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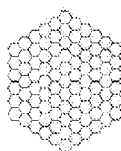
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(54) Title: A TELESCOPE FOR MASS PRODUCTION AT LOW COST

Fiber input lens



Fiber output lens

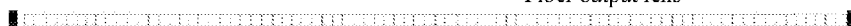


FIG. 1

(57) **Abstract:** A method of producing a plurality of optical components, each having a substantially equivalent optical surface, includes providing a substrate of optical material, the substrate having an optically smooth surface; providing a mandrel having an optically smooth surface of a shape that is an inverse of a shape to be imparted to the optically smooth surface of the substrate; coating the optically smooth surface of the mandrel with a mold release material; changing a temperature of at least one of the substrate or the mandrel to be at a substantially same temperature; disposing the substrate on the mandrel such that the optically smooth surface of the substrate is on the optically smooth surface of the mandrel that is coated with the mold release material; heating the mandrel and the substrate together to soften the substrate to conform the optically smooth surface of the substrate to the shape of the mandrel; cooling the mandrel and the substrate together until the substrate is sufficiently rigid to maintain the optically smooth surface of the substrate as conformed to the shape of the mandrel; removing the substrate from the mandrel to provide a first optical component of the plurality of optical components; providing at least one additional substrate of optical material, each having an optically smooth surface; and repeating at least the changing a temperature, disposing, heating and removing for each at least one additional substrate to thereby produce the plurality of optical components. A telescope includes a plurality of the optical components.

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A TELESCOPE FOR MASS PRODUCTION AT LOW COST

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present patent application claims priority to U.S. Provisional Patent Application No. 63/526,586, filed on July 13, 2023, the entire content of which is incorporated herein by reference. All references cited anywhere in this specification, including the Background and Detailed Description sections, are incorporated by reference as if each had been individually incorporated.

BACKGROUND

[0002] The field of currently claimed embodiments of this invention relates to methods of producing a plurality of equivalent optical components and optical devices and systems using the plurality of optical components as well as optical systems using thermal and/or other active corrections of aberrations and/or environmental defocusing.

SUMMARY

[0003] A method of producing a plurality of optical components according to an embodiment of the current invention, each having a substantially equivalent optical surface, includes providing a substrate of optical material, the substrate having an optically smooth surface; providing a mandrel having an optically smooth surface of a shape that is an inverse of a shape to be imparted to the optically smooth surface of the substrate; coating the optically smooth surface of the mandrel with a mold release material; changing a temperature of at least one of the substrate or the mandrel to be at a substantially same temperature; disposing the substrate on the mandrel such that the optically smooth surface of the substrate is on the optically smooth surface of the mandrel that is coated with the mold release material; heating the mandrel and the substrate together to soften the substrate to conform the optically smooth surface of the substrate to the shape of the mandrel; cooling the mandrel and the substrate together until the substrate is sufficiently rigid to maintain the optically smooth surface of the substrate as conformed to the shape of the mandrel; removing the substrate from the mandrel to

provide a first optical component of the plurality of optical components; providing at least one additional substrate of optical material, each having an optically smooth surface; and repeating at least the changing a temperature, disposing, heating and removing for each at least one additional substrate to thereby produce the plurality of optical components.

[0004] A thermally active mirror assembly according to an embodiment of the current invention includes a mirror formed from a glass substrate with substantially uniform thickness having a front surface and a back surface, said front surface having a specular surface; a plurality of thermoelectric devices (TECs) arranged to be in thermal contact with the mirror at a corresponding plurality of positions of the back surface of the mirror; a plurality of heat sinks thermally connected to the plurality of TECs to transfer heat by convection to and from surrounding air; and an electronic control system electrically connected to each of the plurality of thermoelectric devices. The electronic control system is configured to control selective heating and cooling of glass portions of the mirror in thermal contact with each of the plurality of thermoelectric devices to thereby control changes in shape of the mirror by local thermal expansion or contraction.

[0005] A telescope according to an embodiment of the current invention includes a primary mirror having a substantially spherical reflecting surface; a compound prime focus corrector comprising first, second, third and fourth singlet lenses, each with spherical surfaces; a tracking mount constructed and arranged to hold aligned the primary mirror and the compound prime focus corrector relative to each other and toward a sky target; a camera arranged to receive an image formed by the primary mirror and the compound prime focus corrector; a housing constructed and arranged to hold the first, second and third singlet lenses fixed in position, axisymmetric about an axis of the compound prime focus corrector; a position control assembly constructed and arranged to control a lateral position of the fourth singlet lens relative to the axis and the housing; a positioning assembly constructed and arranged to adjust a position of a center of curvature of the primary mirror relative to the axis of the compound prime focus corrector; and an electronic control system configured to actively control an orientation of the telescope, the center of curvature position and the lateral position of said fourth lens. The telescope, with all four of the first, second, third and fourth singlet lenses and the center of curvature of the primary mirror being coaxial, in the absence of atmospheric

aberrations, has images that are corrected for spherical and chromatic aberrations. When viewing stars through the atmosphere away from the zenith, the telescope corrects for atmospheric chromatic dispersion by driving correlated lateral motions away from the axis, using the mechanisms to move the fourth singlet lens and the center of curvature of the primary mirror under control of the electronic control system. When a star image suffers motion caused by vibrations of the tracking mount or by atmospheric turbulence, detected by the camera, motions of the fourth singlet lens under servo control by the electronic control system is configured to be able to induce equal and opposite motions to stabilize the star image without disrupting image quality.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Further objectives and advantages will become apparent from a consideration of the description, drawings, and examples, as follows.

[0007] FIG. 1 is an illustration of an array of 90 hexagonal lenses (Upper) at the ELT f/20 focus that divides the light across a 1.11 arcsec aperture and directs it into 96 fibers according to an embodiment of the current invention; and a line of 96 lenses (Lower) of the same focal length, now cut into squares of the same area as the hexagons that directs the fiber outputs to form the f/20 slit input to the spectrograph;

[0008] FIG. 2 is a plan view of mount with 20 unit telescopes according to an embodiment of the current invention;

[0009] FIG. 3 shows an example of telescope mounts at 12 m spacing with unobstructed view down to 23° elevation according to an embodiment of the current invention;

[0010] FIG. 4A is a side view of an array of 5 x 550 fibers and hexagonal lenses to combine the light into a single large-scale slit according to an embodiment of the current invention;

[0011] FIG. 4B is a face-on view of the lens array of FIG. 4A in which the light from 20 fibers from one mount is combined by the lenses in the marked trapezoid;

[0012] FIG. 5 is a schematic ray diagram showing how the images of the individual fiber cores formed by the hexagonal lens array overlap at a common exit pupil according to an embodiment of the current invention;

[0013] FIG. 6 shows a telecentric lens at the common exit pupil forming a 67 mm long slit at $f/20$ at the entrance to the spectrograph according to an embodiment of the current invention;

[0014] FIG. 7A shows, from CMM profilometry, departure from a sphere of a 0.76 m Borofloat disc slumped disc, slumped over the prototype spherically ground mandrel, in which the surface contours are at 5 μm intervals according to an embodiment of the current invention;

[0015] FIG. 7B shows a second more rigid and polished mandrel ready for slumping tests according to an embodiment of the current invention;

[0016] FIG. 8 shows optical finishing of the 30" slumped disc with a 36" polishing machine according to an embodiment of the current invention;

[0017] FIG. 9 shows a 0.76 m mirror assembly in which the perimeter TEC units and left and right vanes extending to full width according to an embodiment of the current invention;

[0018] FIGS. 10A and 10B show an example of a 200 mm test mirror with 15 Peltier thermal actuators (front view FIG. 10A, back view FIG. 10B) prior to attachment of heat sinks on the 7 back actuators according to an embodiment of the current invention;

[0019] FIG. 11A shows astigmatism of 2.2 μm P-V induced in the 200 mm BK7 test mirror using only the 8 edge actuators measurements obtained using phase shifting interferometry (shade scale in nm) according to an embodiment of the current invention;

[0020] FIG. 11B shows an ANSYS finite element model of coma induced in the 0.76 m Borofloat mirror assembly of Figure 9 using all 15 actuators;

[0021] FIG. 12 shows rotation angle of slew bearing measured in successive video frames taken at 30 frames/second according to an embodiment of the current invention;

[0022] FIG. 13 shows an example of an optical design layout of the full LFAST unit telescope (above) and a zoomed-in view of the PFC and relay subsystem (below) according to an embodiment of the current invention (L1 through L4 correct aberrations, atmospheric dispersion, and image motion);

[0023] FIG. 14 provides the full optical prescription for the LFAST unit telescope of FIG. 13;

[0024] FIG. 15 is a plot of atmospheric dispersion for the LFAST 380-1700 nm bandpass (left) in which lateral shifts of L4 induce opposite lateral color of similar magnitude, creating a lookup table for correcting atmospheric dispersion with L4;

[0025] FIG. 16 shows (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, and 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 μ m fiber core);

[0026] FIG. 17 shows a two arcsecond perturbation would cause the target to shift by 25 μ m, entirely missing the collection fiber (left) (this spot diagram is for the 50 degree atmospheric dispersion corrected image, from FIG. 16; by shifting L4 by 73 μ m, 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);

[0027] FIG. 18 shows 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);

[0028] FIG. 19 shows 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); and

[0029] FIG. 20 shows 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).

DETAILED DESCRIPTION

[0030] Some embodiments of the current invention are discussed in detail below. In describing embodiments, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. A person skilled in the relevant art will recognize that other equivalent components can be employed and other methods developed without departing from the broad concepts of the current invention. All references cited anywhere in this specification, including the Background and Detailed Description sections, are incorporated by reference as if each had been individually incorporated.

