

The LAMA prototype telescope

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ABSTRACT

As a step toward the Large-Aperture Mirror Array, the LAMA consortium is planning the construction of a prototype telescope. Intended as a test bed for the required technologies, the LAMA Prototype Telescope (LPT) would be a coherent array of six 6.15-m liquid mirrors. Like LAMA, each telescope would be provided with tracking optics, path-length equalization, phase tracking and adaptive systems. The beam combiner, consisting of six concave adaptive mirrors, would have the Fizeau geometry enabling wide-field interferometric imaging.

In order to facilitate construction, testing and operation, the LPT would be located at or near a developed astronomical site in the continental United States. While the primary purpose of the facility is to develop and prove the LAMA concept and technologies, it would also be a powerful instrument for scientific research. With a light-collecting area equivalent to that of a 15-m telescope, the LPT would be capable of interferometric imaging with the resolution of a 20-m telescope. The telescope would be provided with a multi-band infrared imaging camera and visible-wavelength spectrograph.

This paper describes the telescope design and discusses the main technical challenges that must be faced.

1. INTRODUCTION

The Large-Aperture Mirror Array (LAMA) is an ambitious project to build a close packed hexagonal array of 66 liquid mirror telescopes. The individual telescopes will have apertures of 6.15 meter diameter. Each telescope will have adaptive wavefront correction and the images from the individual telescopes will be combined interferometrically to create a diffraction-limited image. The light collecting power of the LAMA array will be equivalent to that of a 50-meter telescope with a resolution in interferometric mode equivalent to a 70-meter aperture. A unique feature of LAMA will be a system of Tracking optics which allow the array to track objects within a 4 degree radius about the zenith.

The goal of the LPT is to develop and prove the technology that will be used in LAMA. The LPT will consist of 6 telescopes, essentially the inner ring of the LAMA array. Not only will the LPT act as a test bed for the optical and servo systems, but it will also provide useful test data on how to construct the enclosure and manage airflow around the mirrors. Located in an accessible location in the United States, development and construction costs will be manageable. Once LAMA construction has begun, the LPT site can be used as a staging and testing facility for the optical subsystems prior to delivery and installation at the remote site envisioned for LAMA.

As an added benefit, the LPT will be an important scientific instrument. Equipped with visible and multi-band infrared cameras and an infrared spectrograph the LPT will make important contributions to the fields of (Ken, can you add a sentence or two here?)

2. GOALS OF THE LPT PROJECT

The LAMA team has identified the 9 critical issues listed below, which need to be developed and/or proven for the project to be successful. The mission of the LPT project is to address and eliminate any uncertainty in these 9 critical items.

2.1 Automatic forming and stabilization of 6.15 meter liquid mirrors

It seems that it should be simple to form a liquid mirror. Pour the liquid into a container and spin the container and a perfect parabola is formed. In practice forming a liquid mirror is a difficult task. The final mirror should have a liquid layer that is as thin as possible to rapidly damp surface waves¹. The high surface tension mercury combined with mercury's inability to wet most surfaces makes it difficult to form a large continuous surface, particularly if the layer is thin. The 6.0 meter Large Zenith Telescope and the smaller liquid mirror telescopes which preceded it have all been formed by manually spinning up the mirror using human muscle and a lot of finesse. Once spinning the mirrors are only halted for occasional cleaning to remove dust and other debris that accumulates on the mirror surface.

Manually starting a mirror once per month after cleaning is an acceptable method of operation. With 66 mirrors and monthly cleaning, at least two mirrors per day will need to be cleaned and restarted making automatic startup a mandatory requirement. Automation of this process will require starting the mirror with sufficient so that the potential energy of surface tension is overcome by gravitational potential energy. Experiments with the LZT indicate that this requires 2-3mm of mercury. Once the mirror has closed and created a continuous surface, it takes about 2 hours for an oxide layer to form. The oxide seals the surface and helps to stabilize the mirror making it possible to remove the excess mercury and reduce the thickness to less than 1 mm. The LZT telescope is testing these assumptions individually. The task of the LPT is to integrate and automate the process.

2.2 Achieve a high quality mirror surface in operation

The imaging goals of the telescope require that the primary mirror surface be parabolic to 20 nm or better. The quality of the mirror surface is affected by the stability of the mirror rotation servo and by airflow over the mirror. Studies performed on earlier mirrors have shown that the mirror rotation rate must be stable to better than 1 ppm. The LZT hopes to reach this goal within the next few months.

