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# Evaluation of the Geotech SMART24BH 20Vpp/5Vpp Borehole Data Acquisition System with Active Fortezza Crypto Card Data Signing and Authentication

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# Evaluation of the Geotech SMART24BH 20Vpp/5Vpp Data Acquisition System with Active Fortezza Crypto Card Data Signing and Authentication

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## Abstract

Sandia National Laboratories has tested and evaluated Geotech SMART24BH borehole data acquisition system with active Fortezza crypto card data signing and authentication. The test results included in this report were in response to static and tonal-dynamic input signals. Most test methodologies used were based on IEEE Standards 1057 for Digitizing Waveform Recorders and 1241 for Analog to Digital Converters; others were designed by Sandia specifically for infrasound application evaluation and for supplementary criteria not addressed in the IEEE standards.

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# 1 Executive Summary

**Objective:**
The objective of this work was to evaluate the overall technical performance of two Geotech SMART24BH digitizers with a Fortezza PCMCIA crypto card actively implementing the signing of data packets. The results of this evaluation were compared to relevant specifications provided within manufacturer's documentation notes. The tests performed were chosen to demonstrate different performance aspects of the digitizer under test. The performance aspects tested include determining noise floor, least significant bit (LSB), dynamic range, cross-talk, relative channel-to-channel timing, time-tag accuracy/statistics/drift, analog bandwidth.

**Description:**
The SMART24BH digitizers under evaluation were manufactured by Geotech Instruments, LLC of Dallas, TX. The SMART24BH was designed to be a high resolution 24-bit data acquisition system, configured for 3-channel or 6-channel operation. SMART24BH digitizers were designed to have the capability to be configured to collect data from either an infrasound or seismic application. An additional requirement for some installations is to have the capability to sign outgoing data packets. The SMART24BH digitizer supports the use of a Fortezza Crypto PCMCIA Card for the purpose of data signing and authentication. Both digitizers used 20 V pp boards but they were configured differently with both configurations being tested. The first digitizer (s/n s1736 ADC Board s/n 1964) was in the standard 20Vpp ADC configuration with no gain. The second digitizer (s/n s1730 ADC board s/n 1952) was configured with hardware jumpers for a 5Vpp output and a firmware gain factor of 4. The 20 Vpp ADC board has a nominal LSB of 1.683e-6 V/count, where as the 5Vpp with gain x4 has a nominal LSB of 1.022e-7 V/count. It is expected that other Geotech SMART24BH units with Fortezza PCMCIA crypto cards will perform in a similar manner. All recorded data was taken at 40 samples per second.

The central recording facility at FACT uses the Geotech GeoHub software suite running on a standard PC for acquisition and data archiving of the test data. The GeoHub system was designed for network and array operators to allow greater control in data acquisition, data concentration and distribution for data archiving via its flexible communication protocol. The basic data transmission path from the data loggers to database starts at the SMART24BH with a RJ45 Ethernet connection to the FACT internal LAN. The PC running the GeoHub software was also connected to the same LAN. The SMART24BH and GeoHub communicate via fixed IP addresses. All test data were acquired in near real-time in CSS 3.0 flat-file database records in S4 format.

Testing was performed in a seismic vault for temperature stability.

## 1.1 SMART24BH w/Fortezza 5Vpp ADC Board - Digitizer Evaluation Summary:

Static Performance:
SMART24BH w/Fortezza DC accuracy errors were within 0.13% for high gain nominal input voltage of 0.03 volts. DC accuracy errors were within 0.14% for the high gain full-scale voltage of 0.625 volts. The input terminated noise was less than 1.36 counts RMS for the 0.5 to 16 Hz application band. The Maximum Potential Dynamic Range was better than 130 dB.

Tonal Dynamic Performance:
The SMART24BH w/Fortezza Total Harmonic Distortion (THD) was better than –120.9 dB. Crosstalk between channels was better than –115.7 dB.

Broadband Dynamic Performance:
Bandwidth measured –3 dB at 17.03 Hz with a relative attenuation of –84.2 dB at the Nyquist. Linearity was demonstrated to be consistently around 21.1 bits.

Timing Performance:

The SMART24BH w/Fortezza time-tagged the data with respect to the digitizer input to better than +/-7.3 microseconds. Time-tag statistics on channel 1 for 120 samples shows a consistent mean around -9.7 microseconds and a standard deviation of 1.34 microseconds. Time-tag drift rate of 11.0 microseconds per hour was observed during loss of GPS signal by digitizer. The digitizer clock and timing was reset within five minute after reacquiring GPS lock. Time-tag recovery rate was 131.0 microseconds after GPS signal returned and clock lock by digitizer occurs.

Application Performance Geotech GS13:
When the ITN spectrum for the Smart24 was corrected for a Geotech GS13 seismometer response, the resulting spectrum was at or below the USGS LNM minimum-earth noise model between 0.055 and 17 Hz.

The ITN-correct noise was better than 0.0856 nm/s RMS for the 0.5 to 16 Hz application band, giving a bandwidth limited dynamic range of better than 127.8 dB.

## 1.2 SMART24BH w/Fortezza 20Vpp ADC Board- Digitizer Evaluation Summary:

Static Performance:
SMART24BH w/Fortezza DC accuracy errors were within 0.52% for a nominal input voltage of 1 volt. DC accuracy errors were within 0.72% for the full-scale voltage of 10.0 volts. The input terminated noise was less than 1.1 counts RMS for the 0.02 to 16 Hz application band. The Maximum Potential Dynamic Range was better than 132 dB.

Tonal Dynamic Performance:
The SMART24BH w/Fortezza Total Harmonic Distortion (THD) was better than –122.7 dB. Crosstalk between channels was better than –126 dB.

Broadband Dynamic Performance:
Bandwidth measured –3 dB at 17.03 Hz with a relative attenuation of –87.6 dB at the Nyquist. Linearity was demonstrated to be consistently around 21.5 bits.

Timing Performance:
The SMART24BH w/Fortezza time-tagged the data with respect to the digitizer input to better than 20 microseconds. Time-tag statistics on channel 1 for 120 samples shows a consistent mean around 16.4 microseconds and a standard deviation of 1.36 microseconds. Time-tag drift rate of 10.4 microseconds per hour was observed during loss of GPS signal by digitizer. The digitizer clock and timing was reset within three minute after reacquiring GPS lock.Time-tag recovery rate was 343.0 microseconds after GPS signal returned and clock lock by digitizer occurs.

Application Performance Guralp CMG 3T:
When the ITN spectrum for the Smart24 was corrected for a Guralp CMG-3T seismometer the resulting spectrum was at or below the USGS LNM minimum-earth noise model between 0.02 and 2 Hz.

The ITN-correct noise was approximately 1.48 nm/s RMS for the 0.02 to 16 Hz application band giving a bandwidth limited dynamic range of better than 132 dB.

## 1.3 Conclusions:

Results, where appropriate, are compared to Manufacturer specifications listed in SMART24BH Series User Manual. Note: manufacturer's specifications taken at 50 sps.

The SMART24BH digitizer with the 5Vpp ADC board with software gain of 4x had performance of 21.0-bits for the 0.5 to 16 Hz passband at 40 samples per second. The total harmonic distortion (THD) of -120.9 dB was within manufacturer specifications of -110 dB. The input terminated noise (ITN) was slightly higher, 1.36 counts RMS, than manufacturer specifications of 0.8 counts RMS. Dynamic range for this high gain application was found to 130 dB or greater. (*Note: The passband used by the manufacturer for RMS calculations is not specified and is sampled at different rate.)* The Data sample time-tag accuracy of better

than +/-7.3 microseconds, was within manufacturer's specifications of 10 microseconds, and meets International Monitoring System requirements. The Analog bandwidth of 17.03 Hz was better than that listed by manufacturer as 80% of Nyquist. The time-tag drift was observed to be 11.0 microseconds per hour. Clock time recovery was within five minutes of reacquisition of the GPS signal.

The SMART24BH digitizer with the 20Vpp ADC board had performance of 21.1 for the 0.02 to 16 Hz passband at 40 samples per second. The total harmonic distortion (THD) of -122.7 dB was within manufacturer specifications of -110dB. The input terminated noise (ITN) was slightly higher, 1.1 counts RMS, than manufacturer specifications of 0.8 counts RMS. Dynamic range was found to 132 dB or greater. (*Note: The passband used by the manufacturer for RMS calculations is not specified and is sampled at different rate.)* The data sample time-tag accuracy of better than +/- 20.0 microseconds, was slightly outside manufacturer's specifications of 10 microseconds. The analog bandwidth of 17.03 Hz was better than that listed by manufacturer as 80% of Nyquist. The time-tag drift was observed to be 10.4 microseconds per hour. Clock time recovery was within three minutes of reacquisition of the GPS signal.

# 2 Introduction

## 2.1 Scope

This Evaluation Report defines the activities that were performed as part of the evaluation of the Geotech SMART24BH configured with a Fortezza Crypto PCMCIA Card describes the results of the testing.

## 2.2 Objectives

The objective of this work was to evaluate the overall technical performance of two Geotech SMART24BH borehole digitizers while the Fortezza Card is enabled and signing data outbound data packets. Basic digitizer characterization includes determining LSB, DC offset, noise, dynamic range, time-tag accuracy, channel-to-channel cross-talk, total harmonic distortion and the calibrator's performance. The results of this evaluation were compared to relevant application requirements or specifications of the SMART24BH provided by the manufacturer.

# 3 DWR Test and Evaluation Program

## 3.1 Test and Evaluation Background

Sandia National Laboratories (SNL), Ground-based Monitoring R&E Department has the capability of evaluating the performance of digitizing waveform recorders and analog-to-digital converters/high-resolution digitizers for geophysical applications.

## 3.2 Standardization/Traceability

Most tests are based on the Institute of Electrical and Electronics Engineers (IEEE) Standard 1057 [Reference 1] for Digitizing Waveform Recorders and Standard 1241 for Analog to Digital Converters [Reference 2]. The analyses based on these standards were performed in the frequency domain or time domain as required. When appropriate, instrumentation calibration was traceable to the National Institute for Standards Technology (NIST).

## 3.3 DWR Test/Evaluation Process

### 3.3.1 SMART24BH Testing

Testing of the SMART24BH w/Fortezza, serial numbers s1730 and s1736, digitizers was performed between June 2009 and July 2009, at the Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT) Site, Albuquerque, NM.

### 3.3.2 SMART24BH General Digitizer Performance Tests

The following tests were conducted on the SMART24BH as described in the test plan: *Test Definition and Test Procedures for the Evaluation of Digitizing Waveform Recorders* [Reference 3].

The tests selected provide a high level of characterization for IMS when evaluating digitizers for seismic or acoustic applications.

**SMART24BH w/Fortezza 20Vpp and 5Vpp w/firmware gain 4x Configurations**

Static Performance Tests
- DC Accuracy Nominal (DWR-DCA)
- DC Accuracy Full-Scale (DWR-DCFS)
- Input Terminated Noise (DWR-ITN)
- Maximum Potential Dynamic Range (DWR-MPDR)

Tonal Dynamic Performance Tests
- Total Harmonic Distortion (DWR-THD)
- Crosstalk (DWR-CTK)

Broadband Dynamic Performance Tests

Analog Bandwidth (DWR-ABW)
Modified Noise Power Ratio (DWR-MNPR)
Timing Tests
Time-Tag Accuracy (DWR-TTA)
Time-Tag Statistics (DWR-TTS)
Time-Tag Drift (DWR-TTD)
Application Tests
Seismic System Noise (DWR-SSN)
Bandwidth Limited Dynamic Range (DWR-BLDR)

## 3.4 Test Configuration and System Specifications

### 3.4.1 SMART24BH Digitizer Description and Test Configuration

The SMART24BH digitizers under evaluation were manufactured by Geotech Instruments, LLC of Dallas, TX. The SMART24BH was designed to be a high resolution 24-bit data acquisition system. The SMART24BH was configured to acquire a primary data stream at 40 samples per second (sps). The system under test used the GeoHub™ data acquisition software for the SMART24BH digitizers. GeoHub operated on a PC running Windows XP and communicated with the SMART24BH digitizers through an Ethernet connection. Data were acquired in real-time in CSS 3.0 flat-file records. Waveform data were archived in "s4" data format.

DWR testing was performed in an underground seismic vault for temperature stability.

Figure 3.4.1 SMART24BH s1730 5Vpp w/Fortezza Card used for testing in FACT Vault located on left and s1736 20Vpp w/Fortezza Card on right.

# 4 DWR – SMART24BH Tests

## 4.1 Static Performance Tests

Static tests provide a constant or non time-varying stimulus to the DWR under evaluation. The purpose of these tests is to determine specific parameters such as: gain (accuracy at nominal, full-scale and over-scale), DC offset, short-term and long-term stability, relationship to quantizing noise floor, and correlated/uncorrelated spurious signals. The results of these tests include measurement of dynamic range and resolution.

### 4.1.1 DC Accuracy Standard (DWR-DCA)

The DWR-DCA test, as defined in [3], was configured for a +/- 1 Volt input for the 20Vpp DWR and +/- 0.03 V for the 5Vpp DWR w/firmware gain 4x.

**Test Results:**
**DWR Serial Number: s1730 DCA Test Data Sheet, Appendix I, Section 5.2.**
**DWR Serial Number: s1736 DCA Test Data Sheet, Appendix I, Section 5.3.**

### 4.1.2 DC Accuracy Full-Scale (DWR-DCFS)

The DWR-DCFS test, as defined in [3], was configured for a +/- 10 Volt input for the 20Vpp DWR and +/- 0.625 V for the 5Vpp DWR w/firmware gain 4x.

