Fast Newtonian Scope for Photometry and Imaging

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Introduction

This paper describes construction, testing, and operation of an 18 inch f3.5 Newtonian telescope. This project is of particular interest because it achieved the goals of light weight (about 90 lb) and low expense (below $5000) while maintaining high resolution and stable operation. The report describes the major design considerations and tradeoffs, as well as the tests and modifications necessary to meet the design goals. I have included many of the details that came up during construction so that those attempting similar projects will have some idea of the types of issues to be handled.

Major Design Goals

I do primarily asteroid photometry, with occasional imaging of deep sky objects as my interest may dictate. In the past I have used a C11 OTA on an Astrophysics 1200 mount for most of my work. The scope is mounted in a PD10 observatory, and is operated remotely. I normally use an ST7 or 402 for imaging or photometry.

However, the desire for faster or deeper imaging drove the decision to construct an 18 inch scope which would roughly double the light gathering power. I purchased a used AP900 mount for use with the C11 and installed the AP1200 in a new ten foot dome (PD10) for the new telescope.

In this section, I discuss the major design issues. In the next section, I go through the design and construction issues associated with each of the telescope components.

The size (18inch) was a compromise: I wanted substantial increase in light, but the higher cost and greater weight limited the choice--18inches was the compromise. I chose the speed of f3.5 to keep tube length to a minimum so that I could keep weight to a minimum, cost to a minimum, moment of inertia to a minimum (to allow fast slewing and easier balancing), and to preserve as much useful space in the ten foot dome as possible. Note that even though the tube length of the completed scope is only 65 in., because the center of gravity of the scope is toward the mirror end, the open end of the tube is only about 10-12 inches from the inner dome surface which places some restrictions on movement in the dome. Very few vendors were willing to do an f3.5, most wanted to do f4.5 or so which would have added an extra 18 in. to the tube length. I could find no available telescope (eg Dobsonian) of the size and speed desired, so I knew I would have to go with a custom mirror. Also, a Dobsonian OTA usually have a sling-type mirror cell which is not suitable for a German Mount on which the tube rotates as it moves across the sky.

Image scale on the telescope would be about 1 a-s/pixel with 9u pixels. I had found this to be a very good value to use for photometry, and with an average seeing of about 3 a-s provides modest oversampling. A small chip size CCD camera is fine for photometry, so long as the chip size is sufficient to allow accurate GOTO pointing: for an ST7/402 (my usual cameras), the field size is about 8x12 a-m which is reasonably easy to use even if the mount is not perfectly aligned. Even with a small CCD chip, coma in an f3.5 system will be an issue. However, the Parracor promised to reduce coma to below one pixel, and would even allow use of a larger chip (eg ST8) if desired.

The environment in Maryland is highly variable, from low temperatures in the winter (10-30F) to high temperatures and humidity in the summer (90-100F, up to 100% humidity), and with fog and dewing events throughout the spring to fall. In past years, I have had several Newtonians up to 10 inches installed in observatories and used hands-on or remotely. All showed aluminized coating failures in less than 10 years, presumably the result of dewing on the mirror (closed tubes S-Cs show a much, much slower degradation). I concluded that I wanted a closed tube (vs. an open truss or similar design), that was capable of being fitted with remote closing or other method of helping protect the mirrors. With a tube design, weight considerations and thermal focus stability immediately dictated use of carbon fiber as the tube material. The cross-section of the tube would be octagonal to provide easy attachment to the flat plate of the AP1200 mount, as well as nice mounting surfaces for appliances on the scope.

Counter-Arguments re a Fast Scope

There are, or course, some negative tradeoffs with a fast (f3.5) scope, in addition to the obvious difficulties of manufacture and coma in the image.

The very short critical focus zone of about .002in.means that the focuser must be capable of fine control. More significantly, the tube must be stable in length (.002in 65 inches is only 30ppm) and shape to the same precision, with regard to orientation and temperature. Even the mirror cell, and the cell in the mirror, must hold to this precision, or one will chase focus forever!

A second issue is that most eyepieces and optics are not designed for such a fast system. This may put severe limits on eyepiece choice.

The highly converging rays also place severe constraints on the optical path--one cannot hang a succession of devices on the end of the optical path. Thus, one must carefully consider whether filters, filter changers, adaptive optics, rotators, etc. will function properly. In my case, although I would love to use the large mirror to improve the sensitivity of a DSS7 spectrometer, it was in fact designed for f/10. A Barlow in principle will give f/10 on this telescope, but the plate scale will also increase so that its sensitivity to extended sources is no better than with my f10 C11 or the FOV will be much reduced (and of course, tracking will be more difficult).

The highly converging rays also cause subtle changes in use of filters. Not only will there likely be vignetting, but the converging rays pass through more filter material compared to those rays on the axis, thus changing the attenuation (and this variation may affect different parts of the FOV differently). This may produce a significant error in the filter calibration. Narrow bandwidth filters may be unusable or not as useful in a fast system.

The Saga of Detailed Design and Construction

The major components of the telescope are

- Primary Mirror
- Tube
- Mirror Cell
- Secondary Holder
- Secondary Mirror
- Focuser

Primary Mirror. Using the Internet, I solicited potential vendors for the main mirror. Of about 20 vendors, a third never responded, and most of the rest declined to do the job. I received one quote of over $5000 from a very reputable company; however, this seemed too high. I finally received a quote for $2000 from ASM Products in Canada with a 90 day delivery. The mirror would be made of BVC glass (softer than Pyrex), and I would also purchase a mirror cell and secondary holder from the same vendor. Unfortunately, although the vendor did send the mirror cell and secondary holder, the mirror was never built. After months of no return calls or emails, I finally found that the business had been sold. However, the new owner had no experience making such large fast mirrors, so I cancelled the order 14 months after placing the order with $1000 deposit. Of course, no one wanted to refund the deposit! However, I had made the deposit with a Visa card. After a month of calls and letters to Visa, they in fact refunded 100% of my deposit!

