PROGRESS REPORT

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Ground-based Monitoring R and E Technology Report

Evaluation of the Refraction Technology RT130HR Remote Seismic System For IRIS/GSN

RT130HR/GainX1 Configuration

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Abstract

Sandia National Laboratories has tested and evaluated the RefTek RT130HR remote seismic system for IRIS/GSN applications. The test results included in this report were for response to static and dynamic input signals, data time-tag accuracy, and seismic application performance. 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 seismic application evaluation and for supplementary criteria not addressed in the IEEE standards. When appropriate, test instrumentation calibration is traceable to the National Institute for Standards Technology (NIST).

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1 Executive Summary

Objectives:
The objectives of this work were (1) to evaluate the overall technical performance of the RefTek RT130HR 6-channel remote seismic system and measure the distortions introduced by the high-resolution digitizers and (2) evaluate the technical performance of the RT130HR for IRIS GSN STS-1, KS54000, STS-2, and CMG-3TB seismic applications. The result of this evaluation can be compared to relevant IRIS application requirements or specifications.

Description:
The RT130HR remote seismic system was built by RefTek, Dallas, TX, and was configured for 6-channel operation. RT130HR/A (Channels 1-3) are low noise, standard resolution (24-bit) and RT130HR/B (Channels 4-6) are standard resolution (24-bit). For these tests the RT130HR was configured to acquire 6 channels of data in combinations of simultaneous acquisition streams at 200, 100, 40, 20, 1 and 0.1 samples per second. RefTek provided RTConfig configuration/control software for the RT130HR digitizer. It operated on a Palm handheld and communicated with the RT130HR through a serial connection. Data were acquired from a removable 2Meg SD memory card in RT Format 32-bit uncompressed flat-file records. The RT130HR tested was set to the preamplifier gain of X1 (0dB). Testing was performed in a seismic vault for temperature stability.

1.1 RT130HR- 200SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.4% for nominal and full-scale. DC offset was less than 65 microVolts. The Input Terminated Noise was less than 5.5 µV RMS for a bandwidth of 0.1 to 100 Hz. The Maximum Potential Dynamic Range was better than 128.2 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 82.3 Hz with a relative attenuation of –126 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 16.6 microseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low-Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

1.2 RT130HR- 100SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.5% for nominal and full-scale. DC offset was less than 65 microVolts. The Input Terminated Noise was less than 4.05 µV RMS for a bandwidth of 0.1 to 50 Hz. The Maximum Potential Dynamic Range was better than 130.8 dB

RT130HR/B DC accuracy errors were within 1.7% for nominal and full-scale. DC offset was less than 350 microVolts. The Input Terminated Noise was less than 5.63 µV RMS for a bandwidth of 0.1 to 50 Hz. The Maximum Potential Dynamic Range was better than 128.0dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 43.07 Hz with a relative attenuation of –96 dB at the Nyquist.

RT130HR/B Bandwidth measured –3 dB at 43.07 Hz with a relative attenuation of –96 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 5.15 microsecond.

<u>Seismic Application Performance:</u>
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 13.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

1.3 RT130HR- 40SPS Digitizer Evaluation Summary:

<u>Static Performance:</u>
RT130HR/A DC accuracy errors were within 1.3% for nominal and full-scale. DC offset was less than 110 microVolts. The Input Terminated Noise was less than 2.68 µV RMS for a bandwidth of 0.01 to 20 Hz. The Maximum Potential Dynamic Range was better than 134.4 dB. The RT130HR/A/B did not hard clip properly at an inputs of > +/- 21 Volts (see Observations/Conclusions 1.7).

RT130HR/B DC accuracy errors were within 1.5% for nominal and full-scale. DC offset was less than 350 microVolts. The Input Terminated Noise was less than 3.7 µV RMS for a bandwidth of 0.01 to 20 Hz. The Maximum Potential Dynamic Range was better than 131.7 dB.

<u>Tonal Dynamic Performance:</u>
The RT130HR/A Total Harmonic Distortion (THD) was better than –120.4 dB. Crosstalk between channels was better than –150 dB. CMR is better than -89 dB at 1 Hz. Common Mode Voltage up to +/- 1 Volt was tolerated by the RT130HR/A. Common Mode Voltages over +/-2 Volts resulted in unstable behavior (see Observations/Conclusions 1.7).

The RT130HR/B Total Harmonic Distortion (THD) was better than – 126.3 dB. Crosstalk between channels was better than –150 dB.

<u>Broadband Dynamic Performance:</u>
RT130HR/A Bandwidth measured –3 dB at 17.17 Hz with a relative attenuation of –110 dB at the Nyquist. RTF indicated channel to channel timing is better than 0.14 microseconds. Timing between the RT130HR/A and RT130HR/B was better than 0.07 microseconds.

RT130HR/B Bandwidth measured –3 dB at 17.17 Hz with a relative attenuation of –110 dB at the Nyquist. RTF indicated channel to channel timing is better than 0.4 microseconds.

<u>Timing Performance:</u>
The RT130HR/A time-tagged the data to better than 2.17 microseconds.

The RT130HR/B time-tagged the data to better than 2.01 microseconds.

<u>Seismic Application Performance:</u>
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 16.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

1.4 RT130HR- 20SPS Digitizer Evaluation Summary:

<u>Static Performance:</u>

RT130HR/A DC accuracy errors were within 1.4% for nominal and full-scale. DC offset was less than 120 microVolts. The Input Terminated Noise was less than 2.02 µV RMS for a bandwidth of 0.01 to 10 Hz. The Maximum Potential Dynamic Range was better than 136.9 dB.

Tonal Dynamic Performance:
The RT130HR/A Total Harmonic Distortion (THD) was better than –120.3 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 8.61 Hz with a relative attenuation of –95 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 2.13 microseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 10.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 10.0 Hz when used with a Guralp CMG-3TB seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 3.0 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 2.0 Hz when used with a Geotech KS54000 seismometer.

1.5 RT130HR- 1SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.5% for nominal and full-scale. DC offset was less than 110 microVolts. The Input Terminated Noise was less than 1.11 µV RMS for a bandwidth of 0.001 to 0.5 Hz. The Maximum Potential Dynamic Range was better than 142.1 dB.

RT130HR/B DC accuracy errors were within 1.7% for nominal and full-scale. DC offset was less than 350 microVolts. The Input Terminated Noise was less than 1.33 µV RMS for a bandwidth of 0.001 to 0.5 Hz. The Maximum Potential Dynamic Range was better than 140.5 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 0.43 Hz with a relative attenuation of –100 dB at the Nyquist.

RT130HR/B Bandwidth measured –3 dB at 0.43 Hz with a relative attenuation of –100 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 914 microseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Geotech KS54000 seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.004 and 0.5 Hz when used with a Geotech KS54000 seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Guralp CMG-3TB seismometer.

1.6 RT130HR- 0.1SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.5% for nominal. DC offset was less than 40 microVolts. The Input Terminated Noise was less than 1.03 µV RMS for a bandwidth of 0.0001 to 0.05 Hz. The Maximum Potential Dynamic Range was better than 142.8 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 0.0431 Hz with a relative attenuation of –75 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 4.2 milliseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.0001 and 0.05 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.0001 and 0.05 Hz when used with a Geotech KS54000 seismometer.

1.7 Observations/Conclusion:

The RT130HR exhibited instability at hard clip levels. As the input signal level exceeded the rated full scale, it was expected that the peaks of the sinusoid would flatten. Instead the positive peaks changed sign to minus full scale and the negative peaks changed sign to positive full scale.

RT130HR Common Mode Rejection was predictable up to +/- 1 Volt. Voltages exceeding approx +/- 1.5 volts resulted in unstable behavior.

2 Introduction

2.1 Scope

This Evaluation Report defines the process that was performed as part of the evaluation and testing of the Refraction Technology (RefTek) RT130HR Digitizing Waveform Recorder (DWR) as a remote seismic system for IRIS GSN application.

A digitizing waveform recorder can consist of a single channel element or multi-channel elements of geophysical digitizers/data acquisition systems. The DWR converts analog signals from the interfaced geophysical sensor(s) to a digital representation of this analog signal without introducing unacceptable distortions. It contains one or more High-Resolution Digitizers (HRD) to convert the analog signals to digital form. The digital samples are either stored on local recording media and/or sent to a central collection point for storage and/or analysis.

2.2 Objectives

The objectives of this work were (1) to evaluate the overall technical performance of the RefTek RT130HR 6-channel remote seismic system and measure the distortions introduced by the high-resolution digitizers and (2) evaluate the technical performance of the RT130HR for IRIS GSN STS-1, KS54000, STS-2, and CMG-3TB seismic applications. The result of this evaluation can be compared to relevant IRIS application requirements or specifications.

3 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 for Digitizing Waveform Recorders [Reference 1] 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 Test/Evaluation Process

3.3.1 RT130HR Testing

Testing of the RT130HR was performed from November through May, 2006, at the Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT Site) and Albuquerque Seismic Labs (ASL) , Albuquerque, NM.

3.3.2 RT130HR General Digitizer Performance Tests

The following tests were conducted on the RT130HR. A detailed Test Plan Matrix is provided in the Test Data Sheet, Appendix I, Section 6.1. This is based on the basic set of tests as outlined in the Sandia Ground-based Monitoring R and E Technology Report: *Test Plan for the Evaluation of Digitizing Waveform Recorder Subsystems for Ground-based Geophysical Monitoring* [Reference 3].

Static Performance Tests

- DC Accuracy Nominal (DCA)
- DC Accuracy Full-Scale (DCFS)
- AC Clip (ACC)
- Input Terminated Noise (ITN)

Maximum Potential Dynamic Range (MPDR)
Tonal Dynamic Performance Tests
Total Harmonic Distortion (THD)
Crosstalk (CTK)
Common Mode Rejection ratio (CMR)
Broadband Dynamic Performance Tests
Modified Noise Power Ratio (MNPR)
Relative Transfer Function (RTF)
Analog Bandwidth (ABW)
Timing Tests
Time-Tag Accuracy (TTA)
Seismic Application Tests
Seismic System Noise (SSN)

3.4 Test Configuration and System Specifications

3.4.1 RT130HR Digitizer Description and Test Configuration

The RT130HR remote seismic system was built by RefTek, Dallas, TX, and was configured for 6-channel operation. RT130HR/A (Channels 1-3) are low noise, standard resolution (24-bit) and RT130HR/B (Channels 4-6) are standard resolution (24-bit). For these tests the RT130HR was configured to acquire 6 channels of data in combinations of simultaneous acquisition streams at 200, 100, 40, 20, 1 and 0.1 samples per second. RefTek provided RTConfig configuration/control software for the RT130HR digitizer. It operated on a Palm handheld and communicated with the RT130HR through a serial connection. Data were acquired from a removable 2Meg SD memory card in RT Format 32-bit uncompressed flat-file records. The RT130HR tested was set to the preamplifier gain of X1 (0dB). Testing was performed in a seismic vault for temperature stability (Figure 3.4.1). The RT130HR description is shown on Test Data Sheet, Appendix I, Section 6.2.

Figure 3.4.1 RT130HR Testing in ASL Tunnel

3.4.2 RT130HR IRIS GSN Seismometer Application Parameters and Response
The IRIS GSN STS1, KS54000, STS2, and CMG-3TB responses are indicated in the Test Data Sheet, Appendix I, Section 6.3. The RT130HR gain configuration characteristics are shown on Test Data Sheet, Appendix I, Section 6.4.

4 RT130HR – Gain X1 Tests

4.1 Static Performance Tests
Static tests provide a constant or non time-varying stimulus to the DWR under test. The purpose of these tests is to determine specific parameters such as: gain (accuracy at nominal and full-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 Nominal (DCA)
Purpose: The purpose of the DC accuracy test was to determine and verify the accuracy of the RT130HR. The bit-weight (LSB) of a non-gain-ranged digitizer is its resolution.

Configuration: The RT130HR inputs were connected to a +/- DC voltage source set to +/- 1 volt.

Evaluation: The DC gain (accuracy) of the RT130HR, DC offset, bit-weight (LSB)/resolution and counts/volt were measured.

Test Results are shown on the DCA/DCFS Test Data Sheet, Appendix I, Section 6.5.

4.1.2 DC Accuracy Full-Scale (DCFS)
Purpose: The purpose of the DC full-scale test was to determine and verify the accuracy of the RT130HR at full-scale. The full-scale value was used in computing Maximum Potential Dynamic Range (MPDR).

Configuration: The RT130HR inputs were connected to a +/- DC voltage source set to +/- 20 volts.

Evaluation: The DC gain (accuracy) of the RT130HR, DC offset, bit-weight (LSB)/resolution and counts/volt at full-scale were measured.

Test Results are shown on the DCA/DCFS Test Data Sheet, Appendix I, Section 6.5.

4.1.3 AC Clip (ACC)
Purpose: The purpose of the AC clip test was to determine and verify the maximum signal or clip level of the RT130HR digitizers.

Configuration: The digitizer inputs were connected to an AC voltage source set to 1 Hz. The amplitude of the sinusoid was increased until the value of hard clip was reached.

Evaluation: The AC clip voltage was measured.

Test Results are shown on the ACC Test Data Sheet, Appendix I, Section 6.6.

4.1.4 Input Terminated Noise (ITN)
Purpose: The purpose of the input-terminated noise test was to determine and verify the static parameters of the RT130HR digitizers. These static parameters were dominated primarily by the random noise generated within the digitizer and from other components within the digitizer package.

Configuration: The RT130HR digitizer inputs were terminated with 100 ohms. This value approximates the output impedance of the GSN application seismometers.

Evaluation: A power density spectrum (PDS) of the input-terminated noise provided a measure of the noise floor of the digitizer. RMS noise in the appropriate bandwidth, short-term and long-term stability, relationship to quantizing noise floor and correlated and uncorrelated spurious signals were measured.

Test Results are shown on the ITN/MPDR Test Data Sheet, Appendix I, Section 6.7.

4.1.5 Maximum Potential Dynamic Range (MPDR) Computation

Computing the RMS value of the full-scale sinusoid (20 Volts) and dividing by the RMS value of the Input Terminated Noise (ITN) test data determined the Maximum Potential Dynamic Range (MPDR) of the RT130HR digitizer. The appropriate bandwidth was used.

Test Results are shown on the ITN/MPDR Test Data Sheet, Appendix I, Section 6.7.

4.2 Tonal Dynamic Performance 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. Multitudes of tests are available to determine the DWR digitizer's self noise, deviation from ideal performance and conversion distortions.

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.

4.2.1 Total Harmonic Distortion (THD)

Purpose: The purpose of the total harmonic distortion test was to verify the linearity and to identify sources of non-linearities of the RT130HR digitizers.

Configuration: The digitizer inputs were connected to an ultra-low-distortion oscillator. The amplitude of the oscillator was set to approximately one-half full scale (21.0 V peak to peak) for the RT130HR. The oscillator was set to a frequency (1.4 Hz) unrelated to the sample rate and with at least nine harmonics observable.

Evaluation: A power density spectrum provided a measure of the non-linearity of the digitizers. THD was calculated by integrating the power density spectral peaks at the fundamental and all harmonics (up to nine) below the Nyquist frequency (one-half the sample rate).

Test Results are shown on the THD Test Data Sheet, Appendix I, Section 6.8.

4.2.2 Crosstalk (CTK)

Purpose: The purpose of the crosstalk test was to determine the extent of crosstalk between channels on the multi-channel RT130HR.

Configuration: The RT130HR channel under test was terminated with 50 ohms. All other RT130HR inputs were connected to a large amplitude (20 volt peak-to-peak) sinusoidal (1 Hz) test signal.

Evaluation: A power density spectrum provided a measure of crosstalk. The ratio of test signal to crosstalk signal was calculated using integrated power density spectra around the signal frequency.

Test Results are shown on the CTK/CMR Test Data Sheet, Appendix I, Section 6.9.

4.2.3 Common-Mode Rejection Ratio (CMR)

Purpose: The purpose of the common-mode rejection test was to determine the RT130's ability to reject a common-mode signal on differential inputs.

Configuration: The individual inputs of each channel of the RT130HR were connected to an isolated, large amplitude (5 Volts peak to peak), sinusoidal (1.1 Hz) test signal. The test generator common was connected to the signal reference on the RT130HR.

Evaluation: A power density spectrum provided a measure of the un-rejected common-mode signal. The ratio of test signal to common-mode signal is the common-mode rejection ratio.

Test Results are shown on the CTK/CMR Test Data Sheet, Appendix I, Section 6.9.

4.3 Broadband Dynamic Performance 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. Multitudes of tests are available to determine the DWR digitizer's self noise, deviation from ideal performance and conversion distortions. Broadband tests are dynamic tests that use Gaussian pseudo-random signal generators as stimuli.

4.3.1 Modified Noise Power Ratio (MNPR)

Purpose: The purpose of the modified noise-power-ratio test was to determine the RT130HR performance compared to n-bit ideal digitizers. This test determined the performance of the RT130HR at all amplitudes from small signal to clip level.

Configuration: The RT130HR inputs were connected to a bandwidth-limited Gaussian signal generator. The bandwidth of the signal generator was set to avoid aliasing the RT130HR and to maximize the power within the passband. The signal generator output was varied from a low level to the RT130HR clip level.

Evaluation: Coherence analysis computation provided a noise-power-ratio value for each level of input signal to the RT130HR. These estimated noise power ratios were compared to the performance model of n-bit ideal digitizers.

MNPR Tests were not performed due to instrumentation problems.

4.3.2 Relative Transfer Function (RTF)

Purpose: The purpose of the relative transfer function test was to determine the relative phase between channels in the multi-channel RT130HR.

Configuration: The RT130HR inputs were connected to a bandwidth-limited Gaussian signal generator. The signal generator output amplitude was set to greater than one-half the full-scale range of the RT130.

Evaluation: Coherence analysis computation provided a measure of relative phase. Channel skew was calculated.

Test Results are shown on the RTF/ABW Test Data Sheet, Appendix I, Section 6.10.

4.3.3 Analog Bandwidth (ABW)

Purpose: The purpose of the analog bandwidth test was to verify the bandwidth of the RT130HR digital FIR filter.

Configuration: The RT130HR inputs were connected to a bandwidth-limited Gaussian signal generator. The signal generator output amplitude was set to greater than one-half the full-scale range of the RT130HR.

Evaluation: A power density spectrum provided a measure of the RT130HR digitizer bandwidth. The 3 dB point and relative attenuation at the Nyquist of the digital FIR filters were measured.

Test Results are shown on the RTF/ABW Test Data Sheet, Appendix I, Section 6.10.

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. The following timing tests determine the accuracy of this time-tag.

4.4.1 Time Tag Accuracy (TTA)

Purpose: The purpose of the time tag accuracy test was to verify the ability of the RT130HR digitizer to accurately time-tag the data samples with respect to the digitizer inputs.

Configuration:
The digitizer inputs were connected to the One Pulse per Minute (PPM) and/or a One Pulse per Hour (PPH) output of an independent running GPS Timing Reference.

Evaluation: The time tags of the data from the digitizer were analyzed for correct time on the hour and/or minute transitions. RT130HR sample rate (samples per second/minute) was verified.

Test Results are shown on the TTA Test Data Sheet, Appendix I, Section 6.11

4.5 Seismic Application Tests

Seismic application tests are those that provide a stimulus to the DWR or interpret data from the DWR that is related to a specific seismic application. The DWR selected for an application should match the characteristics of the interfaced seismometer and the expected seismic 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 seismometer. A properly matched DWR/seismometer can resolve the expected seismic signals and backgrounds while nearly maximizing the system dynamic range.

4.5.1 Seismic System Noise (SSN)

Purpose: The purpose of the seismic system noise test was to determine ability of the RT130HR to resolve the expected seismic background using a specific seismometer. The RT130HR self-noise should be below the expected seismic background and the self-noise of the seismometer. The RT130HR was designed to interface to IRIS GSN STS1, KS54000, STS2, and CMG-3TB seismometers. For reference the seismic background is the USGS Low-Earth Noise Model (LNM).

Configuration: The power spectral density results of the Input Terminated Noise (ITN) test were used to determine the seismic system noise of the RT130HR.

Evaluation: The system noise of the RT130HR was converted to ground motion spectral units using the mathematical model for IRIS GSN STS1, KS54000, STS2, and CMG-3TB responses. The results of these conversions were overlaid with the USGS Low Earth Noise Model (LNM) to demonstrate the ability of the RT130HR to resolve a very quiet seismic background. Seismometer sensor noise models were included when available.

Test Results are shown on the SSN Test Data Sheet, Appendix I, Section 6.12.

5 Summary

Objectives:
The objectives of this work were (1) to evaluate the overall technical performance of the RefTek RT130HR 6-channel remote seismic system and measure the distortions introduced by the high-resolution digitizers and (2) evaluate the technical performance of the RT130HR for IRIS GSN STS-1, KS54000, STS-2, and CMG-3TB seismic applications. The result of this evaluation can be compared to relevant IRIS application requirements or specifications.

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The RT130HR remote seismic system was built by RefTek, Dallas, TX, and was configured for 6-channel operation. RT130HR/A (Channels 1-3) are low noise, standard resolution (24-bit) and RT130HR/B (Channels 4-6) are standard resolution (24-bit). For these tests the RT130HR was configured to acquire 6 channels of data in combinations of simultaneous acquisition streams at 200, 100, 40, 20, 1 and 0.1 samples per second. RefTek provided RTConfig configuration/control software for the RT130HR digitizer. It operated on a Palm handheld and communicated with the RT130HR through a serial connection. Data were acquired from a removable 2Meg SD memory card in RT Format 32-bit uncompressed flat-file records. The RT130HR tested was set to the preamplifier gain of X1 (0dB). Testing was performed in a seismic vault for temperature stability.

5.1 RT130HR- 200SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.4% for nominal and full-scale. DC offset was less than 65 microVolts. The Input Terminated Noise was less than 5.5 µV RMS for a bandwidth of 0.1 to 100 Hz. The Maximum Potential Dynamic Range was better than 128.2 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 82.3 Hz with a relative attenuation of –126 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 16.6 microseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low-Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

5.2 RT130HR- 100SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.5% for nominal and full-scale. DC offset was less than 65 microVolts. The Input Terminated Noise was less than 4.05 µV RMS for a bandwidth of 0.1 to 50 Hz. The Maximum Potential Dynamic Range was better than 130.8 dB

RT130HR/B DC accuracy errors were within 1.7% for nominal and full-scale. DC offset was less than 350 microVolts. The Input Terminated Noise was less than 5.63 µV RMS for a bandwidth of 0.1 to 50 Hz. The Maximum Potential Dynamic Range was better than 128.0dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 43.07 Hz with a relative attenuation of –96 dB at the Nyquist.

RT130HR/B Bandwidth measured –3 dB at 43.07 Hz with a relative attenuation of –96 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 5.15 microsecond.

<u>Seismic Application Performance:</u>
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 13.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

5.3 RT130HR- 40SPS Digitizer Evaluation Summary:

<u>Static Performance:</u>
RT130HR/A DC accuracy errors were within 1.3% for nominal and full-scale. DC offset was less than 110 microVolts. The Input Terminated Noise was less than 2.68 µV RMS for a bandwidth of 0.01 to 20 Hz. The Maximum Potential Dynamic Range was better than 134.4 dB. The RT130HR/A/B did not hard clip properly at an inputs of > +/- 21 Volts (see Observations/Conclusions 1.7).

RT130HR/B DC accuracy errors were within 1.5% for nominal and full-scale. DC offset was less than 350 microVolts. The Input Terminated Noise was less than 3.7 µV RMS for a bandwidth of 0.01 to 20 Hz. The Maximum Potential Dynamic Range was better than 131.7 dB.

<u>Tonal Dynamic Performance:</u>
The RT130HR/A Total Harmonic Distortion (THD) was better than –120.4 dB. Crosstalk between channels was better than –150 dB. CMR is better than -89 dB at 1 Hz. Common Mode Voltage up to +/- 1 Volt was tolerated by the RT130HR/A. Common Mode Voltages over +/-2 Volts resulted in unstable behavior (see Observations/Conclusions 1.7).

The RT130HR/B Total Harmonic Distortion (THD) was better than – 126.3 dB. Crosstalk between channels was better than –150 dB.

<u>Broadband Dynamic Performance:</u>
RT130HR/A Bandwidth measured –3 dB at 17.17 Hz with a relative attenuation of –110 dB at the Nyquist. RTF indicated channel to channel timing is better than 0.14 microseconds. Timing between the RT130HR/A and RT130HR/B was better than 0.07 microseconds.

RT130HR/B Bandwidth measured –3 dB at 17.17 Hz with a relative attenuation of –110 dB at the Nyquist. RTF indicated channel to channel timing is better than 0.4 microseconds.

<u>Timing Performance:</u>
The RT130HR/A time-tagged the data to better than 2.17 microseconds.

The RT130HR/B time-tagged the data to better than 2.01 microseconds.

<u>Seismic Application Performance:</u>
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 16.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

5.4 RT130HR- 20SPS Digitizer Evaluation Summary:

<u>Static Performance:</u>

RT130HR/A DC accuracy errors were within 1.4% for nominal and full-scale. DC offset was less than 120 microVolts. The Input Terminated Noise was less than 2.02 µV RMS for a bandwidth of 0.01 to 10 Hz. The Maximum Potential Dynamic Range was better than 136.9 dB.

Tonal Dynamic Performance:
The RT130HR/A Total Harmonic Distortion (THD) was better than –120.3 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 8.61 Hz with a relative attenuation of –95 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 2.13 microseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 10.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 10.0 Hz when used with a Guralp CMG-3TB seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 3.0 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 2.0 Hz when used with a Geotech KS54000 seismometer.

5.5 RT130HR- 1SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.5% for nominal and full-scale. DC offset was less than 110 microVolts. The Input Terminated Noise was less than 1.11 µV RMS for a bandwidth of 0.001 to 0.5 Hz. The Maximum Potential Dynamic Range was better than 142.1 dB.

RT130HR/B DC accuracy errors were within 1.7% for nominal and full-scale. DC offset was less than 350 microVolts. The Input Terminated Noise was less than 1.33 µV RMS for a bandwidth of 0.001 to 0.5 Hz. The Maximum Potential Dynamic Range was better than 140.5 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 0.43 Hz with a relative attenuation of –100 dB at the Nyquist.

RT130HR/B Bandwidth measured –3 dB at 0.43 Hz with a relative attenuation of –100 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 914 microseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Geotech KS54000 seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.004 and 0.5 Hz when used with a Geotech KS54000 seismometer.

RT130HR/B Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Guralp CMG-3TB seismometer.

5.6 RT130HR- 0.1SPS Digitizer Evaluation Summary:

Static Performance:
RT130HR/A DC accuracy errors were within 1.5% for nominal. DC offset was less than 40 microVolts. The Input Terminated Noise was less than 1.03 μV RMS for a bandwidth of 0.0001 to 0.05 Hz. The Maximum Potential Dynamic Range was better than 142.8 dB.

Broadband Dynamic Performance:
RT130HR/A Bandwidth measured –3 dB at 0.0431 Hz with a relative attenuation of –75 dB at the Nyquist.

Timing Performance:
The RT130HR/A time-tagged the data to better than 4.2 milliseconds.

Seismic Application Performance:
RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.0001 and 0.05 Hz when used with a Streckeisen STS-1 seismometer.

RT130HR/A Seismic Signal Noise (SSN) test indicated that the response corrected noises were at or below the USGS Low Earth Noise Model (LNM) between 0.0001 and 0.05 Hz when used with a Geotech KS54000 seismometer.

5.7 Observations/Conclusion:

The RT130HR exhibited instability at hard clip levels. As the input signal level exceeded the rated full scale, it was expected that the peaks of the sinusoid would flatten. Instead the positive peaks changed sign to minus full scale and the negative peaks changed sign to positive full scale.

RT130HR Common Mode Rejection was predictable up to +/- 1 Volt. Voltages exceeding approx +/- 1.5 volts resulted in unstable behavior.

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., McDonald, Timothy S., Townsend, Toby O., Ground-based Monitoring R and E Technology Report, 'Test Plan for the Evaluation of Digitizing Waveform Recorder Subsystems for Ground-based Geophysical Monitoring', 26 February 2002.

6 Appendix I: RT130HR Test Data Sheets

6.1 RT1330HR Test Data Sheet: RT130HR Test Plan Matrix

****

Test Description: Define RT130HR Test Plan.

200 SPS	RT130HR Group A (Ch 1-3), 0dB Gain		
Test Type	Channel 1 Stream 6	Channel 2 Stream 6	Channel 3 Stream 6
DCA	TEST	TEST	TEST
DCFS	TEST	TEST	TEST
ITN/MPDR	TEST	TEST	TEST
ABW	TEST	NA	NA
TTA	TEST	NA	NA
SSN	TEST	TEST	TEST

100 SPS	RT130HR Group A (Ch 1-3), 0dB Gain			RT130HR Group B (Ch 4-6), 0dB Gain		
Test Type	Channel 1 Stream 5	Channel 2 Stream 5	Channel 3 Stream 5	Channel 4 Stream 5	Channel 5 Stream 5	Channel 6 Stream 5
DCA	TEST	TEST	TEST	TEST	TEST	TEST
DCFS	TEST	TEST	TEST	TEST	TEST	TEST
ITN/MPDR	TEST	TEST	TEST	TEST	TEST	TEST
ABW	TEST	NA	NA	TEST	NA	NA
TTA	TEST	NA	NA	TEST	NA	NA
SSN	TEST	TEST	TEST	TEST	TEST	TEST

40 SPS	RT130HR Group A (Ch 1-3), 0dB Gain			RT130HR Group B (Ch 4-6), 0dB Gain		
Test Type	Channel 1 Stream 4	Channel 2 Stream 4	Channel 3 Stream 4	Channel 4 Stream 4	Channel 5 Stream 4	Channel 6 Stream 4
DCA	TEST	TEST	TEST	TEST	TEST	TEST
DCFS	TEST	TEST	TEST	TEST	TEST	TEST
ITN/MPDR	TEST	TEST	TEST	TEST	TEST	TEST
ACC	TEST	TEST	TEST	TEST	TEST	TEST
THD	TEST	TEST	TEST	TEST	TEST	TEST
RTF	TEST	TEST	TEST	TEST	TEST	TEST
ABW	TEST	NA	NA	TEST	NA	NA
TTA	TEST	NA	NA	TEST	NA	NA
SSN	TEST	TEST	TEST	TEST	TEST	TEST

20 SPS	RT130HR Group A (Ch 1-3), 0dB Gain		
Test Type	**Channel 1 Stream 3**	**Channel 2 Stream 3**	**Channel 3 Stream 3**
DCA	**TEST**	**TEST**	**TEST**
DCFS	**TEST**	**TEST**	**TEST**
ITN/MPDR	**TEST**	**TEST**	**TEST**
ACC	**TEST**	**TEST**	**TEST**
THD	**TEST**	**TEST**	**TEST**
CTK	**TEST**	**TEST**	**TEST**
CMR	**TEST**	**TEST**	**TEST**
ABW	**TEST**	NA	NA
TTA	**TEST**	NA	NA
SSN	**TEST**	**TEST**	**TEST**

1.0 SPS	RT130HR Group A (Ch 1-3), 0dB Gain			RT130HR Group B (Ch 4-6), 0dB Gain		
Test Type	**Channel 1 Stream 2**	**Channel 2 Stream 2**	**Channel 3 Stream 2**	**Channel 4 Stream 2**	**Channel 5 Stream 2**	**Channel 6 Stream 2**
DCA	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**
DCFS	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**
ITN/MPDR	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**
ABW	**TEST**	NA	NA	**TEST**	NA	NA
TTA	**TEST**	NA	NA	**TEST**	NA	NA
SSN	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**	**TEST**

0.1 SPS	RT130HR Group A (Ch 1-3), 0dB Gain		
Test Type	**Channel 1 Stream 1**	**Channel 2 Stream 1**	**Channel 3 Stream 1**
DCA	**TEST**	**TEST**	**TEST**
DCFS	**TEST**	**TEST**	**TEST**
ITN/MPDR	**TEST**	**TEST**	**TEST**
ABW	**TEST**	NA	NA
TTA	**TEST**	NA	NA
SSN	**TEST**	**TEST**	**TEST**

6.2 RT130HR Test Data Sheet: RT130HR Description

****

Test Description: Describe RT130HR under evaluation.