**Test Results:**
**DWR Serial Number: s1730 DCFS Test Data Sheet, Appendix I, Section 5.2.**
**DWR Serial Number: s1736 DCFS Test Data Sheet, Appendix I, Section 5.3.**

### 4.1.3 Input Terminated Noise (DWR-ITN)

The DWR-ITN test, as defined in [3], was configured with 110 Ohm terminators for the 20Vpp DWR and 8.9 kOhm terminators for the 5Vpp DWR w/firmware gain 4x. A bandwidth of 0.5 to 16 Hz was used for the short-period application and 0.02 to 16 Hz was used for the broad-band application to determine the RMS noise for the 40 sps data.

**Test Results:**
**DWR Serial Number: s1730 ITN Test Data Sheet, Appendix I, Section 5.4.**
**DWR Serial Number: s1736 ITN Test Data Sheet, Appendix I, Section 5.5.**

### 4.1.4 Maximum Potential Dynamic Range (DWR-MPDR) Computation

Calculating the RMS value of the full-scale sinusoid (20.0 Volts or 0.625 Volts) and dividing by the RMS value of the Input Terminated Noise (ITN) test data determined the Maximum Potential Dynamic Range (MPDR) of the SMART24BH. A bandwidth of 0.5 to 16 Hz was used for the short-period application and 0.02 to 16 Hz was used for the broad-band application to determine the RMS noise for the 40 sps data.

**Test Results:**
**DWR Serial Number: s1730 MPDR Test Data Sheet, Appendix I, Section 5.4.**
**DWR Serial Number: s1736 MPDR Test Data Sheet, Appendix I, Section 5.5.**

## 4.2 Tonal Dynamic Performance Tests

Tonal tests are dynamic tests that use sinusoids as stimuli. Sine waves are the most popular signals for evaluating analog-to-digital converter performance because of the ease of generation and mathematical analysis. The DWR under test is asynchronously sampled with respect to the signal source for all tonal tests.

Dynamic tests are those that provide a time-varying stimulus to the DWR under evaluation. The purpose of these tests is to determine the DWR performance when digitizing time-varying signals. Several tests are available to determine the DWR digitizer's self noise, deviation from ideal performance and conversion distortions.

### 4.2.1 Total Harmonic Distortion (DWR-THD)

The DWR-THD test, as defined in [3], was configured with an input 10Vpp sine wave from ultra low distortion oscillator. A signal attenuator was built to reduce the amplitude test signal by a factor of x33, prior to input into digitizer s1730. Test signals were verified with HP3458A prior to each test.

**Test Results:**
**DWR Serial Number: s1730 THD Test Data Sheet, Appendix I, Section 5.6.**
**DWR Serial Number: s1736 THD Test Data Sheet, Appendix I, Section 5.7.**

### 4.2.2 Crosstalk (DWR-CTK)

The DWR-CTK test, as defined in [3], was configured with an input 10Vpp sine wave from ultra low distortion oscillator into two of the three channels being tested while the third was terminated with 50 Ohms. A signal attenuator was built to reduce the amplitude of test signal by a factor of x33, prior to input into digitizer s1730. Test signals were verified with HP3458A prior to each test.

**Test Results:**
**DWR Serial Number: s1730 CTK Test Data Sheet, Appendix I, Section 5.8.**
**DWR Serial Number: s1736 CTK Test Data Sheet, Appendix I, Section 5.9.**

## 4.3 Broadband Dynamic Performance Tests

Broadband tests are dynamic tests that use Gaussian pseudo-random signal generators as stimuli.

Dynamic tests are those that provide a time-varying stimulus to the DWR under evaluation. The purpose of these tests is to determine the DWR performance when digitizing time-varying signals. Multitudes of tests are available to determine the DWR digitizer's self noise, deviation from ideal performance and conversion distortions.

### 4.3.1 Analog Bandwidth (DWR-ABW)

The DWR-ABW test, as defined in [3], was configured with an input 10Vpp white noise signal from a Stanford Research Systems DS-360 function generator and simultaneously input into the three active digitizer channels. A signal attenuator was built to reduce the amplitude of test signal by a factor of x33, prior to input into digitizer s1730. Test signals were verified with HP3458A prior to each test.

**Test Results:**
**DWR Serial Number: s1730 ABW Test Data Sheet, Appendix I, Section 5.10.**
**DWR Serial Number: s1736 ABW Test Data Sheet, Appendix I, Section 5.11.**

### 4.3.2 Modified Noise Power Ratio (DWR-MNPR)

The DWR-MNPR test, as defined in [3], was configured with an input white noise signal from a Stanford Research Systems DS-360 function generator and simultaneously input into the three active digitizer channels. Nine separate amplitude levels of bandwidth limited white noise were used in this analysis from 0.521 Vrms to 2.03e-6 Vrms. A signal attenuator was built to reduce the amplitude of test signal by a factor of x33, prior to input into digitizer s1730. Test signals were verified with HP3458A prior to each test.

**Test Results:**
**DWR Serial Number: s1730 MNPR Test Data Sheet, Appendix I, Section 5.12.**
**DWR Serial Number: s1736 MNPR Test Data Sheet, Appendix I, Section 5.13.**

## 4.4 Timing Tests

Geophysical digitizing waveform recorders utilize a Universal Time Code (UTC) source, typically GPS, to time-tag the digitizer data samples. The HRD internal clock is usually synchronized to or phase-locked to this UTC receiver. Timing tests can determine the accuracy of this time-tag.

### 4.4.1 Time Tag Accuracy (DWR-TTA)

The DWR-TTA test, as defined in [3], was configured for input of the time-tag signal from the Sandia owned Zeli Systems model 5190 portable GPS time reference. A signal attenuator was built to reduce the amplitude of test signal by a factor of x33, prior to input into digitizer s1730.

**Test Results:**
**DWR Serial Number: s1730 TTA Test Data Sheet, Appendix I, Section 5.14.**
**DWR Serial Number: s1736 TTA Test Data Sheet, Appendix I, Section 5.15.**

### 4.4.2 Time Tag Statistics (DWR-TTS)

The DWR-TTS test, as defined in [3], was configured for input of the time-tag signal from the Sandia owned Zeli Systems model 5190 portable GPS time reference. Data was collected for just over two hours this allowed for 120 TTA samples for each channel tested. A signal attenuator was built to reduce the amplitude of test signal by a factor of x33, prior to input into digitizer s1730.

**Test Results:**
**DWR Serial Number: s1730 and s1736 TTS Test Data Sheet, Appendix I, Section 5.16.**

### 4.4.3 Time Tag Drift (DWR-TTD)

The DWR-TTD test, as defined in [3], was configured for input of the time-tag signal from the Sandia owned Zeli Systems model 5190 portable GPS time reference. A signal attenuator was built to reduce the amplitude of test signal by a factor of x33, prior to input into digitizer s1730.

**Test Results:**
**DWR Serial Number: s1730 and s1736 TTD Test Data Sheet, Appendix I, Section 5.17.**

## 4.5 DWR Seismic Sensor Application Tests

Sensor application tests are those that provide a stimulus to the DWR or interpret data from the DWR that is related to a specific sensor application. The DWR selected for an application should match the characteristics of the interfaced sensor and the expected sensor signals and background. Seismic applications can use all of the available bandwidth when interfaced to broadband seismic sensors or just a part of the available bandwidth when interfaced to long-period or short-period seismic sensors. The choice of system parameters is partially determined by the background that is expected at the location of the sensor. A properly matched DWR/sensor can resolve the expected seismic signals and backgrounds while nearly maximizing the system dynamic range.

### 4.5.1 Seismic System Noise (DWR-SSN)

The DWR-SSN test, as defined in [3], uses data from the ITN test and corrects for a specific seismic sensor's instrument response and compares this result to a site background model and the sensor noise model to determine the matched system (digitizer and sensor) noise. Sensor correction for s1730 ITN data will be a nominal GS13 response model and s1736 ITN data will be corrected for CMG3T response model. The DWR self-noise should be below the expected seismic background and the self-noise of the seismometer.

**Test Results:**
**DWR Serial Number: s1730 40sps SSN-GS13 Test Data Sheet, Appendix I, Section 5.18.**
**DWR Serial Number: s1736 40sps SSN-CMG3T Test Data Sheet, Appendix I, Section 5.19.**

# 5 Appendix I: DWR Test Data Sheets

## 5.1 SMART24BH Test Data Sheet:

**SMART24BH S/N: 1730** **Firmware Revision: 1.42**
**ADC Full-Scale Jumper: 5 Vpp**
**Firmware gain: 4x**
**Raw Data Format (CH 1-3): 24-bit Integer**
**SMART24BH Sample Rate: 40sps**
**********

**Test Description: Define SMART24BH digitizer gain.**

Manufacturer Specified Nominal Volts/Count Based on Geotech User Manual.
Nominal Volts/Count – 5 Vpp: $0.408887 \times 10^{-6}$
Nominal Volts/Count – 5 Vpp w/firmware gain 4x: $0.102220 \times 10^{-6}$
Nominal Volts/Count – 20 Vpp: $1.635548 \times 10^{-6}$

Nominal Counts/Volt – 5 Vpp: 2445663
Nominal Counts/Volt – 5 Vpp w/firmware gain 4x: 9782941
Nominal Counts/Volt – 20 Vpp: 611416

| ***Characteristics*** | **Minimum Requirement** | **Test Results** | **Manufacture Specifications** |
|---|---|---|---|
| ***Array Pass Band*** | IS :0.5-16 Hz | IS: 0.5 – 17.03 Hz | Approximately 80% of Nyquist |
| ***Sampling Rate*** | ≥ 10 samples per second | 40 sps | 1, 5, 10 , 20, 40, 50, 100, 125, 200, 250, 500, 1000, and 2000 sps, |
| ***Resolution*** | N/A | < 1.36 counts RMS noise | |
| ***Dynamic range*** | ≥ 108 dB | > 130 dB | > 132 |
| ***Timing Accuracy*** | ≥ 1 ms [1] | < 7 µs | ±10 µs |
| ***Cross-talk*** | N/A | < -116 dB | N/A |
| ***Relative timing between channels*** | N/A | N/A | ±50 ns |
| ***Bit-weight Accuracy*** | N/A | < 0.3 % from manufacture specification | 0.102220 e-7 V/Count |
| ***Total Harmonic Distortion*** | N/A | < -110 dB | < -110 dB |

[1] relative timing between array elements.

Table 5.1 SMART24BH – summary of 5 Vpp ADC board

**SMART24BH S/N: 1736** **Firmware Revision: 1.42**
**ADC Full-Scale Jumper: 20Vpp**
**Firmware gain: 1x**
**Raw Data Format (CH 1-3): 24-bit Integer**
**SMART24BH Sample Rate: 40sps**
**********

| ***Characteristics*** | **Minimum Requirement** | **Test Results** | **Manufacture Specifications** |
|---|---|---|---|
| ***Array Pass Band*** | IS :0.02-16 Hz | IS: 0.02 – 17.1 Hz | Approximately 80% of Nyquist |
| ***Sampling Rate*** | ≥ 10 samples per second | 40 sps | 1, 5, 10 , 20, 40, 50, 100, 125, 200, 250, 500, 1000, and 2000 sps, |
| ***Resolution*** | N/A | < 1.1 counts RMS noise | |
| ***Dynamic range*** | ≥ 108 dB | > 132 dB | > 132 |
| ***Timing Accuracy*** | ≥ 1 ms [1] | ~7 µs | ±10 µs |
| ***Cross-talk*** | N/A | < -110 dB | N/A |
| ***Relative timing between channels*** | N/A | N/A | ±50 ns |
| ***Bit-weight Accuracy*** | N/A | < 0.5 % from manufacture specification | 1.6835548 e-6 V/Count |
| ***Total Harmonic Distortion*** | N/A | < -126 dB | < -110 dB |

[1] relative timing between array elements.

Table 5.2 SMART24BH – summary of 20 Vpp ADC board

## 5.2 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Static/DCA/DCFS

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**********

**DCA Test Description: Measure DC Accuracy, and DC Full-Scale.**

DCA- Manufacture Specified Volts/Count (CH 1-3): $0.102220 \times 10^{-6}$

| Channel | Test Input Volts | Counts/Volt | µVolts/Count | % Deviation from Test Input Voltage | DC Offset µVolts | % Deviation from Manufactures LSB Specifications |
|---|---|---|---|---|---|---|
| C1P | 0.0300 | 9755893 | 0.1025 | -0.129 | 3.3 | -0.274 |
| C2P | 0.0300 | 9777305 | 0.1023 | -0.042 | 2.9 | -0.055 |
| C3P | 0.0300 | 9762477 | 0.1024 | -0.050 | -5.7 | -0.207 |

Table 5.2.1 DC Accuracy ± 0.030 Volt Results.

| Channel | Test Input Volts | Counts/Volt | µVolts/Count | % Deviation from Test Input Voltage | DC Offset µVolts | % Deviation from Manufactures LSB Specifications |
|---|---|---|---|---|---|---|
| C1P | 0.625 | 9755294 | 0.1025 | -0.135 | 4.1 | -0.280 |
| C2P | 0.625 | 9776505 | 0.1023 | -0.050 | 3.1 | -0.063 |
| C3P | 0.625 | 9761287 | 0.1024 | -0.062 | -5.2 | -0.219 |

Table 5.2.2 DC Accuracy Full-Scale ± 0.625 Volt Results.

