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Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

The Large Fiber Array Spectroscopic Telescope: Fiber Feed and Spectrometer Conceptual Design

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ABSTRACT

The Large Fiber Array Spectroscopic Telescope, LFAST, will use optical fibers to combine light from thousands of small telescopes at centrally located high-resolution spectrometers. LFAST aims to use mass replication of small, self-contained telescope systems to provide ELT sized collecting area and spectroscopic capabilities at a drastically reduced price. However, fundamental constraints such as étendue, fiber modal noise, and focal-plane sampling that affect the size and complexity of spectrometers for single telescope ELTs also impact LFAST. We are carrying out a three year study to tackle these challenges. In this paper, we describe the conceptual designs for the fiber feed assemblies that carry light from the individual telescopes to a centralized location, and the high-resolution spectrometer that accepts this light.

Keywords: LFAST, telescopes, fiber-feeds, spectrometers

1. INTRODUCTION

The Large Fiber Array Spectroscopic Telescope (LFAST) project is designing a new type of optical array telescope that will provide extremely large telescope class (ELT) aperture dedicated to high-resolution spectroscopy [1]. Many spectroscopic observations utilize their telescopes in the seeing limit, and do not benefit from having a coherent primary aperture. So a telescope architecture based on an array of small, inexpensive telescopes that all feed a common spectrometer has the potential to provide large collecting area at a fraction of the cost of a traditional phased telescope. A large (500m^2) array-based telescope operating at optical and infrared wavelengths, comprised of many small mirrors connected by optical fibers, was proposed by Angel et al. [2]. Such facilities have been built before at smaller scale (e.g., MINERVA, with 4×0.7 m telescopes, [3]), and new facilities using this architecture are being planned (e.g., MARVEL, with 4×0.8 m telescopes, [4]; PolyOculus, with 7×0.28 m telescopes, [5]). These observatories have been designed and built around small, commercially available telescopes, in quantity of a few unit telescopes.

LFAST will greatly expand on this idea of array based telescopes, using unit telescopes with larger aperture than other arrays, in much greater quantity, and without domes. Each LFAST unit telescope [6] will have a spherical primary mirror of 0.76 m diameter, operating at F/3.5. Light from the primary will pass through a transmissive, four element spherical corrector, and be focused onto a fused silica optical fiber with a 17 micron diameter core. This fiber size corresponds to 1.3” on the sky, which we are tentatively setting based on 1” seeing at a notional site. Relay optics will reimage an 8’ diameter field of view surrounding the fiber onto a nearby CMOS camera for acquisition and guiding. Twenty unit telescopes will be combined in a common space frame, on a single altitude-azimuth mount [7], providing a total collecting area equivalent to a traditional 3.5 m single mirror telescope. We will replicate this 20-unit system 132 times, corresponding to 2,640 individual unit telescope, or 1,200 m^2 of collecting area. The optical fiber from each telescope will deliver light to a common instrument location, centrally located in the array. Each fiber will connect into an array based pseudo-slit, which will form the input for one or more spectrometers. By utilizing this mass replication scheme for the telescopes, mounts, and fiber feeds, we expect to drive down the production cost per square meter of collecting area to dramatically lower than other giant telescopes that are current being constructed, such as the GMT,

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Ground-based and Airborne Instrumentation for Astronomy IX, edited by Christopher J. Evans,
Julia J. Bryant, Kentaro Motohara, Proc. of SPIE Vol. 12184, 121844J
· doi: 10.1117/12.2628710

TMT, and ELT, while providing equivalent or larger light collecting capacity. Our current targeted cost for the full telescope array is $60M.

The LFAST project is carrying out a three year design and prototyping phase, which is planned to run from 2022 – 2024. The objectives of this phase are to develop and test the designs of the individual telescope subsystems, culminating with the completion of a fully functional 20-unit prototype on sky in southern Arizona. Construction of the full 1200 m^2 array will commence after the success of this demonstration phase. In this paper, we describe the conceptual design for the LFAST fiber feed. Additional design motivation and details of the LFAST project are provided in Angel et. al, [1]. Optical design of the unit telescope is provided in Berkson et al. [6]. Mechanical design of the 20-unit structure is provided in Young et al. [7].

