SANDIA REPORT
SAND2020-3292
Printed March 2020

Sandia National Laboratories

Comparison of DTRA/NACT Next Generation Digitizer Evaluations

George W. Slad and B. John Merchant

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology & Engineering Solutions of Sandia, LLC.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@osti.gov
Online ordering: http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: https://classic.ntis.gov/help/order-methods/

ABSTRACT

Sandia National Laboratories has tested and evaluated three digitizers, the Affinity, manufactured by Guralp Systems, the Centaur, manufactured by Nanometrics, and the Q330M+, manufactured by Quanterra, a division of Kinemetrics. These digitizers are used to record sensor output for seismic and infrasound monitoring applications. The purpose of this document is to highlight various results and observations collected during comprehensive evaluations conducted on each unit.

ACKNOWLEDGEMENTS

This work was funded by the Defense Threat Reduction Agency (DTRA), Nuclear Arms Control Treaty (NACT) program.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND DEFINITIONS

BB	Broadband
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
dB	Decibel
DOE	Department of Energy
DWR	Digital Waveform Recorder
HNM	High Noise Model
LNM	Low Noise Model
PSD	Power Spectral Density
PSL	Primary Standards Laboratory
SNL	Sandia National Laboratories
SP	Short-period

1 INTRODUCTION

Figure 1 Guralp Affinity digitizer. Photo courtesy of Guralp Systems Limited.

Figure 2 Nanometrics Centaur digitizer. Photo courtesy of Nanometrics, Inc.

Figure 3 Quanterra Q330M+ digitizer. Photo courtesy of Kinematics, Inc

Figure 4 Form Factor Comparison of the Digitizers

The evaluation of the digitizers, (Affinity) serial number 40561C, Centaur serial number 5868, and Q330M+ serial number 036000CACC6030CC, has identified that generally each the unit's performance is consistent with the manufacturer's specifications shown in Figures 5-7.

Affinity

güralp

SPECIFICATIONS

SENSOR INPUTS	
Primary digitisation channels	4-channel 31-bit ADC (3 primary; 1 auxiliary)or 8-channel 31-bit ADC (6 primary; 2 auxiliary)
Input voltage	Differential input: 40 V peak-to-peak (± 20 V). Also compatible with single-ended inputs: 20 V peak-to-peak (± 10 V)
Optional environmental channels	8 multiplexed environmental channels ±10 V single-ended or 16 multiplexed environmental channels, ±10 V single-ended
Input impedence	113 kΩ
PERFORMANCE	
ADC converter type	4th-order, single-bit, low-pass Σ-Δ
Output format	32-bit
Dynamic Range	>138 dB at 100 samples per second
Absolute accuracy	0.5 %
Common-mode rejection	>80 dB
DATA PROCESSING	
Output rates available	1 to 4000 samples per second
Highest output capability	20,000 samples per second aggregate
Decimation filters	2, 4, 5.
Anti-alias filters	3-pole
Low pass filters	FIR (other options available)
Out-of-band rejection	140 dB
Data transmission modes	Continuous
Triggered data	Retrievable using event t able in the Affinity web page. User selectable pre and post event time.
Trigger modes	STA/LTA, level (threshold), external, software
TIMING AND CALIBRATION	
Timing source precision	<42 µs drift per hour when unsynchronised (without GPS) < 0.1 µs when GPS is connected
Timing sources	GNSS, PTP and NTP
Calibration signal generator	Amplitude/frequency adjustable, sine, step or broadband noise
OPERATION AND POWER USAGE	
Power supply	9 - 36 V DC*
Power consumption at 12 V DC	
4 channel	1.2 W (no GPS or ethernet)
	1.55 W (GPS with 10 Mb/s Ethernet output)
8 channel	1.5 W (no GPS or ethernet)
	1.85 W (GPS with 10 Mb/s Ethernet output)

**Power voltage for operation of this unit only. Connection to additional instrumentation or use of longer cables may result in a higher input voltage requirement.*

SOFTWARE PROTOCOLS	
Operating system	Linux
Communication technologies supported	RS232, USB, Ethernet (10BASE-T / 100BASE-T)
Internet technologies supported	TCP/IP, PPP, SSH, HTTP, HTTPS (others on request)
	Firewall and routing capabilities
DATA COMMUNICATION	
Data recording formats	GCF and miniSEED
Seismic network protocols	Scream! (Antelope/Earthworm), CD1.0/1.1, SEEDlink, GDI-Link and others
Data storage	Fixed 64 GB onboard storage Optional external USB storage
PHYSICAL/ENVIRONMENTAL	
Cold-start temperature range Operational temperature range	-25 to +60 °C -40 to +60 °C
Relative humidity range	zero to 100 %
Enclosure ingress protection	IP68 - protection against effects of prolonged immersion at 3 m depth for 72 hours
Enclosure/materials	Stainless steel cylinder
System weight	5.5 Kg (excluding GPS and cables)
Weight with mounting and carry bracket	6.1 Kg (excluding GPS and cables)
Dimensions - cylinder alone	274 mm × 114 Ø, excluding connectors and cables
Dimensions with mounting/ carrying bracket	304 mm × 160 mm × 130 mm, excluding connectors and cables
Standard accessories pack comprises	GNSS receiver (GPS, GLONASS, BeiDou, Galileo) with 10 m Cable (10 way to 10 way); 3 m Power Cable (4 way to Pig-tail); 5 m Ethernet Cable (6 way to Ethernet plug 8P8C); 1.8 m GPIO serial console cable (12 way-USB type A plug); RS422 to RS232 GNSS (GPS) adaptor

Güralp Systems Limited
Midas House
Calleva Park
Aldermaston
Reading
RG7 8EA
United Kingdom

T +44 118 981 9056
F +44 118 981 9943
E sales@guralp.com

www.guralp.com

In the interests of continual improvement with respect to design, reliability, function or otherwise, all product specifications and data are subject to change without prior notice.

DAS-AFT-0001 Issue D

Figure 5 Affinity Manufacturer Specifications

TECHNICAL SPECIFICATIONS CENTAUR (CTR4 SERIES)

Specifications subject to change without notice

SENSOR INPUTS
Channels: Available with 3 or 6 channel inputs
Sampling: Simultaneous on all 3 or 6 channels
Resolution: 24 bits per channel, full 24-bit range to clip level
Input voltage range (Peak-to-peak differential):
- 40 V, 20 V, 10 V, 4 V, 2 V, 1 V (standard)
- 10 V, 5 V, 2.5 V, 1 V, 0.5 V, 0.25 V (high-gain)

Input Impedance: 40 kΩ (standard digitizer) 1.8 MΩ (high-gain digitizer)

SENSOR COMPATIBILITY
Sensor Types: Broadband seismometers, short period geophones, and microbarometers
Control Lines: 6 per connector – typically used for calibration enable, mass center, mass lock/unlock, XYZ/UVW select
Sensor Power:
- Supply power pass-through to sensor (9-36 VDC, 1A)
- Over-current and surge protected

Auto Mass Centering: Configurable thresholds, intervals, retries
Serial Interface: Supports digital management of Nanometrics sensors and connectivity to weather stations

DIGITIZER PERFORMANCE & CAPABILITIES
Type: True 24-bit ADC per channel
Accuracy: Nominal gain accuracy within ±0.5%
Dynamic Range: 142 dB @ 100 sps, 135 dB @ 500 sps (full-scale peak to RMS shorted-input noise)
Preamp Gain:
- Standard: 1x, 2x, 4x, 10x, 20x, 40x
- High Gain: 4x, 8x, 16x, 40x, 80x, 160x

Sample Rates: 1, 2, 5, 10, 20, 40, 50, 80, 100, 125, 200, 250, 500, 1000, 2000, 5000 sps
Dual Sample Rates: A second sample rate can be selected from the sample rates above
Decimation Anti-Aliasing Filter:
- Selectable linear phase (noncausal) or minimum phase (causal)
- -140 dB (linear phase) or -120 dB (minimum phase) at Nyquist frequency, 0 dB at 80% Nyquist

Digital Filters:
- User-configurable low-pass and high-pass
- 1st to 5th order, 0.1 mHz to Nyquist
- Different filters may be configured for primary and secondary sample rates and Sensor A and B

Orientation Correction: User configurable onboard 3-D data rotation for correcting azimuth and tilt

RECORDING (CONTINUOUS)
Formats: MiniSEED
Internal Memory: 8 GB internal memory (32 or 64 GB options available)
Removable Media: SD Card up to 64 GB

RECORDING (EVENTS)
Triggers: Bandpassed STA/LTA, threshold
Captured Data: MiniSEED, ASCII
Data Products: Peak Ground Motion (i.e PGA, PGV, PGD) statistics calculated on the instrument

CALIBRATION
Signal Source: 16-bit DAC with 30 ksps output
Calibration Mode
- Voltage source, 1% accuracy from ±10V to ±5mV
- Current source, 1% accuracy from ±30mA to ±30uA

Waveforms: Synthesized sine, PRB signals
Playback user defined calibration files
User controllable amplitude, frequency, pulse width, duration, lead-in and lead-out silence

STATE-OF-HEALTH INPUTS
Channels: 3 singled-ended inputs, ±5 V range, 50 kΩ input impedance
Sampling Interval: Configurable from 1 to 3600 seconds
Accuracy: 18 bits effective resolution

DATA RETRIEVAL
File Transfer: Via Ethernet, optional WiFi or Ethernet-connected DSL, VSAT, cellular, radio
Media Exchange: SD card field-swappable during continuous recording with no loss of data
Response Metadata: Generate and download full digitizer/sensor response files in RESP or Dataless SEED format

DATA STREAMING
Continuous: Seismic data and State-of-Health data
Formats: SeedLink (not available when authenticating), Nanometrics NP, authenticating models have CD-1.1
Events: Triggered event data: email, secure file transfer, other options available

TIMING - GNSS & PRECISION NETWORK TIMING
Timing System: Internal DCXO clock disciplined to selectable timing source
Timing Source: Select from GNSS, PTP (Precision Timing Protocol), NTP or free-running
Timing Server: Serve PTP or NTP time to other Centaur, Titan SMA/EA or Meridian
Timing Accuracy: <5 µsec (GNSS Always on) <100 µsec (GNSS duty cycled, PTP or local NTP)
GNSS Receiver: Internal 32 channel GNSS receiver
GNSS Power: Selectable: always on, duty cycled or off

LOCAL USER INTERFACE
Removable Media: SD card protected in waterproof media bay
External LEDs: System status, Ethernet link, time quality, media card status, sensor A & B
Buttons: WiFi wakeup, media eject, system shutdown

COMMUNICATIONS
Web-based Graphical UI: Supports standard PC, tablet and mobile devices. Used for waveform and state-of-health monitoring, configuration, maintenance, sensor management and calibration, downloading data and events.

COMMUNICATIONS (CONT'D)
Interfaces: 10/100 Base-T Ethernet, WiFi (optional), Serial via USB (USB unavailable on Authenticating models)
IP Addressing: Static, dynamic (DHCP) or link-local IP
Protocols: UDP/IP unicast/multicast, HTTP data streaming

POWER
Power Supply: 9-36 VDC isolated input
Protection: Electronic resettable fuse design, lightning surge, reverse battery and short circuit protection
Battery Manager: User-configurable low voltage shutdown and restart thresholds

POWER USAGE (TYPICAL)
3 chan. (standard): 850 mW
6 chan. (standard): 1.2 W
Ethernet: Add 0.2 W for 10 Base-T, 0.3 W for 100 Base-T
High Gain: Add 0.2 W for every 3 high-gain channels
Authentication: Authenticating models add 1.2 W if enabled

CONNECTORS
Sensor: 26-pin Mil. circular, shell size 16, female
Power: 3-pin Mil. circular, shell size 8, male
Ethernet: Watertight RJ-45
USB: 2.0 Type A receptacle behind media bay door (USB unavailable on Authenticating models)
GNSS Antenna: TNC (female) with 3.3V supply for active antenna
State-of-Health: 4-pin Mil. circular, shell size 8, female

PHYSICAL CHARACTERISTICS
Housing: Aluminum
Weather Resistance: Rated to IP68 with connectors mated
Humidity: 0 to 100%
Operating Temperature: -20°C to +60°C (Ultra-low temperature option available. Please contact Nanometrics.)
Storage Temperature: -40°C to +70°C
Weight: 2.1 kg (3-channel), 2.2 kg (6-channel), 2.2 kg (CTR4-3A), 2.4 kg (CTR4-6A/S)
Size: 196 mm (L) x 137 mm (W) x 88 mm (H), except CTR4-6A/S which is 196 mm (L) x 137 mm (W) x 93 mm (H)

CENTAUR WITH AUTHENTICATION MODELS: CTR4-3A, 6A/S
Streaming: CD1.1 format
Digital Signature:
Hardware authentication provides
- Digital Signature Algorithm (DSA, SHA-1) and
- Elliptic Curve Digital Signature Algorithm (ECDSA P-256, SHA-256)
- Authentication on Sensor A only

Tamper Detection: Authenticating models have case tamper switch or 3 external switches via SOH connector

Contact a product expert Toll Free: 1 855 792 6776 | sales_mkt@nanometrics.ca

nanometrics

Strategic intelligence fueled by science

250 Herzberg Road, Kanata, Ontario, Canada K2K 2A1 | Tel: +1 613 592 6776

1003.01.21.

Figure 6 Centaur Manufacturer Specifications

QUANTERRA

A Division of Kinemetrics

Q330M+

SPECIFICATIONS

Channels	3, optionally 6, 24-bit main channels; 6 8-bit auxiliary channels
Dynamic Range (0-7Hz bandwidth)	141dB RMS sine wave 144dB zero-to-peak sine wave 150dB peak-to-peak sine wave
Input Impedance	150 kΩ differential for active sensors; 2 MΩ differential at gain ≥8 for passive sensors
Input Range	40Vpp at gain=1
Gain	Selectable per 3-channel group: 1, 2, 4, 8, 16, 32, 64, 128
Digitizer Noise	16dB below NLNM from 0.02 -16Hz used with standard broadband sensors, such as STS-2.5; voltage noise as low as -163dB re $1V^2$/Hz, depending on gain
Filtering	Configurable Linear or Minimum-phase
Sample Rate	1000, 500, 250, 200, 100, 50, 40, 20, 10, 1
Time Accuracy	<1µs when locked to GPS or PTP server
Total Harmonic Distortion	Better than -120dB
Cross-talk	Better than -130dB
Data Storage and Retrieval	PC/MAC/Linux-formatted removable SLC SD card, standard 8GB (up to 32GB possible); optional external USB flash drive for data copying or mirroring, standard 64GB (up to 256GB possible
Sensor Control	Calibrate: step, low-THD sine wave, MLS or random binary; lock/unlock & re-center
Operational Status	Over 50 State-of-Health channels including temperature, voltages, currents, GPS status, Sensor boom position (6 channels)
Network	Ethernet (10/100BT) Full IP Protocol Stack (Linux)
Authentication	Hardware; supported algorithms: DSA 1024 digital signature and key exchange ECDSA Digital Signature Algorithm (in the future)
Protocols	CD1.1, Q330 native, SeedLink
Other Ports	1 x USB2.0 2 X CONSOLE PORTS UP TO 115 kbaud 1 x digital I/O for vault intrusion switch
Power	12VDC nominal (9-36VDC operational) Consumption depending on configuration
Physical	Sealed, Aluminum, 18 x 4 x 6 in., 10 lbs., rubber endcaps, externally visible status and fault indicators; rated IP68 (24 hours immersion at 1m depth)
Temperature	Fully specified -20 to +60° C Guaranteed operative -40 to +70°C

Specifications subject to change without notice

USA - 2 Shaker Rd. Suite F200, Shirley, MA 01464
Tel (978) 425-2100 I www.kinemetrics.com

04-05-18

Figure 7 Q330M+ Manufacturer Specifications

Channel naming of the Affinity data streams followed that recommended by Guralp.

Table 1 Guralp Affinity Channel Naming Convention

Port	Digitizer Channel	Channel Name		
-	-	100 sps	40 sps	20 sps
Sensor A	1	HH1	SH1	BH1
Sensor A	2	HH2	SH2	BH2
Sensor A	3	HH3	SH3	BH3
Auxiliary	4	HDF	SDF	BDF
Sensor B	5	HH5	SH5	BH5
Sensor B	6	HH6	SH6	BH6
Sensor B	7	HH7	SH7	BH7
Auxiliary	8	HH8	SH8	BH8

Channel naming utilized for the Nanometrics Centaur is as follows.

Table 2 Centaur Channel Naming Convention

Digitizer Channel	Channel Name	
	40 sps	20 sps
1	00SHZ	00BHZ
2	00SNN	00BHN
3	00SHE	00BHE
4	01SHZ	01BHZ
5	01SHN	01BHN
6	01SHE	01BHE

The channel map utilized for the Kinemetrics Q330M+ is based on the default convention provided the digitizer's configuration parameters and is as follows.

Table 3 Q330M+ Channel Naming Convention

Digitizer Channel	Channel Name		
	100 sps	40 sps	20 sps
1	HLZ	SLZ	BLZ
2	HLN	SLN	BLN
3	HLE	SLE	BLE
4	HHZ	SHZ	BHZ
5	HHN	SHN	BHN
6	HHE	SHE	BHE

2 EVALUTION HIGHLIGHTS

2.1 Power Consumption

The Power Consumption test is used to measure the amount of power that an actively powered digitizer consumes during its operation.

Table 4 Power Consumption Results

DWR	Supply Voltage	Supply Voltage SD	Supply Current	Supply Current SD	Power Consumption	Power Consumption SD
Affinity	14.04 V	0.0895 mV	0.1906 A	7.788 mA	2.676 W	109.4 mW
Centaur	14.04 V	139 mV	0.1815 A	12.340 mA	2.549 W	173 mW
Q330M+	14.04 V	0.100 mV	0.3053 A	27.397 mA	4.287 W	103.8 mW

Digitizer power consumption varies widely and in one case above that specified by the manufacturer. Measurements were made with the digitizers collecting six channels of data, at 3 sample rates (8 channels for the Affinity, 2 sample rates for the Centaur), authenticating and sending all the respective channels (Centaur limited to authenticating 3 channels).

The Affinity datasheet specifies 1.85 W while streaming data; however, Guralp does not specify that the value provided is with the unit authenticating data. The Q3330M+ data sheet does not provide a power consumption value and Kinemetrics notes the power consumption will vary with configuration. Finally, the Centaur datasheet states the unit will draw approximately 2.8 W to 2.9 W with one set of channels operating at “high” gain settings and 3 channels of data undergoing authentication. As can be seen in Table 4, the Q330M+ consumed more than the other digitizers.

2.2 DC Accuracy

The DC Accuracy test is used to measure the bit weight of a digitizer channel by recording a known positive and negative dc signal at a reference voltage from a precision voltage source.

Table 5 DC Accuracy - Maximum Percent Deviation from Nominal Bit Weights, 40 sps

Gain	Affinity	Maximum Difference from Nominal	Centaur	Maximum Difference from Nominal	Q330M+	Maximum Difference from Nominal
1x	1.0000 uV/count	-0.0090%	2.5000 uV/count	0.0252%	2.3840 uV/count	0.1892%
2x	0.5000 uV/count	-0.0488%	1.2500 uV/count	0.0240%	1.1920 uV/count	0.1644%
4x	0.2500 uV/count	-0.1348%	0.6250 uV/count	0.0245%	0.5960 uV/count	0.1223%
8x	0.1250 uV/count	-0.2712%	-	-	0.2980 uV/count	0.1017%
10x	-	-	0.2500 uV/count	0.0236%	-	-
16x	0.06250 uV/count	-0.3811%			0.1490 uV/count	0.1470%
20x	-	-	0.1250 uV/count	0.0185%	-	-
32x	0.03125 uV/count	-0.1811%	-	-	0.0745 uV/count	0.1859%
40x	-	-	0.06250 uV/count	0.0149%	-	-

Comparison of the highest common sample rate data recorded across the digitizers (40 sps), illustrates that all of the digitizer's bit weights varied less than .38% across all of the gains.

2.3 AC Accuracy

The AC Accuracy test is used to measure the bit-weight of a digitizer channel by recording a known AC signal at a reference voltage from a precision voltage source. The AC accuracy test provides a more representative test of bit weight than the constant value utilized in the DC Accuracy Test, as the sine wave input better simulates the periodic input signals from seismometers and infrasound sensors typically utilized in monitoring applications.