**Test Results: Tables 5.2.1-2 indicate that the SMART24BH w/Fortezza Card accuracy of the measured LSB to ± 0.03 Volt DC input is better than 0.13% of the digitizer stored LSB and better than 0.28% of the manufactures specified LSB. For Full-scale the accuracy of the measured LSB to ± 0.625 Volt DC input is better than 0.14% of the digitizer stored LSB and better than 0.28% of the manufactures specified LSB.**

## 5.3 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Static/DCA/DCFS

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************************

**DCA Test Description: Measure DC Accuracy, and DC Full-Scale.**

DCA- Manufacture Specified Volts/Count (CH 1-3): 1.635548 x $10^{-6}$

| Channel | Test Input Volts | Counts/Volt | µVolts/Count | % Deviation from Test Input Voltage | DC Offset µVolts | % Deviation from Manufactures LSB Specifications |
|---|---|---|---|---|---|---|
| C1P | 1.0000 | 613,100 | 1.6311 | -0.524 | -27.6 | 0.275 |
| C2P | 1.0000 | 613,970 | 1.6287 | -0.438 | 3.2 | 0.416 |
| C3P | 1.0000 | 613,839 | 1.6291 | -0.488 | -42.2 | 0.395 |

Table 5.3.1 DC Accuracy ± 1.000 Volt Results.

| Channel | Test Input Volts | Counts/Volt | µVolts/Count | % Deviation from Test Input Voltage | DC Offset µVolts | % Deviation from Manufactures LSB Specifications |
|---|---|---|---|---|---|---|
| C1P | 10.002 | 611,925 | 1.6342 | -0.720 | -4.9 | 0.354 |
| C2P | 10.002 | 612,793 | 1.6319 | -0.631 | 11.4 | 0.496 |
| C3P | 10.002 | 612,665 | 1.6322 | -0.680 | -6.4 | 0.475 |

Table 5.3.2 DC Accuracy Full-Scale ± 10.00 Volt.

**Test Results: Tables 5.3.1-2 indicate that the SMART24BH w/Fortezza Card accuracy of the measured LSB to ± 1.0 Volt DC input is better than 0.52% of the digitizer stored LSB and better than 0.42% of the manufactures specified LSB. For Full-scale the accuracy of the measured LSB to ± 10.0 Volt DC input is better than 0.72% of the digitizer stored LSB and better than 0.41% of the manufactures specified LSB.**

## 5.4 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Static/ITN/MPDR

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************************

**ITN Test Description: Measure Input Terminated Noise.**

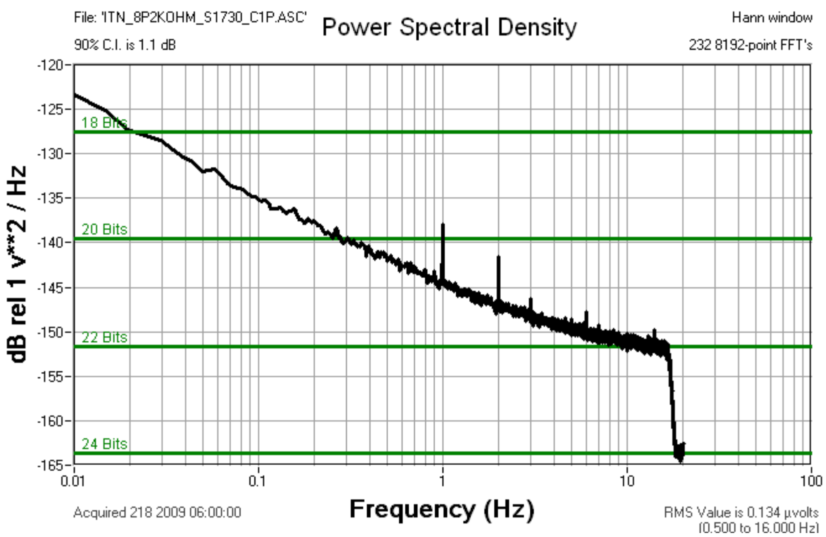


Figure 5.4.1 SMART24BH Channel C1P Input Terminated Noise.

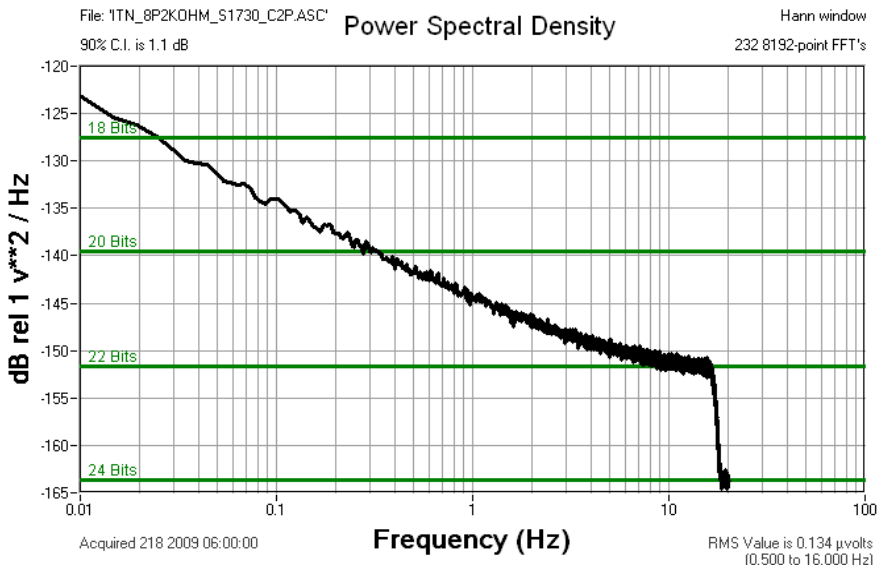


Figure 5.4.2 SMART24BH Channel C2P Input Terminated Noise.

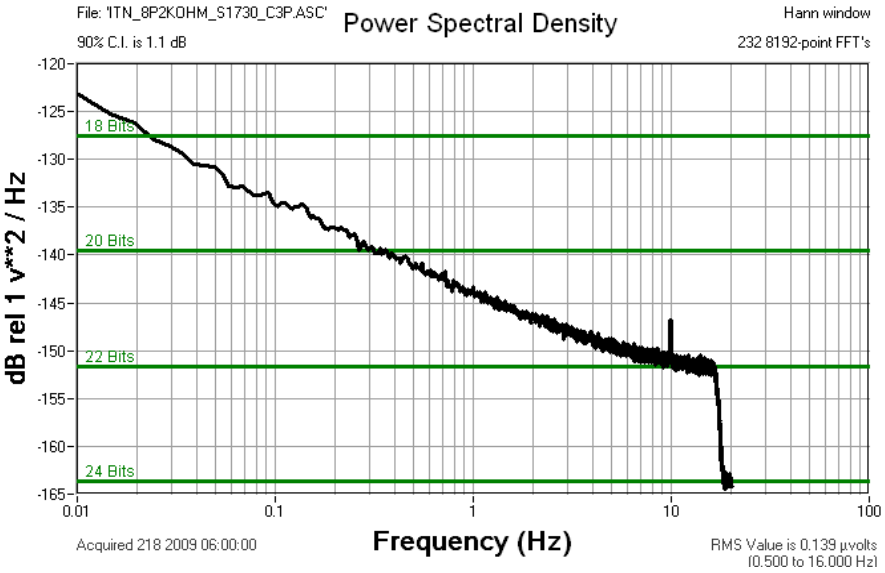


Figure 5.4.3 SMART24BH Channel C3P Input Terminated Noise.

| Channel | RMS Noise µV 0.5 to 16 Hz | Counts RMS |
|---|---|---|
| C1P | 0.134 | 1.307 |
| C2P | 0.134 | 1.310 |
| C3P | 0.139 | 1.357 |

Table 5.4.1 SMART24BH RMS Noise

**Test Results: Figures 5.4.1-3 and Table 5.4.1 indicate that the SMART24BH has less than 1.36 counts RMS noise.**

**MPDR Test Description: Compute Maximum Potential Dynamic Range, using the RMS noise estimate in microvolt's from ITN Test and theoretical RMS full-scale in volts.**

| Channel | RMS Noise µV 0.5 to 16 Hz | RMS Full-Scale Volts | MPDR (dB) |
|---|---|---|---|
| C1P | 0.134 | 0.44 | 130.4 |
| C2P | 0.134 | 0.44 | 130.4 |
| C3P | 0.139 | 0.44 | 130.0 |

Table 5.4.2 SMART24BH MPDR

**Test Results: Table 5.4.2 indicates that the SMART24BH Maximum Potential Dynamic Range is at or around 130 dB.**

## 5.5 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Static/ITN/MPDR

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
*************************************************************************************************

**ITN Test Description: Measure Input Terminated Noise.**

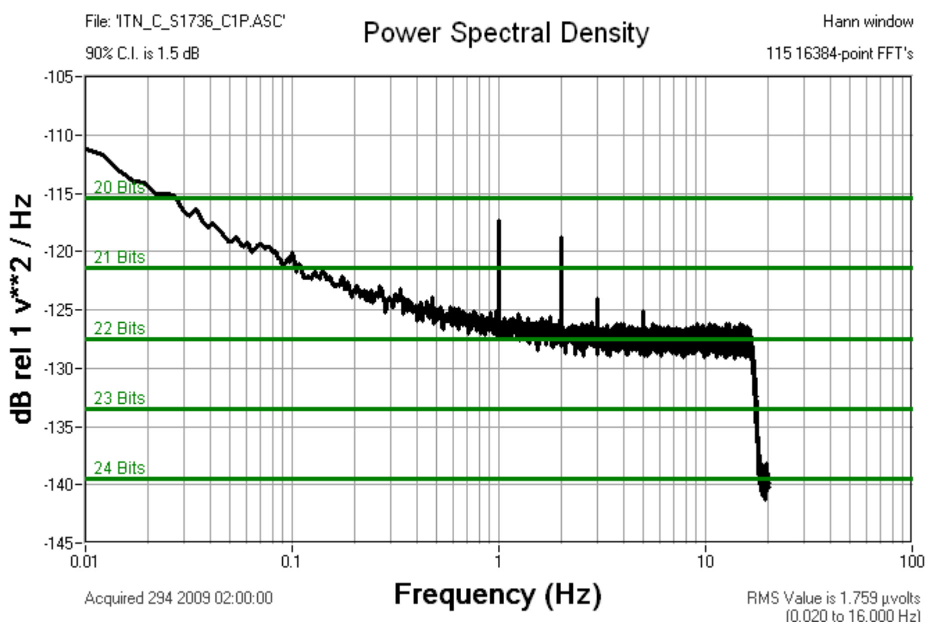


Figure 5.5.1 SMART24BH Channel C1P Input Terminated Noise.

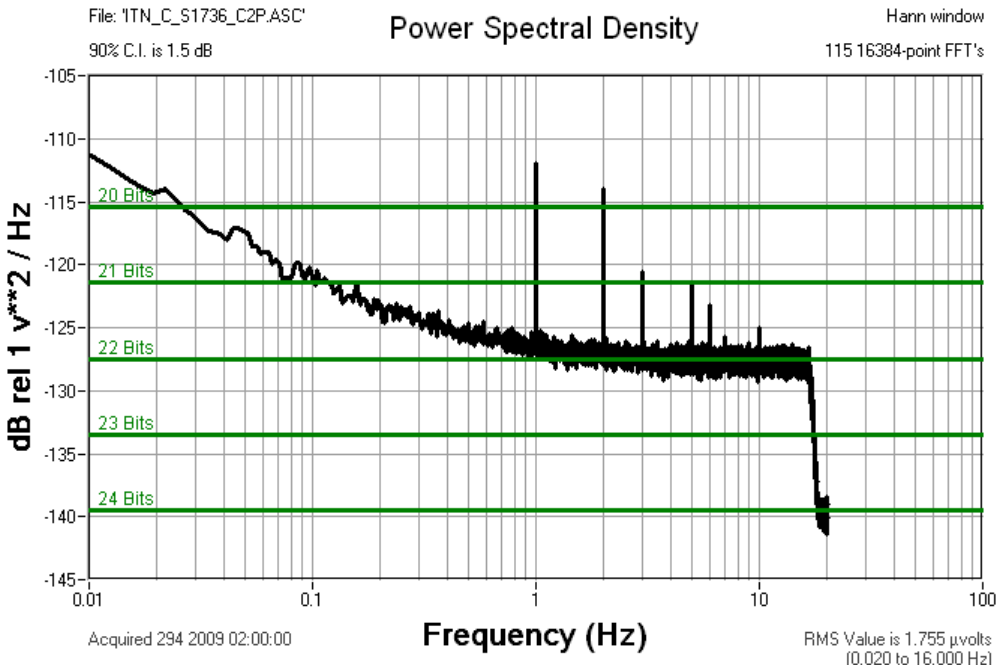


Figure 5.5.2 SMART24BH Channel C2P Input Terminated Noise.

