Large Aperture Mirror Array (LAMA) – project overview

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ABSTRACT

The Large Aperture Mirror Array (LAMA) is a novel concept for an extremely-large telescope. In the current design, light from 66 individual 6.15-meter telescopes would be coherently combined at a common focus. This would give the array the light-gathering power of a 50-meter telescope and the resolving power of a 70-meter telescope. The optics and beam combiner preserve the sine condition, providing interferometric imaging over an extended field of view. The concept is unique in that pointing and tracking is accomplished entirely by secondary optical systems: the primary mirrors are fixed in both position and orientation. This allows rotating liquid-metal primary mirrors to be employed, substantially reducing the project cost. At a 30-degree latitude, the tracking system provides access to approximately 2500 square degrees (6% of the sky) and allows individual fields to be observed for up to 35 min per night. The telescope would be initially equipped with a multi-band optical/infrared imaging camera and a high-resolution optical spectrograph.

Keywords: telescopes, interferometers, adaptive optics, liquid mirrors

1. INTRODUCTION

The next generation of ground-based optical telescopes will have apertures of 20 meters or more, and resolution at the diffraction limit. These telescopes will provide unprecedented scientific opportunities. Their development will provide significant technical challenges. Historical scaling laws for costs of conventional telescopes predict that the costs of such facilities will be truly monumental. These new telescopes will have to break the scaling laws by means of technological breakthroughs and innovative design.

The LAMA project offers the potential of providing the performance of a very large telescope at a cost that is within reach of a consortium of universities and research institutions. LAMA will achieve this cost saving in several ways. The cost of conventional telescopes scales roughly as the 2.6 power of the diameter (i.e. roughly midway between the scaling of surface area and mass). Because LAMA's aperture will be distributed over many individual telescopes, the cost is roughly proportional to the number of elements and therefore grows linearly with collecting area, or as the 2.0 power of the equivalent diameter. This corresponds to a cost savings of about a factor of four for the baseline LAMA design, if the conventional scaling laws remain valid for extremely-large telescopes. Also, the telescopes in an array are less tall than a single large telescope would be, so the enclosure is less expensive. A major cost saving comes from the use of rotating liquid-metal primary mirrors. These mirrors can provide a performance comparable to that of conventional glass mirrors, at about 5% of the cost. Also, because the liquid primary mirrors do not tilt, the telescope structure can be simpler and much less massive.

These savings in cost come at the expense of reduced capability. Specifically, LAMA will only observe near the zenith. The LAMA optical system allows the telescope to achieve diffraction-limited image quality up to a zenith angle of 4 degrees, so it can observe only objects that lie in an 8-degree wide strip of sky centered at declination equal to the observatory latitude. At a latitude of 30 degrees, this area contains approximately 2500 square degrees – about 6% of the sky. The implications of this have been considered in detail by the LAMA team, and we have concluded that this restriction does not rule out many of the most interesting science programs that we can foresee. Science programs for the

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LAMA telescope, and tradeoffs associated with the restricted pointing and tracking capability, are described in some detail in a companion paper in these proceedings[1].

2. CONCEPTUAL DESIGN

Our concept for the LAMA telescope is a set of individual telescopes arranged in a close-packed hexagonal array. Light collected by each telescope is collimated and relayed to a central room. Here the individual light beams are focused to form a common image by means of a Fizeau beam combiner. Each telescope would be provided with an adaptive optics system that would remove phase distortion in the beam to the diffraction limit. Beams from the individual telescopes would be combined either incoherently or coherently. In incoherent mode, the resulting image would have an angular resolution $\theta \sim \lambda/D$ corresponding to the diffraction limit of the individual telescopes (having aperture diameter D) but with an image intensity corresponding to the light collecting area A of the entire array. Coherent beam recombination would provide angular resolution $\theta \sim \lambda/d$ corresponding to the diffraction limit of the array (having outside diameter d). This requires equalization of the optical path lengths for all beams and phase tracking systems to equalize the phases of all beams to within a few hundredths of a radian.

A unique feature of the LAMA telescope is the use of low-cost liquid primary mirrors. The optical axis of a liquid mirror corresponds to the rotation axis, which must be vertical (with the possible exception of tilted viscous liquid mirrors[2]). Therefore, the LAMA primary mirrors cannot be tilted. Pointing and tracking is accomplished by secondary optical elements, which move to acquire and follow targeted fields, while at the same time correcting optical aberrations. Our preliminary tracking-optics design gives diffraction-limited performance for zenith angles up to 4 degrees. This allows the LAMA telescope to access approximately 6% of the entire sky (~2400 square degrees), and track fields for up to 30 min each night, if it is located at moderate latitude.

