# EFFECTS OF AGING HARDWARE ON DATA QUALITY

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**ABSTRACT**

For over twenty years broadband seismometers have been used for nuclear explosion monitoring at teleseismic distances. Short period seismometers have also been used to improve resolution at higher frequencies (> 1 Hz) over regional distances. At the time of installation, a calibration process is implemented to determine the proper scale factor between digital counts and ground motion for the seismic subsystem (seismometer and digital waveform recorder). This scale factor is called “calib” and is applied at a single period called “calper.” Under this framework, the instrument response model is stored in a frequency amplitude phase (FAP) format, which normalizes the response to unity at the calper. The two hardware components at a site that are used to construct the calib are the digital waveform recorder (DWR) and the seismometer of interest. The digital waveform recorder has an associated scale factor from counts to volts and the seismometer scale factor between volts and ground motion (valid in the flat portions of the instruments’ respective passbands). Under proper calibration, the relative gain between co-located broadband and short period seismometers should be 0 dB across their common passband as defined in their FAP files.

Recently, data from eleven stations with co-located broadband and short-period seismometers have been analyzed for their relative gains using a common time window and their most recent calib scale factors. The relative gains vary between 0.4 and 2.0 dB at 1 Hz, which translates into a 4.7% to 26% amplitude scaling difference between the seismometers at 1 Hz. One complicating factor is the calper at 1 Hz for the short-period seismometer. For a GS21 short period seismometer, the 1 Hz calper is the low-frequency corner of the GS21. The “calper” is not in the flat portion of the response file of the GS21 seismometer.

The Sandia National Laboratories (SNL) Facility for Acceptance, Calibration and Testing (FACT) was tasked with assisting our customer in determining the reason for the amplitude scaling differences. The possible areas of potential scaling problems are (1) DWR bit-weight scale factor errors (volts per count), (2) the seismometer output sensitivity scale factor errors (volts per ground motion), (3) a combination of DWR bit-weight and seismometer sensitivity scale factor errors (ground motion per count), or (4) internal changes to either seismometer that may have affected the response parameters near 1 Hz. Another possible issue with the hardware components may be the change in self-noise level.

The SNL FACT site will be receiving and testing instrumentation from a recently decommissioned station with the same (or similar) equipment, known as a “hot-spare.” The site had a significant up-time of 15 years and exhibits the same amplitude scaling problem observed in the other Global Seismic Network stations. Results of this work will be available in the coming year.

This paper presents two main areas:

1. Understanding the scaling problem, the work that was done with existing data to compile the metadata about the instrument response for GS21/KS54000 systems at several stations
2. Outlining a test plan for evaluation of GS21/KS54000 system equipment to be delivered to SNL FACT site

## RESEARCH ACCOMPLISHED

### Introduction

With the existence of seismic stations that are configured with co-located seismometers, a natural expectation is to compare the ground motion recorded by the different systems and make observations on the similarities or differences. One would expect the two systems to report the same ground motion for a common passband of the co-located seismometers. Typically, the instrument response consists of two parts: (1) the calibration factor, or calib, which scales the digital counts to displacement in nanometers and (2) the FAP representation of the instrument response model. (FAPs are normalized to 1 at the calibration period, or calper.) If co-located seismometers are from different manufacturers (e.g., Geotech, Guralp, or Kinemetrics) or of different design (i.e., broadband, mid-period, or short period), knowing and understanding the limitations of instrument response corrections to the digital data collected is critical in determining if the data from a site is credible.

To date, data from 11 seismic monitoring stations have been received from our customer. The data are from stations that are configured with co-located GS21 and KS54000 seismometers and Science Horizons DWRs recording each seismometer's output. The summary of the two systems being compared is shown in Table 1. Basic scaling biases between the two systems can be accounted for by investigating the four primary sources of scaling in the deployed seismic system for the KS54000 sensitivity in V/m/s or V/m/s/s, the GS21 sensitivity in V/m/s, the AIM24S3 bit-weight in V/count, and the AIM24S1 bit-weight in V/count.