I then did a second round of solicitation of vendors. I finally settled on Steve Swayzee in Washington state, and sent him a $1K deposit (even though he would not take Visa!). Although he did not meet his 90 day delivery time, eventually the mirror was done, arriving 10 months after placing the order (Spectrum Coatings did the aluminizing). This mirror was Pyrex (which had actually been my original preference), and weighed 39lb. While it looked beautiful, I had no way to test it until I had it in the telescope (and even if I saw a fault then, how could I distinguish a mirror cell problem from a mirror problem?).

With the mirror actually in hand (and in one piece), I was ready to begin the actual job of building the telescope.

Telescope Tube

Before proceeding, we should discuss the working environment for the tube. At one end would be the 39lb mirror, plus an estimated 5-10lb for the mirror cell. At the other end would be the focuser, camera, secondary and holder, and other assorted devices, perhaps

15 lb. Because it is on a German Equatorial, the tube can not only be horizontal or vertical (as with a Dobson) but also rotates around its axis (which a Dobson does not do). The tube and the mirror cell must be designed to be stiff and stable and safe under all elevations and rotations, and indeed, must hold the mirror even if the scope is tilted below horizontal.

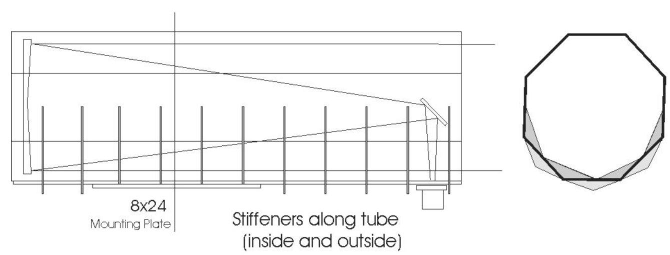
In general, I wanted the OTA stiff enough so that under all conditions the optical axis would shift less than 1 a-m, which is about 0.02" at the camera. This is roughly the maximum deflection that would be allowable anywhere in the system.

The inner size of the tube would allow one inch around the mirror to provide space for the mirror cell, and to allow up to 3/4 degree offaxis without blocking light. Thus, the tube would have an inner (minimum) diameter of 20 in.

The AP1200 mount has an aluminum mounting plate approximately 18x4x1/2 inch to which the tube would be bolted. To match this plate, to provide for easy mounting of accessories onto the tube, and for ease of fabrication, I decided on an octagonal tube having eight (8) panels about 8x65 inches. I designated the panel designed to mount the scope as the "base" or "mounting" panel.

Although I had tentatively settled on a carbon fiber octagonal tube, I still needed to assure myself that it would be mechanically suitable and cost effective. I embarked on measurements of the stiffness of materials, and on rough calculations of how much the tube would flex, and so on. At the least, I needed to decide just how thick (and expensive and heavy) the carbon materials would have to be.

The testing results are shown in Table XXX, and compare various thickness of carbon fiber (4- and 6-layer), carbon fiber with a foam core (for increased stiffness), and other competing construction materials. It was immediately evident that carbon fiber is all that it is claimed--it is much stiffer per unit weight or volume than most materials.



But it is not perfect: it was clear that four or even six layers would flex around the 1/2in thick aluminum mounting plate of the AP1200 when the scope orientation is horizontal and the base side is down. After considering a variety of options, I concluded that the sides of the tube would be four layers, but the base panel side would be four layers plus 1/4 in. of foam plus another two layers. This would give good stiffness in the horizontal when the base is downwards.

When the scope is on the meridian, the base side is in the vertical plane where it is extremely stiff. However, in horizontal mode, the tube will be less rigid as the base will be less rigid, as all the gravitational forces must be carried by the more vertical sides. In the horizontal mode, the tube will also tend to deform along its length, ie., flopping over to the side along its axis. If the deflection were uniform along the length, it would not contribute to optical axis movement. However, the mirror cell was to be an internal octagon which would stiffen the lower end. With the upper end of the tube able to deform, there would be non-uniform distortion. One way to solve this would be to insert rings of say 1 in. radial width inside the tube. However, this would mean increasing the diameter of the tube by another two inches, increasing weight and cost, and decreasing stiffness. An alternative was to use adhesive to apply triangular stiffeners on the inner vertex of the sides (where they would not block light) and corresponding triangles on the outside of the flat sides of the tube. In effect, this produces a one inch radial ring. Because this is expensive and adds weight, I decided to apply these stiffeners only to the half of the tube adjoining the mounting side as the stiffness is not needed all the way out from the mounting plate. If these were insufficient, more could be added later. Incidentally, as applied (with methyacylate adhesive), they were very stiff, but if one needed to be removed, a sharp rap of a hammer would do the job.

With the tube design in hand, how was it built? I constructed what is known as a "Plug" mold, ie., a replica of the tube. I built an accurate octagonal tube of 3/4 plywood. On two opposite sides, I inserted a removable 1 inch piece the length of the tube as part of the sides. After sanding, the fiberglass vendor painted the mold, applied a release agent, and wrapped it with carbon fiber, resin, and the foam core. He took care to squeegee out as much resin as possible to reduce weight. After curing, he removed the wood inserts to collapse and remove the plug from inside the tube. He trimmed the ends, and then applied the triangular stiffeners. I had estimated about 20lb, it ended up just under 25lb. I then applied flat black spray paint inside, and declared victory.

