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Low cost, lightweight, large aperture, laser transmitter/receiver

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ABSTRACT

For many LIDAR and laser atmospheric propagation experiments, large aperture, near diffraction limited optics with very small field of view and wavelength range requirements are needed. These optics should be compact and lightweight so they may be transported to various areas of experimental interest. It is also important that the cost per unit area of aperture be low.

We present an optical and mechanical design of a catadioptric telescope system that meets the above requirements. It is a Cassegrain type telescope design with a Mangin secondary mirror and a low f/#, spherical primary to achieve compactness at low expense. A slumped, lightweight, borosilicate primary mirror keeps the system light weight and inexpensive. An athermal secondary mirror support maintains primary-secondary mirror separation passively. Using this design, a 1.4 m diameter, zenith pointing LIDAR transmitter/receiver fits into a semi tractor-trailer along with all the necessary support hardware. This telescope could be built for about $100 per square inch of aperture and would weigh less than 1200 lbs.

INTRODUCTION

Since the time of Newton, classical Cassegrain and Marsenne telescopes have been used when large apertures are needed for beam expansion or observational uses. With the advent of several newer technologies including the laser, phase locked detection and new mirror blank fabrication methods, it is useful to re-examine the wisdom of this choice. By keeping only the truly essential imaging requirements, we show that the telescope design can be simplified to a point where significant weight and cost savings are achieved.

In the first part of the paper, we examine the imaging requirements necessary for telescopes (and by implication, beam expanders) used near sea level. We also show that highly coherent sources imply the need for good optical performance over a very small field of view. This in turn permits the use of designs with spherical primary mirrors that will satisfy the optical requirements

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while substantially reducing the optical polishing costs. Such designs use a Mangin secondary mirror with the aspheric correction on the concave rear surface, eliminating the need for a large optic to test the usual convex, hyperboloidal secondary.

The mechanical design of the telescope is then considered. The driving factor is the primary mirror and the use of a lightweight, borosilicate primary mirror slumped to the net shape of the desired curvature will eliminate about 3/4 of the weight of a solid blank and the need to generate the sag prior to polishing. The lightweight blank is mounted in a tubular steel, athermalized space frame containing a mount for the secondary. The total package yields a zenith pointing telescope or beam expander that is rugged, high performance and with a quarter the mass of a more conventional telescope. This low mass, simple to manufacture, optical design yields similar weight, and thus cost, savings for instruments throughout the 1 to 2 m aperture range. Examples of several systems are given along with performance figures and alignment tolerances.

OPTICAL SYSTEM REQUIREMENTS

Optical systems for use with LIDAR, laser propagation through the atmosphere or other low to moderate power laser applications, need optimum performance only at the laser wavelength in question and thus can be designed as monochromatic systems. Furthermore, the field of view requirements are limited to the angular divergence of the laser source divided by the beam magnification, typically in the submilliradian regime. The return image will have similar angular divergence so there will be virtually no power more than a few seconds of arc off axis.

In addition, ultimate system performance can realistically be taken as 2 to 3 arc seconds because of atmospheric seeing degradation. While astronomical telescopes sited on tall mountains can, under the best of conditions, have sub arc second seeing, this is not the case near sea level. Local sources of heat, obstacles creating wind drafts and wind currents in general all limit seeing to a couple seconds of arc. For airborne applications as well, seeing will never be better than several arc seconds due to turbulence and boundary layer disturbances so it is unnecessary for the telescope to be designed better than this. Although there is much talk about diffraction limited performance in optical systems, it applies mainly to small aperture systems. There are virtually no large (1 m or larger aperture) telescopes that are diffraction limited in the visible or UV because, in angular terms, the diffraction limit is so small (1.5 μradians for a 1 m system at a wavelength of 0.6 μm) that this perfection is almost impossible to attain in practice. Thus we will take 3 second imagery as our realistic telescope performance goal and tolerance the design with this in mind.

