PROGRESS ON COMPONENT EVALUATION FOR NUCLEAR EXPLOSION MONITORING

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ABSTRACT

The Ground-Based Nuclear Explosion Monitoring Research and Development (GNEM R&D) program at Sandia National Laboratories (SNL) is regarded as the primary center for unbiased expertise in testing and evaluation of geophysical sensors and instrumentation for nuclear explosion monitoring. We had four main areas of interest to make progress on this year; this report will cover the advances made in these areas. First is the continued development and research of the three-component coherence technique of Sleeman et al. (2006). We have reverted back to synthetic testing to develop a firm understanding of the arithmetic limitations in processing to recover small value estimates of noise relative to large input signals. We explored the effects of digital quantization of the analog signal, as well as the limitations of the technique in the presence of high signal-to-noise input signals. The second area of interest is the upgrade of our suite of software used to analyze sensors and digitizer data (e.g., to calculate noise floor, time-tag accuracy). This past year has allowed us time to develop the new data model and relevant meta-architecture, proto-type existing algorithms in MATLAB with validation against existing tool sets, and develop sets of reusable modules (e.g., waveform editing tools and test description). Our third area of concentration over the past year focused on testing new components for both Provisional Technical Secretariat and the Air Force Technical Applications Center (AFTAC). Characterization reports were produced for two infrasound sensors, Chaparral Physics model 2.5 low-gain and the Inter-Mountain Labs model SS avalanche sensor as well as one data logger, Geotech Smart24. For the infrasound sensors tested, the test results allow us to conclude that both sensors had sufficiently quiet noise floor to be at or below the Acoustic low-noise model from 0.1 to 7 Hz, which make these sensors suitable to explosion monitoring. The characterization report on the Smart 24 documented meeting requirements for an International Monitoring System site. The final area of focus for the component evaluation (CE) project has been the maintenance and upgrade of our seismic and infrasound test-beds. Recent additions have included additional reference sensors for monitoring environmental conditions during infrasound testing as well as exploring the necessary requirements needed for an infrasound test chamber. This work directly impacts the Ground-Based Nuclear Explosion Monitoring mission by providing a facility, equipment, and personnel to give the operational monitoring agencies confidence in deployed instrumentation and capability for mission success.

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OBJECTIVES

Over the past year the Component Evaluation project of the GNEM R&D program at SNL has made reportable contributions in four areas. These areas are new component evaluation techniques and visualization methods, the upgrade of our existing methodology for the analysis, reporting and archiving of component evaluation test results, results of characterization testing of infrasound sensors and the upgrade and upkeep of test bed equipment for the Facility for Acceptance, Calibration, and Testing site.

Introduction

AFTAC is tasked with monitoring compliance of existing and future nuclear test treaties. To perform this mission, AFTAC uses several different monitoring techniques to sense and monitor nuclear explosions, each designed to monitor a specific domain (e.g., space, atmosphere, underground, oceans, etc.). Together these monitoring systems, equipment, and methods form the United States Atomic Energy Detection System (USAEDS). Some USAEDS seismic stations may be included in the International Monitoring System (IMS). Each agency involved in the monitoring community has requirements which the system and components (sensors and data loggers) must pass before deployment and later certification. Historically, SNL has been involved in the testing of seismic systems to monitor for compliance with terms of nuclear weapon test ban treaties. With the recent addition of infrasound and seismo-acoustic stations, SNL has worked to develop the capability and procedures to perform the characterization of infrasound sensors, infrasound systems, and seismo-acoustic systems.

Over the past year Sandia has characterized more than 60 Chaparral Physics model 2.5 (CP2.5) low gain sensors. The CP2.5 sensors were characterized for sensitivity, amplitude response, linearity and self-noise. Two internal SAND reports (Hart, 2007a and 2007b) and one in progress detail the characterization of the individual sensors, here, we will summarize the results as related to the monitoring community. A second infrasound sensor, the Inter-Mountain Labs model SS infrasound sensor, was evaluated as a possible sensor for the monitoring community. The results were reported in Hart (2007c) and will be summarized here. Recently, we have started to investigate the effects porous-hose filters have on the characterized sensors. We find an unexpected filter response, at a lower frequency than expected. Sandia was also asked to evaluate the Geotech Smart24 data logger for qualification as a replacement to the Geotech DL24 data logger in US IMS stations. The results of testing the Smart24 data logger can be found in Hart (2008), the relevant aspects of bit-weight and timing accuracy and self-noise will be shown.