In imaging mode, the LAMA telescope will observe fields surrounding stars, of approximately 14^{th} magnitude, that will serve as reference sources for the adaptive and phase tracking systems. There are several hundred thousand suitable stars within the accessible area of sky.

The LAMA telescope would also have the capability for high-resolution optical spectroscopy. This mode would be used, for example, to obtain spectra of the Lyman-α forest in high-redshift quasars, absorption spectra of the atmospheres of planets transiting in front of their host stars, etc. In this mode, light from individual telescopes would be transported by optical fibers to a number of fixed echelle spectrographs. As the targets are relatively bright, and spatially-resolved spectroscopy is not required, low-order adaptive correction (tip-tilt, focus) is all that is required. This will be accomplished by diverting a few percent of the light from the target star or quasar to the wavefront sensors of the individual telescopes.

3. ARRAY CONFIGURATION

There are many possible configurations for the array that meet the requirements of light collecting area and resolution. Obviously, one can have a small number of large apertures, or a large number of small apertures. For simplicity and to reduce costs, we require that all individual telescopes in the array be identical as far as possible, and therefore have the same aperture size. The resolution and sensitivity of a coherent array is a function of the array configuration (i.e. entrance pupil geometry).

3.1. Sensitivity

For a given total light collecting area, large separations between apertures give higher resolution but lower sensitivity to faint point sources (when fluctuations in the intensity of background or foreground light provide the dominant source of noise). As is well known, the point-spread function (PSF) of a coherent array consists of a central core surrounded by side-lobes or "satellite images". To a good approximation, the fraction of the total light that falls in the central core is equal to the filling factor of the array (the ratio of light collecting area to the total geometrical area within a circular area bounding the array)[3]. However, as has been emphasized by Angel[4], one should make use of not just the core but also the sidelobes. The most efficient way to do this is to weight each pixel in the image by the PSF. This technique (called matched filtering or PSF fitting) produces the maximum signal-to-noise ratio for the detection and measurement of faint point sources against a uniform noise background. In this case, the sensitivity of the telescope (defined here as the reciprocal of the time required to reach a given signal to noise ratio) is proportional to the integral of the *square* of the PSF,

$$S \sim A \int I^2(x,y)\,dxdy$$

where A is the total light-collecting area and, $I(x,y)$ is the PSF, normalized so that $I(0,0)=1$. By Parseval's theorem, this equation may be written in terms of the modulation transfer function (MTF) $\tau(u,\nu)$, which is proportional to the Fourier transform of the PSF,

$$S \sim A^{-1} \int |\tau(u,\nu)|^2\,dud\nu.$$

From Fourier optics theory, the MTF is the autocorrelation of the pupil function $P(u,\nu)$, which takes the value 1 inside the aperture of any telescope in the array and 0 elsewhere. Therefore the sensitivity is proportional to the integral of the square of the autocorrelation of the array pupil function. For a circular aperture of diameter D, the MTF is a circularly-symmetric cone-shaped function, having a height of $(\pi D/4)^2$ and a base diameter of $2D$. The integral of the square of this function is therefore proportional to D^6. For an array of such apertures, the MTF is the sum of many such cones – one of unit amplitude located at the tip of each baseline vector in the u-ν plane, and one of amplitude N at the origin.

If the array is sparse (widely separated apertures) and non-redundant (all baselines differ by more than $2D$) then there is no overlap of these cones. As there are N(N-1) baselines in an N-element array, the ratio of sensitivity of such an array, compared to a single equivalent-area aperture of diameter $N^{1/2}D$ will be

$$Q = \frac{N^2 + N(N-1)}{N^3} = \frac{2N-1}{N^2}.$$

This shows that sparse, non-redundant imaging arrays have a sensitivity loss, of order N^{-1} when N is large, compared to an equivalent-area filled aperture telescope. Note that, for a sparse array, when the entire PSF is used instead of just the core, the sensitivity depends only on the number of elements and not on the filling factor.

The situation is improved if the baselines have a high degree of redundancy or if the separations between apertures is made less than $2D$. This causes the cones to overlap and, by virtue of the square in the integrand, results in a boost in sensitivity. For dense highly-redundant arrays, the sensitivity approaches that of a filled-aperture telescope. (These results, obtained by analysis in the Fourier domain, agree with those of Angel[4] whose analysis was done in real image space.)

For this reason, we have chosen to place the individual telescopes of the LAMA array as close together as is practical. A hexagonal geometry is adopted, in order to maximize redundancy and minimize separations. The final choice of aperture size vs. number of elements has not yet been made. It will be driven in part by practical considerations such as costs and available sizes of air bearings, adaptive mirrors, aspheric optics, etc.

