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LFAST, the Large Fiber Array Spectroscopic Telescope

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ABSTRACT

The LFAST concept is to use thousands of small telescopes combined by fibers for high resolution (R=150,000) spectroscopy, in a way that will realize large cost savings and lead to an affordable aperture as large as 20,000 m^2. Such large aperture is needed, for example, to make a comprehensive search for biosignatures in the atmospheres of transiting exoplanets. Each unit telescope of 0.76 m aperture (0.43 m^2) will focus the image of a single star onto a small (17 µm core) fiber, subtending 1.32 arcsec. Our telescope design calls for a spherical mirror, with a 4-lens assembly at prime focus that corrects not only for spherical aberration, but also for atmospheric dispersion down to 30° elevation, from 390 nm – 1700 nm, and for rapid image motion caused by seeing or wind jitter. A method for rapid production of such mirrors has been tested, in which a disc of borosilicate float glass is slumped over a high-precision polished mandrel to an accuracy that greatly reduces subsequent optical finishing time. A method for active thermal control of mirror figure using Peltier devices will be incorporated. The projected cost of each unit telescope, when mass produced by the thousand, would then be approximately $8,000. The telescopes will be mounted in the open in groups of 20 located 12 m apart. The mirrors will be arrayed on either side of a central, pedestal-mounted alt-az drive using commercial worm gear bearings. Protection against rain and dust will be provided by automated covers above and below the mirrors, and by pointing the mirrors down (– 20° elevation). The first LFAST array, some 150 m in diameter, will comprise 132 mounts carrying a total of 2,640 mirrors and having 1,200 m^2 in collecting area. The light from all the fibers is combined at the central spectrographs, with little increase in etendue, by a 5 x 528 array of adjacent hexagonal lenses. A telecentric lens is used to reimage the lens array at the entrance slits of two echelle spectrographs. Together, these two cover simultaneously the full 390 nm – 1700 nm spectral range of the star being observed. The targeted cost for the installed LFAST telescope and fiber array is $60M.

Keywords: telescope arrays, LFAST, high resolution spectroscopy, fiber-feed, etendue, exoplanet transit spectroscopy

1. GOALS FOR LFAST

The Large Fiber Array Spectrographic Telescope, LFAST, is a new type of telescope with very large collecting area for very high-resolution spectroscopy, designed for construction at very low cost. The motivation for LFAST is not simply to duplicate the spectroscopic sensitivity of the coming generation of Extremely Large Telescopes (ELTs), but to demonstrate that such capability can be realized at just a few percent of the cost. This would the open the path to a still much larger telescope, ~ 20,000 m^2 aperture, at a cost of no more than a 1,000 m^2 ELT. Such a large increase would enable much more extensive exploration of fundamental physical laws, and of the first objects formed after the big bang. It is also needed if a comprehensive study is to be made of the chemical composition of the atmospheres of Earth-mass exoplanets in the habitable zone during transits, by detection of molecular absorption features, including hoped-for biosignatures. The ELTs now under construction will be able to reach the very nearest such planets transiting small, late M stars, such as Trappist 1 (M8, 10 pc distance, 2-day orbits), which are by far the most accessible for transit spectroscopy. However, a much larger

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telescope is needed to reach a broader sample of planets orbiting a range of earlier and less active stellar types, which are rarer and thus generally more distant, and with less frequent transits and shallower absorption features, such as TOI 700 d, (M2, 30 pc, 31-day orbit).

To best exploit the full potential of very large telescope aperture, a major requirement is for broad spectral coverage, extending through the optical spectrum into the near infrared, at resolution ≥ 100,000, and for very high signal to noise ratio, sufficient to reach absorption feature depths ≤ 10^{-5}.

2. TECHNICAL BACKGROUND

Analysis of costs by Van Belle, and Meinel [1] of observatories with single telescopes have shown that, for construction in the same era and style, cost varies as diameter $D^{2.77}$, i.e. cost per unit area increases as $D^{0.77}$, and thus a given collecting area could be built at lower cost in the form of many smaller telescopes rather than as a single large aperture. We cannot take this power law too literally, as the architectures of very large and small telescopes will differ, but there is certainly the potential for major cost savings.

A path for using many small telescopes to make a relatively inexpensive very large telescope for spectroscopy was proposed by Angel et al. [2]. The idea was to use fused silica fibers to gather the light at the prime foci and bring it all to the entrance slit of a spectrograph. Sensitive imaging detectors at each prime focus would be used to guide the individual telescope images onto the fiber, and deep images could be obtained by digital summation of all the individual images.

Such use of fused silica fibers has not yet been realized, but fibers have been extensively developed for astronomy in other ways with large single focus telescopes for: 1) multi-object spectroscopy, with as many as 5000 fibers to line up the light from 5000 galaxies along the slits of ten spectrographs [3], and 2) to reformat the light from a single star along the length of a long, narrow spectrograph slit, for high resolution spectroscopy. An example of the latter use is the ultra-high resolution ANDES spectrograph designed for the 39 m aperture telescope ELT, Oliva et al.[4]. In this case, a hexagonal array of 96 adjacent lenses at the f/20 focus reformats the light from a 1.11 arcsec diameter aperture into 96 fused silica fibers, each with 75 µm core diameter, at f/3.5. At the spectrograph, the fibers direct their outputs into 96 square lenses in a line, to restore the f/20 beam now as the spectrograph slit, as shown in Figure 1.

