Chapter Six
Tube Components

The OTA, of course, is not empty. Whether tube, truss or simple board, it needs to have components added that hold the optics and do other necessary functions. These components are the topic of this chapter.

I. Mirror Cells

The first and most obvious need is for some way to hold the primary mirror. The requirements for a mirror cell seem contradictory; it must be adjustable to allow precise positioning of the objective; once set, it must hold the mirror within thousandths of an inch of its aligned position, but it must not exert pressure on it. Pressure will cause the mirror to deform, and surface changes with sizes on the order of millionths of an inch will result in noticeable optical aberrations (mirrors are worse in this respect than lenses). Despite all this, the problem has been solved. As with the rest of the mount, the problem is made easier when an altazimuth approach is used. As most builders will be building a reflector, let's look at a mirror cell first.

Mirror cells are increasingly being analyzed and optimized with Finite Element analysis programs, to minimize the distortion that a mirror suffers from the cell. This started out as an area of professional research, due to the more common use of thin mirrors in observatories, and spread quickly into amateur use. Still, I have not read anything that convinces me that the millions of already existing mirror cells are not adequate, especially for “full thickness” mirrors, so you shouldn't panic and tear apart an existing scope. It just seems that you can simplify the cell and use fewer support points. Many of the errors that a cell induces can be accommodated by using more supports than you really need. Some are actually fixed by refocusing; you're doing it already without knowing it.

Historically, the development of the cell comes from the work of Hindle and Couder, who did early research on the support of mirrors. This work was based on three fundamentally sound ideas:

1) You have to support a mirror by a controlled kinematic structure - you can't just let the weight hit haphazardly.

2) Long, unsupported areas of glass should be minimized by increasing the number of floating points.

3) It makes sense to support approximately equal weights on each floating point. The longer the focal length of the mirror, the closer equal weights come to being equal areas of glass. The thickness of the glass is more constant as you go

from the center of the mirror to the edge in a long focal length mirror. As the focal length shortens, however, more and more glass is “missing” from the volume over the inner support points. This changes the weight on the support points and leads to needing to shift the supports slightly outward.

The changes to historical mirror cell designs found by Finite Element Analysis should be viewed as refinements and not a replacement of everything early workers have done. Just as Newtonian physics is a pretty good model of the world when we confine ourselves to slow speeds and low accelerations, but we need to use relativity when we go to extremes of speed and acceleration; historical mirror cells are adequate for thicker, slower mirrors. As we refine to thinner and faster mirrors, we need to change to the refined cells derived by FEA.

The Three Point Cell

Let's begin by considering the simplest common cell, one that uses three support points. An example of a simple three point support cell, of a type that amateurs can easily make, is seen in figure one.

The placement of the support points is the first question. In light of the third point above, and the fact that so-called “full thickness” mirrors of long focal length (f8 or greater) were the norm historically, you would think that equal areas would be supported by each support point. Since equal areas of glass are found on either side of the 70% zone (more precisely, 70.71%), the supports would go there. They would be arranged every 120 degrees around the circle, so that the supported glass would look like a large slice or pie. Indeed, this is what the historical three point cell is like.

Surprisingly, FEA has shown that for a three point support cell, the optimum support is not at 70.71%, but at the 40.1% point. This was derived by Luc Arnold, published in Optical Engineering, 1995, and re-discovered by David Lewis in 1998. The supports cause the glass to distort over them but much of the distortion can be removed by re-focusing. When refocusing is considered, the supports at 40.1% leave a smaller residual error (that can't be focused out). This is a surprising result!

Additionally the three point support need not be relegated to the mirror smaller than 6", and can be used for glass much larger than most of us would ever have used a three point cell for. According to data derived by David Lewis of the University of Toronto with software he developed, the following is a table of maximum diameters given blank thickness. I've included the thickness of a “Full Thickness” (1/6 diameter) blank. You can see that the mirror on a three point cell not only can be up to almost 13", but it can be a thin blank in many cases, too. Note that the clear aperture of a 13" mirror might well be 12.8 inches.