Experience with the Tube

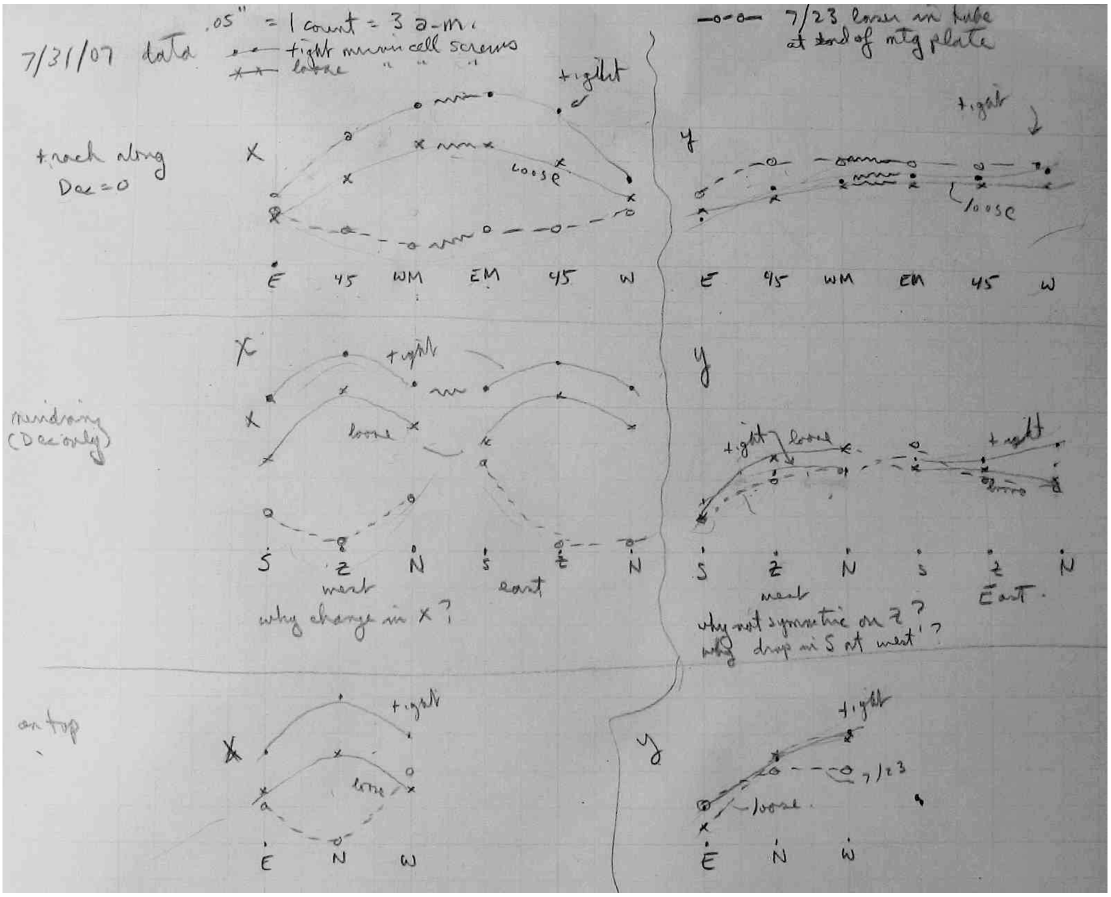
After several months of testing, it became clear that the tube had more flex than I wished. The most significant error was that the OTA axis shifted relative to the mount support plate. These shifts had several bad effects (a) introduce pointing errors up to 9 a-m in GOTO mode, (b) degrade the collimation (the center of the FOV would no longer be the point of minimum coma, (c) limit the unguided tracking durations (2 a-m shift per hour of tracking introduces a 2 a-s pointing error per minute of exposure). Note in regard to (b) that a modest change in the collimation, ie, the OTA axis, can significantly degrade the image quality. Even with a Parracor in place, the displacement of the OTA axis from the Parracor may further reduce its effectiveness. That is, the Parracor may be designed for use on a symmetric centered system.

The shape changes of the tube were extremely complex to evaluate as the tube shifts in elevation and in rotation (remember, a GEM mounted telescope rotates as it crosses the sky), so I was led to establish a series of test positions for the scope and measurements to be made. The test positions included (a) S,Z,N on the meridian with the scope on the E,W sides of the mount (these moves are in dec only and keep the base panel in the vertical plane only), (b) at DEC=0, go from E to S, switch sides, then S to W at 45 deg intervals (these moves are HA only), and with the scope on top of the mount E,N,W.

I first tried to make measurements of tube flex using dial indicators and an aluminum angle bolted to the mount. However, the movements are too complex, and it was hard to measure to better than 0.01". I eventually used a $3 laser that I could mount inside the tube. I bounced the light off the mirror, up to the secondary, to a thin graph paper on an empty eyepiece tube where I could measure the beam center to substantially better than 0.05" (equal to about 3 a-m shift in the axis). With the laser mounted on the inside of the tube just above the AP mounting plate, I realized that tube flex was shifting the laser so that measurements of tube flexure were ambiguous. I then cut a hole in the tube base panel so that I could mount the laser directly on the AP mount, free of the tube. Because it was too far in to reach, I also cut a 3x4 inch hole in the opposite panel so that I could reach in and adjust the laser. In the graphs below, x at the eyepiece is toward the mirror, and y is perpendicular (x, y are positive in the RA and DEC directions, respectively), and each unit of measurement is .05 in=3 a-min at the eyepiece. The graphs below show the laser beam movement for the various test positions listed above.

With this setup, I could make highly reproducible measurements of the shift of the optical axis with scope direction. I found shifts of up to 9a-m in various moves. Although reproducible, the results were still surprisingly difficult to interpret in terms of exactly how/where the tube was flexing. It was clear that the tube was flexing in large part because the shape was not remaining perfectly octagonal. That is, the panels that calculated to have more than sufficient rigidity in their planes were in fact twisting and thus allowing their more flexible side movements. Thus, the OTA axis shift was due to tube flex changing the alignment of the parts, and not by flex in the secondary holder or mirror cell.

To reduce the flex to a reasonable value (preferably well below 4 a-m), the rigidity of the tube in virtually all directions would need to be doubled at least. This was not a change that could be done with a few strengthenings here and there, but would require a major modification. Options included covering the whole tube with composite and an additional layer(s) of carbon fiber, modifying the base panel to be almost perfectly rigid, or adding circumferential rings the length of the tube. I opted to add composite and additional carbon fiber on the entire outer surface to (in theory) increase stiffness by more than x10. Although this would add about 15lb to the weight of the tube, it would also have the effect of moving the CG of the assembly toward the open end, thus allowing a shift of the telescope on the mount in the direction that would gain more space in the dome: Tis an ill wind that blows no good!



