Laser Beam Projection for Starshot Launch

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ABSTRACT

The Breakthrough Starshot Initiative aims to send a nanocraft to the Proxima Centauri system. Light sails 4 m in diameter will be accelerated by a 100 GW laser beam projected from a segmented aperture of several kilometer diameter. Adaptive optics to maintain a coherent beam require wavefront and phase sensing across the entire aperture.

One projection system considered here comprises millions of 1 m^2, 20 kW block of lasers each passing through beam expanding and beam directing units with a steering flat to project a 2 m x 2 m square diffraction limited beam. These units are packed close together for ~70% filled aperture. The beam expanders allow for mechanical and servicing access between the laser blocks. The off-axis Mersenne beam expanders both project the outgoing laser beam and receive incoming light from a beacon or the spacecraft for wavefront detection. A dichroic mirror separates the outgoing and incoming light. A wavefront sensor measures the atmospheric aberration across each 2 m aperture, and an adaptive deformable mirror is used to correct the projected beam to the diffraction limit over each 2 m aperture. Our approach is compatible with fixed frequency or tunable lasers. For fixed frequency lasers, a dichroic coating that transmits 99.99% at 1060 nm and reflects 90% of the redshifted return beam from the spacecraft accelerated beyond 70 km/s for P polarization.

The 2m square beams will be steered over 2.5° to aim the beam during the 10 minute launch interval. Atmospheric wavefront tilts will be measured and the beam wavefront will be adaptively corrected by modulating laser phases. A preliminary trade study will compare performance and material and mass production costs for these two options.

Keywords: Wavefront sensing, phase sensing, laser beam steering.

1. INTRODUCTION

Starshot is an effort to design a mission to send a spacecraft to the Proxima Centauri system (the nearest known star to the sun) and send back pictures of the star and its planet(s). The destination is approximately 4 light years from earth, which is unreachable by traditional propulsion systems. The Parker Solar Probe is the fastest humanmade object ever flown reaching over 1,500 kilometers per second[1]. At that speed it would take over 6000 years to reach Proxima Centauri. Instead of the historical approach, Starshot plans to launch a 4 g "nanocraft" and accelerate it to 0.2 times the speed of light. At that rate, it will reach its destination in 20 years. In order to accelerate the nanocraft, Starshot plans to push on it with a high power laser beam. As laser light reflects off the craft's sail, momentum will be transferred to accelerate the craft. Preliminary system models describe a 4 m diameter light sail that receives 8 GW/m^2 of laser light. The baseline design uses a laser wavelength of $\lambda = 1.06$ µm [2] and accelerates the craft for 10 minutes until it reaches a velocity of 1/5 the speed of light at a distance of 18 Gm from earth. The size of the needed array can be calculated as follows: In the far field limit, the angle, θ at which the first null ring in the diffraction pattern occurs is:

$$\sin\theta = 1.22\frac{\lambda}{D}$$

where λ is the wavelength of monochromatic light and D is the diameter of the diffracting aperture. From geometry we can calculate that $\sin\theta = 0.5\frac{d}{z}$ where d is the diameter of the diffraction spot and z is the distance from the aperture to the spot. Combining these equations, the equation to determine the size of the required laser array is

$$D = 2.44\frac{\lambda z}{d}.$$

To have a diffraction-limited spot 4 m in diameter at a distance of 18 Gm, the array of lasers must be 12 km across. This is the extreme limit to have the first nulls of the diffraction pattern at the edge of the sail at the farthest distance. Current system models have optimized the trade between laser array cost and beam efficiency to determine an array of approximately 4 km diameter[2]. This size will be used in the analyses below.

This paper focusses on three aspects of this project: Shaping the beam to maintain a sail stable in its trajectory, maximizing the projector fill factor to increase the efficiency of the beam, and cophasing subapertures across the array.

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2. BEAM SHAPING

According to the Starshot baseline design, the nanocraft will experience acceleration starting at 14,900 g's and decreasing to 2,500 g's over 9 minutes [2]. It is not possible to prevent all irregularities in the beam or in the sail surface. Also, the craft will encounter interstellar particles during acceleration, which could cause the sail to fall out of the launch beam. While the beam can be modulated to steer the craft, it cannot be done with closed-loop active control. Because of the speed of the craft, it is not possible to see the position or orientation of the craft from the ground and compensate with the beam in time. The sail must be self-stabilizing. Early studies explored conical sails that are concave towards earth. These were found to be unstable[5]

[4]. Manchester suggests a spherical sail be launched with a beam where the intensity profile has a low spot in the center. Manchester suggested a lobed Gaussian beam profile comprised of four offset Gaussian beams (See Figure 1.) and found it to maintain a spherical sail in a stable trajectory.