The more difficult challenge will be to manage the airflow around the mirror. The air velocity at the mirror surface must be less than 1.5 m/s to achieve better than 20 nm rms surface error. Airflow near the mirror has two sources, the rotation of the mirror itself and environmental wind. The goal will be to keep the air velocity at the mirror surface laminar and lower than 1.5 m/s in the presence of and outside wind velocity up to the 80% probability velocity at the selected site.

2.3 Achieve diffraction limited imaging performance

The goal for LAMA is to achieve a Strehl ratio of greater than 0.5 for each telescope at 1 μm for 80% of the observing conditions. Reaching this goal requires that the primary mirror, tracking optics, relay optics and beam combining optics together produce a diffraction limited wavefront. The implications are that the optical design must have very low residual error, and the optical fabrication and mounting tolerances are very precise. In addition, optical alignment must be done very accurately and it must be maintained as the optics move for tracking and optical path length compensation.

2.4 Develop tracking servo and software

No currently available telescope control software packages are configured to handle the requirements of a zenith pointing liquid mirror telescope. The LPT requires either the adaptation of a current telescope pointing and tracking package or the creation of a new package designed specifically for this telescope.

2.5 Interferometric beam combination

Successful interferometric combination of all 6 telescope images at 1 micron and longer wavelengths

2.6 Achieve greater than 90% observing efficiency

Unlike other telescopes, LAMA and the LPT have a maximum observing time on any one object of 30 minutes per day. Typical observation will be between 20 and 30 minutes. The telescope will therefore observe an average of 12 fields per night. Maintaining observational efficiency of 90% requires that all 6 telescopes be capable of slewing to a new object and acquiring lock of the adaptive system and the interferometers within 2.5 minutes with a goal of 1 minute. Meeting this aggressive time goal will require that the absolute pointing uncertainty of each telescope be smaller than the capture range of the adaptive system or about 2 arc seconds. This is an aggressive goal for any telescope. The LPT has the advantage that it only needs to achieve this accuracy over an 8° diameter tracking field.

2.7 Achieve extrapolated reliability of better than 90%

Achieving operational reliability of 90% for the full 66 element LAMA array requires that the reliability of any one telescope be better than 99.84% or less than one disabling failure every 2 years of operation (assuming 80% of nights are observable). Therefore the reliability of the 6 element LPT array must be better than 99%.

2.8 Develop an observatory structure with adequate wind protection and acceptable seeing

Requirement 2.2 for a stable, accurate mirror surface during 80% probability wind velocity implies that the observatory enclosure must provide adequate baffling of the mirror surface from the effects of environmental wind. This runs counter to recent practice where telescope enclosures have become more open to eliminate the effects of dome seeing. The enclosure will need to be designed to both protect the mirror from air velocities above 1.5 m/s while providing adequate flushing airflow to reduce dome seeing to a level that can be corrected with the adaptive mirror.

2.9 Prove that mercury vapors can be kept within an acceptable range

Once a liquid mercury mirror has formed and stabilized an oxide layer quickly forms² on the surface of the mercury. The oxide layer seals the surface and prevents further evaporation of the mercury. With previous smaller mercury mirrors the oxide seal allows the mercury vapors to return to background levels in 24-48 hours. With a large number of mirrors cycling through a regular mirror cleaning/reforming process special air handling will be required to avoid environmental contamination.