Table 6 AC Accuracy - Maximum Percent Deviation from Nominal Bit Weights, 40 sps

Gain	Affinity	Maximum Difference from Nominal	Centaur	Maximum Difference from Nominal	Q330M+	Maximum Difference from Nominal
1x	1.0000 uV/count	-0.0120%	2.5000 uV/count	0.0388%	2.3840 uV/count	0.7987%
2x	0.5000 uV/count	-0.0528%	1.2500 uV/count	0.0368%	1.1920 uV/count	0.7743%
4x	0.2500 uV/count	-0.1380%	0.6250 uV/count	0.0373%	0.5960 uV/count	0.7322%
8x	0.1250 uV/count	-0.2744%	-	-	0.2980 uV/count	0.6513%
10x	-	-	0.2500 uV/count	0.0368%	-	-
16x	0.06250 uV/count	-0.3850%			0.149 uV/count	0.6275%
20x	-	-	0.1250 uV/count	0.0312%	-	-
32x	0.03125 uV/count	-0.1862%			0.0745 uV/count	0.5866%
40x	-	-	0.0625 uV/count	0.0277%	-	-

Comparison of the highest common sample rate data recorded across the digitizers (40 sps), at all of the gain settings shows that the Affinity and Centaur bit weights deviate little from their values in the DC accuracy test. The Q330 variations in bit weight, though still less than 1%, were noticeably higher than the DC accuracy test.

2.4 Self noise

The Self-Noise test measures the amount of noise present on a digitizer by collecting waveform data from an input channel that has been terminated with a resistor whose impedance matches the nominal impedance of a chosen sensor at 1 Hz. Thus, any signal present on the recorded waveform should be solely due to any internal noise of the digitizer. Channels names in the following plots utilize a naming convention combining the gain value and the channel names as described in Table 1, Table 2 or Table 3; for example, regarding the Affinity digitizer, the channel name "4xHDF" in Figure 8 represents data collected with a gain of 4x from channel 4.

The self-noise results herein are based upon 12 hours of data utilizing an 8K sample length windows resulting in a 0.6 dB 95% confidence interval. Data recording at the various gain settings were split amongst the available channels, e.g. channels 1-3 (or 1-4) recorded at gains of 1x, 2x and 4x and channels 4-6 (or 5-8) recorded at, gains of 8x (10x), 16x (20x) and 32x (40x).

Figure 8, Figure 9 and Figure 10 illustrate the self-noise of the highest sample rate data recorded at the gain settings evaluated, for each of the digitizers.

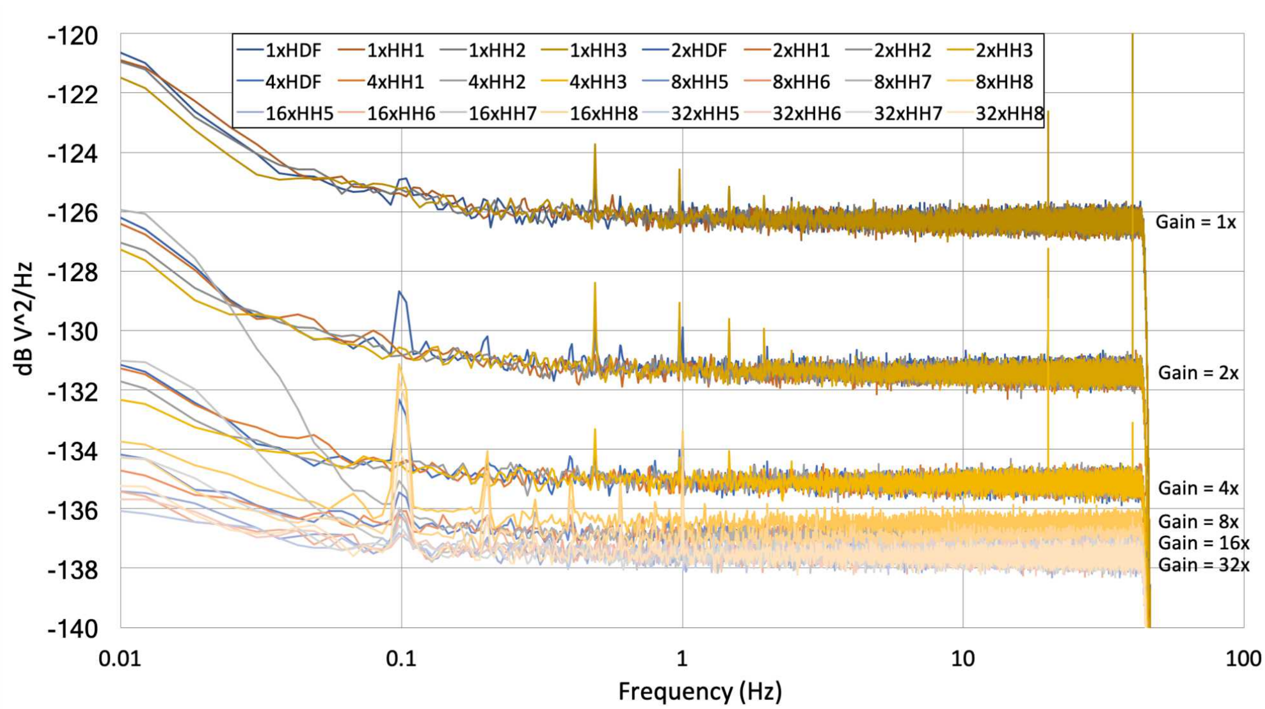

Figure 8 Affinity Self-noise Power, Gains: 1x, 2x, 4x, 8x, 16x and 32x, 100 sps

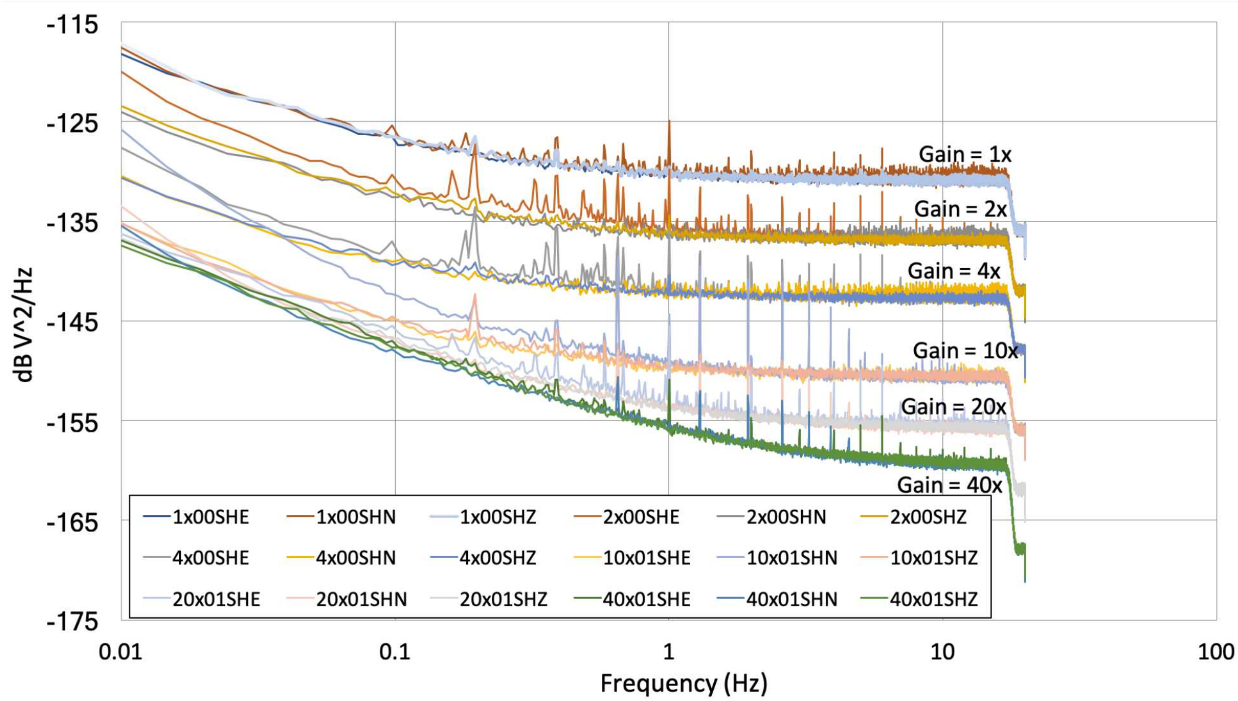

Figure 9 Centaur Self-noise Power, Gains: 1x, 2x, 4x, 10x, 20x and 40x, 40 sps

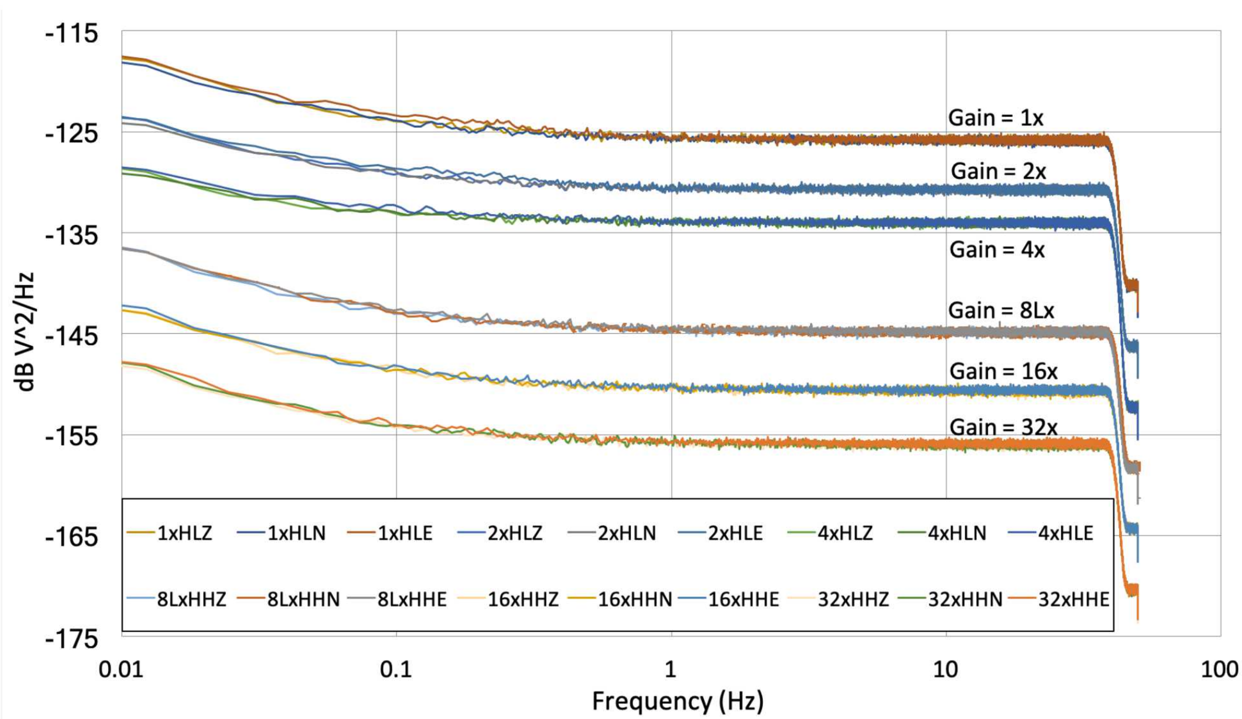

Figure 10 Q330M+ Self-noise Power, Gains: 1x, 2x, 4x, 8x, 16x and 32x, 100 sps

The Affinity plot, Figure 8, shows, while self-noise improves with increasing gain, the rate of self-noise improvement with gain decreases. The Centaur plot, Figure 9, shows how self-noise improves as gain increases, however, self-noise increases significantly as frequency decreases.

Finally, Figure 10, shows the relatively flat self-noise of the Q330M+ across the frequency band, and its uniform improvement in self-noise with gain.

Figure 11, Figure 12 and Figure 13 illustrate the self-noise of a representative digitizer channel (either channel 1 (gains 1, 2 and 4) or channel 4 or 5 (gains 8x, 10x, 16x, 20x, 32x or 40x) at the evaluated sample rates.

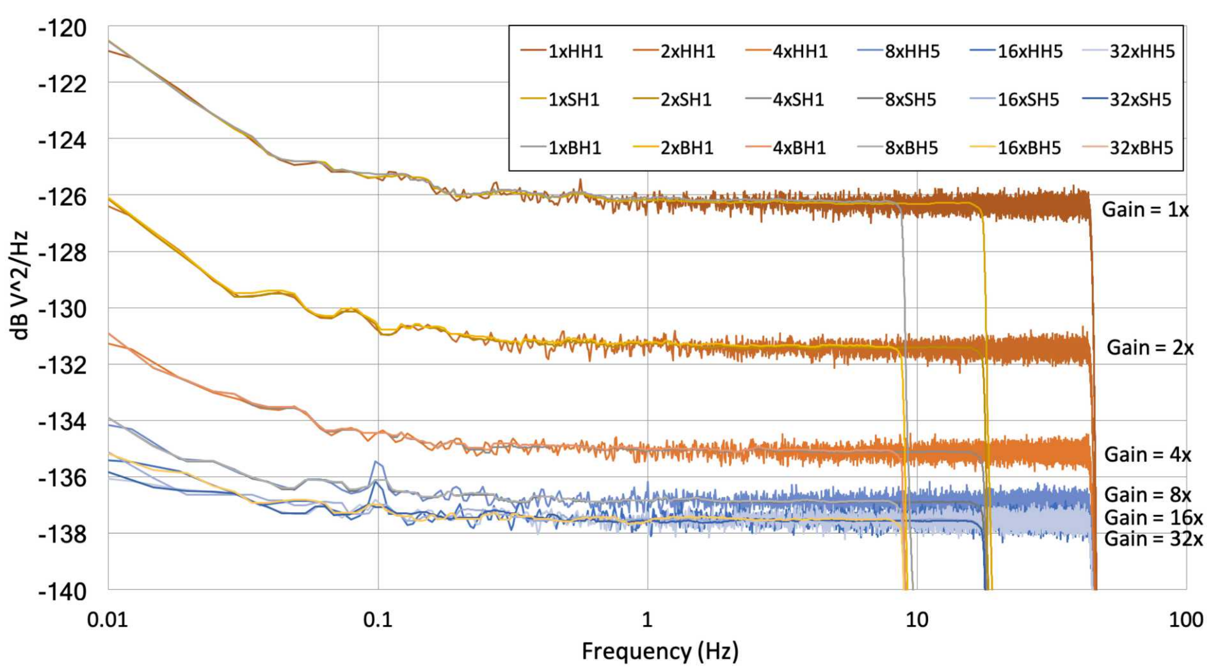

Figure 11 Affinity Self-noise Power as Recorded at 100 sps, 40 sps and 20 sps

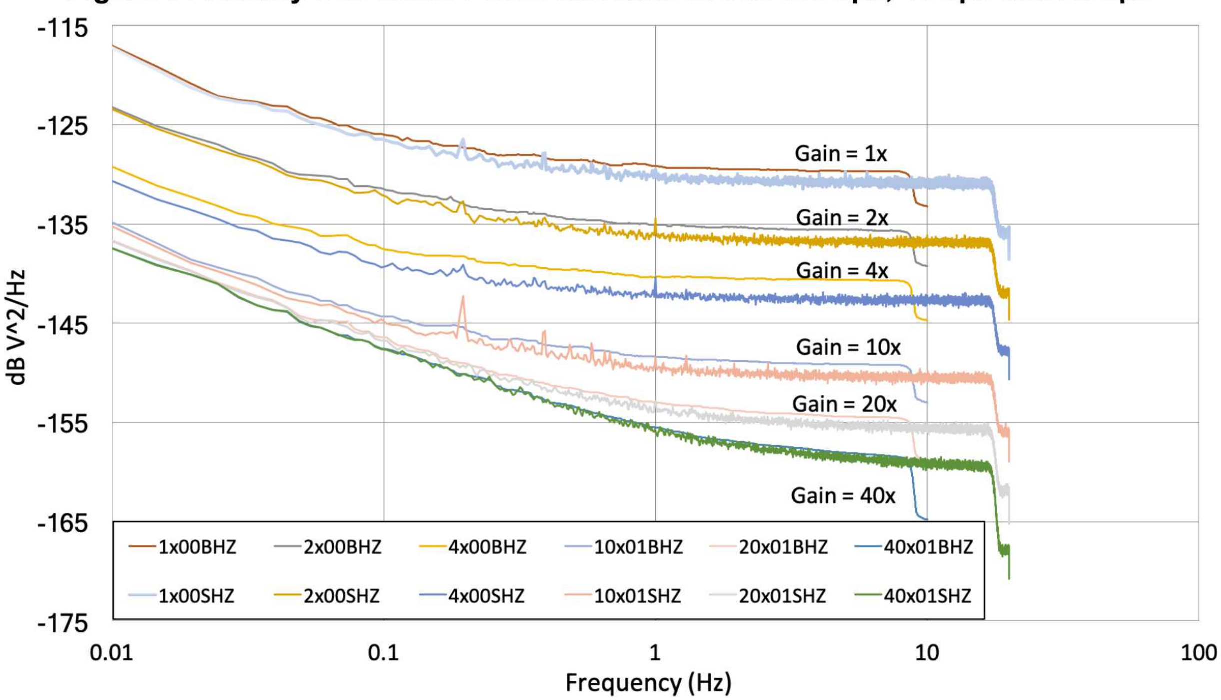

Figure 12 Centaur Self-noise Power as Recorded on 40 sps and 20 sps

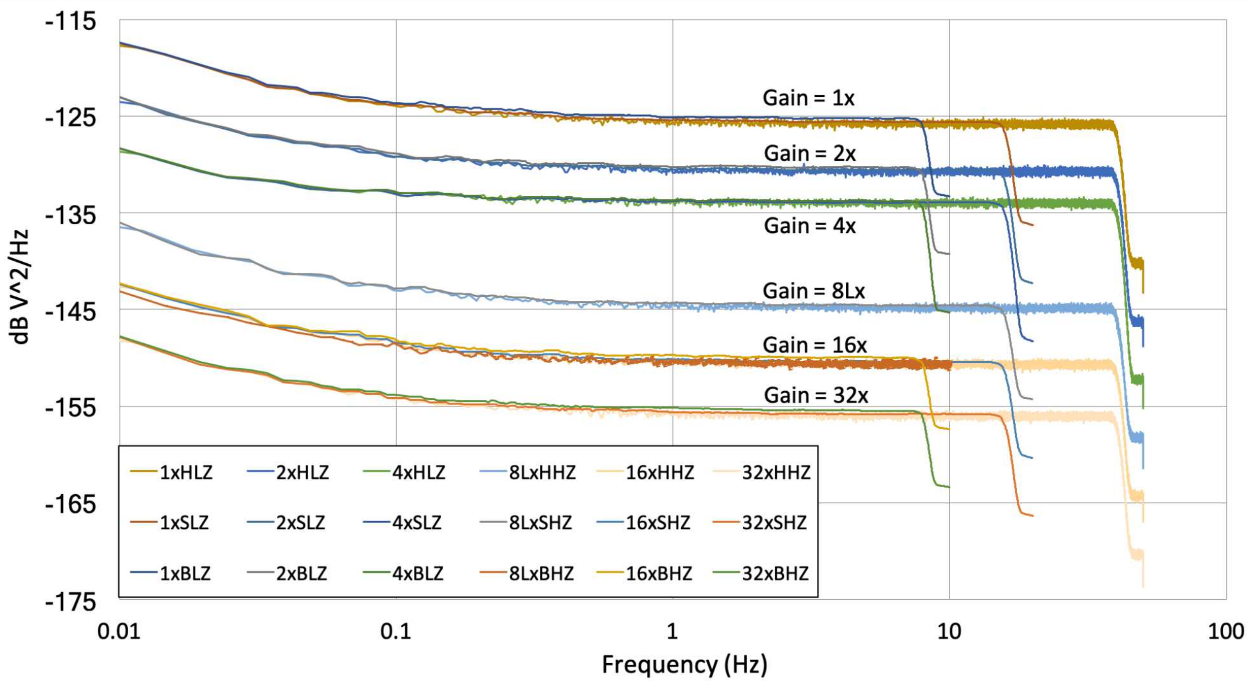

Figure 13 Q330M+ Self-noise Power as Recorded at 100 sps, 40 sps and 20 sps

Notice the stability in self-noise power across sample rates of the Affinity digitizer, Figure 11, while Figure 12, illustrates the varying self-noise power across sample rates, at any given gain, for the Centaur digitizer. Finally, Figure 13 shows the slight variation (often near the 90% confidence value of 0.60 dB of the computations) in self-noise across sample rates of the Q330M+.

