A LASER INTERFEROMETRIC MINIATURE SEISMOMETER

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ABSTRACT

The threat of nuclear proliferation remains a critical issue in our society. Prevention requires knowledge, and there is no greater indicator of the capability and intent of a nation than observation of actual detonation tests being conducted. Ground-based monitoring systems have proven to be very capable in identifying nuclear tests and can provide somewhat precise information on the location and yield of the explosive device. Making these measurements, however, currently requires very expensive and bulky seismometers that are difficult to deploy in places where they are most needed. A high-performance, compact device can enable rapid deployment of large-scale arrays, which can in turn be used to provide higher-quality data during times of critical need.

During our Phase I Small Business Innovation Research (SBIR) work, we designed and built a seismic sensor prototype that is 40 times smaller than existing state-of-the-art sensors. This acceleration sensor integrates optoelectronics, passive optics, and micromechanical structures in a compact assembly that is robust and extensible to manufacturing. The use of an optical interference transducer provides very high gain in the displacement measurement, which in turn leads to mechanical design parameters that are optimal for miniaturization without performance being sacrificed.

We extended this work in the first year of our Phase II research. Compact sensors were assembled in a robust connectorized housing. This sensor demonstrated substantial progress towards the goal of a very low noise seismometer, with a noise floor approaching –150 dB/Hz relative to 1 m^2/s^4. These prototypes shed light on the remaining issues to be addressed in order to reduce the noise to the target level of –168 dB/Hz from 0.1 Hz to 40 Hz. We need improvement in our sensor control electronics, in addition to compensation for the nonlinear optical response curve. These improvements will be implemented in the next prototypes to be built by the end of FY 2010.

OBJECTIVES

This goal of this work is to create a much smaller seismic sensor that is optimized for nuclear test ban treaty monitoring. Such a device would substantially reduce the deployment cost for temporary or permanent monitoring stations. The ultimate objective, as defined by the National Nuclear Security Administration (NNSA) in the original call for proposals, is to make a 1" sensor with performance that is equivalent to or better than the new low-noise model from 0.2 to 40 Hz, with a digital output and total power consumption of 100 mW. Such a device would represent a tremendous advance in the state of the art.

The technical objectives of our 2-year Phase II research, as established in our original proposal, are as follows:

1. Refine our sensor designs from Phase I so that they may extend to N-layer normal mode (NLNM**)** limited performance, along with the commensurate testing and verification procedures necessary to prove this performance.
2. Establish robustness and reliability testing for this new technology to enhance the opportunity for rapid acceptance in the marketplace.
3. Execute field tests using arrays of devices (10 to 100), in collaboration with systems-integration companies and/or government test facilities.
4. Establish collaborations with chip manufacturers and system integrators to create a digital output sensor that can be rapidly deployed in arrays.
5. Packaging of a compact, 3-axis digital sensor prototype that can be operated in any orientation and meets the specifications as spelled out by the Department of Energy.

RESEARCH ACCOMPLISHED

We did not explicitly separate the above objectives into yearly segments, but instead we presented a continuous 2-year plan for the accomplishment of these objectives. However, success of the first objective was determined to be the most important to focus on early in the project, as the sensor performance is the driver for all other progress. We successfully progressed through the design phases for the sensor, housing, and electronics. We designed a robust sensor with a standard connector that could survive in harsh environments. We then established a test plan for in-house testing, and we acquired the necessary data-acquisition and reference-sensor components that are required for this task. We then built several sensors and tested them. Our initial measurements showed a higher-than-expected noise floor but still a 10 dB improvement over our Phase I prototypes.

Our Phase I protoypes were very good for miniature seismometers, but they were still about 25 dB higher than the targeted noise floor. Those prototypes were intended to be a significant advance forward, and they were indeed about 30 dB better than previous attempts to make robust compact accelerometers. We began Phase II with a design phase to address the issues identified with the Phase I prototypes. We made numerous design changes in order to make improvements in the device noise floor. We increased our proof mass substantially and modified our spring design to increase sensitivity, while reducing our noise floor. These design changes resulted in the theoretical physical noise limits, defined by the mechanical thermal noise and the photodiode shot noise, being pushed to below the target levels.

We designed a housing made from anodized aluminum. A connector from Fischer was used for all of the I/O. This circular connector is the smallest that is readily available, while still meeting the requirements of robustness. It is a watertight, submersible connector (IP68). We also acquired custom cables built by Fischer. The completed sensor design is shown in Figure 1, along with a photo of an assembled device.