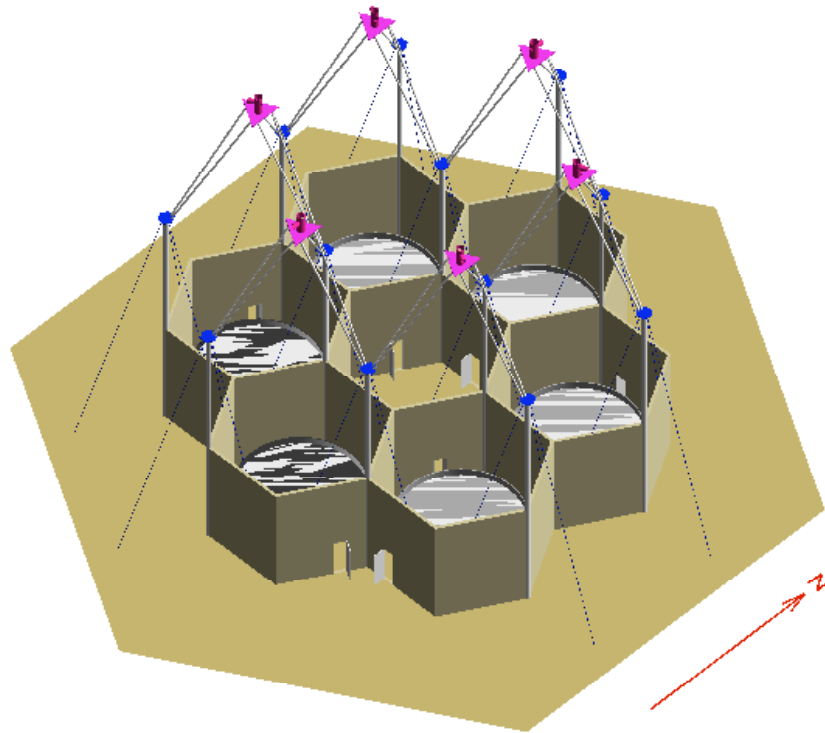


Figure 1. LPT Telescope Layout

3. LPT PROPOSED DESIGN

3.1 Optics

A proposed layout for the 6 element LPT array is shown in Figure 1. Figure 2 shows the optical layout of a single telescope. The key parameters of the individual telescopes are given in Table 1. The six telescopes are arranged in a Hexagonal array. The tracking optics are approximately 18 meters above the primary mirror. The tracking optics assembly is mounted on a hexapod translation stage with approximately two meters of lateral motion and 0.5 meter of vertical motion. The light from the tracking optics is directed to the path length compensation system located in the gap between the mirrors. The path length compensation optics directs the collimated light to the pupil positioning telescope and finally to the beam combining mirror which doubles as the adaptive mirror. The beam samplers for the adaptive wavefront sensor and the interferometer are located between the beam combiner and the focal plane (not shown). Hickson presents a complete description of the optical system in the LAMA Project Overview.³

The optical throughput of each telescope module is important to scientific productivity. The path length compensation for interferometry and the pupil imaging requirements for interferometry and adaptive optics add many optical surfaces to the telescope modules. The LPT design has minimized the number of optics needed to meet all of these requirements. Each module currently contains 15 mirrors in addition to the primary, plus a beam sampler. All of the telescope mirrors except for primary will be coated with protected silver. An estimate of the throughput of a single telescope is given in Table 2.