Figure 14 through Figure 19 provide a visual comparison of self-noise power of the digitizers at the same, or similar, gain settings.

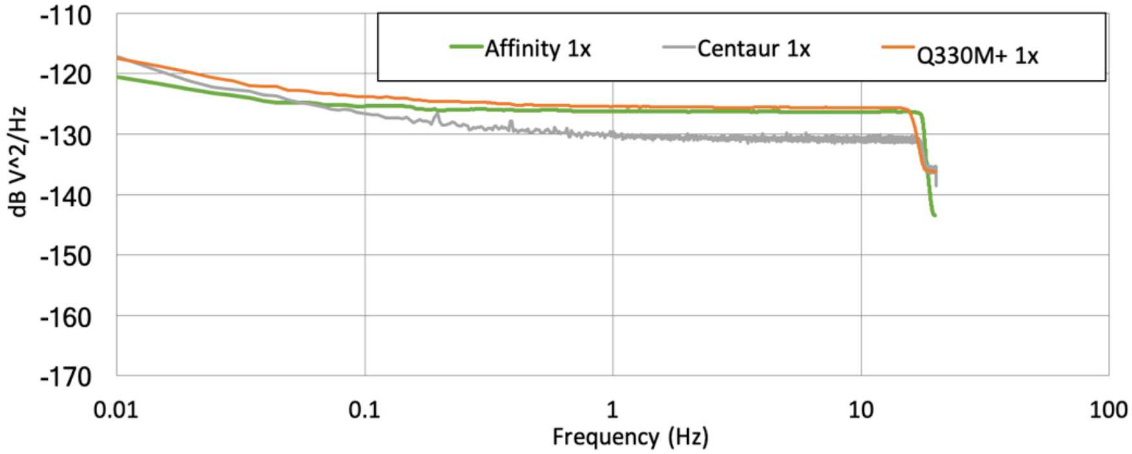

Figure 14 Self-noise Power, All Digitizers, Gain 1x

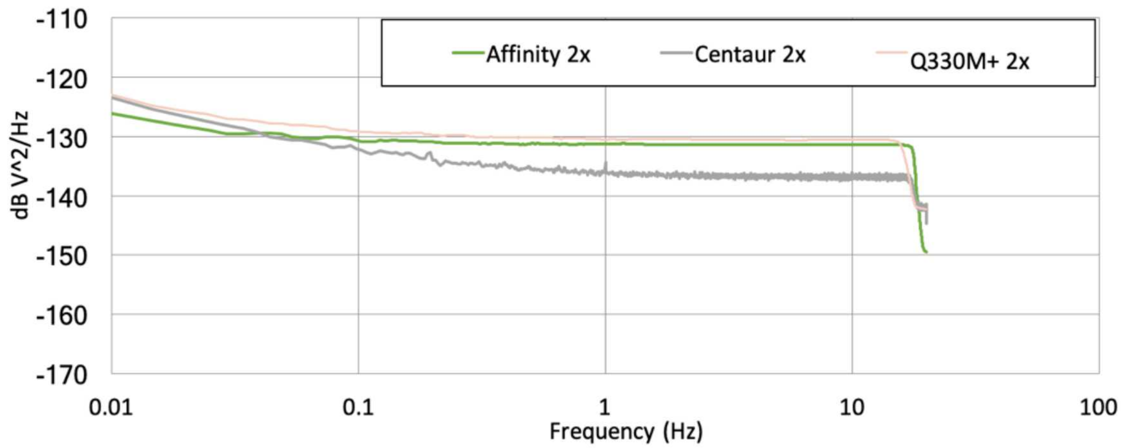

Figure 15 Self-noise Power, All Digitizers, Gain 2x

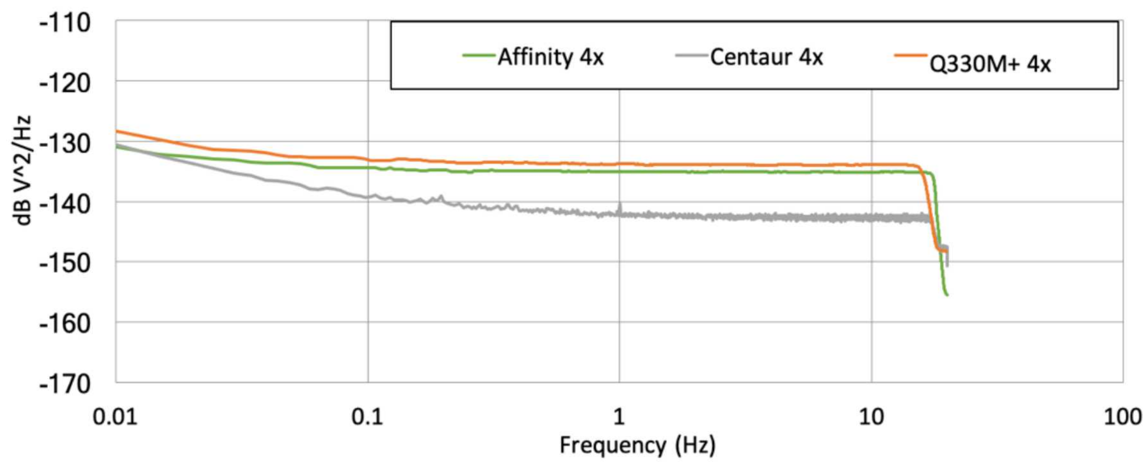

Figure 16 Self-noise Power, All Digitizers, Gain 4x

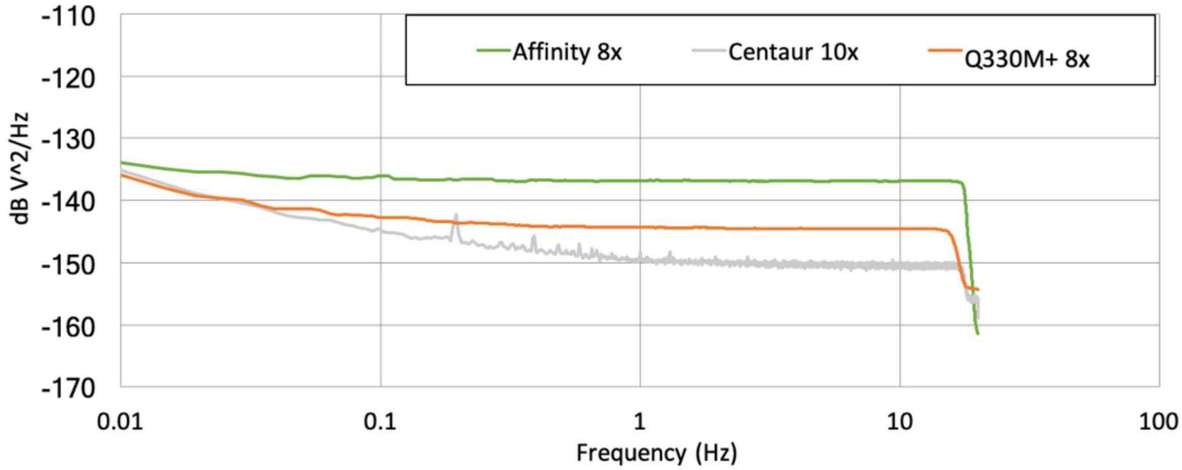

Figure 17 Self-noise Power, Affinity (8x), Centaur (10x) and Q330M+ (8x)

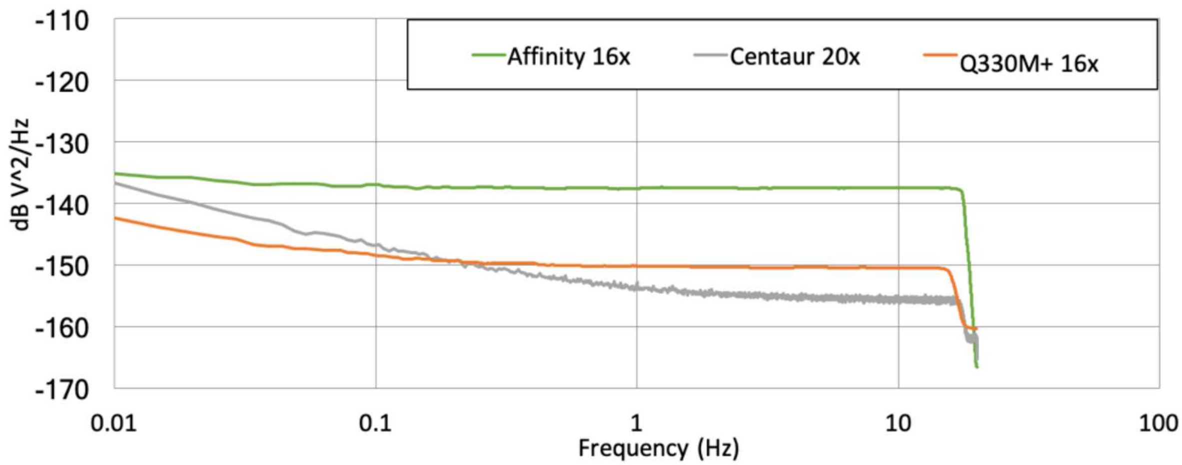

Figure 18 Self-noise Power, Affinity (16x), Centaur (20x) and Q330M+ (16x)

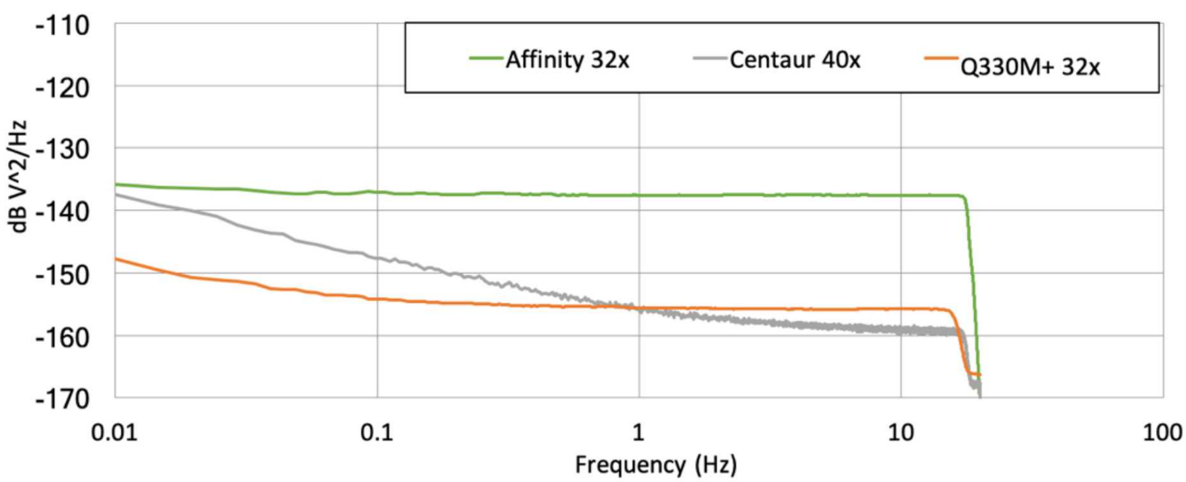

Figure 19 Self-noise Power, Affinity (32x), Centaur (40x) and Q330M+ (32x)

Several trends are readily apparent in Figure 14 through Figure 19. The Affinity and Q330M+ have relatively comparable self-noise power at the lower gain values of 1x, 2x and 4x. The Q330M+ has continuing improvement in self-noise power at higher gain settings relative to smaller, incremental improvements in self-noise of the Affinity. The Centaur has relatively low self-noise power at higher frequencies compared that of the Affinity and Q330M+ values.

2.5 Dynamic Range

Dynamic range is defined to be the ratio between the power of the largest and smallest signals that may be measured on the digitizer channel.

The following tables contain the peak-to-peak full scales, noise levels, and dynamic ranges that were identified in the evaluations of 40 sps data and across all evaluated gain settings (1x, 2x, 4x, 8x, 10x, 16x, 20x, 32x and 40x) over the passband 0.01 Hz to 10 Hz. Data collected for the self-noise tests were utilized for computation of dynamic range, therefore dynamic range computed at the various gain settings are split amongst the available channels, e.g. channels 1-3 (or 1-4) recorded at gains of 1x, 2x and 4x and channels 4-6 (or 5-8) recorded gains of 8x (10x), 16x (20x) and 32x (40x).

Table 7 Dynamic Range, Affinity, 0.01 Hz to 10 Hz, 40 sps

Gain	Channel SH1	Channel SH2	Channel SH3	Channel SDF	Channel SH5	Channel SH6	Channel SH7	Channel SH8
1x	139.24 dB	139.19 dB	139.21 dB	139.21 dB	-	-	-	-
2x	138.36 dB	138.32 dB	138.33 dB	138.24 dB	-	-	-	-
4x	136.04 dB	136.02 dB	136.05 dB	136.04 dB	-	-	-	-
8x	-	-	-	-	131.81 dB	131.82 dB	131.77 dB	131.39 dB
16x	-	-	-	-	126.44 dB	126.45 dB	126.44 dB	125.96 dB
32x	-	-	-	-	117.94 dB	117.94 dB	117.95 dB	117.95 dB

Table 8 Dynamic Range, Centaur, 0.01 Hz to 10 Hz, 40 sps

Gain	Channel 00SHZ	Channel 00SHN	Channel 00SHE	Channel 10SHZ	Channel 10SHN	Channel 10SHE
1x	143.46 dB	143.27 dB	143.44 dB	-	-	-
2x	143.40 dB	143.42 dB	142.84 dB	-	-	-
4x	143.32 dB	143.19 dB	143.04 dB	-	-	-
10x	-	-	-	142.82 dB	142.02 dB	142.94 dB
20x	-	-	-	141.20 dB	141.19 dB	140.73 dB
40x	-	-	-	137.60 dB	137.69 dB	137.45 dB

Table 9 Dynamic Range, Q330M+, 0.01 Hz to 10 Hz, 40 sps

Gain	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	138.49 dB	138.52 dB	138.44 dB	-	-	-
2x	137.48 dB	137.48 dB	137.42 dB	-	-	-
4x	134.84 dB	134.86 dB	134.80 dB	-	-	-
8x	-	-	-	139.41 dB	139.42 dB	139.31 dB
16x	-	-	-	139.21 dB	139.20 dB	139.13 dB
32x	-	-	-	138.61 dB	138.57 dB	138.47 dB

Table 10 Average Dynamic Range 0.01 Hz to 10 Hz, All Digitizers, 40 sps

Gain	Affinity	Centaur	Q330M+
1x	139.21 dB	143.39 dB	138.48 dB
2x	138.31 dB	143.22 dB	137.46 dB
4x	136.04 dB	143.18 dB	134.83 dB
8x	131.70 dB	-	139.38 dB
10x	-	142.59 dB	-
16x	126.32 dB	-	139.18 dB
20x	-	141.04 dB	-
32x	117.95 dB	-	138.55 dB
40x	-	137.58 dB	-

The widely varying self-noise observed is readily apparent in varying dynamic ranges computed from the evaluations conducted. Notice the Affinity and Centaur dynamic range drops as gain increases. Recall, the cases of the Centaur and the Affinity, the self-noise improvements were incrementally smaller as gain increased. The Q330M+, on the other hand, maintains a relatively consistent dynamic range as gain is increased, which is clearly supported by the consistent improvement in self-noise as gain increases.

2.6 System Noise

The System Noise test determines the amount of digitizer self-noise expressed in units of a sensor.

The PSD of the system noise is shown in the plots below. A representative channel's data, from the self-noise tests, has the response and sensitivity of a selection of sensors applied to it, allowing the digitizer's self-noise to be presented in equivalent infrasound or seismic system noise for a given sensor. Plots are arranged such that the three respective digitizers' system noise plots for the same sensor are in a column and share common scales for ease of comparison.

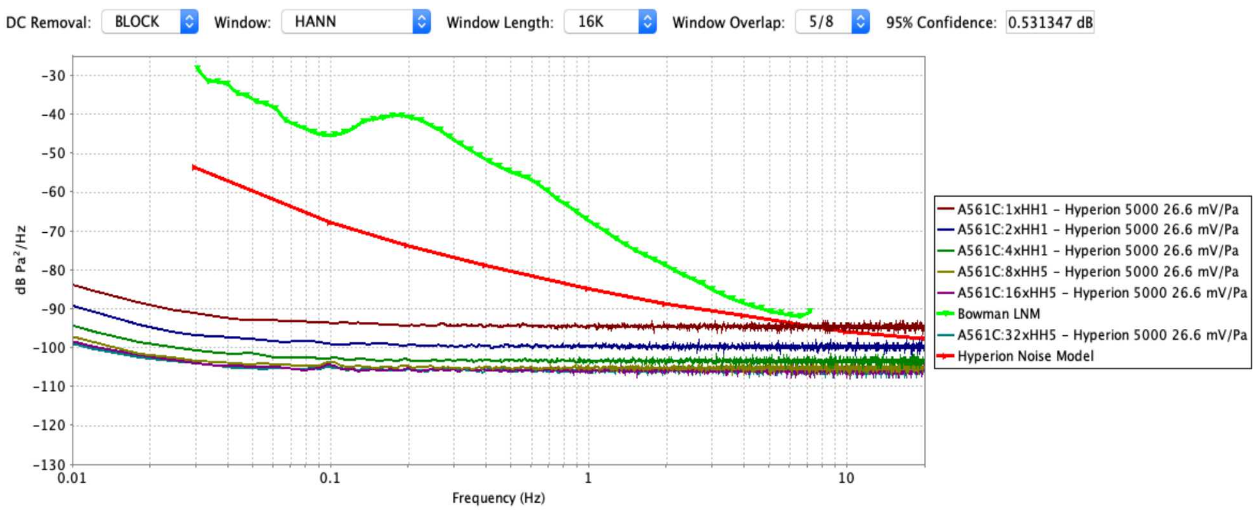

Figure 20 System Noise Hyperion 5113a, Affinity Digitizer

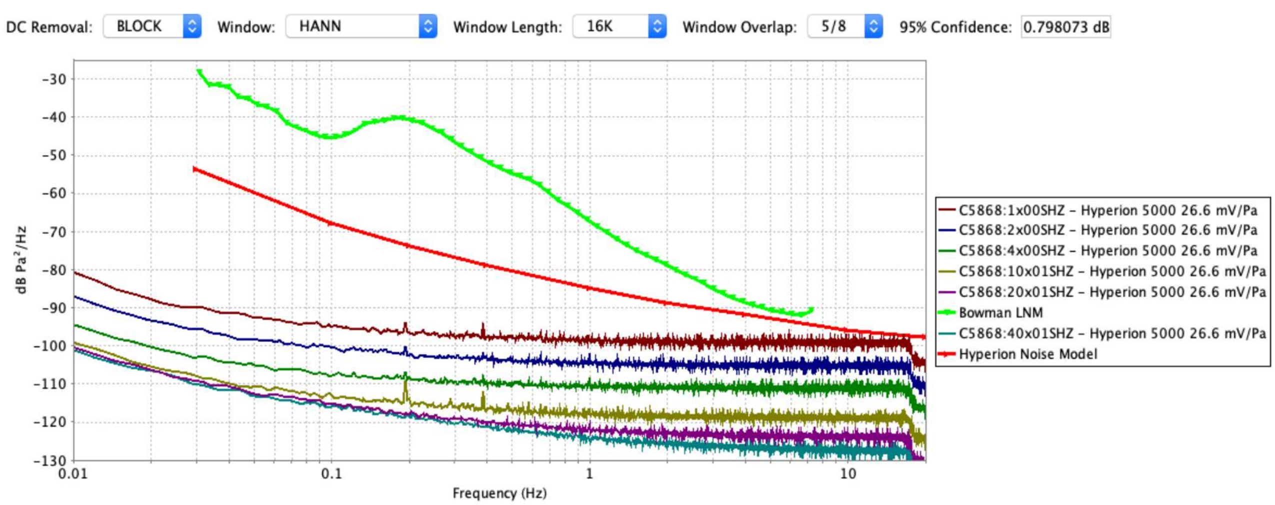

Figure 21 System Noise Hyperion 5113a, Centaur Digitizer

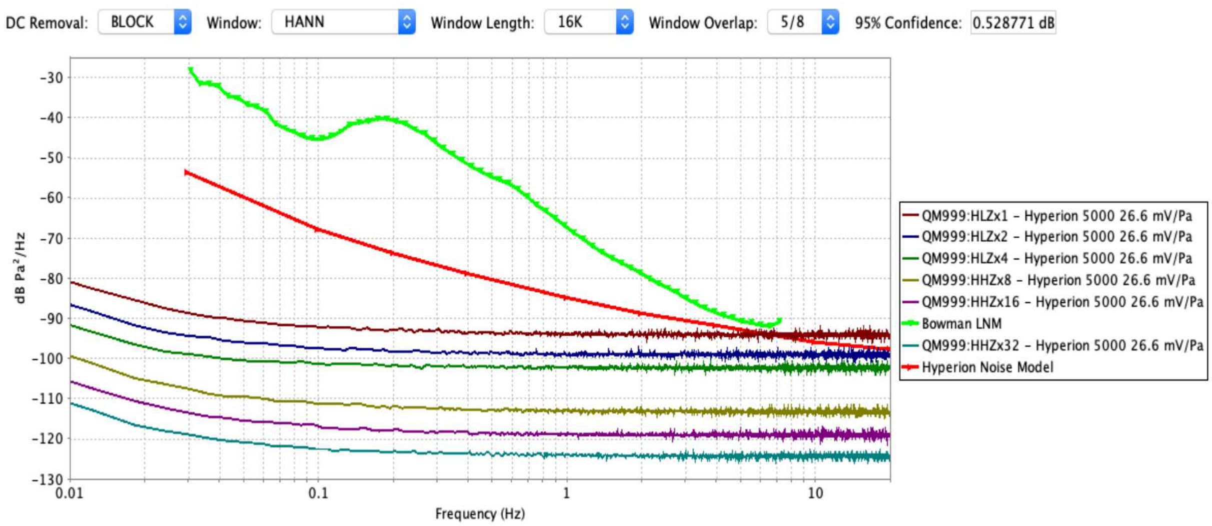

Figure 22 System Noise Hyperion 5113a, Q330M+ Digitizer

System noise, in equivalent units of the Hyperion 5113a with 26.6 mV/Pa exceeds that of the sensor at a gain of 1x for the Affinity and Q330M+ digitizer above 5 Hz.

