Measuring environmental noise for Cosmic Explorer site selection

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November 11, 2026

Abstract

Cosmic Explorer (CE) is a proposed next-generation gravitational wave observatory to be built in the US, consisting of an observatory 10x the arm length of current LIGO observatories. Working in concert with the European Einstein Telescope, CE will observe gravitational wave sources across cosmic time, including black hole mergers from the first stars to form in the universe. To select a site for CE, it is important to understand sources of potential noise from various sources, including seismic, electromagnetic, and more. We are working on improving standalone datalogger kits, consisting of seismometers, magnetometers, and microphones, used to assess potential sites. We have developed a new kit that uses two seismometers in tandem to understand surface wave propagation from various sources. We have also written new code that uses this data to calculate wave velocity, which is useful to understand the quality factor of different sediment types and interpret coupling. We tested our kit at various locations around LHO to better understand local wave propagation velocity, as well as at Goose Prairie Solar Farm in order to understand the constraints of solar farm locations near gravitational wave observatories. Results from this study will be helpful in future site evaluation for CE.

1 Introduction

Cosmic Explorer (CE) is a proposed next-generation ground-based gravitational wave observatory to be built in the US, consisting of an observatory with 40 km long arms. CE is expected to begin operation around 2040, with a long list of sites to be submitted to the NSF planned for late 2026 [1]. When selecting a potential site, it is important to consider where CE can (1) Reach its science goals, (2) Be cost efficient, and (3) Be aligned with social and cultural goals.

My work this summer focused on helping CE accomplish its first goal by understanding physical environmental factors that may affect potential sites. Seismic noise from 1-30 Hz can directly couple into instruments, while lower frequency seismic noise down to 10 mHz can lead to up-converted noise through building motion. The 0.1 Hz microseism peak with an amplitude of around 1 μm can interfere with interferometer control [2]. Seismic noise can have a major impact on our interferometer, and it is important that we minimize its effects by understanding where it is highest, and how it propagates. To do this, I worked on developing tools to study the attenuation of seismic waves around LIGO, and sites across the US. Attenuation is the gradual loss of energy as a wave propagates through a medium. A "lossy" medium has high attenuation, meaning energy is lost quickly.

The main goal of my project has been to build and test a new seismic datalogger kit, which will use two seismometers in tandem. Existing kits only use one seismometer at a time. Using two has allowed us to understand surface wave propagation and attenuation from various sources in various mediums.

2 Methods

2.1 Introduction to the Kits

The seismometer kits are portable and compact kits to transport seismometers, magnetometers, and their necessary equipment to potential sites across the country for use in ground seismicity and noise measurements. The kits consist of 3 Pelican cases: a Van case, a Seis case, and a Field case. The Van case contains cables to connect the equipment to power from the van, a magnetometer, and a slab used to provide a stable platform for the seismometer. The Seis case contains a seismometer and the equipment to set up and level it. The Field case contains various electrical equipment used to record and convert the seismometer and magnetometer measurements.

Current kits contain only one seismometer. By adding a second seismometer to the kits, we will be able to collect seismic data from two locations in parallel. This will allow us to calculate surface wave propagation velocity and other aspects of wave propagation and attenuation. Furthermore, having two seismometers also allows us to discern between global events (such as signals from distant sources) and local events (such as wind-induced glitches) that affect each seismometer differently. Since the majority of our site evaluation relies on surface level seismometer measurements, having two seismometers is essential for mitigating localized wind-based noise in the field.

2.2 Kit Development

Our new dual seismometer kit uses two 40T seismometers. When building the new kits, an primary challenge was working with the limitations of our analog-digital conversion device, a Digilent WebDAQ with four input channels. Each seismometer has three output motion channels, East, North, and Zed. Due to our hardware limitations, we could only use two channels per seismometer. We chose Zed, the vertical direction, as an overall indicator of ground motion, and North, a horizontal direction, to be pointed towards noise sources of interest.

Another goal when initially developing the kits was to reduce weight. One major target for weight reduction was the granite slab used to provide a stable platform for the seismometers. Using a slab to stabilize the seismometers is essential for a few reasons: (1) If the seismometers are not level, they will have inaccurate recordings, and (2) If placed directly on earth, the thermal expansion of the seismometer feet on grains of dirt will cause low frequency noise. Our current granite slabs are heavy and expensive to transport. Using a glass slab is a much lighter potential replacement, so we needed to test to ensure that using glass would not introduce any new sources of noise.