2. UNIT TELESCOPE TOP END

2.1 General Design and Operations Overview

Each LFAST unit telescope will focus the light collected by its primary mirror into a modular top-end unit comprised of prime focus corrector (PFC) optics, a fiber puck and optical fiber, and guider camera and relay optics, as shown in Figure 1. The PFC is a four lens spherical corrector, which will feed the fiber at F/3.5. The optical design and design

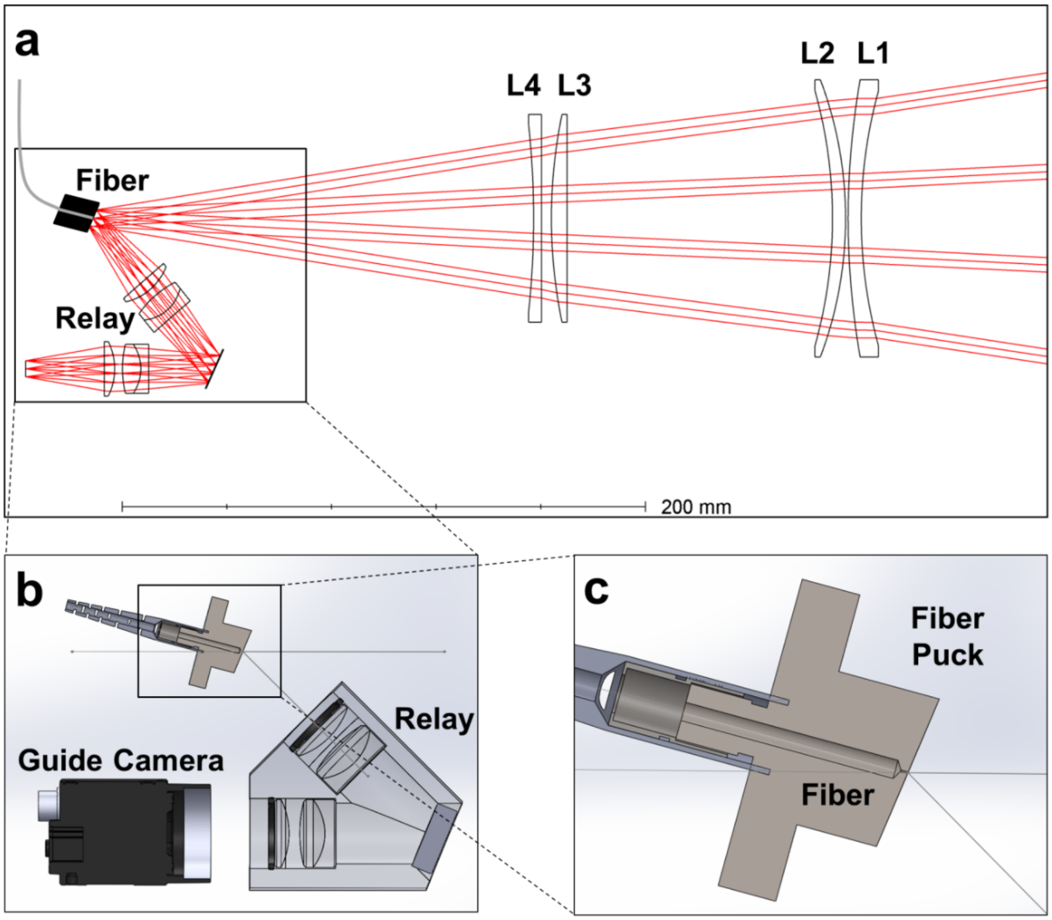

Figure 1: The LFAST unit telescope top end. (a) shows the optical ray trace with the F/3.5 beam coming from the primary to the right of the figure, through the four element prime focus corrector optics, reflecting off of the fiber puck, through the relay optics, and into the guide camera. (b) shows an enlargement of the fiber puck and guider relay optics, with some of the mechanical housing removed. (c) shows an enlargement of the fiber puck and the axis of the chief ray.

trades that were carried out are described in detail in [6]. Briefly, L1 and L2 provide the spherical correction over the 8' field-of-view, while L3 and L4 correct atmospheric dispersion and provide fine positioning adjustment by translating L4 relative to L3. Motions of a few mm provide atmospheric dispersion correction over the full range of zenith angles; motions of a few microns provide fine positioning adjustment of the prime focus image. Large position adjustments can be facilitated by tip-tilt of the primary mirror, which being spherical has no principle axis.

