Second interim report: Toward a scalable framework for evaluation of potential Cosmic Explorer sites

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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 results from Cosmic Explorer's expansive 40-km arms, allowing it to detect gravitational wave sources across the universe that remain unresolved by existing detectors. In developing Cosmic Explorer, it is important to identify sources of ambient noise near potential sites that could limit its high sensitivity, as well as ensure sufficient land clearance for its extensive arm length. In this paper, we propose a method for identifying noise sources and surveying land availability around candidate sites using geographic information systems. With hundreds of suitable locations, we aim to develop a scalable approach for remote evaluation of Cosmic Explorer sites to hone in on those most promising for eventual on-ground testing.

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 detection of gravitational waves has resulted in discoveries such as the first observation of coalescing binary black hole systems and the multi-messenger 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 300 observations of gravitational waves, establishing gravitational-wave astronomy as a novel way of observing the universe.

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 remain 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 widely separated 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 will consist of one observatory with 40 km-long arms and another observatory with 20 km-long arms.

While many locations in the United States can physically host a 40 km detector, it is important to choose a site with minimal 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 $1(\mu\text{m/s}^2)/\sqrt{\text{Hz}}$. 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 noise couples into the detector through direct modulation of the vacuum envelope and the associated motion of the detector components, amplifying scattered light within the detector. In addition, 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 $\text{mPa}/\sqrt{\text{Hz}}$. 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 frequency band; radio frequency interference can disrupt the modulation and demodulation techniques used for controlling Cosmic Explorer's interferometer.

- Environment: Weather conditions such as wind and thunderstorms and anthropogenic sources such as vehicles, air traffic, and rail lines can induce noise. It is critical to study seasonal weather changes over year-long timescales, as well as to investigate the susceptibility of potential sites to natural disasters such as earthquakes and hurricanes.

Preliminary evaluation of Cosmic Explorer sites began in the mid-2020s. Hundreds of sites that can physically house a 20 km and 40 km L-shaped interferometer have been algorithmically identified using publicly available topological and land use data, with the identification parameters including elevation, land cover, and proximity to cities. Fig. 1 shows a site with a cluster of potential L-shaped detector configurations in a rural location in the United States.

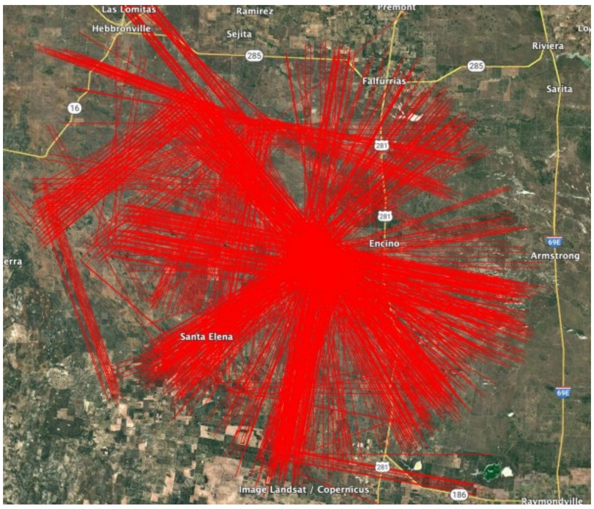

Figure 1. Potential configurations of the 40-km L-shaped detector at a candidate location. Many such locations have been identified around the United States, with hundreds of similarly clustered configurations.

The current timeline of Cosmic Explorer projects an 8- to 10-year-long site selection phase. Construction will begin in the early 2030s, and Cosmic Explorer is expected to make its first detections in the mid-2030s.