[0031] The term “light” is intended to have a broad definition that can include light in the visible as well as non-visible regions of the electromagnetic spectrum. For example, the term “light” can include, but is not limited to, visible, infrared and ultraviolet light. Similarly, the term “optical” has a corresponding broad definition as with the term “light”.

[0032] The term “optically smooth” is intended to mean that the surface acts sufficiently as a specular surface with sufficiently low optical scattering, sufficiently small-scale ripples and sufficiently small scale sub-surface damage for the intended application.

[0033] The term “substantially same temperature” means close enough in temperature so that thermal gradients on contact will not be large enough to risk fracture or other thermal damage.

[0034] The term “substantially equivalent optical surface” means the optical effects on incoming light are the same to within the desired tolerance levels for the particular application. For example, the optical surfaces could be surfaces of a primary

mirror of a telescope. However, the general concepts of the current invention are not limited to only this example.

[0035] Some embodiments of the current invention are directed to a telescope of aperture 0.5 – 1 m diameter for mass production at low-cost. In some embodiments, the telescope's mirror is made by a novel rapid replication process, and is equipped with novel, computer-controlled Peltier coolers for active shape adjustment. In some embodiments, an optical corrector near the telescope's focus incorporates a lens articulated in a novel way to reduce atmospheric image blurring. Applications can include astronomical spectroscopy and laser communications, for example.

[0036] The following describes some aspects of the current invention in more detail.

[0037] Some embodiments of the current invention are directed to a method to replicate optical surfaces on large glass substrates. In particular, a method to replicate large optical surfaces on glass substrates according to some embodiments for a glass substrate that is made with a smooth surface; a mandrel that is made with polished or fine ground surface that has accurately the inverse of the required shape in which the mandrel is coated with a thin layer of mold release, the glass substrate is replicated by the following sequence of steps: the substrate is heated if needed to the same temperature as the mandrel and placed on it; the mandrel and the substrate are heated together to soften the substrate enough so it slumps to conform accurately to the shape of the mandrel; the mandrel and the substrate are cooled together until the substrate is at least rigid enough to hold its slumped shape accurately; the now replicated substrate is removed and a next substrate is heated if needed to be at the same temperature as the mandrel and is placed on the mandrel to repeat the sequence of steps; and the previous said substrate is cooled slowly as needed for annealing and return to room temperature.

[0038] In some embodiments, the substrates have a specular finish, as for example float glass. In some embodiments, the mandrel is made of stainless steel, silicon carbide, fused silica or ULE (Corning Ultra-Low Expansion glass). In some embodiments, the mold release is boron nitride. In some embodiments, multiple substrates are heated in a tunnel kiln to the temperature of the mandrel ready to receive a new substrate. In some

embodiments, the shape of the substrate, after shaping and cooling to room temperature, is measured accurately by optical metrology, and a surface map of its departure from the desired replica shape is computed by subtraction; and if the departure from the desired shape is larger than the acceptable tolerance, then the shape of the mandrel is worked to reduce the departure; a new replica is formed according to this method and its shape is measured. The cycle of replication, measurement and mandrel shape correction is repeated until the replicas are measured to be within acceptable tolerance.

[0039] Other embodiments of the current invention are directed to a mirror with active thermal shape adjustment using Peltier devices. For example, a circular mirror with active thermal shape adjustment according to some embodiments of the current invention includes a glass disc substrate with approximately uniform thickness and polished to a specular finish with the desired figure on its front surface; a ring of Peltier thermoelectric devices (TECs) set around the perimeter of the disc; sections of bent copper sheet attached using thermally conductive adhesive to the disc to transfer heat between each of the active surfaces of the TECs and the front and back perimeter surfaces of the glass disc; an electronic system under computer control to adjust the voltages, positive or negative, applied to the TECs. The TECs are controlled to transfer heat through the glass thickness around the perimeter to cause expansion and contraction by heating and cooling on opposite surfaces so as to apply bending moments around the perimeter of the disc to the disc. The bending moments are controlled by varying the voltages applied to different TECs so as to induce controlled modes of bending, such as astigmatism and trefoil.

[0040] In some embodiments, the mirror can also include additional TECs devices set across the back face of the mirror; sections of flat copper sheet attached on a first side to the back face of the glass disc, and on a second side to a first active face of a the TEC; heat sinks attached to the second active surfaces of the TEC; and additional electronics under computer control to adjust the voltages, positive or negative, applied to said additional TECs.

[0041] In some embodiments, the TECs can be in the form of 40 mm square Peltier coolers.

[0042] Some embodiments can include a method to calculate all of the different voltages to be applied to each TEC to obtain a given change of shape. The influence functions for given voltage applied to each individual TEC can be obtained by optical metrology measurement or by finite element modelling; the different amplitude and sign of each the influence function which in a linear superposition with best replicate such given change of shape is computed; and the control system can be used to apply the set of influence functions.

[0043] Some other embodiments of the current invention are directed to a telescope with spherical primary mirror and prime focus corrector lens. A telescope according to an embodiment of the current invention includes a primary mirror with spherical surface figure and a compound prime focus corrector including four singlet lenses, each with spherical surfaces; a tracking mount to hold aligned the primary and the corrector relative to each other, and toward a given target in the sky; a camera to view the image formed by the mirror and the corrector; a housing to hold the first, second and third of the lenses fixed in position, axisymmetric about the axis of said corrector; a mechanism to control the lateral position of the fourth of the lenses relative to the axis and the housing; a mechanism to adjust the position of the center of curvature of the primary spherical mirror relative to the corrector axis; and an electronic and computer system to actively control the telescope orientation, the center of curvature position and the lateral position of the fourth lens. The telescope, with all four the lenses and the center of curvature coaxial will, in the absence of atmospheric aberrations, deliver sharp images, corrected for spherical and chromatic aberrations. When viewing stars through the atmosphere away from the zenith, the telescope will correct for atmospheric chromatic dispersion by driving correlated lateral motions away from the axis, using the mechanisms to move the fourth lens and the center of curvature, under control of the computer system. When a star image suffers small but rapid motion caused by vibrations of the tracking mount or by atmospheric turbulence, detected by the camera, small motions of the fourth lens under servo control by the computer may be used to induce equal and opposite motions to stabilize the star image without disrupting sharp image quality.

[0044] The following describes some examples that include some embodiments of the current invention. The general concepts of this invention are not limited to only these examples.

EXAMPLE 1

Large Fiber Array Spectroscopic Telescope (LFAST)

[0045] LFAST's goal is to use thousands of small telescopes and fiber combination for high resolution ($R=150,000$) spectroscopy, in a way that will realize large cost savings and ultimately make affordable apertures much larger than 1000 m^2 . Each unit telescope of 0.76 m aperture (0.43 m^2) will focus the image of a single star onto a small ($17 \text{ }\mu\text{m}$) core fiber, subtending 1.3 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 reduces subsequent optical finishing time to a couple of days. A method for active thermal control of mirror figure using Peltier devices is incorporated. The projected cost of each telescope, when mass produced in thousands, is approximately $\$8,000$. The telescopes can be mounted in the open air in groups of 20, located 12 m apart. The mirrors can be configured in arrays of 2×10 , set on either side of a central, pedestal-mounted alt-az drive using commercial worm gear bearings. Protection against rain and dust can be provided by automated covers above and below the mirrors, and by pointing the mirrors down (-20° elevation) when not in use. The first LFAST array, $1,200 \text{ m}^2$ in collecting area and some 150 m in diameter, comprises 132 mounts with 2,860 fibers carrying the light to central spectrographs. The light from all the fibers can be combined without loss of etendue by a 5×528 array of adjacent hexagonal lenses. These reimage all the individual fiber cores to a single overlapping core image, where a telecentric lens reimages the lens array as the entrance slit of an echelle spectrograph.

GOALS FOR LFAST

[0046] 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 their cost. This would open the path to a still much larger telescope, $\sim 20,000 \text{ m}^2$ aperture, at a cost of no more than a $1,000 \text{ m}^2$ ELT. Such 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 telescope is needed to reach a broader sample of planets orbiting a range of earlier and less hostile stellar types, which are rarer and thus generally more distant, and with less frequent transits and shallower absorption features, such as TOI 700, (M2, 30 pc, 31-day orbit).

[0047] To best exploit the full potential of very large telescope aperture, a major requirement is for broad spectral cover, extending through the optical spectrum into the near infrared, at resolution $\geq 100,000$, and for very high signal to noise ratio, sufficient to reach absorption feature depths $\leq 10^{-5}$.

TECHNICAL BACKGROUND

[0048] Analyses 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 $D^{0.77}$ [1. Van Belle, Meinel and Meinel], 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 exponent too seriously, as the architectures of very large and small telescopes will differ, but there is certainly the potential for major cost savings.

[0049] 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 to the entrance slit of the 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.

[0050] 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 500 fibers to line up the light from 500 galaxies along a long spectrograph slit [4], 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 in the ultra-high resolution ANDES spectrograph to be built for the ELT. At the $f/20$ focus of the 39 m aperture telescope, a hexagonal array of 96 adjacent lenses will reformat 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 create an $f/20$ beam into the spectrograph slit, as shown in FIG 1. [Oliva]

[0051] In a simple extension of this concept to a fiber linked telescope array, in a system with the same etendue the same fibers could be fed directly by 96 4 m telescopes. At $f/3.5$, 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 cost would be six times less.

THE LFAST DESIGN

Unit telescope and coupling into the fiber

[0052] 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 numbers 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 lend themselves to mass production.

[0053] 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.

[0054] Based on these considerations, we have settled on a primary mirror aperture of 0.76 m diameter, 0.454 m² in area. This is a size which lends itself to mass production. The disc substrates can be cut out from mass-produced Borofloat glass, available in 25 mm thickness at relatively low cost, and can be slumped over a precisely-shaped mandrel to minimize the optical processing time, as outlined 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.

