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The Large Fiber Array Spectroscopic Telescope: Optical Design of the Unit Telescope

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ABSTRACT

The concept for the Large Fiber Array Spectroscopic Telescope (LFAST) (Angel et al, these proceedings) is to collect the light from a target object using thousands of individual, small, low-cost telescopes, and bring it via optical fibers to a high resolution (R=150,000) spectrograph. Each mirror has a prime focus corrector feeding a 17 micron fiber at f/3.5, subtending a 1.3 arcsec diameter on the sky. Each LFAST unit has 20 separate 30 inch telescopes carried by a single alt-az mount to provide collecting area equivalent to a 3.5 m traditional aperture. Each mirror has a 4-element corrector provides sub-arcsecond imaging over an 8 arcmin field. The field is reflected by a mirror puck (which contains the receiving fiber) through relay optics to a CMOS camera for rapid guiding and wavefront measurement. The corrector optical design incorporates elements of common crown and flint glass to obtain achromaticity over a broad wavelength range of 380 nm – 1700 nm. Large, slow lateral translations of the final 4th element correlated with primary mirror tilt correct for atmospheric dispersion, and small, rapid lateral translations correct for image motion without significantly disrupting atmospheric dispersion correction. We have explored both aspherical and spherical primary mirror designs and have chosen spherical, based on impacts to unit telescope cost.

Keywords: Large telescopes, optical design, atmospheric dispersion correction, spectroscopic telescopes, LFAST

1. INTRODUCTION

The Large Fiber Array Spectroscopic Telescope (LFAST) is a concept for a scalable large telescope array. It is well known that the cost of a large telescopes increases rapidly with primary mirror size due to the increasing cost of mirror manufacturing, control systems, and facilities.[1] The cost of large telescopes is quickly becoming unsustainable if we wish to observe still fainter objects with enough signal. To circumvent this cost trend, LFAST aims to take advantage of rapid manufacturing of many "small" 0.76 m mirrors, each making its own separate telescope, and combining the light from each telescope via optical fibers, originally proposed by Angel et al in 1977.[2] This creates the potential for very large effective collecting area that can be directly used for spectroscopy. The current goal is to build 2640 individual telescopes, making up 132 mounts, each carrying 20 individual unit telescopes. This results in a collecting area of 1,200 m^2. Because this concept is scalable, there is potential to increase this collecting area arbitrarily, with no more than linear cost increase.

However, the design and construction of this telescope has different challenges than traditional large telescopes. Since the components of each individual telescope will be replicated 2640 times, great care must be taken in the optical design to reduce costs and complexities before high volume production. In this paper, we will discuss the current optical design being made the first LFAST prototype unit telescope, as well as the considerations needed for manufacturing the unit telescope in volume at low cost. In this case cost and functionality are primary drivers of performance.

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2. DESIGN REQUIREMENTS CONSIDERATIONS

For each unit telescope, the most important task can be boiled down to one performance goal: maximize the light incident on the primary that enters the optical fiber, while keeping the cost in volume manufacture as low as possible. Each telescope

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requires a few basic features in order to function properly and take full advantage of the large collection area, a short list and description below:

1. The primary mirrors must be simple to manufacture, limiting the shape to spherical (or potentially parabolic if needed)
2. A prime focus corrector must be used to create a near diffraction limited image at f/3.5 at the fiber input, and an 8 arcminute guide field. The fiber diameter of 1.3 arcsec is chosen to match the expected atmospheric seeing, and the overall imaging performance goal for the telescope itself is > 80% encircled energy in this diameter
3. The image at prime focus will be reflected by a tilted mirror at prime focus, and relayed to a guide camera with arcsecond image quality for guiding on the fiber and field stars
4. The prime focus corrector must be achromatic over a broad wavelength range, from 380 nm to 1700 nm, consistent with the fused silica fiber transmission, and in anticipation of future scientific goals and spectrograph options
5. The prime focus corrector must incorporate the means for atmospheric dispersion correction and rapid seeing image motion correction, in anticipation of wind-shake, atmospheric seeing, or other disturbances.
6. The design must provide commercially loose tolerances to reduce cost of optomechanics and lens manufacturing at scale

