DEVELOPMENT OF A LASER INTERFEROMETRIC MINIATURE SEISMOMETER

Dustin W. Carr, Gregory R. Bogart, Seth Goodman, Patrick Baldwin, Howard Milburn, and David Robinson

Symphony Acoustics, Inc.

Sponsored by the National Nuclear Security Administration

Award No. DE-FG02-08ER85108

ABSTRACT

Miniature seismic sensors that maintain very low noise performance are a critical need for nuclear test monitoring. 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 high-quality data.

During our Phase I SBIR research, 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.

During this phase of the project, our goal was to gain a better understanding of the capabilities and limitations of such a sensor, especially with regard to low-frequency noise sources. We employed techniques for the reduction of these noise sources and tested the optoelectronics and control circuits in a laboratory test stand. We showed that we could reduce the dominant source of low-frequency noise in lasers 40 dB by using a simple wavelength control system. This was then implemented in an acceleration sensor that was initially designed to achieve an equivalent acceleration noise of –145 dB/Hz relative to 1 (m^2/s^4). Initial characterization showed that we achieved –139 dB/Hz down to 1 Hz. The sensor capsule was 15 mm in diameter by 15 mm high.

Our next step is to transfer this to a mechanical system that is capable of achieving –168 dB/Hz, which would be lower than the new low-noise model down to 0.1 Hz. This design is currently under development and will be the subject of our Phase II research.

OBJECTIVES

A smaller, simpler-to-deploy seismic sensor is highly desirable for a number of applications, including the monitoring of nuclear testing. A significant fraction of the cost of a sensor station is related to the environmental requirements of the sensors and to the cost of putting large sensors deep underground in borehole installations. Reducing the sensor size and mass can greatly simplify these deployments. There are, however, fundamental limits associated with the extent to which existing sensors can be size reduced. In our previous paper at this conference (Carr, 2008), we described our planned research and development on a sensor that uses a new type of optical interference transducer. The performance of this transduction mechanism does not depend on the size, enabling an optimal mechanical design for the sensor.

We had four objectives for this SBIR Phase I project that guided our work.

1. Development of a robust mechanical design that will result in a sufficient range of motion and a thermal noise limit that is below the low-noise model (LNM) target, combined with an optical design that will result in the required motion sensitivity.
2. Characterization of optical sources and identification of methods to mitigate the effects of wavelength noise.
3. Development of an electronics design that will not contribute to the noise floor defined by the photodiode shot noise and the mechanical thermal noise and that maintains an overall power consumption below 30 mW per axis.
4. Assembly and testing of a compact single-axis sensor capsule that will demonstrate the feasibility of this approach.

RESEARCH ACCOMPLISHED

For our transducer, we are using a simple Fabry-Perot transducer that is composed of two dielectric mirrors that are bound in an optical cavity, as shown in Figure 1. In our original proposal, we described the fundamental noise floor for such a system as being the sum of the shot noise in the detection photodiodes and the thermally driven mechanical noise of the spring-mass system. The latter noise source is common to all approaches and does not depend on the transduction technology used.

