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LIHE Spectral Dynamics and Jaguar Data Acquisition System Measurement Assurance Results 2014

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Abstract

The Light Initiated High Explosive (LIHE) facility performs high rigor, high consequence impulse testing for the nuclear weapons (NW) community. To support the facility mission, LIHE's extensive data acquisition system (DAS) is comprised of several discrete components as well as a fully integrated system. Due to the high consequence and high rigor of the testing performed at LIHE, a measurement assurance plan (MAP) was developed in collaboration with NW system customers to meet their data quality needs and to provide assurance of the robustness of the LIHE DAS. While individual components of the DAS have been calibrated by the SNL Primary Standards Laboratory (PSL), the integrated nature of this complex system requires verification of the complete system, from end-to-end. This measurement assurance plan (MAP) report documents the results of verification and validation procedures used to ensure that the data quality meets customer requirements.

ACKNOWLEDGMENTS

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NOMENCLATURE

DAS	Data Acquisition System
DI	Deionized
DMM	Digital Volt Meter
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMI	Electromagnetic Interference
LIHE	Light Initiated High Explosive
MAP	Measurement Assurance Plan
NIST	National Institute of Standards and Technology (or Testing)
NW	Nuclear Weapons
PSL	Primary Standards Laboratory
RFI	Radio-Frequency Interference
SNL	Sandia National Laboratories

1. INTRODUCTION

The Light Initiated High Explosive (LIHE) facility performs high rigor, high consequence impulse testing for the nuclear weapons (NW) community. To support the facility mission, LIHE has an extensive data acquisition capability, comprised of several discrete components as well as a fully integrated system. This integrated data acquisition system, henceforth referred to as DAS, includes the Spectral Dynamics primary system, the Jaguar back-up system, and the associated cable plant and ancillary system components. The primary system has 16-bit resolution with a sample rate of 2.5MSamples/second. The backup system also has 16-bit resolution, but a sample rate of 102kSamples/second. The complete system includes the power supply for excitation voltage, Wheatstone bridge completion resistors, range selection relay circuitry, and the required cable plant. A complete description of the integrated DAS can be found in a recent SAND report[7]. Due to the high consequence and high rigor of the testing performed at LIHE, a measurement assurance plan (MAP) was developed. This MAP was developed in collaboration with NW system customers to meet their data quality needs and to provide assurance of the robustness of the LIHE DAS. While individual components of the DAS have been calibrated by the SNL Primary Standards Laboratory (PSL), the integrated nature of this complex system required verification of the complete system, from end-to-end. This MAP report documents the results of the verification and validation procedures used to ensure that the data quality meets customer requirements.

2. REQUIREMENTS AND LIMITATIONS

The MAP requirements are as follows:

- Noise floor less than +/-2% of band edge (95% confidence interval)
- Amplitude within 10%
- Frequency within 1%
- Phase within 10°
- Voltage offset within 10%
- Time synchronization of the data acquisition system will result in a phase error of less than 10° at 10kHz (2.8E-6 seconds)

Testing at LIHE utilizes the discharge of a high voltage capacitor bank. Such a discharge can generate a significant electromagnetic noise environment. If the noise from the bank discharge persists, it has the potential to contaminate the data measurements; therefore, the MAP assesses the susceptibility of the DAS to noise and its ability to recover.

- Instrumentation system will recover from capacitor bank discharge noise to within 5% of band edge within 50 μs

The primary system operates from a triggering event. The back-up system is manually initiated prior to initiating an experiment to mitigate trigger failure risk. Due to the manual start of the Jaguar system, the Jaguar time base will be independent of the test execution time base as well as the Spectral Dynamics time base. Post-processing of the Jaguar data is expected to time shift the data relative to a timing fiducial available on the data record. Typically, the noise pulse produced by the capacitor bank discharges has served as the timing fiducial. The noise pulse is evident in both the Spectral and Jaguar data records. However, later in this report the suitability of this fiducial is discussed. Due to the manual start of the Jaguar system, it is not expected to satisfy the phase error and time synchronization requirements. Post-processing of the Jaguar data will be required to overcome this limitation.

The primary system and backup systems share the cable plant, bridge completion resistors, excitation voltage, and range selection relay circuitry. The shared architecture for the different acquisition systems introduces limitations into the system. It is common for a data acquisition system to have the ability to self-correct for internal resistances and slight deviations in excitation voltages. In the case of the LIHE DAS system, the Spectral Dynamics system is primary and has this ability to self-correct. The self-corrections enforced by the primary system prohibit self-correction by the back-up Jaguar system. The consequence of this architecture is that voltage and signal offsets manifest in the Jaguar data. Therefore, the Jaguar system is not expected to satisfy the offset requirements stated in this MAP. Post-processing of the Jaguar data is anticipated to correct for these offsets.

3. MAP REVIEW

Although this MAP has been primarily developed by LIHE personnel, customer requirements have been negotiated with the nuclear weapon systems personnel. Personnel from the PSL have been consulted regarding this MAP. Component calibration performed by the PSL is an essential element of the LIHE MAP. Manufacturer's technical representatives perform annual system and software maintenance and have contributed to this process. Results of this effort will be shared with customers, PSL personnel, and DAS equipment manufacturer's representatives.

4. SUMMARY OF VALIDATION STEPS

Step 1: The Spectral Dynamics digitization cards (VXI 2824) were sent to the SNL PSL to verify the calibration of the cards.

Step 2: The Spectral Dynamics digitization cards (VXI 2824) were returned to the manufacturer for card calibration (non-SNL accredited calibration), testing, cleaning, and updating as necessary.

Step 3: The Spectral Dynamics digitization cards (VXI 2824) were returned through the SNL PSL to calibrate the cards.

Step 4: The Spectral Dynamics and Jaguar manufacturer's representatives performed on-site system tests using on-board voltage sources as well as software maintenance.

Step 5: The performance of the entire system was verified using simulated strain measurements. For the null test, a precision 350 ohm (.01%) resistor was added to each channel to simulate a null microstrain condition. For the 5k test, a parallel 34,650 ohm (.01%) resistor was added to each channel to simulate a 5000 microstrain condition. In addition to testing the digitization of microvoltages, the test verified the performance of the bridge completion resistors, excitation supply, and relay circuitry. The results of the Spectral system were compared with the results of the Jaguar system.

Step 6: The performance of the entire system was verified using a voltage injection. A sinusoidal voltage source was used to inject a one volt (peak to peak) voltage at two discrete frequencies: 1kHz and 10kHz. The voltages measured on the Spectral Dynamics channels and Jaguar channels were compared against voltages measured by calibrated Tektronix digitizers. Higher frequency voltage was injected into a single channel to investigate the system response.

Step 7: The electromagnetic noise immunity was verified for the entire system. The LIHE capacitor banks were discharged near a noise test fixture with 60 accelerometers and 60 strain gauges to verify the noise immunity and recovery of the system. Two tests were performed and documented: In the first noise immunity test, no attempt was made to shield the system from noise to verify the system did not "upset" in response to the noise environment. In the second test, electromagnetic shielding was added to achieve acceptable noise recovery.

4.1. Results

4.1.1. Initial Card Calibration (Step 1) Results

All Spectral Dynamics digitization cards (17 cards at 8 data channels per card) were removed from the LIHE VXI racks and sent to the SNL PSL. The PSL calibration verified the "as found" state of the Spectral Dynamics cards. The cards were tested on a PSL automated tester at the PSL.

4.1.2. Manufacturer's Updating and Testing (Step 2) Results

All Spectral Dynamics digitization cards (17 cards at 8 data channels per card) were sent to the Spectral Dynamics facility. Once received at the facility, the cards were placed on an automated

tester and run through a complete series of tests (bandwidth, frequency response, amplitude, excitation, channel-to-channel cross-talk, phase, etc.). The cards were tested to full manufacturer's operational specifications. If the card failed, the failure was documented, and the card was repaired and retested. All cards returned to LIHE successfully passed manufacturer's testing. Once all of the cards passed the incoming test, the boards were disassembled from housing, DI water cleaned, and baked out in an oven. The cards were reassembled and then re-tested. Internal electrically erasable programmable read-only memory (EEPROM) was flashed for NIST traceable voltage reference taps as well as the factory and field calibration date. Completed test reports were provided to the LIHE facility.

4.1.3. Final Card Calibration (Step 3) Results

All Spectral Dynamics digitization cards were returned through the SNL PSL. The PSL verified the calibration of the Spectral Dynamics cards. The cards were tested on a PSL automated tester to PSL standards. Documentation of results was provided to LIHE. All cards (132 channels total) passed calibration and are ready for use. The PSL does not have the capability to calibrate the Jaguar system. Comparison of the Jaguar data with calibrated Tektronix digitizers and calibrated Spectral Dynamics cards serves as a field calibration of the Jaguar system.

4.1.4. Manufacturer's On-Site Testing (Step 4) Results

The manufacturer's representatives performed on-site testing and verification at LIHE. The Spectral Dynamics and Jaguar systems have on-board voltage sources. The systems performed self-calibration verifications and all channels passed.

4.1.5. Stain Gauge Simulation (Step 5) Results

<u>MAP requirement: Noise floor less than +/-2% of band edge (95% confidence interval), assuming 5000 microstrain band edge.</u>

<u>MAP requirement: Amplitude within 10%, assuming 5000 microstrain band edge.</u>

The performance of the entire system was verified by simulating two different strain conditions for each channel of the Spectral Dynamics and Jaguar systems: zero microstrain and 5000 microstrain. These strain calibration tests were very sensitive tests that had the ability to expose several types of subtle problems in the system, such as cold solder joint problems, corrosion on or in connector assemblies, poor contact resistance in the internal relays, excitation voltage deviations, and other cable plant resistance issues that could not otherwise be detected with conventional digital volt meter (DMM) tests. For example, a resistance shift of tens of milliohms due to contact resistance in the cable plant or a relay would have caused strain measurement shift of greater than 4% relative to a 5000 micro strain measurement. A 1% shift in the 350 ohm strain gage corresponds to a 5000 microstrain measurement.

This test simulated two different strain gauges at the cable plant interface. The cable plant interface used multiple six-channel connectors. Resistors that simulated a specified strain level were incorporated into plugs that interfaced with the cable plant. The strain simulations were completed 24 channels at a time using four plugs. Four plugs (plus a spare) were fabricated for the null test, simulating zero microstrain. Four plugs (plus a spare) were fabricated for the shunt test, simulating 5000 microstrain. The plugs were fabricated from precision resistors with resultant resistances for the null and shunt tests shown in Table 1 and Table 2 respectively. Using

the null plug, the noise floor (with a 95% confidence interval) was determined for the Spectral Dynamics System and Jaguar System. Figure 1 shows the null results for the Spectral Dynamics system. Both the strain offset (mean) and the 95% confidence interval are shown. All channels, except channel 72, passed the noise floor MAP requirements. Figure 2 shows the null results for the Jaguar system. The data indicated a baseline error as expected. This baseline offset will need to be removed during post-processing of the data. Baseline offset of the Jaguar data will not result in channel failure. The 95% confidence interval width indicates the noise floor MAP requirement was met for all channels except for channel 72. The tabular data for the null test is shown in Table 3.

After the null test was used to verify the noise floor, the null plugs were replaced with the shunt plugs. The shunt test data for the Spectral Dynamics and Jaguar systems are shown in Figure 3 and Figure 4 respectively. The tabular data for the shunt data is shown in Table 4. The mean values and 95% confidence intervals are shown. This shunt test did not differentiate between amplitude errors and offset errors. For both the Spectral Dynamics and Jaguar systems, the composite amplitude and offset error were less than 7% for all channels; satisfying the 10% MAP requirement. The noise about the mean was also determined at the 95% confidence interval width shown below. With the exception of channel 72, all Spectral Dynamics and Jaguar system channels passed the noise floor requirements.

Table 1: Null Plug Resistances

Null Plug A Resistances (350Ω)					
Channel	Plug 1	Plug 2	Plug 3	Plug 4	Plug5 (Spare)
1	350.042	350.017	349.936	349.999	350.010
2	350.024	350.031	349.991	350.001	350.040
3	350.019	350.059	349.999	350.017	350.050
4	350.040	350.026	349.988	349.998	350.040
5	350.036	350.036	349.975	349.992	350.011
6	350.010	350.022	349.983	349.998	350.023

Table 2: Shunt Plug Resistances

Shunt Plug B Resistances (350Ω // 34,650Ω)					
Channel	Plug 1	Plug 2	Plug 3	Plug 4	Plug5 (Spare)
1	346.521	346.471	346.454	346.525	346.392
2	346.519	346.481	346.498	346.492	346.450
3	346.523	346.505	346.482	346.476	346.520
4	346.522	346.348	346.466	346.488	346.330
5	346.504	346.647	346.499	346.497	346.440
6	346.515	346.466	346.433	346.466	346.360

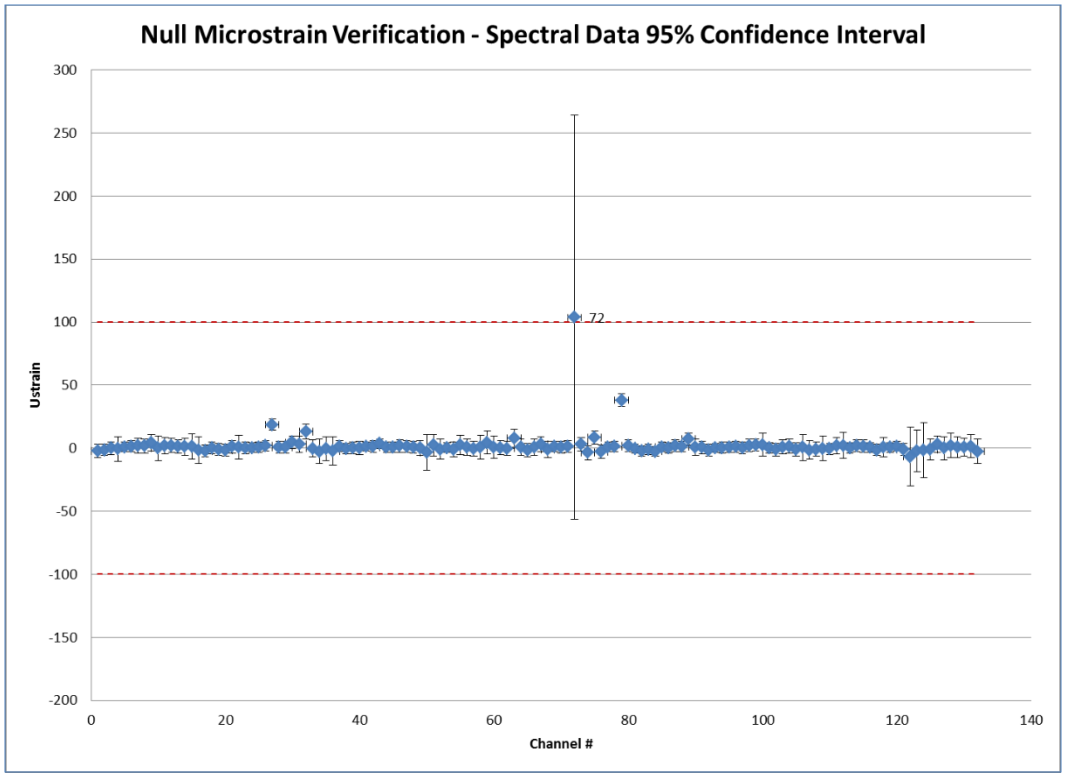

Figure 1: Null (zero microstrain) test results for the Spectral Dynamics system showing noise floor results at a 95% confidence interval

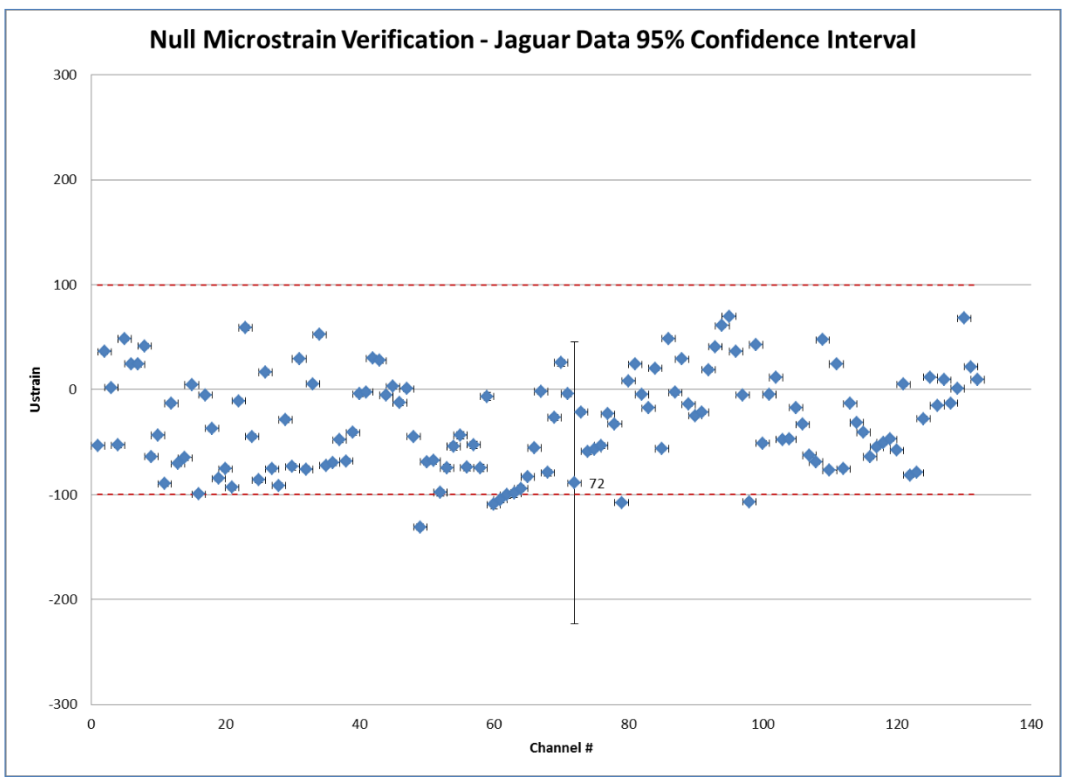

Figure 2: Null (zero microstrain) test results for the Jaguar system showing noise floor results at a 95% confidence interval

Table 3: Null (zero microstrain) test data for the Spectral Dynamics and Jaguar systems

	Spectral Dynamics					Jaguar				
Channel	Mean Value (Offset)	Standard Deviation	Lower Bound (95% CI)	Upper Bound (95% CI)	95% CI Width (Noise Floor)	Mean Value (Offset)	Standard Deviation	Lower Bound (95% CI)	Upper Bound (95% CI)	95% CI Width (Noise Floor)
1	-2.24	2.63	-7.40	2.92	10.32	-53.50	1.19	-55.84	-51.16	-57.03
2	-1.31	2.36	-5.93	3.31	9.24	36.09	1.22	33.70	38.48	32.48
3	-0.04	2.52	-4.98	4.89	9.87	2.04	1.24	-0.39	4.48	-1.63
4	-0.68	5.02	-10.52	9.17	19.68	-52.95	1.17	-55.24	-50.67	-56.40
5	0.97	1.87	-2.70	4.65	7.35	48.50	1.16	46.23	50.78	45.06
6	1.46	2.24	-2.92	5.85	8.77	24.58	1.12	22.39	26.77	21.27
7	1.91	3.12	-4.20	8.03	12.23	24.14	1.20	21.77	26.50	20.57
8	1.68	2.83	-3.86	7.23	11.09	41.64	1.14	39.40	43.89	38.25
9	4.23	3.33	-2.29	10.75	13.04	-63.71	1.15	-65.98	-61.45	-67.13
10	0.03	4.97	-9.71	9.76	19.47	-43.59	1.14	-45.83	-41.34	-46.97
11	2.00	3.28	-4.42	8.42	12.84	-89.67	1.20	-92.03	-87.32	-93.23
12	2.20	2.81	-3.32	7.72	11.03	-13.20	1.12	-15.39	-11.01	-16.50
13	1.29	2.73	-4.07	6.65	10.72	-70.66	1.14	-72.90	-68.42	-74.04
14	1.25	3.45	-5.51	8.02	13.53	-65.09	1.17	-67.39	-62.80	-68.56
15	1.28	5.15	-8.82	11.37	20.18	4.42	1.18	2.11	6.73	0.93
16	-1.70	5.40	-12.28	8.87	21.15	-99.70	1.09	-101.84	-97.56	-102.93
17	-2.23	2.30	-6.74	2.28	9.02	-5.18	1.34	-7.81	-2.56	-9.14
18	0.30	2.35	-4.32	4.91	9.23	-37.03	1.39	-39.77	-34.30	-41.16
19	-1.06	2.47	-5.90	3.79	9.69	-84.78	1.38	-87.48	-82.08	-88.86
20	-1.55	2.35	-6.15	3.06	9.22	-75.52	1.40	-78.28	-72.77	-79.68
21	1.11	2.66	-4.11	6.32	10.43	-93.29	1.39	-96.01	-90.57	-97.40
22	0.69	4.70	-8.52	9.91	18.44	-10.77	1.36	-13.44	-8.10	-14.80
23	0.26	2.41	-4.47	4.99	9.46	59.06	1.35	56.42	61.70	55.08
24	0.36	2.04	-3.65	4.36	8.01	-44.73	1.30	-47.28	-42.18	-48.59
25	0.60	2.17	-3.64	4.85	8.49	-86.17	1.32	-88.76	-83.58	-90.09
26	2.17	2.12	-1.98	6.32	8.31	16.44	1.33	13.83	19.06	12.50
27	18.67	2.35	14.07	23.27	9.20	-75.62	1.45	-78.45	-72.78	-79.90
28	0.77	2.46	-4.05	5.60	9.65	-91.37	1.39	-94.09	-88.64	-95.48
29	0.71	2.33	-3.85	5.27	9.12	-28.75	1.33	-31.36	-26.15	-32.68
30	4.71	2.57	-0.32	9.75	10.07	-73.56	1.61	-76.71	-70.41	-78.32
31	3.03	3.36	-3.56	9.62	13.19	29.35	1.56	26.29	32.40	24.74
32	13.18	3.03	7.25	19.12	11.87	-76.00	1.64	-79.21	-72.78	-80.85
33	-0.13	3.36	-6.72	6.46	13.17	5.41	1.25	2.95	7.87	1.70
34	-2.62	4.90	-12.22	6.98	19.20	52.34	1.31	49.77	54.91	48.45

35	-0.42	4.81	-9.85	9.01	18.87	-72.20	1.36	-74.86	-69.54	-76.22
36	-2.21	5.61	-13.20	8.79	21.99	-69.76	1.34	-72.38	-67.14	-73.72
37	1.62	2.27	-2.84	6.07	8.91	-48.04	1.39	-50.76	-45.32	-52.15
38	-0.30	2.12	-4.46	3.86	8.32	-68.06	1.35	-70.70	-65.42	-72.05
39	0.12	2.51	-4.80	5.03	9.83	-40.92	1.44	-43.74	-38.10	-45.18
40	0.15	2.59	-4.93	5.22	10.15	-4.13	1.45	-6.98	-1.28	-8.43
41	1.46	1.79	-2.04	4.96	7.00	-2.32	1.34	-4.95	0.32	-6.30
42	1.55	2.36	-3.08	6.17	9.25	29.82	1.42	27.04	32.59	25.63
43	3.54	1.97	-0.32	7.40	7.72	27.66	1.25	25.21	30.10	23.96
44	0.76	2.03	-3.21	4.73	7.94	-5.36	1.26	-7.82	-2.89	-9.07
45	0.72	2.14	-3.47	4.91	8.38	2.93	1.30	0.38	5.48	-0.92
46	1.73	2.63	-3.42	6.87	10.30	-12.39	1.28	-14.90	-9.88	-16.18
47	1.29	2.30	-3.22	5.80	9.02	0.86	1.31	-1.70	3.42	-3.01
48	0.80	2.51	-4.13	5.72	9.85	-44.70	1.35	-47.36	-42.05	-48.72
49	0.18	2.91	-5.52	5.88	11.40	-131.01	1.57	-134.08	-127.94	-135.65
50	-3.62	7.20	-17.73	10.50	28.23	-68.68	1.44	-71.50	-65.86	-72.94
51	2.39	4.39	-6.21	11.00	17.22	-67.89	1.59	-71.01	-64.76	-72.61
52	-0.78	4.04	-8.70	7.13	15.83	-97.99	1.63	-101.18	-94.80	-102.81
53	0.34	2.03	-3.64	4.32	7.96	-74.64	1.72	-78.01	-71.27	-79.72
54	-0.97	2.95	-6.75	4.81	11.56	-54.23	1.76	-57.67	-50.78	-59.43
55	2.59	3.81	-4.88	10.06	14.94	-43.59	1.79	-47.10	-40.09	-48.89
56	0.85	3.21	-5.44	7.15	12.59	-74.10	1.55	-77.15	-71.06	-78.70
57	-0.39	3.11	-6.49	5.72	12.21	-52.54	1.83	-56.14	-48.95	-57.97
58	0.59	4.79	-8.80	9.98	18.78	-74.61	1.66	-77.87	-71.36	-79.53
59	4.39	4.61	-4.65	13.43	18.08	-6.51	2.10	-10.63	-2.38	-12.74
60	0.74	4.46	-8.01	9.48	17.49	-109.60	2.02	-113.57	-105.64	-115.59
61	0.37	2.80	-5.12	5.85	10.97	-104.75	1.58	-107.85	-101.66	-109.42
62	-0.16	2.97	-5.99	5.66	11.65	-100.28	1.80	-103.81	-96.75	-105.61
63	7.75	3.65	0.59	14.91	14.32	-98.99	1.89	-102.70	-95.27	-104.60
64	0.66	3.28	-5.77	7.10	12.87	-94.11	1.57	-97.19	-91.03	-98.77
65	-1.35	2.71	-6.66	3.96	10.62	-83.16	1.47	-86.04	-80.28	-87.51
66	0.65	3.30	-5.83	7.12	12.95	-55.55	1.30	-58.10	-52.99	-59.41
67	3.01	2.98	-2.82	8.85	11.68	-1.76	1.50	-4.69	1.17	-6.19
68	-1.03	3.23	-7.36	5.31	12.67	-79.17	1.50	-82.10	-76.23	-83.60
69	1.32	2.24	-3.07	5.71	8.78	-26.62	1.56	-29.68	-23.56	-31.24
70	0.84	2.42	-3.91	5.59	9.50	25.63	1.68	22.34	28.93	20.66
71	1.24	2.44	-3.55	6.03	9.58	-4.06	1.36	-6.72	-1.40	-8.08
72	103.71	81.77	-56.58	264.01	320.58	-89.03	68.53	-223.35	45.29	-291.87
73	3.02	2.76	-2.39	8.44	10.84	-21.27	1.32	-23.87	-18.68	-25.19
74	-3.60	2.89	-9.26	2.06	11.32	-58.80	1.53	-61.81	-55.79	-63.34
75	8.40	2.60	3.30	13.50	10.20	-56.78	1.33	-59.38	-54.18	-60.71

