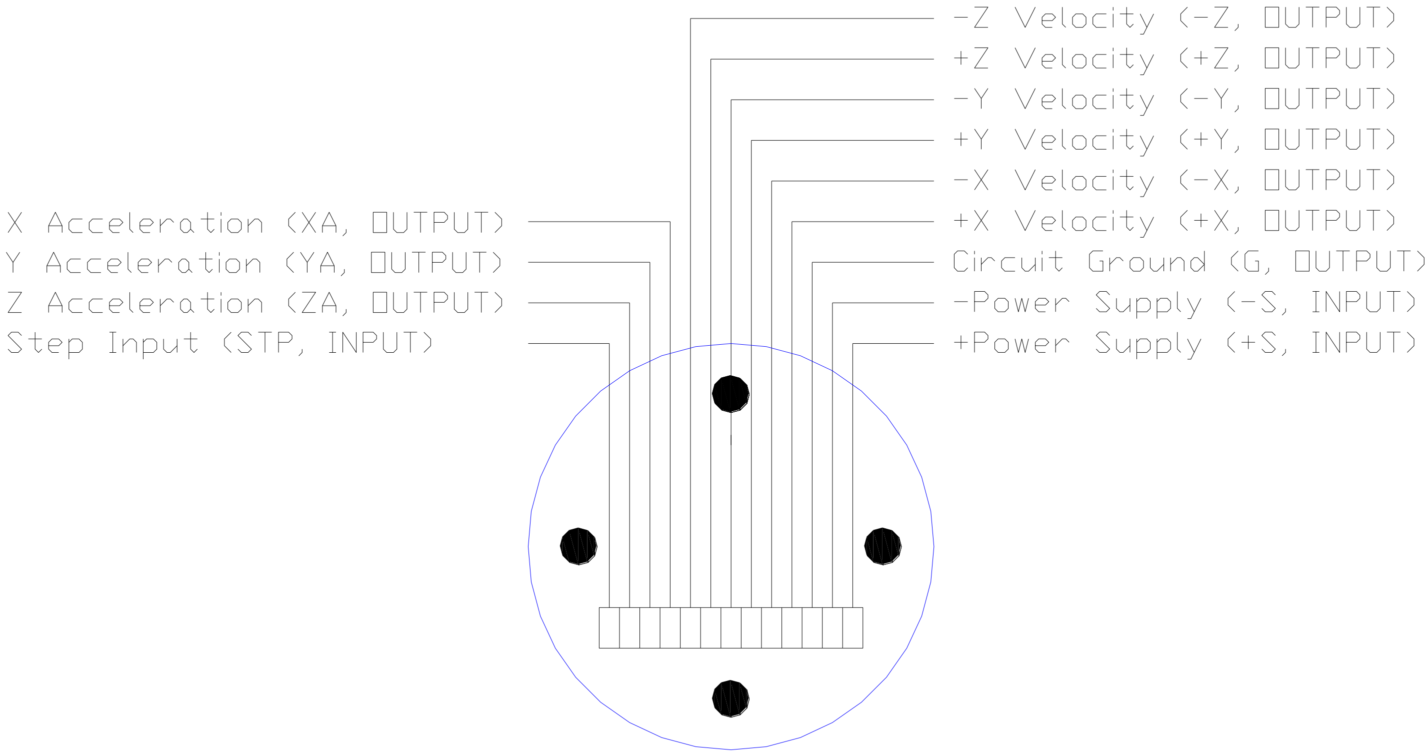


Figure 2. Electrical connection to BH-1 (Version 5) electronics board. The connections are made to the thirteen-contact terminal block. Exercise care when making connections. Note that Circuit Ground (G) is an active output, with a voltage midway between +S and –S.

The power inputs are NOT reverse polarity protected. There is also NO external overvoltage protection in the electronics. Exercise care in making connections. The absolute maximum differential input power voltage is 15V. Do not connect active sources to the outputs.