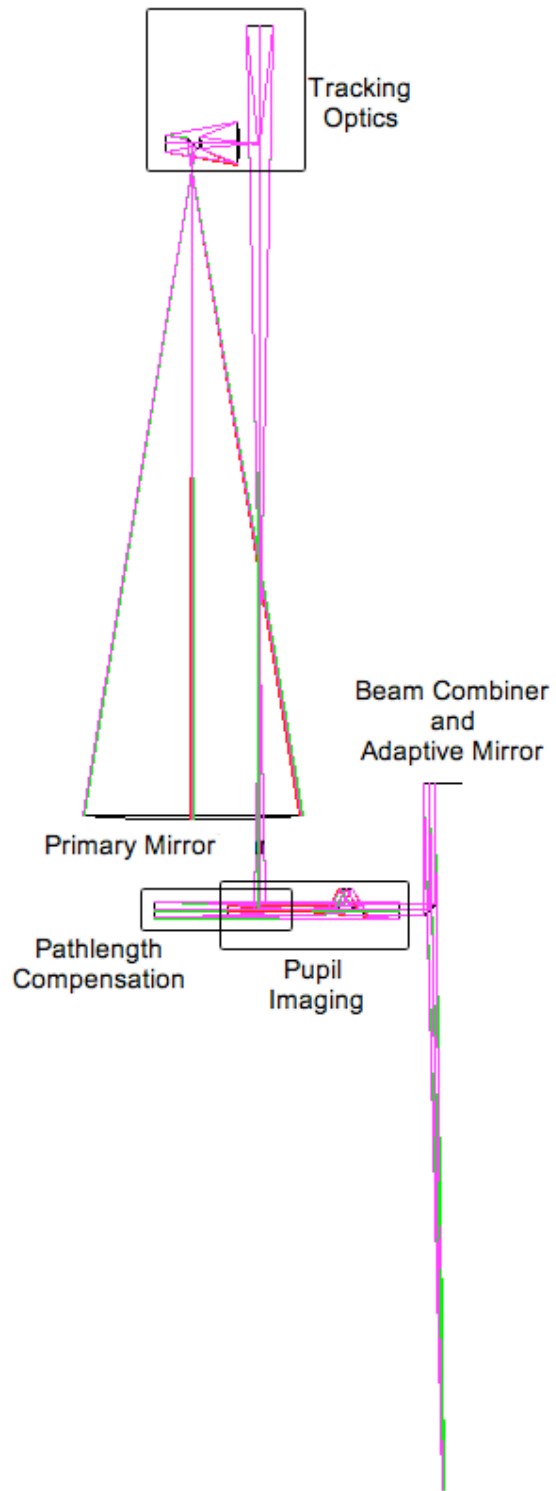


Figure 2. LPT Optical Schematic

Parameter	Value
Mirror diameter	6.1 meters
Primary mirror f-ratio	3.0
Instantaneous field of view	1 arc minute
Tracking Range	4 degree radius centered on the Zenith
F-ratio of beam emerging from tracking optics assembly	∞ (collimated)
Diameter of beam emerging from secondary	1/20 th of diameter of Primary

Table 1. LPT Telescope Parameters

3.2 Servo Systems

The current design requires 20 unique servo axis. Of these 20 servos, 16 are controlled by the pointing and tracking software. These 16 axes track the object on the sky, maintain approximately equal path between all of the telescopes, maintain the proper pupil position on the beam-combining mirror and position the parabolic compensator to properly remove the wavefront errors introduced by the primary mirror. Three additional servo axes are for high speed tip/tilt tracking and high speed interferometric path length compensation. These three servos will be controlled independently of the pointing and tracking systems but they will feed back their average positions to the pointing and tracking system to correct for long term drift. The 20th servo axis is for the rotation of the primary mirror. The primary mirror servo is completely independent of the pointing and tracking system. The proposed error budget for the 16 tracking servo axes and the primary mirror rotation servo are given in table 3.

Wavelength (μm)	Protected Silver	Hg	Beam Sampler	Total
.4	.955	.76	.9	34%
.5	.978	.76	.9	49%
.6	.978	.77	.9	49%
1.0	.98	.784	.9	52%
1.5	.983	.802	.9	56%
2.5	.988	.829	.9	62%

Table 2. Estimated Light Efficiency of LPT Telescope

3.3 Primary Mirror Support System

Achieving a high quality primary mirror surface depends on precise and well controlled mirror rotation, a rigid and accurate primary mirror support surface, a thin layer of mercury and well controlled air flow over the mirror surface. These requirements are intimately related. A thin layer of mercury damps out disturbances more effectively making it less susceptible to distortions caused by air flow over the surface. The goal of the LPT is to reduce the mercury layer thickness to less than 1 mm. In order to achieve such a thin, stable layer of mercury, the underlying support surface must have a shape which is accurate to better than 100 microns. Finally, a stable rotation rate is critical to maintaining a constant surface shape.

The primary mirror support structure will be made from a center hexagonal segment and eight “petal” segments. Each of these 9 segments consists of a monolithic front skin backed by ribs in a triangular cell pattern. Additional stiffness and a more aerodynamic shape will be achieved by welding a bottom skin to each of the segments. Figure 3 shows the proposed construction for the center segment and one of the petals. The nine segments will be bolted and pinned together and the gaps between the segments filled with adhesive to form a continuous top surface. Each individual segment will be machined to an accuracy which allows the segments to be bolted together to the required precision. Figure 4 shows how the segments are assemble to form a complete mirror.

The entire mirror assembly is mounted at its center to a Precision Instruments 23R air bearing. The air bearing provides smooth, frictionless rotation avoiding the “rumble” of mechanical bearings that would disturb the mirror surface. The air bearing also contains the drive motor and encoder required for the primary mirror rotation servo.