A shaped intensity profile can be formed by modulating the phase of the lasers in the launch aperture. A method using vortex or spiral phase gradients in the launch array creates a donut-shaped beam profile. A four lobed beam profile can be generated by dividing the laser array into four quadrants and modulating the lasers in adjacent quadrants to be π out of phase in a Secchi pattern. Figure 2 shows a flat circular aperture (with no phase modulation) and its corresponding point spread function (PSF). It also shows a vortex phase aperture that creates a donut shaped PSF on the sail and a Secchi pattern phase aperture with its four-lobed PSF. Finally The last phase pattern uses a linear gradient to steer the outgoing beam slightly off center. By rapidly flashing the beam between four locations in a circular pattern around the sail, a time averaged net force on the sail could be achieved that is similar to that of a shaped four-lobed beam.

The donut and the four-lobed beam profiles maintain a spherical sail oscillating about the center of the beam, however, they come with a cost: The PSF is larger than that of a flat circular aperture. This means that the power pushing on a 4 m diameter sail is less.

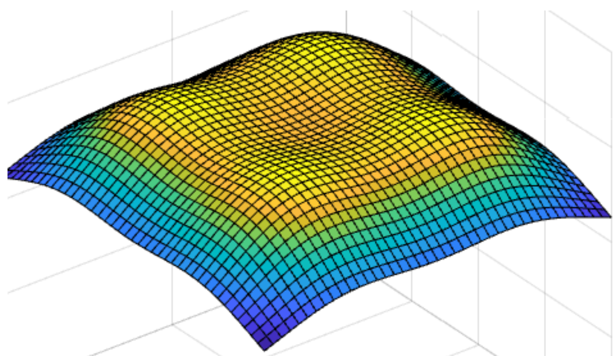

Figure 1 An example lobed beam profile created by summing the intensity of four offset Gaussian beams.

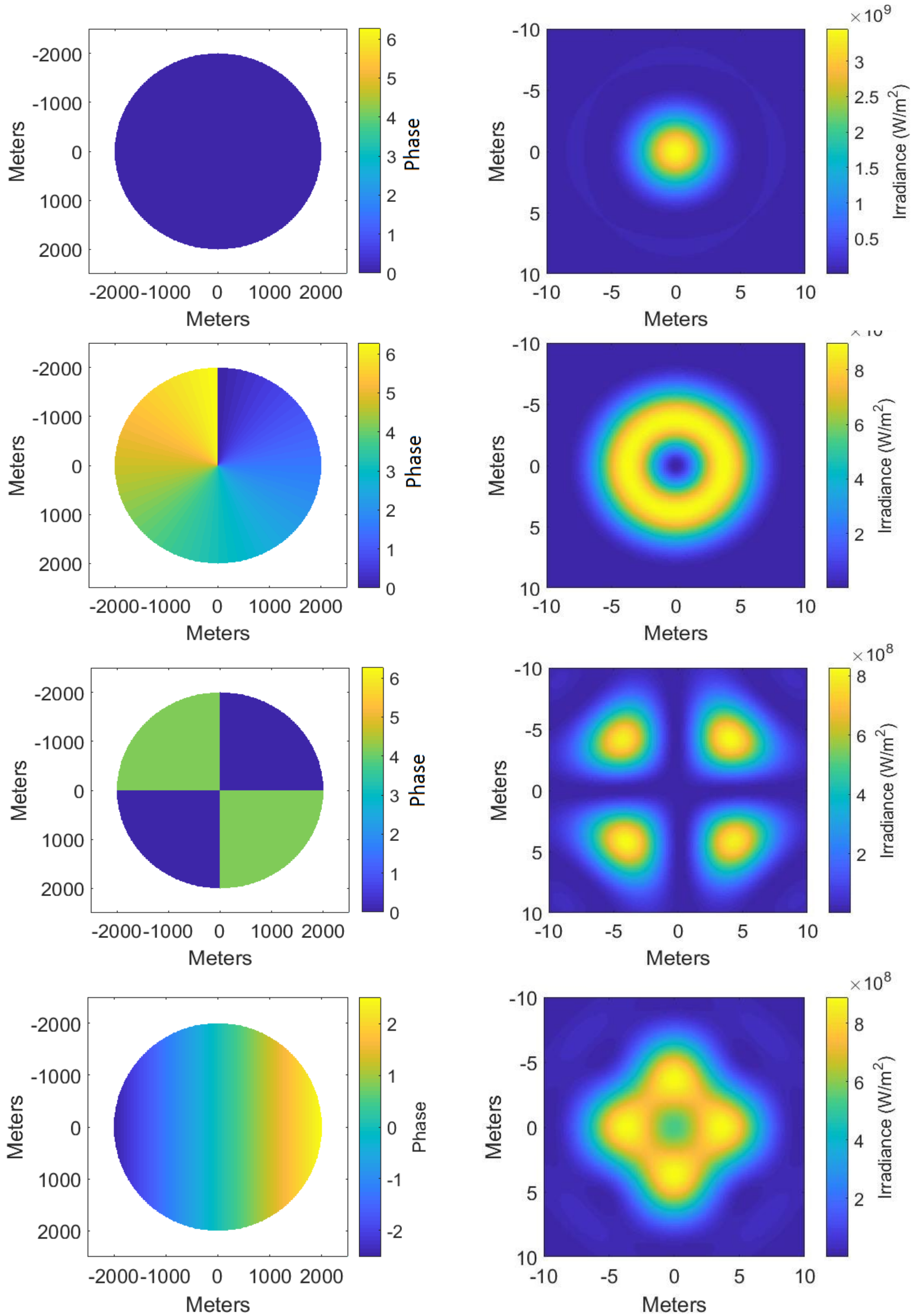

Figure 2 Beam aperture phase plots (left) and their corresponding point spread functions at the spacecraft sail (right). Note that the color scales on the PSF plots are not the same. The bottom PSF plot is the sum of four PSFs each generated by a phase distribution rotated 0, 90, 180, 270 degrees respectively from the one shown on the bottom left.