While it is possible that additional stiffeners might have been enough to solve the problem, we did not want to risk another round of correction. After consideration of many alternatives, we added 1/2inch of stiff composite material all the way around the tube, with careful beveling to minimize gaps. Another two layers of carbon fiber were added, again with major efforts to squeegee excess resin to reduce weight. The mounting surface already had 1/4in. of composite. However, tests had shown that very local forces at the mounting points could produce deformations that would shift with direction. Therefore, we emplaced two aluminum blocks 3x6 in. in the two mounting bolt areas, filled the gaps with 1/2in. composite, and added carbon fiber layers over all.

The completed, more rigid tube was then redrilled for the various fittings, including provision for a movable 5lb counterweight to be fitted at any position along the axis of the scope. The new tube weighed 43lb, and was much more rigid than before. With a slightly modified design, it is clear that we could build a rigid, closed tube in the 35lb area (the cost is proportional to the weight).

Mirror Cell

A major question related to the mirror cell design. To keep weight down, I wanted as thin a mirror as the optician was willing to make (I got 1 5/8" at the edge of the Pyrex mirror). However, a thin mirror requires proper mounting to avoid major distortions.

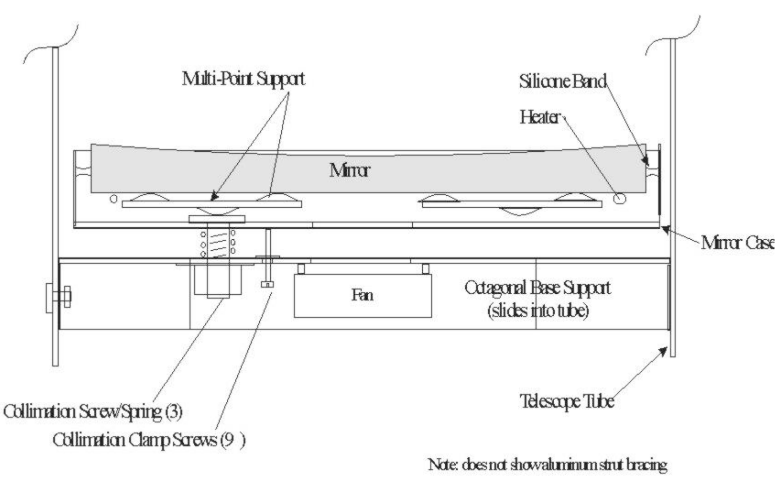
While some distortion would not prevent photometry, I certainly wanted as good an image as I could get, which in turn dictated use of a multipoint cell design.

In the past few years, several freeware programs to calculate support geometries have become available. I used GUIPLOP to analyze my mirror. In brief, the results suggested that a 6 point support was much better than 3 point, and was also better than a 9 point (contrary to one's intuition). An 18 point support would have 1/10 the deflection as the 6 point, but would require two levels of support vs. one. I decided to try the six point.

Unfortunately, there is little on the web about how to design a practical cell. Calculations show that support placement with 1-2 mm accuracy is important: while this seems easy, in practice, it is not so easy to handle a 30lb mirror and position it with an accuracy of 1 mm (remember, you can't see under the mirror to verify placements!). There is also no discussion of the effects of deflection of the support structure, how to arrange and attach the mirror to the supports, how to make pivots, the materials, and how to transfer the weight to the tube. In addition, as the scope changes elevation and rotational orientation, how is the mirror supported on its side: measurements and calculations show that uneven support on the edges can distort the mirror as much as poor location of support points underneath! And no one addressed sideways motion of the mirror cell on its three collimation/support bolts (interestingly, the tube flex measurements showed that this was not important, at least in my installation). All in all, the devil is clearly in the details!

As noted above, I had received a mirror cell from the first (aborted) mirror vendor. After much consideration, I decided not to use the cell. It was constructed primarily of wood, was heavy, and not very rigid. The nine pivot points were significantly different in position from GUI-PLOP's recommendation, at least for my pyrex mirror. The side supports were metal brackets, so it would not have symmetric continuous side support.

I started with a basic design of a mirror cell containing the mirror and support points, itself supported on three collimation screws on a mirror cell support octagon that would bolt to the tube walls. The floors of the cell and support would be of six layer composite for stiffness, with the rims being four layers of carbon fiber.



To minimize the space taken by the mirror support points, I made the three supports of 1/8 in. steel to minimize flexure (aluminum would bend too much), each with three homemade HDPE little domed supports (like rivets) in press fit holes. With the mirror upside down, I positioned the three support bars accurately, and used thin dollops of silicone caulk on their ends to hold them in place on the mirror. This was done in a way that allowed the support bars to pivot and tilt, but to keep them in place, did not allow rotation in their plane. This system worked very well, and allowed careful survey of the geometry.

When the mirror was right side up and in place, the three support pivots, each carrying about ten pounds, would rest on the heads of the collimation bolts (described below).

Not finding suitable collimation bolts, I made them (really not a big deal). I decided on 1/2-24 bolts to give fine collimation adjustment (turns out to have been a wise choice). I turned and threaded brass stock for the bolts, then made the three thick collimation adjusting nuts (I cheated and used 1 in. hex stock and a commercial tap). I made three 1/4 inch thick nuts to serve as the heads of the bolts. After soldering them to the threaded rod, I turned them to 1/8 thick to support the mirror pivots (the large size makes it easy to get the pivots right onto the collimation bolt heads). I made collimation springs using standard stock spring material. This required some trial and error to get proper stiffness and lengths. A Dremel cutoff is useful in cutting the springs, while a propane torch allows one to bend the ends to reasonable flatness.

After assembling the parts, I lowered the mirror and support assembly into the cell so that it rested on the collimation bolts. In fact, this is somewhat tricky, as there is not space around the mirror for one's fingers: To lift and lower the mirror, I used nylon cord handles epoxied and duct-taped to the underside of the mirror. When assembled, the cords are tucked out of the way.