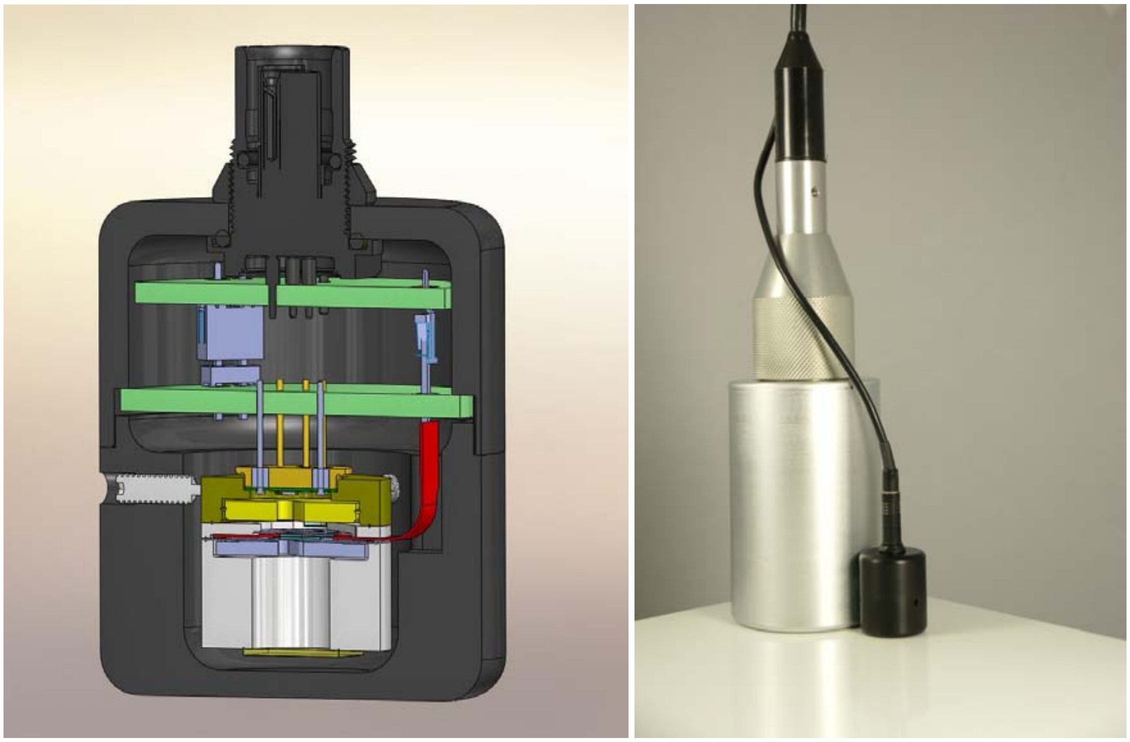

Figure 1. Left is a modeled cross-sectional view showing the sensor capsule, electronics, and housing. On the right is a completely assembled sensor, placed next to a 1-Hz geophone for reference.

The noise performance of the SA1210 was a considerable step forward, although we still have some ways to go before we achieve low-noise model performance. In Figure 2, we compare the low-frequency noise performance of devices from Phase I with the most recent devices from Phase II. The noise is dominated by our implementation of a mass-centering control loop that operates at very low frequencies to maintain the sensor at an optimal operating point. We are also impacted by the temperature sensitivity of the sensor and the very short time constant of the thermal coupling between the outer housing and the sensor capsule. As such, low-frequency noise measurements are usually dominated by ambient temperature fluctuations, an issue that would be greatly reduced in a typical shallow borehole deployment. Nonetheless, we are substantially altering the sensor design to eliminate these thermal issues.

The nonlinearity of the optical signal also must be accounted for, as aliased high-frequency signals (>100 Hz) can produce noise in the baseband. Since we are developing our own digital output implementation, compensation for this will be straightforward.

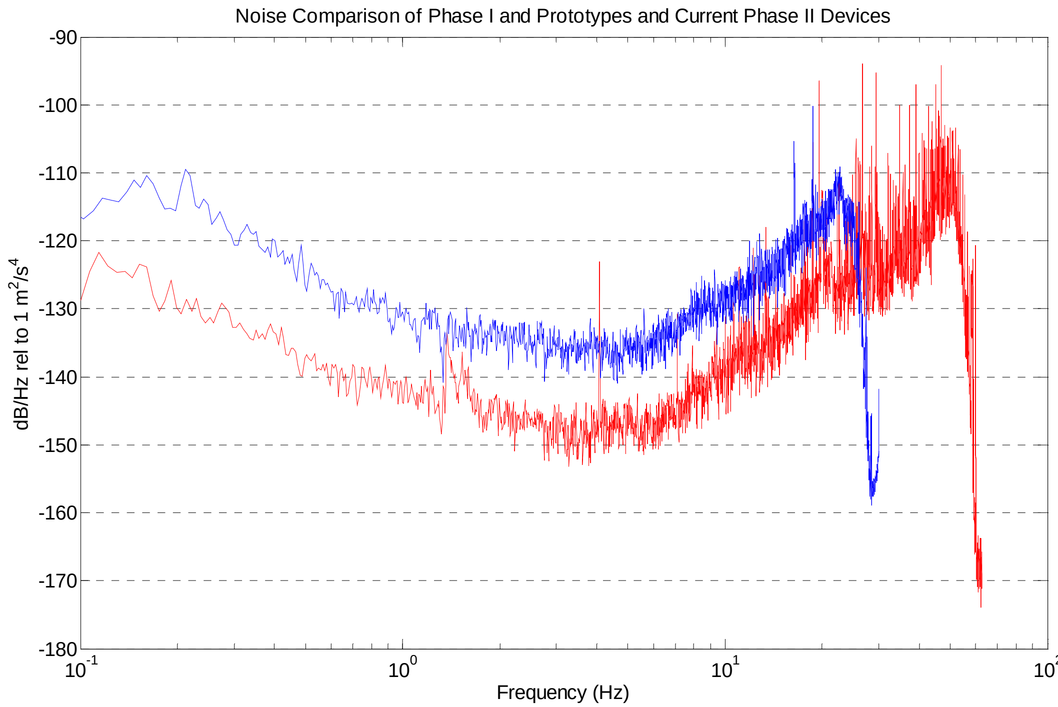

Figure 2. A comparison of the noise floor of our Phase I devices and our most recent Phase II devices. Above a few Hz, the ambient noise dominates in both spectra.

CONCLUSIONS AND RECOMMENDATIONS

The full SBIR project funding arrived very late in the fiscal year, which slowed our progress considerably. We are now developing a single-axis design that would more readily extend to three axes, in an effort to make rapid progress over the coming months. We have a good grasp of the various sources of noise in the sensor, and recent experiments indicate that we will be able to come very close to NLNM performance over the desired bandwidth.

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REFERENCES

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