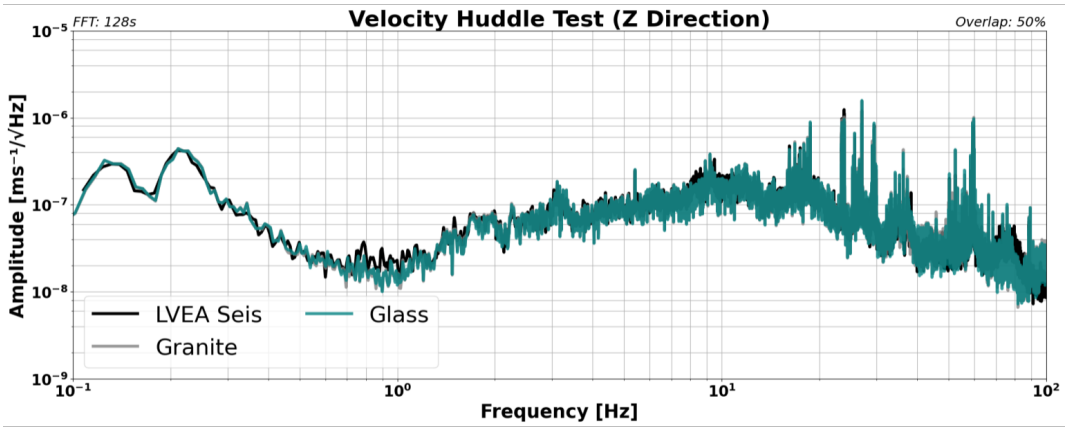


Figure 1: Data from glass versus granite tests in the LVEA.

First, we tested glass versus granite slabs in the Laser Vaccuum Equipment Area (LVEA), comparing our 2 seismometer kit measurements with LVEA seismometer data as a "true" reference measurement. As shown in Figure 1, we found a consistently high agreement between the two seismometers

on glass and granite, indicating that in a controlled indoor environment, glass is equal to granite for stabilization purposes.

We then began testing outside, using two 40T seismometers on glass and granite slabs outside, with identical cardboard covers. Initially, we noticed some elevated noise in the horizontal (North) direction in the glass measurements. We realized that the thinner glass slab may have been tilting on bumps in the ground more than the thicker granite slab, which could be planted more firmly into the ground due to its height. We corrected this problem by using epoxy to glue two glass slabs together, giving the combined slab more height. The plots of our data in the horizontal (North) direction before and after doubling the height of the glass slab are shown in Figure 2. After doubling the height of the glass slab, the two agree much more closely.