The theoretical limit to the efficiency of coupling light from the primary mirror to the fiber is set by diffraction, so it is highly desired that the nominal design starts with diffraction limited for on-axis imaging. It is expected that image degradation will occur due to telescope pointing, component alignment, wind shake, and other manufacturing errors. So, regardless of primary mirror shape (spherical or aspherical) some image correction will be required before the fiber, to create a wider corrected field, so as to give some margin for error on target alignment, atmospheric seeing and overall telescope as-built performance. In order to properly guide faint targets onto the fiber on each telescope, a number of reference guide stars must be visible at the guide camera even at the galactic poles, with lowest star density. Based on the collecting area, each telescope should be able to easily detect a magnitude V=16 star, since within an 8x8 arcminute field there should be several stars at V=16 and brighter available for guiding. These stars also need to have some “reasonable” image quality to be reliable. The diffraction limit is unnecessary for the guide stars, so a requirement of an RMS spot diameter of 2 arcseconds was used as a benchmark for the entire 8x8 arcminute field. To make the LFAST concept as versatile as possible, we designed each telescope to be corrected for 380-1700 nm bandpass. This keeps options open for a variety of different spectrographs to cover as many science applications as possible. However, because of the broad wavelength coverage, atmospheric dispersion is significant even at small zenith angles and must be corrected. The component that corrects for this must be placed somewhere in the optical path before the fiber. In addition, the telescope will be directly exposed to the environment, meaning it will experience wind shake, which will ultimately cause image motion at the fiber, in addition to the rapid motion caused by atmospheric seeing. Thus to keep the desired astronomical target placed on the fiber, rapid image motion correction is also needed. Each of these requirements are successfully incorporated in the current prototype design, which is being manufactured to perform on-sky testing in late Fall 2022.

3. OPTICAL DESIGN

We began by exploring designs using spherical primary mirror with a simple prime focus corrector to see what on and off-axis image quality and correction could be realized. The results are encouraging, and the best of these designs is currently being built as a prototype. Below is the design layout and optical prescription of the LFAST unit telescope.

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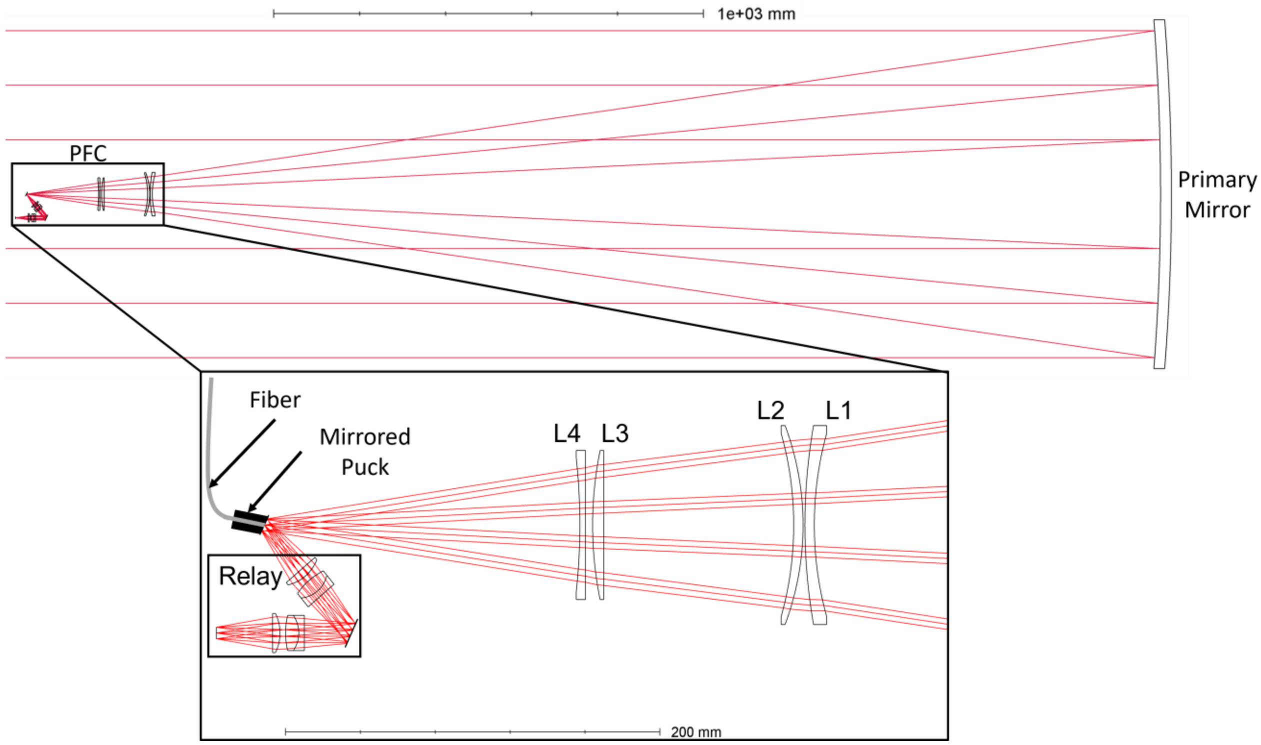

