

Main-Reflector Manufacturing Technology for the Deep Space Optical Communications Ground Station

M. J. Britcliffe¹ and D. J. Hoppe¹

The Deep Space Network (DSN) has plans to develop a 10-m-diameter optical communications receiving station. The system uses the direct detection technique, which has much different requirements from a typical astronomical telescope. The receiver must operate in daylight and nighttime conditions. This imposes special requirements on the optical system to reject stray light from the Sun and other sources. One of the biggest challenges is designing a main-reflector surface that meets these requirements and can be produced at a reasonable cost. The requirements for the performance of the reflector are presented. To date, an aspherical primary reflector has been assumed. A reflector with a spherical reflector has a major cost advantage over an aspherical design, with no sacrifice in performance. A survey of current manufacturing techniques for optical mirrors of this type was performed. Techniques including solid glass, lightweight glass, diamond-turned aluminum, and composite mirrors were investigated.

I. Introduction

The ground station for deep-space optical communications is a unique instrument [1], operating at a wavelength of $1\ \mu\text{m}$ as the ground-based asset in a deep-space optical communications link. It has no imaging requirement but must effectively focus incident photons onto a detector of relatively large but finite diameter. In this respect it operates much like a very high quality solar collector. The ground station must also operate at very small Sun–Earth–probe angles in order to minimize communication outages. The ability to operate in the daytime, near the Sun, is another characteristic the ground station shares with a solar collector. However, while operating near the Sun, the ground station must not lose sensitivity to the incoming spacecraft signal due to stray sunlight impinging on the detector. The requirement that the ground station have excellent stray-light rejection characteristics is one that is common with high-quality astronomical telescopes.

The purpose of the survey was to identify applicable technologies for manufacturing the main reflector of the ground station. Since the main reflector is likely to be one of the significant cost drivers for

¹ Communications Ground Systems Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

the telescope, the manufacturing techniques must be judged on this criterion as well as light-focusing capability and stray-light rejection of the main reflector.

The next section reviews the requirements for the main-reflector surface of the ground station. The following sections describe the available approaches for manufacturing the main-reflector surface. These include slumped glass, conventional polished glass, spherical glass segments, diamond-turned aluminum, and composite materials.

II. Main-Reflector Requirements

In this section, the requirements on the ground-station main reflector will be summarized. The rationale for each requirement is also provided. Most requirements can be traced back to some system-level requirement or desire for the overall deep-space optical link. Others have been arrived at through additional analysis.

A. Aperture Size

The nominal size of the main reflector is chosen to be 10 m in diameter. This requirement is based on past analysis of the deep-space optical communications link and reasonable assumptions for the spacecraft transmitter parameters [2]. The number of photons collected by the ground station is of course critical in the overall communications link. Increased collection aperture would allow for higher data rates, lower spacecraft transmitter power, larger communication distances, or any combination of the above. For this reason, it is desirable to use a main-reflector manufacturing technology and telescope construction method that is scalable to larger diameters.

B. Surface Shape

The shape of the ground-station main reflector is a free optical design parameter. In imaging telescopes, the field of view (FOV) required for imaging determines the primary and secondary prescriptions. Some previous designs have followed the imaging telescope path, requiring an aspheric main reflector. For example, a Ritchey–Chretien design calling for a hyperbolic main reflector is discussed in [3].

As is discussed below, the field-of-view requirement for the ground station is quite relaxed compared to that of imaging telescopes. This allows consideration of a spherical main reflector. The potential cost savings of this approach have already been demonstrated by the Hobby–Eberly telescope [4]. The estimated cost of producing a segmented aspherical reflector is ten times higher than the cost of a similar spherical surface. Given these considerations, the survey was limited to the fabrication techniques used for production of spherical reflectors.

C. Collection-Efficiency Considerations

The primary reflector must concentrate the incident photons onto the communications detector. In general, the incident photons will be distributed within a certain spot size in the focal plane, typically referred to as the blur circle. Even for a perfect primary mirror, the blur circle diameter will be non-zero due to diffraction and atmospheric turbulence.

For a 10-m aperture at $1\ \mu\text{m}$, the diffraction-limited spot size is $0.1\ \mu\text{rad}$ in the focal plane. If the main reflector is manufactured using 1-m-diameter segments and no effort is made to phase them with each other, a spot size of approximately $1.0\ \mu\text{rad}$ is expected.