Individual Sensor Response Curves

Due to the use of an upgraded electronics design, GEOSense felt that it was necessary to perform new active shaker tests to verify the frequency response of the sensors. This was performed using an APS-113 electrodynamic shaker (at Navcon Engineering, Fullerton, CA). A triaxial sensor is mounted to the shaker together with a high-performance, reference accelerometer (Allied Signal QA-3000). The shaker is excited with white noise and the relative response of the sensor is measured using a dynamic signal analyzer (Stanford Research Systems, SR780). This allows generation of the amplitude and phase response of each sensor axis. Active vibration of mechanical objects of this size, over a 200 Hz bandwidth, is challenging. Typically, resonances in the mounting structures are observed in the vicinity of 100 Hz. Fortunately, the sensor response can be accurately defined by a number of high level parameters. These include:

Low frequency corner frequency (Hz)
Related to two-stages of high-pass filtering;
-6 dB point; +90 degree phase point

High frequency natural resonance frequency (Hz)
Standard, second-order, damped resonance
-90 degree phase point

High frequency damping ratio (fraction of critical)
Standard second order resonance

Amplitude response (V/m/sec)

In order to remove the mounting-induced resonances from the data, we generate synthetic transfer functions, which provide a best-fit to the shaker data. The values of the above parameters are adjusted so that the amplitude and phase of the synthetic transfer function matches that of the shaker data (away from the mechanical resonances). An example of such a fit is shown in Figure 3. In this way an accurate transfer function (the synthetic transfer function) can be generated for each sensor axis. An example of a synthetic transfer function is shown in Figure 4. We include (in the appendix) plots of all of the sensor response functions.

