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Evaluation of Three Refurbished Guralp CMG-3TB Seismometers

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Abstract

The overall objective of testing the Guralp CMG-3TB refurbished seismometers is to determine whether or not the refurbished sensors exhibit better data quality and require less maintenance when deployed than the original Guralp CMG-3TBs. SNL will test these 3 refurbished Guralps to verify performance specifications. The specifications that will be evaluated are sensitivity, bandwidth, self-noise, output impedance, clip-level, dynamic range over application passband, verify mathematical response and calibration response parameters for amplitude and phase.

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NOMENCLATURE

CRF	Central Recording Facility
GOVC	Government Customer
GOVR	Government Representative
GOVTC	Government Test Coordinator
FACT	Facility for Acceptance, Calibration and Testing
OOT	Out of Tolerance
SNL	Sandia National Laboratories
SPS	Samples per second
SNR	Signal-to-Noise Ratio

1 INTRODUCTION

The overall objective of testing the Guralp CMG-3TB refurbished seismometers is to determine whether or not the refurbished sensors exhibit better data quality and require less maintenance when deployed than the original Guralp CMG-3TBs.

Guralp Systems Limited (GSL) refurbished the 3 sensors under test. GSL performed the following tasks to complete the refurbishment:

a. Repaired/replaced the CMG-3TB sensor locking mechanism so that the CMG-3TB motors will function properly without sticking or grinding (wearing) when locking or unlocking the sensor.
b. Repaired/replaced the CMG-3TB centering mechanism so that the CMG-3TB will settle in the borehole within 2 weeks after install.
c. Repaired/replaced the sensor mass-locking assembly to determine the end of motor travel. This improvement will eliminate the jamming of motors at their travel ends and ensure that under no circumstances the motors will be stuck at their travel points.
d. Repaired/replaced the micro-controller of the sensor to avoid confusion of the CMG-3TB, on occasion, when performing locking/centering functions.
e. Ensure the measured self-noise of the CMG-3TB is 6 dB below the Peterson's new low noise model (NLNM) across the passband (0.02 Hz – 16 Hz).
f. Lubricants. The oil that will be used in the motors shall be thermally, and chemically stable and shall not out gas during storage or operation.
g. Magnet material. Current magnets are all neodymium based magnets which are occasionally prone to corrosion. In order to eliminate any corrosion due to anaerobic effects, a different type of magnet material will be used. The magnets used shall have the same magnetic characteristics as that of the neodymium and the sensor performance shall not degrade.

SNL will test these 3 refurbished Guralps to verify performance specifications. The specifications that will be evaluated are sensitivity, bandwidth, self-noise, output impedance, clip-level, dynamic range over application passband, verify mathematical response and calibration response parameters for amplitude and phase. The details concerning the specifications listed above are described in the tests below. Tests conducted by Sandia will not address listed repairs items a, c, d, f or g.

2 EXECUTIVE SUMMARY

CMG-3TB S/N T35093

Requirement category	**AFTAC Seismometer Requirements**	**Guralp CMG-3TB Measurements**	**Pass/Fail/ Indeterminate**
Pass Band (flat to velocity or acceleration)	BB: 0.02 – 16 Hz	Flat to acceleration from 120 sec to 50 Hz.	Pass
Seismometer noise (self-noise)	>= 6 dB below the NLNM over the pass band of interest	>= 6 dB below the NLNM over 0.03 – 10 Hz. >= 3 dB below the NLNM over 0.02 – 16 Hz.	Ind[1]
Calibration response	Within 3% in amplitude and 3 degrees in phase over the pass band	Within 3% in amplitude and 3 degrees in phase over the pass band	Pass
Dynamic range	>= 100 dB over the pass band	>= 100 dB over the pass band	Pass[2]
Output Impedance	Measure to factory specifications. Must not negatively affect calibration and data waveforms (impedance mismatch).	100-ohm serial resistance per line 200-ohm output impedance	Pass
Sensor response verification	The derived or measured response must be within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	The derived or measured response is within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	Ind[3]
Mass position stability	The seismometer mass must stabilize within two weeks and remain stable in a controlled borehole environment.	The seismometer mass will stabilize within two weeks and remain stable in a controlled borehole environment.	Pass
Sensor clip	The measured sensor clip voltage must be > max. factory positive voltage spec. and < min. factory negative voltage spec.	+/- 20 V, differential, 40 Vpeak-to-peak	Pass

1. Testing was unable to observe incoherence self-noise of the sensor 6 dB or more below the NLNM.
2. Although the computed dynamic range did exceed the 100 dB specification, this estimate included the use of suspect self-noise data. The actual dynamic range likely exceeds this estimate.
3. There was insufficient coherence between the sensor under test and the reference sensors to validate the response to these specifications.

CMG-3TB S/N T35466

Requirement category	**AFTAC Seismometer Requirements**	**Guralp CMG-3TB Measurements**	**Pass/Fail/ Ind**
Pass Band (flat to velocity or acceleration)	BB: 0.02 – 16 Hz	Flat to acceleration from 120 sec to 50 Hz.	Pass
Seismometer noise (self-noise)	>= 6 dB below the NLNM over the pass band of interest	>= 6 dB below the NLNM over 0.03 – 10 Hz. >= 3 dB below the NLNM over 0.02 – 16 Hz.	Ind[1]
Calibration response	Within 3% in amplitude and 3 degrees in phase over the pass band	Within 3% in amplitude and 3 degrees in phase over the pass band	Pass
Dynamic range	>= 100 dB over the pass band	>= 100 dB over the pass band	Pass[2]
Output Impedance	Measure to factory specifications. Must not negatively affect calibration and data waveforms (impedance mismatch).	100-ohm serial resistance per line 200-ohm output impedance	Fail[3]
Sensor response verification	The derived or measured response must be within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	The derived or measured response is within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	Ind[4]
Mass position stability	The seismometer mass must stabilize within two weeks and remain stable in a controlled borehole environment.	The seismometer mass will stabilize within two weeks and remain stable in a controlled borehole environment.	Pass
Sensor clip	The measured sensor clip voltage must be > max. factory positive voltage spec. and < min. factory negative voltage spec.	+/- 20 V, differential, 40 Vpeak-to-peak	Pass

1. Testing was unable to observe incoherence self-noise of the sensor 6 dB or more below the NLNM.
2. Although the computed dynamic range did exceed the 100 dB specification, this estimate included the use of suspect self-noise data. The actual dynamic range likely exceeds this estimate.
3. The E channel of T35466 measured twice the expected impedance. The Z and N channels measured impedance values as expected. See section 4.4.1 for additional details.
4. There was insufficient coherence between the sensor under test and the reference sensors to validate the response to these specifications.

CMG-3TB S/N T34868

Requirement category	**AFTAC Seismometer Requirements**	**Guralp CMG-3TB Measurements**	**Pass/Fail/ Ind**
Pass Band (flat to velocity or acceleration)	BB: 0.02 – 16 Hz	Flat to acceleration from 120 sec to 50 Hz.	Pass
Seismometer noise (self-noise)	>= 6 dB below the NLNM over the pass band of interest	>= 6 dB below the NLNM over 0.03 – 10 Hz. >= 3 dB below the NLNM over 0.02 – 16 Hz.	Ind[1]
Calibration response	Within 3% in amplitude and 3 degrees in phase over the pass band	Within 3% in amplitude and 3 degrees in phase over the pass band	Pass
Dynamic range	>= 100 dB over the pass band	>= 100 dB over the pass band	Ind[2]
Output Impedance	Measure to factory specifications. Must not negatively affect calibration and data waveforms (impedance mismatch).	100-ohm serial resistance per line 200-ohm output impedance	Pass
Sensor response verification	The derived or measured response must be within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	The derived or measured response is within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	Ind[3]
Mass position stability	The seismometer mass must stabilize within two weeks and remain stable in a controlled borehole environment.	The seismometer mass will stabilize within two weeks and remain stable in a controlled borehole environment.	Pass
Sensor clip	The measured sensor clip voltage must be > max. factory positive voltage spec. and < min. factory negative voltage spec.	+/- 20 V, differential, 40 Vpeak-to-peak	Pass

1. Testing was unable to observe incoherence self-noise of the sensor 6 dB or more below the NLNM.
2. The computed dynamic range did not exceed the 100 dB specification. However, this estimate included the use of suspect self-noise data. The actual dynamic range likely exceeds this estimate.
3. There was insufficient coherence between the sensor under test and the reference sensors to validate the response to these specifications.

3 TEST CONFIGURATION

The evaluation following the test plan is written in accordance with Government Customer (GOVC) Instruction (CENI) 99-103, 9 May 2011.

3.1 Purpose

The purpose of this evaluation is to verify performance specification of three refurbished Guralp CMG-3TB seismometers. The performance specifications that will be evaluated are sensitivity, bandwidth, self-noise, output impedance, mass-position stability, clip-level, dynamic range over application passband, verify mathematical response and calibration response parameters for amplitude and phase.