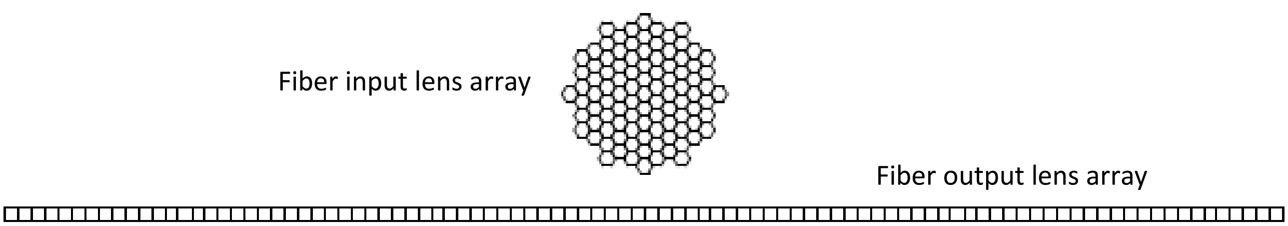


Figure 1. Upper, an array of 96 hexagonal lenses at the ELT f/20 focus divides the light across a 1.11 arcsec aperture and directs it into 96 fibers. Lower, a line of 96 lenses of the same focal length, now cut into squares of the same area as the hexagons, directs the fiber outputs to form the f/20 slit input to the spectrograph.

In a simple extension of this concept to a fiber linked telescope array, a system with the same etendue could be made with the same 96 fibers, but now fed directly by 96 4 m telescopes. Fed at f/3.5 at each telescope focus, the same fiber cores would subtend the same 1.11 arcsec aperture. If the $D^{0.77}$ cost per m^2 holds, the total telescope would cost six times less.

3. THE LFAST DESIGN

3.1 Unit telescope and coupling into the fiber

The LFAST design aims for still lower cost and rapid construction by using an even larger number of smaller telescopes to collect the light. One great cost advantage of small unit telescopes is that their design can be refined and improved by quickly building initial test units and obtaining actual on-sky experience. Another is that when large quantities are to be built, we can benefit from the economies of mass production. Thus, the first task being undertaken by LFAST is to design, make and test one or two small telescopes for fiber feed at prime focus, using manufacturing methods that will lend themselves to mass production.

Another consideration that favors small telescopes is their potential to increase the fraction of light encircled by a given aperture (in arcseconds) in the presence of atmospheric seeing. For large aperture telescopes, such reduction requires full adaptive optics. But for small telescopes, with apertures not much larger than the scale length of atmospheric turbulence, a significant image sharpening and increase in encircled energy may be obtained at low cost, simply by rapid tip/tilt correction of the star image to center it on the fiber entrance aperture. Obtaining such improvement is valuable, because atmospheric seeing over the large ground area needed for many small telescopes will not be as good as for a single very large telescope on a single peak.

Based on these considerations, we have settled on a primary mirror aperture of 0.76 m diameter, 0.454 m^2 in area. This is a size which lends itself to mass production. The disc substrates will be cut out from mass-produced Borofloat glass, available in 25 mm thickness at relatively low cost, and will be slumped over a precisely shaped mandrel to minimize the optical processing time, as outlined in Section 4.1 below.

The focal ratio at prime focus is set at f/3.5, as favored in many astronomical fiber applications, to minimize losses due to focal ratio degradation in the fiber. The plate scale for the 0.76 m aperture is then 12.9 µm/arcsec.

We have chosen a fiber core size of 17 µm, to obtain an aperture on the sky of diameter 1.32 arcsec. This strikes a balance between being too small and losing flux and being too big which increases etendue, instrument size and sky background. Based on the analysis of Christou [5], under good seeing condition (r_0=20 cm at 500 nm wavelength), for zenith pointing a 1.3" diameter aperture will encircle ≥ 90% of the starlight at 0.5 µm wavelength. In poorer seeing, r_0 = 10 cm, without motion correction the encircled energy is reduced to 55%, for both small and large telescopes. But for a 0.76 m aperture with fast image centroid centering, the encircled energy fraction is increased to 72%. A similar improvement is obtained at 1 µm wavelength, in the same seeing condition. The same kind of relative improvement will be obtained for off-zenith targets.

To sense rapid image motion away from the fiber center, the fiber end will be embedded in a mirror that will reflect all the field, except for that entering the 17 µm circular core, to a fast-framing imaging CMOS camera. Then a decentration of the star centroid that reduces the core encircled energy would be detected as a brightening on one side of the core and a dimming on the other. We estimate that correction of stars at 50 Hz update rate will be possible for stars as faint as R magnitude 14, limited by photon noise. For fainter targets, guiding at a slower rate will be made using field stars. For this purpose, the same tilted mirror about the fiber at the telescope prime focus will be made large enough to direct an 8-arc minute diameter field to the guide camera.

The optical design of the individual prime focus telescopes meeting these requirements is described by Berkson et al. [6]. For on-axis imaging, we want achromatic diffraction limited images over 400 nm – 1,700 nm wavelength range, corrected for atmospheric dispersion down to 30° elevation, and the ability to move these images rapidly (20 Hz) over an amplitude of ± 1 arcsec. For the off-axis image, as relayed from the prime focus mirror to a guide camera, the FWHM is to be no larger than 1.5 arcsec out to a 4-arcminute radius, over the wavelength range 500 nm – 800 nm.

Design alternatives using primary mirrors of either spherical or aspheric figure were developed. Our choice is for a spherical figure for the first telescopes. The prime focus corrector in this case comprises just four spherical elements, one of which is moved to obtain both fast image motion and atmospheric dispersion correction. It is not much more expensive to manufacture than the simpler corrector for a paraboloid, while the cost of mirror polishing is significantly reduced for the spherical figure.

3.2 Telescope mounts and array size

In the LFAST array, the unit telescopes are configured in groups of 20 on a 4.8 x 4.8 x 3 m spaceframe, as shown in Figures 2 and 3. The total collection area is 9.1 m^2, equivalent to a single 3.4 m aperture. Because there is no single, central focus, the bearings and drives are placed directly on top of a pedestal at the center of gravity of the spaceframe, as described by Young et al. [7]. This allows use of commercially mass-produced slewing drives. To reduce overall cost, the mounts will be operated in the open air with no enclosure, as for most radio telescopes. To seal the mirrors against inclement weather and dust, they are provided with automated removable covers, above and below. In addition, the mount is constructed so that when not in use it may be turned to point down to 20° below the horizon, to avoid dust settling on the mirror surfaces.