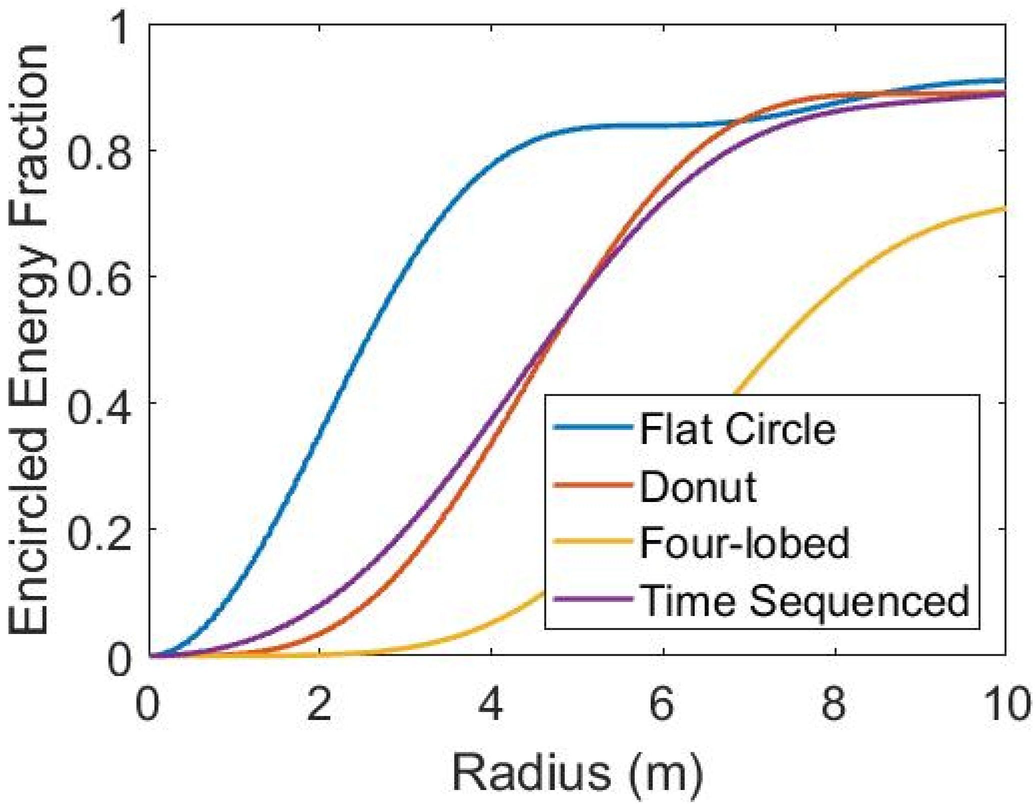

Figure 3 Encircled Energy of the four beam profiles shown in Figure 2.

Figure 3 shows the encircled energy of the four beam profiles. For the modulated profiles, relatively little power hits the 2 m radius sail. In order to shrink the size of the PSF, the laser array aperture would need to grow proportionally. Using a shaped beam is possible, but requires a trade optimization with the size of the laser array.

3. ALIGNING LASER PHASE ACROSS THE FULL APERTURE

In order to shape the beam profile, the relative phase of the laser light across the aperture must be tightly controlled. Maintaining a diffraction limited beam across such a large aperture will be a challenge. To accomplish this, all the lasers in the array must be in phase within a fraction of a wavelength. In order to co-phase an array of lasers, the outgoing beams can be sampled. Light from pairs of lasers may be interfered with each other or with a master oscillator to determine the phase difference between them. Adjacent beams may be sampled according to the schematic In Figure 4.

The Keck telescopes require similar phase measurements with 36 meter-scale apertures that need to be phased for infrared observation. The literature discusses the physical procedure of measuring phase differences between adjacent apertures in some detail[3]. Another relevant analog is radio telescope arrays such as the Very Large Array (VLA). This array of 27 independently steerable apertures combines the signals for interferometric observations. To computationally interfere the signals, the central computer needs to precisely know the phase difference between each pair of antennas. The phase is adjusted in several ways including a system that adjusts the phase based on the pointing angle. As the earth turns, the antennas change their pointing angle to compensate. This changing angle elongates the optical path length of some subapertures with respect to others. The individual antennas communicate with the central computer through wave guides, which are analogous to the fiber optic samplers in the laser beam launcher. The VLA central computer sends a signal to ping each antenna. By measuring the phase change after the round trip, it can remove any phase difference caused by the lengths of the wave guides[5]. Similar methods could be used while measuring the phase differences between laser beam launcher sub apertures.