Axis	Description	Range	Accuracy
1	PM Rotation	Continuous	1 ppm
2	M2 Rotation about horizontal axis	±10 degrees	0.25 arc seconds
3	M2 Rotation about vertical axis	0	
4	M5 Rotation about horizontal axis	TBD	TBD
5	M5 Rotation about vertical axis	TBD	TBD
6	Tracking optics horizontal motion (North/South)	2.6 meters	20 μm
7	Tracking optics horizontal motion (East/West)	2.6 meters	20 μm
8	Tracking Optics rotation about vertical axis (perpendicular to optical axis)	±15 degrees	0.25 arc seconds
9	Tracking Optics rotation about horizontal axis (parallel to optical axis)	±20 degrees	0.25 arc seconds
10	Tracking Optics rotation about horizontal axis	±20 degrees	0.25 arc seconds
11	Tracking optics vertical motion	45 mm	20 μm
12	Path length compensator horizontal motion	± 1.5 meters	1 μm
13	Path length compensation mirror rotation about vertical axis	±15 degrees	0.25 arc seconds
14	Path length compensation mirror rotation about horizontal axis	±10 degrees	0.125 arc seconds
15	Pupil relay vertical motion	±10 mm	25 μm
16	Pupil relay horizontal motion (along optical axis)	±1.0 meter	10 μm
17	Pupil relay horizontal motion	±10 mm	10 μm

