

Lightweight Mirror Developments

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Abstract

One goal of the Alt-Az Initiative is the development of transportable 1.5 meter class research telescopes. To this end, several Initiative members are developing lightweight, low cost, primary mirrors. Both multiple and single mirror telescope configurations are being considered. Thin meniscus mirrors are being slumped, and approaches for actively correcting these thin mirrors are being investigated. Sandwich mirrors with glass spacers and others with Foamglas cores are under development. Nanocomposite, polyurethane, and glass replica mirrors, which do not require optical grinding or figuring during production, are being evaluated. Finally, spin-cast polymer mirrors are being explored. Although several of these mirror developments are still very experimental, and some may only be useful in optically undemanding applications such as on-axis aperture near IR photometry or low resolution spectroscopy, it is our hope that these efforts will enable the development of transportable, low cost, lightweight, 1.5 meter class telescopes.

1. Introduction

The Alt-Az Initiative (www.AltAzInitiative.org), launched in June 2007 at workshops in Portland and San Luis Obispo, is a catalyst for the development of lightweight, low cost modest aperture (2 meters and less) alt-az research telescopes. To date the Initiative has convened two full conferences and eleven workshops, launched or completed twelve technical initiatives, and this fall will release an edited book, *Lightweight Alt-Az Research Telescope Developments* (Genet et al., 2009). Many of the topics discussed below will be covered in greater detail in this book.

The Initiative's first alt-az technical demonstration telescope, the Cal Poly 18, recently saw first light. It has no gears, belts, or friction wheels; instead it incorporates direct drive motors and high resolution

encoders into the telescope's structure. The structure, designed by California Polytechnic State University students using finite element analysis, has an unusually high natural frequency. The use of direct drives combined with a stiff structure counters wind gusts.

In May 2008, the Alt-Az Initiative issued a challenge to develop lightweight, low cost, 1.5-meter, transportable telescopes that could, as a minimum, produce useful scientific results in at least one area of research. We reasoned that the cost, aperture, and transportability requirements were difficult enough to require the innovative application of technology, yet not so difficult as to discourage a spectrum of low-budget efforts to meet this challenge. Key is the development of lightweight, low cost primary mirrors. This paper, with an eye on the 1.5 meter challenge, discusses a number of approaches undertaken by Initiative members to reduce mirror weight and cost.

We recognize that some of the primary mirror approaches we are investigating will only be applicable to less demanding, dedicated, special-purpose research telescopes, and in all likelihood will not meet the stringent demands of high optical quality, general purpose telescopes. Telescopes that must perform well across a wide range of instruments/scientific programs – including some that are optically demanding – may inherently be more expensive than specialized telescopes dedicated to less optically demanding programs. There is, for example, a world of difference between 1.5-meter telescopes intended for high quality, wide-field imaging that requires sub-arc second image quality, and telescopes dedicated to on-axis applications such as near IR aperture photometry with a 1 mm diameter photodiode or low resolution spectroscopy. Initiative members have an interest in both high and low optical quality telescopes, and both are being pursued.

2. Multiple Mirrors

The weight and cost of mirrors is roughly proportional to the third power of their aperture, while their light gathering area is, obviously, only proportional to their second power. Thus, other things being equal (including equivalent light collecting area), a telescope with multiple smaller mirrors will have mirrors that, in total, are lighter in weight and lower in cost than a telescope with a single large mirror – a fact not overlooked by the Keck, Thirty Meter, Giant Magellan, and other large telescope designers. Of course multiple mirrors create serious complications, and that is why they have rarely been used in 1-2 meter class telescopes. Initiative members are considering two multiple mirror approaches – one with multiple independent optical systems on the same mount (requiring multiple instruments or fiber feeds), and the other with multiple mirrors bringing light to focus on a single instrument or fiber feed.

2.1 Multiple Foci

Josh Schmidt, a mechanical engineering student at California Polytechnic State University, used finite element analysis to design the optical tube assembly for a “four shooter,” 1.5-meter telescope. Each $f/3.5$ mirror was 0.75 meters in aperture – well within the state-of-the-art for affordable, lightweight mirrors.