We will limit our discussion to telescopes of 1 to 2 m in aperture. Smaller telescopes are commercially available, often as catalog items, and larger telescopes have specific engineering problems and are not conveniently transported from site to site. In keeping with the idea of moving the telescope, it is obvious that it should be as light and compact as possible. This implies a fast primary mirror to keep the system length short as possible and the use of a lightweight primary.

OPTICAL DESIGN

The classical approach to the design problem set out above would use a Cassegrain or Mersenne system with an aspheric primary and secondary. If a wider field were needed, a Ritchey-Chretien design would be used requiring double the asphericity on the secondary. To achieve the short overall length, an f/2 primary is probably the upper limit of the curvature to be polished without causing undo problems. For a 1 m aperture system, even this entails generating a 32 mm sag into the primary and then polishing in 125 μm of asphericity to produce the desired parabola. To test the parabola would require either a full aperture flat or a rather fast null lens.

The convex, hyperboloidal Cassegrain secondary has only 27 μm of asphericity but the surface requires a Hindle test sphere about the same diameter as the primary and twice as fast, that is, a 1 m sphere with a 2 m radius. Of course there are other ways to test the secondary[1,2] but these require additional test optics.

Our suggested alternative design just satisfies the optical requirements and no more. Assuming it is desired to design a receiver for an eximer laser LIDAR with 275 nm radiation, we propose using a spherical primary and a Mangin secondary mirror made of fused silica. As shown in Table 1 and Figure 1, the design has a biconcave secondary with an asphere of only 15 μm departure on the low curvature rear surface. This surface can be tested with a simple Offner null lens with 2 elements each about 50 mm in diameter. The design is diffraction limited on axis, and has a half field of 1 arc minute before the image increases to the tolerance limit of 3 arc seconds. The half field height at 1 arc minute is 5 mm.

Tables 1a and 1b. UV optical design.

Table 1a. Nominal design parameters

Primary aperture diameter	1100 mm
Effective focal length	16500 mm
Primary f/#	2
System f/#	15
Design wavelength	275 nm

Sperical primary and Mangin secondary.
Diffraction limited on axis.

Table 1b. Nominal UV (275 nm) telescope design.

Radius	Thickness	Diameter	Index
-4400.00	-1800.00	1100.0	Reflect
784.13	-15.00	200.0	Quartz
-3195.98*	15.00	194.0	Reflect
784.13	2915.35**	191.0	Air

*Asphere 15 μm departure from sphere.
**Back focus for visible (589 nm) light, 2125 mm.
Spot size 0.4 mm diameter.

Although the design is optimized to operate at 275 nm, a useful image is produced at 589 nm, for example, that can be used to verify alignment by observing a lack of coma in the image. This image is some 790 mm inside the 275 nm focal plane and the image has a diameter of 0.4 mm on axis.

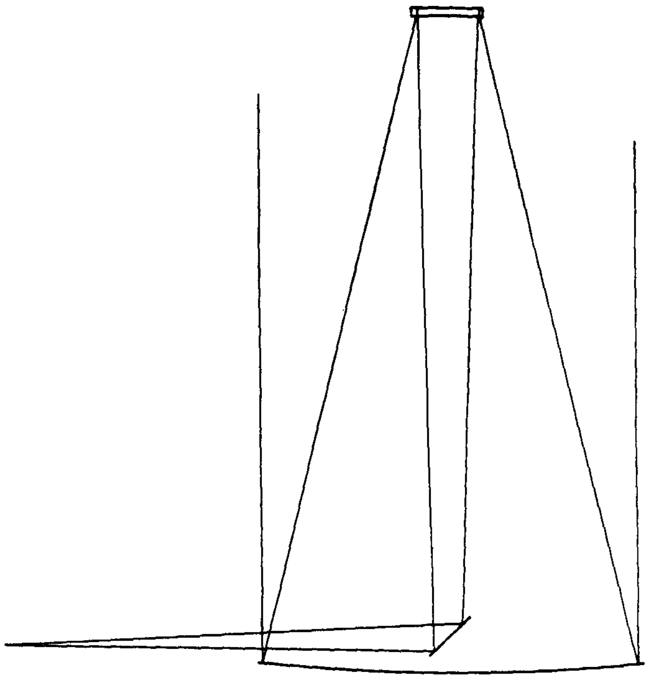

Figure 1. Optical layout of a 1.4 m telescope.