76	-2.96	2.75	-8.35	2.43	10.77	-53.52	1.35	-56.18	-50.87	-57.53
77	0.86	1.96	-2.98	4.71	7.69	-23.34	1.32	-25.92	-20.76	-27.23
78	1.23	2.13	-2.93	5.40	8.33	-32.58	1.30	-35.13	-30.03	-36.43
79	38.04	2.48	33.18	42.91	9.73	-107.59	1.37	-110.27	-104.90	-111.64
80	2.06	2.44	-2.72	6.83	9.55	8.24	1.40	5.50	10.99	4.09
81	-0.17	1.81	-3.72	3.39	7.11	24.15	1.10	21.99	26.31	20.88
82	-2.11	2.15	-6.32	2.10	8.42	-4.64	1.11	-6.81	-2.47	-7.92
83	-1.07	2.10	-5.19	3.05	8.24	-17.66	1.10	-19.82	-15.50	-20.92
84	-2.55	1.88	-6.24	1.14	7.38	20.36	1.06	18.28	22.44	17.22
85	0.85	2.00	-3.06	4.77	7.83	-56.36	1.12	-58.55	-54.17	-59.66
86	0.19	2.11	-3.95	4.32	8.27	48.66	1.22	46.27	51.04	45.05
87	1.85	2.35	-2.75	6.45	9.20	-2.86	1.10	-5.01	-0.71	-6.10
88	1.18	2.08	-2.90	5.26	8.16	29.07	1.11	26.89	31.25	25.77
89	7.35	2.47	2.50	12.20	9.70	-14.09	1.13	-16.30	-11.87	-17.43
90	0.96	3.28	-5.48	7.40	12.88	-24.90	1.11	-27.07	-22.72	-28.18
91	0.48	2.63	-4.68	5.65	10.32	-21.74	1.09	-23.88	-19.60	-24.98
92	-1.61	2.39	-6.29	3.07	9.36	18.96	1.29	16.43	21.48	15.14
93	0.24	1.87	-3.43	3.92	7.35	40.76	1.09	38.63	42.88	37.54
94	0.31	2.29	-4.18	4.79	8.97	60.85	1.07	58.75	62.95	57.68
95	0.90	2.08	-3.17	4.98	8.15	69.74	1.12	67.53	71.94	66.41
96	1.12	2.16	-3.11	5.35	8.46	36.31	1.11	34.13	38.49	33.02
97	0.31	2.44	-4.49	5.10	9.58	-5.02	1.14	-7.26	-2.78	-8.40
98	2.12	2.63	-3.03	7.26	10.29	-106.93	1.08	-109.06	-104.80	-110.14
99	2.35	2.44	-2.43	7.13	9.57	42.70	1.13	40.48	44.92	39.35
100	2.68	4.72	-6.58	11.94	18.52	-50.99	1.10	-53.14	-48.84	-54.24
101	0.00	2.13	-4.17	4.16	8.33	-4.56	1.03	-6.58	-2.54	-7.61
102	-1.25	2.57	-6.29	3.80	10.09	11.49	1.08	9.38	13.60	8.30
103	1.04	2.82	-4.48	6.56	11.04	-47.49	1.05	-49.55	-45.43	-50.60
104	1.55	2.80	-3.93	7.03	10.96	-47.38	1.02	-49.39	-45.38	-50.41
105	-0.88	2.67	-6.11	4.34	10.45	-17.16	1.06	-19.23	-15.09	-20.29
106	0.62	5.20	-9.58	10.82	20.40	-33.07	1.06	-35.14	-31.00	-36.20
107	-1.31	3.70	-8.57	5.95	14.52	-62.75	1.20	-65.10	-60.41	-66.29
108	-0.88	2.84	-6.44	4.68	11.12	-68.91	1.13	-71.13	-66.69	-72.26
109	-0.21	4.95	-9.91	9.48	19.39	47.46	1.12	45.27	49.64	44.15
110	-0.45	2.25	-4.87	3.97	8.83	-76.72	1.14	-78.95	-74.49	-80.09
111	1.76	3.36	-4.83	8.34	13.17	24.23	1.11	22.05	26.42	20.93
112	2.05	5.25	-8.25	12.34	20.59	-75.61	1.16	-77.88	-73.33	-79.04
113	0.09	2.19	-4.21	4.39	8.60	-13.28	1.10	-15.44	-11.12	-16.54
114	1.69	2.38	-2.97	6.36	9.33	-31.43	1.26	-33.89	-28.96	-35.15
115	1.44	2.54	-3.55	6.42	9.97	-40.78	1.11	-42.95	-38.61	-44.06
116	0.58	1.94	-3.23	4.38	7.61	-64.15	1.12	-66.35	-61.95	-67.47

117	-1.33	2.35	-5.93	3.27	9.20	-54.73	1.04	-56.77	-52.69	-57.82
118	0.77	3.95	-6.97	8.52	15.49	-50.72	1.06	-52.78	-48.65	-53.84
119	0.51	2.05	-3.52	4.53	8.05	-47.31	1.04	-49.36	-45.27	-50.40
120	1.37	1.95	-2.46	5.19	7.65	-57.86	1.16	-60.14	-55.59	-61.30
121	-0.96	2.28	-5.44	3.52	8.95	4.96	1.02	2.96	6.95	1.94
122	-6.67	11.81	-29.83	16.48	46.31	-81.55	1.29	-84.08	-79.02	-85.37
123	-2.15	8.43	-18.67	14.36	33.03	-79.18	1.04	-81.21	-77.15	-82.24
124	-1.52	11.13	-23.34	20.30	43.63	-27.75	1.15	-30.00	-25.50	-31.15
125	-0.91	4.30	-9.35	7.52	16.86	11.93	1.04	9.90	13.97	8.86
126	3.18	3.39	-3.46	9.83	13.29	-15.24	1.19	-17.56	-12.91	-18.74
127	-0.07	4.72	-9.32	9.18	18.50	9.19	1.16	6.91	11.46	5.75
128	2.21	4.90	-7.40	11.82	19.22	-12.83	1.23	-15.24	-10.42	-16.47
129	0.74	4.10	-7.30	8.78	16.08	1.05	0.97	-0.85	2.95	-1.82
130	0.66	3.62	-6.43	7.75	14.18	67.87	0.98	65.94	69.79	64.95
131	1.55	4.59	-7.44	10.54	17.98	21.85	1.04	19.81	23.88	18.77
132	-2.61	4.92	-12.25	7.02	19.27	9.43	0.96	7.56	11.31	6.60

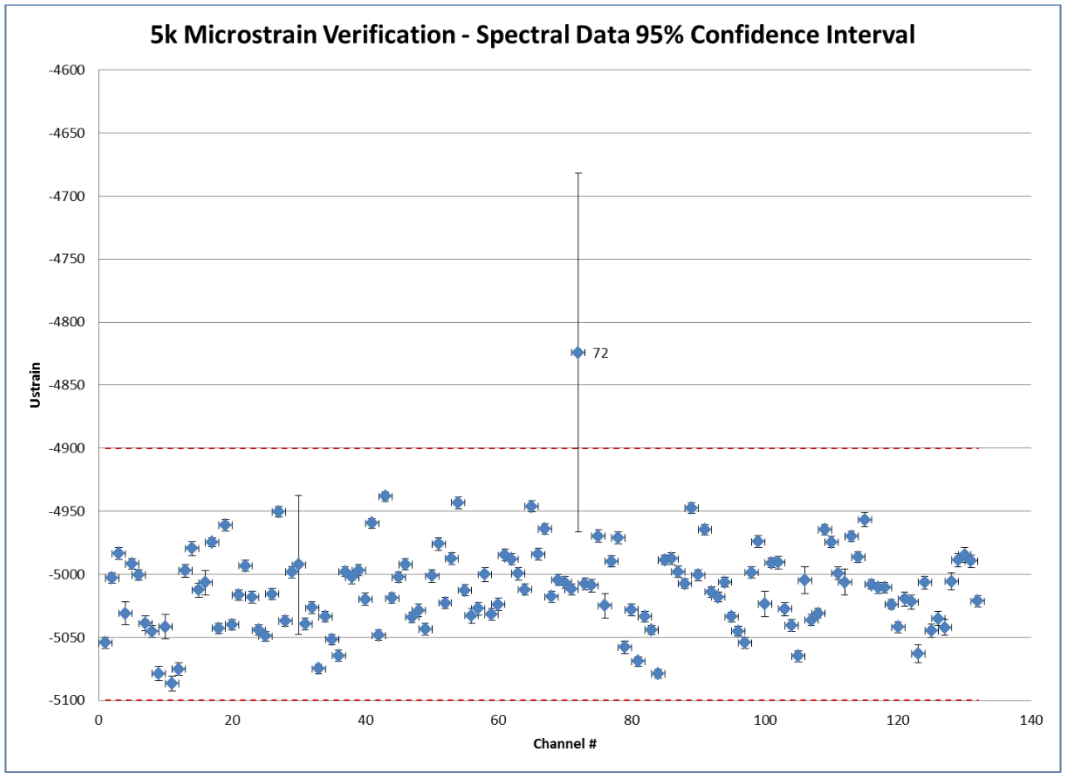

Figure 3: Shunt (5000 microstrain) test results for the Spectral Dynamics system showing amplitude/offset error as well as 95% confidence interval of noise

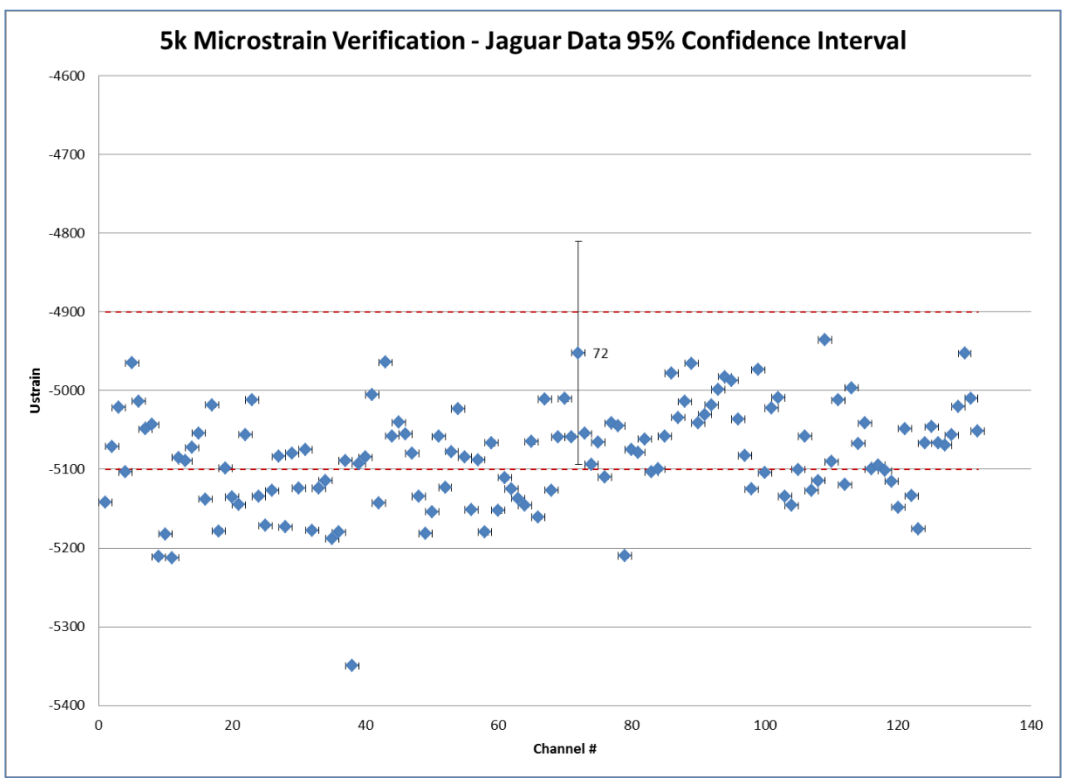

Figure 4: Shunt (5000 microstrain) test results for the Jaguar system showing amplitude/offset error as well as 95% confidence interval of noise

Table 4: Shunt (5000 microstrain) test data for the Spectral Dynamics and Jaguar systems

	Spectral Dynamics					Jaguar				
Channel	Mean Value (Offset)	Standard Deviation	Lower Bound (95% CI)	Upper Bound (95% CI)	95% CI Width (Noise Floor)	Mean Value (Offset)	Standard Deviation	Lower Bound (95% CI)	Upper Bound (95% CI)	95% CI Width (Noise Floor)
1	-5054.4	2.2	-5058.7	-5050.1	8.6	-5141.9	1.2	-5144.2	-5139.6	4.7
2	-5003.0	2.1	-5007.0	-4998.9	8.2	-5070.9	1.2	-5073.3	-5068.4	4.9
3	-4983.7	2.5	-4988.5	-4978.8	9.7	-5021.5	1.2	-5023.9	-5019.0	4.9
4	-5031.0	4.7	-5040.2	-5021.8	18.4	-5103.4	1.2	-5105.7	-5101.2	4.5
5	-4991.7	2.1	-4995.9	-4987.6	8.3	-4965.0	1.2	-4967.3	-4962.8	4.6
6	-5000.5	2.2	-5004.8	-4996.3	8.6	-5013.4	1.1	-5015.6	-5011.1	4.5
7	-5039.0	3.0	-5045.0	-5033.1	11.9	-5048.9	1.2	-5051.2	-5046.7	4.6
8	-5045.4	2.4	-5050.0	-5040.7	9.4	-5043.3	1.1	-5045.6	-5041.1	4.4
9	-5078.7	2.7	-5084.1	-5073.3	10.7	-5211.1	1.2	-5213.3	-5208.8	4.6
10	-5041.7	5.0	-5051.5	-5031.9	19.6	-5182.0	1.1	-5184.2	-5179.8	4.4
11	-5086.6	3.0	-5092.4	-5080.7	11.7	-5212.5	1.2	-5214.8	-5210.1	4.7
12	-5075.2	2.6	-5080.3	-5070.2	10.1	-5085.2	1.2	-5087.5	-5082.9	4.6
13	-4997.1	2.5	-5002.1	-4992.2	9.9	-5089.4	1.2	-5091.8	-5087.1	4.7
14	-4979.6	2.8	-4985.1	-4974.1	11.0	-5072.6	1.2	-5074.9	-5070.3	4.7
15	-5012.5	2.8	-5018.0	-5007.0	11.0	-5054.0	1.1	-5056.2	-5051.7	4.5
16	-5006.7	4.9	-5016.3	-4997.1	19.2	-5138.0	1.2	-5140.4	-5135.6	4.8
17	-4974.7	1.9	-4978.5	-4970.9	7.5	-5018.2	1.3	-5020.9	-5015.6	5.3
18	-5042.9	2.1	-5046.9	-5038.8	8.1	-5178.3	1.5	-5181.2	-5175.4	5.8
19	-4961.1	2.4	-4965.7	-4956.4	9.2	-5098.6	1.4	-5101.4	-5095.7	5.7
20	-5040.1	2.0	-5044.1	-5036.1	8.0	-5135.2	1.4	-5138.0	-5132.4	5.7
21	-5016.5	2.1	-5020.6	-5012.3	8.2	-5145.2	1.4	-5148.0	-5142.5	5.5
22	-4993.3	2.2	-4997.6	-4989.1	8.5	-5055.9	1.3	-5058.4	-5053.3	5.2
23	-5018.3	2.4	-5023.1	-5013.5	9.5	-5011.9	1.3	-5014.4	-5009.3	5.1
24	-5044.3	2.1	-5048.5	-5040.2	8.3	-5134.5	1.3	-5137.0	-5132.0	5.0
25	-5049.2	2.1	-5053.2	-5045.1	8.1	-5171.5	1.2	-5173.9	-5169.1	4.8
26	-5015.8	2.2	-5020.1	-5011.4	8.7	-5127.3	1.2	-5129.7	-5124.9	4.8
27	-4950.5	2.1	-4954.7	-4946.3	8.4	-5083.9	1.3	-5086.5	-5081.3	5.2
28	-5037.2	2.1	-5041.4	-5033.0	8.4	-5173.4	1.2	-5175.8	-5171.0	4.8
29	-4998.3	2.3	-5002.8	-4993.9	8.9	-5079.8	1.4	-5082.5	-5077.1	5.4
30	-4992.6	28.2	-5047.9	-4937.4	110.5	-5124.0	1.4	-5126.6	-5121.3	5.3
31	-5039.5	2.4	-5044.3	-5034.7	9.5	-5075.0	1.4	-5077.9	-5072.2	5.7
32	-5026.7	2.4	-5031.4	-5022.0	9.5	-5177.3	1.5	-5180.2	-5174.5	5.7
33	-5075.0	2.0	-5079.0	-5071.1	7.9	-5124.2	1.3	-5126.7	-5121.6	5.1
34	-5033.7	2.0	-5037.7	-5029.7	7.9	-5114.2	1.3	-5116.8	-5111.6	5.2

35	-5051.7	2.1	-5055.9	-5047.5	8.3	-5188.1	1.3	-5190.7	-5185.6	5.1
36	-5064.5	2.2	-5068.8	-5060.3	8.5	-5180.0	1.3	-5182.6	-5177.3	5.2
37	-4998.0	2.0	-5001.9	-4994.1	7.8	-5089.2	1.2	-5091.6	-5086.7	4.9
38	-5002.4	2.5	-5007.4	-4997.4	10.0	-5349.8	1.3	-5352.4	-5347.3	5.1
39	-4996.8	2.1	-5001.0	-4992.6	8.4	-5093.4	1.3	-5096.0	-5090.8	5.2
40	-5019.8	2.4	-5024.5	-5015.0	9.6	-5084.9	1.3	-5087.4	-5082.4	5.1
41	-4959.5	1.9	-4963.3	-4955.7	7.5	-5005.3	1.3	-5007.9	-5002.7	5.2
42	-5048.5	2.1	-5052.6	-5044.3	8.3	-5142.9	1.4	-5145.7	-5140.1	5.6
43	-4938.4	2.0	-4942.4	-4934.4	8.0	-4964.2	1.4	-4966.8	-4961.5	5.3
44	-5019.0	2.1	-5023.1	-5014.9	8.2	-5057.8	1.3	-5060.4	-5055.2	5.1
45	-5002.6	2.1	-5006.7	-4998.4	8.3	-5040.6	1.3	-5043.1	-5038.1	5.0
46	-4992.3	2.3	-4996.7	-4987.8	8.9	-5055.1	1.3	-5057.5	-5052.6	4.9
47	-5034.0	2.2	-5038.3	-5029.8	8.5	-5079.9	1.3	-5082.4	-5077.3	5.1
48	-5028.6	2.4	-5033.4	-5023.9	9.6	-5134.5	1.3	-5137.0	-5132.0	5.0
49	-5043.6	2.3	-5048.1	-5039.0	9.1	-5181.7	1.5	-5184.5	-5178.8	5.7
50	-5001.4	2.5	-5006.3	-4996.4	9.9	-5153.9	1.4	-5156.7	-5151.1	5.5
51	-4976.1	2.6	-4981.1	-4971.1	10.0	-5058.4	1.3	-5061.1	-5055.8	5.3
52	-5022.9	2.3	-5027.3	-5018.4	8.9	-5123.2	1.4	-5126.0	-5120.5	5.5
53	-4987.6	2.4	-4992.2	-4982.9	9.3	-5077.7	1.5	-5080.6	-5074.8	5.8
54	-4943.3	2.3	-4947.9	-4938.8	9.1	-5023.2	1.5	-5026.1	-5020.3	5.8
55	-5012.7	2.4	-5017.4	-5008.1	9.3	-5084.6	1.5	-5087.5	-5081.7	5.8
56	-5032.9	3.0	-5038.8	-5027.0	11.8	-5151.5	1.4	-5154.1	-5148.8	5.4
57	-5027.3	2.5	-5032.2	-5022.3	9.9	-5087.9	1.7	-5091.1	-5084.7	6.5
58	-5000.2	2.8	-5005.7	-4994.6	11.0	-5179.8	1.8	-5183.3	-5176.3	7.1
59	-5031.8	2.3	-5036.3	-5027.3	9.0	-5066.3	1.8	-5069.9	-5062.7	7.2
60	-5023.9	2.6	-5028.9	-5018.9	10.0	-5152.0	2.0	-5155.9	-5148.1	7.7
61	-4984.8	2.3	-4989.4	-4980.2	9.2	-5110.4	1.5	-5113.4	-5107.4	6.0
62	-4988.0	2.2	-4992.4	-4983.6	8.8	-5125.1	1.5	-5128.1	-5122.2	5.9
63	-4999.5	2.5	-5004.5	-4994.5	10.0	-5137.0	1.5	-5139.9	-5134.0	6.0
64	-5012.2	2.4	-5016.8	-5007.5	9.2	-5145.8	1.5	-5148.8	-5142.9	5.9
65	-4946.1	2.2	-4950.4	-4941.9	8.5	-5065.0	1.6	-5068.2	-5061.9	6.3
66	-4984.3	2.4	-4989.1	-4979.6	9.5	-5160.9	1.6	-5164.0	-5157.8	6.3
67	-4964.1	2.1	-4968.3	-4959.9	8.3	-5010.8	1.6	-5014.0	-5007.7	6.3
68	-5017.9	2.4	-5022.5	-5013.3	9.2	-5126.7	1.6	-5129.8	-5123.6	6.1
69	-5004.5	2.1	-5008.7	-5000.3	8.4	-5058.9	1.6	-5062.0	-5055.7	6.3
70	-5006.4	2.4	-5011.0	-5001.8	9.3	-5010.3	1.6	-5013.5	-5007.1	6.4
71	-5012.0	2.2	-5016.4	-5007.7	8.7	-5058.8	1.6	-5061.8	-5055.7	6.2
72	-4824.2	72.7	-4966.7	-4681.7	284.9	-4952.0	72.3	-5093.7	-4810.3	283.4
73	-5007.6	2.5	-5012.5	-5002.7	9.8	-5054.5	1.4	-5057.3	-5051.8	5.5
74	-5009.0	2.5	-5013.9	-5004.1	9.7	-5094.0	1.4	-5096.8	-5091.2	5.6
75	-4969.8	2.5	-4974.7	-4964.9	9.8	-5065.5	1.4	-5068.2	-5062.8	5.3

76	-5024.9	4.9	-5034.5	-5015.3	19.2	-5109.8	1.4	-5112.4	-5107.1	5.3
77	-4989.8	2.2	-4994.1	-4985.5	8.6	-5041.5	1.4	-5044.4	-5038.7	5.7
78	-4971.2	2.4	-4975.8	-4966.5	9.3	-5044.8	1.4	-5047.6	-5042.0	5.6
79	-5058.0	2.6	-5063.1	-5052.9	10.2	-5210.0	1.5	-5212.9	-5207.1	5.8
80	-5028.3	2.3	-5032.8	-5023.8	9.1	-5075.2	1.5	-5078.1	-5072.3	5.8
81	-5069.1	1.9	-5072.8	-5065.4	7.4	-5078.5	1.1	-5080.6	-5076.4	4.2
82	-5033.7	2.1	-5037.8	-5029.5	8.3	-5061.5	1.1	-5063.6	-5059.4	4.2
83	-5044.2	1.9	-5047.9	-5040.4	7.5	-5103.2	1.0	-5105.2	-5101.1	4.1
84	-5079.0	1.9	-5082.6	-5075.4	7.3	-5099.9	1.1	-5102.0	-5097.8	4.2
85	-4988.7	2.0	-4992.6	-4984.8	7.8	-5058.1	1.1	-5060.2	-5055.9	4.3
86	-4987.8	2.4	-4992.5	-4983.1	9.3	-4977.8	1.1	-4980.0	-4975.6	4.3
87	-4998.0	2.2	-5002.3	-4993.8	8.4	-5034.3	1.1	-5036.5	-5032.1	4.4
88	-5007.5	1.9	-5011.3	-5003.8	7.6	-5014.2	1.1	-5016.4	-5012.0	4.4
89	-4947.5	2.2	-4951.7	-4943.2	8.5	-4965.2	1.1	-4967.4	-4963.0	4.4
90	-5000.8	2.2	-5005.2	-4996.4	8.8	-5040.9	1.1	-5043.1	-5038.8	4.3
91	-4964.6	2.2	-4969.0	-4960.3	8.7	-5030.4	1.1	-5032.6	-5028.2	4.3
92	-5014.0	2.2	-5018.2	-5009.8	8.5	-5018.5	1.3	-5021.0	-5015.9	5.1
93	-5018.1	1.9	-5021.9	-5014.3	7.6	-4998.5	1.1	-5000.6	-4996.4	4.3
94	-5006.2	1.9	-5009.9	-5002.5	7.4	-4982.2	1.1	-4984.3	-4980.2	4.2
95	-5033.7	1.9	-5037.5	-5030.0	7.4	-4986.9	1.1	-4989.1	-4984.7	4.4
96	-5045.1	2.1	-5049.2	-5041.0	8.2	-5036.4	1.1	-5038.6	-5034.2	4.4
97	-5054.4	2.3	-5058.9	-5049.8	9.1	-5082.5	1.1	-5084.6	-5080.3	4.4
98	-4998.6	2.3	-5003.0	-4994.2	8.9	-5125.2	1.2	-5127.5	-5123.0	4.6
99	-4974.2	2.5	-4979.0	-4969.4	9.6	-4973.5	1.1	-4975.7	-4971.3	4.4
100	-5023.6	5.0	-5033.4	-5013.7	19.7	-5104.5	1.1	-5106.7	-5102.2	4.5
101	-4990.9	2.0	-4994.9	-4987.0	7.9	-5022.3	1.0	-5024.3	-5020.2	4.1
102	-4990.9	2.5	-4995.7	-4986.0	9.6	-5008.9	1.1	-5011.0	-5006.8	4.2
103	-5027.6	2.7	-5033.0	-5022.2	10.8	-5134.4	1.0	-5136.4	-5132.3	4.1
104	-5040.8	2.4	-5045.4	-5036.2	9.2	-5146.1	1.0	-5148.0	-5144.1	3.9
105	-5065.1	2.4	-5069.7	-5060.4	9.3	-5100.2	1.1	-5102.2	-5098.1	4.1
106	-5004.8	5.3	-5015.3	-4994.4	20.9	-5058.1	1.1	-5060.2	-5056.0	4.2
107	-5036.4	2.2	-5040.7	-5032.0	8.7	-5127.3	1.2	-5129.7	-5124.9	4.7
108	-5031.1	2.0	-5034.9	-5027.2	7.8	-5114.2	1.1	-5116.4	-5111.9	4.5
109	-4964.6	2.1	-4968.7	-4960.4	8.4	-4935.6	1.1	-4937.8	-4933.4	4.4
110	-4974.5	2.2	-4978.9	-4970.2	8.7	-5090.5	1.2	-5092.8	-5088.3	4.5
111	-4999.2	2.7	-5004.4	-4994.0	10.4	-5012.1	1.1	-5014.1	-5010.0	4.2
112	-5006.2	5.3	-5016.6	-4995.8	20.8	-5119.6	1.1	-5121.7	-5117.5	4.2
113	-4970.0	2.0	-4974.0	-4966.0	8.0	-4996.3	1.1	-4998.5	-4994.2	4.3
114	-4986.5	2.2	-4990.9	-4982.2	8.7	-5067.2	1.1	-5069.4	-5065.0	4.4
115	-4956.9	2.9	-4962.5	-4951.3	11.2	-5041.3	1.1	-5043.5	-5039.1	4.4
116	-5008.1	2.0	-5012.0	-5004.2	7.8	-5099.9	1.2	-5102.2	-5097.6	4.6