Mirror Thickness (inch)	**Maximum diameter** (inch)	**"Full Thickness"** (inch)
0.875	8.7	1.45
1.0	9.3	1.55
1.25	10.4	1.73
1.5	11.0	1.83
1.75	12.2	2.03
2.125	12.8	2.13

Three point cells are available commercially, but as of the last time I checked none were available that put the support points at the 40.1% point.

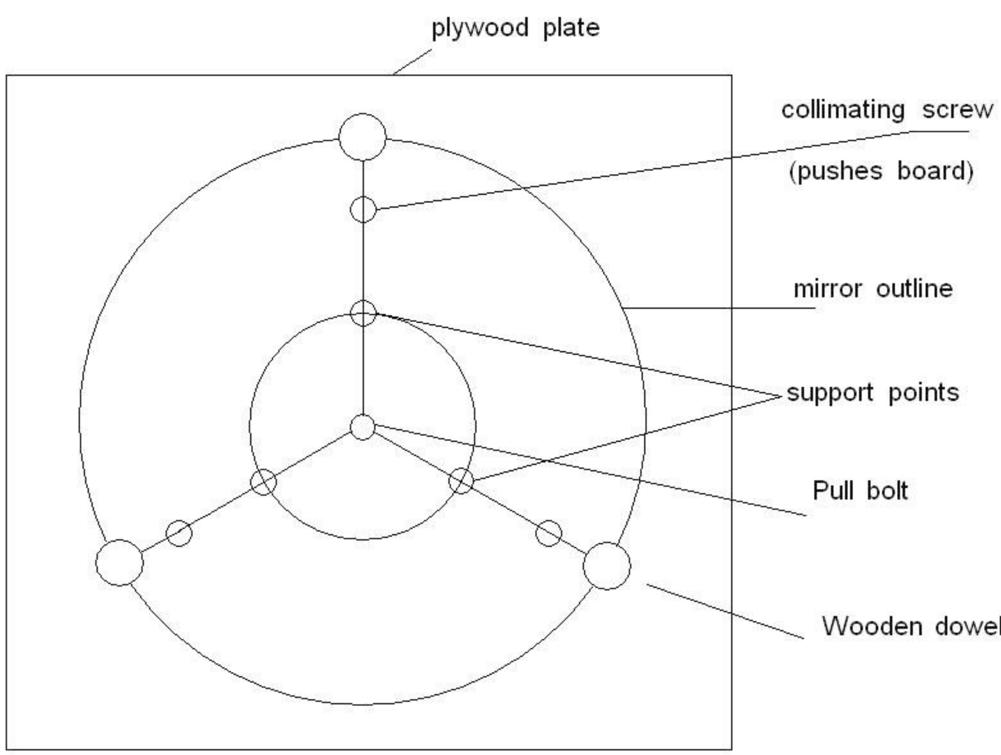

Figure 1 - A Simple Three Point Cell

Simpler Cells

If you are not a metal worker you can still make a serviceable mirror cell. A simple version of a three point cell as might be used in a small to moderate sized Dobsonian can be made from two pieces of plywood, a few T-nuts, matching bolts and some wooden dowel rod, Figure 1 . The plywood is made into two pieces of equal size which become the front and back plates of the cell. The back plate gets three holes at 120^{o} angles with T-nuts on the far side, and a center hole for a fourth bolt. This center bolt pulls the mirror mounting board against the collimating bolts and keeps the assembly tight. The center bolt screws into a tee-nut in the mirror side of the front board. When the support points were at 70.7% of radius, it made more sense to put the collimation points there. With the adjustments at the 40.1% point, they will be more sensitive and it will be harder to get optical alignment “tweaked” just right. It’s better to put adjustments farther out to get the sensitivity back.