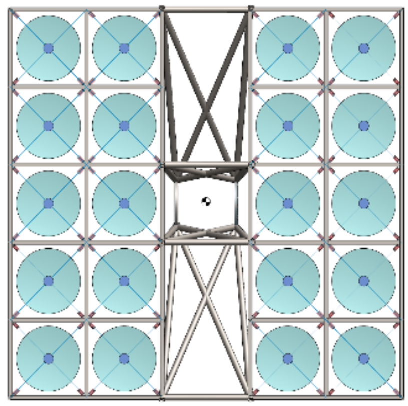


Figure 2. Plan view of mount with 20-unit telescopes

Wind buffeting is an important consideration for an optical telescope out in the open. Young et al [7] have used finite element analysis to model and optimize the stiffness of the mount structure. The optimized design, shown in Figure 2, has a moving mass of 1.5 tons of steel and hardware to support the 20 unit telescopes weighing 1.2 tons, for a total moving mass per square meter of mirror area of 300 kg/m^2, an order of magnitude less than the average for ELTs. The lowest modes have resonant frequencies of 4 and 5.5 Hz, for oscillations in azimuth and elevation. Their expected amplitudes, when excited by 10 m/sec wind, are ~ 1 arcsec. This is consistent with the amplitudes projected for the 12 m ALMA sub-mm wavelength radio telescopes, which are also in the open and have 5 Hz lowest resonant frequencies. In LFAST, we will correct in real time the image motion caused by windshake, using the same image motion servo control system in the prime focus assembly as is used to correct seeing motion. Accelerometers will be installed to measure the wind shake, and for fainter targets this data will be combined with that from image sensing to maintain the star image at the fiber entrance.

The overall size of the LFAST array is limited by absorption at shorter wavelengths in the fused silica fibers that bring light to the single central instrument. We set this radius to be 75 m, the length through which silica fibers absorb 50% at 400 nm wavelength. The ground area is then 18,000 m^2. The pedestal mounts, shown in Figure 3, will be set 12 m apart, giving unobstructed access to the sky down to 23° elevation, and minimizing local seeing caused by turbulence generated by neighboring mounts. The total number of mounts is then 132, for a total of 2,640-unit telescopes and fibers, and total collecting area 1,200 m^2.

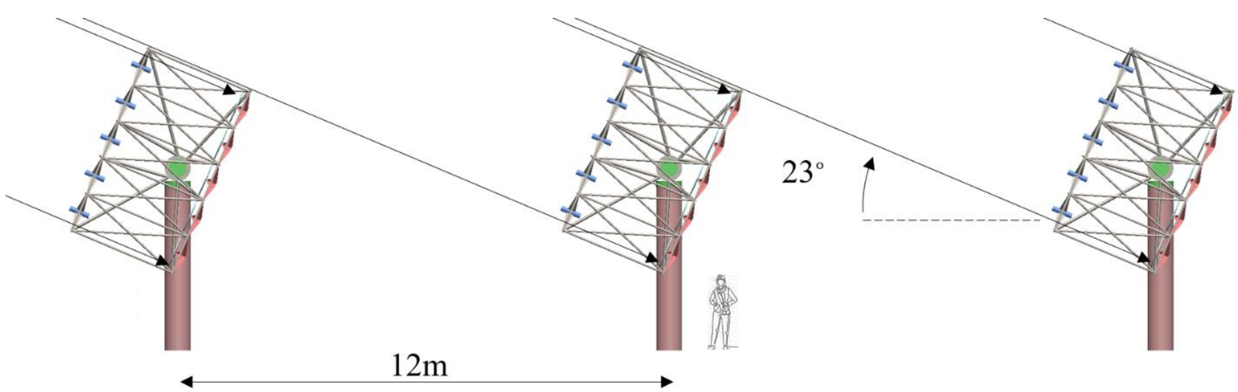


Figure 3. Telescope mounts at 12 m spacing, with unobstructed view down to 23° elevation

3.3 Spectrograph design for LFAST

Our target for LFAST is to cover simultaneously the full optical and infrared spectral ranges at resolution R=150,000. The optical range from 390 nm to 940 nm requires 132,000 resolution elements, and the near-infrared wavelength range from 0.96 µm to 1.72 µm needs70,000 resolution elements.

A fundamental consideration in spectrograph design is etendue, which sets the minimum possible areas for the detectors and gratings. Because etendue cannot be reduced without loss of light, the minimum area on the detector A_{Dmin} to record a single spectral resolution element is given by equating input and output etendues:

$$A_{tel}\,\Omega_{tel} = A_{Dmin}\,\Omega_{cam} \qquad (1)$$

where A_{tel} is the total telescope area, Ω_{tel} is the solid angle on the sky of the entrance aperture, A_{Dmin} is the smallest area on the detector per spectral resolution element for a spectrograph camera with solid angle Ω_{cam} for light focused onto the detector. For LFAST with 2,640 apertures each of area 0.454 m^2, A_{tel} = 1,198 m^2. For the 1.32 arcsec apertures Ω_{tel} = 3.22 $.10^{-11}$ ster., for an input etendue of 0.038 mm^2.

The design published by Oliva et al. [4], for the ELT ANDES spectrographs, accommodates comparably large etendue and a similar number of spectral resolution elements. The 39 m aperture of the ELT is 1200 m^2, and for the 1.11 arcsec aperture used for the UHR R=150,000 mode the input etendue is 0.027 mm^2, 70% that of LFAST. The design concept is thus well suited to LFAST's needs. We show below how the light collected by the 2,640 LFAST fibers may be combined, while preserving etendue, into a slit format of similar size to that used in the ANDES design, shown in Figure 1 above.