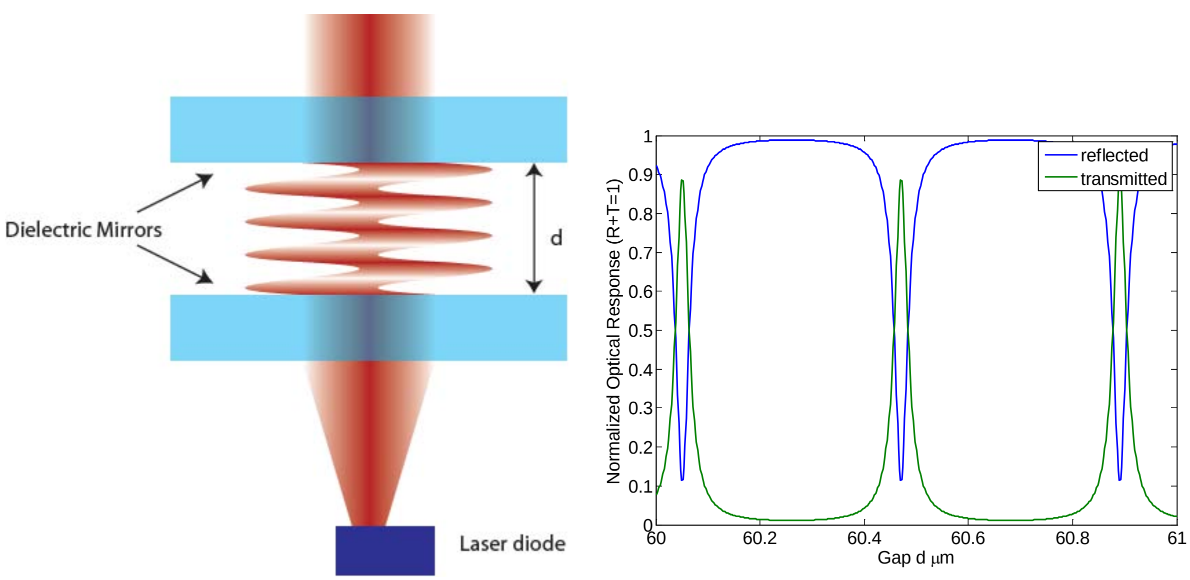

Figure 1. A simplified diagram of an optical interference transducer.

A plot of the combined noise floor is shown in Figure 3, with assumed values for the laser intensity, cavity finesse factor, and the quality factor of the proof mass fundamental resonance.

Our approach is to make a relatively high resonant frequency device, above 100 Hz, that is highly underdamped. The amount of damping determines the mechanical thermal noise force amplitude. While an underdamped system may have a problematic response function, this will be at a frequency that is well above the intended operating bandwidth of these seismic devices. The packaging can also be designed to reduce the transfer of high-frequency vibration to the device and thus eliminate large amplitudes at the resonance that could result in intermodulation distortion.

The green shaded region in the plot (Figure 2) indicates where the device is limited by mechanical thermal noise. Operation at a higher frequency also means that the proof mass must be increased to about 1 gram. Such masses cannot be achieved in a compact form factor unless materials of high density, compared with silicon, are used.

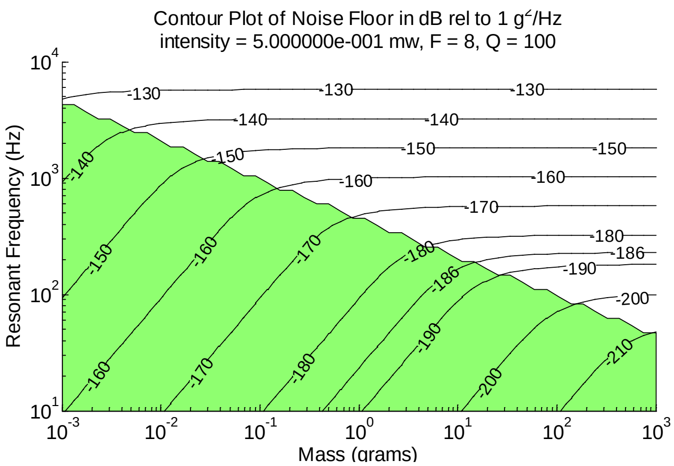

Figure 2. Contours of the white noise spectral density. Within the shaded area, the noise floor is dominated by thermal noise in the spring and mass. In the unshaded region, the photodiode shot noise is the dominant factor.

Evaluation of Optoelectronic Noise Sources

Low-frequency 1/f noise has also been a major area of focus during this study. The primary sources of 1/f noise are the optoelectronic components, including the lasers and photodiodes. For the lasers, there are two types of 1/f noise to consider: intensity noise and wavelength noise. Intensity noise can be eliminated very effectively in a balanced receiver, wherein all of the light that is reflected or transmitted from our sensor cavity is collected, and the balanced differential is our output signal. Wavelength noise is more problematic, as it is indistinguishable from a change in cavity length and can thus not be separated from the desired sensor output signal.

We have built a few laboratory test stands that have enabled us to explore these noise sources and develop solutions for eliminating them from the system. An optical ray-trace of the initial test stand design is shown in Figure 4, along with an image of the implementation on our optical table. This system has an extremely quiet current source, along with a detector circuit that is shot-noise limited. We use this to probe a fixed etalon that consists of a 120-µm-thick fused silica die that is coated on both sides with an 85% reflecting mirror.

