Spin-Cast Polymer Mirrors

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Introduction

There is a real need for low cost telescopes in the 1-2 meter aperture range. Giant research telescopes are getting ever larger and fewer in numbers. While these mountaintop behemoths are making many exciting discoveries, they are now so expensive that there can only be a few of them. Thus, there is insufficient observing time to make the more detailed, time consuming follow-up observations required for solid science in many areas. This task falls to smaller telescopes, but they are also quite expensive. The solution, as pointed out in a recent report to the National Academy of Sciences (Genet *et. al.* 2010), is to advance the technologies that will allow smaller telescopes to be produced at low cost.

The cost of telescopes depends in a large part on both the cost of their primary mirrors and the weight of these mirrors, since a heavy mirror requires a heavy, expensive telescope for support. Most of the cost of mirrors is in "figuring" the mirrors—the tedious process of shaping the surface of a mirror within nanometers to an exact figure such as a parabola. If such figuring could be avoided, then mirrors would be much lower in cost.

One way to avoid expensive figuring is to spin a liquid material in a container at a constant speed. The material will naturally assume a parabolic shape. If the material is an epoxy, it will harden while spinning and a mirror of the correct optical shape will have been formed without the expense of optical figuring.

Though there is yet no epoxy mirror that provides diffraction-limited performance for visible light, one seems possible in the near future and we have already demonstrated mirrors suitable for light bucket astronomy (Genet *et. al.* 2009). Given the results of our investigations to date, we foresee the ability to produce very lightweight, low cost, large-aperture mirrors at a very small fraction of the cost of current parabolic mirrors. It has not escaped our notice that it might cost more to vacuum aluminize and overcoat these mirrors than it would to make the mirrors themselves. To avoid this eventuality, we launched a parallel program to develop a low cost, non-vacuum silvering and overcoating process for large mirrors (Brodhacker *et. al.* 2011).

Such spin-cast epoxy mirrors would make it economically feasible to deploy entire arrays of 2-meter portable telescopes with combined apertures rivaling those of some of the giant mountaintop telescopes but at a small fraction of the cost. Unlike the large mountaintop telescopes, these portable telescopes with their lightweight 2-meter spin-cast epoxy mirrors will be deployable to many different locations where they could be configured in patterns optimized for the task at hand. They might, for instance be spread out in line formation for high speed occultations of asteroids or trans-Neptunian objects, or they might be assembled in a relatively compact cluster to image the surface of nearby stars via intensity interferometry.

To set the stage, we mention previous epoxy spin-cast mirror developments and discuss the closely related, constantly-spinning liquid mirror telescopes which, instead of an epoxy layer, have a thin reflective layer of liquid mercury. We also discuss why, based on signal-to-noise and economic considerations, mirrors of low optical quality can be advantageous in some situations such as aperture photometry and spectroscopy (although we hope to eventually achieve high optical quality spin-cast epoxy mirrors). While our mirrors are conceptually simple—spin some low cost epoxy at constant speed to form a parabola and let it harden—the devil is in the details, so we delve into the details of our developments below. A quick preview:

In designing our polymer system, we had to consider viscosity, surface temperature, the glass transition temperature, shrinkage and the polymerization rate, and the coefficient of thermal expansion. To spin our mirrors, we started out modestly with a 33 1/3 rpm long-play (LP) record turntable to spin small test mirrors and evolved into a giant turntable on air bearings enclosed in a large custom oven to make 2-meter mirrors. Testing flux collection mirrors requires a somewhat different figures-of-merit, which we discuss. Our optical evaluations have included visual inspection, test chart imaging, Ronchi tests, Foucault tests, modified Hartman tests, and telescope tests, and we are planning interferometric tests. Finally, we are investigating several methods for light-weighting our mirrors since we want them to be both low cost and light-weight.

Previous and Related Efforts

Over the last 30 years, spin-casting has become an important technique in astronomical instrumentation. The Arizona Mirror Lab and others now routinely use the technique to form, roughly, the parabolic surface of glass mirror blanks, thus saving tons of glass and years of grinding (Hill *et. al.* 1998). Beginning with Borra (1982) the “spinning” approach, applied to a thin layer of liquid mercury, has proven cost effective in making large instruments at a fraction of the cost of a conventional telescope. The six-meter zenith telescope with a constantly spinning liquid mercury mirror, that saw first light in the last decade, represents the current state of the art (Hickson 2004).

Nor is fabricating polymeric mirrors a new approach, since the literature dates back to the 1950s. Hass and Erbe (1955) reported on replica mirrors made of epoxy resin in 1954, and soon Archibald (1957) was spin-casting epoxy mirrors as large as 36 inches in diameter for use in solar furnaces. Although Archibald reported vibration problems with his approach, he nonetheless concluded that astronomical quality mirrors might be possible by spin-casting. Only a few reports in the three decades following Archibald are recorded (Schmidt 1966, Ninomiya 1979, and Lindblom 1980). One of these efforts included a 62-inch resin mirror for a two-micron survey of the sky (Neugebauer and Leighton 1968). The 1990’s saw a rebirth in the idea which resulted in research quality spin-cast polymeric mirrors including a 30 cm mirror for OP/FT-IR spectrometry (Richardson *et. al.* 1997) and a 1.8-meter off-axis paraboloid for a submillimeter cosmic microwave background survey from the Antarctic (Alvarez *et. al.* 1993).

Optimizing the SNR

The signal-to-noise-ratio (SNR or S/N) of observations made with all telescope systems depends on many factors. The signal part of the ratio (in the numerator) depends directly on the program object brightness and may be maximized by using a telescope with a large aperture and a high reflectivity optical train. The signal term depends also on the detector quantum efficiency and atmospheric extinction due to the air-mass through which the program object flux must traverse. In contrast, the noise part of the ratio (in the denominator) depends on detector noises, atmospheric scintillation, and photon arrival (shot) noises from both the program object and the sky background flux.

For many scientific applications, the mirrors in telescopes do not have to be optically perfect; they just need to concentrate a large amount of light within a single, on-axis spot. Much of photometry and spectroscopy falls into this "light bucket astronomy" category. For these applications it is actually better to invest in larger aperture, low optical quality, on-axis only (non-imaging) telescopes than to spend the same amount on telescopes that had near perfect mirrors and wide fields-of-view but, as a consequence, were of much smaller aperture. A careful examination of the expected SNR for a particular observing program must be made so that the overall SNR of measures is optimized.