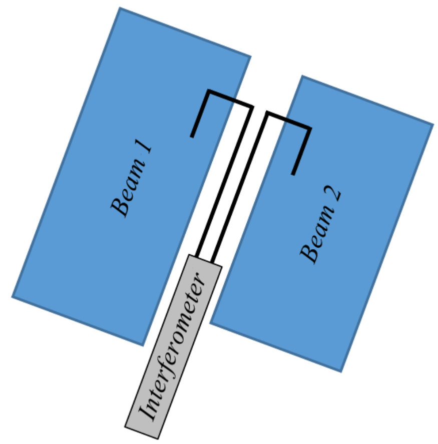

Figure 4. A schematic diagram showing fiber optics sampling two laser beams and combining the samples to measure the phase difference between them.

Theoretically fibers from any two subapertures in a large array could be brought together and the phase difference measured. The problem is that building a structure to hold the sampling fibers that is rigid on the order of fractions of a wavelength across large distances (kilometers) is not feasible. However, the phase difference between adjacent lasers could be reasonably measured. Differences could be added along a path of consecutive aperture boundaries to calculate the phase difference between a pair of two lasers that are separated by a long distance. This is a path-following algorithm, and is similar to quality guided flood fill unwrapping techniques used in phase retrieval for fringe projection measurement of three dimensional surfaces[6]. The problem with this approach is that errors will compound across a large numbers of steps. The random error could be reduced by averaging multiple paths between the two distant lasers. However, systematic error will simply add. Systematic error could be caused by deflections or rotations in the structure that holds the sampling fibers. In addition to phasing the array by making local boundary measurements, the array could also be phased by directing the beam onto a screen on an orbiting satellite. This approach remains to be explored in detail.

4. LASER LAUNCHER CONFIGURATION FOR HIGH BEAM EFFICIENCY

System models have specified that the maximum required power from the laser array is 200 GW. Based on laser technology projected to be available in the near future, models calculate that the laser array will be on the order of 4 km x 4 km. The irradiance needed at the sail to accelerate the nanocraft is 8.7 GW/m^2 [2]. For a sail with a circular shadow of radius 2 m, that comes to 109 GW of power on the sail. That assumes that 55% of the power leaving the laser array hits the sail. This section discusses subaperture spacing requirements to attain that efficiency as well as a design configuration that can meet those requirements.

Early concepts of the laser beam launcher showed a field of isolated lasers that are each aimed individually (Figure 5). Ignoring other nonscientific aspects of the image, it is important to note that this approach is problematic because the gaps in the aperture act as a diffraction grating, diverting significant amounts of energy away from the central beam of the launcher. Figure 6 shows how increasing the gap between subapertures quickly decreases the efficiency. For the spaced, inefficient apertures, the power has been increased so that the peak irradiance matches that of the ideal plot. Their higher side lobes (lost power) can be seen in the irradiance cross section in Figure 6 d.