If the spherical primary is a lightweight, borosilicate mirror blank and is slumped to the desired 4 meter radius, the blank will be within 1.5 mm of the desired curve and can be ground and polished without having to be generated. Polishing the blank to an f/2 sphere of about 1/2 wave peak-to-valley accuracy is all that is necessary to achieve a 2 second image quality. Examples of lightweight slumped and plano borosilicate blanks are shown in Figure 2.

Not only is this telescope design relatively easy to build, but the alignment tolerances are rather loose except for the primary secondary despace as shown in Table 2. The fairly high despace sensitivity is due to the high primary-secondary magnification and would be the same for a true Cassegrain design of the same magnification. As described below, this sensitivity can be eliminated using an athermal secondary mirror support structure.

Table 2. Alignment tolerances.
Toleranced for a 3 arc second image diameter (approximately 0.25 mm).

3 arc minute secondary tilt
1.2 mm secondary decenter
66 μm primary/secondary despace
1 arc minute half field
(approximately 5 mm)

To illustrate that this basic telescope design using a spherical primary is useful at other wavelengths, a visible light solution was found using an F2 glass Mangin secondary and the design

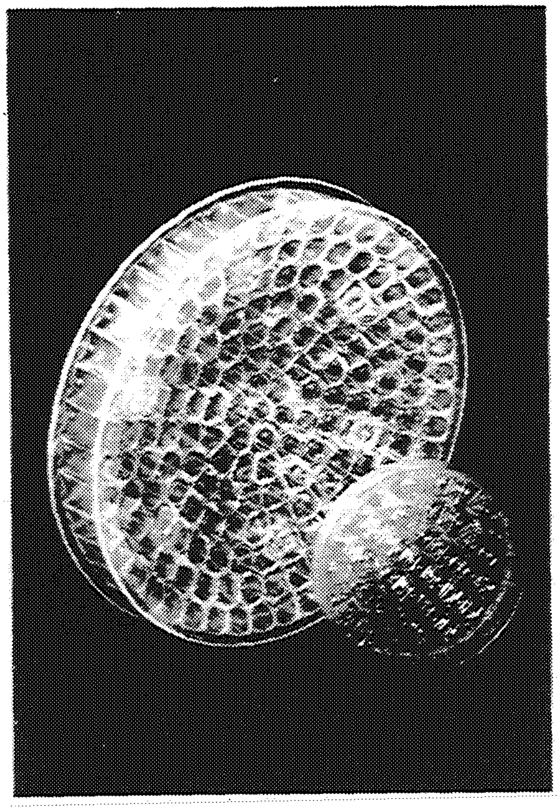

Figure 2. Examples of 1 m, f/0.5 slumped and 0.45 m ultralightweight plano borosilicate blanks.

of a 10.6 μm version is given in Table 3. This infrared design has the aspheric on the front, concave surface of the germanium Mangin secondary and has a diffraction limited performance over a 1 degree half field. We were not trying to achieve wide field performance, it just fell out of the design.

Table 3. Nominal IR (10.6 μm) telescope design.

Radius	Thickness	Diameter	Index
-4400.00	-1870.00	1100.0	Reflect
387.34*	-27.50	182.0	Ge
651.45	27.50	184.0	Reflect
387.34*	2498.50	180.0	Air

*Asphere 75 μm departure from sphere.

Because these designs are useful outside the visible, there should be a concern as to how the primary/secondary alignment will be achieved even though it is fairly loose. As we have already shown, a visible focus is available for the UV design and the long wavelength makes the despace less critical for the IR design. For tilts and decenters, we have found a very useful method of alignment that is equally applicable to these Mangin designs and classical Cassegrain telescopes. This method is based on the assumption that the primary is carefully centered and edged as the method makes use of the primary surface and edge for alignment.