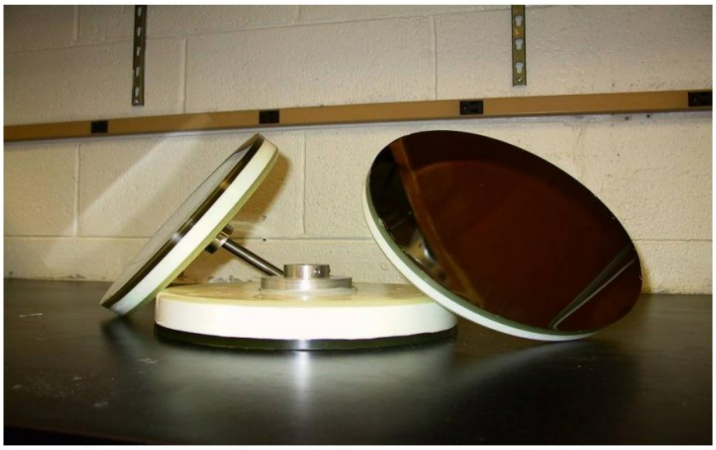
A telescope that can be transported to a high elevation mountaintop will benefit from the reduced scintillation and sky background noises, plus the signal will be improved due to lower atmospheric extinction. So, is it better to build a small telescope with excellent optics or spend the same amount building a much larger light bucket telescope that has poorer optics and tracking? Should funds be used on a high-precision mount or in building a mountaintop observatory? Questions like these take a lot of analysis to answer well.

Specifically, what has been found is that general purpose, diffraction limited telescopes with sub-arc second tracking, zero-expansion glasses, and a small focal plane point spread function (PSF) may reduce the sky background noise factor but fail, in some cases, to provide the best SNR for the money because other noise factors dominate (Holenstein *et. al.* 2010, Genet *et. al.* 2010b). Spin cast epoxy mirrors, in contrast, are ideal in many situations for light bucket (*i.e.* non-imaging) telescopes because they provide near-optimal choices to the question of what type and optical quality of primary mirror is needed to maximize the SNR of the program object measures.

Epoxy Compared to Glass

A comparison of epoxy mirrors to conventional mirrors composed of borosilicate glass reveals the advantages and limitations of the epoxy mirror approach, and indicates areas where improvements in polymer characteristics might be directed. The clear advantage of the epoxy mirror approach is both its low cost and the ease and speed of production. A 4-meter spin-cast epoxy mirror could be completed in the same amount of time as a 40-centimeter glass mirror!

Although much less fragile than glass, and thus less likely to be broken, epoxy, just like glass, is not the ideal material for telescope mirrors primarily because of the thermal behavior of unmodified epoxy. Its thermal diffusivity, a measure of how rapidly the material adjusts to ambient temperatures, as well as its thermal figure of merit that takes into account the coefficient of thermal expansion (CTE), are respectively lower and higher values than desired. This circumstance arises because the large CTE for epoxy when coupled with its large heat capacity counteracts the advantage provided by the relatively low density of epoxy.



Three small experimental epoxy telescope mirrors made by spin-casting.

However, several methods are available to reduce these undesirable properties. The thermal conductivity of epoxy can be substantially elevated with a conductive additive without significantly affecting other desirable properties. Additionally, studies underway by our group have already demonstrated a reduction in the CTE by the inclusion of components with a negative CTE. How far this approach can be taken and whether the method adversely affects other desirable properties is yet to be ascertained. Furthermore the lightweighting of mirrors discussed below also reduces the negative effects of thermal properties by reducing the mirror's mass. What seems clear is that the thermal properties of epoxy require some modification if the material is to be viable for meter-class mirrors.

The density of epoxy is less than half that of other mirror materials, yet owing to its relatively low Young's modulus, unmodified epoxy's structural performance is still comparable to glass. Its specific stiffness, the ratio of Young's modulus to the density, is half that of borosilicate glass; however, composite materials utilizing epoxy are two orders of magnitude better in specific stiffness than glass or simple epoxy (Bely 2003). It is possible that a mirror of epoxy built up in layers, with the first layer a composite with appropriate reinforcing, could produce a strong yet lightweight mirror.

Polymer System Selection Criteria

There is no perfect polymer system available for optical quality spin-cast mirrors. A good system would, of course, have as many desirable characteristics as possible, but there are always tradeoffs to be made. Those characteristics that have been identified as important for epoxy mirrors include: a low viscosity and surface tension, a relatively high glass transition temperature, high strength and hardness, low shrinkage on curing, a slow reaction rate, and the lowest possible CTE given the relatively high values associated with most epoxies.

Viscosity and Surface Tension

Viscosity and surface tension act to counter the parabola-forming forces of the spinning process, so that keeping their values as low as possible are necessary for obtaining the best surface figure. In addition, complete mixing of the epoxy components is essential for uniform properties throughout the final mirror, and low values for viscosity and surface tension also aid in mixing since epoxy components are relatively larger molecules. Given the viscosity of even the most fluid of epoxies, the addition of a diluent is indicated. Since surface tension usually increases proportionately with viscosity, the diluent aids in lowering surface tension as well.

The specific polymer chosen and its curing agent affect the viscosity and surface tension in several ways. Not only is the viscosity of the mixture important, but also its cure temperature. If the system requires an elevated temperature to cure in a reasonable period of time, the process benefits from the lower viscosity that heating provides. There are epoxy systems that require days to gel at 70 °C and their viscosity is significantly lower at the elevated temperature. This situation aids both in mixing and in achieving a satisfactory surface figure.

Glass Transition Temperature

In a polymerization reaction there are several important transformations that occur. The point at which the viscous liquid changes to an elastic gel is the gel point. This gelation is somewhat sudden and irreversible and marks the point at which a network of essentially infinite molecular weight first appears. After some interval of time following gelation comes vitrification, the point at which the gel becomes a glassy solid and has a maximum crosslink density. If the glassy solid is heated above the glass transition temperature, T_g, the polymer will lose its glasslike properties and assume those similar to a rubber until its temperature is reduced below T_g. This temperature is one of the most important characteristics of a polymer and those polymers with a high T_g have high crosslink densities and good strength.