Atmospheric turbulence also limits the available blur circle. Excellent astronomical sites have atmospheric-limited seeing in the range of 5 to $10\ \mu\text{rad}$. Worst-case daytime seeing could be up to 10 times worse [2].

The communications detector on the ground station must, at a minimum, accommodate the rss sum of the diffraction-limited size and the assumed atmospheric size of the blur. Finite primary-mirror surface-roughness and surface-figure error will also cause an increase in blur diameter. Thus, a fundamental trade-off between overall performance and cost exists regarding the primary mirror. As the allowable blur size due to the primary mirror increases, the mirror cost will decrease. This decrease in cost is realized at the expense of increasing the angular coverage of the communications detector. The noise level due to background light is directly related to the detector’s coverage in the sky.

The blur circle determines the minimum detector field of view. This parameter is critical to the communications performance of the receiver. Detector field of view is analogous to system-noise temperature in a microwave link. The designs considered to date assumed a 100- μrad detector field of view. The link performance of a Mars mission would be improved by 7 dB by reducing the detector field of view from 100 μrad to 10 μrad [5].

The relationship between the main reflector surface quality and blur circle have been discussed in [1] and in detail in [6]. For the purpose of this discussion, the surface errors will be broken into two types: surface finish and slope error [7,8]. We use surface finish to describe small-scale roughness, with periods on the order of 1 mm or smaller. These features are typically measured using a profilometer or microscope. For features of larger period, the slope error of the surface is specified and measured, typically using interferometry. Here we are concerned with feature sizes up to the diameter of an individual panel. Features with still larger scale are related to the placement of the individual panels on the backup structure. These errors are not directly related to the method employed to fabricate the panels and are not considered further in this article.

1. Surface Finish. For surface finish, we assume that the surface errors have a Gaussian distribution, are small with respect to the operating wavelength, λ , and have an rms value of σ . In this case, the relative amount of energy collected by the detector is independent of its angular coverage and is given by the well-known formula

$$\frac{P_{\text{collected}}}{P_{\text{incident}}} = e^{-([4\pi\sigma]/\lambda)^2}$$

For a wavelength of 1 μm and 85 percent capture efficiency, the above formula gives $\sigma < 32$ nm, which will be used as the surface-finish requirement for the primary mirror. The effect of the surface finish on stray-light performance is described in the next subsection.

2. Surface Figure. The above criteria are to be used for determining the surface finish required on the reflectors only. Surface figure errors, which may approach or exceed λ , depending on their period, will be described in terms of surface-slope error. If we assume the slope errors on the main reflector have a Gaussian distribution and an rms value of θ_{rms} , then the energy collected by a detector with angular coverage of θ rad in diameter is given by

$$\frac{P_{\text{collected}}}{P_{\text{incident}}} = 1 - e^{-(1/32)^{[\theta/\theta_{\text{rms}}]^2}}$$

Assuming 85 percent collection efficiency once again, the following relationship may be derived: $(\theta/\theta_{\text{rms}}) = 7.8$. For a detector with a coverage of 20 μrad (± 10 μrad), we find $\theta_{\text{rms}} < 2.56$ μrad . The above equation contains the fundamental trade-off. Large θ_{rms} corresponds to an inexpensive main reflector but requires a correspondingly large value of θ for the detector, which implies higher values of background light intercepted.

D. Stray-Light Considerations

The optical communications ground station should be capable of tracking within 10 deg of the Sun, while maintaining a stray-light level within 3 dB of that when pointed away from the Sun. Tracking to within 1 deg of the Sun is considered a goal. This requirement is intended to supply DSN-like coverage of missions.

The stray-light performance of the primary mirror is described by its bidirectional reflectance distribution function (BRDF). The BRDF is the scattered surface radiance ($\text{W}/\text{m}^2/\text{sr}$) in a particular scatter direction divided by the incident surface irradiance (W/m^2) [7].

We are concerned with sunlight at an incident angle, θ , being collected by a detector having a field of view Ω positioned to receive boresight ($\theta = 0$) light. The total power collected by the detector due to the sunlight scattered by the main reflector is given by

$$P_{\text{scat}} = P_{\text{sun}} \times \text{BRDF}(\theta, 0) \times \Omega$$

The incident sunlight irradiance, P_{sun} , is approximately $0.5 \text{ W}/\text{m}^2/\text{nm}$, and we are concerned with a value of θ equal to 10 deg.