Table 3. LPT Servo Summary

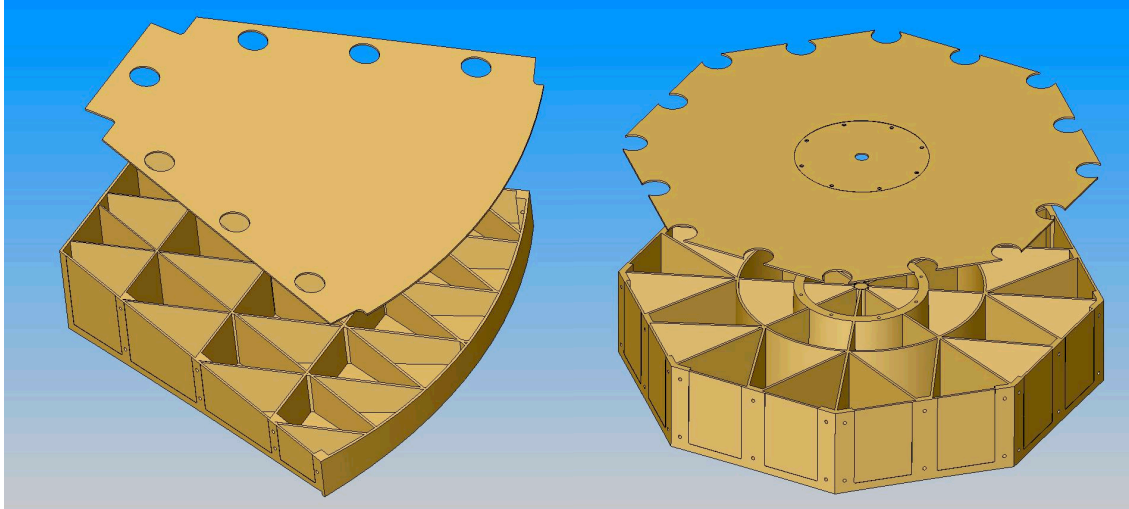


Figure 3. LPT primary mirror edge and center segments

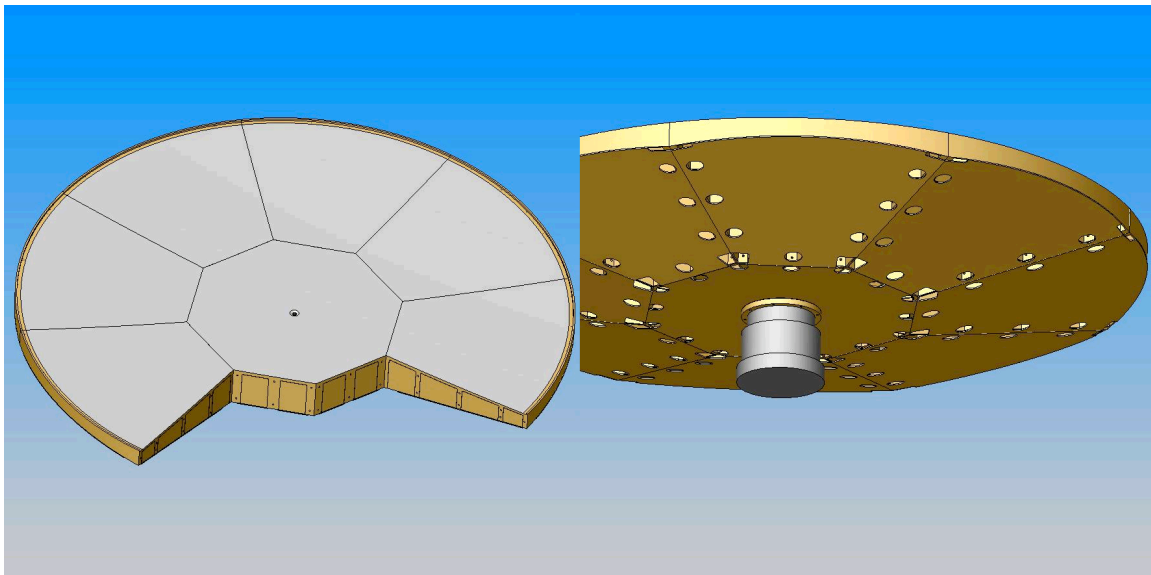


Figure 4. Primary mirror assembly

3.4 Observatory

The current plan is to locate the LPT observatory on a ridge approximately 2 km south of Apache Point Observatory. The telescope enclosure itself will be positioned at the edge of the ridge, partially embedded in the ground. The side walls of the observatory will extend to the approximate height of the tracking optics, 18 meters above the surface of the primary mirrors. During observing the roof of the observatory will roll back on tracks completely opening the top of the enclosure. Figures 5 and 6 show a proposed schematic layout for the observatory. Not shown in these views are the internal wind baffles that are required to control the airflow in the vicinity of the primary mirrors.