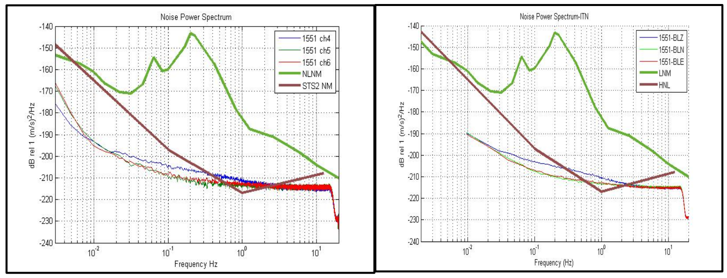
As part of a continuing effort to develop an improved technique to estimate a components (data logger, sensor, etc.) self-noise and relative response between three co-located and similar sensors or recording channels. The technique described by Sleeman et al. (2006) and results presented in Hart et al. (2007) on the three-component coherence algorithm were tested using synthetic data as input to verify and document the numerical limitations in calculation. Comparisons were made between the levels of coherent signal to incoherent noise to determine the maximum signal-to-noise ratio allowed by the technique. A second effect that was addressed is related to the digital sampling of the analog signal input. The resolution (24-bit versus 26-bit format) and rounding effects of digital sampling of the input signals as compared to double-precision float are shown.

SNL has developed and refined, over a number of years, several unique analysis techniques used in the evaluation of data loggers, and infrasound and seismic sensors. Due to the desire to increase the efficiency and traceability of our testing capability the component evaluation project is developing a new software tool for this purpose. At the current stage of development, a new underlying architecture has been developed with the intent of multi-platform compatibility, connection with research tools, traceability of testing with defined database schema, and an easy to use user interface.

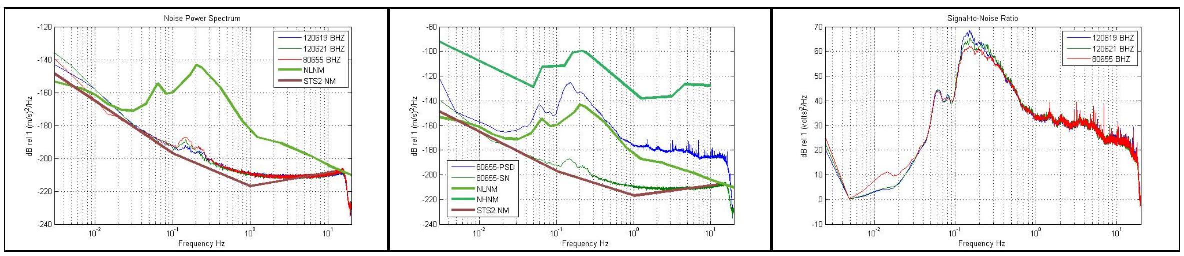
RESEARCH ACCOMPLISHED

New Synthetic Test for Three Component Coherence

From our original paper, Hart et al. (2007), and continuing work that was presented at the annual fall meeting of the American Geophysical Union 2007 on the application of the three component coherence technique, two primary observations were made from our results. The first observation showed an accurate estimate of digitizer (i.e., Q330, Q330HR and Smart24) self-noise was produced and matched the results of an independent self-noise estimator – Input Terminated Noise. Figures 1a and b illustrate for the Q330HR the accuracy of the estimation of noise for the three channels tested. The second observation was related to the results of processing of STS2 data. We observed a deviation in the self noise estimates for the three seismometers tested. The deviation from smooth noise is observed between 0.1 and 0.3 Hz. This band correlates in frequency with highest signal-to-noise ratio (SNR) of the power spectrum. Figures 2a, 2b, and 2c show these observations.



Figures 1a and b. Self noise estimates for Q330HR channels 4-6, comparison results from 3C technique and ITN. The thick green line is the USGS low noise model. The thick brown line is the STS2 noise model. The thin blue, red and green lines are the noise estimates for the channels 4, 5 and 6 respectively.



Figures 2a, b, and c. Self noise estimates for three STS2 illustrating the observed deviation in noise between frequencies 0.1 and 0.3 Hz (a), this correlates to the peak in the background power spectrum (b) and the regions of highest signal-to-noise (c).

To determine if the observed deviation was an artifact of the numerical limitations of the calculations we devised a set of tests using synthetic data in which we could vary the absolute level and level of separation between the noise and coherent signals. The tests consisted of generating four random sequences, three are used for the incoherent noise signals and the fourth is used as the coherent signal. We chose to use normally distributed, randomly generated, double precision numbers. The sequences ranged between approximately, ± 5.5. The absolute scaling ranged from -213 to 27 dB, while the SNR was varied from 0 to 240 dB. Assuming a purely linear system, we add each noise signal to the coherent signal to get the three new signals for processing with the 3C technique. The results are shown in Figure 3 and display 156 realizations of the technique. The graph is read from left to right for any one line type, at equal or greater scaling of the coherent signal to that of the three random sequences the 3C technique adequately resolves the power levels of the incoherent noise up seven orders of magnitude. At separations of SNR greater than seven, the estimated noise by the technique is greater than the actual noise levels.