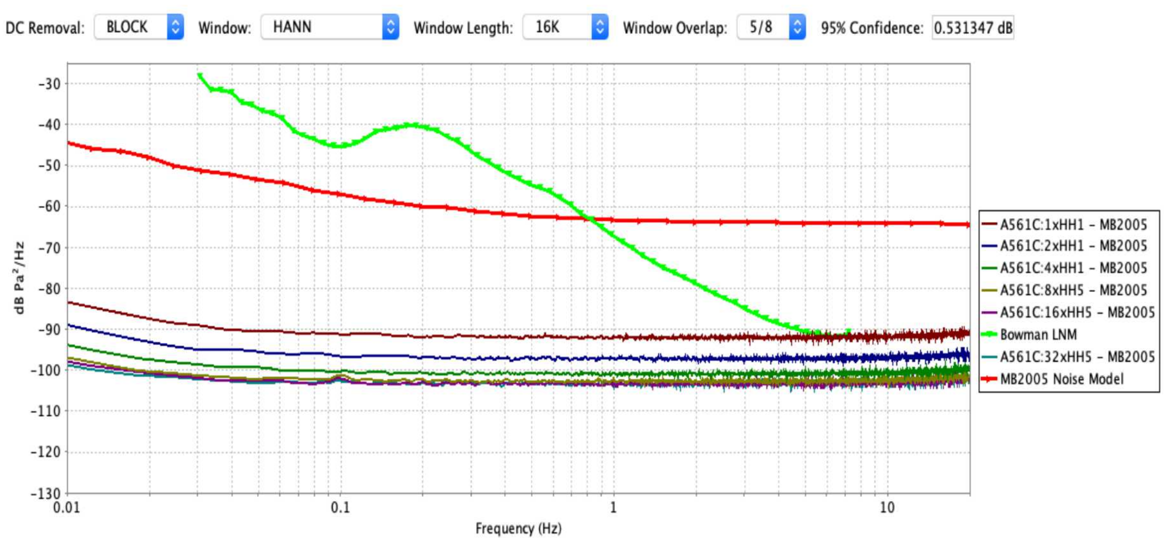

Figure 23 System Noise MB2005, Affinity Digitizer

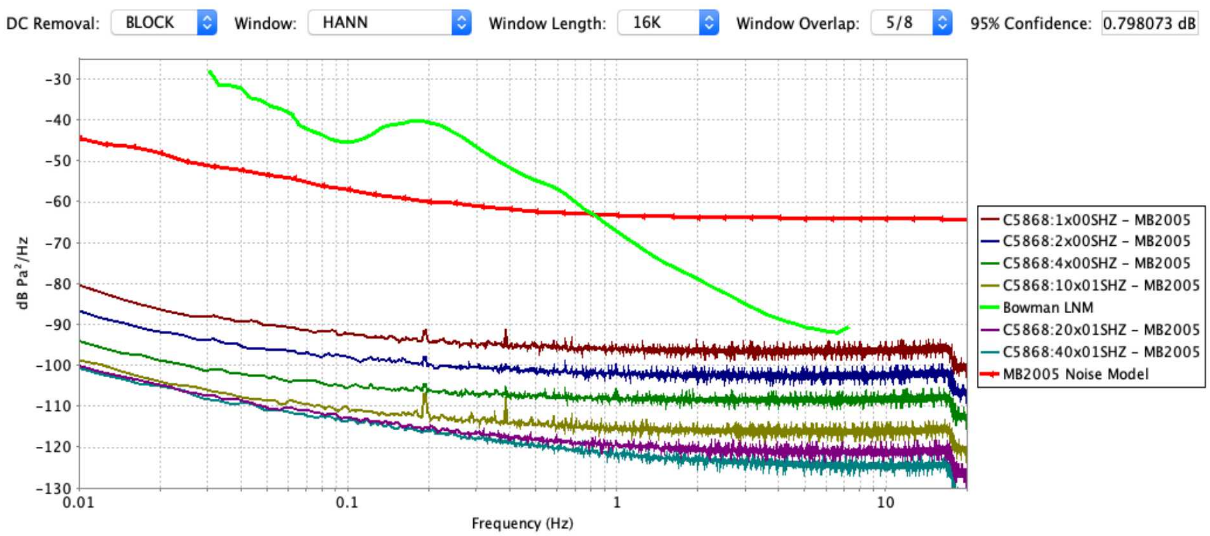

Figure 24 System Noise MB2005, Centaur Digitizer

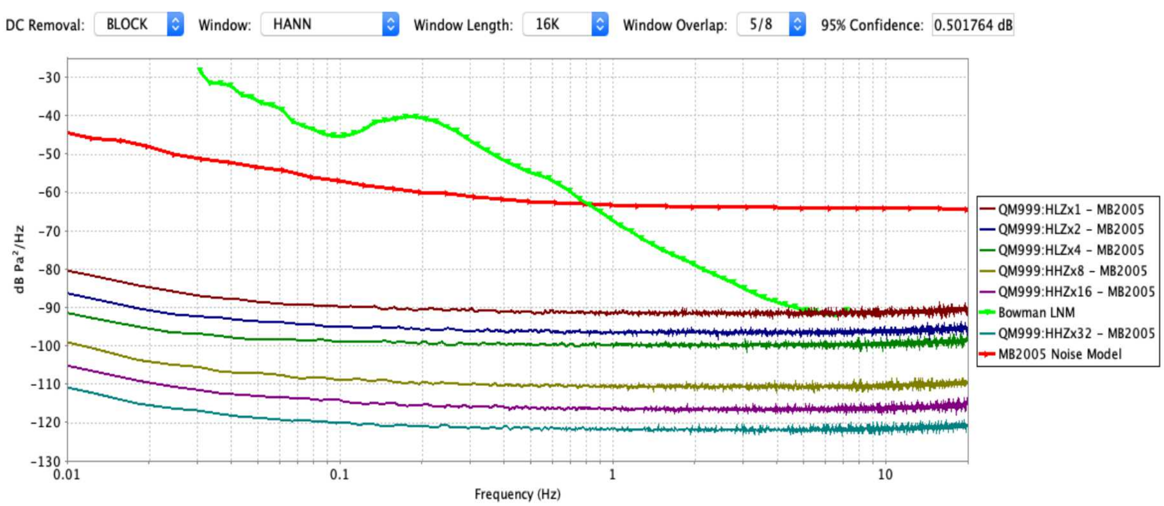

Figure 25 System Noise MB2005, Q330M+ Digitizer

System noise while in units of the MB2005, is well below the self-noise of each sensor, for all digitizers at all evaluated gains.

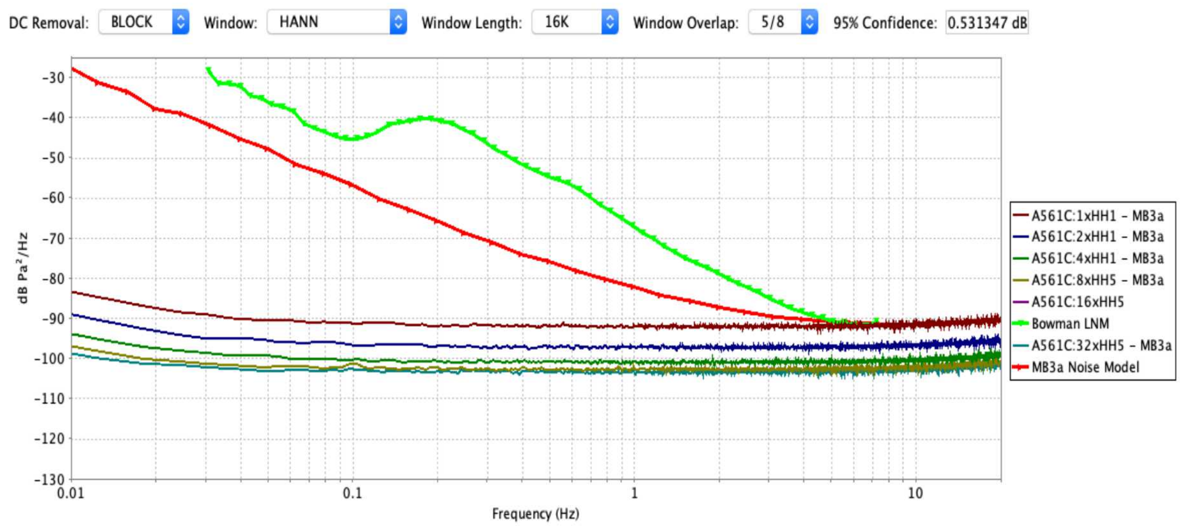

Figure 26 System Noise MB3a, Affinity Digitizer

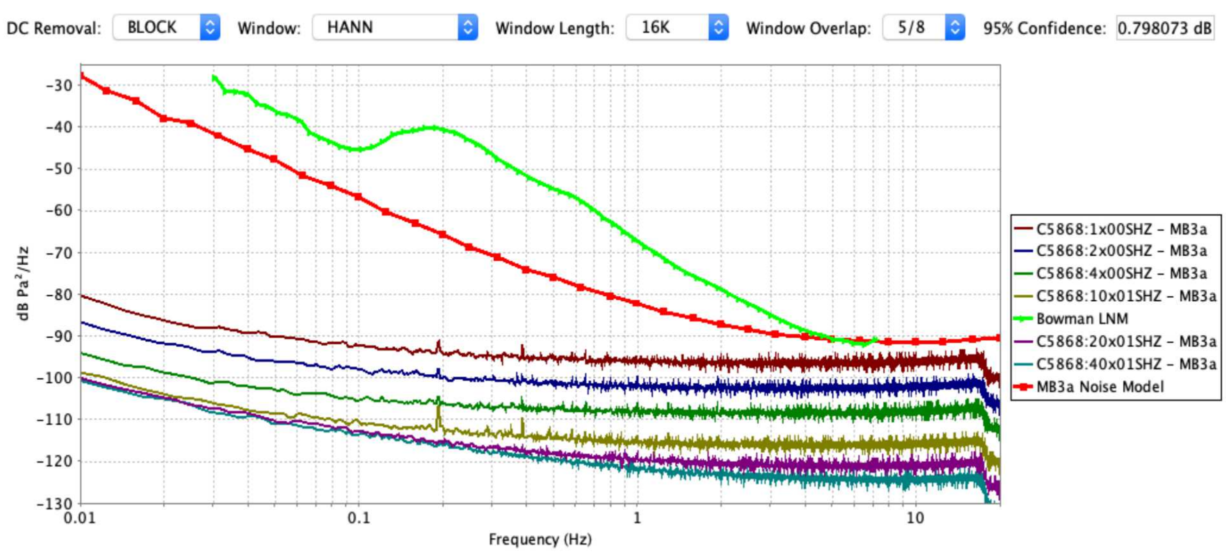

Figure 27 System Noise MB3a, Centaur Digitizer

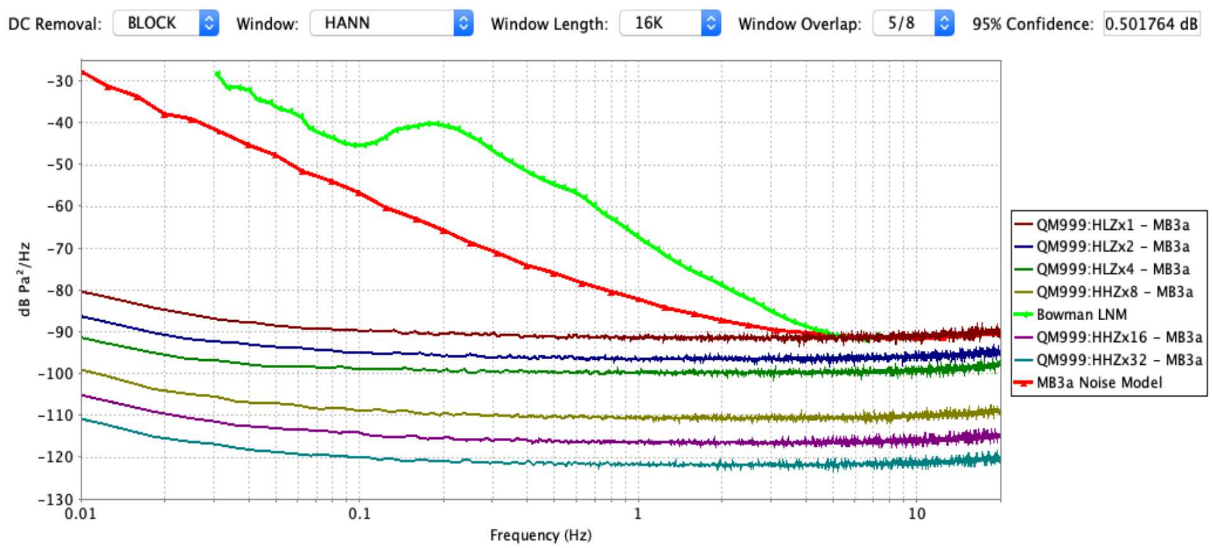

Figure 28 System Noise MB3a, Q330M+ Digitizer

Given the relatively low self-noise of the MB3a, both the Affinity and Q330M+ require the use of gains of at least 2x to ensure the digitizer noise is below that of the sensor. The Centaur though may be operated with a gain of 1x as its equivalent system noise is at least 2 db to 3 db lower than the MB3a's self-noise and the Centaur's equivalent self-noise only rises this close to the MB3a's self-noise above those frequencies typically utilized by the infrasound community.

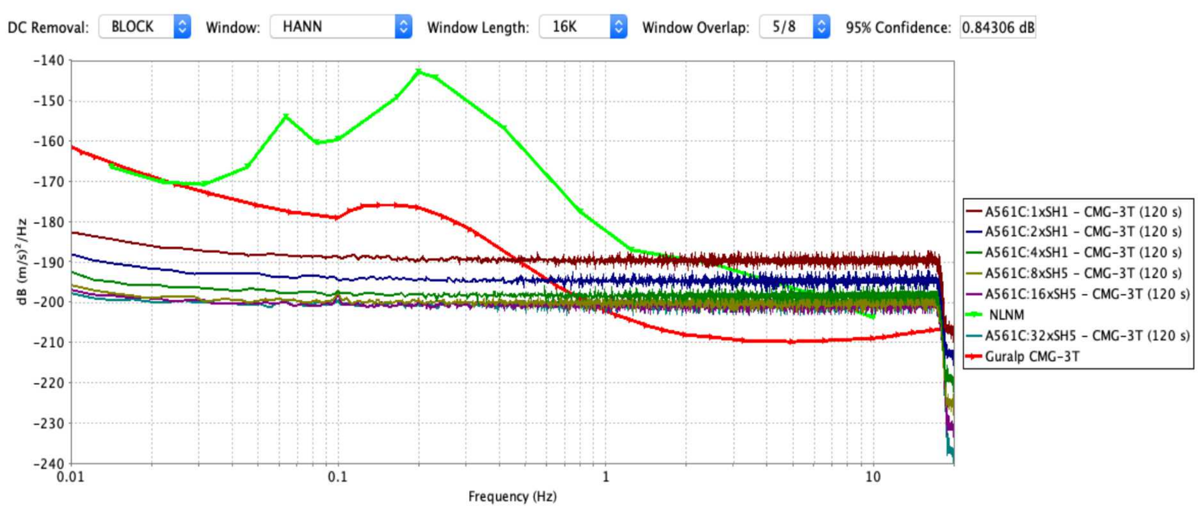

Figure 29 System Noise CMG-3T, Affinity Digitizer

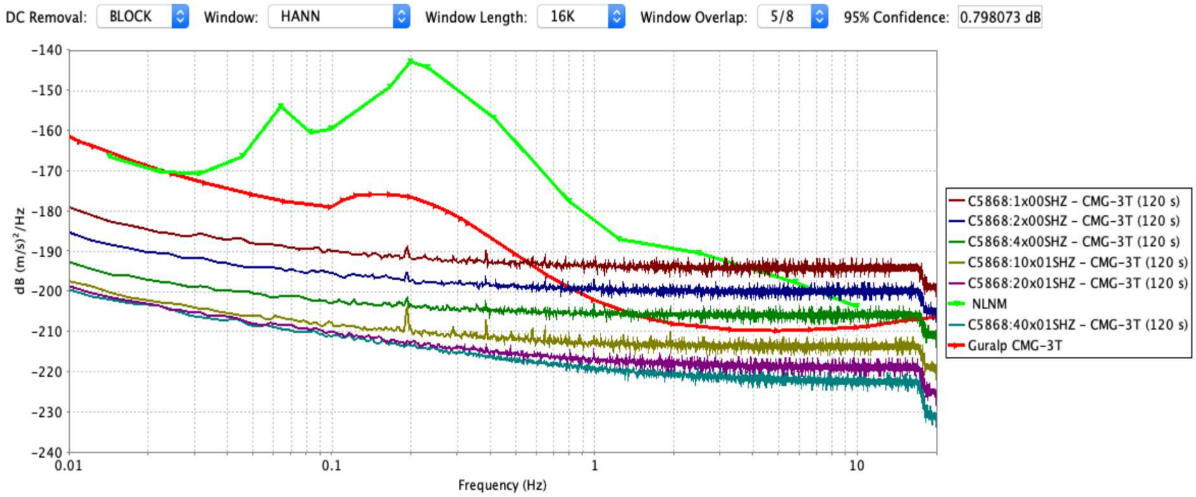

Figure 30 System Noise CMG-3T, Centaur Digitizer

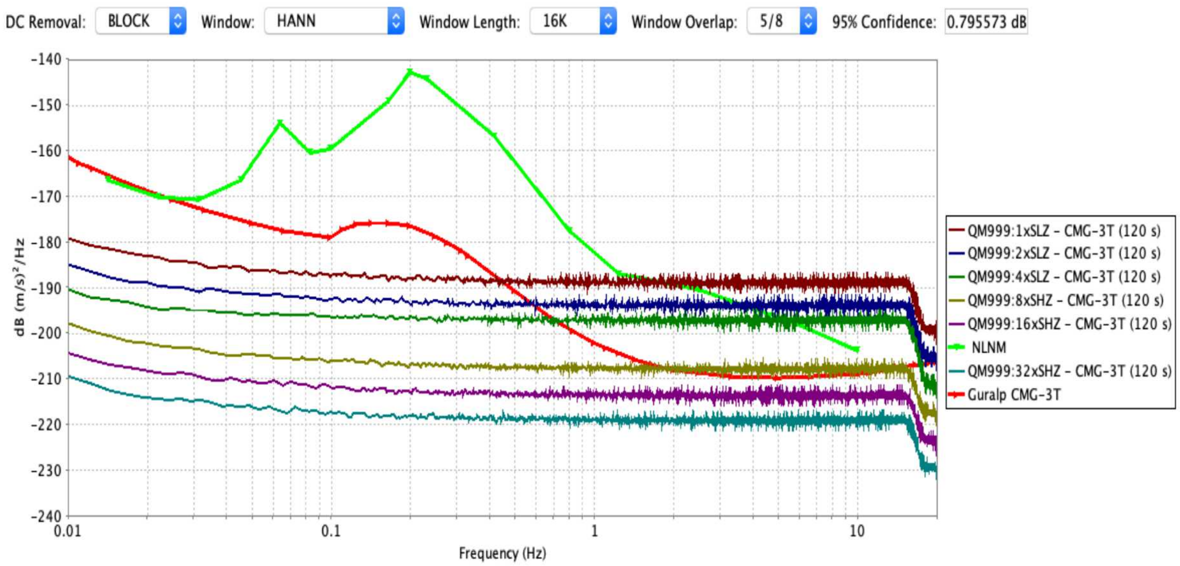

Figure 31 System Noise CMG-3T, Q330M+ Digitizer

System noise of the Affinity in CMG3-T equivalent units exceeds that of the CMG-3T noise model at all gain settings, starting as low as 0.47 Hz at gain of 1x. The Centaur system noise in equivalent units of the CMG-3T exceed that of the CMG-3T noise model at gains of 1x, 2x and 4x, at frequencies as low as 0.58 Hz (1x gain). Finally, the Q330M+ system noise in CMG3-T equivalent units exceeds that of the CMG-3T noise model at gains of 1x, 2x, 4x and 8x, at frequencies as low as 0.47 Hz (1x gain).