II. OBJECTIVES

The focus of this project, in particular, is the 40 km Cosmic Explorer detector. The primary goal of this project is to evaluate sources of ambient noise and survey for 40 km of land clearance near potential sites to identify those most suitable for further assessment and on-ground testing. Hundreds of candidate locations have been identified in earlier stages of site selection, but conducting field surveys at each of the sites to evaluate noise levels and ensure significant stretches of land clearance would be both resource-intensive and time-consuming. Therefore, it is critical to develop scalable approaches for remote identification of noise sources and land obstructions. We will also 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 narrow the list down to a few locations that seem most promising in meeting or exceeding Cosmic Explorer's target sensitivity, that will then be investigated on-site using seismometers, magnetometers, and microphones.

III. APPROACHES & CHALLENGES

The project evolved into two distinct phases. The first half of the program focused on visual identification of noise sources and land clearance, whereas in the second half we pivoted toward developing a more efficient and scalable approach for site evaluation. We focus on anthropogenic noise sources, namely vehicles, roads, rail lines, power lines, and air traffic. Looking for land clearance involves identifying any buildings that are close to or intercept the 40-km beam tubes of a potential Cosmic Explorer site.

A select 7 Cosmic Explorer sites in Colorado, Utah, and Arizona were selected as part of a geographical case study in the initial phase of the project. Satellite imagery from Google Earth Pro was used to survey sources of environmental noise around these sites. The Keyhole Markup Language (KML) files of the L-shaped detector configurations were imported into Google Earth Pro, the satellite imagery from which was used for visual identification of buildings and noise sources.

All highways and railroads within 10 km and 20 km of each site were recorded, respectively. Then, we 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), while making particular note of any highways, power lines, or railroads that intercepted the length of the 40 km arms. Using satellite imagery in Google Earth Pro, we counted the number of vehicles along all highways within a 10 km radius of each station and used Google Earth's historical satellite imagery to repeat this count for three different years. To look for buildings, we inspected a 50 m region on either side of the two 40 km beam tubes on Pro's satellite images. Fig. 2 depicts the approach to visual identification.

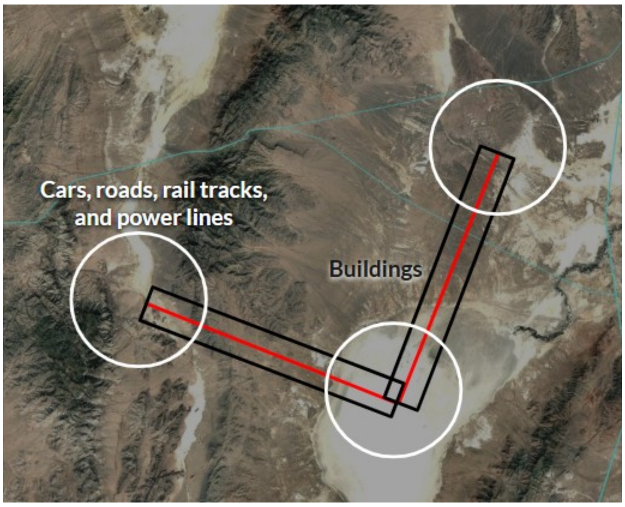

Figure 2. Depiction of a potential site (in red) with the extents for visual identification marked. The circles around each of the 3 stations represent the regions inspected for vehicle counts and transportation line measurements. The rectangular extents enclosing the beam tubes show the 100 m regions scanned for buildings. Note that the L shape shown is not a real potential site and the depiction is not to scale.

In compiling the 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, visual inspection of satellite imagery is not a scalable solution for remote site evaluation. This challenge motivated the second phase of our project, where we began to explore approaches for automating the identification of buildings and anthropogenic noise sources.

ArcGIS Pro is a Windows desktop application that provides satellite imagery, geospatial analysis tools, a native Python environment, and access to pre-trained deep learning models for vehicle detection and building footprint extraction. To test the building extraction model, we defined a 50 m buffer around the 40 km beam tube and set the buffer as a spatial mask to constrain the model's inference region. We then ran the model on smaller parts of the arm. A successful test result is shown in Fig. 3.