117	-5010.9	2.2	-5015.3	-5006.5	8.7	-5094.5	1.1	-5096.6	-5092.4	4.2
118	-5010.5	2.2	-5014.7	-5006.3	8.4	-5101.8	1.0	-5103.9	-5099.8	4.1
119	-5023.9	1.9	-5027.7	-5020.1	7.6	-5115.1	1.1	-5117.2	-5113.0	4.1
120	-5042.1	2.1	-5046.3	-5037.9	8.4	-5148.4	1.2	-5150.7	-5146.1	4.6
121	-5019.7	2.8	-5025.1	-5014.3	10.8	-5048.2	1.0	-5050.2	-5046.1	4.1
122	-5022.1	2.9	-5027.8	-5016.4	11.4	-5133.8	1.1	-5135.9	-5131.6	4.3
123	-5063.0	3.7	-5070.3	-5055.8	14.5	-5175.6	1.9	-5179.4	-5171.8	7.6
124	-5006.6	2.6	-5011.7	-5001.5	10.2	-5066.7	1.2	-5069.2	-5064.3	4.9
125	-5044.9	2.6	-5049.9	-5039.8	10.2	-5046.2	1.1	-5048.5	-5044.0	4.4
126	-5035.2	2.9	-5040.9	-5029.5	11.4	-5066.8	1.2	-5069.2	-5064.4	4.8
127	-5042.2	3.1	-5048.3	-5036.0	12.3	-5069.4	1.1	-5071.6	-5067.1	4.5
128	-5005.7	3.4	-5012.3	-4999.0	13.3	-5056.3	1.1	-5058.5	-5054.2	4.3
129	-4988.8	2.7	-4994.0	-4983.5	10.5	-5020.2	1.1	-5022.3	-5018.1	4.2
130	-4984.7	2.9	-4990.3	-4979.1	11.2	-4952.7	1.1	-4954.8	-4950.5	4.4
131	-4989.6	2.6	-4994.8	-4984.4	10.3	-5010.1	1.1	-5012.2	-5008.1	4.2
132	-5021.4	2.2	-5025.7	-5017.1	8.5	-5051.5	1.0	-5053.6	-5049.5	4.1

4.1.6. Voltage Injection (Step 6) Results

MAP requirement: Amplitude within 10%.

MAP requirement: Frequency within 1%.

MAP requirement: Phase within 10°.

MAP requirement: Voltage offset within 10%.

The performance of the entire system was verified by using a sinusoidal voltage signal with an amplitude of 1 volt, peak to peak, which was injected into every channel. Two discrete frequencies were used: 1kHz and 10kHz. To efficiently complete this step, a multi-channel splitter was used. Due to the loading limitations of the signal generator, a maximum of 18 channels, plus a reference channel, were tested at a time. Although the signal generator was not calibrated, the reference channel was recorded by a calibrated Tektronix digitizer. This calibrated digitizer was installed as close as was practical to the signal generator. The accuracy of the voltage input test is limited by the precision and balance of the splitter. In order to define this limitation, the performance of the splitter was characterized. The voltage output of the splitter was measured using calibrated Tektronics digitizers. The results of the splitter performance tests are shown below. After the splitter was characterized, the voltage signal was injected at the cable plant interface to test 18 channels at a time using the splitter. A reference channel was measured with a digitizer to provide a calibrated reference. The voltage inputted into Spectral Dynamics and Jaguar systems through the cable plant was compared with the calibrated reference measurement.

The analysis was completed using a MATLAB routine using the following methodology: The reference sinusoid measurement was fit to the equation listed in Equation 1 below. The Spectral Dynamics and Jaguar measurements were similarly fit to Equation 2. The quality of the sinusoidal fit was calculated for both the reference measurements and DAS measurements. The adjusted goodness of fit (R^2) was determined for each sinusoidal fit. The 95% confidence intervals were also calculated based on the fit residuals.

Equation 1: reference sinusoid measurement

$$V_{Ref} = A_{ref}\sin\left(2\pi\left(f_{Ref}t + \emptyset_{Ref}\right)\right) + V_{Offset_Ref}$$

Equation 2: Spectral Dynamics and Jaguar measurements

$$V_{Meas} = A_{Meas}\sin\left(2\pi\left(f_{Meas}t + \emptyset_{Meas}\right)\right) + V_{Offset_Meas}$$

The measured data and the calibrated reference data were compared as follows: The amplitude, frequency, phase and voltage offset comparisons, and MAP requirements are shown below in Equations 3 through 6. Due to limitations of the Jaguar System as previously noted, a voltage offset was expected and observed, requiring post-processing of the data to remove this potential offset. Additionally, the Jaguar is manually started to mitigate against trigger failure resulting in Jaguar data that is not time synchronized with the Tektronix reference, for example. The manual triggering will result in a significant phase error, requiring post-processing of the data to synchronize the time base using the timing fiducial available on the data record.

Equation 3:

Amplitude Error Fraction: $$1 - \frac{A_{Meas}}{A_{Ref}} < 0.10$$

Equation 4:

Frequency Error Fraction: $$1 - \frac{f_{Meas}}{f_{Ref}} < 0.01$$

Equation 5:

Voltage Phase Error: $$\varphi_{Meas} - \varphi_{Ref} < 10°$$

Equation 6:

Voltage Offset Error: $$\frac{V_{Offset_Meas} - V_{Offset_Ref}}{A_{Ref}} < 0.10$$

4.1.6.1 Splitter Characterization

As described, a multi-channel splitter was used to distribute the sinusoidal voltage. To characterize the splitter, calibrated Tektronix digitizers were used to measure the splitter output. To clarify, a sinusoidal waveform is fit to voltage data as shown in Figure 5. Figure 6 shows the voltage input, waveform fit, and fit residuals for channel 1 of the splitter. The fit waveforms from splitter channels 1 through 18 were compared, with channel 0 used as a reference. Figure 7 shows the frequency error fraction of the splitter was less than 4.1×10^{-5}. Figure 8 shows the amplitude error fraction was less than 1.3×10^{-3}. The voltage phase error shown in Figure 9 was less than 0.7 degrees. Finally, the voltage offset error fraction shown in Figure 10 was less than 0.02. The splitter verification tests an assessment of the error introduced into the end-to-end verification data as a result of the splitter.

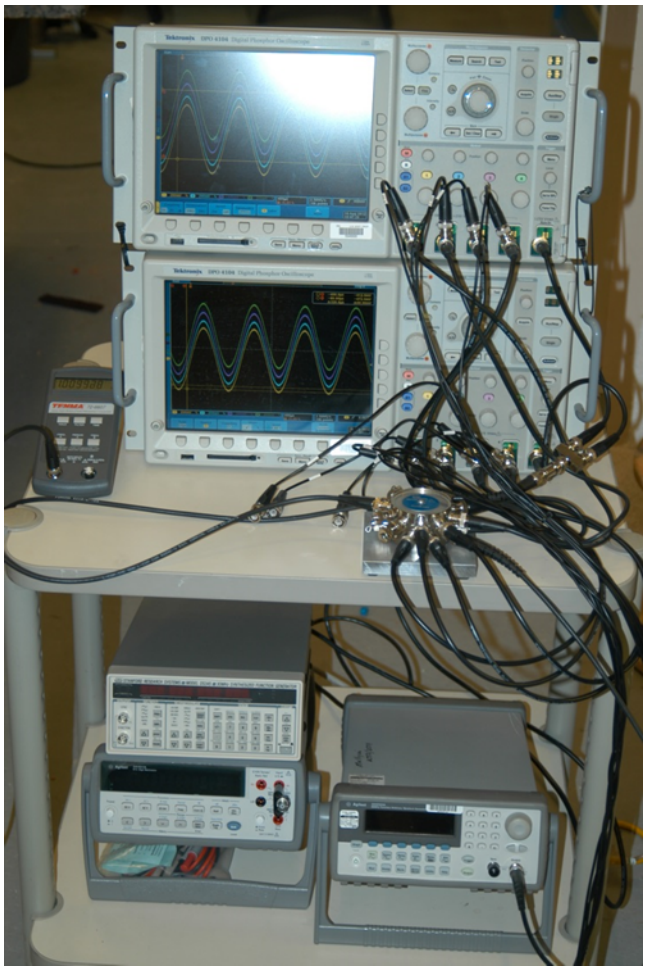

Figure 5: Splitter characterization using calibrated digitizers

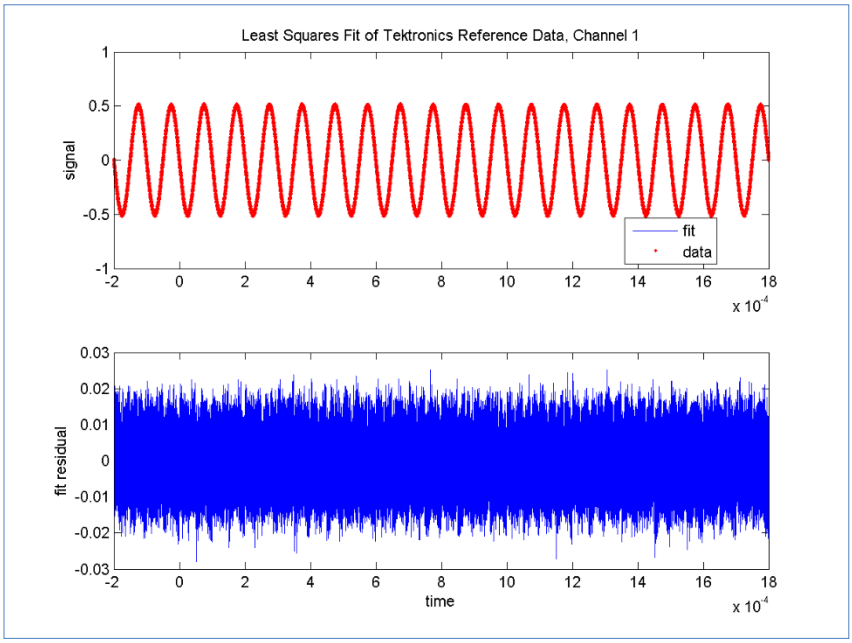

Figure 6: Sinusoid voltage injection into calibrated Tektronix digitizer with sinusoidal fit overlay and plotted residuals

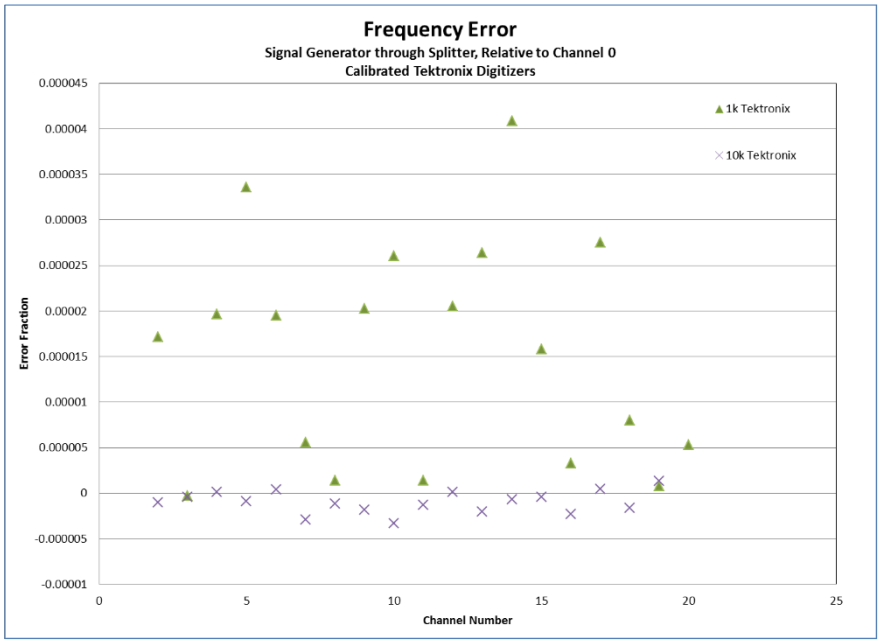

Figure 7: Splitter characterization testing into calibrated digitizers showing the frequency error fraction. Maximum error fraction was -4.1X10-5.

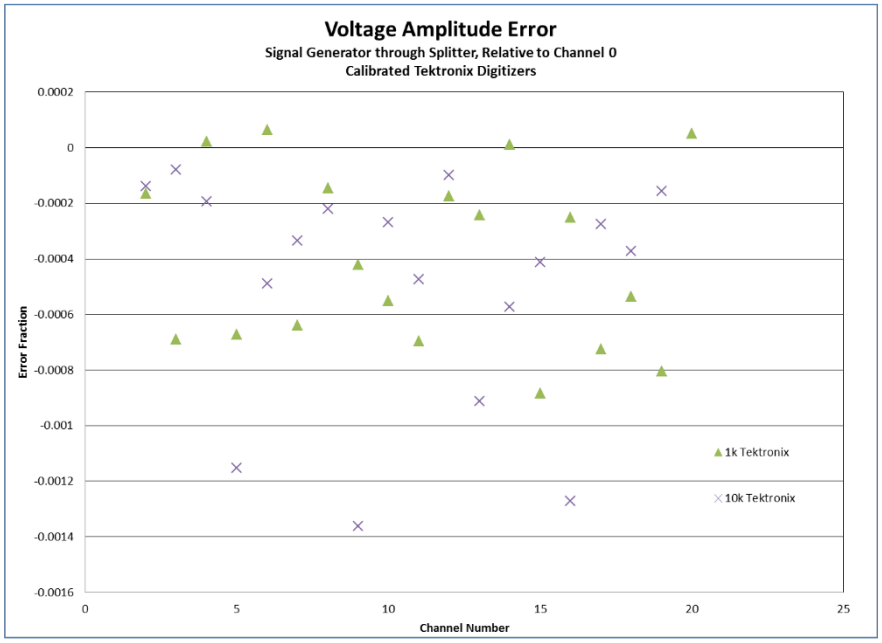

Figure 8: Splitter characterization testing into calibrated digitizers showing the voltage amplitude error fraction. Maximum error fraction was 1.36X10-3.

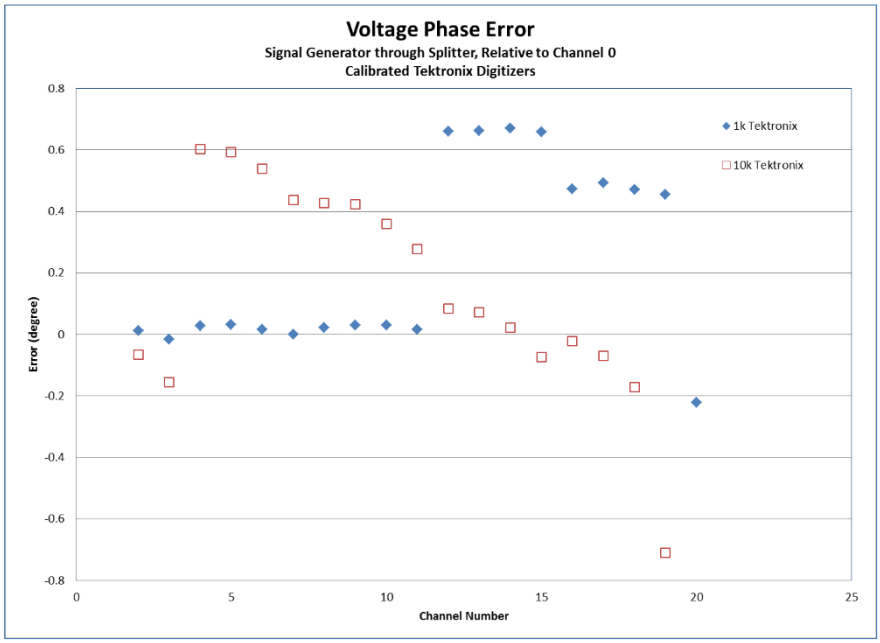

Figure 9: Splitter characterization testing into calibrated digitizers showing the phase error. Maximum error fraction was 0.7 degrees.

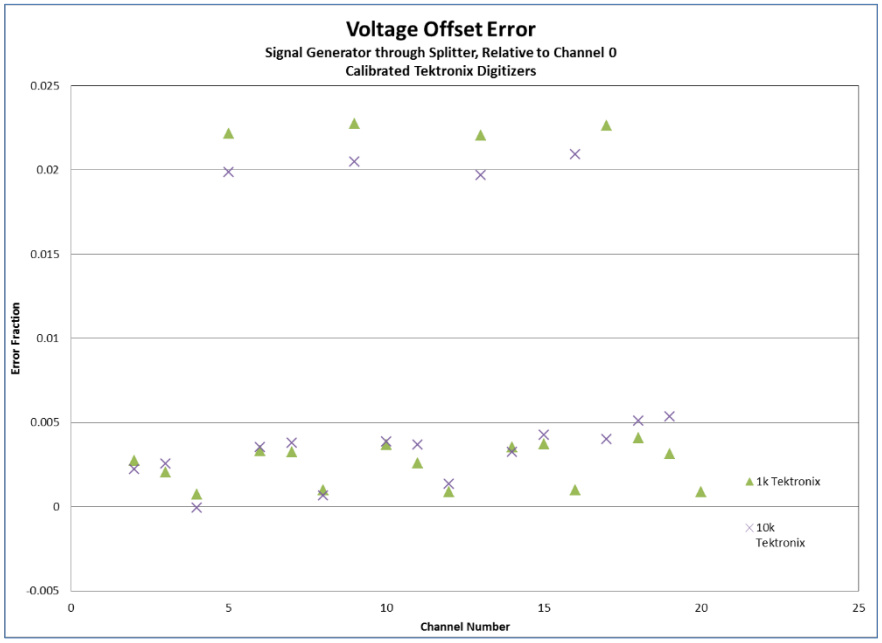

Figure 10: Splitter characterization testing into calibrated digitizers showing the voltage offset error fraction. Maximum error fraction was 2.3X10-2.

4.1.6.2 Voltage Results

The voltage injection tested 18 channels against a calibrated reference. The reference and the DAS system data records were fit to the sinusoidal waveform. The adjusted goodness of fit (R^2) was calculated to determine the quality of the waveform fit. The data from channels 1 through 18, plus the calibrated Tektronix reference, are shown in Figure 11 for both 1kHz and 10kHz data. The 95% confidence intervals of the fit residuals were also calculated. Data from the Spectral system channels 1 through 18 as well as the Tektronix reference channel 0 are shown in Figure 12 for both 1kHz and 10kHz data. The fit quality results for all data channels of the Spectral and Jaguar systems are shown in Figures 13 and 14. Comparing the fit reference with the DAS measurement fit using Equations 3 through 6 above, the frequency error fraction, voltage amplitude error fraction, voltage offset fraction, and phase angle error were calculated for each Spectral and Jaguar channel as shown in Figures 15 through 18. The data values for the 132 channels of Spectral and Jaguar data at 1kHz and 10kHz are listed in Table 5.

All channels of the Spectral Dynamics system passed the voltage input MAP requirements; however, the performance of channel 72 deviated significantly from every other channel and will not be utilized for data acquisition. Similarly, the Jaguar system met the voltage input requirements for amplitude and frequency for every channel with degraded performance for channel 72. Due to the previously discussed limitations, the Jaguar is expected to have an offset error and phase error that will require post-test processing.

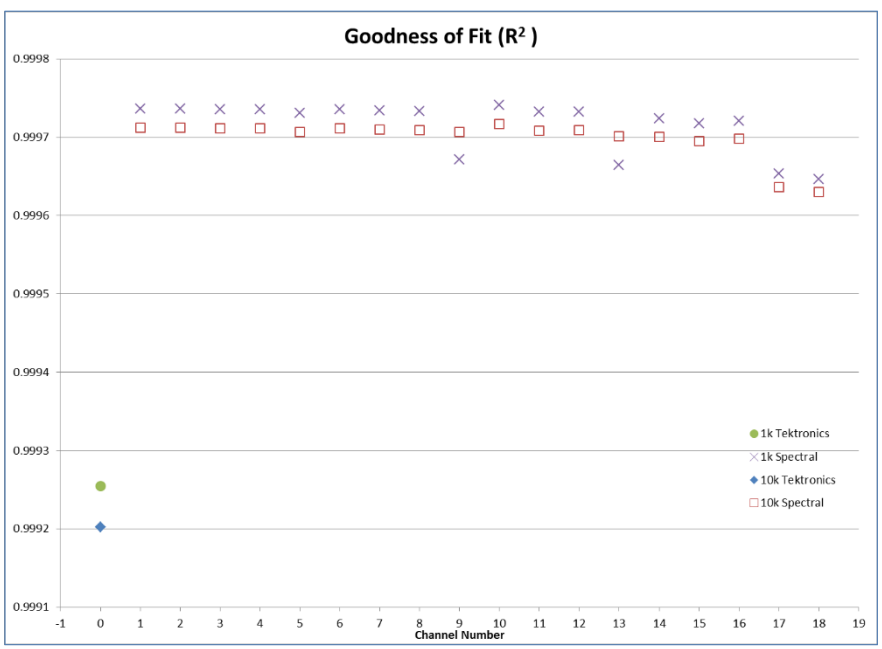

Figure 11: The adjusted goodness of fit (R2) for the voltage injection testing fit results for Spectral channels 1-18, as well as the calibrated reference, shown as channel 0

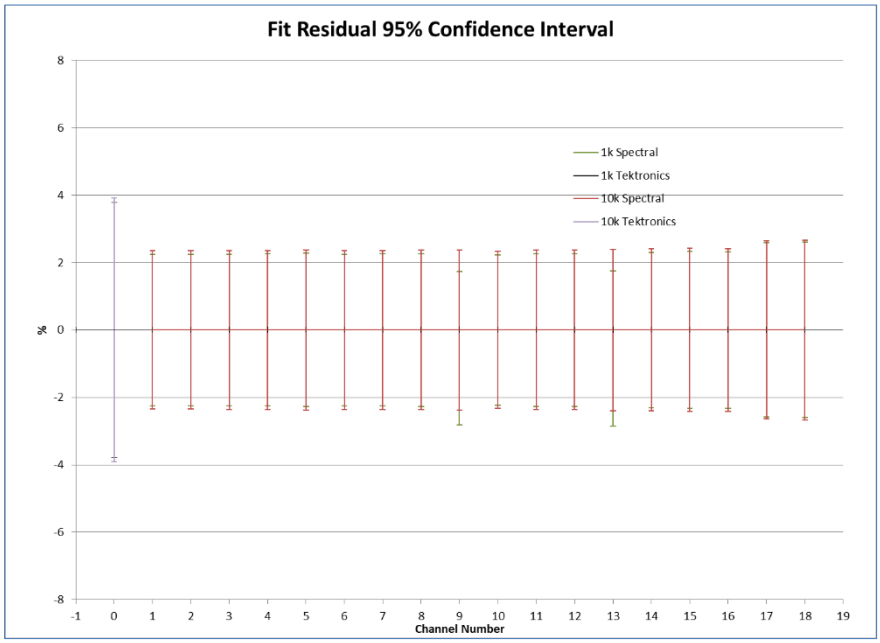

Figure 12: The 95% confidence intervals (%) of the fit residuals for Spectral channels 1-18, as well as the calibrated reference channel zero

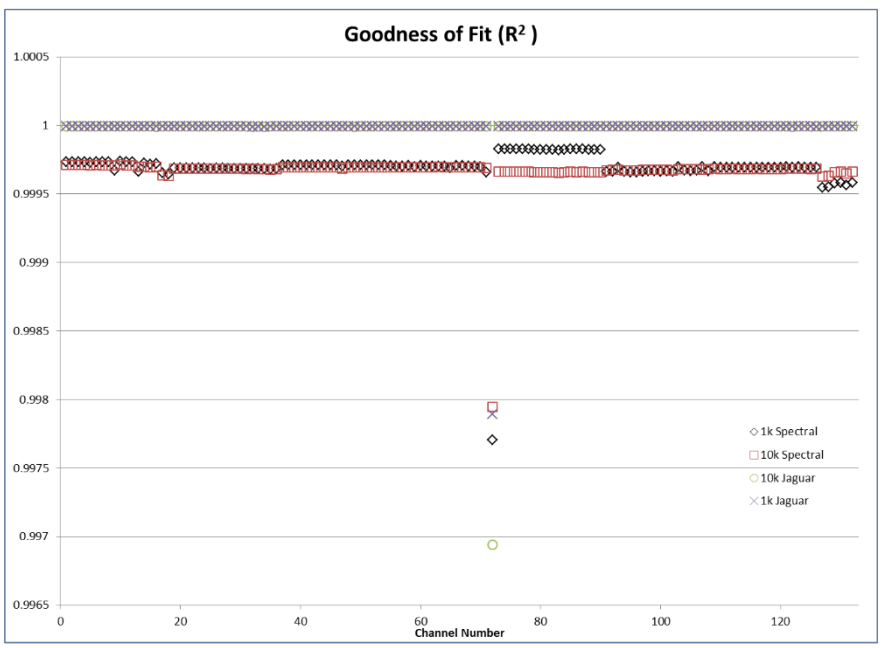

Figure 13: The adjusted goodness of fit (R2) for the voltage injection testing fit results for Spectral and Jaguar data acquisition systems