For the baseline LAMA design, we have selected a configuration that employs 66 apertures, each having a clear diameter of 6.15 m. The array geometry is illustrated in Figure 1. The elements are placed on a hexagonal lattice, filling an annular region with outer diameter of 100 m and inner diameter of 20 m. The center-to-center separation of array elements is 7.5 m. The sensitivity of this configuration, compared to a

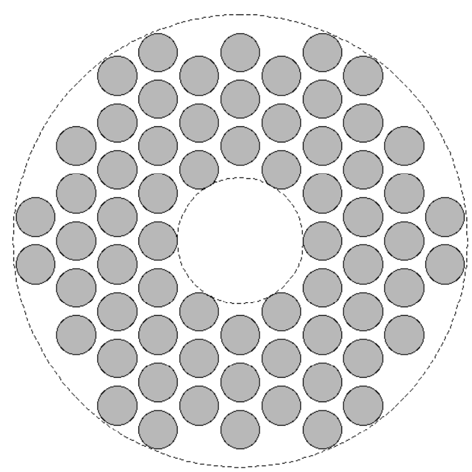

Figure 1. Array geometry for the baseline LAMA design. 66 apertures, of diameter 6.15 m, are deployed in an annular region of outer diameter 70 m and inner diameter 20 m.

single-aperture 50-meter telescope is 0.512, which makes LAMA equal in sensitivity to a filled-aperture telescope of diameter 35.8 m.

An advantage of the 6.15 m aperture size is that it is well-matched to dynamic range and actuator density of available piezoelectric deformable mirrors. In a simple adaptive optics system, the deformable mirror must remove atmospheric phase errors of higher order than wavefront tilt (which is removed by a separate tip-tilt mirror). For a Kolmogorov turbulence spectrum, the residual RMS atmospheric phase error over a diameter D, after removal of tip-tilt, is $\sigma_{\phi} = 0.94\left(D / r_0\right)^{5/6}$. The actuator stroke needed to correct this (at the 5σ level) is approximately $\Delta z = 0.37\lambda\left(D / r_0\right)^{5/6}$, which is independent of wavelength since $r_0 \propto \lambda^{6/5}$. If the required phase correction exceeds the stroke of the actuator, phase coherence across the pupil will be momentarily lost. In normal AO imaging this means that image quality is momentarily lost, then restored after the atmospheric excursion. For interferometry, the situation is more critical. Loss of phase coherence can lead to loss fringes in the phase tracking system, resulting in loss of coherence in the entire array. Phase tracking can only be re-established by scanning the piston mirrors until the fringes are found, a process that could require some time. Therefore it is important that the deformable mirrors have sufficient dynamical range. The maximum stroke that can be obtained with commercially-available piezoelectric deformable mirrors, of which we are aware, is 8 um. If we adopt a value of $r_0 \approx 0.1$ m at $\lambda = 0.5$ um (the 90-percentile value recorded at the WHT site at La Palma [5]), we find that $D < 9.2$ m.

The number of actuators required for high-Strehl AO correction is of order $N_A = \left(D / r_0\right)^2$. At present, deformable mirrors have been made with ~ 10^3 actuators. This limits the telescope diameter to $D \sim 30 r_0$ if full AO performance is to be achieved. The 6.15 m diameter allows high-Strehl AO performance to be achieved for r_0 as small as 0.20 m, which is found 90% of the time at a wavelength of 0.9 um at La Palma.

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4. OPTICS

The optical design is perhaps the most challenging aspect of the LAMA telescope. Not only do the individual elements have to point and track, without moving their primary mirrors, but also, the beams from all telescopes need to be brought to a single common focus. In coherent mode, the optical pathlengths must be equalized and the beams must all be co-phased. At the same time, we aim to do all this over an extended field of view. A complete and final optical design has not yet been achieved. Rather, progress has been made in all areas resulting in at least a conceptual design for all aspects of the system. Here we provide only an example of an optical system that can, at least in principle, achieve our requirements.

4.1. Requirements

The optical design is driven by two unique features of the LAMA concept – the need to point and track, without moving the primary mirrors, and the need to combine the light from many telescopes to provide coherent imaging over an extended field of view. The optical system is divided into two main subsystems that address these needs. The *tracking* system consists of the primary mirror and a set of "secondary" mirrors that move to acquire and follow the field, and which must correct all aberrations, to the diffraction limit. The pathlength-compensation and pupil-relay system receives light from the tracking system and relays it to the final combined focus. This system includes mirrors that move in order to equalize the optical path lengths, and mirrors that re-image the telescope entrance pupil, producing an exit pupil having the required characteristics.