Two instrumental modes were considered. In one mode, the primary mirrors were fixed in position with cameras placed at each of the four prime foci. Such a system could be used for simultaneous four color photometry or, alternatively, single color photometry with co-added images.

In the other mode, either the four primary mirrors or four small steering mirrors were tip/tilted to compensate for differential flexure between the four optical systems as the telescope changed altitude. In this mode, each optical system needed to have its own autoguider. A 1.5-meter equivalent “four shooter” could, for instance, feed an off-telescope spectrograph with four fibers aligned along the spectrograph’s slit for optical efficiency (Barry, 1995).

One objective of Schmidt’s (unpublished) analysis was to determine if the optical paths for multiple fiber feeds could be kept sufficiently aligned with fixed primary mirrors in a rigid structure to avoid the need for tip/tilt adjustments. Schmidt concluded this would be difficult, although his analysis did not entirely rule it out.

2.2 Single Focus

More traditionally, many multiple mirror telescopes bring light to a single focus to avoid the difficulties inherent with multiple instruments. To achieve the highest possible resolution (approaching the theoretical limit for their aperture), large multiple-mirror telescopes at prime mountaintop sites require their multiple primary mirrors to be co-aligned with a precision that maintains optical coherence, a demanding and expensive undertaking.

At less than pristine sites and, especially for less optically demanding dedicated applications such as on-axis aperture photometry or low resolution spectroscopy, there is no reason to maintain optical coherence – the resolution of a single mirror is more than sufficient for the task at hand. Similarly, while many general-purpose telescopes strive for wide fields-of-view, specialized telescopes may only require a very narrow, essentially just on-axis field-of-view.

High quality, large aperture, multiple mirror telescopes utilizing matching sets of aspheric primary mirrors, such as off-axis paraboloids, are difficult and expensive to manufacture. Multiple spherical primary mirrors, on the other hand, are relatively easy to produce, although the individual mirrors still need to be tip-tilted with considerable precision. Furthermore, the sizeable spherical aberration produced by a large effective aperture spherical primary with a fast effective primary f /ratio needs to be corrected – a difficult task for large fields-of-view. A spherical primary with aspheric secondary optical configuration, such as used in Pressman Carmichael systems, can produce reasonably wide fields-of-view, although the convex aspheric secondary is somewhat difficult to produce. However, if only a very narrow, prime focus, field-of-view is required, then a two-element, all-spherical surfaces refractive corrector can provide

sufficient correction at an affordable cost. Initiative member Dave Rowe has designed such a corrector for a 1.5-meter, $f/3.5$ telescope.

3. Meniscus Mirrors and Active Optics

Small telescope opticians have extended the routine production of 2-inch thick Pyrex glass to 32-inch diameter mirrors as fast as $f/3.5$. Such Pyrex mirrors have been pushed experimentally to an aperture of 48 inches and as fast as $f/3.0$. Although eminently suitable for multiple mirror 1.5 meter telescopes (such as one with four 30 inch mirrors), these Pyrex mirrors may not be suitable for single-mirror 1.5 meter telescopes because Pyrex sheet widths are normally limited to 48 inches and, of greatest import, a 60-inch (1.5 meter) two-inch thick Pyrex disk weighs about 600 pounds – not exactly lightweight.

Initiative members are working on an alternative that may overcome these difficulties by switching from Pyrex to ordinary soda-lime float glass (plate glass) and limiting mirror thickness to $\frac{3}{4}$ of an inch or, at most, 1 inch. Plate glass is low in cost, readily obtainable, and can be purchased in widths up to 96 inches. Of course a 60-inch mirror only 1 inch thick is very floppy and will almost certainly require active control of some sort to maintain its shape.

