First interim report: Assessing ambient seismic, acoustic, electromagnetic, and environmental noise to identify viable sites for Cosmic Explorer

Tooba Ansar
Amherst College, Amherst, MA 01002

Mentors: Michael Landry and Robert Schofield
LIGO Hanford Observatory, Richland, WA 99352

(Dated: July 2025)

Cosmic Explorer is a third-generation gravitational-wave observatory concept that will offer an order-of-magnitude improvement in broadband sensitivity over current gravitational-wave observatories. This leap in sensitivity will allow Cosmic Explorer to detect gravitational wave sources across the universe that are barely resolved by existing detectors. In developing Cosmic Explorer, it is important to evaluate the ambient noise of potential observatory sites, as seismic, acoustic, electromagnetic, and environmental disturbances can limit its high sensitivity. In this project, we conduct geological and geographical case studies of the potential locations for Cosmic Explorer, in addition to improving the portable site-testing instruments that will enable efficient and convenient site assessment. With hundreds of potential sites, we aim to identify those most suitable for hosting Cosmic Explorer, allowing for future on-ground site assessment with the compact site-testing kits.

I. INTRODUCTION

Gravitational waves are ripples in spacetime produced by events such as black hole mergers and colliding neutron stars; these ripples travel at the speed of light and carry information about their astronomical sources. The observation of gravitational waves has resulted in discoveries such as the first detection of a binary black hole merger and the multimessenger observation of a neutron-star merger. Since the first gravitational wave detection in 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO), Virgo, and KAGRA collaboration have made more than 290 observations of gravitational waves and expanded the field of gravitational-wave astronomy.

The next step in the advancement of ground-based gravitational-wave astronomy is the proposed Cosmic Explorer, a third-generation gravitational-wave observatory ten times as sensitive as LIGO. With its high sensitivity, Cosmic Explorer offers great potential for discovery. It will detect gravitational waves from the universe's binary black hole and neutron star populations throughout cosmic time, most interestingly providing evidence for the first stars by detecting black hole mergers that occur in their wake. It will also detect rare gravitational wave events that we could not previously observe, providing us a window into new and novel physics.

Like LIGO, the Cosmic Explorer concept consists of two L-shaped observatories at two different locations in the United States, where each of the observatories will house a Michelson interferometer. However, while LIGO's interferometer consists of two 4 km-long interferometer arms, Cosmic Explorer consists of one observatory with 40 km-long arms and another with 20 km-long arms.

While many locations in the United States can host a 40 km detector, it is important to choose a site that is isolated from ambient noise. Gravitational waves are detected by measuring infinitesimally small displacements in the interferometer arms, and ambient noise can therefore obscure these desired displacements and limit the sensitivity of Cosmic Explorer. Ambient noise can be caused by the following:

- Seismicity: Seismic activity such as ground vibrations can cause the detector parts to vibrate, resulting in seismic noise. It can also lead to fluctuations in the local gravitational field, generating what is known as local gravity noise. Seismic noise in the 1-30 Hz range can potentially couple into the detector mechanically. The current sensitivity estimate for Cosmic Explorer assumes ground motion dominated by Rayleigh waves, with an amplitude of $1(\mu\mathrm{m/s^2})/\sqrt{\mathrm{Hz}}$. In general, the best sites for Cosmic Explorer are those with low ground motion across the 10 mHz to 30 Hz frequency band.

- Acoustics: Acoustic waves can change the air pressure near the detector and cause fluctuations in the local gravitational field to introduce local gravity noise. The current sensitivity model for Cosmic Explorer assumes typical ambient acoustic levels of $1\mathrm{mPa}/\sqrt{\mathrm{Hz}}$. To properly assess the suitability of a potential location, we must evaluate the ambient acoustics of the site.

- Electromagnetic fields: Electromagnetic noise can interfere with Cosmic Explorer's sensitive band. Radio frequency interference can disrupt the modulation and demodulation techniques used for controlling Cosmic Explorer's interferometer.

- Environment: Long-term measurements of the environment are required to determine the noise variation introduced by weather and anthropogenic sources. For example, wind, rain and nearby airplanes, cars, and trains can introduce both seismic and acoustic noise. It is also critical to study seasonal weather changes over year-long timescales, as well as investigate the susceptibility of potential sites to natural disasters such as earthquakes and hurricanes.

The projected timeline of Cosmic Explorer anticipates an 8- to 10-year-long site selection phase, with the evaluation of suitable sites having begun in the mid-2020s. Construction will begin in the early 2030s, and Cosmic Explorer is expected to make its first detections in the mid-2030s.