In order for an interferometer to produce extended coherent images, it is necessary that differences in optical path lengths for points in the image plane that are not on the optical axis exactly compensate for differences produced by the slope of the incident wavefront coming from the corresponding field angles. A necessary and sufficient condition for this is that the array satisfy the Abbé sine condition: *the sin of the angle of incidence of every ray reaching the axial focal point must be strictly proportional to the (projected) distance from the axis of the corresponding ray in the entrance pupil*. This condition can be achieved, for example, by arranging the exit pupils of the individual telescopes on a sphere centered on the axial focal point and requiring that 1) the angle between the axis and the center of each exit pupil, measured at the focal point, is proportional to the radial distance of the center of the entrance pupil from the axis, projected on a plane perpendicular to the line of sight to an object at the center of the field of view, 2) The angular position, seen from the focal point, of any point in the exit pupil of any telescope be proportional to the radial position of the corresponding point in the telescope entrance pupil, with the same proportionality factor as above, 3) The azimuth angles of corresponding points in the entrance and exit pupils be identical. Effectively this means that the entrance pupil of the array must map homogeneously onto the exit pupil with constant magnification. There can be no significant distortion of the pupils, no pupil rotation, and the parity of the exit pupil must match that of the entrance pupil. Imaging interferometer that satisfy these requirements are said to be *Fizeau*.

The accuracy with which the Fizeau requirements are satisfied determines the field of view of the interferometer. For example, a radial distortion $\Delta r/r$ in the entrance pupil, will result in a phase error of one radian for marginal rays at a field angle $\theta \approx r\theta_0/\Delta r$, where $\theta_0 \approx \lambda/d$ is the angular resolution of the coherent array. Therefore, in order to obtain an image having, say, 10^6 resolution elements, the pupil distortion must be less than ~ 0.06%.

The complexity of the optical design problem can be illustrated by itemizing the requirements of the system. It must

- Deliver light to fixed common focus with no focal plane curvature or tilt
- Point and track within 4º of the zenith (without moving the primary mirrors)
- Have no field distortion, or variation in image scale, during tracking
- Image the pupil with negligible distortion and correct orientation and parity
- Provide optical path length variation and control over ~ 5 m during tracking
- Provide longitudinal and lateral control of the pupil position during tracking
- Allow no rotation, or change in magnification, of the pupil image during tracking
- Provide a deformable mirror at a pupil and fast tip-tilt and piston mirrors
- Employ reflecting optics only (except windows, filters)
- Minimize the number of reflections, obscuration and vignetting
- Provide diffraction-limited image quality in all configurations

To achieve these goals, we divide the optical system into several functional groups – the tracking system, the pathlength control system, and the pupil relay system. These are now discussed in turn.

4.2. Tracking system

The telescopes must point and track without moving the primary mirrors. This can in principle be achieved, in each telescope, by moving an optical relay system that traverses the focal surface of the primary mirror, much like the imaging system of the Arecibo radio telescope. A critical requirement is that the optical system not only remove the off-axis aberrations of the primary mirror, but that it also be free from distortion and focal-plane tilt. Because LAMA will take extended exposures, up to ~ 30 min, no differential image motion can be tolerated.

These requirements can be met providing that the axis of optical system passes through the center of curvature of the primary mirror at all times during the tracking[6]. If the primary mirrors were spherical, such a system would naturally have no zenith-angle-dependent distortion, and need correct only spherical aberration. For parabolic primary mirrors (as is the case with rotating liquid mirrors), the situation is more complex but can be solved by providing a "parabolic compensator" optically conjugate to the primary mirror, which has the effect of converting the parabolic form back into a sphere. This mirror must move laterally during tracking, in order to remain conjugate to the primary mirror.

One possible configuration for this system is shown in Figure 2. A small Schmidt telescope forms a high-quality distortion-free image of the primary mirror. This image is located at the position of parabolic compensator mirror and the curvature of this image is matched to the curvature of the parabolic compensator. This mirror has a large aspheric departure, equal and opposite to that of the primary mirror.

Upon reflection from the parabolic compensator, the beam contains a considerable amount of spherical aberration, equal to that of a spherical primary mirror. The spherical aberration is removed by a two-mirror corrector. The beam exiting this corrector is directed to the central beam combining room by means of a flat "tertiary" mirror located a short distance above the primary mirror. In addition to these elements, two flat mirrors are used to fold the beam before it enters the Schmidt telescope. These allow us to direct the axis of the tracking system, and therefore the output beam, to the tertiary mirror.