3.2 Background

Sandia National Laboratories has provided GOVC with an independent system and component evaluation capability since the 1960s. Sandia has developed the expertise and facilities necessary to perform such system and component testing.

3.3 Test Management and Participation

The management of the testing will be under control of SNL with onsite participation by interested parties. The list of personnel and their tasks are included below:

SNL Test Site Manager – Mr. Randy Rembold
SNL Test Director – Mr. Darren M. Hart
Government Customer – Mr. Brett Moeller
Government Test Coordinator- Mr. James Neely

3.4 General Test Schedule

Laboratory testing took place at the SNL FACT site. Evaluation at the SNL FACT site took place over a six month period starting in October 2013.

3.5 Test Resources

3.5.1 Seismic Test bed

Laboratory testing for seismometer specification was made in the SNL FACT Site underground seismic vault.

3.5.2 Seismic Test Reference Sensors

Testing for low-frequency (<1Hz) seismic specifications was made with two reference sensors the STS2 seismometer in high-gain configuration serial number 90032 and a STS2 seismometer in low-gain configuration serial number 19037. Testing for high-frequency (>1Hz) seismic specifications was made with a Geotech GS13 seismometer, serial number 882.

3.5.3 Data Acquisition / Storage Device

The Quanterra Q330 Dual HR data logger serial numbers 3095 was used for all data acquisition and short-term storage of data taken for the STS2 reference sensors over the testing period. The high frequency data from the GS13 was collected on a Geotech Smart24 digitizer serial number S1036. The data for the Guralp CMG-3TB seismometers was recorded by a Guralp DM24S6EAM six channel digitizer serial number 1709. The Guralp digitizer has the limitation that it can only command-and-control channels 1-3 for locking and unlocking seismometer masses and mass position centering.

No gain will be applied to reference sensors or Sensor Under Test (SUT) by the Q330 dual HR or DM24S6EAM. Each sensor was powered by an isolated source during laboratory testing. The primary sample rate was set to 200 samples per second (sps); this allowed analysis of the data to 80 Hz, which is 20% below the sample rate Nyquist (100 Hz). Low frequency test data (0.1 Hz and below) was analyzed at a lower sample rate of 1 Hz.

3.5.4 Test Facilities

The testing was performed at the Sandia FACT Site. The FACT site is Sandia's seismic and infrasound test facility located in Albuquerque, New Mexico. SNL has developed verification technologies since the early 1960s. The resulting expertise and technology base, along with Sandia's Facility for Acceptance, Testing, and Calibration (FACT) site, gives Sandia a unique ability to support the testing of components (sensors and digitizers) and complete monitoring systems in various configurations.

3.6 Limitations

Pre-Evaluation: The limitations foreseen for the laboratory testing are:

3.6.1.1 Only two seismometers can be tested at one time.

3.6.1.2 The digitizer that will be used to record the test data for the SUT can only command-and-control channels 1-3 of the six available channels of recording capability.

3.6.1.3 Our ability to comment on the low-frequency corner of the seismometer will depend upon the natural occurrence of a seismic event to provide a common input signal above background.

Post-Evaluation: New limitations discovered during laboratory testing are:

3.6.1.4 Site power was lost on a few occasions during the evaluation; this compromised data recording and had implications on data quality for tests of mass position stability and response verification.

3.6.1.5 The method used to install the seismometers for testing is not the recommended method for installing the sensors for a field deployment. A test fixture should be designed to allow the seismometers to be tested in a manner closer to the methodology used in the actual field deployment.

3.7 Security Requirements

The test will be conducted at the UNCLASSIFIED level. Raw data collected during the test will be unclassified. All data handling and analysis of the processed data will be in accordance with the appropriate Security Classification Guide(s).

3.8 Safety Requirements

A controlled area with secure workspace was provided at the test facility.

4 TESTING AND EVALUATION

4.1 General

SNL Ground-based Monitoring Research & Engineering Department has the capability to evaluate the performance of seismic sensors for explosion monitoring and other geophysical applications within the bandwidth of 120 sec to 100 Hz. The CMG-3TB seismometers application bandwidth of ***120 sec to 50 Hz*** is at or within this range.

4.1.1 Components

The gain, bandwidth, self-noise, output impedance, clip-level, dynamic range over application passband, verify mathematical response and calibration response parameters for amplitude and phase are all specifications that must be tested and evaluated. See [Kromer, 2007] and [Merchant, 2011] for a more detailed description of the component tests.

The data from the sensors must be collected by a computer at the CRF. Currently there is no plan to forward data to external sources.

4.2 Critical Test Issues

The laboratory test is intended to address the following Critical Test Items:

- Mass position stability
- Sensitivity
- Amplitude and phase response
- Bandwidth
- Self-noise
- Output impedance, clip-level
- Dynamic range over application passband

Given the known background noise levels at the FACT site and the non-standard installation technique involved with testing a borehole sensor within a vault, it is expected that resolution of the sensor's full bandwidth, self-noise, and dynamic range will be challenging.

4.3 Test Objectives

The objective of this evaluation is to provide an independent evaluation and verify the individual sensor specifications (i.e. gain, bandwidth, self-noise, output impedance, clip-level, dynamic range over application passband, verify mathematical response and calibration response parameters for amplitude and phase) prior to field deployment.

Requirements provided by the customer requesting evaluation of Guralp Systems, Limited, CMG-3TB seismometer is flat to acceleration output response. The following table will be completed after evaluation and placed in Evaluation Executive Summary.

Requirement category	**AFTAC Seismometer Requirements**	**Guralp CMG-3TB Specifications**	**Pass/Fail**
Pass Band (flat to velocity or	BB: 0.02 – 16 Hz	Flat to acceleration from 120 sec to 50 Hz.	-

acceleration)			
Seismometer noise (self-noise)	>= 6 dB below the NLNM over the pass band of interest	>= 6 dB below the NLNM over 0.03 – 10 Hz. >= 3 dB below the NLNM over 0.02 – 16 Hz.	-
Calibration response	Within 3% in amplitude and 3 degrees in phase over the pass band	Within 3% in amplitude and 3 degrees in phase over the pass band	-
Dynamic range	>= 100 dB over the pass band	>= 100 dB over the pass band	-
Output Impedance	Measure to factory specifications. Must not negatively affect calibration and data waveforms (impedance mismatch).	100-ohm serial resistance per line 200-ohm output impedance	-
Sensor response verification	The derived or measured response must be within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	The derived or measured response is within 5% in amplitude and 5 degrees in phase over the pass band when compared against the provided factory model.	-
Mass position stability	The seismometer mass must stabilize within two weeks and remain stable in a controlled borehole environment.	The seismometer mass will stabilize within two weeks and remain stable in a controlled borehole environment.	-
Sensor clip	The measured sensor clip voltage must be > max. factory positive voltage spec. and < min. factory negative voltage spec.	+/- 20 V, differential, 40 Vpeak-to-peak	-

4.4 Test Approach & Methods

Sandia has developed a standardized set of tests that are used for sensor and digitizer characterization as well as the instrumentation evaluation software used for data analysis. Some of these tests are based on the Sandia SAND reports SAND2007-5025 [reference 1], SAND2007-5037 [reference 2], SAND2007-5038 [reference 3] and SAND2007-6440 [reference 4]. Analysis techniques have been documented in the report SAND2011-8265.

4.4.1 Output Impedance Verification

Purpose: The purpose of the seismic sensor output impedance verification test is to verify the seismic sensor's output impedance.

Configuration: The seismic sensor is powered, unlocked and the outputs are connected to a calibrated impedance measuring device, e.g. HP 3458A 8 digit multimeter, and the sensors output impedance measured.

Evaluation: The measured output impedance of the sensor is compared to that stated by manufacture. The result is expressed as percent difference from manufactures given value.

Results: The following tables show the results of the impedance measurements on the three seismometers.

T35466

Measurement Pins / Component	Impedance (Ohms)
A-N / Acceleration Z+	102
B-N / Acceleration Z-	103
A-B / Acceleration Z+/-	208
C-N / Acceleration N+	104
D-N / Acceleration N-	106
C-D / Acceleration N+/-	208
E-N / Acceleration E+	194*
F-N / Acceleration E-	195*
E-F / Acceleration E+/-	398*

*The output impedance for unit T35466 channel E was twice as high, approximately 400 Ohms, than the expected nominal value of 200 Ohms. This difference in impedance is noted and will be considered when evaluating data from this channel.