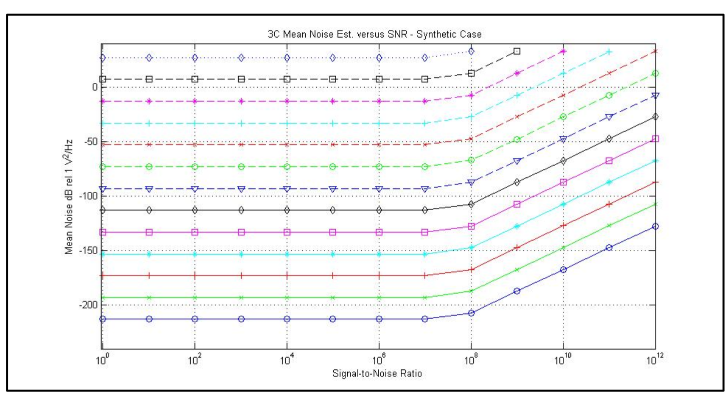


Figure 3. Results of synthetic testing to determine numerical limitations of 3C technique showing 156 realizations each line common line type shows the results for a single absolute scale value, the effects of varying the separation of the combined coherent and incoherent signals.

Varying the absolute level start which the analysis was done did not change the relative SNR level at which the technique started to break down, between 140 and 160 dB of SNR. To rule out the cause of the 140 dB limitation on the analog to digital conversion of the input signal, we devised another test to explore this. After the coherent and incoherent signals are combined, divide the series by the least-significant bit (LSB), then round the sequence to integer values and then multiple the series by the same LSB. Two different LSB were used to represent the 24-bit and 26-bit digitations. Figure 4 shows the results, on the left are results using floating point double precision correct extraction incoherent signal level of -133 dB across the 140 dB of SNR. The middle axes shows the results for the 24-bit LSB, with just over 1.5 dB of over-estimation of incoherent signal level, and the right axes showing results for 26-bit LSB with 0.2 dB over estimation. From this test we find that the digital conversion of the analog signal does not account for the band-limited deviation observed in the STS2 data, but one should consider the amount of over-estimates of noise when recording on 24-bit format. Through this synthetic test, we conclude that the 3C technique can produce reliable results when the scaling between the coherent and incoherent signals is less than 140 dB. Further thought will be given to deviating a suite of tests to understand these observations.

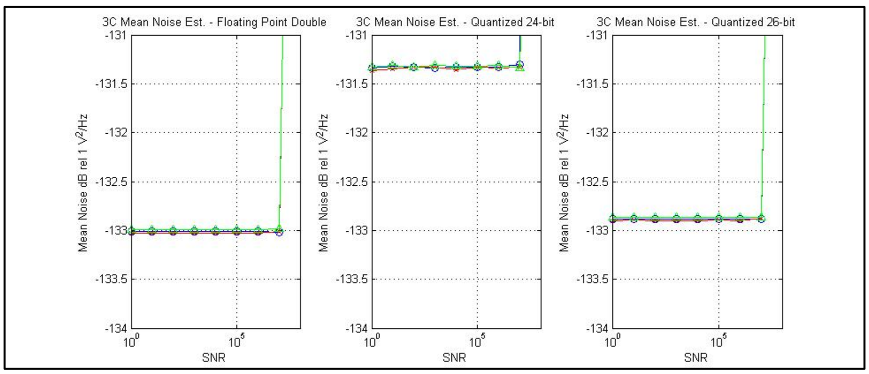


Figure 4. Results of synthetic testing to determine limitations of 3C technique with respect to rounding effects; as pertaining to the digital conversion of an analog signal. Left axes shows results of using double-precision floating point, the middle axes shows results using 24-bit quantization and the right axes are results of using 26-bit quantization.

Characterization Geotech Smart24 Data-Logger with Active Fortezza Crypto Card Data Signing

Over the spring of 2008 we have characterized the Geotech Smart24 data-logger with active data encryption as required for certain deployment applications. A complete characterization report can be fond in Hart, 2008a. Our characterization was done on two different configurations of the possible Smart24 Analog-to-Digital conversion boards, the first allows for maximum of 20 Vpp and second allows for a maximum of 40 Vpp. The 20Vpp ADC board had a serial number of 1360 and the 40Vpp ADC board had a serial number of 1724.