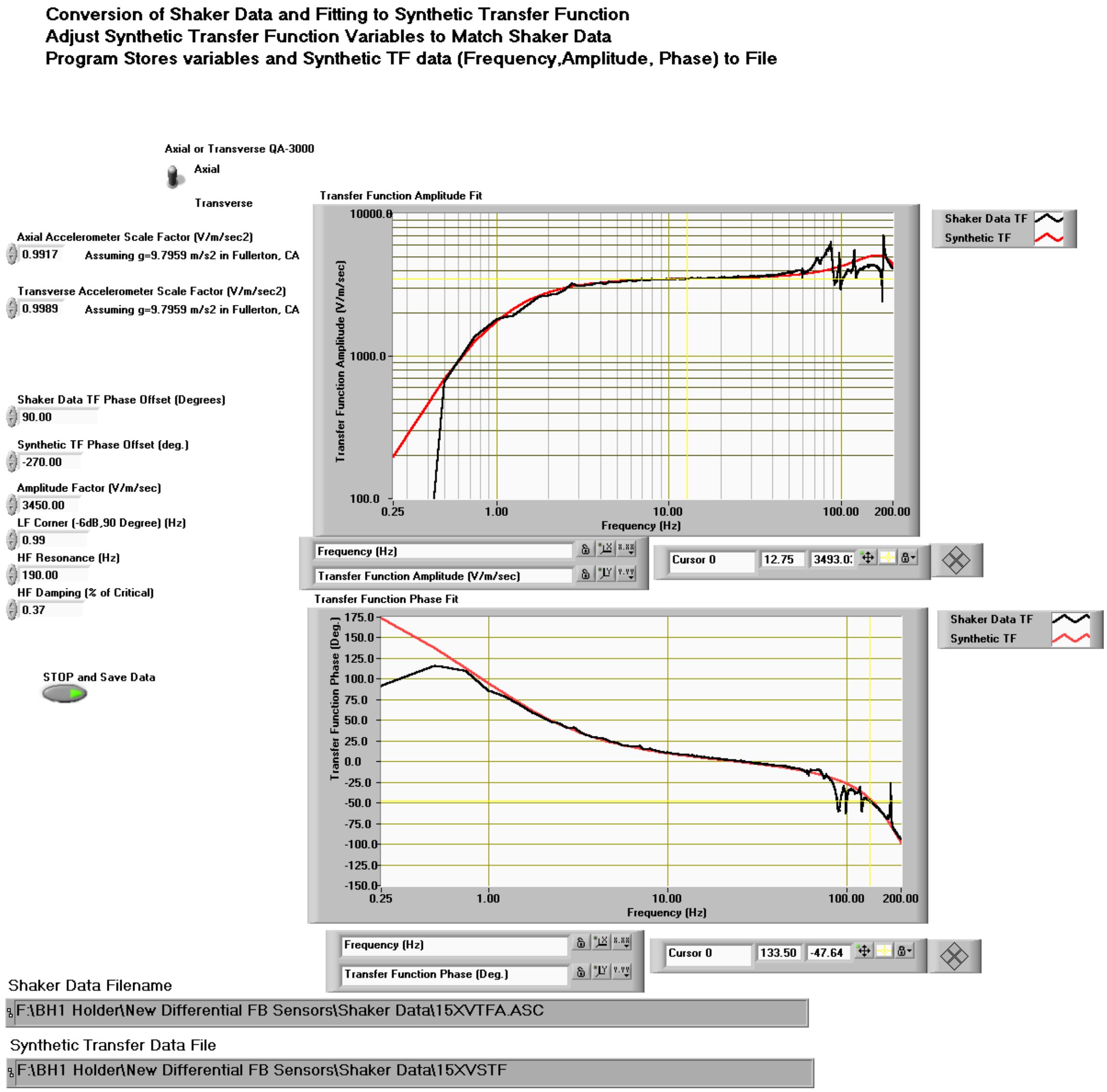


Figure 3. Fit of synthetic velocity transfer function to shaker data. The synthetic transfer function is generated from four variables: low frequency corner frequency (Hz), amplitude response constant (V/m/sec), high frequency natural resonant frequency (Hz), and high frequency damping (fraction of critical). A LabVIEW program allows one to modify the values of these variables in order to provide a best fit to the amplitude and phase data from the shaker. Mechanical resonances in the sensor mounting are evident in the shaker data beginning at about 80 Hz. These can be ignored ("fit around") during optimization of the synthetic transfer function variables.

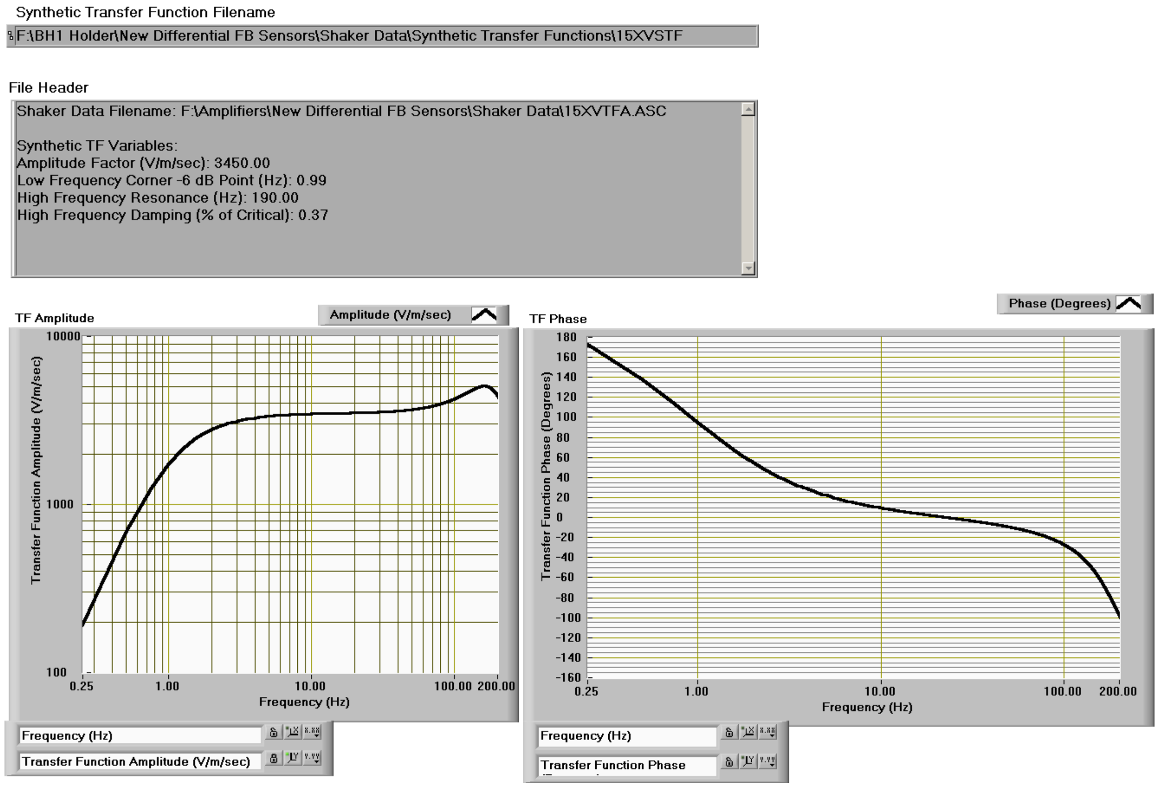


Figure 4. Plot of synthetic transfer function data from the fit of Figure 3. The file containing this data includes a header listing the variables from which the synthetic transfer function is generated.