Shrinkage and Polymerization Rate

As a polymerization reaction proceeds there are volume changes that occur in the matrix. These changes induce stresses in the final product that can cause warping and cracking. It is important to note that any shrinkage in volume prior to gelation does not induce any stress in the final material (Schoch 2004). Studies by Russell and Lee (1997) have proven that tuning the cure process can eliminate most of the shrinkage in the thermosetting resin.

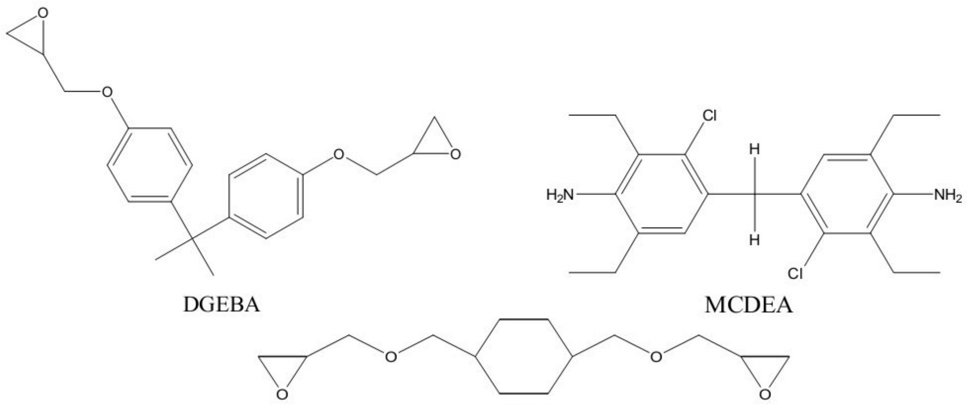
During the curing process the mixture undergoes a thermosetting reaction in which the monomers are converted into a cross-linked matrix. A cure study we performed has revealed that the gel point of the system can be postponed for days, allowing the matrix to undergo slow shrinkage without inducing significant stress. If the gel point can be avoided long enough, only a small amount of residual stress will be present in the final material. Given these considerations, a low polymerization rate was given the highest priority in our selection criteria.

Coefficient of Thermal Expansion

As discussed previously, thermal qualities are a serious potential liability of epoxy mirrors; however, if the thermal conductivity can be enhanced by a highly conductive fill agent, the CTE of the polymer system alone has little significance and therefore the CTE was considered of minor importance in resin selection when the initial chemicals were chosen.

A Specific Polymer System

Given the considerations just discussed, the resin system consisting of diglycidyl ether of bisphenol A (DGEBA) epoxy with 4,4-methylen-bis-3-chloro-2,6-diethylaniline (MCDEA) as the curing agent is a reasonable selection. Most commercial resins are a mixture of monomers. For consistent and uniform mirror properties we purchase purified reagents with a uniform molecular weight. In addition, the reactive diluent ED757 (cyclohexane dimethanol diglycidyl ether) is used to lower the viscosity of the mix. This polymer system requires up to 100 hours at 70 °C to reach gelation, thus allowing enough time for thorough mixing before pouring a layer of the mirror. The T_g for this combination is 137.9 °C.



DGEBA

MCDEA

ED757

Chemical structures of the three compounds used to make epoxy mirrors.

Equipment Design & Mirror Casting

Production of optical-quality liquid or solid spin-cast mirrors requires a smooth, vibration-free mechanism with a constant rotation rate. Our system has a spinning platform holding the epoxy container, a controller to precisely maintain the spinner rotation speed, and an oven to modulate the cure rate of the epoxy.

It took considerable time to design, manufacture, and install these components. While that effort was in progress, testing began with off-the-shelf hardware. Thus, the first generation mirrors were fabricated using a direct-drive record turntable with quartz crystal control as the spinner. The turntable supported an insulated platform that extended some distance through the bottom of an oven above the turntable. This platform protected the turntable from oven heat and also served as the support for the epoxy container. The oven was a conventional electric lab oven that was configured with its backside facing down and a circular hole cut through the back as the opening for the insulated platform. A number of 30 cm mirrors were produced with this system. However, the slowest rotation rate possible was 33.3 rpm, and this high rotation speed produced fast, f/1.3 mirrors that were difficult to test by the methods available to us.

First generations epoxy mirrors were manufactured on a record turntable using a conventional electric lab oven for the heat source.

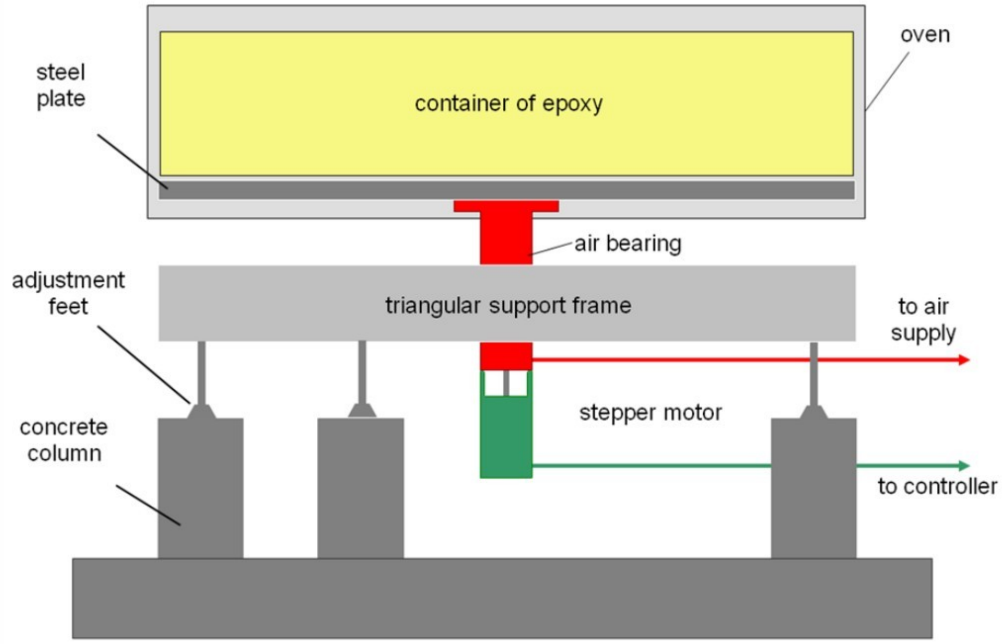
After the addition of a new quartz crystal control to the turntable, second generation mirrors were formed using a rotation speed of 19.2 rpm. These mirrors were no faster than f/4 depending on the diameter chosen. Over a dozen mirrors up to 30 cm in diameter were made with this arrangement as testing progressed using different formulations and additives, as well as the installation of the larger and more advanced spinner.