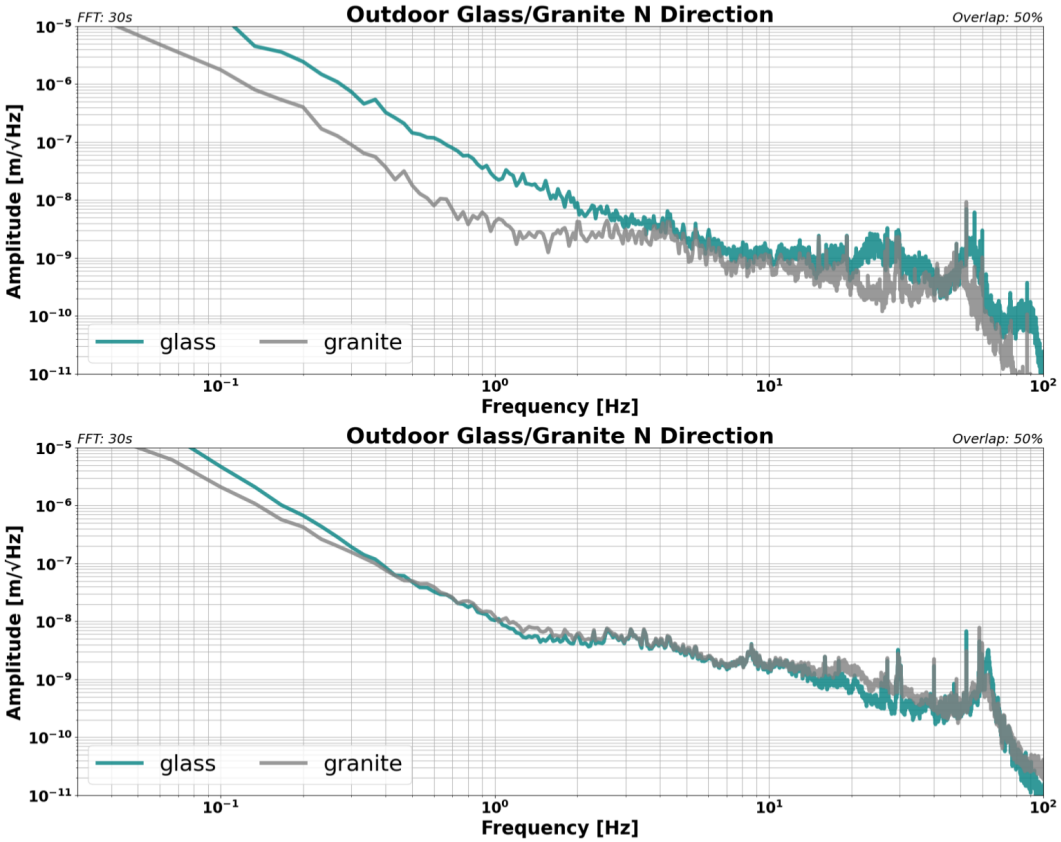


Figure 2: Data from glass versus granite tests outside, before and after increasing the height of the glass slab.

2.3 Writing New Code for the Kits

We have written new code to analyze the data from our new two seismometer kit. Using data from two seismometers, a known distance away from each other, we can calculate the propagation velocity of surface waves from their relative phase difference. The formula to do so is below:

$$v = \frac{f \cdot d}{\varphi/360} \tag{1}$$

Here, v is velocity [m/s], f is frequency [Hz], d is distance [m], and φ is the phase difference [deg]. Using this, we can calculate the propagation velocity, which is important for calculating the quality

factor of different mediums.

We calculate the relative phase difference using a cross spectral density function. In Python, we use the scipy.signal csd function. A cross spectral density takes two recorded signals and returns the cross spectral power density, which represents the shared power and timing relationship between two different signals across various frequencies, using complex numbers. The np.angle function is applied to the power density function to find the phase shift between the two signals at each frequency. Mathematically, this is done by finding the geometric direction of the imaginary part of the cross spectral power density. We also use np.unwrap on the phase shift function to smooth any phase wrapping.

3 Evaluation

3.1 Introduction

Our major test of our new seismic kit was a visit to Goose Prairie Solar Farm. Not only was this trip a valuable test of our new equipment and code, but it was also crucial due to the US Department of Energy's plan to build a solar farm, east of Route 10, in the near future. The data from this test will be valuable in explaining our constraints and limits to the DOE. It is also important to understand the noise generated by solar farms when evaluating sites for future gravitational wave observatories, namely Cosmic Explorer. At the site, we measured seismic and electromagnetic noise generated by solar panels, inverters, and a substation, as well as RF noise, stray voltage, and the height of the water table.

3.2 Results

From magnetometer data taken near the substation, as shown in Figure 3, the level of electromagnetic noise is very comparable to LHO levels, but the 60 Hz peak is higher, likely due to the separation of 3 phases coming out of the substation, but more measurements are needed. The ground potentiometer data indicated a very high water table, likely due to the dense, clay-like soil with high irrigation we observed at the site.