The final issue was how to support the mirror against sideways motion, and to hold it in the cell if the scope tilts below horizontal. The mirror in the cell has 3/8-1/2 inch space between the edge of the mirror and the inner surface of the mirror cell. I obtained urethane foam used as caulking "backing rods", and inserted two inch lengths around the perimeter of the mirror, with two inch spacings (the spaces allow ventilation air from the fan to circulate past the mirror). Using a simple wooden fixture, I pushed each one down to just below the midline of the mirror. I then laid about 3/16 to 1/4 inch of silicone caulk on each piece of urethane, and worked it against the mirror and cell perimeter with a small stick. The result is about 20 sections of silicone band around the perimeter connecting the mirror to the cell wall. I had done a simulation, and showed that this geometry allows the mirror easily to move vertically (but not fall out), but restricts radial motion of the mirror with support all the way around. Because the side forces are on the midplane of the mirror, there are virtually no distortions to the mirror. Later vertical and horizontal measurements on the actual mirror and cell verified this design. When disassembling the mirror and cell, the silicone is easy to remove with a razor knife.

After several weeks of use, it was clear that the mirror cell support was more flexible than desired. Over a two month period, I several times disassembled the mirror and cell and made a series of revisions:
* Installed 1 1/2 in. aluminum angle in a triangular pattern on the underside, with bolts to stiffen the support floor especially near the collimation bolts.
* Installed three mirror cell lock screws around each collimation bolt, to reduce any side motion of the mirror cell.
* Installed three handles on the rear of the cell support to make the cell easier and safer to install.
* I changed the 1 1/2 x 1/8 pivot supports to 2 x 1/4 steel supports to reduce flexure (measured at about .005".
* I changed the HDPE pivots to brass, as measurements showed the HDPE would deform up to about .005".
* I installed aluminum plates around each collimation bolt (not shown in picture), and used resin to mount the plates and the angles onto the carbon fiber. This was in response to measurements that showed substantial flexing (.01") from local forces on the composite carbon fiber.

A very important aspect of cell design is the heating and ventilation of the primary mirror. Heating the mirror when not in use is vital (in Maryland) to prevent condensation. Condensation, especially combined with atmospheric dust on the mirror, leads to chemical attack on the coating. My experience has shown that even when kept in an observatory, the coatings of exposed mirrors will totally fail in ten years (but in an SCT, coatings will last indefinitely). I initially installed flexible heaters as shown in the picture, driven by a lamp dimmer. I normally operated with the mirror about 10F above ambient.

After about one year, the heater failed even though it was only operating at about 20% of its heater rating. I replaced it with two rings of 24 1 ohm resistors soldered together and epoxied to the back of the mirror. With 12v applied, this provides 12w of heating, while each resistor is operating at about 25% of its rating (to keep the temperature imposed on the epoxy as low as possible). At 12v, the temperature rise of the mirror in the cell (horizontal orientation) was about 25F, while at half power (one ring at a time), the temperature rise was 10F at about 1F per hour. With the goal to keep the temperature rise to a minimum, I initially operated with 6v on two rings (about 3-4w) giving a temperature rise of about 5F. However, with an open telescope in extreme dewing conditions, some condensation still occurred on the mirror, so I increased the power to about 6w (12v onto the two heater rings through a diode).

The ventilation of the mirror during observing is particularly important with a heated mirror, as the mirror takes many hours to cool to ambient unless ventilation is provided. Note: big mirrors, even one this thin (1 5/8") take many hours to cool, and in fact will not cool fast enough to track a dropping ambient temperature. I initially installed a three inch fan on the back of the cell, but this was insufficient to prevent thermal problems: cooling a large mirror is very slow whether blowing air onto its back or sucking air from the front around to the back.

Reversing the ventilation design, I added two 2.5inch fans on the sides of the telescope blowing partially tangentially across and onto the front of the mirror, plus the 3.5inch fan exhausting this air around and from behind the mirror. All fans were mounted with soft foam. With the mirror about 10F warmer than ambient, the star size is about 10-20a-s due to the near mirror temperature gradients. Using the fans, within a few minutes the star size is down to our seeing level of 2.5-3.5 a-s, and remains at that level even with varying ambient temperatures. That is, providing even a fairly low volume of fresh air across the mirror surface eliminates all thermal problems because the Pyrex mirror holds its shape sufficiently well even with several degree temperature gradients within it. Operating the fans at full (12v) ratings produces substantial noise, and some evidence of vibration; however, solid state switching fans cannot simply be run at low voltage (they stop at about 5v). To assure proper operation, I built a small circuit that applies 12v for several seconds (to assure starting) that drops to about 6v for operation. The fans run much quieter, and there is no sign of vibration while the cooling works perfectly.

In summary, the cell design has worked very well, with excellent star images. It is easy to fabricate, and is extremely rigid and stable, yet easy to collimate. Total weight as modified is around 11 lb. If I had it to do again, I would build an open aluminum frame cell support system (similar to what I ended up with), perhaps with no carbon fiber at all except for the mirror cell where it provides essential circumferential/lateral support.

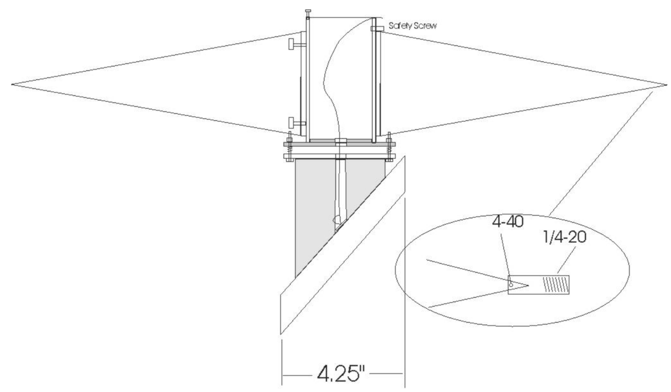
Secondary Mirror

Simple calculations showed the need for a secondary mirror in the 4 inch range. Very few vendors had them available, and those that did were very expensive (well over $500). Eventually I contacted Antares Optics, who did not have the inexpensive four inch advertised. However, they did have a much more expensive 4 1/4 inch quartz flat left over from another job. When I indicated my unwillingness to pay a high premium for this super quality flat since all I needed was photometry, they asked who had made my mirror. When I told them "Swayzee", the optician sternly and firmly instructed me that a Swayzee mirror was too good to have a lower class secondary applied: I should be ashamed! After negotiation, they gave me the nice secondary for little more than the unavailable, smaller, not as good one. It pays to negotiate! The secondary is 1/20 wave, 3/4 in. thick, quartz, and beautiful. And it weighs over a pound!