II. OBJECTIVES

The primary goal of this research project is to investigate sources of ambient noise near potential Cosmic Explorer sites to identify those most suitable for housing its two observatories. We will improve the robustness of the portable field kits for our site-testing instruments, as well as the user-friendliness of the custom Python codes for data analysis. In addition, we will survey publicly available data on weather and anthropogenic activity (e.g., monthly average wind speeds, rail and airline schedules) to further assess the suitability of potential sites. This will ultimately allow us to determine locations that will meet or exceed Cosmic Explorer's specifications, as well as to develop a compact, travel-friendly site-testing kit for convenience in future site surveying and assessment.

III. PROGRESS

I began by setting up and testing the site-assessment kits designed to analyze ambient noise at potential observatory sites. Our kits include a seismometer to measure ground vibrations and a magnetometer to measure electromagnetic interference, both of which are set up in portable Pelican cases along with their respective cables, power equipment, and data acquisition systems. After familiarizing myself with the data acquisition systems for our instruments, namely the WebDAQ and Guralp Minimus, I followed the manual for the site-testing kits to set up the instruments out in the field. I collected test seismic and magnetic data from our instruments and ran it through our custom Python program to identify any major bugs in the analysis code.

As part of the geographical case study on potential Cosmic Explorer sites, I used Google Earth Pro to survey sources of environmental noise around seven different potential sites in Colorado, Utah, and Arizona. After importing the KML files of the sites into Google Earth, I recorded all highways and railroads within 10 km and 20 km of each site, respectively. Then, I measured the smallest distance from these transportation lines to the three Cosmic Explorer stations (the corner station and the end stations of the X- and Y-arms) and made note of any highways, power lines, or railroads that intercepted the length of the 40 km arms. Using satellite imagery in Google Earth Pro, I counted the number of cars within a 10 km radius of each station along the nearby highways and used Google Earth's historical satellite imagery to repeat this measurement for three different years.

I conducted internet searches to acquire the average wind speeds of the city closest to each candidate site. Data were obtained from Visual Crossing, which was found using the National Weather Service's Enterprise Resources webpage. To compare the average monthly wind speeds of the sites with those at LIGO Hanford in Washington, I plotted the wind speeds against those at LIGO Hanford. For example, Fig. 1 shows the average monthly wind speeds for 2024 at a site near Cedar City, Utah, along with those at Hanford.

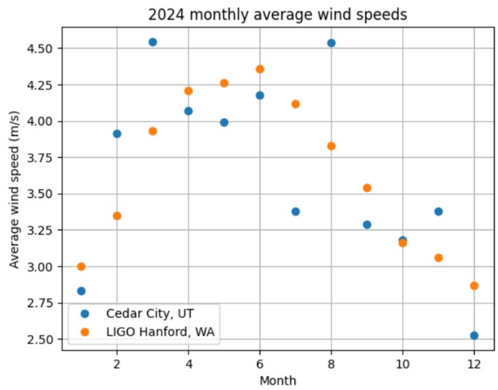

Figure 1. Average monthly wind speeds at Cedar City, Utah and LIGO Hanford, Washington.

IV. CHALLENGES & FUTURE PROSPECTS

One of the main challenges while setting up the site-testing kits was the absence of labels on the many cables and equipment, as well as some of the instructions in the manual that were unclear. Based on my experience, I have provided suggestions to improve the clarity of the manual; the next step is to begin labeling the contents of the kits.

In terms of wind data, we noted that the closest cities with publicly accessible wind data were located a significant distance from the potential sites, and that we needed to validate the data from multiple different sources. Given the expansive 40-km length of the interferometer arms, we also anticipate the wind conditions at each of the three stations to be considerably different. Therefore, we are now looking to contact the National Oceanic and Atmospheric Administration to acquire historical wind data specific to the locations of the three stations.

In compiling our environmental noise case study using Google Earth Pro, a significant challenge was the manual, repetitive, and time-consuming nature of the work and the great potential for human error. Given the large number of candidate sites for Cosmic Explorer, I am now looking at ways of automating the identification of anthropogenic noise sources in satellite images of the candidate sites. One potential solution is to use the deep learning models available in ArcGIS Pro, an application that offers satellite imagery and object detection tools; of particular interest to us are models capable of detecting cars, roads, buildings, and windmills. However, ArcGIS Pro is a paid desktop application, and I have not yet been able to access and explore this option.

In tandem, I have tested pre-trained deep learning models for object detection and semantic segmentation such as LRASPP, FCN, FCOS, and RetinaNet. However, these models appear to be ineffective when used on screenshots from Google Earth Pro due to the resolution of the images and the type of datasets the models have been pre-trained on. I am now considering training my own deep learning model for object detection in aerial images. Among the suitable training datasets I found is the SpaceNet repository, which provides labeled satellite imagery for road and building extraction. Training my own deep learning model appears to be a promising direction for improving the efficiency and scalability of remote site-evaluation using satellite images.

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