Using ArcGIS Pro's Python environment, we created workflows for mass image processing, deep learning, and counting and coordinate extraction of detected objects (namely vehicles and buildings). However, running the model on the entire 40km × 100m extent of the arm proved to be highly computationally intensive, and the Windows machine available to us only marginally satisfied the hardware specifications suggested for efficient model inference. The best overnight run of the building extraction model only processed 2% of an entire arm in 16 hours. The model also persistently failed to identify the smaller shacks that are especially prevalent in our rural areas of interest. Additionally, ArcGIS's pre-trained models work best on input raster datasets of 10 cm to 40 cm spatial resolution, while the best spatial resolution we could source was that offered by the National Agriculture Imagery Program's publicly available aerial imagery at 1 m.

Figure 3. Successful test of a pre-trained building extraction model in ArcGIS Pro. The red line depicts part of the beam tube, while the translucent blue is part of the 50 m buffer. The building enclosed within the buffer extent is identified by the blue polygon.

Given the limitations with computing power and spatial resolution, we turned toward looking for alternatives. We found that ArcGIS utilizes Federal Emergency Management Agency data to provide a vector dataset of footprints of all buildings greater than 450 square feet in the United States. A similar vector dataset uses data from National Geospatial Data Asset to display highways, gravel roads, and railroads in the United States. The latter is a particularly important breakthrough for us owing to its identification of gravel roads, the unmarked nature of which makes them otherwise harder to delineate.

By writing a Python workflow for spatially filtering the vector dataset for buildings, we were able to successfully identify and count the number of buildings within the specified region around an entire 40 km arm. A successful run is shown in Fig. 4.

IV. FUTURE WORK

Within the remaining three weeks, we intend to develop infrastructure for identifying buildings and roads in an environment that allows for sharing and collaboration. Currently, I have built a Python-based workflow for automated building identification within ArcGIS Pro, which is a relatively expensive, Windows-specific desktop application intended for individual use. To allow for use by multiple people in the future, I am exploring the feasibility of migrating all my workflows to ArcGIS Online, which allows for web-

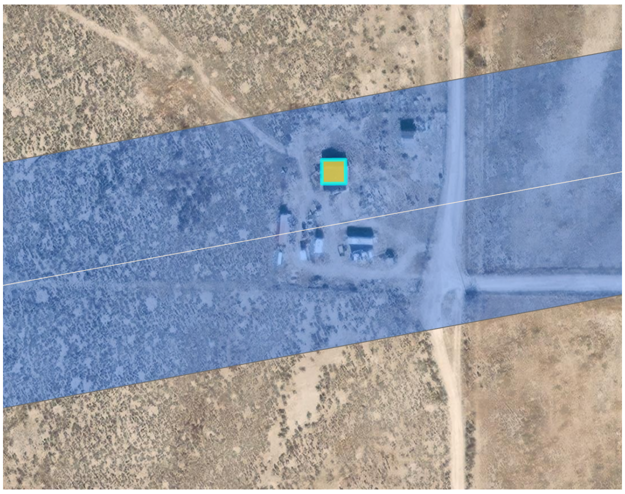

Figure 4. A building near a detector arm successfully identified on the vector dataset of buildings in the United States.

based sharing. The online version, however, limits use of resources such as deep learning models and Python notebooks to "credits" (an ArcGIS currency that must be purchased), which we need to manage carefully. Another option is ArcGIS Enterprise, but that is an expensive alternative and perhaps too large-scale for the scope of this project.

I also intend to map the number of kilometers of different types of roads within 10 km of each of the three Cosmic Explorer stations. Vehicle identification is proving to be a challenge, particularly given the limitations with computing power and input raster resolution, and is perhaps beyond the scope of what is achievable within the remaining time. An alternative to obtaining vehicle counts for noise evaluation is a publicly available dataset that maps noise levels of roads, railways, and aviation in the United States averaged over a 24-hour period.

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