In the ANDES design, a single echelle grating is used for each of the optical and infrared spectrograph modules, in a white pupil configuration with anamorphic beams. In each module the light dispersed by the grating is separated using dichroic beam-splitters into four spectral ranges, covering 400 nm – 833 nm in the optical module and 830 nm – 1800 nm in the infrared. Each spectral range is passed through a cross dispersion grating and into a fast (~f/1) Schmidt camera that images the cross dispersed spectra onto a detector 61 mm square. The optical cameras use CCDs with 10 µm pixels, while Teledyne H4RG 17-megapixel infrared arrays with 15 µm square pixels are used in the infrared.

LFAST plans to scale up the ANDES optical module design by ~30%, to accommodate its 40% larger etendue and 20% larger number of resolution elements to cover a broader spectral range. The scaled up optical module will take advantage of larger 92 mm square CCDs, also with 10 µm pixels. For the infrared spectrograph, LFAST's larger etendue is compensated by smaller spectral range, and scaling up will likely not be needed. To obtain the full spectrum across the optical and infrared, we plan to use an initial dichroic beam-splitter to direct light from the same star into both of the modules.

3.4. Combining the light from all the fibers at the spectrograph slit

A novel requirement for LFAST is to combine the thousands of fiber outputs into a single 100:1 aspect ratio slit at each spectrograph module, while maintaining etendue and minimizing flux loss, and maintaining the full spectral cover. In a preferred method, all 2,640 fibers are brought to a combiner similar to that in figure 1, except that the adjacent lenses are now in a two-dimensional array, and are much larger. Each lens images a 17 µm fiber core at very long focal ratio (f/2,000) to a single distant 10 mm exit pupil where all the core images are superposed. Here a telecentric lens is used to reimage the slit 100 times smaller, at f/20.

As shown in Figure 4, a two-dimensional, 5 x 528 array of hexagonal lenses receives the light from all the fibers. The fibers will be terminated in ferrules that can be adjusted in position manually to better than 1 µm precision. The lenses are identical apochromats designed to cover the full spectral range from 390 nm – 1700 nm, cut with hexagonal perimeters (1 cm flat-to-flat) and bonded together in an array 5 cm high and 5.3 m long. The lenses have 1 cm diameter and 3.5 cm focal length so that etendue is conserved relative to the f/3.5 input into each fiber, and for the entire array. This arrangement, with individually adjustable fiber positions spaced by 1 cm, is made so that individual fibers can be replaced if damaged, thus addressing the issue of fiber fragility and the likelihood of damage and losses during the assembly process.

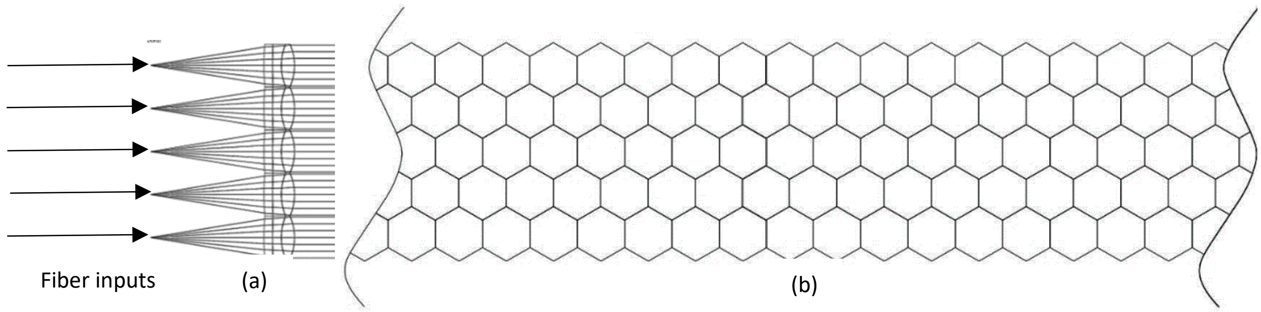


Figure 4. An array of 5 x 528 fibers and hexagonal lenses to combine the light into a single large-scale slit. (a) Side view (b) face-on view of a section of the array.

Figure 5 shows schematically the configuration after the fiber positions have been adjusted, with all 2,640 images formed by the apochromats overlapping at a distance of 20 m in a common pupil. Figure 6 shows the telecentric lens at the common exit pupil forming a 44 mm long, 450 µm wide slit image at f/20. Accounting for the fractional area of the beam not inscribed by a hexagon and also for small focal ratio degradation of the f/3.5 beam, we project a total flux loss of ~ 20%.

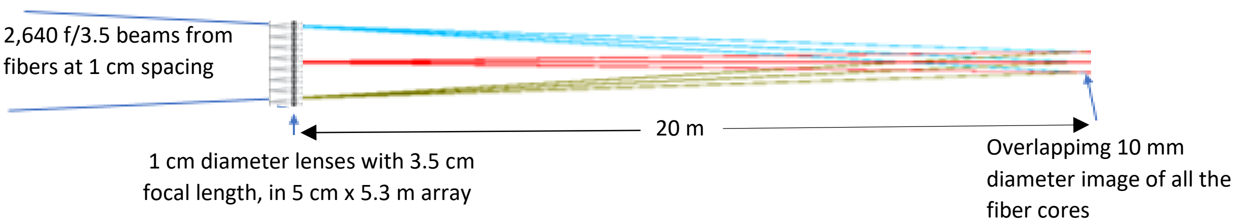


Figure 5. Schematic ray diagram, not to scale, showing how the images of the individual fiber cores formed by the hexagonal lens array overlap at a common exit pupil

If in operation a few of the 2,640 fibers are not illuminated, the center of gravity of light across the slit width will move slightly. To avoid a corresponding shift in measured wavelength, the slit image formed by the telecentric lens may be homogenized by use of a light pipe. As an example, multiple internal reflections within a meter long plate of fused silica, having flat polished sides and a cross section the same as the width and length of the slit, will homogenize the output without degrading the f/20 focal ratio.