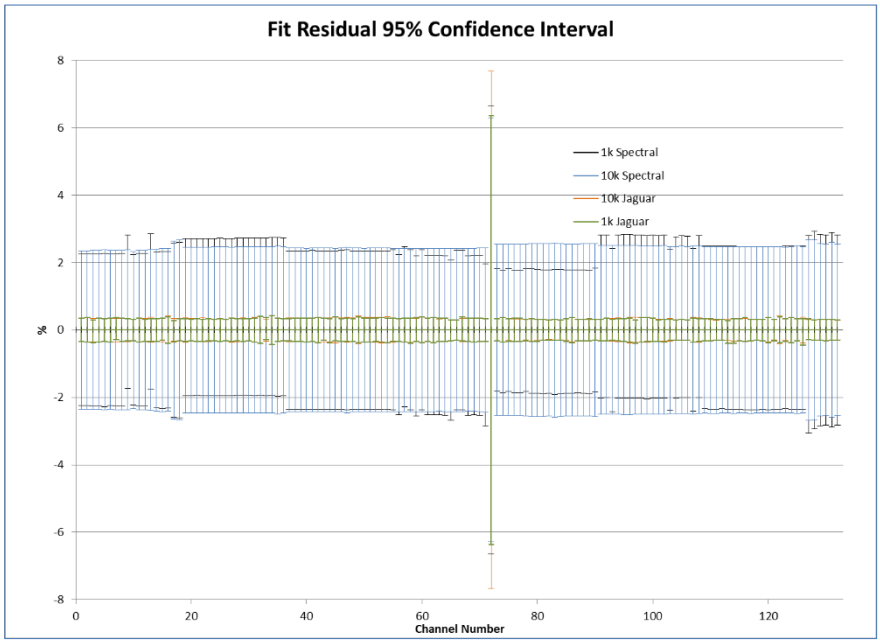

Figure 14:The 95% confidence intervals (%) of the fit residuals for the Spectral and Jaguar systems

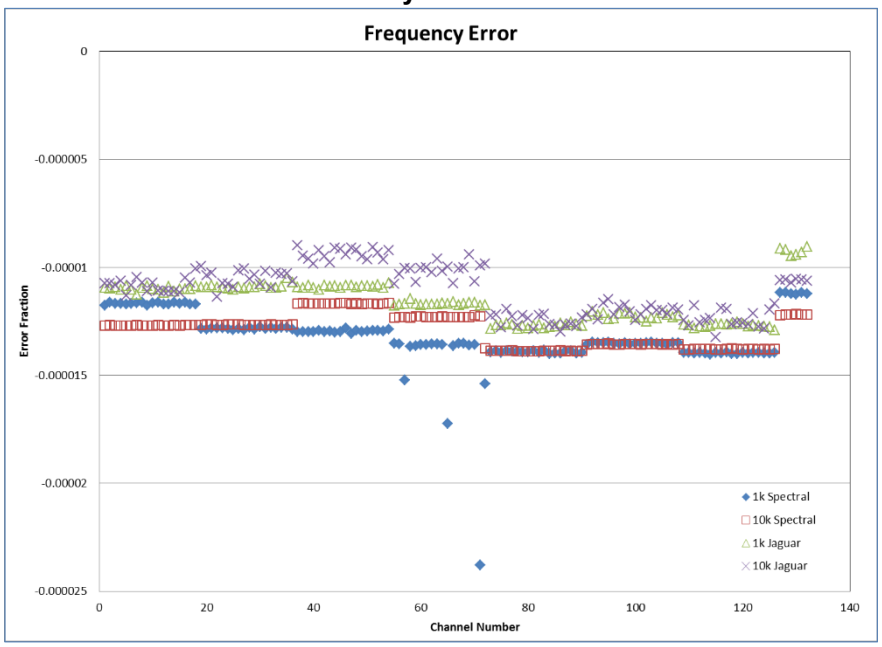

Figure 15: Frequency error fraction for the Spectral and Jaguar data acquisition channels

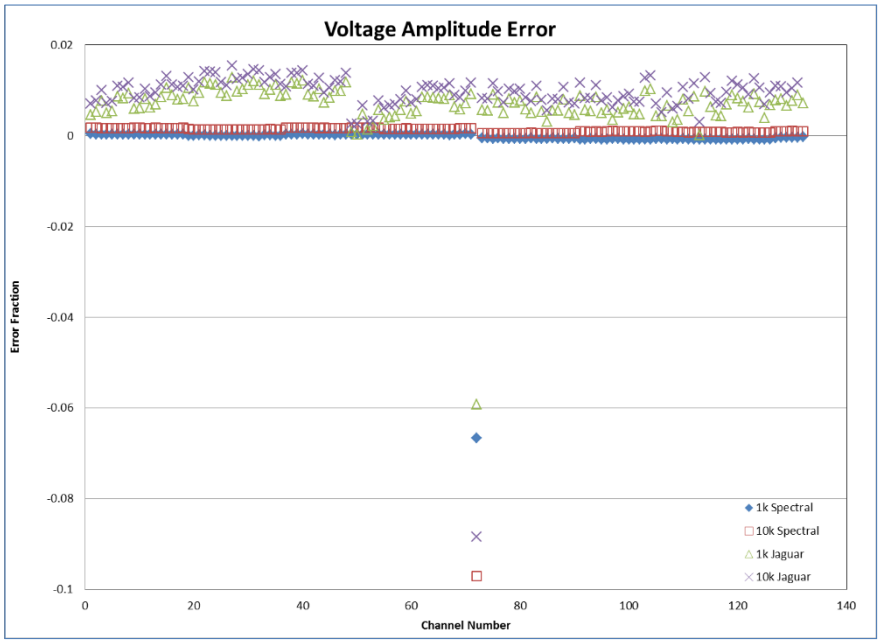

Figure 16:Voltage amplitude error fraction for the Spectral and Jaguar data acquisition channels

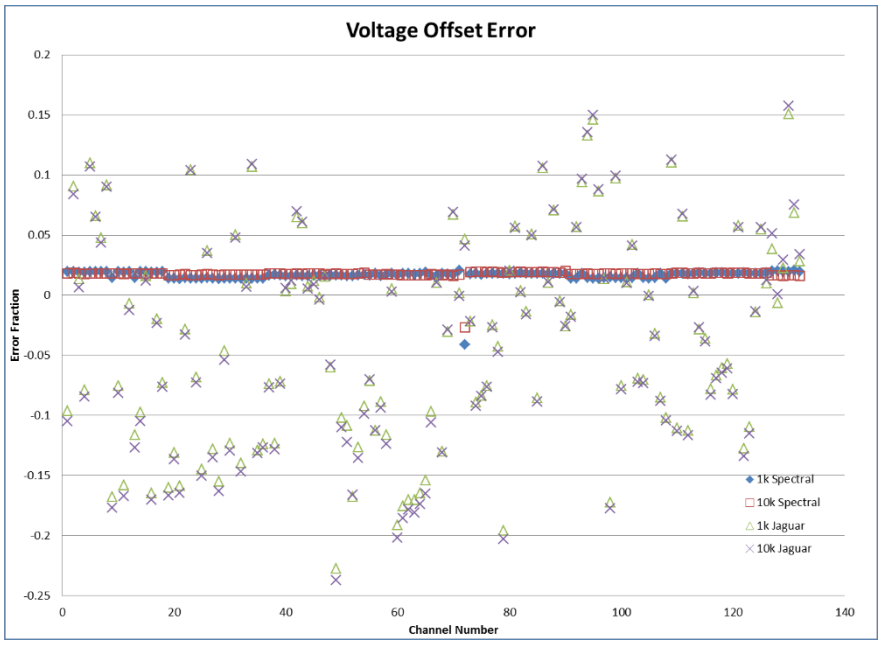

Figure 17: Voltage offset fraction for the Spectral and Jaguar data acquisition channels

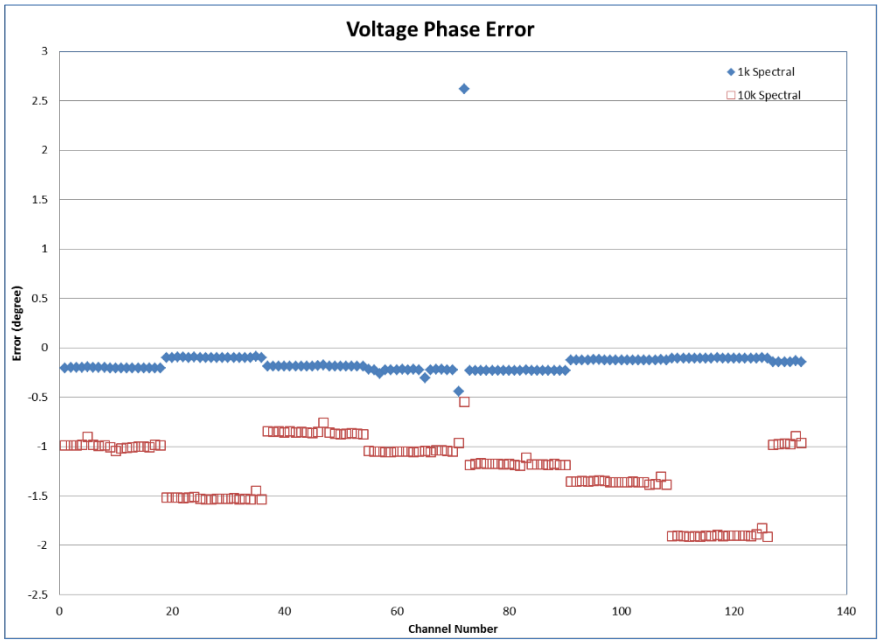

Figure 18:Phase error (degrees) for the Spectral and Jaguar data acquisition channels

Table 5: Voltage sinusoid injection error for Spectral and Jaguar system verification

	1k Spectral				10k Spectral				1k Jaguar			10k Jaguar		
channel	Frequency Error Fraction	Voltage Offset Error Fraction	Voltage Amplitude Error Fraction	Phase Error	Frequency Error Fraction	Voltage Offset Error Fraction	Voltage Amplitude Error Fraction	Phase Error	Frequency Error Fraction	Voltage Offset Error Fraction	Voltage Amplitude Error Fraction	Frequency Error Fraction	Voltage Offset Error Fraction	Voltage Amplitude Error Fraction
1	-1.2E-05	0.020	3.8E-04	-0.21	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	-0.096	4.6E-03	-1.1E-05	-0.105	7.1E-03
2	-1.2E-05	0.020	3.3E-04	-0.20	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	0.090	5.3E-03	-1.1E-05	0.084	7.7E-03
3	-1.2E-05	0.019	3.1E-04	-0.20	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	0.013	7.8E-03	-1.1E-05	0.006	1.0E-02
4	-1.2E-05	0.019	2.8E-04	-0.20	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	-0.079	5.1E-03	-1.1E-05	-0.085	7.1E-03
5	-1.2E-05	0.020	3.0E-04	-0.20	-1.3E-05	0.018	1.6E-03	-0.90	-1.1E-05	0.110	5.4E-03	-1.1E-05	0.107	7.6E-03
6	-1.2E-05	0.020	3.1E-04	-0.20	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	0.066	8.6E-03	-1.1E-05	0.065	1.1E-02
7	-1.2E-05	0.020	2.4E-04	-0.20	-1.3E-05	0.018	1.6E-03	-1.00	-1.1E-05	0.048	8.3E-03	-1.0E-05	0.044	1.1E-02
8	-1.2E-05	0.019	2.8E-04	-0.20	-1.3E-05	0.018	1.6E-03	-0.99	-1.1E-05	0.091	9.3E-03	-1.1E-05	0.090	1.2E-02
9	-1.2E-05	0.014	3.5E-04	-0.21	-1.3E-05	0.018	1.7E-03	-1.01	-1.1E-05	-0.168	5.9E-03	-1.1E-05	-0.177	8.3E-03
10	-1.2E-05	0.020	3.0E-04	-0.21	-1.3E-05	0.018	1.7E-03	-1.05	-1.1E-05	-0.075	6.1E-03	-1.1E-05	-0.081	8.4E-03
11	-1.2E-05	0.019	2.7E-04	-0.21	-1.3E-05	0.018	1.7E-03	-1.02	-1.1E-05	-0.158	8.1E-03	-1.1E-05	-0.167	1.0E-02
12	-1.2E-05	0.019	3.4E-04	-0.21	-1.3E-05	0.018	1.7E-03	-1.01	-1.1E-05	-0.007	6.2E-03	-1.1E-05	-0.013	8.6E-03
13	-1.2E-05	0.014	3.2E-04	-0.21	-1.3E-05	0.018	1.7E-03	-1.01	-1.1E-05	-0.116	6.9E-03	-1.1E-05	-0.127	9.5E-03
14	-1.2E-05	0.020	3.3E-04	-0.21	-1.3E-05	0.018	1.7E-03	-1.00	-1.1E-05	-0.097	8.5E-03	-1.1E-05	-0.105	1.1E-02
15	-1.2E-05	0.019	2.5E-04	-0.21	-1.3E-05	0.018	1.6E-03	-1.01	-1.1E-05	0.016	1.1E-02	-1.1E-05	0.012	1.3E-02
16	-1.2E-05	0.019	3.0E-04	-0.21	-1.3E-05	0.018	1.6E-03	-1.01	-1.1E-05	-0.165	8.9E-03	-1.0E-05	-0.170	1.1E-02
17	-1.2E-05	0.019	3.1E-04	-0.21	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	-0.019	7.9E-03	-1.1E-05	-0.023	1.1E-02
18	-1.2E-05	0.020	3.1E-04	-0.20	-1.3E-05	0.018	1.7E-03	-0.99	-1.1E-05	-0.073	8.1E-03	-1.0E-05	-0.076	1.1E-02
19	-1.3E-05	0.014	6.9E-05	-0.10	-1.3E-05	0.017	1.4E-03	-1.52	-1.1E-05	-0.160	1.1E-02	-9.9E-06	-0.167	1.3E-02
20	-1.3E-05	0.014	-4.0E-06	-0.10	-1.3E-05	0.016	1.4E-03	-1.52	-1.1E-05	-0.131	7.5E-03	-1.0E-05	-0.137	1.0E-02
21	-1.3E-05	0.014	9.2E-05	-0.10	-1.3E-05	0.017	1.3E-03	-1.52	-1.1E-05	-0.159	9.4E-03	-1.0E-05	-0.165	1.2E-02
22	-1.3E-05	0.015	9.0E-05	-0.10	-1.3E-05	0.018	1.4E-03	-1.52	-1.1E-05	-0.029	1.2E-02	-1.1E-05	-0.033	1.4E-02
23	-1.3E-05	0.014	-1.2E-05	-0.10	-1.3E-05	0.017	1.4E-03	-1.52	-1.1E-05	0.105	1.1E-02	-1.1E-05	0.104	1.4E-02

24	-1.3E-05	0.014	-3.7E-05	-0.10	-1.3E-05	0.017	1.3E-03	-1.51	-1.1E-05	-0.068	1.1E-02	-1.1E-05	-0.073	1.4E-02
25	-1.3E-05	0.014	6.3E-05	-0.10	-1.3E-05	0.017	1.4E-03	-1.53	-1.1E-05	-0.145	9.4E-03	-1.1E-05	-0.150	1.2E-02
26	-1.3E-05	0.015	5.2E-05	-0.10	-1.3E-05	0.017	1.4E-03	-1.53	-1.1E-05	0.037	8.8E-03	-1.0E-05	0.035	1.1E-02
27	-1.3E-05	0.014	2.7E-06	-0.10	-1.3E-05	0.017	1.3E-03	-1.54	-1.1E-05	-0.128	1.3E-02	-1.0E-05	-0.135	1.5E-02
28	-1.3E-05	0.014	-1.8E-05	-0.10	-1.3E-05	0.017	1.3E-03	-1.53	-1.1E-05	-0.155	9.8E-03	-1.1E-05	-0.163	1.2E-02
29	-1.3E-05	0.014	2.0E-05	-0.10	-1.3E-05	0.017	1.3E-03	-1.53	-1.1E-05	-0.046	1.0E-02	-1.0E-05	-0.054	1.3E-02
30	-1.3E-05	0.014	8.0E-05	-0.10	-1.3E-05	0.017	1.4E-03	-1.53	-1.1E-05	-0.123	1.1E-02	-1.1E-05	-0.129	1.4E-02
31	-1.3E-05	0.014	4.1E-05	-0.10	-1.3E-05	0.017	1.3E-03	-1.52	-1.1E-05	0.050	1.2E-02	-1.0E-05	0.048	1.5E-02
32	-1.3E-05	0.014	-5.8E-05	-0.10	-1.3E-05	0.017	1.3E-03	-1.54	-1.1E-05	-0.140	1.1E-02	-1.1E-05	-0.147	1.4E-02
33	-1.3E-05	0.014	1.1E-04	-0.10	-1.3E-05	0.017	1.4E-03	-1.53	-1.1E-05	0.010	9.2E-03	-1.0E-05	0.007	1.2E-02
34	-1.3E-05	0.014	2.0E-04	-0.10	-1.3E-05	0.017	1.5E-03	-1.54	-1.1E-05	0.107	1.0E-02	-1.0E-05	0.109	1.3E-02
35	-1.3E-05	0.014	8.2E-05	-0.09	-1.3E-05	0.017	1.3E-03	-1.45	-1.0E-05	-0.129	1.1E-02	-1.0E-05	-0.132	1.4E-02
36	-1.3E-05	0.014	7.2E-05	-0.10	-1.3E-05	0.017	1.4E-03	-1.54	-1.1E-05	-0.124	8.9E-03	-1.1E-05	-0.127	1.1E-02
37	-1.3E-05	0.016	3.5E-04	-0.19	-1.2E-05	0.018	1.8E-03	-0.85	-1.1E-05	-0.074	9.0E-03	-9.0E-06	-0.077	1.1E-02
38	-1.3E-05	0.017	3.3E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.85	-1.1E-05	-0.123	1.2E-02	-9.5E-06	-0.128	1.4E-02
39	-1.3E-05	0.016	3.5E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.85	-1.1E-05	-0.072	1.2E-02	-9.6E-06	-0.074	1.4E-02
40	-1.3E-05	0.016	3.7E-04	-0.19	-1.2E-05	0.018	1.8E-03	-0.86	-1.1E-05	0.003	1.2E-02	-9.8E-06	0.006	1.4E-02
41	-1.3E-05	0.016	3.0E-04	-0.19	-1.2E-05	0.018	1.8E-03	-0.85	-1.1E-05	0.009	9.1E-03	-9.2E-06	0.012	1.1E-02
42	-1.3E-05	0.017	3.2E-04	-0.19	-1.2E-05	0.018	1.8E-03	-0.86	-1.1E-05	0.065	8.7E-03	-9.5E-06	0.070	1.1E-02
43	-1.3E-05	0.016	2.5E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.86	-1.1E-05	0.060	1.0E-02	-9.8E-06	0.061	1.3E-02
44	-1.3E-05	0.016	2.9E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.86	-1.1E-05	0.007	7.4E-03	-9.1E-06	0.005	9.5E-03
45	-1.3E-05	0.016	2.9E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.87	-1.1E-05	0.012	8.5E-03	-9.2E-06	0.009	1.1E-02
46	-1.3E-05	0.017	2.2E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.85	-1.1E-05	-0.002	9.9E-03	-9.4E-06	-0.004	1.2E-02
47	-1.3E-05	0.016	2.4E-04	-0.18	-1.2E-05	0.017	1.6E-03	-0.76	-1.1E-05	0.016	9.9E-03	-9.1E-06	0.017	1.2E-02
48	-1.3E-05	0.016	2.4E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.86	-1.1E-05	-0.060	1.2E-02	-9.2E-06	-0.058	1.4E-02
49	-1.3E-05	0.016	2.9E-04	-0.19	-1.2E-05	0.018	1.8E-03	-0.87	-1.1E-05	-0.227	8.6E-04	-9.5E-06	-0.237	2.6E-03
50	-1.3E-05	0.017	2.9E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.88	-1.1E-05	-0.102	2.8E-04	-9.6E-06	-0.110	2.6E-03
51	-1.3E-05	0.016	2.7E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.87	-1.1E-05	-0.109	4.7E-03	-9.1E-06	-0.122	6.6E-03
52	-1.3E-05	0.016	3.0E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.87	-1.1E-05	-0.168	1.3E-03	-9.3E-06	-0.166	3.1E-03
53	-1.3E-05	0.016	2.7E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.88	-1.1E-05	-0.126	2.1E-03	-9.6E-06	-0.136	3.3E-03

54	-1.3E-05	0.017	2.7E-04	-0.19	-1.2E-05	0.018	1.7E-03	-0.88	-1.1E-05	-0.092	5.7E-03	-9.2E-06	-0.099	7.7E-03
55	-1.4E-05	0.017	2.3E-04	-0.22	-1.2E-05	0.017	1.6E-03	-1.04	-1.2E-05	-0.071	3.6E-03	-1.1E-05	-0.070	6.1E-03
56	-1.4E-05	0.018	2.4E-04	-0.22	-1.2E-05	0.017	1.6E-03	-1.05	-1.2E-05	-0.113	4.0E-03	-1.0E-05	-0.113	6.6E-03
57	-1.5E-05	0.016	2.5E-04	-0.26	-1.2E-05	0.017	1.6E-03	-1.05	-1.2E-05	-0.089	4.3E-03	-1.0E-05	-0.094	6.8E-03
58	-1.4E-05	0.017	3.4E-04	-0.23	-1.2E-05	0.018	1.6E-03	-1.06	-1.1E-05	-0.116	5.7E-03	-1.0E-05	-0.124	8.0E-03
59	-1.4E-05	0.018	3.1E-04	-0.22	-1.2E-05	0.017	1.6E-03	-1.06	-1.2E-05	0.005	7.5E-03	-1.1E-05	0.003	1.0E-02
60	-1.4E-05	0.016	2.5E-04	-0.22	-1.2E-05	0.017	1.6E-03	-1.06	-1.2E-05	-0.191	4.8E-03	-1.0E-05	-0.202	7.3E-03
61	-1.4E-05	0.018	2.5E-04	-0.22	-1.2E-05	0.017	1.6E-03	-1.05	-1.2E-05	-0.176	5.4E-03	-1.0E-05	-0.185	8.0E-03
62	-1.4E-05	0.018	2.5E-04	-0.22	-1.2E-05	0.017	1.5E-03	-1.05	-1.2E-05	-0.171	8.5E-03	-1.0E-05	-0.178	1.1E-02
63	-1.4E-05	0.018	2.6E-04	-0.22	-1.2E-05	0.017	1.5E-03	-1.06	-1.2E-05	-0.170	8.6E-03	-9.6E-06	-0.181	1.1E-02
64	-1.4E-05	0.018	2.6E-04	-0.22	-1.2E-05	0.016	1.5E-03	-1.05	-1.2E-05	-0.165	8.5E-03	-1.0E-05	-0.174	1.1E-02
65	-1.7E-05	0.019	2.9E-04	-0.30	-1.2E-05	0.016	1.5E-03	-1.05	-1.2E-05	-0.154	8.3E-03	-1.0E-05	-0.165	1.0E-02
66	-1.4E-05	0.017	2.4E-04	-0.23	-1.2E-05	0.017	1.6E-03	-1.06	-1.2E-05	-0.097	8.2E-03	-1.1E-05	-0.106	1.1E-02
67	-1.4E-05	0.016	2.2E-04	-0.22	-1.2E-05	0.017	1.5E-03	-1.04	-1.2E-05	0.011	9.0E-03	-1.0E-05	0.010	1.2E-02
68	-1.4E-05	0.018	2.3E-04	-0.22	-1.2E-05	0.017	1.5E-03	-1.04	-1.2E-05	-0.130	6.3E-03	-1.0E-05	-0.131	9.0E-03
69	-1.4E-05	0.018	2.6E-04	-0.22	-1.2E-05	0.017	1.6E-03	-1.04	-1.2E-05	-0.031	5.8E-03	-9.4E-06	-0.029	8.3E-03
70	-1.4E-05	0.017	3.7E-04	-0.23	-1.2E-05	0.016	1.7E-03	-1.05	-1.2E-05	0.067	7.3E-03	-1.1E-05	0.069	9.9E-03
71	-2.4E-05	0.021	2.3E-04	-0.44	-1.2E-05	0.017	1.6E-03	-0.97	-1.2E-05	0.002	9.2E-03	-9.9E-06	-0.001	1.2E-02
72	-1.5E-05	-0.041	-6.7E-02	2.62	-1.4E-05	-0.027	-9.7E-02	-0.55	-1.2E-05	0.047	-5.9E-02	-9.8E-06	0.041	-8.8E-02
73	-1.4E-05	0.018	-5.8E-04	-0.23	-1.4E-05	0.019	6.1E-04	-1.19	-1.3E-05	-0.022	5.7E-03	-1.2E-05	-0.022	8.2E-03
74	-1.4E-05	0.018	-5.3E-04	-0.23	-1.4E-05	0.020	6.0E-04	-1.17	-1.3E-05	-0.089	5.5E-03	-1.2E-05	-0.092	8.1E-03
75	-1.4E-05	0.017	-6.4E-04	-0.23	-1.4E-05	0.019	6.1E-04	-1.17	-1.3E-05	-0.084	9.0E-03	-1.3E-05	-0.084	1.1E-02
76	-1.4E-05	0.018	-5.8E-04	-0.23	-1.4E-05	0.019	6.0E-04	-1.18	-1.3E-05	-0.076	7.3E-03	-1.2E-05	-0.076	9.8E-03
77	-1.4E-05	0.018	-6.3E-04	-0.23	-1.4E-05	0.019	5.6E-04	-1.18	-1.3E-05	-0.025	5.0E-03	-1.2E-05	-0.027	7.4E-03
78	-1.4E-05	0.018	-5.9E-04	-0.23	-1.4E-05	0.019	6.2E-04	-1.18	-1.3E-05	-0.043	8.1E-03	-1.3E-05	-0.047	1.0E-02
79	-1.4E-05	0.018	-6.0E-04	-0.23	-1.4E-05	0.019	5.4E-04	-1.18	-1.3E-05	-0.196	7.3E-03	-1.2E-05	-0.203	9.8E-03
80	-1.4E-05	0.018	-6.9E-04	-0.23	-1.4E-05	0.019	5.6E-04	-1.18	-1.3E-05	0.021	7.7E-03	-1.2E-05	0.020	1.0E-02
81	-1.4E-05	0.018	-6.3E-04	-0.23	-1.4E-05	0.019	6.2E-04	-1.19	-1.3E-05	0.058	5.8E-03	-1.3E-05	0.056	8.4E-03
82	-1.4E-05	0.019	-5.9E-04	-0.23	-1.4E-05	0.019	6.6E-04	-1.19	-1.3E-05	0.004	5.0E-03	-1.2E-05	0.002	7.6E-03
83	-1.4E-05	0.018	-6.5E-04	-0.22	-1.4E-05	0.019	5.4E-04	-1.11	-1.3E-05	-0.013	8.6E-03	-1.2E-05	-0.016	1.1E-02