The diffuse skylight collected by the same detector is given by

$$P_{BG} = P_{\text{diffuse}} \times \Omega$$

The diffuse skylight radiance, P_{diffuse} , is approximately $0.01 \text{ W}/\text{sr}/\text{m}^2/\text{nm}$. For a 3-dB increase in background, we need P_{sun} equal to P_{diffuse} at θ equal to 10 deg. This results in the BRDF specification, $\text{BRDF}(10 \text{ deg}) < 0.02$, for the primary mirror.

The BRDF specification is the most direct method for assuring the stray-light performance of the primary mirror. It is also useful to relate the BRDF to the surface-roughness and slope error descriptions of the surface, which were discussed in the previous subsection.

1. Surface Finish. For surface finish, we assume a power-law form for the BRDF and relate it to the total integrated scatter (TIS). For the BRDF at normal incidence, we assume a form

$$\text{BRDF}(\theta) = C \times (100 \times \sin[\theta])^s$$

Experimental measurements of a number of surfaces dominated by scattering from surface finish give an empirical value for the constant, s , of -1.8 .² The total integrated scatter for the surface-finish model described in the previous subsection is given by

$$\text{TIS} = \left(\frac{4\pi\sigma}{\lambda} \right)^2$$

By integrating the BRDF times $\cos(\theta)$ over the forward hemisphere, we may compute the TIS for the power-law model. Setting the two TIS results to be equal, we may solve for the constant, C . The final result for the BRDF is then

²G. Peterson, personal communication, Breault Research Organization, Inc., Tucson, Arizona, January 12, 2001.

$$\text{BRDF}(\theta) = \frac{(s+2)}{2\pi} \times \left(\frac{4\pi\sigma}{\lambda}\right)^2 \sin(\theta)^s$$

For a wavelength of 1 μm and an angle, θ , of 10 deg, a $\sigma < 13$ nm will satisfy the $\text{BRDF} < 0.02$ requirement. Next we consider the BRDF due to slope error on the main reflector.

2. Slope Error. The BRDF for Gaussian-distributed slope errors for the special case of normal incidence is given by [8]

$$\text{BRDF}(\theta) = \frac{1}{8\pi\theta_{\text{rms}}^2} e^{-(1/8)[\theta/\theta_{\text{rms}}]^2}$$

In this case, meeting the BRDF requirement of $\text{BRDF} < 0.02$ at 10 deg requires $\theta_{\text{rms}} < 0.072$ rad.

For the given collection efficiency and BRDF requirements, we find that the surface-finish requirement is driven by stray-light considerations, while the slope error is driven by collection efficiency.

E. Field of View

In an astronomical telescope, image quality is typically specified over some field of view, an area of the sky that is imaged simultaneously through an array of detectors. In contrast, the ground-station detector will cover an area of sky equal to the size of the telescope blur circle plus the atmospheric blur circle. This coverage is just large enough to capture the entire downlink signal, while minimizing the capture of stray light. The field of view and corresponding image quality of the ground station is determined through pointing requirements. The field of view must be larger than the coarse pointing accuracy of the telescope, which is assumed to be 200 μrad . The quality of the spot generated over this FOV must be sufficient for obtaining the approximate location (centroid) that is used to update the telescope pointing. As the spot is drawn toward the center of the FOV, the quality will improve, but a high-quality, wide FOV is not required. As was discussed above, reducing the FOV to its absolute minimum opens up the possibility of employing spherical main reflectors and correctors.

F. Mechanical Considerations

Another key parameter to be considered is the final weight of the primary mirror when manufactured by each of the candidate techniques. A lighter main reflector will require a less expensive backup structure. It is important to point out that a lightweight structure is not a requirement for a ground-based telescope. Any costs incurred in manufacturing a lightweight main reflector must be recovered directly in the reduced cost of the associated backup structure.

Gravity distortion is also a concern. It is assumed that the segments will be mounted kinematically and will act as rigid bodies when installed on the antenna. The individual segments must retain their curvature when subjected to rotating gravity forces. The segments need to be dimensionally stable over time.

G. Thermal Properties

The thermal properties of the primary mirror are important since the telescope must operate during the daylight hours and may experience a thermal gradient across the 10-m diameter and the panel diameter as well. Normally, astronomical imaging telescopes are manufactured from special glass with a low coefficient of thermal expansion (CTE) glass such as Schott Zerodur or Corning ULE. The special glass is required to prevent fractional wavelength changes in the surface shape due to operational temperature changes. It is expected that the ground station will employ a real-time sensing system for correcting panel tip, tilt, and focus. It is not expected that thermal properties of the candidate techniques will cause any significant higher-order effects that cannot be corrected in real time.