A further consideration in fiber coupling, separate from etendue and minimizing flux loss, is reducing modal noise to be less than photon noise. While modal noise in LFAST is averaged over thousands of many small fibers, for each fiber there is only a small number of modes, because the core size of 17 µm is smaller than usual. Modal noise thus remains a significant consideration, especially when very high accuracy measurements of very narrow line depths, to a few parts per million, are desired. Our strategies for mode scrambling to minimize noise, including the possibility of using fibers with octagonal cores, are discussed by Bender et al [8] in these proceedings.

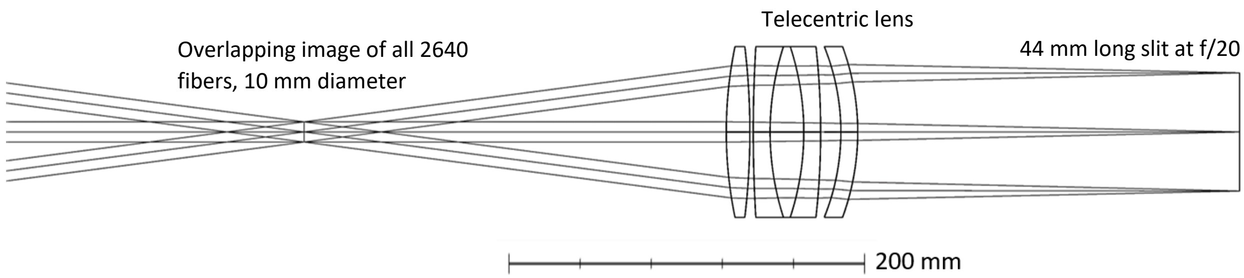


Figure 6. Telecentric lens at the common exit pupil, forming a 44 mm long slit at f/20 at the entrance to the spectrograph

4. FIRST YEAR PROGRESS IN HARDWARE DEVELOPMENT

We report in this section on the design, lab development and tests of key LFAST elements made so far in 2022, and the plan to combine these elements in the first unit telescope and test its on sky performance.

4.1 Toward mass production of 0.76 m spherical mirrors

In general, glass mirrors are made in two stages: first the glass is formed and shaped by thermal processes, then mechanical processes are used to shape and polish to meet the optical specification. When only a few mirrors are required of any given shape, the mechanical processes of machining, grinding and polishing will likely dominate the manufacture, and result in high costs for labor as well as equipment.

In our case, with thousands of identical spherical mirrors to be made, it pays to take the thermal processing steps as far as possible toward the desired shape, to minimize subsequent optical processing costs. The thermal forming is in two stages. First Schott Borofloat glass is mass produced by the float glass process, as a continuous 25 mm thick sheet with flat, specular surfaces. Then 0.81 m discs, cut out by water jet, are reheated and slumped over a convex spherical mandrel. The thermal cycle, including the heating, annealing and cooling, takes little more than a day, thus a single mold will yield close to 300 shaped discs in a year, and just 4 molds and furnaces will be sufficient to slump all the mirrors for LFAST in the targeted manufacturing period of 3 years.

Initial tests of slumping have been made at the Steward Observatory Caris Mirror Lab at the University of Arizona, using a small programmable furnace. A mandrel was made from a plate of 316 stainless steel, stiffened by a welded egg-crate backing, then machined and lapped to a convex sphere with 5.3 m convex radius of curvature. Figure 7a shows a contour map of the slumped glass disc, as a departure from the ideal spherical surface. The rms error is 5.6 µm.

A second, stiffer mandrel has now been made to a higher accuracy and additionally polished, as shown in Figure 7b. A sequence of 0.81 m diameter replicas will be obtained from it, and based on CMM and optical measurements, the mandrel figure will be reworked as needed to obtain high accuracy, with a target of 1 µm rms error.

Tests of optical finishing of the first slumped disc have begun, using the 36" polishing machine shown in Figure 8. Here the disc is being stroked over a convex lap with Trizact diamond pads on pitch. It took about 10 hours to remove the errors of Figure 7. Once more accurate discs are slumped using the second, precision mandrel, we expect that the Trizact stage may be unnecessary, and the optical finishing can proceed directly with polyurethane pads [9], to obtain a total optical processing time of no more than a day. Optical metrology of the polished discs will use phase shifting interferometry.

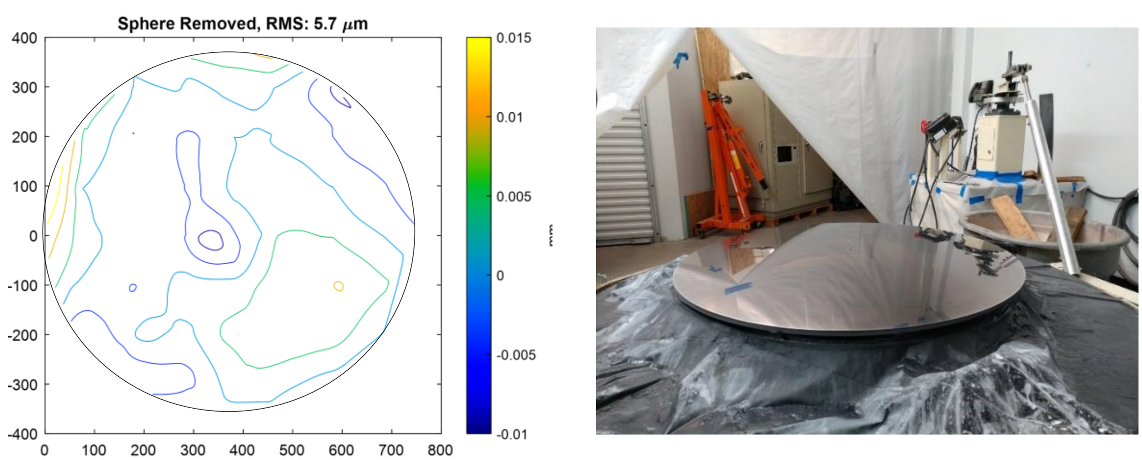


Figure 7. Left, departure from a sphere of a 0.76 m Borofloat disc slumped disc, slumped over the prototype spherically ground mandrel. The surface contours are at 5 µm intervals, from CMM profilometry. Right, a second, more rigid and polished mandrel ready for slumping tests of 0.81 m substrates.