As the telescope points and tracks, this system moves horizontally, and vertically to a lesser extent, in order to follow the image produced by the primary mirror. As required to eliminate focal plane tilt and distortion, the optical axis of this system is constrained to pass through the image of the center of curvature formed by the large flat mirror at the top of the picture.

This system can provide diffraction-limited images over a 30 arcsec field of view up to 4° from the zenith. The main disadvantage of this configuration is the obscuration produced by the parabolic compensator. At approximately 16%, this is not insignificant. We are currently investigating alternative designs with the aim of reducing the obscuration and extending the instantaneous field of view to at least one arcmin.

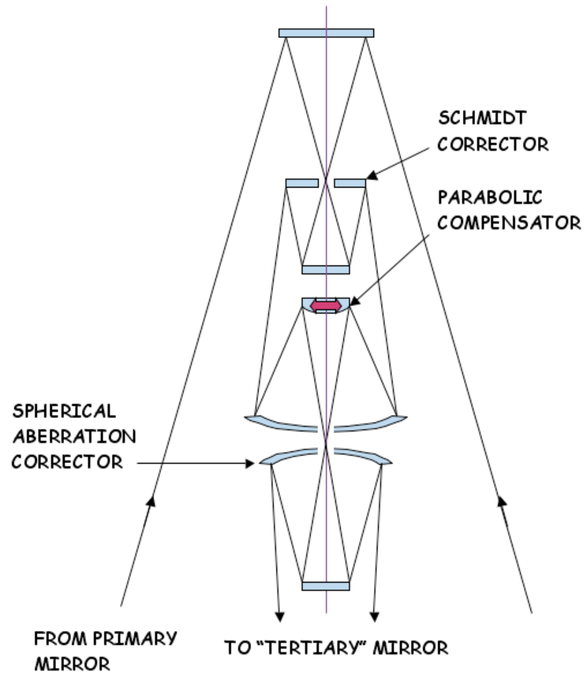

Figure 2. Optical configuration of the tracking system. During tracking, the system moves laterally, traversing the focal surface of the primary mirror. At the same time, the parabolic compensator pivots about its center of curvature in order to maintain alignment with the image of the primary mirror. The flat mirror at the top of the figure tilts slightly to ensure that the (reflected) axis of the tracking system passes through the center of curvature of the primary mirror.

4.3. Pathlength compensation and pupil relay system

The Large-Aperture Mirror Array will achieve high angular resolution by coherently combining light from many individual telescopes. As with any interferometer, the total optical path length, measured from an incident wavefront to the final focus, must be the same for all rays, to within a fraction of the coherence length $R\lambda$, where $R = \lambda/\Delta\lambda$ is the spectral resolving power. For broad-band imaging, $R \sim 5$ so the required path-length tolerances are of the same order as the wavelength. The optics must therefore provide a means for controlling the optical path length, and varying it smoothly as the telescope tracks. This problem has been solved by other interferometers, which employ a combination of slow-moving long-travel and short-throw high bandwidth mirrors. For LAMA, the problem is simplified somewhat because the telescope never points far from the zenith. The varying component of optical path length is $r\sin\theta$ where r is the horizontal distance of the telescope from the center of the array and θ is the zenith angle. This term takes values up to ± 2.23 m for the baseline design, which is much less than that required by other interferometers such as VLTI. The optics for each telescope must therefore provide a variable path length, between the entrance and exit pupil, of about 5 m.

A complication results from the need to provide coherent imaging over an extended field of view. As described above, this requires that the exit pupil of the array be a demagnified copy of the entrance pupil. The LAMA optics must therefore control the longitudinal position of the exit pupil, while the optical pathlength changes, in order to keep it at the appropriate position on the beam combiner mirror. During this motion, there must be no change in the exit pupil diameter. Also, the exit pupil must move laterally a few mm in order to compensate for the $\cos\theta$ compression of the projected (perpendicular to the line of sight) distance of the individual telescope entrance pupil from the geometrical center of the array.

An optical configuration that can perform all of these functions is illustrated in Figure 3. Lateral motion of the concave “pathlength control” mirror changes the optical path length of the system. At the same time, the flat “focus” mirror moves to ensure that the focal point of the pathlength control mirror remains coincident with the intermediate image produced by the tracking system. Thus, while the optical path length from this image to the pathlength control mirror does not change, the distance from the pathlength control mirror to the final focus does change, as required.

The pupil positioning system is a pair of mirrors that form an afocal beam compressor. Longitudinal translation of this pair of mirrors has no effect on the magnification or position of the final image because both the input and output beams remain afocal. It also has no effect on the optical path length. However, translation of this system does change the position of the pupil image. A small range of travel (less than a meter) is sufficient to keep the pupil image at the desired exit pupil location on the beam combiner “deformable mirror”. A small lateral translation of the diagonal flat mirror (less than 2 mm) suffices to compensate for the cos□ compression of the corresponding entrance pupil position.