Two sets of 3 equal length radius rods with tooling ball ends are made up, one set about half the primary/secondary spacing and the other slightly less long than the separation. The radius rods are set up as tripods using the surface and edge of the primary as references as shown in Figure 3. The triangular hole formed by each set of three balls at the upper end of the rods lies precisely on the axis of the primary. By adjusting a HeNe laser to shine through both sets of balls, the laser beam is made coaxial with the optical axis of the primary (and by definition, the system axis). The secondary, fabricated with a circular alignment mark at its vertex, is first translated until it is coaxial with the laser beam. The secondary is then tilted until the beam retraces itself back to the laser. Using this technique, Cassegrain telescopes with primaries as fast as f/1.5 can be readily aligned to produce coma free images on axis.

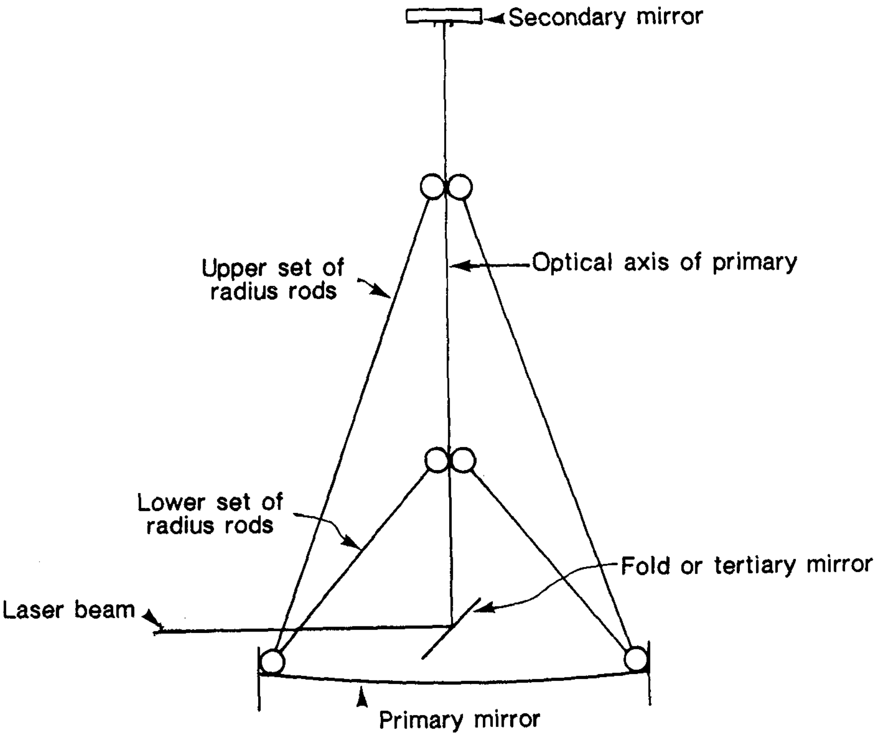

Figure 3. Schematic diagram of secondary mirror alignment method.

MECHANICAL IMPLEMENTATION

The primary mirror is the key factor around which the mechanical design must center. A lightweight, slumped mirror blank drives the telescope weight down in its own right and also drives the weight down because the supporting structure can be similarly reduced in mass. The curved backplate and nonstructural side plates constrain the choices for mirror support approaches to controlling the necessary six degrees of freedom from the rear plate alone.

Fully fused, lightweight, borosilicate mirror blanks are made of circular glass tubing fused between facesheets.[3] These sandwich panel construction mirror blanks have the same or greater self weight stiffness as solids of the same outside dimensions even though they weigh about 25% of the solid.[4] The slumped blanks are even stiffer than plano ones but all the calculations done here are based on flat plate theory. This gives conservative results and the calculations are much easier to do. We find that 2 m blanks with diameter-to-thickness ratios of as high as 10:1 have sufficient stiffness to have less than 0.3 arc second bending under their own weight when mounted on six points at the 7/10 zone.