Figure 1. Optical design layout of the full LFAST unit telescope (above) and a zoomed-in view of the PFC and relay subsystem (below). L1 through L4 correct aberrations, atmospheric dispersion, and image motion (to be described in upcoming sections).

Primary Mirror	R	5275.0 mm	***Fiber Puck***	Tilt Angle	25 degrees
	Substrate	BOROFLOAT		Spacing to Relay Singlet	30 mm
	Clear Aperture	30 inches	**Relay**		
	Spacing to L1	2353.83 mm	***Singlet***	R1	Infinity
Prime Focus Corrector				R2	21.66 mm
L1	R1	168.97 mm		Thickness	4.0 mm
	R2	284.47 mm		Substrate	N-BK7
	Thickness	5.0 mm		Aperture	19.0 mm
	Substrate	N-BK7	***Doublet***	R1	37.47 mm
	Aperture	101.6 mm		R2	15.37 mm
	Spacing to L2	1.0 mm		R3	896.37 mm
L2	R1	138.75 mm		Thickness 1	7.0 mm
	R2	166.23 mm		Thickness 2	3.0 mm
	Thickness	5.0 mm		Substrate 1	N-BK7
	Substrate	F2		Substrate 2	F2
	Aperture	101.6 mm		Aperture	19.0 mm
	Spacing to L3	101.43 mm		Distance to Fold Mirror	25.0 mm
L3	R1	Infinity	***Fold Mirror***	Fold Angle	25 degrees
	R2	181.37 mm			
	Thickness	6.0 mm			
	Substrate	N-BK7			
	Aperture	76.2 mm			
	Spacing to L3	3.8 mm			
L4	R1	138.75 mm			
	R2	306.94 mm			
	Thickness	3.0 mm			
	Substrate	F2			
	Aperture	76.2 mm			
	Spacing to Fiber	168.43 mm			

Figure 2. Full optical prescription for the LFAST unit telescope.

3.1 General Design Procedure and Aberration Correction

The concept for this design began as a simple procedure. First, the thought was to set the primary mirror at the correct focal ratio to begin with, that way the PFC lenses only need to apply small ray deviations to correct the aberrations inherent to

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spheres. Since only small ray deviations are required, it was thought that traditional optical glass materials could be used for the PFC lenses, and still operate sufficiently across the broad 380-1700 nm spectrum. First, L1 and L2 (N-BK7 and F2, respectively) were placed in the optical path. All 4 surface radii on the two lenses were set as variable, as well as the distance from the primary mirror. The trade-off here is the closer the lenses get to the primary mirror, the easier the aberration correction is,[3] however obscuration of the primary mirror by a large PFC is undesirable, and the lens cost increases with aperture diameter. Then, more N-BK7 and F2 lenses were added until diffraction limited image quality was obtained within a 1 arcminute field, with image quality of a few arcseconds for the full 8x8 arcminute field. We found that pair of 4" lenses followed by a pair of 3" lenses could properly correct the full spectrum for the on-axis field and a local 1x1 arcminute region with diffraction limited performance, with still adequate correction for the off-axis field out to 4' radius. Each pair of lenses consisted of a N-BK7 and F2 component. These 4" lenses in a 6" housing will result in a 4% obscuration loss.