**Table 1. Basic information on equipment under evaluation for scaling issues**

| Seismometer—manufacturer, model, and design | DWR—manufacturer, model |
|---|---|
| Geotech KS54000 broadband (acceleration/velocity) | Science Horizons AIM24S3 |
| Geotech GS21 short period | Science Horizons AIM24S1 |

The first seismic system configuration shown in Table 1 (Geotech KS54000 with Science Horizons AIM24S3) was initially evaluated in a report by Kromer (2003). The nominal manufacture specification for the volt-to-count conversion was set to 3.815 e-6 volts/count. This bit-weight scaling allows for a full-scale range of +/- 5,242,880 counts, or +/- 20 volts. The expected 24-bit range in counts is +/- 8,388,608, or approximately +/- 32 volts. The difference between the bit-weight scaled output and the 24-bit full-scale output is the over-range voltage capability of the DWR. If the Science Horizons DWR is matched with the KS54000, then using the nominal sensitivity for a Geotech KS54000 (15000 V/m/s/s at 1 Hz) we can estimate the calib at 1 Hz. This is shown in Table 2.

**Table 2. DWR nominal bit-weight and seismometer sensitivity for three different output unit bases (acceleration, velocity, and displacement) and the nominal calib**

| Seismometer/DWR | Nominal bit-weight (μV/count) | Seismometer sensitivity (V/m/s/s) | Seismometer sensitivity (V/m/s) | Seismometer sensitivity (V/m) | Calib (nm/count) @ 1 Hz |
|---|---|---|---|---|---|
| KS54000/AIM24S3 | 3.815 | 15000 | 94247.8 | 592176 | 0.006442 |

The second seismic system configuration shown in Table 1 (Geotech GS21 with Science Horizons AIM24S1) was not found to have a similar evaluation report completed, but the report by Kromer (2003) did include a similar seismic system of a Geotech 23900 and Science Horizons AIM24S1. Although this is not an identical system, it shows the process involved in documenting the nominal configuration of a Science Horizons AIM24S1 with a short-period seismometer. The nominal manufacture specification for the volt-to-count conversion was set to 23.073e-9 volts/count (i.e., 43,340,701 counts/volt). This bit-weight scaling allows for a full-scale range of +/- 5,242,880 counts, or +/- 121 milliVolts. The expected 24-bit range in counts is +/- 8,388,608, or approximately +/-194 mVolts. The difference between the bit-weight scaled output and the 24-bit full-scale output is the over-range voltage capability of the DWR. If the Science Horizons DWR is matched with the GS21, then by using the nominal sensitivity for a Geotech GS21 (413.2 V/m/s at 20 Hz), we can estimate the calib at 1 Hz. This is shown in Table 3.

**Table 3. DWR nominal bit-weight and seismometer sensitivity for three different output unit bases (acceleration, velocity, and displacement) and the nominal calib**

| Seismometer/DWR | Nominal bit-weight (uV/count) | Seismometer sensitivity (V/m/s/s) @ 1Hz | Seismometer sensitivity (V/m/s) @ 1 Hz | Seismometer sensitivity (V/m) @ 1 Hz | Calib (nm/count) @ 1 Hz |
|---|---|---|---|---|---|
| GS21/AIM24S1 | 0.023073 | 46.486 | 292.08 | 1835.19 | 0.0126 |

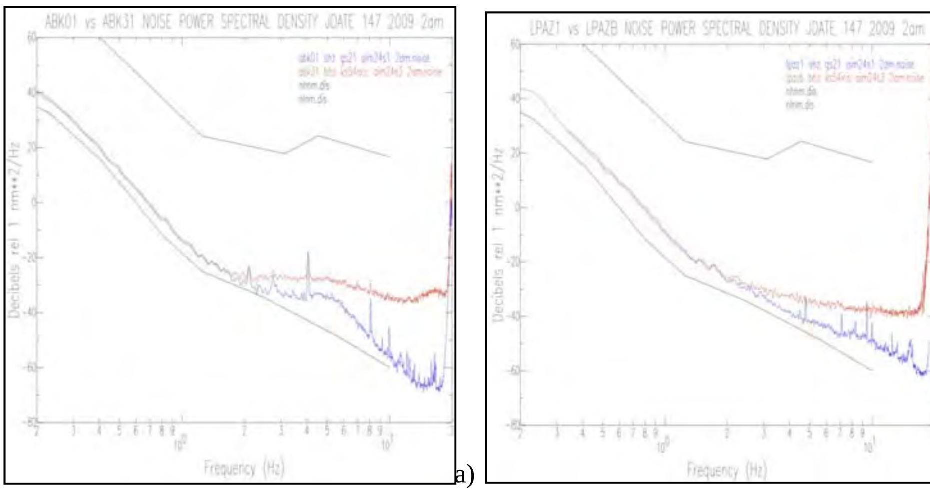
**Received Data**

The customer initially sent us sample data from 11 stations with the co-located Science Horizons GS21/KS54000 configuration. See Table 4 for a summary of the metadata obtained from the instrument response files for the listed stations/channels. The instrument response files were provided in FAP format.