With additional hardware, the rotation speed for the second generation mirrors could be controlled leading to several f/4 30 cm epoxy mirrors.

The third generation mirrors were manufactured on our advanced spinner modeled after the one employed by Borra (1997). This spinner can fabricate mirrors up to 60 cm in diameter.

Left: Third generation mirrors were manufactured on more advanced equipment. The spinner consisted of a precisely machined stainless steel platter supported by a precision air bearing held in place by a triangular frame with three point support. Right: The hexagonal oven has a formaldehyde melamine insulation that protects the resistive heating elements located on three of the six sides.

In 2009 we developed a lab at Lander University in Greenwood, SC, to manufacture 2-meter mirrors. Just as with the third generation mirrors described above, this lab employs equipment modeled after the setups used for spinning the large liquid mercury mirror telescopes. There is an air bearing supporting a steel platter. The air bearing is driven by a stepper motor and speed controller and is held by a triangular frame resting on three cast concrete supports. Leveling mechanisms are installed where the triangular frame meets the supports.



Schematic showing the equipment used to make 2-meter epoxy telescope mirrors.

Lisa assembling the arms on the platter for spin-casting 2-meter epoxy mirrors. The oven panels with heating elements can be seen in the background.

Since gelation and vitrification occur above ambient temperatures, the platter and container of spinning epoxy are enclosed in an oven heated by electrical resistance and modulated by thermostatic controls. Since the mirror is built up from successively smaller pours of epoxy, the oven has a small opening in the top for adding epoxy while maintaining the temperature.

Kevin is on the catwalk above the oven for 2-meter mirrors pouring a second layer onto a mirror.

Epoxy has a relatively large CTE which comes into play when casting a mirror. Since the polymer system used needs a temperature of about 120 °C for vitrification, and since the material is a rigid solid of fixed shape when below that temperature, there is considerable thermal shrinkage as the mirror is brought back to room temperature. If the shape of the disk includes a flat bottom, the thinner center (due to the sagitta of the mirror) will contract less on cooling than the edge. In even modest size mirrors this differential shrinkage amounts to tens of wavelengths of visible light. Therefore it is clear to minimize this effect, the mirror must be a constant thickness meniscus similar to many glass mirrors.

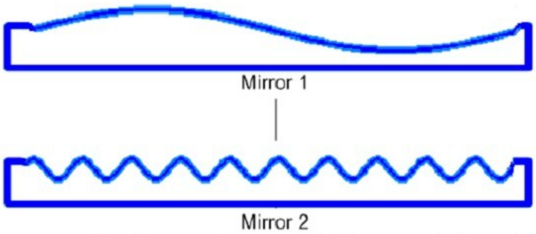
To this end, the container could have an insert of the correct curvature or could be filled with a liquid of greater density than the polymer to provide a parabolic bottom. A combination of these two approaches seems even better. A paraboloid bottom of epoxy could be spin-cast into the container. After curing, a relatively thin layer of liquid such as an ionic liquid, mercury or a bismuth casting alloy which melts below the gelation temperature could serve a uniform surface for spin-casting the epoxy mirror. Experiments with metal have shown that the thermal expansion of the metal as the oven is raised to T_g is a problem. The expansion of the metal can damage the figure of the mirror, thus a means of relieving this effect must be provided. Research into this approach is ongoing.

We have conducted a number of experiments with custom containers of various materials from metal lined with a plastic coating to containers machined from a solid block of polymer material. With the idea of producing mirrors of a meter or more, off-the-shelf containers of polyethylene, polypropylene, and Teflon FEP now seem the most practical.

Lisa and her student, Kevin, holding a 25 inch epoxy mirror. The oven for spinning 2-meter mirrors is in the background.

Theory and Optical Evaluation of Flux Collection Mirrors

While epoxy spin-cast mirrors may, after further development, end up being of high optical quality, to start with our intent is to develop a process for making very low cost mirrors of lower optical quality. These mirrors could be well-suited to astronomical tasks such as aperture photometry or spectroscopy that only require very modest spot sizes or even just on-axis light gathering. As quasi-imaging or non-imaging mirrors, their evaluation may benefit from using different figures of merit than the usual peak-to-valley (PV), Strehl ratio, or other common performance indicators. Specifically, what matters most for lower optical quality mirrors is the averaged local departures of the mirror *slope* from the slope of the desired perfect mirror surface, as those errors contribute directly to the size of the spot, more formally called the focal plane circle of confusion (Holenstein *et. al.* 2010). Mathematically, this measure is represented by multiples of the rms gradient norm, informally called the "rms slope" (S_{rms}), values which are often measured in radians. The rms slope for a mirror surface may be calculated from interferogram Zernike coefficients, or estimated from measurements of the encircled energy of the point spread function.



Cutaway side views (exaggerated) of two mirrors with the same PV and Strehl ratios. Mirror 2 has a larger spot size because the local rms slope errors from a perfect figure are greater.

