LAST: Laser Array Space Telescope

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ABSTRACT

A phased array operates by modulating the phases of several signals, allowing electronic control over the locations that these signals interfere constructively or destructively, allowing the beam to be steered. A space-based laser phased array, called the Directed Energy System for Targeting of Asteroids and exploRation (DE-STAR) has previously been posited by our group for a number of uses, from planetary defense to relativistic propulsion of small probes. Here we propose using the same basic system topology as a receiver rather than a transmitter. All of the components in the system, excluding the laser, are bidirectional. Rather than each element transmitting laser light, they would instead receive light, which would then be combined to create an interference pattern that can be imaged onto a focal plane. The Laser Array Space Telescope (LAST) uses most of the same components and metrology as DE-STAR and could thus be integrated into a singular system, allowing both transmit and receive modes. This paper discusses the possible applications of this system from laser communications to astrophysics.

Keywords: DE-STAR, LAST, Directed Energy, Laser Phased Array, Telescope

1. INTRODUCTION

To gain resolution we have to think smaller, using arrays of small optics to accomplish what a single large optic cannot. We propose a complete redesign: LAST. The LAST is a multifunctional, cost-efficient, modular telescope capable of being both a transmitter and a receiver. The modular nature of the telescope would allow for the continued expansion of the system, thereby removing the physical size limitations of current designs. This would lead the LAST to become the largest telescope ever built. Moreover, with the emergence of single mode, kilowatt class Yb3+-doped fiber lasers in the last decade, the LAST's function as an optical transmitter will enable further applications.

2. TELESCOPES TODAY

Since the beginning of civilization, humans have always been curious; looking to the stars. With the use of telescopes, we have given ourselves a closer view of these mesmerizing bodies of matter. Thanks to technologies developed in the fields of astronomy and optics, our capability to see further has progressed in leaps and bounds in the last century, with the Hubble Telescope being a pinnacle of scientific and technological achievement.

This telescope has provided us with incredibly detailed images, in turn offering us glimpses of the universe from up to 10-15 billion light years away. However, if our curiosity for the stars and our universe is so great, why do we have so few telescopes of this caliber scanning the universe? In order to see further into the universe at high resolution, we will need bigger telescopes and an even bigger wallet. A study shows that for large, ground-based, monolithic telescopes, the construction cost increases by a power scale of 2.46 in relation to the aperture size[1]. The LAST does not follow this trend

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because it departs from using a single large aperture. Arrays with modular sub-elements, such as LAST, can rival those such as the Hubble Telescope and the James Webb Telescope both economically and optically.

The LAST can be implemented in both a ground-based and space-based system, each one with its own distinct advantages. The ground-based system is cost-effective, because it would not need to be transported to or assembled in space; however, the telescope must actively adapt to various sources of atmospheric interference. These sources of interference include atmospheric and weather conditions, aviation, and wildlife. This system would allow for greater flexibility in energy sources, as it would not be bound to solar power like a satellite. A ground-based system would also be more accessible for maintenance and modification. Although lacking in these respects, a space-based system is much less susceptible to atmospheric interference, permitting it to receive and transmit information with greater resolution. The space-based system would allow for clearer images and decreased danger for people and wildlife in the local area surrounding a ground-based site.

3. LAST DESIGN

3.1. Concept

Although conventional telescopes have made phenomenal technological leaps in the last century, they are limited to a size of several meters by the nature of their monolithic mirrors. The proposed phased array telescope is modular, allowing it to be scaled to sizes exceeding a square kilometer. This large aperture enables the generation of images with substantially greater resolution than conventional optical telescopes. Instead of creating an image by directing light into an aperture limited by mirror size, the LAST accumulates data gathered from millions of smaller sub-apertures—called Optical Sub-Elements (OSEs)—to generate an image. This imaging is accomplished by collecting the interference patterns that are created when light from a source is separated into two or more OSEs. The LAST utilizes its many OSEs to produce an interference pattern with a very large central constructive spike and minimal residual noise from the side lobes. The phase of the light is then shifted to maximize the constructive interference based on the observed shape of the incoming wavefront. To generate an image, the LAST assigns a value to each pixel, such as intensity, by maximizing the total constructive interference and correlating peak amplitude with the value of the pixel. The LAST then scans its field of view, assigning values to each pixel as it does so. After scanning the entire area, the combination of the pixels creates a full image.