III. Fabrication Techniques

A. Solid-Glass Mirrors

This is the standard approach used with astronomical segmented telescopes. This technique involves grinding a flat glass blank to a spherical shape and then polishing the surface to the required finish. Periodically the mirror is removed from the machine and measured with an interferometer. In the case of imaging telescope mirrors, the final figuring is done by hand or with a process like ion figuring. The final mirror blank is then coated with the reflecting metal with a vacuum deposition process.

Manufacturing spherically figured mirrors has many advantages. Spherical mirrors can be produced with high accuracy using planetary polishing, which inherently produces a high-quality spherical surface. It is expected that the DSN mirrors can be used with no figuring beyond the planetary polish. The spherical segments are all identical. This allows all the mirrors to be tested with a single test set-up. It is estimated that the cost of producing an aspherical mirror is ten times higher than a spherical one.

Glass mirrors produce the best optical performance of any known technique. The Hobby–Eberly telescope (HET) mirrors were manufactured to a surface accuracy of $0.033 \mu\text{m}$ rms. The surface finish of the finished mirrors was less than 1 nm rms. This value is an order of magnitude better than required for the DSN application.

The stray-light performance (BRDF) of the HET mirrors was not measured. The measured BRDF of similar mirrors is on the order of 1×10^{-5} . This is three orders of magnitude better than required for the DSN application. The stray-light performance of any polished-glass mirror is expected to meet the requirement.

The effect of gravity on surface shape of the HET solid mirrors is well known [9]. The measured gravity-induced wavefront distortion for the solid HET segments was $0.3 \mu\text{m}$ rms when the panel was moved from horizontal to 55 deg. This error is acceptable for the DSN application. In practice, the mirrors would be manufactured for a specified “rigging angle,” as with microwave reflectors. Operation above and below this angle would result in this gravity deformation.

The choice of glass has a major cost effect. The HET mirrors were produced with Schott Zerodur. The cost of the raw Zerodur for the HET was $\$8,300/\text{m}^2$ [9]. Other glass types considered for the reflector include borosilicate and Pyrex. These glasses can be purchased for less than one-tenth the cost of Zerodur. The inexpensive glasses are slightly less dense and will result in a lighter primary mirror.

The total cost for fabricating the segments from rough glass—including cutting the glass into hexagonal shapes, grinding, planetary polishing, and ion figuring the mirrors—was $\$1,600,000$ [9]. The DSN mirrors are not expected to require ion figuring. Solid-glass mirrors are, as expected, the heaviest construction technique. The HET mirrors are 50-mm thick and weigh $127 \text{ kg}/\text{m}^2$.

The environmental effect on coated glass mirrors is well known. Protected aluminum coating is ideal for this application. Protected aluminum typically produces mirrors with 98 percent reflectivity at a $1\text{-}\mu\text{m}$ wavelength. The lifetime of protected aluminum is expected to be 3 to 10 years before the reflectivity of the surface degrades to 85 percent. Coated glass mirrors can be restored to new condition by recoating. This is a simple operation that can be performed on-site.

B. Lightweight Glass Mirrors

The weight of conventional monolithic glass mirrors is the biggest drawback. The stiffness required determines the thickness of the mirror segment. If the mirror is too thin, the segment will distort due to gravity. It is possible to reduce the weight of the mirror segment by forming a truss structure in the glass by removing material behind the mirror surface that retains the cross section of the blank. Water-jet

milling has been used to reduce the weight of mirrors that require lightweight surfaces, such as mirrors for flight applications. This process is time consuming and expensive.

Another approach is to build the segment with a thin reflecting surface and fuse it to a backup structure of the same material [10]. The process results in a mirror with the optical performance of a monolithic mirror that is much lighter. It is expected that segments can be produced for this application with a density of 50 kg/m² or lighter.

C. Diamond-Turned Aluminum Mirrors

This technique involves machining a metal substrate (typically an aluminum alloy) to the desired surface shape. The machining process is similar to standard machine-shop fabrication using a lathe. The substrate is mounted on a spindle and is rotated. The cutting surface is a single-point diamond cutter that is moved across the work piece with a computer-controlled actuator. Depending on the substrate material, it may be necessary to plate the substrate with an undercoat of nickel and then aluminum to provide a surface that can be polished to the required surface finish.