For science applications, the full width half-maximum (*FWHM*) measure is often used to describe the PSF. It is related to the rms slope measure for a Gaussian PSF by this formula:

$$\textit{FWHM spot size} = 4.70 \text{ x } S_{rms}$$

Using this formula, one can calculate that one microradian rms slope produces a one arc second spot *FWHM*. A second formula serves as a rule-of-thumb:

$$\textit{FWHM spot size} \text{ (arc sec)} \approx 10^6 \; E/D,$$

where D is the telescope aperture, and the wavefront error, E, divided by D approximates the rms slope error. E is a function of the types of aberration present on the surface and may be calculated from the Zernike wavefront representation (Holenstein *et. al.* 2011). For example, one wave of astigmatism in the visible on a 1-m mirror corresponds to about an arc second *FWHM* spot. Note that higher-order aberrations scatter flux more than lower-order aberrations of the same magnitude and the exact formula for a particular aberration type differs by a constant. It is often useful to work in reverse and measure the *FWHM* from a CCD image of a star and calculate the rms slope value for the mirror as a specification for mirror quality.

Initial Optical Testing and Results

The optical testing of astronomical mirrors is a mature field with textbooks detailing procedures as well as advantages and disadvantages of the different methods. Thus our task seemed to be a simple matter of method selection and implementation. We sought to evaluate surface characteristics and surface figure. In addition, budget constraints dictated a simple test that could be accomplished quickly and easily with the equipment on hand or constructed in our shop. The test had to be easily adapted to mirrors with a range in sizes and focal lengths. For initial testing, methods based on interference were eliminated because of their complexity and cost. After simple visual inspections, the methods deemed most practical and cost effective for our purposes were the Ronchi test (Cornejo-Rodrigues 1992), the Foucault test (Texereau 1984), and a modified version of the Hartman test (Suiter 1994).

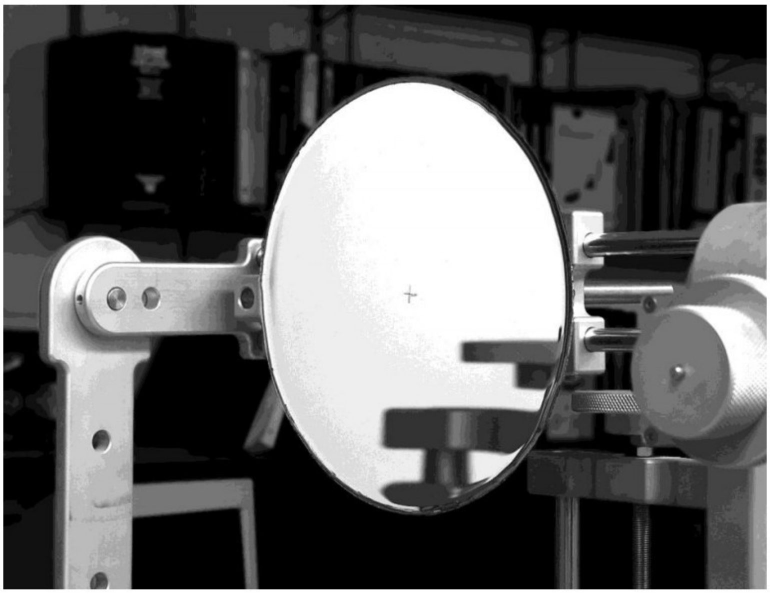
Terry in the optics lab preparing to test a 0.5 meter epoxy mirror.

Visual inspection

With the first mirrors, a crude evaluation by visual inspection was possible. Surface defects and distortion of the surface were visible by eye, while improvements could be gauged by comparing subsequent mirrors to earlier ones. As the fabrication methods improved, observation of the image in a Newtonian telescope gave the impression of a fine image buried within a halo of unfocused light. An examination of the point-spread function (PSF) confirmed this impression. The complete PSFs were quite large, measuring some minutes of arc across, rather than seconds of arc; however, there was an irregular core to the PSF that extended seconds of arc across. Whether the large halo was scattered light due to surface effects, or unfocused light due to figure errors, or a combination of the two was unclear. Since the reflections from the surface of these mirrors seemed flawless when examined outside the telescope, the suspicion was that figure errors created the large PSFs.

Test Chart Imaging

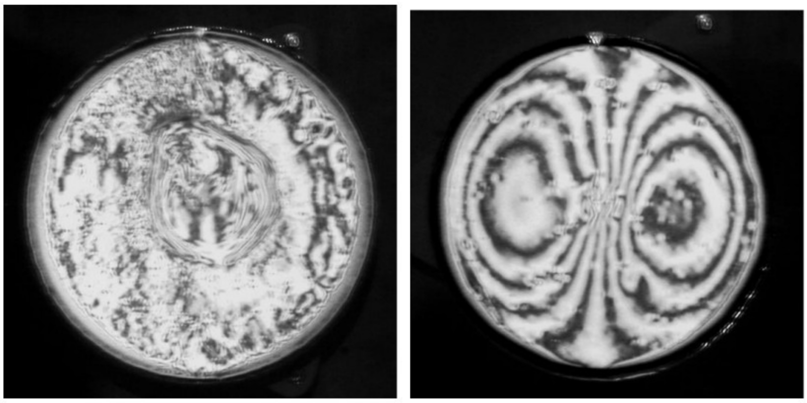
In order to quantify improvements in mirror quality while other testing methods were being prepared, we mounted mirrors into a Newtonian telescope on the optical bench and measured image resolution using a standard bar test-chart (USAF 1951) situated outside the lab window on an adjacent building. The distance was sufficient so that spherical aberration was minimal, although all observations were conducted through the window glass. The image was magnified by eyepiece projection and observed with a video camera, with output directed to a computer. Images were recorded by frame grabbing from the video feed. Outside environmental effects and the window glass limited the utility of this approach and it was discarded after work with only a few mirrors.



Testing a 20 cm epoxy mirror on the optical bench at the University of South Carolina where the initial research of spin-cast epoxy mirrors began under the supervision of Walter Scrivens.