**Table 4. Summary of the metadata (calib and calper) obtained from the instrument response files for the provided data for the listed station channel pairs and our estimates of bit-weight and seismometer sensitivity**

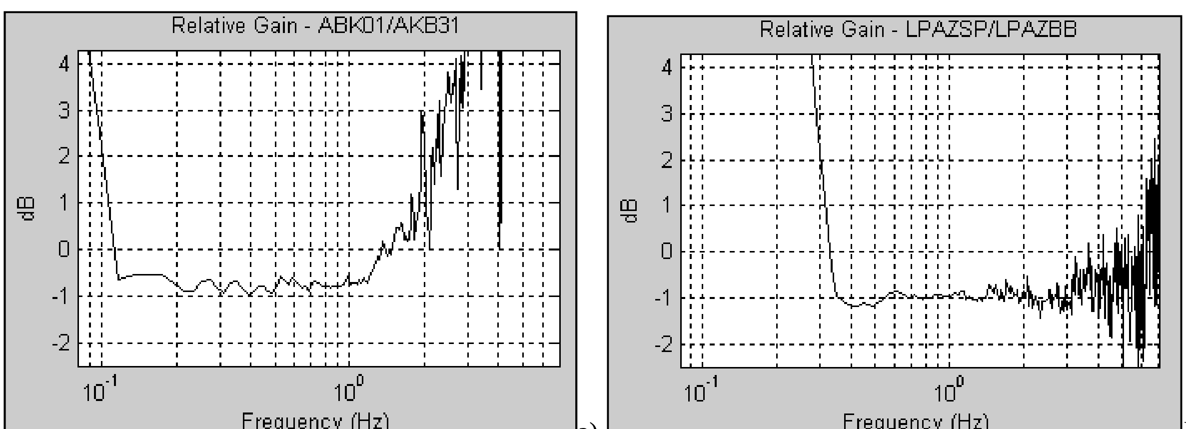
| Station | Channel | Sensor | Calib (nm/count) | Bit-weight (counts/volt) | Calper (seconds) | Sensitivity (V/m/s) or (V/m/s/s) |
|---|---|---|---|---|---|---|
| ABKAR | SHZ(01) | GS21vel | 0.0118 | 43340701 | 1 | 311.2 |
| | BHZ(31) | KS54000acc | 0.00645 | 262144 | 1 | 14981.0 |
| BOSA | SHZ(01) | GS21vel | 0.01224 | 43340701 | 1 | 300.0 |
| | BHZ(B) | KS54000vel | 0.02014 | 262144 | 1 | 30145.4 |
| BURAR | SHZ(08) | GS21vel | 0.01335 | 43340701 | 1 | 275.1 |
| | BHZ(31) | KS54000acc | 0.00628 | 262144 | 1 | 15386.5 |
| CPUP | SHZ(01) | GS21vel | 0.01223 | 43340701 | 1 | 300.3 |
| | BHZ(B) | KS54000acc | 0.00635 | 262144 | 1 | 15216.9 |
| DBIC | SHZ(01) | GS21vel | 0.01169 | 43340701 | 1 | 314.1 |
| | BHZ(B) | KS54000vel | 0.0203 | 262144 | 1 | 29907.8 |
| KKAR | SHZ(02) | GS21vel | 0.01231 | 43340701 | 1 | 298.3 |
| | BHZ(31) | KS54000acc | 0.00613 | 262144 | 1 | 15763.0 |
| LBTB | SHZ(01) | GS21vel | 0.01294 | 43340701 | 1 | 283.8 |
| | BHZ(B) | KS54000vel | 0.02049 | 262144 | 1 | 29630.5 |
| LPAZ | SHZ(01) | GS21vel | 0.01232 | 43340701 | 1 | 298.1 |
| | BHZ(B) | KS54000vel | 0.02065 | 262144 | 1 | 29400.9 |
| MKAR | SHZ(05) | GS21vel | 0.01037 | 43340701 | 1 | 354.1 |
| | BHZ(31) | KS54000acc | 0.00675 | 262144 | 1 | 14315.2 |
| PLCA | SHZ(01) | GS21vel | 0.01234 | 43340701 | 1 | 297.6 |
| | BHZ(B) | KS54000vel | 0.02149 | 262144 | 1 | 28251.6 |
| VNDA | SHZ(01) | GS21vel | 0.01436 | 43340701 | 1 | 255.7 |
| | BHZ(B) | KS54000vel | 0.02044 | 262144 | 1 | 29702.9 |