Figure 8. Optical finishing of the 30” slumped disc with a 36” polishing machine

For optical finishing of 2,640 mirrors, it may be attractive to use a single planetary polishing machine rather than run several machines in parallel. The larger machine would work 5 mirrors at once over a single 3 m diameter spherical lap, with a heavy, stiff “bruiser” to control figure and radius of curvature.

We have considered the possibility of back-silvered mirrors, as used in heliostats for solar thermal plants, to eliminate the need for re-silvering as the mirror surfaces degrade, and this maintenance cost. Silvering the back side of the primary mirrors would yield high reflectivity lasting for 30 years. BK7 type glass has the high transmission and likely the required high refractive index homogeneity needed for a 25 mm thick mirror. The substrate in this case would be spun cast from a single slab of glass to form a paraboloidal meniscus substrate, which would need to be ground and polished on both sides. We are leaning now toward front-silvered Borofloat and will use this for the first prototype. This glass is less expensive, and lends itself to high accuracy slumping on one side that greatly simplifies optical finishing. Furthermore, the technology is improving for providing front surface silver reflectors with robust protection, to the point where a coating lifetime of at least 10 years looks realistic.

4.2 Servo control of mirror figure and image quality

LFAST plans to implement active control of mirror shape to ensure good image quality. Such control is standardly used for large telescope mirrors – typically mechanical force actuators react on a stiff backing structure, controlled in a servo loop closed around measurements of wavefront error. Such control is not used for small conventional research telescopes, where typically, for mirrors of < 1 m diameter, mechanical and thermal stability is obtained passively by use of mirror substrates made of zero expansion material with a thickness 1/10 of the diameter.

In our case, the thin, rapidly replicated mirrors described above, lacking such high passive stability, will incorporate active control to ensure high quality imaging, as is the case for much larger mirrors. In order to minimize the additional cost, we have developed a different system using thermal shape actuation, implementing controlled thermal expansion and contraction at different localized regions on the glass surface. The advantages over mechanical actuation are that the bending forces are induced within the glass, no external reaction body is required, and the actuating thermoelectric devices used to transfer heat are inexpensive, about $3 apiece.

Figure 9 shows a complete 0.76 m mirror assembly. The mechanical support is provided by four vanes from the corners of the mount spaceframe, together with an 18 point whiffle tree. Adjustment of temperature and heat flow is obtained using 40 mm square Peltier coolers (thermoelectric coolers, TECs). In the present design, to be implemented on the first 0.76 m test mirror, a total of 132 TECs will be used. 24 will be located around the circumference of the mirror, configured as shown to transfer heat through the glass thickness, between perimeter annular copper plate arcs attached to the front and back surfaces. The effect of expansion and contraction on the opposite sides is to apply edge bending moments, and is used to induce controlled astigmatism, trefoil and similar bending modes. The substrate diameter is increased by 50 mm to 0.81 m, so that the front perimeter copper arcs do not intrude into the optical clear aperture of 0.76 m. Control of additional modes is obtained with the aid of another 108 of the same Peltier devices attached across the back surface of the mirror. These are used to induce local heating and cooling of the back surface by heat transfer to the air, via the heatsinks shown.

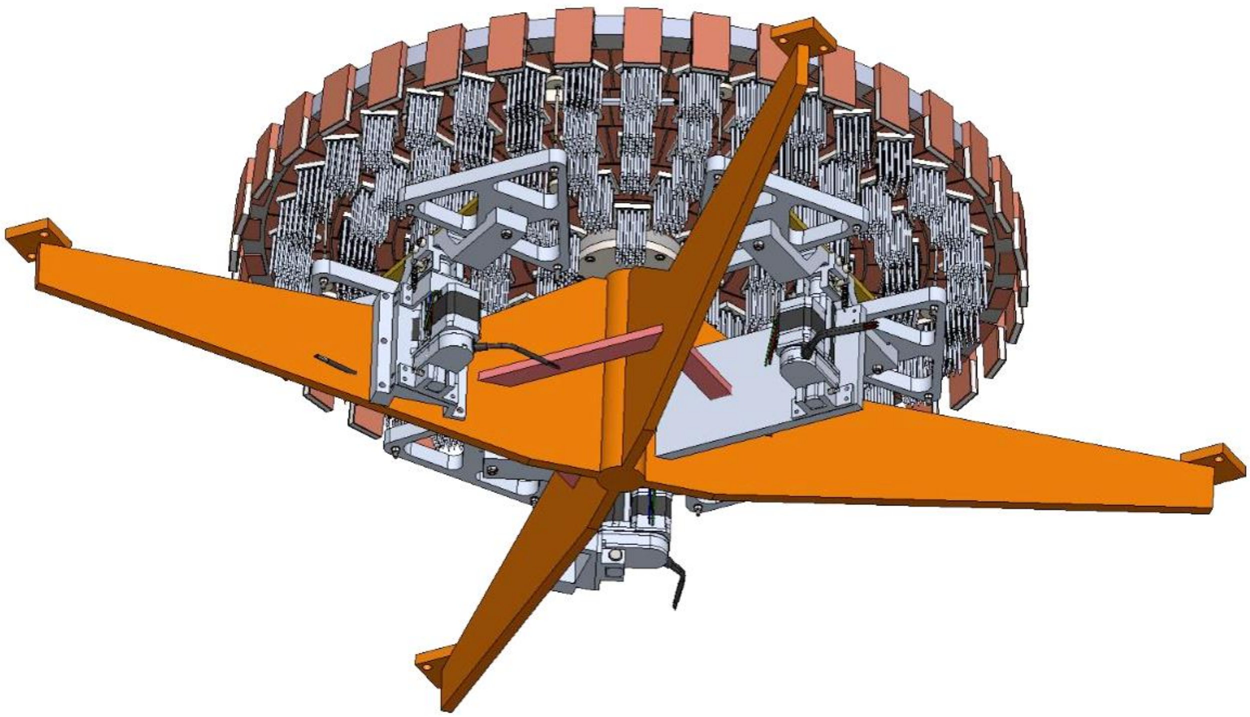
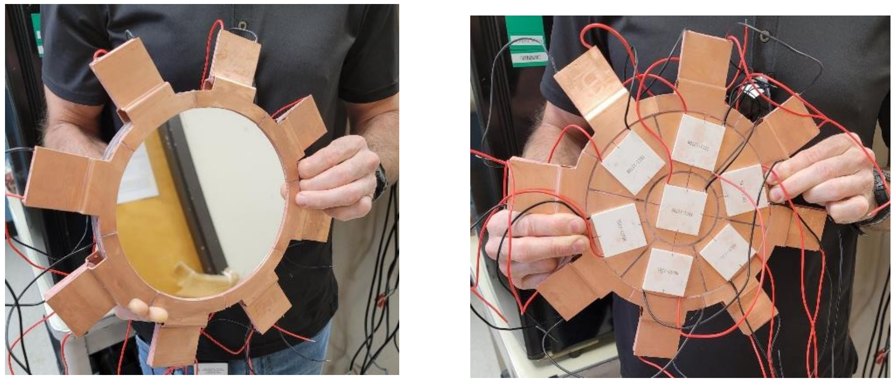