Ronchi Testing

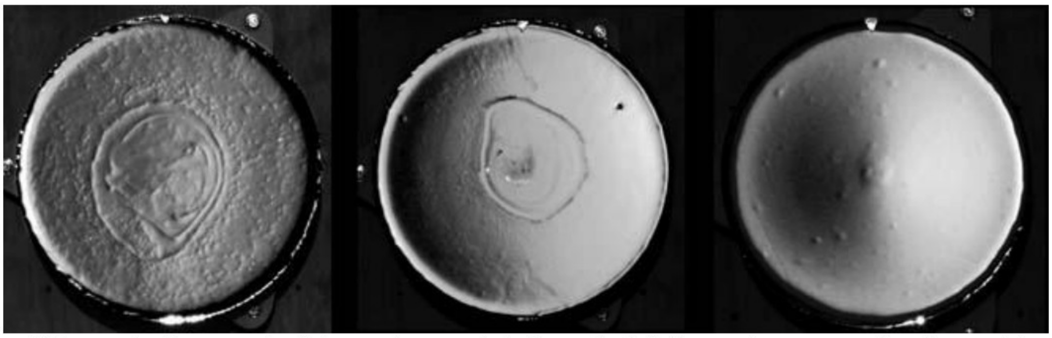
The Ronchi test with a diffused yellow LED source and 50 to 150 line screens in a double pass arrangement proved informative. Some mirrors failed to produce a Ronchi pattern, however analysis of these results enabled us to identify and correct a variety of surface effects discussed later in this paper. Some mirrors showed a coherent Ronchi pattern over only a few localized regions. One such mirror was installed in a telescope with a mask covering the mirror except where the Ronchi test indicated continuity. This telescope permitted visual observation of large craters on the Moon and the Galilean moons of Jupiter, although the image quality fell below that expected in a first-quality scope. The latest mirrors show a classic aspheric Ronchi pattern broken up by the occasional surface defect usually caused by dust that bypassed our filtering process. Unfortunately, the simple Ronchi test could not provide details on the surface figure.



The left frame shows an early mirror, the right frame shows a mirror after some improvements in technique. Since a spherical surface would show linear parallel bands in the Ronchi test, the surface of the mirror is clearly aspheric. The effects of dust on the surface can also be seen in the photograph.

Foucault Testing

Like the Ronchi test, the Foucault provided useful information about the mirror surface and helped identify several problems.



A Foucault photograph of three mirrors. As before, the left frame shows an early mirror with multiple problems. The middle frame shows an improved mirror as manufacturing problems were corrected, while the final frame shows a more recent mirror with a relatively smooth surface, thus underscoring the progress made to date.

Three surface defects were identified. First, there were perturbations of the surface caused by oils from the container having persisted through all the applied layers of polymer to affect the final surface. Changing the composition of the container eliminated that difficulty, though initially it introduced another problem (see the next section). Secondly, the test revealed regions of surface damage due to sputter on the surface from heating the aluminum too rapidly during the vacuum coating process after the epoxy mirror was made. Making adjustments in the coating method and reducing the rate of aluminum deposition rectified that difficulty. In addition to the localized effects due to sputter, visual inspection revealed something about the surface not recorded in a photograph. In the Foucault setup, the surface had an appearance of harshness or brightness that was not visible in mirrors after the aluminizing process was changed or in aluminized glass mirrors. The third surface problem was from dust settling on the casting surface. That problem is solvable simply by removing all dust from the casting environment.

The Foucault test requires some skill for quantitative measurements and, even with a Couder screen, tests of our mirrors did not give meaningful results for reasons we understood later. Tests of a commercially produced fast paraboloid verified our methodology, so we turned to the Hartman test, which we modified for our purposes.

A Modified Hartman Test

In the conventional Hartman test, a disk with regularly spaced openings is placed over a mirror. A light source is located near the center of curvature (CoC) and the mirror is photographed twice, once with the film plane (or CCD) inside the CoC and the other with it outside. The geometry of the test allows the calculation of the surface slope at each point on the mirror, illuminated by an opening and, by numerical integration, the surface shape.

We determined for some of our mirrors that the Hartman test performed at the CoC would be problematic. Some mirrors had a caustic curve that folded back on itself over the range of longitudinal aberrations. This condition means the caustic horn opened away from the mirror, then moved back toward the mirror before it opened outward again. This aspect of the caustic horn would cause ambiguities in identifying the photographed spots in the test. We now know that these characteristics are what made the Foucault results so strange.

For these reasons, we performed the Hartman test with a linear screen consisting of two small (2 mm) movable openings. Each opening was set the same distance from the mirror center and the openings observed at the CoC with an eyepiece. We recorded the position where the images of the openings were superimposed. From the geometry, we calculated, using an Excel spreadsheet, the slope and surface figure just as in the conventional Hartman test. A paper detailing this testing approach is in preparation (Richardson).

By measuring the longitudinal aberrations using this hybrid test, a graph is provided by plotting the value of the mirror surface minus the ideal parabola's surface. A perfect mirror in this analysis would graph as a straight horizontal line. All the mirrors produced from this mold have results with this same general form: a center depressed by tens of wavelengths, a level region with a surface deviations less than 0.1 λ (where 1.0 λ = 500 nm), and an outside edge that is turned up.

The center depression was perplexing at first until we realized the depression resulted from the changes in container composition that unwittingly led to changes in mold form as well. The mold was machined out of a solid block of metal with angled sides. The mold unfortunately was deeper than necessary at the center and resulted in mirrors with the center half of the mirror being thick, which tapered to zero at the edge. Since the mirrors are solidified at higher temperatures, there is thermal contraction when they are brought to room temperature. Rough calculations show that the center depression is equal to the shrinkage expected for the given temperature change. Mirrors made prior to the mold change did not show this central depression. Mirrors produced in a new mold are expected to verify this idea.

The parabolic portion of each mirror indicated by the level portion of the graph is a very good parabola. The test indicates surface deviations are less than 0.1 λ. The surface could be better than those measurements indicate. One early mirror sent to an outside lab for testing shows rms surface variations of 0.01 λ. If the upcoming tests indicate a resolution of the central depression problem, then we are ready to scale up to meter class mirrors.

Telescope Testing

Given the apparent quality of the parabolic region, the best mirror to date was installed in a Newtonian telescope for observations and photography. The mirror was fitted with a mask which covered the central depression and the turned up outside edge, leaving exposed only an annulus which contained the parabolic region. Below is a photograph of the Moon with all the common features of our satellite easily identifiable. This photograph was produced by the afocal method with an unguided telescope. The moon was allowed to drift through the field of view and the photograph was obtained as the moon crossed the center of the field of view. The image was adjusted for brightness and contrast but no other image enhancements were applied.