Co-planarity of the images from all systems is ensured by requiring that the concave beam-combiner mirrors for all telescopes lie on a parent sphere whose focus coincides with the final combined image.

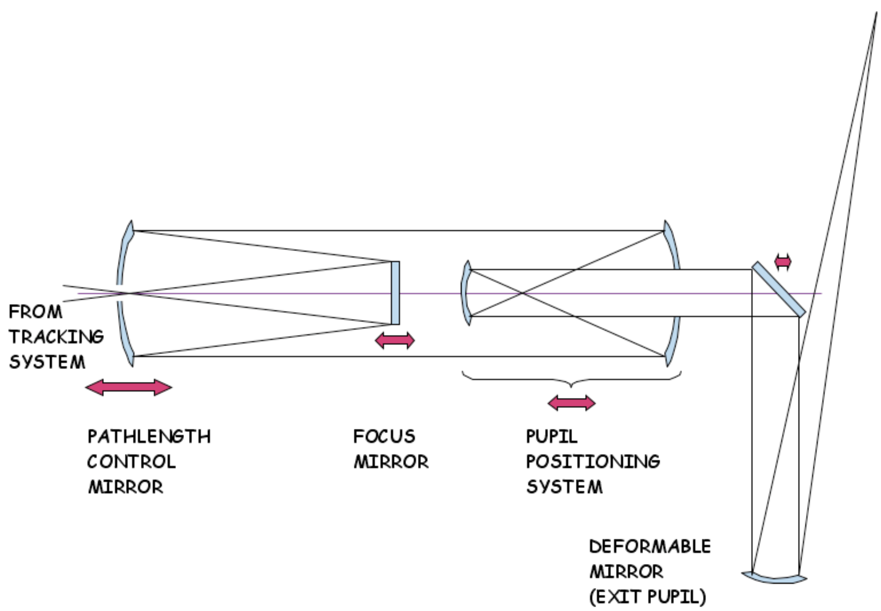

Figure 3. Optical configuration of the pathlength compensation and pupil relay system. As described in the text, this system is capable, in principle, of satisfying the optical path length, exit pupil location and beam recombination requirements for coherent imaging over an extended field of view.

4.4. Adaptive and phase tracking systems

Each telescope in the LAMA array will be equipped with an adaptive-optics (AO) system capable of near-diffraction-limited performance at least for near-infrared wavelengths. The current baseline design requires only conventional AO employing a single wavefront sensor and deformable mirror for each telescope. However, we are considering the potential use of multi-conjugate adaptive optics (MCAO), at least for some fields. LAMA would not require laser guide stars. Instead, one would target fields that contain one or more natural stars suitable for AO reference. There are many suitable fields available within the area of sky accessible to the telescope[1].

The adaptive system for each telescope will include a deformable mirror located at a pupil that provides ground-layer turbulence compensation in addition to removing small residual optical aberrations of the tracking system. A second deformable mirror could also be included, located conjugate to high-altitude turbulence, for MCAO. A fast tip-tilt mirror and focus mirror would be used to lower the dynamic range and stroke required of the deformable mirrors. A dichroic beam splitter, located in the beam converging to the final focus would feed conventional wave-front sensors. A control system would be provided for each telescope. These systems would act independently in removing phase errors for each telescope.

Pathlength and phase control would be accomplished by slow-moving the pathlength control mirrors and fast-moving piezoelectric piston mirrors. This system would be controlled by a closed-loop control system employing optical metrology for mirror position information, and a high-speed phase tracking system. The phase tracking system would employ high-sensitivity solid Michelson interferometers (Figures 4 and 5) to detect and track interference fringes between pairs of telescopes. These interferometers would be located in parallel light beams reflected from a parabolic window located in front of the combined focus. The interferometer units would straddle adjacent beams, with each beam feeding up to three interferometers. In this way, phase coherence can be achieved for the entire array by combining pair-wise phase measurements. Redundancy would be provided to control propagation errors in this scheme.