ASCII data files have been generated for each sensor axis. These are included on a disk with the sensors. The filenames are:

“NNMVSTF” Synthetic Velocity Transfer Function for the M-axis of Sensor NN

NN = 14, 15, 16, or 18
M=X, Y, or Z

The file contains a header that lists the optimum, high-level parameters for the synthetic transfer function. The data is presented from DC to 200 Hz, on 0.25 Hz spacing, using a tab-delimited format:

“f(Hz) Velocity Amplitude Response (V/m/sec) Phase Response (degrees)”

Depending upon the accuracy requirements of MBARI’s future seismic applications, it may be desirable to conduct shaker testing on selected, earlier-generation sensors (BH-1, versions 3 and 4). If this is necessary, please contact GEOSense.

Step Testing

Application of a +5V signal to the STP input lifts the coils of the three geophones (simultaneously). When this signal is removed (i.e., when the STP input is held at circuit ground), the step response of the sensor can be recorded. Note that as the STP input is pulled down (to circuit ground) with a 100K resistor, no connection is required during normal sensor operation. The *acceleration* step response for a typical sensor is shown in Figures 5 and 6. Figure 6 is simply an expanded view of the earliest part of the complete plot of Figure 5. The step response signal is a superposition of a low frequency exponential decay with a damped, high frequency ringing. As shown in Figure 5, the time constant of the low frequency decay is directly related to the accelerometer’s low frequency corner (-3 dB point, about 0.098 Hz for this sensor). As shown in Figure 6, the period and decay rate of the high frequency ringing are directly related to the frequency and damping, respectively, of the high frequency resonance. For this sensor, analysis of the step response indicates a natural resonance of 194.5 Hz and a damping of 0.37 of critical. This compares closely with the values (195 Hz and 0.33 of critical) determined through shaker testing. The step response of the *velocity* output is shown in Figure 7. Note that because of the significant gain in the signal conditioning electronics (converting acceleration to differential velocity), the quantitative analysis of the *velocity* step response is difficult. One observes clipping within the output amplifiers early in the step response record. It is recommended that the velocity step response be used only to provide a test of the functionality of the sensor.