[0055] We have chosen a fiber core size of 18 μm, to obtain an aperture on the sky of diameter 1.40 arcsec. This strikes a balance between being too small and losing flux and being too big, with increased etendue, instrument size and sky background. Based on the analysis of Christou [4], under good seeing condition ($r_0=20$ cm at 500 nm wavelength), for zenith pointing a 1.4" diameter aperture will encircle $\geq 90\%$ 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.

[0056] 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 18 μm circular core, to a fast-framing imaging CMOS camera. Then a decentration of the star centroid that reduced 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.

[0057] The optical design of the individual prime focus telescopes meeting these requirements is described by Berkson et al, [5]. For on axis imaging, we want achromatic diffraction limited images over 400 nm – 1,600 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.

[0058] 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 figuring is significantly reduced for the spherical figure.

Telescope mounts and array size

[0059] 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 FIG. 2. The total collection area is 9.1 m², 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. [6]. 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.

[0060] Wind buffeting is an important consideration for an optical telescope out in the open. Young et al [6] have used finite element analysis to model and optimize the

stiffness of the mount structure. The optimized design as shown in FIG. 3, has a moving mass of 1.5 tons of steel and hardware to support the 20 telescopes weighing 1.2 tons, for a total moving mass per unit mirror area an order of magnitude less than the ELT average. 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 amplitude projected for the ALMA 12 m sub-mm wavelength radio telescopes, which are also in the open and have 5 Hz lowest resonant frequencies. In LFAST, we will correct the image motion caused by windshake in real time using the same image motion correction servo control system used to correct seeing motion. Accelerometers can be installed to measure the wind shake, and this data can be combined with that from image sensing to maintain the star image at the fiber entrance.

[0061] 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 m². The pedestal mounts, shown in FIG. 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 m².

Spectrograph design for LFAST

[0062] Here we address the question of how best to configure LFAST for high resolution spectroscopy, given light delivered by thousands of small individual fibers. Both fundamental and practical constraints come into play. On the fundamental side, etendue sets the minimum possible detector area. Because etendue cannot be reduced without loss of light, the minimum area on the detector A_D to record simultaneously N_R spectral resolution elements is given equating input and output etendues:

$$A_{Dmin} = N_R A_{tel} \Omega_{tel} / \Omega_{cam} \quad (1)$$

where A_{tel} is the total telescope area, Ω_{tel} is the solid angle on the sky of the entrance aperture, and Ω_{cam} is the solid angle of light focused by the spectrograph camera onto the detector. For LFAST, $A_{tel} = 1,200$ m², $\Omega_{tel} = 3.62e-11$ ster. for 1.4 arcsec aperture, and $\Omega_{cam} = 0.55$ ster., assuming f/1.2 Schmidt spectrograph cameras.

[0063] We will suppose the spectral range 390 nm – 940 nm will be covered at $R=150,000$, by an LFAST spectrograph using CCDs and requiring $N_{\text{RCCD}} = 132,000$ resolution elements. With these parameters, $A_{\text{CCD min}} = 105 \text{ cm}^2$. In practice, allowing for gaps between and at the ends of echelle spectrograph orders, the total CCD area must be several times this illuminated area. For the wavelength range 0.96 μm – 1.72 μm N_{IR} at $R=120,000$ requires 70,000 resolution elements and $A_{\text{IRmin}} = 55 \text{ cm}^2$.

[0064] A practical constraint on the configuration of the fibers along the spectrograph, and the optimum number of spectrographs, comes from matching available detector pixel size to slit width. LFAST plans to use in its spectrographs the largest available imaging detectors for the optical and infrared, the 93 mm square, 84.6 cm^2 Teledyne CCD290-99, with 85 megapixels each 10 μm square, and the 61 mm square, 37.2 cm^2 , Teledyne H4RG 17-megapixel infrared array with 15 μm pixels. Choosing a slit width of 27 microns at the detector it will be sampled by 2.7 10 μm CCD pixels, and 1.8 15 μm pixels. From equation 1, the minimum area on the detector of a single spectral resolution element at the $f/1.2$ camera focus is 0.081 mm^2 , thus the slit length must be 3 mm, and the aspect ratio 110:1.

[0065] Our current concept is to build first the optical spectrograph, using 4 of the Teledyne CCDs in a copy of the ELT optical UHR ANDES [Oliva et al.], scaled up in size by 50%, with 2.25 larger area for the grating and camera CCDs, to accommodate LFAST's nearly twice as large etendue and 16% more resolution elements. ANDES is a spectrograph well optimized for large etendue and very high spectral resolution, 150,000.

[0066] It uses the 96-fiber slit of FIG. 1 above, and a single echelle grating for each of the optical and infrared spectrographs, in a white pupil configuration with an anamorphic beam. In the optical spectrograph, the optical grating output is separated using dichroic beamsplitters into the four spectral ranges, covering 400 nm – 833 nm. Each spectral range is passed through a cross dispersion grating and into an $f/1.2$ camera that images the cross dispersed spectra onto a 61 mm square CCD. LFAST will use also 4 cameras, taking advantage of its larger CCDs to accommodate its larger etendue and to cover its 20% larger spectral range, from 390 nm to 940 nm.

[0067] Table 1 lists the key parameters for the LFAST and ANDES optical UHR spectrographs. The infrared spectrograph for LFAST will use three cameras with HR4G arrays to cover each of the Y, J and H bands at resolution 120,000.

1	2	3	4	5	6	7	8	9	10	11	12
Telescope	Mirror area m ²	Mirror Seg-ments	Seeing FWHM	Aperture diameter (arcsec)	AΩ (mm ²)	# Fibers	Slit aspect ratio	Slit image on CCD	Camera pupil and focal length	CCD size mm	R4 grating size
LFAST	1,200	2,800 x 0.76 m	1.0"	1.4"	0.079	2,800 @ 18 μm	112:1 5 x 560	27 μm x 3.0 mm	450 mm, 540 mm	93 x 93	0.3 m x 2.4 m
ELT + ANDES UHR	1,000	800 x 1.4 m	0.7"	1.11"	0.042	96 @ 75 μm	96:1 1 x 96	21 μm x 2.0 mm	300 mm, 360 mm	61 x 61	0.2 m x 1.6 m

Table 1. Parameters of LFAST and ELT ANDES UHR optical spectrographs

Combining the light from all the fibers at the spectrograph slit

[0068] A method to combine the output of 2,840 fibers into a 106:1 aspect ratio slit at $f/20$, while maintaining etendue and minimizing flux loss, is shown in FIGS. 4A, 4B, 5 and 6. All 2,840 fibers will be configured in a 5 x 528 hexagonal array, 5 cm high and 5.3 m long, to illuminate an array of hexagonal lenses, as shown in FIGS. 4A and 4B. The 17-μm core fibers will be terminated in ferrules that can be adjusted in position manually with 1 μm precision. The lenses are identical apochromats, cut with hexagonal perimeters (1 cm flat-to-flat). With 3.5 cm focal length, etendue is conserved relative to the $f/3.5$ inputs into the fibers, and also for the entire array. This arrangement, with individually adjustable fiber positions, addresses the issue of the fragility and likelihood of some damage and losses during the assembly process. It is at a scale where individual fibers can be replaced if damaged.

[0069] The fibers will be adjusted in position so that all 2840 images formed by the apochromats overlap at a distance of 20 m in a common pupil 12 mm in diameter, as shown in FIG. 5. FIG. 6 shows how a telecentric lens at the common exit pupil is used to form a 67 mm long slit image at $f/20$, as needed for the spectrograph.

[0070] To preserve etendue, the hexagonal lenses will be sized to subtend a solid angle equal to that of the circular $f/3.5$ beam entering the fibers at each telescope. Accounting for the fractional area of the beam not inscribed by a hexagon and also for the small focal ratio degradation of the $f/3.5$ beam, we project a total loss of ~ 15%.

[0071] 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 18 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.

EXAMPLE HARDWARE DEVELOPMENT

[0072] We report in this section on the design, lab development and tests of some key LFAST elements.

Toward mass production of 0.76 m spherical mirrors

[0073] 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.

[0074] 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 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 1000 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.

[0075] 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.

FIG. 7A shows a contour map of the slumped glass disc, as a departure from the ideal spherical surface, with contours at 5 μm . The rms error is 5.6 μm .

[0076] A second, stiffer mandrel has now been made to a higher accuracy and in addition polished, as shown in FIG. 7B. A sequence of 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.

[0077] Tests of optical finishing of the first slumped disc have begun, using the 36" polishing machine shown in FIG. 8. Here the disc is being stroked over a convex lap with Trizact pads on pitch. It took about 10 hours to remove the errors of FIG. 7A. 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.

[0078] For optical finishing of 3,000 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.

Servo control of mirror figure and image quality

[0079] The LFAST telescopes will 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 their being made of zero expansion material with a thickness 1/10 of the diameter.

[0080] In our case, the thin, rapidly replicated mirrors described above, lacking such passive stability, will incorporate active control to ensure high quality imaging, as for big mirrors. But in order to minimize the additional cost, we have developed a different system for thermal shape actuation, using 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.

[0081] FIG. 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 will be used. 24 will be located around the circumference of the mirror, configured 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, used to induce controlled astigmatism, trefoil and similar bending modes. Control of additional modes is obtained with the aid of another 108 of these 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.

[0082] A first test of this type of thermal shape actuation has been made using an 8" spherical mirror of BK7 glass equipped with 15 TECs, attached with copper sheet sections using thermally conductive adhesive, as shown in FIGS. 10A and 10B. FIG. 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 was within 10% of that calculated using an ANSYS finite element model.

[0083] 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 FIG. 9. The superposition of these functions to optimize individual Zernicke polynomials has been calculated, and hence the voltages and powers to be applied to each TEC for each polynomial. FIG. 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.