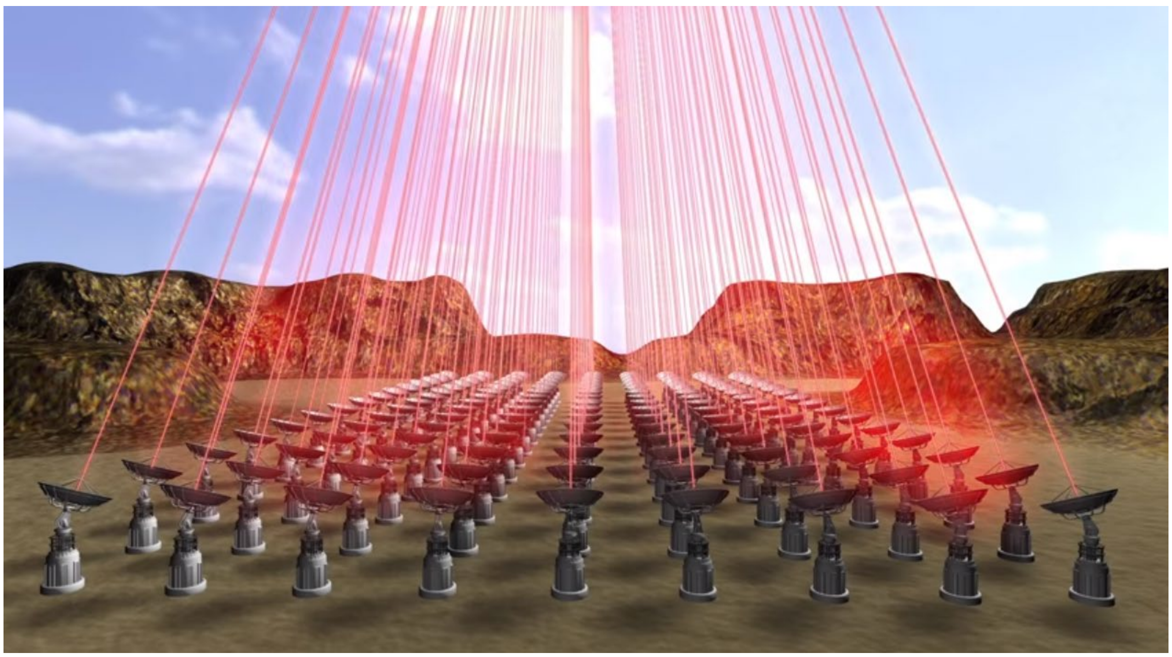

Figure 5. Early graphic of a laser array beam launcher. Image courtesy of breakthroughinitiatives.org.

In order to minimize diffraction loss, a continuous, uniform aperture is ideal. A major difficulty in achieving this is that a solid 4 km x 4 km laser block would be difficult to access for alignment and maintenance. Also, high power lasers require power and control wiring, as well as liquid cooling. As a baseline, assume that individual 10 cm lasers will be clustered into meter-sized blocks, each with ~ 70 kW output. The technical challenge is to find a practical architecture to combine these outputs with high filling factor (70% filled aperture) in order to put > 60% of the energy into the diffraction-limited core. Also, the output beams must be steerable to keep the beam directed at the sail despite the earth's rotation. This requires a range of 70° to 90° in elevation and ±10° in azimuth. These engineering problems are complicated by Starshot's very low cost targets. Two possible solutions follow.

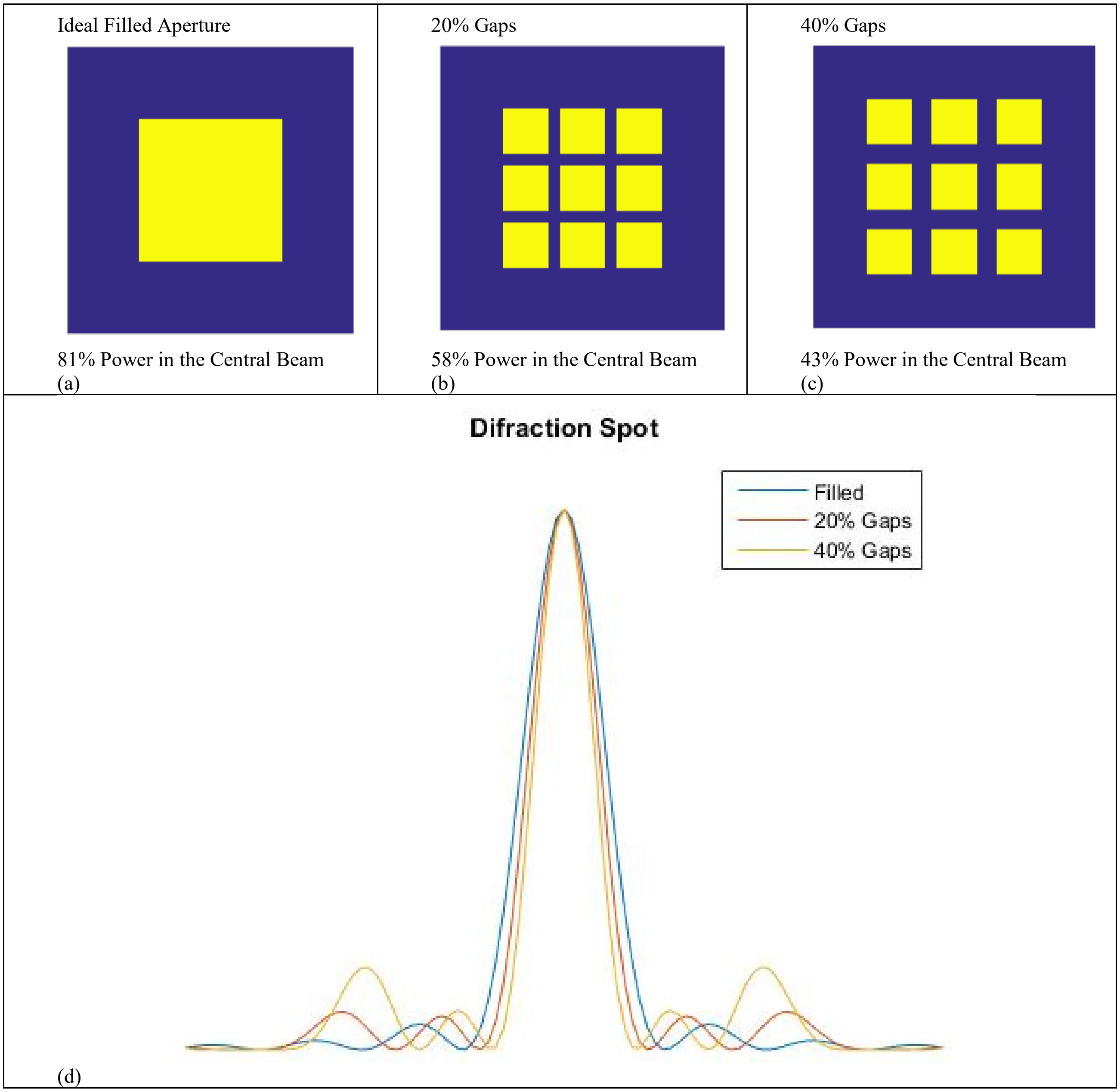

Figure 6. (a)An ideal filled aperture. (b)An aperture with 20% spacing between subapertures. (b)An aperture with 40% spacing between subapertures. (d) A plot of the irradiance cross sections of the diffraction patterns of the apertures shown in (a),(b), and (c).