T35093

Measurement Pins / Component	Impedance (Ohms)
A-N / Acceleration Z+	108
B-N / Acceleration Z-	104
A-B / Acceleration Z+/-	211
C-N / Acceleration N+	104
D-N / Acceleration N-	105
C-D / Acceleration N+/-	207

E-N / Acceleration E+	106
F-N / Acceleration E-	107
E-F / Acceleration E+/-	206

T34868

Measurement Pins / Component	Impedance (Ohms)
A-N / Acceleration Z+	105
B-N / Acceleration Z-	105
A-B / Acceleration Z+/-	208
C-N / Acceleration N+	110
D-N / Acceleration N-	102
C-D / Acceleration N+/-	204
E-N / Acceleration E+	116
F-N / Acceleration E-	90
E-F / Acceleration E+/-	194

4.4.2 Mass Position Stability Verification

Purpose: The purpose of the mass position stability verification test is to verify the amount of time necessary for seismometer masses to stabilize and not require further mass re-centerings.

Configuration: The seismic sensor is installed in temperature stable environment, leveled and then powered. The mass positions for the seismometer are recorded by high resolution digitizer.

Evaluation: Once a day the mass positions are reviewed to determine if they are still within operational tolerance. If mass positions are OOT, then make note in test log and reset mass positions. If mass positions are within tolerance, then make note in test log and continue recording data. If no mass re-centerings are done in seven consecutive days, the test is considered complete. For each day the test is run the mass position drift rate and DC offset will be measured from recorded mass position channels.

Results: Unit T35093: was installed on October 9, 2013, powered and started recording around 18:00. Mass position data was collected on October 24, 2013 at ~16:30. Mass re-centering occurred on 10/10 at 16:00, 10/11 at 15:00, 10/14 at 21:00, 10/17 at 17:00 and 10/22 at 20:00. A total of 61 analysis windows were analyzed for DC offset of mass positions channels. Figure 4.4.2.1 shows the mass position DC-offset over the duration of the test. Only once during the test did one of the masses pass outside the OOT specification.

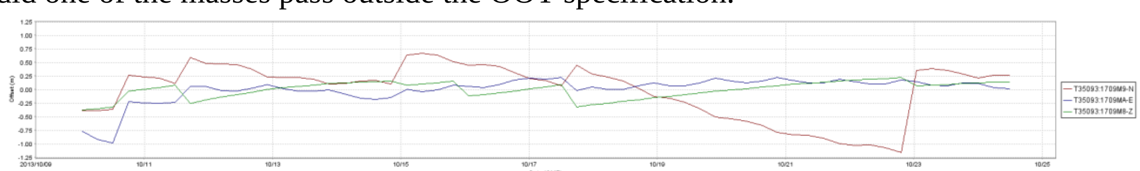

Figure 4.4.2.1 Mass position DC-offset for unit T35093.

Unit T35466: was installed and powered at the same time as T35093, but mass position recording didn’t start until October 24, 2013 at ~20:00. The only mass centering was done on 10/25 at 19:50, not surprising since the sensors have been powered and running since October

9th. Figure 4.4.2.2 shows the mass position DC-offset over the duration of the test. Only once during the test did one of the masses pass outside the OOT specification.

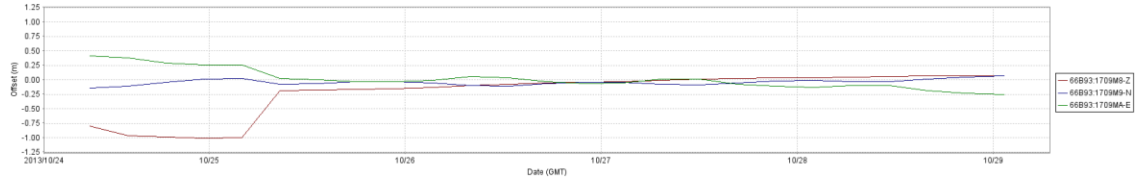

Figure 4.4.2.2 Mass position DC-offset for unit T35466.

Unit T35466 channel Z, drifted to the OOT specification of 1 Volt. The following day the masses were re-centered and masses stayed within tolerance for the duration of the test.

Unit T34868: was installed and powered on February 6, 2014 at ~20:00. During February FACT site lost power several times due to unknown reasons. This limited the initial review of mass position stability data. Notes indicate that three mass centering's were done on 2/6 at 21:30, 2/7 at 18:30, 2/10 at 19:46 (due to power outage), and 2/14 at 20:00 after running calibrations on seismometer. On March 12, 2013 mass position data was collected and reviewed for the time period February 27 to March 12, 2014. Figure 4.4.2.3 shows the mass position DC-offset over the duration of the test.

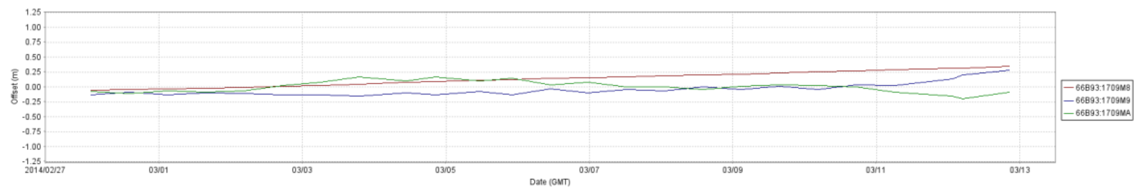

Figure 4.4.2.3 Mass position DC-offset for unit T34868.

Due to the sensor running for an extended period of time to allow for thermal stabilization and minimal activity at the site during this time period the DC-offset of the masses never reach an OOT limit.

4.4.3 Sensitivity and Passband Verification

Purpose: The purpose of the seismic sensor response verification test is to verify the seismic sensor sensitivity and response using seismic background signals and a reference seismic sensor.

Configuration: A characterized reference sensor and one or more of the sensors under test, are installed side-by-side in a seismic vault or in an adjacent borehole. The seismic sensor outputs are connected to a data acquisition system that samples the data synchronously. Data are acquired during moderate to high seismic backgrounds and events.

Evaluation: Convert the data from each seismic sensor to ground motion using the sensor response mathematical model for each sensor. If the sensor response models are correct, the amplitude response measurements in earth-motion units will be identical.

Results: Passband verification was done for units T35093 and T35466 for the low and high frequency corner using data from the Magnitude 7.9 earthquake on 11/17/2013. Passband verification was done for T34868 for the low and high frequency corner using data from the

Magnitude 6.7 earthquake on 3/16/2014. The STS2 serial number 19037 was used as the reference seismometer for the analysis. The -3dB roll-off frequency was estimated for each sensor and each of the three primary channels. Tables 4.4.3.1, 4.4.3.2, and 4.4.3.3 list the -3 dB points for sensors T35093, T35466, and T34868 respectively.

Table 4.4.3.1 Passband Verification for T35093

	Low Frequency Corner (Hz)	High Frequency Corner (Hz)
T35093 Z	0.00763 Hz (-3.13 dB)	51.56 Hz (-3.02 dB)
T35093 N	0.00763 Hz (-3.21 dB)	> 40 Hz
T35093 E	0.00763 Hz (-3.00 dB)	> 50 Hz

Table 4.4.3.2 Passband Verification for T35466

	Low Frequency Corner (Hz)	High Frequency Corner (Hz)
T35466 Z	0.00763 Hz (-3.17 dB)	51.61 Hz (-3.08 dB)
T35466 N	0.00610 Hz (-3.23 dB)	> 40 Hz
T35466 E	0.00687 Hz (-3.44 dB)	> 50 Hz

Table 4.4.3.3 Passband Verification for T34868

	Low Frequency Corner (Hz)	High Frequency Corner (Hz)
T34868 Z	< 0.01 Hz	> 40 Hz
T34868 N	< 0.01 Hz	> 30 Hz
T34868 E	< 0.02 Hz	> 40 Hz

Note that for the evaluation of T34868, the Magnitude 6.7 earthquake did not have sufficient energy in the low or high frequencies to allow for the corner frequencies to be resolved. However, the passband was still able to be resolved out to at least the passband of interest, 0.02 – 16 Hz.

High frequency passband verification was attempted during the evaluation, but definitive results could not be achieved for the horizontal channels (N and E). This is due to limitations in the high frequency coherence of the recorded seismic signal.

Although the high frequency passband could not be quantitatively verified for the horizontal channels due to the lack of coherence, qualitatively all of the horizontal channels remained flat (~ 0 dB) relative to the STS-2 reference up to 30-50 Hz before the coherence began to break down excessively. Given these observations, a high frequency corner above 50 Hz on the horizontal channels is not unreasonable. In all cases, the measured passband exceeded the 0.02 – 16 Hz passband requirement.

In addition, the passband was also verified using the calibrator as described in section 4.4.8.

4.4.4 Self-Noise Verification

Purpose: The purpose of the seismic sensor self-noise test is to determine the sensor self-noise in the presence of low seismic background signals.

Configuration: Two or more sensors are installed side-by-side in a seismic vault or stacked vertically in a borehole. The sensor outputs are connected to a data acquisition system that samples the data synchronously. Data are acquired during low seismic backgrounds.

Evaluation: Coherence analysis noise-power computation provides the noise-floor of the sensor pair for low seismic background stimulus. If three or more sensors are available, the use of Three-Channel Coherence Analysis techniques can derive individual sensor responses and self-noise.

