Low-cost Large Aperture Telescopes for Optical Communications

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ABSTRACT

Low-cost, large-aperture optical receivers are required to form an affordable optical ground receiver network for laser communications. Among the ground receiver station's multiple subsystems, here, we only discuss the ongoing research activities aimed at reducing the cost of the large-size optics on the receiver. Experimental results of two different approaches for fabricating low-cost mirrors of wavefront quality on the order of 100-200X the diffraction limit are described. Laboratory-level effort are underway to improve the surface figure to better than 20X the diffraction limit.

1. INTRODUCTION

Effective aperture diameters on the order of several meters to tens of meters are required for planetary laser-communication receivers. Since a worldwide network of such ground receivers, consisting of eight 10m-equivalent apertures (each at a different site) or three sites, each with a cluster of three 10m-equivalent telescopes (total of 9) is prohibitively expensive to establish at this time, development of technologies to reduce the cost of each telescope is essential.

Fortunately, diffraction-limited quality telescopes, such as those utilized in imaging are not required. However, the optical systems would have to be of sufficient quality to focus a beam that has traversed through the atmosphere to a spot size few hundred microns in diameter, and to have adequately narrow field-of-view to mitigate much of the background light. Analysis has shown that an overall surface error of up to 20 times greater than the diffraction limit may be tolerated.[1] Table 1 compares the requirements for astronomical telescopes with photon-collectors for laser-communications. Monolithic or segmented primary mirror single large apertures, or an array of multi-meter (0.5 to 2.5 m) diameter telescopes are suitable for the formation of an effectively large diameter ($\geq$10 m) telescope. Today's ultra-low-noise photon-counting detectors or array of such detectors allow for efficient signal summing from individual detectors associated with discreet telescopes in a telescope array concept.[2, 3] Our objective is to lower the cost of constructing networks of large apertures, while meeting the requirements for laser-communications.

Table 1. Comparison of requirements for astronomical telescopes and optical apertures for lasercom

Requirement	Astronomical Telescope	Photon-Collector for Lasercom
Image quality	Diffraction limited	$\leq$ 20X diffraction limit
Field-of-view	Large	Small
Operation	Night-time	Daytime and night-time
Quantity	One-of a kind	Multiple
Reliability	Moderate	High

Cost of a ground-based lasercom receiver is driven by the cost of:

- The collecting aperture, which consist of primary and secondary mirrors, aft optics, and mechanical structures
- A high precision 2-axis telescope gimbal and associated software for command and control
- The opto-electronic receiver and other auxiliary electronics
- The telescope dome or enclosure
- Site preparation and accommodations
- Staffing to operate and maintain the facilities.

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Each of these areas are being investigated to decrease the overall system cost. Here, we emphasize only the activities associated with reduction of the primary mirror's cost. The high-level requirements for the telescope may be summarized as:

Transmit/receive:	Receive only	**Field-of-view:**	~ 50 µrad
Wavelength:	500 to 1600 nm	**Strehl:**	> 0.8
Equivalent aperture:	0.5-1m (near-Earth)	**Spot diameter:**	<0.05-1mm (higher w/ arrays)
	10m (deep space)	**Atmospheric seeing:**	5-10 µrad (night-time)
Telescope surface figure:	< 20X diffraction limit		25-100 µrad (daytime)
Sky coverage within:	5° of the Sun (1° goal)	**Tracking:**	Sidereal and HEO rates

The field-of-view requirement stated above is driven by the requirements for quality of the optics constituting the telescope, alignment requirements, tracking requirements and seeing requirements.

Assuming a 1.5-m diameter, F/2 telescope, 20X diffraction limit quality, and no adaptive optics system, as shown in Figure (1), the actual spread function size is driven by atmospheric turbulence, as quantified by the Fried parameter (r_0).

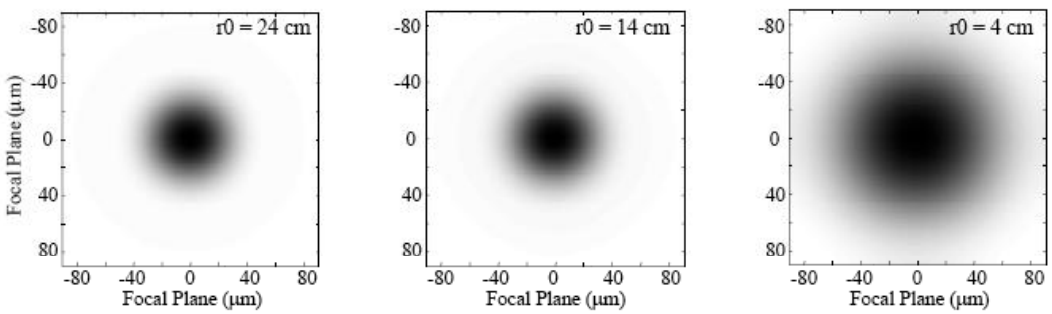

Figure (1). Influence of atmospheric turbulence on the spot size generated by a 1.5m, 20X diffraction limit mirror