First, a beam expander can be used on each meter sized laser block that quadruples the area of the outgoing beam. This allows for mechanical access to each laser block and allows for individual blocks to be removed for maintenance. Beam expanders could use off axis confocal paraboloidal mirrors to expand each 1 m collimated beam into a 2 m beam. The exit pupils of the system can be tens of centimeters apart, yielding relatively low diffraction loss. Mirrors in the system can also be used for wavefront correction and steering. A conceptual design is shown in Figure 7. By using a convex smaller mirror, the expander can be more compact and avoid passing the high -powered laser beam through a focus.

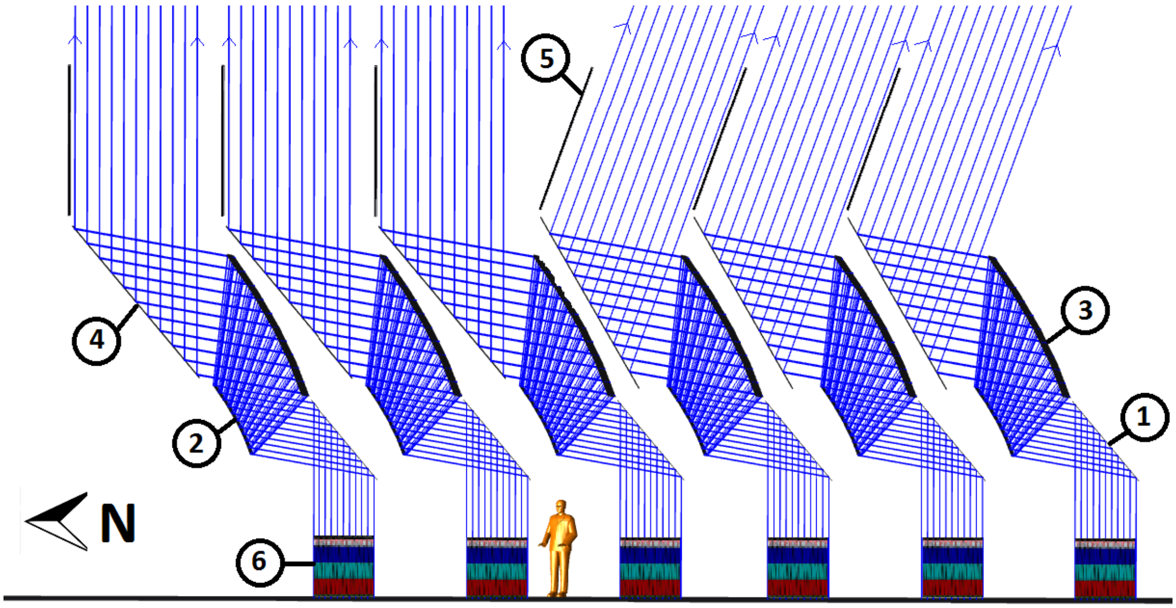

Figure 7. Six projector units, each with a fixed laser block and 2x beam expander where light passes through a focus, seen from the west. The 3 steering flats on the left direct the beams to the zenith, those on the right to 65° elevation. Mirror 1 is a segmented adaptive fold flat. Mirrors 2 and 3 constitute a beam expander. Mirror 4 is a steering flat. 5 are hinged roof hatches. 6 are laser blocks.

The concept is to combine the outputs from fixed blocks of lasers using stationary beam expanding and correcting optics followed by steering flats, as shown in Figure 7. This model supposes that each laser block (**6**) is 1 m square and delivers power of 70 kW. A flat adaptive mirror (**1**) directs the beam expander optics (mirrors **2** and **3**) will double its size to 2 m x 2 m. The articulated flat (mirror **4**) allows the beams to be steered 30° in elevation and ± 30° side-to side.

The large ends of the laser beam expander units have 0.5 m spaces between them in the N-S direction, and 0.3 m E-W gaps, yielding the beam profile shown in Figure 8 with filling factor of 70%, when pointed at zenith. A rectangular grid geometry has advantages over hexagonal such as better access with straight line N-S paths, as shown also in Figure 8.

2.8 million units, each delivering about 70 kW of laser power, will make up a 4 km^2, 140 GW beam. If the 1 m square block has a 10x10 array, then each 10 cm beam will need to deliver 700W.