84	-1.4E-05	0.018	-6.9E-04	-0.23	-1.4E-05	0.019	5.8E-04	-1.19	-1.3E-05	0.051	5.3E-03	-1.3E-05	0.050	7.9E-03
85	-1.4E-05	0.018	-6.5E-04	-0.23	-1.4E-05	0.019	5.5E-04	-1.18	-1.3E-05	-0.086	3.2E-03	-1.3E-05	-0.089	5.6E-03
86	-1.4E-05	0.018	-5.7E-04	-0.23	-1.4E-05	0.020	5.9E-04	-1.18	-1.3E-05	0.106	5.6E-03	-1.3E-05	0.107	8.1E-03
87	-1.4E-05	0.018	-6.7E-04	-0.23	-1.4E-05	0.019	5.6E-04	-1.19	-1.3E-05	0.011	5.6E-03	-1.3E-05	0.011	8.0E-03
88	-1.4E-05	0.018	-6.7E-04	-0.23	-1.4E-05	0.019	5.2E-04	-1.18	-1.3E-05	0.071	8.0E-03	-1.3E-05	0.071	1.1E-02
89	-1.4E-05	0.018	-6.1E-04	-0.24	-1.4E-05	0.019	6.1E-04	-1.19	-1.3E-05	-0.005	5.1E-03	-1.3E-05	-0.006	7.4E-03
90	-1.4E-05	0.018	-5.6E-04	-0.23	-1.4E-05	0.020	6.0E-04	-1.19	-1.3E-05	-0.026	4.7E-03	-1.2E-05	-0.026	7.1E-03
91	-1.4E-05	0.014	-7.9E-04	-0.13	-1.4E-05	0.018	9.5E-04	-1.36	-1.2E-05	-0.016	8.8E-03	-1.2E-05	-0.018	1.2E-02
92	-1.3E-05	0.014	-7.9E-04	-0.12	-1.4E-05	0.018	9.7E-04	-1.36	-1.2E-05	0.057	5.7E-03	-1.2E-05	0.056	8.2E-03
93	-1.4E-05	0.018	-7.2E-04	-0.13	-1.4E-05	0.018	9.0E-04	-1.35	-1.2E-05	0.094	5.5E-03	-1.2E-05	0.097	8.2E-03
94	-1.4E-05	0.015	-6.8E-04	-0.12	-1.4E-05	0.018	9.9E-04	-1.36	-1.2E-05	0.133	8.5E-03	-1.2E-05	0.135	1.1E-02
95	-1.3E-05	0.014	-7.7E-04	-0.12	-1.4E-05	0.017	8.9E-04	-1.35	-1.2E-05	0.146	5.0E-03	-1.1E-05	0.150	7.8E-03
96	-1.4E-05	0.014	-7.9E-04	-0.12	-1.4E-05	0.018	9.1E-04	-1.35	-1.2E-05	0.087	5.8E-03	-1.2E-05	0.088	8.4E-03
97	-1.4E-05	0.014	-5.9E-04	-0.12	-1.4E-05	0.018	1.1E-03	-1.35	-1.2E-05	0.014	3.5E-03	-1.2E-05	0.014	6.2E-03
98	-1.3E-05	0.015	-7.0E-04	-0.12	-1.4E-05	0.018	9.4E-04	-1.36	-1.2E-05	-0.172	5.2E-03	-1.2E-05	-0.177	7.7E-03
99	-1.4E-05	0.015	-8.0E-04	-0.13	-1.4E-05	0.018	9.0E-04	-1.37	-1.2E-05	0.097	6.0E-03	-1.2E-05	0.099	8.7E-03
100	-1.4E-05	0.015	-7.6E-04	-0.13	-1.4E-05	0.018	9.7E-04	-1.36	-1.2E-05	-0.075	6.4E-03	-1.2E-05	-0.079	9.2E-03
101	-1.4E-05	0.015	-8.2E-04	-0.13	-1.4E-05	0.018	9.1E-04	-1.37	-1.2E-05	0.011	4.8E-03	-1.2E-05	0.010	7.5E-03
102	-1.3E-05	0.015	-8.1E-04	-0.13	-1.4E-05	0.018	9.2E-04	-1.36	-1.3E-05	0.042	4.8E-03	-1.2E-05	0.041	7.5E-03
103	-1.3E-05	0.018	-7.7E-04	-0.13	-1.4E-05	0.018	8.9E-04	-1.36	-1.2E-05	-0.069	9.9E-03	-1.2E-05	-0.072	1.3E-02
104	-1.4E-05	0.015	-7.9E-04	-0.12	-1.4E-05	0.018	9.2E-04	-1.37	-1.2E-05	-0.070	1.0E-02	-1.2E-05	-0.073	1.3E-02
105	-1.4E-05	0.014	-7.1E-04	-0.13	-1.4E-05	0.018	1.0E-03	-1.39	-1.2E-05	0.000	4.4E-03	-1.2E-05	-0.001	7.0E-03
106	-1.4E-05	0.015	-7.0E-04	-0.13	-1.4E-05	0.018	1.1E-03	-1.38	-1.2E-05	-0.032	4.4E-03	-1.2E-05	-0.034	5.2E-03
107	-1.3E-05	0.018	-7.4E-04	-0.12	-1.4E-05	0.018	9.5E-04	-1.31	-1.2E-05	-0.085	6.7E-03	-1.2E-05	-0.088	9.5E-03
108	-1.4E-05	0.014	-7.2E-04	-0.13	-1.4E-05	0.018	9.9E-04	-1.39	-1.2E-05	-0.102	3.0E-03	-1.2E-05	-0.105	5.9E-03
109	-1.4E-05	0.018	-7.3E-04	-0.11	-1.4E-05	0.018	8.3E-04	-1.91	-1.3E-05	0.111	3.5E-03	-1.2E-05	0.112	6.6E-03
110	-1.4E-05	0.018	-7.1E-04	-0.11	-1.4E-05	0.019	8.3E-04	-1.90	-1.3E-05	-0.111	8.0E-03	-1.3E-05	-0.113	1.1E-02
111	-1.4E-05	0.018	-7.8E-04	-0.11	-1.4E-05	0.018	7.6E-04	-1.91	-1.3E-05	0.066	5.4E-03	-1.2E-05	0.067	8.2E-03
112	-1.4E-05	0.018	-7.4E-04	-0.11	-1.4E-05	0.018	8.1E-04	-1.92	-1.3E-05	-0.112	8.6E-03	-1.3E-05	-0.117	1.2E-02
113	-1.4E-05	0.018	-7.6E-04	-0.11	-1.4E-05	0.018	8.2E-04	-1.91	-1.3E-05	0.002	1.7E-04	-1.2E-05	0.004	3.0E-03

114	-1.4E-05	0.018	-7.3E-04	-0.11	-1.4E-05	0.019	8.7E-04	-1.92	-1.3E-05	-0.029	9.8E-03	-1.2E-05	-0.027	1.3E-02
115	-1.4E-05	0.018	-8.1E-04	-0.11	-1.4E-05	0.018	7.9E-04	-1.91	-1.3E-05	-0.036	6.3E-03	-1.3E-05	-0.039	9.4E-03
116	-1.4E-05	0.018	-7.7E-04	-0.11	-1.4E-05	0.018	8.2E-04	-1.91	-1.3E-05	-0.078	4.5E-03	-1.2E-05	-0.083	7.5E-03
117	-1.4E-05	0.018	-7.8E-04	-0.10	-1.4E-05	0.018	8.0E-04	-1.89	-1.3E-05	-0.067	4.3E-03	-1.2E-05	-0.069	7.2E-03
118	-1.4E-05	0.019	-8.4E-04	-0.11	-1.4E-05	0.019	7.4E-04	-1.91	-1.3E-05	-0.061	6.9E-03	-1.3E-05	-0.064	9.7E-03
119	-1.4E-05	0.018	-7.9E-04	-0.11	-1.4E-05	0.018	7.6E-04	-1.90	-1.3E-05	-0.057	9.0E-03	-1.3E-05	-0.061	1.2E-02
120	-1.4E-05	0.018	-7.9E-04	-0.11	-1.4E-05	0.018	7.7E-04	-1.91	-1.3E-05	-0.079	8.3E-03	-1.3E-05	-0.083	1.1E-02
121	-1.4E-05	0.018	-8.2E-04	-0.11	-1.4E-05	0.018	7.5E-04	-1.90	-1.3E-05	0.058	7.7E-03	-1.3E-05	0.056	1.1E-02
122	-1.4E-05	0.018	-7.1E-04	-0.11	-1.4E-05	0.019	8.0E-04	-1.90	-1.3E-05	-0.127	6.2E-03	-1.2E-05	-0.134	9.1E-03
123	-1.4E-05	0.018	-8.3E-04	-0.11	-1.4E-05	0.018	7.1E-04	-1.91	-1.3E-05	-0.110	9.2E-03	-1.3E-05	-0.115	1.3E-02
124	-1.4E-05	0.018	-8.2E-04	-0.11	-1.4E-05	0.018	7.6E-04	-1.89	-1.3E-05	-0.014	7.5E-03	-1.3E-05	-0.014	1.1E-02
125	-1.4E-05	0.018	-8.3E-04	-0.10	-1.4E-05	0.018	7.1E-04	-1.83	-1.3E-05	0.055	3.9E-03	-1.2E-05	0.056	6.9E-03
126	-1.4E-05	0.018	-7.8E-04	-0.11	-1.4E-05	0.019	7.6E-04	-1.91	-1.3E-05	0.010	6.8E-03	-1.2E-05	0.013	9.5E-03
127	-1.1E-05	0.020	-5.5E-04	-0.14	-1.2E-05	0.016	9.4E-04	-0.98	-9.1E-06	0.039	7.8E-03	-1.1E-05	0.051	1.1E-02
128	-1.1E-05	0.020	-4.2E-04	-0.14	-1.2E-05	0.016	1.0E-03	-0.98	-9.2E-06	-0.007	8.1E-03	-1.1E-05	0.001	1.1E-02
129	-1.1E-05	0.020	-4.3E-04	-0.14	-1.2E-05	0.016	1.0E-03	-0.97	-9.5E-06	0.023	6.7E-03	-1.1E-05	0.029	9.5E-03
130	-1.1E-05	0.020	-3.4E-04	-0.14	-1.2E-05	0.016	1.1E-03	-0.98	-9.4E-06	0.151	7.7E-03	-1.1E-05	0.158	1.0E-02
131	-1.1E-05	0.021	-4.5E-04	-0.14	-1.2E-05	0.017	1.0E-03	-0.90	-9.3E-06	0.069	8.9E-03	-1.1E-05	0.075	1.2E-02
132	-1.1E-05	0.020	-3.0E-04	-0.14	-1.2E-05	0.016	9.9E-04	-0.97	-9.0E-06	0.028	7.2E-03	-1.1E-05	0.034	1.0E-02

The voltage input test verified the operation of each Spectral and Jaguar channel at two discrete frequencies: 1kHz and 10kHz. The two chosen frequencies were the most relevant for the structural response data collected at LIHE; however, the ability to measure higher frequency content is also valuable (for example to determine whether an accelerometer has resonated). Therefore, a single Spectral channel was injected with higher frequency sinusoidal voltages to explore the system response as a function of frequency. A 250kHz voltage measurement, sinusoidal least squares fit, and the fit residuals are shown in Figure 19. The response of Spectral channel 3 relative to a calibrated Tektronix reference is shown in Figure 20, revealing the voltage amplitude error fraction, voltage offset error fraction, and frequency error fraction as a function of frequency. Up to 250kHz, little degradation occurs.

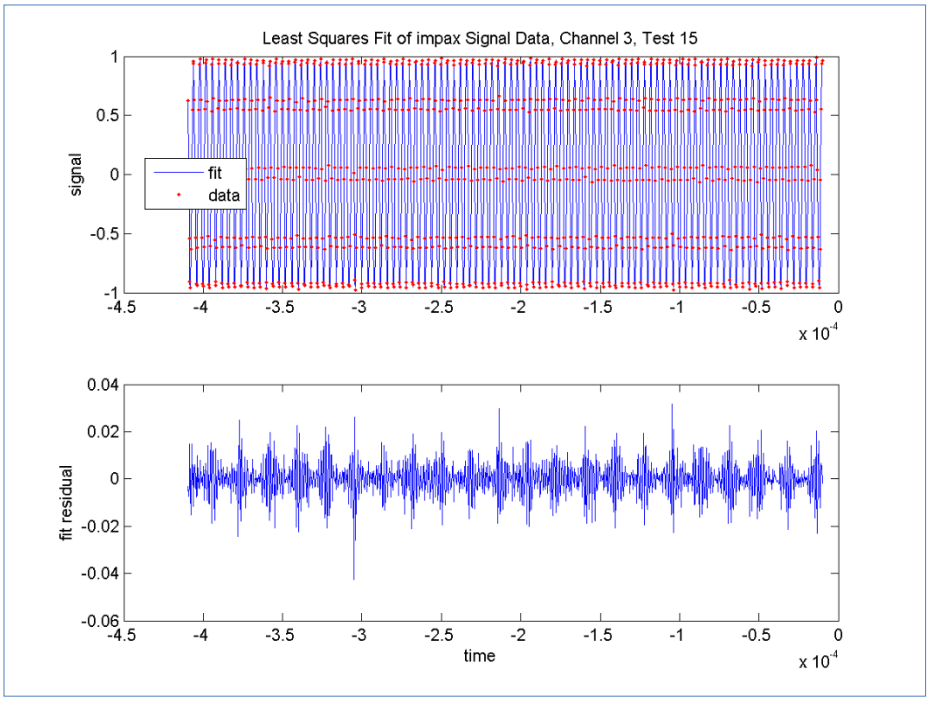

Figure 19: 250kHz sinusoidal voltage measurement data, sinusoidal fit, and fit residuals for Spectral channel 3

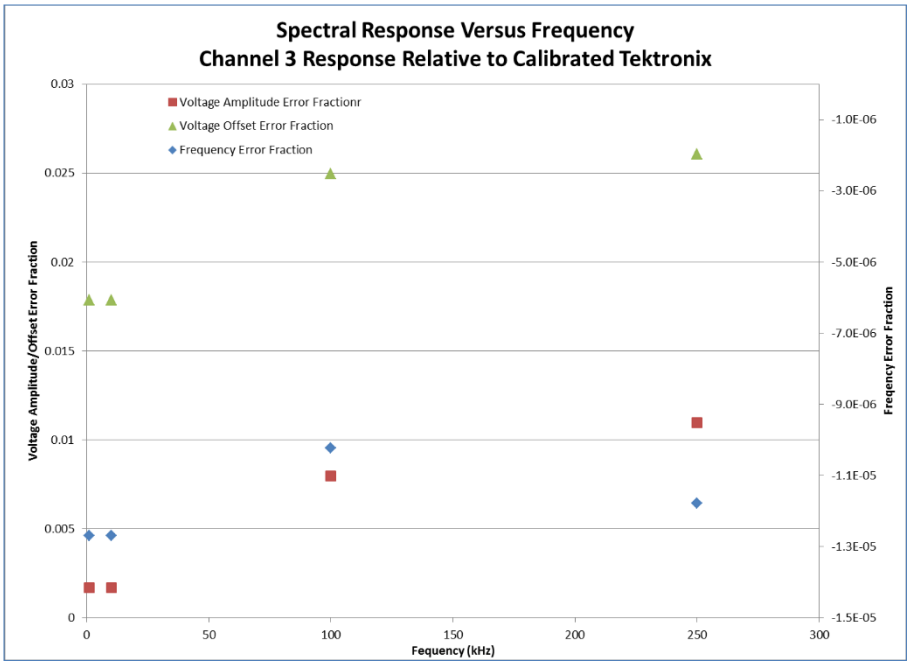

Figure 20: Spectral response to varying frequency, channel 3 response relative to calibrated Tektronix

4.1.7. Details (Step 7)

<u>MAP requirement: The time synchronization of the data acquisition system will result in a phase error of less than 10° at 10kHz (2.8E-6 seconds).</u>

<u>MAP requirement: Instrumentation system will recover from capacitor bank discharge noise to within 5% of band edge (assuming band edge of 60kG acceleration or 5000 microstrain) within 50 µs.</u>

Testing at LIHE utilizes the discharge of a high voltage capacitor bank. Such a discharge can generate significant electromagnetic noise environment. If the noise from the bank discharge persists, it has the potential to contaminate the data measurements. For structural response tests, the structure requires a finite time to respond to the mechanical shock environment. The MAP defines the required DAS recovery time as 50µs from bank discharge initiation. Noise recovery by this time will have minimal effect on the structural response measurements.

A noise test fixture with 4 faces, a total of 60 Vishay strain gages, and 56 Endevco 7270-60K accelerometers mounted to aluminum 4’ x 4’ x 24” long square tubing is shown in Figure 21. This test fixture was placed on the ground in the test cell near the large bank and was exposed to EMI/RFI noise during bank discharge. The remaining 16 DAS channels have resistors installed to approximate strain gauges. Note: this fixture has been used repeatedly, resulting in several gauges failing on the fixture. These failed gauges have been replaced with resistors in the patch panel to approximate strain gauges.

Using this noise fixture, a noise immunity test was conducted. For this test, in order to intentionally maximize noise contamination of this DAS, no electromagnetic noise shielding was employed. The purpose of this test was to verify the immunity of the DAS to upsets caused by

electromagnetic noise. The DAS successfully recorded and stored data during this maximized noise event.

Following the immunity test, a noise recovery test was conducted using the noise fixture. In the recovery test, noise mitigation strategies were employed to meet the MAP requirement of noise recovery. In addition, the capacitor bank discharge noise pulse provided a timing fiducial to verify the time synchronization of the DAS.

The capacitor bank was discharged, resulting in a large input into the data; however, this electromagnetic noise typically dissipated before the 50µs time requirement. A MATLAB program was written to identify the onset of noise above a threshold (t_o). The data was evaluated at t_o+50µs. **Note: all evaluations were performed using unfiltered data.** Figure 22 shows the noise recovery for Spectral channel 3. The data was evaluated for the maximum value (absolute) occurring after t_o+50µs as shown in Figure 23. A fast Fourier transform (FFT) is shown in Figure 24 for the channel 3 data measured after t_o+50µs.

Figure 21:Noise fixture with 60 strain gauges and 60 accelerometers to characterize noise response and recovery

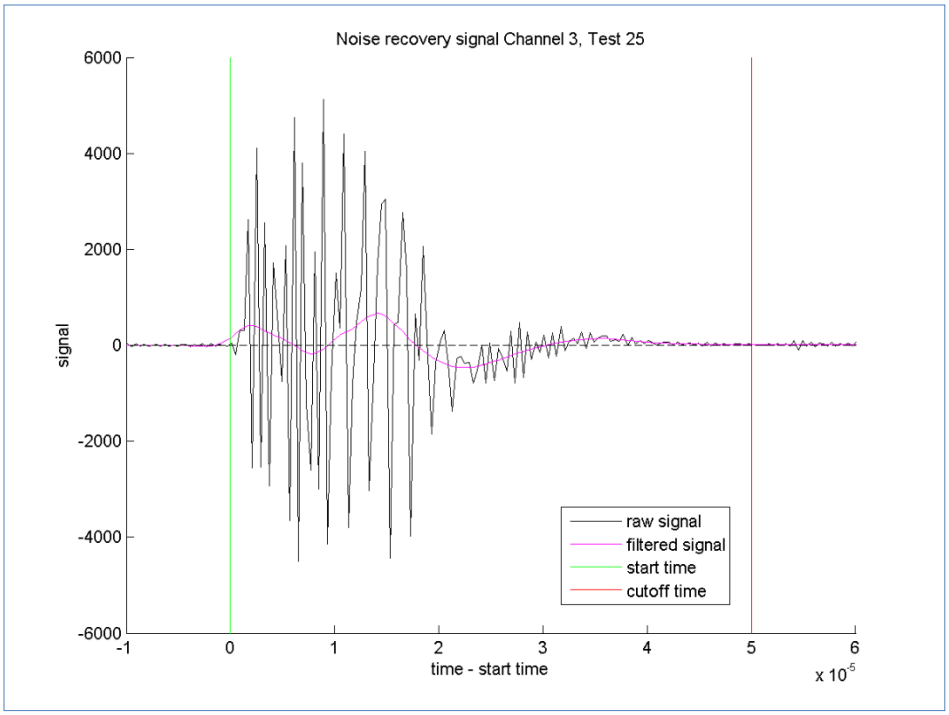

Figure 22: Noise recovery test for channel 3 of the Spectral system. The noise levels were evaluated at 50µs

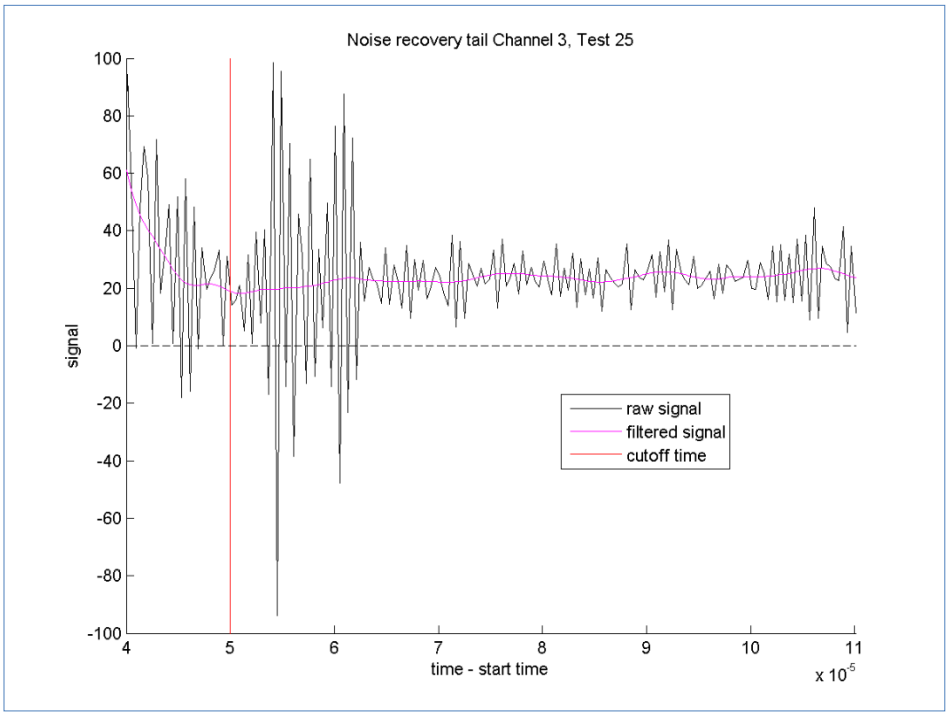

Figure 23: Noise recovery data for Spectral channel 3 beyond t0+50µs

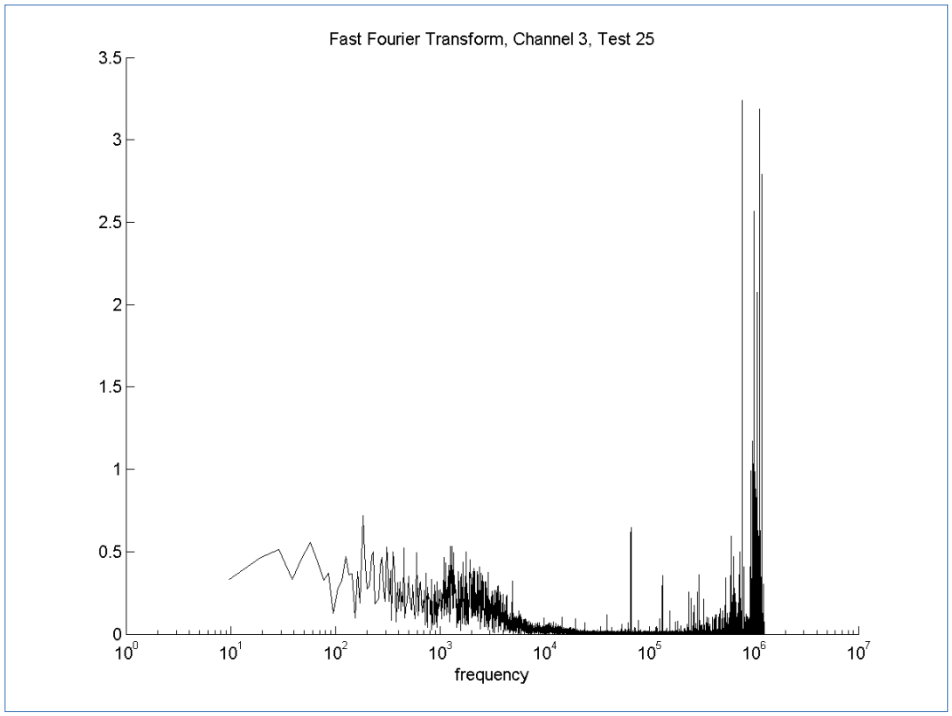

Figure 24: FFT of noise recovery data beyond t0+50µs for Spectral channel 3

Excluding channel 72, the worst noise recovery measurement was 74 (kG or µstrain) at 50µs as shown in Figure 25. This clearly meets the MAP requirement of 5% band edge. Band edge is assumed to be 5000µstrain or 180kG, depending upon the measurement type. The maximum value could occur after 50µs as shown in Figure 23. Figure 26 shows the maximum (absolute) measurement occurring after 50µs was 229 (kG or µstrain). This result also satisfies the 5% noise recovery requirement.