[0084] Accordingly, FIGS. 8 and 9 show an example of a thermally active mirror assembly 100 according to an embodiment of the current invention. The thermally active mirror assembly 100 includes a mirror formed from a glass substrate 102 with substantially uniform

thickness having a front surface and a back surface in which the front surface is a specular surface. The thermally active mirror assembly 100 further includes a plurality of thermoelectric devices (TECs) 104 arranged to be in thermal contact with the mirror 102 at a corresponding plurality of positions of the back surface of the mirror 102. One of the plurality of TECs 104 is labeled 106 as an example. The remaining plurality of TECs 104 are not labeled in FIG. 9 for clarity. The thermally active mirror assembly 100 also includes a plurality of heat sinks 108 thermally connected to the plurality of TECs 104 to transfer heat by convection to and from surrounding air. One of the plurality of heat sinks 108 is labeled 110 while the remaining heats sinks of the plurality of heats sinks 108 are not labeled for clarity. The thermally active mirror assembly 100 further includes an electronic control system electrically connected to each of the plurality of thermoelectric devices 104 (not visible in FIG. 9). The electronic control system is configured to control selective heating and cooling of glass portions of the mirror 102 in thermal contact with each of the plurality of thermoelectric devices 104 to thereby control changes in shape of the mirror 102 by local thermal expansion or contraction.

[0085] The mirror 102 is formed from a glass disc substrate with approximately uniform thickness that is polished to a specular finish with the desired shape on said front surface. The term “desired” shape refers to its optical properties such as, but not limited to, a spherical or parabolic reflecting surface, for example. The desired shape is one close enough to the ideal optical design shape so that it can be corrected by controlled patterns of bending achievable with TEC actuation.

[0086] The plurality of thermoelectric devices 104 includes a ring of Peltier thermoelectric devices (TECs) set around a perimeter of the glass disc, each TEC being attached thereto with sections of bent copper sheet (see FIGS. 10A and 10B) and thermally conductive adhesive to create a closed conduction path in which said TEC drives heat between its two active surfaces of the TECs, and flows it out between the front and back perimeter surfaces of the glass disc. The TECs are controlled to transfer heat through a thickness of the glass disc around a perimeter thereof to cause expansion and contraction by heating and cooling on opposite surfaces of the glass disc so as to apply bending moments around the perimeter of the glass disc. The bending moments are controlled by varying voltages applied to different TECs so as to induce controlled patterns of bending, such as astigmatism and trefoil.

[0087] In some embodiments, the electronic control system can be further calibrated by use of at least one of metrology measurements or finite element modelling to thereby control desired changes in shape of the mirror 102.

Slew Bearings and test measurements of tracking accuracy and stiffness

[0088] The 20-telescope mounts for LFAST illustrated in FIG. 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.

[0089] A microscope with CMOS camera was 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 102:1 worm gear with a stepper motor through a 100:1 gearbox. With a motor step size of 0.72° , the gear motion per step was 0.26 arcsec per step. The motor rate was run at 10 steps/sec, and the motion recorded by a video camera at 30 frames/second. FIG. 12 shows the rotation measured over a 0.3 second interval to be very smooth, with 0.06 arcsec rms error.

[0090] The same viewing system was used to measure bearing stiffness, by measuring rotation angle for a range of applied torque. The response was linear, with a torsional stiffness constant of 5 MN.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.

CONCLUSIONS AND COSTS

[0091] We have described a technical path to making LFAST, and of coupling 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; and
- Economy of scale by manufacture as thousands of identical small telescopes.

[0092] 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 method, ending with construction of a complete 20-mirror mount, with 20 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 LFAST 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 its cost, but expect it to be comparable to the BVRI part of the ANDES instrument being built for the ELT.

[0093] We can, however, estimate the cost of the installed LFAST array, and at this point our goal of around \$60 million appears realistic. For each unit telescope, the cost of all commercially produced components, when 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 will run the project and make the mirror, prime focus and fiber assemblies at the University of Arizona Tech Park, with a further 20 people at the site. Labor costs for the staff of 50 over the 3 years are projected to be \$40M. This leads to the estimated overall installed cost for the telescope and fiber array of \$60 million.

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EXAMPLE 2

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

[0094] The concept for the Large Fiber Array Spectroscopic Telescope (LFAST) (Angel et al) 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.

INTRODUCTION

[0095] 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 m². Because this concept is scalable, there is potential to increase this collecting area arbitrarily, with no more than linear cost increase.

[0096] 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 section, 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 according to an embodiment of the current invention. In this case cost and functionality are primary drivers of performance.

DESIGN REQUIREMENTS CONSIDERATIONS

[0097] 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 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; and
6. The design must provide commercially loose tolerances to reduce cost of optomechanics and lens manufacturing at scale.

[0098] 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 8×8 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 8×8 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.

OPTICAL DESIGN

[0099] 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.

General Design Procedure and Aberration Correction

[00100] 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 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. (FIGS. 13 and 14.) 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.

[00101] Accordingly, a telescope 201 according to an embodiment of the current invention is illustrated in FIG. 13 with parameters for one possible embodiment presented in the table of FIG. 14. The telescope 201 is one of an array of identical telescopes on mount 200. It includes a primary mirror 202 having a substantially spherical reflecting surface 204. The telescope 201 also includes a compound prime focus corrector 206, which includes first 208, second 210, third 212 and fourth 214 singlet lenses, each with spherical surfaces. The telescope 200 also includes a tracking mount constructed and arranged to hold aligned said primary mirror and said compound prime focus corrector relative to each other and toward a sky target (not shown in FIG. 13; see, e.g., FIGS. 2 and 3). The telescope 201 also includes a camera 216 arranged to receive an image formed by said primary mirror and said compound prime focus corrector. The telescope 200 also includes a housing 218 constructed and arranged to hold the first, second and third singlet lenses (208, 210, 212) fixed in position, axisymmetric about an axis of said compound prime focus corrector. The telescope 201 also includes a position control

assembly 220 constructed and arranged to control a lateral position of the fourth singlet lens 214 relative to the axis and the housing 218; a positioning assembly 222 constructed and arranged to adjust a position of a center of curvature of the primary mirror 202 relative to the axis of the compound prime focus corrector 206; and an electronic control system 224 configured to actively control an orientation of the telescope mount 200, the center of curvature position and the lateral position of the fourth lens 214. The telescope 201, with all four of said first, second, third and fourth singlet lenses (208, 210, 212, 214) and the center of curvature of the primary mirror 202 being coaxial, in the absence of atmospheric aberrations, has images that are corrected for spherical and chromatic aberrations. When viewing stars through the atmosphere away from the zenith, the telescope 201 corrects for atmospheric chromatic dispersion by driving correlated lateral motions away from the axis, using the mechanisms to move the fourth singlet lens 214 and the center of curvature of the primary mirror 202 under control of said electronic control system. When a star image suffers motion caused by vibrations of the tracking mount 200 or by atmospheric turbulence, detected by the camera, motions of the fourth singlet lens 214 under servo control by the electronic control system 224 is configured to be able to induce equal and opposite motions to stabilize the star image without disrupting image quality.

Atmospheric Dispersion Correction

[00102] 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 $36.7 \mu\text{m}$, 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 $340 \mu\text{m}$, 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. 15 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.

[00103] For example, at 50 degrees from Zenith, the atmospheric dispersion is significant, 2.35 arcseconds (shown in FIG. 15). 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. 16.

Image Motion Correction

[00104] 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 $100 \mu\text{m}$ of lens lateral translation, the image shifts by $34 \mu\text{m}$. 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 $25 \mu\text{m}$, 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 $73\ \mu\text{m}$ lateral shift in L4 will move the image $25\ \mu\text{m}$. 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. 17).

Relay Optics

[00105] 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 8×8 arcminute field to a CMOS camera 216, as shown in FIG. 13. The relay consists of a singlet and doublet collimator, a fold mirror, and the same singlet and doublet reversed.

[00106] This focal plane mirror is completely silvered, except for the $17\ \mu\text{m}$ core. The target image thus appears with a dark $17\ \mu\text{m}$ obscuration at the guide camera, giving direct feedback on its coupling into the collecting fiber. FIG. 18 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.

DESIGN TOLERANCES

[00107] 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^{9,30} to each component, running 30 Monte Carlo analyses, and maximizing the diffraction encircled energy within a $17\ \mu\text{m}$ 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 $17\ \mu\text{m}$ fiber with

perfect transmission and no surface reflection), with the worst performer at 70%. FIG. 19 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.

[00108] Note from FIG. 19 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.

DISCUSSION: SPHERICAL VS. ASPHERICAL PRIMARY MIRROR

[00109] 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.

[00110] On its own, an aspherical mirror clearly has better on-axis image quality, (FIG. 20). 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.

[00111] 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 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.

CONCLUSION

[00112] 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.

[00113] REFERENCES FOR EXAMPLE 2

- [1] van Belle, G. T., Meinel, A. B., and Meinel, M. P., "The scaling relationship between telescope cost and aperture size for very large telescopes," in [*Ground-based telescopes*], **5489**, 563–570, Spie (2004).