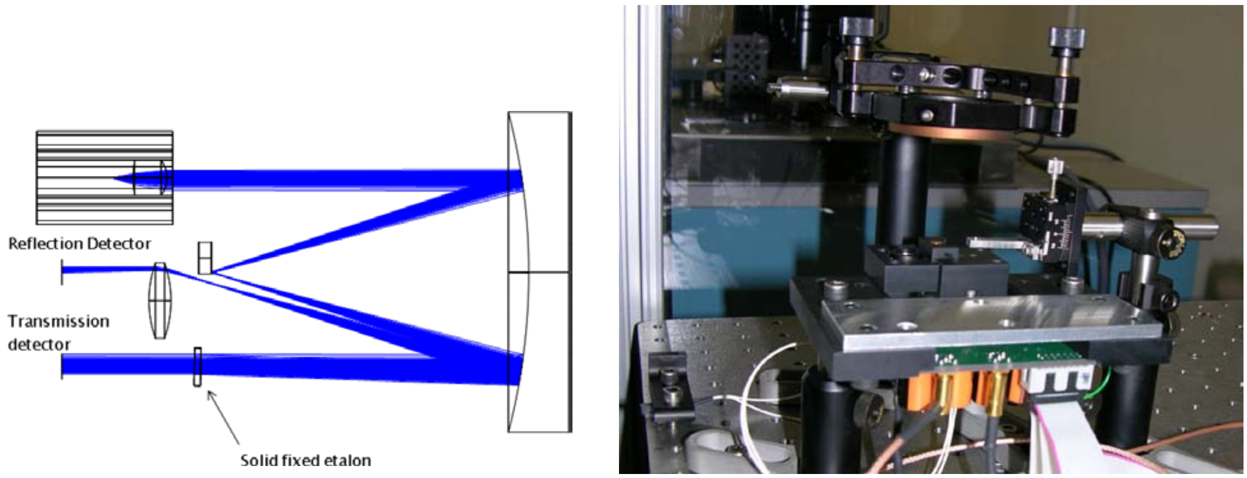

Figure 3. Test stand system design and implementation. The purpose of this system was to provide a way to characterize noise sources in diode lasers and optical sources. Collimated light is directed to a solid. fixed etalon, which could be tilted to position the optical response at the point of maximum sensitivity to wavelength variation.

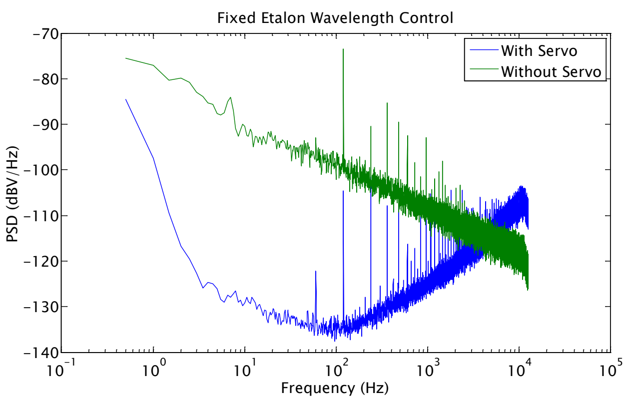

Figure 4. This is the observed noise spectrum at the differential output of our system. The 60-Hz peaks are present due to the ambient light in our laboratory. The 1/f spectrum shown is entirely due to wavelength noise. When we employed a servo to the laser current, we could suppress this noise by 40 dB within the bandwidth of the servo controller.

This fixed etalon is about 30 dB more sensitive to variations in wavelength than our typical sensor design would be. As such, it allows us to magnify the effect of wavelength noise in the hope that we may better understand and control it at the source.

Because the laser output wavelength varies with laser current, we made modifications to the test stand wherein we created a closed-loop current controller to stabilize the laser wavelength. We used the fixed etalon to convert laser wavelength changes to intensity changes detected at the photodiodes. The resulting detected signal then becomes the input to our control loop. Our first attempt used a controller that had a limited frequency range, as this was implemented in a piggyback board that interfaced with the original test stand. With that approach we achieved a reduction in wavelength noise by 40 dB (Figure 4) over the range of 10–100 Hz. As mentioned above, this fixed etalon had a wavelength sensitivity that was intentionally 30 dB higher than that of a typical sensor etalon. This type of wavelength control has since been implemented in our sensor capsules, enabling the suppression of this noise source to frequencies below 0.1 Hz.