The weight of aluminum mirrors for this application is difficult to estimate. Aluminum has a higher density than glass (2.7×10^3 kg/m³ compared to 2.3×10^3 kg/m³), although aluminum primary mirrors have been produced for millimeter-wave reflectors with reflector weights of 30 kg/m². The surface-accuracy requirement for the optical mirrors is 50 times more stringent. The mirror thickness required to meet the optical surface-figure specification may make aluminum mirrors heavier than glass.

There are no known 1-m-sized diamond-turned optical mirrors. Lawrence Livermore National Laboratory has a diamond-turning capability large enough to produce a 1-m or larger segment [11]. The capability was developed for large laser mirrors for the Department of Defense. They think that the mirrors can be manufactured to meet the requirements. However, they do not have the capability of producing the quantity of segments required.

Some concern has been noted in previous work about the surface roughness produced with this process. Although diamond-turned surfaces have produced surface finishes of less than 10 nm [12], the diamond cutter has a small radius that leaves a periodic groove in the surface. The dimensions of this groove and the size are determined by several factors, including the type of material being machined, the cutting speed, and the feed rate of the cutter. The effect that this pattern would have on the scattered-light performance has been questioned. Church et al. measured the scattered-light performance of several metal mirrors [12]. The BRDF that is calculated from these data shows that the mirrors may not meet the stray-light requirement.

The operational concerns of using metal mirrors for a telescope main reflector are uncertain. Most metal mirrors to date are used in laboratory environments or in vacuum. Metal mirrors used for diffraction-limited applications have problems associated with changes in surface figure over time. The metal substrate has internal stresses associated with the grain structure of the material. Thermal expansion due to temperature changes can exhibit hysteresis, resulting in slight changes in shape over time.

The coefficient of thermal expansion (CTE) of 6061 aluminum is 23 PPM/C compared to 3 PPM/C for borosilicate glass. Although the CTE is nearly ten times higher, the thermal conductivity is 100 times higher (180 W/m-K compared to 1.5 W/m-K). It is expected that any differential heating of an individual aluminum segment would result in a focus shift that would be corrected by active control and would not pose a serious optical-performance problem.

The effect of the environment on the surface roughness due to corrosion for solid-aluminum mirrors is also unknown. The surface would have a finite life similar to typical aluminum coating on glass mirrors. Oxidized mirror segments would require repolishing and possibly replating on a periodic basis. This would probably require the mirrors to be shipped to an off-site facility.

D. Composite Mirrors

Composite technology has been used to produce very lightweight mirrors for near-infrared applications. They are particularly attractive for space applications. Composite mirrors have been produced with weights as low as 4 kg/m^2 [13].

Small composite flat mirrors with suitable optical performance have been manufactured [13]. The manufacturing process involves building a mandrel or mold, typically from ground glass that is a negative of the required surface. Layers of composite fiber are then applied. After curing, the surface is coated with a reflecting material. The surface finish of the replicated optical mirrors was less than 2.5 nm [13].

The technology required to fabricate large optical mirrors is still largely conceptual. There are no known large (1-m) composite optical mirrors. Composite Optics Incorporated (COI) has been awarded a NASA Small Business Innovation Research (SBIR) Program contract to investigate the feasibility of composite materials for this application.

Environmental effects are also a concern in using composite reflectors for a ground-based application. The composite material absorbs moisture from the air. Relative-humidity changes affect the surface shape. The effects of the environment and the life of a composite mirror in this application are unknown.

Composite mirrors have been constructed with near-zero CTEs. The thermal performance of a composite mirror should not be a factor.

E. Slumped-Glass Mirrors

Ultra-low-cost mirrors for solar collectors and for telescopes designed for studying Cherenkov radiation have been produced with the slumped-glass technique [14]. A flat glass blank is heated in an oven over a mold that is a negative of the desired shape. The glass melts slightly and “slumps” over the mold. The resulting mirror is then coated like ground glass. The surface figure obtained by this process alone results in a blur circle much greater than $100 \mu\text{rad}$, which is not suitable for the DSN receiver, and is not considered as a candidate.

It is possible to combine the use of slumping borosilicate glass to rough shape with the use of planetary polishing to final finish. The finished mirror would be similar in weight and performance to ground glass. This process may result in cost savings.