The 95% confidence interval was calculated for the noise data measured after t_0+50µs as shown in Figure 27. Finally, the time synchronization error was calculated for every Spectral channel using the onset of bank noise as the timing fiducial. The maximum time synchronization error was 2.6µs as shown in Figure 28. Although this result satisfies the MAP requirement, this timing error is greater than the error indicated in the sinusoid voltage test. Upon closer examination of the data, the timing error is significantly affected by the channel's susceptibility to noise. The time synchronization error shown in Figure 28 is dominated by using the noise as the fiducial.

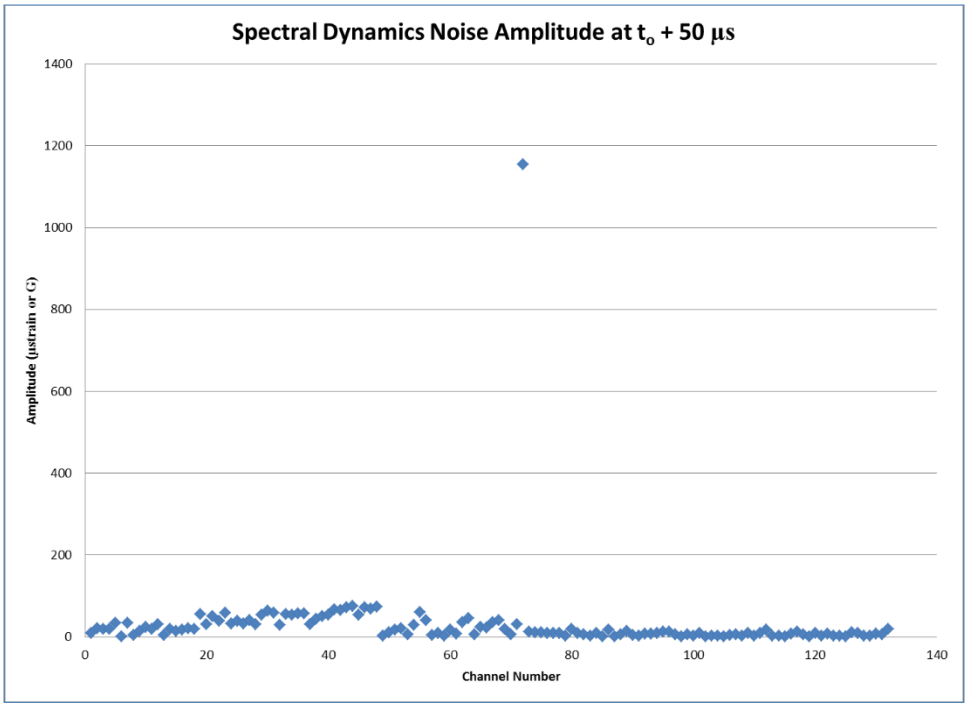

Figure 25: Measured noise at 50µs for every Spectral channel

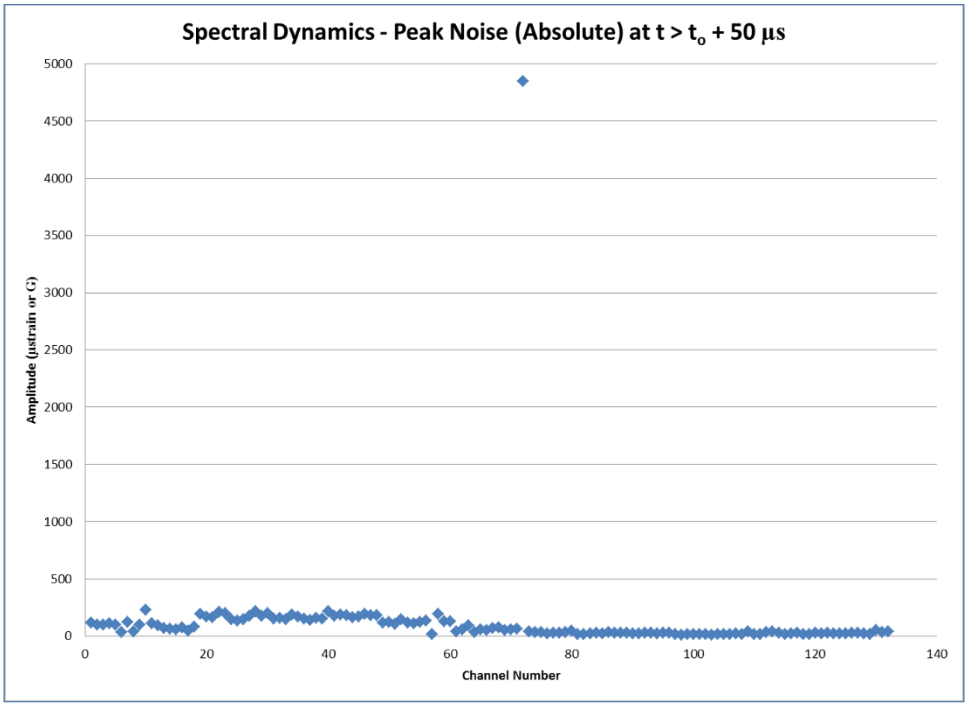

Figure 26: Maximum data (absolute) measured after to+50µs for every Spectral channel

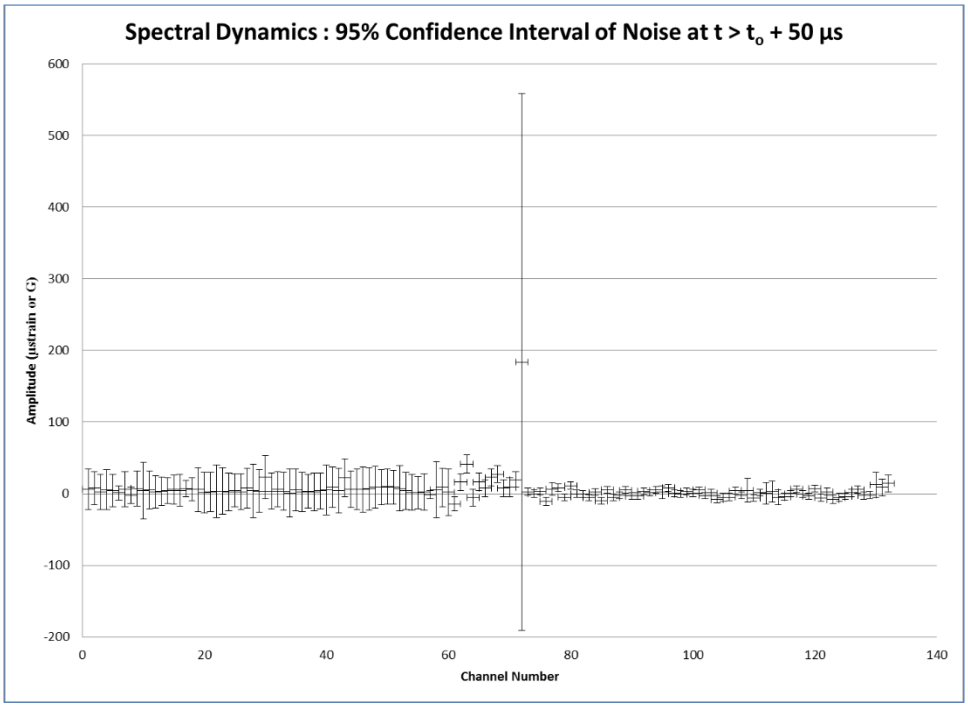

Figure 27: 95% confidence interval of data measured after to+50µs for every Spectral channel

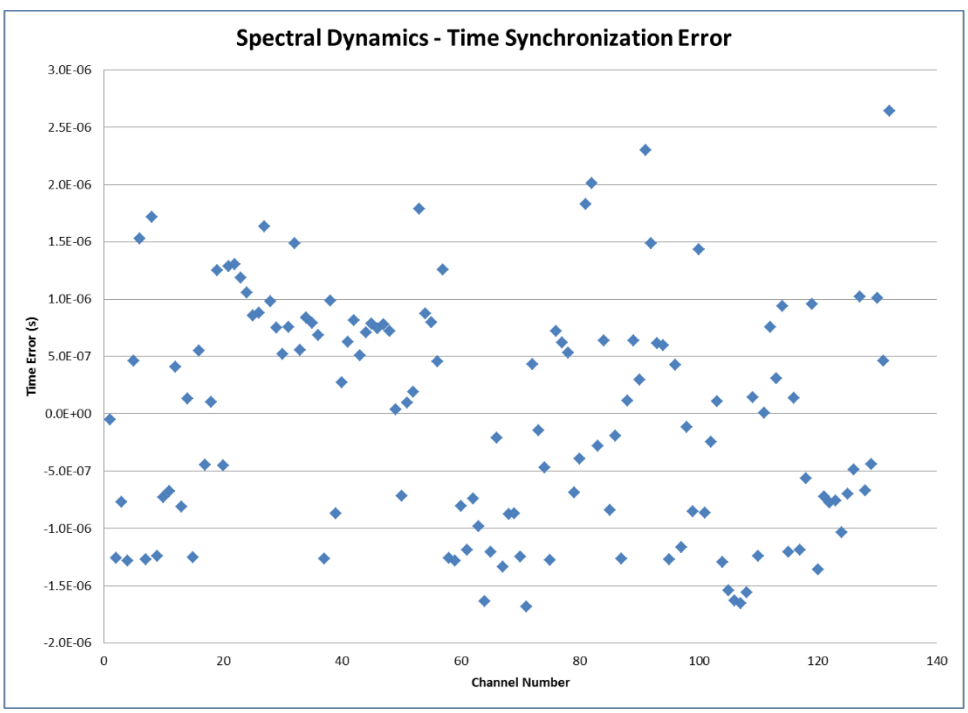

Figure 28: Time synchronization error (s) for every Spectral channel based on the onset of capacitor bank discharge noise fiducial

The Spectral system responds to the capacitor bank discharge with a very fast rising response and a relatively fast dissipation. The Jaguar response, however, was much different. The electromagnetic noise required greater than 100µs to achieve maximum noise amplitude as shown in Figure 29. The noise response and recovery is shown in Figure 30 for channel 3 of the

Spectral and Jaguar systems. Maximum noise amplitude occurs after bank discharge is complete; therefore, the Jaguar system does not satisfy the requirement to achieve 5% band edge at 50µs. In order to quantify the noise recovery of the Jaguar system, the noise was evaluated at 250µs. Every Jaguar channel was evaluated using the MATLAB noise recovery program with channel 3 and the cutoff time defined at t_0+250µs as shown in Figure 31. Consistent with other MAP results, channel 72 results indicated a faulty channel. For channel 40, peak noise amplitude occurred after t_0+250µs as shown in Figure 32. Excluding channels 72 and 40, the maximum noise amplitude at t_0+250µs was 290 (kG or µstrain) as shown in Figure 33. For times after t_0+250µs, the maximum noise amplitude was 348 (kG or µstrain) excluding channels 40 and 72. 95% confidence intervals were also calculated for noise amplitudes after t_0+250µs as shown in Figure 35. As with the Spectral system, the Jaguar noise recovery data was used to estimate the time synchronization error; however, the bank discharge proved to be an unreliable timing fiducial. The response of the Jaguar system varied greatly depending on the noise susceptibility of a particular channel. For some channels, no discernable noise response was observed. Figure 36 reveals the erratic response to the noise. Excluding channels that were minimally contaminated with noise reveals a time synchronization error of approximately 0.5ms as shown in Figure 37. To reiterate, this error is indicative of the channel response to noise rather than synchronization errors.

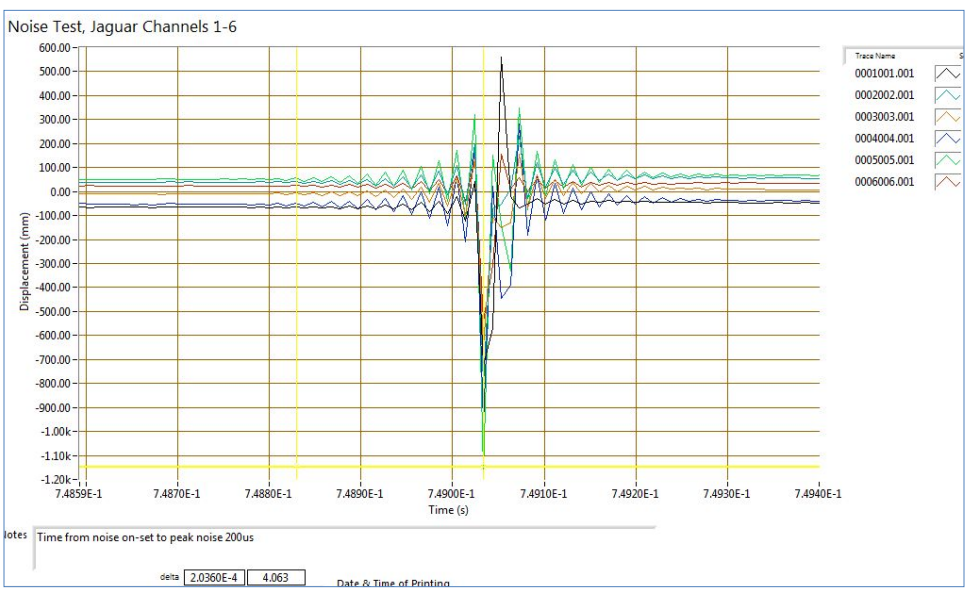

Figure 29: The Jaguar response to the capacitor bank discharge required greater than 100µs to achieve maximum amplitude, channels 1-6 shown

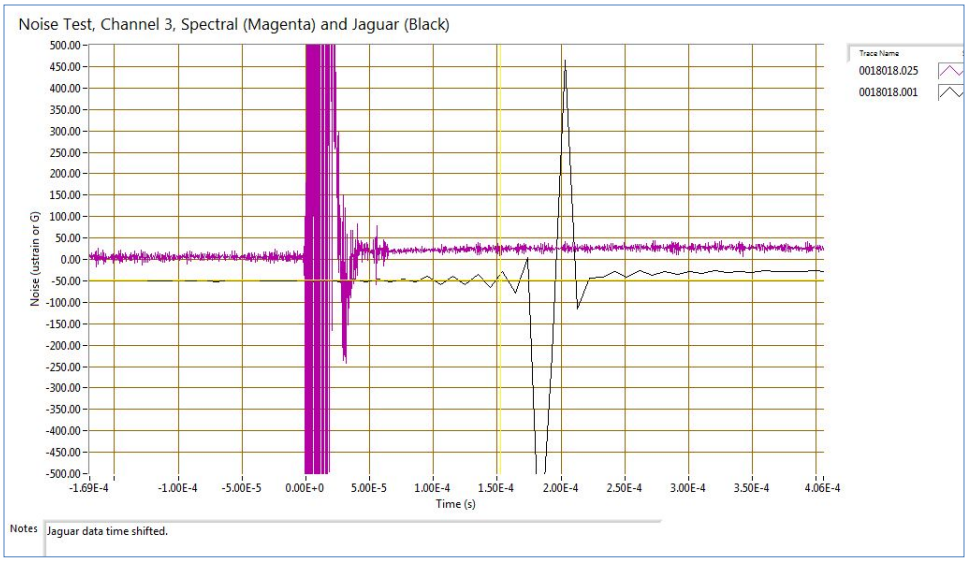

Figure 30: Noise response and recovery for channel 3 of the Spectral and Jaguar systems

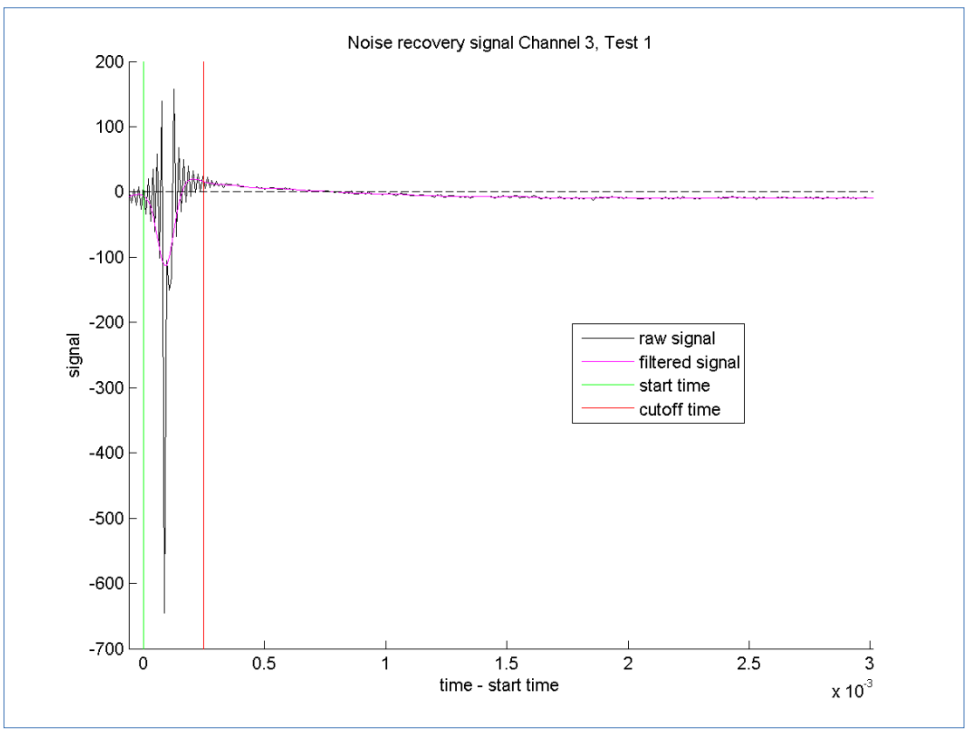

Figure 31: Noise response and recovery for Jaguar channel 3

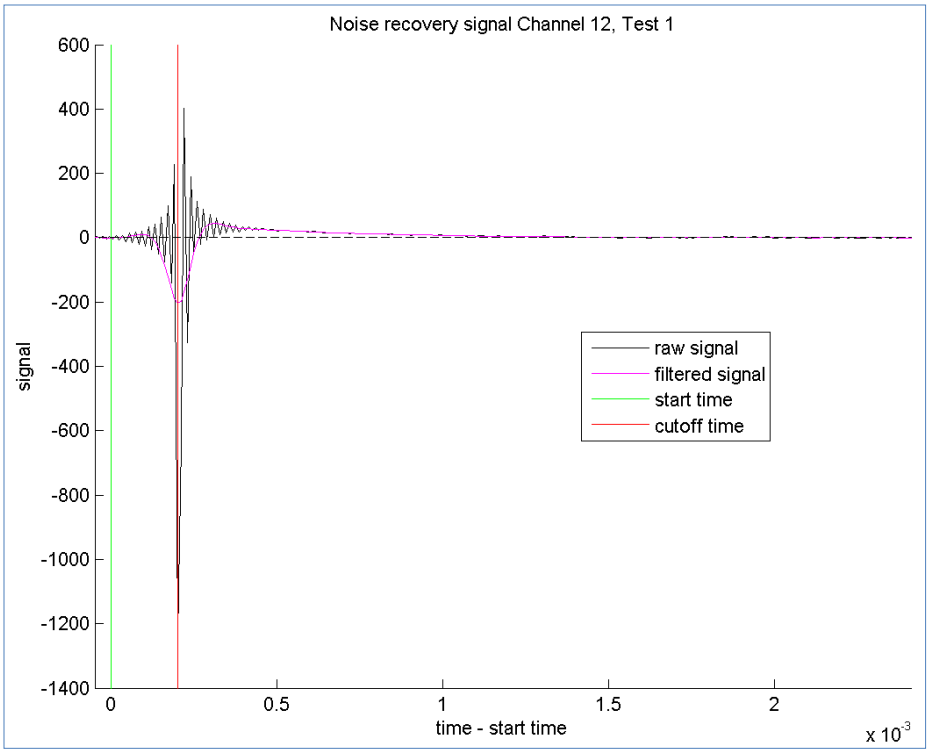

Figure 32: Peak noise amplitude for Jaguar channel 40 occurs after t0+250µs (channel 40 is channel 12 of ACP2)

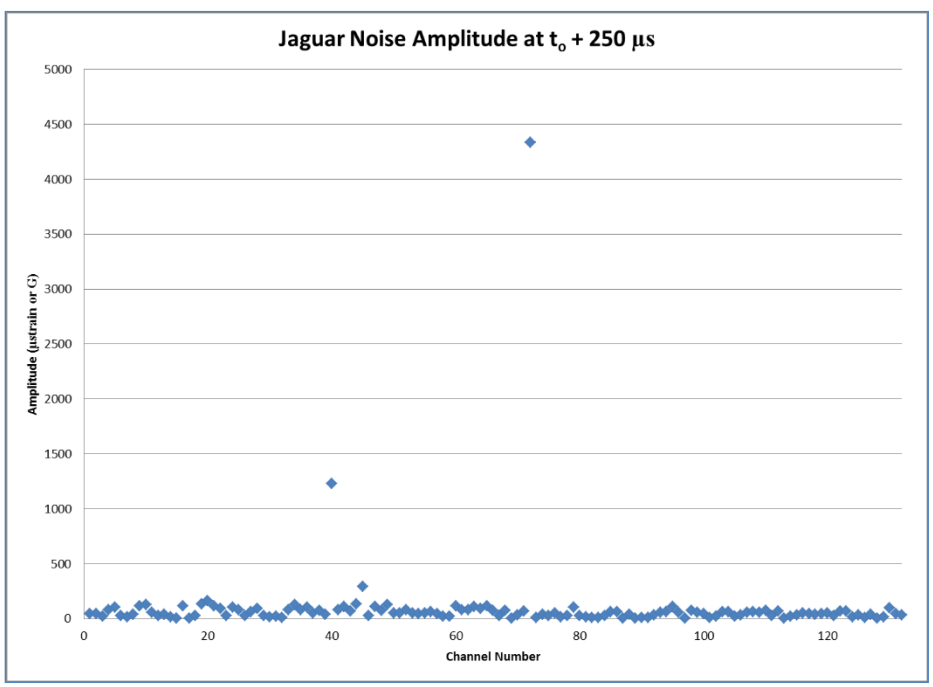

Figure 33: Noise amplitude at t0+250µs for the Jaguar system

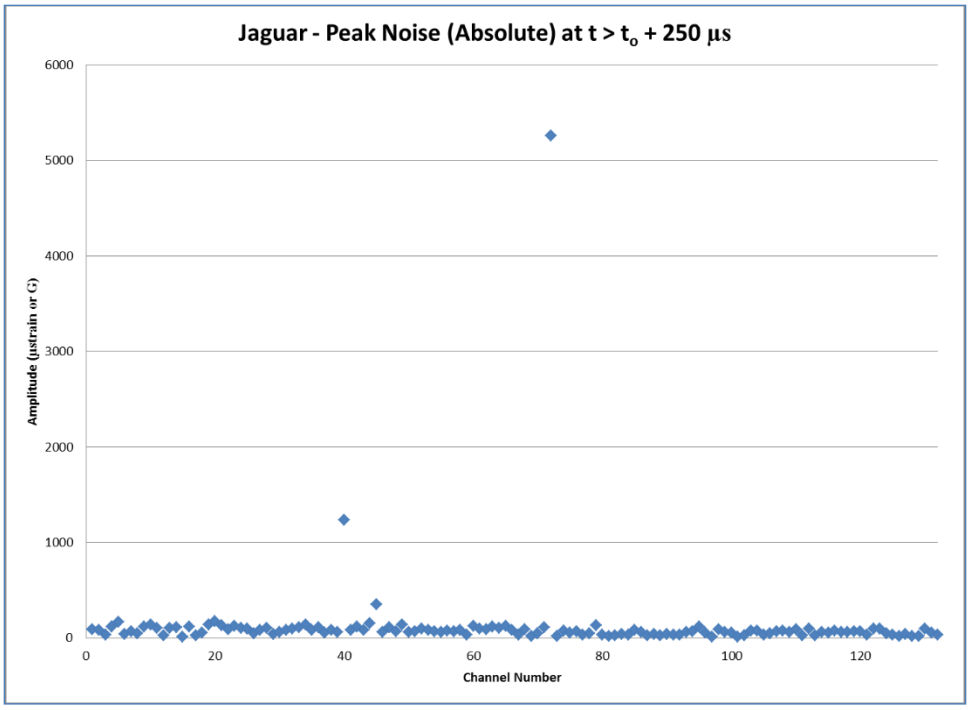

Figure 34: Peak noise amplitude for times after t0+250µs for the Jaguar system

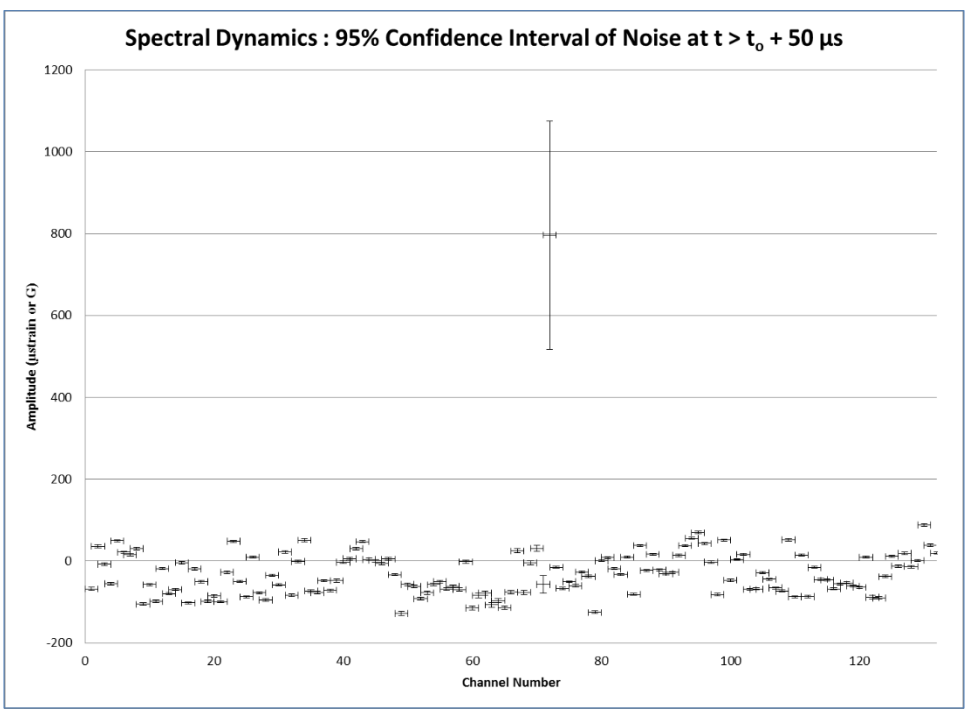

Figure 35: 95% confidence interval for noise amplitude for times after t0+250µs for the Jaguar system