- [2] Angel, J., Adams, M., Boroson, T., and Moore, R., “A very large optical telescope array linked with fused silica fibers,” *The Astrophysical Journal* **218**, 776–782 (1977).
- [3] Jones, D. J. and James, W. E., “Prime focus correctors for the spherical mirror,” *Applied optics* **31**(22), 4384–4388 (1992).
- [4] Bahrami, M. and Goncharov, A. V., “The achromatic design of an atmospheric dispersion corrector for extremely large telescopes,” *Optics express* **19**(18), 17099–17113 (2011).
- [5] Saunders, W., Gillingham, P., Smith, G., Kent, S., and Doel, P., “Prime focus wide-field corrector designs with lossless atmospheric dispersion correction,” in [*Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation*], **9151**, 519–528, SPIE (2014).
- [6] Wynne, C., “A new form of atmospheric dispersion corrector,” *Monthly Notices of the Royal Astronomical Society* **262**(3), 741–748 (1993).
- [7] Seidelmann, P., [*Refraction-Numerical Integration*], vol. 3 (1992).
- [8] Hohenkerk, C. and Sinclair, A., “Nao technical note 63,” *HM Nautical Almanac Office* (1985).
- [9] Schwertz, K., [*Field guide to optomechanical design and analysis*] (2012).
- [10] Nelson, J. D., Youngworth, R. N., and Aikens, D. M., “The cost of tolerancing,” in [*Optical System Alignment, Tolerancing, and Verification III*], **7433**, 130–141, SPIE (2009).

[00114] The embodiments illustrated and discussed in this specification are intended only to teach those skilled in the art how to make and use the invention. In describing embodiments of the invention, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. The above-described embodiments of the invention may be modified or varied, without departing from the invention, as appreciated by those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the claims and their equivalents, the invention may be practiced otherwise than as specifically described.

We claim:

1. A method of producing a plurality of optical components, each having a substantially equivalent optical surface, comprising:

providing a substrate of optical material, said substrate having an optically smooth surface;

providing a mandrel having an optically smooth surface of a shape that is an inverse of a shape to be imparted to said optically smooth surface of said substrate;

coating said optically smooth surface of said mandrel with a mold release material;

changing a temperature of at least one of said substrate and said mandrel to be at a substantially same temperature;

disposing said substrate on said mandrel such that said optically smooth surface of said substrate is on said optically smooth surface of said mandrel that is coated with said mold release material;

heating said mandrel and said substrate together to soften said substrate to conform said optically smooth surface of said substrate to said shape of said mandrel;

cooling said mandrel and said substrate together until said substrate is sufficiently rigid to maintain said optically smooth surface of said substrate as conformed to said shape of said mandrel;

removing said substrate from said mandrel to provide a first optical component of said plurality of optical components;

providing at least one additional substrate of optical material, each having an optically smooth surface; and

repeating at least said changing a temperature, disposing, heating and removing for each at least one additional substrate to thereby produce said plurality of optical components.

2. The method of producing said plurality of optical components according to claim 1, further comprising:

measuring a profile of said optically smooth surface of said substrate as conformed to said shape of said mandrel for at least said first optical component of said plurality of optical components using optical metrology;

comparing said measured profile to a planned profile; and

modifying a shape of said mandrel to reduce discrepancies of said measured profile to said planned profile.

3. The method of producing said plurality of optical components according to claim 1 or 2, wherein said substrate is a float-glass substrate.

4. The method of producing said plurality of optical components according to claim 3, wherein said float-glass substrate comprises at least one of Schott Borofloat or Schott N-BK7 type optical glass or equivalent.

5. The method of producing said plurality of optical components according to any one of claims 1 to 4, wherein said mandrel is at least one of stainless steel, silicon carbide, fused silica or ULE (Corning Ultra-Low Expansion glass).

6. The method of producing said plurality of optical components according to any one of claims 1 to 5, wherein said mold release is boron nitride.

7. The method of producing said plurality of optical components according to any one of claims 1 to 6, further comprising heating a plurality of substrates in a tunnel kiln to a temperature substantially equal to a temperature of said mandrel when said mandrel is ready to receive one of said plurality of substrates.

8. A thermally active mirror assembly, comprising:

a mirror formed from a glass substrate with substantially uniform thickness having a front surface and a back surface, said front surface having a specular surface;

a plurality of thermoelectric devices (TECs) arranged to be in thermal contact with said mirror at a corresponding plurality of positions of said back surface of said mirror;

a plurality of heat sinks thermally connected to said plurality of TECs to transfer heat by convection to and from surrounding air; and

an electronic control system electrically connected to each of said plurality of thermoelectric devices,

wherein said electronic control system is configured to control selective heating and cooling of glass portions of said mirror in thermal contact with each of said plurality of thermoelectric devices to thereby control changes in shape of said mirror by local thermal expansion or contraction.

9. The thermally active mirror assembly according to claim 8, wherein said mirror is formed from a glass disc substrate with approximately uniform thickness that is polished to a specular finish with the desired shape on said front surface.

10. The thermally active mirror assembly according to claim 9, wherein said plurality of thermoelectric devices includes a ring of Peltier thermoelectric devices (TECs) set around a perimeter of said glass disc, each TEC being attached thereto with sections of

bent copper sheet and thermally conductive adhesive to create a closed conduction path in which said TEC drives heat between its two active surfaces of said TECs, and flows it out between the front and back perimeter surfaces of said glass disc,

wherein said TECs are controlled to transfer heat through a thickness of said glass disc around a perimeter thereof to cause expansion and contraction by heating and cooling on opposite surfaces of said glass disc so as to apply bending moments around said perimeter of said glass disc, and

wherein said bending moments are controlled by varying voltages applied to different TECs so as to induce controlled patterns of bending, such as astigmatism and trefoil.

11. The thermally active mirror assembly according to claim 10, wherein said electronic control system is further calibrated by use of at least one of metrology measurements or finite element modelling to thereby control desired changes in shape of said mirror.

12. A telescope comprising:

a primary mirror having a substantially spherical reflecting surface;

a compound prime focus corrector comprising first, second, third and fourth singlet lenses, each with spherical surfaces;

a tracking mount constructed and arranged to hold aligned said primary mirror and said compound prime focus corrector relative to each other and toward a sky target;

a camera arranged to receive an image formed by said primary mirror and said compound prime focus corrector;

a housing constructed and arranged to hold the first, second and third singlet lenses fixed in position, axisymmetric about an axis of said compound prime focus corrector;

a position control assembly constructed and arranged to control a lateral position of the fourth singlet lens relative to said axis and said housing;

a positioning assembly constructed and arranged to adjust a position of a center of curvature of the primary mirror relative to said axis of said compound prime focus corrector; and

an electronic control system configured to actively control an orientation of said telescope, said center of curvature position and said lateral position of said fourth lens;

wherein said telescope, with all four of said first, second, third and fourth singlet lenses and said center of curvature of said primary mirror being coaxial, in the absence of atmospheric aberrations, has images that are corrected for spherical and chromatic aberrations,

wherein, when viewing stars through the atmosphere away from the zenith, said telescope corrects for atmospheric chromatic dispersion by driving correlated lateral motions away from the axis, using said mechanisms to move said fourth singlet lens and said center of curvature of said primary mirror under control of said electronic control system, and

wherein, when a star image suffers motion caused by vibrations of said tracking mount or by atmospheric turbulence, detected by said camera, motions of said fourth singlet lens under servo control by said electronic control system is configured to be able to induce equal and opposite motions to stabilize said star image without disrupting image quality.

13. An optical system comprising a plurality of optical components produce according to the method of any one of claims 1-7.