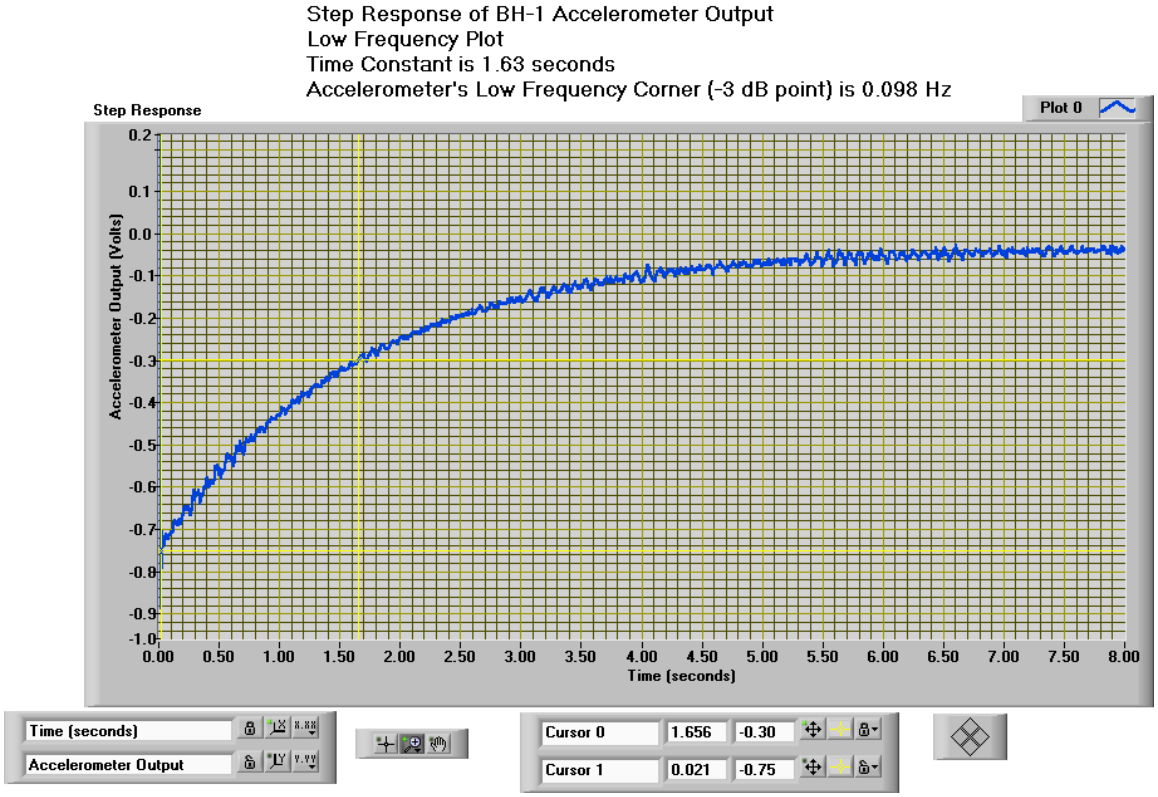


Figure 5. Low frequency portion of *acceleration* output step response from a typical sensor. The step was removed at approximately T=0.00. The accelerometer step response is an exponential decay. The 1/e time constant is directly related to the low frequency corner (-3 dB point) of the accelerometer. This sensor axis shows a corner at 0.098 Hz.