F. Results

Table 1 summarizes the key parameters of the reflector manufacturing technologies considered. Glass mirrors provide the best optical performance at the lowest cost. Any advantage of using an alternative to glass would largely be based on weight savings. Any cost reduction achieved by using a composite or aluminum technique must be offset by a reduction in the cost of the support structure and gimbal.

IV. Conclusions

A spherical main-reflector shape is the optimum option for the proposed DSN optical ground station. Using a spherical reflector results in a ten-fold cost advantage with negligible performance disadvantage. A glass reflector will provide the best performance from an optical standpoint. The cost for solid glass is well known. Solid glass is the most conservative and has the lowest technical risk. No other technology is expected to produce better optical performance. Lightweight glass is an attractive option. This technique results in a reflector with the performance of solid glass that weighs less than half as much. Diamond-turned aluminum does not appear to be a good candidate based on availability, maturity of technology, or optical performance. Slumped glass alone will not meet the requirements. It may be possible to

combine slumping and polishing to reduce fabrication cost. Composite technology is attractive due to the weight-savings potential, but it is uncertain if the weight savings will be worth the technical risk in terms of optical performance and operational life.

Table 1. Summary of estimated reflector characteristics.

Reflector type	Surface finish, nm	Coating life, yr	Total weight, kg	Maturity of technology
Solid glass, Zerodur (HET)	<1	3 to 10	9930	High
Solid glass, borosilicate	<1	3 to 10	8830	High
Lightweight borosilicate	<1	3 to 10	3925	Medium
Composite	1 to 8	Unknown	1180 to 2400	Low
Diamond-turned aluminum	2 to 10	Unknown	5800 to 11,700	Low
Slumped-polished borosilicate	<2.5	3 to 10	8635	Medium

References

- [1] K. Shaik, "Progress on Ten-Meter Optical Receiver Telescope," *Free Space Laser Communication Technologies IV*, SPIE vol. 1635, pp. 109–117, 1992.
- [2] G. G. Ortiz, J. V. Sandusky, and A. Biswas. "Design of the Opto-Electronic Receiver for Deep Space Optical Communications," *Free-Space Laser Communication Technologies XII*, SPIE vol. 3932, pp. 127–138, May 2000.
- [3] K. Shaik, D. Wonica, and M. Wilhelm, "Optical Subnet Concepts for the Deep Space Network," *The Telecommunications and Data Acquisition Progress Report 42-115, July–September 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 153–181, November 15, 1993.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-115/115m.pdf
- [4] <http://hyperion.as.utexas.edu/mcdonald/het/>, March 3, 2001.
- [5] J. R. Lesh and D. L. Robinson, "A Cost-Performance Model for Ground-Based Optical Communications Receiving Telescopes," *The Telecommunications and Data Acquisition Progress Report 42-87, July–September 1986*, Jet Propulsion Laboratory, Pasadena, California, pp. 56–64, November 15, 1986.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-87/87G.PDF
- [6] J. V. Sandusky, D. J. Hoppe, and M. J. Britcliffe, "Deep-Space Optical Reception Antenna (DSORA): Aperture Versus Quality," *The Telecommunications and Mission Operations Progress Report 42-143, July–September 2000*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–11, November 15, 2000.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-143/143C.pdf
- [7] P. Beckmann and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces*, Norwood, Massachusetts: Pergamon Press, 1963.
- [8] J. C. Stover, *Optical Scattering*, Bellingham, Washington: SPIE Optical Engineering Press, 1995.

- [9] V. L. Krabbendam, T. A. Sebring, F. B. Ray, and J. R. Fowler, “Development and Performance of the Hobby–Eberly Telescope 11 meter Segmented Mirror,” *Proceedings of the SPIE*, vol. 3352, pp. 436–445, August 1998.
- [10] <http://www.hextek.com/products.html>, March 3, 2001.
- [11] <http://www-eng.llnl.gov/eetd/infosys/precMfg.html>, March 3, 2001.
- [12] E. L. Church, H. A. Jenkinson, and J. M. Zavada, “Measurement of the Finish of Diamond-Turned Metal Surfaces By Differential Light Scattering,” *Optical Engineering*, vol. 16, no. 4, pp. 360–374, July–August 1977.
- [13] P. C. Chen, C. W. Bowers, D. A. Content, M. Marzouk, and R. C. Romeo, “Advances in Very Lightweight Composite Mirror Technology,” *Optical Engineering*, vol. 39, no. 9, pp. 2320–2329, September 2000.
- [14] <http://glassmountain.com/largeap.htm>, March 2, 2001.