Results: Seismometer self-noise estimation was limited to using the 2-channel coherence technique because our recording system limited us to acquiring data from 2 seismometers at a time. Using the 2-channel coherence technique, the measurement of incoherent noise was assumed to be equally distributed between pair of sensors.

Due to the amount of background present during testing and the non-standard method of installation, the incoherent self-noise of the CMG-3TB was not able to be determined. The observed incoherent noise contains remnants of the observed background and should not be considered representative of the self-noise of the CMG-3TB.

Figures 4.4.4.1, 4.4.4.2, and 4.4.4.3 display the noise estimate for the T35093 – T35466 pair for channels Z, N, and E respectively. Figures 4.4.4.4, 4.4.4.5, and 4.4.4.6 display the noise estimate for the T35093 - T34868 pair for channels Z, N, and E respectively.

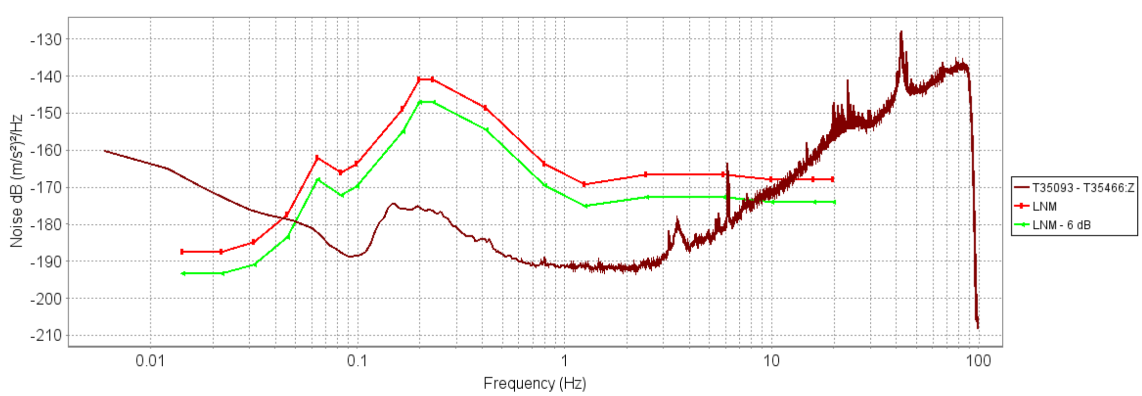

Figure 4.4.4.1 Incoherent noise for the Z channel of T35093 and T35466 shown relative to the Low Noise Model and 6 dB below the Low Noise Model on December 2, 2013.

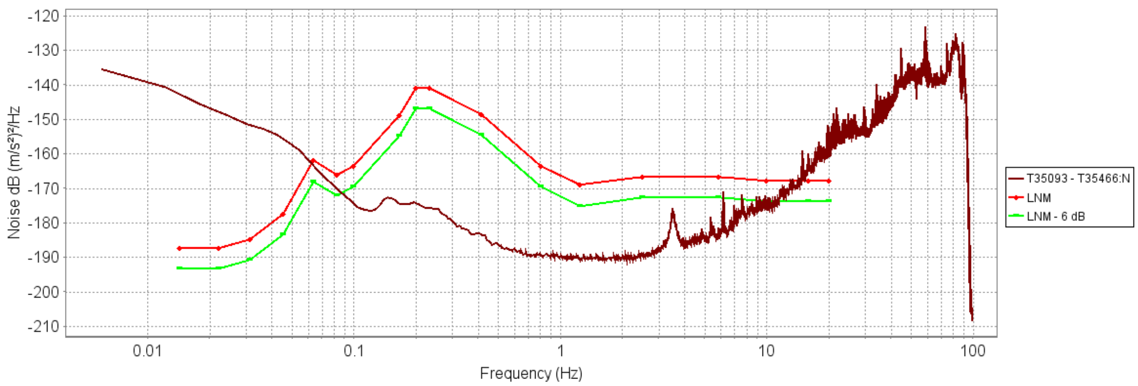

Figure 4.4.4.2 Incoherent noise for the N channel of T35093 and T35466 shown relative to the Low Noise Model and 6 dB below the Low Noise Model on December 2, 2013.

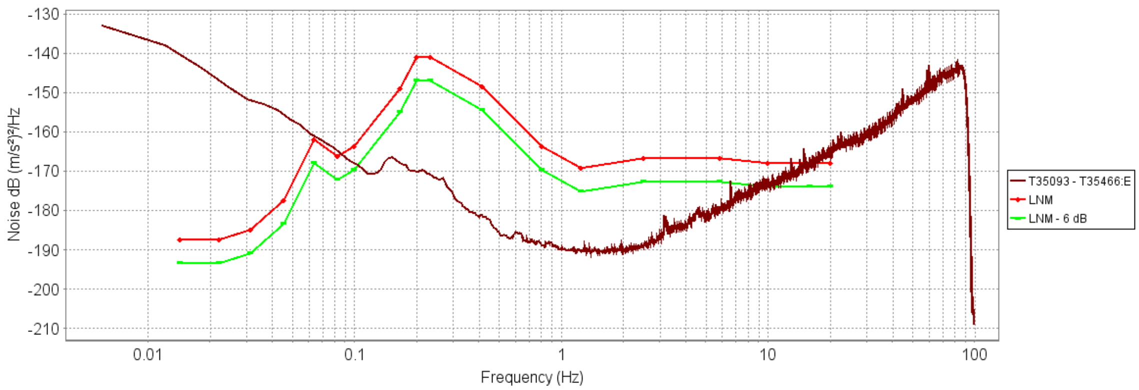

Figure 4.4.4.3 Incoherent noise for the E channel of T35093 and T35466 shown relative to the Low Noise Model and 6 dB below the Low Noise Model on December 2, 2013.

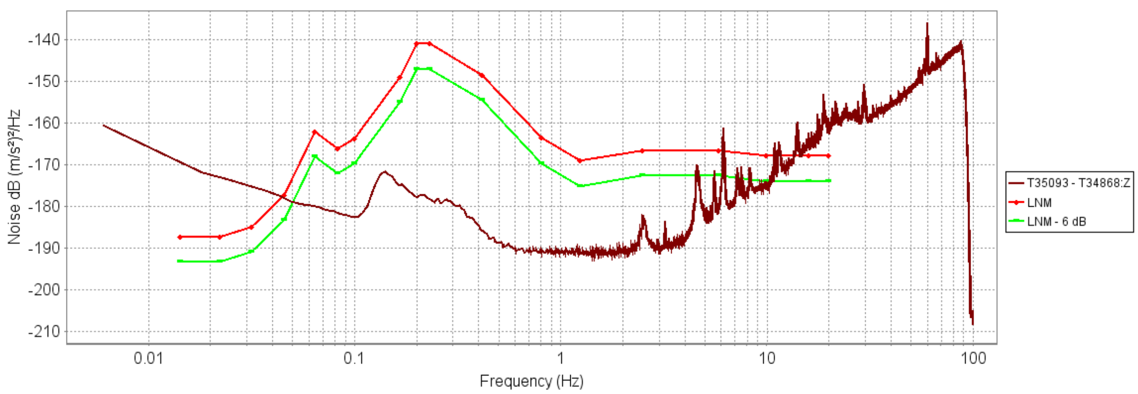

Figure 4.4.4.4 Incoherent noise for the Z channel of T35093 and T34868 shown relative to the Low Noise Model and 6 dB below the Low Noise Model on March 3, 2014.

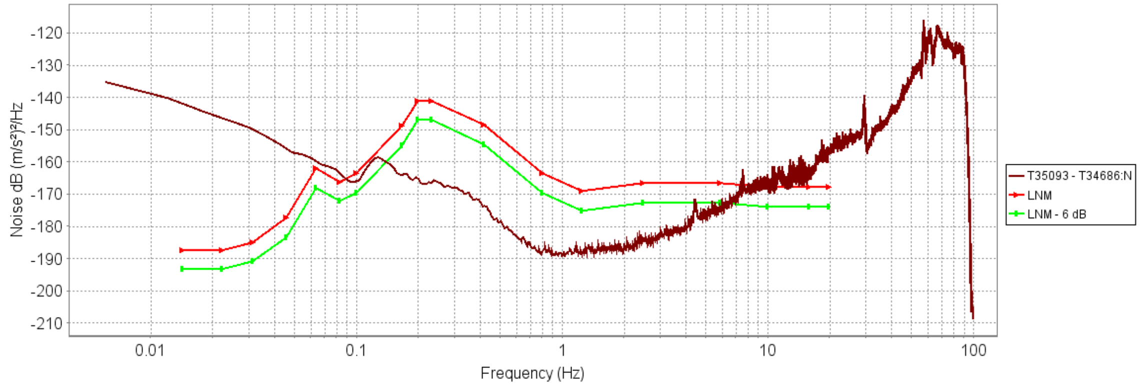

Figure 4.4.4.5 Incoherent noise for the N channel of T35093 and T34868 shown relative to the Low Noise Model and 6 dB below the Low Noise Model on March 16, 2014.