The overall performance of the Smart24 meets or exceeded the manufactures specifications for pass-band, dynamic range, bit-weight accuracy, and total harmonic distortion. The bit-weight accuracy was within 0.5% of nominal, RMS noise was below 1.5 μV for the 0.02 to 10 Hz band, maximum potential dynamic range was better than 131 dB, total harmonic distortion was better than -121 dB and channel-to-channel cross-talk was better than -122 dB. One area of issue was the time-tag accuracy, which fell just outside the manufactures specifications of ±10 μs at ~18 μs. Through working with the vendor we determined that configurations issues may exist between our test equipment and the Smart24 and are working to better understand the complexities of the interaction.

A follow up report on the application of a Smart24 matched with a Streckeisen STS2 low and high gain, Guralp CMG3T and a generic Geotech GS13 is currently underway. This will document the pass band is these sensors if matched with the Smart24.

Characterization Inter-Mountain Labs Model SS Infrasound Sensor

Our goal in testing the Inter-Mountain Labs infrasound sensors was to determine and document the performance of this sensor as pertaining to the monitoring community. Three sensors were evaluated, serial numbers 605368, 605408, and 605488, for the 0.1 to 10 Hz pass band, sensitivity, linearity between 0.007 and 11 Pa, amplitude response, and self-noise. The three sensors varied from there average 5 Hz sensitivity, mean sensitivity of 0.369 mV/Pa, by up to 5.3%. The sensors were linear in their sensitivity to within 1% between pressures ranging from

0.007 to 7.3 Pa. From our amplitude response verification test shown in Figure 5, we found the sensors to be flattest between 2 and 10 Hz and more than 3 dB of roll-off, relative to 5 Hz, at 1 Hz.

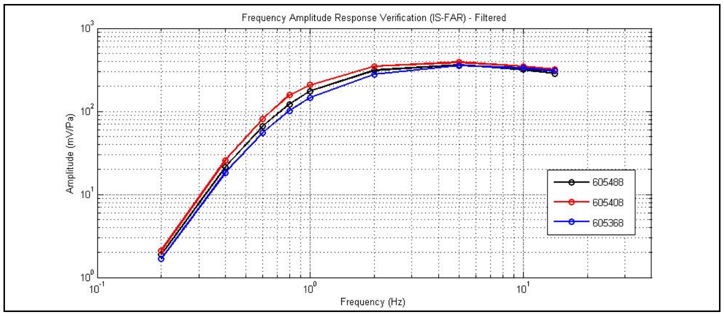


Figure 5. Amplitude response model for the IML Model SS infrasound sensors.

Using this response model, we correct self-noise power spectrum into units of Pa^2/Hz, shown in Figure 6. Plotting the noise of the IML sensor with the Acoustic Low Noise Model (ALNM), shows the IML sensor at or below the ALNM between 0.2 and 10 Hz, therefore this sensor would be capable of observing a broad range of signal levels due to its low noise characteristics.

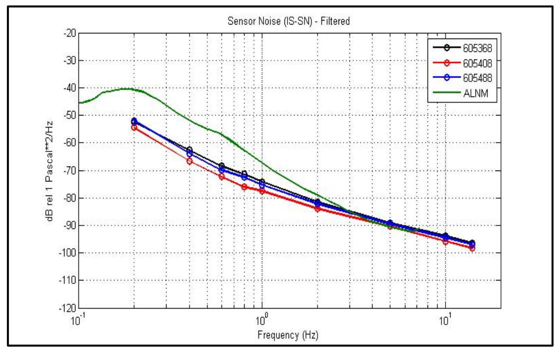


Figure 6. Self-noise estimates for the Inter-Mountain Labs sensor, corrected using amplitude response model shown in Figure 5. ALNM is shown in green.

Characterization Chaparral Physics Model 2.5 Low Gain Infrasound Sensor

One sensor type we have characterized a large number of prior to deployment is the CP2.5 low-gain. Typical characterization of these sensors includes sensitivity at 1 Hz, amplitude response between 0.02 and 5 Hz, linearity between 0.1 and 5 Pa, and noise characteristics of electronics and transducer. Typically, when a new set of CP2.5 sensors arrives for testing, we'll review the provided data sheets, and take relevant notes adding necessary information into a spreadsheet for reference. The sensors are tested and, where possible, we compare our results with those of the manufacture, noting any discrepancies. Two noteworthy observations have been made as a result of testing these sensors. The primary one being the 1 Hz sensitivity has been recorded as deviating from the manufactures specified value of 0.400 V/Pa (±5% for individual sensor sensitivities). Our testing has shown variability in 1 Hz sensitivities from 0.373 to 0.486 V/Pa, with our test results typically higher than those documented in the sensors data sheets. Table 1 shows a comparison between results of common tests: on average, we report a 25% higher sensitive and slightly less than half the frequency of the low frequency associated to the -3 dB roll-off point of the amplitude response.