3.2 Atmospheric Dispersion Correction

While the primary function of the four lens PFC is for spherical aberration correction, variable lateral chromatic aberration needs to be also incorporated to correct for atmospheric dispersion as a function of zenith distance. Some telescopes have used lateral motion in the lenses of different instruments to correct for atmospheric dispersion.[4–6]. However the design still needs to maintain good image quality, even when the lens motion is applied. In our optical design, L3 and L4 were constrained to contribute nearly zero power to the total system as a pair. Since most aberrations are power dependent, this eliminates much of the monochromatic aberrations induced by lens misalignment, which in this case may be exploited to induce lateral chromatic aberration. This optimization resulted in a pair of lenses; L3 converging to planoconvex (N-BK7) and L4 to plano-concave (F2). Either lens can be translated laterally in the vertical direction to correct for atmospheric dispersion, but L4 was chosen since it is the last element in the PFC, which gives easier mechanical access for actuation. For every 1 mm lateral shift of L4, the chief ray height difference at the image plane changes by 36.7 µm, which corresponds to 2.87 arcseconds, and the relationship of lens translation to induced lateral chromatic aberration is linear. Translating L4 by 1 mm also shifts the image by 340 μm, so a primary mirror tilt of 13.3 arcseconds is required to deviate to recenter the target on the fiber. This tilt causes little to no effect on image quality since the primary mirror is spherical and therefore has no defined axis. Atmospheric dispersion was modeled using Zemax Opticstudio's built in 'Atmospheric' surface,[7,8] with default parameters of altitude 798 meters, 293 degrees Kelvin, an atmospheric pressure of 1013 millibars, a relative humidity of 50%, and a latitude of 0 degrees. These parameters are conservative compared to likely sites for LFAST, but if the correction can work for these parameters, it would work for any potential site. Fig. 3 is a plot of the linear atmospheric dispersion based on this model as a function of elevation angle relative to zenith as well as the induced lateral color as a function of L4 lateral translation.

For example, at 50 degrees from Zenith, the atmospheric dispersion is significant, 2.35 arcseconds (shown in Fig. 3). Based on the known effects of the laterally translating L4, a translation of 0.82 mm of L4 should correct for atmospheric dispersion, to the first order. The performance of this correction is shown in Fig. 4.

3.3 Image Motion Correction

As was stated in the previous section, we found that translating L4 to correct for atmospheric dispersion also translates the image. This means it can also be used for correcting rapid, small image motions. It is likely image motion will be from a high frequency and low frequency source, atmospheric seeing and wind shake, respectively. While shifting L4 induces lateral chromatic aberration, L4 also applies a small image shift. For 100 μm of lens lateral translation, the image shifts by 34 μm. This corresponds to 2.66 arcseconds, which is sufficient range to correct for the image motion sources, without degrading the image quality from the small induced lateral chromatic aberration from the small corrections. For example, if observing a target at 50 degrees from zenith as in Section 3.2, and there is a 2 arcsecond alignment error in the x-direction, from windshake, or otherwise, the image is shifted by 25 μm, completely moving the target off the collection fiber. The lens is already shifted 0.82 mm from the nominal alignment vertically, but we know that a 73 μm lateral shift in L4 will move the image 25 μm. Adding this x-direction motion to L4 will then recenter the target on the optical fiber. Since the L3 and L4 lens pair is designed to contribute zero power to the system, the aberrations caused by the purposeful misalignment is minimal (Fig. 5).

