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Report on the Test and Evaluation of the Kinematics/Quanterra Q730B Borehole Digitizers

Richard P. Kromer and Timothy S. McDonald

Prepared by

Sandia National Laboratories

Albuquerque, New Mexico 87185 and Livermore, California 94550

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Report on the Test and Evaluation of the Kinematics/Quanterra Q730B Borehole Digitizers

Richard P. Kromer and Timothy S. McDonald
Monitoring Technologies Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0655

Abstract

Sandia National Laboratories has tested and evaluated the Kinematics/Quanterra Q730B-bb (broadband) and Q730B-sp (short period) borehole installation remote digitizers. The test results included in this report were for response to static and dynamic input signals, seismic application performance, data time-tag accuracy, and reference signal generator (calibrator) performance. Most test methodologies used were based on IEEE Standards 1057 for Digitizing Waveform Recorders and P1241 (Preliminary Draft) 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).

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-ACO4-94AL85000. This work was sponsored by the U.S. Department of Energy.

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1 EXECUTIVE SUMMARY

Objective:

The objective of this work was to evaluate the technical performance of the Kinometrics/Quanterra Q730B 3-channel Long-period/Broadband Borehole remote digitizer (Q730B-bb) and the Kinometrics/Quanterra Q730B 1-channel Short-period Borehole remote digitizer (Q730B-sp).

Description:

The Q730B-bb included a full-function calibration card and active-sensor unity-gain buffer/amplifier. The Q730B-bb was designed to interface to a Geotech KS54000 with acceleration response and sensitivity of $15,000 \text{ v/m/s}^2$.

The Q730B-sp included a full-function calibration card and passive-sensor impedance matching pre-amplifier with a gain of 26 dB. The Q730B-sp was designed to interface to a Geotech GS-13 seismometer with velocity response and a sensitivity of 2000 v/m/s .

Data acquisition software for both digitizers, provided by Quanterra, operates on a Sun Workstation under Solaris OS and communicates with them through a direct-connect serial port. Both digitizers were configured to acquire data at 1, 10, 20 and 40 samples per second simultaneously.

Observations:

The Q730B-bb operated for 88 days continuously with no data gaps. The Q730B-sp operated for 24 days continuously with no data gaps.

It was not possible to test the Q730Bs in a standalone configuration. Data could be acquired only through the use of a UNIX workstation. Calibration commands were cryptic and could use some simplification.

1.1 Q730B-bb Broadband Remote Digitizer Evaluation Summary:

Static Performance:

The input terminated noise (<0.44 counts RMS @40 samples per second and <0.35 counts RMS @10 samples per second) were very low for long-period/broadband seismic applications. DC offset was low and could be remotely trimmed. DC accuracy errors were within 1%. The Maximum Potential Dynamic Range was 142 dB @40 samples per second and 145 dB @10 samples per second.

Dynamic Performance:

Non-linearity did not limit large-signal performance. The Q730B-bb Total Harmonic Distortion (THD) was -124 dB or better. Modified Noise Power Ratios indicated >23 -bit performance; if over-range was considered, performance was 24-bits. For broadband signals, the maximum signal-to-noise ratio was 130 dB. Crosstalk was insignificant. Channel-to-channel timing skew was $<1 \text{ }\mu\text{second}$.

Timing Performance:

The Q730B-bb time-tagged the data with respect to the digitizer input to considerably better than 1 millisecond ($\approx 5 \mu\text{sec}$). It removed the digital FIR filter delay at all sample rates. The standard deviation of time-tag accuracy drift was $3.8 \mu\text{sec}$ over seven days. There was no noticeable effect during GPS loss.

Calibrator Performance:

The Q730B-bb calibrator was not tested.

Seismic Application Performance:

The Seismic Signal Resolution (SSR) and Seismic Signal Noise (SSN) tests indicate that the resolution and noise of the Q730B-bb digitizer were below the USGS New Low Earth Noise Model (NLNM) for use with a Geotech KS54000 seismometer. Seismic Bandwidth Limited Dynamic Range for a broadband

seismometer with bandwidth of 0.02 – 16 Hz was 143 dB. Seismic Bandwidth Limited Dynamic Range for a long-period seismometer with bandwidth of 0.02 – 1.0 Hz was 150 dB.

1.2 Q730B-sp Short-period Remote Digitizer Evaluation Summary:

Static Performance:

The input terminated noise (<0.68 counts RMS @40 samples per second and <0.57 counts RMS @10 samples per second) was very low for short-period seismic applications. DC offset was low and could be remotely trimmed. DC accuracy errors were within 1%. The Maximum Potential Dynamic Range was 139 dB @40 samples per second and 140 dB @10 samples per second.

Dynamic Performance:

Non-linearity may be a limiting factor for large-signal performance. The distortions from non-linear performance could add to the digitizer noise floor, decreasing the signal-to-noise ratio. The Q730B-sp Total Harmonic Distortion (THD) was – 90 dB. This is not abnormal for a digitizer with 26 dB of gain.

Timing Performance:

The Q730B-sp time-tagged the data with respect to the digitizer input to better than 1 millisecond ($\approx 340\mu\text{sec}$). It removed the digital FIR filter delay at all sample rates.

Calibrator Performance:

The Q730B-sp calibrator correctly programmed sine amplitudes and frequency, step amplitude and duration, and white noise/random binary functions. Calibrator linearity was –90 dB THD for voltage and current outputs.

Seismic Application Performance:

The Seismic Signal Resolution (SSR) and Seismic Signal Noise (SSN) tests indicate that the resolution and noise of the Q730B-sp digitizer were below the USGS New Low Earth Noise Model (NLNM) for use with a Geotech GS-13 seismometer. Seismic Bandwidth Limited Dynamic Range for a short-period seismometer with bandwidth of 0.5 – 16 Hz was 141 dB.

1.3 Conclusion:

The Q730B digitizers had performance to >23 bits at 40 samples per second. The digitizer system noise of this remote digitizer implementation was exceptionally quiet.

2 Introduction

2.1 Scope

This report on the *Test and Evaluation of the Kinometrics/Quanterra Q730B Borehole Digitizers* describes the results of the testing and evaluation of the Q730Bs borehole-installation Digitizing Waveform Recorders (DWR) as sub-systems of a geophysical data acquisition system.

2.2 Background

A Digitizing Waveform Recorder (DWR) can consist of a single channel element, a multi-channel element, or an array of single/multi-channel elements. The DWR element 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 or sent to a central collection point for storage and/or analysis.

2.3 Objectives

The objective of this work was to evaluate the overall technical performance of the Q730B, measure the distortions introduced by the Q730B high-resolution digitizers and provide a general performance check of the internal calibrator. The results of this evaluation can be compared to the manufacturer's specifications and any relevant application requirements or specifications.

3 Test and Evaluation Program

3.1 Test and Evaluation Background

Sandia National Laboratories (SNL), Monitoring Technologies 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 P1241 (Preliminary Draft) for Analog to Digital Converters [Reference 2]. The analyses based on these standards are performed in the frequency domain or time domain as required. When appropriate, instrumentation calibration is traceable to the National Institute for Standards Technology (NIST).

3.3 Q730B Digitizer Description

The Q730B is a remote digitizer designed to record geophysical data in a borehole environment. It is based on the Quanterra Q730 vault-installation remote digitizer. It provides high resolution and dynamic range for digitizing data from up to three sensor channels at various sample rates. Data samples are synchronized to an internal GPS receiver. The Q730B is designed for data acquisition at permanent remote locations where data are transmitted back to a central data-collection site in real-time.

Kinometrics provided two "first production run" remote digitizers which were developed for specific seismic applications. The Q730B-bb is a long-period/broadband digitizer designed to interface to a 3-component Geotech KS54000 long-period active seismometer. The Q730B-sp is a short-period digitizer with internal preamplifier designed to interface to a vertical component Geotech GS-13 short-period seismometer. Each digitizer, as tested, includes a full-function calibration card. An internal GPS receiver provides a time-base to time-tag the samples. Data acquisition software provided by Quanterra communicates with the data port on the remote digitizer.

3.4 Test/Evaluation Process

3.4.1 Q730B Testing

Testing of the Q730B remote digitizers was performed during June through September at the Sandia National Laboratories Facility for Acceptance, Calibration and Testing (FACT Site), Albuquerque, NM.

3.4.2 Q730B General Digitizer Performance Tests

The following tests were conducted on the Q730Bs. This is the basic set of tests as outlined in the Sandia CTBT Research and Development Technology Report: *Test Plan for the Evaluation of Digitizing Waveform Recorders with High Resolution Digitizers* [Reference 3].

Static Performance Tests

- DC Accuracy (DCA)
- Input Terminated Noise (ITN)
- Maximum Potential Dynamic Range (MPDR)

Dynamic Performance Tests

Tonal Tests

- Total Harmonic Distortion (THD)
- Crosstalk (CTK)

Broadband Tests (for multi-channel DWRs)

- Relative Transfer Function (RTF)
- Modified Noise Power Ratio (MNPR)

Timing Tests

- Time-tag Accuracy (TTA)
- Time-tag Accuracy Drift (TTD)

Analog/Digital Filter Performance

Analog Bandwidth (ABW)

Calibrator Performance Tests

Sine Calibrator Amplitude (CAT)

Sine Calibrator Frequency (CFT)

Sine Calibrator THD (CHD)

Calibrator Loopback THD (CLB)

Step Calibrator Amplitude/Duration (SCA)

White-noise Calibrator Amplitude/Duration (WCA)

Random-Binary Calibrator Amplitude/Duration (RCA)

3.4.3 Q730B Seismic Application Tests

The following application tests were conducted on the Q730Bs. This is an optional set of tests for seismic digitizers as outlined in Appendix I of the Sandia CTBT Research and Development Technology Report: *Test Plan for the Evaluation of Digitizing Waveform Recorders with High Resolution Digitizers*.