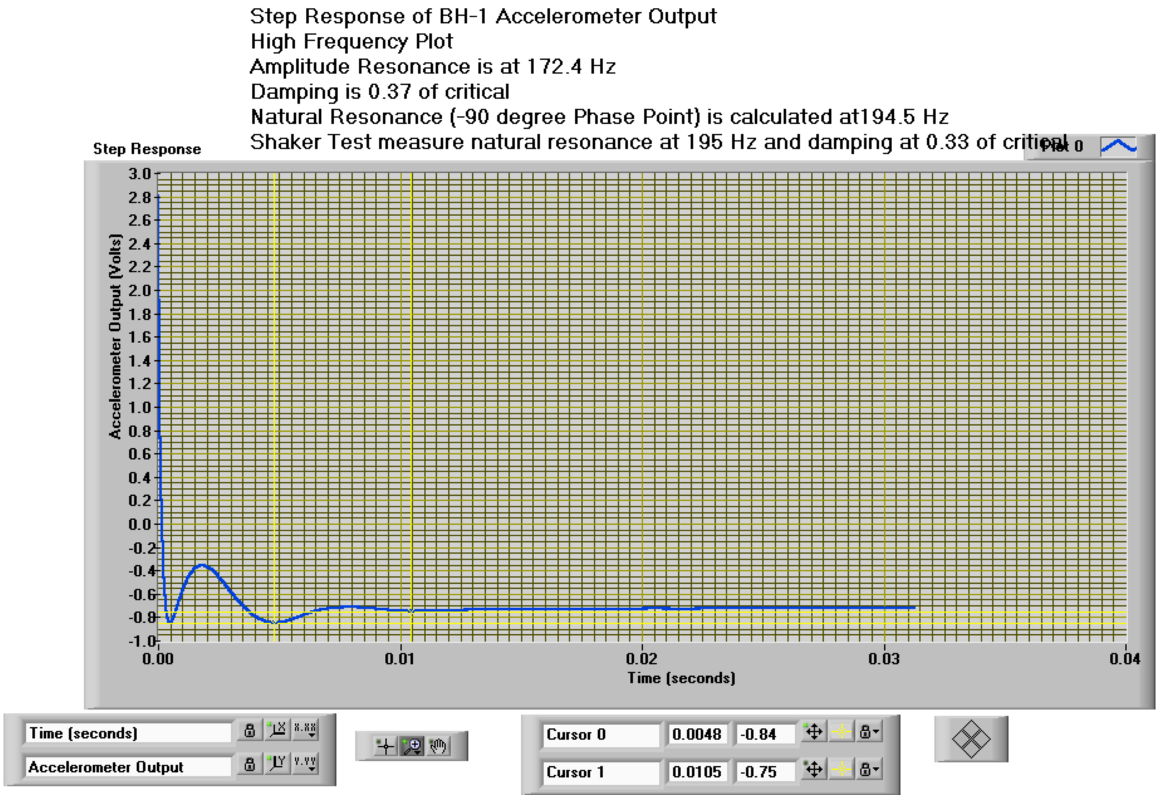


Figure 6. High frequency portion of acceleration output step response from a typical sensor. The step was removed at approximately T=0.000. The initial portion of the accelerometer step response is an exponentially-decaying oscillation, consistent with the step response of a damped harmonic oscillator. The oscillation frequency (so-called "amplitude resonance frequency") is determined from the period of oscillation. It is 172.4 Hz. The 1/e time constant of the oscillation is directly related to the damping. In this case, the damping is measured as 0.37 of critical. The natural resonance of the sensor (and the -90 degree phase point of the sensor) is computed from these two quantities. It is calculated to be 194.5 Hz. The step testing-derived values agree well with that of the shaker data, for this sensor (195 Hz natural resonance and damping of 0.33 of critical).

Step Response of BH-1 Differential Velocity Output
Low Frequency Plot

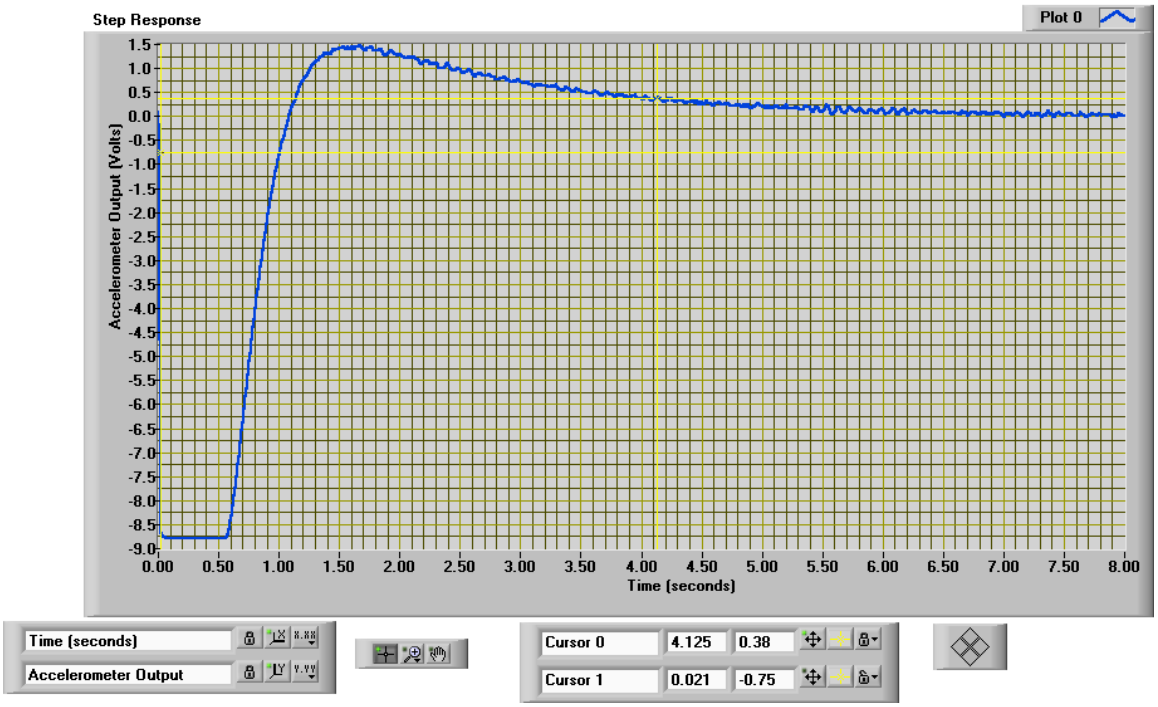


Figure 7. Low frequency portion of differential velocity output step response from a typical sensor. The quantitative analysis of the output signal is more complicated than with the acceleration output, given amplifier clipping effects in the integrator electronics (for converting acceleration to velocity). The velocity step response is best used as a simple, high level check of system functionality.