Secondary Holder

In addition to the mirror cell in the original-failed-mirror order, I had also received a secondary holder. Although the spider was reasonably robust, the holder for the secondary mirror was a 2 inch plastic disc on the end of a 3/8in. bolt providing vertical adjustment. The tilting adjustments were by three small screws. Given that the secondary mirror itself weighed over a pound and was 4 1/4 in. in diameter, I felt this was not sufficient.

I wanted a rigid, solid support system. I made the spider as shown, using aluminum tubing and flat sheet. The support tube for the mirror is vertically adjustable, and carries three adjusting screws on its lower end. The upper end has a safety screw to prevent the support tube from ever sliding out of the spider (down onto the main mirror!). The wisdom of the octagonal tube comes in here: with forethought, the alignment screws are all easily accessible, with one in the plane of the eyepiece to keep directionality during collimation.



Secondary Holder

For lack of time, I at first used a Styrofoam support for the mirror. However, this proved to flex nearly .04 in. under the load of the secondary as the telescope moved, so replaced it with cardboard tube, fiberglassed inside, carbonfibered outside (two layers). The secondary is attached using silicone. There is a safety string epoxied to the back of the secondary mirror that runs through the whole assembly up to the spider. The secondary mirror is too expensive to lose!

The secondary holder design has worked very well. Aside from eliminating the Styrofoam, the only change has been to reinforce the four flats of the octagonal telescope tube so that the spider can be tightened without deforming the tube.

The rebuilt, stiffened tube made the spider mounting much more rigid. To achieve the range of tightening needed, I soldered 1/4-20 nuts onto weld nuts, thus allowing wide adjustment with nice appearance.

Focusser

To keep the secondary relatively small, one would like a focuser of minimum height, while frequent changes in the setup call for a wide range of focus height. The focuser must be remotely operable, able to carry at least five pounds, and must be rock solid. Tilt or slop in the optical train is especially serious with a fast system such as this. This telescope has a critical focus zone of about .002inch with a CCD camera having 9u pixels. Thus, to avoid poor focus, not only must the focuser be capable of at least .001 inch movement, but it must also hold the camera square to the optical axis to a precision of about .001inch (about 5 a-m for a 0.5 inch CCD chip).

The Clement focuser is an unusual design, but exactly matches these requirements. Although expensive (about $600), it has been well worth it. It has a 1 inch minimum height, but still provides a three inch range of motion. The only significant limitation is that the focus knob placement limits the size and orientation of certain CCD cameras; however, mine fitted with no problem. Measurements show that the backlash in the focuser is under 0.001 in. The focuser is driven by a Robofocus stepping motor that provides a focuser step size of about 0.0001 inch.

Coma Corrector

The coma in a fast Newtonian is a notorious problem: even in a small chip (5x7mm) camera, the coma at the corners of an ST7 was predicted to enlarge the spot by nearly 50%. While one could live with this in some photometric applications, the appearance of the stars in the corners of the images are pretty ugly!

However, there are several correctors available. After investigation, I chose a Parracor, which promised spot sizes of well under 1 pixel (9u) on my ST7, and only about 9u on an ST8 (if I had one). Even better, the Parracor adds less than 10% to the f-ratio, so does not change the plate scale too much. It also does not radically change the focus position, and it provides strong physical support for the optical train. And it is reasonably priced!

The Parracor is designed for the optical axis to be centered on the corrector. This places a high demand on both good initial collimation of the scope, as well as the stability for he collimation. For the Parracor to work properly, it must be installed with spacing close to the specified 55mm (an initial installation with about 75mm produced very poor images).

Ancillary Equipment

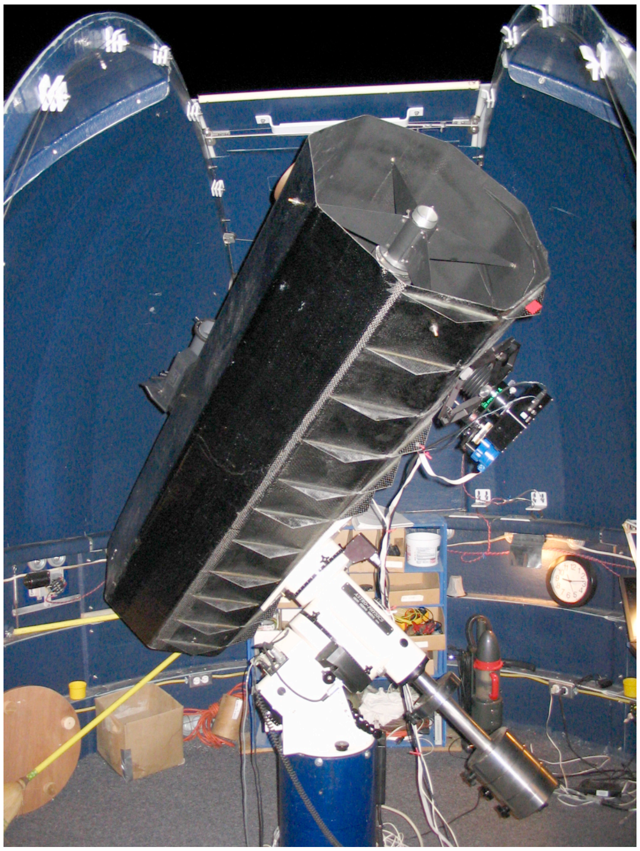
I mounted the usual Telrad and 7x50 finder (with illuminated reticle). These are easy to mount on those nice flat sides of the octagonal tube!