Seismic Application Tests

DWR Seismic System Resolution (SSR)

DWR Seismic System Noise (SSN)

Seismic System Dynamic Range

DWR Seismic Bandwidth-Limited Dynamic Range (SBLDR)

3.5 Digitizer Test Matrix

Test Type	Sample Rates	Channel 1	Channel 1-3
Passive Tests			
DCA	40, 20, 10, 1		X
ITN	40, 20, 10, 1		X
MPDR	40, 20, 10, 1		X
Active Tests			
Tonal Tests			
THD	40		X
CTK	40		X
Broadband Tests			
MNPR	40		X
RTF	40		X
Timing Tests			
TTA	40, 20, 10, 1	X	
TTD	40	X	
Analog/Digital Filter Performance Tests			
ABW	40	X	
Seismic Application Tests			
SSR	40	X	
SSN	40	X	
SBLDR	40		X

Table 2.1 Q730B-bb Tests

Test Type	Sample Rates
Passive Tests	
DCA	40, 20, 10, 1
ITN	40, 20, 10, 1
MPDR	40, 20, 10, 1
Active Tests	
Tonal Tests	
THD	40
Timing Tests	
TTA	40
Analog/Digital Filter Performance Tests	
ABW	40, 20, 10, 1
Calibrator Performance Tests	
CAT	NA
CFT	NA
CHD	NA
CLB	40
SCA	NA
WCA	NA
RCA	NA
Seismic Application Tests	
SSR	40
SSN	40
SBLDR	40

Table 2.2 Q730B-sp Tests

3.6 Q730B Test Configuration

The Q730B-bb s/n 0102 tested included:
Buffer-amplifier gain of 1
Calibrator

The Q730B-sp s/n 0108 tested included:
Pre-amplifier gain of 26dB
Calibrator

Lab Test Configuration:

The Q730B remote digitizers were configured to acquire and store data at 40, 20, 10 and 1 sample per second on all channels simultaneously.

The Q730B-bb and Q730B-sp were interfaced to a SPARC 20 workstation via asynchronous serial data ports. Data were archived on the SPARC 20 in Steim-2 compressed format using Quanterra Comserv software. Data were converted to 4K Mini-SEED blocks using the Quanterra 'qmerge' software. Data were transferred to a PC via ftp and converted to Sandia ASCII count format for analysis.

The Q730B remote digitizers were installed and tested in a sealed, insulated tube to simulate installation in a borehole; see Figure 2.1.

The Q730B-sp calibrator was controlled using a laptop computer connected to the Q730B maintenance port.

Power Consumption: (includes GPS Receiver)

Q730B-bb = 458ma @ 24.25V = 11.7 Watts

Q730B-sp = 440ma @ 24.25V = 10.7 Watts

Physical Size:

3" X 3.5" X 27"

Manufacturer's Specifications:

Manufacturer's specifications were not provided.

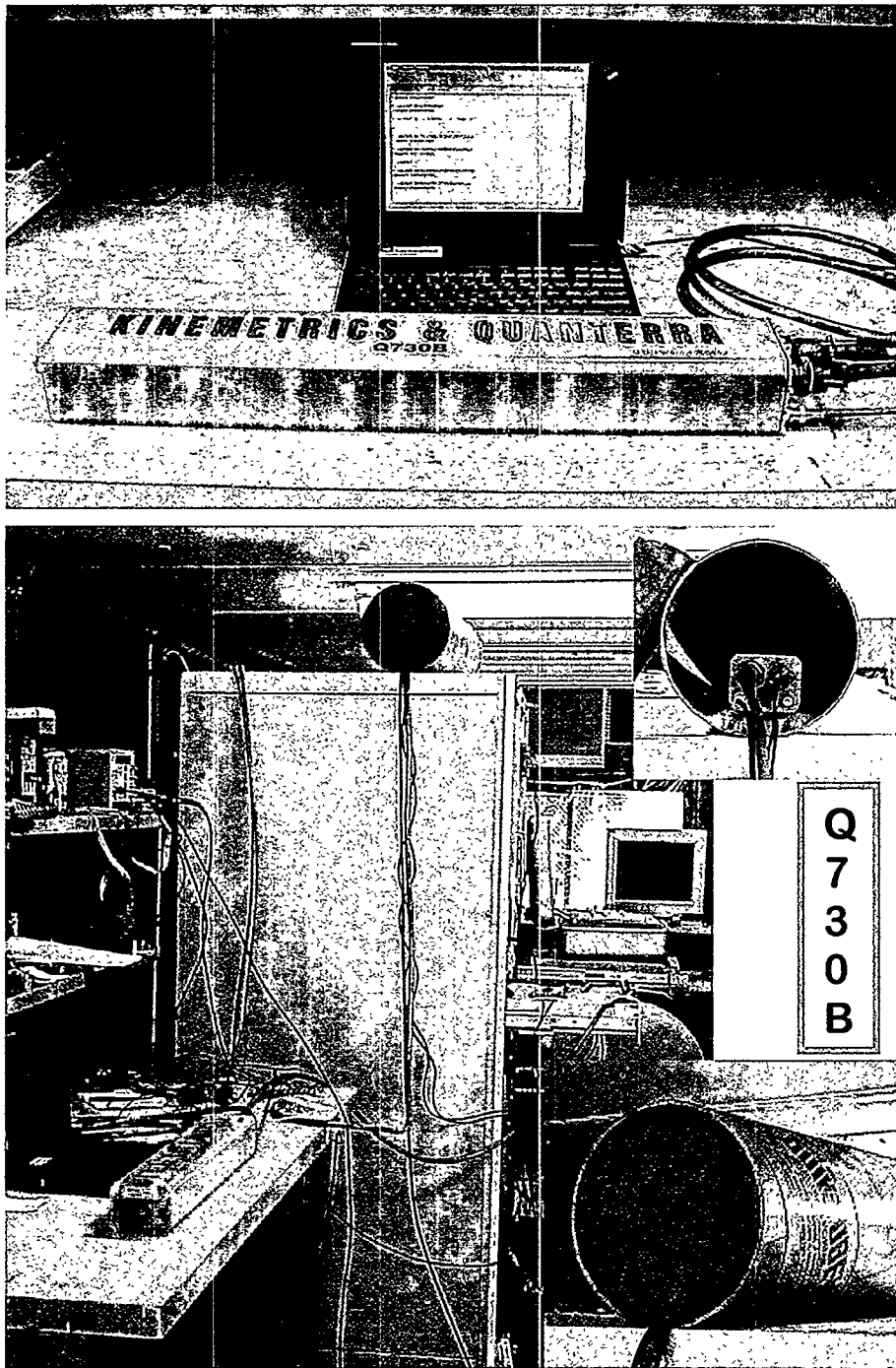


Figure 2.1 Q730B Testing at SNL FACT Site

4 Q730B 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: short-term and long-term stability, relationship to quantizing noise floor, correlated and uncorrelated spurious signals, gain (accuracy) and dc offset. The results of these tests include measurement of dynamic range and resolution.

4.1.1 DC Accuracy (DCA)

Purpose:

The purpose of the DC accuracy test was to verify the accuracy of the Q730B digitizer. The bit-weight (LSB) of a non-gain-ranged digitizer is its resolution.

Configuration:

The Q730B-bb digitizer inputs were connected to a +/-10V DC voltage source. The Q730B-sp digitizer inputs were connected to a +/-0.5V DC voltage source.

Evaluation:

The dc gain (accuracy) of the Q730B digitizer, dc offset and bit-weight (LSB)/resolution were computed.

DC Accuracy (DCA) Test Results

Q730B-bb

- The nominal bit-weight of the Q730B-bb digitizer is **2.4 μ Volts/count** (416667 counts/volt). DC accuracy of the Q730B-bb digitizer is within 1% of nominal. A summary of the test results is shown in Table 3.1.

Channel	Sample Rate	Bit-weight μ Volts/count	Counts/volt	Deviation from nominal	DC Offset mVolts
1	40	2.39128	418186	0.365%	-0.196
	20	2.39112	418213	0.371%	-0.191
	10	2.39128	418185	0.364%	-0.189
	1	2.39770	417066	0.096%	-0.192
2	40	2.39360	417780	0.267%	-1.017
	20	2.39345	417806	0.274%	-1.017
	10	2.39361	417779	0.267%	-1.020
	1	2.40003	416661	-0.001%	-1.022
3	40	2.38490	419305	0.633%	0.393
	20	2.38475	419331	0.640%	0.394
	10	2.38490	419304	0.633%	0.391
	1	2.39130	418182	0.364%	0.390

Table 3.1 DC Accuracy (DCA) Q730B-bb digitizer

Q730B-sp

- The nominal bit-weight of the Q730B-sp digitizer is **0.12 μ Volts/count** (8333333 counts/volt). DC accuracy of the Q730B-sp digitizer is within 1% of nominal. A summary of the test results is shown in Table 3.2.

Sample Rate	Bit-weight μ Volts/count	Counts/volt	Deviation from nominal	DC Offset μ Volts
40	0.11936	8377761	0.533%	-48.6
20	0.11936	8378285	0.539%	-48.6
10	0.11936	8377726	0.533%	-47.7
1	0.11968	8355337	0.264%	-46.1

Table 3.2 DC Accuracy (DCA) Q730B-sp digitizer

4.1.2 Input Terminated Noise (ITN)

Purpose:

The purpose of the input-terminated noise test was to verify the static parameters of the Q730B. These static parameters were dominated primarily by the random noise generated within the digitizer and from other components within the Q730B package.

Configuration:

The Q730B-bb digitizer inputs were terminated with 50 ohms. The Q730B-sp digitizer input was terminated with 10K ohms.