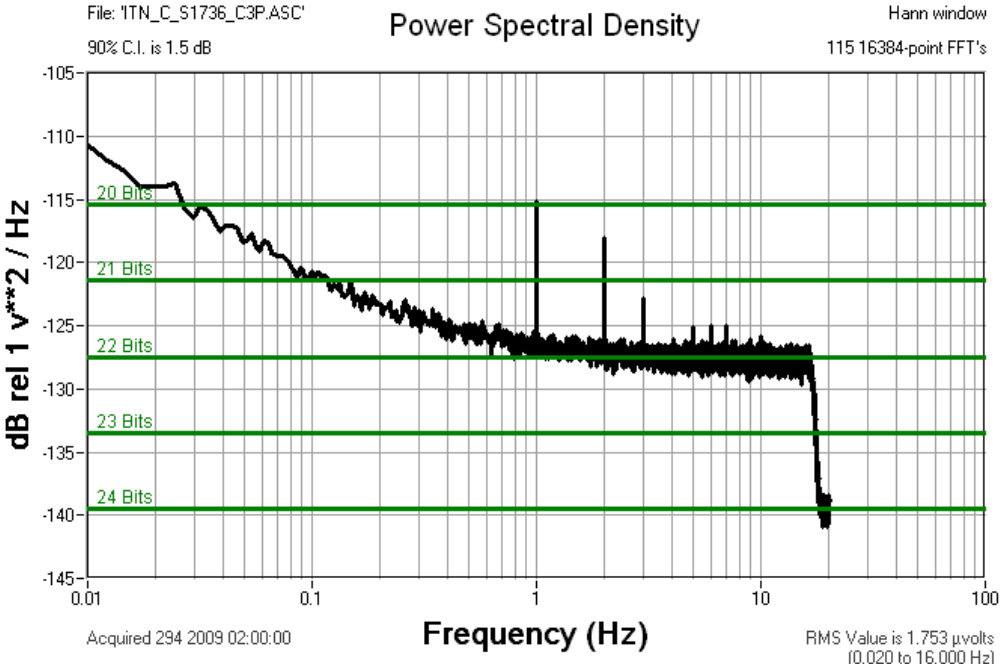


Figure 5.5.3 SMART24BH Channel C3P Input Terminated Noise.

| Channel | RMS Noise µV 0.02 to 16 Hz | Counts RMS |
|---|---|---|
| C1P | 1.759 | 1.078 |
| C2P | 1.755 | 1.078 |
| C3P | 1.753 | 1.076 |

Table 5.5.1 SMART24BH 40sps RMS Noise

**Test Results: Figures 5.5.1-3 and Table 5.5.1 indicate that the SMART24BH has < 1.1 counts RMS noise. Integer hertz coupling was observed, although total power of integer hertz is minimal it suggests design considerations could be made to improve this effect.**

**MPDR Test Description: Compute Maximum Potential Dynamic Range, using the RMS noise estimate in microvolt's from ITN Test and theoretical RMS full-scale in volts**

| Channel | RMS Noise µV 0.02 to 16 Hz | RMS Full-Scale Volts | MPDR |
|---|---|---|---|
| C1P | 1.759 | 7.07 | 132.1 |
| C2P | 1.755 | 7.07 | 132.1 |
| C3P | 1.753 | 7.07 | 132.1 |

Table 5.5.2 SMART24BH 40sps MPDR

**Test Results: Table 5.5.2 indicates that the SMART24BH Maximum Potential Dynamic Range is at or around 132 dB.**

## 5.6 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Dynamic Tonal/THD

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
***********************************************************************************************

**THD Test Description: Measure the linearity of the SMART24BH using Total Harmonic Distortion.**

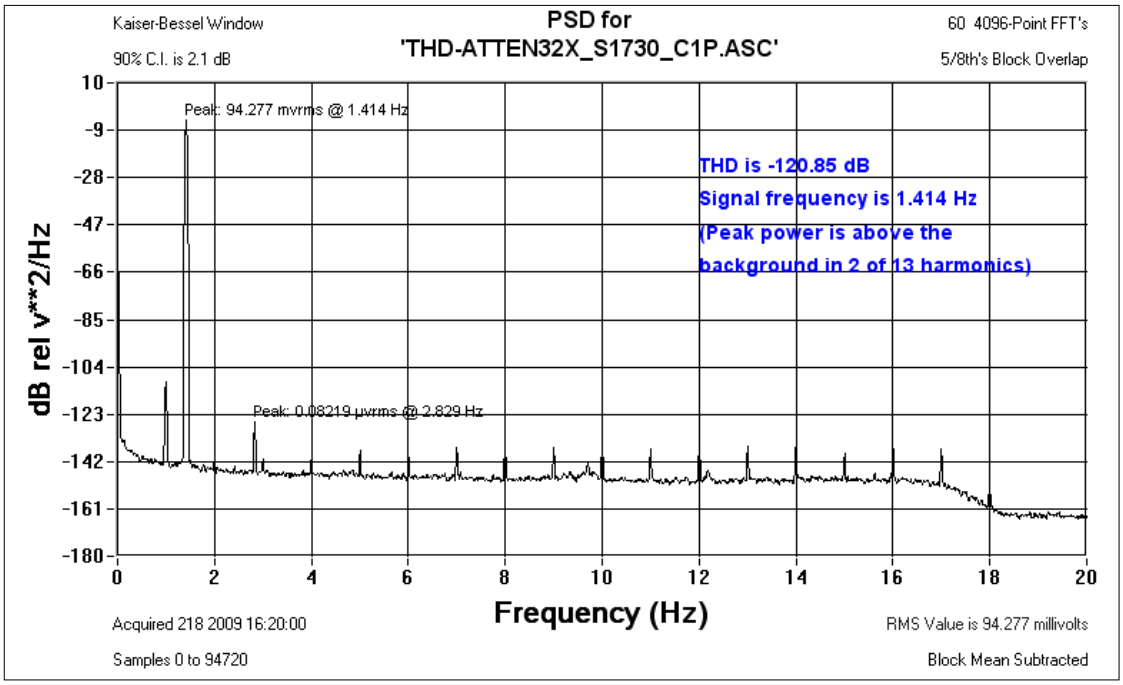


Figure 5.6.1 SMART24BH Total Harmonic Distortion with Attenuator in circuit.

| Channel | THD (dB) |
|---|---|
| 3458A Reference THD | -123.7 |
| C1P | -120.9 |
| C2P | -127.3 |
| C3P | -125.4 |

Table 5.6.1 SMART24BH THD

**Test Results: Table 5.6.1 indicates that the SMART24BH Total Harmonic Distortion is better than -120.9 dB.**

## 5.7 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Dynamic Tonal/THD

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**********

**THD Test Description: Measure the linearity of the SMART24BH using Total Harmonic Distortion.**

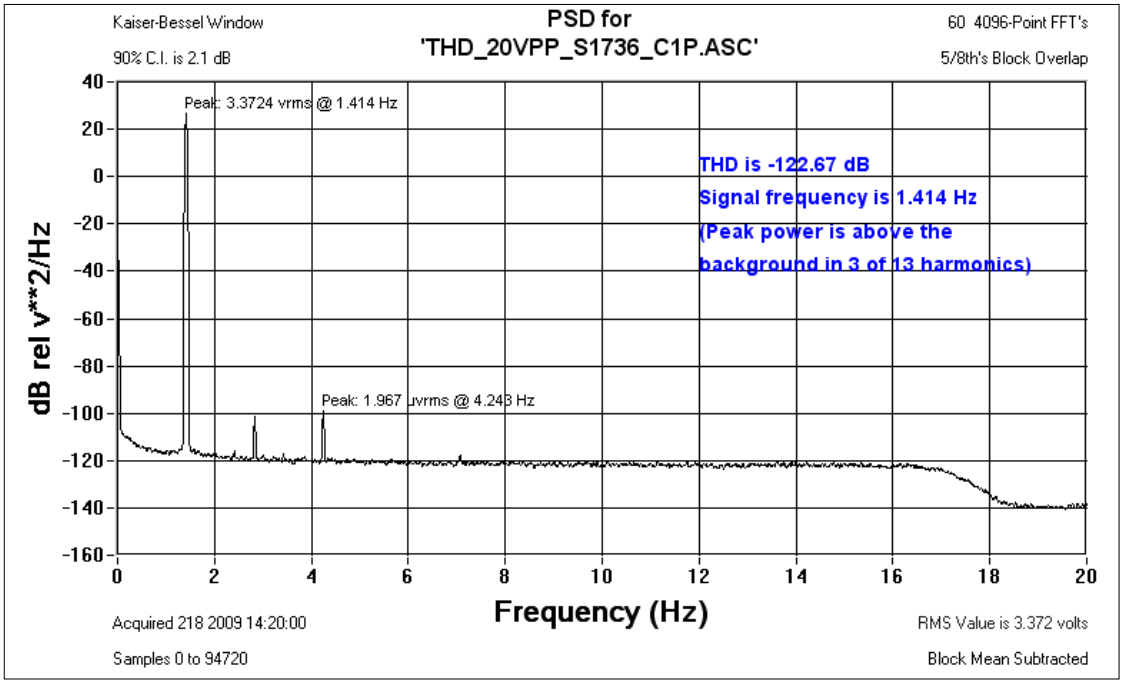


Figure 5.7.1 SMART24BH Total Harmonic Distortion.

| Channel | THD (dB) |
|---|---|
| 3458A Reference THD | -123.7 |
| C1P | -122.7 |
| C2P | -128.7 |
| C3P | -124.3 |

Table 5.7.1 SMART24BH THD

**Test Results: Table 5.7.1 indicates that the SMART24BH Total Harmonic Distortion is better than -122.7 dB.**

## 5.8 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Dynamic Tonal/CTK

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**********

**CTK Test Description: Measure the amount of SMART24BH channel-to-channel crosstalk.**

| Channel | RMS Input | RMS Crosstalk | Crosstalk (dB) |
|---|---|---|---|
| C1P | 0.118 V | 0.19 µV | -116.0 |
| C2P | 0.118 V | 0.18 µV | -116.2 |
| C3P | 0.118 V | 0.19 µV | -115.7 |

Table 5.8.1 SMART24BH Crosstalk

**Test Results: Table 5.8.1 indicates that the SMART24BH crosstalk is better than –115.7 dB.**

## 5.9 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Dynamic Tonal/CTK

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**********

**CTK Test Description: Measure the amount of SMART24BH channel-to-channel crosstalk.**

| Channel | RMS Input | RMS Crosstalk | Crosstalk (dB) |
|---|---|---|---|
| C1P | 4.21 V | 2.07 µV | -126.2 |
| C2P | 4.21 V | 1.91 µV | -126.9 |
| C3P | 4.21 V | 2.12 µV | -126.0 |

Table 5.9.1 SMART24BH Crosstalk

**Test Results: Table 5.9.1 indicates that the SMART24BH crosstalk is better than –126 dB.**

## 5.10 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Dynamic Broadband/ABW

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**********

**ABW Test Description: Measure SMART24BH the bandwidth/corner frequency (–3 dB point) and attenuation at the Nyquist (20 Hz).**

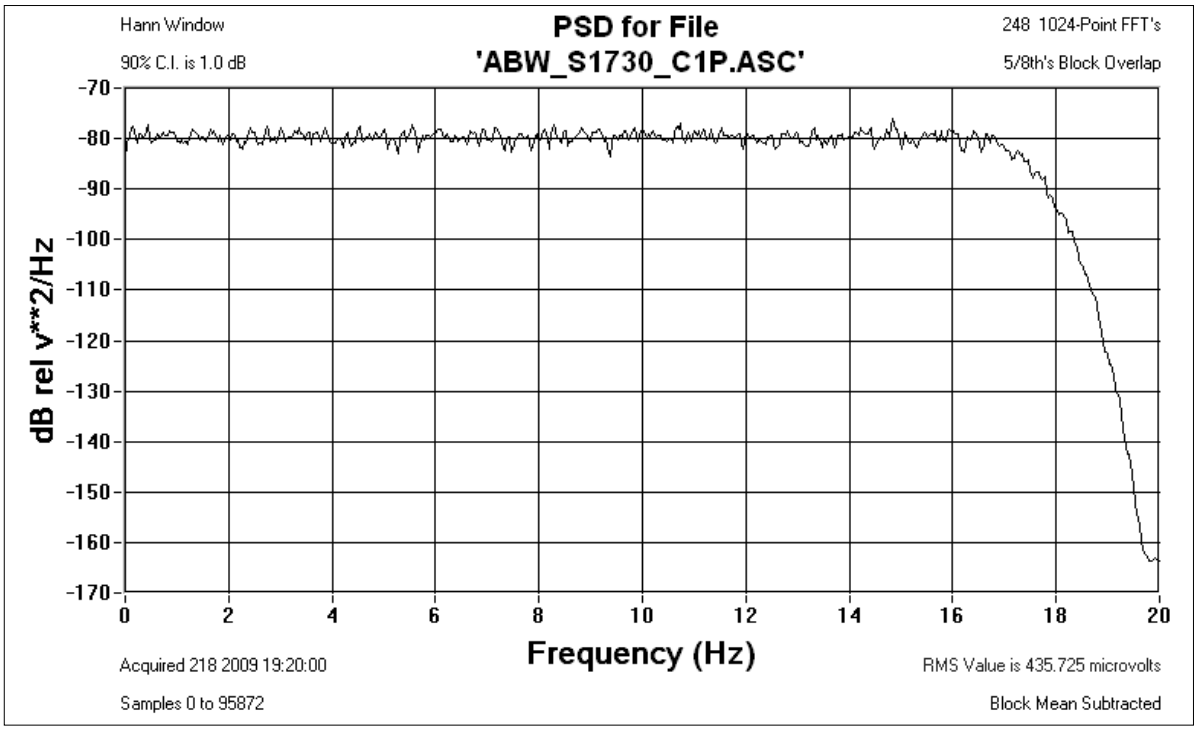


Figure 5.10.1 Response of the SMART24BH to Broadband Noise

| Channel | 10 Hz 5-point Average (dB) | -3 dB from 10 Hz Reference | -3 dB Frequency (Hz) | Attenuation at Nyquist (dB) | Relative Attenuation @ Nyquist (dB) |
|---|---|---|---|---|---|
| C1P | -79.21 | -82.21 | 17.03 | -163.41 | -84.20 |
| C2P | -79.14 | -82.14 | 17.03 | -163.52 | -84.38 |
| C3P | -79.14 | -82.14 | 17.03 | -163.48 | -84.34 |

Table 5.10.1 Compiled results of analysis of ABW power spectrum using a 5-point moving average.