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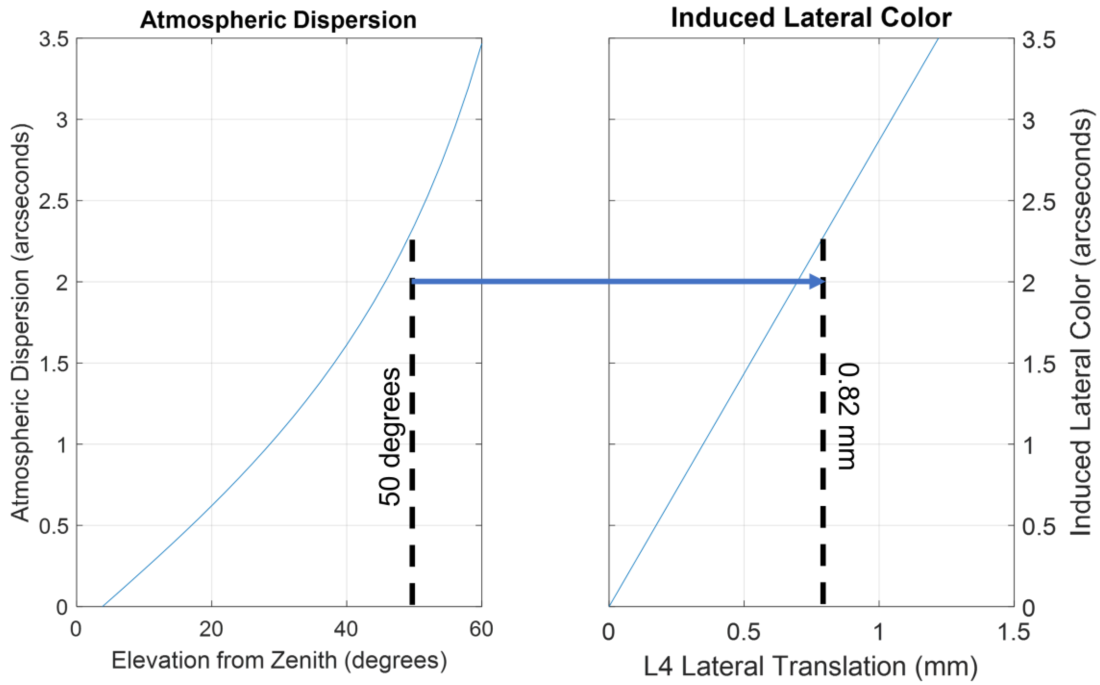

Figure 3. Plot of atmospheric dispersion for the LFAST 380-1700 nm bandpass (left). Lateral shifts of L4 induce opposite lateral color of similar magnitude, creating a lookup table for correcting atmospheric dispersion with L4.

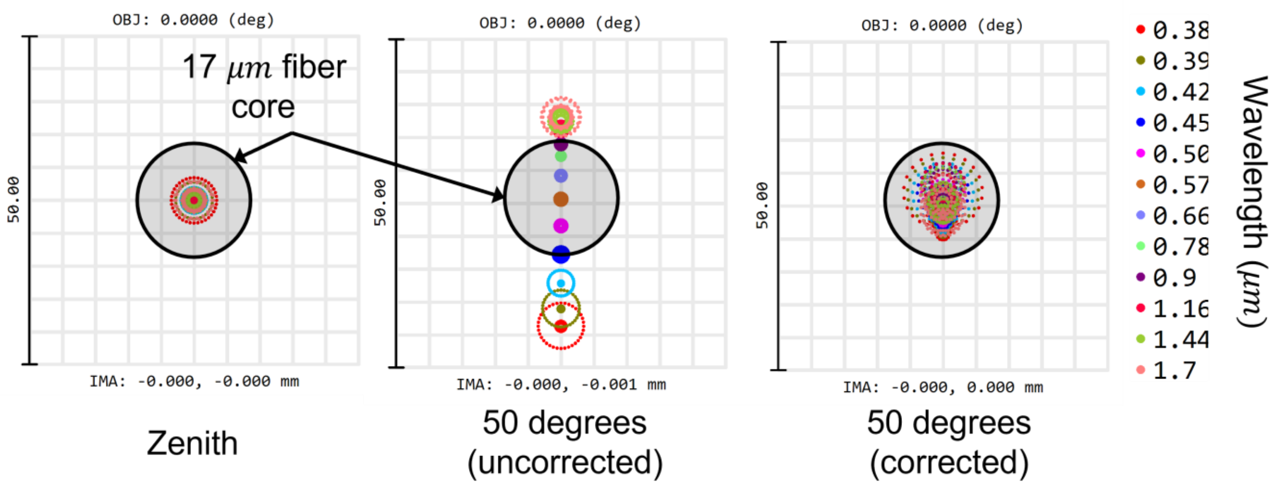

Figure 4. (left) Nominal on-axis spot diagram at zenith pointing, no atmospheric dispersion, (middle) on-axis spot diagram with atmospheric dispersion at 50 degrees from Zenith, causing 2.35 arcseconds of dispersion across the LFAST telescope bandpass. Applying 0.82 mm lateral translation to L4 induces an equal and opposite 2.35 arcseconds of lateral color, correcting for atmospheric dispersion(right). the corrected on-axis spot diagram is shown, along with the to-scale outline of the 17 μm fiber core.