The fiber is potted into a puck, which has a face tilted 22.5° from the chief ray. The fiber itself is tilted 7.5° from the puck axis to compensate for refraction at the surface of the fiber tip. The fiber puck provides an 8' field surrounding the fiber, which is reflected into the guide camera relay optics. Our preliminary design for these optics consists of two identical sets of a singlet and a cemented doublet lens, which provide sufficient image quality over the field for guiding under seeing limited conditions. An unpowered fold mirror improves the compactness of the assembly housing to reduce the obscured area of the primary mirror. The relay feeds a CMOS camera (Figure 1b). All lenses in the current top end are spherical. We are currently having fabricated prototype sets of PFC and relay optics, and are also evaluating design alterations that would utilize molded aspheric lenses with the goal of improving image quality while also reducing fabrication costs.

This design attempts to break down each unit telescope into a self-contained opto-mechanical system. The 20 individual telescopes on a single space frame will be roughly co-pointed to a target by their common alt-az mount, which will also provide standard tracking. Once in position, the guide camera in each system will adjust the primary and L4 to bring the target onto the fiber and hold it there during an exposure. We are designing the systems to be modular. Should a unit telescope require maintenance of a subsystem in its top end, ideally the entire top end will be swapped with a spare. This should allow for rapid recovery of failed components, and shift detailed troubleshooting and repair to an enclosed maintenance facility.

2.2 Fiber Puck Design and Fabrication

The fiber puck (Figure 1c) will be fabricated out of either stainless steel or 3D micro-fabricated glass. We are currently fabricating pucks from stainless to simplify production during the early prototyping phase of the project. The puck is designed with a mounting flange that is pinned and bolted from the rear. The center of each puck is drilled out to accommodate the fiber, which will be potted into place with low-expansion Epotek 301-2 epoxy. We will then fine polish the assembly, and aluminize the polished face everywhere except for the fiber core to provide higher reflection and facilitate off-axis guiding on faint guide stars down to V=16. We are exploring two methods for carrying out this coating: UV photoresist, and back illumination with a pulsed laser during coating. In the photoresist method we use a small evaporative coating chamber to coat the entire puck face with a thin (~80 nm) layer of Al. Photoresist is then applied, and UV light is coupled backwards through the output end of the fiber. This light exposes the photoresist at the core of the fiber only, creating a mask that allows the core to be etched. The remaining photoresist is then removed, leaving a puck face that is coated with Al everywhere except the fiber core. In the back illumination method, we plan to illuminate back illuminate the fiber with a pulsed laser during the coating process to ablate material as it forms on the core. This is potentially simpler than the photoresist method, but has not yet been proven to produce a clean edge at the fiber core.

3. FIBER FEED

3.1 Fiber Feed Requirements and Baseline Design

Light from the LFAST unit telescopes will be combined into a common pseudo-slit, which will then be reimaged and serve as the input for one or more spectrometers. LFAST is essentially a seeing limited extremely large telescope, and so spectrometers designed for it are governed by the same limitations as those being built for GMT, TMT, and ELT. Design of the fiber feed is being driven by four primary requirements:

1. Preserve the étendue of the overall telescope system, which is set by the fiber size on the sky and the telescope aperture. The size of the spectrometer dispersion grating is directly tied to the system étendue; any increases result directly in cost and complexity increases in the spectrometer design. There are several places throughout the fiber feed where étendue can increase, such as focal-ratio degradation from the fiber, or imperfect packing of fibers at a pseudo-slit head, so we will take great care in both the design and fabrication of the fiber feed to minimize these effects.