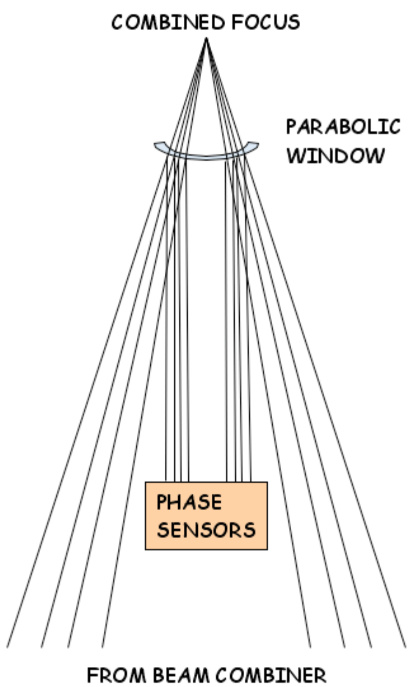

Figure 4. Location of phase sensors used for interferometric imaging. A parabolic window placed before the focus reflects a few percent of the light downward in parallel beams having the same geometry as the exit pupil. Phase sensors, shown in Figure 5, intercept a portion of light from adjacent beams, thereby measuring the pairwise phase differences.

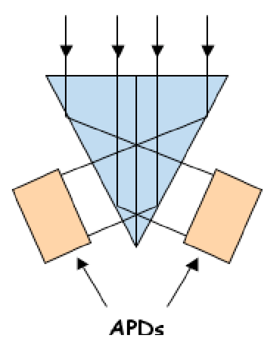

Figure 5. Solid Michelson interferometer phase sensor. Two prisms employ total internal reflection to direct incoming light to a partially aluminized interface. The intensities of the exiting beams are measured by avalanche photodiode detectors

5. TELESCOPE STRUCTURE

As illustrated in Figure 6, the major components of each individual LAMA telescope will be the primary mirror system, a tracking optical system located near the prime focus, a flat "tertiary" mirror located a short distance above the primary mirror vertex, and a hexapod structure that supports the tracking system and provides the motion needed for pointing and tracking. The principal mechanical components of the telescope structure are the hexapod, and a spider that supports the tertiary mirror. The LAMA telescopes would therefore resemble the Large Zenith Telescope (LZT), which has both a hexapod and a spider (see Figure 6 of the next section). However, the LAMA hexapod must be capable of greater displacement, as the top end needs to move approximately 2.5 m horizontally and a few cm vertically during tracking. As the hexapod partly obscures the primary mirror, its cross-sectional area will be made as small as is feasible. At the same time, it must be sufficiently stiff to resist excitation of its lowest frequency eigenmodes by wind within the enclosure. The LZT hexapod obscures 6% of the incident light; experience indicates that this can be reduced for the LAMA design.

The spider provides bracing, bearing lateral loads produced by the weight of the hexapod and tracking system. It supports the tertiary mirror and its baffle. The tertiary mirror, and its baffle, must articulate to follow the motion of the tracking system, delivering light to a fixed location in the central beam-combiner room.

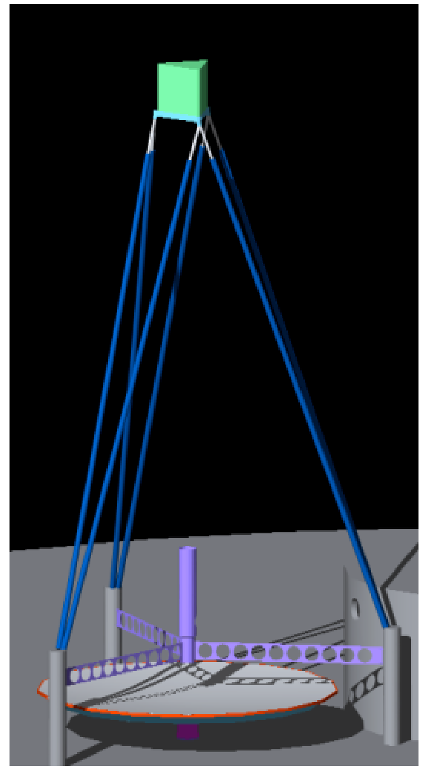

Figure 6. Schematic model of an individual telescopes in the LAMA array. Shown are the rotating liquid primary mirror, a hexapod supporting the optical tracking system, and a spider supporting the tertiary mirror and baffle system.

6. PRIMARY MIRRORS

To reduce cost, LAMA will employ rotating liquid-metal primary mirrors. Liquid mirror telescopes, employing a film of mercury as the reflecting surface, have been in operation now for more than a decade. One of these, the 3-meter NASA Orbital Debris Observatory (NODO), has been used both for the detection and characterization of space debris, and for astronomical observations[7]. Details of its operation and performance have been documented by Mulrooney[8]. A recent analysis[9] of its image quality indicates that the surface accuracy of its liquid mirror is approximately 80 nm RMS.