3.4 Relay Optics

The previously described optics have all the tools available to correct for any expected perturbation to the telescope. However, feedback is needed in order to properly control the atmospheric dispersion and image motion to maximize the energy coupled into the collecting fiber. To accomplish this, the collecting fiber is mounted into a mirror tilted at 25 degrees that diverts the beam out of the optical path and reflects the full 8x8 arcminute field to a CMOS camera, as shown in Fig. 1. The relay consists of a singlet and doublet collimator, a fold mirror, and the same singlet and doublet reversed.

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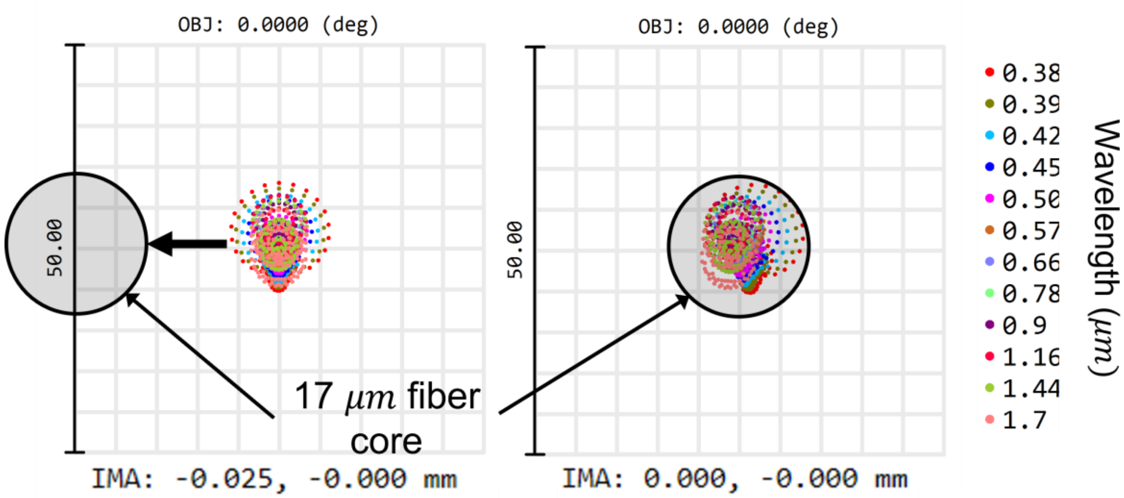

Figure 5. A two arcsecond perturbation would cause the target to shift by 25 μm, entirely missing the collection fiber (left). This spot diagram is for the 50 degree atmospheric dispersion corrected image, from Fig. 4. By shifting L4 by 73 μm, the image is shifted by 2 arcseconds in the equal and opposite direction, realigning the spot with the collection fiber without significant loss of image quality.

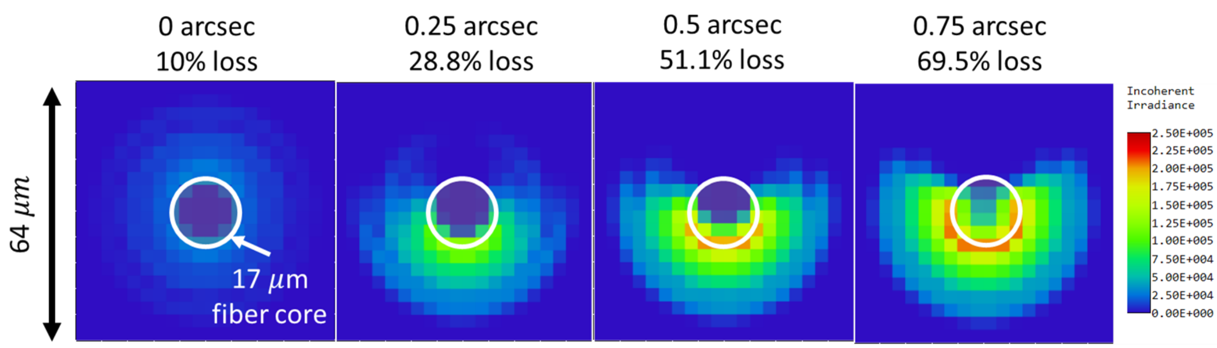

Figure 6. Simulation of star image on guide camera after 1 arcsecond seeing error is applied before the primary mirror. Successive offset steps of 0.25 arcsecond misalignment are introduced. The star is sampled with 0.25 arcsecond pixels.