Evaluation:

A power density spectrum (PDS) of the input-terminated noise provided a measure of the noise floor of the digitizer. Short term and long term stability, relationship to quantizing noise floor and correlated and uncorrelated spurious signals were computed.

Maximum Potential Dynamic Range Computation:

The maximum potential dynamic range of the Q730B digitizer was determined by computing the RMS value of a full-scale sinusoid and dividing by the RMS of the Input Terminated Noise (ITN) test data within a specified bandwidth.

Input Terminated Noise (ITN) Test Results

Q730B-bb

- The input terminated noise of the Q730B-bb digitizer was **1.063 μ V (0.44 Counts) RMS @40 samples per second**. A summary of the test results for various sample rates is shown in Table 3.3. A PDS of the noise is shown in Figure 3.1.

Sample Rate	Channel	Bandwidth	RMS (μ Volts)
40	1	0.01-20 Hz	1.063
	2		1.064
	3		1.077
20	1	0.01-10 Hz	0.932
	2		0.937
	3		0.946
10	1	0.01-5 Hz	0.842
	2		0.850
	3		0.859
1	1	0.001-0.5 Hz	0.883
	2		0.891
	3		0.905

Table 3.3 Input Terminated Noise (ITN)

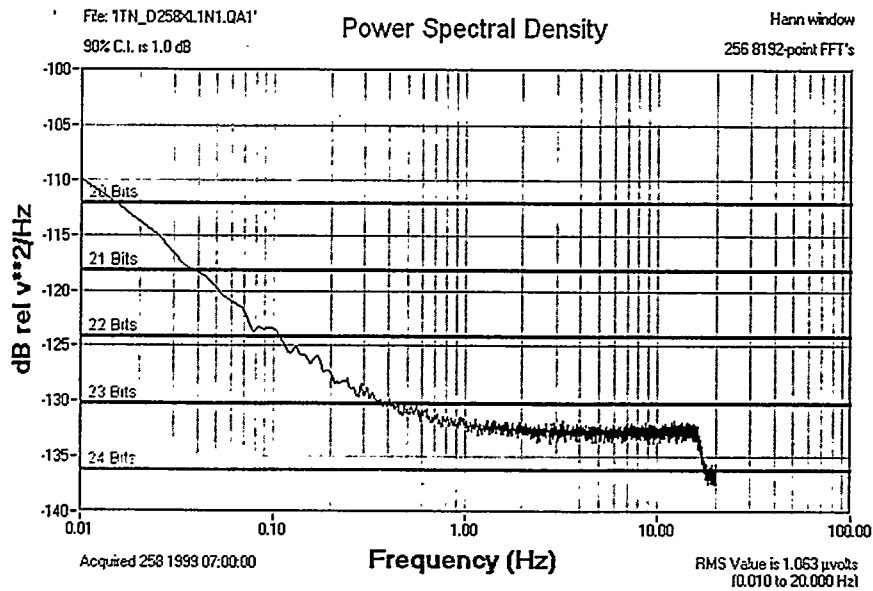


Figure 3.1 Q730B-bb 40 samples per second Input Terminated Noise PDS

Q730B-sp

- The input terminated noise of the Q730B-sp digitizer was **0.081 μV (0.68 Counts) RMS @40 samples per second**. A summary of the test results for various sample rates is shown in Table 3.4. A PDS of the noise is shown in Figure 3.2.

Sample Rate	Bandwidth	RMS (μVolts)
40	0.01-20 Hz	0.081
20	0.01-10 Hz	0.074
10	0.01-5 Hz	0.068

Table 3.4 Input Terminated Noise (ITN) 40 samples per second

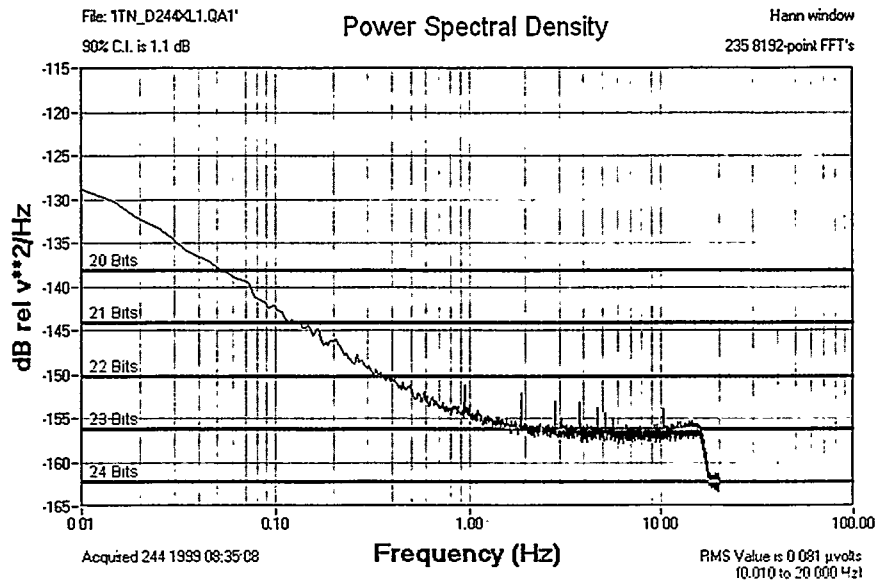


Figure 3.2 Q730B-sp 40 samples per second Input Terminated Noise PDS

Maximum Potential Dynamic Range (MPDR) Computation:

The Maximum Potential Dynamic Range (MPDR) of the Q730B digitizer was determined by computing the RMS value of a full-scale sinusoid and dividing by the RMS (standard deviation) of the Input Terminated Noise (ITN) test data. The full-scale of the Q730B-bb was determined to be 40.12 V p-p differential (14.23 V_{RMS}). The full-scale of the Q730B-sp was determined to be 2.06 V p-p differential (.712 V_{RMS}).

Q730B-bb

- At 40 samples per second, the Maximum Potential Dynamic Range of the Q730B-bb digitizer was 142.5 dB. A summary of the test results is shown in Table 3.5.

Sample Rate	Channel	RMS full-scale/ RMS ITN	MPDR
40	1	14.23 V/1.063 μ V	142.5 dB
	2	14.23 V/1.064 μ V	142.5 dB
	3	14.23 V/1.077 μ V	142.4 dB
20	1	14.23 V/0.932 μ V	143.7 dB
	2	14.23 V/0.937 μ V	143.6 dB
	3	14.23 V/0.946 μ V	143.5 dB
10	1	14.23 V/0.842 μ V	144.6 dB
	2	14.23 V/0.850 μ V	144.5 dB
	3	14.23 V/0.859 μ V	144.4 dB
1	1	14.23 V/0.883 μ V	144.1 dB
	2	14.23 V/0.891 μ V	144.1 dB
	3	14.23 V/0.905 μ V	143.9 dB

Table 3.5 Maximum Potential Dynamic Range (MPDR) Q730B-bb digitizer

Q730B-sp

- At 40 samples per second, the Maximum Potential Dynamic Range of the Q730B-sp digitizer was **138.9 dB**. A summary of the test results is shown in Table 3.6.

Sample Rate	RMS full-scale/ RMS ITN	Channel 1 MPDR
40	0.712 V/.081 μ V	138.9 dB
20	0.712 V/.074 μ V	139.7 dB
10	0.712 V/.068 μ V	140.4 dB

Table 3.6 Maximum Potential Dynamic Range (MPDR) Q730B-sp digitizer

4.2 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.

4.2.1 Tonal 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. As digitizers exceeded 16-bit resolution/dynamic range, commercially available precision sinusoidal signal sources became inadequate for use as standards. Seismic waveform recorders utilize very low sample rates and have short term stability characteristics that can be misinterpreted using traditional time domain analysis techniques. However, ultra-low-distortion oscillators have recently become available and some variations of the traditional tonal tests can be performed for high-resolution digitizers. The DWR under test is asynchronously sampled with respect to the signal source for all tonal tests.

4.2.1.1 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 Q730B digitizers. At present, ultra-low-distortion oscillators with 140 dB (23-bit) linearity are available for THD testing of digitizers.

Configuration:

The Q730B digitizer inputs were connected to an ultra-low-distortion oscillator. The amplitude of the oscillator was set to approximately one-half full scale; 20.0 V p-p for the Q730B-bb digitizer and 1.0 V p-p for the Q730B-sp. The oscillator was set to a frequency (1.9 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 Q730B digitizer. THD was computed by integrating the power density spectral peaks at the fundamental and all harmonics below the Nyquist frequency (one-half the sample rate).

Total Harmonic Distortion (THD) Test Results

Q730B-bb

- The THD of the Q730B-bb digitizers was from -123 to -130 dB. A summary of test results is shown in Table 3.7.

Channel	THD @ -6 dB FS
1	-130.3 dB
2	-128.1 dB
3	-123.5 dB

Table 3.7 Total Harmonic Distortion (THD) Q730B-bb digitizers

Q730B-sp

- The THD of the Q730B-sp digitizer was -90 dB. A summary of test results is shown in Table 3.8.

Channel	THD @ -6 dB FS
1	-90

Table 3.8 Total Harmonic Distortion (THD) Q730B-sp digitizer

4.2.1.2 Crosstalk (CTK)Purpose:

The purpose of the crosstalk test was to determine the extent of crosstalk between channels on multi-channel Q730B-bb digitizers.

Configuration:

The Q730B-bb digitizer channel under test was terminated with 50 ohms. All other digitizer inputs were connected to a large amplitude (20.0V p-p) sinusoidal test signal set to a frequency unrelated to the sample rate and below the Nyquist frequency.

Evaluation:

Power density spectra provided a measure of crosstalk. The ratio of test signal to crosstalk signal was computed using integrated power density spectra around the signal frequency.

Crosstalk (CTK) Test Results

- Analog crosstalk in the Q730B-bb digitizer was better than -145 dB. A summary of test results is shown in Table 3.9.