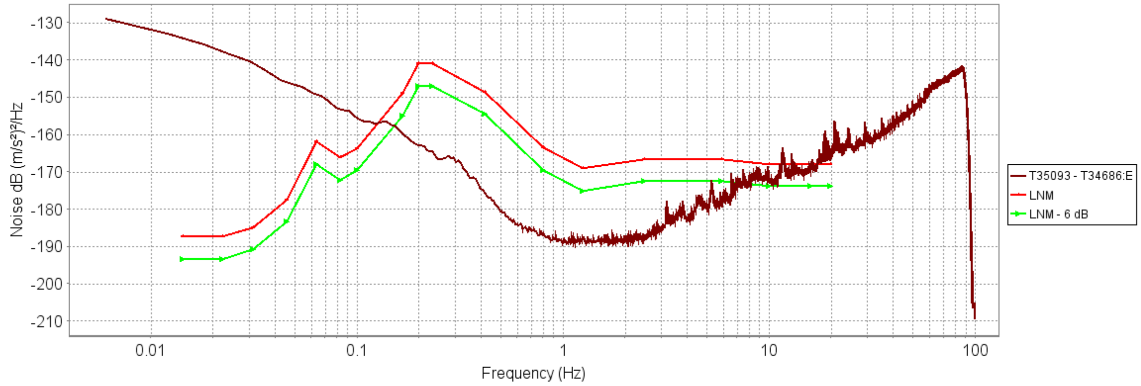

Figure 4.4.4.6 Incoherent noise for the E channel of T35093 and T34868 shown relative to the Low Noise Model and 6 dB below the Low Noise Model on March 3, 2014.

Table 4.4.4.1 summarizes the approximate frequency band over which the incoherent noise between the seismometer pairs T35093 / T35466 and T35093 / T34868 were observed to be at least 6 dB below the low noise model.

Table 4.4.4.1 Summary of frequency bands at least 6 dB below the low noise model.

Seismometer Pair / Component	Low Frequency (Hz)	High Frequency (Hz)
T35093 – T35466 / Z	0.05 Hz	8.5 Hz
T35093 – T35466 / N	0.09 Hz	11.3 Hz
T35093 – T35466 / E	0.104 Hz	9.2 Hz
T35093 – T34868 / Z	0.05 Hz	10 Hz
T35093 – T34868 / N	0.14 Hz	6.6 Hz
T35093 – T34868 / E	0.154 Hz	7.0 Hz

The observed self-noise in this deployment environment does not meet the AFTAC requirement of being 6 dB below the low noise model over the 0.02 – 16 Hz passband.

Table 4.4.4.2 summarizes the self-noise estimates for seismometer pairs T35093 / T35466 and T35093 / T34868 over the frequency bands 0.02-16 Hz and 0.5-2 Hz. These noise values will be used in estimating the dynamic range in section 4.4.7.

Table 4.4.4.2 Summary of RMS self-noise estimation for two passbands.

Seismometer Pair / Component	RMS Noise 0.02-16 Hz	RMS Noise 0.5-2 Hz
T35093 – T35466 / Z	12.64 nm/s^2 rms	0.3341 nm/s^2 rms
T35093 – T35466 / N	9.93 nm/s^2 rms	0.3952 nm/s^2 rms
T35093 – T35466 / E	9.47 nm/s^2 rms	0.4221 nm/s^2 rms
T35093 – T34868 / Z	11.03 nm/s^2 rms	0.3451 nm/s^2 rms
T35093 – T34868 / N	17.60 nm/s^2 rms	0.5967 nm/s^2 rms
T35093 – T34868 / E	18.53 nm/s^2 rms	0.5379 nm/s^2 rms

4.4.5 Sensor Response Verification

Purpose: The purpose of the seismic sensor response verification test is to verify the seismic sensor sensitivity and response using seismic background signals and a reference seismic sensor.

Configuration: A characterized reference sensor and one or more of the sensors under test, are installed side-by-side in a seismic vault or in an adjacent borehole. The seismic sensor outputs are connected to a data acquisition system that samples the data synchronously. Data are acquired during moderate seismic backgrounds and events.

Evaluation: Convert the data from each seismic sensor to ground motion using the sensor response mathematical model for each sensor. If the sensor response models are correct, the amplitude response measurements in earth-motion units will be identical.

Results: We have been able to successfully confirm sensitivities and responses of the three CMG-3TB seismometers by comparing the recorded output of the sensors, corrected for the manufacturer's provided responses, to the recorded output of the reference STS-2, also corrected for its response, as described in section 4.4.3 Sensitivity and Passband Verification. However, we were unable to verify the flatness of the response to within 5% due to an overall lack of coherence across the passband. A 5% deviation in sensitivity is equivalent to less than 0.45 dB of deviation from nominal in the response across frequency.

The best result we were able to obtain was in the vertical channels of the T35093 and T35466 during the Magnitude 7.9 earthquake on 11/17/2013. Figures 4.4.5.1, 4.4.5.2, and 4.4.5.3 below present the coherence, relative magnitude, and relative phase between the response corrected outputs of the STS-2 and the T35093 and T35466 vertical channels.

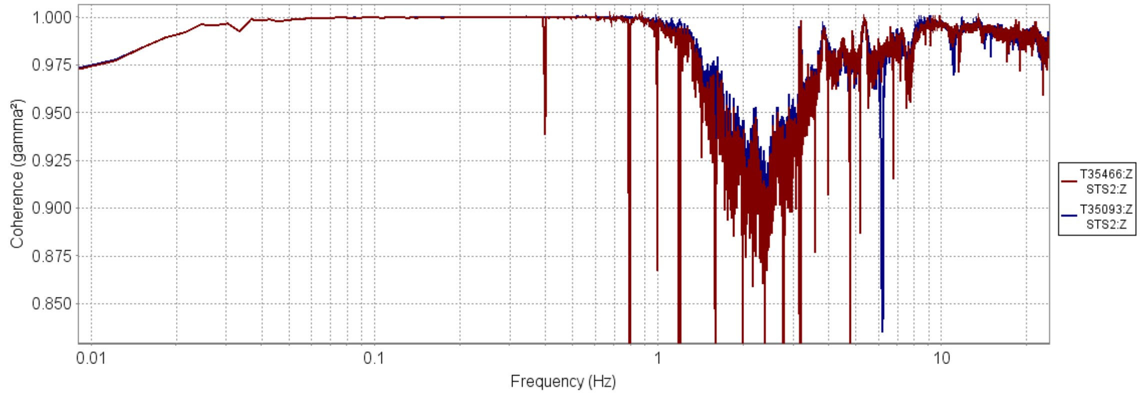

Figure 4.4.5.1 Coherence between reference STS2 and T35466 and T35093

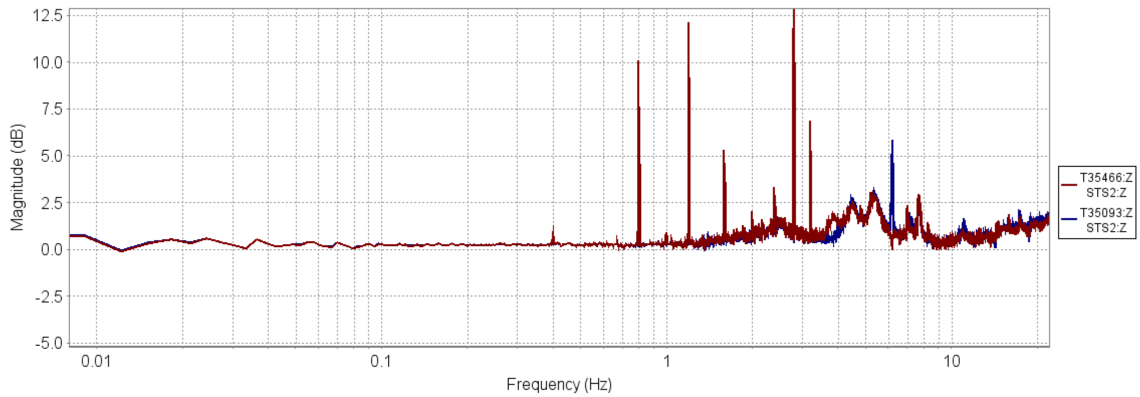

Figure 4.4.5.2 Relative magnitude between reference STS2 and T35466 and T35093

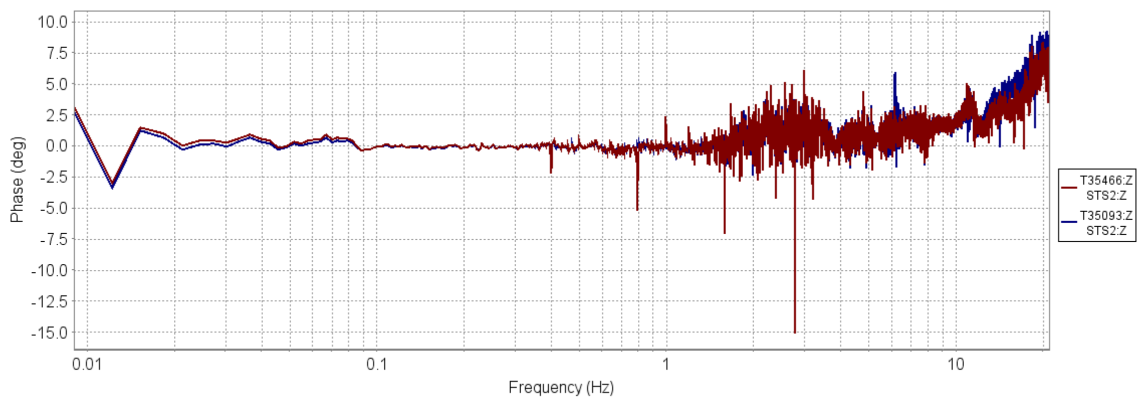

Figure 4.4.5.3 Relative phase between reference STS2 and T35466 and T35093

As can be seen in the relative response plots, there is insufficient coherence within the passband to comment on the degree of response flatness with sufficient confidence for a 5% and 5 degree requirement.