3.1 Slumped Float Glass Mirrors

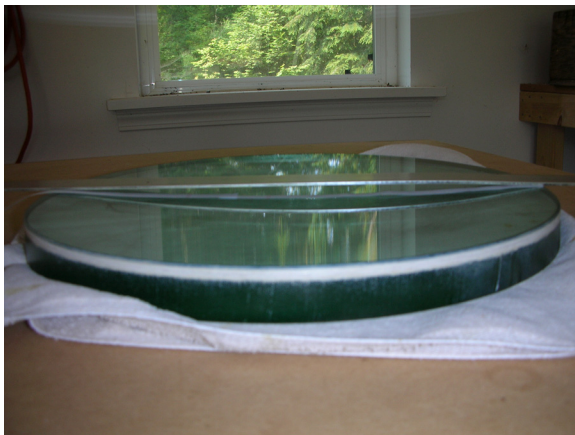


Figure 1. Deep sagitta plate glass $f/3$ mirror. An amateur slumped the blank in his home-made kiln.

Initiative member David Davis, using low cost and easily constructed kilns he designs and builds himself, has worked out a process to slump common plate glass “table tops.” A 60 inch diameter, $\frac{3}{4}$ inch thick glass disk from Glass Tops Direct costs \$374 plus \$135 shipping, and weighs about 200 pounds.

Initiative member Mel Bartels suggests that meniscus plate glass (soda lime float glass) mirrors rep-

resent a new approach for large, fast telescopes. The synthesis of thermally controlled mirrors (fans), inexpensive plate glass, and computer controlled kilns for slumping is producing promising results.

Meniscus mirrors, other things being equal, are significantly stronger than flat back mirrors. Consider a piece of paper – it is very floppy. Contrast it with a coned shaped coffee filter, which is very strong. A 12 inch standard thickness Pyrex mirror is often used with a 9 point back support. A 13 inch diameter 1 inch thick meniscus mirror needs but a 3 point back support as determined empirically with a star test at a 1 mm exit pupil. Meniscus mirrors can be slumped to very fast speeds, maintaining constant thickness from center to edge.

Compared to Pyrex, plate glass mirrors are an order of magnitude less costly. Thin plate glass meniscus mirrors can be cooled rapidly with a fan, reaching equilibrium in minutes. However, plate glass mirrors have a pejorative reputation which may hamper their widespread adoption. They are difficult to figure due to their sensitivity to small temperature changes. These mirrors require aggressive measures to keep them at ambient temperature to properly test them. On the other hand, plate glass does grind and polish quicker than Pyrex, and some commentators state that it takes a better polish with less scattered light.

3.2 Active Primary Mirrors

As apertures increase, the downside of large aperture, lightweight, thin meniscus mirrors is that at some point they require active support. While such support is, obviously, a complication, the actual cost may be modest, and actively supported thin meniscus plate glass mirrors may be a cost-effective approach to achieving large apertures in lightweight, transportable telescopes.

Initiative member Mike Connelley has developed an “active” mirror cell for an 8-inch, $f/4.5$ plate glass mirror that is $\frac{1}{2}$ inch thick. His goal was to determine whether he could correct astigmatism and perhaps a few higher order aberrations (such as trefoil) by hand. To this end he built a very simple warping cell. He reasoned that if he could warp the mirror to compensate for the astigmatism in his eyes, then he might be able to compensate for the warping of a much larger mirror due to changes induced by gravity loading.

His mirror is glued onto 8 aluminum pads with silicone adhesive. Each of 8 screws is threaded through a hole near the tip of each of 8 wooden fingers. The head of each screw is captured in the aluminum pads so that each screw is free to turn inside the pad but can't move around (side to side or in and out). Each pad is made of two plates. The lower plate

(cell side) has a large countersunk hole for the machine bolt head. The upper plate (mirror side) glues to the top to trap the bolt head. Turning the screw changes the separation between a wooden finger and the mirror, deflecting the finger. The spring force made by deflecting a finger applies a force to the mirror via the screw connecting them.



Figure 2. Mike Connelley's manually adjusted active primary mirror. Note the 8 wooden flex fingers.