This image will have a greater resolution than previously possible, because the design of a modular telescope allows for the comparison of interference patterns from a wide array of individual telescopes—called Base Optical Assemblies (BOAs). This provides a more accurate representation of a pixel in the sky than the light entering through a single lens. The motion of the array as a whole is precise, because each BOA relies solely on piezo actuators for movement. The modular design of the array allows the size of the telescope to be scaled for specific missions. Even if a square kilometer array were constructed, an image could still be created without using all of the BOAs. Additionally, the small size of each BOA makes for easier assembly and maintenance than the larger structures that make up telescopes currently in use across the world. Every BOA is identical, meaning that replacement parts could be purchased in large quantities and kept nearby the LAST to minimize costs and expedite repairs. The LAST would be the largest optical telescope on Earth and would take the eyes of humanity farther than ever before.

3.2. Design

The central idea motivating the design is modularity. The design consists of arrayed BOAs which are modular, hexagonal panels machined out of aluminum. While other BOA geometries were explored, as discussed later, it was found that hexagonal BOAs produced the best results. The BOA is mounted by means of a rigid truss system on top of a high-load-capacity hexapod that boasts micrometer precision in six degrees of motion using piezo linear actuators, as shown in Figure 1. Underneath each BOA are 19 OSEs that act as mounts for individual optical fibers and use fiber actuators to position the fiber tips with micrometer precision relative to the center of their respective lenses. Since each BOA is modular, an array of BOAs can be designed and constructed to work together. In order to achieve the desired interstellar results mentioned above, a ground-based square-kilometer array of BOAs will be designed.

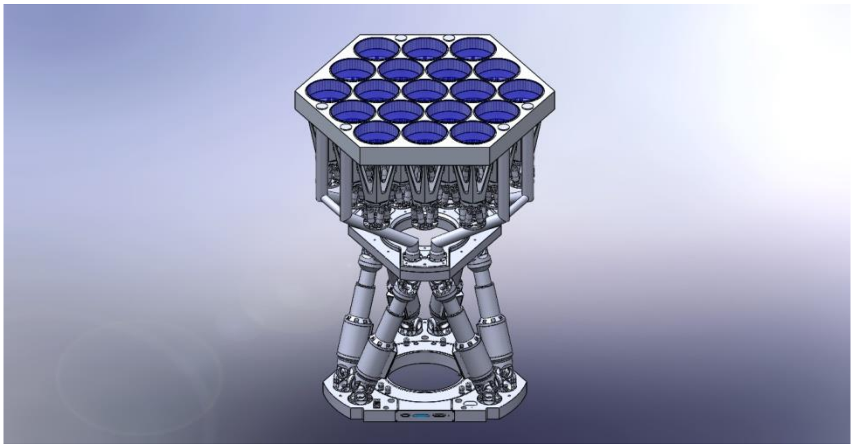
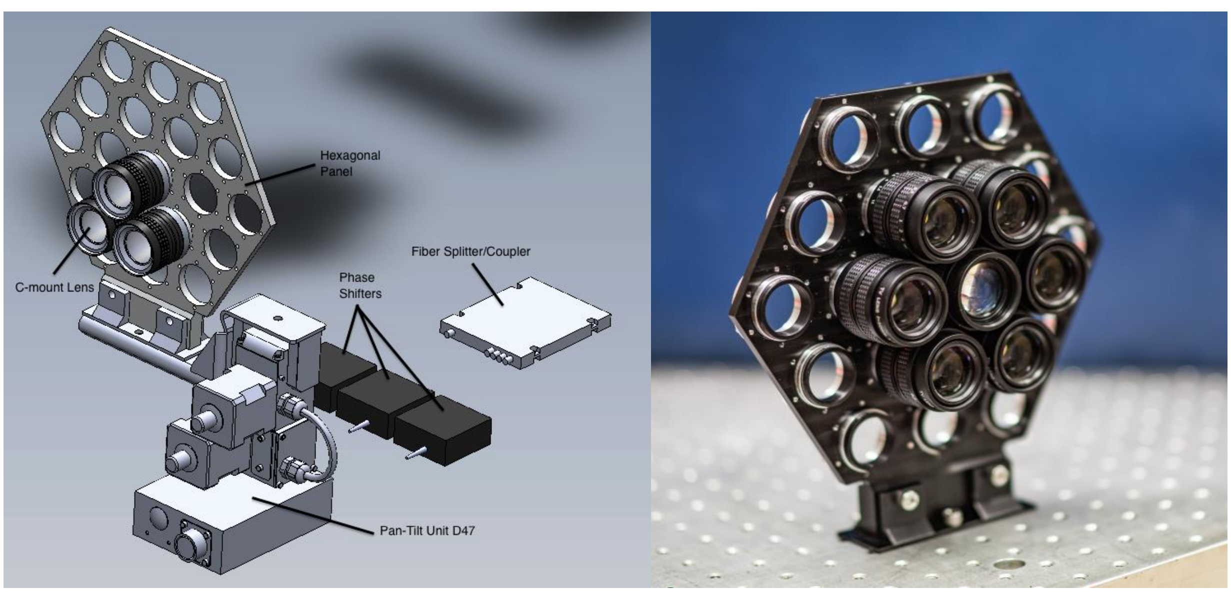