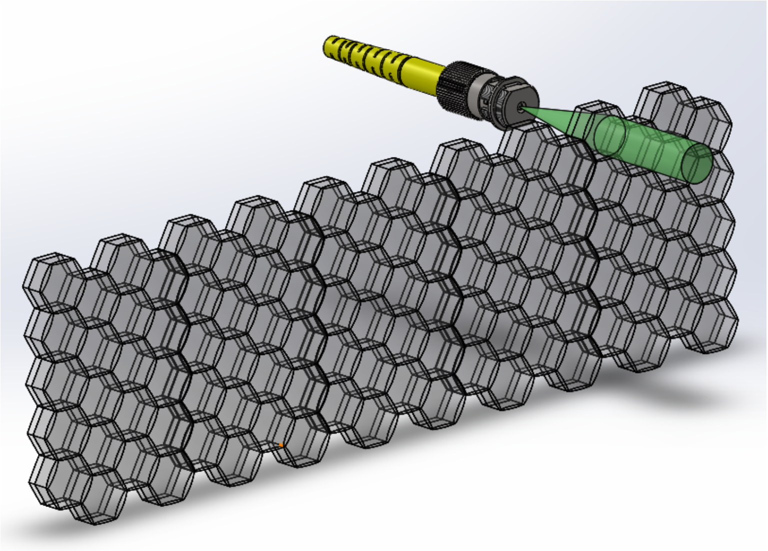

Figure 2: A section of the LFAST baseline fiber feed pseudo-slit. A representative fiber is shown feeding one element in a lens array that is 5 elements across and 528 elements long, although only a section is shown here for clarity. The lenses are hexagonally shaped apochromats designed to support the wide band pass of LFAST and sized so that the output circular beam of the fiber is inscribed within the hexagon. Offsets in the x-y position of each fiber result in an image shift on the output and allow the individual images to fall on top of each other.

2. Maximize system throughput over the 0.4 – 1.7 μm LFAST band pass, within the constraints imposed by the étendue requirement. This may appear to be an obvious requirement, as a primary goal of building larger telescopes is to capture as much light as possible. However, the interplay between trading throughput in exchange for preserving étendue is complicated technically and from the perspective of overall system cost.
3. Maximize scrambling of fiber modal noise and input illumination variations to provide a stable, uniform output for the spectrometer.
4. Minimize construction complexity to improve operational robustness, reduce assembly cost, and facilitate maintenance when required.

Our baseline fiber feed design utilizes step index fibers with 17 μm diameter octagonal core, running from each prime focus corrector unit to a station at the center of the LFAST array, near the spectrometer. The fiber exiting each unit telescope fiber puck will be terminated and coupled to a bulkhead panel on the 20-unit telescope. Relay fibers will then connect from that panel to a sister panel at the central station. Short fibers will run from this panel to a pseudo-slit head, arranged in a grid pattern with dimensions 5 fibers across by 528 fibers long. This arrangement of fiber with multiple bulkheads will result in throughput losses that we would not incur if each fiber were a continuous run from the puck to the pseudo-slit. However, we deem the manufacturing advantages and ability to easily replace individual fiber segments worth these losses.

Each fiber at the pseudo-slit will feed an apochromat lens, hexagonal shaped, and packed into a matching grid array. Figure 2 shows a rendering of a short section of this array. Small offsets in the x-y position of the fiber shift the images of the fiber cores so that they overlap at a distance of 20m. A telecentric lens placed at these overlapping images reimages the 5×528 array and feeds a spectrometer at F/20. Implementing this design is made complicated both by the large number of components and also the need for high thermal stability to preserve alignment. We are considering modifications that utilize microlens arrays and precision drilled 2D matrix fiber arrays to reduce some of the assembly and alignment complexity, but it is not yet clear if manufacturing tolerances can achieve the requisite precision required to co-align the full array of fibers. We are currently assembling a test bed fiber feed in the lab with 20 fibers and a grid of lenses to assess performance and construction complexity.