Table 1. Table comparing test results for 1 Hz sensitivity and the 3 dB corner frequency reported by Chaparral Physics in their data sheets and Sandia.

Serial Number	1.0 Hz sensitivity (V/Pa) Chaparral	1.0 Hz sensitivity (V/Pa) Sandia	3 dB frequency - Chaparral	3 dB frequency - Sandia
061752	0.391	0.439	0.087	0.0459
061753	0.376	0.446	0.093	0.0436
061754	0.387	0.443	0.094	0.0435
061755	0.403	0.465	0.098	0.0457
061773	0.396	0.480	0.085	0.04
061778	0.411	0.472	0.088	0.0423
051756	0.392	0.392	0.1	0.0496
051757	0.396	0.445	0.095	0.0433
Average	**0.394**	**0.448**	**0.0925**	**0.0442**

The second observation is associated to the variability of the self-noise estimates of the individual chaparral sensors tested. The typical method for determining self-noise is done in one of two configurations. The first configuration is done to test for electronics noise, in which a relay is energized opening a circuit switching a fixed CR-circuit for the transducer element. The second configuration is done to measure transducer noise, in this case all the sensors pressure inlets are covered and the sensor is isolated in a chamber to dampen the effects of atmospheric influence. Figure 7 shows the results electronic noise tests for 61 different CP2.5 sensors. Typically, the sensors are below the ALNM at frequencies below 1.5 Hz and above the ALNM at frequencies above 1.5 Hz. This makes the CP2.5 not suitable for sites where their average background above 1 Hz is below -70 dB rel 1 Pa^2/Hz and another quieter sensors may be desired .

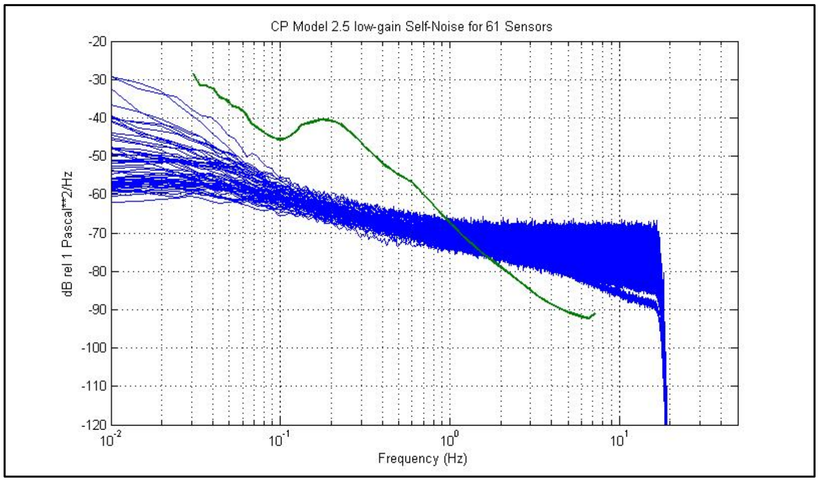


Figure 7. Self-noise estimates for 61 Chaparral Physics model 2.5 low gain infrasound sensors. The ALNM shown as the green line. Sensors are typically at or below the ALNM from below 0.01 Hz to 1.0-1.8 Hz.

As part of our tasking, we are looking for new ways of processing and visualizing the results from our testing. One new addition to our visualization capability has been to implement a similar analysis of our computed power spectral density (PSD) of sensors noise to that done by McNamara and Buland (2004) for ambient seismic background noise of the continental U.S. Instead of computing a single PSD for our analysis window, we compute several hundred for each analysis window. By statistical analysis of the power bins for each frequency, for the hundreds of compiled PSDs, yields probability density functions (PDFs) as a function of power. Comparison of related sensor self-noise PDFs show interesting artifacts related to sensor uniqueness and overall sensor quality. Figure 8 shows an example of the value of viewing sensors noise data as a PDF. The two plots (top and bottom) are of the same data, shown in different x-axis scales (top-logarithmic and bottom-linear). We can clearly see two dominant trends in the sensors noise characteristics at frequencies higher than 1 Hz, below 1 Hz the sensor's noise mergers into a single dominant feature of high probability. Using typical methods for noise analysis, one might only see the lower or upper noise features, masking the duality of the noise in this sensor. Further work will be done to migrate this technique into our routine analysis.