**Test Results: Figure 5.10.1 and Table 5.10.1 indicates that the SMART24BH 40 sps -3dB point is at 17.03 Hz and relative attenuation at the Nyquist is between -84.2 and -84.4 dB.**

## 5.11 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Dynamic Broadband/ABW

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**********

**ABW Test Description: Measure SMART24BH the bandwidth/corner frequency (–3 dB point) and attenuation at the Nyquist (20 Hz).**

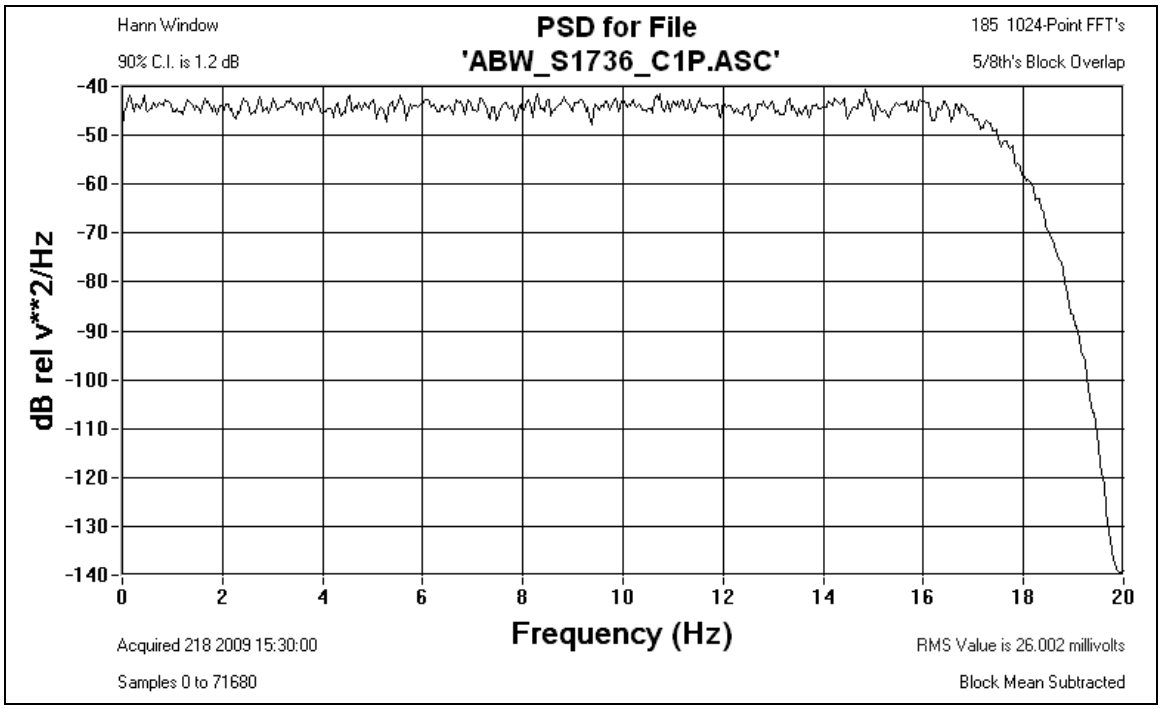


Figure 5.11.1 Response of the SMART24BH to Broadband Noise

| Channel | 10 Hz 5-point Average (dB) | -3 dB from 10 Hz Reference | -3 dB Frequency (Hz) | Attenuation at Nyquist (dB) | Relative Attenuation @ Nyquist (dB) |
|---|---|---|---|---|---|
| C1P | -43.45 | -46.45 | 17.03 | -131.01 | -87.56 |
| C2P | -43.55 | -46.55 | 17.03 | -133.03 | -89.48 |
| C3P | -43.58 | -46.58 | 17.03 | -134.45 | -90.87 |

Table 5.11.1 Compiled results of analysis of ABW power spectrum using a 5-point moving average.

**Test Results: Figure 5.11.1 and Table 5.11.1 indicates that the SMART24BH 40 sps -3dB point is at 17.03 Hz and relative attenuation at the Nyquist is between -87.6 and -90.9 dB.**

## 5.12 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Dynamic Broadband/MNPR

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************************

**MNPR Test Description: Measure the linearity of bit-resolution versus increasing levels of bandwidth limited white noise.**

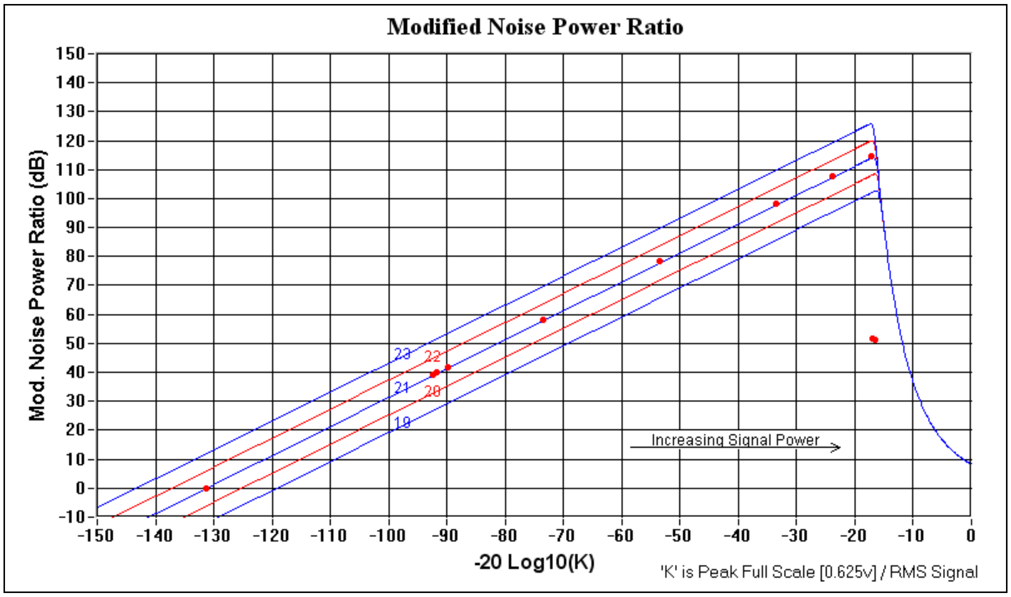


Figure 5.12.1 Noise Power Ratios (NPR) samples resulting from different input signal levels.

| Channel | Data Source | RMS of BWL-WN Signal (V) | Peak Full-Scale (V) | MPDR (dB) |
|---|---|---|---|---|
| C1P-C2P | ITN – 8.2 kOhm | 2.75-6 | 0.625 | 0.121 |
| C1P-C2P | SRS DS360 | 2.41e-4 | 0.625 | 39.3 |
| C1P-C2P | SRS DS360 | 2.57e-4 | 0.625 | 39.9 |
| C1P-C2P | SRS DS360 | 3.22e-4 | 0.625 | 41.8 |
| C1P-C2P | SRS DS360 | 2.13e-3 | 0.625 | 58.3 |
| C1P-C2P | SRS DS360 | 2.12e-2 | 0.625 | 78.3 |
| C1P-C2P | SRS DS360 | 0.212 | 0.625 | 98.1 |
| C1P-C2P | SRS DS360 | 0.637 | 0.625 | 107.7 |
| C1P-C2P | SRS DS360 | 1.38 | 0.625 | 114.5 |
| C1P-C2P | SRS DS360 | 1.40 | 0.625 | 114.5 |
| C1P-C2P | SRS DS360 | 1.43 | 0.625 | 51.6 |
| C1P-C2P | SRS DS360 | 1.49 | 0.625 | 51.0 |

Table 5.12.1 Compiled results of MNPR analysis.

**Test Results: Figure 5.12.1 and Table 5.12.1 indicates that the SMART24BH serial number s1730 in this high gain configuration performs with 21.1 bits of linearity for a range of input signal levels. The degradation of the digitizer linearity occurs at high signal levels above ~1.40 Volts RMS for bandwidth limited white noise.**

## 5.13 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Dynamic Broadband/MNPR

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************************

**MNPR Test Description: Measure the bit linearity of the digitizer with increasing levels of bandwidth limited white noise.**

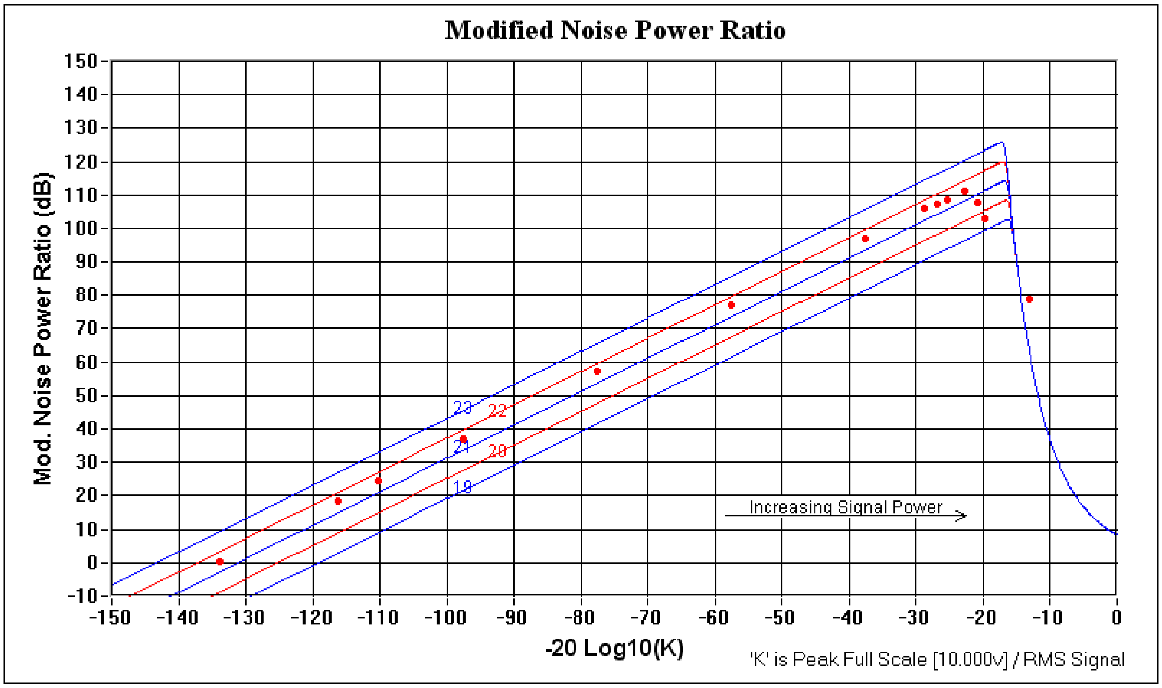


Figure 5.13.1Noise Power Ratios (NPR) samples resulting from different input signal levels.

| Channel | Data Source | RMS of BWL-WN Signal (V) | Peak Full-Scale (V) | MNPR (dB) |
|---|---|---|---|---|
| C1P-C2P | ITN – 110 Ohm | 2.03e-6 | 10.0 | 0.339 |
| C1P-C2P | SRS DS360 | 1.55e-5 | 10.0 | 18.5 |
| C1P-C2P | SRS DS360 | 3.06e-5 | 10.0 | 24.4 |
| C1P-C2P | SRS DS360 | 1.32e-4 | 10.0 | 37.2 |
| C1P-C2P | SRS DS360 | 1.32e-3 | 10.0 | 57.1 |
| C1P-C2P | SRS DS360 | 1.32e-2 | 10.0 | 77.1 |
| C1P-C2P | SRS DS360 | 0.132 | 10.0 | 97.1 |
| C1P-C2P | SRS DS360 | 0.365 | 10.0 | 105.9 |
| C1P-C2P | WaveTek 132S | 0.453 | 10.0 | 107.7 |
| C1P-C2P | SRS DS360 | 0.541 | 10.0 | 108.8 |
| C1P-C2P | WaveTek 132S | 0.728 | 10.0 | 111.0 |
| C1P-C2P | WaveTek 132S | 0.900 | 10.0 | 107.7 |
| C1P-C2P | WaveTek 132S | 1.017 | 10.0 | 103.0 |
| C1P-C2P | WaveTek 132S | 2.210 | 10.0 | 78.7 |

Table 5.13.1 Compiled results of MNPR analysis.

**Test Results: Figure 5.13.1 and Table 5.13.1 indicates that the SMART24BH serial number s1736 performs with 21.5 bits of linearity for a range of input signal levels. The degradation of the digitizer linearity occurs at high signal levels above ~0.73 Volts RMS for bandwidth limited white noise.**

## 5.14 SMART24BH Test Data Sheet: 5 Vpp ADC Test – Timing/TTA

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************************

**TTA Test Description: Determine the accuracy of the time-tags of the SMART24BH data samples.**

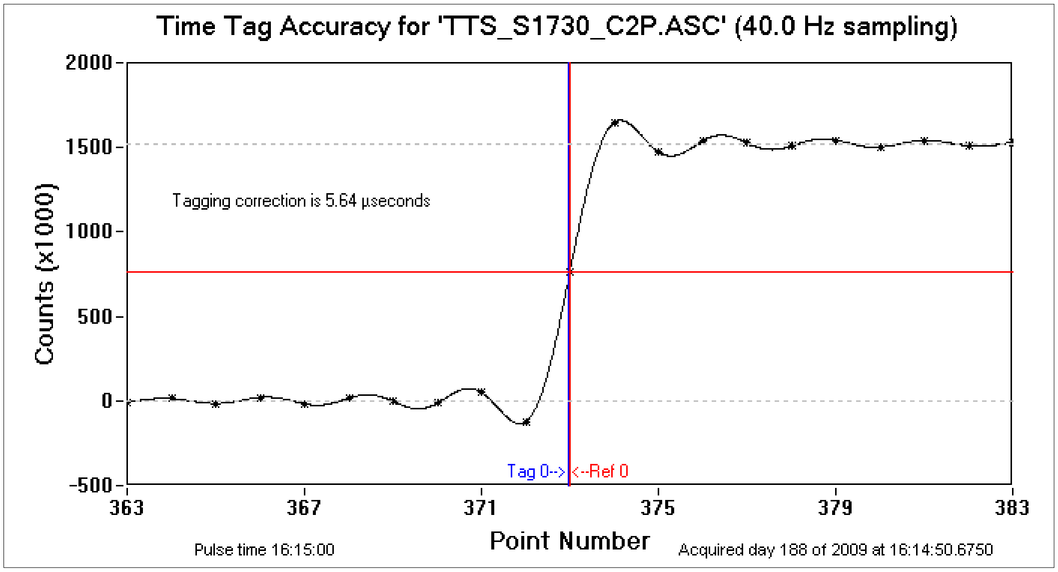


Figure 5.14.1 SMART24BH s1730 configured for 20Vpp full-scale input; allowing the direct time-tag signal input without attenuation.