In parallel with this effort, we are pursuing an alternative approach for combining the light from unit telescopes that would utilize multi-mode photonic lanterns [9]. Such devices have been generated for single mode fibers, using a tapered transition to combine several single-mode fibers into a single multi-mode fiber. This is the scheme being implemented by the PolyOculus project [5], although their fibers have smaller cores than LFAST and are nearly single-mode. If executed well, lanterns have the potential to greatly simplify the fiber feed by reducing the total number of fibers running to the spectrometer, while increasing the fiber core size to improve modal characteristics. A properly constructed lantern should not increase the system étendue and should also have good throughput, likely better than the free space optics described above. However, multi-mode fiber has a substantially different core to clad ratio than single-mode fiber, so the ability to manufacture a functional lantern out of this material is untested. We plan to model the light propagation properties of such a device, and if the results are promising, then to attempt fabrication. Should this be successful, we envision combining the light from a 20-unit telescope (or 19, due to optimal packing geometries) into a single large multi-mode fiber. Each telescope would then output that fiber to the spectrometer, resulting in a 1D pseudo-slit array that is much simpler in construction than that shown in Figure 2.

3.2 Modal Noise Testing and Mitigation

The number of propagation modes in a step index fiber is well known to be given by the equation,

$$N = 2\left(\frac{\pi\, a\, NA}{\lambda}\right)^2 \tag{1}$$

where a is the core radius, NA is the numerical aperture, and λ is the wavelength of light. If LFAST uses 17 μm core fiber with NA=0.22, and fully fills the fiber NA (which our F/3.5 beam will not do), the number of modes propagated at 550 nm is only about 230. At 1.6 μm, only a handful of modes are propagated, making each telescope a “few mode” system. Modes manifest at the output of a fiber as interference speckles, whose spatial distribution is dependent on the illumination of the fiber and its physical position in the system [8]. The distribution of speckles determines the photocenter of the output, which when injected into a high-resolution spectrometer will impact the stability of the effective line-spread-function (LSF) and limit the effective signal-to-noise, independent of the photon signal to noise that is achieved. Changes in the speckle pattern will result in changes in the LSF and can masquerade as Doppler velocity shifts. A common and effective way of mitigating this is to actively agitate the fiber during an integrated exposure, thus causing the modal pattern to average over time and produce a relatively flat output. This has been implemented in high-precision radial velocity spectrometers (e.g., [10]), but typically for systems with much larger core fibers, and hence many more modes, than LFAST will have.

LFAST will require a custom drawn fiber with a unique preform, which is both costly and has a large lead time. Prior to investing in that procurement, we have obtained a sample of available multi-mode fiber with small circular core from CeramOptec, for laboratory testing. This fiber is Optran WF and has a 20 μm core diameter and 40 μm clad, coated in 5 μm of polyimide, with NA=0.22; a sample piece is shown in Figure 3a. The 40 μm clad is 1/3 the diameter of standard single-mode fiber, making this sample exceptionally difficult to handle. To facilitate terminating and polishing the fiber, we potted the end of several pieces into small capillary tubes with inner diameter a few microns larger than the fiber’s polyimide coating, and with outer diameter well matched to available ferrules. This modification was carried out by hand under a stereo microscope, slowly advancing the fiber into the tubing using precision xyz stages. Figure 3b shows the static modal pattern of this fiber illuminated with a 635 nm single mode fiber laser diode; the number of interference speckles is well matched to the theoretical number of propagation modes. We are in the process of obtaining custom low-OH step index fiber from CeramOptec with a 17 μm core and NA=0.22. This fiber will be overclad to a standard 125 μm diameter to improve handling and allow us to utilize common, inexpensive ferrules and connectors. The overclad silica material has the potential to propagate cladding modes, so care must be taken to avoid illuminating this region. This requirement makes more critical our desire to aluminize the top end fiber puck, leaving only the core exposed.