This focal plane mirror is completely silvered, except for the 17 micron core. The target image thus appears with a dark 17 μm obscuration at the guide camera, giving direct feedback on its coupling into the collecting fiber. Figure 6 is a simulation of star image broadened by 1 arcsecond seeing as it will appear at the guide camera with 0.25 arcsecond pixels. Offset steps of 0.25 arcsecond misalignment are introduced. From this image, it is clear from the irradiance distribution in which direction and by how much the image needs to be moved to be centered on the fiber.

4. DESIGN TOLERANCES

As mentioned previously, loose tolerances are desirable for LFAST to be able to produce thousands of low cost telescopes. The initial goal was to specify as many 'commercial' tolerances as possible. The tolerance process began with assigning 'standard' commercial tolerances[9,10] to each component, running 30 Monte Carlo analyses, and maximizing the diffraction encircled energy within a 17 μm diameter as the criterion. The worst offenders were then adjusted until the trial average met 85 % encircled energy (92% is the polychromatic diffraction limit in the 17 μm fiber with perfect transmission and no surface reflection), with the worst performer at 70%. Fig. 7 shows the final tolerances that met this requirement, and the compensators used in the tolerance process. Tolerance parameters were set to uniform distribution rather than normal distribution in order to better capture practical errors.

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Note from Fig. 7 that the primary mirror radius tolerance is least critical (±50 mm). Because the approach to this design utilized a prime focus corrector with zero power, a telescope with a primary mirror with a large radius error can simply be corrected with an axial shift of the primary mirror to refocus the image, effectively creating the same incident wavefront to the PFC. In addition, nearly all parameters that change the system power are loose since primary mirror piston is a compensator. The only parameters that could be considered 'precision' are the primary mirror rms surface error of 20 nm rms on scales of 200 mm and less to obtain Strehl ratio of 80% at 400 nm wavelength, and the PFC lens wedge.

Tolerances					Classification
Primary Mirror	R	±	50	mm	Commercial
	Irregularity	±	1	fringe	Precision
L1-L4	R	±	5	fringe	Commercial
	Center Thickness	±	150	µm	Commercial
	Irregularity	±	1	fringe	Precision
	Wedge	±	1	arcmin	Precision
	Decenter	±	75	µm	Commercial
	Tilt	±	3	arcmin	Commercial
	Refractive Index	±	0.001	a.u.	Commercial
	Abbe Number	±	0.8	%	Commercial
PFC Assembly	Tilt	±	3	arcmin	Commercial
	Decenter	±	2	mm	Commercial

Figure 7. Tolerances for LFAST unit telescope, used in uniform statistics in 30 Monte Carlo trials. The trials were run with primary mirror piston, tip and tilt compensations, maximizing diffraction encircled energy into the fiber core.

5. DISCUSSION: SPHERICAL VS. ASPHERICAL PRIMARY MIRROR

At this point in the design, we have settled on using a spherical rather than aspheric primary mirror, for a variety of reasons. The potential advantage of an aspheric mirror is that performance could be achieved with a simpler, smaller prime focus corrector. This gain would come from either reducing the number of lenses required and/or reducing the size of those lenses, and improved energy collection by reducing the obscuration footprint and reducing the number of losses at refracting surfaces. But in comparing optimized designs for both types, we find these gains to be small, not worth the significantly greater cost and mirror manufacturing time.

On its own, an aspherical mirror clearly has better on-axis image quality, (Fig. 8). However, the image from an asphere alone doesn't meet requirements for a diffraction limited 1 arcminute field, needed for correction of mount flexure by primary mirror tilt, as well as correction for chromatic atmospheric dispersion as a function of elevation, and for small-amplitude, rapid image motion.