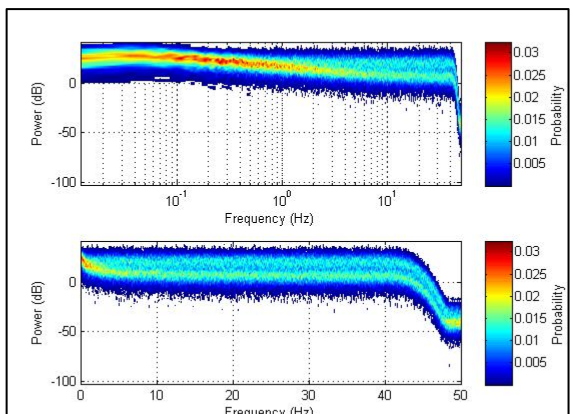


Figure 8. Self-noise estimate for one Chaparral Physics model 2.5 low gain infrasound sensor shown as Probability Density Function (PDF) of power.

Characterization Porous Hose Filters used with Chaparral Physics 2.5 Infrasound Sensor Array

As part of our on going effort to support operational needs of our customers, Sandia has built the capability to test and characterize the porous-hose filters used in some infrasound arrays for the monitoring purpose. The initial test configuration was designed around one deployment method for CP2.5 sensors. Each CP2.5 sensors inlet (each sensors has four inlets) is connected to a solid hose (1–3 feet in length), which is connected to environmental housing (EH). The outside of the EH then connects to a single inlet-to-double output Y connector. At each end of the Y connector a 50-foot porous hose is connected. At each sensor there are eight porous hoses aligned approximately π/2 radians apart from each other. The sites aperture is around 100 feet. A second CP2.5 sensor is co-located with the first, and has only a single short solid hose attached to one of its inlets, the other three inlets are left uncapped to reduce unwanted high frequency harmonics. A time segment was selected for processing and PSD were computed for the two co-located sensors. To determine the relative amplitude response of the porous-hose filter system the two PSD were divided. We were expecting to see some sort of low pass filter characteristics, but what we saw was not anticipated. The filter can be characterized as low pass with little or no attenuation of acoustic signals with period longer than 50 seconds, while signals with shorter periods attenuated 15 dB at 0.1 Hz and ~25 dB at 1 Hz (Figure 9). With no correction for the amplitude reduction of the porous hose filter any analysis using amplitude measurements between 0.1 ands 10 Hz will under estimate the association.

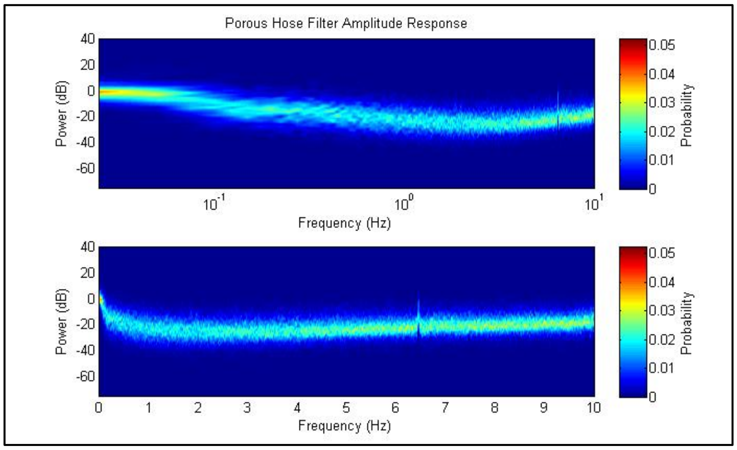


Figure 9. Amplitude response of an 8-arm porous hose filter system. Filter can be characterized as low pass with little or no attenuation of acoustic signals with period longer than 50 seconds, while signals with shorter periods attenuated 15 dB at 0.1 Hz and ~25 dB at 1 Hz.

Component Evaluation Software Upgrade

The current software used to analyze data collected from testing is called the Instrumentation Evaluation Software (IES) and was written for the component evaluation program in the late 1980's. The software was written as a collection of custom and distinct C utilities that perform the various aspects of the test analysis:

- Waveform file conversion
- Waveform time segmenting
- Manage sensor responses and apply responses to waveforms
- Compute PSD, THD, DC Accuracy, Coherency, Sine Fits, Time tag accuracy, etc

In order to run the analysis tools, the user must first load the waveform data recorded from the test and specify a time window to segment the waveform. The resulting segment is then stored in an ASCII file format that each of the analysis tools can read.