RT130 Serial Number: 9814
Circuit Boards:
Ref Tek 130 v2.7.0 (2005:266)
RT0569- S/N 0005 0 (LID)
RT0506G S/N 1895 1 (CPU)
RT0527B S/N 1171 1 (SCB)
RT0567_ S/N 0005 1 (ATD)
RT0505D S/N 1844 1 (ATD)
RT0576- S/N 0004 1 (AUX)
RT0506A1 C03 (11FA1063)
AD1 FPGA: RT0567_1 _06 (023710C0)
AD2 FPGA: RT0505A1 F02 (11F91046)

Linear Phase FIR 200/100/40/20/1/0.1 SPS

Input Impedance:
Ch1-6 24.5K ohms

6.3 RT130HR Test Data Sheet: GSN Seismometer Responses

****

6.3.1 Streckeisen STS1:

Test Description: Define STS1 Seismometer Response.

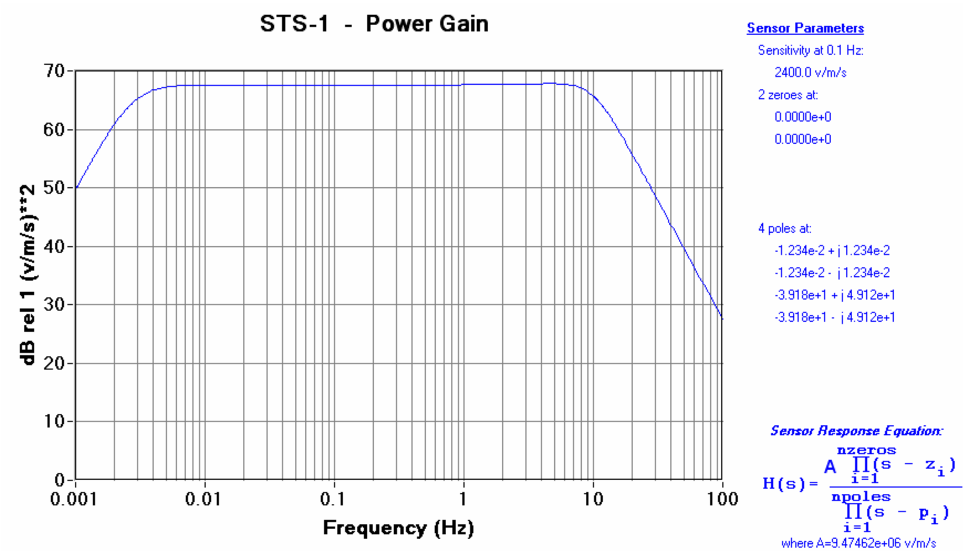

Figure 6.3.1 IRIS/GSN STS1 Gain Plot

6.3.2 Streckeisen STS2 High Gain:

Test Description: Define STS2 Seismometer Response.

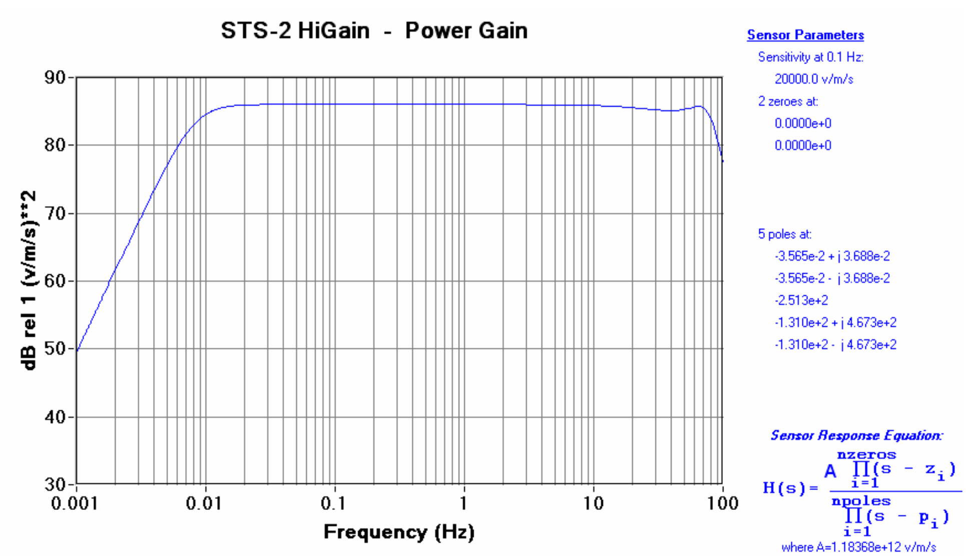

Figure 6.3.2 IRIS/GSN STS2 Gain Plot

6.3.3 Streckeisen STS2 Low Gain:

Test Description: Define STS-2 Seismometer Response.

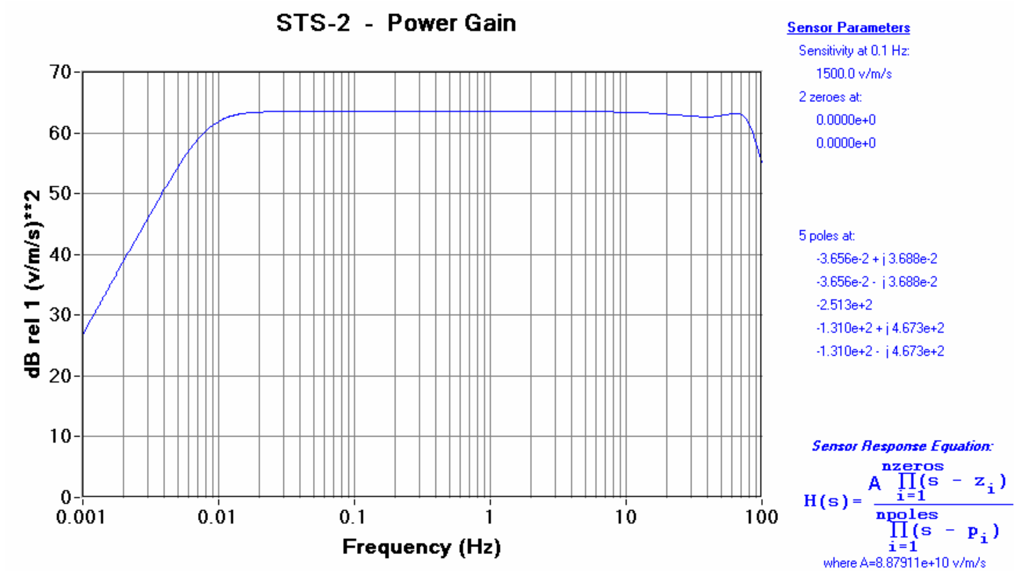

Figure 6.3.3 IRIS/GSN STS-2 Low Gain Plot

6.3.4 Guralp CMG-3TB High Gain:

Test Description: Define CMG-3TB Seismometer Response.

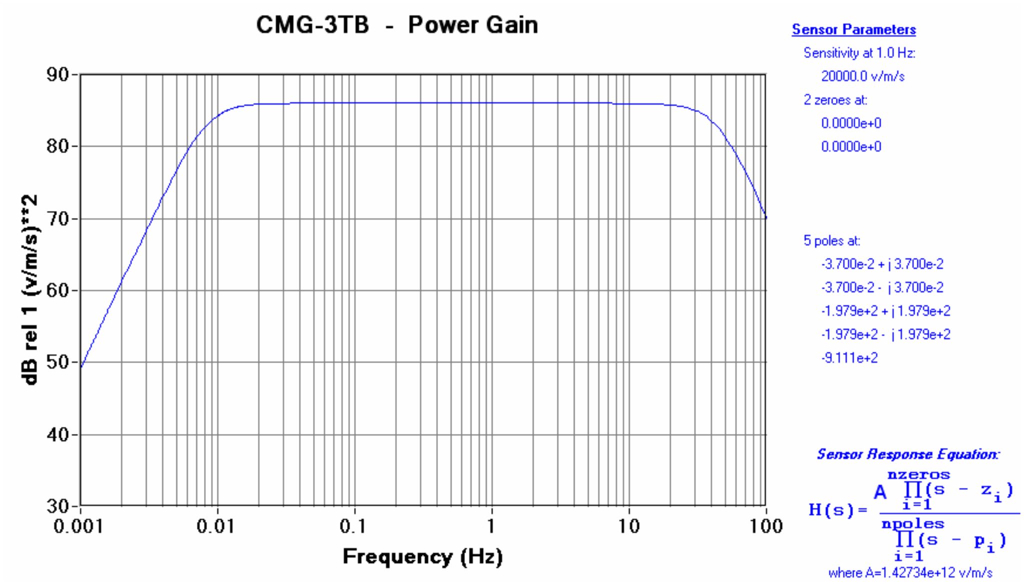

Figure 6.3.4 IRIS/GSN GMG-3TB Gain Plot

6.3.5 Geotech KS54000:

Test Description: Define KS54000 Seismometer Response.

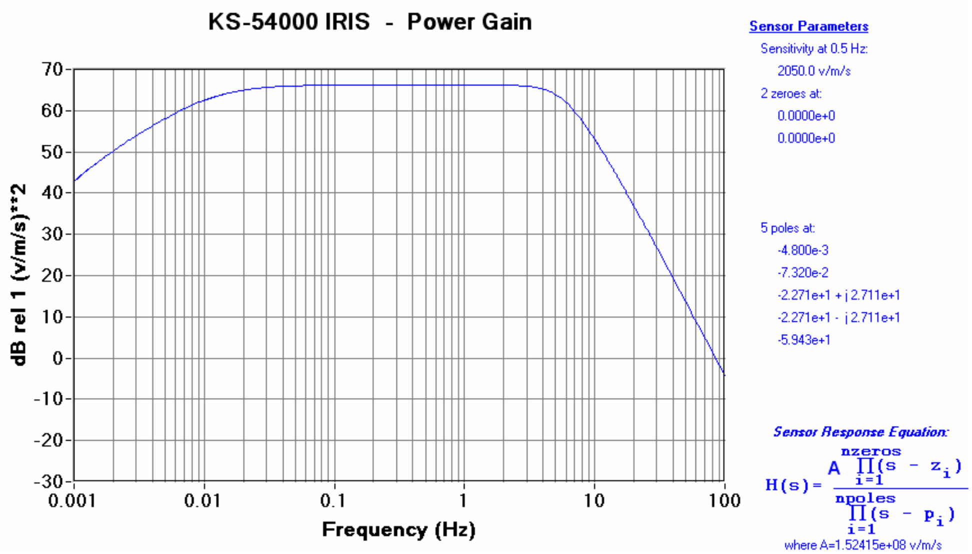

Figure 6.3.5 IRIS/GSN KS54000 Gain Plot

6.4 RT130HR Test Data Sheet: RT130HR Gain Configuration

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 200, 100, 40, 20, 1, 0.1 sps
****

Gain Configuration:

Volts/Count for preamplifier gain=1 (per RefTek) **2.75116 µV/count**

Manufacturer Specified Nominal Volts/Count.
Nominal Volts/Count: **2.75116×10^{-6}**
Nominal Counts/Volt: 363483
Nominal Full-Scale: (+7,269,660 to –7,269,660 counts full scale) +/-20.00 V
Maximum Data Range: 24 Bits (+/-8,388,608 counts) +/-23.08 V

6.5 RT130HR Test Data Sheet: Test – Static/DCA/DCFS

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 200, 100, 40, 20, 1, 0.1 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

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

DCA- Specified Nominal Volts/Count: $2.751x10^{-6}$
DCFS- Specified Full-Scale Volts: +/- 20.0V differential

6.5.1 RT130HR/A Sample Rate 200 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	1.000	358485	2.78951	-1.375	-17
2	1.000	358710	2.78776	-1.313	-31
3	1.000	358452	2.78977	-1.384	-20

Table 6.5.1a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	20.0	358464	2.78967	-1.381	-61
2	20.0	358654	2.78820	-1.328	-47
3	20.0	358418	2.79004	-1.393	-39

Table 6.5.1b DC Full-Scale Nominal Results

Test Results:
Tables 6.5.1a-b indicate that the RT130HR/A DC accuracy errors were within 1.4% for nominal and full-scale at 200 sps. DC offset was less than 65 microVolts.

6.5.2 RT130HR/A Sample Rate 100 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	1.000	358162	2.79203	-1.464	-17
2	1.000	358386	2.79028	-1.402	-34
3	1.000	358129	2.79229	-1.473	-22

Table 6.5.2a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	20.0	358142	2.79219	-1.469	-64
2	20.0	358331	2.79071	-1.417	-44
3	20.0	358095	2.79255	-1.482	-47

Table 6.5.2b DC Full-Scale Nominal Results

<u>Test Results:</u>
Tables 6.5.2a-b indicate that the RT130HR/A DC accuracy errors were within 1.5% for nominal and full-scale at 100 sps. DC offset was less than 65 microVolts.

6.5.3 RT130HR/B Sample Rate 100 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
4	1.000	357481	2.79735	-1.651	299
5	1.000	357891	2.79415	-1.538	310
6	1.000	357923	2.79389	-1.530	307

Table 6.5.3a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
4	20.0	357467	2.79746	-1.655	344
5	20.0	357760	2.79438	-1.547	343
6	20.0	357896	2.79411	-1.537	335

Table 6.5.3b DC Full-Scale Nominal Results

<u>Test Results:</u>
Tables 6.5.3a-b indicate that the RT130HR/B DC accuracy errors were within 1.7% for nominal and full-scale at 100 sps. DC offset was less than 350 microVolts.

6.5.4 RT130HR/A Sample Rate 40 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	1.000	358842	2.78674	-1.277	-17
2	1.000	359067	2.78499	-1.215	-33
3	1.000	358808	2.78700	-1.286	-22

Table 6.5.4a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	20.0	358824	2.78687	-1.282	-105
2	20.0	359010	2.78543	-1.230	-44
3	20.0	358777	2.78724	-1.295	-61

Table 6.5.4b DC Accuracy Full-Scale Results

<u>Test Results:</u>
Tables 6.5.4a-b indicate that the RT130HR/A DC accuracy errors were within 1.3% for nominal and full-scale at 40 sps. DC offset was less than 110 microVolts.

6.5.5 RT130HR/B Sample Rate 40 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
4	1.000	358159	2.79205	-1.465	299
5	1.000	358570	2.78885	-1.352	312
6	1.000	358602	2.78860	-1.343	310

Table 6.5.5a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
4	20.0	358150	2.79212	-1.467	349
5	20.0	358542	2.78907	-1.359	348
6	20.0	358579	2.78878	-1.349	348

Table 6.5.5b DC Accuracy Full-Scale Results

<u>Test Results:</u>
Tables 6.5.5a-b indicate that the RT130HR/B DC accuracy errors were within 1.5% for nominal and full-scale at 40 sps. DC offset was less than 350 microVolts.

6.5.6 RT130HR/A Sample Rate 20 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	1.000	358519	2.78925	-1.366	-17
2	1.000	358743	2.78751	-1.304	-34
3	1.000	358485	2.78951	-1.375	-22

Table 6.5.6a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	20.00	358501	2.78939	-1.370	-111
2	20.00	358687	2.78794	-1.319	-47
3	20.00	358453	2.78976	-1.384	-58

Table 6.5.6b DC Accuracy Full-Scale Results

Test Results:
Tables 6.5.6a-b indicate that the RT130HR/A DC accuracy errors were within 1.4% for nominal and full-scale at 20 sps. DC offset was less than 120 microVolts.

6.5.7 RT130HR/A Sample Rate 1 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	1.000	358229	2.79151	-1.445	-17
2	1.000	358453	2.78976	-1.384	-34
3	1.000	358195	2.79177	-1.455	-22

Table 6.5.7a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	20.0	358212	2.79164	-1.450	-103
2	20.0	358397	2.79020	-1.399	-44
3	20.0	358164	2.79201	-1.463	-55

Table 6.5.7b DC Full-Scale Nominal Results

Test Results:
Tables 6.5.7a-b indicate that the RT130HR/A DC accuracy errors were within 1.5% for nominal and full-scale at 1 sps. DC offset was less than 110 microVolts.

6.5.8 RT130HR/B Sample Rate 1 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
4	1.000	357547	2.79683	-1.633	299
5	1.000	357959	2.79363	-1.520	310
6	1.000	357990	2.79337	-1.511	310

Table 6.5.8a DC Accuracy Nominal Results

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
4	20.0	357538	2.79690	-1.635	346
5	20.0	357930	2.79384	-1.528	349
6	20.0	357966	2.79356	-1.518	349

Table 6.5.8b DC Full-Scale Nominal Results

Test Results:
Tables 6.5.8a-b indicate that the RT130HR/B DC accuracy errors were within 1.7% for nominal and full-scale at 1 sps. DC offset was less than 350 microVolts.

6.5.9 RT130HR/A Sample Rate 0.1 sps:

Channel	Test Input Volts	Counts/Volt	µVolts/Count	% Deviation from Nominal	DC Offset µV
1	1.000	358290	2.791	-1.43	-19.5
2	1.000	358514	2.789	-1.37	-36.3
3	1.000	358253	2.791	-1.44	-19.5

Table 6.5.9 DC Accuracy Nominal Results

Test Results:
Table 6.5.9 indicates that the RT130HR/A DC accuracy errors were within 1.5% for nominal at 0.1 sps. DC offset was less than 40 microVolts.

6.6 RT130HR Test Data Sheet: Test – Static/ACC

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 40, 20 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

ACC Test Description: Measure the actual clip voltage of the RT130HR digitizers using a sinusoidal signal.

6.6.1 RT130HR/A Sample Rate 40 sps:

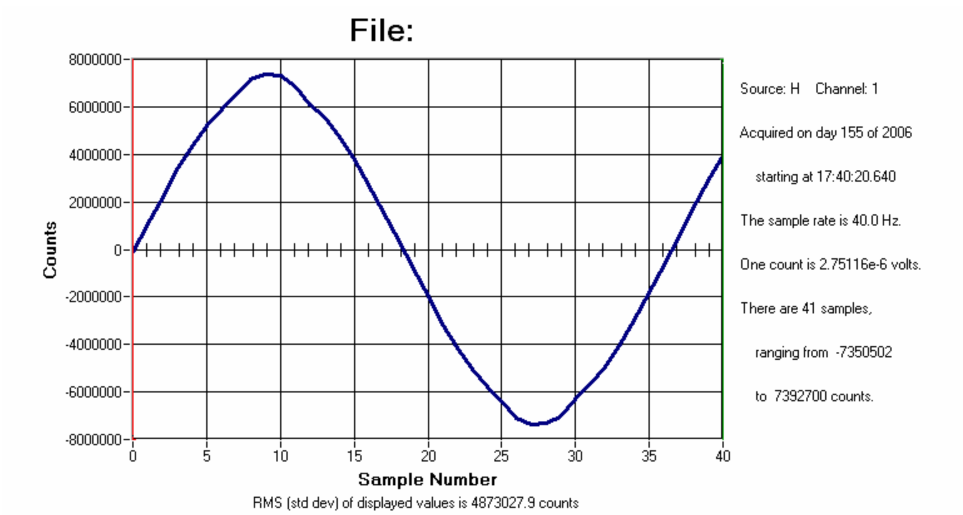

Figure 6.6.1a AC Clip Results (at Full-scale)

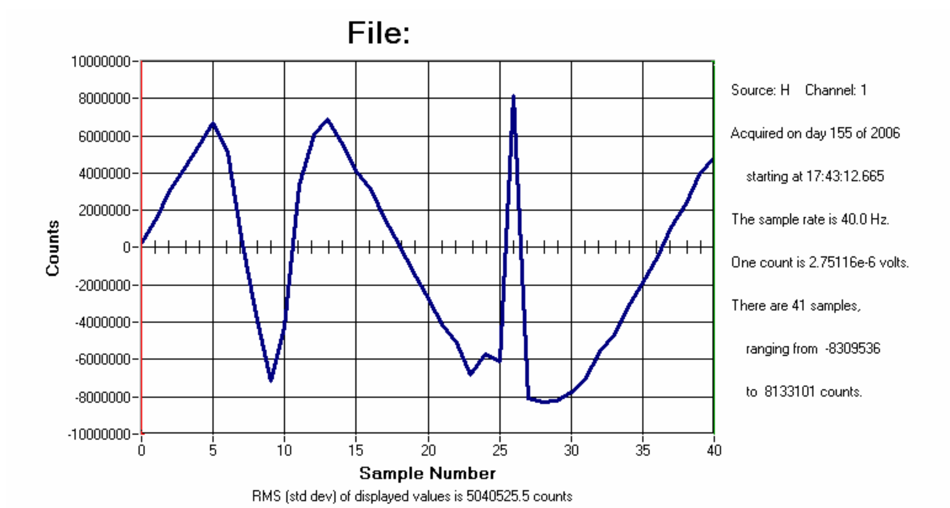

Figure 6.6.1b AC Clip Results (at Hard Clip)

Channel	Positive Clip Voltage	Negative Clip Voltage
1	NA	NA
2	NA	NA
3	NA	NA

Table 6.6.1 AC Clip Results

<u>Test Results:</u>
Figures 6.6.1a-b indicate that the RT130HR/A is unstable at hard clip.

6.6.2 RT130HR/B Sample Rate 40 sps:

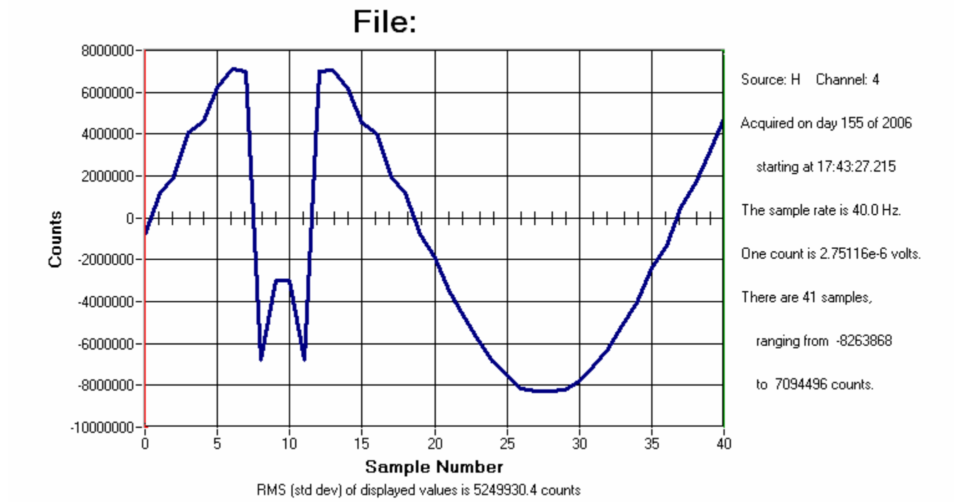

Figure 6.6.2 AC Clip Results (at Hard Clip)

Channel	Positive Clip Voltage	Negative Clip Voltage
4	NA	NA
5	NA	NA
6	NA	NA

Table 6.6.2 AC Clip Results

<u>Test Results:</u>
Figure 6.6.2 indicates that the RT130HR/B is unstable at hard clip.

6.6.3 RT130HR/A Sample Rate 20 sps:

Not Tested

6.6.4 RT130HR/B Sample Rate 20 sps:

Not Tested

6.7 RT130HR Test Data Sheet: Test – Static/ITN/MPDR

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 200, 100, 40, 20, 1, 0.1 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

ITN Test Description: Measure Input Terminated Noise. Calculate Maximum Potential Dynamic Range using data from ITN Test.

6.7.1 RT130HR/A Sample Rate 200 sps:

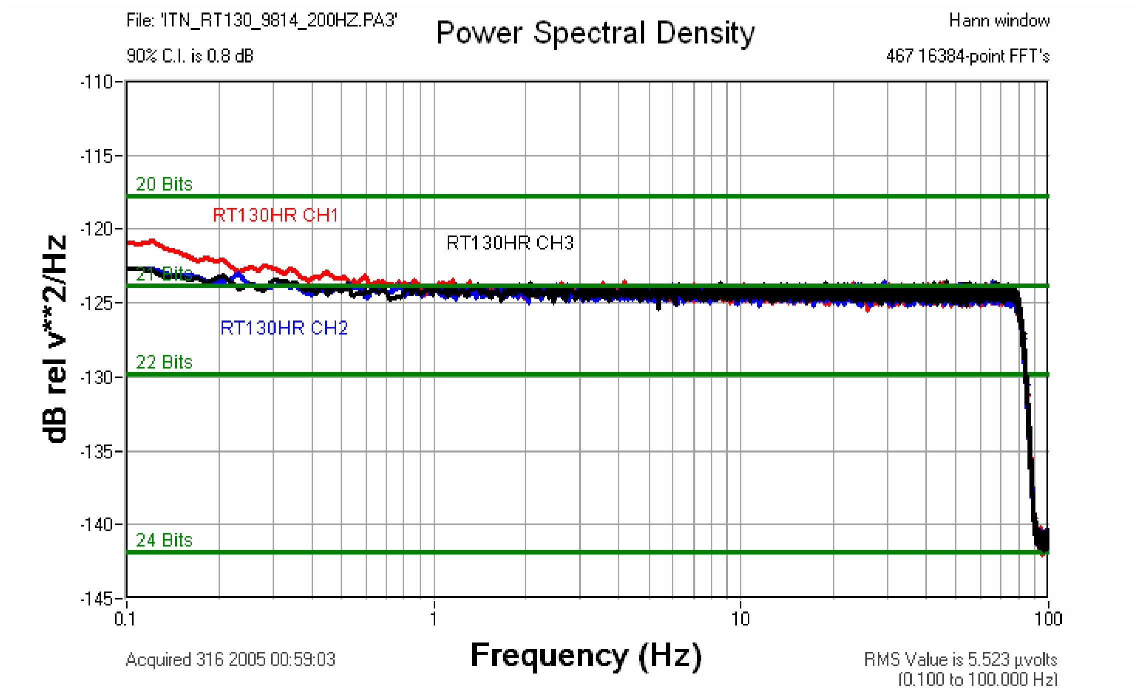

Figure 6.7.1 RT130HR 200SPS Channel 1-3 Input Terminated Noise

Channel	ITN RMS Noise μV 0.1 to 100 Hz	RMS Full-Scale Volts	MPDR (dB)
1	5.485	14.14	128.2
2	5.470	14.14	128.2
3	5.523	14.14	128.2

Table 6.7.1 RT130HR 200SPS MPDR

Test Results:
Figure 6.7.1 and Table 6.7.1 indicate that the RT130HR/A has < 5.5 μV RMS noise at 200 sps. MPDR is better than 128.2 dB.

6.7.2 RT130HR/A Sample Rate 100 sps:

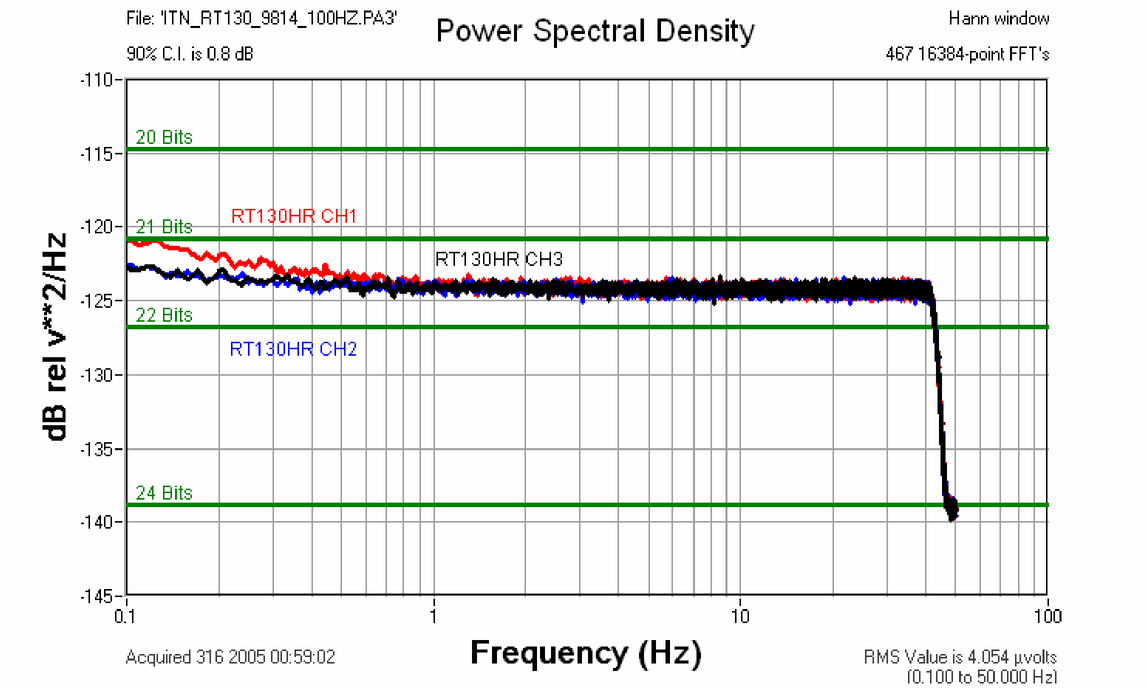

Figure 6.7.2 RT130HR 100SPS Channel 1-3 Input Terminated Noise

Channel	ITN RMS Noise μV 0.1 to 50 Hz	RMS Full-Scale Volts	MPDR (dB)
1	4.045	14.14	130.9
2	4.028	14.14	130.9
3	4.054	14.14	130.8

Table 6.7.2 RT130HR 100SPS MPDR

Test Results:

Figure 6.7.2 and Table 6.7.2 indicate that the RT130HR/A has < 4.05 μV RMS noise at 100 sps. MPDR is better than 130.8 dB.