Our baseline fiber feed combines the light from the telescope array onto a common pupil. The number of modes propagated by each fiber will be identical, within manufacturing tolerances, but will be distributed spatially in a unique pattern. Each fiber will be actively agitated to scramble its limited number of modes. The LSF stability that the LFAST fiber feed can achieve will then be dictated by the effect of combining a small number of modes from each of a large number of fibers. Our laboratory test bed fiber feed will enable us to evaluate in the lab the impact of adding additional unit telescopes on both the LSF stability and signal-to-noise ceiling.

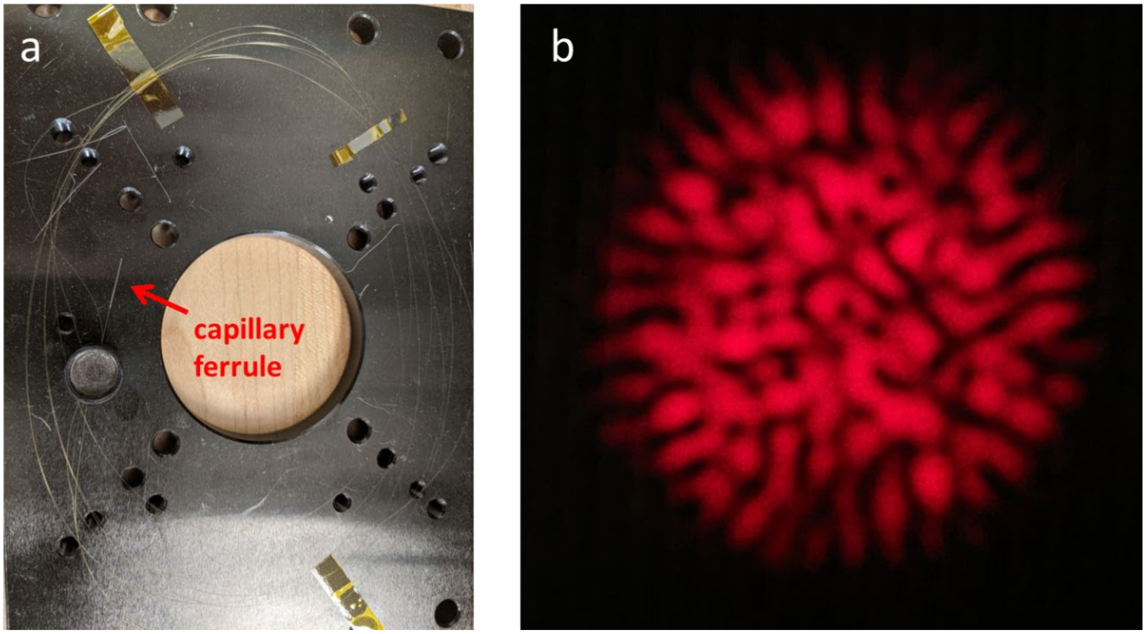

Figure 3: (a) CeramOptec WF 20/40/45 P, NA=0.22 test fiber that we obtained as an off the shelf prototype for the 17 µm LFAST fiber. The 40 µm core makes this fiber extremely difficult to handle and terminate. The arrow points to a short piece of capillary tubing that we inserted the fiber end into to facilitate termination in standard ferrules. (b) Static speckle pattern caused by mode interference, imaged in the 20 µm fiber when illuminated with a 635nm laser diode. The number of interference speckles shown is well matched to the theoretical number of propagation modes given by Equation 1.

3.3 Illumination Variation Mitigation

Even if our modal noise scrambling were perfect, the LFAST pseudo-slit will still be impacted by factors that are unique to array telescopes. Changes in the illumination of any individual telescope will be seen as a shift in the photo-center of the pseudo-slit. We envision several sources for such changes, some of which will be grey and some of which will be chromatic. Individual telescopes that are offline for maintenance will result in a constant grey offset to the photo-center. Telescopes with poor or variable guiding will result in a grey offset with varying intensity. Telescopes with a poorly functioning ADC may result in chromatic variability. Clouds that are moving across the array, impacting telescopes differentially, will also result in chromatic variability. We will probe the effects of these scenarios, first using our laboratory test bed fiber feed, and then later on-sky with the full LFAST prototype. We are also developing a prototype rectangular glass light-pipe that would accept as its input the light from our telecentric lens and output a highly scrambled slit image that mixes the contributions from each unit telescope.