However, using the calibration response data as described in section 4.4.8, it was still possible to make estimates of the magnitude and phase flatness.

4.4.6 Sensor Clip Verification

Purpose: The purpose of the seismic sensor clip test is to determine and verify the maximum signal or clip level of the sensor (in voltage or relevant seismic units, i.e. displacement, velocity or acceleration).

Configuration: The seismic sensor is installed in its typical deployment configuration. Using an active seismic source (e.g., hammer-drop on plate, shake-table or vibration source) excite large amplitude seismic signals within passband of interest. Visually inspect recorded time series for large amplitude signals and document characteristics of signals near, at or above stated clip level of sensor.

Evaluation: The seismic sensor clip voltage, or relevant earth-motion unit is measured.

Results: Data was collected in which hard clip was observed on each of the three channels of the units under test. The digitizer used to record the seismometer clip test data has an over-ranged full-scale of ~±26.5 Volts, if the recorded clip level is less than 26 Volts or greater than -26 Volts; then the clip can be associated with the seismometer. Figure 4.4.6.1 is an example of the clip data, from unit T35093, used to estimate the voltage clip level for the seismometers.

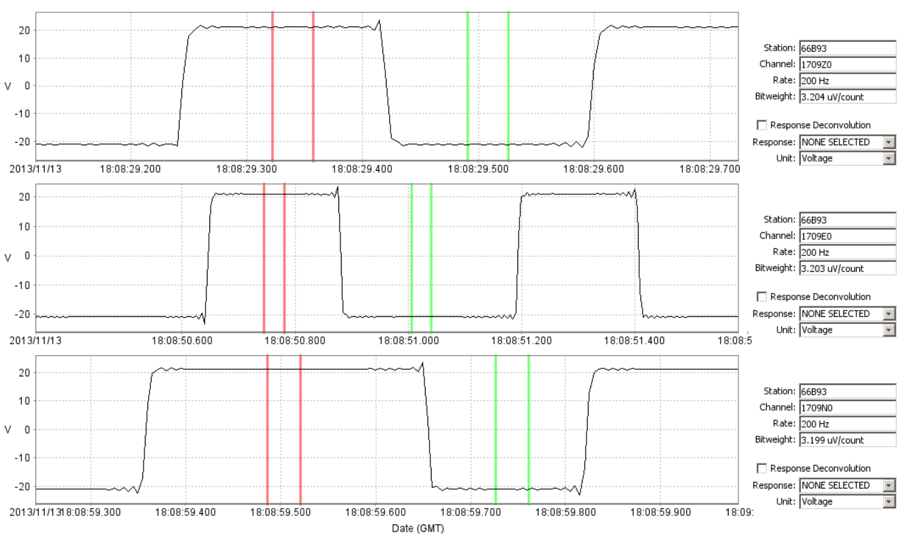

Figure 4.4.6.1 Seismometer clip data set for unit T35093.

Tables 4.4.6.1, 4.4.6.2, and 4.4.6.3 list the positive and negative voltages and their standard deviations (1σ) for a standard analysis window of 5 samples at the maximum and minimum of the clip data.

Table 4.4.6.1 Clip data for unit T35093

Unit/Channels	Positive Mean	Pos. Standard Deviation	Negative Mean	Neg. Standard Deviation
T35093/Z0	21.16 V	0.1019 V rms	-21.10 V	0.1306 V rms
T35093/N0	20.94 V	49.95 mV rms	-20.83 V	14.71 mV rms

T35093/E0	21.10 V	21.97 mV rms	-21.04 V	0.1591 V rms

Table 4.4.6.2 Clip data for unit T35466

Unit/Channels	Positive Mean	Pos. Standard Deviation	Negative Mean	Neg. Standard Deviation
T35466/Z0	21.11 V	49.58 mV rms	-21.04 V	29.26 mV rms
T35466/N0	21.06 V	0.3420 V rms	-20.98 V	0.3169 V rms
T35466/E0	21.19 V	0.2317 V rms	-21.13 V	37.48 mV rms

Table 4.4.6.3 Clip data for unit T34868

Unit/Channels	Positive Mean	Pos. Standard Deviation	Negative Mean	Neg. Standard Deviation
T34868/Z0	21.03 V	0.3466 V rms	-20.82 V	0.3628 V rms
T34868/N0	21.01 V	0.1048 V rms	-20.90 V	0.5318 V rms
T34868/E0	20.94 V	0.3840 V rms	-21.00 V	0.4286 V rms

Seismometer clip voltage is approximately ± 21 Volts.

4.4.7 Dynamic Range

Purpose: The purpose of the seismic sensor dynamic range test is to quantify the seismic sensor's ability to resolve seismic signals.

Configuration: The seismic sensors test results for self-noise and clip-level are used to estimate dynamic range.

Evaluation: The sensor full-scale is determined from the recorded data from the clip level test. Convert the data from each seismic sensor to relevant ground-motion units using the sensor response mathematical model for each sensor. By using results for the sensor's noise test and the determined full-scale the sensor's dynamic range is estimated.

Results: Noise values were obtained from Table 4.4.4.2 and full-scale clip voltage used was 21 Volts. Table 4.4.7.1 summarizes the results of estimating the seismometers dynamic range for the passbands: 0.02-16 Hz and 0.5 – 2 Hz.

Table 4.4.7.1 Summary of seismometers dynamic range for two passbands.

Seismometers / Component	Dynamic Range 0.02-16 Hz	Dynamic Range 0.5-2 Hz
T35093 – T35466 / Z	101.7 dB	133.3 dB
T35093 – T35466 / N	103.8 dB	131.8 dB
T35093 – T35466 / E	104.2 dB	131.2 dB
T35093 – T34868 / Z	102.9 dB	133.0 dB
T35093 – T34868 / N	98.9 dB*	124.4 dB
T35093 – T34868 / E	98.4 dB*	129.1 dB

*The reduction in dynamic range in these two channels is due to the increased estimate of self-noise observed at frequencies below 1 Hz, documented in table 4.4.4.2. The self-noise of the sensors is believed to be considerably lower than what was observed which would result in a significantly larger dynamic range value.

4.4.8 Calibration Response

Purpose: The purpose of the seismic calibration response verification test is to verify the seismic sensor calibration transfer response using voltage or current signals from a signal generator. Calibration signals can be flat to velocity or acceleration.

Configuration: Sensor outputs are connected to a data acquisition system that samples the data synchronously. Use sensor appropriate method for initiating electronics step or other calibration signal.

Evaluation: Use analysis method appropriate to input calibration signal type to extract sensor transfer function and gain for sensor under test.

Results: Using the Guralp Scream 4.5 software program, calibrations were run on the three sensors under evaluation. Each sensor had a broadband and two sinusoid (1 Hz and 10 Hz) calibrations performed. The resulting calibration data sets were then analyzed using the same Scream 4.5 software program. The results of the analysis of the broadband, and two sinusoid calibrations are presented below in Table 4.4.8.1.

Table 4.4.8.1 Summary of calibration sensitivity results

Unit ID/Channel	Broadband Sensitivity (0.15 – 1.5 Hz) ($V/m/s^2$)	1 Hz Sensitivity ($V/m/s^2$)	10 Hz Sensitivity ($V/m/s^2$)
T35093/Z	9628.0	9631.1	9423.2
T35093/N	9658.7	9533.1	9441.5
T35093/E	9660.9	9672.9	9442.9
T35466/Z	9660.6	9661.0	9417.4
T35466/N	9654.3	9654.7	9487.3
T35466/E	9591.8	9601.5	9460.1
T34868/Z	9625.5	9626.1	9424.2
T34868/N	9571.6	9573.8	9359.9
T34868/E	9632.5	9634.0	9397.4

The measured deviations from the manufacturer's provided calibration sheet for each of the seismometers are presented below in Table 4.4.8.2.