6.7.3 RT130HR/B Sample Rate 100 sps:

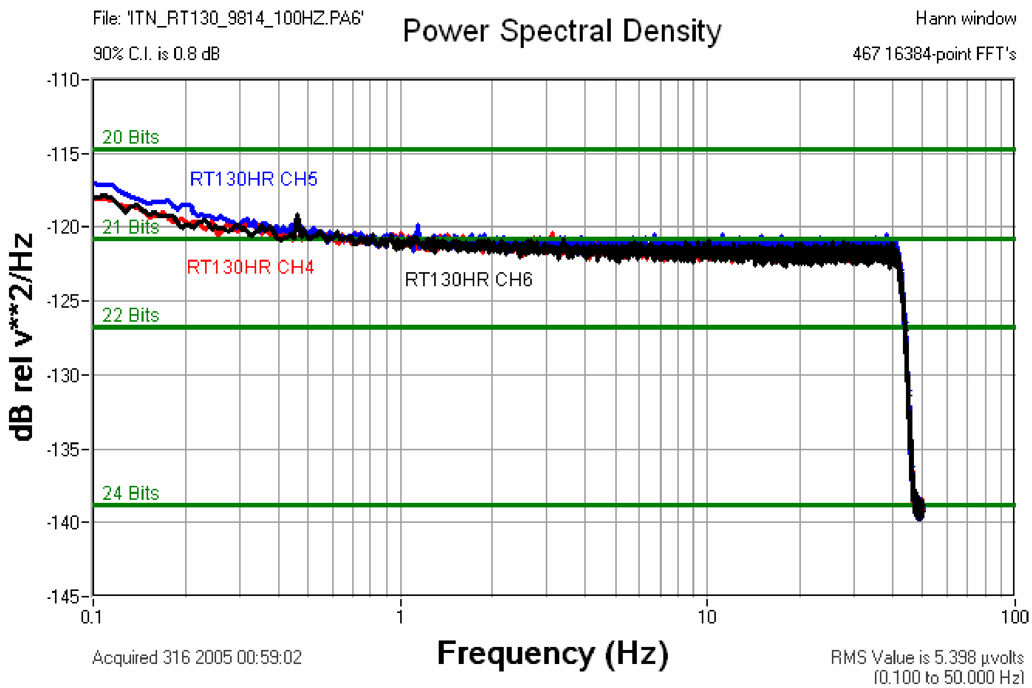

Figure 6.7.3 RT130HR 100SPS Channel 4-6 Input Terminated Noise

Channel	ITN RMS Noise µV 0.1 to 50 Hz	RMS Full-Scale Volts	MPDR (dB)
4	5.520	14.14	128.2
5	5.628	14.14	128.0
6	5.398	14.14	128.4

Table 6.7.3 RT130HR 100SPS MPDR

<u>Test Results:</u>
Figure 6.7.3 and Table 6.7.3 indicate that the RT130HR/B has < 5.63 µV RMS noise at 100 sps. MPDR is better than 128.0 dB.

6.7.4 RT130HR/A Sample Rate 40 sps:

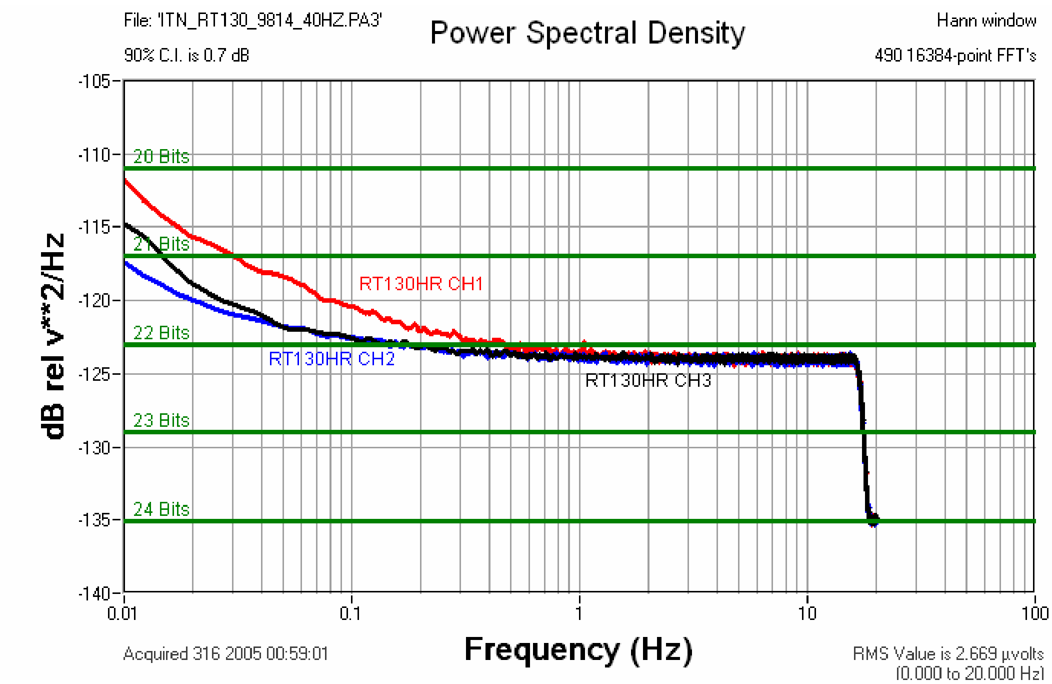

Figure 6.7.4 RT130HR 40SPS Channel 1-3 Input Terminated Noise

Channel	ITNRMS Noise µV 0.01 to 20 Hz	RMS Full-Scale Volts	MPDR (dB)
1	2.679	14.14	134.4
2	2.636	14.14	134.6
3	2.658	14.14	134.5

Table 6.7.4 RT130HR 40SPS MPDR

Test Results:
Figure 6.7.4 and Table 6.7.4 indicate that the RT130HR/A has < 2.68 µV RMS noise at 40 sps. MPDR is better than 134.4 dB.

6.7.5 RT130HR/B Sample Rate 40 sps:

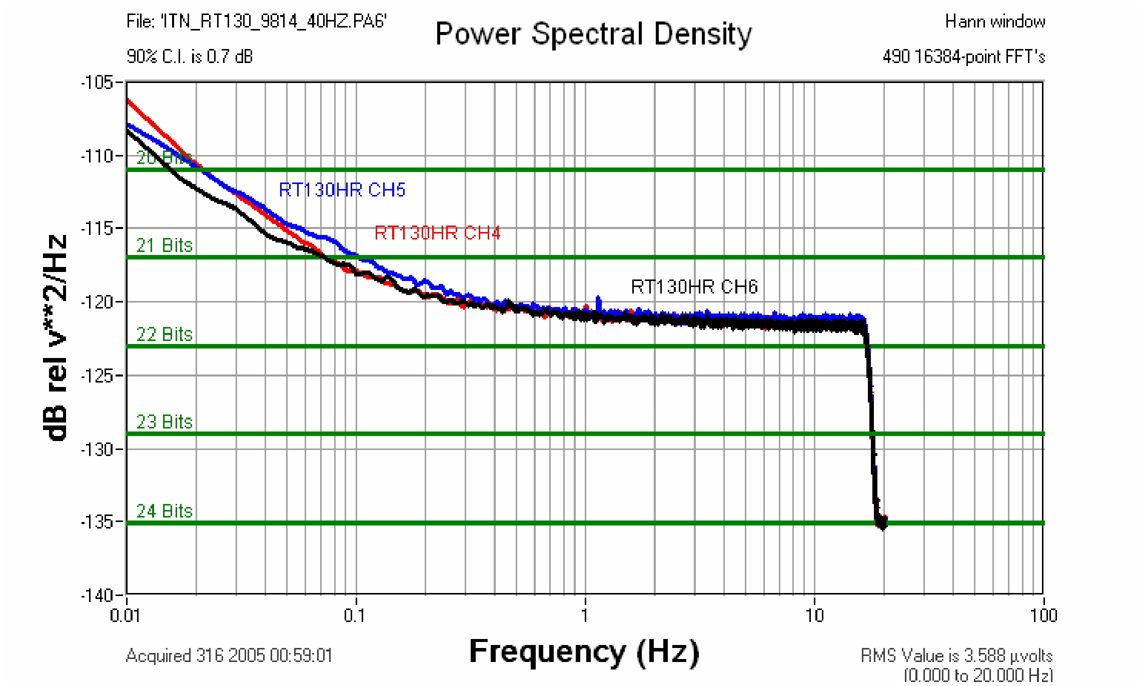

Figure 6.7.5 RT130HR 40SPS Channel 4-6 Input Terminated Noise

Channel	ITNRMS Noise µV 0.01 to 20 Hz	RMS Full-Scale Volts	MPDR (dB)
4	3.627	14.14	131.8
5	3.696	14.14	131.7
6	3.551	14.14	132.0

Table 6.7.5 RT130HR 40SPS MPDR

<u>Test Results:</u>
Figure 6.7.5 and Table 6.7.5 indicate that the RT130HR/B has < 3.7 µV RMS noise at 40 sps. MPDR is better than 131.7 dB.

6.7.6 RT130HR/A Sample Rate 20 sps:

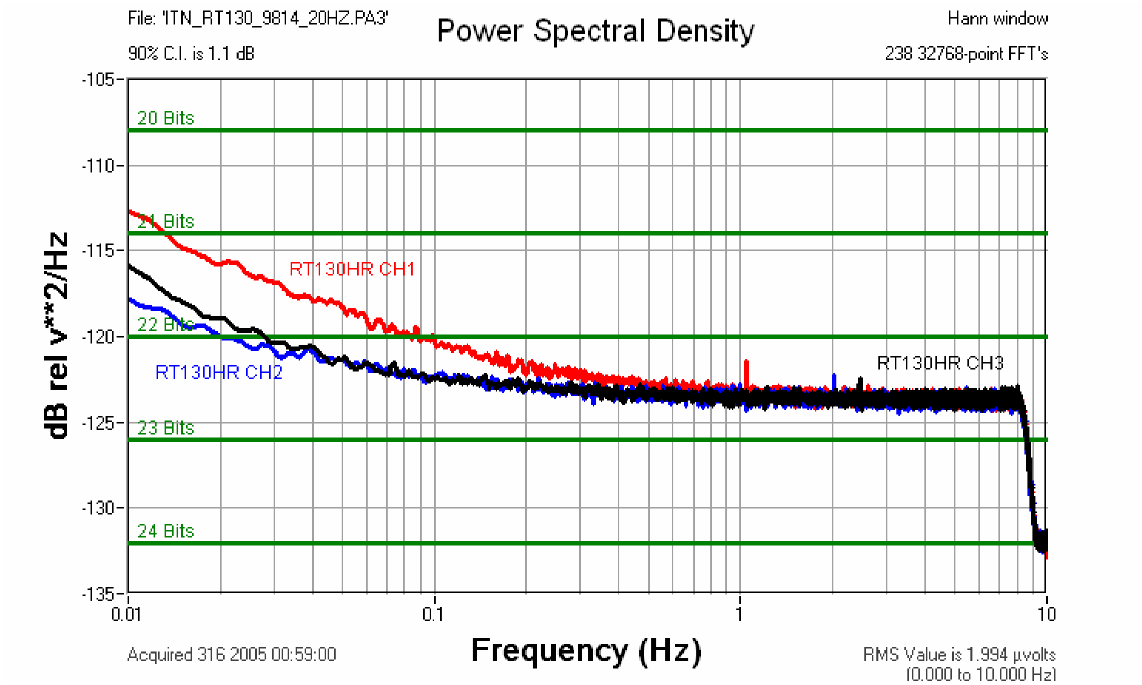

Figure 6.7.6 RT130HR 20SPS Channel 1-3 Input Terminated Noise

Channel	RMS Noise µV 0.01 to 10 Hz	RMS Full-Scale Volts	MPDR (dB)
1	2.014	14.14	136.9
2	1.960	14.14	137.2
3	1.972	14.14	137.1

Table 6.7.6 RT130HR 20SPS MPDR

Test Results:
Figure 6.7.6 and Table 6.7.6 indicate that the RT130HR/A has < 2.02 µV RMS noise at 20 sps. MPDR is better than 136.9 dB.

6.7.7 RT130HR/A Sample Rate 1 sps:

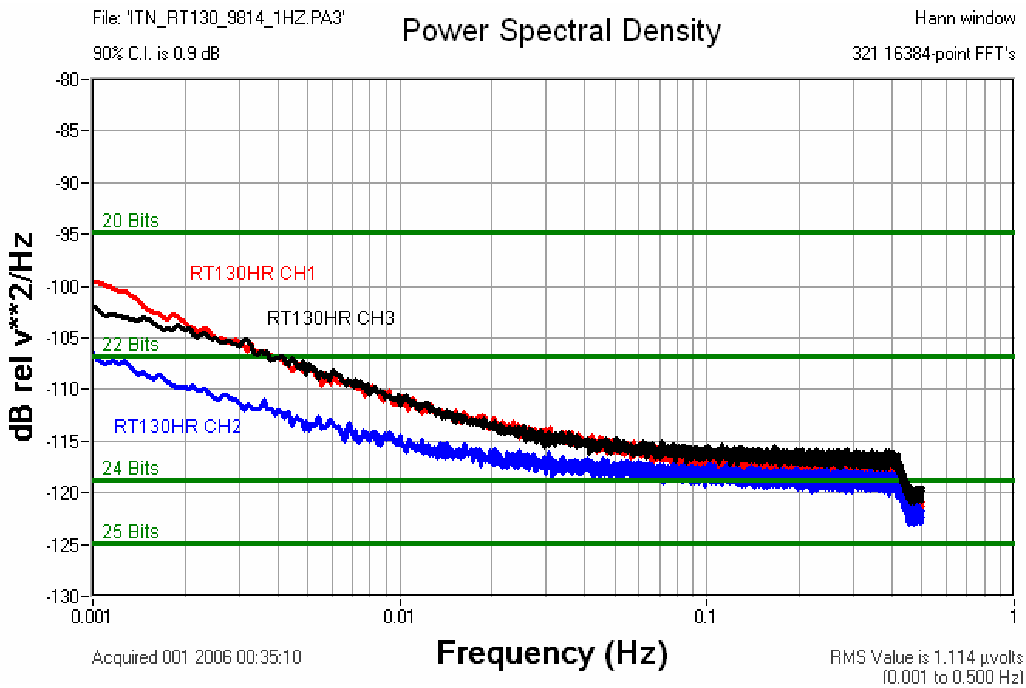

Figure 6.7.7 RT130HR 1SPS Channel 1-3 Input Terminated Noise

Channel	ITN RMS Noise µV 0.001 to 0.5 Hz	RMS Full-Scale Volts	MPDR (dB)
1	1.038	14.14	142.7
2	0.837	14.14	144.6
3	1.114	14.14	142.1

Table 6.7.7 RT130HR 1SPS MPDR

Test Results:
Figure 6.7.7 and Table 6.7.7 indicate that the RT130HR/A has < 1.11 µV RMS noise at 1 sps. MPDR is better than 142.1 dB.

6.7.8 RT130HR/B Sample Rate 1 sps:

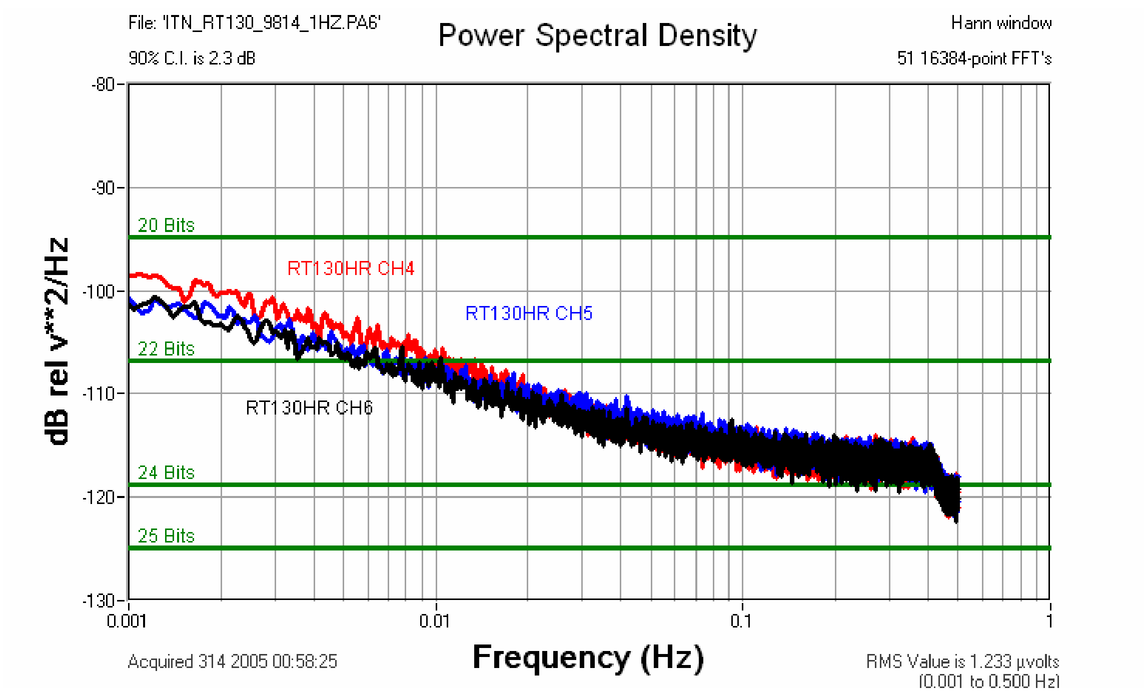

Figure 6.7.8 RT130HR 1SPS Channel 4-6 Input Terminated Noise

Channe l	ITN RMS Noise µV 0.001 to 0.5 Hz	RMS Full-Scale Volts	MPDR (dB)
4	1.329	14.14	140.5
5	1.306	14.14	140.7
6	1.233	14.14	141.2

Table 6.7.8 RT130HR 1SPS MPDR

Test Results:
Figure 6.7.8 and Table 6.7.8 indicate that the RT130HR/B has < 1.33 µV RMS noise at 1 sps. MPDR is better than 140.5 dB.

6.7.9 RT130HR/A Sample Rate 0.1 sps:

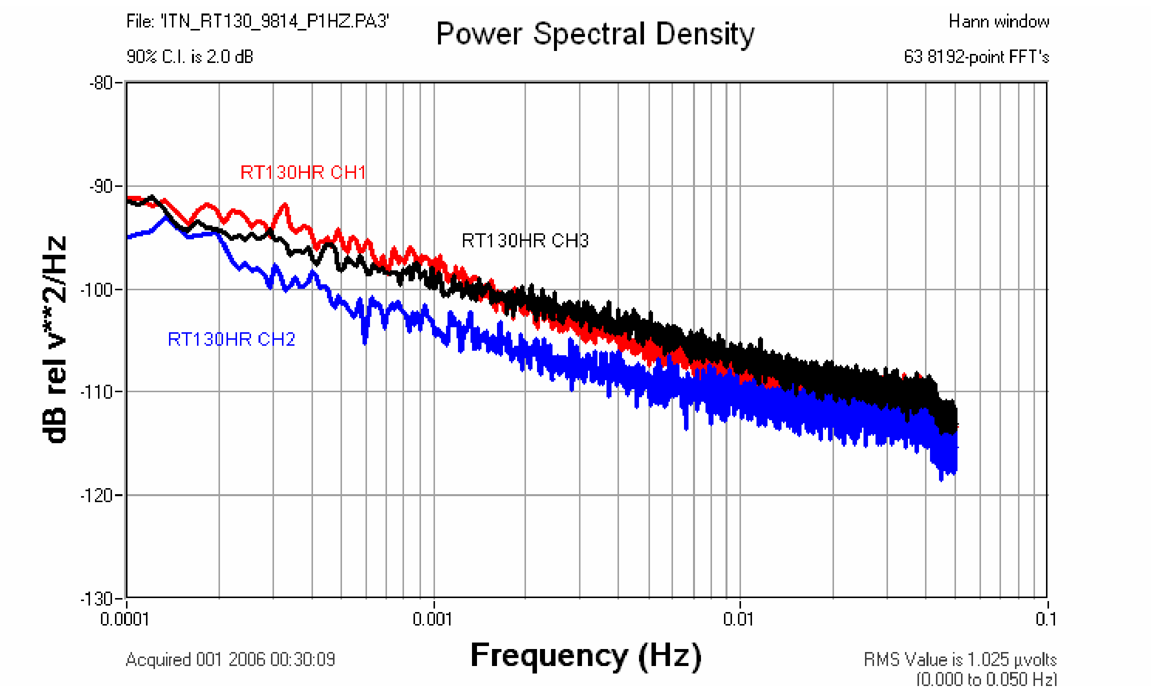

Figure 6.7.9 RT130HR 0.1SPS Channel 1-3 Input Terminated Noise

Channe l	ITN RMS Noise µV 0.0001 to 0.5 Hz	RMS Full-Scale Volts	MPDR (dB)
1	0.996	14.14	143.0
2	0.688	14.14	146.3
3	1.025	14.14	142.8

Table 6.7.9 RT130HR 0.1SPS MPDR

Test Results:
Figure 6.7.9 and Table 6.7.9 indicate that the RT130HR/A has < 1.03 µV RMS noise at 0.1 sps. MPDR is better than 142.8 dB.

6.8 RT130HR Test Data Sheet: Test – Dynamic Tonal/THD

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 40, 20 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

THD Test Description: Measure the linearity of the RT130HR digitizers using Total Harmonic Distortion.

6.8.1 RT130HR/A Sample Rate 40 sps:

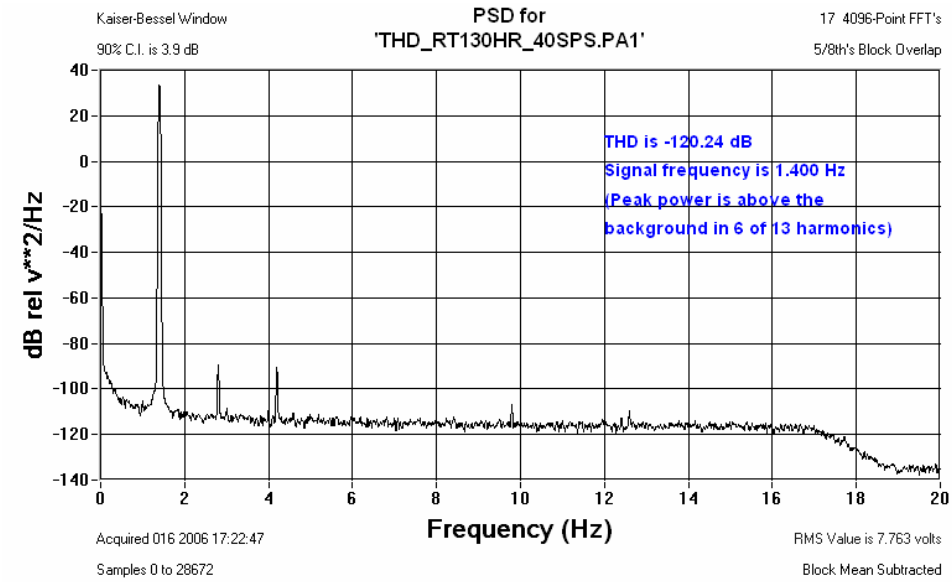

Figure 6.8.1 RT130HR Channel 1 Total Harmonic Distortion

Channel	THD (dB)
1	-120.2
2	-120.4
3	-121.1

Table 6.8.1 RT130HR 40SPS Channel 1-6 THD

<u>Test Results:</u>
Figure 6.8.1 and Table 6.8.1 indicate that the RT130HR/A Total Harmonic Distortion is better than -117.5 dB at 40 sps.

6.8.2 RT130HR/B Sample Rate 40 sps:

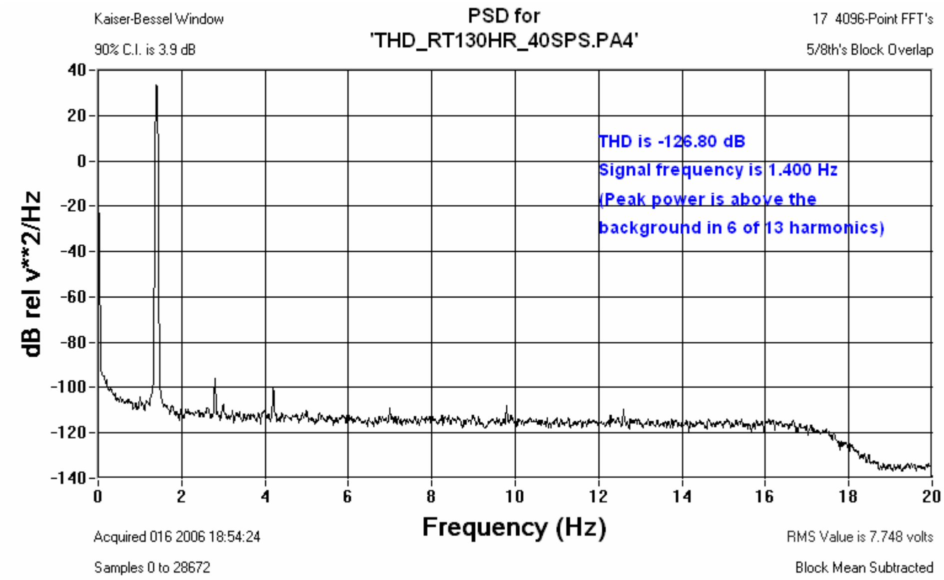

Figure 6.8.2 RT130HR Channel 4Total Harmonic Distortion

Channel	THD (dB)
4	-126.8
5	-126.3
6	-126.5

Table 6.8.2 RT130HR 40SPS Channel 1-6 THD

Test Results:
Figure 6.8.2 and Table 6.8.2 indicate that the RT130HR/B Total Harmonic Distortion is better than -120.4 dB at 40 sps.

6.8.3 RT130HR/A Sample Rate 20 sps:

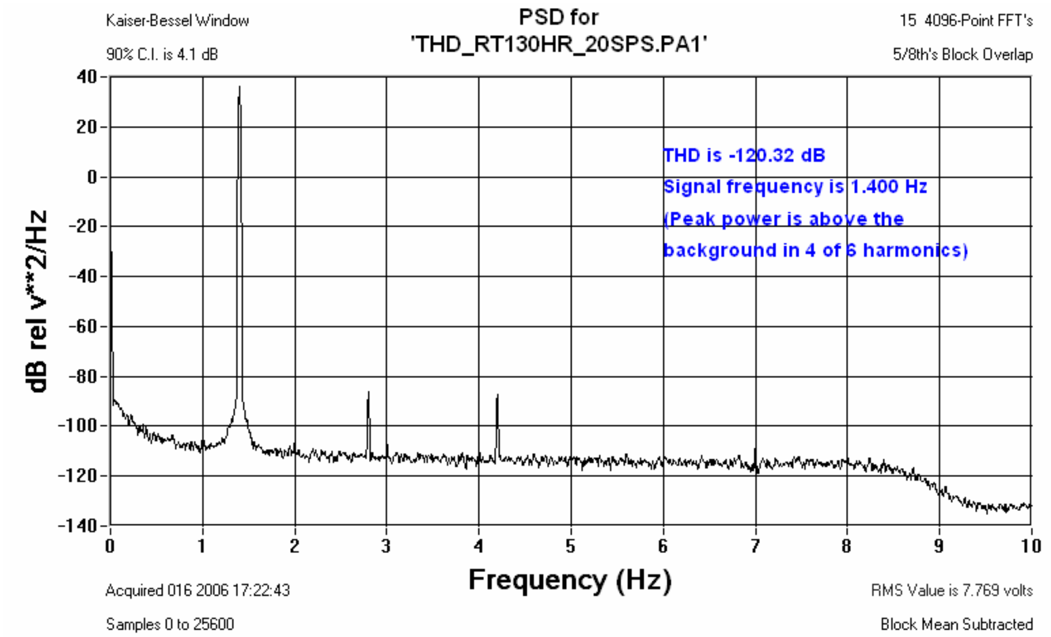

Figure 6.8.3 RT130HR Channel 1 Total Harmonic Distortion

Channel	THD (dB)
1	-120.3
2	-120.4
3	-121.2

Table 6.8.3 RT130HR 20SPS Channel 1-3 THD

<u>Test Results:</u>
Figure 6.8.3 and Table 6.8.3 indicate that the RT130HR/A Total Harmonic Distortion is better than –126.3 dB at 20 sps.

6.8.4 RT130HR/B Sample Rate 20 sps:

Not Tested

6.9 RT130HR Test Data Sheet: Test – Dynamic Tonal/CTK/CMR

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 40, 20 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

CTK/CMR Test Description: Measure the amount of digitizer channel-to-channel crosstalk. easure the ability of the digitizer to reject common-mode signals.