Connelley's experiment was just a quick, low cost demonstration on a small telescope. Implementing active control "for real" on a big mirror would be more complex. For example, the warping plate probably wouldn't be just a chunk of plywood with N fingers sticking out. There might need to be an inner ring of actuators. In Connelley's experiment the screws carried the full weight of the mirror even when the scope was pointed horizontally (i.e. when the mirror was vertical), so that the force on the screws was perpendicular to the screws. Although this wasn't unreasonable for an 8-inch mirror, it probably would not work for much larger mirrors. A sling or other radial support system would be required. Finally, it would probably be inappropriate for a large research telescope to utilize hand adjustments. Such adjustments could be made via motors turning screws, or by forces imposed on the mirror via "voice coils," i.e. linear motors.

We are only concerned with making very low frequency (much less than once per second) adjustments of primary mirrors to correct for the lower order Zernike terms, especially astigmatism as altitude changes. The requisite adjustments could be determined by observing "off-line" a number of bright stars distributed in altitude using an automated coefficient determination algorithm that minimizes the spread of the stellar image. During operation, the current altitude of the telescope would be noted, and the required settings interpolated from a lookup table.

This approach is used by the eight-meter Subaru telescope with recalibration of their table only required about once a year.

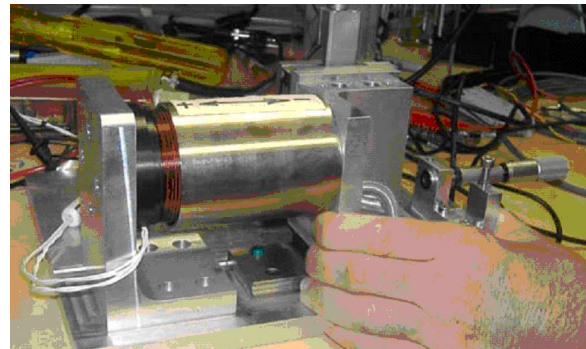


Figure 3. Gemini active mirror voice coil. Genet visited to Gemini to discuss active mirror support with control systems engineer Chris Carter.

Two undergraduate electrical engineering students at California Polytechnic State University, Eric Mendez and Efrain Villasenor, are currently developing low cost electronic controls for voice coil meniscus mirror adjustment that features both hand pad and computer (PC) control of D/A converters that translate interpolated digital values from a look up table to analog signals. These analog signals are amplified by power operational amplifiers that drive the active mirror's voice coils.

3.3 Active Auxiliary Mirrors

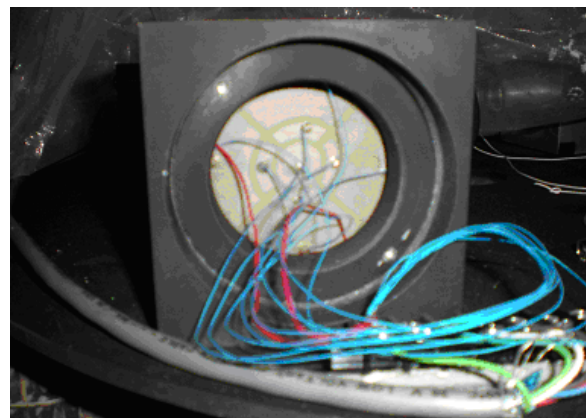


Figure 4. Rear of Greg Jones' semi-passive bimorph mirror. Wires are connected to individual sectors.

Initiative member Greg Jones is working on an entirely different approach to active optical correction: a small, semi-passive bimorph mirror. Instead of using actuators to apply forces directly to the primary mirror itself, a much smaller, semi-passive bimorph mirror near the instrumental payload is distorted via applied voltages in a manner that cancels out the

gravity-induced distortions in a lightweight primary mirror. These corrections can be applied via a lookup table versus altitude as discussed above.