Having been provided with power spectral density plots for all 11 stations, we show two examples in Figure 1 for two stations: ABKAR and LAPZ. The plots provided were displayed using a frequency band of 0.2 to 20 Hz, which clearly shows the high-frequency separations but prevents observing the low-frequency separation between these co-located seismometers. The method and parameters for producing the original plots were unknown, i.e., time segment length, window type, fast Fourier transform (FFT) length, window overlap amount, or confidence interval. The collocated seismometers at station ABKAR are in moderate agreement, 0.5 to 0.98 dB of gain difference, between 0.102 and 1.0 Hz. This translates into a 6.0% to 12.0% difference in amplitude scaling across this narrow passband. The relative gain plot for ABKAR is shown in Figure 2a. For station LPAZ we performed a similar analysis and observe an average of 1 dB of gain difference between 0.4 and 3 Hz. The relative gain plot for station LPAZ is shown in Figure 2b. The spectral separation above 1 Hz to 2 Hz is due to the SHI/KS54000 system noise being higher than the system noise for the SHI/GS21.




a) b)

**Figure 1. The provided power spectral density (PSD) plots for two of the 11 stations, ABKAR (left 1a) and LAPZ (right 1b). The high- and low-noise models are shown as solid black lines, the GS21 as a solid blue line, and the KS54000 as a solid red line.**




a) b)

**Figure 2. The relative gain between the short-period GS21 and the broadband KS54000 for ABKAR (left, a) and LPAZ (right, b).**

We re-created the power SDPs to verify the data scaling from counts to nanometers for both of the two example stations (ABKAR and LPAZ). By extending the displayed frequency range (Figure 3), we are able to show the extent of the low-frequency separation between the co-located seismometers. Most notably, the two stations presented here were calibrated for different passbands; i.e., at station ABKAR the calibrated passband is 0.1025 to 20 Hz, and at station LPAZ the calibrated passband is 0.335 to 20 Hz.

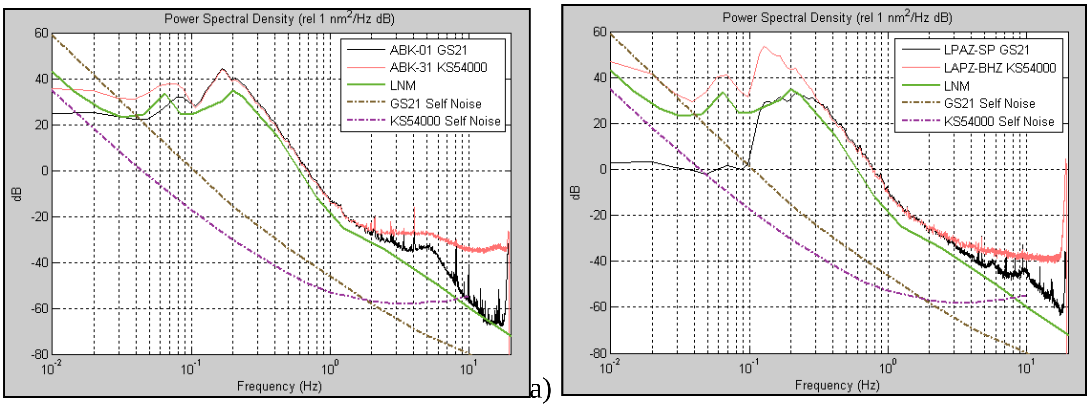



**Figure 3. The re-created PSD plots for the two stations in Figure 1, ABKAR (left, a) and LPAZ (right, b). The low-noise model is shown as solid green line, the GS21 self-noise model as a dash-dot brown line, and the KS54000 self-noise model as a dash-dot purple line.**

The upper frequency at which the PSDs separate varies, depending on the time window used to make the PSD plots. In Figures 1b and 2b for station LPAZ, the separation occurs at ~2 Hz, while LPAZ in Figure 4 has better agreement up to ~ 7 Hz. We were not provided with the information necessary to duplicate the individual station plots similar to the ones shown in Figure 1. We were provided with approximately 2 hours of data for each station. Originally, we re-created the PSD from Figure 1b using the entire time window of data and discovered that it did not agree with the plot provided (Figure 1b) in terms of where the high-frequency separation occurred. When looking at the time series provided for this station, we noticed that there was an unidentified seismic event that occurred toward the latter half of the time series. We then re-created the PSD plot without the event included (~45 minutes) and found that there was significantly better agreement between the two plots.