4.1 Optical Design

The beam expander design uses a concave/convex pair of confocal paraboloids. This off-axis Mersenne optical design yields a collimated output beam. This configuration has the advantage of delivering uniform collimated output power when the input power is also collimated and uniform. The beam is simply magnified, with no distortion. Thus when the input power is uniform across the square entrance aperture, the output power is also uniform over a square exit aperture. The output beam must be uniform on all scales as any periodic fluctuation will cause diffraction losses. The beam expander optics, along with the laser block, are fixed in position.

There are two flat folding mirrors, one fixed (**1**) and one (**4**) steerable. The first, fixed fold mirror reflects the vertical, 1m square beam from the laser block into the beam expander. This mirror could be an adaptive wavefront control element. The design has as its last element a 2 m steering flat (mirror **4**), with a targeted motion of 15° of tilt in any direction from nominal. The Starshot requirements of 70° to 90° in elevation and 180°±5° in azimuth lie well within this range. Figure 7 shows two orientations of the steering flat to produce beam elevations of 65° and 90°.

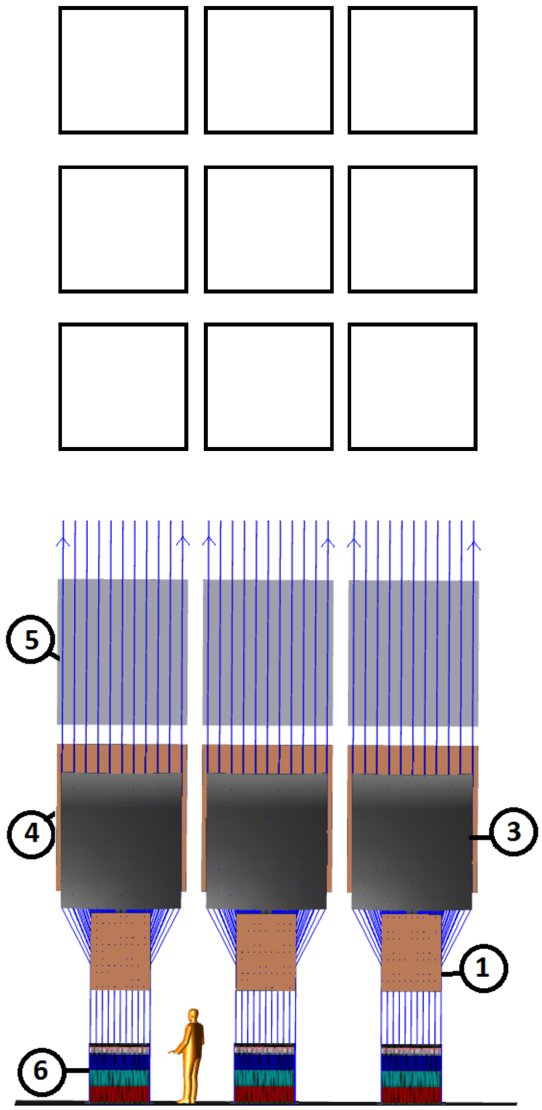

Figure 8. Top: the beam pattern for a 3x3 group (zenith pointing) as seen from the spacecraft. Bottom: a view of the beam expanders looking south.

4.2 Mechanical Supporting Structures

The smaller elements, the laser cluster blocks (**6**) and the adjustment flat (**1**) and convex first mirror (**2**) of the beam expander, are arranged in 1m wide rows, with 1.5 meter wide access corridors between. The larger fixed beam expander mirrors (**3**) and articulated beam steering mirrors (**4**) are above, with little room between for access. These mirrors will be supported on columns from the floor. Initial placement of these larger mirrors, row by row, will be straightforward, however, later access of mirrors in the completed array for service or cleaning could be accomplished from a series of bridge cranes that pass above the array, each straddling several rows. Mirror **3** could be mounted to and with mirror **4** of the adjacent expander. These assemblies could be lifted out by the crane or lowered to the floor by moving the laser block and smaller mirrors (**1** and **2**) to one side.

If the large curved beam expander mirrors, are ~25 mm thick, they can be supported to high accuracy on three points only, with the 6 degrees of freedom adjusted by three tangent arms and three axial rods. This takes advantage of the fact that they remain in fixed position, and the fact that a small fraction of the deformable mirror stroke can be used to correct moderate errors of low and medium orders. Also, shell stiffness provided by the curved shape significantly resists deformation.

Because the steering mirror (**4**) does change its orientation, it will need support at multiple points to limit changing bending under gravity. Because orientation changes are limited to ~ ± 15° and some correction with the deformable flat (**1**) will be possible, the mount can be much simpler than is needed for mirrors in conventional telescopes.

Protecting the projection array against the weather, including dust, rain and wind, is a challenge. The optics could be mounted on an internal structure. A structurally independent external building would protect the mirrors and lasers from wind and other elements, analogous to telescope housings. This outer structure could have hinged roof hatches (**5**) that can be lowered in inclement weather and can pivot when open to align with the outgoing beam (see Figure 7).