Table 4.4.8.2 Calibration sensitivity deviation from manufacturer's specification

Unit ID/Channel	Manufacturer's 1 Hz Sensitivity ($V/m/s^2$)	Measured 1 Hz Sensitivity ($V/m/s^2$)	Percent Deviation
T35093/Z	9607.0	9631.1	0.25%
T35093/N	9670.6	9533.1	-1.42%
T35093/E	9687.8	9672.9	-0.15%
T35466/Z	9643.4	9661.0	0.18%
T35466/N	9662.6	9654.7	-0.08%

T35466/E	9660.4	9601.5	-0.61%
T34868/Z	9608.2	9626.1	0.19%
T34868/N	9576.6	9573.8	-0.03%
T34868/E	9642.2	9634.0	-0.09%

The deviations in sensitivity from the manufacturer's provided sensitivities are all within +/- 1.5 %, which is less than the AFTAC seismometer sensitivity requirement of 3 %.

The broadband calibration data was analyzed for low and high frequency -3dB roll-off frequencies that partially define the passband of the sensors. The calibration data was also examined to identify the deviation in amplitude and phase from the nominal response. Table 4.4.8.3 summarizes the -3dB roll-off frequencies and amplitude and phase deviation for the three sensors under evaluation.

Table 4.4.8.3 Summary of -3dB roll-off frequencies and response flatness for sensor passband

Unit ID/Channel	Low Corner 3dB roll-off Frequency (Hz)	High Corner -3dB roll-off Frequency (Hz)	Amplitude Deviation (dB) over 0.02 – 16 Hz	Phase Deviation (deg) over 0.02 – 16 Hz
T35093/Z	0.0084	50.51	0.24	2.5
T35093/N	0.0084	49.61	0.37	2.0
T35093/E	0.0084	49.19	0.4	2.5
T35466/Z	0.0084	49.85	0.34	2.28
T35466/N	0.0084	49.90	0.27	2.1
T35466/E	0.0084	50.24	0.27	2.25
T34868/Z	0.0084	50.04	0.26	2.25
T34868/N	0.0084	50.05	0.31	2.4
T34868/E	0.0084	49.90	0.37	2.45

The passband for these sensors, defined by broadband calibration data, is 120 second period to 50 Hz, which matches the specification provided by manufacturer. This passband exceeds the AFTAC seismometer passband requirement of 0.02 – 16 Hz.

The magnitude and phase deviations for all of the sensors were near zero at the low end of the passband, 0.02 Hz, and gradually increased to the maximum of approximately 2.5 degrees (phase) and 0.4 dB (magnitude) at the high end of the passband, 16 Hz, as shown in the representative plots in figures 4.4.8.1 and 4.4.8.2 below.

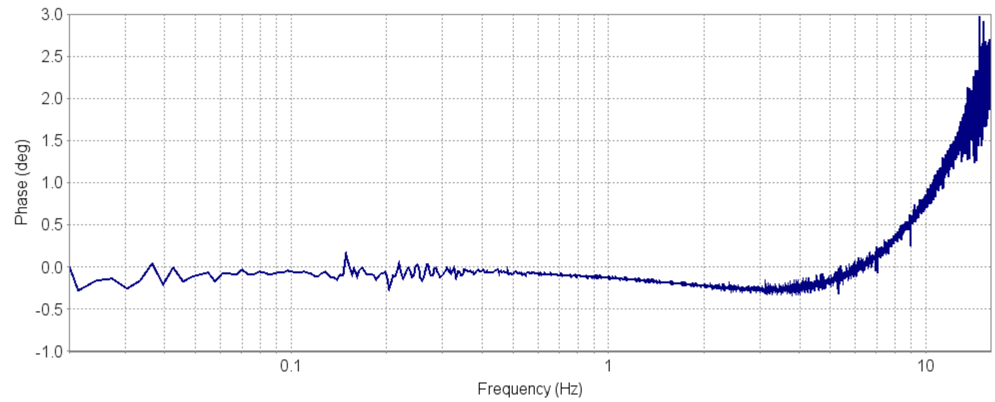

Figure 4.4.8.1 Representative Seismometer Phase Deviation

The observed phase deviations are entirely within the AFTAC seismometer phase requirement of 3 degrees.

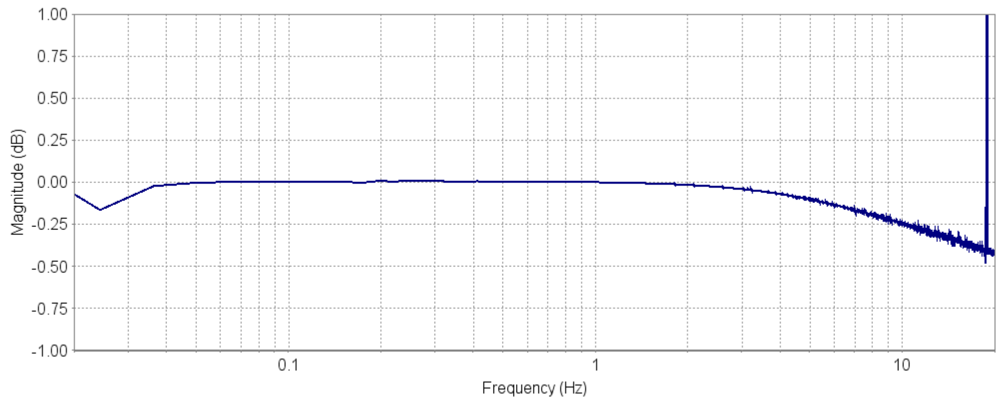

Figure 4.4.8.2 Representative Seismometer Magnitude Deviation

The observed magnitude deviations, plus or minus the 90% confidence interval of approximately 1.085 dB for the spectral estimate, fall within the AFTAC seismometer magnitude requirement of 3% (0.25 dB).

4.5 Detailed Test Schedule

Testing of the Guralp CMG-3TB seismometers took place at the SNL FACT site.

FACT component testing:

October, 2013

Received delivery of equipment, assembled seismometers, and configured testbed acquisition systems for sensor testing requirements (e.g., sample rate, active channels, gain on/off, etc.). Measured each of the channels output impedance.

Powered up and performed Mass Position Stability tests of T35093 and T35466 while waiting for the sensors to thermally stabilize.

November, 2013

Performed Calibration testing of T35093 and T35466. Began examining the coherence between T35093, T35466 and the reference sensors. Adjusted the installation configuration (mounting fixtures, granite block, insulation, etc.) to improve coherence between the sensors. Performed clip testing of T35093 and T35466.

December, 2013

Performed response verification testing and waiting for earthquake activity.

January, 2014

Continued evaluation of T35093 and T35466 while waiting for additional earthquake activity.

February, 2014

Installed T34868 in place of T35466. Powered up and performed initial mass Position stability testing of T34868 while waiting for the sensor to thermally stabilize. Performed calibration testing of T34868. Performed clip testing of T34868.

March, 2014

Completed mass position stability testing of T34868. Performed response verification testing and waiting for earthquake activity.
Testing completed, began writing report.

April, 2014

Writing report.

4.6 Test Risk Management

4.6.1 Schedule

Sufficient time for the tests specified has been allocated however any risk in the schedule will be mitigated through the use of extended hours of operation and adding additional days into the test schedule. However, an inability to quickly rectify any problems that arise may result in the postponement of all or part of the testing schedule.

A significant portion of the time taken in the testing was waiting for a sufficiently large earthquake source to occur that would provide measurable ground motion and the low and high corners of the sensor passband.

4.6.2 Equipment

Equipment failures that impact the completion of scheduled tests may occur. All possible repairs and additional equipment requisitions will be performed to remedy any problems that arise.

The only serious issues that occurred during the sensor testing were occasional power-outages that interrupted the testing. The most significant impact of these occurrences was during the testing of mass position stability. However, even with the presence of these outages, we were still able to demonstrate that the sensors stabilized within a timeframe consistent with the manufacturer’s predictions.

4.7 Test Completion Criteria

Testing was completed at SNL FACT site once all the data and results have been verified to the satisfaction of the customer test director.

5 TEST ANALYSIS AND REPORTING

5.1 General

This section summarizes the steps for mission planning, test execution, and post processing. The test procedures will consist of:

Pre-mission briefings
Equipment setup and initial checkouts
Test Execution
End-of-day / Post-mission debriefing
Data Analysis

Prior to any testing the Test Director verified the functionality of all equipment. All components were determined to meet the required specifications by report or measurement. All pre-test evaluations took place at the SNL FACT site.

The test director conducted a mission briefing prior to each test. This briefing explained the day's mission activities with respect to the overall test schedule.

5.2 Data Management

All relevant test data from the test sensors and reference sensors was collected by the Test Director and archived at SNL for additional analysis. Data collected during testing is available to those interested parties involved in the testing. SNL has archived the initial test data and representative samples of the long term test data.