Preliminary architecture trades indicate that:

- An array of telescopes 1 to 2 m in diameter meets the requirements and provides the lowest cost option
- A spherical primary mirror along with a spherical aberration compensator yields lower cost
- A 200X diffraction-limited (10-wave optical figure accuracy) mirror corrected to 20X diffraction limit (1-wave) also lowers costs significantly

Non-conventional options for developing large diameter mirrors include:

- Replicated (slumped glass) mirrors (scalable to > 5 m);
- Composite optics mirrors (scalable to > 5 m);
- Electro-formed mirrors (Scalable to multi-meters);
- Nano-laminate mirrors (scalable to > 10 m);
- Spin-cast polymer mirrors (scalable to > 10 m);
- Inflatable parabolidal mirrors (5m and 10m prototypes demonstrated)[4];
- Parabolic membrane mirrors (14-m prototype demonstrated)[4];
- Cylindrical primary mirrors (scalable to > 25 m)[5]
- Dual anamorphic reflector (scalable to > 25 m)[5]

2. MIRROR CHARACTERIZATION

Two different types of low-cost mirrors with promising performance were examined. These included four replicated slumped glass mirrors and two spin-cast polymer mirrors. With all mirrors, particularly those with a thin substrate, the mirror holder (mount) can adversely affect the surface figure. We observed significant wave-front degradation due to gravity sag during characterization of the mirror while rested on one edge, including when rested on thick foam.

Test Setup: Proper characterization of large diameter mirrors with conventional laboratory instruments is challenging. A Foucault test with a beam scanned across the mirror surface can provide valuable but incomplete data on the mirror surface quality. Availability of a well-collimated beam covering the entire mirror aperture quickly provides a complete picture of the surface. For this purpose, as shown in Fig. 2, we developed a 1.5m-diameter collimated beam utilizing a 1.5m diameter parabolic mirror with a 10-cm thick ULE substrate and a concave surface figure of better than $\lambda/4$ (at 633nm). The mirror is supported by strap/sling mounting around the edge with the optical axis horizontal. This method minimizes additional aberrations that might be introduced by the mount into the mirror's surface figure. The collimator is equipped with 850-nm and 1064-nm fiber coupled lasers at its focus.

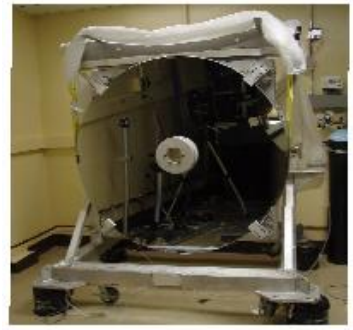

Figure 2. A high-quality 1.5 diameter parabolic mirror is used to produce a collimated 1.5-m diameter beam for characterization of lower-cost mirrors.

Replicated Mirrors:
Slumped glass mirrors are fabricated by utilizing a pre-fabricated precision mold. Several manufacturers have fabricated 3.5-m diameter molds. With investment, it is possible to extend the precision mold's diameter to 5-meters or more. Minimal post polishing of the mirror surface is typically performed for the low-cost mirrors. For our application, parabolic mirrors are preferred over spherical mirrors since the later suffers from significant spherical aberrations. However, cost of polishing parabolic mirrors is higher since more time is required for polishing these mirrors than spherical mirrors. Figure 3, shows the picture of a replicated slumped glass mirror, mounted kinematically on a mirror holder cell.

Figure (3). Picture of a mounted 1.2-m diameter slumped glass replicated parabolic mirror under test condition

Table (2) summarizes the experimental results of several slumped glass mirrors that we tested.

Mirror Diameter (m)	F/#	Glass Substrate Thickness (mm)	Type	Focal Spot Size (mm)	Surface Figure (waves RMS at 1064 nm)
1.2	~0.45	7	Parabolic	3	~185
1.2	~0.45	7	Parabolic	2.9	~160
1.5	~1	14	Spherical	2.1	~120
1.5	~1	14	Spherical	1.5	~70±10
1.5	~1	21	Spherical	0.9	~40±5

Table (2). Experimental data with first generations of low-cost slumped glass mirrors developed for the optical system of future ground receiver station

As expected, thicker substrates result in a higher mirror quality. Analysis indicates that a spherical mirror with substrate thickness in the 25 to 30mm range plus better polishing of the mirror surface relative to those shown in Table (2) above, in conjunction with a secondary mirror aimed at compensating for spherical aberrations will result in a mirror with surface figure of about 10-waves. Below, a low-cost active compensation technique is described to reduce the surface figure from 10's of waves to 1-wave or less.