6.9.1 RT130HR/A/B Sample Rate 40 sps:

Channel	RMS Input	RMS Crosstalk	Crosstalk
1	6.9 V	Not Observ.	< -150 dB
2	6.9 V	Not Observ.	< -150 dB
3	6.9 V	Not Observ.	< -150 dB
4	6.9 V	Not Observ.	< -150 dB
5	6.9 V	Not Observ.	< -150 dB
6	6.9 V	Not Observ.	< -150 dB

Table 6.9.1a RT130HR 40SPS Channel 1-6 Crosstalk

CMR

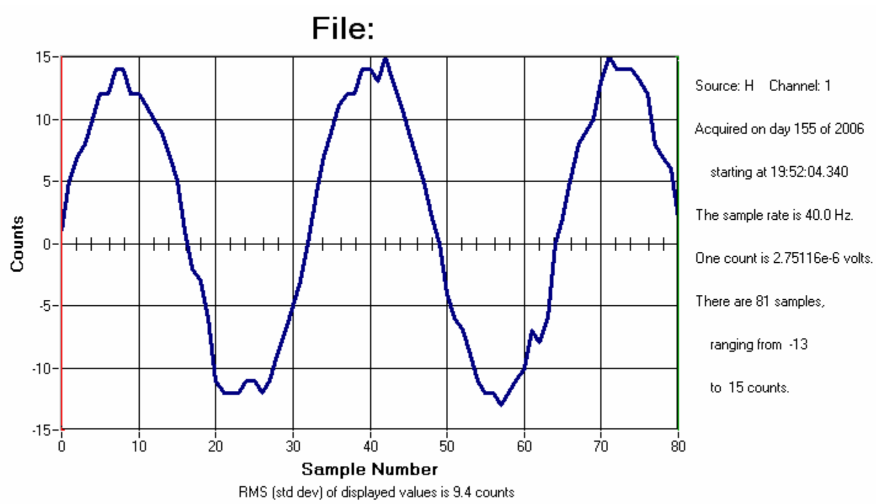

Figure 6.9.1a CMR at 1.0V peak

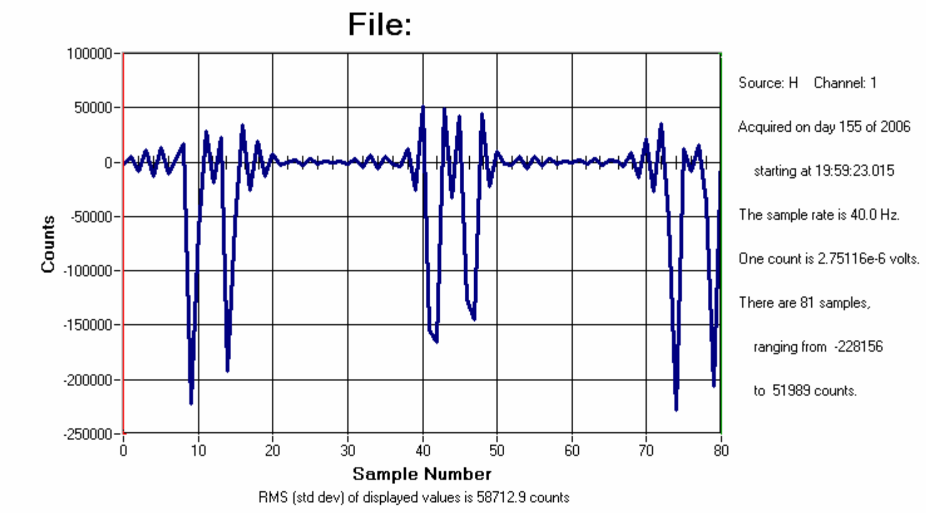

Figure 6.9.1b CMR at 2.0V peak

Channel	RMS Input	RMS CM	CMR
1	0.707	26 uV	-89 dB
2	0.707	16 uV	-92 dB
3	0.707	25 uV	-89 dB

Table 6.9.1b RT130HR 40SPS Channel 1-6 Common Mode Rejection

Test Results:
Table 6.9.1a indicates that the RT130HR/A/B Crosstalk is better than-150 dB at 40 sps.

Table 6.9.1b indicates that the RT130HR/A CMR is better than -85 dB at 1 Hz for 40 sps. Common Mode Voltage up to +/- 1 Volts was tolerated by the RT130HR/A. Figures 6.9.1a-b indicate Common Mode Voltages over +/-2 Volts resulted in unstable behavior.

6.10 RT130HR Test Data Sheet: Test – Dynamic Broadband/RTF/ABW

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 200, 100, 40, 20, 1, 0.1 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

RTF/ABW Test Description: Measure channel-to-channel relative phase and compute channel skew. Measure the bandwidth/corner frequency (–3 dB point) and attenuation at the Nyquist (20 Hz).

6.10.1 RT130HR/A Sample Rate 200 sps:

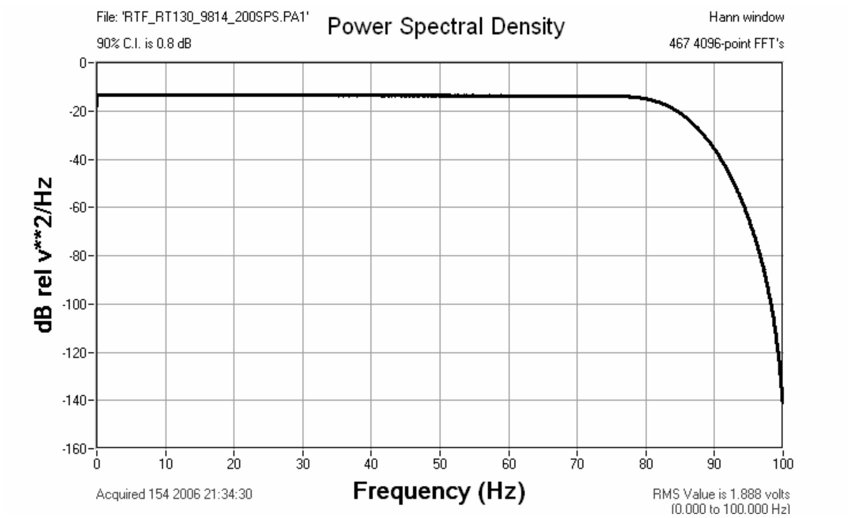

Figure 6.10.1a Response of the RT130HR to Broadband Noise

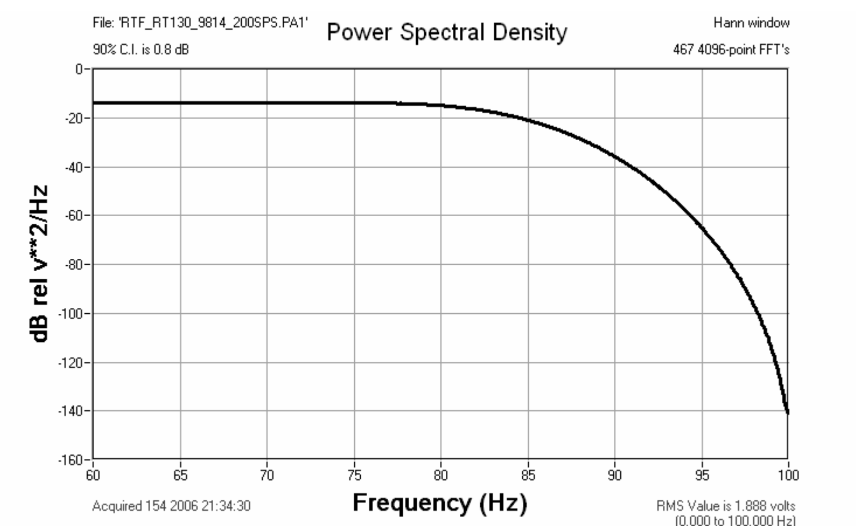

Figure 6.10.1b Response of the RT130HR to Broadband Noise

<u>Test Results:</u>

Figures 6.10.1a-b indicate that the RT130HR/A –3dB point is at 82.3 Hz with a relative attenuation of -126 dB at the Nyquist.

6.10.2 RT130HR/A Sample Rate 100 sps:

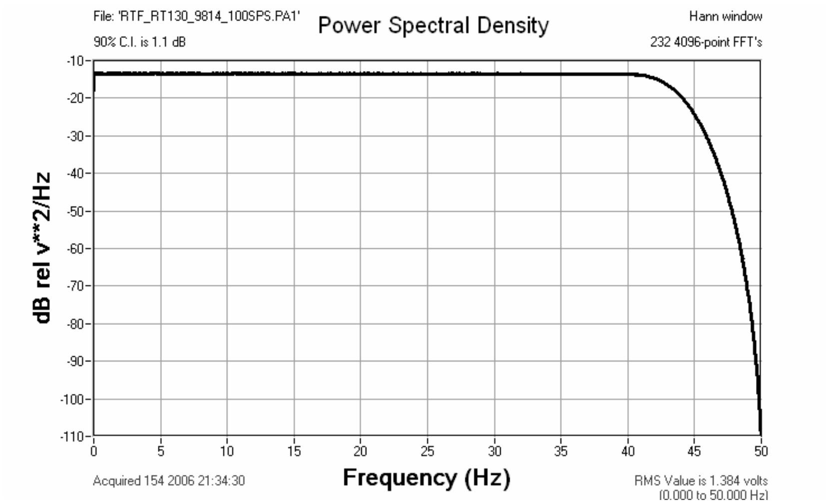

Figure 6.10.2a Response of the RT130HR to Broadband Noise

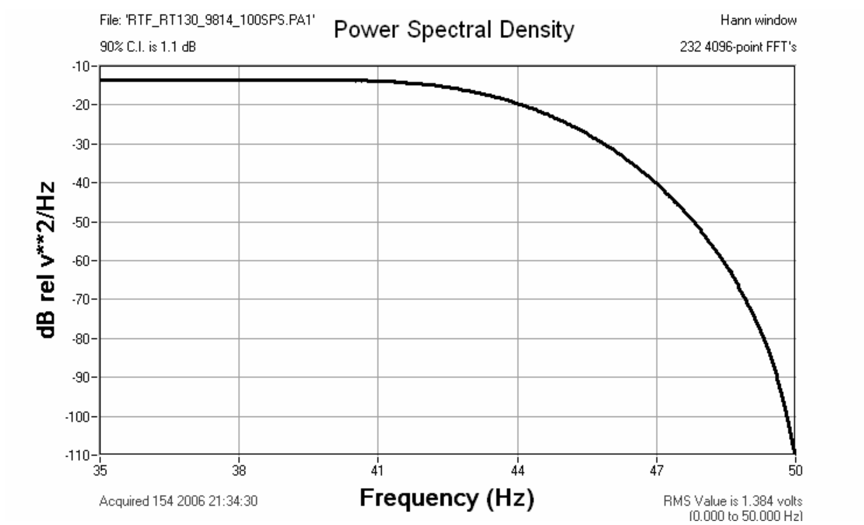

Figure 6.10.2b Response of the RT130HR to Broadband Noise

<u>Test Results:</u>
Figures 6.10.2a-b indicate that the RT130HR/A –3dB point is at 43.07 Hz with a relative attenuation of 96 dB at the Nyquist.

6.10.3 RT130HR/A/B Sample Rate 40 sps:

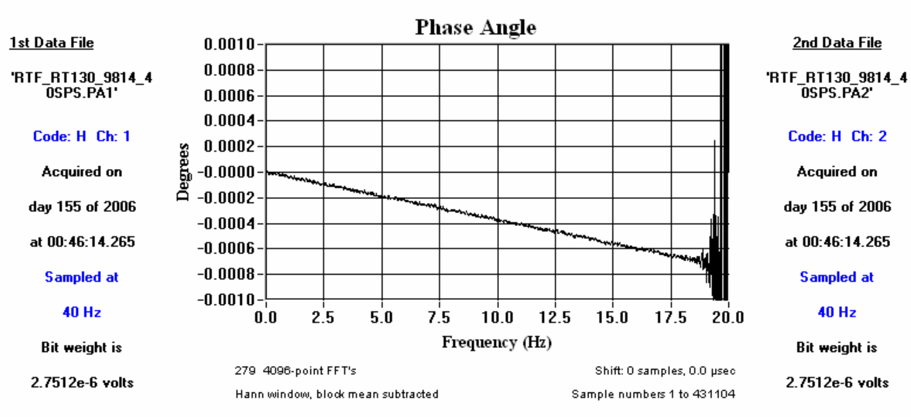

Figure 6.10.3a RT130HR 40SPS Channel 1-2 Relative Phase/Skew

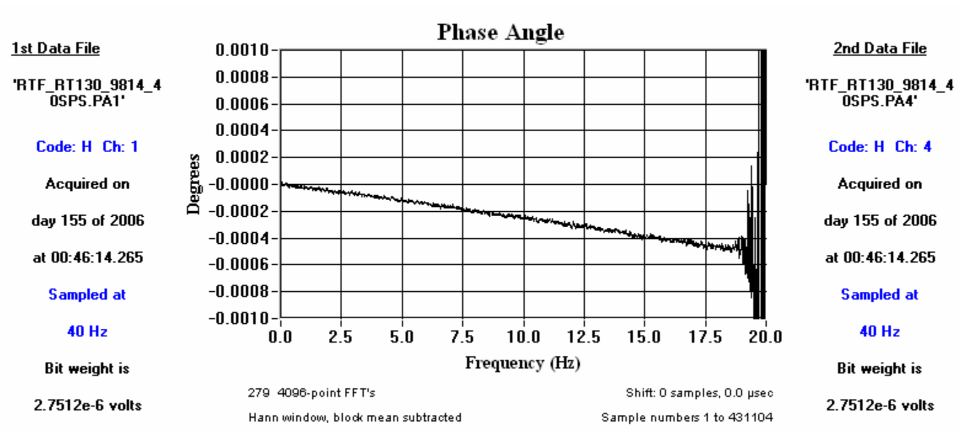

Figure 6.10.3b RT130HR 40SPS Channel 1-4 Relative Phase/Skew

Channel	Relative Phase @ 10 Hz	Channel Skew (Microseconds)
1-2	-0.0004	-0.11
1-3	0.0001	0.027
2-3	0.0005	0.14
4-5	-0.0016	-0.4
4-6	-0.0016	-0.4
5-6	0.0001	0.027
1-4	-0.00025	-.07

Table 6.10.3 RT130HR 40SPS Channel Relative Phase/Skew

Test Results:

Figure 6.10.3a-b and Table 6.10.3 indicate that the RT130HRA/B has less than 0.4 microseconds of channel to channel skew.

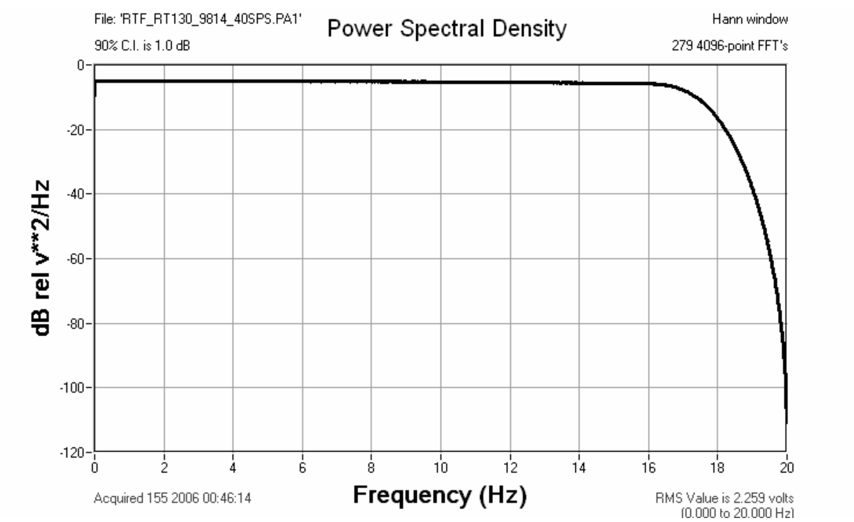

Figure 6.10.3c Response of the RT130HR to Broadband Noise

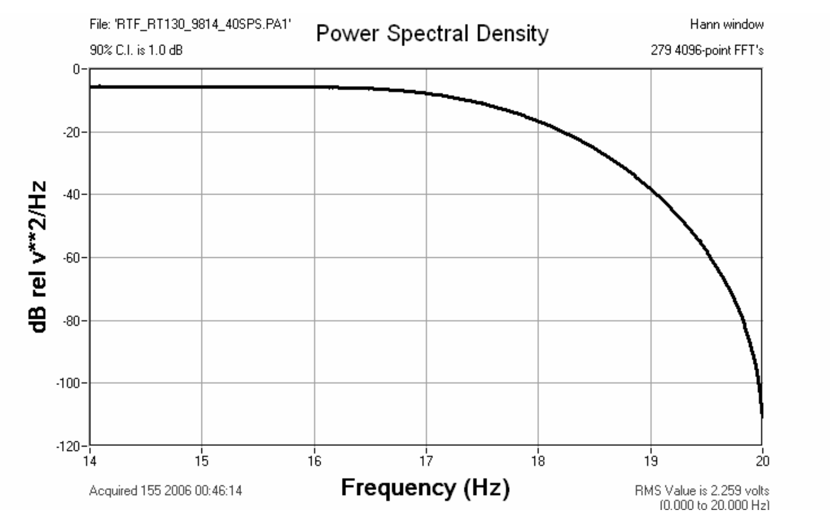

Figure 6.10.3d Response of the RT130HR to Broadband Noise

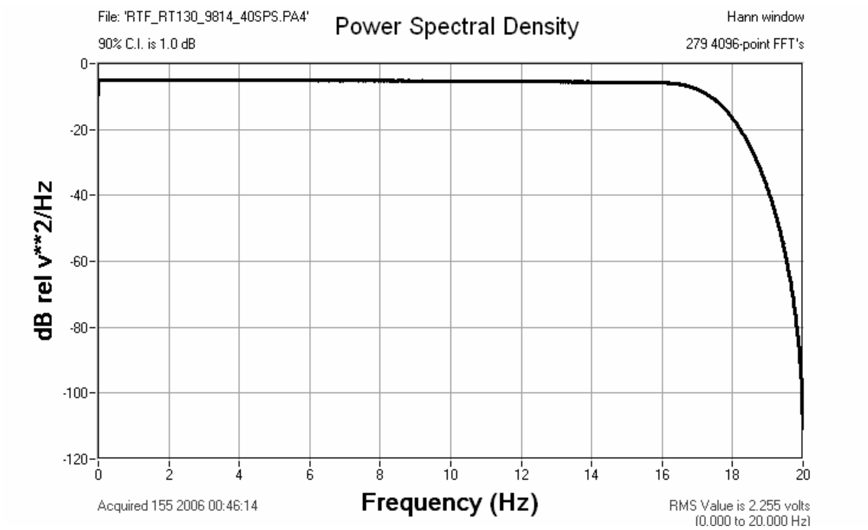

Figure 6.10.3e Response of the RT130HR to Broadband Noise

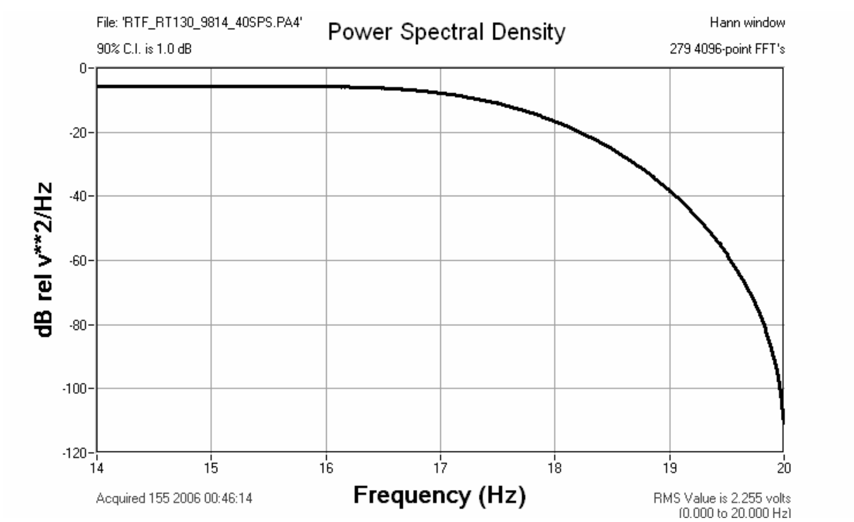

Figure 6.10.3f Response of the RT130HR to Broadband Noise

Test Results:
Figures 6.10.3c-f indicate that the RT130HR/A/B –3dB point is at 17.17 Hz with a relative attenuation of 110 dB at the Nyquist.

6.10.4 RT130HR/A Sample Rate 20 sps:

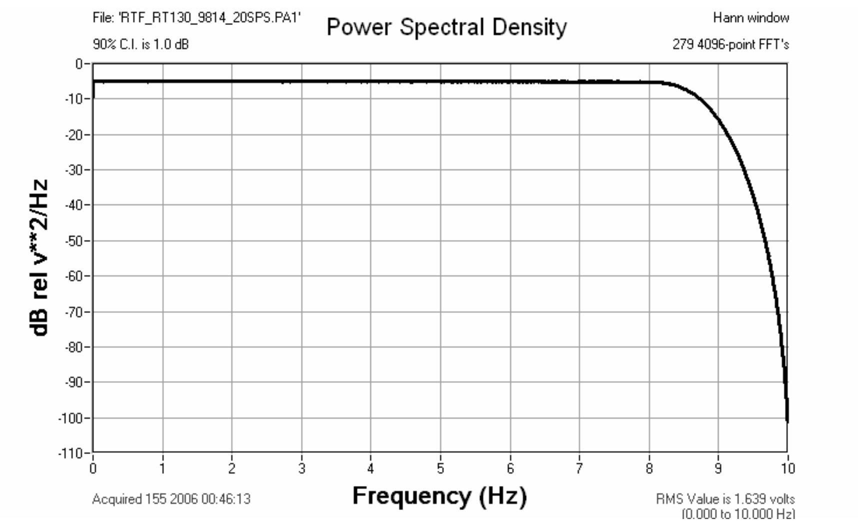

Figure 6.10.4a Response of the RT130HR to Broadband Noise

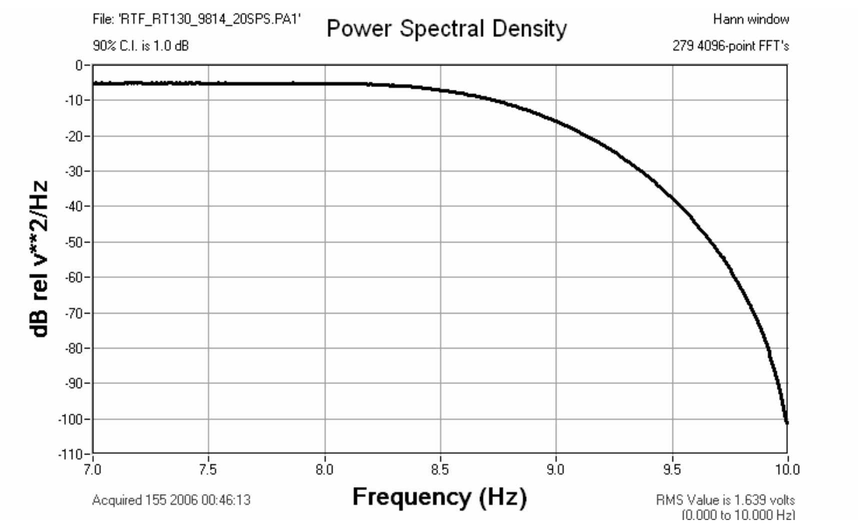

Figure 6.10.4b Response of the RT130HR to Broadband Noise

<u>Test Results:</u>
Figures 6.10.4a-b indicate that the RT130HR/A –3dB point is at 8.61 Hz with a relative attenuation of 95 dB at the Nyquist.

6.10.5 RT130HR/A/B Sample Rate1 sps:

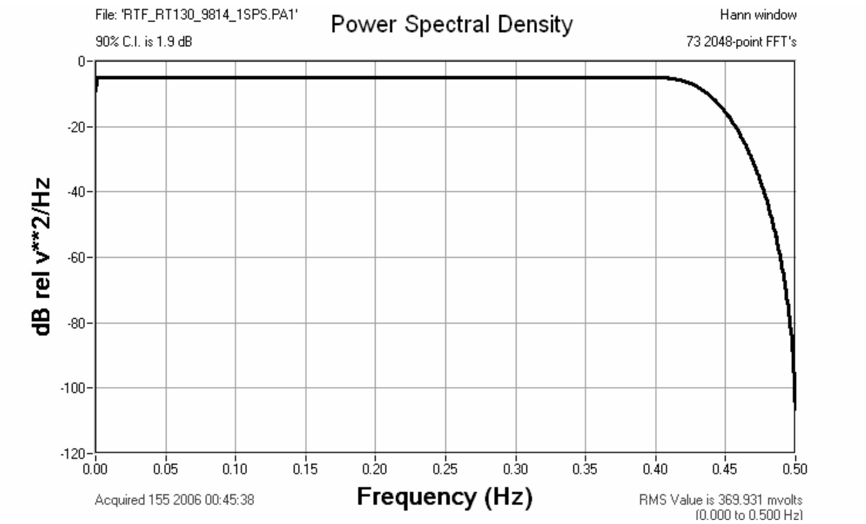

Figure 6.10.5a Response of the RT130HR to Broadband Noise

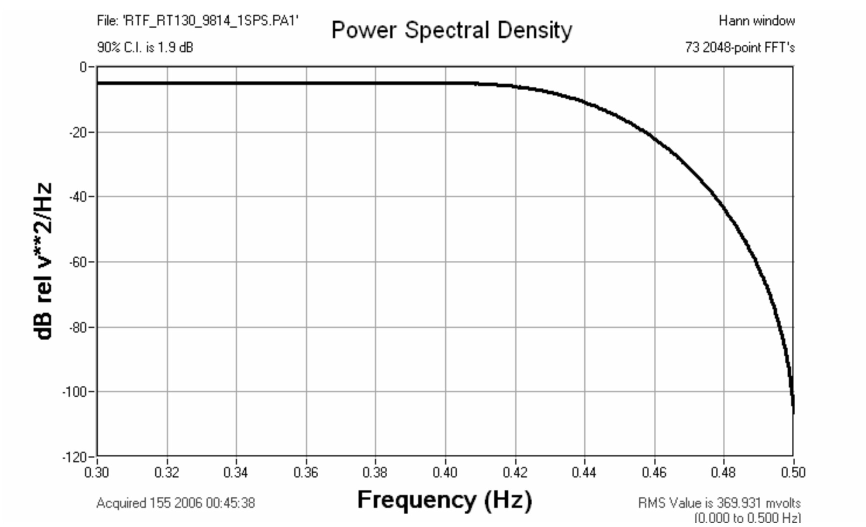

Figure 6.10.5b Response of the RT130HR to Broadband Noise

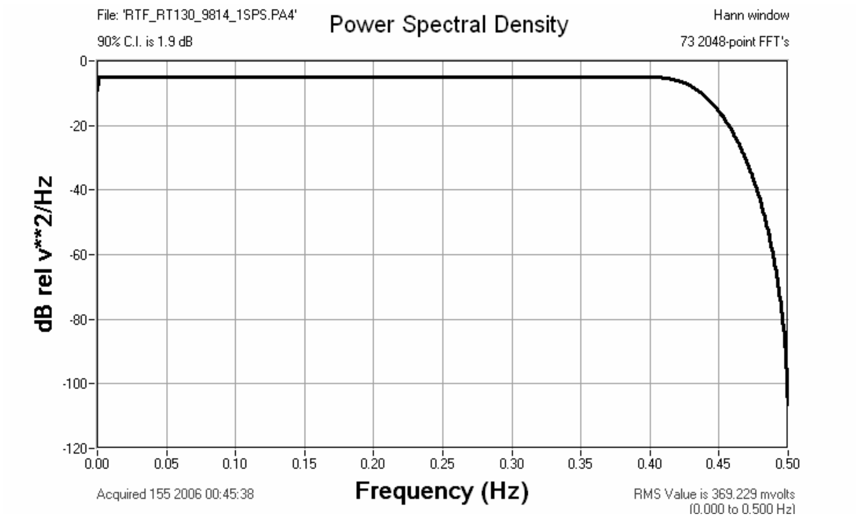

Figure 6.10.5c Response of the RT130HR to Broadband Noise

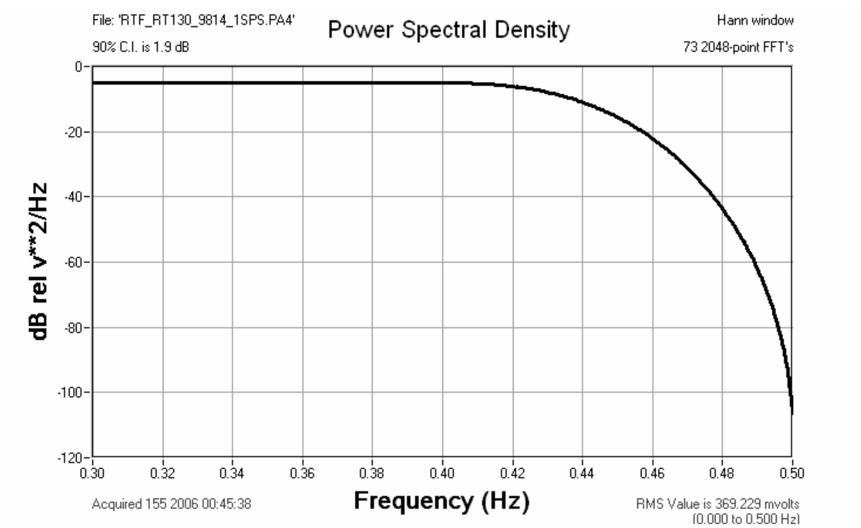

Figure 6.10.5d Response of the RT130HR to Broadband Noise

Test Results:

Figures 6.10.5a-d indicate that the RT130HR/A/B –3dB point is at 0.43 Hz with a relative attenuation of 100 dB at the Nyquist.