Channel	Crosstalk
1	<-145 dB
2	<-145 dB
3	<-145 dB

Table 3.9 Crosstalk (CTK) Q730B-bb digitizers

4.2.2 Broadband Tests

Broadband tests are dynamic tests that use Gaussian pseudo-random signal generators as stimuli. The use of broadband signals for evaluating analog-to-digital converter performance is uncommon, but for seismic applications, it is relevant. Seismic backgrounds and events are generally considered broadband. Traditional Noise Power Ratio (NPR) evaluation techniques using broadband signals require notch filters to determine digitizer noise floors. An alternative to that technique is to use side-by-side digitizer testing and coherence analysis to estimate performance. A multi-channel DWR can use the relationships between its channels in estimating performance. The technique is described in the Sandia Report SAND94-0221 *Modified Noise Power Ratio Testing of High Resolution Digitizers* [Reference 4].

4.2.2.1 Multi-channel Relative Transfer Function (RTF)Purpose:

The purpose of the relative transfer function test was to determine the relative gain and phase between channels in a multi-channel Q730B-bb digitizer.

Configuration:

The Q730B-bb digitizer inputs were connected to a bandwidth-limited Gaussian signal generator. The signal generator output amplitude was set to approximately half full-scale of the Q730B digitizer inputs in order to avoid data clipping.

Evaluation:

Coherence analysis provided a measure of relative gain and phase.

Multi-channel Relative Transfer Function (RTF) Test Results

- Relative power gains were within +/- .002 dB. Q730B digitizers Channel 1 vs. 2 test results are shown in Figure 3.3.
- The Q730B-bb digitizer displayed a linear phase difference with a slope of 7.5×10^{-6} degree/Hz between channels 1 and 2. Q730B-bb digitizers Channel 1 vs. 2 test results are shown in Figure 3.4. This translates to 0.021 μ seconds skew @40 samples per second.

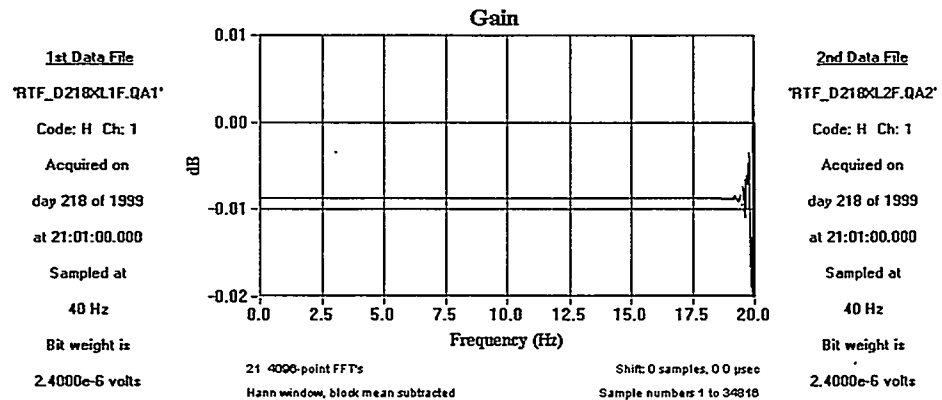


Figure 3.3 Relative Gain - Q730B-bb digitizer Channel 1 vs. 2

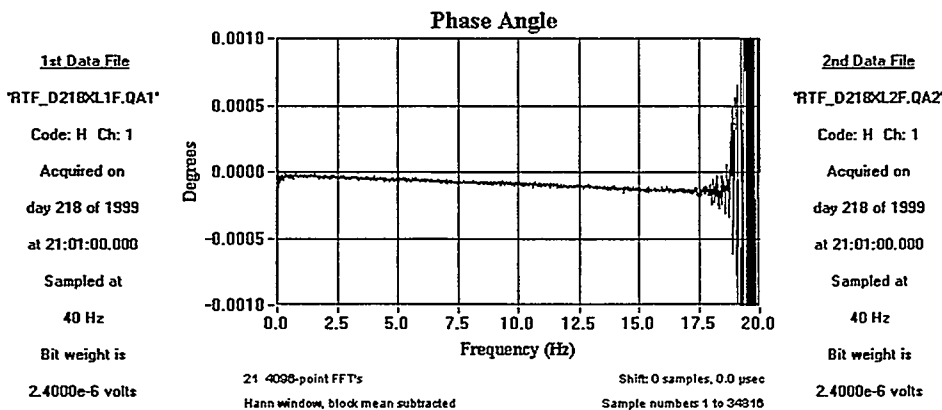


Figure 3.4 Relative Phase (skew) - Q730B-bb digitizer Channel 1 vs. 2

4.2.2.2 Modified Noise Power Ratio (MNPR)

Purpose:

The purpose of the modified noise-power-ratio test was to determine the Q730B digitizer performance compared to n-bit ideal digitizers at several amplitudes from small signal to clip level.

Configuration:

The Q730B digitizer inputs were connected to a bandwidth-limited Gaussian signal generator. The bandwidth of the signal generator was set to avoid aliasing the Q730B digitizer and to maximize the power within the Q730B digitizer passband. The signal generator output was varied from 100 microvolts RMS to voltages above the Q730B digitizer clip level.

Evaluation:

Coherence analysis provided a noise power ratio value for each level of input signal to the Q730B digitizer. These estimated noise power ratios were compared to the performance model of n-bit ideal digitizers.

Modified Noise Power Ratio (MNPR) Test Results

- MNPR tests indicated that the Q730B digitizers have a maximum **broadband signal-to-noise ratio of 130 dB**. A summary of test results is shown in Table 3.10. MNPRs indicate the Q730B digitizers approximate the performance of ideal **23.0 to 23.2 bit** digitizers. MNPR plots are shown in Figures 3.5-7.

Note that the data do not follow the performance curves for large signals. This indicates a significant over-range capacity. Test signals were not large enough to clip this digitizer. If the over-range capacity had been included in the test, a performance of about 24-bits would have been measured.

- Linearity is usually the limiting factor for large-signal performance. The distortions from non-linear performance add to the digitizer noise floor, decreasing the signal-to-noise ratio. The Q730B THD test indicated linearity of > 124 dB. For broadband signals, the signal-to-noise ratios were 127-130 dB. For a full-scale broadband noise signal, there was little reduction in dynamic range due to non-linearities. For the Q730B-bb, large signals will not cause an increase in the noise floor.

MNPR Data File	Ch 1-2 SNR	Ch 1-3 SNR	Ch 2-3 SNR
MNPR-A (ITN)	0.49	0.50	0.50
MNPR-B	82.3	82.2	82.3
MNPR-C	102.5	102.4	102.5
MNPR-D	115.8	115.9	116.0
MNPR-E	121.7	121.0	122.0
MNPR-F	125.0	124.0	125.0
MNPR-G	127.0	126.2	127.1
MNPR-H	128.0	126.8	127.9
MNPR-I	129.0	127.1	128.1
MNPR-J	130.1	127.0	128.2

Table 3.10 MNPR SNR - Q730B-bb digitizer

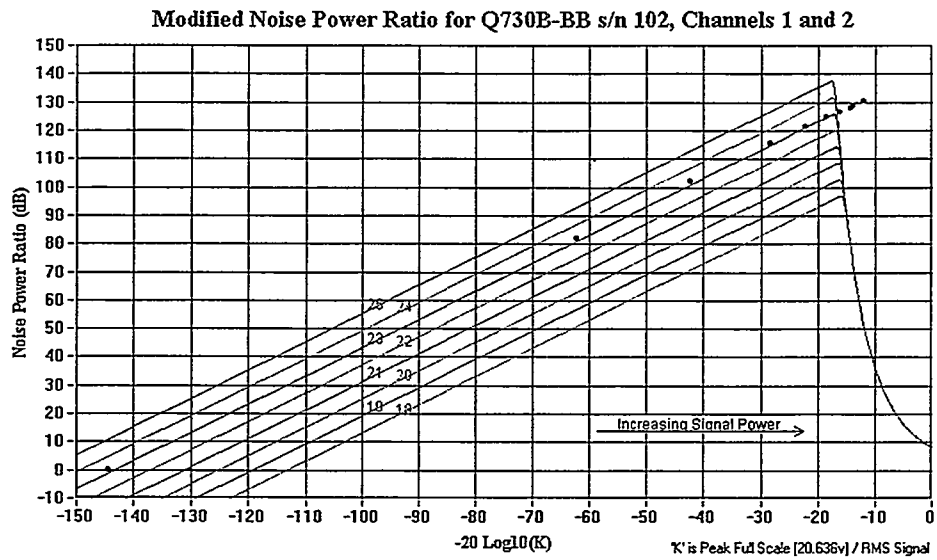


Figure 3.5 Modified Noise Power Ratio Q730B-bb digitizer (Ch1/Ch2)

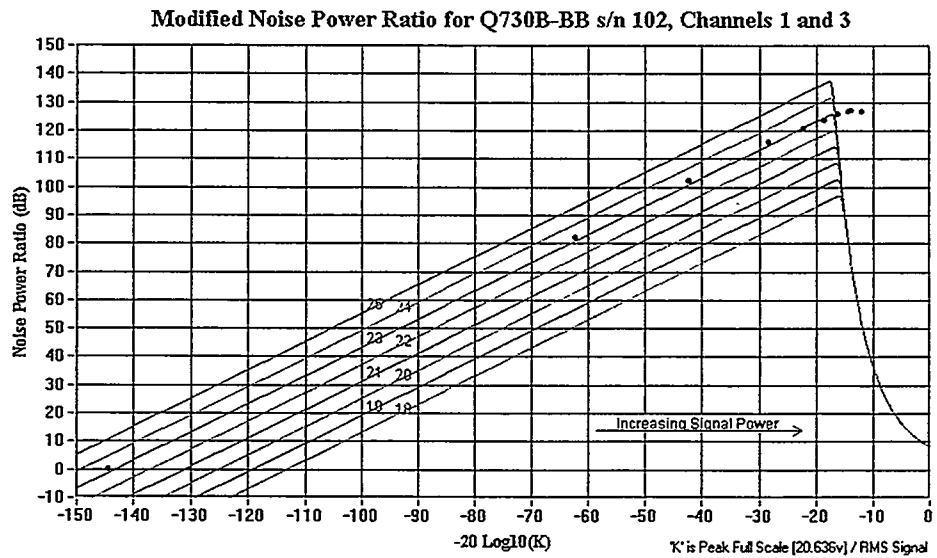


Figure 3.6 Modified Noise Power Ratio Q730B-bb digitizer (Ch1/Ch3)

