Cosmic Explorer Site Search

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Technical Note CE-T2000016-v2 August 1, 2020

https://cosmicexplorer.org/

This document describes some of the criteria used to select candidate sites for a Cosmic Explorer facility with 40 km long arms. Section 1 describes the topography of bowl-like sites which minimize the volume of dirt needing to be moved in order to build such a facility and Section 2 describes the quantitative search used to identify such sites in the continental United States.

1 Topography of Sites

The lasers in an interferometer used to detect gravitational waves travel in straight lines, so the vacuum tubes used to house these beams must also travel in straight lines. The surface of the earth is a sphere, however, and is not flat in the same sense. The left panel of Fig. 1 shows an exaggerated cartoon of the relevant topography for one of the beamtubes. The green curve represents a perfectly flat region on the surface of the earth. By "perfectly flat" we mean that it's a perfect sphere with no mountains or valleys. In order to fit a straight beamtube in such a "flat" site, dirt would have to be excavated in the middle of the tube and mounds (or berms) built at the ends of the tube with a total vertical change along the length of the arm of $L_{\mathrm{arm}}^2/8R_\oplus \approx 30\,\mathrm{m}$, where L_{arm} is the length of the arm and $R_\oplus$ is the radius of the earth. The site that minimizes the total dirt necessary to move needs about 10 m to be cut in the middle and 20 m to be filled at the ends. The orange dashed line going through the middle of this segment of earth (in reality it would be about 10 m deep) shows the location of such a beamtube.

It would be advantageous to find sites that are curved in the same shape as the straight beamtubes instead. Such sites look like bowls to an observer standing on the surface of the earth. A perfect "bowl" with no mountains or valleys would require no dirt to be excavated or filled. The blue line in Fig. 1 shows an imperfect bowl with some peaks and valleys. The orange dashed line going through this blue region shows the location of a beamtube at this site which minimizes the volume of dirt needing to be cut and filled.

When evaluating candidate sites, it is useful to plot the elevation along each arm of the interferometer. The right panel of Fig. 1 shows the type of plot used in this study for the specific case of the exaggerated cartoon in the left panel. The elevation is plotted as the height above the mean elevation along the tube. This is essentially the height relative to the "perfectly flat" sphere along the beamtube in this location. By definition, the elevation of such a "flat" region is zero, as shown by the green line in the figure. The dashed orange line shows the elevation of the straight beamtube. Dirt will need to be cut and filled to have the site match this elevation. (This also shows the 10 m of cut and 20 m of fill for an ideal site.) Finally, the solid blue line shows the actual elevation of the site along the beamtube. The actual blue elevation and desired orange elevation closely match and so relatively little dirt would have to be moved to build a beamtube at this site.

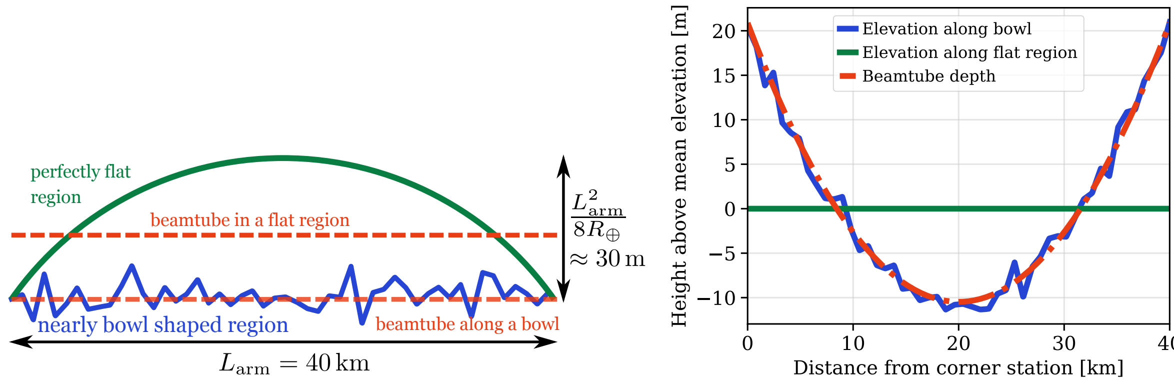

Figure 1: *Left*: Cartoon of the topography of a site along one of the beam tubes. The curvature is greatly exaggerated. *Right*: The elevation profile plot used throughout this search, for example in Fig. 3, corresponding to the specific topography shown on the left. The earth's curvature has been removed and so the perfectly "flat" surface of the earth looks flat and the bowl-like nature of desirable sites is apparent.

2 Site Search

We obtained elevation data for the continental United States at the 100 m scale from the USGS. This was downsampled to 1 km for initial searches. We then did a brute force search for sites with a corner station every 1 km. Different site orientations for each corner station location were evaluated for arms rotated in increments of $360°/32 = 11.25°$. A cost function was computed for each location and orientation for the beamtube configuration that minimized the volume of dirt needing to be moved. Sites with low cost functions were further analyzed for things like earthquake, flood, and wind hazard, land ownership, site seismicity, and proximity to civilization. These considerations are not discussed further here.

The cost function used for this search

$$C_{\rm tot} = C_{\rm elev} + C_{\rm tilt} \tag{1}$$

is the sum of two pieces: a cost $C_{\rm elev}$ quantifying the volume of dirt needing to be moved and a cost $C_{\rm tilt}$ penalizing sites that are severely tilted.