5.3 Data Analysis Plan

Sandia National Laboratories analyzed all test sensor data and reference sensor data collected during the tests and issued a report to the customer detailing the findings of the test.

5.4 Data Evaluation and Reporting

A preliminary report was issued within 15 days of the completion of the tests at the FACT. The final report will be delivered within 30 days of the completion of the long term testing.

6 SAFETY

6.1 Known Hazards/Limitations/Issues to Success

All known hazards are detailed in *Appendix A2: Safety* and are described in the Sandia National Laboratories documentation Component Evaluation (CE) – Technical Work Document (TWD) [reference 6] and Sandia National Laboratories Primary Hazard Screening (PHS) PHS Number 9719045530-106 FACT site [reference 7].

6.2 Mitigating Actions

Safety precautions detailed in *Appendix A2: Safety* will be followed to mitigate against any safety hazards.

In addition, the Test Site Manager will conduct and document a pre-deployment safety meeting detailing the following:

Natural hazards
Job/Physical/Electrical hazards
Driving hazards/local hazards
Buddy system, CPR, and emergency aid

7 REFERENCES

Kromer, Richard P. and Hart, Darren M. and J. Mark Harris (2007), 'Test Definition for the Evaluation of Seismic Sensors, SAND2007-5025.

Kromer, Richard P. and Hart, Darren M. and J. Mark Harris (2007), 'Test Definition for the Evaluation of Digital Waveform Recorders, SAND2007-5037.

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Kromer, Richard P. and Hart, Darren M. and J. Mark Harris (2007), 'Test Definition for the Evaluation of Sensor Sub-Systems, SAND2007-6440.

Merchant, B. John and Hart, Darren M. (2011), 'Component Evaluation Testing and Analysis Algorithms', SAND2011-8265.

Hart, Darren M. (2010), 'Component Evaluation (CE) – Technical Work Document (TWD)'. Sandia internal documentation – not for public release.

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APPENDIX

A1: Security

A1.1. Test Specific Security Guidance

A1.1.1 General Classification Level: The specific objectives and associations inherent in this test are UNCLASSIFIED.

A1.1.2 Purpose: Verify performance specifications of refurbished seismometers.

A1.1.3 Location and Date of Test: SNL FACT site, October 2013 to April 2014.

A1.1.4 Test Participant Clearance Requirements: There is NO clearance requirement for this test.

A1.2 Classification of Data

Raw data collected during testing operation is UNCLASSIFIED. Reduced or analyzed data will be FOR OFFICAL USE ONLY.

A1.3 Oversight

Collected data will not be analyzed as to its specific origin.

A1.4 Supplemental Controls for Physical Security

No supplemental controls for physical security are required since this testing is unclassified and is contained within fenced Government property.

A1.5 Other Controls to Limit Inadvertent Release

No other controls to limit inadvertent release of interception are required since this testing is unclassified.

A1.6 Public Release of Information

A1.6.1 The on-site release of information to the public is NOT authorized.

A1.6.2 Unilateral Public Release: Unilateral public release of marked or unmarked information pertaining to this test is expressly prohibited.

A1.6.3 Public Release Approval: Only information that has been coordinated for public release with the customer may be released.

A1.6.4 Export Controlled Material: No material in this test is export controlled.

A1.7 Specific Classification Guidance

General classification guidance for this test has been provided by customer. NO specific classification guidance has been provided.

A1.8 Handling Possible Compromise of Classified Data

No classified information will be used or collected during this test.

A1.9 Site Communications and Protocol and Controls

Enhanced OPSEC principals shall be applied for all test and communication measures.

A2: Safety

A2.1 Pre-Departure Safety Briefing

Not Applicable.

A2.2 UXO, Unidentified Ground Objects

This test will not occur in a weapons area or ordnance range. Explosive ordnance is neither employed nor stored in the areas where test personnel will be operating.

A2.3 Alcohol/Vehicle Use

There will be no alcohol use at least 8 hours before scheduled work requiring the use of a government vehicle.

A2.4 Declination of Task

Any personnel can decline to perform an assigned task because of a reasonable belief that the task poses an imminent risk of death or serious bodily harm. The person and local management may request an assessment by installation safety, fire protection, or health professionals before proceeding.

A2.5 Team Member Accountability

The Test Director is responsible for maintaining complete accountability of test personnel throughout the test sequence. Any changes in the status of test members must be immediately reported to the Test Director.

A2.6 Contractor Safety

No contractors will be used during the duration of this test sequence.

A2.7 Safety/Hazards Issues

Personnel will be working with low voltage (< 50 V) electrical and radio equipment. The risk of lightning or other electrical shock does exist. To mitigate this risk, no work will be performed outdoors if wet weather or lightning conditions exist.

Any work performed outdoors will involve exposure to the weather (sun, wind, rain, snow, etc.) and may risk contact with wildlife such as rattle snakes, scorpions, and poisonous spiders. Personnel will remain aware of their surroundings and avoid unsafe outdoor conditions. In addition, personnel will wear suitable protective clothing including sturdy shoes, long pants, and other weather appropriate attire.

A2.8 Overall Risk Assessment

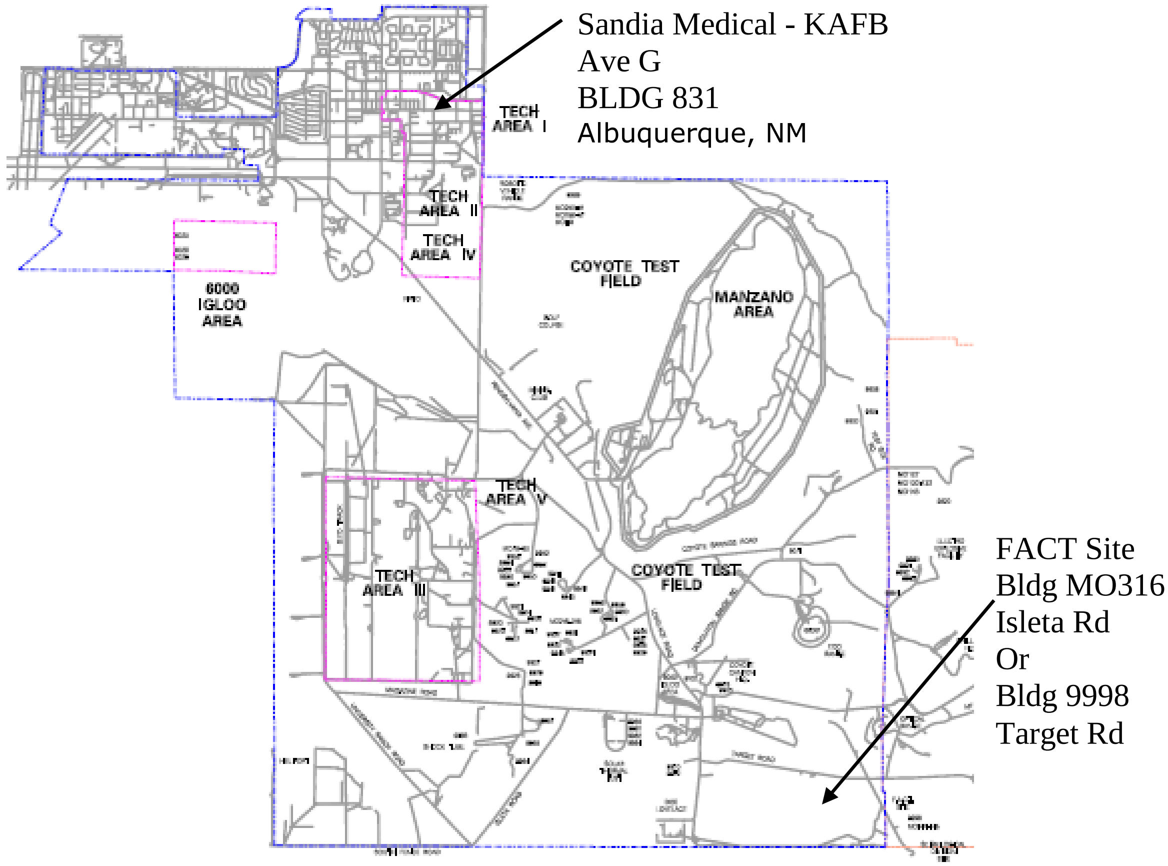
The overall risk assessment for this testing is low and within acceptable levels for work plans.

A2.9 Medical Emergency Facilities

The nearest medical facility is the Sandia Medical building.

Sandia Medical – KAFB
Ave G
BLDG 831
Albuquerque, NM

SNL does have 911 capabilities, for emergencies on-site phone 911 using a cell phone 844-0911. Non-emergencies on-site phone use 311 using a cell phone 844-6515.



A2.10 Safety Documentation.

The Sandia National Laboratories safety documentation is available upon request.

DISTRIBUTION

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