6.10.6 RT130HR/A Sample Rate 0.1 sps:

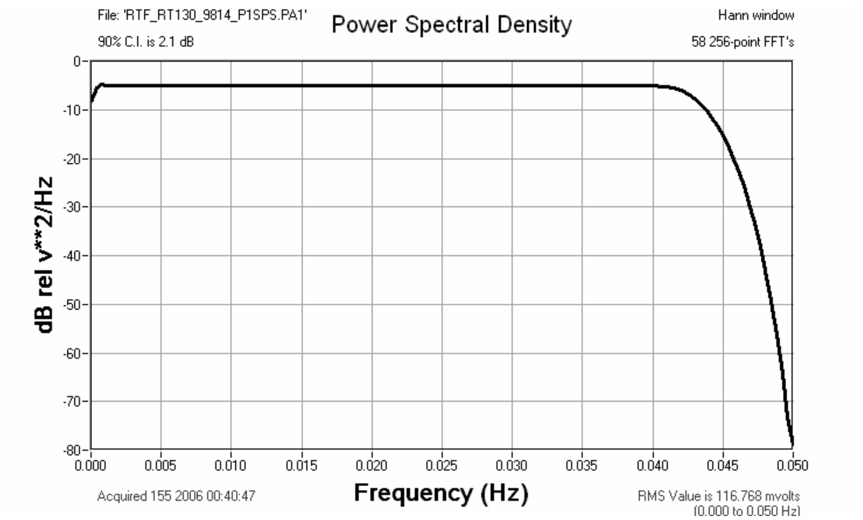

Figure 6.10.6a Response of the RT130HR to Broadband Noise

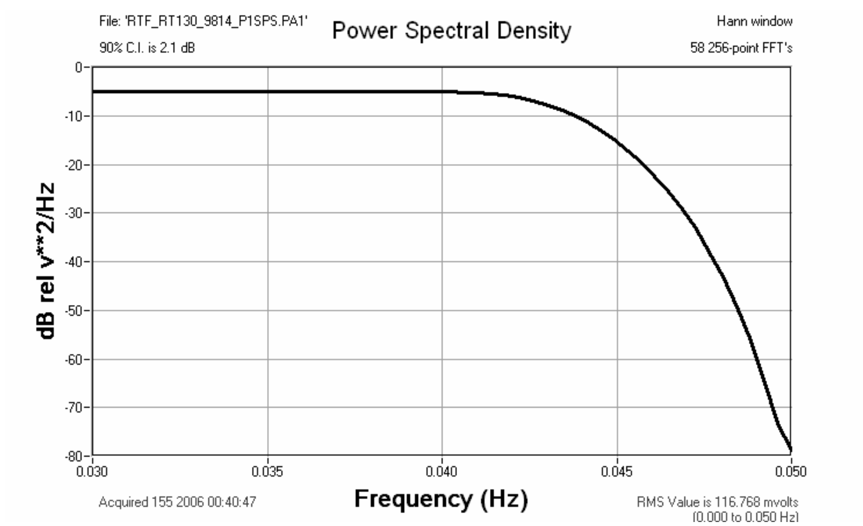

Figure 6.10.6b Response of the RT130HR to Broadband Noise

Test Results:
Figures 6.10.6a-b indicate that the RT130HR –3dB point is at 0.0431 Hz with a relative attenuation of 75 dB at the Nyquist.

6.11 RT130HR Test Data Sheet: Test – Timing/TTA

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 200, 100, 40, 20, 1, 0.1 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

TTA Test Description: Determine the accuracy of the time-tags of the RT130HR data samples.

6.11.1 RT130HR/A Sample Rate 200 sps:

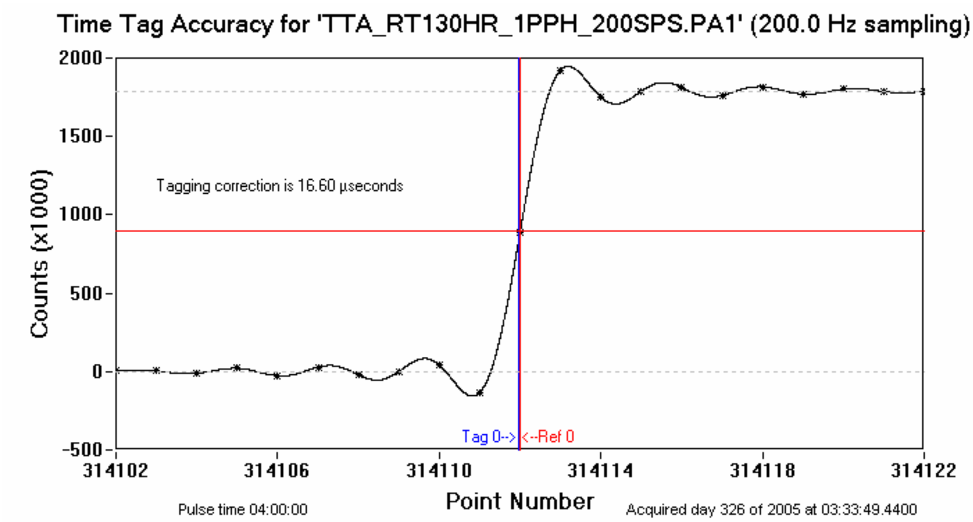

Figure 6.11.1 RT130HR Time-Tag Accuracy

<u>Test Results:</u>
Figure 6.11.1 indicates that the RT130HR can time-tag data samples to within 16.6 microseconds for 200 sps.

6.11.2 RT130HR/A Sample Rate 100 sps:

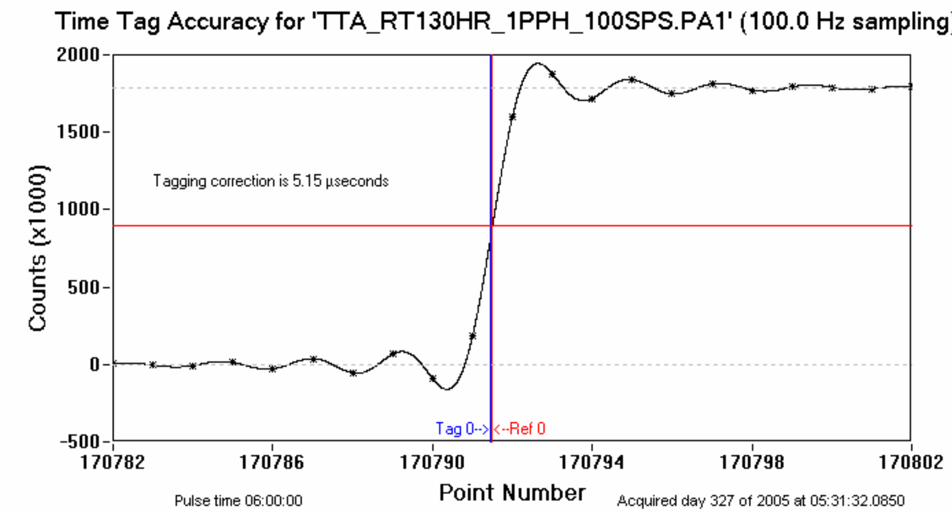

Figure 6.11.2 RT130HR Time-Tag Accuracy

<u>Test Results:</u>

Figure 6.11.2 indicates that the RT130HR can time-tag data samples to within 5.15 microseconds for 100 sps.

6.11.3 RT130HR/A Sample Rate 40 sps:

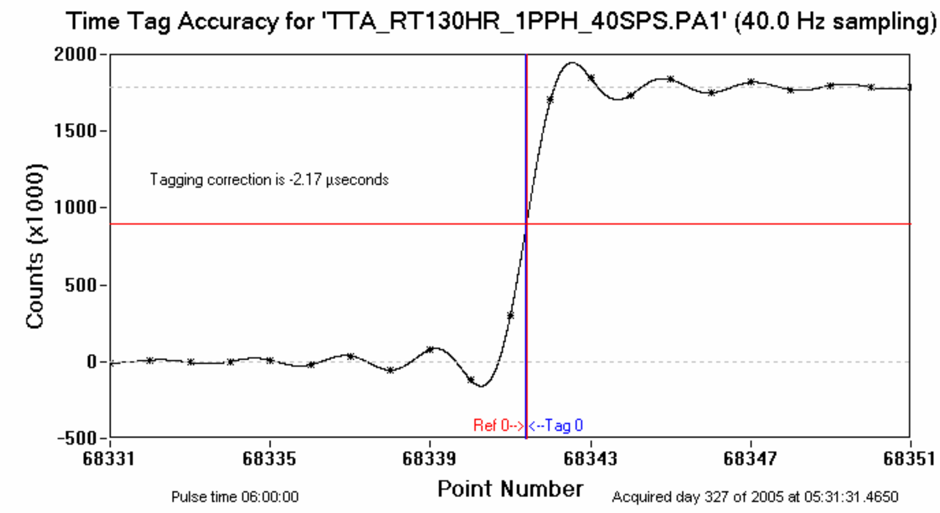

Figure 6.11.3 RT130HR Time-Tag Accuracy

<u>Test Results:</u>
Figure 6.11.3 indicates that the RT130HR can time-tag data samples to within 2.17 microseconds for 40 sps.

6.11.4 RT130HR/B Sample Rate 40 sps:

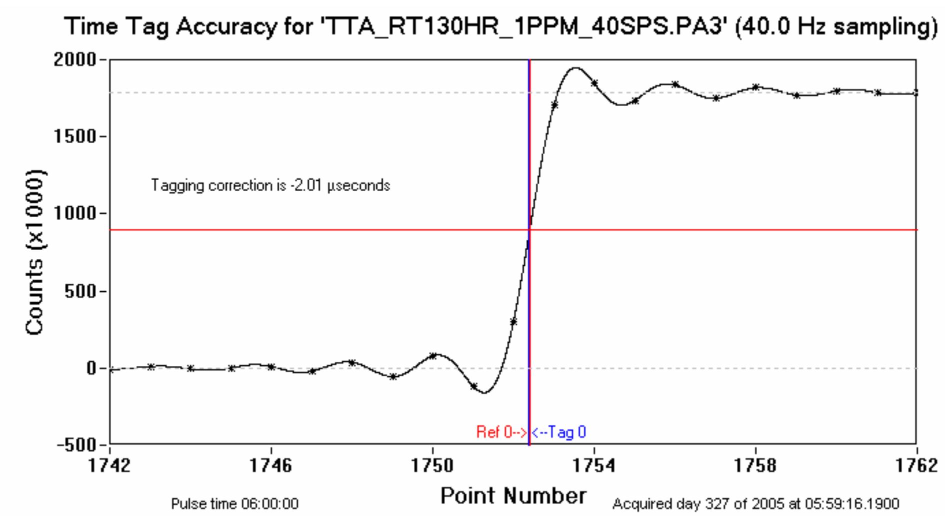

Figure 6.12.4 RT130HR Time-Tag Accuracy

<u>Test Results:</u>
Figure 6.11.4 indicates that the RT130HR can time-tag data samples to within 2.01 microseconds for 40 sps.

6.11.5 RT130HR/A Sample Rate 20 sps:

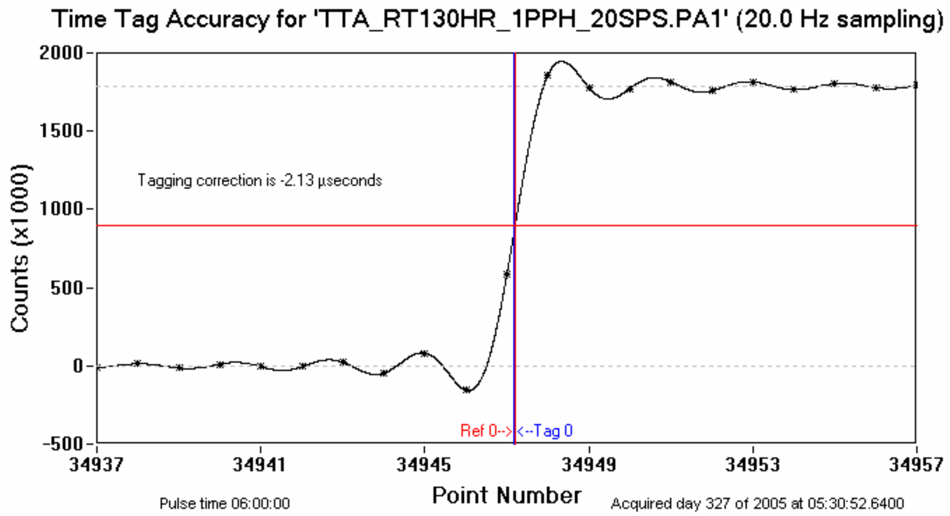

Figure 6.11.5 RT130HR Time-Tag Accuracy

<u>Test Results:</u>
Figure 6.11.5 indicates that the RT130HR can time-tag data samples to within 2.13 microseconds for 20 sps.

6.11.6 RT130HR/A Sample Rate 1 sps:

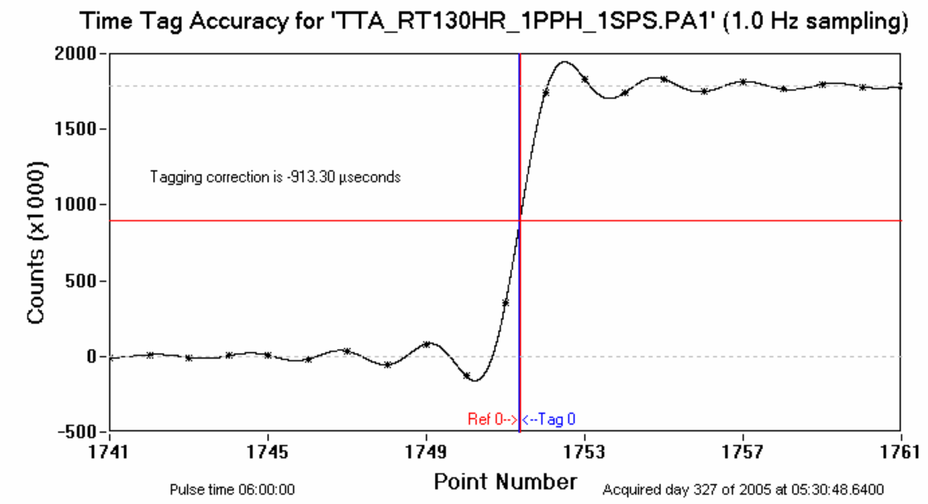

Figure 6.11.6 RT130HR Time-Tag Accuracy

__**Test Results:**__
Figure 6.11.6 indicates that the RT130HR can time-tag data samples to within 914 microseconds for 1 sps.

6.11.7 RT130HR/B Sample Rate 1 sps:

Not Tested

6.11.8 RT130HR/A Sample Rate 0.1 sps:

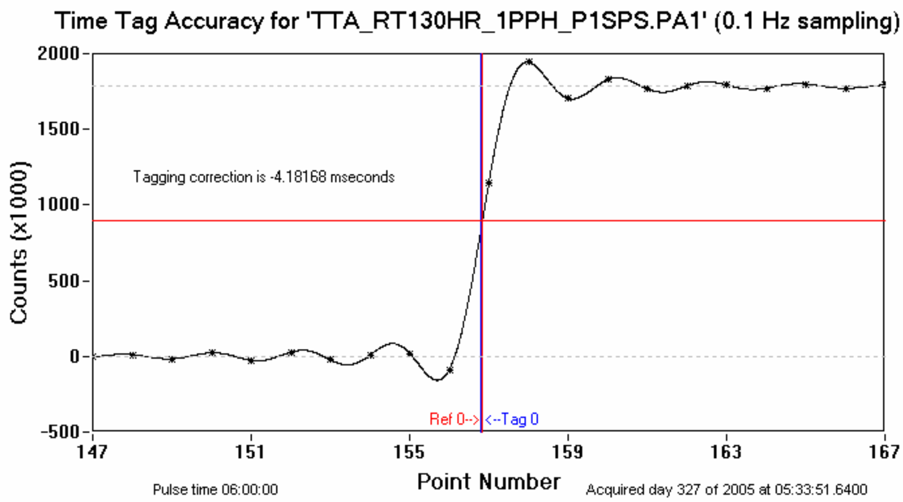

Figure 6.11.8 RT130HR Time-Tag Accuracy

<u>Test Results:</u>
Figure 6.11.8 indicates that the RT130HR can time-tag data samples to within 4.2 milliseconds for 0.1 sps.

6.12 RT130HR Test Data Sheet Test – Seismic/SSN

RT130HR S/N: 9814 **Software Version: 2.70**

RT130HR Sample Rate: 200, 100, 40, 20, 1, 0.1 sps
Specified Nominal Volts/Count: CH1-6 2.751 x 10^{-6}
****

SSN Test Description: Determine ability of the RT130HR to resolve the expected seismic background using the appropriate seismometer.

6.12.1 RT130HR/A Sample Rate 200 sps/STS-2 High Gain:

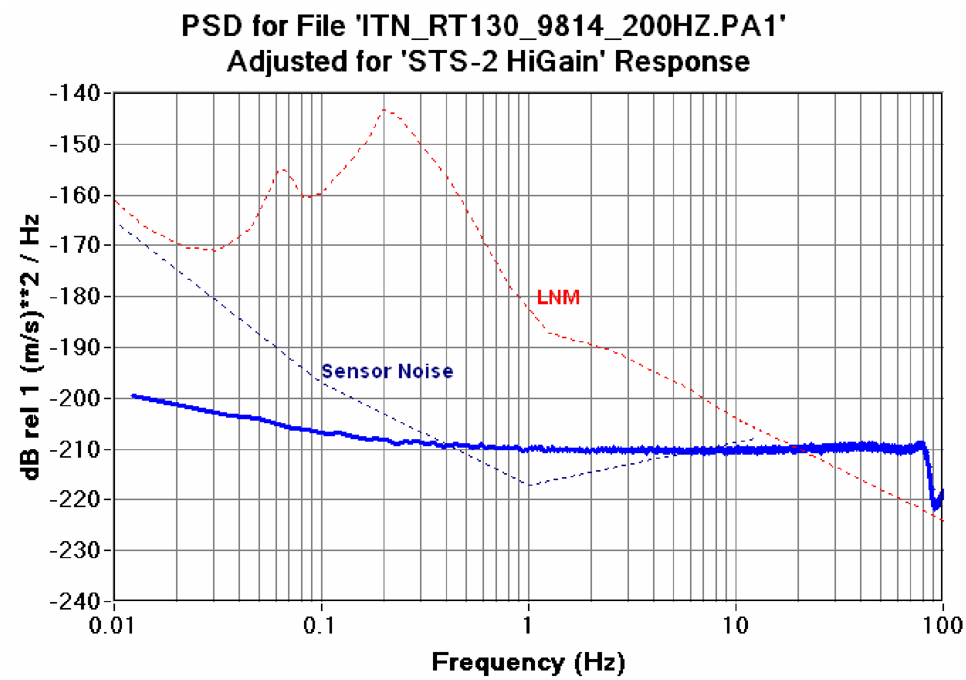

Figure 6.12.1a RT130HR 200SPS CH1 Seismic System Noise STS-2 High Gain

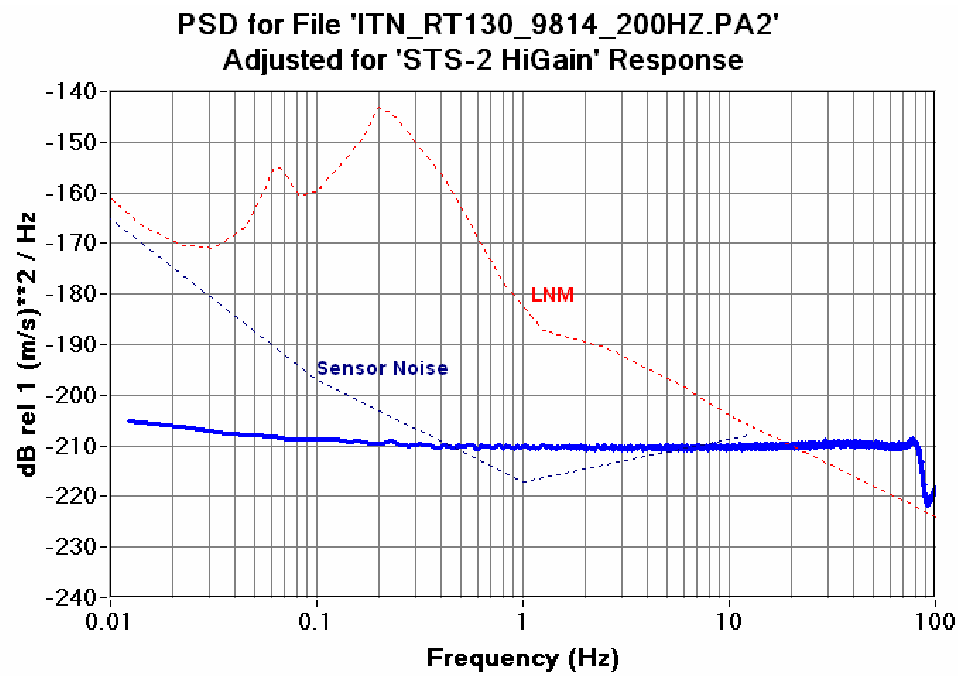

Figure 6.12.1b RT130HR 200SPS CH2 Seismic System Noise STS-2 High Gain

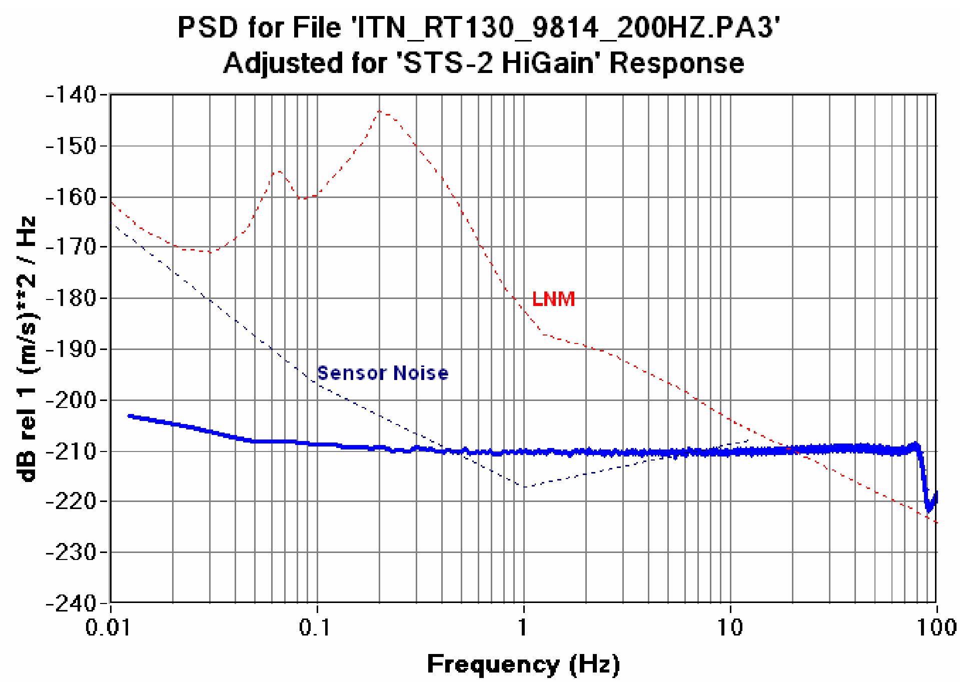

Figure 6.12.1c RT130HR 200SPS CH3 Seismic System Noise STS-2 High Gain

Test Results:

Figures 6.12.1a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

6.12.2 RT130HR/A Sample Rate 100 sps/STS-2 High Gain:

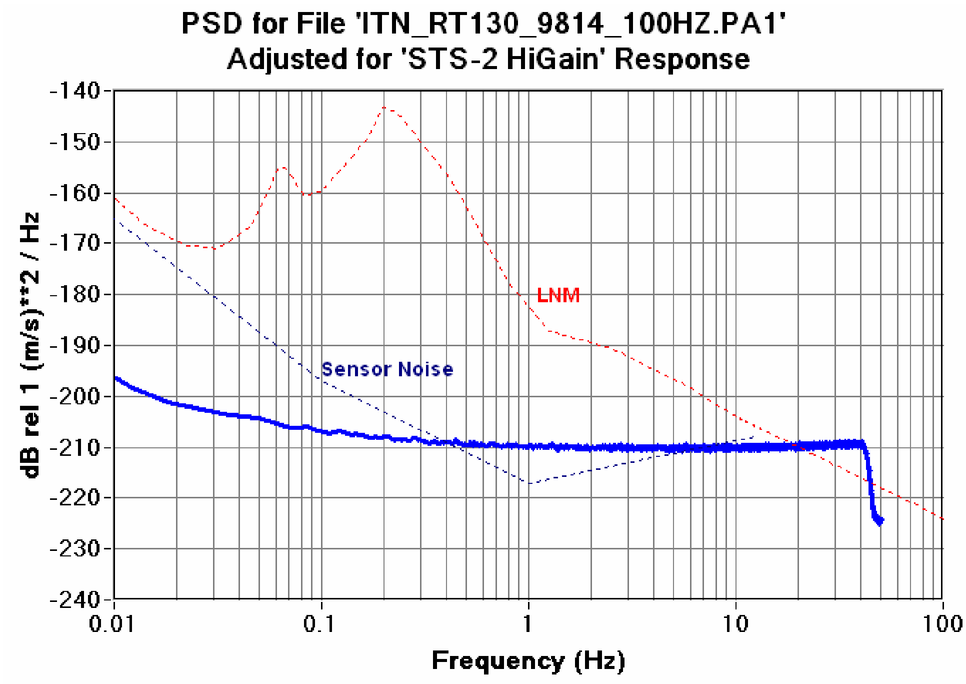

Figure 6.12.2a RT130HR 100SPS CH1 Seismic System Noise STS-2 High Gain

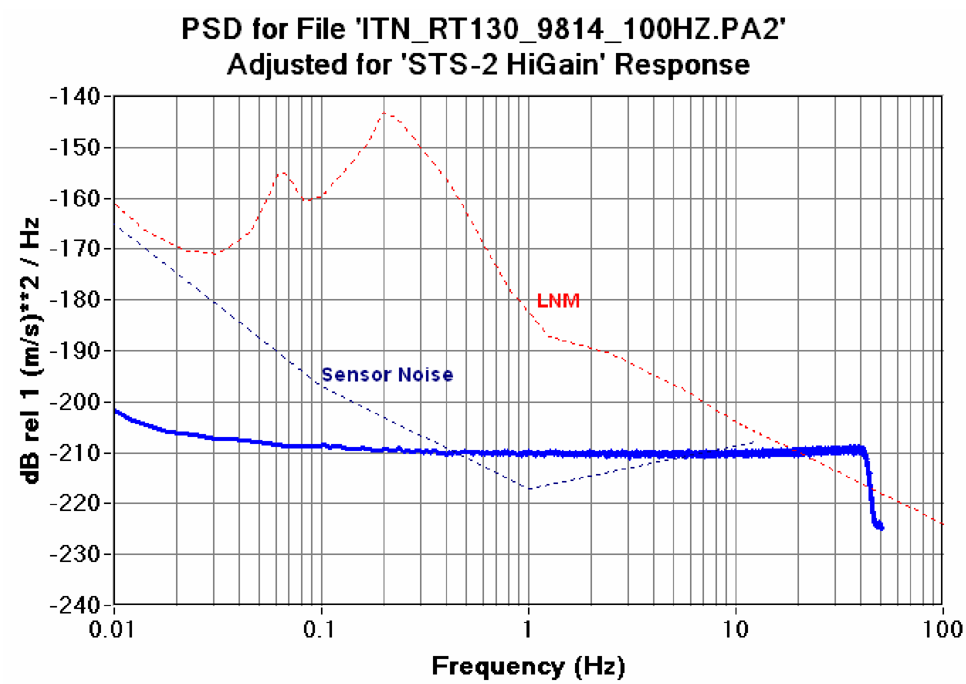

Figure 6.12.2b RT130HR 100SPS CH2 Seismic System Noise STS-2 High Gain

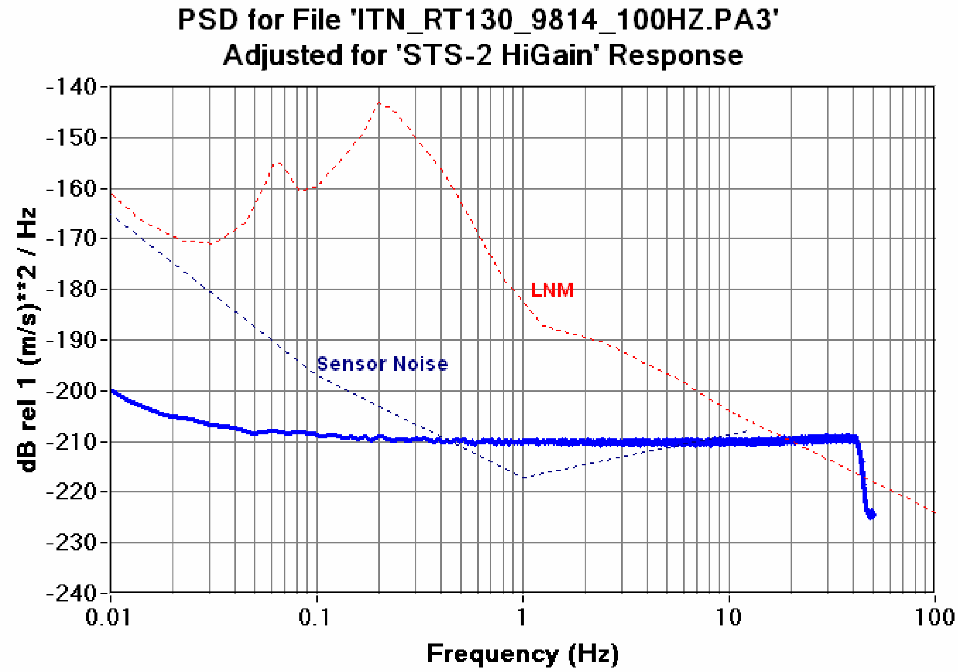

Figure 6.12.2c RT130HR 100SPS CH3 Seismic System Noise STS-2 High Gain

<u>Test Results:</u>
Figures6.12.2a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