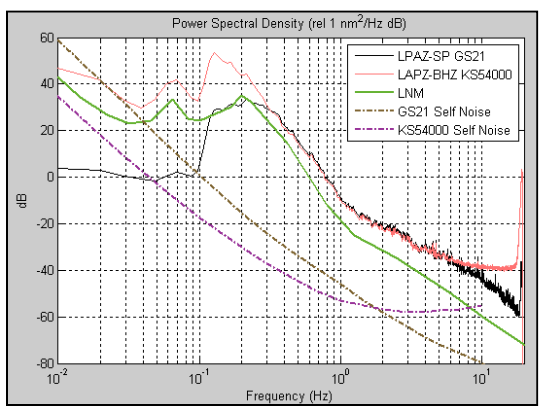



**Figure 4. The recreated PSD plot for 2 hours of data for station LPAZ. A seismic event in the data caused the frequency separation to occur around 7 Hz instead of around 2 Hz, as in the provided PSD plot.**

It is important to note that a standard needs to be used when comparing the data. As shown above, how the time window is selected can play an important role in assessing the quality of each sensor. More data is needed to quantitatively assess the true offset between the two sensors.

A summary of the FAP response files for all 11 stations, indicating the calibrated passbands, is included in Table 5. From those response values, we see that there is little to no consistency in resolution between short-period and broadband FAP files and a high degree of variability in the calibrated low frequency of the short-period seismometers. Our recommendation would be to develop a set of standards to follow when generating FAP files for broadband and short-period stations, requiring a fixed resolution and a common, calibrated, low frequency starting point. Given a set of requirements for FAP file generation, this can easily be implemented with software.

**Table 5. A summary of the response files indicating the calibrated passbands, low-frequency variability in the short-period seismometers, and little-to-no consistency in resolution between short-period and broadband FAP files**

| Station | Channel | Sensor | Low-frequency limit (Hz) | High-frequency limit (Hz) | Calib (nm/count) | Resolution (# samples in FAP file) |
|---|---|---|---|---|---|---|
| ABKAR | SHZ(01) | GS21vel | 0.1025 | 20 | 0.01184 | 4075 |
| | BHZ(31) | KS54000acc | 0.0098 | 20 | 0.00637 | 2047 |
| BOSA | SHZ(01) | GS21vel | 0.163 | 19 | 0.01285 | 55 |
| | BHZ(B) | KS54000vel | 0.01 | 19 | 0.021443 | 80 |
| BURAR | SHZ(08) | GS21vel | 0.1172 | 20 | 0.01349 | 1018 |
| | BHZ(31) | KS54000acc | 0.01 | 19 | 0.00669 | 70 |
| CPUP | SHZ(01) | GS21vel | 0.33 | 19 | 0.01198 | 40 |
| | BHZ(B) | KS54000acc | 0.009 | 20 | 0.00665 | 2047 |
| DBIC | SHZ(01) | GS21vel | 0.102 | 20 | 0.01198 | 4075 |
| | BHZ(B) | KS54000vel | 0.0098 | 20 | 0.02037 | 2047 |
| KKAR | SHZ(02) | GS21vel | 0.102 | 20 | 0.01246 | 4075 |
| | BHZ(31) | KS54000acc | 0.0098 | 20 | 0.00611 | 2047 |
| LBTB | SHZ(01) | GS21vel | 0.1025 | 20 | 0.01212 | 4075 |
| | BHZ(B) | KS54000vel | 0.0098 | 20 | 0.02045 | 2047 |
| LPAZ | SHZ(01) | GS21vel | 0.335 | 19 | 0.012557 | 40 |
| | BHZ(B) | KS54000vel | 0.0098 | 20 | 0.02062 | 2047 |
| MKAR | SHZ(05) | GS21vel | 0.01 | 20 | 0.010373 | 262 |
| | BHZ(31) | KS54000acc | 0.0098 | 20 | 0.00635 | 2047 |
| PLCA | SHZ(01) | GS21vel | 0.0098 | 20 | 0.01234 | 4094 |
| | BHZ(B) | KS54000vel | 0.01 | 19 | 0.02151 | 1899 |
| VNDA | SHZ(01) | GS21vel | 0.1025 | 20 | 0.01441 | 4075 |
| | BHZ(B) | KS54000vel | 0.01 | 19 | 0.0217 | 70 |