The most recent, and largest, liquid-mirror telescope is the 6-meter Large Zenith Telescope[10] (Figure 7) which has recently seen first light (Figure 8). The LZT employs two new features that are expected to result in a mirror surface accuracy that is substantially better than that of previous liquid-mirror telescopes. The first of these is improved rotational speed stability. Previous liquid-mirror telescopes such as NODO employ open-loop speed control, in which the rotation frequency of the magnetic field generated by the motor windings is precisely controlled As this system has no feedback, the instantaneous speed of the mirror is subject to fluctuations, of as much as 100 ppm, caused by wind and other disturbances. Such fluctuations result in flow of mercury on the surface, degrading image quality. The LZT, which employs closed-loop servo control of the primary mirror rotation, achieves a constant mirror rotation speed to within 1 ppm under all environmental conditions.

The second feature of the LZT is the thinness of the mercury layer. Laboratory tests of liquid-mirrors[11] indicate that surface waves, induced by vibrations and air turbulence, essentially disappear when the thickness of the mercury film is reduced to 1 mm or less. Because a film several mm thick is required to overcome surface tension whcn starting the mirror, the LZT is equipped with a pumping system capable of removing mercury from the rotating mirror after the mercury film has stabilized and oxidized.

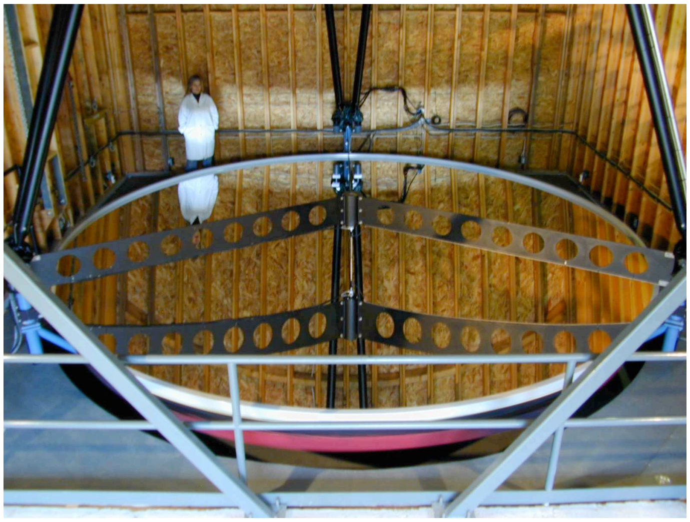

Figure 6. The 6-m liquid mirror of the Large Zenith Telescope.

Figure 7. A "first-light" image obtained with Large Zenith Telescope.

Fabrication possibilities for the LAMA primary mirrors are presently being investigated. It appears likely that these can be most conveniently made by machining aluminum sectors. These sectors could be readily transported and assembled on site to make complete mirrors. Further details are given in an accompanying paper, in these proceedings, that describes the LAMA Prototype Telescope[12].

7. INSTRUMENTATION

The initial complement of instruments for LAMA would include an optical/infrared imaging camera and a high-resolution spectrograph. These would be the primary dark-time and bright-time instruments, respectively. The imaging camera would be located at the combined focus of the array where it would be used in both incoherent and coherent imaging mode. Different images scales would be provided for these two modes in order to properly sample the respective PSFs. This camera would employ dichroic beam splitters in order to provide simultaneous broad-band imaging, with spectral resolving power $R \sim 5$ over the 0.3-2.5 um wavelength range. As currently foreseen, this camera would employ 4k x 4k CCDs for the optical channels and 2k x 2k HgCdTe arrays for the infrared channels.

The high-resolution spectrograph would be designed for $R \sim 300{,}000$ spectroscopy of individual objects, such as high-redshift quasars, host stars of transiting planets, etc. It would consist of a bank of approximately 10 cross-dispersed echelle spectrographs. Each spectrograph would receive light from several individual telescopes via optical fibers. Each fiber would sample the intermediate image produced by the tracking system. These images are located inside the beam combiner room, at the entrance to the pathlength compensation systems (see Figure 3). By dividing the light between a number of individual spectrographs, each sized for the individual LAMA telescopes, one avoids the considerable difficulty of designing and building a high-resolution spectrograph for a 50-m telescope.

8. SUMMARY

This paper has outlined current ideas for the LAMA telescope array. The central aim of this project is to achieve the light-gathering power and resolution of a 50-metre telescope by combining the light from a large number of individual liquid-mirror telescopes. We have shown how these telescope can be made to point and track, near the zenith, providing access to 6% of the sky and exposure times of up to 30 min. Adaptive optics systems yield the diffraction limit of the individual telescope apertures. Coherent Fizeau beam combination can, at least in principle, yield the diffraction limit of the 70-meter array configuration. The low cost of liquid mirrors makes LAMA attractive for the many scientific programs that can be accomplished within the constraints imposed by its design.

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