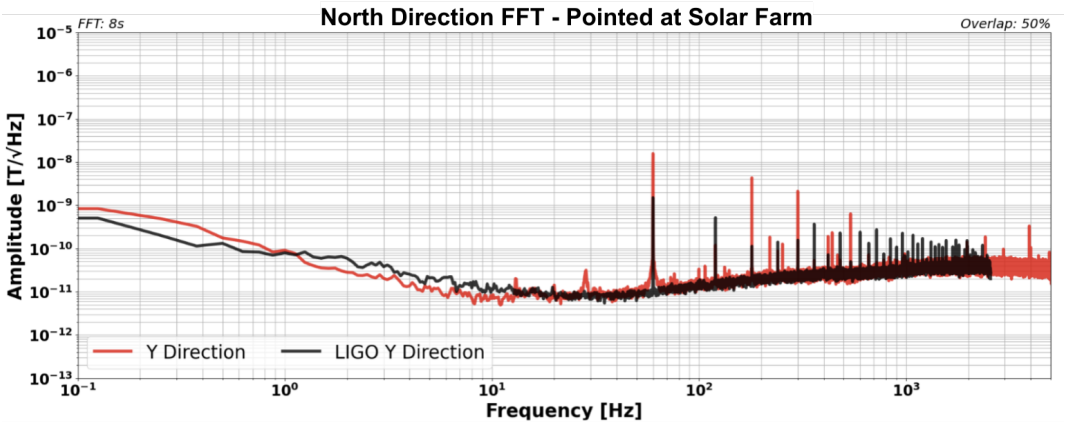


Figure 3: Magnetometer data taken outside Goose Prairie Solar Farm by the substation. The red trace is measured data and the black trace is LHO comparison data.

In our seismometer data, we expect to see elevated noise coming from the solar panels during periods of high wind due to panels shaking in the wind. During our visit, the maximum wind speed observed was 11.6 mph.

Our recorded data, shown in Figure 4, contains noise levels mostly comparable to what we see at LIGO Hanford. However, between 1-10 Hz, we saw small peaks above what we typically see. Phase

difference analysis from our two systems indicated that the source of the noise was not in the direction of the solar farm, but rather from the direction of the road, with many trucks and cars. At the wind speed of 11 mph and below, we do not see wind induced seismic noise from solar panels, but more analysis up to 25 mph is needed.

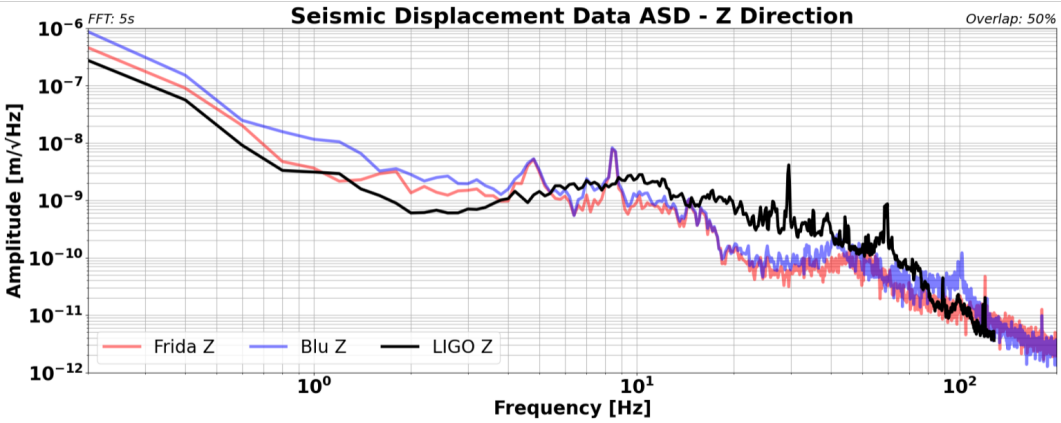


Figure 4: FFT of Seismometer data from Goose Prairie Solar Farm. The red trace is from the first seismometer (Frida). The blue trace is from the second seismometer (Blu). The black trace is LHO reference data.

4 Analyzing Data from Utah

4.1 Introduction to Utah Data

In early April, one of my mentors, Robert Schofield, collected seismometer data near the Great Salt Lake Desert in Utah. The goal is to understand the sources and propagation of signals in an environment distinct from LHO as preparation for CE site evaluation and eventual selection. My goal is to analyze these data and see what we can uncover about the attenuation of noise in this environment.