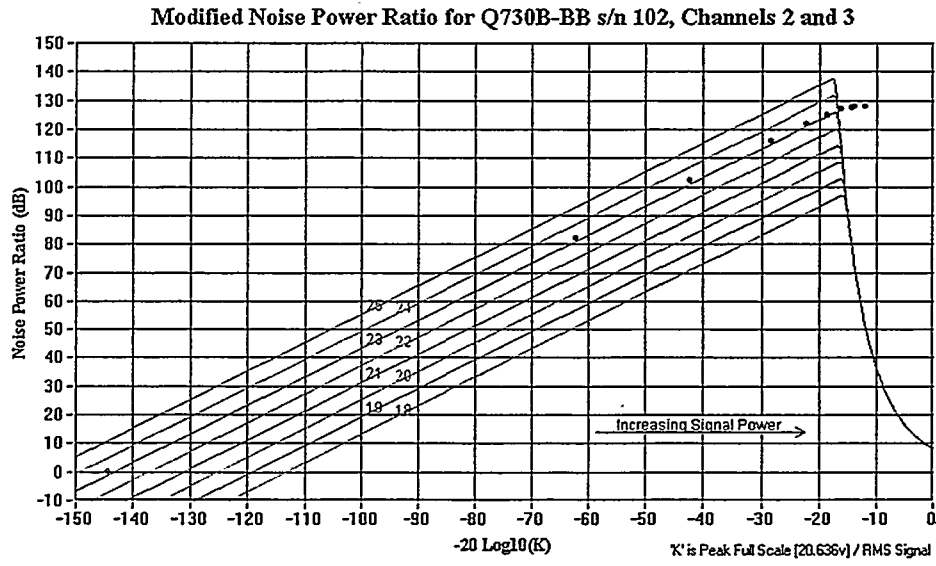


Figure 3.7 Modified Noise Power Ratio Q730B-bb digitizer (Ch2/Ch3)

4.3 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, the response of the DWR to UTC loss and power cycling, and the short-term stability of the HRD timebase.

4.3.1 Time Tag Accuracy (TTA)

Purpose:

The purpose of the time tag accuracy test was to verify the ability of the Q730B to accurately time-tag the data samples with respect to the Q730B inputs.

Configuration:

One Q730B digitizer input was connected to the One Pulse per Minute output of an independent running GPS Timing Reference. A second input was connected to a One Pulse per Hour output of an independent running GPS Timing Reference.

Evaluation:

The time tags of the data from the Q730B were analyzed for correct time on the hour and minute transitions.

Time Tag Accuracy (TTA) Test Results

- The Q730B-bb time-tag exhibited an error of 3.43 μ seconds at 40 samples per second. Q730B-bb digitizer Channel 1 test results are shown in Table 3.11 and Figure 3.8.

Sample Rate	Time-tag Error
40	3.43 μ seconds
20	3.33 μ seconds
10	3.79 μ seconds
1	21.0 μ seconds

Table 3.11 Time-tag accuracy - Q730B-bb digitizer

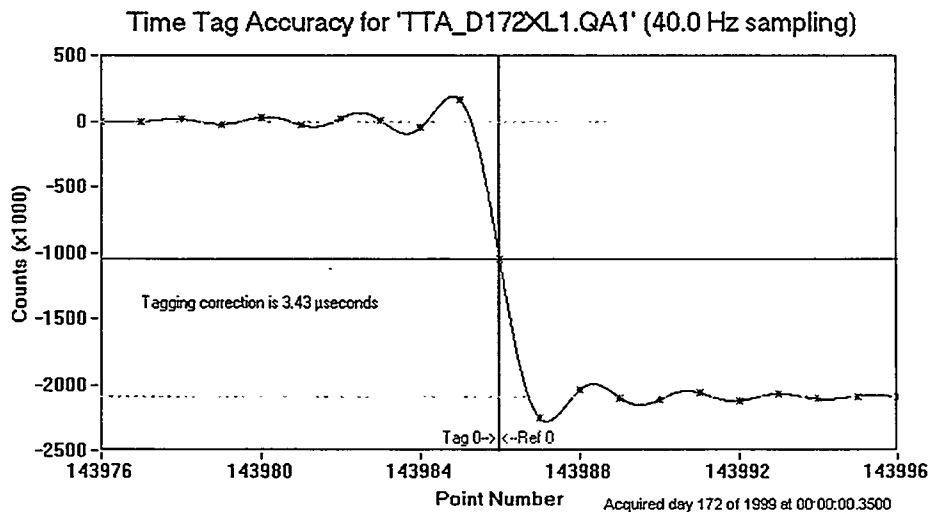


Figure 3.8 Time-tag Accuracy - Q730B-bb digitizer Channel 1

- The Q730B-sp time-tag exhibited an error of 340 μ seconds. Q730B-sp digitizer Channel 1 test results are shown in Figure 3.9.

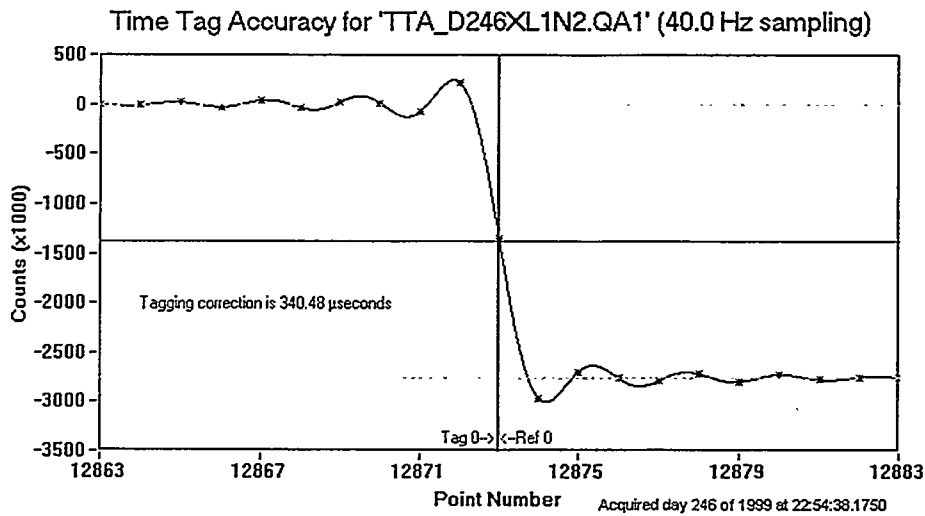


Figure 3.9 Time-tag Accuracy - Q730B-sp digitizer Channel 1

4.3.2 Time Tag Accuracy Drift (TTD)

Purpose:

The purpose of the time-tag accuracy drift test was to verify the ability of the Q730B-bb to time-tag the data accurately with respect to GPS receiver variations.

Configuration:

One Q730B-bb input was connected to the 1 PPM output of an independent running GPS Timing Reference. The GPS receiver was turned on and allowed to stabilize. Data were collected over a 7-day period. During this period, the GPS antenna was covered to "hide the sky" for approximately one hour and then uncovered.

Evaluation:

The time tags of the 40 samples per second data from the Q730B-bb were analyzed for correct time on the minute transitions.

Time-Tag Accuracy Drift (TTD) Test Results

- The Q730B-bb time-tag exhibited a mean error of -0.4 μ seconds and standard deviation of 3.8 μ seconds. Q730B-bb digitizer Channel 1 test results are shown in Figure 3.10. There was no indication of change when the GPS antenna was covered.

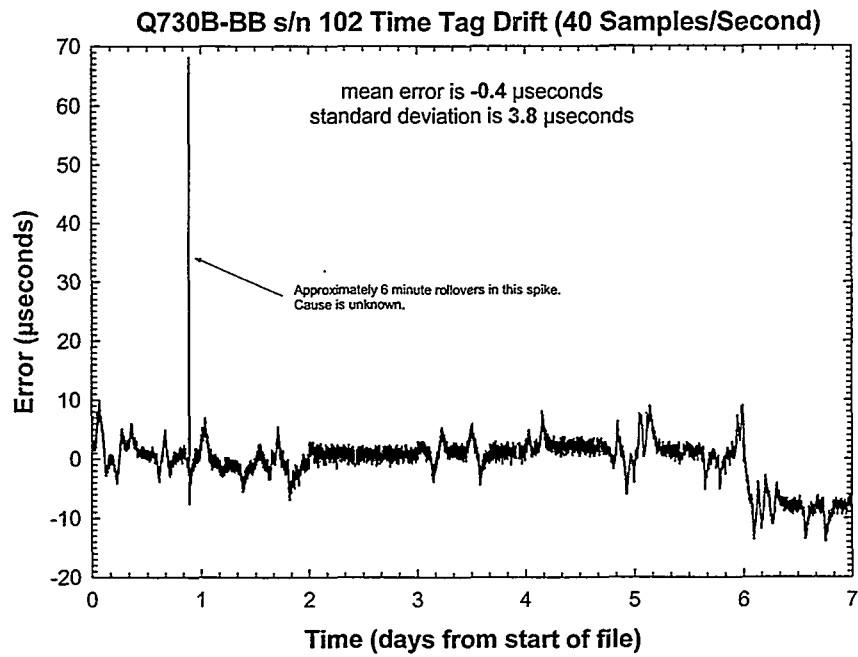


Figure 3.10 Time-tag Accuracy Drift - Q730B-bb digitizer Channel 1

4.4 Analog/Digital Filter Performance

DWR HRDs can have a combination of analog and digital filters to set bandwidth and prevent aliasing of input signals.