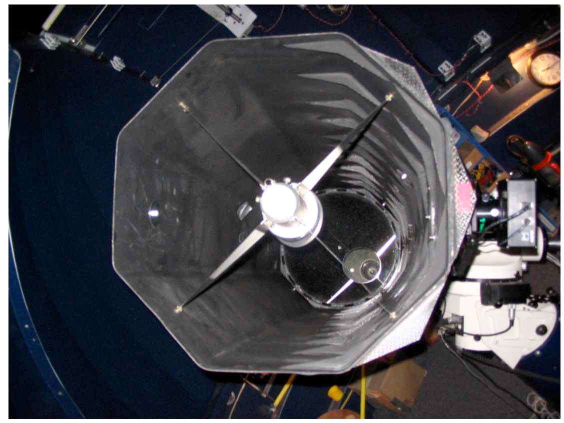
I also mounted an external guide scope. I first used a 3 inch 18 inch, then a three inch 24 inch of better quality. At the moment, it has a DSI camera for guiding tests.

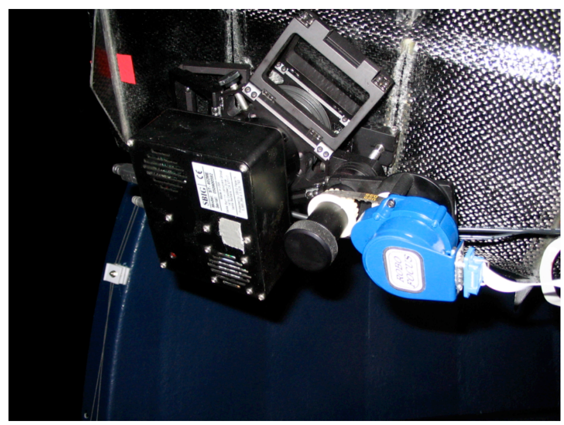
The telescope is also fitted with a "video viewfinder". This is a standard small cheap video camera mounted onto an old 50mm f1.8 projection lens. This gives about 3x4deg FOV, and will show 3.5-4 mag stars without integration. This allows rough pointing of the scope to about 10a-m precision. This allows remote recalibration (repointing) of the scope even if a major pointing error has occurred.

I made a thin plywood cover for the open end of the telescope. Being interested for many years in thin mylar optical windows, I was finally able to locate supplies of 1.4 and 2u material. However, the thicker mylar (4u) has substantial absorption of light, while the thinner mylar is very, very difficult to use for spanning large 18inch spaces. At the moment, I continue to use the plywood cover, but intend to install a remote/automatic cover.

Test Results







I have subjected the scope system to a variety of tests so that there are no surprises during future research use. The tests include collimation methods, stability of collimation with time and with scope direction, focus stability with temperature and scope direction, stability of the optical axis, and other similar measurements.

Collimation Method

In contrast to the horror stories about collimation, I found this very easy. In designing the scope, I made a point of orienting all the relevant parts so that they are aligned with the focuser--a fixed point of reference. Thus, the number 1 collimation screw is facing the base side of the main tube, as is the Number 1 secondary holder screw. The mirror is also marked so that it is always installed the same way in the cell. I installed an accurately placed mark at the center of the mirror--use a triangle with its number 1 point oriented to the focuser. Numbering the adjustments lets you keep track of what you are doing, and make a record of how to correct collimation errors.

To adjust the 1" collimation nuts, I epoxied a suitable socket (from a cheap socket wrench set) to a nice large wood knob. Thus, I need no special tools to adjust the collimation, and I can easily just reach around the bottom of the scope and fumble the socket onto the proper collimation nut.

I made a simple Cheshire eyepiece (a simple plastic eyepiece with small holes to get the eye on the centerline. Although there exist fancier devices, including lasers, I find they are unnecessary.

I do rough collimation using the Cheshire to center the triangle mark in the reflected mirror images. After trying other methods for fine collimation, I found it far easier to collimate using the very optical parameter one wants to minimize: coma. Using a CCD camera (with parracor removed!), I aim the scope at a suitable star (wow, this 18 inch saturates a camera at 0.1 second with a mag. 7 star!). Using MaximDL to view the star image, I stretch the image to show the faint coma. I then adjust the mirror cell collimation screws to minimize the coma at the center of the FOV. The proper direction of adjustment will cause the star to "move" in the direction of the tail, thus requiring repointing of the scope (easy to do using the Maxim recentering command or TheSky to make small scope movements). Making a simple sketch so you can see what you are doing, one learns very, very fast which screw in which direction corrects the coma. One is, of course, aiming for zero coma for a star centered in the FOV. Starting from scratch, I can collimate the scope in 5-10 minutes with no frustration. Typically, I might make 10-20 successive collimation adjustments and recenterings of the target star to achieve collimation. The corners of the FOV will show coma aimed away from the center. Installing the Parracor greatly reduces the coma.

Collimation Stability

A major design goal was to build a scope that would hold collimation under all operating conditions including elevation and orientation, time, and temperature. The shift in the optical axis as the scope was moved (discussed above) meant that this requirement was not met with the original tube design.

After the tube revision, the scope collimated easily. Collimation appears to remain stable under all directions and time to about 5 a-m or better (the limit of measurement).

Mirror Image Quality

The mirror has shown no apparent signs of turned edges or other distortion, thus supporting both the mirror and cell designs.

As noted above, a warm mirror shows thermal problems with star image size in the 15-20 a-s range until cooldown which takes at least 3-4 hours. Using the fans discussed above, within a few minutes the star size is down to the local seeing of 2.5-3.5 a-s. That is, providing a modest amount of fresh air across the mirror and exhausting it out the back eliminates the problem, while the Pyrex mirror holds its shape sufficiently well even with several degree temperature gradients within it. While I have not seen condensation during operation, if it occurs, I can easily run the heater and fans together which still provides excellent operation. I have not seen condensation on the secondary, so have not provided a heater (it would be easy to add).

Focus

A major benefit to using carbon fiber for the tube should be a relative insensitivity of focus with temperature. In addition, stiff construction should allow the focus to hold under all operating conditions.

Early on, I found that the focus changed inward as the scope lowered to the horizontal. The change was some 500 RoboFocus counts, equal to about .05 inch of focuser travel, which was intolerable. I suspected the mirror cell flexing, and this was one of the reasons for rebuilding and stiffening the cell. However, that work had absolutely no effect on the focus shift (though was surely worthwhile anyway). Replacing the Styrofoam secondary support reduced the effect by 80%. With this and other changes, the focus shift is essentially zero as the scope is moved in the meridian, but about 100 units (0.01") in other directions as the elevation changes from about 25 to 85 deg. After reconstructing the tube to the thicker version, the focus shows no apparent focus change with altitude (elevation). This was a relief, as focus change would be a major operational headache!