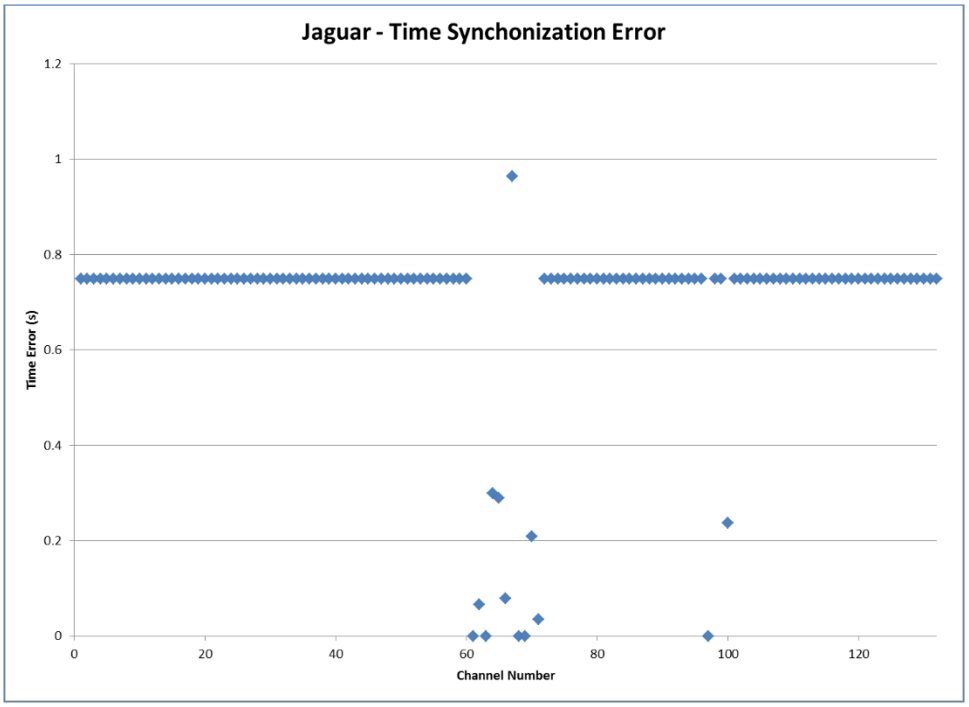

Figure 36: Time synchronization error for the Jaguar system using capacitor bank discharge as a timing fiducial

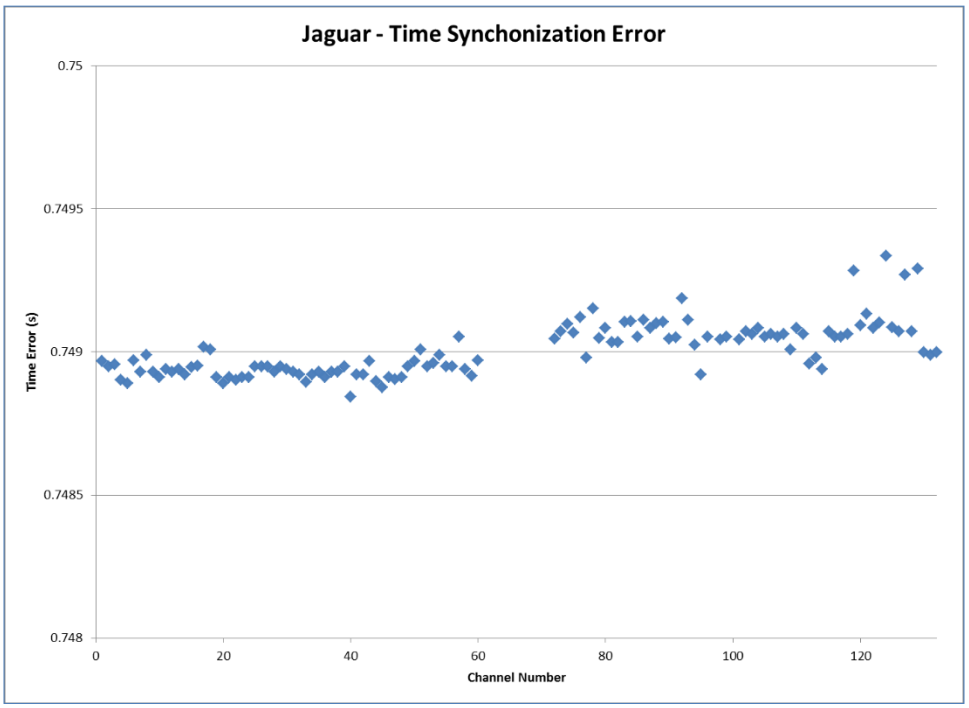

Figure 37: Time synchronization error for the Jaguar system using capacitor bank discharge as a timing fiducial, excluding channel without discernable bank noise

5. CONCLUSION

The Spectral Dynamics digitization cards were calibrated by the SNL PSL. The measurement assurance plan successfully verified that the performance of the entire system met customer requirements. The MAP revealed that channel 72 is faulty. The MAP also highlighted limitations of the integrated system, such as offset errors and time synchronization errors with the Jaguar system. The offset errors in the Jaguar data will require post-test processing (base-line shift) to obtain valid data. Similarly, the phase errors and time synchronization errors can be corrected through post-test processing of a time shift based on a robust fiducial. The MAP results indicate that the capacitor bank discharge noise response is not a reliable timing fiducial. Therefore, one channel of the DAS will be reserved specifically for a timing fiducial to aid in post-processing of the data for all NW data acquisition. Finally, the Jaguar response and recovery to capacitor bank noise contamination is too slow to satisfy the MAP requirements. Even extending the response recovery time from 50µs to 250µs, one channel failed the MAP requirements (excluding the faulty channel 72).

Table 6: MAP results summary

	Spectral	Jaguar
Noise floor less than +/-2% of band edge (95% confidence interval)	Yes Excl Ch72	Yes Excl Ch72
Amplitude error within 10%	Yes	Yes
Frequency error within 1%.	Yes	Yes
Phase error within 10°.	Yes	No [2]
Voltage offset within 10%.	Yes	No [1]
Time synchronization/phase error of less than 10° at 10kHz (2.8E-6 seconds)	Yes	No [2]
Instrumentation system recovery to within 5% of band edge within 50 µs.	Yes Excl Ch72	No [3]

[1] Post processing of the Jaguar data required to correct voltage offset errors

[2] Post processing of the Jaguar data required to correct phase and synchronization errors based on robust timing fiducial

[3] The slow response of the Jaguar system to the electromagnetic noise stimulus and slow recovery from the noise results in failure of the Jaguar to satisfy this MAP requirement.

6. REFERENCES

1. *Spectral Dynamics Dummy Strain and Shunt Calibrations*, Rev 2.1 mdw, 08/2011
2. *Pre-shot testing and verification of PCB and Endevco Accelerometers*, Rev 1.0, mdw 05/2011
3. *Spectral and Jaguar Startup /Shutdown Sequence*, Rev 2.6, 10/2011, mdw
4. *LIHE STRAIN/ACCLEROMOTER TEST CELL CABLE RUNS and System Troubleshooting examples*, Rev 2.0 mdw, 05/2011
5. *End to End Noise Fixture Spectral Cannon Plug Table*, Rev. Initial 08/2012
6. *Injecting Signals into the Spectral and Jaguar Systems (The Basics) and Utilizing Output Waveform Control*, mdw Rev 2.1, 10/2011
7. *Light Initiated High Explosives (LIHE) DAS operational procedures and system capabilities*, SAND2014-20098, Michael Willis, November 2014.

APPENDIX A

Strain Simulation MATLAB Analysis

```
function [ ] = shunt_test( input_dir, output_dir, offset, P, Cmax,...
    Tmax )
%Data signal analysis utility developed for analyzing the shunt test at the
%Light Initiated High Explosives Facility at Sandia National Laboratories.
%
%  Requires: (1) MATLAB Statistics Toolbox
%            (2) impax2mat.m function for converting a Spectral Dynamics
%                IMPAX file into a MATLAB structure
%
%  ==========================================================================
%  Written by:     Gregg Radtke, Org 2552
%                  garadtk@sandia.gov
%  Version Date:   9/25/2014
%  MATLAB Version: 2014a
%  ==========================================================================
%
%  [ Ntest ] = shunt_test( input_dir, output_dir, offset, P, Cmax, Tmax )
%
%  ==========================================================================
%  INPUT PARAMTERS
%  ==========================================================================
%
%  input_dir (optional, string): specify directory where data files are
%  located. If not specified, program will load files from the current
%  directory. Note, this should ideally end with the '/' charecter.
%
%  output_dir (optional, string): specify directory where result files are
%  to be saved. If not specified, function will save in current directory.
%   Note, this should ideally end with the '/' charecter.
%
%  offset (optional, real): specify expected offset of the shunt test for
%  plots. If not specified, function will not plot an offset.
%
%  P (optional, real): specify the two-sided confidence level. If not
%  specified, the default value of 95% (0.95) will be used.
%
%  Cmax (optional, integer): specify maximum number of channels to look
%  for. If not specified, the default value of 132 will be used.
%
%  Tmax (optional, integer): specify maximum number of tests to look for.
%  If not specified, the default value of 20 will be used.
%
%  ==========================================================================
%  OUTPUT
%  ==========================================================================
%
%  Ntest(integer): the single output variable indicates the number of tests
%  for which data was located and analyzed. Returning zero indicates no
%  data was found.
%
%  This function will also produce an EXCEL worksheet file
%  (shunt_statistics_test*.xlsx) and an image file of plotted figure
%  (shunt_plot_test*.png) for each test analyzed. This same information is
```

```
%  also output to the screen.
%
%  The EXCEL worksheet file has the following six columns:
%
%  channel: the channel being analyzed
%
%  data_size: the number of points in the signal
%
%  mean_value: the sample mean
%
%  std_dev: the (unbiased) sample standard deviation
%
%  lower_bound, upper_bound: the two-sided P-confidence intervals
%
%  error: the minimum signal error consistent with the P-confidence
%  intervals

%  ==========================================================================

tic
close all
display(' ')

% process optional input arguements
if ~nargin
    input_dir = [];
end
if nargin < 2
    output_dir = [];
end
if nargin < 3
    offset = [];
end
if nargin < 4
    P = 0.95;
end
if nargin < 5
    Cmax = 132;
end
if nargin < 6
    Tmax = 20;
end

% convert 2-sided confidence bound to upper (symmetric) percentage bound
Pb = 1 - (1-P)/2;

% create output directory if it doesn't exist
if ~isempty( output_dir )
    if ~exist( output_dir, 'dir' )
        mkdir(output_dir)
    end
end

% loop over all tests
Ntest = 0;
maxerror = 0;
```

```
fig = 0;
for k = 1: Tmax

    % preallocate statistics vectors
    channel = zeros(Cmax,1);
    data_size  = zeros(Cmax,1);
    mean_value = zeros(Cmax,1);
    std_dev = zeros(Cmax,1);
    lower_bound = zeros(Cmax,1);
    upper_bound = zeros(Cmax,1);
    error = zeros(Cmax,1);

    % loop over all channels
    Nc = 0;
    for j = 1: Cmax

        % test for jth channel data
        file = strcat( [ input_dir, '0', num2str( sprintf('%03d',j) ),...
            num2str( sprintf('%03d',j) ), '.',...
            num2str( sprintf('%03d',k) ) ] );
        if exist( file, 'file' )

            % perform analysis when jth channel data exists
            Nc = Nc + 1;
            channel(Nc) = j;
            data = impax2mat(file);
            data_size(Nc) = int64( length(data.y) );
            mean_value(Nc) = mean(data.y);
            std_dev(Nc) = std(data.y);
            cf = icdf( 't', Pb, length(data.y)-1 );
            lower_bound(Nc) = mean_value(Nc) - cf * std_dev(Nc);
            upper_bound(Nc) = mean_value(Nc) + cf * std_dev(Nc);
            error(Nc) = max( offset - lower_bound(Nc),...
                upper_bound(Nc) - offset );
        end
    end

    % perform analysis for tests where data exists
    if Nc
        Ntest = Ntest + 1;

        % output to screen that data has been found
        display(' ')
        display( [ num2str(Nc), ' files for test ', num2str(k),...
            ' were analyzed' ] )

        % truncate statistics vectors
        channel = channel(1:Nc);
        data_size = data_size(1:Nc);
        mean_value = mean_value(1:Nc);
        std_dev = std_dev(1:Nc);
        lower_bound = lower_bound(1:Nc);
        upper_bound = upper_bound(1:Nc);
        error = error(1:Nc);
```

```
        % create tabular output
        shunt_test_statistics = table( channel, data_size, mean_value,...
            std_dev, lower_bound,...
            upper_bound, error ) %#ok<NOPRT>
        file = strcat( [ output_dir, 'shunt_statistics_test',...
            num2str(k), '.xlsx' ] );

        % display max error for test
        display(' ')
        display( strcat( [ 'maximum error for test ',...
            num2str(k), ' is: ', num2str(max(error)) ] ) )
        display(' ')
        if max(error) > maxerror
            maxerror = max(error);
        end
        display(' ')

        % save tabular output
        writetable( shunt_test_statistics, file )
        display( [ 'printed ', file ] )

        % create confidence interval plot
        fig = fig + 1;
        figure(fig)
        clf
        hold on
        if ~isempty(offset)
            plot( [ min(channel), max(channel) ], offset*[1,1], 'k-' )
        end
        errorbar( channel, mean_value, mean_value - lower_bound,...
            upper_bound - mean_value, '.' )
        xlabel('channel')
        ylabel('signal')
        title( strcat( [ num2str(100*P),...
            '% confidence intervals on shunt signal for test ',...
            num2str(k) ] ) )
        file = strcat( [ output_dir, 'shunt_plot_test', num2str(k),...
            '.png' ] );
        print( fig, '-dpng', '-painters', file )
        display( [ 'printed ', file ] )

    end

end

% display output stamp
display(' ')
if Ntest
    display( strcat( [ 'overall maximum error for all tests is ',...
    num2str(maxerror) ] ) )
    display(' ')
    display( 'stunt_test finished successfully' )
    display( strcat( [ 'Found data for ', num2str(Ntest), ' tests' ] ) )
else
    display( 'shunt_test failed to find data for any tests:' )
    display( '  check that the correct input directory was specified' )
```

```
    display( '  and that files are in the expected format' )
end
display( strcat( [ 'run time: ', num2str(toc), ' s' ] ) )
display( strcat( [ '----------------------------------------',...
    '----------------------------------------'] ) )
display(' ')

end
```