Figure 9. 0.76 m mirror assembly

A first test of this type of thermal shape actuation has been made using an 200 mm spherical mirror of BK7 glass equipped with 15 TECs attached with copper sheet sections using thermally conductive adhesive, as shown in Figure 10. Figure 11a shows astigmatic bending induced in this mirror using simply the 8 edge actuators, with a total power dissipation of 1.6 watts, measured using phase shifting interferometry. The measured amplitude of 2.25 µm P-V was within 10% of that calculated using an ANSYS finite element model.

An extension of the same model has been used to calculate the influence functions for all the actuators on the 0.76 m Borofloat mirror assembly of Figure 9. The superposition of these functions to optimize individual Zernike polynomials has been calculated, and hence the voltages and powers to be applied to each TEC for each polynomial. Figure 11b shows the calculated shape expected for the optimal combination of influence functions to obtain comatic surface bending with 1 µm P-V amplitude. The fractional error in shape is 1%, and the electrical power required for all the TECs is 4W.



(a) (b)

Figure 10. 200 mm test mirror with 15 Peltier thermal actuators. a) Front view, b) back view, prior to attachment of heat sinks on the 7 back actuators.

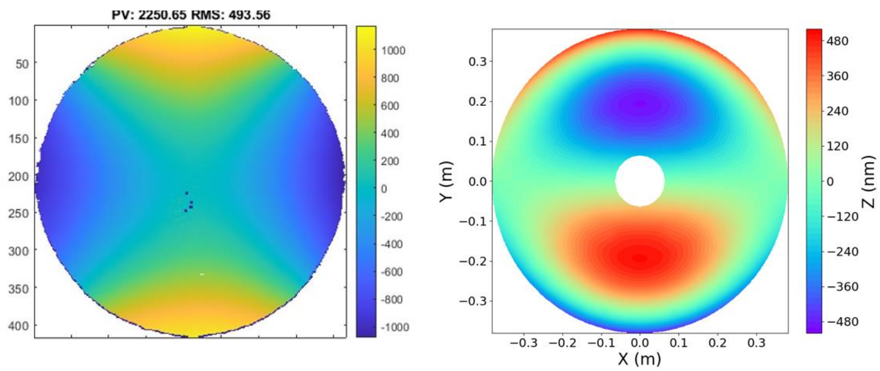


Figure 11 a) Astigmatism of 2.2 µm P-V induced in the 200 mm BK7 test mirror, using only the 8 edge actuators, measured using phase shifting interferometry. Color scale in nm. Figure 11 b) ANSYS finite element model of coma induced in the 0.76 m Borofloat mirror assembly of Figure 9, using all 132 actuators.

4.3 Slew Bearings and test measurements of tracking accuracy and stiffness

The 20-telescope mounts for LFAST illustrated in Figure 3 are designed to take advantage of commercial 25" Fang slewing bearings, each one with dual worm drives, to be driven using encoded servo motors operating through 60:1 gearboxes. Two of these bearings have recently been received. While being very sturdily built, to resist very large applied forces and moments, these drives are not well characterized. However, from previous measurements of a similar but smaller 17" bearing of the same type, we can expect precision of rotation and stiffness against applied torques to be well suited to LFAST needs.

A measurement of rotation accuracy was made using a microscope with CMOS camera attached to the fixed 17" bearing ring, and positioned to view edge-on a razor blade attached to the worm-driven ring. The precision of the rotation was measured by driving the 102:1worm gear with a stepper motor through a 100:1 gearbox. A motor step size of 0.72° was used, to obtain a motion averaging 0.26 arcsec per step. The motor was run at 10 steps/sec, and the motion recorded by a video camera at 30 frames/second. Figure 12 shows the rotation measured over a one second interval to be very smooth, with 0.06 arcsec rms error.

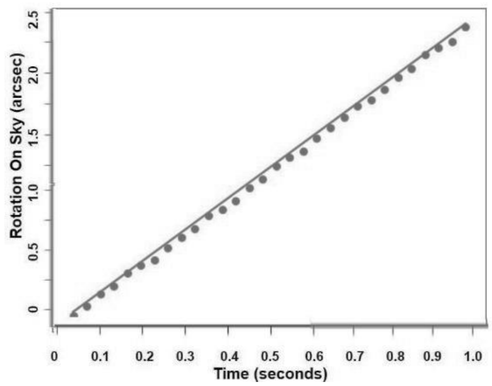


Figure 12. Rotation angle of slew bearing measured in successive video frames, taken at 30 frames/second.