Figure 1: CAD rendering of a square-meter telescope; LAST will contain over one million of these sub-arrays.

3.3. Quarter-Scale Model

Current and forthcoming experiments do and will make use of a smaller, ¼ scale model of the BOA assembly depicted in Figure 2 and 3. Used to both transmit and receive light, the scaled model consists of a smaller hexagonal panel on which 19 modular lens assemblies can be mounted. The panel is attached to a dual-use mount that can adapt to both an optical bench and a pan-tilt mount. The lens assemblies consist of fixed-focal-length C-Mount lenses that are secured to the panel by means of a removable circular adapter mounted to the backside of the panel. Threaded into the back of each lens assembly are C-Mount to FC/APC fiber adapters that allow incoming light to couple through the lenses into single mode, polarization-maintaining fibers and for outgoing light to exit via the lenses. The current assembly emits beams in the visible light spectrum, while future models will be compatible with infrared light and eventually a broadband spectrum.

The final scaled system will include the panel and lens assembly and an additional fiber assembly that consists of fiber-coupled phase shifters and a fiber coupler. The circular adapters mounted on the backside of the panel will allow for coarse beam steering through the loosening and tightening of each of its screws. Fine beam steering is possible using phase shifters in which light is phase shifted to maximize constructive interference in the resulting interference pattern.



Figures 2 and 3: CAD rendering and photo of the quarter-scale model, including lenses mounted in an aluminum panel.

3.4. Optics

The optical components of the array are shown in Figure 4. Light enters through the OSE, an individual optical element that connects to the fiber for transmitting (laser amplifier) and receiving information. The OSE is mounted directly to the BOA, which is the sub array collection of OSEs in a common mount. The BOA then forms the basic building block that we replicate to form the full array. These lenses focus the incoming light onto the tips of fiber optic cables, which are positioned by XYZ piezo-actuators. The actuators allow for fine steering of the fiber tip as well as the ability to compensate for any structural variation due to thermal expansion or vibrations. Each fiber is connected to a phase shifter, allowing the phase of each input signal to be shifted to maximize the constructive interference when the input signals are combined by the fiber coupler. Additional information on the properties of the original light is gathered from a record of the phase shifts applied to the inputs. The combined signal is then sent to a detector to be processed. This detector can be as simple as a photosensitive diode; however, more complex sensors can be used to improve the quality of the data. One such improved detector system uses beam splitters to send the combined signal to two different CCD cameras, allowing both narrow and wide field of view images to be captured[2].