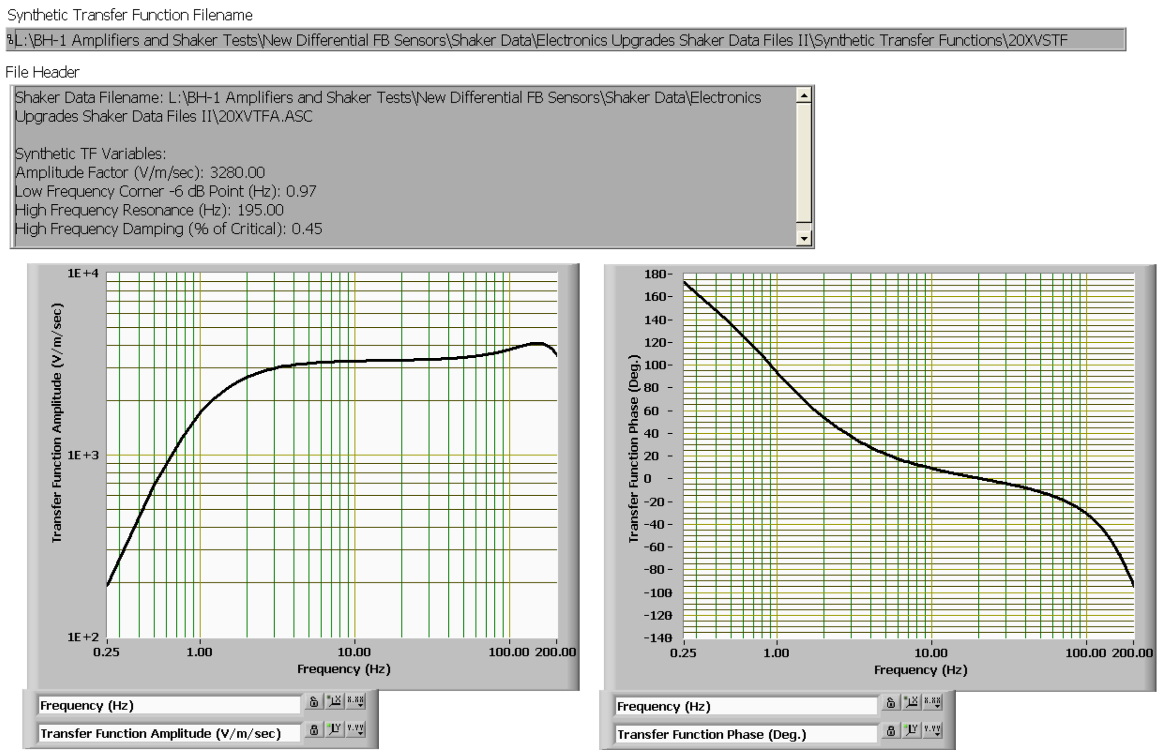
Contact GEOSense

If there are any questions, problems, or needs regarding these sensors, please contact:

Tom VanZandt
GEOSense, LLC
409 N. Pacific Coast Hwy., #427
Redondo Beach, CA 90277
310-371-0150 Phone
818-388-2826 Mobile
tom.vanzandt@geosense.com

Appendix

Individual Sensor Axis Velocity Synthetic Transfer Functions



Sensor 20X. “20XVSTF”