Spin-cast Polymer Mirrors:
Our second approach for the development of low-cost, rapidly manufactured mirrors is spin casting of polymers. With further technology development this approach is expected to results in multi-meter diameter parabolic mirrors of adequate surface figure. Many of the larger diameter (e.g. 8-m) mirrors for astronomical telescopes are now fabricated via spin casting of melted glass, followed by several months of cooling and an additional several months of post-polishing[6]. Excellent quality mirrors are achieved in this manner. However, cost is high and development time is long. Spin casting of multiple-layers of polymers will achieve a significantly lower surface quality, but in a much shorter time (weeks) and much lower cost. Currently, thinner and thinner layers of polymers are spun on top of each other to improve the surface figure of the final layer. No post polishing is performed at this time to minimize the cost. Polymers are highly susceptible to thermally induced surface figure fluctuations. The low-cost active optic correction system, described next, is expected to mitigate these fluctuations.

Fig. (4) shows a 0.6-m diameter, 5-cm thick spun-cast polymer mirror. Despite the considerable thickness of the mirror, its weight is fairly low relative to a glass mirror. Therefore, it is easier to handle. As shown in Fig (4), during testing, this mirror was simply supported by a strap/sling around the edge. This approach is expected to minimize the mount-induced distortions of the mirror. Masking out a 7-cm inner diameter (where the primary mirror hole would have been), this mirror produced a spot size of about 0.46 mm (80% encircled energy).

Figure (4). A 60-cm diameter spun-cast polymer mirror

Development of higher quality 60-cm mirrors, and fabrication of spin-casting hardware and oven extending the mirror diameter to 2-meters is now in progress.

Low-cost Active-Optics Wavefront Compensation Technique:
By applying a deformable mirror in an active optics system to a 30-cm telescope, we have shown recently in a proof-of-concept demonstration, that it is possible to reduce the slowly varying surface wavefront error of low-cost large diameter mirrors from about 10 waves peak-to-valley, at 1 μm wavelength, to approximately 1-wave or less[7]. Our goal is to extend this technique to multi-meter diameter mirrors.

In this scheme a deformable mirror, with adequate number of actuators and sufficient stroke per actuator, is located in the beam path behind the mirror to compensate for the mirror wavefront aberrations arising from either manufacturing or thermally and gravitationally induced aberrations. The higher the wavefront aberrations, the higher the required quantity of the actuators and the higher the stroke per actuator that is needed for the deformable mirror.

The deformable mirror obtains the data that it needs for wavefront compensation from a wavefront sensor, or a simple focal plane array with the capability to measure beam spot size, or a single element detector where the aim is to optimize the intensity on a detector equipped with a small (sub-mm) aperture. Figure (5) shows a schematic of the original implementation.

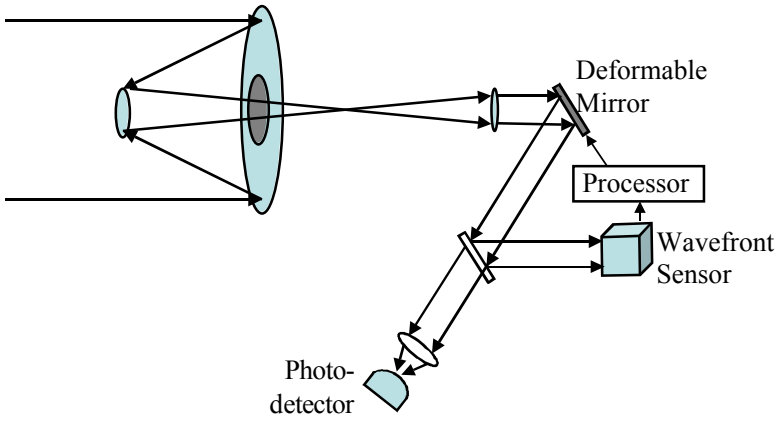

Figure 5. Schematic of a generic active optics system for compensation of optical system's aberrations.

In summary, viable approaches for reducing the cost of large optics in a lasercom ground receiver station are emerging. This includes the development of higher wavefront quality mirrors while maintaining the cost low, and moderately low cost deformable mirrors with high (>100) number of actuators and sufficient stroke per actuator (~50 μm) to compensate for the mirror's aberrations.

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