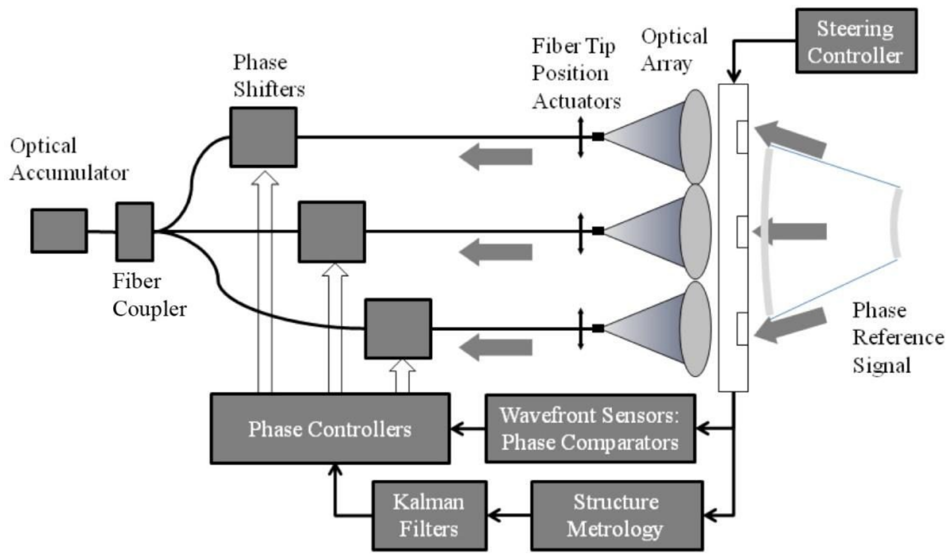


Figure 4: Annotated schematic of the optical assembly

4. POTENTIAL FEEDBACK LOOPS

Due to the unpredictable nature of the light inputs, the phase shifters need to be controlled by a closed feedback loop instead of preprogrammed software. The modularity and potential final size of LAST present obstacles to obtaining the data needed to run the feedback loops. Most phased arrays in use today employ a single beamsplitter that acts on all of the OSEs of the array. A portion of each input/output is then directed to a photodetector, allowing the phase of each beam to be detected in relation to the others[3]. This is a tried and tested approach, but it presents significant restraints on possible designs. First, present technology limits the maximum size of beamsplitters. In addition, beamsplitters are not readily modular. A new beamsplitter is required for every element added to the array, and each new beamsplitter needs to be rigorously calibrated before mounting to account for any defects and irregularities in the splitter.

Alternative approaches exist, but they are mainly designed for transmission-based arrays. One approach, called "phase tapping", involves precision measurements of the position of two arms placed over two adjacent OSEs[3]. The exact phase of the outgoing beams at an arbitrary targeting plane can then be calculated from these measurements. This is a very promising approach, as the phase taps are modular and can be easily added to the array, preserving the modularity of LAST's design. Unfortunately, the taps are intended for a transmitting array where the position of the source is well known. It is currently unknown if the taps can be used when the array is receiving light from a source whose position is not well known.

Another approach would simply use the collective output of the array instead of registering the individual phases entering each OSE. This approach would measure the total power of the combined output of the OSEs and then use a Stochastic Parallel Gradient Descent (SPGD) algorithm to maximize the power, thus maximizing the constructive interference of the inputs and synchronizing their phases[2]. The fact that there is a relatively large number of OSEs on each BOA presents some technical difficulties. Specifically, a misalignment of one of the 19 elements by one tenth of a wavelength will only result in a 1% change in the summed intensity. The detector would have to be very precise in order to detect small phase discrepancies between the nineteen OSEs.