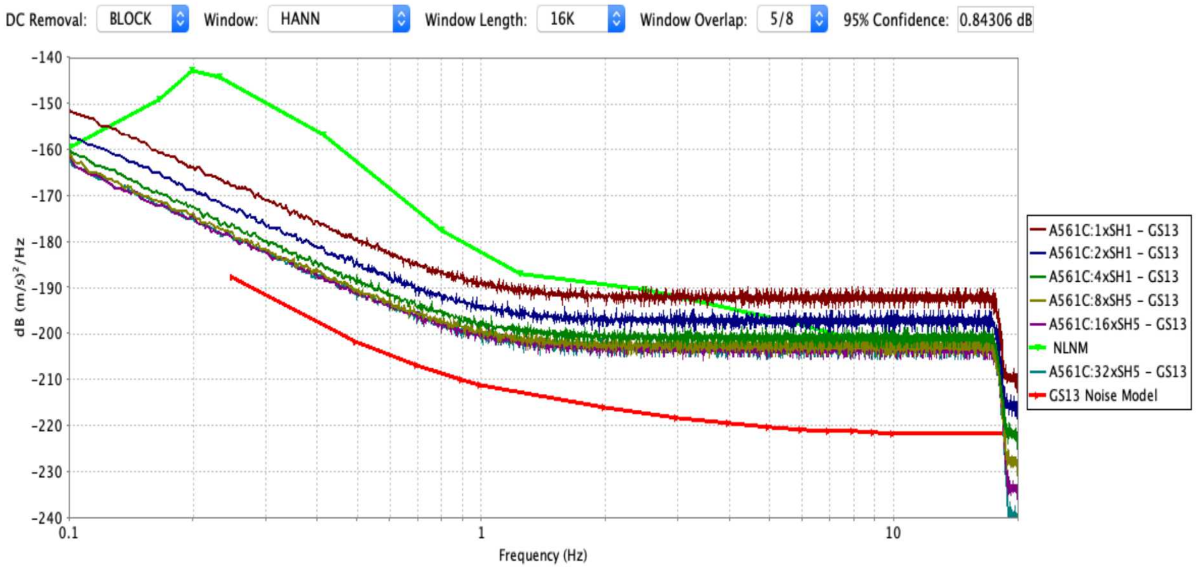

Figure 32 System Noise GS-13, Affinity Digitizer

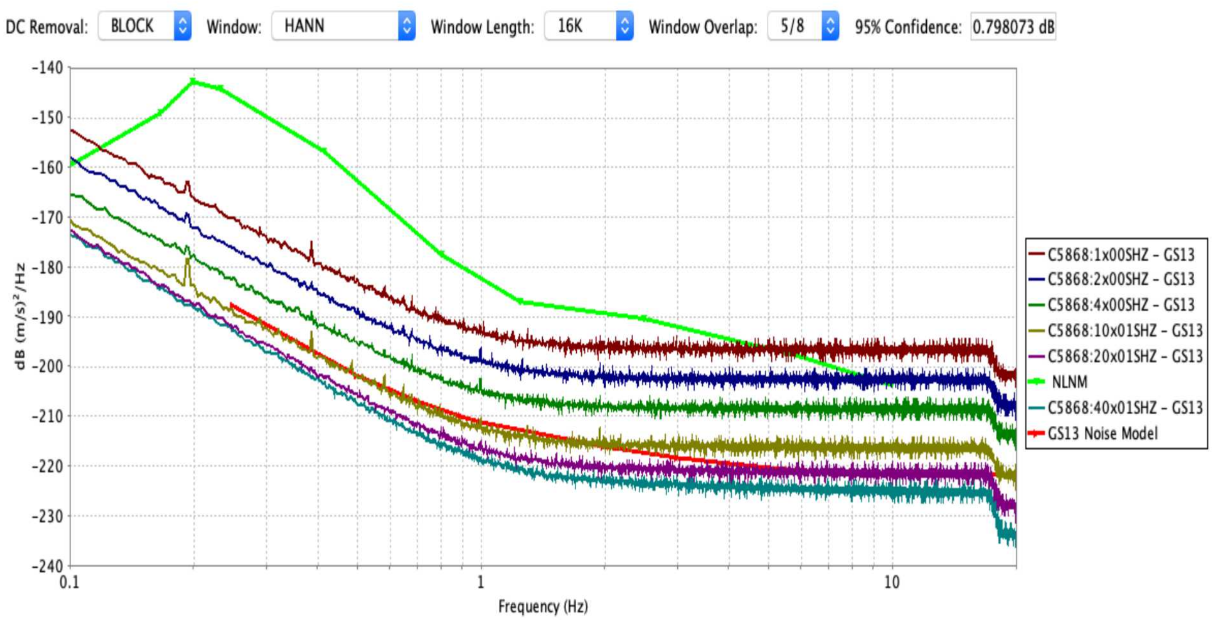

Figure 33 System Noise GS-13, Centaur Digitizer

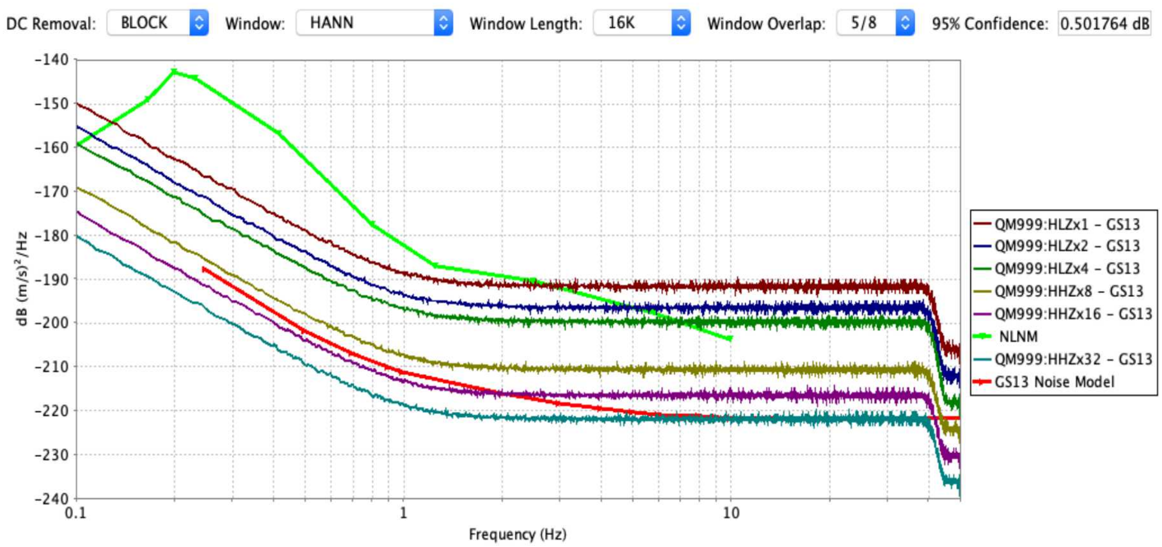

Figure 34 System Noise GS-13, Q330M+ Digitizer

While the Affinity's system noise in equivalent units of a GS-13 exceeds the self-noise of the sensor at all evaluated gains, the Centaur at a gain of 40x has system noise below that of the GS-13 self-noise. At a gain of 20x the Centaur's system noise exceeds the self-noise of the GS-13 above 5.7 Hz and at lower gains the Centaur's system noise exceeds the GS-13 self-noise across the entire frequency range evaluated: < 0.1 Hz to 20 Hz. When the system noise of the Q330M+ is evaluated with the GS-13 response applied, only at a gain of 32x is its system noise below that of the GS-13 at frequencies below 7.9 Hz; above this frequency system noise approximates that of a GS-13.

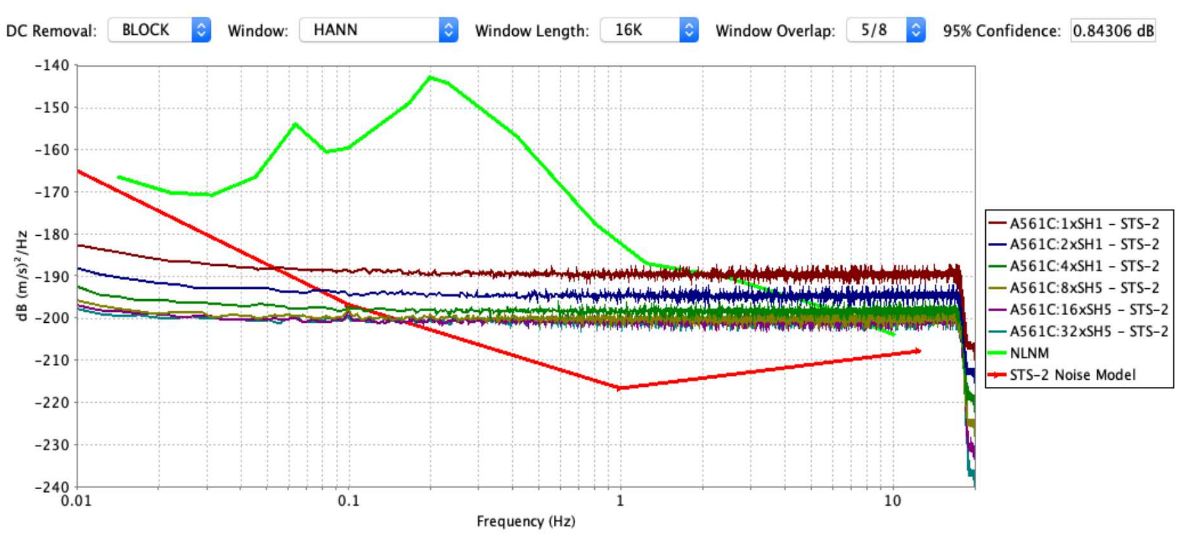

Figure 35 System Noise STS-2, Affinity Digitizer

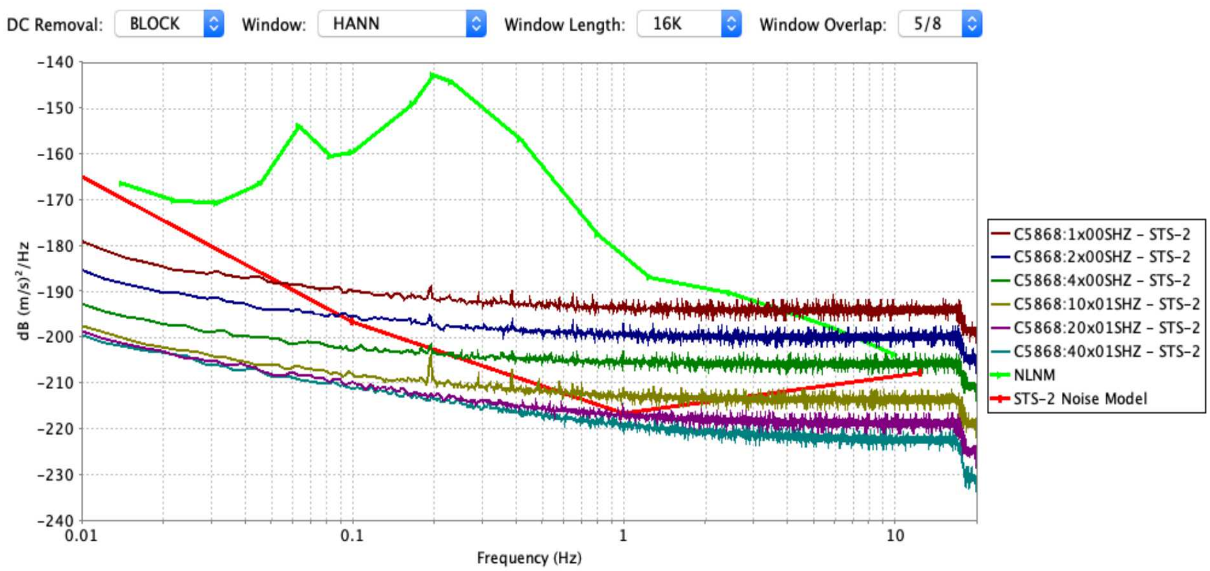

Figure 36 System Noise STS-2, Centaur Digitizer

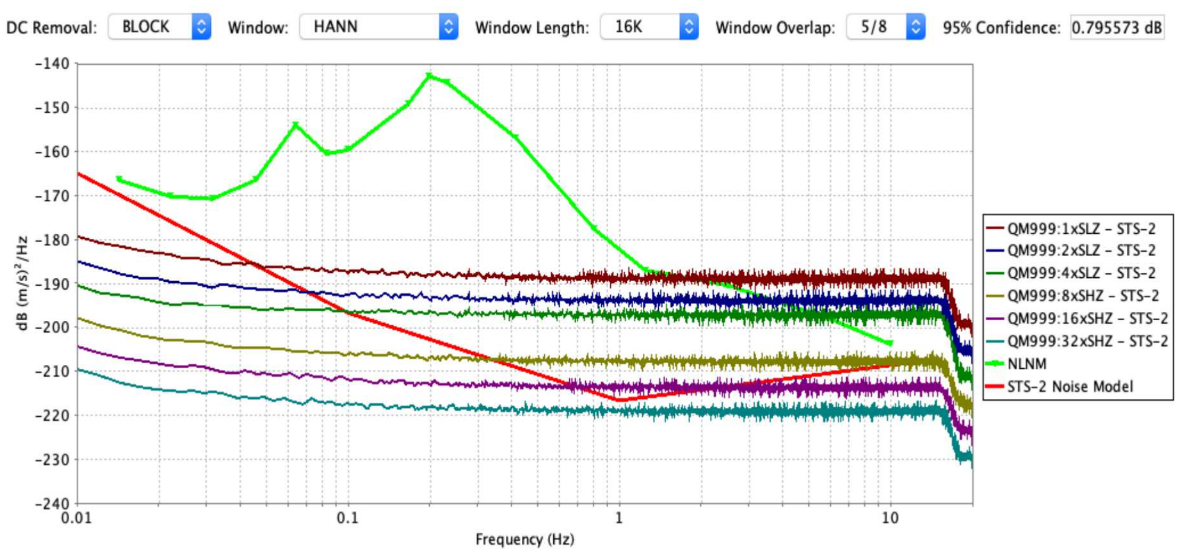

Figure 37 System Noise STS-2, Q330M+ Digitizer

With respect to the STS-2, the Affinity's system noise, exceeds the sensor's self-noise at all gains evaluated, as low as 0.055 Hz at a gain of 1x. The Centaur and Q330M+ require gains of 40x and 32x respectively, for their system noise to remain below the noise model of the STS-2. The Centaur, with a 20x gain, has system noise below that of the STS-2 except where the system noise approximates the STS-2 self-noise level near 1.0 Hz.