Each of the analysis tools must then be run individually and manually pointed to the cut waveform segment for that particular test. Once the analysis tool has been run, the results are presented to the user in the form of a graphical window. The user must then capture the results of that test either by transcribing values into a spreadsheet, printing the window, or capturing a screen shot to a file or embedded into a document. To be able to save the results (and later regenerate the test, if necessary), the user must retain a copy of the input waveform as well as all of the parameters that were used to generate the results. This typically results in a proliferation of various files saved in a folder on disk.

The major problems faced by the current set of analysis tools are that there is too much overhead involved in using the analysis tools and transferring the results of that analysis to a report. Also, the current methodologies in place for capturing the data and results for a test are inadequate.

Some of the goals of the proposed test analysis utility that could help to improve the Evaluators performance are to

- Streamline the analysis process to eliminate the need to shift from tool to tool.
- Ensure that the entire state of a test process is retained in a single easy to access location. This would also have the advantage of eliminating the clutter that is generated by having to store each stage of the analysis as a file on disk
- Provide users with the ability to return to a historical test and re-run the analysis with slightly different parameters (filter, window, etc). Possibly re-generate the updated report with a push of a button.
- Provide a mechanism for the results of the test analysis to be fed directly into a report.

One of the first steps in building a replacement for the IES tools was to ascertain what exactly the current analysis tools were doing. Towards that end, prototypes of the algorithms were implemented in MATLAB and the results compared against those of the IES analysis tools. Verifying the functionality of the analysis tools is important to validate our understanding of the algorithms and to provide traceability in the results of any future analysis tools. Also, wherever possible, the implementation of the algorithms is being tied to an IEEE reference.

A database schema must be designed to capture and archive the state of the hardware being tested, the suite of tests to be run on each piece of hardware, and the results of each test. In the schema diagram in Figure 10, the schema is divided into four regions: Systems, Responses, Tests, and Models.

The System tables define the physical components that are to be tested and how those components are organized into subsystems. A component could be a seismometer, acoustic sensor, digitizer, meter, or even a cable. The Response tables define the response of a particular component in either pole-zero or FAP format. The Test tables provide a generic mechanism for capturing relevant information about any type of test by associating any arbitrary number of waveforms, parameters, and results. In addition, tests are associated with the particular component or subsystem that is being tested. Finally, the Model tables allow for capturing models that may be used for comparison within the testing system.

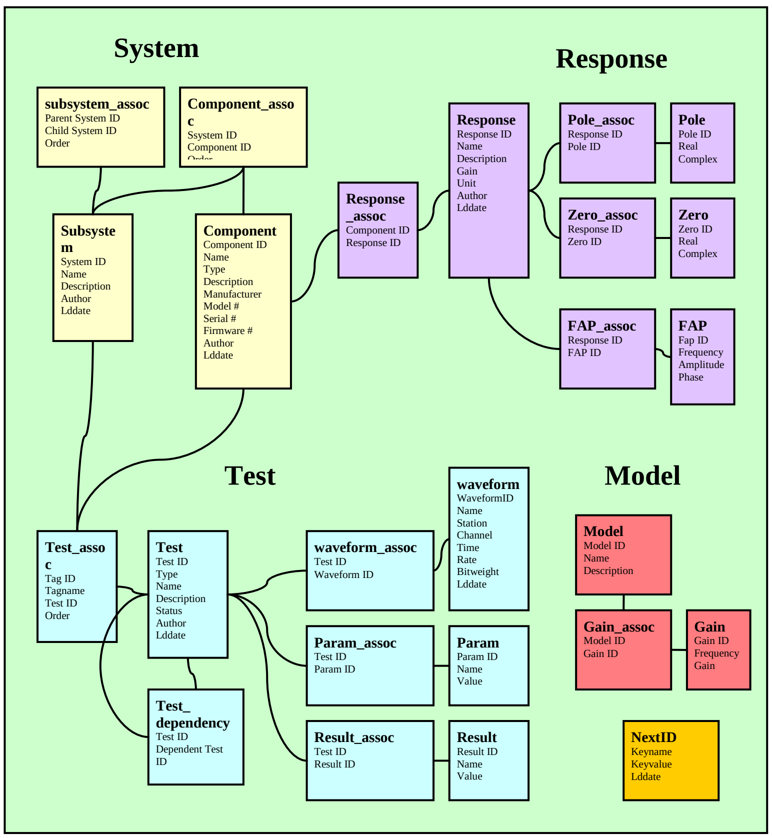


Figure 10. Database Schema Diagram

In addition to defining the database schema, the core set of functionality for the test system has been implemented, as described in the Object Model Diagram below (Figure 11). The object model lays out the bulk of the implementation: A database interface, waveform access, viewers for many of the objects, and signal processing algorithms. The bulk of the effort, however, is aimed at implementing the multitude of tests that are needed. A test interface is defined that supports the generic capability for the storage of the parameters, results, and waveforms within a test. Each test defines its own set of parameters, results, and waveforms as well as the computation that is necessary to complete the test analysis.