In addition, feedback loops are integral for correcting the optical wavefront since the atmosphere can cause distortions which must be corrected. In order to correct the distortions, the LAST relies on a combination of filtering techniques: adaptive optics and Kalman filters. Delay times must be taken into account, due to the large number of individual components in the LAST's modular design. Certain adaptive optics systems' response times depend on the longest propagation delay of its wavefront correctors[4]. This approach is not conducive to the LAST, where atmospheric distortions should be accounted for as soon as possible. As such, Voronotsov proposes an adaptive optics system that uses the SPGD method as a control algorithm. In addition, the Kalman filter is used to remove noise from the signal before it is transmitted into the phase controllers. The Kalman filter is a two-step algorithm that combines both the current information of the system's state along with corresponding predictions and estimations to produce data of greater accuracy in real time.

5. PACKING DENSITY

To increase image quality and resolution, one of the main objectives of the LAST is to maximize packing efficiency of the array by determining the most efficient shape for both the individual BOA and the overall LAST. Packing efficiency is defined as the ratio between the total OSE area and the total area covered by the LAST. Finding an efficient packing method for the BOAs within the LAST requires determining the most logical shape of each BOA, achieving optimal tilt angles, and obtaining the overall LAST shape.

In order to determine the best shape for the BOA, the packing densities of various shapes were calculated to obtain the most efficient structure for packing the largest number of OSEs per BOA while minimizing the area occupied by the aluminum frame. Three different BOA shapes were compared via derived mathematical formulas: a square, an equilateral triangle, and a hexagon. The square BOA had a maximum packing efficiency of 77.95%, with an ability to hold 20 identically sized OSEs. In comparison, an equilateral triangle BOA had a maximum packing efficiency of 82.81%, with an ability to hold 15 of the OSEs of the same size. Lastly, the hexagonal BOA had the highest packing efficiency overall, with the ability to hold 19 OSEs with a maximum packing efficiency of 86.47%. These calculations and results are shown in Figure 5.