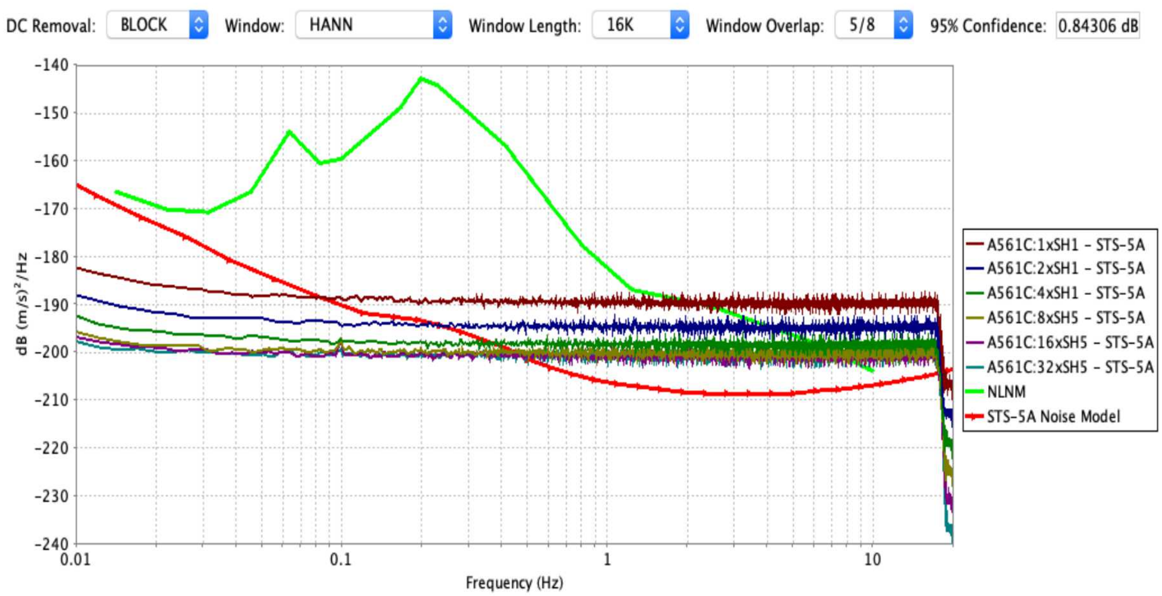

Figure 38 System Noise STS-5a, Affinity Digitizer

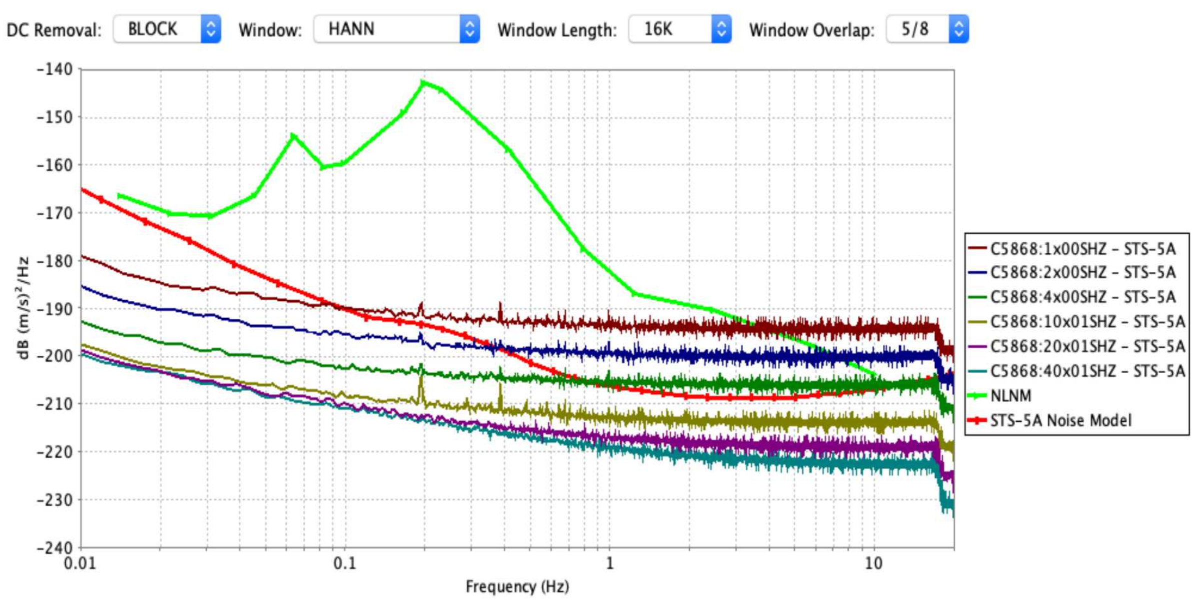

Figure 39 System Noise STS-5a, Centaur Digitizer

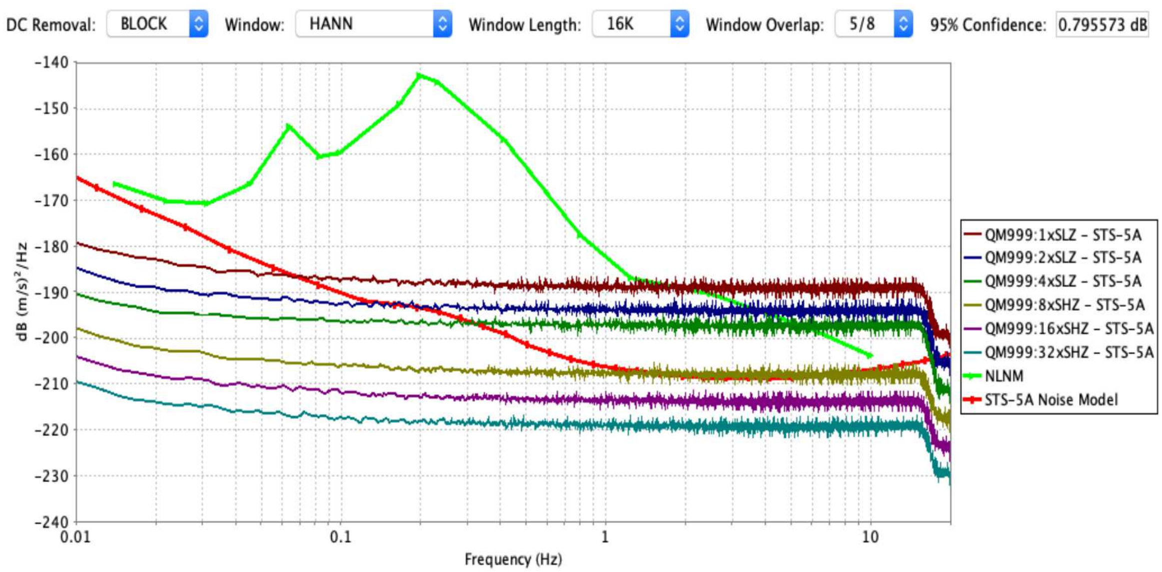

Figure 40 System Noise STS-5a, Q330M+ Digitizer

The Affinity system noise is above the STS-5a self-noise, at a frequencies as low as 0.085 Hz (1x gain). The Centaur's system noise, expressed in STS-5a units exceeds the self-noise of the sensor at gains of 1x, 2x and 4x, at a frequencies as low as 0.093 Hz (1x gain). System noise of the Q330M+ expressed STS-5a units, exceeds the self-noise of the sensor at 1x, 2x, 4x and 8x, at a frequencies as low as 0.07 Hz.

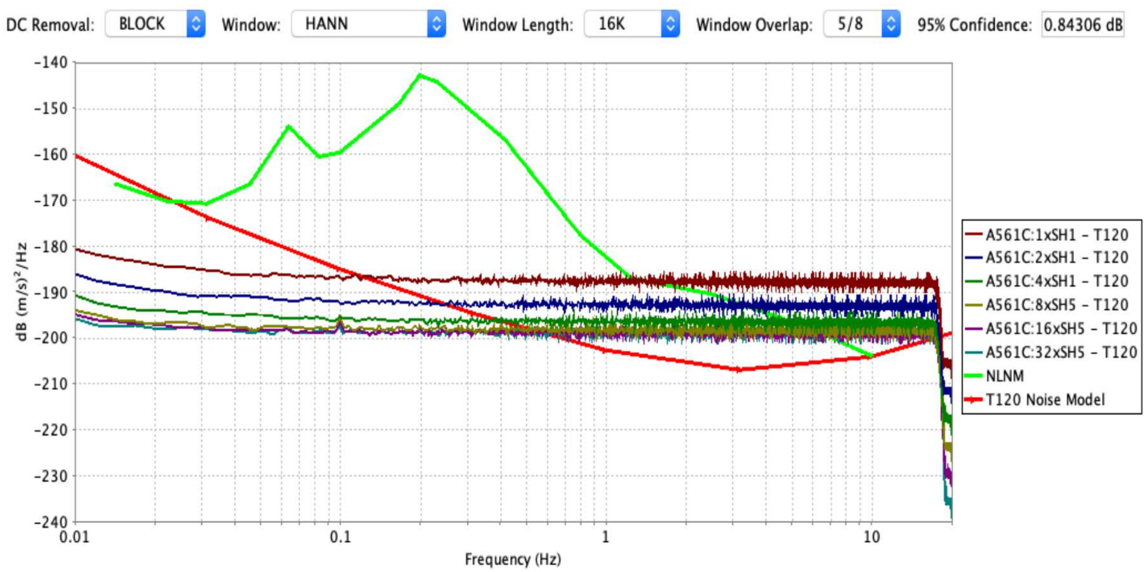

Figure 41 System Noise T-120, Affinity Digitizer

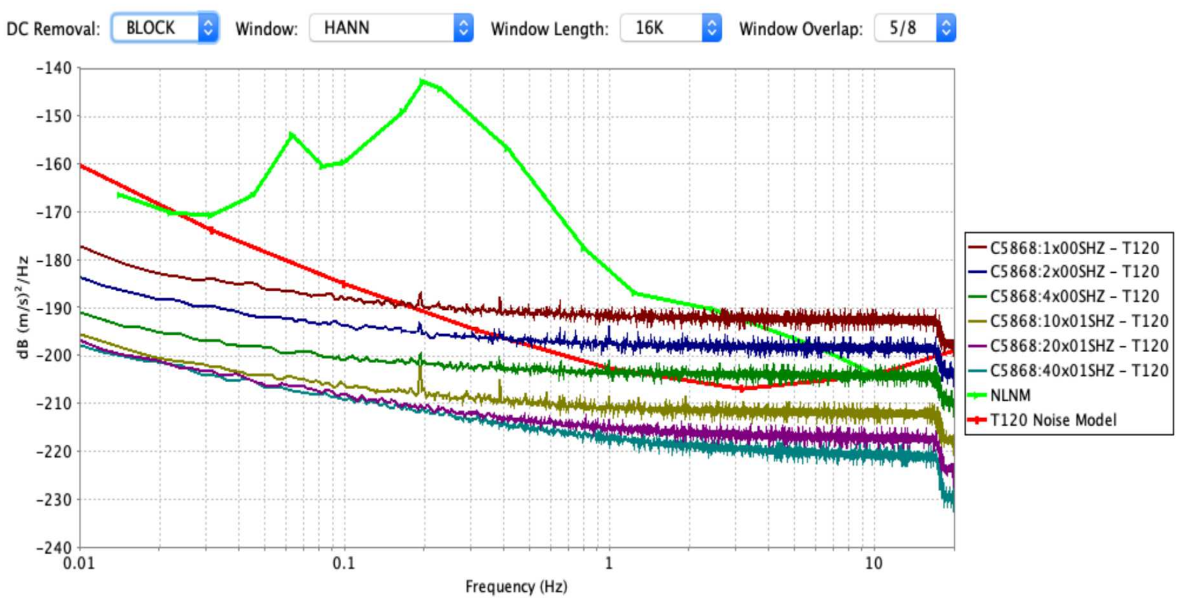

Figure 42 System Noise T-120, Centaur Digitizer

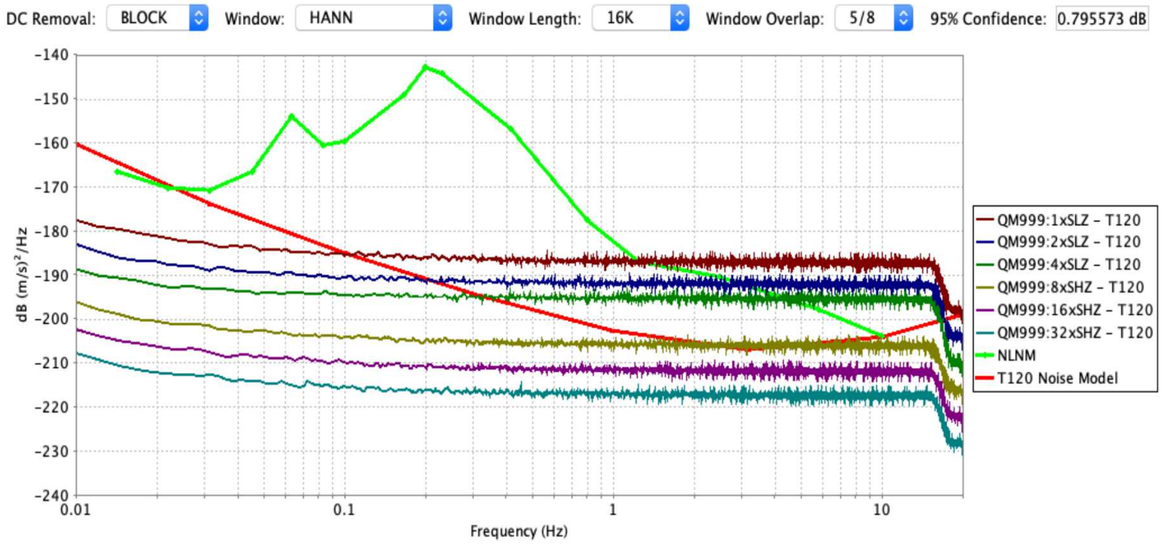

Figure 43 System Noise T-120, Q330M+ Digitizer

Affinity system noise in T-120 units exceeds the self-noise of the T-120 at all gain settings and at frequencies as low as 0.13 Hz (1x gain). Centaur system noise in T-120 units exceeds self-noise of the sensor at gains 1x, 2x and 4x at frequencies as low as 0.17 Hz (1x gain). At gains below 16x, system noise of the Q330M+, with a T-120 response applied, exceeds self-noise the sensor. At a gain of 1x, for example, sensor self-noise is exceeded at frequencies as low as 0.11 Hz.

2.7 Temperature Self-Noise

The Temperature Self-Noise test measures the amount of noise present on a digitizer by collecting waveform data from an input channel that has been terminated with a resistor whose impedance matches the nominal impedance of a chosen sensor at 1 Hz while the digitizer is being maintained at a specific temperature.

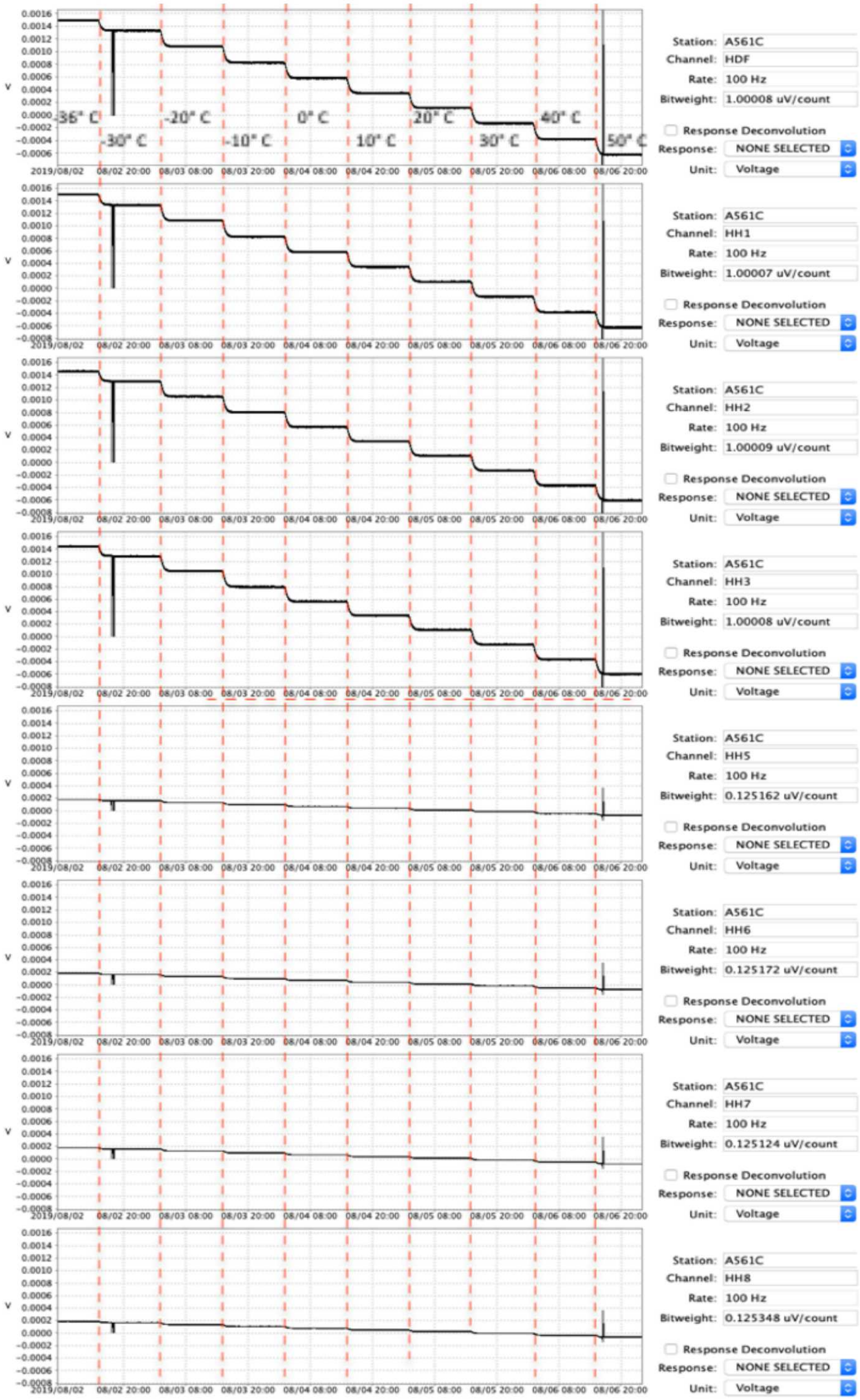

Figure 44 Affinity Self-noise Time Series over -36° C to 50° C

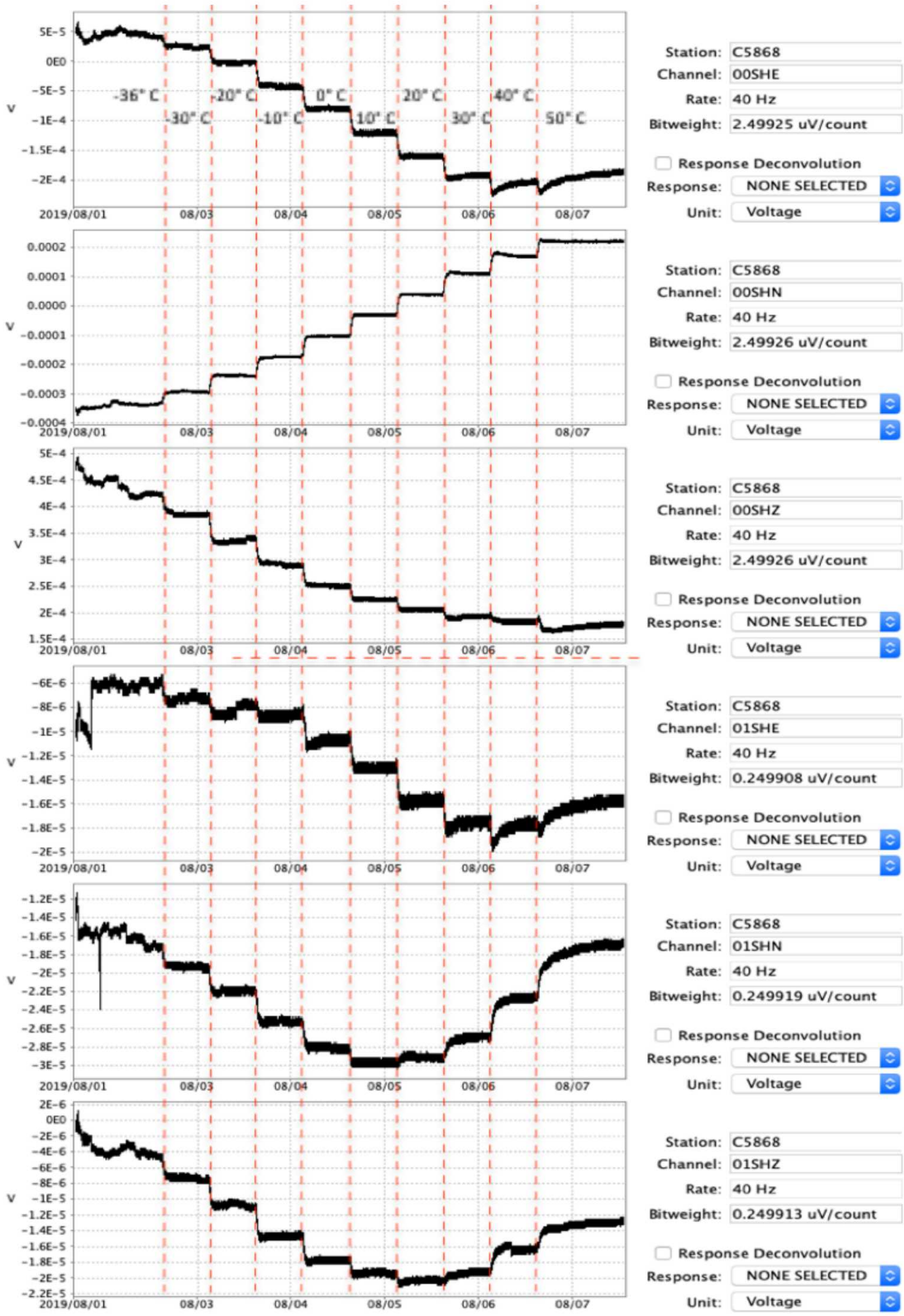

Figure 45 Centaur Self-noise Time Series over -36° C to 50° C

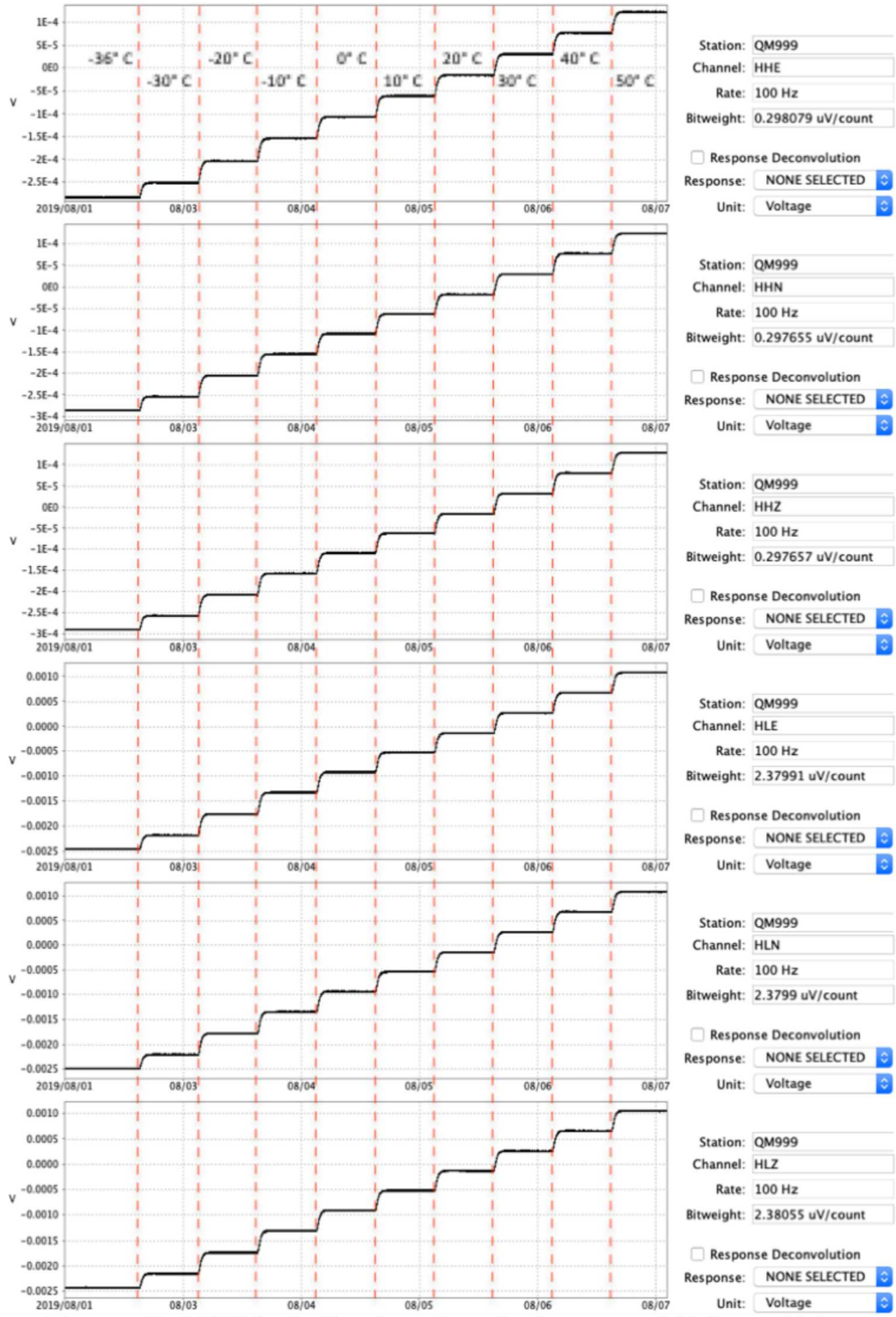

Figure 46 Q330M+ Self-noise Time Series over -36° C to 50° C

Figure 44 and Figure 46 illustrate changes in input shorted offset voltage with temperature were relatively consistent for the Affinity and Q330M+ across their respective channels over the temperature range evaluated.