6.12.3 RT130HR/B Sample Rate 100 sps/STS-2 High Gain:

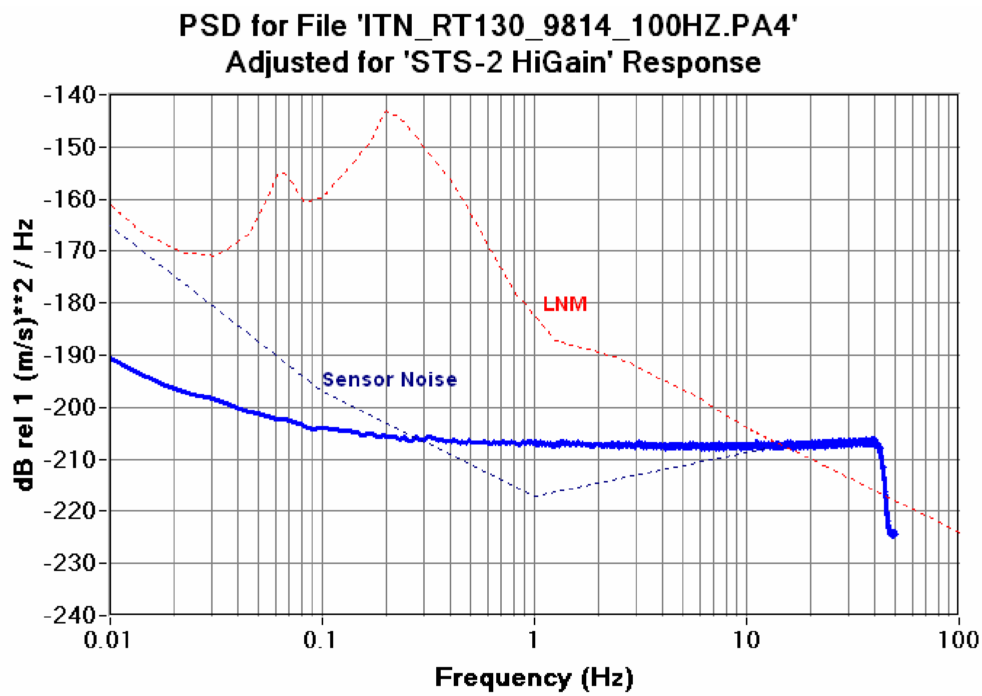

Figure 6.12.3a RT130HR 100SPS CH4 Seismic System Noise STS-2 High Gain

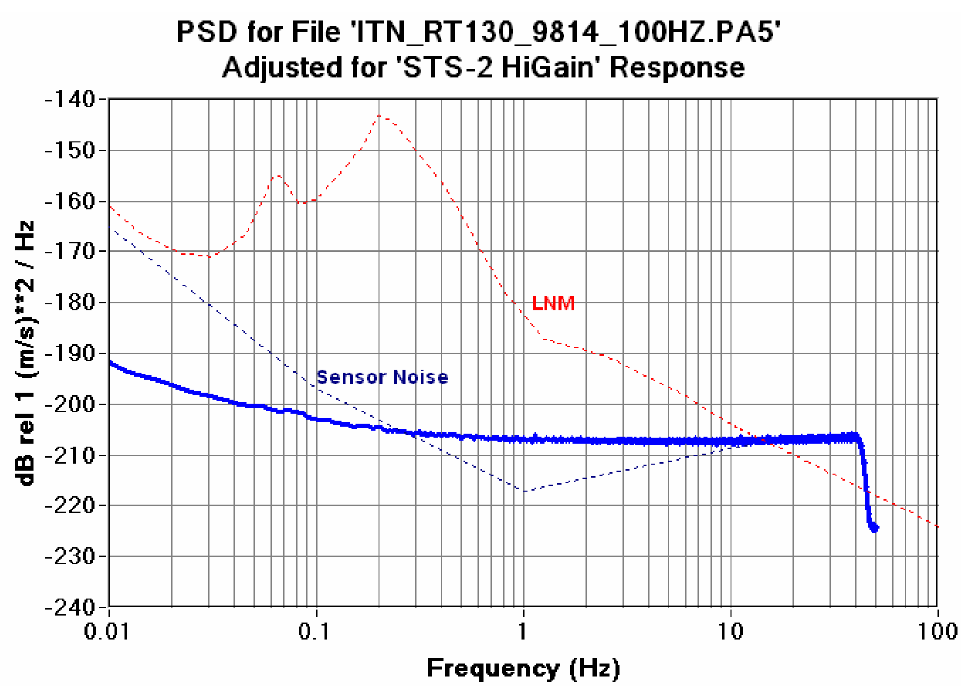

Figure 6.12.3b RT130HR 100SPS CH5 Seismic System Noise STS-2 High Gain

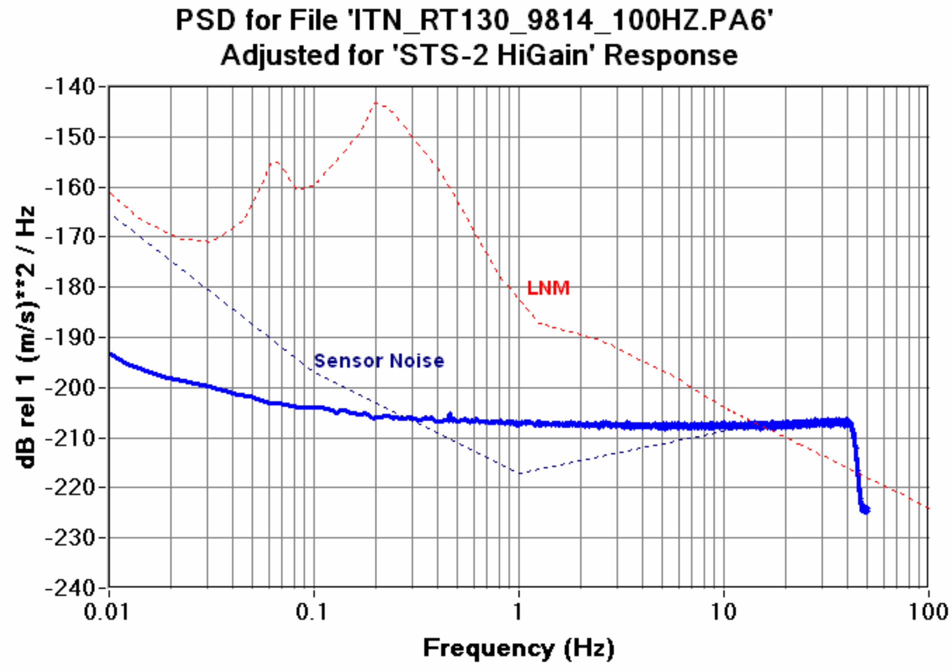

Figure 6.12.3c 330HR 100SPS CH6 Seismic System Noise STS-2 High Gain

<u>Test Results:</u>

Figures 6.12.3a-cicate that the response corrected noises of the RT130HR/B were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 13.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

6.12.4 RT130HR/A Sample Rate 40 sps/STS-2 High Gain:

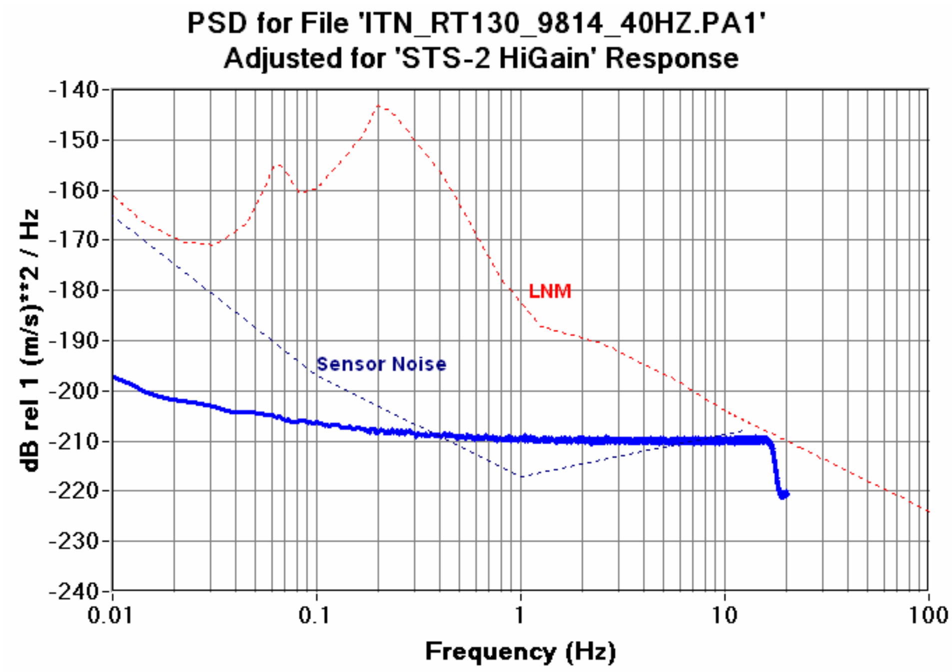

Figure 6.12.4a RT130HR 40SPS CH1 Seismic System Noise STS-2 High Gain

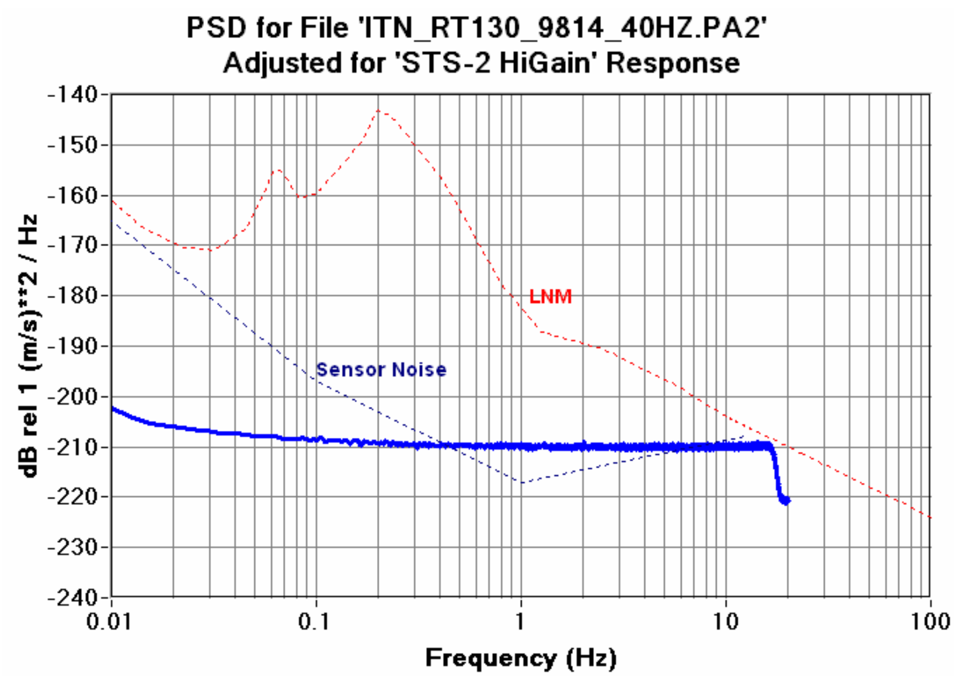

Figure 6.12.4b RT130HR 40SPS CH2 Seismic System Noise STS-2 High Gain

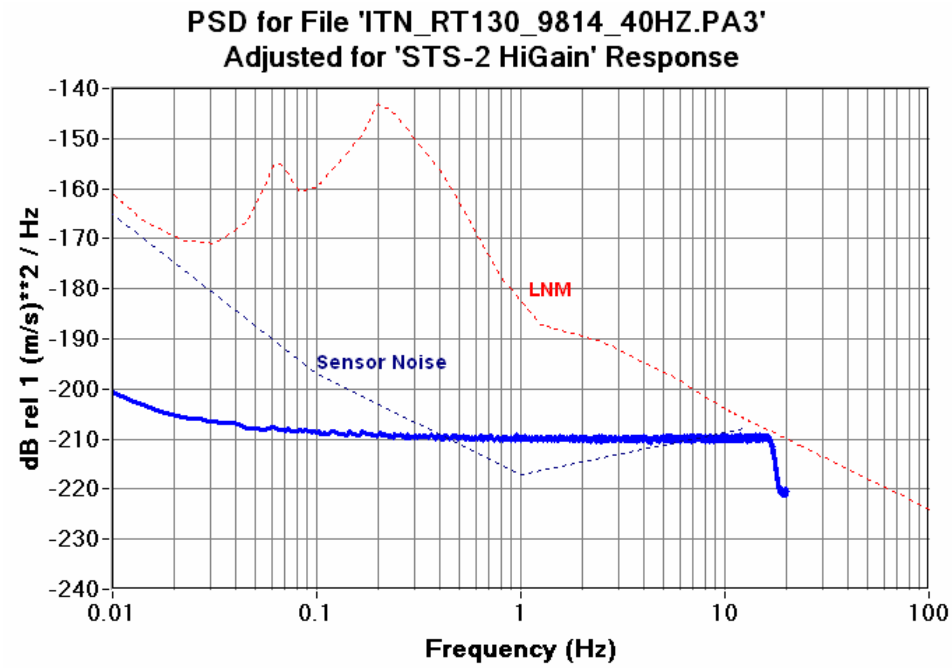

Figure 6.12.4c RT130HR 40SPS CH3 Seismic System Noise STS-2 High Gain

<u>Test Results:</u>
Figures 6.12.4-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 20.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

6.12.5 RT130HR/A Sample Rate 40 sps/STS-2 Low Gain:

Not Tested

6.12.6 RT130HR/B Sample Rate 40 sps/STS-2 High Gain:

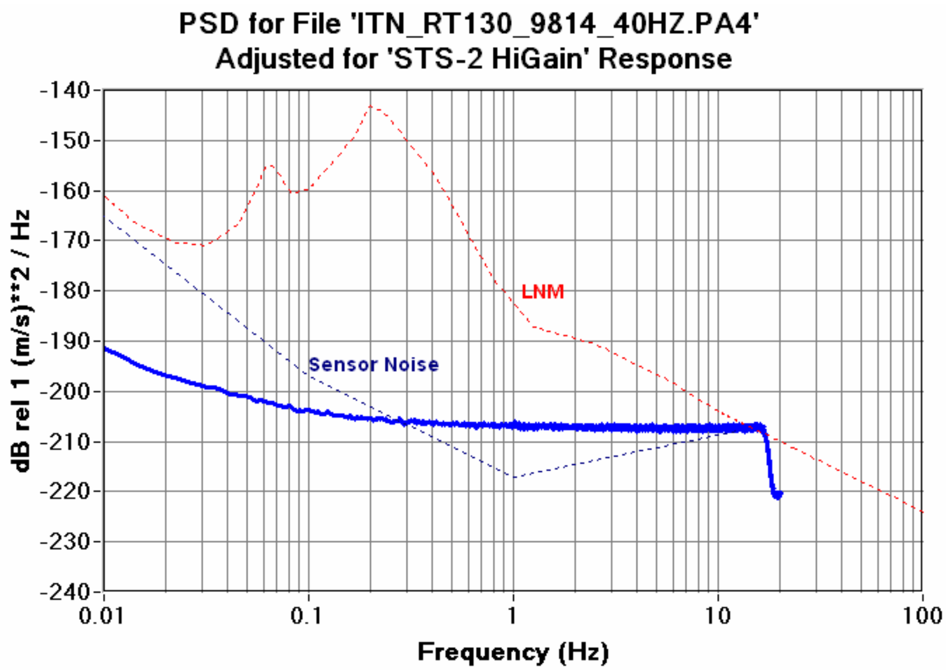

Figure 6.12.6a RT130HR 40SPS CH4 Seismic System Noise STS-2 High Gain

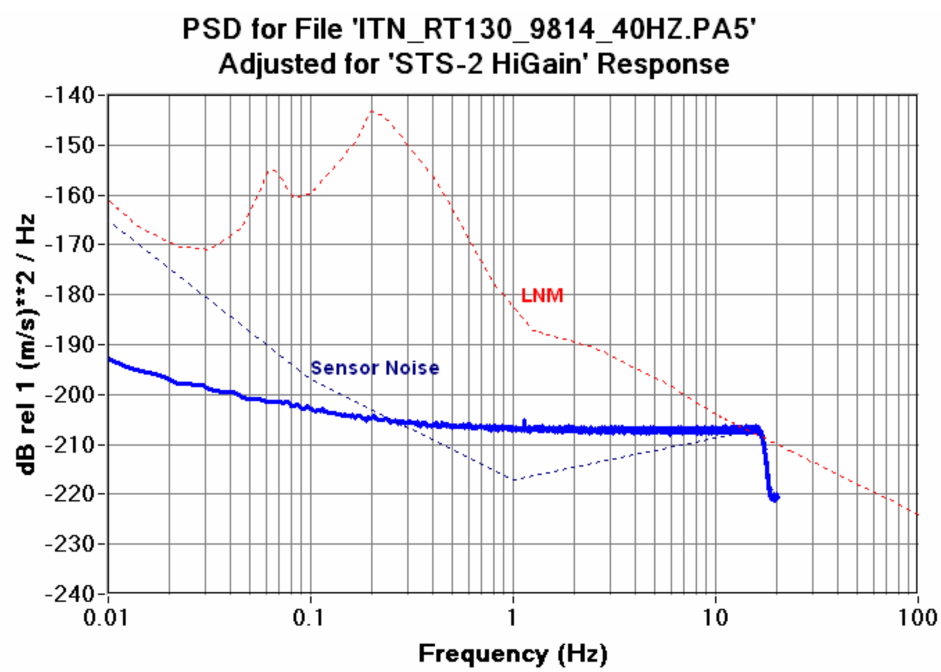

Figure 6.12.6b RT130HR 40SPS CH5 Seismic System Noise STS-2 High Gain

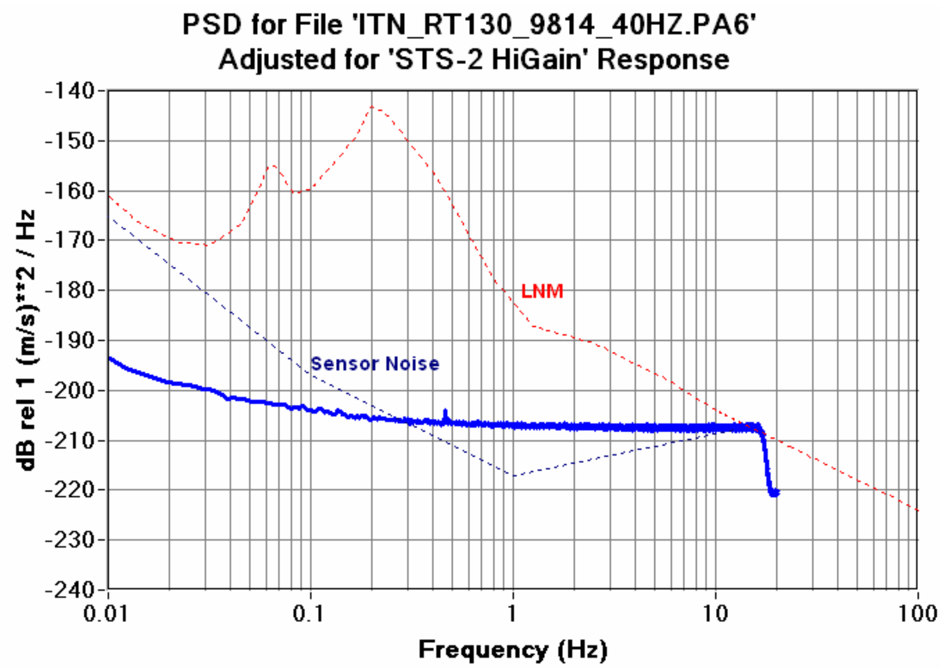

Figure 6.12.6c RT130HR 40SPS CH6 Seismic System Noise STS-2 High Gain

<u>Test Results:</u>

Figures 6.12.6a-c indicate that the response corrected noises of the RT130HR/B were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 16.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

6.12.7 RT130HR/A Sample Rate 20 sps/STS-2 High Gain:

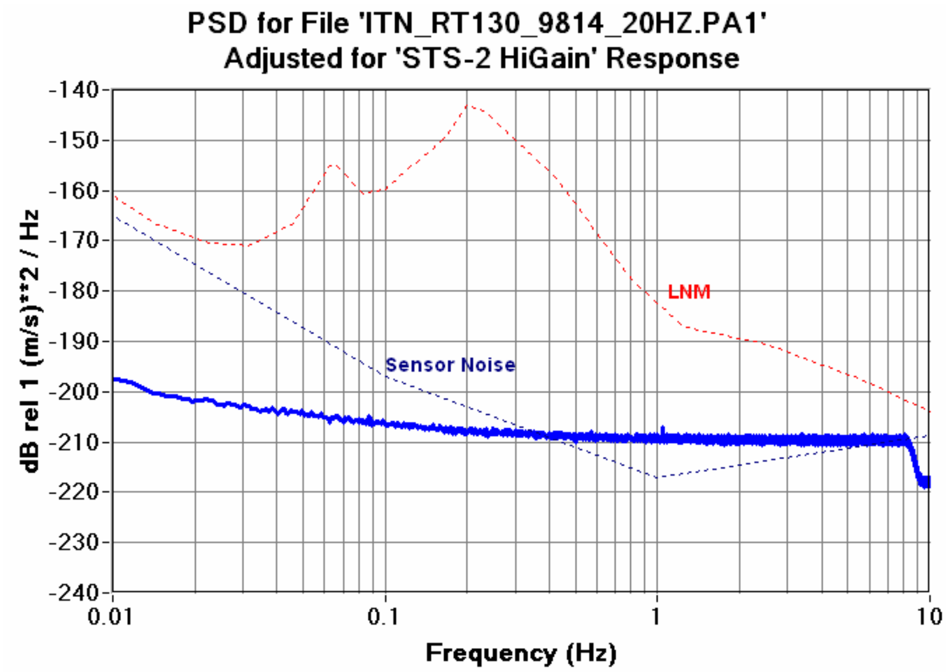

Figure 6.12.7a RT130HR 20SPS CH1 Seismic System Noise STS-2 High Gain

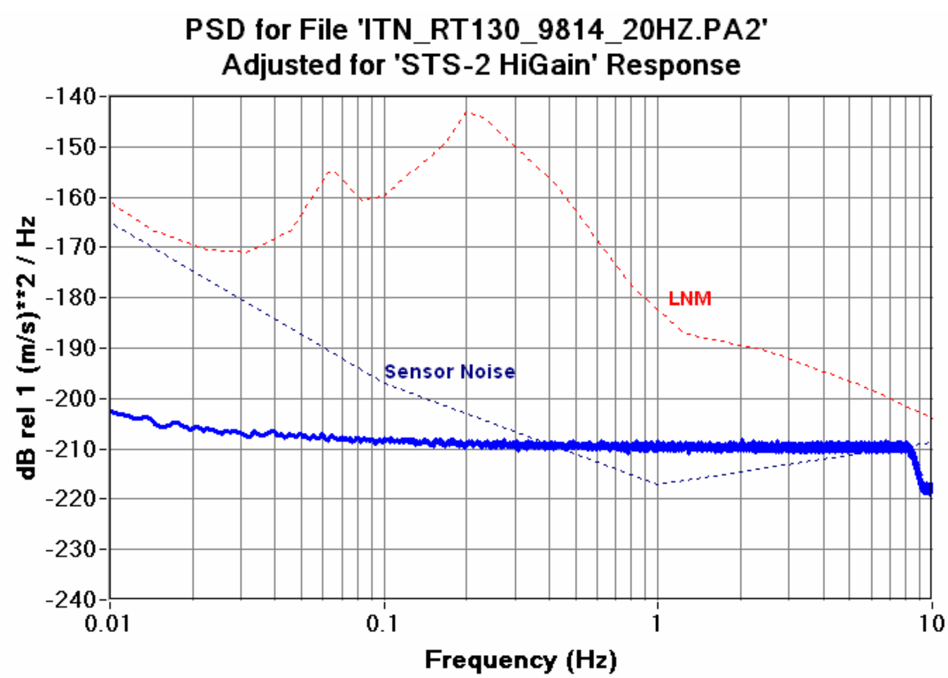

Figure 6.12.7b RT130HR 20SPS CH2 Seismic System Noise STS-2 High Gain

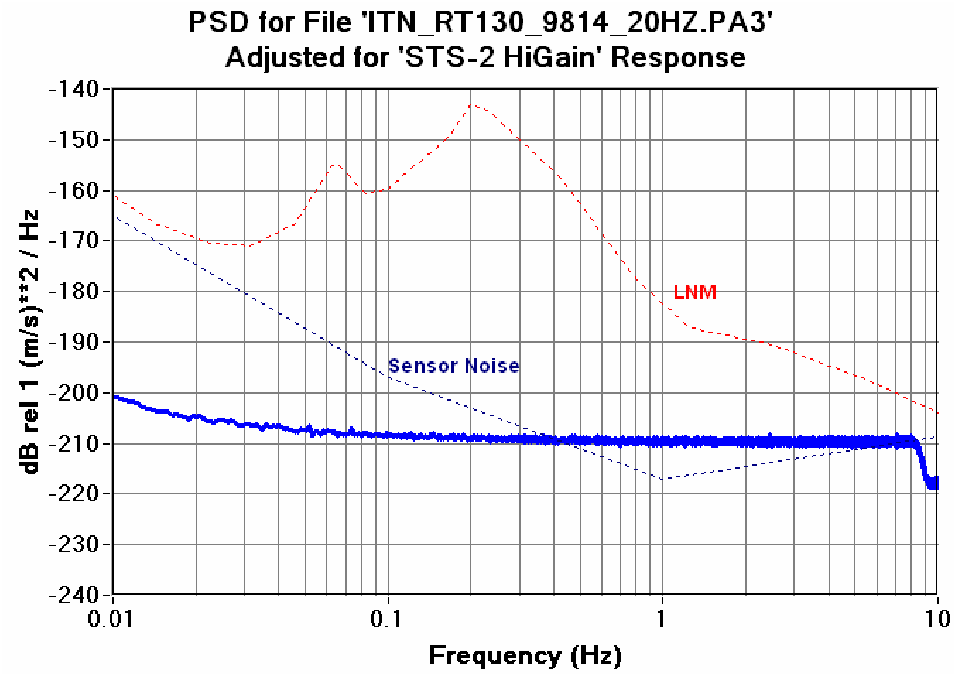

Figure 6.12.7c RT130HR 20SPS CH3 Seismic System Noise STS-2 High Gain

Test Results:
Figures 6.12.7a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.01 and 10.0 Hz when used with a Streckeisen STS-2 High Gain seismometer.

6.12.8 RT130HR/A Sample Rate 20 sps/CMG-3TB High Gain:

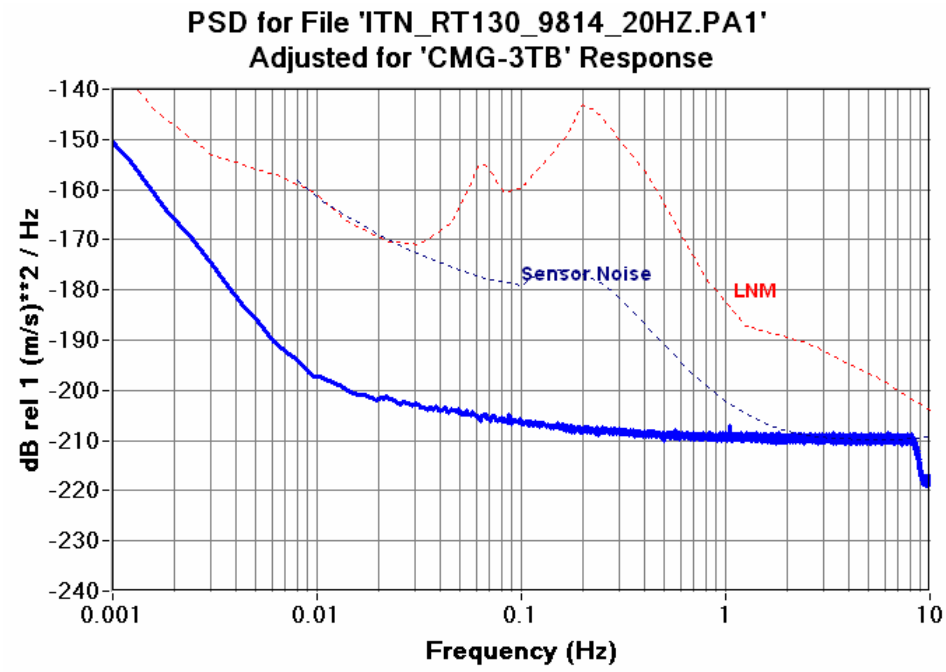

Figure 6.12.8a RT130HR 20SPS CH1 Seismic System Noise CMG-3TB

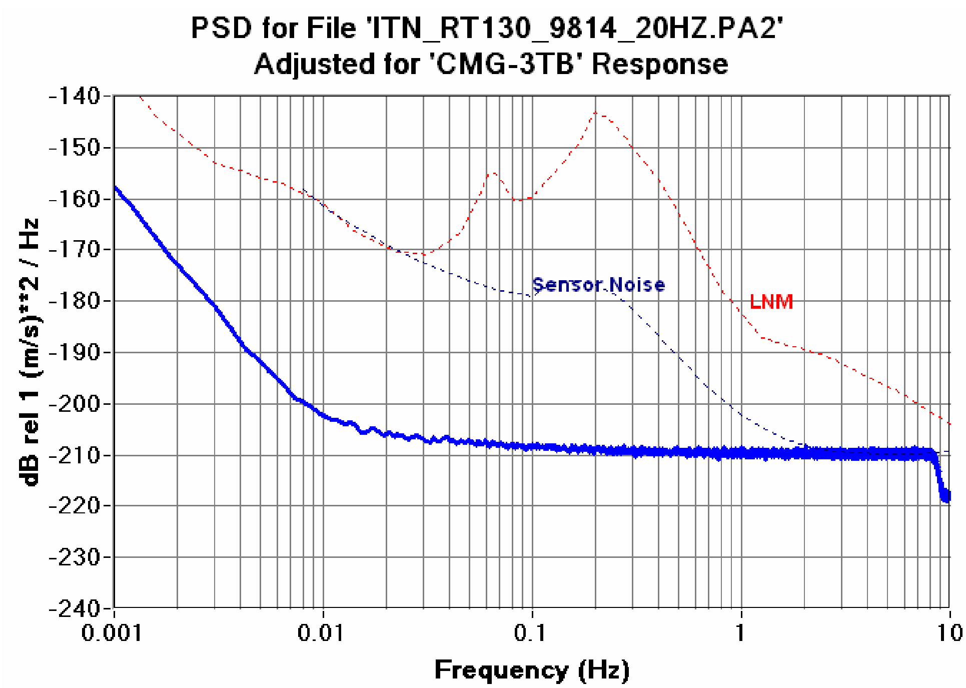

Figure 6.12.8b RT130HR 20SPS CH2 Seismic System Noise CMG-3TB

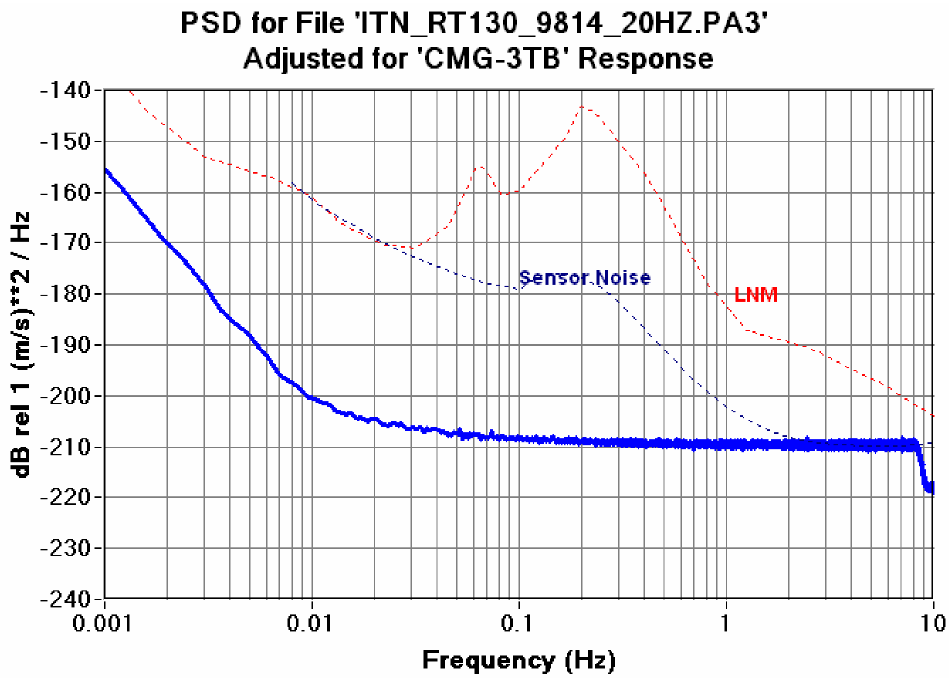

Figure 6.12.8c RT130HR 20SPS CH3 Seismic System Noise CMG-3TB

<u>Test Results:</u>
Figures 6.12.8a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 10.0 Hz when used with a Guralp CMG-3TB seismometer.