4.2 My Analysis

Figure 5 shows a time series from data taken right along highway I-80. This is the noise we will be studying to understand attenuation. Figure 6 shows data taken from 3 different distances from the road. For each measurement, the average ASD in 3 bands, 1.5-3 Hz, 3-6 Hz, and 6-12 Hz was taken. Figure 7 is a plot of these average ASDs over distance. To this, we fit an attenuation function of the following form:

$$A = A_0 e^{-\alpha d} \tag{2}$$

We also tried to fit an attenuation function that combined both exponential and geometric fit functions, as in the following form:

$$A = A_0 \sqrt{d} * e^{-\alpha d} \tag{3}$$

However, the fit was not good, likely because of the uncertainty in distance for the only data point in the region where geometric attenuation dominates. At farther distances, the exponential linear attenuation from friction inevitably dominates, because it is an exponential instead of a power law. This cross-over happens around the 1/e distance. The geometric attenuation beyond the 1/e distance is much smaller, and as such can be ignored. Our measurements stretch well beyond the 1/e distance, and as such are in the region where exponential attenuation dominates. As such, we can use a purely exponential function to fit to our data.

From the fitted alpha value, we calculated the 1/e distance at each frequency. This is the distance a wave travels in a medium before its amplitude decreases by 1/e (37%). Figure 8 displays the 1/e

distance at each frequency, both the values calculated from Utah data, and values previously measured around LIGO [3]. The Great Salt Lake Desert site has higher observed attenuation than LHO, meaning we can be closer to noisy sources than LHO.

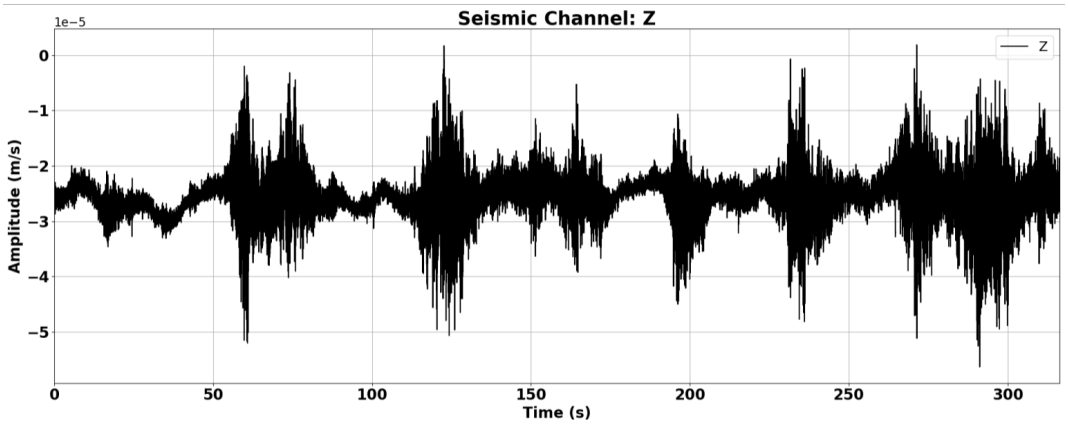


Figure 5: Time series of seismometer data taken close to the I-80 highway at the Great Salt Lake Desert site.

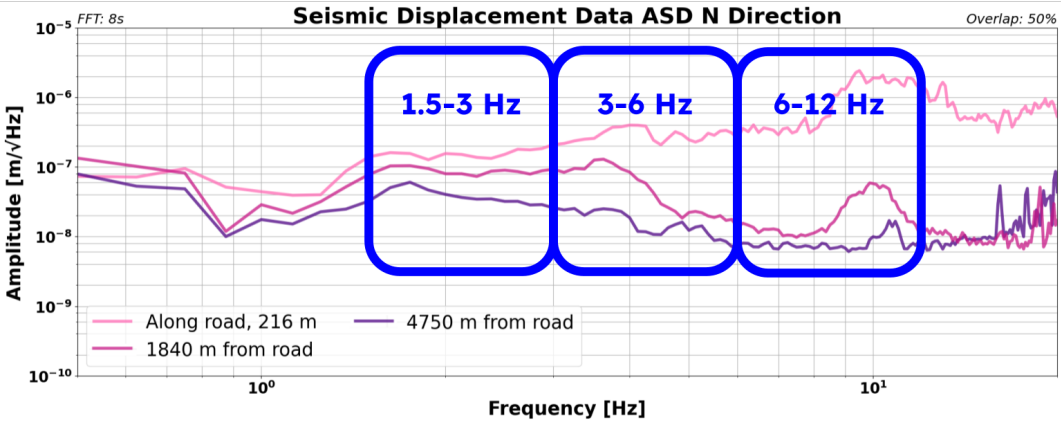


Figure 6: Data taken at the Great Salt Lake Desert, near the I-80 highway. The pink data is from next to the road. The magenta data is from 2km away. The purple data is from 5km away. The bins in which averaging was done are labeled in blue.