The implementations of the test interface are defined as plug-ins that can automatically register themselves at application startup time. The advantage of using this type of plug-in architecture is that the remainder of the application can interact with the test implementations just as generic tests. No prior assumption of a specific test is required. Also, the choice of possible tests that can be performed for each system or component is determined dynamically. Additional tests can be defined without making any changes to the system other than the specific implementation of the test.

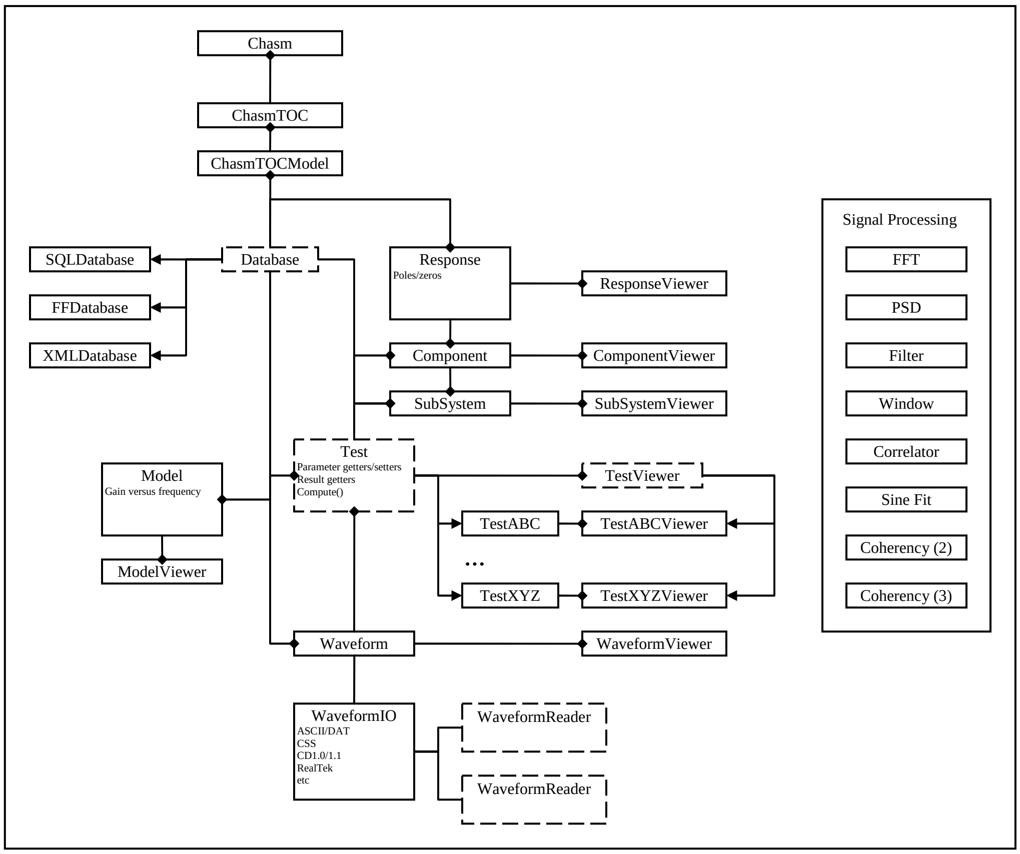


Figure 11. Object Model Diagram

CONCLUSIONS AND RECOMMENDATIONS

Continuing work on three sensor coherence has allowed us to explore the numerical limitations of the technique with synthetic data. As well as, rule out possible causes for deviations observed in the self-noise estimates of STS2 seismometers. We continue to seek out new sensors technologies (primarily seismic and infrasound types) that may have value to the explosion monitoring community. New methods for the visualization of results from testing have led to the use of probability density functions to characterize self-noise of sensors, as well as to characterize the amplitude response of porous-hose filter system used at some monitoring infrasound stations. With continued support we hope to maintain an active role and add value to the nuclear explosion monitoring community.

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