Bimorph semi-passive mirrors consist of two thin disks: one an active piezoelectric material coated with a thin layer of conductive metal on each side, and the other a thin front surface mirror. The two disks are bonded together with a low shrinkage adhesive. The metal coating on the back of the piezoelectric disk is divided into sections. When a high voltage (100-350 volts) is applied to these sections, the piezoelectric material in each section contracts or expands an amount dependent on the applied voltage and its polarity. The combination of these expansions and contractions warp the thin mirror disc in a modal manner. A computer controls these voltages through digital-to-analog converters and high voltage operational amplifiers.

4. Glass Sandwich Mirrors

A sandwich mirror can be thought of as thin meniscus mirror that has been sliced in half to form two very thin disks. When these two disks are separated by lightweight glass spacer material of one sort or another, the resulting mirror can be as stiff as a conventional “full thickness” mirror, yet as lightweight as a thin meniscus mirror. The potential advantage of sandwich over meniscus mirrors is that while their structure is more complex, they should not require active support. Initiative members have been pursuing two types of glass sandwich mirrors: one uses small-diameter, solid glass disks as the spacers, while the other, still very experimental, uses a lightweight glass foam spacer.

4.1 Fused Sandwich Mirrors

Ritchey made the first “fused” mirror, an egg-crate structure – just one of his many innovations. The Hubble Space Telescope features what is, perhaps, the most famous fused mirror. Hextek mirrors are made from hollow glass tubes stacked between two thin glass plates. The entire assembly is fused together in a kiln while injecting gas under pressure into the tubes which, when molten, fuse together into hexagonal shapes – hence the company’s name. While fused mirrors are lightweight, they are not generally low cost due to their intricate nature.

Initiative member Tong Liu has developed an unusually simple, low cost, lightweight sandwich mirror blank which is comprised of an optical front plate, a backing plate, intermediate reinforcing plate(s) if needed, and many small, identical disk-support spacers between the plates. The plates and

spacers are all made from readily available and low cost soda lime float glass. The entire assembly is slumped and fused together in a kiln. By using the same low cost material for all the plates and spacers, a mirror blank of essentially any size up to the width limit of the basic material (96 inches) can be constructed. A key feature of Liu’s approach is the use of thin plate glass material throughout the mirror in order to obtain favorable thermal performance.

Currently the size of Liu’s sandwich mirrors is limited by his kiln and polishing machines to 20 inches. However, he is developing mirrors up to 40 inches in diameter, and a 60 inch sandwich mirror is not out of the question.

4.2 Foamglas Sandwich Mirrors

Initiative members have been investigating the use of foam glass as lightweight spacer material between the top and bottom glass plates of a primary mirror. Foamglas, a cellular glass product manufactured by Pittsburgh Corning, made its debut in 1942. Cellular glass has a unique combination of properties which includes being chemically stable, thermally insulating, compression-resistant, and nonflammable. One of the first uses of Foamglas was the flotation of anti-submarine nets, buoys and minesweepers during WWII. Since that time, cellular glass has been widely utilized in many industries, primarily as an insulation material.

Steve Badger, Director of Development at Pittsburgh Corning, points out that Foamglas is made from sand, recycled glass, and other abundantly available materials which are mixed to produce a specific composition of molten glass. The glass is extruded into a hollow tube, ground into a fine powder, and mixed with a gas-generating agent. The powder is then put into molds which pass through a cellulating oven where the material is heated to produce a cellular glass block with millions of hermetically sealed glass cells. The Foamglas insulation blocks are then passed through an annealing furnace to allow carefully controlled cooling of the blocks. Finally, the blocks are cut to size, tested, and packed.

Soda lime Foamglas comes in three densities, and there is also a single density, low coefficient of temperature expansion (CTE) borosilicate version of Foamglas. The soda lime version of Foamglas is quite inexpensive, lightweight, readily available, and easily milled. With a Foamglas core and thin top and bottom float glass plates, the materials for a two meter mirror blank might only cost \$700 and weigh 300 pounds. This could bring large optics into the range of the serious amateur.