The trenches and berms need to have a width $w \approx 4$ m to accommodate the beamtubes. The slopes of the walls of the trenches and the sides of the berms will be the angle of repose θ_r of the dirt if the dirt is simply piled; see Fig. 2. An angle of repose of $\theta_r = 45°$ was used for the initial search, which is on the upper end of reasonable, but the relative ranking of sites is hardly effected by this choice. The volume of dirt needing to be excavated or piled along a short section of tube of length ℓ is

$$V = \ell h (w + h \cot\theta_r), \tag{2}$$

where h is the depth of the trench or the height of the berm needed for this section of the tube. The cost to move dirt is roughly \$10 /m^3. If there is more than 5×10^5 m^3 to be cut in a given km we switch to tunneling. This caps the volume to be cut at 5×10^5 m^3 for a given

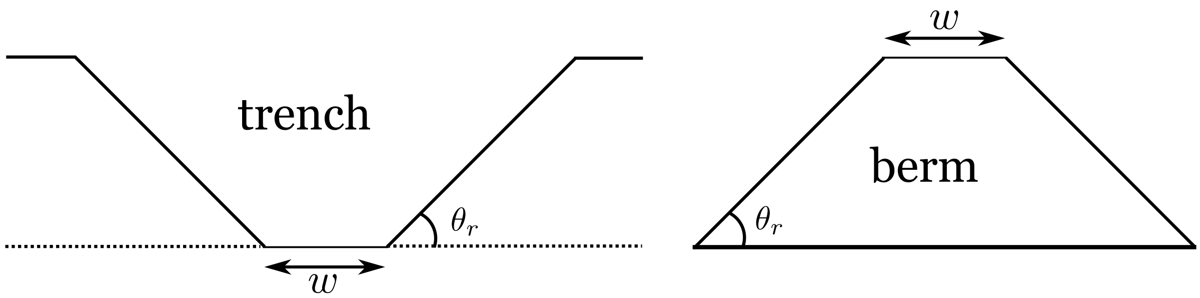

Figure 2: Geometry of trenches and berms. The slopes of the walls of the trenches and the sides of the berms are the angle of repose θ_r.

km. Finally, the dirt that is cut can be used to fill in the regions needing fill with any excess needing to be brought in or taken away. We thus use the cost function

$$C_{\text{elev}} = \frac{V_{\text{cut}} + V_{\text{fill}} + |V_{\text{cut}} - V_{\text{fill}}|}{10^5 \text{ m}^3} \tag{3}$$

to quantify the cost of moving the dirt. The order of magnitude cost for excavating trenches, building berms, and tunneling is, using the \$10 /m^3 etimate, C_{elev} M\$. This is very crude and doesn't take into account things like how far dirt needs to be moved. However, the important point is that the relative cost of sites, and thus the search itself, should be minimally effected by such considerations.

It is also desirable to have sites where the bowl-shaped regions are not significantly tilted. To that end, we define the cost function

$$C_{\text{tilt}} = 10 \left[\left(\frac{\theta_x}{\theta_0} \right)^2 + \left(\frac{\theta_y}{\theta_0} \right)^2 \right], \tag{4}$$

where θ_x and θ_y are the tilts of the X and Y arms, respectively. The angle used to normalize this cost is $\theta_0 = L_{\text{arm}}/2R_\oplus \approx 3$ mrad. When a mirror is suspended from a pendulum it follows the local gravitational field at that location of the earth, i.e. it hangs perpendicular to the earth's surface at that point if the local gravity at that point is that of a uniform sphere. A straight beam between two mirrors separated by a distance L_{arm} is not perpendicular to the mirrors due to the curvature of the earth, however. The angle used to normalize this cost θ_0 is the angle between the local gravitational field which the mirrors follow and the straight beam between the two mirrors.

Minimizing the cost function Eq. (1) does find several bowl-shaped sites in the continental US. Two representative examples of such bowls are shown in Fig. 3 using the elevation profile plots introduced in Fig. 1. The volume of dirt needing to be cut and filled as calculated by (2) as well as the tilts of the two arms is also shown in the legends. Note that the volume of dirt needing to be moved for a "perfectly flat" spherical site is of order 10^7 m^3, so it is conceivable that these bowls can reduce this cost by roughly a factor of 10.

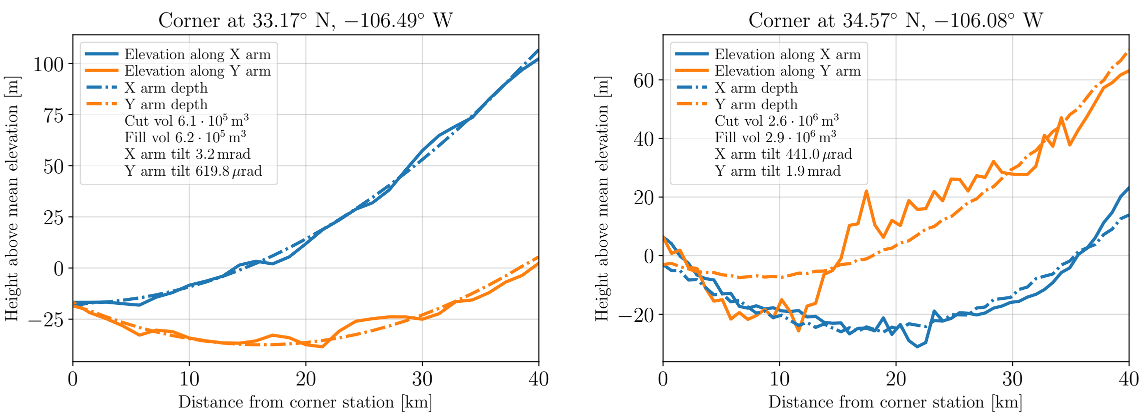

Figure 3: Examples of bowl shaped sites plotted as shown in Fig. 1. *Left*: White Sands, NM (the best site); *Right*: Albuquerque, NM (one of the worst of the "good" sites). The cut and fill volumes were calculated for $\theta_r = 45°$.