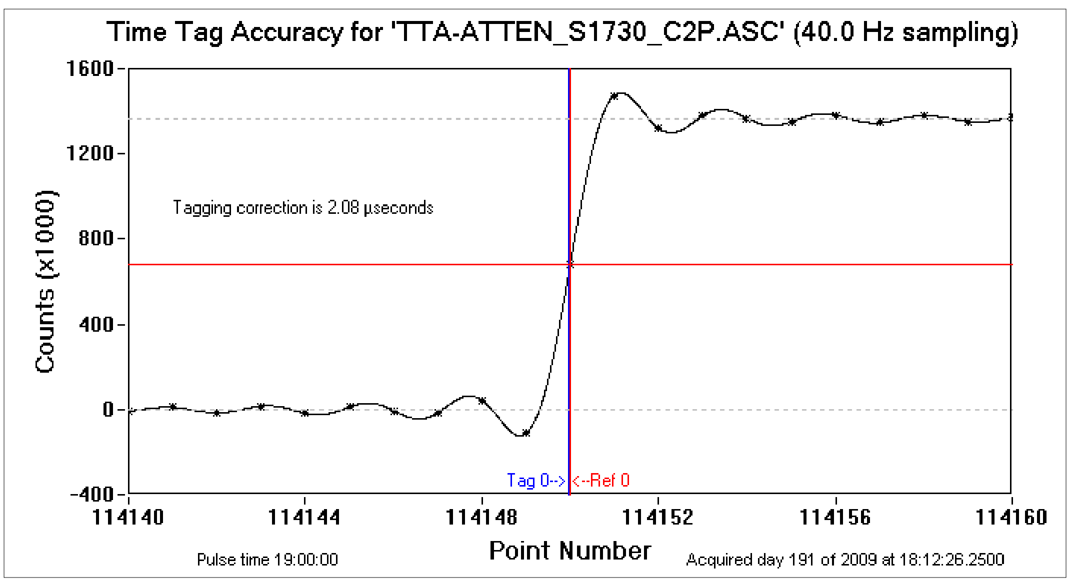


Figure 5.14.1 SMART24BH s1730 configured for 1.25 Vpp full-scale input; requiring the use of a signal attenuator for the time-tag signal input.

| Channel | TTA μseconds |
|---|---|
| C1P – w/attenuator | -7.3 |
| C2P – no attenuator | 5.6 |
| C2P – w/attenuator | 2.1 |
| C3P – w/attenuator | -5.6 |

Table 5.14.1 SMART24BH Time-Tag Accuracy

**Test Results: Table 5.14.1 indicates that the SMART24BH can time-tag data samples to within 10.0 microseconds.**

## 5.15 SMART24BH Test Data Sheet: 20 Vpp ADC Test – Timing/TTA

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************************

**TTA Test Description: Determine the accuracy of the time-tags of the SMART24BH data samples.**

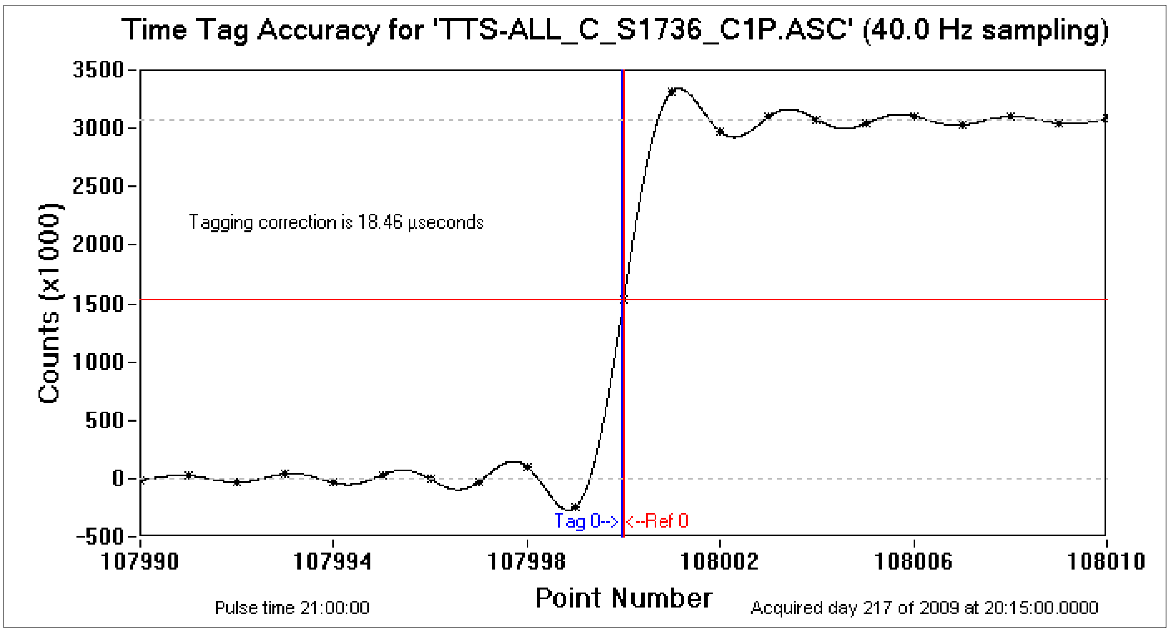


Figure 5.15.1 SMART24BH Time-Tag Accuracy.

| Channel | TTA μseconds |
|---|---|
| C1P | 17.8 |
| C2P | 19.6 |
| C3P | 19.2 |

Table 5.15.1 SMART24BH Time-Tag Accuracy

**Test Results: Table 5.15.1 indicates that the SMART24BH can time-tag data samples to within 20.0 microseconds.**

## 5.16 SMART24BH Test Data Sheet: 5 AND 20 Vpp ADC Test – Timing/TTS

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**************************************************************************************

**TTS Test Description: Determine the statistical significance of the time-tags of the SMART24BH.**

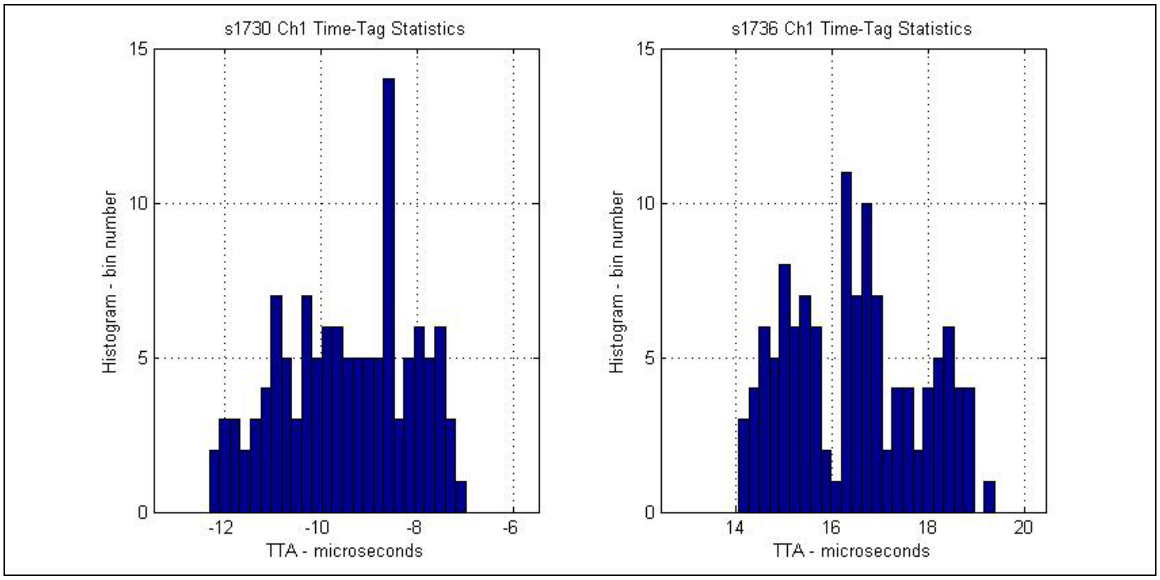


Figure 5.16.1 SMART24BH Time-Tag Accuracy.

| Channel | Mean TTA (microseconds) | Standard Deviation TTA (microseconds) |
|---|---|---|
| S1730 – C1P | -9.5 | 1.34 |
| S1736 – C1P | 16.44 | 1.36 |

Table 5.16.1 SMART24BH Time-Tag Accuracy

**Test Results: Figure 5.16.1 indicates that both SMART24BH units tested time-tag data samples to within 20.0 microseconds and low scatter <1.4 microseconds. Two hours of time pulses (n=120) were analyzed.**

## 5.17 SMART24BH Test Data Sheet: 5 and 20 Vpp ADC Test – Timing/TTD

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
***********************************************************************************************

**TTD Test Description: Determine ability SMART24BH to accurately time-tag data samples with respect to GPS receiver variations.**

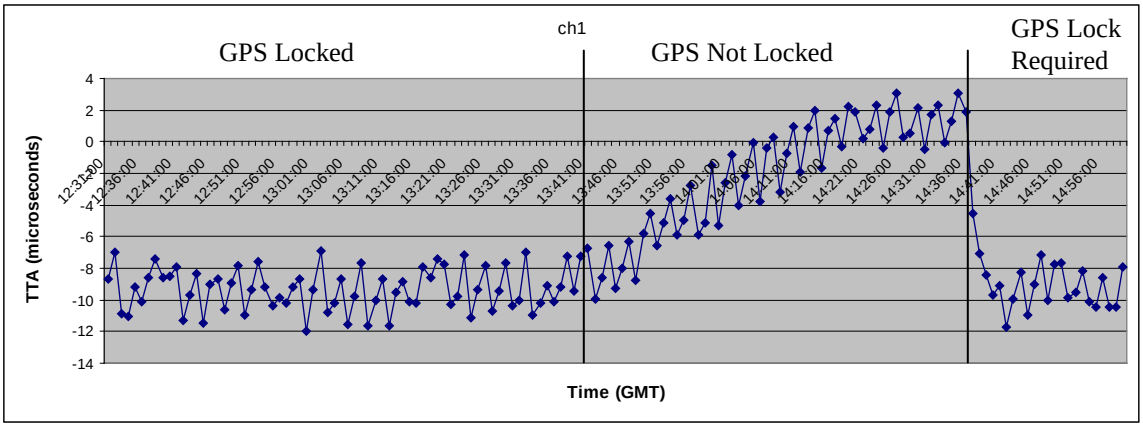


Figure 5.17.1 SMART24BH time-tag drift and recovery response to sustained GPS loss followed by subsequent reacquisition of GPS signal and resynchronization of clock timing.

| Channel | Absolute Drift Rate (microseconds/hour) | Absolute Recovery Rate (microseconds/hour) |
|---|---|---|
| S1730 - C2P | 11.0 | 131 |

Table 5.17.1 Time-tag drift and recovery rates.

**Test Results: Figure 5.17.1 indicates that SMART24BH unit s1730 timing oscillator varied at a nearly constant rate for the first 40 minutes of the test and then tended to flatten during the last 20 minutes of GPS loss. Time-tag accuracy returned to initial time-tag accuracy after GPS was reacquired and the internal clock was reset to GPS time.**

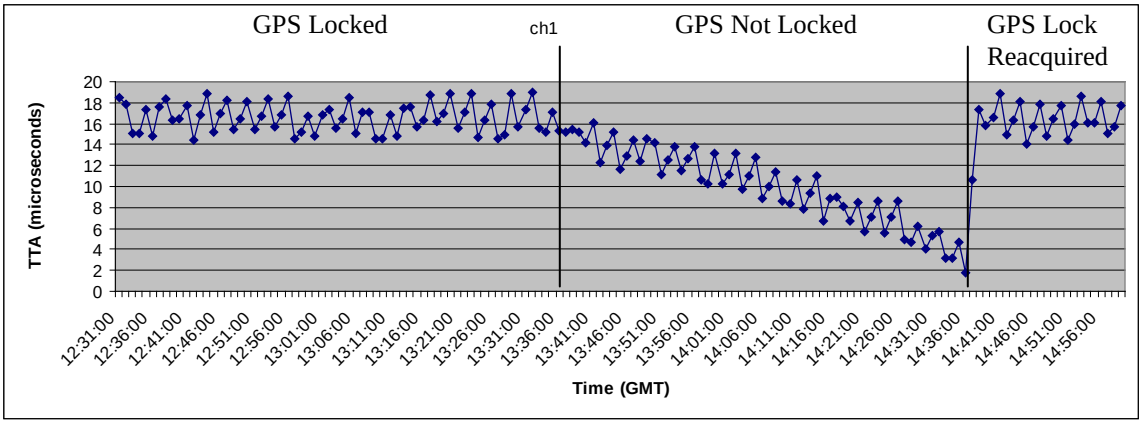


Figure 5.17.2 SMART24BH time-tag drift and recovery response to sustained GPS loss followed by subsequent reacquisition of GPS signal and resynchronization of clock timing.

| Channel | Absolute Drift Rate (microseconds/hour) | Absolute Recovery Rate (microseconds/hour) |
|---|---|---|
| S1736 – C1P | 10.4 | 343 |

Table 5.17.2 Time-tag drift and recovery rates.