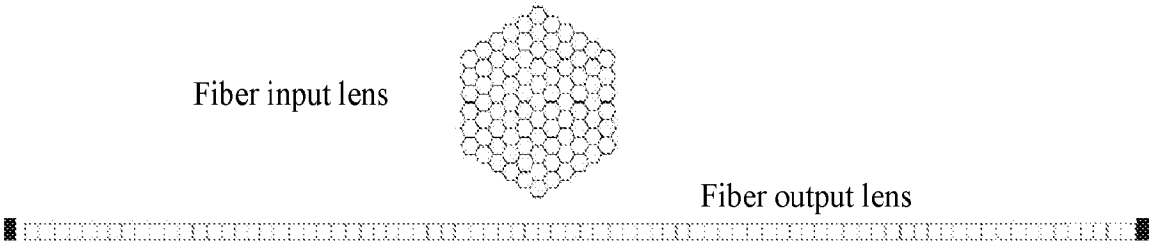


FIG. 1

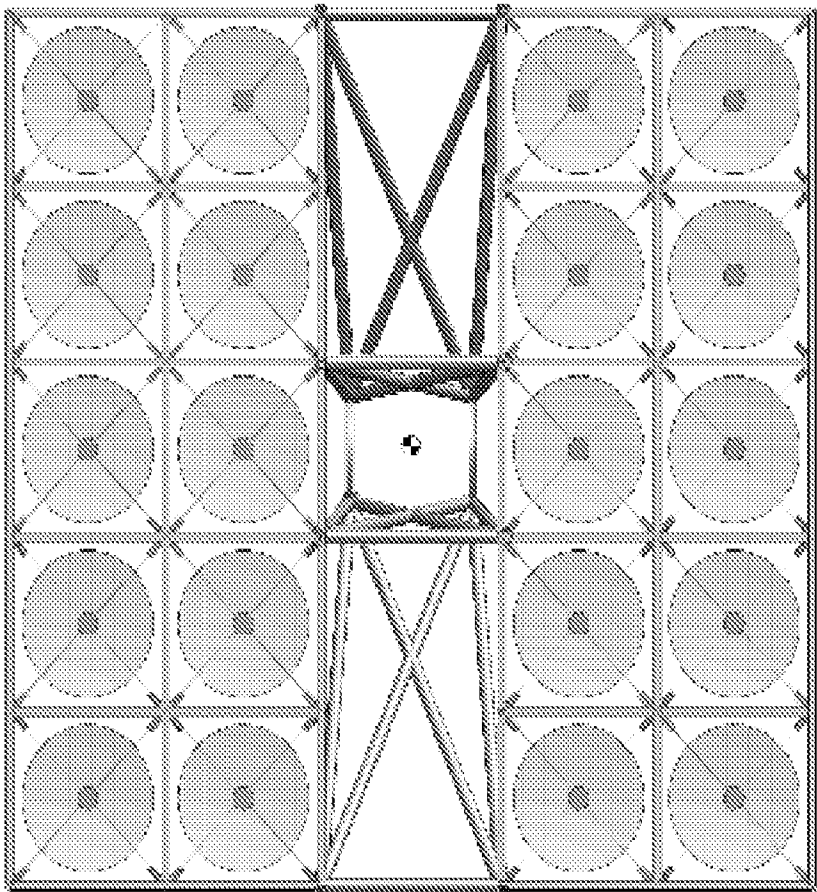


FIG. 2

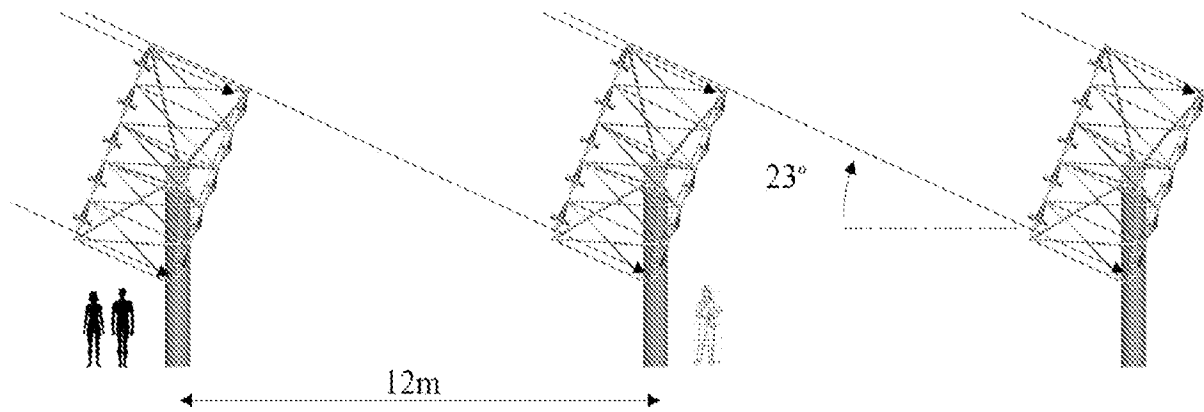


FIG. 3

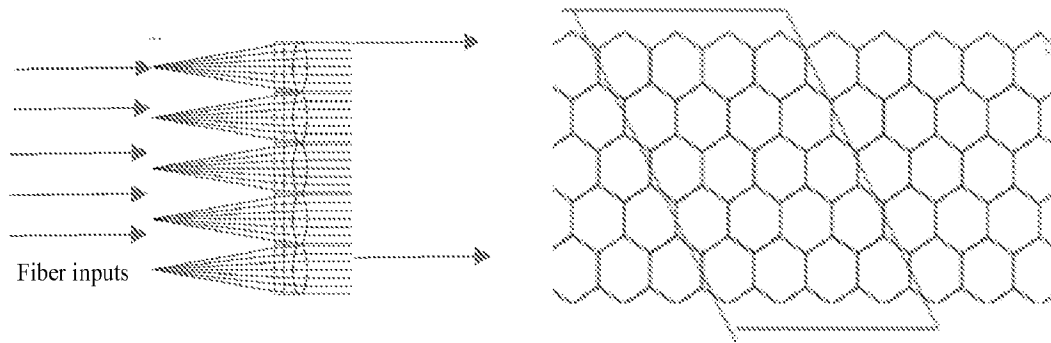


FIG. 4A

FIG. 4B

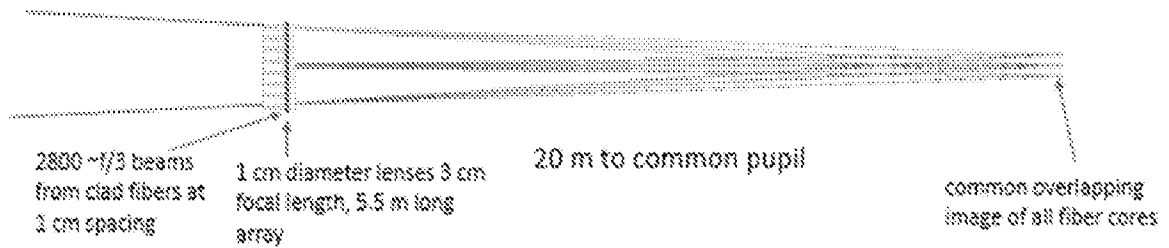


FIG. 5

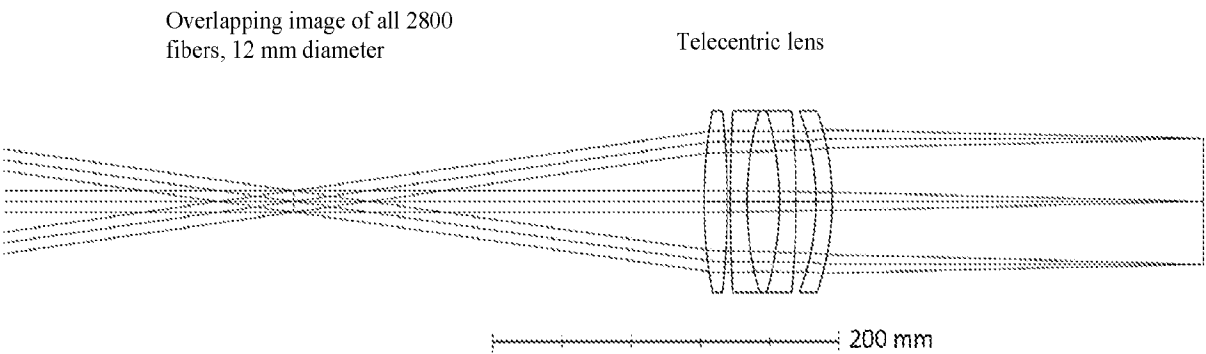


FIG. 6

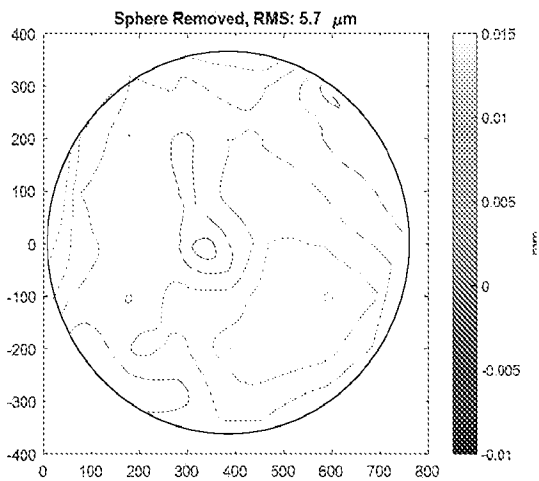


FIG. 7A

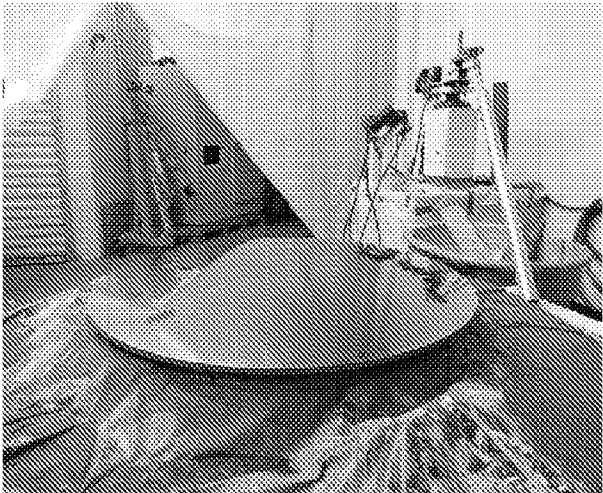
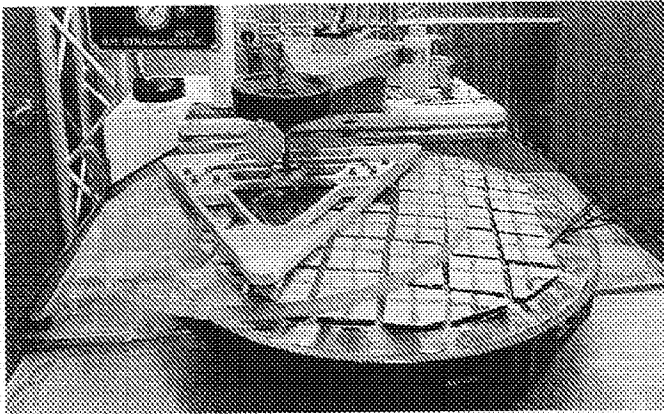