Figure 5. Foamglas puck being machined by Andrew Arigema. Plate glass can be fused or cemented to the finished pucks. Still highly experimental.

Initiative member Andrew Aurigema has been machining concave surfaces in the tops of Foamglas blocks, while David Davis has been slumping and fusing glass plates to Foamglas in his kilns. Both have been investigating the use of adhesives instead of kiln fusion to fasten glass plates to Foamglas cores. Attendees at the recent Alt-Az Initiative conference in Hawaii were intrigued when Davis pointed out that Foamglas sandwich mirrors float on water. He then proceeded to toss a Foamglas mirror blank on the floor without damage.

The brittle nature of the Foamglas cell walls allows easy shaping with simple power equipment. Final shaping can be done with simple flexible surfaces or the slumped glass shell itself. Aurigema found that the easiest way to shape the surface was to build a pendulum cutter – a Dremel tool suspended on a wire rope or thin metal rod whose length matched the desired radius of curvature. He recommends using ultra low CTE epoxy mixed with glass micro balloons as the bonding agent. The resulting "frosting like substance" spreads easily and fills voids. This mixture is also suitable for sealing the outer side walls of a Foamglas core.

5. Replica Mirrors

We have, above, considered several ongoing developments that could significantly reduce the weight and cost of 1-2 meter mirrors. We now turn to methods that could, potentially, not only reduce their weight, but drastically reduce their cost through the elimination, during production, of grinding and figuring mirrors (albeit the convex master molds used in the replication process would still need, one time, to be ground and figured).

5.1 Nanocomposite Replica Mirrors

Initiative member Peter Chen has been developing very lightweight carbon fiber replica mirrors for several years and is achieving success with this approach. Previous work at NASA's Goddard Space Flight Center had demonstrated that diffraction limited optical telescope mirrors were achievable using a combination of polymer resins and graphite fiber laminates. However, tests showed that these 'composite mirrors' became severely distorted when subjected to moderate cooling (from 20°C to 0°C). The cause of this undesirable behavior was traced to an inherent incompatibility between the two basic components of a composite mirror.



Figure 6. Carbon fiber composite mirror. The cat weighs more than the mirror. New mirror materials now allow much larger temperature changes.

Over the past four years, major steps have been taken to resolve this problem. A new class of 'nanocomposite' replica mirrors has been developed using a radically different structure incorporating cryogenic polymers, carbon nanotubes, and carbon nanofibers. Tests have shown that nanocomposite replica mirrors can withstand cooling by liquid nitrogen to -150° C without damage or distortion. Work is currently focused on the development of meter class mirrors, mirrors with built-in active figure control, and ultra-smooth mirrors for space ultra-violet astronomy.

5.2 Polyurethane Replica Mirrors

Initiative member Kiran Shah is experimenting with polyurethane replica mirrors. These mirrors have a solid polyurethane front surface supported by a dense polyurethane foam puck which can be either cast or machined. The concave top of this puck is coated with a solid, thin layer of polyurethane resin that is pressed against a convex master that has been coated with a release agent. Successive thin layers of

solid polyurethane are added until the built up solid surface develops a reasonable inverse replica of the master.

This work is highly experimental, and Shah does not expect high optical quality. However, the cost to make these mirrors, in volume, could be extraordinarily low and, thanks to their very light weight, a number of spherical replica mirrors could potentially be assembled into an unusually low cost and light-weight, large aperture, multiple mirror telescope with an instrument and refractive spherical corrector at prime focus. The instrument might consist of a near infrared aperture photometer or low resolution spectrograph.

5.3 Glass Replica Mirrors

A team at the Brera Observatory in Italy, consisting of doctoral student Rodolfo Canestrari and his advisors Mauro Ghigo and Giovanni Pareschi, is working on Foamglas sandwich mirrors that do not require optical finishing. In his approach Canestrari is gluing to a Foamglas core two thin borosilicate glass sheets, each about 1.5 mm thick. The front sheet is pre-shaped to the desired optical figure. This step can be accomplished following either one of two different processes, both based on the replica concept.