The same viewing system was used to measure bearing stiffness, by measuring rotation angle for a range of applied torques. The response was linear, with a torsional stiffness constant of 5MN.m/radian. The desired stiffness for both the azimuth and elevation bearings for the 20-mirror mount is 20 MN.m/radian, for 8 Hz resonant frequency. We expect to exceed this stiffness by using two dual-worm bearings for each of azimuth and elevation. Each bearing, having two worms and with larger diameter, is expected to have ~15 MN.m/radian torsional stiffness.

4.4 Test of the first unit telescope prototype

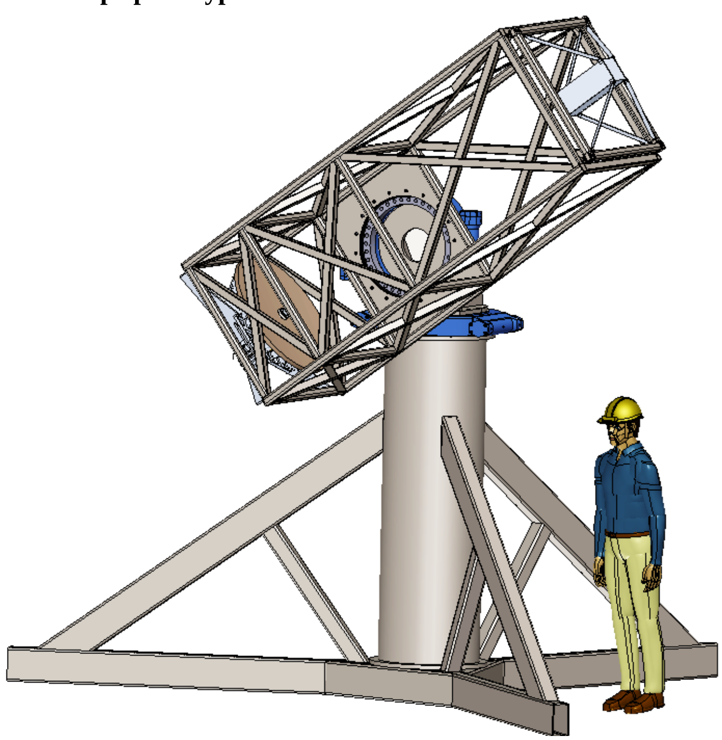


Figure 13. Single unit telescope prototype on an alt-az test mount

Once the first mirror and top end assemblies are completed, they will be incorporated into the portable tracking mount shown in Figure 13. This system will be tested first at the University of Arizona Tech Park, and then taken to a high-altitude site with good atmospheric seeing. This will allow a critical evaluation of many of the novel elements of the LFAST unit telescope, including its active control elements for image stabilization and correction of atmospheric dispersion, and efficiency of coupling of starlight into the 17 µm optical fiber. The small alt-az mount will use the same 25” slewing bearings as will be used for the 20-telescope mount, and provide further characterization.

CONCLUSIONS AND COSTS

We have described a technical path to making LFAST, and the coupling of its fiber outputs to central high-resolution optical and infrared spectrographs. The design has been chosen to enable manufacture, replication, and installation of thousands of telescopes at low cost. Key cost saving elements compared to conventional telescopes are:

- Rapid replication of small primary mirrors from float glass substrates
- Use of spherical surfaces for all optical elements
- Mounting of the unit telescopes 20 at a time using commercial slewing bearings for alt-az motion, realizing a ten-fold reduction in moving mass per square meter of aperture
- No enclosures
- Economy of scale by manufacture as thousands of identical small telescopes

The sequence we envisage to complete LFAST started this year with a 3-year development program. Its goal is to validate the design and mass production methods, ending with construction of a complete 20-mirror mount, with 20 telescopes and fibers feeding a small spectrograph, and its installation and evaluation at a site with good seeing. As part of this program, a detailed costing for the full LFAST array will be completed, and a site for the full array chosen. Construction of the full array would then take place in a second 3-year period, with mass production of the primary mirrors, purchase of all the commercially manufactured parts and construction and installation. We plan that the initial commissioning will be with the optical R=150,000 spectrograph. We have not made an independent estimate of the cost of the spectrograph, but expect it to be comparable to the BVRI module of the ANDES instrument being built for the ELT.

We can, however, estimate the cost of the installed LFAST telescope array and fiber link, and at this point our goal of around \$60 million appears realistic. For each unit telescope, the cost of all commercially produced components, purchased in quantity 3000, will be about \$4,000, giving a total of \$12 million. The cost of equipment for custom manufacturing, including for mold fabrication, glass slumping and polishing, optical metrology, and robotic assembly, will amount to some \$5 million. The total mass of all the fabricated steel, including for the telescopes, mounts and pedestals, is around 700 tons, costing some \$3 million. A team of around 30 people at the University of Arizona Tech Park will run the project and make the mirror, prime focus and fiber assemblies. A further 20 people will be employed at the installation site. Labor costs for the staff of 50 over the 3 years are projected to be \$30M. Then with a \$10M contingency, this leads to the estimated overall installed cost for the telescope and fiber array of \$60 million.

Compared to the very large telescopes now under construction, \$50,000/m^2 for the installed 1,200 m^2 LFAST array may sound unrealistically low, but the architectures are very different. Our array is in many ways more like the fields of heliostats used to direct solar energy to a tower-mounted central receiver. These have installed costs of about \$140 per square meter of mirror area, hundreds of times less than LFAST. While heliostats are far less accurate, they similarly use silvered glass mirrors carried on dual-axis tracking mounts, using the same bearings we have chosen. They similarly are installed in remote areas, operate in the open and are robustly built to survive wind gusts up to 90 mph, as must also be the LFAST mounts. We will strive to exploit learning from the design and installation of both giant astronomical telescopes and solar heliostat fields, in order to drive down the cost of LFAST.

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