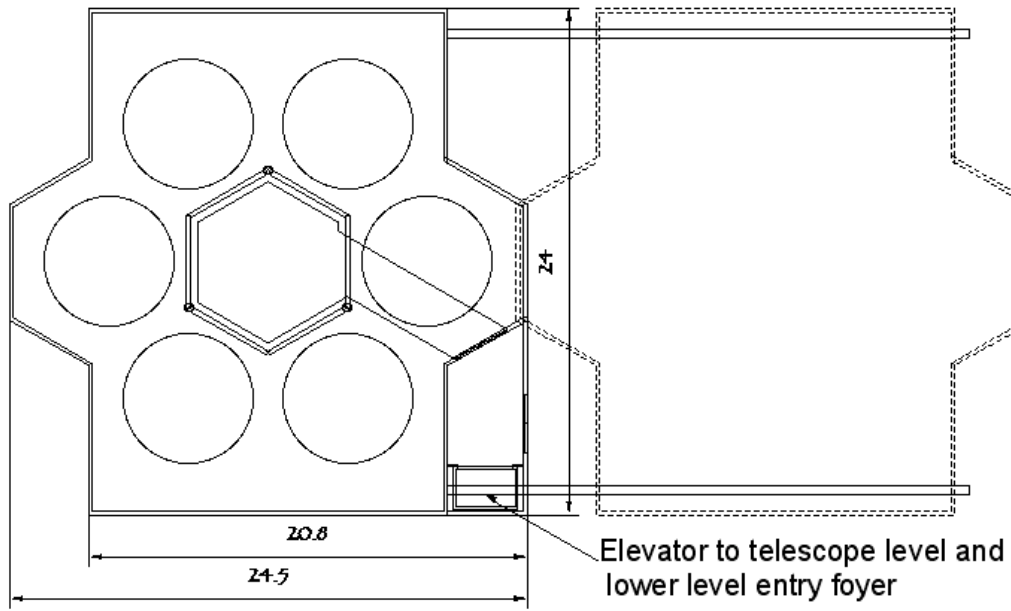


Figure 5. Proposed Observatory Plan View

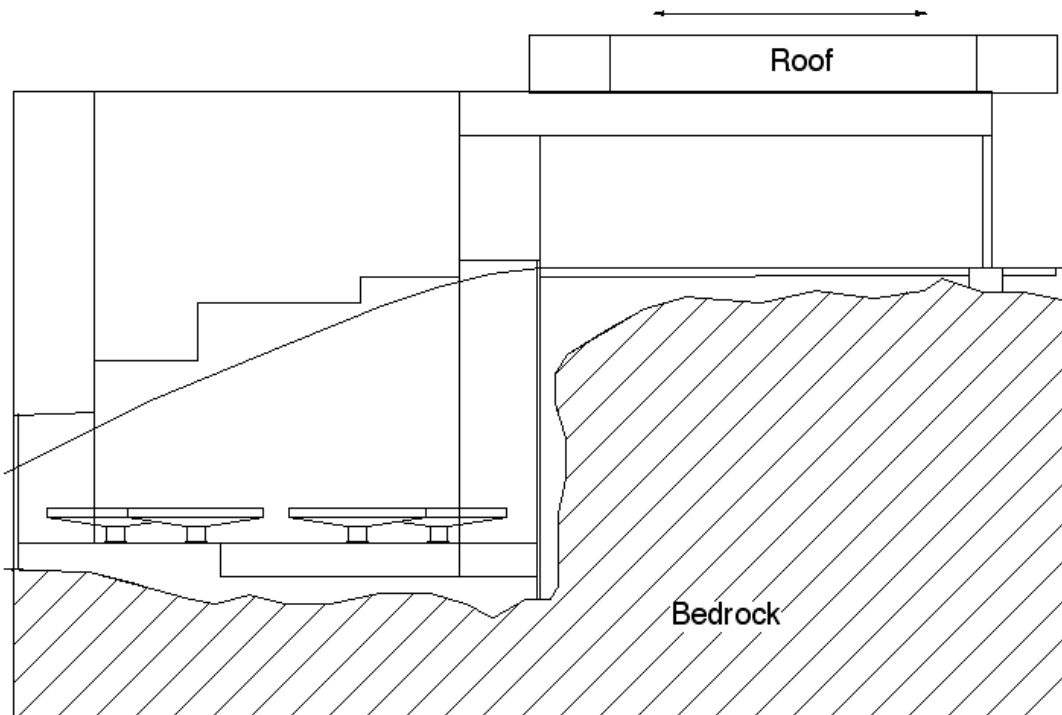


Figure 6. Proposed Observatory Elevation View

4. BACKUP AND SAFETY SYSTEMS

Protection of the environment as well as the telescope infrastructure are important goals of the LPT. Each time a primary mirror stops and restarts the oxide layer on the top of the mercury is broken and mercury vapors are emitted into the atmosphere. Therefore it is desirable to run the mirrors continuously, stopping them only when necessary for cleaning or maintenance. Reliability of the mirror drive system is critically important. At most observing sites, the biggest reliability problem is typically related to interruptions in mains power. Typical of other observatories, the LPT will have a backup generator which will automatically come on line quickly after a power failure. The air to support the air bearings will be supplied by a system containing dual, redundant air compressors and filters as well as a large air storage tank capable of keeping the bearings floating for at least 15 minutes. During the period required to start the generator, the drive motors will not be powered, but because of the near zero friction of the air bearings the speed will not slow significantly during the time required to bring the generator on line. If the mains power and generator both fail, then after about 5 minutes an automatic braking system will bring the primary mirrors to a safe halt before the air reservoir is exhausted.

Another possible failure mode is an imbalance in the primary mirror dish. If the dish is disturbed causing it to tilt slightly, the mercury will become thicker in the lower region. The high density of mercury will cause the mirror to quickly become unbalanced. To avoid a mercury spill under these conditions, the outer rim of the primary mirror will ride a few millimeters above a series of safety wheels which will catch the edge and keep it from tipping far enough to spill any mercury.

In the unlikely event that a mirror does fail and cause a mercury spill, the area containing the primary mirrors will be designed as a containment area. This area will trap the mercury and keep it from escaping into the environment.

5. SUMMARY

The LPT is a critical intermediate step on the path to the full LAMA array. It will allow the technologies which are critical to the success of LAMA to be proven and refined at a convenient site in the United States. Once LAMA begins construction, the LPT site can be used as a staging and test area for telescope modules prior to shipment to LAMA for installation. The LPT will also be a powerful telescope in its own right capable of significant scientific work.

Current estimates are that the LPT can be designed, built and commissioned for a cost of \$10 million to \$15 million.

¹ Tremblay, Grégoire and Borra, Ermanno F. "Optical Tests of a 3.7-m diameter Liquid Mirror: Behavior under External Perturbations", *Applied Optics*, Vol. 39, No. 36, 5651

² Hickson, Paul, Cabanac, Remi, and Watson, Suzanne, "A study of mercury vapor concentrations at the UBC/Laval 2.7 meter Liquid-Mirror Observatory", 13 November 1993, University of British Columbia Internal Paper

³ Hickson, Paul and Lanzetta, Ken, "Large Aperture Mirror Array – Project Overview", 2nd Bäckaskog Workshop on Extremely Large Telescopes, September 9-11, 2003