### Observed Calibration Differences at 0.1 and 1 Hz

For the 11 stations, the following steps were taken to evaluate the relative gain difference between each co-located seismometer pair at 0.1 and 1 Hz. The calib values from Table 4 were used to scale the data to nanometers, and the provided FAP files were used to shape the amplitude response. We calculated the PSD ratio between the broadband and short-period seismometers for each station to estimate the relative gain. Two frequencies (0.1 and 1 Hz) were chosen to show the relative gain differences for each station. The relative gain results are shown in Table 6.

**Table 6. The relative gain results in dB relative to 1 $nm^2$ /Hz between broadband and short-period seismometer stations for 0.1 and 1 Hz**

| Station | 0.1 Hz | 1 Hz |
|---|---|---|
| ABKAR | 0.5 dB | -0.7 dB |
| BOSA | 10 dB | -1.2 dB |
| BURAR | 4 dB | -2 dB |
| CPUP | 30 dB | -1 dB |
| DBIC | 2.6 dB | -1 dB |
| KKAR | -1 dB | -1 dB |
| LBTB | 1.6 dB | -0.6 dB |
| LPAZ | -30 dB | -1 dB |
| MKAR | -3 dB | -0.4 dB |
| PLCA | -1 dB | 1 dB |
| VNDA | -3.8 dB | -1.9 dB |

### Hardware Test Plan

Because of the relative gain differences observed in Table 6, it becomes necessary to evaluate aged hardware, similar to the stations listed above, in an attempt to understand the possible sources of the scaling problem. The possible sources could be the DWR bit-weight scale factor in V/count, the seismometer output sensitivity scale factor in V/m/s or V/m/s/s, a combination of DWR bit-weight and seismometer sensitivity scale factor in nanometer/count, or internal changes to either seismometer that may have affected the response parameters near 1 Hz. Based on these observations, the suspect hardware components, i.e., DWRs and seismometers, from a recently decommissioned station with a significant up-time of 15 years, will be shipped to Sandia for testing. These components are considered hot-spares and represent equipment still in operation in the field.

In our proposed test plan we will begin by evaluating DWR bit-weights for nominal and full-scale voltages. This will be followed by the deployment of the KS54000 and GS21 to a reference seismometer, which will allow us to verify the sensitivity of the hot-spare seismometers.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

In comparing the relative gain scaling between co-located seismometers, it is necessary to know the limitations in calibration passband when comparing a broadband seismometer to a short-period seismometer. The main limitation we observed was the passband of the calibration in the FAP file. The KS54000/SHI system noise appears to limit how we can interpret the performance between the co-located seismometers above 2 Hz. Currently, little or no standardization exists in how FAP files are generated. The FAP file resolution and calibration frequencies are not the same for all seismometers of a common response type, e.g., short period. Obtaining a complete system that has been running for an extended time may allow us to determine which components are the primary cause of the observed scaling differences between co-located short-period GS21/SHI systems and broadband KS54000/SHI systems.

### Recommendations

In order to reduce the confusion from long-term installations, a tool needs to be developed to produce standard FAP response files. The FAP files need to contain the same resolution and common low-frequency starting point regardless of who writes the file.

## ACKNOWLEDGEMENTS

We are grateful for the use of data documented in the following reports:

- D. M. Hart and K. R. Jones, Ground-based Monitoring R&E Test Plan, "*Test Plan for Station Calibration Research,*" 20 April 2011
- R. P. Kromer, Ground-based Monitoring R&E Technology Report, "*Evaluation of the Science Horizons AIM24S1 DWR for the GS21A Seismometer AFTAC EL090 Application,*" 27 August 2004
- T. O. Townsend and R. P. Kromer, Ground-based Monitoring R&E Technology Report, "*Evaluation of the Geotech GS21A Seismometer for AFTAC EL090 Application,*" 24 February 2004.

## REFERENCE

Kromer, R. P. (2003). Ground-based Monitoring R&E Technology Report, "*Evaluation of the Science Horizons AIM24S Borehole Digitizer for BRTR/Turkey IMS Application,*" 30 December 2003.