Laboratory Prototype Sensors

Our first prototype sensor capsules integrated the optics, mechanics, and sensor electronics into a compact 15-mm-diameter package, as shown in Figure 6. The initial mechanical design for these devices was designed as a significant step towards a LNM device. We intentionally aimed for an intermediate point because the complexities involved in this design demanded that we first and foremost build a sensor that shed light on the dominant remaining issues to be addressed in the next phase. The mechanical resonant frequency of this device was 380 Hz, with a quality factor of around 100.

This device plugs into a signal conditioning and control circuit board. For these initial tests, the board was 50×50 mm^2. This is not indicative, however, of the size required for these electronics, as we have since reduced this to a 22-mm-diameter printed circuit board (PCB) design. We placed the capsule and the board in a housing as shown in Figure 5 for our initial testing.

We acquired the output acceleration from these capsules simultaneously with the output from a Sercel L4C geophone co-located in our facility. In the bandwidth of interest, the L4C certainly has a lower noise floor than that of the Symphony Acoustics prototype, and so by compensating the L4C output so that its response is expressed in terms of acceleration, we were able to determine the approximate noise floor of our device. A power spectral density (PSD) plot is shown below, expressed in dB relative to 1 m^2/s^4/Hz. While we are still well above our target performance, this is still a major step forward and rivals the performance of any known miniature acceleration sensors reported in the literature over this range of frequencies (Krishnamoorthy, 2008). During our acquisition, we also acquired a low-frequency seismic event, which helped to demonstrate our coherence down to very low frequencies.

The noise sources that dominate at low frequencies are related to our digital control implementations, as well as our sensitivity to thermal fluctuations. We have a clear path to further reducing this noise floor by at least 25 dB with mechanical and electronic design enhancements during the next phase of this project.

Figure 5. On the left is an image of our sensor capsule. On the right is the laboratory prototype sensor, including signal conditioning and control electronics that were integrated in a "debug" form factor for this phase. The L4C sensor used for device characterization is also shown.

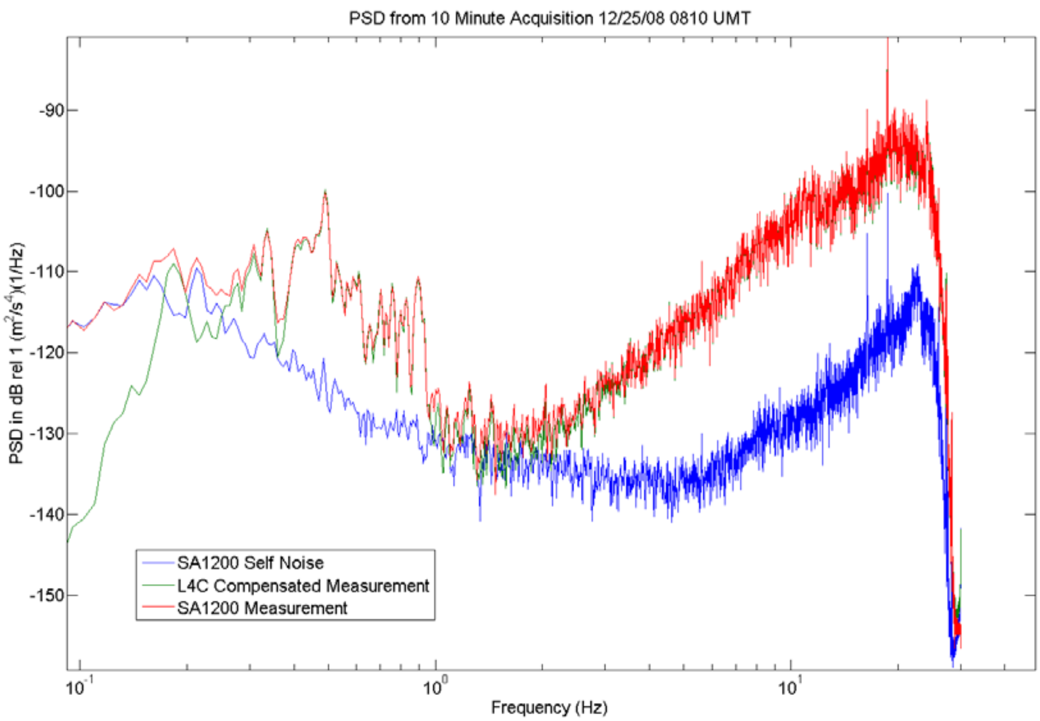

Figure 6. A power spectral density of our device (red) along with that of a Sercel L4C 1 Hz geophone sensor, compensated to provide an acceleration output. The difference signal from these two is representative of our noise floor, at frequencies below 4 Hz. At higher frequencies, we still see a common mode signal in the PSD due to imperfect coherence, which could easily be caused by a slight angular misalignment.