The telescope has shown very little focus change with temperature swings of 20F.

Stability of the Optical Axis

Mirror shifts and the like can suddenly shift the optical axis, while slow shifts in the optical axis will show as some form of tracking error. Sudden changes, of course, will ruin long exposure images unless the mount is selfguided. In all the imaging to date, I have seen no sudden changes.

In remote operation, one must be able to point the scope around the sky accurately enough so that the target is in the FOV of the camera. In my case, using a small chip camera at f3.5 gives about 8x12 a-m, while f6.8 (as with a Barlow) would give only 4x6 a-m. Accurately separating out the effect of an optical axis shift relative to the elescope mount mounting plate vs. errors in the mount alignment requires use of mount characterization software such as Tpoint. Alternatively, I adjusted the mount as well as possible (estimated precision of 1-2 a-m, and then tested how well the telescope points in GOTO mode. Note that refraction and other effects also apply. Actually achieving several a-m pointing under all conditions is not trivial even for this level of equipment.

I was able to try this mount using Tpoint. With five full rounds of calibration over a period of six months, the general experience according to Tpoint is an rms uncorrected pointing error of about 8 a-m, and a corrected rms pointing error of about 20-30a-s (with 8 or 9 terms). The contributors to this include residual mount alignment errors and orthogonality (each of which have amplitudes in the range of 300a-s and can be reduced by tweaking the adjustments). The most intractable component is the effect of tube flex with an effective amplitude of about 400a-s. A major effort has been made to reduce this; however, it does not appear cost-effective to reduce it further.

While the adverse effects of these errors on pointing can be almost eliminated using Tpoint, they still contribute to tracking errors during long, unguided exposures. In most parts of the sky, the error amounts to approximately 1 a-s/60 sec of exposure which sets the limit on unguided exposures. However, I have developed software (Telescope Tool Box or TTB) that compensates for this. In one mode, the software simply sends a Tpoint slew command every minute to keep the pointing within 1a-s, while another mode measures the image drift in successive images and adjusts the drive rate to compensate. These types of measures allow 5-10 minute unguided exposures.

Focuser and Optics

The focuser has worked perfectly--what more can one say? The Clement focuser is a perfect fit for my application.

The Parracor also works perfectly, though often I can forgo its use. In the initial installation, the Parracor did not eliminate coma, even on the small 402 chip. However, I found that the lens to CCD distance was approximately 75mm vs the 55mm specified for the Parracor. To achieve the correct spacing, I had to make a special nosepiece for the 402 camera. When that was done, there was no detectable coma in the 402 image. The specifications imply that an ST8 could also be used with barely detectable coma, but I have not tried that.

I have operated with a 1.8 Televue Barlow (producing approximately f/6). While the operation is acceptable, the star images are little smaller (in a-s) than at f3.5 so there is little to be gained by using the Barlow. However, it should be noted that most Barlows are probably not well corrected for f3.5, so this should not be considered a definitive test.

Mount Behavior

The AP1200 mount is robust. The revised tube with all components is in the 90-100 lb range; however, the mount handles this weight and counterweights (75lb) with no apparent strain whatever, including slewing at 1200x. When I first installed the new heavier tube, I did see worm occasional large displacements of some 15a-s; however, a simple removal of backlash solved the problem. The uncorrected periodic error is about 3.5 a-s P-P (as it was with a much lighter scope), and the alignment has limited drift to below 2a-s per 6.3 minute worm cycle in RA, and 1-2 a-s per worm cycle in Dec.

With typical star sizes (seeing) of 2.7-3.5 a-s, unguided operation for 1-2 minutes is entirely feasible with virtually no loss of resolution. Adding PEC allows unguided exposures up to five minutes or more if the residual tube flex and misalignments are managed by appropriate software (see above).

Telescope Installation

One unstated design goal was that I wished to be able to handle the telescope by myself. While the overall weight is at the upper end of feasible, its large size and strange balance prevent one from handling it as a unit. However, I have developed several methods and jigs to make it safe and easy and fast to do any level of installation by myself. I will describe the process I use.

The AP1200 mounting plate has 1/2 in locating holes at its upper and lower ends (in addition to the usual mounting bolt holes). I fabricated two smooth alignment pins and installed them on the base side of the tube. I also installed a long steel handle on one side of the tube. With the AP1200 mounting plate aligned toward the north pole, I can then lift the empty tube and by feel can insert the alignment pins into the holes which both align the tube and hold it in place on the mounting plate. I can then "let go" while I install the permanent mounting bolts. One nice thing about a big scope is that you can literally get into the tube to reach inside!

With the heavier, revised tube, this method no longer is suitable. Instead, I install the four mounting bolts from the inside and duct tape them in position. With an assistant, I can then install the empty tube onto the mounting plate. After the bolts are tightened, I proceed as below.

I then swing the scope tube horizontal. I have a vertical jig pole (old broomstick) that is secured by a packing crate and cinder block. The end of the jig pole has a screw that inserts into a 1/4 in. hole near the open end of the tube. The pole is secured by a wing nut, thus anchoring the open end of the tube so that it cannot move in any direction.

Then comes installing the mirror and cell assembly. I check the orientation of all parts, and plan out my moves. I then pick up the mirror (nearly forty pounds with cell!) and insert it into the rear of the tube. Using guide markings, I nudge the cell forward to line up the screw holes and install and tighten the screws holding the cell support to the tube. I then connect the fan and heater wires, and doublecheck all bolts and screws. During this pushing and shoving, it is vital that the scope tube be held securely by the jig pole--you don't want the tube swinging around while trying to manhandle forty pounds of mirror!

If the focuser and secondary holder are not installed, I then do so. After a final check and interior dusting, I disconnect the tube from the jig pole and check the scope balance.

Summary and Conclusion

This design is successful, and meets all the design objectives. It is especially suitable for photometry, however, within the limits of the ability to handle the coma, it is suitable for deep sky imaging as well.