In the first process, a precise copy is made from a high optical quality ceramic convex mold using a hot slumping process (Ghigo, 2007) and then glued to a Foamglas substrate (Canestrari, 2008). Although the mold itself can be quite expensive, this cost can be amortized through the mass production of many replica mirrors. In principle, the optical quality reachable on the replicated thin glass meniscus mirrors is high enough that no further figuring is required.

In the second process, a glass copy of a diamond milled aluminum convex master (Pareschi, 2008) is formed at room temperature by adhering an initially flat thin glass sheet to the master using vacuum suction. A Foamglas substrate is then glued to the back side of this now slightly concave glass sheet. One side of the Foamglas core is pre-shaped with a computer controlled mill-like tool to match the curvature of the front glass sheet. The gluing is accomplished with very low shrinkage epoxy and thermal curing. Because the mirror quality is only that of float glass, and this glass must be flexed, this process is only suitable for less demanding optical quality mirrors (an arc minute or slightly better) with a long radius of curvature (tens of meters), such as those used in Cherenkov radiation telescopes.

With either approach, stiff and lightweight mirrors can be produced with mass-to-area ratios of only 15-20 kg/m².

5.4 Polymer Spin-Cast Mirrors

A liquid revolving at a constant speed naturally assumes a parabolic shape. Spin-casting is capable of pre-forming large monolithic glass mirror blanks (Hill 1989), and has been used by Roger Angel and others to produce large-diameter, light weight, open-back, monolithic cellular glass mirrors, such as the 8-meter mirrors on the Large Binocular Telescope. Peter Wangness has successfully applied this technology to 1-2 meter class mirrors. Although saving much material and grinding, such spin cast mirrors still require normal optical finishing.

A diffraction-limited surface can be created on spinning liquid mercury mirrors (Borra et al., 1989). If, instead of mercury, one spun a liquid polymer (epoxy), once it sets the spin table could be turned off and the parabolic shape would be retained. For optical quality, the ideal materials (chemical system) for polymer spin-casting should have low viscosity and surface tension, a high glass transition temperature, good strength and hardness, low shrinkage, and a slow reaction rate.

Archibald (1957) produced spin-cast epoxy solar collectors almost a meter across and concluded astronomical mirrors were possible. Ninomiya (1979) investigated this method with various materials and identified several problems. His epoxy mirror was superior to those made from other materials. Alvarez et al. (1993) produced 1.8-meter off-axis mirrors for millimeter wavelengths while Richardson and Griffiths (2001) fabricated mirrors for use at 2.5 microns. Chen et al. (2008) demonstrated a composite spin-cast mirror containing simulated Moon dust as a prototype for lunar solar collectors and telescopes.

A group in South Carolina headed by W. A. Scrivens (with Initiative members K. Lisa Brodhacker and Terry Richardson) has progressed toward spin-cast epoxy mirrors for visible wavelengths using a resin system of diglycidyl ether of bisphenol A (DGEBA) epoxy with 4,4-methylen-bis-3-chloro-2,6-diethylaniline (MCDEA) as the curing agent and an industrial diluent, cyclohexane dimethanol diglycidyl ether, known as ED757. They use two spinning mechanisms with air-bearing supported platters with diameters of 0.7 and 2.0 meters. Though some problems remain, this group has obtained a sub-arc minute resolution image of the Moon with a masked off epoxy mirror. A paper on this work is currently being prepared for publication.

6. Conclusion

We expect that several but not all of the developments discussed above will lead to relatively low

cost, lightweight primary mirrors for 1.5-meter class transportable telescopes. The achievable optical quality may differ greatly from one approach to another, so while some types of mirrors may be suitable for high quality optical imaging, others may only be suitable for the least optically demanding dedicated research applications such as aperture photometry or low resolution spectroscopy. Whatever the outcome of these developments, we hope that they will help pave the way toward larger aperture, lightweight, low cost, transportable telescopes.

7. Acknowledgements

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