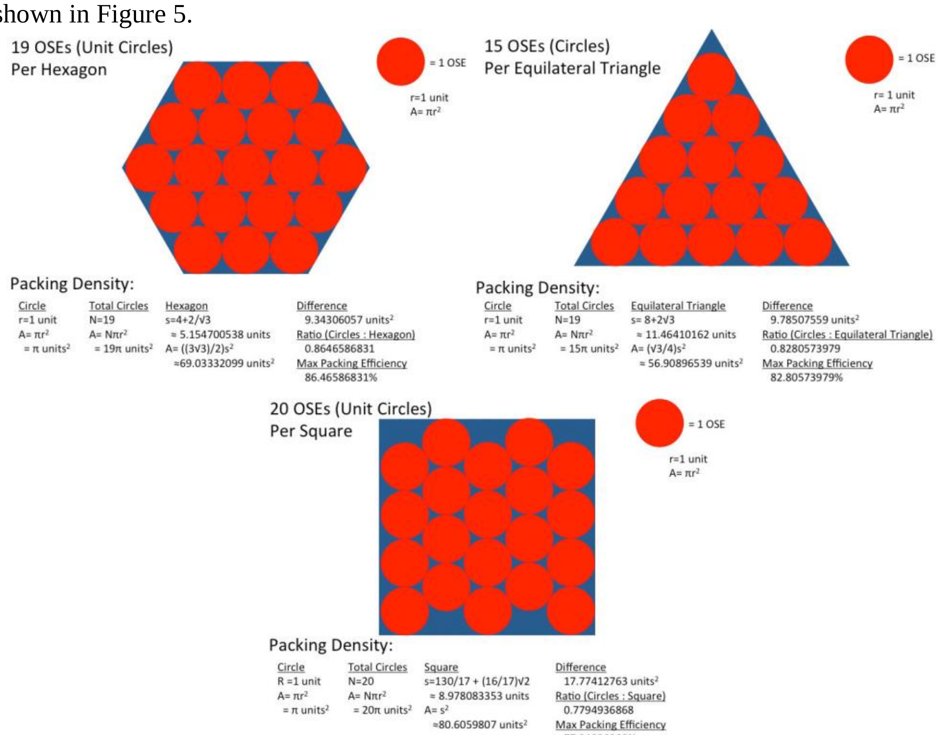


Figure 5: Triangular, Hexagonal, and Square BOA with Maximum OSEs

Wide fields of view and off-axis target acquisition require coarse mechanical pointing of the entire LAST, which is accomplished by tilting each BOA. Tilting each BOA can potentially cause overshadowing onto adjacent BOAs.

The last consideration was the packing efficiency of the BOAs in the LAST. The general method for calculating the packing efficiency was to find the number of BOAs that can fit in a row of the LAST and multiply that by the number of rows that can fit in the entire array.

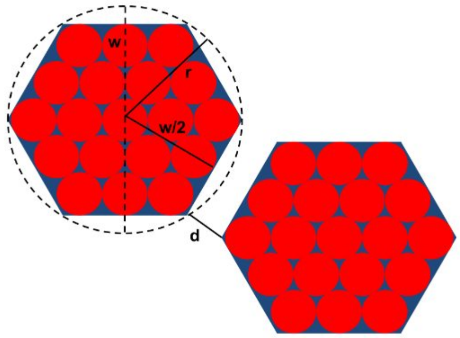


Figure 6: Variables used in the Equations 5.1-5.4

Given the tilt angle θ of the module in degrees and w is the width of the hexagon from side to side (0.866 m), the spacing between the hexagons from side to side is

$$d = w\sin(\theta)\tan(\theta) \tag{5.1}$$

Given r as the radius of the circle encompassing each BOA, the variable d can also be represented as

$$d = 2\left(r - \frac{w}{2}\right) \tag{5.2}$$

Equation 5.3 results by solving equations 5.1 and 5.2 for r.

$$r = \frac{w\sin(\theta)\tan(\theta)}{2} + \frac{w}{2} \tag{5.3}$$

After evaluating equation 5.3, with s being the length of the array's base, the number of BOAs in a given row, X_r, of LAST is given by equation 5.4.

$$X_r = \frac{s - r}{2r} \tag{5.4}$$

Similarly, the number of BOAs per column, X_c, can be represented as

$$X_c = \frac{s + 2r\left(\sqrt{3} - 1\right)}{r\sqrt{3}} - 1 \tag{5.5}$$

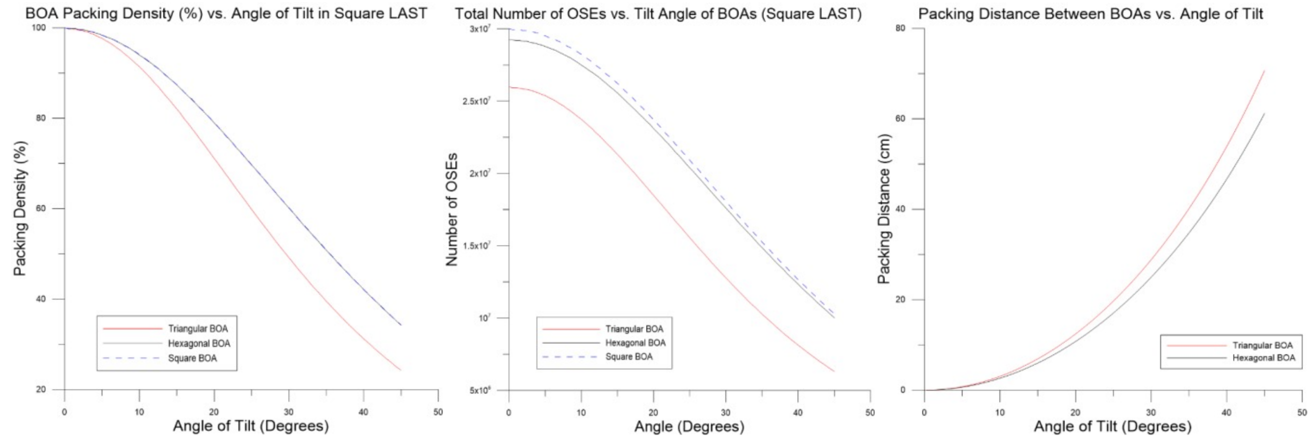
Multiplying X_r by X_c results in the total number of BOAs in the array. In order to obtain the total number of OSEs in the given array, multiply the total number of BOAs in the array by the amount of OSEs per BOA.