4.4.1 Analog Bandwidth (ABW)

Purpose:

The purpose of the analog bandwidth test was to verify the bandwidth of the Q730B analog/digital filter.

Configuration:

The Q730B inputs were connected to a bandwidth-limited Gaussian signal generator.

Evaluation:

A power density spectrum provided a measure of the Q730B bandwidth. The 3 dB and attenuation at the Nyquist of the composite analog/digital Q730B filters were computed.

Analog Bandwidth (ABW) Test Results

- For 40 samples per second, the Q730B analog/digital filter -3 dB point was at 16.24 Hz. The filter attenuation was -105 dB at the Nyquist. Low frequency response was to DC. Test results are shown in Figure 3.11.

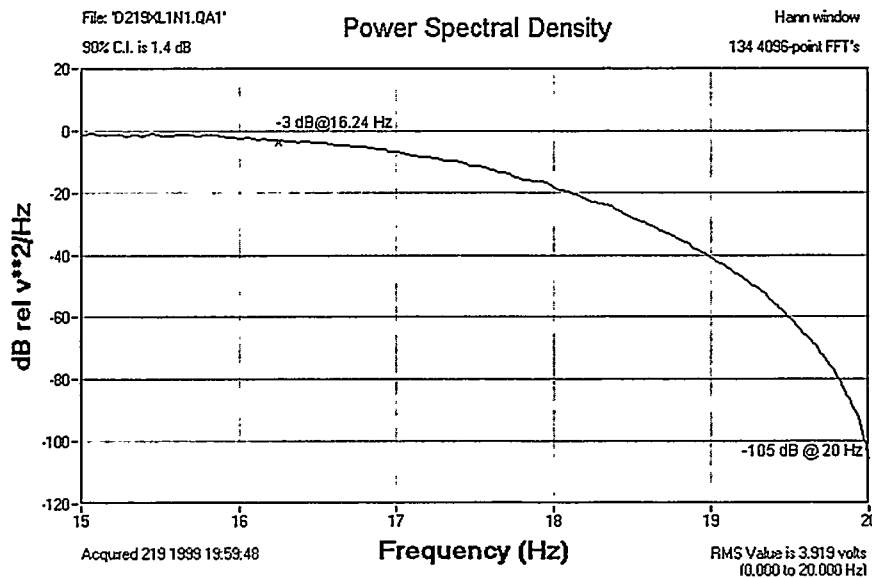


Figure 3.11 Q730B Analog Bandwidth

4.5 Calibrator Performance Tests

Digitizing Waveform Recorders frequently include a programmable voltage or current calibrator source to drive a sensor calibration input. The calibrator can generate sinusoidal, step, white or colored noise, random binary (RB) or a combination of these. The calibrator performance can be tested to determine parameters such as amplitude accuracy, frequency/duration, and distortion.

4.5.1 Sine-Calibrator Amplitude (CAT)

Purpose:

The purpose of the calibrator amplitude test was to verify if the Q730B calibrator accurately programs the correct amplitude for seismometer calibrations

Configuration:

The Q730B-sp calibrator output was connected to an independent, HP3458A-based signal measurement system. The amplitude of the Q730B-sp calibrator was set to various levels at 1 Hz.

Evaluation:

Measured amplitudes, using a sine-fit computation, were compared to the programmed amplitudes.

Sine-Calibrator Amplitude (CAT) Test Results

- The Q730B-sp sine-calibrator amplitudes were within 1% of nominal. Test results are shown in Table 3.12.

Calibrator Amplitude @ 1 Hz	Measured Amplitude	Error (%)	Signal to Noise Ratio
10 V	9.978 V	-0.22%	95.9 dB
5 V	4.998 V	-0.04%	96.7 dB
2 V	1.995 V	-0.25%	98.5 dB
1 V	0.997 V	-0.30%	99.9 dB
500 mV	499 mV	-0.20%	94.5 dB
200 mV	199 mV	-0.50%	84.2 dB
100 mV	99.6 mV	-0.40%	85.1 dB
50 mV	49.8 mV	-0.40%	80.4 dB
20 mV	19.9 mV	-0.50%	73.5 dB
10 mV	9.96 mV	-0.40%	64.7 dB
5 mV	4.98 mV	-0.40%	59.1 dB
2 mV	1.99 mV	-0.50%	51.6 dB
1 mV	0.993 mV	-0.70%	47.1 dB

Table 3.12 Sine Calibrator Amplitudes for Q730B-sp

4.5.2 Sine-Calibrator Frequency (CFT)

Purpose:

The purpose of the calibrator frequency test was to verify if the Q730B-sp calibrator accurately programs the correct frequency for seismometer calibrations.

Configuration:

The Q730B-sp calibrator output was connected to an independent, HP3458A-based signal measurement system. The frequency of the Q730B-sp calibrator was set to various levels at 10 volts.

Evaluation:

Measured frequencies, using a sine-fit computation, were compared to the programmed frequencies.

Sine-Calibrator Frequency (CFT) Test Results

- The Q730B-sp sine-calibrator frequencies were **correct to 0.001 Hz**. Test results are shown in Table 3.13.

Calibrator Frequency @ 10 Volts	Measured Frequency
10 Hz	9.999 Hz
5 Hz	4.999 Hz
2 Hz	1.999 Hz
1 Hz	0.999 Hz
0.5 Hz	0.4999 Hz
0.2 Hz	0.1999 Hz
0.1 Hz	0.1000 Hz
0.05 Hz	0.0500 Hz

Table 3.13 Sine Calibrator Frequencies for Q730B-sp

4.5.3 Sine-Calibrator THD (CHD)Purpose:

The purpose of the calibrator THD test was to verify the linearity of the Q730B-sp calibrator.

Configuration:

The Q730B-sp calibrator output was connected to an independent, HP3458A-based signal measurement system. The amplitude and frequency of the Q730B calibrator were set to known levels. The calibrator output was set for both voltage (10 Volts, 500 mV), and current (10ma) output.

Evaluation:

A power density spectrum provided a measure of the linearity of the calibrator. THD of the recorded calibrator signals were computed.

Sine-Calibrator THD (CHD) Test Results

- The Q730B-sp sine-calibrator THD is -90 dB. Test results are shown in Table 3.14.

Calibrator Amplitude @ 1 Hz	Measured THD
10 V	-90 dB
500 mV	-89 dB
10 ma	-90 dB

Table 3.14 Sine Calibrator Distortion (THD) for Q730B-sp

4.5.4 Calibrator Loopback THD (CLB)Purpose:

The purpose of the calibrator loopback THD test was to verify the linearity of the Q730B-sp calibrator using the Q730B-sp digitizer.

Configuration:

The Q730B-sp calibrator output was looped back to the Q730B-sp digitizer input. The amplitude and frequency of the Q730B-sp calibrator were set to 500 mV @1 Hz.

Evaluation:

A power density spectrum provided a measure of the linearity of the calibrator. THD of the recorded calibrator signal was computed. The THD using the Q730B-sp digitizer should be the same as the CHD test.

Sine-Calibrator Loopback (CLB) Test Results

- The Q730B-sp sine-calibrator loopback THD was the same as the CHD Test: -89 dB.

4.5.5 Step-Calibrator Amplitude/Duration (SCA)**Purpose:**

The purpose of the step-calibrator amplitude/duration test was to verify if the Q730B-sp calibrator accurately programs the correct step amplitude and duration for seismometer calibrations.

Configuration:

The Q730B-sp calibrator output was connected to an independent, HP3458A-based signal measurement system. The amplitude and duration of the Q730B-sp calibrator were set to 1 volt for a 2-second duration.

Evaluation:

Measured amplitude and duration was compared to the programmed amplitudes/duration.

Step-Calibrator Amplitude/Duration (SCA) Test Results

- The Q730B-sp calibrator provided the correct step amplitude and duration.

4.5.6 White-Noise Calibrator Amplitude/Duration (WCA)**Purpose:**

The purpose of the white-noise amplitude/duration test was to verify if the Q730B-sp calibrator accurately programs the correct amplitude and duration of a white noise signal for seismometer calibrations.

Configuration:

The Q730B-sp calibrator output was connected to an independent, HP3458A-based signal measurement system. The seed, amplitude and duration of the Q730B-sp calibrator were set to 11223344h at 1 volt for 50 seconds.

Evaluation:

Measured amplitude and duration was compared to the programmed amplitude/duration. A power density spectrum provided a measure of the calibrator output.

White-Noise Calibrator Amplitude/Duration (WCA) Test Results

- The Q730B-sp calibrator provided the correct white noise amplitude and duration.
The seed was not verified.

4.5.7 Random-Binary Calibrator Amplitude/Duration (RCA)**Purpose:**

The purpose of the RB amplitude/duration test was to verify if the Q730B-sp calibrator accurately programs the correct amplitude and duration of a RB signal for seismometer calibrations.

Configuration:

The Q730B-sp calibrator output was connected to an independent, HP3458A-based signal measurement system. The seed, amplitude and duration of the Q730B-sp calibrator were set to 112233h at 1 volt for 60 seconds.

Evaluation:

Measured amplitude and duration was compared to the programmed amplitude/duration. A power density spectrum provided a measure of the calibrator output.

Random-Binary Calibrator Amplitude/Duration (RCA) Test Results

- The Q730B-sp calibrator provided the correct RB amplitude and duration. The seed was not verified.