To estimate the resolution of this mirror, craters were identified along the terminator and their sizes recorded if they were under 25 km in diameter. These craters are listed in Table 1. The average value for the crater size was 17 km corresponding to a resolution of 9.0 arc seconds.

The waxing gibbous moon photographed using an epoxy mirror.

Crater Name	Diameter (km)	Resolution (sec of arc)
Birt	17	9.1
ThebitA	21	11
Lelande	24	13
Mosting A	13	6.9
Ammonius	9	4.8
Average	17	9.0

Identified craters on the moon and their diameters are used to estimate the resolution of an epoxy mirror.

Potential Additional Optical Evaluation

A formal program is contemplated to characterize progress by additional repeatable means in the laboratory and field. We plan to supplement the above measures with interferograms taken at various temperatures and orientations (i.e. the mirror rotated at various angles) and reduce the measures with *OpenFringe*, an open source interferogram analysis program. The analysis software will provide PV, Strehl ratio, rms surface error, and Zernike coefficient measures. The size of the PSF will be estimated from these measures and verified by actual images of stars in the field. If the larger mirrors have such large aberrations that an interferogram of the entire surface is impossible, then interferograms of smaller regions may be made and a stitching process may be used to characterize the surface quality (Holenstein *et. al* 2010).

Design of Lighter Weight Mirrors

For several reasons, it is important that mirrors be designed with the lightest weight possible while satisfying constraints on performance and cost. For larger mirrors, the forces of gravity tend to distort the mirror's shape as a telescope points at different altitudes; a high ratio of stiffness to weight is needed to minimize this effect. Heavier mirrors must be supported by stiffer and hence heavier telescope structures; this greatly increases the cost of the structures. In addition, the costs of manufacturing and shipping mirrors increase with mirror weight; and for telescopes which are intended to be portable, system weight is of great importance.

Currently we are investigating several design methods for lightweight epoxy mirrors. In the first method, a lightweight spin-cast face sheet could be glued to a ribbed core and bottom plate formed of fiber reinforced epoxy or other suitable material. Several problems must be addressed in order for this method to work. The process of gluing the face sheet to the support structure must be accomplished in such a way that stresses will not be introduced which warp the face sheet. Such stresses could be caused by shrinkage of the adhesive during curing, by uneven support of the face sheet or the support structure while the adhesive cures, or by thermal expansion or contraction of either component.

A second problem is that differences in the coefficients of thermal expansion between the face sheet and support structure will cause distortion of the mirror while it is in operation. Although fiber reinforced epoxy can be much stiffer than unreinforced epoxy, the coefficient of thermal expansion is generally much lower than that of unreinforced epoxy, and this difference in expansion rate causes the distortion. A possible solution to this problem is to place a very thin meniscus epoxy mirror on a support structure separated by a thin layer with give. This layer could possibly be an ionic liquid. Ionic liquids are becoming more popular and are now being used for applications such as engineering fluids, electrolytes, liquid crystals, and catalysts and solvents for chemical reactions. It has also been proposed to use ionic liquids as a surface upon which to spin mercury mirrors for lunar telescopes (Borra *et.al.* 2007),

An alternative would be to spin-cast a mirror with the appropriate thickness and then remove material by machining from the rear of the mirror, producing a ribbed support structure in that manner. Given the low hardness of cured epoxy, removing material would be relatively easy. If there were no significant residual stresses in the body of the mirror, the machining should not have an adverse affect on the mirror's surface figure, as long as the machining process does not cause a great deal of heating of the material or cause large residual stresses in machined surfaces due to the cutting action. However, a machining process which minimizes heating and residual stresses in the machined surface generally tends to have low feed rates and utilize liquid cooling, making such machining slow and expensive. Furthermore, casting such a thick mirror without introducing significant residual stresses may not be possible, as heat produced by the exothermic curing process cannot easily be conducted out through a large thickness; a process in which a much thinner layer is spin-cast will most likely be preferred.

In order to mitigate problems and costs due to machining, the mirror could be cast with blocks of polystyrene foam occupying the volumes from which epoxy would otherwise be removed by machining; then the foam blocks could be dissolved away with solvent. In this method, which is similar to that commonly used to spin-cast borosilicate mirror blanks, a system of voids is created with ceramic fiber core boxes that protrude into the glass during casting, and the mirrors are cooled at a very slow rate. The rate of cooling of glass mirrors can be adjusted to be as slow as needed (within reason) to reduce residual stresses.

As stated above (see section on polymer system selection criteria) the polymerization rate can be controlled simply by tuning the cure process, and when the epoxy mirror is complete, a long cooling period allows us to control some of the residual stress that is built up. In addition, the chemistry can be modified by incorporating ring systems into the polymer system that will open up during the curing reaction. This expansion has the potential of counteracting the shrinkage induced in the cooling period.

Glass mirror materials can be chosen with a near-zero coefficient of thermal expansion. Likewise, inorganic materials which have a negative coefficient of thermal expansion can be incorporated into the epoxy mixture to reduce its large CTE. However, those who spin-cast glass mirrors have an advantage because glass mirrors are ground and polished after casting, removing the effect of any "print through" of support ribs to the outer surface; not so with epoxy mirrors, for which optical figuring methods have yet to be developed—and in any event would be so expensive as to negate the advantages of spin-casting if used. Calculations show that differential thermal shrinkage in unmodified epoxy mirrors during cooling from the cure temperature to the operating temperature would result in a "print through" of the ribbing pattern of the cores. Thus casting a ribbed backing with an unmodified epoxy mirror seems problematic.

One other method for producing lightweight epoxy spin-cast mirrors would involve the construction of a fiber-reinforced epoxy structure by a traditional method such as casting, wet layup, or resin infusion molding; to this structure would be spin-cast a very thin layer of epoxy which would form the optical surface. In one proposed implementation, the mirror's base structure would be cast from epoxy reinforced by milled fibers, using foam blocks as previously described to produce the desired structural shape. The top (mirror side) of the base structure would be molded into a shape as close to the desired optical surface as possible, and the layer of epoxy spin-cast atop the base structure would be the thinnest layer which could reliably form an optical surface to the needed accuracy, given the effects of surface tension and differential thermal expansion. Because the surface layer would be very thin, its thermal expansion would not significantly affect the shape held by the thicker support layer—a situation somewhat similar to a thin reflective layer of aluminum on a glass mirror. The most serious concern for this method is that if the coefficient of thermal expansion of the unreinforced epoxy surface layer is much higher than that of the carbon or glass fiber reinforced epoxy base, when the mirror is cooled from its curing temperature to operating temperature, the surface layer may delaminate or crack. Therefore, investigating the potential of lowering the CTE of the epoxy is most important.