FIG. 7B



100

FIG. 8

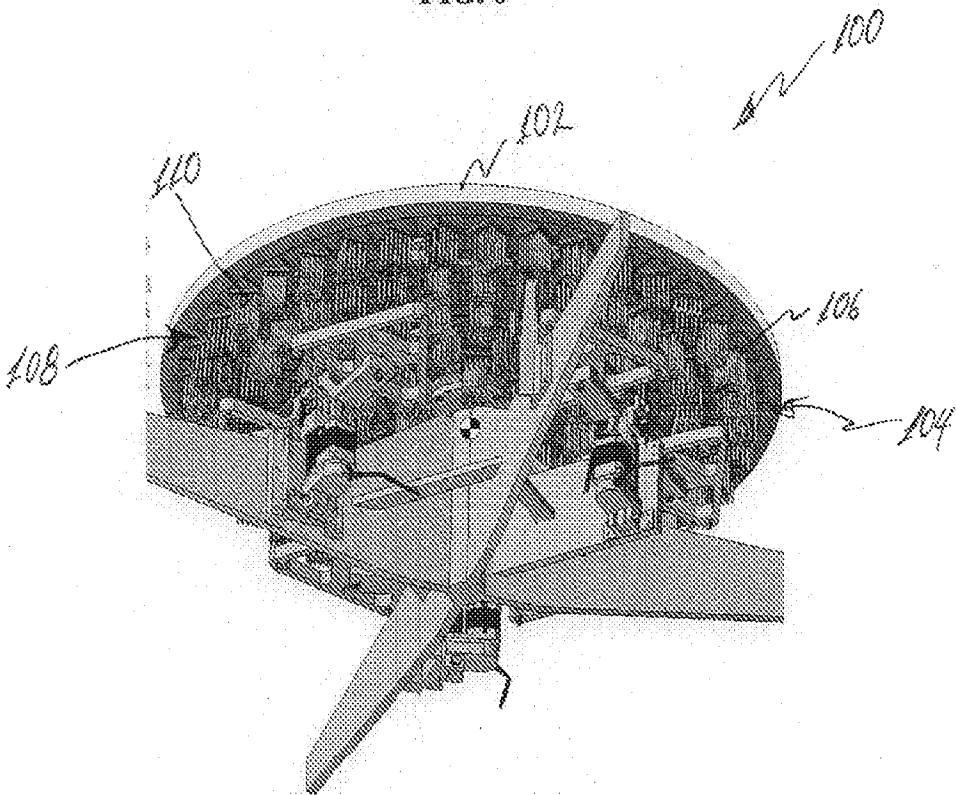


FIG. 9

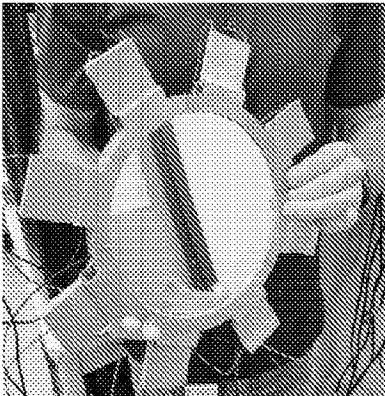


FIG. 10A

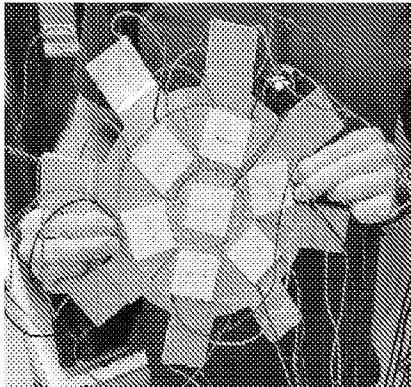


FIG. 10B

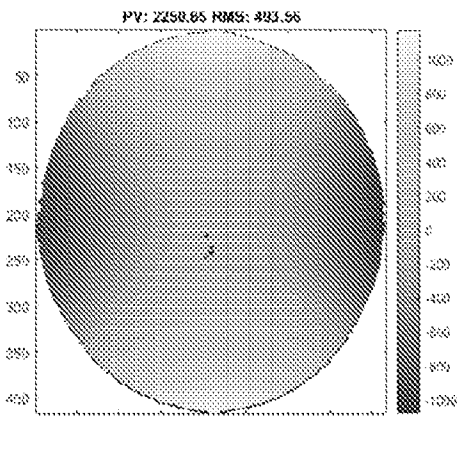


FIG. 11A

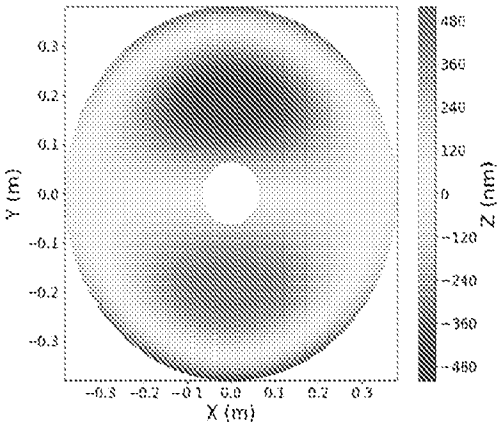


FIG. 11B

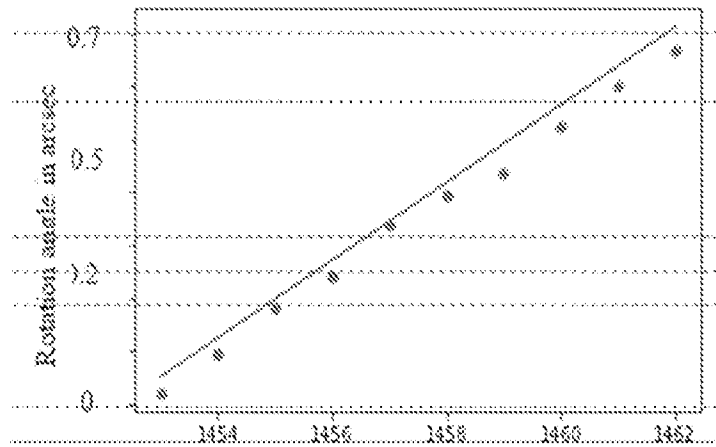


FIG. 12

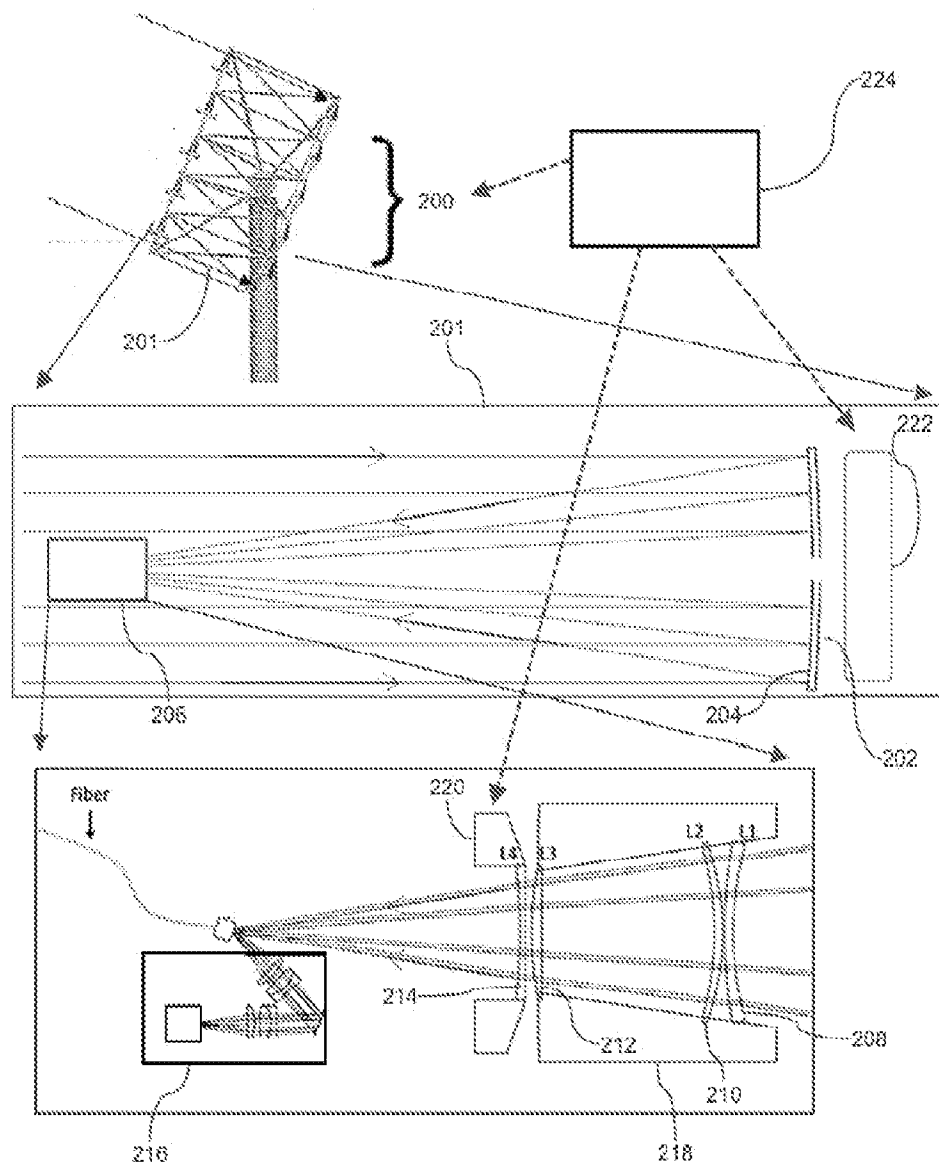


FIG. 13

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				
Prime Focus Corrector			Singlet	R1	Infinity	
L1	R1	168.97 mm		R2	21.66 mm	
	R2	284.47 mm	Thickness	4.0 mm		
	Thickness	5.0 mm	Substrate	N-BK7		
	Substrate	N-BK7	Aperture	19.0 mm		
	Aperture	101.6 mm	Doublet	R1	37.47 mm	
	Spacing to L2	1.0 mm		R2	15.37 mm	
	L2	R1		138.75 mm	R3	896.37 mm
R2		166.23 mm		Thickness 1	7.0 mm	
Thickness		5.0 mm		Thickness 2	3.0 mm	
Substrate		F2	Substrate 1	N-BK7		
Aperture		101.6 mm	Substrate 2	F2		
Spacing to L3		101.43 mm	Aperture	19.0 mm		
L3	R1	Infinity	Fold Mirror	Distance to Fold Mirror	25.0 mm	
	R2	181.37 mm		Fold Mirror	Fold Angle	25 degrees
	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				