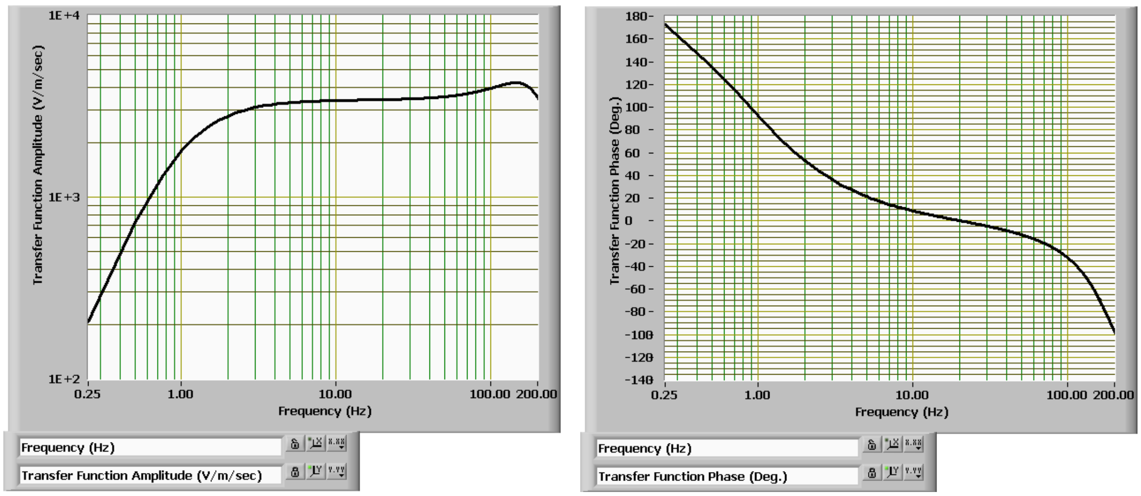
Synthetic Transfer Function Filename

L:\BH-1 Amplifiers and Shaker Tests\New Differential FB Sensors\Shaker Data\Electronics Upgrades Shaker Data Files II\Synthetic Transfer Functions\20YVSTF

File Header

Shaker Data Filename: L:\BH-1 Amplifiers and Shaker Tests\New Differential FB Sensors\Shaker Data\Electronics Upgrades Shaker Data Files II\20YVTFA.ASC

Synthetic TF Variables:
Amplitude Factor (V/m/sec): 3390.00
Low Frequency Corner -6 dB Point (Hz): 0.95
High Frequency Resonance (Hz): 188.00
High Frequency Damping (% of Critical): 0.45



Sensor 20Y. “20YVSTF”

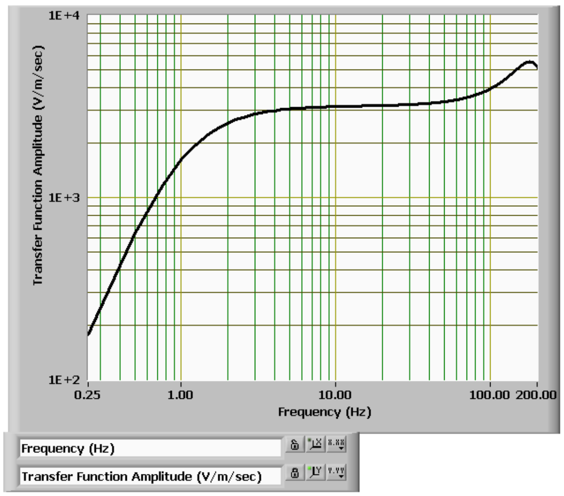
Synthetic Transfer Function Filename

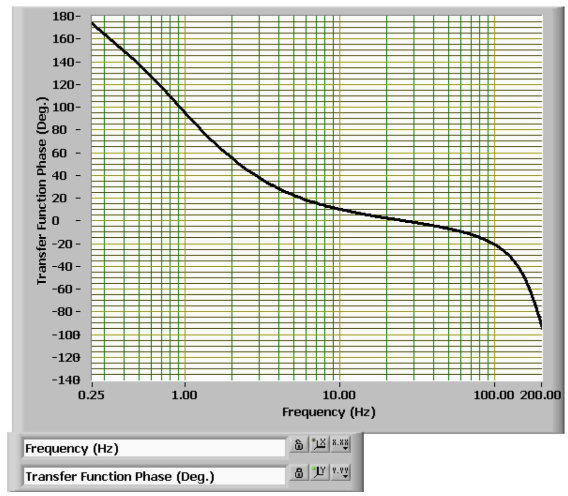
L:\BH-1 Amplifiers and Shaker Tests\New Differential FB Sensors\Shaker Data\Electronics Upgrades Shaker Data Files II\Synthetic Transfer Functions\20ZVSTF

File Header

Shaker Data Filename: L:\BH-1 Amplifiers and Shaker Tests\New Differential FB Sensors\Shaker Data\Electronics Upgrades Shaker Data Files II\20ZVTFA.ASC

Synthetic TF Variables:
Amplitude Factor (V/m/sec): 3150.00
Low Frequency Corner -6 dB Point (Hz): 0.99
High Frequency Resonance (Hz): 198.00
High Frequency Damping (% of Critical): 0.30





Sensor 20Z. "20ZVSTF"