4.6 Seismic Application Tests

Seismic application tests are those that provide a stimulus to the DWR or interpret a data set 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 matched DWR/seismometer can resolve the expected seismic signals and backgrounds while nearly maximizing the system dynamic range.

4.6.1 Q730B Seismic System Resolution (SSR)

Purpose:

The purpose of the seismic signal resolution test was to determine the ability of the Q730B digitizers to resolve small seismic signals using a specific seismometer. The theoretical minimum level of ground motion that the Q730B can sense is determined by its bit-weight (LSB). The Q730B-bb was designed to interface to a Geotech KS54000 with acceleration response and sensitivity of 15,000 v/m/s². The Q730B-sp was designed to interface to a Geotech GS-13 seismometer with velocity response and a sensitivity of 2000 v/m/s.

Configuration:

The results of the DC Accuracy (DCA) were used to determine the bit-weight (LSB) of the Q730Bs. If a sensor preamplifier was installed, the DC Accuracy test was rerun using an appropriate DC voltage source.

Evaluation:

The quantizing noise floors, as determined by the bit-weight of the Q730B-bb and Q730B-sp, were converted to ground motion spectral units using the KS54000 and GS-13 response mathematical models. The results of these computations were overlaid with the USGS New Low Earth Noise Model (NLNM) [Reference 5] to demonstrate the ability of the Q730Bs to resolve small seismic signals. (When appropriate, a model of the power density spectrum at the proposed deployment site can be substituted for the NLNM.)

Q730B Seismic System Resolution (SSR) Test Results

- The Q730B-bb resolution is shown in Figure 3.12. The gray background in that figure denotes frequencies often disregarded for broadband seismic applications.

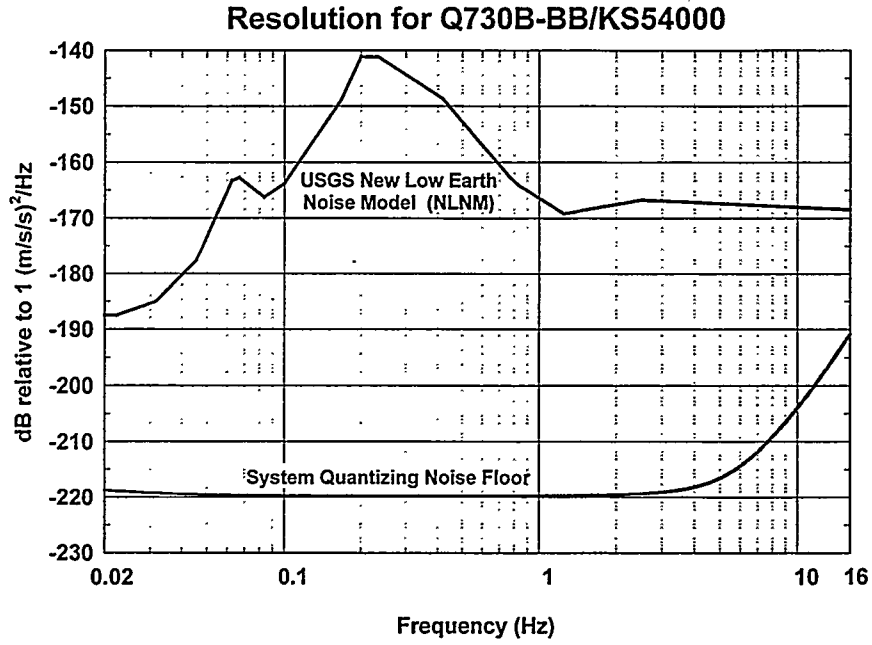


Figure 3.12 Resolution of Q730B-bb for KS54000 Seismometer

- The Q730B-sp resolution is shown in Figure 3.13. The gray background in that figure denotes frequencies often disregarded for short-period seismic applications.

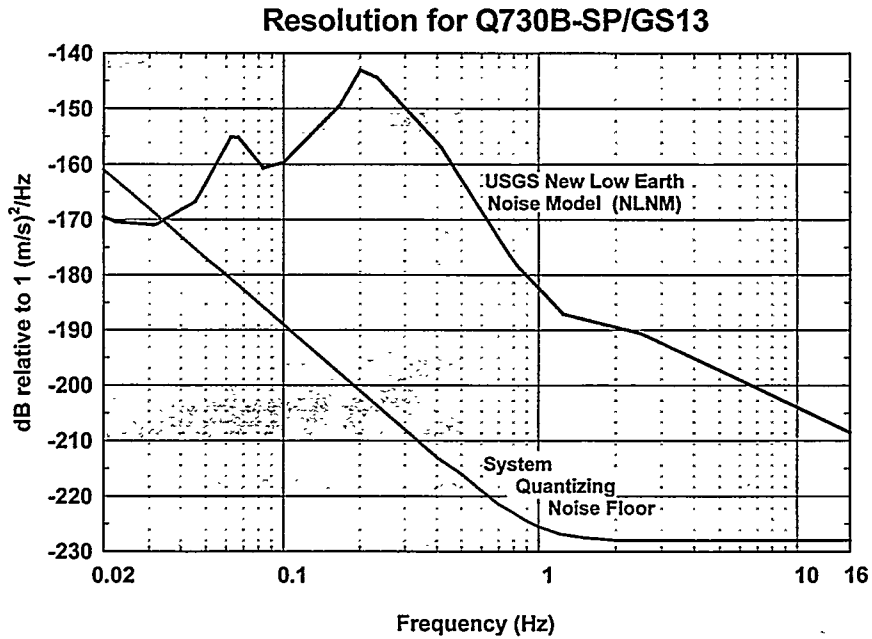


Figure 3.13 Resolution of Q730B-sp for GS-13 Seismometer

4.6.2 Q730B Seismic System Noise (SSN)

Purpose:

The purpose of the seismic system noise test was to determine ability of the Q730B to resolve the expected seismic background using a specific seismometer. The Q730B self-noise should be below the expected seismic background and the self-noise of the seismometer. The Q730B-bb was designed to interface to a Geotech KS54000 with acceleration response and sensitivity of $15,000 \text{ v/m/s}^2$. The Q730B-sp was designed to interface to a Geotech GS-13 seismometer with velocity response and a sensitivity of 2000 v/m/s .

Configuration:

The power spectral density results of the Input Terminated Noise (ITN) test were used to determine the seismic system noise of the Q730Bs. If a sensor preamplifier was installed, the ITN test was rerun after terminating the preamplifier with an appropriate resistance.

Evaluation:

The system noises of the Q730B-bb and Q730B-sp were converted to ground motion spectral units using the KS54000 and GS-13 response mathematical models. The results of these computations were overlaid with the USGS New Low Earth Noise Model (NLNM) to demonstrate the ability of the Q730Bs to resolve a very low seismic background. (When appropriate, a model of the power density spectrum at the proposed deployment site can be substituted for the NLNM.)

Q730B Seismic System Noise (SSN) Test Results

- The Q730B-bb system noise is shown in Figure 3.14. The gray background in that figure denotes frequencies often disregarded for broadband seismic applications.

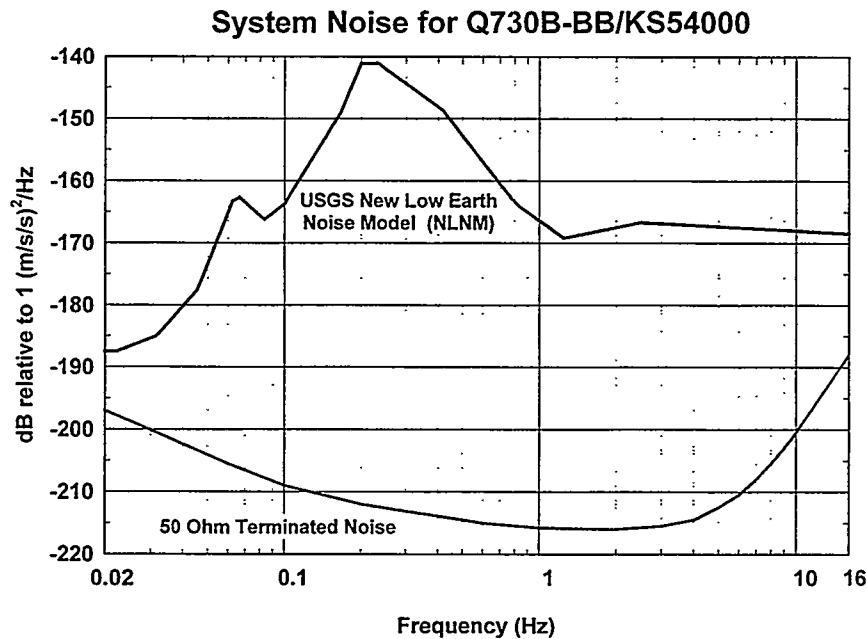


Figure 3.14 System Noise of Q730B-bb for KS54000 Seismometer

- The Q730B-sp system noise is shown in Figure 3.15. The gray background in that figure denotes frequencies often disregarded for short-period seismic applications.