Table 11 Average Offset Rate of Change with Temperature, Affinity and Q330 Digitizers

Channel	1	2	3	4	5	6	7	8
Affinity								
Gain	1x	1x	1x	1x	8x	8x	8x	8x
Affinity	0.025 mV/°C	0.024 mV/°C	0.024 mV/°C	0.025 mV/°C	0.0029 mV/°C	0.0030 mV/°C	0.0030 mV/°C	0.0029 mV/°C
Q330M+								
Gain	1x	1x	1x	8x	8x	8x	-	-
Q330M+	-2.4444 mV/C	-2.5022 mV/C	-2.4699 mV/C	-0.2910 mV/C	-0.2875 mV/C	-0.2860 mV/C	-	-

The average rate of change of voltage offset with temperature for the Centaur is not calculated as the rate of change was not uniform across the temperatures evaluated, and the voltage offsets were the lowest of the three digitizers.

Table 12 Change in Input Shorted Offset as Percentage of Full Scale Voltage

Gain	Affinity	Centaur	Q330M+
1x	0.00354%	0.00277%	0.0178%
8x	0.00402%	-	0.0166%
10x	-	0.000820%	-

The maximum change in input shorted offset voltage over temperature as a percentage full scale input voltage is smallest for the Centaur, Table 12.

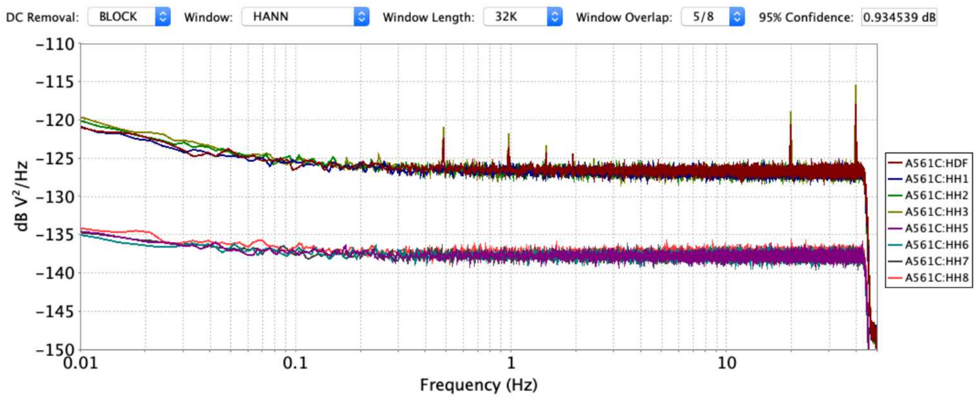

Figure 47 Affinity Self-noise Power Gain 1x and 8x, -36° C

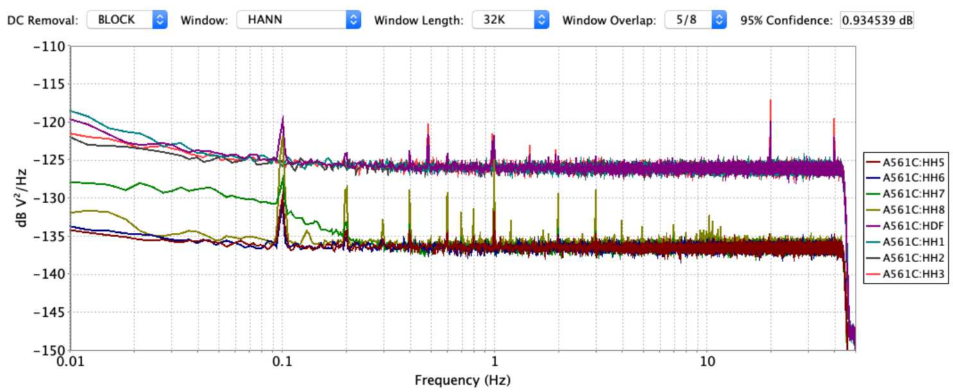

Figure 48 Affinity Self-noise Power Gain 1x and 8x, 50° C

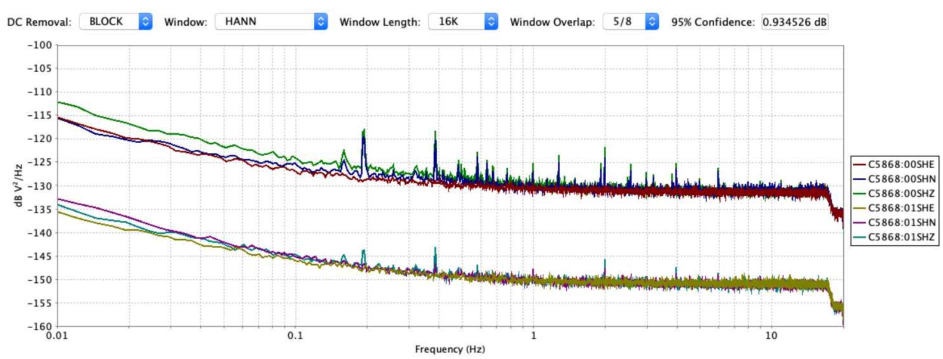

Figure 49 Centaur Self-noise Power, Gain 1x and 8x, -36° C

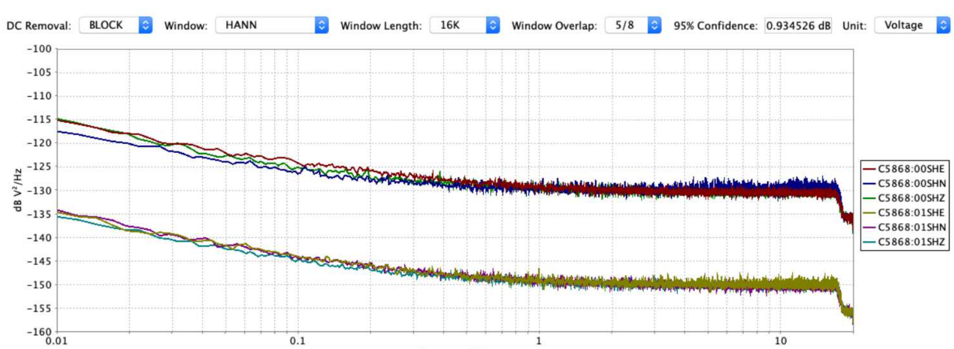

Figure 50 Centaur Self-noise Power, Gain 1x and 8x, 50° C

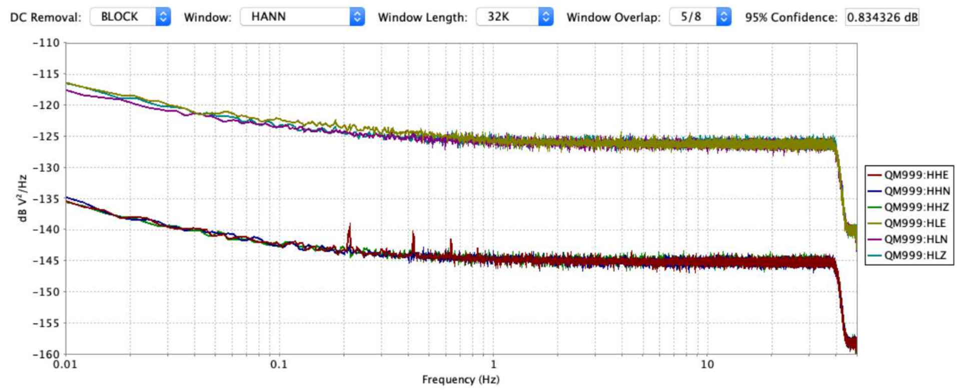

Figure 51 Q330M+ Self-noise Power, Gain 1x and 8x, -36° C

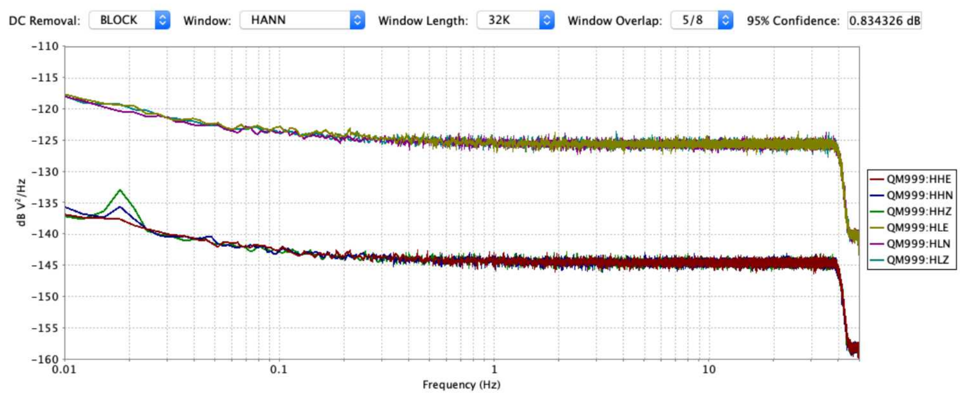

Figure 52 Q330M+ Self-noise Power, Gain 1x and 8x, 50° C

Figure 47 and Figure 48 illustrate that the Affinity self-noise increases slightly on all channels, approximately 1 dB (essentially equivalent at the 95% confidence limit) at gains x1 and 2 dB at a gain of 8x. More noteworthy however, are spectral noise spikes at 0.1 Hz through 1.3 Hz visible in the 8x gain channels (HH5 - HH8), and the increase in noise near 10 Hz illustrated in the 50° C which are nearly absent in the -36° C data.

Figure 49 and Figure 50 illustrate that the Centaur self-noise increases slightly on all channels, approximately 1 dB (essentially equivalent at the 95% confidence limit) at 1 Hz and 10 Hz. More noteworthy however spectral noise spikes over the frequency range 0.16 to 6.0 Hz Hz visible in the -36° C data, which are not visible in the 50° C data.

Figure 51 and Figure 52 illustrate that the Q330M+ self-noise increases slightly on all channels, approximately 4 dB and 1 dB higher, for the gains of 1x and 8x, respectively, at 50° C, over that of the -36° C.

2.8 Total Harmonic Distortion

The Total Harmonic Distortion test is used to measure the linearity of a digitizer channel by recording a known AC signal at a reference voltage from an ultra-low distortion oscillator.

The figures below show the power spectra of the THD for each of the sample rates and gains evaluated.

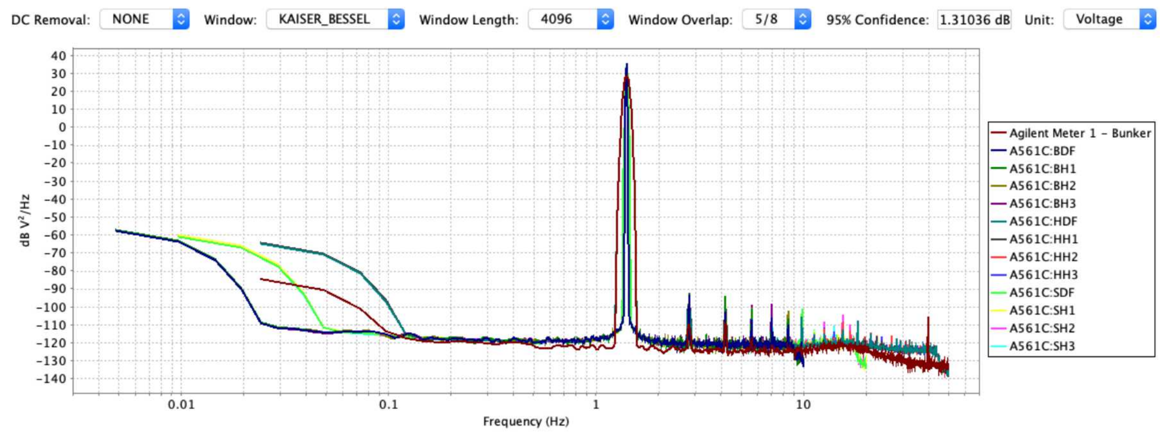

Figure 53 Affinity THD Power Spectra, Gain 1x

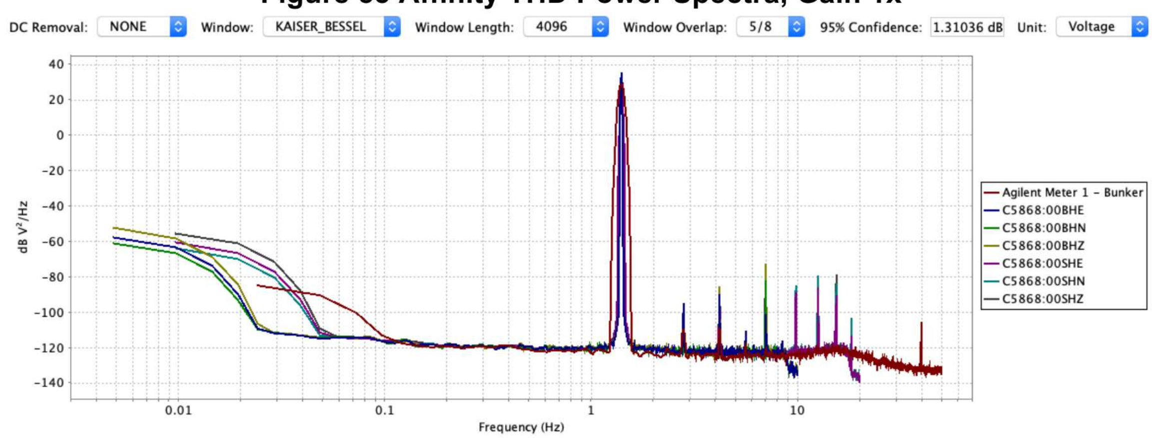

Figure 54 Centaur THD Power Spectra, Gain 1x

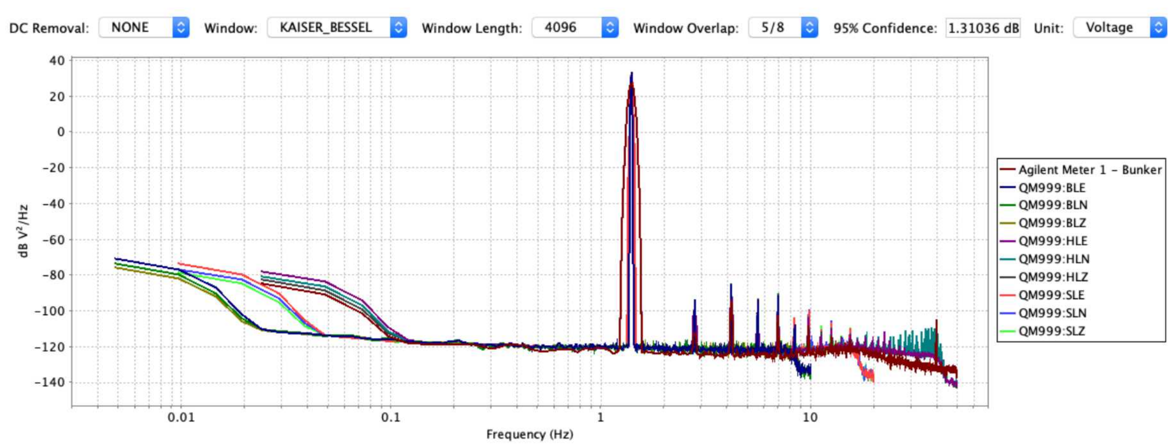

Figure 55 Q330M+ THD Power Spectra, Gain 1x

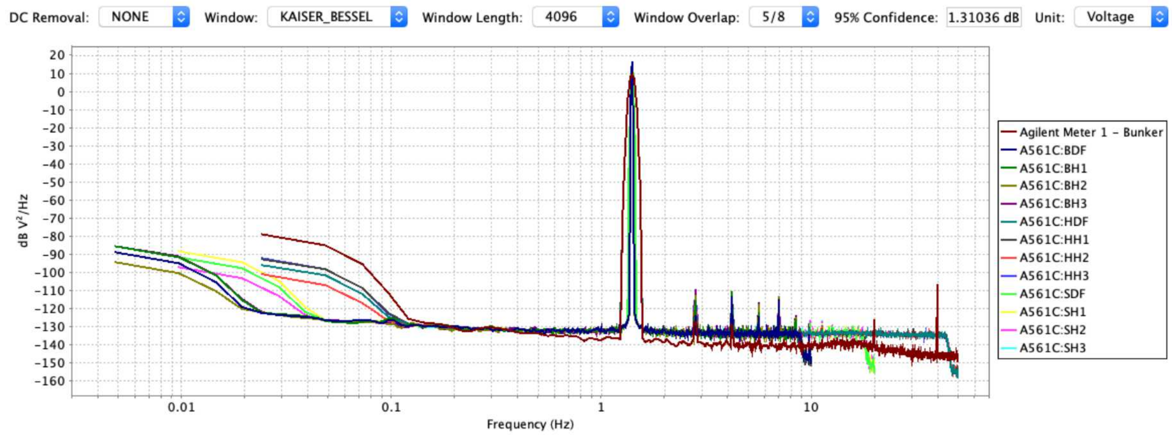

Figure 56 Affinity THD Power Spectra, Gain 4x

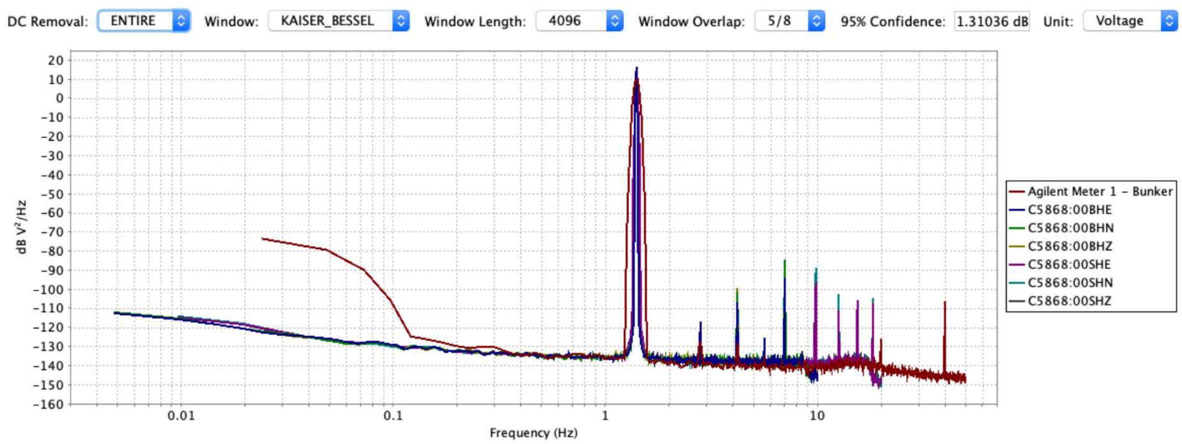

Figure 57 Centaur THD Power Spectra, Gain 4x

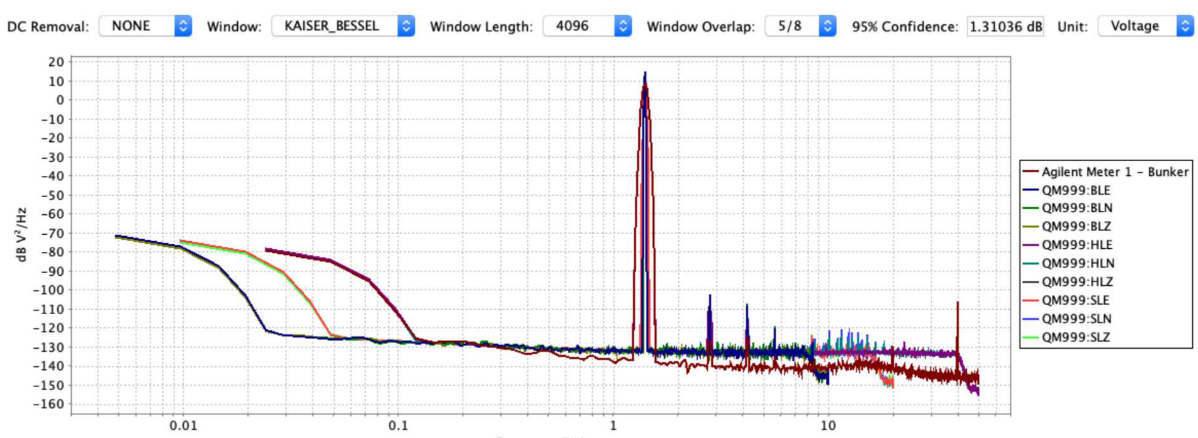

Figure 58 Q330M+ THD Power Spectra, Gain 4x

Table 13 Affinity, Total Harmonic Distortion, 40 sps

Gain	Reference Meter	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7	Channel 8
1x	-133.96 dB	-124.34 dB	-125.21 dB	-125.59 dB	-126.52 dB	-	-	-	-
2x	-134.72 dB	-124.09 dB	-123.68 dB	-123.19 dB	-120.37 dB	-	-	-	-
4x	-132.69 dB	-123.76 dB	-122.89 dB	-122.23 dB	-125.61 dB	-	-	-	-
8x	-132.66 dB	-	-	-	-	-122.90 dB	-123.12 dB	-121.92 dB	-120.93 dB
16x	-131.47 dB	-	-	-	-	-114.87 dB	-117.17 dB	-116.39 dB	-116.00 dB