4. NOTIONAL SPECTROMETER

The LFAST array will feed one or more spectrometers, positioned at the geometric center of the array, and housed in a custom-built spectrometer building. Spectrometer design efforts have been deferred to 2023, but we have established several requirements. The scientific promise of LFAST is broadband, high-resolution spectroscopy. The facility should be able to obtain useful spectra of very faint targets, and very high-signal-to-noise spectra of bright targets. To achieve this, we have a spectral resolution baseline requirement of $R = \lambda/\Delta\lambda = 100{,}000$, and a goal of $R = 150{,}000$. The LFAST telescope optics and fiber feed will provide light from 0.4 µm - 1.7 µm, but it is not feasible to build a single spectrometer to accept this full bandwidth. Instead, we consider splitting the bandpass at 0.8 µm, into visible and infrared arms, using a dichroic at the output of the fiber feed to feed two physically different spectrometers. The visible arm should accept light from 0.4 µm - 0.8 µm and provide a cross-dispersed echellogram with minimal wavelength gaps that can be imaged onto either the Teledyne CCD290-99 or the STA1600 CCD with N>2.5 pixels per resolution element. The infrared arm should accept light from 0.85 μm – 1.7 μm, and provide a cross-dispersed echellogram that can be imaged onto the Teledyne Hawaii-4RG array; choice of array pitch, 10 μm or 15 μm, will be determined later in the design phase.

These design requirements are challenging for a telescope with such a large étendue, but are very similar to the requirements that have driven the design of the ELT Andes spectrometer [11] Within each spectrometer unit, dichroics split the light from a common echelle grating into several arms with individual camera optics and detectors. The efforts of the Andes team demonstrate that it is possible to meet our requirements for resolution, bandpass, and sampling for a ELT sized telescope like LFAST; the challenge for LFAST will be to avoid designing a spectrometer with a construction cost equal to or greater than our entire telescope array. One possible approach we are evaluating is to apply the same design principles of replication used on the LFAST telescopes to the spectrometer: rather than build a single large spectrometer for each bandpass, split the telescope array into a few subarrays and build several (4-6) smaller spectrometers. Such a design would reduce fiber length, increasing throughput, and would also reduce the grating area required for each spectrometer. However, the design must be made to work with proper sampling on the pixel pitch of available large format detectors. This trade will be fully explored during our spectrometer design phase in 2023.

5. FUTURE WORK

The LFAST project is only six months into our three year design and prototyping phase, but is already progressing at a rapid and productive pace. We have already developed and tested procedures in house to fabricate our primary mirrors. Prototype optics for the PFC and guider relay have been ordered and are expected in Fall 2022. And our initial custom fiber will be drawn in the coming months. By winter 2022, we anticipate having the first unit telescope completed and conducting testing on-sky. Once our fiber testbed is completed, we will carry-out extensive testing of the baseline pseudo-slit head and refine the preliminary design. In 2023, we plan to focus on the mechanical design of the 20-unit telescope, and expand our mirror and top end production capabilities. During this time we will also begin developing serious designs for the LFAST spectrometers, although actual fabrication of these instruments is not part of the current three year project. During 2024, we will fully populate a 20-unit telescope frame, equivalent to a single mirror 3.5 m telescope, and deploy the system on sky at a site in southern Arizona for testing and demonstration.

ACKNOWLEDGEMENTS

This research was funded by the generosity of Eric and Wendy Schmidt, by recommendation of the Schmidt Futures program. Our thanks to Stu Feldman of Schmidt Futures who has contributed significantly to the development of LFAST from our early proposal through the current development phase; Jeff Kingsley of Steward Observatory, who has done much to help LFAST become a real project; Daniel Eisenstein for thoughtful discussions of the concept; and Martin Roth for substantial discussions about the construction and utility of multi-mode photonic lanterns.

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