Another important consideration for the beam-launch optics is that the atmospheric distortion of the wavefront needs to be measured across the entire aperture so it can be compensated for. The beam expander optics can also serve as telescopes to receive light from a beacon, guide star, or reflected from the nanocraft itself. A dichroic reflector can be inserted that allows the outgoing laser light to pass through while diverting the incoming light for wavefront sensing. The baseline design wavelength of the laser beam is 1064 nm. Light from a beacon (for example mounted on the spacecraft that releases the nanocraft into the launch beam) could be at a different wavelength. The launch laser light reflected by the nanocraft sail will be increasingly red-shifted as the nanocraft accelerates. Ryker Eads designed a multilayer coating that will pass 99.9% of the laser light and reflect >95% of the return light at longer wavelengths (>1064.7 nm). The dichroic mirror (**7**) could be located as shown in Figure 9.

Literature shows that a curved dichroic does not have a large impact on the transmitted light, but will change the size, shape, and location of the spot imaged with the reflected light[7]. This would be especially problematic for wavefront sensing, which often depends on spot location to measure the slopes of the wavefront. A flat dichroic could be used, which would require an additional focusing element.

This beam expander design addresses the need of easy access to laser blocks while maintaining a high fill factor in the outgoing beam aperture. However it does introduce complexity. The 7 additional mirrors (including the two expander mirrors, the fold flat, steering flat, dichroic flat, and signal focusing mirror) add to the material cost. Also, the effort required to align millions of these modules increases with each additional optic. Future trade studies between this and other approaches will determine the best solution.

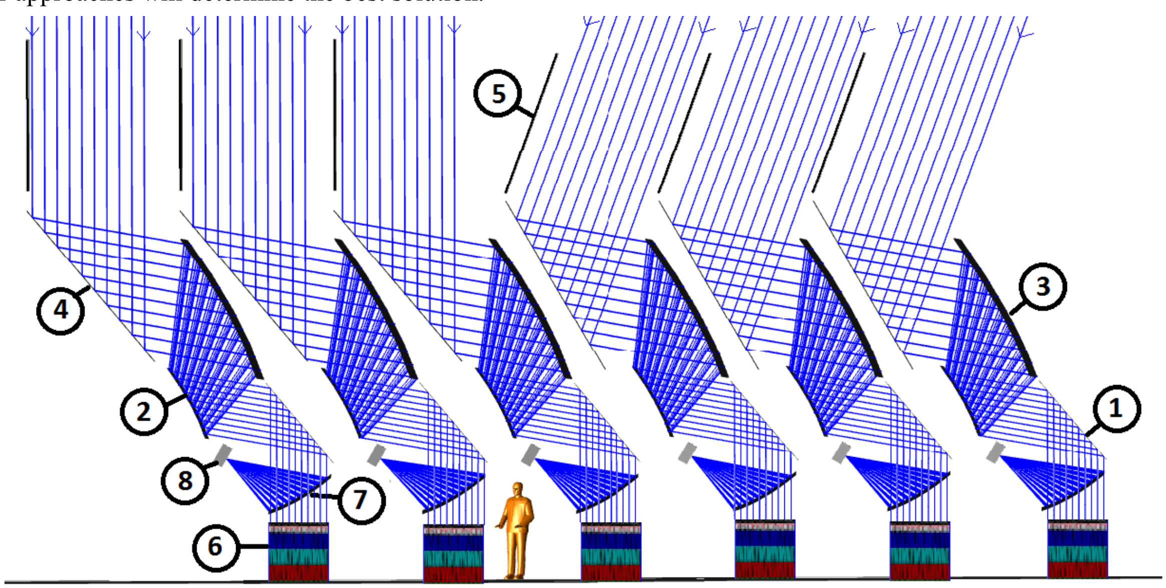

Figure 9. Using the beam expander optics to receive a signal for atmospheric correction by inserting a dichroic mirror (7) between the laser block (5) and the beam expander optics.

5. CONCLUSION

The Breakthrough Starshot Initiative poses several complex challenges. Computer simulations of the launch laser beam show that by modulating the phase of the subapertures, the beam can be shaped into multiple beam profiles that have a central depression. These profiles can maintain a spherical sail oscillating about the axis of the launch beam while accelerating it along that axis. However, by using phase modulation to shape the beam, the size of the beam at the sail grows requiring either higher power or a larger aperture at the laser array to compensate. Modulating the phase also requires precise knowledge of the relative phase across the array. This can be achieved by measuring the phase differences at the boundaries between adjacent subapertures. However, even with averaging multiple paths of consecutive apertures, the uncertainty of the relative phase across the aperture grows with the aperture dimension. This can be partially mitigated by averaging repeated phase measurements. Also important to maintaining a tight PSF is minimizing gaps between subapertures. Beam expanders can be used to allow access to the laser blocks while maintaining a nearly continuous outgoing beam aperture. Many challenges remain in the Starshot project. The information in this paper will hopefully provide helpful constraints to those efforts.

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