Table 14 Centaur, Total Harmonic Distortion, 40 sps

Gain	Reference Meter	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	133.63 dB	-106.43 dB	-108.95 dB	-115.27 dB	-	-	-
2x	-134.21 dB	-111.31 dB	-111.88 dB	-111.88 dB	-	-	-
4x	-133.61 dB	-103.76 dB	-101.24 dB	-110.47 dB	-	-	-
10x	-132.00 dB	-	-	-	-106.26 dB	-107.50 dB	-116.26 dB
20x	-131.64 dB	-	-	-	-106.38 dB	-106.45 dB	-104.67 dB

Table 15 Q330M+ Total Harmonic Distortion, 40 sps

Gain	Reference Meter	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1x	-120.98 dB	-116.45 dB	-116.56 dB	-116.77 dB	-	-	-
2x	-121.96 dB	-118.14 dB	-118.01 dB	-118.63 dB	-	-	-
4x	-130.51 dB	-116.06 dB	-117.21 dB	-116.14 dB	-	-	-
8x	-114.38 dB	-	-	-	-113.78 dB	-113.75 dB	-113.57 dB
16x	-114.38 dB	-	-	-	-113.78 dB	-113.75 dB	-113.57 dB

Given challenges ensuring an unambigious measurement of digitizer THD, the focus of comments on THD results are with each datalogger configured with a gain of 1x, 2x and 4x. Calculated THD of the Affinity is highest consistently across all evaluated channels when compared against the Centaur and Q330M+ THD calculations.

The THD values measured at gains of 8x and 16x on the Q330M+ are not representative of the performance of the Q330M+ as they are consistent with the signal quality

2.9 Modified Noise Power Ratio

The Modified Noise Power Ratio test measures the linearity of the digitizer channels across a range of amplitudes.

Modified Noise Power Ratio (MNPR) plots were relatively consistent across channels for each respective digitizer. The following plots are representative of each datalogger at a gain of 1x.

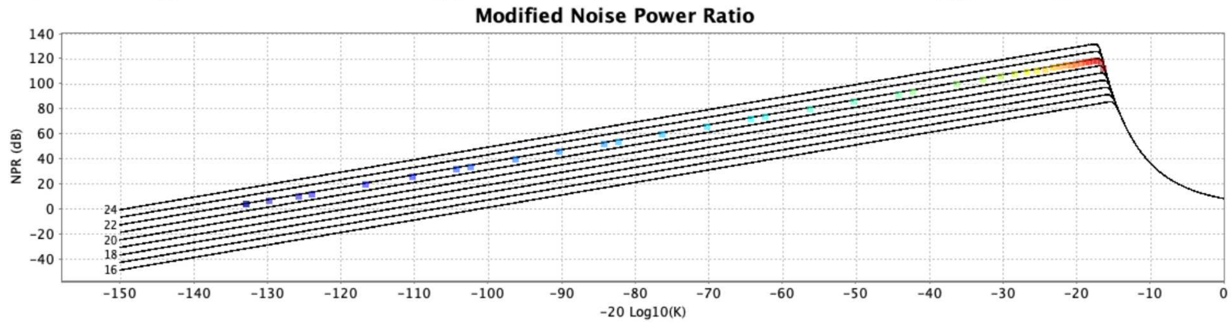

Figure 59 Affinity Modified Noise Power Ratio, Channels 1 and 2, Gain 1x

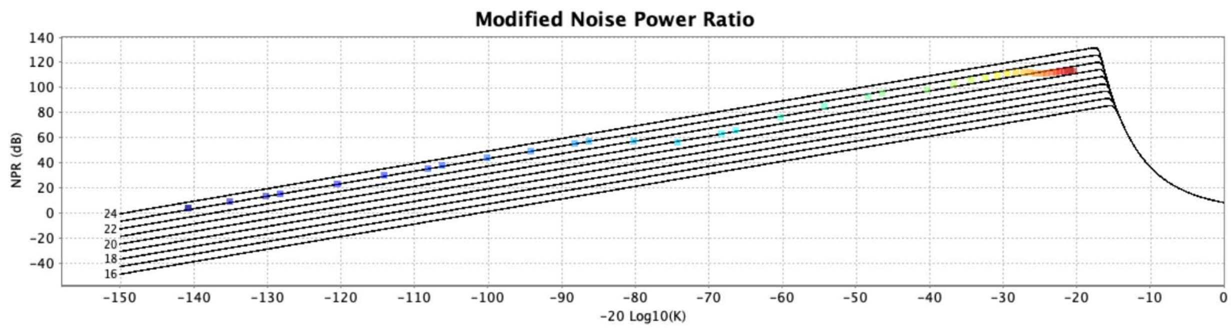

Figure 60 Centaur Modified Noise Power Ratio, Channels 1 and 2, Gain 1x

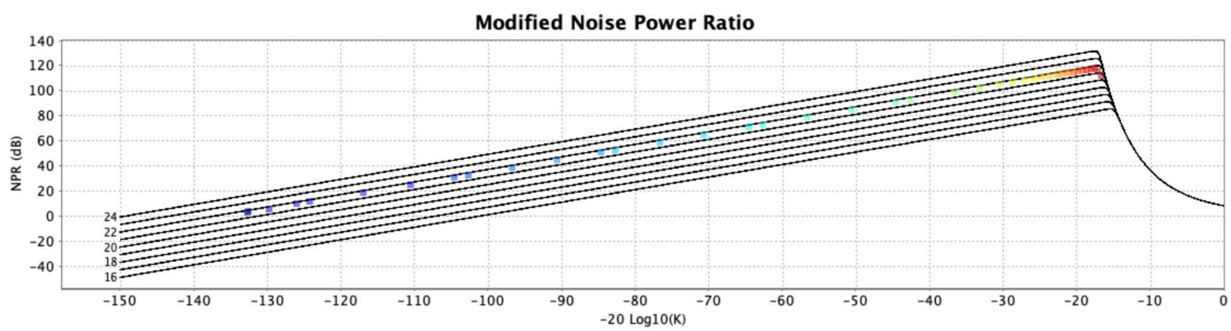

Figure 61 Q330M+ Modified Noise Power Ratio, Channels 1 and 2, Gain 1x

At a gain of 1x, the Affinity consistently has slightly less than 22 bits of performance across the amplitude range across the channels evaluated. The Centaur exhibits variations in modified noise power ratios across the range of amplitudes of input voltage. At a gain of 1x performance varies from as high as 23 bits at low amplitudes to as low as 21bits at high amplitudes. The Q330M+ has slightly less than 22 bits of linear performance over the entire range of amplitudes.

2.10 Timing Drift

The Time Tag Drift test measures how the digitizer's timing accuracy drifts when the digitizer's clock is not locked and recovers once lock is restored.

A one pulse per minute (PPM) signal is provided as input to all digitizers and recorded as shown in the representative example plotted in Figure 62, for the Affinity unit.

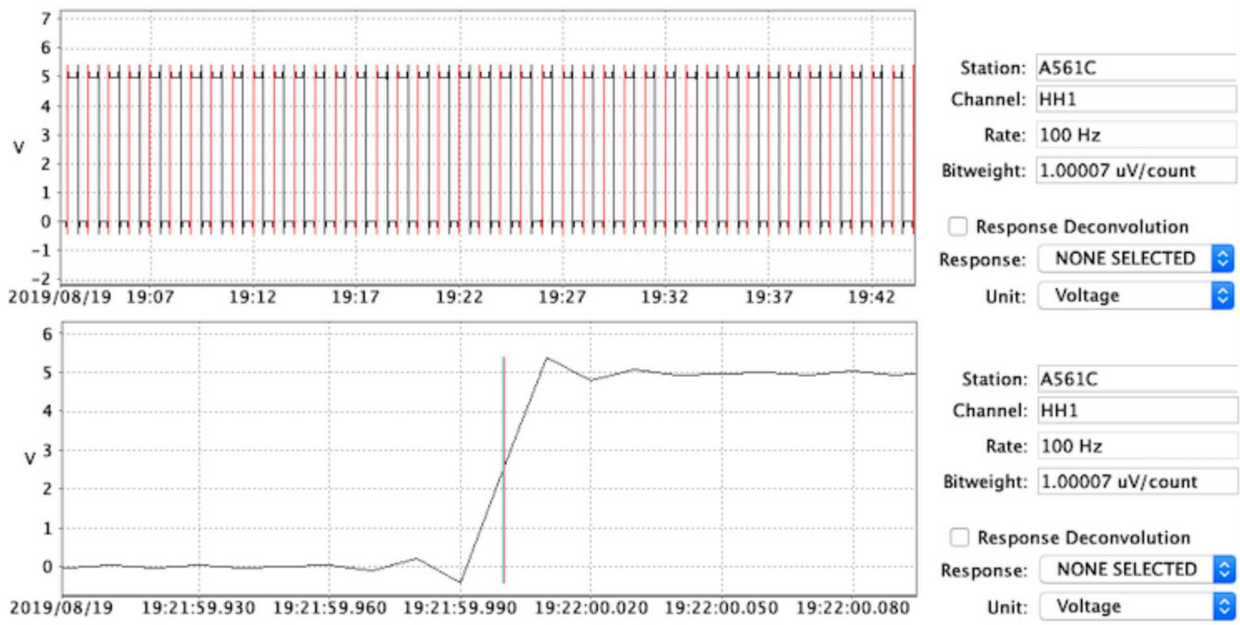

Figure 62 Example PPM Time Series

The following figures show the timing offsets over time as the digitizer channels drift and subsequently as the digitizers recover timing.

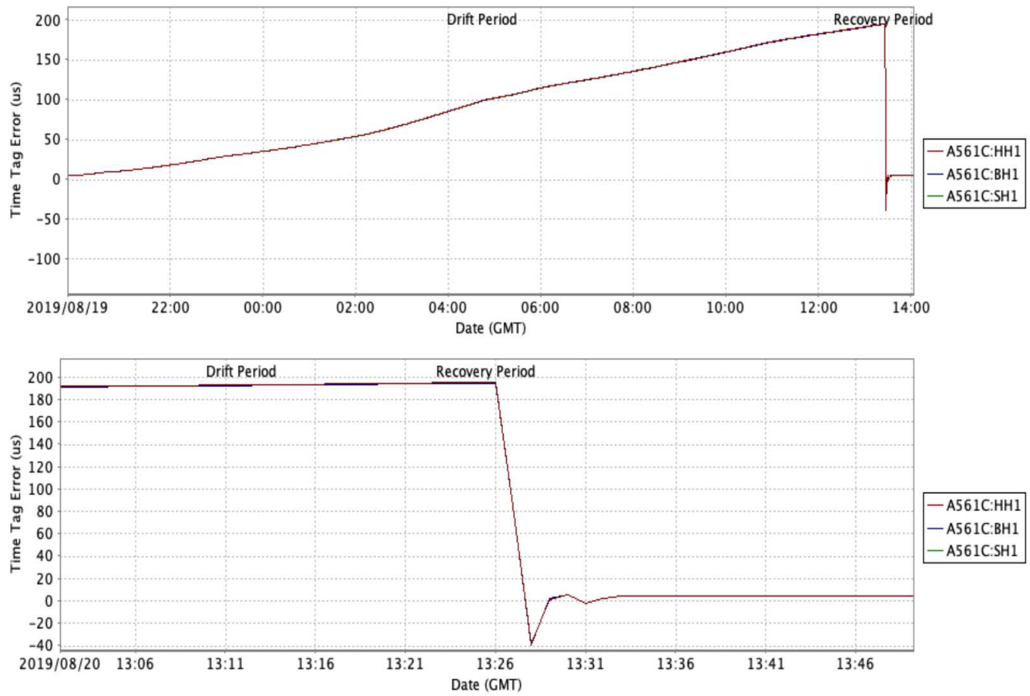

Figure 63 Affinity, Timing Drift and Moment of Recovery

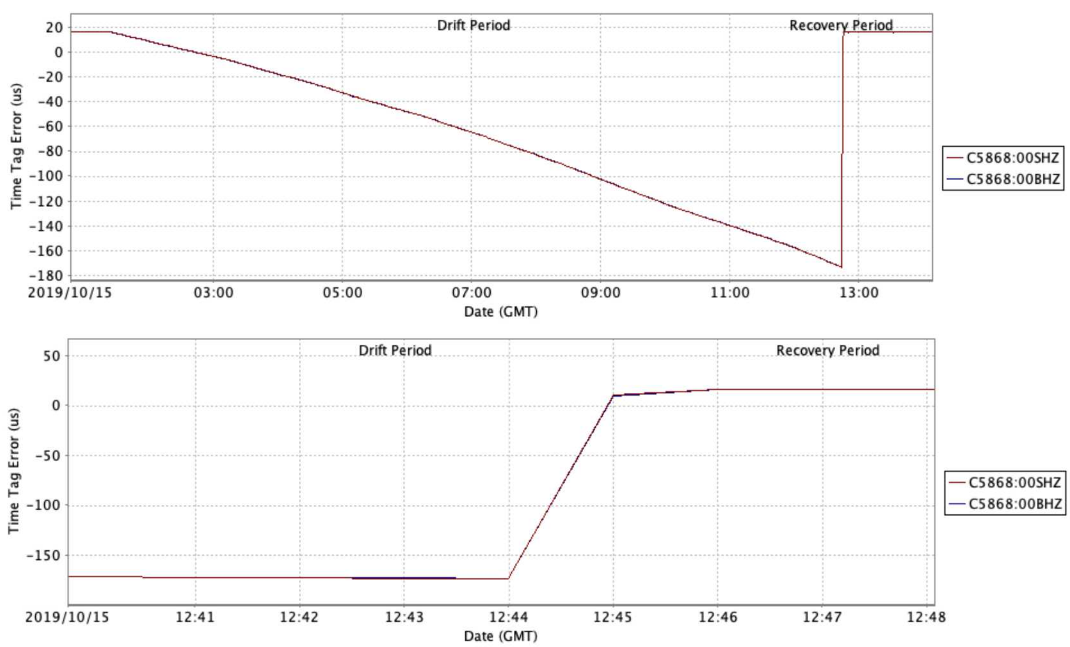

Figure 64 Centaur, Timing Drift and Moment of Recovery

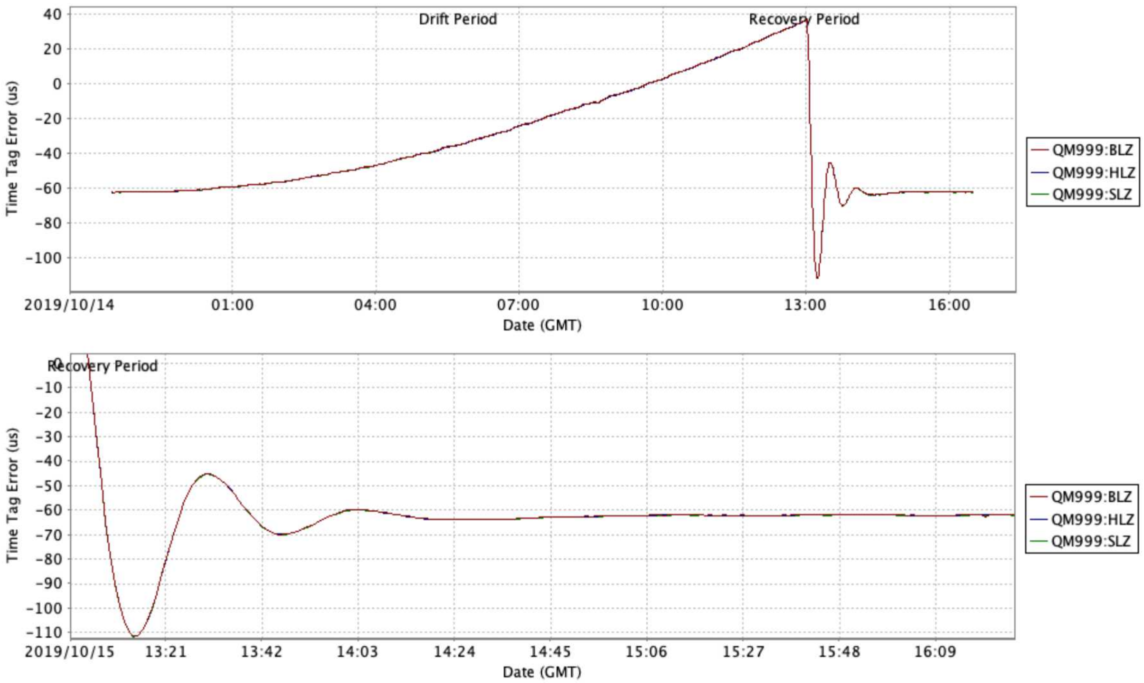

Figure 65 Moment of Timing Recovery, Internal GPS-Based Timing

The following table contains the computed timing offsets when locked, drifting, and recovering and the estimated rate at which each digitizer was observed to drift and recover.

Table 16 Time Tag Drift and Recovery, Gain 1x

	Affinity	Centaur	Q330M+
Stabilized offset – pre-drift	5.0306 us	16.208 us	-62.164 us
Initial Drift Rate	-11.865 us/h	16.96 us/h	-7.004 us/hr
Recovery Rate	-1,971 us/h	5,500.3 us/h	-206.39 us/hr
Stabilized offset – post-drift	4.7684 us	15.863 us	-62.191 us

When the GPS antennas were uncovered, the Affinity regained lock and recovered to a stabilized offset within 7 minutes after drifting 190 us over 12 hours, the Centaur recovered within 4 minutes after drifting 157 us over 16 hours, and the Q330M+ recovered within 1 hour 30 minutes after drifting 98.95 us over 12 hours.

DISTRIBUTION

Name	Org.	Sandia Email Address
Technical Library	9536	libref@sandia.gov

REFERENCES

1. Slad, George W. and B. John Merchant, *Evaluation of the Nanometrics Centaur Digitizer*, SAND2020-3029.

2. Slad, George W. and B. John Merchant, *Guralp Affinity Digitizer Evaluation*, SAND2020-3031.

3. Slad, George W. and B. John Merchant, *Kinemetrics Q330M+ Digitizer Evaluation*, SAND2020-3030.

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.