6.12.9 RT130HR/A Sample Rate 20 sps/STS-1:

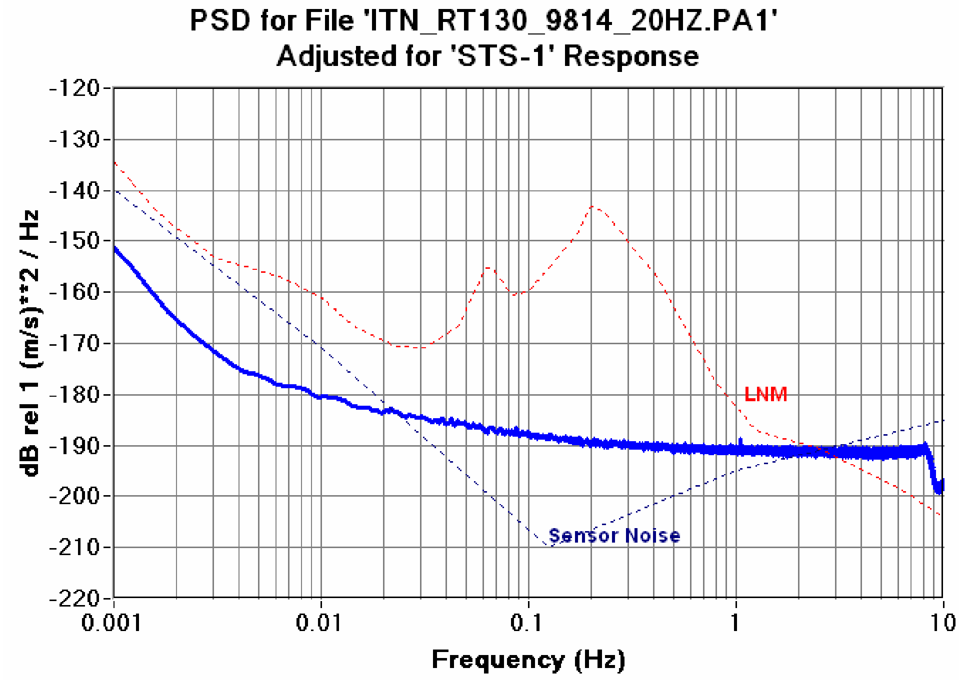

Figure 6.12.9a RT130HR 20SPS CH1 Seismic System Noise STS-1

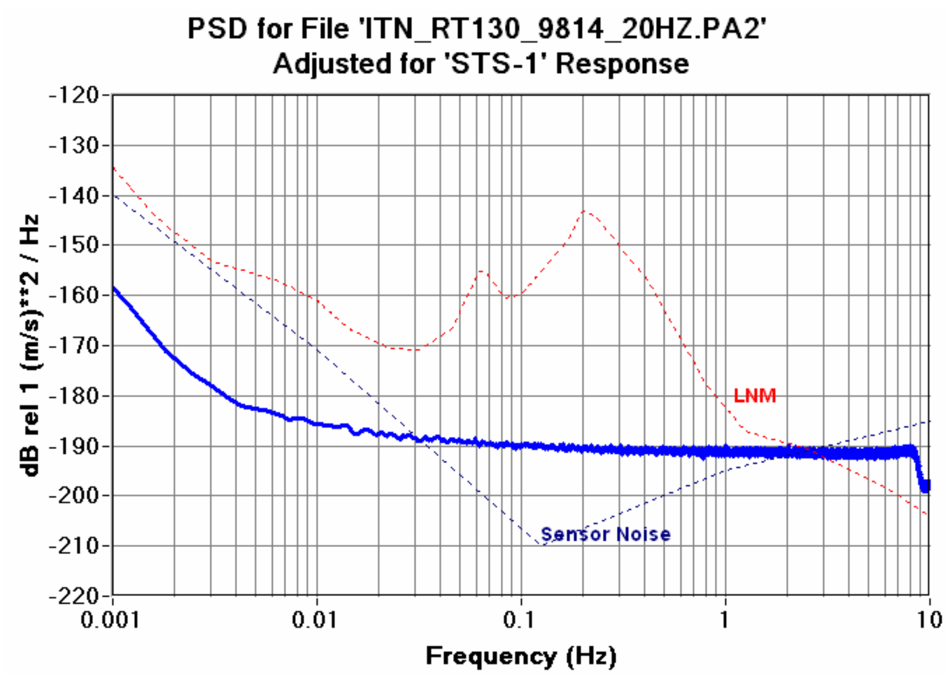

Figure 6.12.9b RT130HR 20SPS CH2 Seismic System Noise STS-1

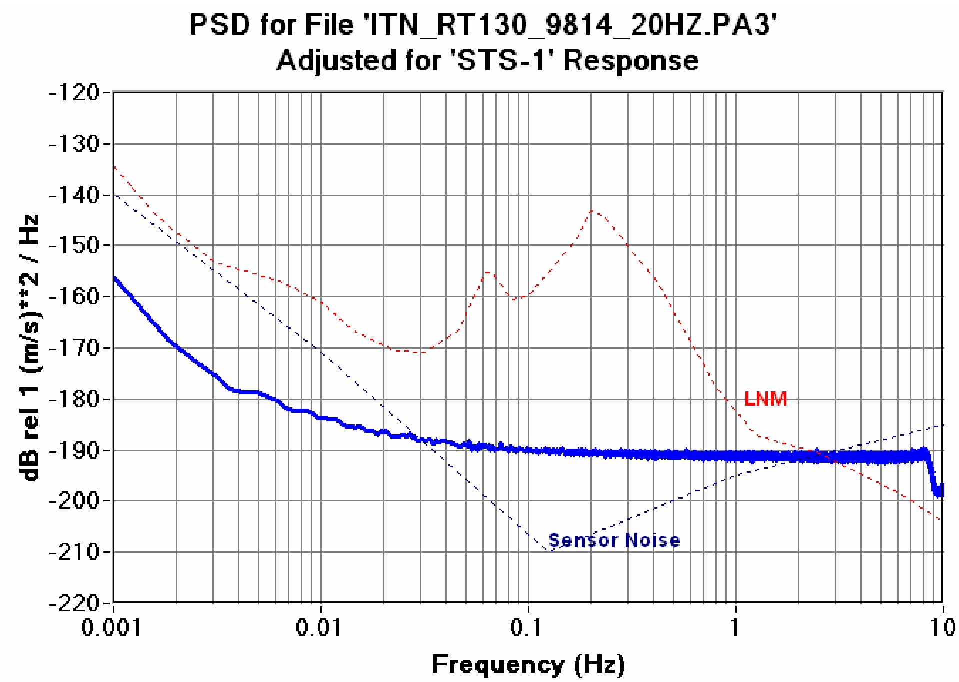

Figure 6.12.9c RT130HR 20SPS CH3 Seismic System Noise STS-1

<u>Test Results:</u>
Figures 6.12.9a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 3.0 Hz when used with a Streckeisen STS-1 seismometer.

6.12.10 RT130HR/A Sample Rate 20 sps/KS54000:

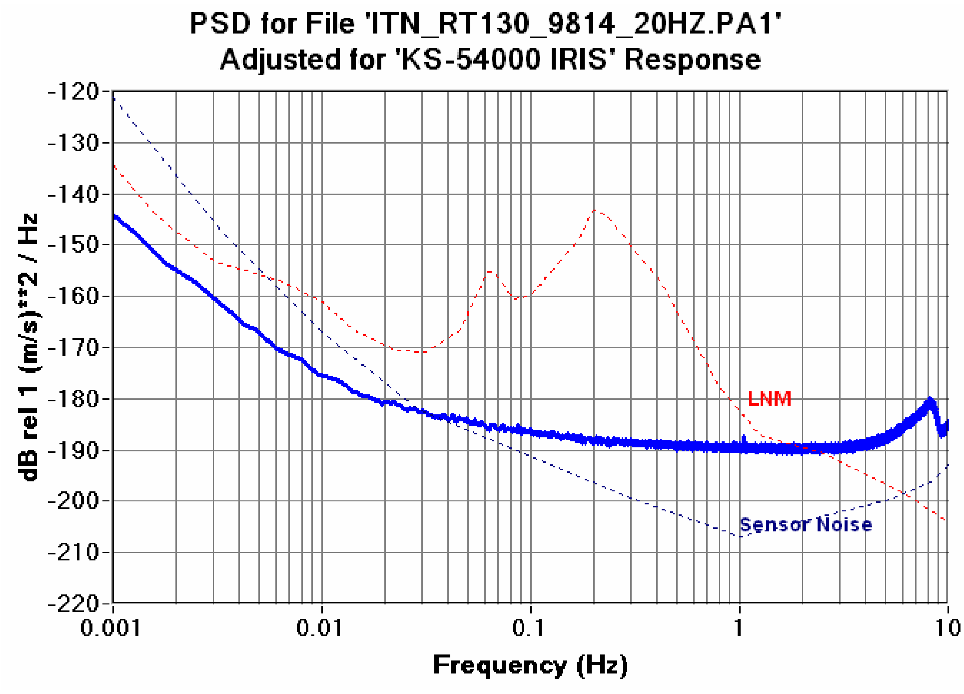

Figure 6.12.10a RT130HR 20SPS CH1 Seismic System Noise KS54000

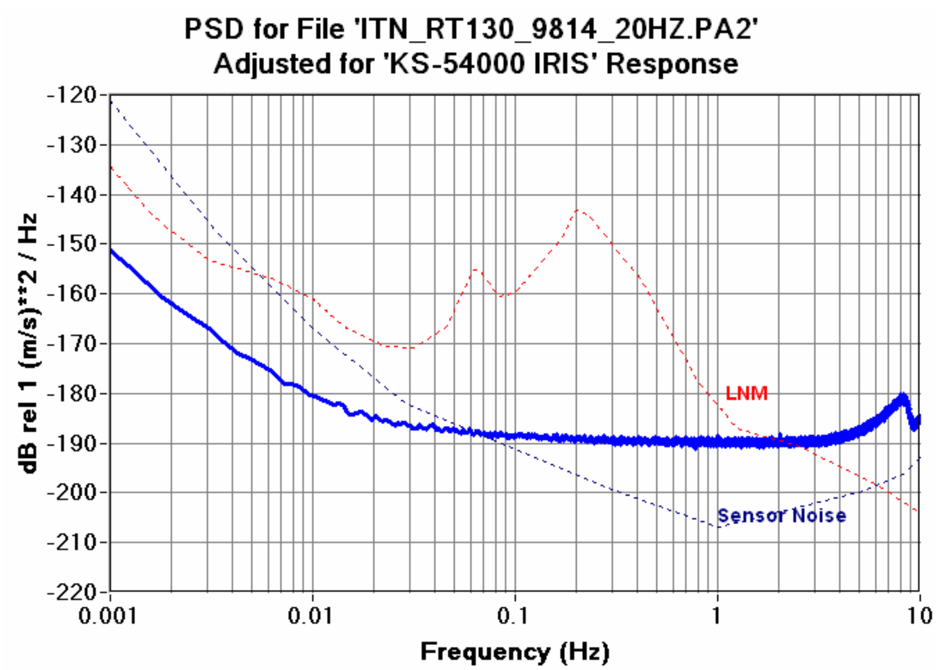

Figure 6.12.10b RT130HR 20SPS CH2 Seismic System Noise KS54000

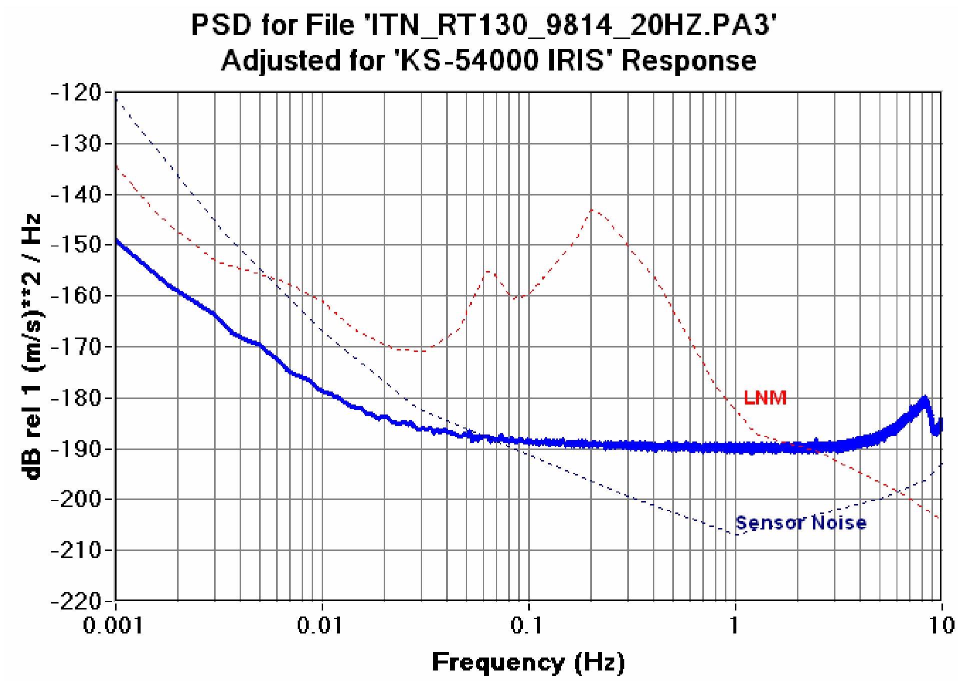

Figure 6.12.10c RT130HR 20SPS CH3 Seismic System Noise KS54000

<u>Test Results:</u>

Figures 6.12.10a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 2.0 Hz when used with a Geotech KS54000 seismometer.

6.12.11 RT130HR/A Sample Rate 1 sps/STS-1:

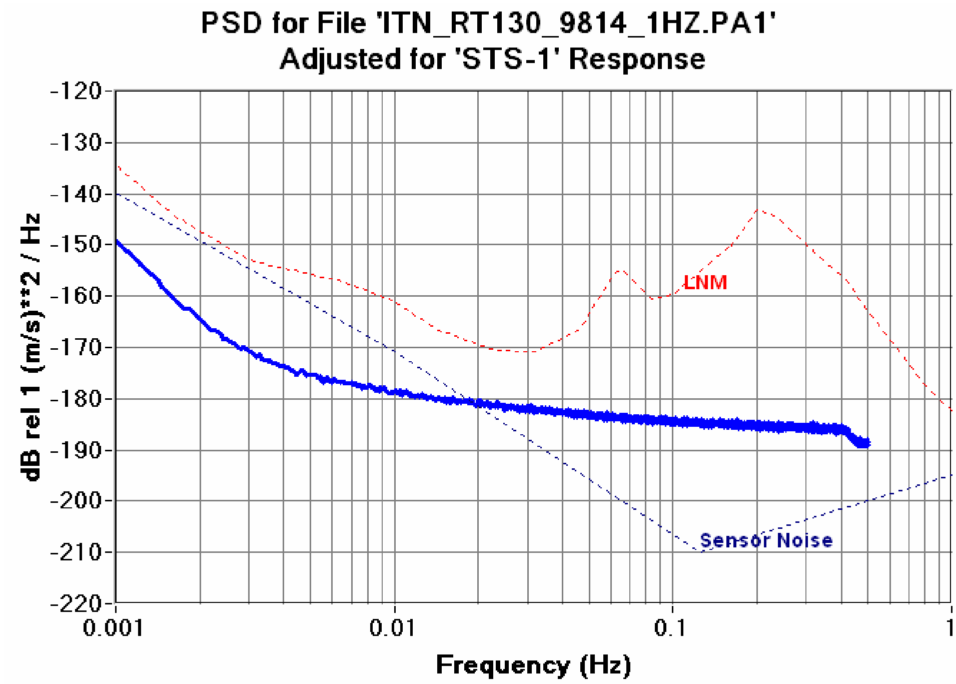

Figure 6.12.11a RT130HR 1SPS CH1 Seismic System Noise STS-1

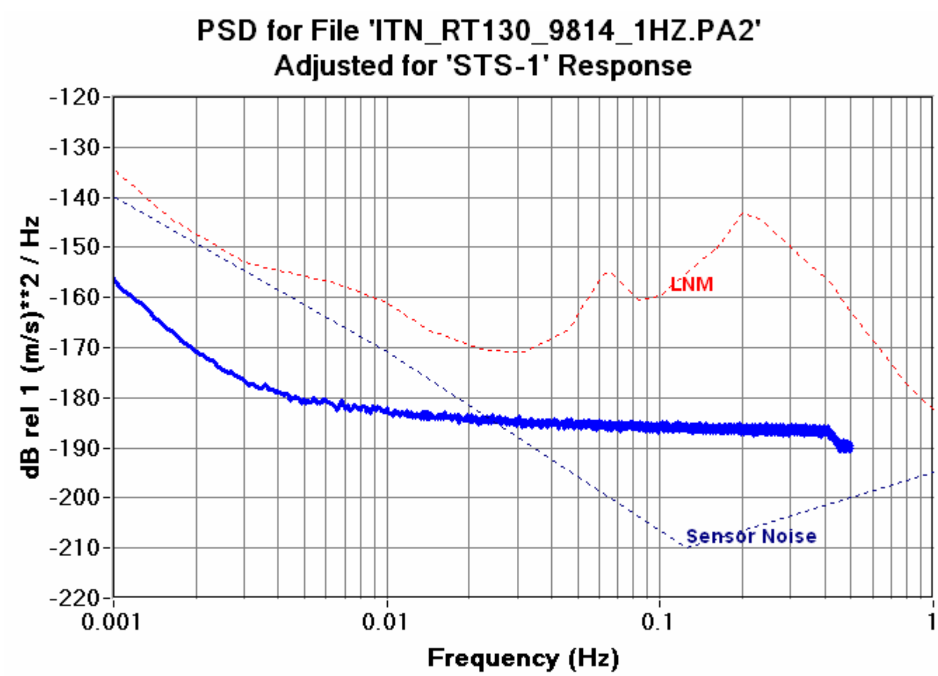

Figure 6.12.11b RT130HR 1SPS CH2 Seismic System Noise STS-1

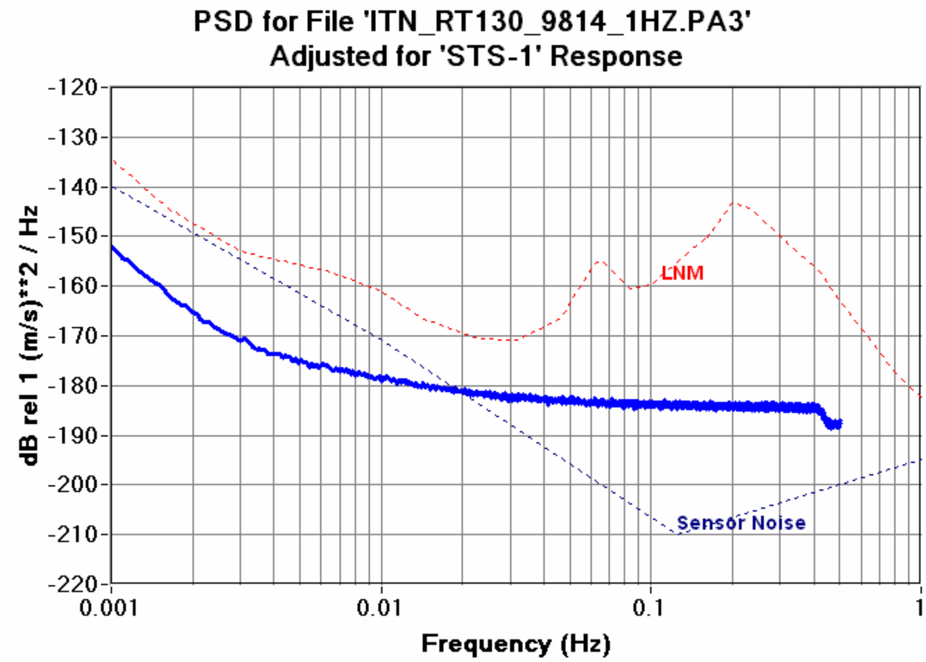

Figure 6.12.11c RT130HR 1SPS CH3 Seismic System Noise STS-1

<u>Test Results:</u>

Figures 6.12.11a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Streckeisen STS-1 seismometer.

6.12.12 RT130HR/A Sample Rate 1 sps/KS54000:

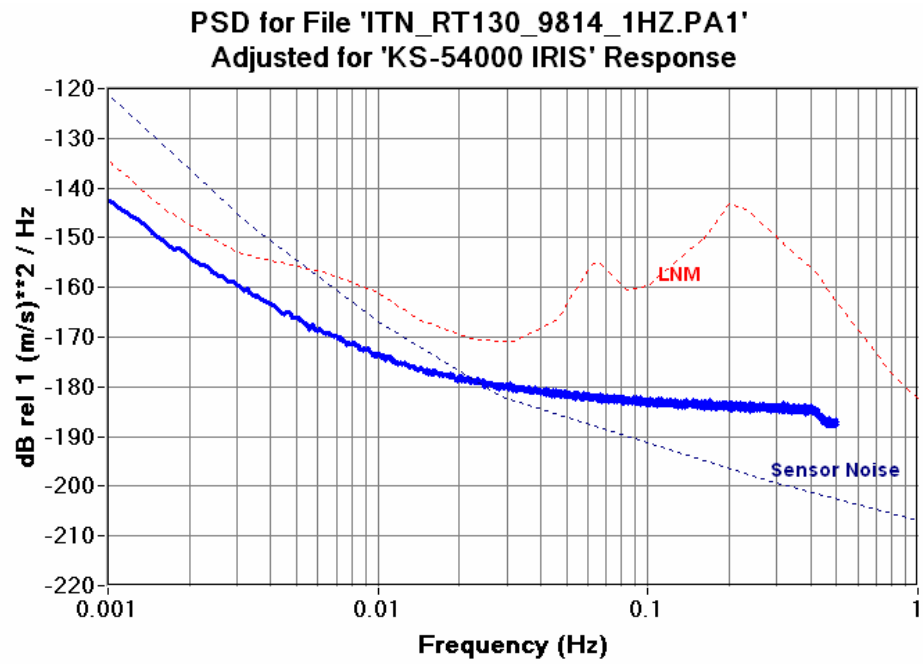

Figure 6.12.12a RT130HR 1SPS CH1 Seismic System Noise KS54000

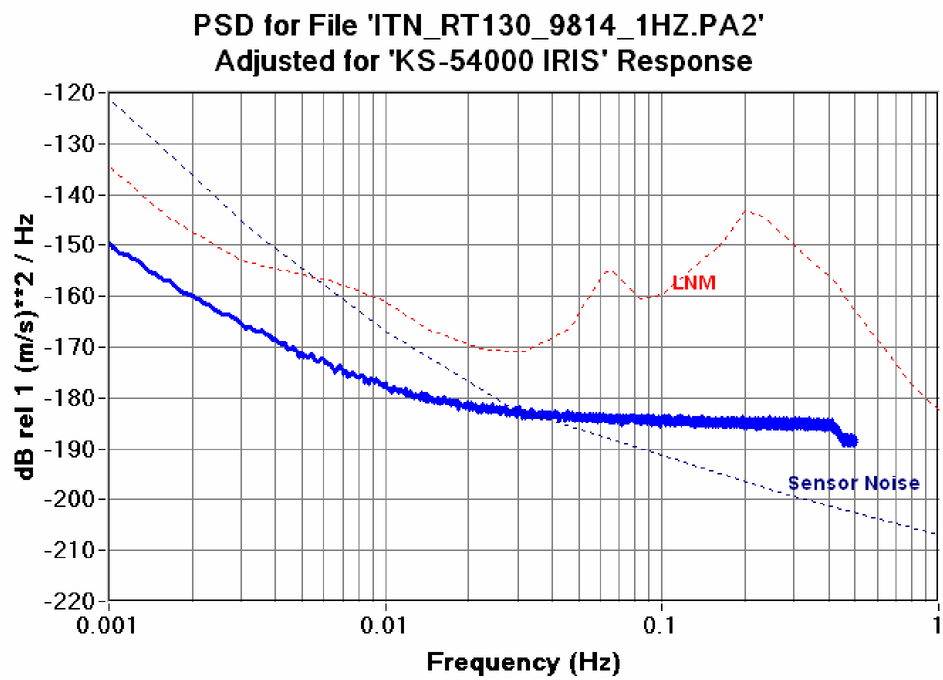

Figure 6.12.12b RT130HR 1SPS CH2 Seismic System Noise KS54000

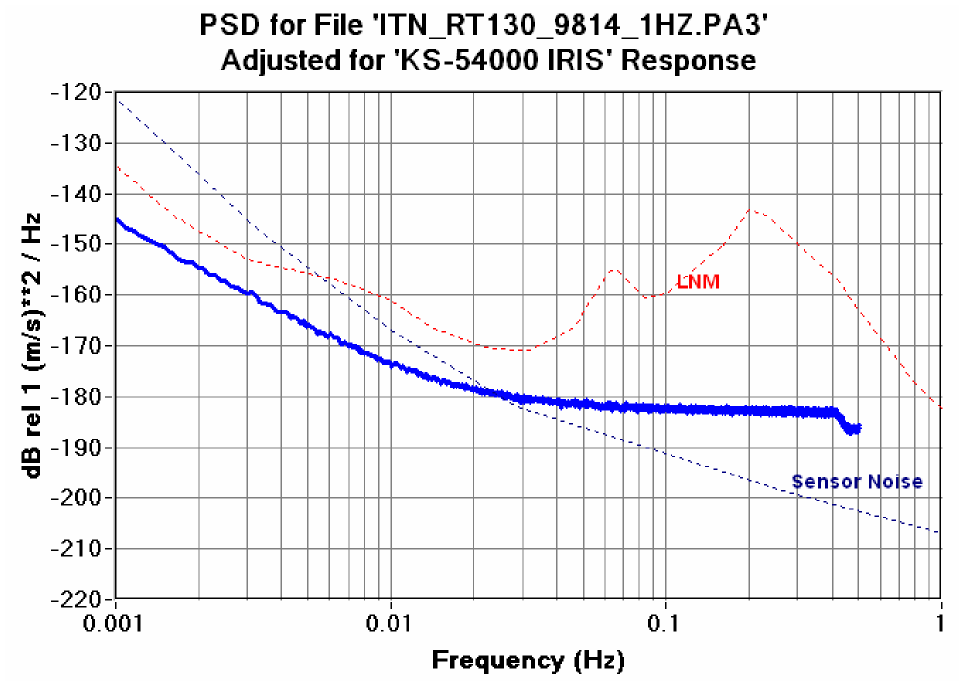

Figure 6.12.12c RT130HR 1SPS CH3 Seismic System Noise KS54000

<u>Test Results:</u>
Figures 6.12.12a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a KS54000 seismometer.