Using this background, a space frame of tubular steel was designed to support the primary and secondary. Six bipods were brought up to the rear of the primary and bonded in place. Flexure attachments at both ends of the bipods decouple the mirror from thermal deformation of the steel structure. While it is a rule of thumb that the primary cell weighs about the same as the mirror in a tracking telescope, in this zenith pointing version, the entire structure weighs about the same as the primary. Thus this telescope weighs less than 1/4 of what a tracking telescope would weigh if a solid mirror blank were used. This weight savings translates directly into a proportional cost savings.

Because of the high optical magnification of the telescope (7.5×), the image size will be out of spec if the tubular steel structure under went more than a 3°C thermal soak. To counter this problem, the secondary headring is made of aluminum so that as the steel structure expands upward from the primary, the headring expands outward more rapidly causing the secondary to drop toward the primary just enough to keep the primary-secondary spacing constant. The drawing of the structure in Figure 4 is to scale to show the typical headring location. The method of design for athermalization is described in the Appendix.

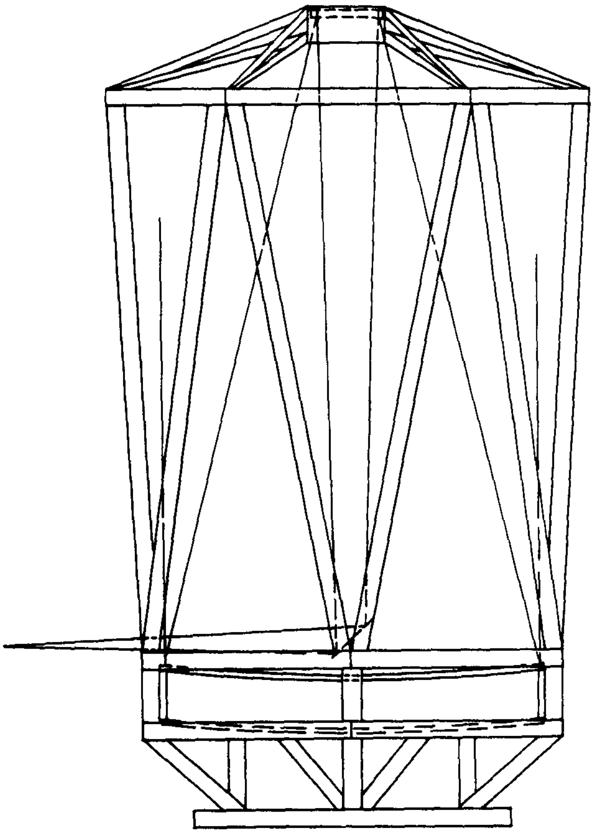

Figure 4. Tubular steel telescope structure, athermalized with aluminum headring.

TELESCOPE SIZE COMPARISONS

To give a feel for a typical packing arrangement, Figure 4 shows a 1.4-m aperture, f/2 primary system in an air ride furniture moving van trailer. There is room to move past the telescope on both sides and comfortable space at the top of the van to install a roll back opening. The standard van trailer adds assurance that the system is transportable to almost any location.

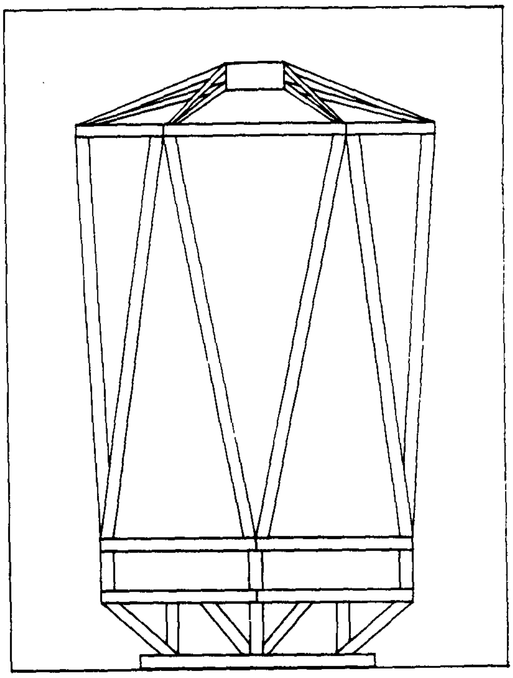

Figure 5. End view of air ride furniture van showing clearance around a 1.4 m aperture telescope with an f/2 primary.