**Test Results: Figure 5.17.2 indicates that SMART24BH unit s1736 timing oscillator varied at a constant rate during GPS loss. Time-tag accuracy returned to initial time-tag accuracy after GPS was reacquired and the internal clock was reset to GPS time.**

## 5.18 SMART24 Test Data Sheet: 5 Vpp ADC Test – Seismic System Noise

**SMART24BH S/N: s1730** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 4x**
**CH 1-3: Single Three Channel 5 Vpp ADC Board - S/N 1952**
**SMART24BH Sample Rate: 40sps**
**Seismometer Application (CH 1-3): Geotech GS13 Generic 2100 V/m/s @ 2.5 Hz**
****************************************************************************************************

**SSN Test Description: Determine ability of the Smart24 to resolve the expected seismic background using a Geotech GS13 velocity seismometer. Results are referenced relative to GS13 noise model, NVAR seismic background model and NLNM.**

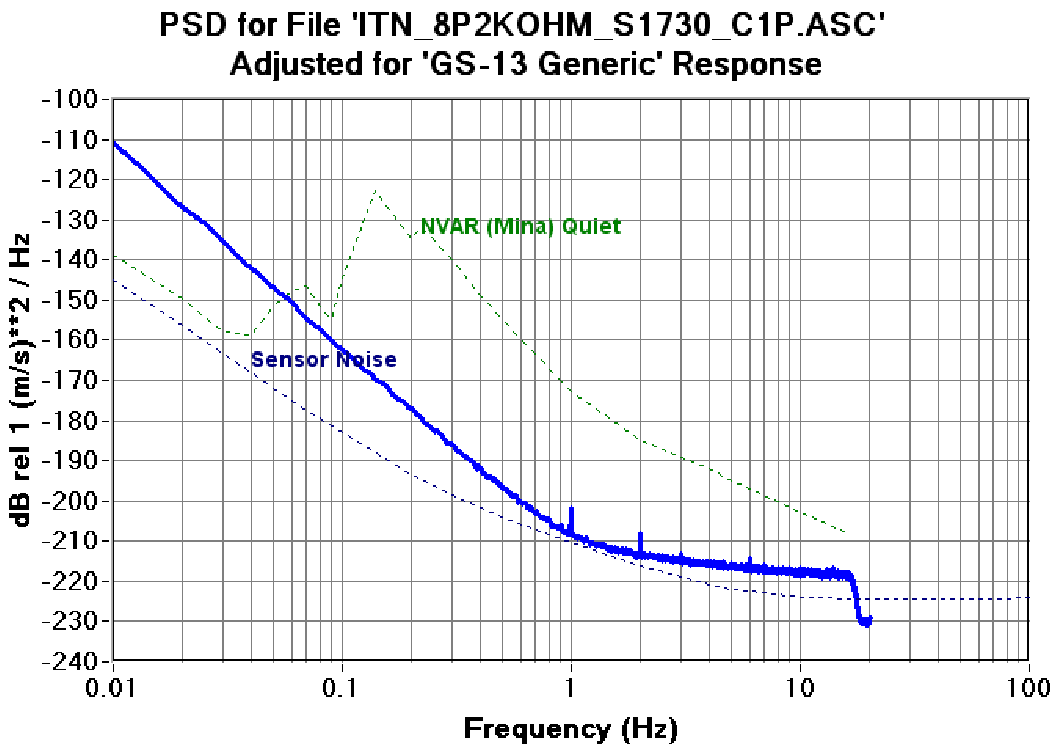


Figure 5.18.1 SMART24 SSN relative to a Geotech GS13 seismometer.

**Test Results: Figures 5.18.1 indicates that the noise of the individual channels were at or below the NVAR noise model between 0.06 and 16 Hz when used with a Geotech GS13 seismometer. The Smart24BH channels were ~23 db above the NVAR noise model at 0.02 Hz, 14 db below at 0.1 Hz, 37 db below at 1 Hz and 15 dB below at 10Hz.**

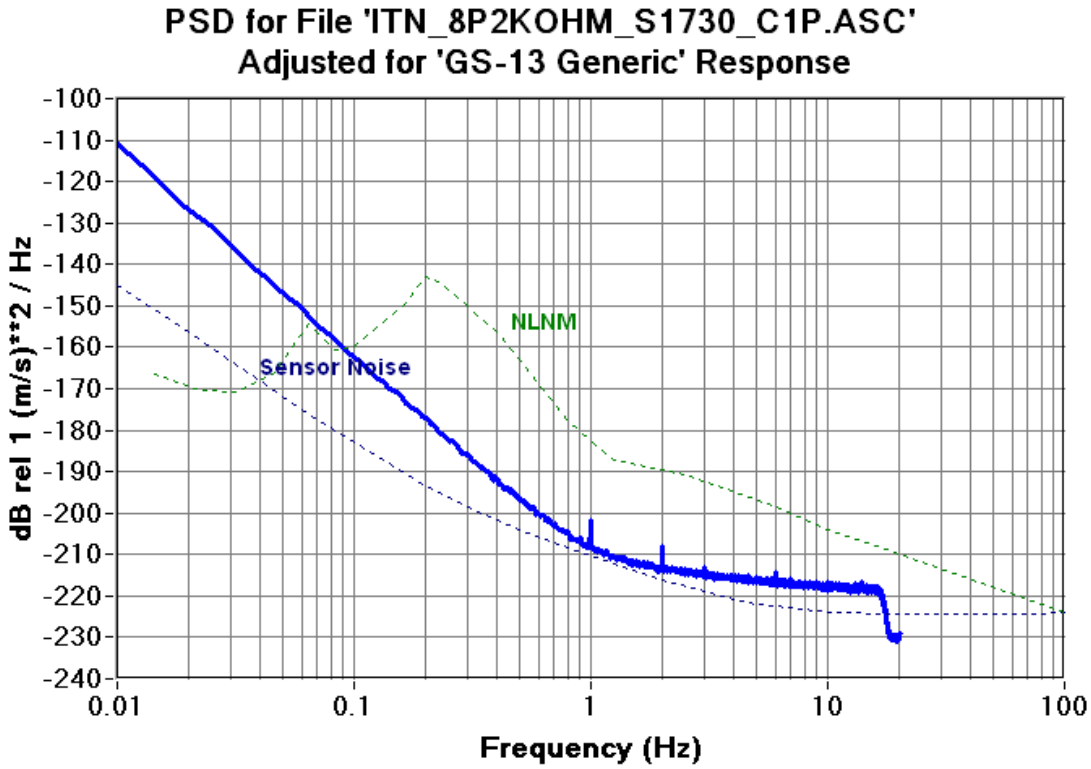


Figure 5.18.2 SMART24 SSN relative to a Geotech GS13 seismometer.

**Test Results: Figures 5.18.2 indicates that the noise of the individual channels were at or below the NLNM between 0.09 and 16 Hz when used with a Geotech GS13 seismometer. The Smart24BH channels were ~43 db above the NLNM noise model at 0.02 Hz, 2 db below at 0.1 Hz, 27 db below at 1 Hz and 14 dB below at 10Hz.**

| Channel | RMS Noise (nm/s) 0.5 to 16 Hz |
|---|---|
| C1P | 0.0817 |
| C2P | 0.0823 |
| C3P | 0.0856 |

Table 5.18.1 Smart24 RMS Noise meters/second

**Test Results: Figures 5.18.1 and Table 5.18.1 indicate that the Smart24 has less than 0.0856 nm/s RMS noise when corrected for the GS13 seismometer response shown in Section 5.20.**

**BLDR Test Description: Compute Bandwidth Limited Dynamic Range using data from SSN Test.**

| Sensor Type | Channel | RMS Noise (nm/s) 0.5 to 16 Hz | RMS Full-Scale Voltage (V) | RMS Full-Scale Velocity (m/s) | BLDR (dB) |
|---|---|---|---|---|---|
| Geotech GS13 Generic | C1P | 0.0817 | 0.441 | 2.104e-4 | 128.2 |
| Geotech GS13 Generic | C2P | 0.0823 | 0.441 | 2.104e-4 | 128.2 |
| Geotech GS13 Generic | C3P | 0.0856 | 0.441 | 2.104e-4 | 127.8 |

Table 5.18.2 Smart24 RMS Noise nanometers/second

**Test Results: Table 5.18.2 indicates that the Smart24 Maximum Bandwidth Limited Range is greater than 127.8 dB when corrected for the generic GS13 seismometer shown in Section 5.20.**

## 5.19 SMART24 Test Data Sheet: 20 Vpp ADC Test – Seismic System Noise

**SMART24BH S/N: s1736** **Firmware Revision: 1.42**
**Authentication: Enabled** **Firmware gain: 1x**
**CH 1-3: Single Three Channel 20 Vpp ADC Board - S/N 1964**
**SMART24BH Sample Rate: 40sps**
**Seismometer Application (CH 1-3): Guralp CMG3T 1200 V/m/s @ 1 Hz**
**************************************************************************************************

**SSN Test Description: Determine ability of the Smart24 to resolve the expected seismic background using a Guralp CMG3T velocity seismometer. Results are referenced relative to CMG3T noise model, NVAR seismic background model and NLNM.**

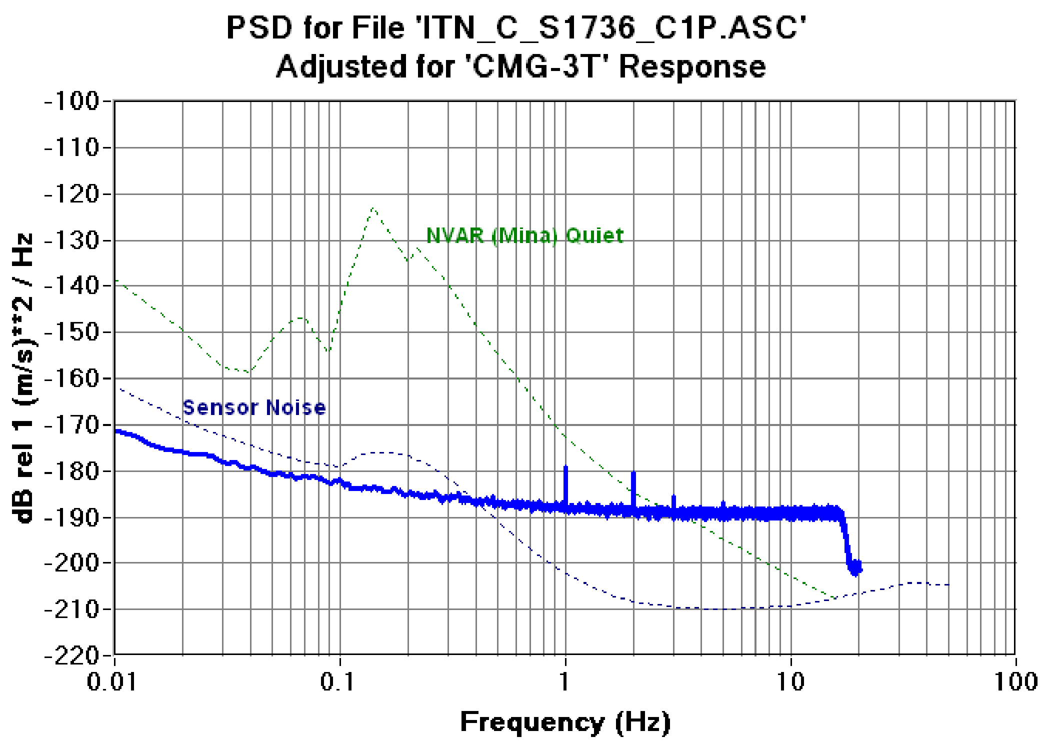


Figure 5.19.1 SMART24 SSN relative to a Guralp CMG3T seismometer, CMG3T noise model and NVAR seismic noise model for reference.

**Test Results: Figure 5.19.1 indicates that the noise of the individual channels were at or below the NVAR noise model between 0.01 and 2.7 Hz when used with a Guralp CMG3T seismometer. The Smart24BH channels were ~26 db below the NVAR noise model at 0.02 Hz, 38 db below at 0.1 Hz, 15 db below at 1 Hz and 14 dB above at 10Hz. The digitizer noise is below sensor noise from 0.01 to 0.4 Hz and will dominate the system noise above 0.4 Hz**

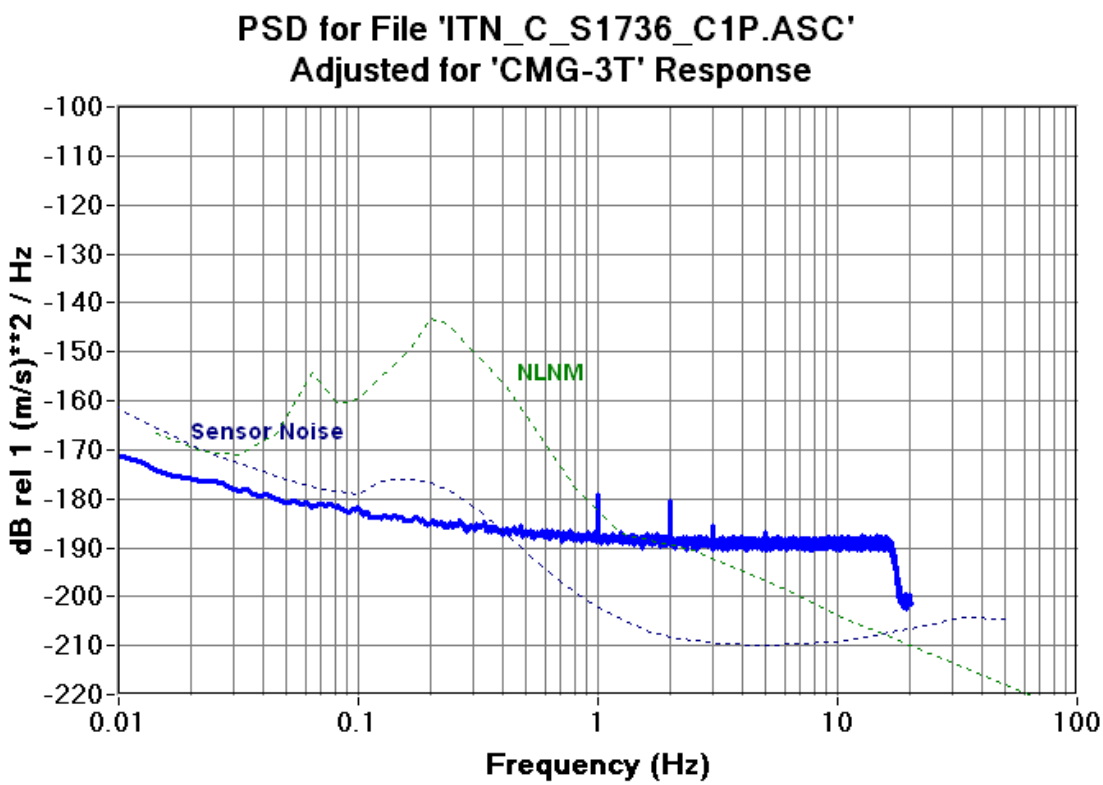


Figure 5.19.2 SMART24 SSN relative to a Guralp CMG3T seismometer, CMG3T noise model and NLNM for reference.