Following these equations for a hexagonal BOA within a square LAST with side length s = 1 km at the intended maximum angle θ = 30° results in values of r = 0.56 m, $X_r \approx 895$ BOAs per row, and $X_c \approx 1{,}034$ BOAs per column. In total, this would be equivalent to 925,430 BOAs or 17,583,170 OSEs in a square-kilometer array.

The array density of hexagonal BOAs within a circular LAST array can also be computed numerically. A Matlab simulation first creates a grid of BOA elements, then compares the spatial coordinates of each BOA to those of the bounding circle. BOAs that exceed the bounds of the telescope are removed from the grid; those that are inside are kept and tallied. The spacing between the BOAs is determined from the size and tilt angle of each element. The simulation shows that, at a maximum angle of thirty degrees, the array contained approximately 927,000 BOAs. At a maximum tilt angle of two degrees, approximately 1,540,000 BOAs could fit within the same area. The substantial difference in these two values highlights the trade-off between the optical power of the telescope in a given area and the section of the sky that the telescope can scan.

Additionally, mathematical formulas were derived in order to compare various BOA shapes and tilt angles. They were then graphed to illustrate the impact of each BOA shape on the overall packing efficiency and required spacing between BOAs versus tilt angle.

The results of our calculations indicate that the greater the number of lenses per BOA, the higher the possible packing density of OSEs in the array. Thus, a square shape for the BOA, having the highest area per BOA and greatest number of OSEs per BOA, has the most efficient packing density in the overall LAST array. However, due to higher compatibility with the hexapod system present in each BOA, a hexagonal form was selected. The packing efficiencies of square BOAs and hexagonal BOAs are very similar due to their comparable area for OSEs; hence, a hexagonal shape for the BOA was concluded as the most practical option.



Figures 7, 8, and 9: 7) Packing density, **8)** Total number of OSEs, **9)** BOA packing density all versus the maximum tilt array of a square LAST.

6. APPLICATIONS

In addition to providing a closer look at the stars, the imaging capabilities of the telescope could serve several other purposes. One such example is the ability of the telescope to communicate with spacecraft by light. With bidirectional optical components, the LAST could exchange information via both transmission and reception with spacecraft fitted for photonic communication. The reception of signals from a spacecraft involves aiming each BOA in the direction of the spacecraft and observing light that is emitted from an onboard laser. Through the modulation of the laser, information such as images, messages, and scientific data can be transmitted. The array would receive data from the spacecraft and phase shift the information into a coherent transmission. To send information to the spacecraft, the array would aim the BOAs at the spacecraft and use actuators to focus the laser, emanating from the OSEs, onto the spacecraft. Imaging equipment onboard the spacecraft would then detect the light signal sent from the array and interpret it. In this manner, information could be sent from space to Earth and commands could be sent from Earth to the spacecraft.

The LAST can also function as a laser radar system[5,6]. By using a passive phased array, the LAST minimizes mechanical motion by utilizing phase shifting to improve precision and energy efficiency. The combination of the LAST's precision and large angular travel is the critical element that increases its field of view. In addition, the LAST's modularity allows the array to scan multiple areas at the same time by dividing the large array into smaller arrays each scanning a certain area.