Table 4 gives a comparison of the parameters of three sizes of the nominal system. Even the 2 m system is rather modest weightwise considering the over 3-sq meter collecting aperture.

APPENDIX

Telescope Structure Athermalization

We consider the structure shown in Figure A1 where all members are steel accept the headring which is aluminum. We want to keep primary/secondary distance constant independent of temperature and can treat the problem in 2 dimensions because of rotational symmetry. We assume the expansion of the primary is small compared to the steel and take as a reference the rear surface of the primary. The object is to find the lengths of members L and ℓ such that S remains constant with temperature because the aluminum member expands faster than the steel members.

Table 4. Physical parameters of various aperture telescopes.

Primary aperture	1.0 m	1.5 m	2.0 m
System focal length	15 m	22.5 m	30 m
Overall system height	2.4 m	3.6 m	4.8 m
Primary sag	31.25 mm	46.88 mm	62.50 mm
Primary thickness	175 mm	250 mm	350 mm
Solid primary weight	302 kg	972 kg	2420 kg
Telescope with solid primary (approx)	680 kg	2180 kg	5220 kg
Lightweight primary	76 kg	243 kg	605 kg
Telescope with lightweight primary (approx)	190 kg	560 kg	1520 kg

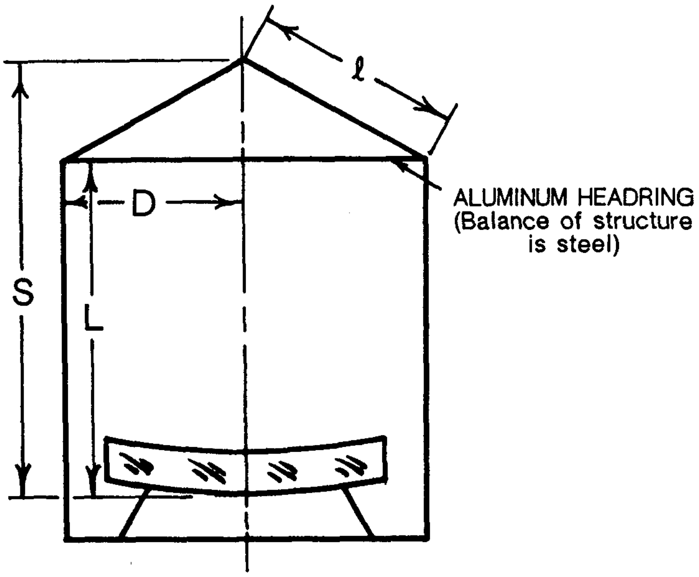

Figure A1. Model of athermal telescope structure.

Noting that

$$\ell^2 = (S - L)^2 + D^2$$

and taking the differentials of the three variable quantities we get

$$\ell \Delta \ell = -(S - L)\Delta L + D\Delta D.$$

Taking α_s and α_a as the coefficients of expansion of steel and aluminum, respectively, we have

$$\Delta \ell = \alpha_s \ell$$

$$\Delta L = \alpha_s L$$

and $\Delta D = \alpha_a D$.

Thus $\ell^2\alpha_s = -(S - L)L\alpha_s + D^2\alpha_a$.

With the help of the first equation we find

$$L = \frac{S^2 + D^2(1 - \alpha_a/\alpha_s)}{S} .$$

Using the parameters of the UV system we have $\alpha_s = 11.6\times10^{-6}$, $\alpha_a = 23.8\times10^{-6}$, S = 1852 and D = 528. This gives L = 1694 mm or about 91.5% of S. Clearly we have only illustrated the main concept of this method of athermalization, the higher expansion of the heading. The length L can be further modified to include the expansion and radius change of the primary and the index variation of the refracting secondary. These effects are small however, compared to the overall structure.

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