**Test Results: Figure 5.19.2 indicates that the noise of the individual channels were at or below the NLNM between 0.01 and 1.4 Hz when used with a Guralp CMG3T seismometer. The Smart24BH channels were ~6 db below the NLNM noise model at 0.02 Hz, ~22 db below at 0.1 Hz, ~6 db below at 1 Hz and 16 dB above at 10Hz. The digitizer noise is below sensor noise from 0.01 to 0.4 Hz and will dominate the system noise above 0.4 Hz**

| Channel | RMS Noise (nm/s) 0.02 to 16 Hz |
|---|---|
| C1P | 1.48 |
| C2P | 1.47 |
| C3P | 1.41 |

Table 5.19.1 Smart24 RMS Noise nanometers/second

**Test Results: Figure 5.19.1 and Table 5.19.1 indicate that the Smart24 has less than 1.48 nm/s RMS noise when corrected for the Guralp CMG 3T seismometer response shown in Section 6.3.**

**BLDR Test Description: Compute Bandwidth Limited Dynamic Range using data from SSN Test.**

| Sensor Type | Channel | RMS Noise (nm/s) 0.02 to 16 Hz | RMS Full-Scale Voltage (V) | RMS Full-Scale Velocity (m/s) | BLDR (dB) |
|---|---|---|---|---|---|
| Guralp CMG 3T | C1P | 1.48 | 7.071 | 5.893E-03 | 132.0 |
| Guralp CMG 3T | C2P | 1.47 | 7.071 | 5.893E-03 | 132.0 |
| Guralp CMG 3T | C3P | 1.41 | 7.071 | 5.893E-03 | 132.0 |

Table 5.19.2 Smart24 RMS Noise meters/second

**Test Results: Table 5.19.2 indicates that the Smart24 Maximum Bandwidth Limited Range is approximately 132 dB when corrected for the Guralp CMG 3T seismometer shown in Section 5.21.**

## 5.20 Seismometer Test Data Sheet: GS13 Seismometer Response

**Geotech GS13 Generic: 2100 v/m/s**
**Application Bandwidth: 0.5 to 16 Hz for 40 SPS Broadband Application**
****************************************************************************************************

**Test Description: Define Geotech GS13 Generic Seismometer Velocity Response.**

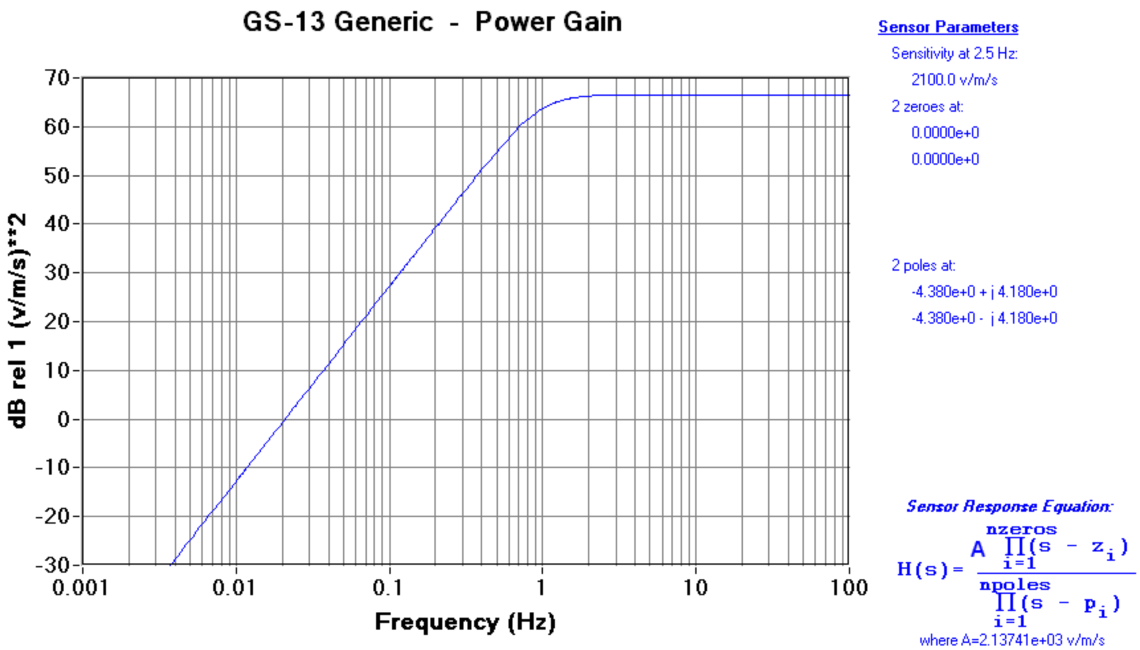


Figure 5.20.1 GS13 Generic Gain Plot

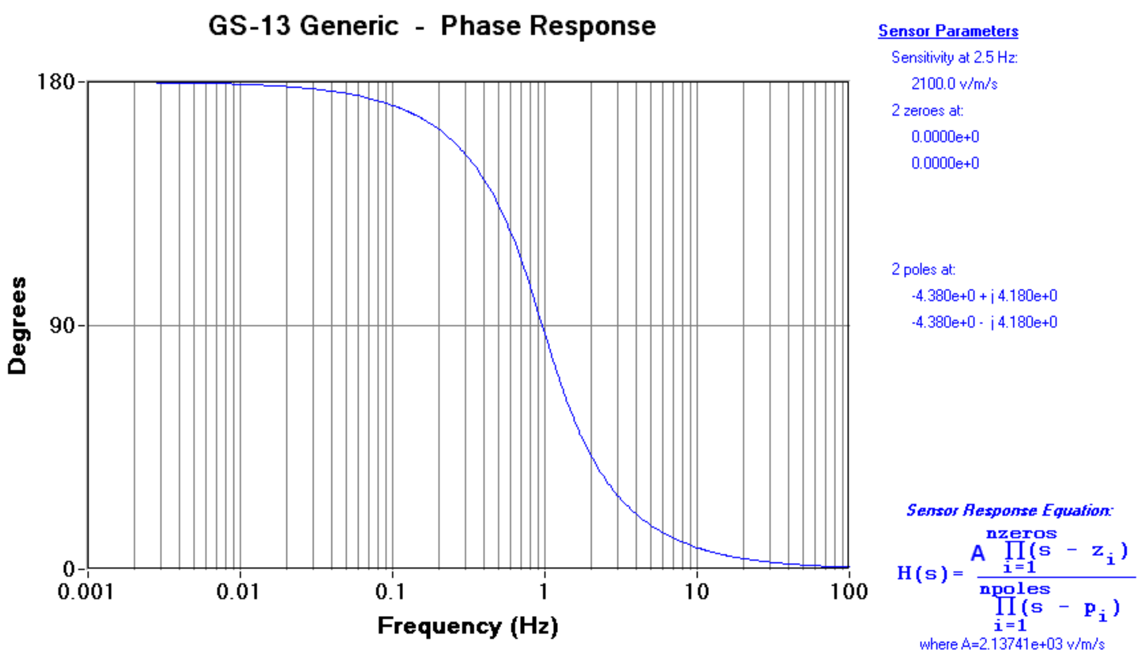


Figure 5.20.2 GS13 Generic Phase Plot

## 5.21 Seismometer Test Data Sheet: CMG3T Seismometer Response

**Guralp CMG3T: 1200 v/m/s**
**Application Bandwidth: 0.02 to 16 Hz for 40 SPS Broadband Application**
**********

**Test Description: Define Guralp CMG3T Seismometer Velocity Response.**

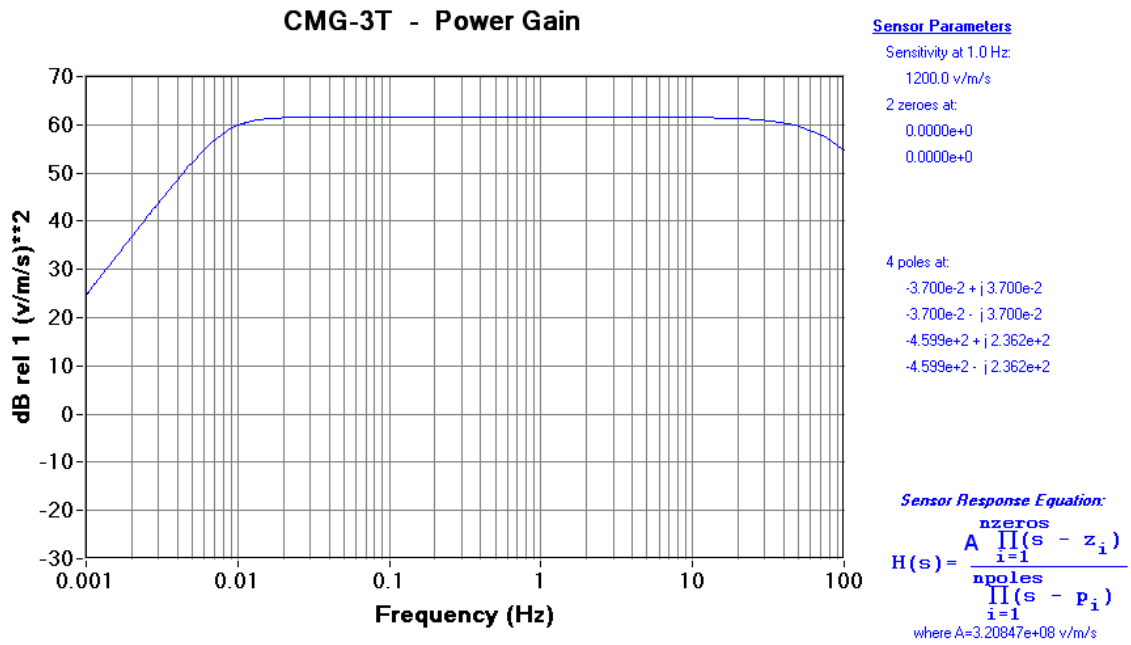


Figure 5.21.1 CMG3T Amplitude Plot

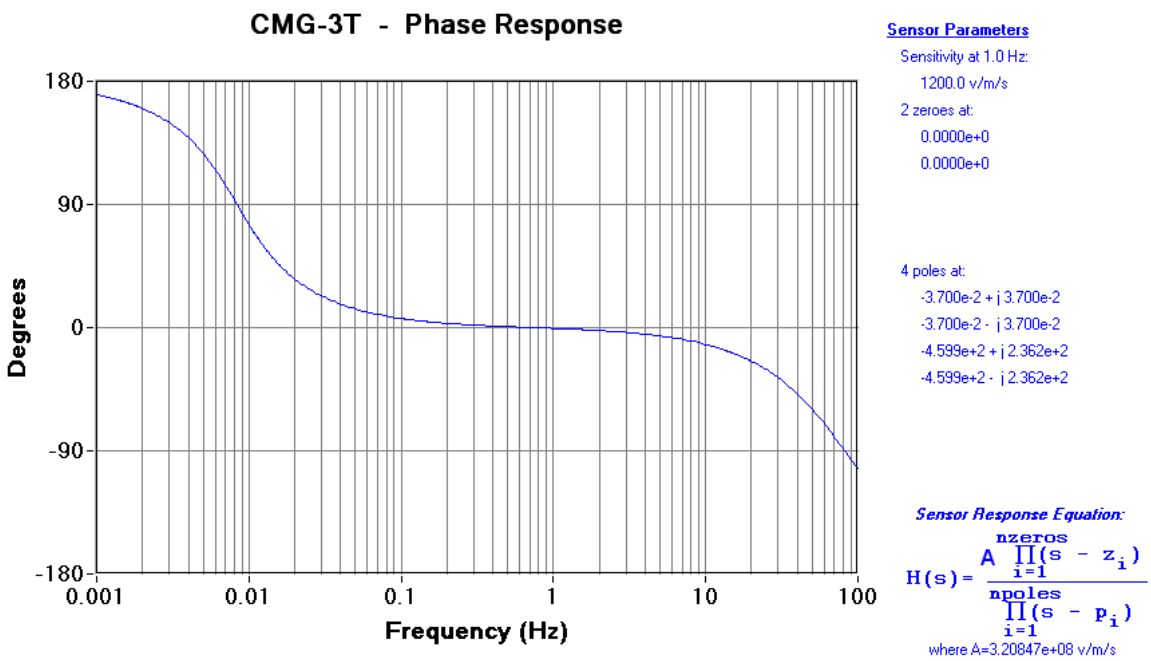


Figure 5.21.2 CMG3T Phase Plot

# 6 References


1. IEEE Standard for Digitizing Waveform Recorders, IEEE Std. 1057-1994.

2. IEEE Standard for Analog to Digital Converters, IEEE Std. 1241-2001.

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

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