Conclusion

Although still experimental, the development of spin-cast epoxy mirrors has made real progress in the past several years. Given even modest success with the light weighting approaches we are investigating, a 2-meter spin-cast epoxy mirror should see “first light” in a portable, on-axis, light bucket telescope within a year or two. As our techniques for making spin-cast epoxy mirrors continue to improve, so should the optical quality of these mirrors. We anticipate that there will be many applications for these lightweight, low cost mirrors in astronomy and perhaps other applications.

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References

Alvarez, D., M. Dragovan, G. Novak. 1993. Large Off-Axis Epoxy Paraboloids for Millimetric Telescopes and Optical Light Collectors. *Rev. Sci. Instrum.* 64, 261.

Archibald, P. 1957. A Method for Manufacturing Parabolic Mirrors. *J. Solar Energy Science and Engineering*. 44, 669.

Bely, P. 2003. *The Design and Construction of Large Optical Telescopes*. New York: Springer.

Brodhacker, K. L., G. Harris, B. Holenstein, S. Venkateswaran, and R. Genet. 2011. Non-Vacuum Silvering and Overcoating of Telescope Mirrors. *Amateur Astronomy,* #70.

Borra, E. 1982. The Liquid Mirror Telescope as a Viable Astronomical Tool. *J. Roy. Astron. Soc. Can.* 76 (4) 245.

Borra, E., M. Ferrari, L. Girard, B. Moretto, and G. Tremblay. 1997. Liquid Mirrors, A Progress Report. *Proc. SPIE*. 2871, 32611.

Borra, E., O. Seddiki, R. Angel, D. Eisenstein, P. Hickson, K. Seddon, and S. Worden. 2007. Deposition of Metal Films on an Ionic Liquid as a Basis for a Lunar Telescope. *Nature.* 447, 979.

Cornejo-Rodrigues, A. 1992. Wavefront Slope Measurements in Optical Testing, in *Optical Shop Testing*, ed. D. Malacara. New York: John Wiley and Sons, 321.

Genet, R., A. Aurigema, M. Bartels, K.L. Brodhacker, R. Canesstrari, P. Chen, M. Connelley, D. Davis, G. Jones, T. Liu, E. Mendez, T. Richards, D. Rowe, J. Schmidt, K. Shah, and E. Villasenor. 2009. Lightweight Mirror Developments. *Proceedings for the 28th Annual Conference of the Society for Astronomical Sciences.* Big Bear Lake, CA.

Genet, R., A. Henden, and B. Holenstein. 2010. *Light Bucket Astronomy,* in Society for Astronomical Science 2010 Symposium Proceedings.

Genet, R., D. Rowe, D. Gray, and 22 co-authors. 2010. The Small Research Telescope Challenge. *The Astronomy and Astrophysics Decadal Survey,* Position Paper 17. National Academies of Science.

Hass, E. and W. Erbe. 1954. Method for Producing Replica Mirrors with High Quality Surfaces. *JOSA*. 48, 86.

Hickson, P. and K. Lanzetta. 2004. Large Aperture Mirror Array (LAMA): Project Overview. *Proc. SPIE.* 5382, 115.

Hill, J., J. Angel, R. Lutz, B. Olbert, and P. Strittmatter. 1998. Casting the First 8.4 Meter Borosilicate Honeycomb Mirror for the Large Binocular Telescope. *SPIE Proc. On Advanced Technology Optical/IR Telescopes IV.* 3352, 172, Kona, HI.

Holenstein, B., R. Mitchell, and D. Holenstein. 2011. Aberration Theory and Prototype Mirror Experiment, presented at the *2010-2011 Alt-Az Initiative Hawaii Conference on Light Bucket Astronomy*. http://starsociety.org/Word%20Documents/PdfsLBConf.2010/Hawaii.LBA2010-11.Aberration&ProtoMirrors-Holenstein.pdf

Holenstein, B., R. Mitchell, and R. Koch. 2010. Figures of Merit for Light Bucket Mirrors, in *The Alt-Az Initiative: Telescope, Mirror, and Instrument Developments*, eds. R. Genet, J. Johnson, and V. Wallen. Santa Margarita, CA: Collins Foundation Press.

Lindblom, P. and B. Sandberg. 1980. A Method for Producing Concave Paraboloidal Mirrors. *Physica Scripta*. 21, 828.

Neugebauer, G. and R Leighton. 1968. Two-Micron Sky Survey: A Preliminary Catalog. *Scientific American*. 219, 51.

Ninomiya, Y. 1979. Parabolic Mirror Made by the Rotation Method: Its Fabrication and Defects. *Applied Optics*. 18, 1835-1841.

Richardson, R., and P. Griffiths. 1997. Retroreflectors for Open-Path FT-IR. *Proc. Optical Sensing for Environmental and Process Monitoring.* O.A. Simpson ed., 50-54, VIP-67.

Richardson, T. and K.L. Brodhacker. Optical Shop Testing of Epoxy Telescope Mirrors. In preparation.

Russell, J. and A. Lee. 1997. Effect of cure cycle on the specific volume of 3501-6 epoxy. *29th International SAMPE Technical Conference*. October28-November 1, 289.

Schmidt, F. 1966. Electroforming of Large Mirrors. *Applied Optics*. 5, 719.

Schoch, K., P. Panackal, and P. Frank. 2004. Real-time measurement of resin shrinkage during cure. *Thermochimica Acta*. 417, 115.

Suiter, H. 1994. *Star Testing Astronomical Telescopes*. Richmond VA: Willmann-Bell.

Texereau, J. 1984. *How to Make a Telescope*. Richmond VA: Willmann-Bell.