6.12.13 RT130HR/B Sample Rate 1 sps/STS-1:

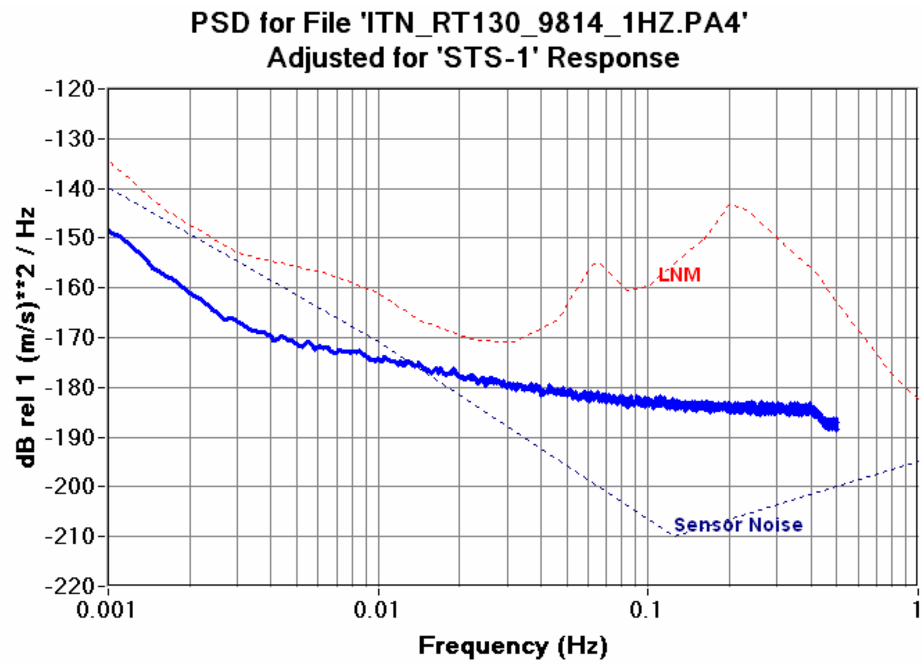

Figure 6.12.13a RT130HR 1SPS CH4 Seismic System Noise STS-1

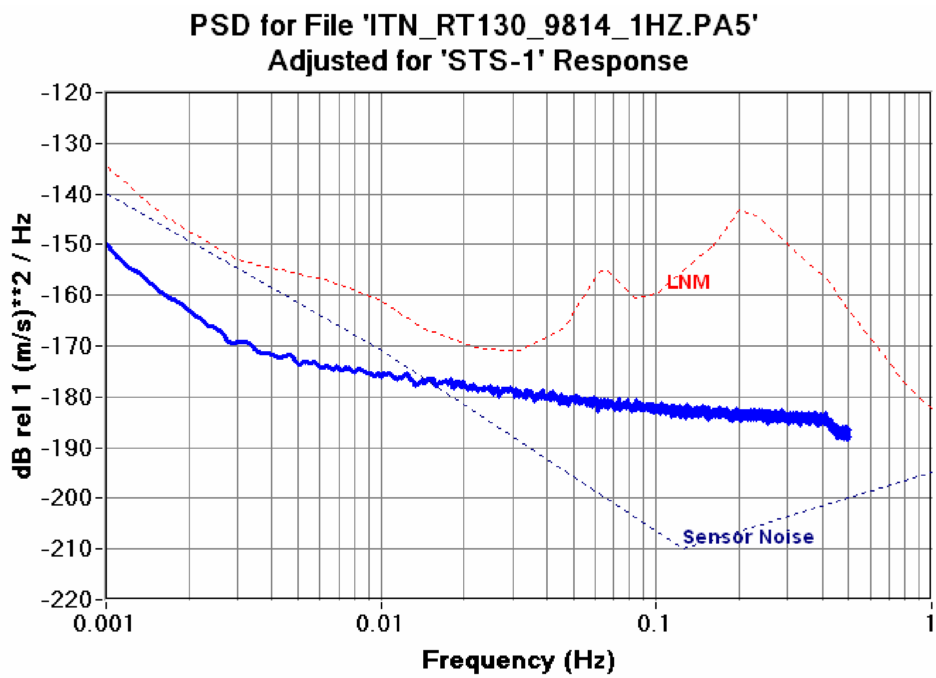

Figure 6.12.13b RT130HR 1SPS CH5 Seismic System Noise STS-1

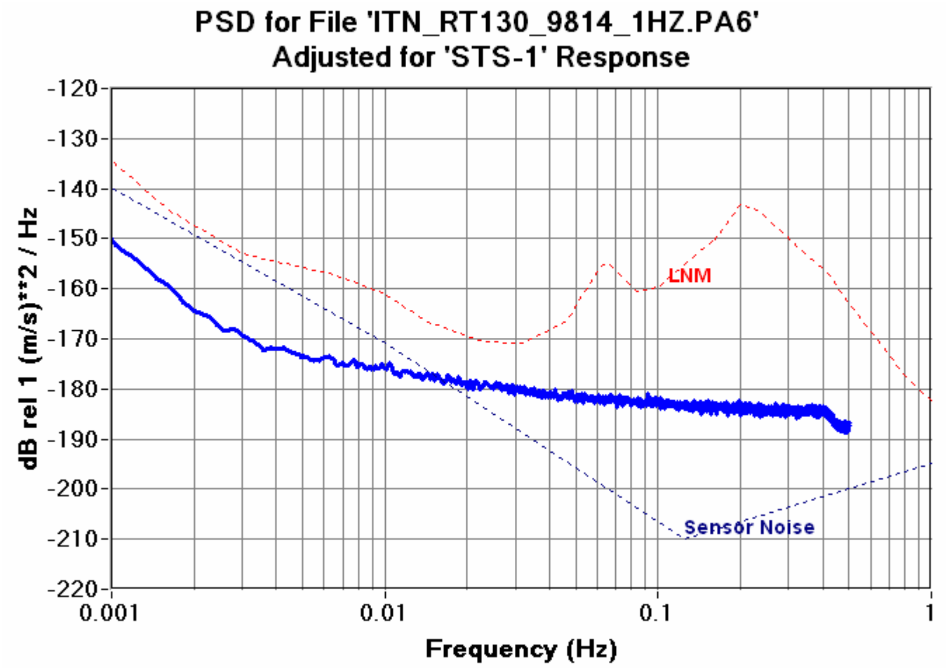

Figure 6.12.13c RT130HR 1SPS CH6 Seismic System Noise STS-1

<u>Test Results:</u>
Figures 6.12.13a-c indicate that the response corrected noises of the RT130HR/B were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Streckeisen STS-1 seismometer.

6.12.14 RT130HR/B Sample Rate 1 sps/KS54000:

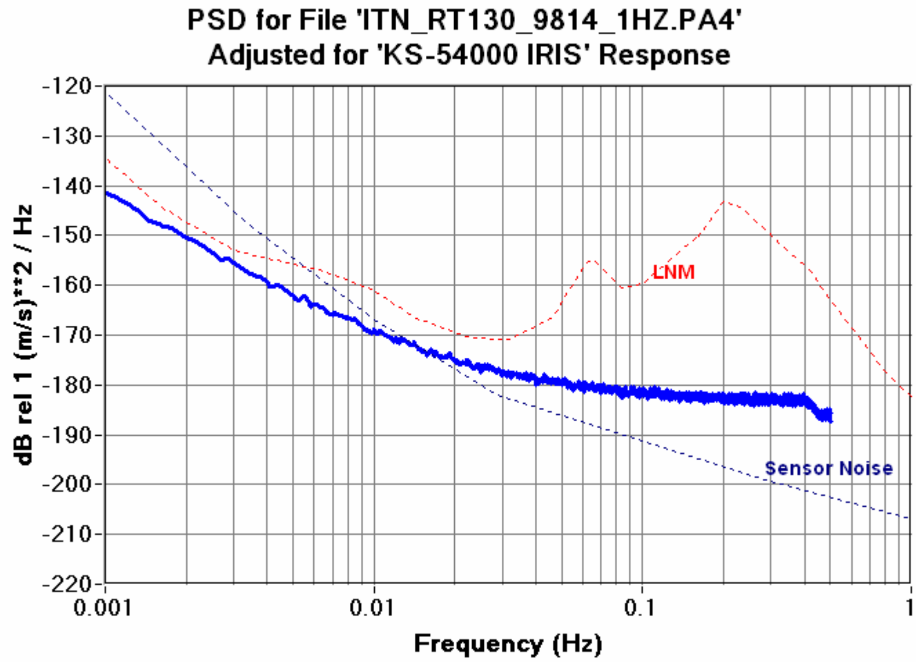

Figure 6.12.14a RT130HR 1SPS CH4 Seismic System Noise KS54000

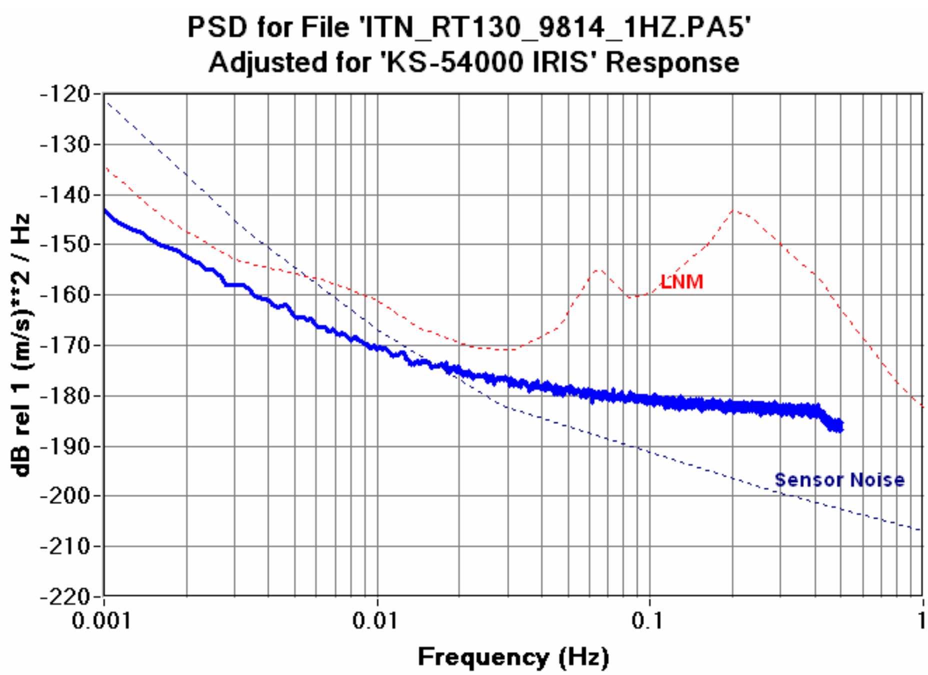

Figure 6.12.14b RT130HR 1SPS CH5 Seismic System Noise KS54000

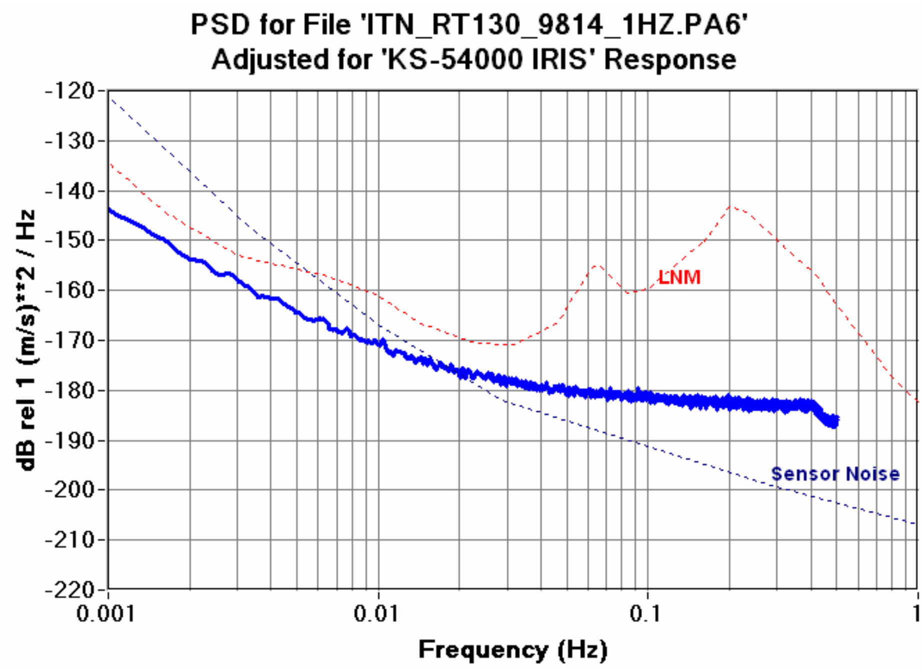

Figure 6.12.14c RT130HR 1SPS CH6 Seismic System Noise KS54000

<u>Test Results:</u>
Figures 6.12.14a-c indicate that the response corrected noises of the RT130HR/B were at or below the USGS Low Earth Noise Model (LNM) between 0.004 and 0.5 Hz when used with a KS54000 seismometer.

6.12.15 RT130HR/B Sample Rate 1 sps/CMG-3TB:

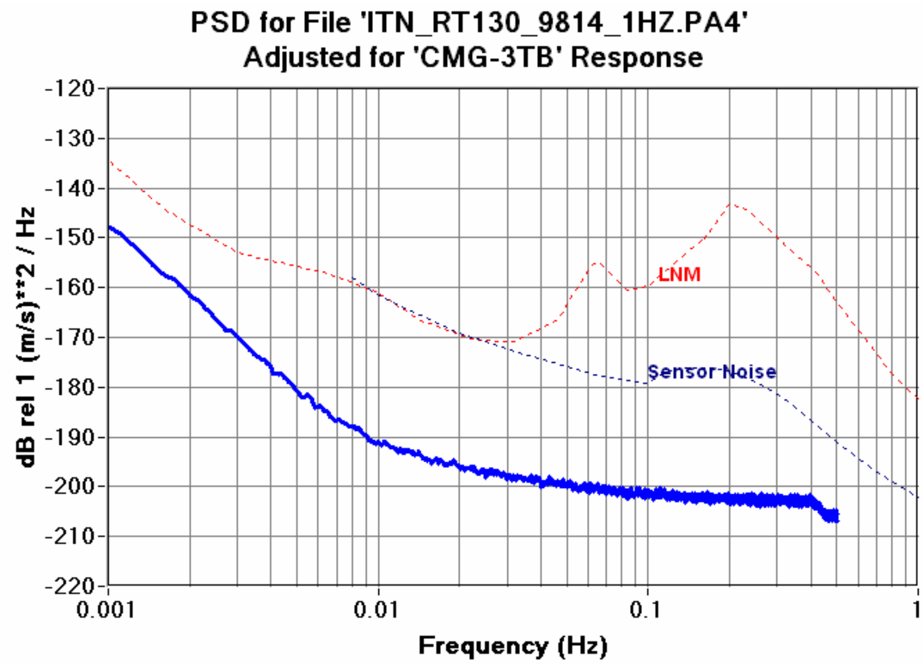

Figure 6.12.15a RT130HR 1SPS CH4 Seismic System Noise CMG-3TB

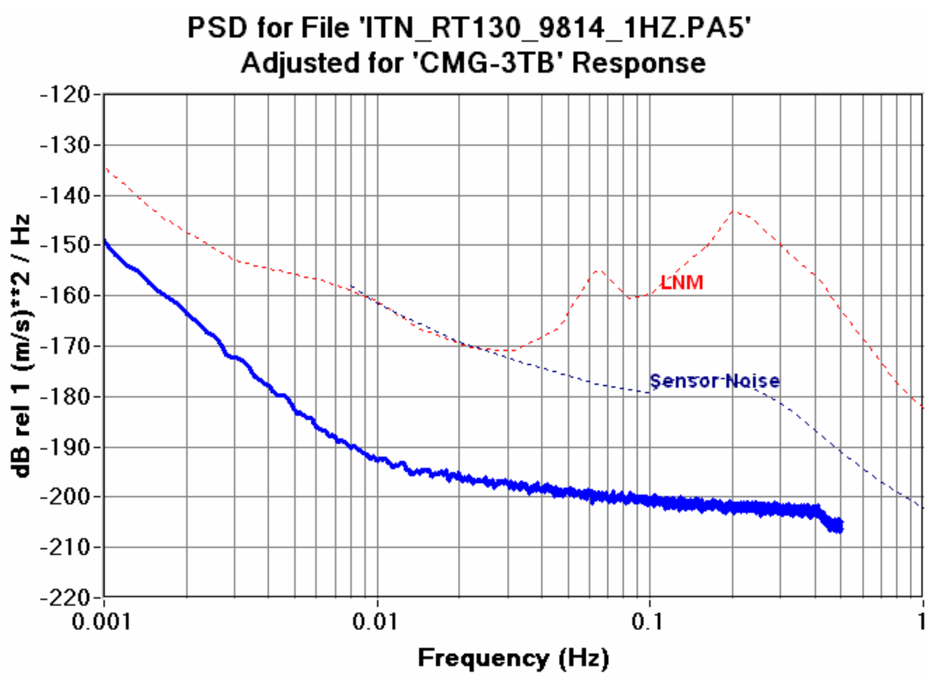

Figure 6.12.15b RT130HR 1SPS CH5 Seismic System Noise CMG-3TB

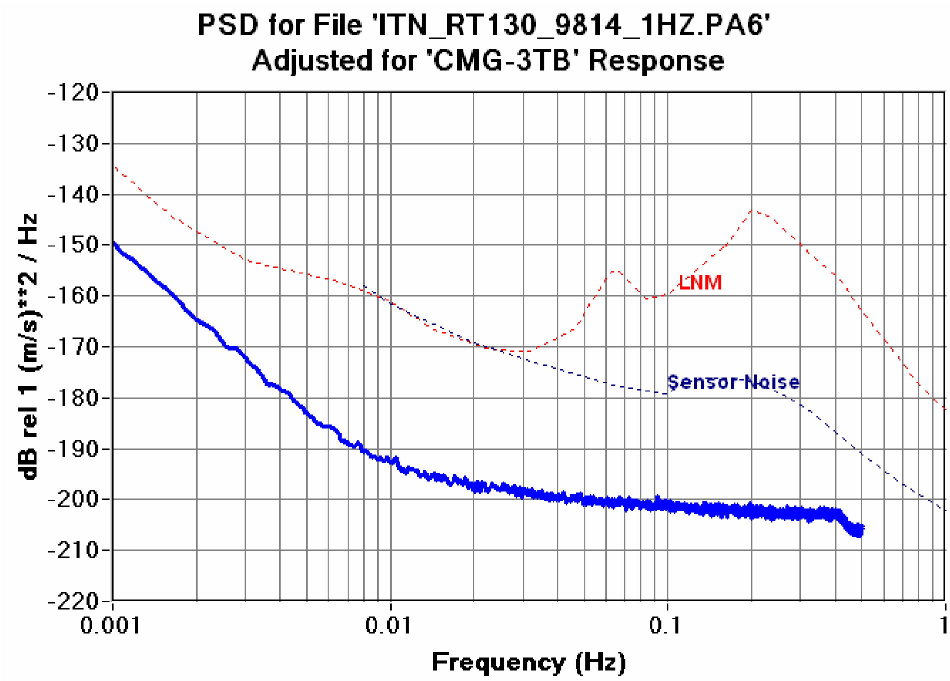

Figure 6.12.15c RT130HR 1SPS CH6 Seismic System Noise CMG-3TB

<u>Test Results:</u>
Figures 6.12.15a-c indicate that the response corrected noises of the RT130HR/B were at or below the USGS Low Earth Noise Model (LNM) between 0.001 and 0.5 Hz when used with a Guralp CMG-3TB seismometer.

6.12.16 RT130HR/A Sample Rate 0.1 sps/STS-1:

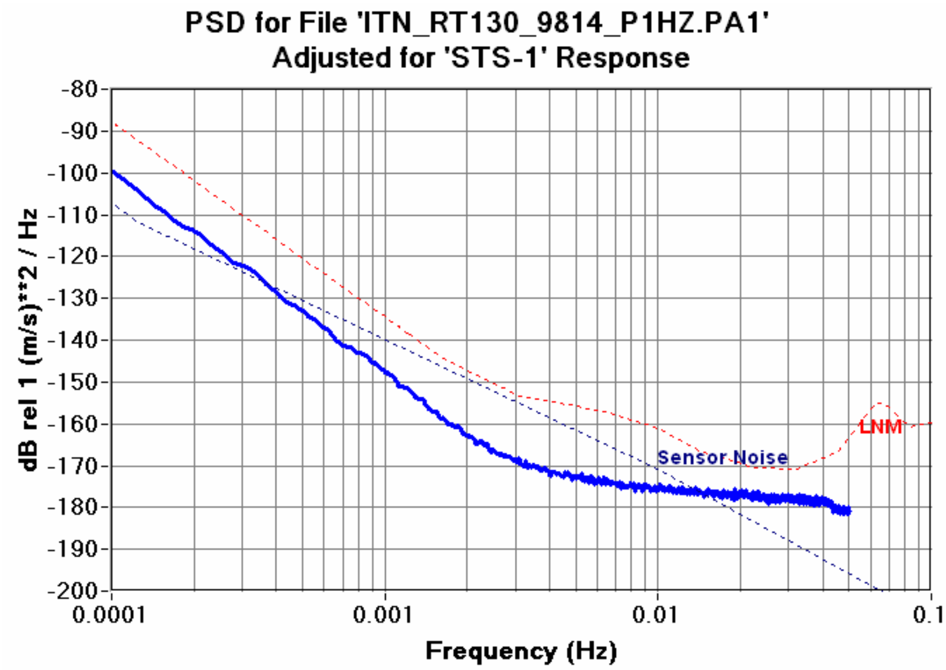

Figure 6.12.16a RT130HR 0.1SPS CH1 Seismic System Noise STS-1

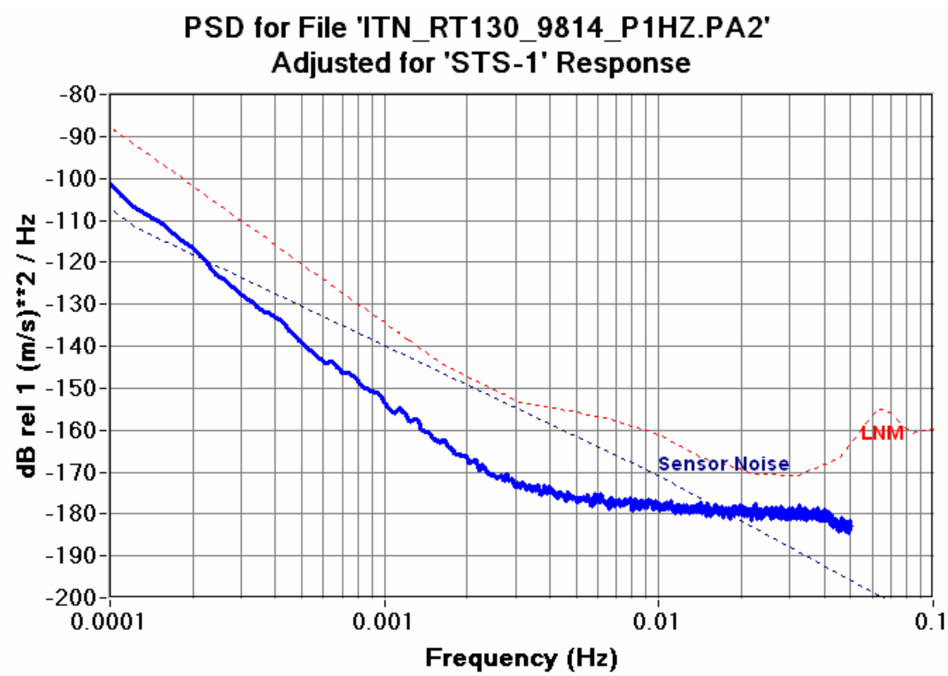

Figure 6.12.16b RT130HR 0.1SPS CH2 Seismic System Noise STS-1

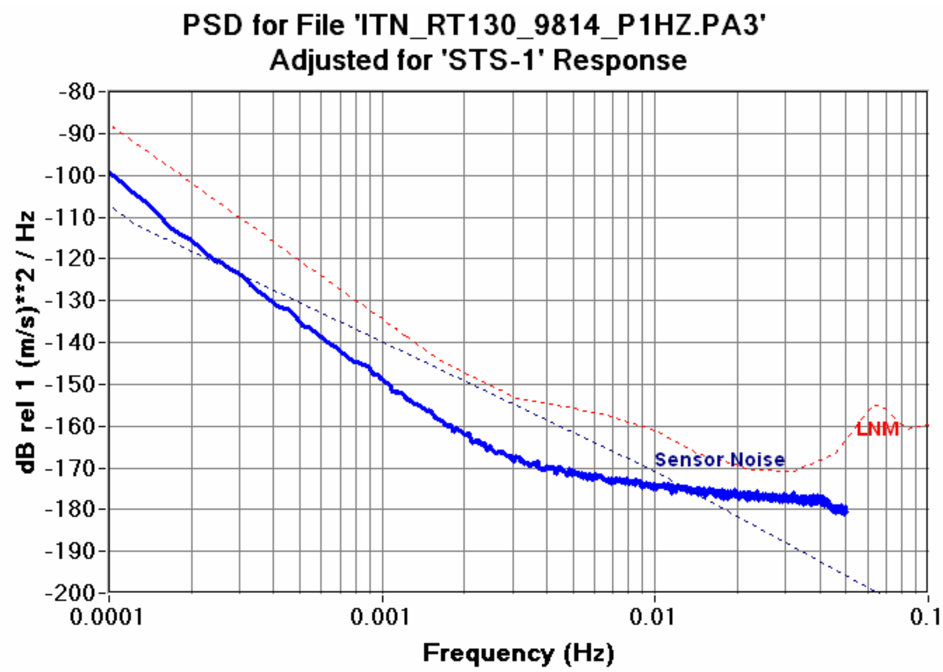

Figure 6.12.16c RT130HR 0.1SPS CH3 Seismic System Noise STS-1

<u>Test Results:</u>
Figures 6.12.16a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.0001 and 0.05 Hz when used with a Streckeisen STS-1 seismometer.

6.12.17 RT130HR/A Sample Rate 0.1 sps/KS54000:

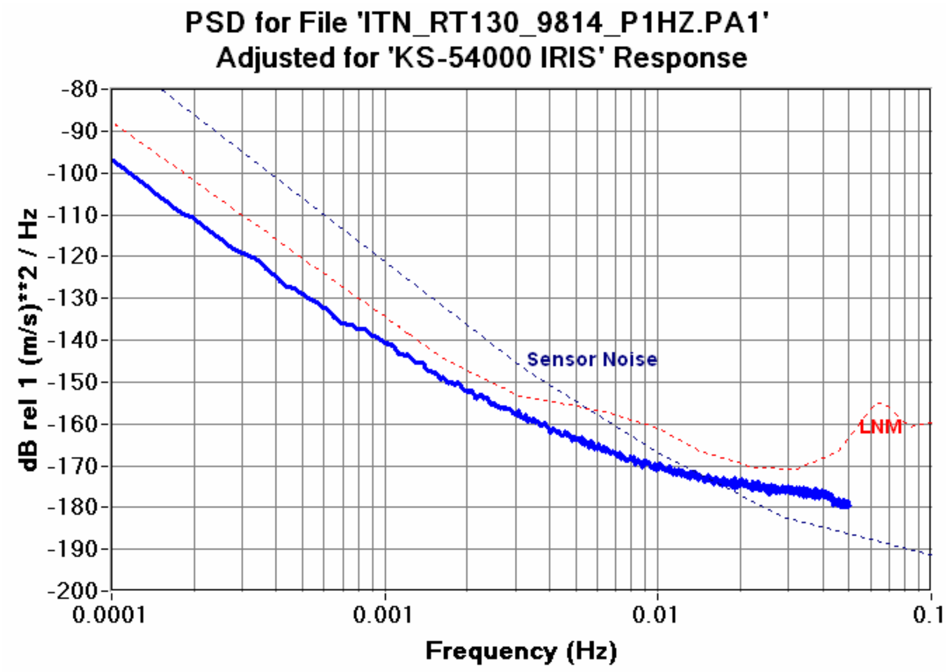

Figure 6.12.17a RT130HR 0.1SPS CH1 Seismic System Noise KS54000

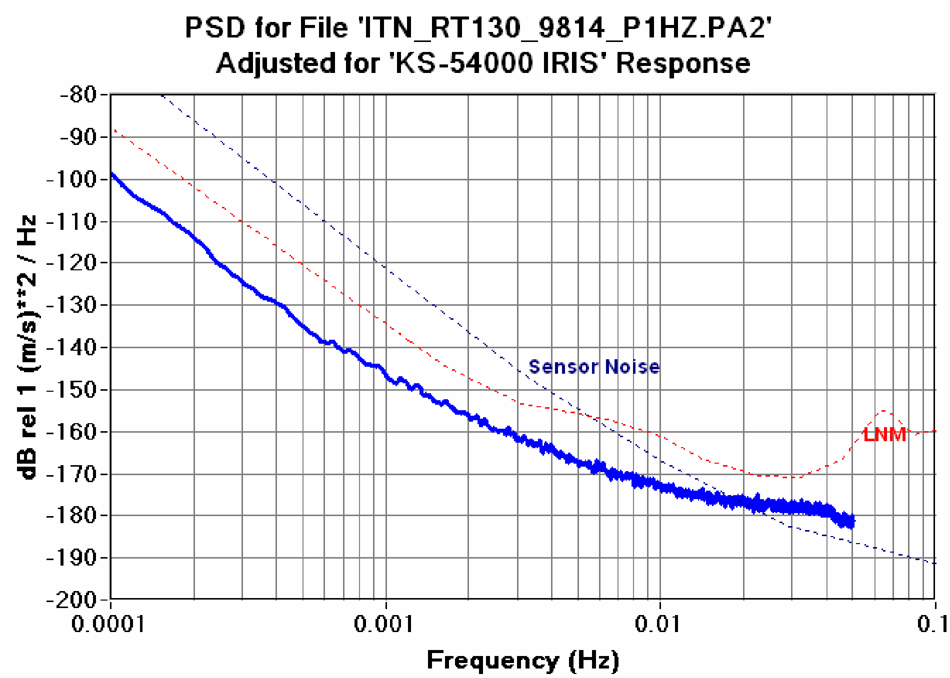

Figure 6.12.17b RT130HR 0.1SPS CH2 Seismic System Noise KS54000

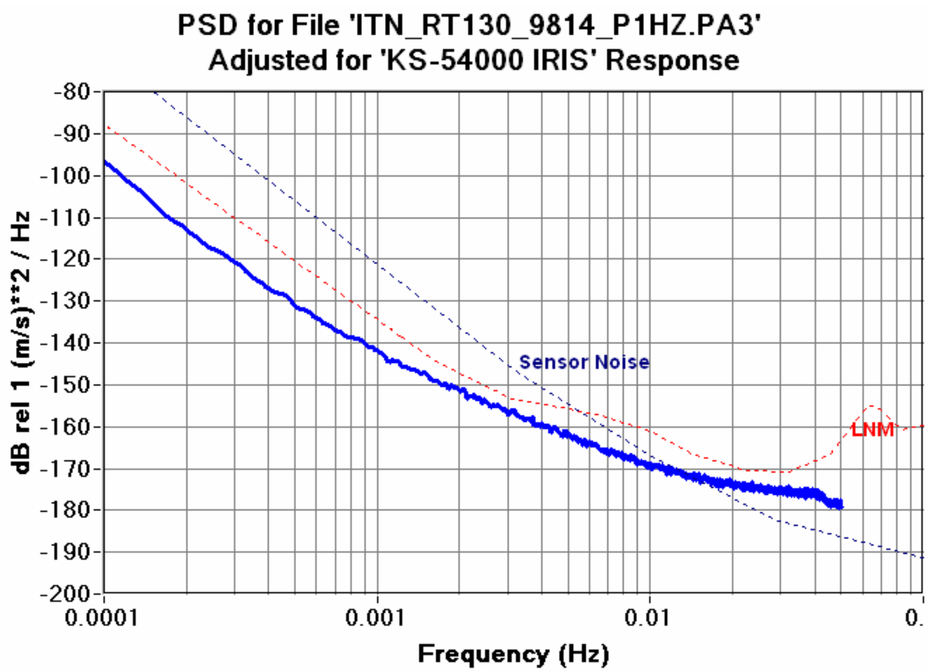

Figure 6.12.17c RT130HR 0.1SPS CH3 Seismic System Noise KS54000

<u>Test Results:</u>
Figures 6.12.17a-c indicate that the response corrected noises of the RT130HR/A were at or below the USGS Low Earth Noise Model (LNM) between 0.0001 and 0.05 Hz when used with a KS54000 seismometer.