FIG. 14

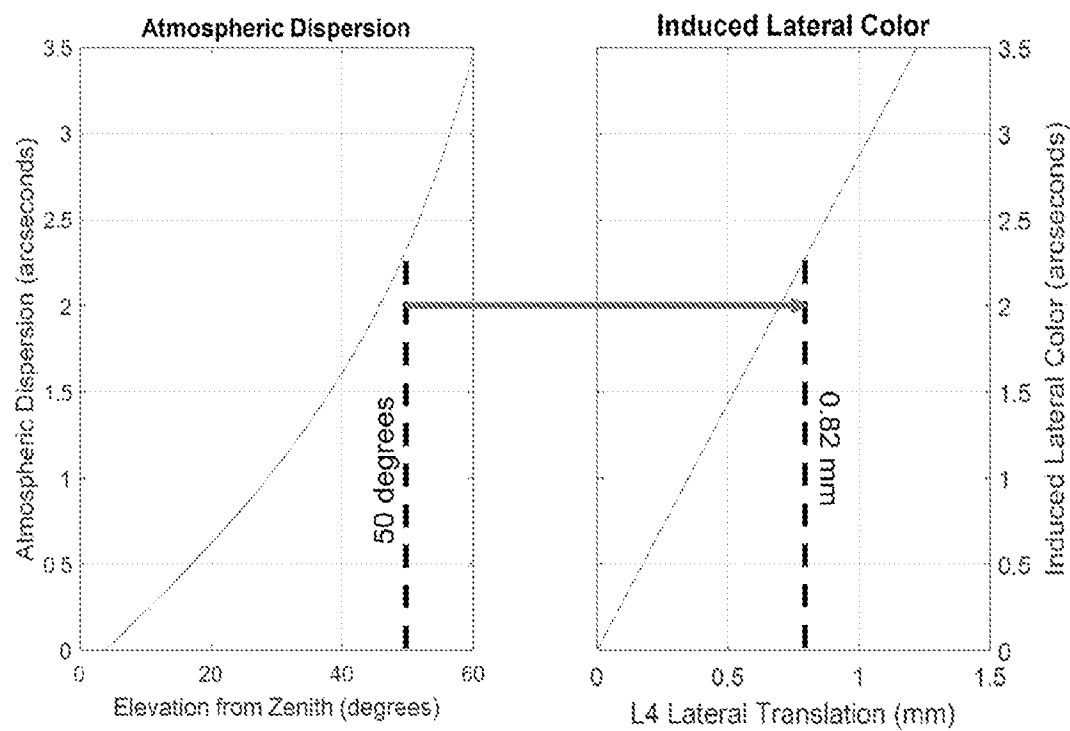


FIG. 15

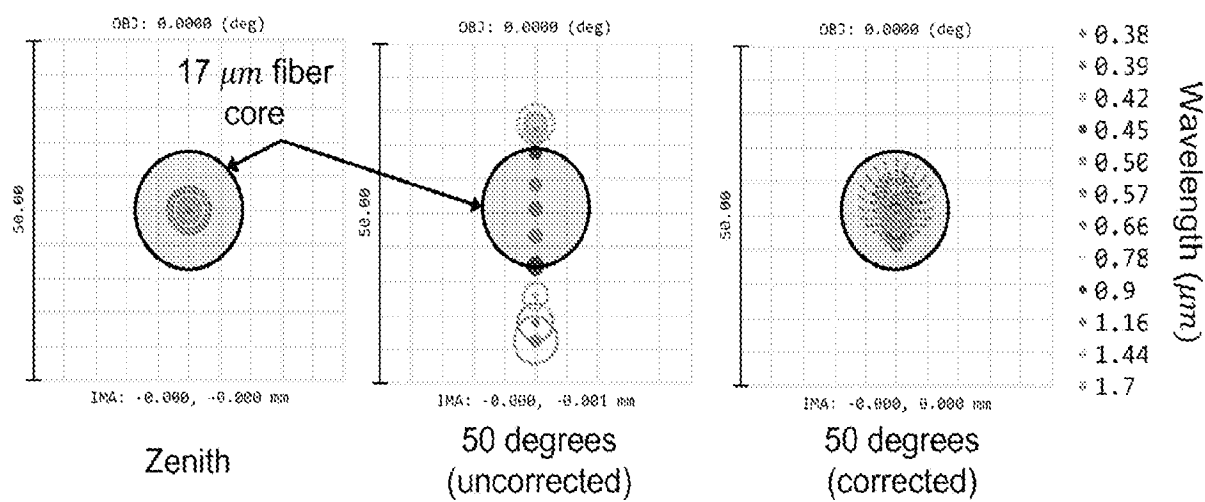


FIG. 16

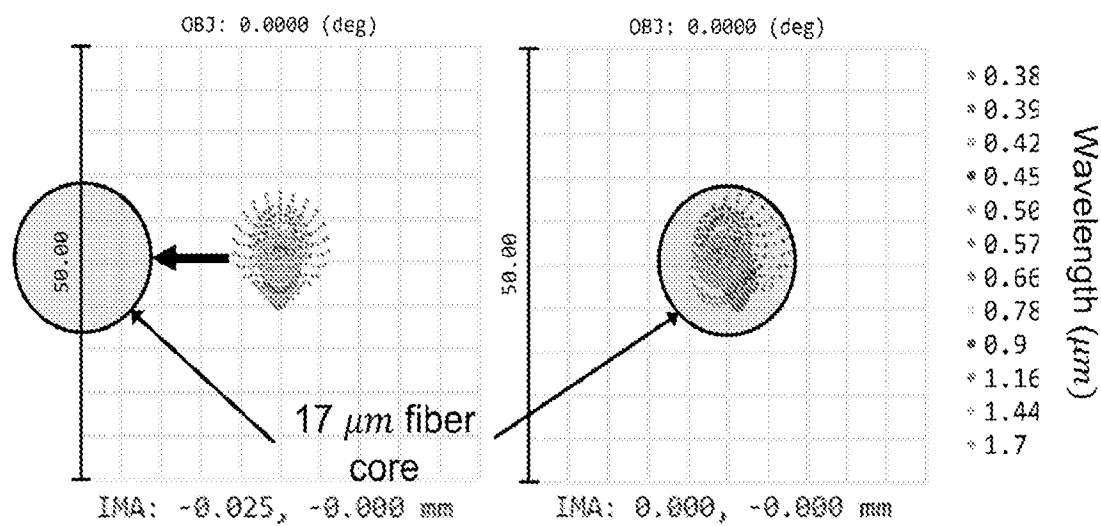


FIG. 17

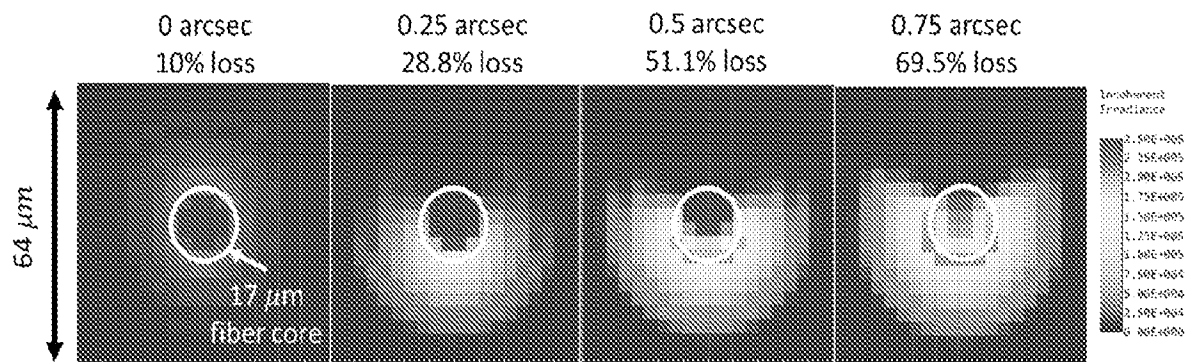


FIG. 18

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

FIG. 19

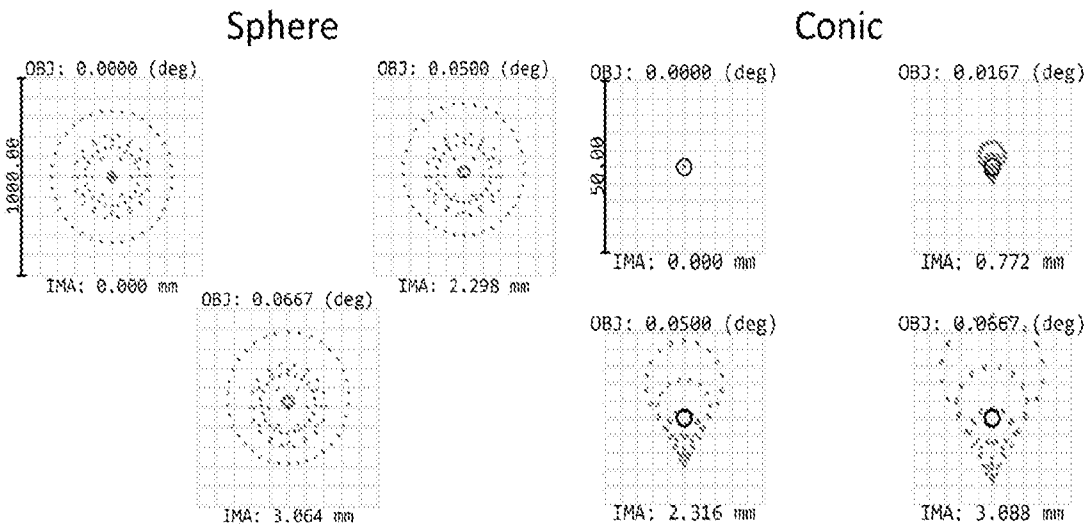


FIG. 20