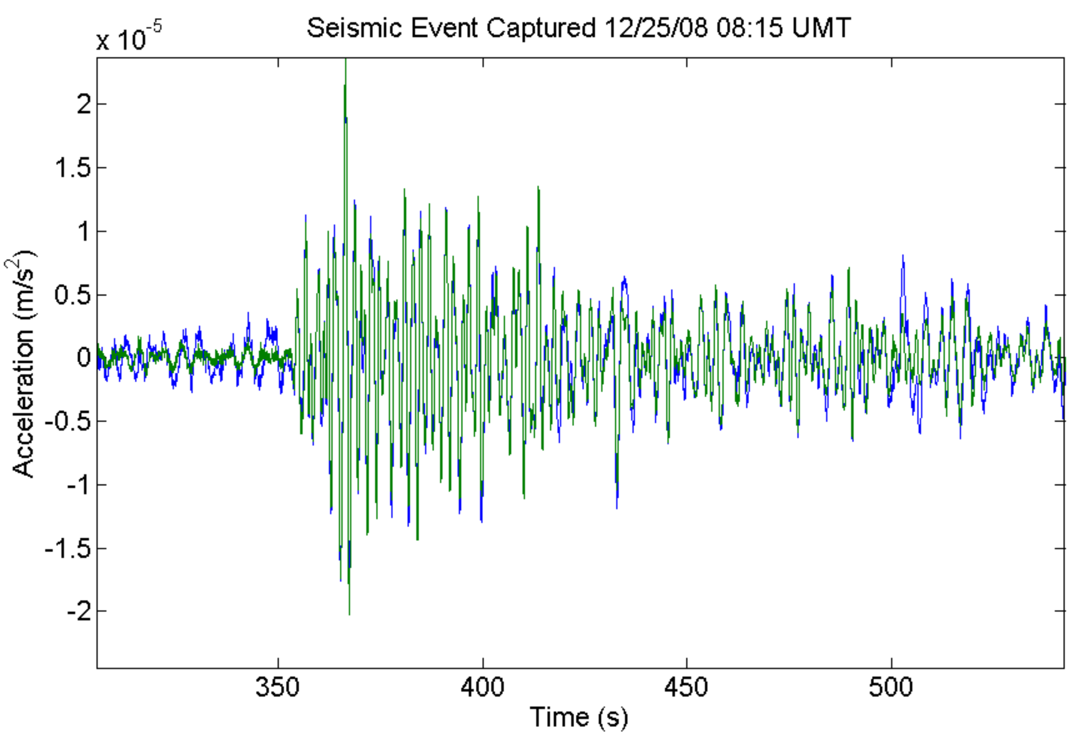

Figure 7. Time series data of a low-frequency seismic event captured by the two sensors.

CONCLUSIONS AND RECOMMENDATIONS

We adhered well to our original proposed plan and made considerable strides towards the realization of a miniature seismic sensor that is capable of LNM limited operation. There is still much more work to be done in Phases II and III, and we are committed to pursuing this effort. We have not yet achieved the ultimate acceleration noise floor required, but that is primarily because we aimed for an intermediate point that would allow us to better understand the remaining issues. Time constraints also prevented us from pursuing a complete testing plan with a qualified external facility.

The technical objectives of our Phase II research are as follows:

1. Refine our sensor designs from Phase I so that they may extend to new LNM 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. Package a compact 3-axis digital sensor prototype that can be operated in any orientation and that meets the specifications as spelled out by the Department of Energy.

ACKNOWLEDGEMENTS

We acknowledge the management and technical staff at Science Horizons, Inc., who provided the digitizing equipment and geophone used for the characterization of these devices.

REFERENCE

Krishnamoorthy, U., D. W. Carr, G. R. Bogart, M. S. Baker, P. J. Clews, T. P. Swiler, and Olsson, R. H. (2008). In-plane MEMS-based nano-G accelerometer with sub-wavelength optical resonant sensor, *Sens. Act. A.* 145: 283–290.