APPENDIX B

Sinusoid Voltage MATLAB Analysis

```
function [ ] = voltage_response_test( input_dir, output_dir,...
    ref_channels, periods, fit_f, P, Cmax, Tmax )
%Data signal analysis utility developed for the voltage response test at
%the Light Initiated High Explosives Facility at Sandia National
%Laboratories.
%
%  Requires: (1) MATLAB Statistics Toolbox
%            (2) impax2mat.m function for converting a Spectral Dynamics
%                IMPAX file into a MATLAB structure
%
%  ========================================================================
%  Written by:     Gregg Radtke, Org 2552
%                  garadtk@sandia.gov
%  Version Date:   10/28/2014
%  MATLAB Version: 2014a
%  ========================================================================
%
%   [ Ntest ] = voltage_response_test( input_dir, output_dir,...
%      ref_channels, periods, fit_f, P, Cmax, Tmax )
%
%  ========================================================================
%  FIT MODEL
%  ========================================================================
%
%  The primary function of this code is to analyze the voltage response
%  both on the basis of a fast Fourier transform (FFT) and a regression
%  based on a sinusoidal fit model. The fit is obtained by nonlinear
%  least-squares regression based on the fit function:
%
%    f(z,t) = offset + z(1) * sin( 2*pi * ( z(2) * t - z(3) ) )
%
%  Here, offset is a (user specified, fixed) offset, z(1) is the amplitude,
%  z(2) is the frequency, and z(3) is the period [0,1). The regression is
%  performed by minimizing the objective function with respect to the fit
%  parameters z,
%
%    g(z) = sum ( y(t) - f(z,t) )^2.
%
%  Here, the sum is performed over all t-values from the data set y(t).
%
%  ========================================================================
%  INPUT PARAMETERS
%  ========================================================================
%
%  input_dir (optional, string): specify directory where data files are
%  located. If not specified, program will load files from the current
%  directory. Note, this should ideally end with the '/' charecter. This
%  function will look for both Spectral/Jag (impax) and Tektronics (csv)
%  files, but the reference file(s) must be Tektronics files only.
%
%  output_dir (optional, string): specify directory where result files are
%  to be saved. If not specified, function will save in current directory.
%  Note, this should ideally end with the '/' charecter.
```

```
%
%  ref_channels (optional, list of integers): set the channel numbers to
%  specify which channels are used for reference channels. If not
%  specified, the default of 0 will be used. Note that only Tektronics
%  files will be used as a reference.
%
%  periods (optional, integer): set a cutoff number of integer periods for
%  truncating longer signals. If not supplied, the default value of 100
%  will be set. Setting this number too high might results in convergence
%  problems for the fit values.
%
%  fit_f (optional, string): switch to change the fitting method. 'FFT'
%  will fix the frequency to that found by the FFT, while 'fit' will
%  determine the frequency by fitting. All other values will cause the
%  program to exit with an error message. 'fit' is the default setting.
%
%  P (optional, real): specify the two-sided confidence level. If not
%  specified, the default value of 95% (0.95) will be used.
%
%  Cmax (optional, integer): specify maximum number of channels to look
%  for. If not specified, the default value of 132 will be used.
%
%  Tmax (optional, integer): specify maximum number of tests to look for.
%  If not specified, the default value of 20 will be used.
%
%  ==========================================================================
%  OUTPUT
%  ==========================================================================
%
%  Ntest(integer): the single output variable indicates the number of tests
%  for which data was located and analyzed. Returning zero indicates no
%  data was found.
%
%  This function will also produce several types of EXCEL worksheet files
%  and plot image files as described below:
%
%  The FFT and fit properties (freqency, offset, amplitude, phase,
%  confidence bounds, and adjusted R-squared) are listed by channel for
%  both the reference data (reference_data.xlsx) and signal data
%  (signal_data.xlsx). The offset and are normalized by the amplitude, and
%  the phase is specified in degrees. The confidence bounds are computed
%  based on two-sided P-confidence intervals. The adjusted R-squared value
%  is a measure of the goodness of fit, and approaches unity for increasing
%  fit quality.
%
%  The signal data is also compared to each reference signal
%  (difference_signal-reference*.xlsx), where now each column is a
%  normalized difference (signal/reference - 1) for all values except
%  offset, which is the difference normalized by the reference amplitude,
%  and phase, which is a raw difference (signal - reference).
%
%  Two plots are produced for each reference and signal channel. First, a
%  FFT plot, showing the FFT and the frequency chosen by taking the maximum
%  of the FFT {FFT_plot_signal/reference_{signal/reference}_channel_*...
%  test_*.png). Second, a fit plot showing the overall fit to the data and
%  the residual (fit+residual_plot_{signal/reference}_channel*_test_*.png).
```

```
%  ========================================================================

tic
close all
display(' ')

% process optional input arguements
if ~nargin
    input_dir = [];
end
if nargin < 2
    output_dir = [];
end
if nargin < 3
    ref_channels = 0;
end
if nargin < 4
    periods = 100;
end
if nargin < 5
    fit_f = 'fit';
else
    switch fit_f
        case 'fit'
        case 'FFT'
        otherwise
            error( 'fit_f value must be either ''FFT'' or ''fit''!' )
    end
end
if nargin < 6
    P = 0.95;
end
if nargin < 7
    Cmax = 132;
end
if nargin < 8
    Tmax = 20;
end

% optimization settings
opt = optimset( 'MaxIter', 1e6, 'MaxFunEvals', 1e6, 'TolFun', 1e-6,...
    'TolX', 1e-6 );

% convert 2-sided confidence bound to upper (symmetric) percentage bound
Pb = 1 - (1-P)/2;

% create output directory if it doesn't exist
if ~isempty( output_dir )
    if ~exist( output_dir, 'dir' )
        mkdir(output_dir)
    end
end

% preallocate reference data structure
data.Reference.channel = NaN(Cmax+1,1);
data.Reference.FFT_f = NaN(Cmax+1,1);
```

```
data.Reference.fit_f = NaN(Cmax+1,1);
data.Reference.offset = NaN(Cmax+1,1);
data.Reference.amplitude = NaN(Cmax+1,1);
data.Reference.phase = NaN(Cmax+1,1);
data.Reference.lower_res_bnd = NaN(Cmax+1,1);
data.Reference.upper_res_bnd = NaN(Cmax+1,1);
data.Reference.adjusted_R2 = NaN(Cmax+1,1);

% least-squares fitting functions
fit = @(z,t) z(1)* ones(size(t)) + z(2) * sin( 2*pi*( z(3) * t -
z(4)*ones(size(t)) ) );
FIT = @(Z,t,F) Z(1)* ones(size(t)) + Z(2) * sin( 2*pi*( F * t -
Z(3)*ones(size(t)) ) );

% loop over all tests (test 0 checks for csv Tektronics files)
Nref = 0;
Ntest = 0;
fig = 0;
for k = 0: Tmax

    % preallocate signal data structure
    data.Signal.channel = NaN(Cmax+1,1);
    data.Signal.FFT_f = NaN(Cmax+1,1);
    data.Signal.fit_f = NaN(Cmax+1,1);
    data.Signal.offset = NaN(Cmax+1,1);
    data.Signal.amplitude = NaN(Cmax+1,1);
    data.Signal.phase = NaN(Cmax+1,1);
    data.Signal.lower_res_bnd = NaN(Cmax+1,1);
    data.Signal.upper_res_bnd = NaN(Cmax+1,1);
    data.Signal.adjusted_R2 = NaN(Cmax+1,1);

    % loop over all channels
    Nsig = 0;
    for j = 0: Cmax

        % test for jth channel data
        if k

            % check for impax format files
            file = [ input_dir, '0', num2str( sprintf('%03d',j) ),...
                num2str( sprintf('%03d',j) ), '.',...
                num2str( sprintf('%03d',k) ) ];
            found = exist( file, 'file' );
            sigref = 'Signal';
            if found
                ftype = 'impax';
                Nsig = Nsig + 1;
                N = Nsig;
                data.Signal.channel(N) = int64(j);
                impax_data = impax2mat(file);
                y = impax_data.y / 1000;
                dt = impax_data.dt;
                t = dt * ( 0: length(y)-1 )'...
                    + impax_data.t0 * ones(size(y));
                clear impax_data
            end
```

```
else

    % check for Tektronics format files
    file = [ input_dir, 'tek0', num2str( sprintf('%03d',j) ),...
        '.csv' ];
    found = exist( file, 'file' );
    if isempty( find( ref_channels == j, 1, 'first' ) )
        sigref = 'Signal';
    else
        sigref = 'Reference';
    end
    if found
        ftype = 'Tektronics';
        if strcmp( sigref, 'Signal' )
            Nsig = Nsig + 1;
            N = Nsig;
            data.Signal.channel(N) = int64(j);
        else
            Nref = Nref + 1;
            N = Nref;
            data.Reference.channel(Nref) = int64(j);
        end
        Tektronics_data = csvread( file, 21, 0 );
        y = Tektronics_data(:,2);
        t = Tektronics_data(:,1);
        dt = csvread( file, 8, 1, [8 1 8 1] );
    end

end

% perform analysis with data
if found
    NFFT = 2 ^ nextpow2(length(y));
    FFT = fft(y,NFFT)/length(y);
    FFT = 2*abs(FFT(1:NFFT/2+1));
    f = linspace(0,1,NFFT/2+1)'/dt/2;
    data.(sigref).FFT_f(N) = f( find( FFT == max(FFT), 1 ) );
    imax = find( FFT == max(FFT), 1, 'first' );
    if find( FFT == max(FFT), 1, 'last' ) > imax
        if strcmp( ftype, 'impax' )
            display( [ 'WARNING: multiple FFT  frequency peaks',...
                ' observed for impax signal  file, channel ',...
                num2str(j), ', test ', num2str(k) ] )
        else
            display( [ 'WARNING: multiple FFT  frequency peaks',...
                ' observed for Tektronics ', lower(sigref),...
                ' file, channel ', num2str(j) ] )
        end
        display( '         but only the first is reported ' )
    end

    % quadratic interpolation to improve max FFT estimate
    a = [ ones(3,1), f(imax-1:imax+1), f(imax-1:imax+1).^2 ]...
        \ FFT(imax-1:imax+1);
    data.(sigref).FFT_f(N) = -0.5 * a(2) / a(3);
```

```
% truncate data for fit computations
yy = y; tt = t;
F = data.(sigref).FFT_f(N);
per = min( periods, floor( F *(t(2)-t(1))*length(t) ) );
if per >= 1
    NN = round( per / F / (t(2)-t(1)) );
    y = y(1:NN);
    t = t(1:NN);
else
    if strcmp( ftype, 'impax' )
        display( [ 'WARNING: impax signal file, channel ',...
            num2str(j), ', test ', num2str(k),...
            ' has less than one full period of data.' ] )
    else
        display( [ 'WARNING: Tektronics ', lower(sigref),...
            ' file, channel ', num2str(j),...
            ' has less than one full period of data.' ] )
    end
end

% fit computations, default method (fit frequency)
if strcmp( fit_f, 'fit' )
    z0 = [ mean(y), range(y)/2, data.(sigref).FFT_f(N), 0 ];
    z4 = 0:0.1:0.9;
    z = [];
    g = Inf;
    for q = 1: length(z4)
        z0(4) = z4(q);
        [ zt, gt ] = fminsearch( @(z)...
            sum( ( y - fit(z,t) ).^2 ), z0, opt );
        if gt < g
            g = gt;
            z = zt;
        end
    end

    % repeat data truncation and fit based on fit frequency
    F = z(3);
    per = min( periods, floor( F *(t(2)-t(1))*length(tt) ) );
    if per >= 1
        NN = round( per / F / (t(2)-t(1)) );
        y = yy(1:NN);
        t = tt(1:NN);
    else
        if strcmp( ftype, 'impax' )
            display( [ 'WARNING: impax signal file, ',...
                'channel ', num2str(j), ', test ',...
                num2str(k),...
                ' has less than one full period of data.' ] )
        else
            display( [ 'WARNING: Tektronics ',...
                lower(sigref), ' file, channel ',...
                num2str(j),...
                ' has less than one full period of data.' ] )
        end
```

```
    end
    z = fminsearch( @(z) sum( ( y - fit(z,t) ).^2 ), z, opt );

    % save fit data
    cf = icdf( 't', Pb, length(y) );
    data.(sigref).offset(N) = z(1);
    data.(sigref).amplitude(N) = z(2);
    data.(sigref).fit_f(N) = z(3);
    data.(sigref).phase(N) = ( z(4)-floor(z(4)) ) * 360;
    data.(sigref).lower_res_bnd(N) = ( mean( y - fit(z,t) )...
        - cf * std( y - fit(z,t) ) ) / z(2);
    data.(sigref).upper_res_bnd(N) = ( mean( y - fit(z,t) )...
        + cf * std( y - fit(z,t) ) ) / z(2);
    data.(sigref).adjusted_R2(N) = 1 - sum( ( y...
        - fit(z,t) ).^2 ) / sum( ( y...
        - ones(size(y))*mean(y) ).^2 ) ...
        * ( length(y) - 1) / ( length(y) - 4 - 1);

% fit computations, optional method (fix frequency from FFT)
else
    Z0 = [ mean(y), range(y)/2, 0 ];
    F = data.(sigref).FFT_f(N);
    Z3 = 0:0.1:0.9;
    Z = [];
    g = Inf;
    length(y)
    for q = 1: length(Z3)
        Z0(3) = Z3(q);
        [ Zt, gt ] = fminsearch( @(Z)...
            sum( ( y - FIT(Z,t) ).^2 ), Z0, opt );
        if gt < g
            g = gt;
            Z = Zt;
        end
    end
    cf = icdf( 't', Pb, length(y) );
    data.(sigref).offset(N) = Z(1);
    data.(sigref).amplitude(N) = Z(2);
    data.(sigref).fit_f(N) = NaN;
    data.(sigref).phase(N) = ( Z(3)-floor(Z(3)) ) * 360;
    data.(sigref).lower_res_bnd(N) = ( mean( y -...
        FIT(Z,t,F) ) - cf * std( y - FIT(Z,t,F) ) ) / Z(2);
    data.(sigref).upper_res_bnd(N) = ( mean( y -...
        FIT(Z,t,F) ) + cf * std( y - FIT(Z,t,F) ) ) / Z(2);
    data.(sigref).adjusted_R2(N) = 1 - sum( ( y...
        - FIT(Z,t,F) ).^2 ) / sum( ( y...
        - ones(size(y))*mean(y) ).^2 ) ...
        * ( length(y) - 1) / ( length(y) - 3 - 1);
end

% FFT plot
fig = fig + 1;
figure(fig)
clf
semilogx(f,FFT,'k-')
hold on
```

```
semilogx( data.(sigref).FFT_f(N)*[1,1], max(FFT)*[0,1],...
    'b-' )
semilogx( data.(sigref).fit_f(N)*[1,1], max(FFT)*[0,1], 'r--' )
legend( 'FFT', 'FFT max frequency', 'fit frequency',...
    'Location', 'Best' )
xlabel( 'frequency' )
if k
    title( [ 'Fast Fourier Transform of impax  Signal ',...
        'data, Channel ', num2str(j), ', Test ', num2str(k) ] )
    file = [ output_dir, 'FFT_plot_signal_impax_ch_',...
        num2str(j), '_test_', num2str(k) ];
else
    title( [ 'Fast Fourier Transform of Tektronics ',...
        sigref, ' data, Channel ', num2str(j) ] )
    file = [ output_dir, 'FFT_plot_', lower(sigref),...
        '_tek_ch_', num2str(j) ];
end
xlim( [ 10^(round(log10(data.(sigref).FFT_f(N)))-2),...
    10^(round(log10(data.(sigref).FFT_f(N)))+2) ] )
print( fig, '-dpng', '-painters', file )
display( [ 'printed ', file ] )

% plot fit and residual
if strcmp( fit_f, 'fit' )
    fit_func = fit(z,t);
    res_func = y-fit(z,t);
else
    fit_func = FIT(Z,t,F);
    res_func = y-FIT(Z,t,F);
end
fig = fig + 1;
figure(fig)
clf
subplot(2,1,1)
plot( t, fit_func, 'b-' )
hold on
plot( t, y, 'r.' )
ylabel('signal')
if k
    title( [ 'Least Squares Fit of impax Signal',...
        ' Data, Channel ', num2str(j), ', Test ',...
        num2str(k) ] )
    file = [ output_dir, 'fit+residual_plot_',...
        lower(sigref), '_impax_ch_', num2str(j),...
        '_test_', num2str(k) ];
else
    title( [ 'Least Squares Fit of Tektronics ', sigref,...
        ' Data, Channel ', num2str(j) ] )
    file = [ output_dir, 'fit+residual_plot_',...
        lower(sigref), '_tek_ch_', num2str(j) ];
end
legend( 'fit', 'data', 'Location', 'Best' )
subplot(2,1,2)
plot( t, res_func, 'b-' )
xlabel('time')
ylabel('fit residual')
print( fig, '-dpng', '-painters', file )
```

```
        display( [ 'printed ', file ] )

    end
end

% when data was found, export files
if k
    if Nsig
        Ntest = Ntest + 1;
    end
else
    if or( Nsig, Nref )
        Ntest = Ntest + 1;
    end
end

% when signal files found, export output
if Nsig
    display(' ')
    if k
        display( [ 'Found ', num2str(Nsig), ' channels of ',...
            'impax signal data for test ', num2str(k) ] )
    else
        display( [ 'Found ', num2str(Nsig), ' channels of ',...
            'Tektronics signal data' ] )
    end

    % truncate signal file structure
    data.Signal.channel = data.Signal.channel(1:Nsig);
    data.Signal.FFT_f = data.Signal.FFT_f(1:Nsig);
    data.Signal.fit_f = data.Signal.fit_f(1:Nsig);
    data.Signal.offset = data.Signal.offset(1:Nsig);
    data.Signal.amplitude = data.Signal.amplitude(1:Nsig);
    data.Signal.phase = data.Signal.phase(1:Nsig);
    data.Signal.lower_res_bnd = data.Signal.lower_res_bnd(1:Nsig);
    data.Signal.upper_res_bnd = data.Signal.upper_res_bnd(1:Nsig);
    data.Signal.adjusted_R2 = data.Signal.adjusted_R2(1:Nsig);

    % create tabular signal output
    signal_data = table( data.Signal.channel, data.Signal.FFT_f,...
        data.Signal.fit_f,...
        data.Signal.offset./data.Signal.amplitude,...
        data.Signal.amplitude, data.Signal.phase,...
        data.Signal.lower_res_bnd, data.Signal.upper_res_bnd,...
        data.Signal.adjusted_R2,...
        'VariableNames', { 'channel' 'FFT_frequency' 'fit_frequency'...
        'offset' 'amplitude' 'phase' 'lower_res_bnd' 'upper_res_bnd'...
        'adjusted_R2' } ) %#ok<NOPRT>
    if k
        file = [ output_dir, 'signal_impax_test_', num2str(k),...
            '.xlsx' ];
    else
        file = 'signal_tek.xlsx';
    end
    writetable( signal_data, file )
    display( [ 'saved ', file ] )
```

```
end

% when reference files found, export output
if and( not(k), Nref )
    display(' ')
    if k
        display( [ 'Found ', num2str(Nref), ' channels of ',...
            'impax reference data for test ', num2str(k) ] )
    else
        display( [ 'Found ', num2str(Nref), ' channels of ',...
            'Tektronics reference data' ] )
    end

    % truncate reference file structure
    data.Reference.channel = data.Reference.channel(1:Nref);
    data.Reference.FFT_f = data.Reference.FFT_f(1:Nref);
    data.Reference.fit_f = data.Reference.fit_f(1:Nref);
    data.Reference.offset = data.Reference.offset(1:Nref);
    data.Reference.amplitude = data.Reference.amplitude(1:Nref);
    data.Reference.phase = data.Reference.phase(1:Nref);
    data.Reference.lower_res_bnd = data.Reference.lower_res_bnd(1:Nref);
    data.Reference.upper_res_bnd = data.Reference.upper_res_bnd(1:Nref);
    data.Reference.adjusted_R2 = data.Reference.adjusted_R2(1:Nref);

    % create tabular reference output
    reference_data = table( data.Reference.channel,...
        data.Reference.FFT_f, data.Reference.fit_f,...
        data.Reference.offset./data.Reference.amplitude,...
        data.Reference.amplitude, data.Reference.phase,...
        data.Reference.lower_res_bnd,...
        data.Reference.upper_res_bnd, data.Reference.adjusted_R2,...
        'VariableNames', { 'channel' 'FFT_frequency' 'fit_frequency'...
        'offset' 'amplitude' 'phase' 'lower_res_bnd' 'upper_res_bnd'...
        'adjusted_R2' } ) %#ok<NOPRT>
    file = [ output_dir, 'reference_tek.xlsx' ];
    writetable( reference_data, file )
    display( [ 'saved ', file ] )

end

% create tabular differences from references
if and( Nsig, Nref )

    % difference data structure
    del.type = cell(Nsig,1);
    del.channel = zeros(Nsig,1);
    del.FFT_f = zeros(Nsig,1);
    del.fit_f = zeros(Nsig,1);
    del.offset = zeros(Nsig,1);
    del.amplitude = zeros(Nsig,1);
    del.phase = zeros(Nsig,1);

    % loop over all reference channels
    for j = 1: Nref
```

```
            del.channel = data.Signal.channel;
            del.FFT_f = data.Signal.FFT_f/data.Reference.FFT_f(j)...
                - ones(Nsig,1);
            del.fit_f = data.Signal.fit_f/data.Reference.fit_f(j)...
                - ones(Nsig,1);
            del.offset = ( data.Signal.offset - data.Reference.offset(j)...
                * ones(Nsig,1) ) / data.Reference.amplitude(j);
            del.amplitude = data.Signal.amplitude ...
                / data.Reference.amplitude(j) - ones(Nsig,1);
            del.phase = data.Signal.phase - ones(Nsig,1)...
                * data.Reference.phase(j);
            display(' ')
            if k
                display( [ ' comparison between impax signal test ',...
                    num2str(k), ' and Tektronics reference channel ',...
                    num2str(data.Reference.channel(j)) ] )
                file = [ output_dir, 'impax_test_', num2str(k),...
                    '-to-Tektronics_reference_ch_',...
                    num2str(data.Reference.channel(j)),...
                    '_comparison.xlsx' ];
            else
                display( [ ' comparison between Tektronics signal and',...
                    ' Tektronics reference channel ',...
                    num2str(data.Reference.channel(j)) ] )
                file = [ output_dir, 'Tektronics_signal-to-Tektronics',...
                    '_reference_channel_',...
                    num2str(data.Reference.channel(j)),...
                    '_comparison.xlsx' ];
            end
            difference = table( del.channel, del.FFT_f, del.fit_f,...
                del.offset, del.amplitude, del.phase, 'VariableNames',...
                { 'channel' 'FFT_frequency' 'fit_frequency' 'offset'...
                'amplitude' 'phase' } ) %#ok<NOPRT>
            writetable( difference, file )
            display( [ 'saved ', file ] )
        end

    end

end

% display output stamp
display(' ')
if Ntest
    display( 'voltage_response_test finished successfully' )
    display( [ 'Found data for ', num2str(Ntest), ' tests' ] )
else
    display( 'voltage_response_test failed to find data for any tests:' )
    display( '  check that the correct input directory was specified' )
    display( '  and that files are in the expected format' )
end
display( strcat( [ 'run time: ', num2str(toc), ' s' ] ) )
display( strcat( [ '----------------------------------------',...
    '----------------------------------------'] ) )

end
```

APPENDIX C

Noise Recovery MATLAB Analysis

```
function [ ] = noise_recovery_test( input_dir, output_dir, delay,...
    offset, w_filter, N_filter, P, Cmax, Tmax, start_sens )
%Data signal analysis utility developed for analyzing the noise recovery
%test at the Light Initiated High Explosives Facility at Sandia National
%Laboratories.
%
%  Requires: (1) MATLAB Statistics Toolbox
%            (2) MATLAB Signal Processing Toolbox
%            (3) impax2mat.m function for converting a Spectral Dynamics
%                IMPAX file into a MATLAB structure
%            (4) find_start_time.m function for computing a start time from
%                noisy data
%
%  ========================================================================
%  Written by:     Gregg Radtke, Org 2552
%                  garadtk@sandia.gov
%  Version Date:   12/3/2014
%  MATLAB Version: 2014a
%  ========================================================================
%
%  [ Ntest ] = noise_recovery_test( input_dir, output_dir, delay,...
%      offset, w_filter, N_filter, P, Cmax, Tmax, start_sens )
%
%  ========================================================================
%  INPUT PARAMTERS
%  ========================================================================
%
%  input_dir (optional, string): specify directory where data files are
%  located. If not specified, program will load files from the current
%  directory. Note, this should ideally end with the '/' charecter.
%
%  output_dir (optional, string): specify directory where result files are
%  to be saved. If not specified, function will save in current directory.
%  Note, this should ideally end with the '/' charecter.
%
%  delay (optional, string): specify the delay time after the initiation of
%  the signal for which the signal level will be computed. If not
%  specified, the default value of 50e-6 will be used.
%
%  offset (optional, real): specify the offset of the signal response. The
%  specified value will be subtracted from the signal data prior to
%  analysis and plotting. If not specified, the default value of zero will
%  be used.
%
%  w_filter (optional, real): specify the frequency cutoff for the
%  Butterworth low-pass filter in terms of the data frequency. Must be a
%  positive number less than 1/2, where unity corresponds to the sampling
%  frequency of the data. If unspecified, the default value of 1/16 will be
%  used.
%
%  N_filter (optional, integer): specify the order of the Butterworth
%  low-pass filter. Must be a positive, even number. If unspecified, the
```

```
%  default value of 4 will be used.
%
%  P (optional, real): specify the two-sided confidence level. If not
%  specified, the default value of 95% (0.95) will be used.
%
%  Cmax (optional, integer): specify maximum number of channels to look
%  for. If not specified, the default value of 132 will be used.
%
%  Tmax (optional, integer): specify maximum number of tests to look for.
%  If not specified, the default value of 100 will be used.
%
%  start_sense (optional, real): specify the sensitivity parameter for the
%  start time finding algorithm. This value should be significantly less
%  than unity to avoid false start times, and greater than zero in order to
%  avoid failing to find a start time. The default value is 1/3, and it is
%  strongly recommended that all results with larger sensitivities than
%  this value should be visually scrutinized to avoid spurious results.
%
%  ==========================================================================
%  OUTPUT
%  ==========================================================================
%
%  Ntest(integer): the single output variable indicates the number of tests
%  for which data was located and analyzed. Returning zero indicates no
%  data was found.
%
%  This function will also produce an EXCEL worksheet file
%  (noise_recovery_results_test_*.xlsx) for every test where data exists.
%  In addition, three plot images for every channel of every test where
%  data exists will be plotted. First, the overall signal will be saved
%  (noise_recovery_signal_plot_ch_*_test_*.png), and a version centered
%  about the tail (noise_recovery_signal_plot_tail_ch_*_test_*.png).
%  Finally an FFT of the noise region (noise_FFT_plot_ch_*_test_*.png).
%
%  The EXCEL worksheet file has the following eleven columns:
%
%  channel: the channel being analyzed
%
%  start_time: the computed start time
%
%  cutoff_time: the cutoff time is simply start_time + delay
%
%  raw_peak: the absolute peak of the signal - offset computed for the raw
%  data.
%
%  filter_peak: the absolute peak of the signal with the offset subtracted
%  off computed for the filtered data.
%
%  raw_signal: the absolute signal - offset interpolated to the cutoff-time
%  computed for the raw data.
%
%  filter_signal: the absolute signal - offset interpolated to the cutoff-
%  time computed for the filtered data.
%
%  raw_max: the maximum of absolute signal - offset for values occuring at
%  or after the cutoff_time computed for the raw data.
%
```

```
%  filter_max: the maximum of absolute signal - offset for values occuring
%  at or after the cutoff_time computed for the filtered data.
%
%  noise_L: the lower two-sided P confidence interval for the signal past
%  the cutoff time.
%
%  noise_U: the upper two-sided P confidence interval for the signal past
%  the cutoff time.

%  ========================================================================

tic
display(' ')

% process optional input arguements
if ~nargin
    input_dir = [];
end
if nargin < 2
    output_dir = [];
end
if nargin < 3
    delay = 50e-6;
elseif isempty(delay)
    delay = 50e-6;
end
if nargin < 4
    offset = 0;
elseif isempty(offset)
    offset = 0;
end
if nargin < 5
    w_filter = 1/16;
elseif isempty(w_filter)
    w_filter = 1/16;
end
if nargin < 6
    N_filter = 4;
elseif isempty(N_filter)
    N_filter = 4;
end
if nargin < 7
    P = 0.95;
elseif isempty(P)
    P = 0.95;
end
if nargin < 8
    Cmax = 132;
elseif isempty(Cmax)
    Cmax = 132;
end
if nargin < 9
    Tmax = 100;
elseif isempty(Tmax)
    Tmax = 100;
end
```

```
if nargin < 10
    start_sens = 1/3;
elseif isempty(start_sens)
    start_sens = 1/3;
end

% correct filter to half of even number for symmetric filtfilt operation
N_filter = ceil( N_filter/2 );

% create output directory if it doesn't exist
if ~isempty( output_dir )
    if ~exist( output_dir, 'dir' )
        mkdir(output_dir)
    end
end

% loop over all tests
Ntest = 0;
fig = 0;
for k = 1: Tmax

    % preallocate results vectors
    channel = zeros(Cmax,1);
    start_time = NaN(Cmax,1);
    cutoff_time = NaN(Cmax,1);
    raw_peak = zeros(Cmax,1);
    filter_peak = NaN(Cmax,1);
    raw_signal = NaN(Cmax,1);
    filter_signal = NaN(Cmax,1);
    raw_max = NaN(Cmax,1);
    filter_max = NaN(Cmax,1);
    noise_L = NaN(Cmax,1);
    noise_U = NaN(Cmax,1);

    % loop over all channels
    Nc = 0;
    for j = 1: Cmax
        close all

        % test for jth channel data
        file = strcat( [ input_dir, '0', num2str( sprintf('%03d',j) ),...
            num2str( sprintf('%03d',j) ), '.',...
            num2str( sprintf('%03d',k) ) ] );
        if exist( file, 'file' )

            % when jth channel data load file
            Nc = Nc + 1;
            channel(Nc) = j;
            data = impax2mat(file);
            data.y = data.y - offset * ones(size(data.y));
            y = abs(data.y);
            raw_peak(Nc) = max(y);
            t = (1:length(y))' * data.dt;

            % use Butterworth filter to find filtered signal
```

```
Wn = 2*w_filter;
if Wn < 1
    avg = mean( data.y );
    [B,A] = butter( N_filter, Wn, 'low' );
    yf = filtfilt( B, A, data.y - avg ) + avg * ones(size(y));
    filter_peak(Nc) = max(abs(yf));
    filter_max(Nc)  = max( raw_signal(Nc),...
        max( ( t > cutoff_time(Nc) ) .* abs(yf) ) );
end

% find start and end times
[ t0, flag ] = find_start_time( t, y, 0.001, start_sens );
if flag == 1
    start_time(Nc) = t0;
else

    % alternate method for finding start times
    display( [ '----------------------------------------', ...
        '----------------------------------------' ] )
    display( [ 'WARNING: poor signal-to-noise ratio for ',...
        'Channel ', num2str(j), ' Test ', num2str(k), '.' ] )
    display( [ 'Switching to robust start time solver--',...
        'check signal plot to ensure validity.' ] )
    display( [ 'Start time precision may be highly ',...
        'dependent on filter frequency.' ] )
    display( [ '----------------------------------------', ...
        '----------------------------------------' ] )
    [ ~, m ] = max( abs( y - mean(y) ) );
    [ ~, m ] = max( abs( diff( yf(1:m) ) ) );
    start_time(Nc) = t(m);
end
cutoff_time(Nc) = start_time(Nc) + delay;

% compute filtered signal and filtered max signal
if Wn < 1
    filter_signal(Nc) = interp1( t, abs(yf),...
        cutoff_time(Nc) );
    filter_max(Nc)  = max( raw_signal(Nc),...
        max( ( t > cutoff_time(Nc) ) .* abs(yf) ) );
end

% compute raw signal and raw max signal
raw_signal(Nc) = interp1( t, y, cutoff_time(Nc) );
raw_max(Nc) = max( raw_signal(Nc),...
    max( ( t > cutoff_time(Nc) ) .* y ) );

% compute confidence intervals
i = find( t >= cutoff_time(Nc), 1, 'first' );
yn = data.y(i:length(y));
noise_L(Nc) = quantile( yn, (1-P)/2 );
noise_U(Nc) = quantile( yn, 1 - (1-P)/2 );

% create recovery signal plots
for q = 1: 2
    fig = fig + 1; figure(fig), clf, hold on
    plot( t - start_time(Nc)*ones(size(t)), data.y, 'k-' )
```

```
xlabel('time - start time')
if offset == 0
    ylabel('signal')
else
    ylabel('signal - offset')
end

% plot filtered signal
if Wn < 1
    plot( t - start_time(Nc)*ones(size(t)), yf, 'm-' )
end

% fix time axis limits
if q == 1
    t1 = - 0.2*delay;
    t2 = 12*delay; %originally 1.2*delay TTC
    digits = ceil( log10(t2) );
    mag = 10 ^ ( floor( log10(t2) ) + digits );
    t1 = floor( t1 / mag ) * mag - eps;
    t2 = ceil( t2 / mag ) * mag + eps;
else
    t1 = 0.8*delay;
    t2 = 20*delay; %originally 2.2*delay TTC
    digits = ceil( log10(t2) );
    mag = 10 ^ ( floor( log10(t2) ) + digits );
    t1 = floor( t1 / mag ) * mag - eps;
    t2 = ceil( t2 / mag ) * mag + eps;
end
xlim( [ t1, t2 ] );

% plot start and cutoff times
yrange = ylim;
if q == 1
    plot( [0,0], yrange, 'g-' )
end
plot( delay*[1,1], yrange, 'r-' )
if Wn < 1
    if q == 1
        legend( 'raw signal', 'filtered signal',...
            'start time', 'cutoff time', 'Location',...
            'Best' )
    else
        legend( 'raw signal', 'filtered signal',...
            'cutoff time', 'Location', 'Best' )
    end
else
    if q == 1
        legend( 'raw signal', 'start time',...
            'cutoff time', 'Location', 'Best' )
    else
        legend( 'raw signal', 'cutoff time',...
            'Location', 'Best' )
    end
end
plot( xlim, [0,0], 'k--' )
ylim( yrange )
```

```
            % print noise recovery test plot
            if q == 1
                tail = 'signal';
            else
                tail = 'tail';
            end
            title( strcat( [ 'Noise recovery ', tail, ' Channel ',...
                num2str(j), ', Test ', num2str(k) ] ) )
            file = strcat( [ output_dir,...
                'noise_recovery_', tail, '_plot_ch_', num2str(j),...
                '_test_', num2str(k), '.png' ] );
            print( fig, '-dpng', '-painters', file )
            display( [ 'printed ', file ] )
        end

        % create FFT plot for noise region
        NFFT = 2 ^ nextpow2(length(yn));
        FFT = fft(yn,NFFT)/length(yn);
        FFT = 2*abs(FFT(1:NFFT/2+1));
        f = linspace(0,1,NFFT/2+1)'/data.dt/2;
        fig = fig + 1; figure(fig), clf, hold on
        plot( f, FFT, 'k-' )
        set( gca, 'XScale', 'log' )
        xlabel( 'frequency' )
        title( [ 'Fast Fourier Transform, Channel ', num2str(j),...
            ', Test ', num2str(k) ] )
        file = [ output_dir, 'noise_FFT_plot_ch_', num2str(j),...
            '_test_', num2str(k) ];
        print( fig, '-dpng', '-painters', file )
        display( [ 'printed ', file ] )

    end
end

% save tabular data for tests where data exists
if Nc
    Ntest = Ntest + 1;

    % output to screen that data has been found
    display(' ')
    display( [ num2str(Nc), ' channels for test ', num2str(k),...
        ' were analyzed' ] )

    % truncate statistics vectors
    channel = channel(1:Nc);
    start_time = start_time(1:Nc);
    cutoff_time = cutoff_time(1:Nc);
    raw_peak = raw_peak(1:Nc);
    filter_peak = filter_peak(1:Nc);
    raw_signal = raw_signal(1:Nc);
    filter_signal = filter_signal(1:Nc);
    raw_max = raw_max(1:Nc);
    filter_max = filter_max(1:Nc);
    noise_L = noise_L(1:Nc);
    noise_U = noise_U(1:Nc);
```

```
        % create tabular output
        noise_recovery_results = table( channel, start_time,...
            cutoff_time, raw_peak, filter_peak, raw_signal,...
            filter_signal, raw_max, filter_max, noise_L, noise_U )
%#ok<NOPRT>
        file = strcat( [ output_dir, 'noise_recovery_results_test_',...
            num2str(k), '.xlsx' ] );
        writetable( noise_recovery_results, file )
        display( [ 'printed ', file ] )
    end
end

% display output stamp
display(' ')
if Ntest
    display('noise_recovery_test finished successfully')
    display( strcat( [ 'Found data for ', num2str(Ntest), ' tests' ] ) )
else
    display( 'noise_recovery_test failed to find data for any tests:' )
    display( '  check that the correct input directory was specified' )
    display( '  and that files are in the expected format' )
end
display( strcat( [ 'run time: ', num2str(toc), ' s' ] ) )
display( strcat( [ '----------------------------------------',...
    '----------------------------------------'] ) )

end
```

7. DISTRIBUTION

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