A design with an aspheric mirror would require at least two lenses or prisms to create a dispersion differential. However, the requirement for the atmospheric dispersion corrector to operate is that it has zero power as a pair, so it is difficult to use it to correct for coma from an aspheric primary mirror as well as create enough dispersion differential to create significant lateral color as a function of lens decenter. There simply aren't enough degrees of freedom, so another lens is needed. Three lens PFC designs with aspheric primary mirrors were developed to meet these requirements, but a 4" lens was needed, just as in the spherical mirror design. This means that there would be no gain in obscuration reduction, and the only gain in Fresnel reflection losses compared to the spherical primary mirror design would be by eliminating the two surfaces of one lens. Adding a 4th lens as with the spherical primary mirror design allows for the lenses to reduce to 3" apertures, but this only improves the obscuration by 1%. In summary, using an aspherical primary mirror instead of a

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spherical primary mirror either gains 1% in collected energy, or a reduces the total cost by the cost of a single 4” lens. Both of these gains are small, but the difference in cost and time involved with making 2640 aspheric compared spherical mirrors is large, and likely outweighs this marginal gain. For this reason, we believe that a spherical primary mirror is the optimal choice for LFAST’s thousands of telescopes.

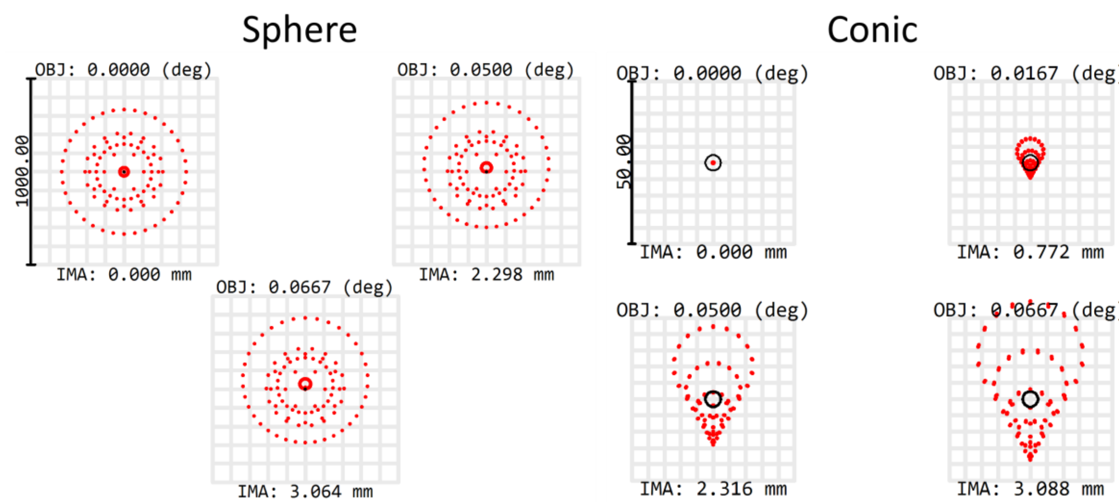

Figure 8. Spot diagrams for an f/3.5 sphere and an f/3.5 parabola, both at best focus. Left, sphere is showing on-axis, 3 arcminute and 4 arcminute fields, all with 200 μm RMs spot size. Right, paraboloid showing on-axis, 1 arcminute, 3 arcminute and 4 arcminute fields. While the RMS spot size is significantly reduced for the paraboloid, Coma at even the 1 arcminute field radius means that the diffraction limit is not met.

6. CONCLUSION

We have designed a telescope that is highly optimized to be cost-efficient and high performing, with minimal complexity. The design process and goals for this large telescope is quite different from other large telescopes currently in operation and currently in construction. By not focusing on maximizing performance for a large single aperture, LFAST has the unique feature of scalability, uncommon in astronomical telescope design. A unique feature of the LFAST unit telescope design is its use of a single laterally translating lens to correct atmospheric dispersion as well as image motion. The design has been made with much attention to the impact that design decisions have on the cost of the unit telescopes, and ultimately the entire array of telescopes, when manufactured in high volume.

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