The LAST is not only able to communicate with distant spacecraft but can also accelerate them into the universe. The premise of the Breakthrough Starshot program is the use of momentum from photons impacting a lightsail on an ultralight wafer-thin satellite, or "WaferSat", to accelerate the spacecraft to over ¼ the speed of light in 10 minutes[7]. At this speed, a WaferSat would reach the nearest star, Alpha Centauri, in just 20 years. This photon-driven propulsion system is discussed in detail in "A Roadmap to Interstellar Flight."

Propelling a WaferSat is similar to the process of communicating with a spacecraft. After aiming the BOAs in the array at the WaferSat, each BOA would focus its lasers on the lightsail on the WaferSat. Although each photon in the laser beam has little momentum, the sum of the momenta is not negligible for an ultralight spacecraft and kilowatt class lasers. The continuous impact of photons in conjunction with an orbit that increases in eccentricity would accelerate the WaferSat to relativistic speeds. There is also potential to use photon recycling through a system of mirrors to increase the efficiency of the laser propulsion. The same system could be used to propel thousands of WaferSats towards very distant sources, providing close-up photos and data from places that were previously thought impossible to reach.

Although a space-based laser array provides greater propulsion due to proximity of the spacecraft and the lack of an atmosphere, the Breakthrough Starshot program can still operate using an Earth-based array such as the LAST. The use of an adaptive optics system allows the LAST to adjust in real time to atmospheric conditions and the modularity of the array allows the laser intensity to be scaled to the demands of various missions, whether the WaferSats remain within this solar system or have interstellar destinations. The array could similarly adjust to the size of the satellite, as larger WaferSats would require greater light intensity than smaller, less massive spacecrafts. This multifunctional design greatly increases the value of constructing the LAST as it allows humanity to venture farther into space than ever before without being behind the lens of a telescope.

The same phased array that could image astronomical objects is also capable of conducting planetary defense from asteroids. Explained in detail in the DE-STAR and DE-STARLITE papers, the same BOA units that make up the LAST could focus directed energy on any distant asteroid projected to impact the Earth[8]. The high power of the phased array heats the asteroid's surface to cause high surface vapor pressure that ejects enough of the asteroid's mass to alter its trajectory, avoiding life-threatening impacts. Unlike other currently proposed methods, DE-STAR and DE-STARLITE are able to deflect an asteroid away from Earth using the ablated material of the asteroid itself as propellant to fuel the asteroid's redirection.

The method of ablating the asteroid is scalable to the size of the threat. The DE-STAR project proposes a large array similar to the LAST that would remain in orbit around the Earth and focus its lasers on a larger, more distant threat for an extended period of time. The DE-STARLITE project envisions a much smaller array that would be sent on a spacecraft to a location near a small asteroid to focus its lasers at a much closer distance. These systems are referred to as "stand-off" and "stand-on" respectively.

A further benefit of the LAST is its ability to transport power from the Earth to distant spacecraft or locations. Currently, spacecraft must rely on light from the sun or limited onboard power sources to maintain their functionality. However, if all of the lasers in the array were focused on a spacecraft, similar to the premise of the Breakthrough Starshot program, the incoming photons could be absorbed by solar panels and then converted to electrical energy. Being able to transport energy via directed energy would allow for deeper exploration into our universe.

7. CONCLUSION

Constructing the LAST would generate a wave of new knowledge about space that would potentially unlock the mysteries of the universe. Only by rethinking the design of the conventional optical telescope can we make larger and more powerful imaging devices. A modular, bidirectional, phased array would allow us not only to look into the stars through the lens of a telescope, but would also enable us to send our own spacecraft to these distant bodies to study them in close proximity. The multifunctional and arrayed design of the LAST may be the future standard for the most powerful optical telescopes on Earth.

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