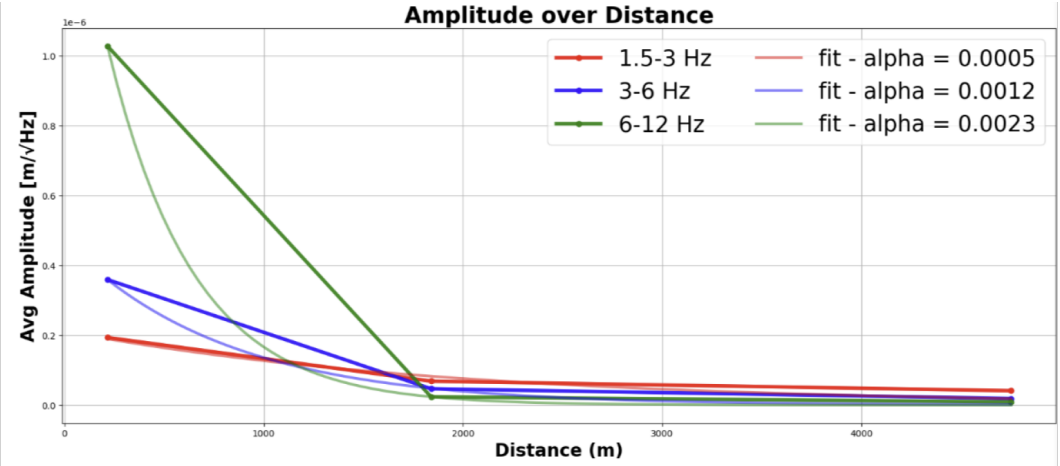


Figure 7: Average amplitude correlated with distance across 3 frequency bands. 1.5-3 Hz is in red. 3-6 Hz is in blue. 6-12 Hz is in green.

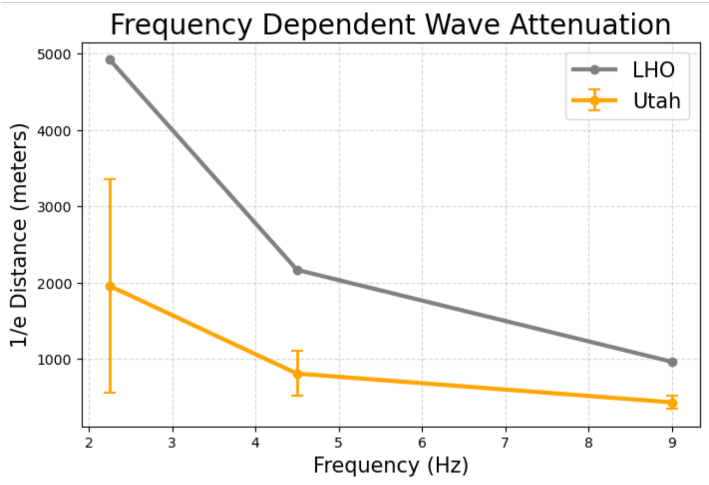


Figure 8: Plot of 1/e distance over frequency. The yellow trace is values computed from measurements near the Great Salt Lake Desert. The gray trace is previously acquired LHO reference data.

5 Future Work

The kits and code developed in this project are fully operational and ready to deploy. They will be used for future site selection studies, at sites across the country. As of September 2026, the kits and software have already been successfully used in CE site evaluation studies in one region of Oregon and in two regions of Eastern Colorado.

6 Acknowledgments

This work was completed as a part of the LIGO SURF program. Support for this program was provided by the NSF under grant 2547402.

I'm extremely grateful to my mentors, Mike and Robert, for all their knowledge and guidance. Thank you to Carlos for showing me the ropes and to Miranda for all the seismometer shenanigans

together. Special thanks to the fellows for driving me home and taking me to yoga. Many thanks to everyone at LHO for making this site such a welcoming place to be for the summer. And of course, thank you to my fellow SURFs, Khanh and Matilda, for being incredible friends and making this summer so fun and memorable.

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