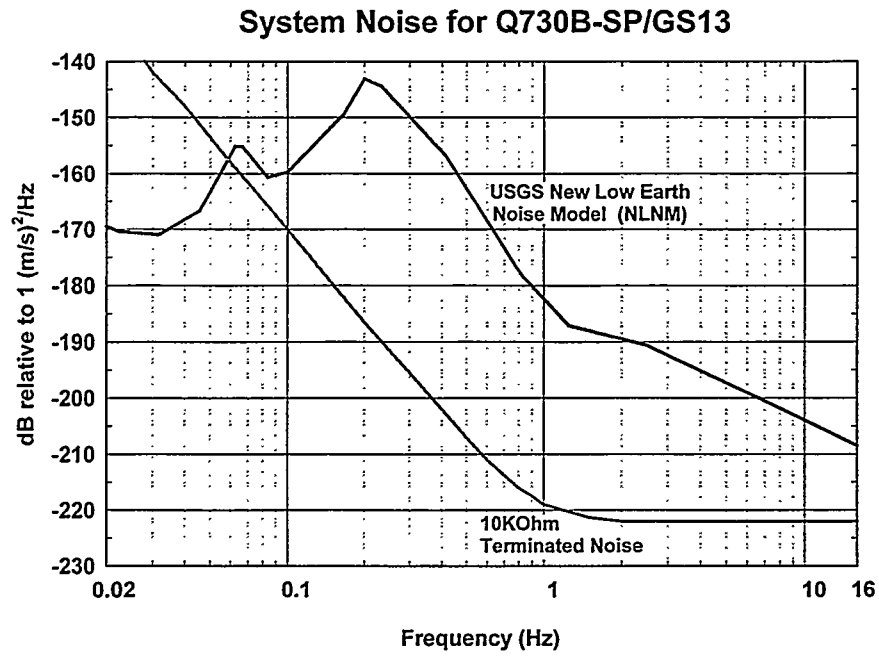


Figure 3.15 System Noise of Q730B-sp for GS-13 Seismometer

4.6.3 Seismic System Dynamic Range

The actual seismic signal dynamic range depends on the bandwidth of the application seismometer, the resolution/dynamic range of the application seismometer, and the resolution/dynamic range of the seismic DWR. A broadband application can utilize the entire bandwidth of the DWR. A long-period application utilizes only the low frequency end of the DWR bandwidth, while a short-period application utilizes only the high frequency end of the DWR bandwidth.

For this evaluation, dynamic range is defined to be the ratio of the RMS value of the largest signal that the DWR can measure without clipping to the RMS system noise of the DWR within some specified bandwidth.

4.6.3.1 Q730B Seismic Bandwidth-Limited Dynamic Range (SBLDR)

Purpose:

The purpose of the bandwidth-limited dynamic range test was to measure the signal-to-noise ratio capability of the Q730 for a specified seismic bandwidth.

Configuration:

The results of the Input Terminated Noise (ITN) test were used to determine the seismic system noise of the Q730Bs. If a sensor preamplifier was installed, the ITN test was rerun after terminating the preamplifier with an appropriate resistance.

Evaluation:

The seismic bandwidth-limited dynamic range (SBLDR) of the Q730B was determined by computing the RMS value of a full-scale sinusoid and dividing by the RMS of the Input Terminated Noise (ITN) test data over the specified seismic bandwidth.

DWR Seismic Bandwidth-Limited Dynamic Range (SBLDR) Test Results

Q730B-bb

- The Seismic Bandwidth Limited Dynamic Range of the Q730B-bb digitizer for a broadband seismometer (BW = 0.02-16 Hz) was **143 dB @40samples per second**. The Seismic Bandwidth Limited Dynamic Range of the Q730B-bb digitizer for a Long-period seismometer (BW = 0.02-1 Hz) was **151 dB @40samples per second**. A summary of the test results is shown in Table 3.15.

Sample Rate/ Bandwidth	Channel	RMS full-scale/ BWL RMS ITN	SBLDR
40 Samples/second Broadband (0.02-16.0 Hz)	1	14.23 V/0.998 μ V	143.1 dB
	2	14.23 V/0.989 μ V	143.2 dB
	3	14.23 V/1.001 μ V	143.1 dB
40 Samples/second Long-Period (0.02-1.0 Hz)	1	14.23 V/0.412 μ V	150.8 dB
	2	14.23 V/0.411 μ V	150.8 dB
	3	14.23 V/0.409 μ V	150.8 dB

Table 3.15 Seismic Bandwidth Limited Dynamic Range (SBLDR) Q730B-bb digitizer

Q730B-sp

- The Seismic Bandwidth Limited Dynamic Range of the Q730B-sp digitizer for a short-period seismometer (BW = .5-16 Hz) was **141.5 dB @40samples per second**. A summary of the test results is shown in Table 3.16.

Sample Rate/ Bandwidth	RMS full-scale/ BWL RMS ITN	Channel 1 SBLDR
40 Samples/second Short-Period (0.5-16.0 Hz)	0.712 V/.060 μ V	141.5 dB

Table 3.16 Seismic Bandwidth Limited Dynamic Range (SBLDR) Q730B-sp digitizer

5 Summary

Observations:

The Q730B-bb operated for 88 days continuously with no data gaps. The Q730B-sp operated for 24 days continuously with no data gaps.

It was not possible to test the Q730Bs in a standalone configuration. Data could be acquired only through the use of a UNIX workstation. Calibration commands were cryptic and could use some simplification.

5.1 Q730B-bb Broadband Remote Digitizer Evaluation Summary:

Static Performance:

The input terminated noise (<0.44 counts RMS @40 samples per second and <0.35 counts RMS @10 samples per second) were very low for long-period/broadband seismic applications. DC offset was low and could be remotely trimmed. DC accuracy errors were within 1%. The Maximum Potential Dynamic Range was 142 dB @40 samples per second and 145 dB @10 samples per second.

Dynamic Performance:

Non-linearity did not limit large-signal performance. The Q730B-bb Total Harmonic Distortion (THD) was -124 dB or better. Modified Noise Power Ratios indicated >23-bit performance; if over-range was considered, performance was 24-bits. For broadband signals, the maximum signal-to-noise ratio was 130 dB. Crosstalk was insignificant. Channel-to-channel timing skew was <1 µsecond.

Timing Performance:

The Q730B-bb time-tagged the data with respect to the digitizer input to better than 1 millisecond (≈5µsec). It removed the digital FIR filter delay at all sample rates. The standard deviation of time-tag accuracy drift was 3.8 µsec over seven days. There was no noticeable effect during GPS loss.

Calibrator Performance:

The Q730B-bb calibrator was not tested.

Seismic Application Performance:

The Seismic Signal Resolution (SSR) and Seismic Signal Noise (SSN) tests indicate that the resolution and noise of the Q730B-bb digitizer were below the USGS New Low Earth Noise Model (NLNM) for use with a Geotech KS54000 seismometer. Seismic Bandwidth Limited Dynamic Range for a broadband seismometer with bandwidth of 0.02 – 16 Hz was 143 dB. Seismic Bandwidth Limited Dynamic Range for a long-period seismometer with bandwidth of 0.02 – 1.0 Hz was 150 dB.

5.2 Q730B-sp Short-period Remote Digitizer Evaluation Summary:

Static Performance:

The input terminated noise (<0.68 counts RMS @40 samples per second and <0.57 counts RMS @10 samples per second) were very low for short-period seismic applications. DC offset was low and could be remotely trimmed. DC accuracy errors were within 1%. The Maximum Potential Dynamic Range was 139 dB @40 samples per second and 140 dB @10 samples per second.

Dynamic Performance:

Non-linearity may be a limiting factor for large-signal performance. The distortions from non-linear performance could add to the digitizer noise floor, decreasing the signal-to-noise ratio. The Q730B-sp Total Harmonic Distortion (THD) was -90 dB. This is not abnormal for a digitizer with 26 dB of gain.

Timing Performance:

The Q730B-sp time-tagged the data with respect to the digitizer input to better than 1 millisecond (≈340µsec). It removed the digital FIR filter delay at all sample rates.

Calibrator Performance:

The Q730B-sp calibrator correctly programmed sine amplitudes and frequency, step amplitude and duration, and white noise/random binary functions. Calibrator linearity was -90 dB THD for voltage and current outputs.

Seismic Application Performance:

The Seismic Signal Resolution (SSR) and Seismic Signal Noise (SSN) tests indicate that the resolution and noise of the Q730B-sp digitizer were below the USGS New Low Earth Noise Model (NLNM) for use with a Geotech GS-13 seismometer. Seismic Bandwidth Limited Dynamic Range for a short-period seismometer with bandwidth of 0.5 – 16 Hz was 141 dB.

5.3 Conclusion:

The Q730B digitizers had performance to >23 bits at 40 samples per second. The digitizer system noise of this remote digitizer implementation was exceptionally quiet.

References:

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2. IEEE Standard for Analog to Digital Converters, IEEE Std 1241 (Preliminary Draft), VS012799
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4. McDonald, Timothy S., "Modified Noise Power Ratio Testing of High Resolution Digitizers", SAND 94-0221, May 1994
5. Peterson, Jon, "Observations and Modeling of Seismic Background Noise", USGS Open-File Report 93-322, 1993

Distribution

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Carol Finn (TT)
Joseph Schrodt (TT)
Eugene Smart (TT)
Bruce Varnum (TT)
Mike Baker (TT)
1030 South Highway A-1A
Patrick Air Force Base, FL 32925-3002
- 4 Air Force Technical Applications Center (AFTAC)/Command Technologies, Inc
ATTN: Robert Kemerait
Tom Kelly
John Dwyer
Brett Moeller
1030 South Highway A-1A
Patrick Air Force Base, FL 32925-3002
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ATTN: Dr. Bob Blandford
Suite 1450
1300 North 17th Street
Arlington, VA 22209
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ATTN: Leslie Casey/NN-20
1000 Independence Ave. SW
Washington, DC 20585-0420
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ATTN: Wendee Brunish, MS F659
PO Box 1663
Los Alamos, NM 87545
- 2 Lawrence Livermore National Laboratory
ATTN: Jay Zucca, MS L-205
Dave Harris, MS L-205
PO Box 808
Livermore, CA 94551
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ATTN: Yuri Starovoit
Vienna International Centre
PO Box 1200
Vienna, A-1400 Austria
- 1 Defense Threat Reduction Agency
ATTN: Gus Gustafson
45045 Aviation Drive
Dulles, VA 20166-7517

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ATTN: Tim Ahern
1408 NE 45th Street
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ATTN: Paul Golden
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Dallas, TX 75275
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