The board that the mirror mounts to often has large cutouts to encourage air circulation around the mirror, and has to have a method of attaching the mirror so that it won't fall out. It is best to reinforce the back of the cell where the screws will contact it by attaching a piece of metal; a penny will do fine if you don't have any scrap metal handy. A good choice for both places is silicone RTV. The wooden dowels, and this approach is used by Berry in his designs, are located so that half of their diameter is outside the mirror outline and half is inside. They are then cut away so that the dowel presents the flat side of a semicircle to the mirror. The clearance between the dowel and the mirror isn't very critical, since the RTV fills gaps well and the mirror won't slide around in the cell. You probably wouldn't want to go much more than 1/10" (or 2.5 mm) for optimum adhesion.

The mirror is attached to the cell in this design with RTV beads. This is done by putting a large bead in at least three places on the back surface of the mirror and also between the dowels and the mirror's side. It's easier to get the RTV between the dowel and the mirror side by drilling a hole in the dowel large enough to pass the tip of the dispenser nozzle. Likewise, the surface of the cell that faces the mirror can hold the RTV better if you countersink a few depressions into its surface.

The actual gluing is done carefully, as you would think, to keep the RTV from getting on the surface of the mirror. Place three spacers of equal size, such as nails or screws, on the mirror mounting board. Fill the countersink depressions with enough RTV to overflow and protrude higher than the spacers. Once this is in place gently lower the mirror onto the adhesive blobs and let it settle (do this on a level surface, like a table). Center the mirror with a playing card or some other shim at all three dowels. Then put the nozzle of the adhesive tube into the holes in the dowels and gently squeeze a little into the gap between the dowel and the glass. Use enough to contact the mirror and the dowel, but not enough to glop up onto the mirror surface. Repeat this for the other two dowels. Then go someplace else for a day while the RTV fully cures. Once it is cured, pull out the spacers and you'll find the mirror held in place by the six blobs of RTV.

If your mirror was scrupulously clean, as will be when it arrives from plating, the RTV will form a strong bond. Berry has used this technique on mirrors up to at least

10", and has no qualms about turning the cell upside down so that the entire weight of the mirror is held by the RTV. The down side of this approach is that the mirror can not be easily removed from the cell, something you may want to do for an occasional cleaning in water.

Nine Point Cells

Probably the most common cell currently in use supports the mirror in nine places and allows push-pull adjustment of its surface with collimating bolts. Figure two shows the general layout of a type of nine point mirror cell. The dimensions for the radii of the support points are taken from FEM analysis by David Lewis at the University of Toronto. They are similar to the radii suggested by other workers, and the older cells are probably just fine. It's just that as diameter increases and thickness decreases, it matters more and more to use these radii. Using these proportions, though, a nine point cell will adequately support a 2 1/8 thick mirror up to 20 inches in diameter.

The mirror support points can be screw heads, or softer material like nylon screws or cork pads. The best material for these pads is probably compliant like the cork; however, starting a discussion of the use of RTV here on the ATM mailing list is likely to start a 10 day long heated argument. The collimating screw attachment to the triangular pieces ideally will allow the plate to “float” and rotate through several degrees. Note that the geometry of this cell is based on 120 degree angles; the three main mirror radii shown are at 120 degrees to each other, and the outer support pads on each of these are at 120 degrees from the inner pad. The supports are at **0.33 radius** and **0.78 radius**. The triangles that hold the pads can be sized in any convenient manner. To maintain the relationships shown between the support points, the distances between the supports are approximately **0.521 radius** in the short dimension, and the long side is therefore approximately **0.78 radius**.

David comments that he has had better results on a thick mirror with the outer supports at **0.720 radius**, but goes on to say, “The fact that the best radii are different from the starting point by a large amount, but the error is not much different is also a piece of good news; it hints that cell error is not highly sensitive to placement of the supports.” Later, he goes on to say, “We use Plop's scan feature to investigate this, by varying the inner support from .32 to .34, and the outer support from .71 to .73, and looking at the variation in error. It turns out that it is insignificant - less than 1%. Therefore, don't kill yourself getting the cell accurate to .001 inch - even .1 inch will do fine!”

The triangular pieces that hold the supports can be made from 1/8" (3.2mm) aluminum or brass sheet, or even fiberglass cut to size and laid up on a piece of plate glass. Note that since the collimation bolts do not contact the mirror, but merely move the triangles of support points, their position is not very critical.

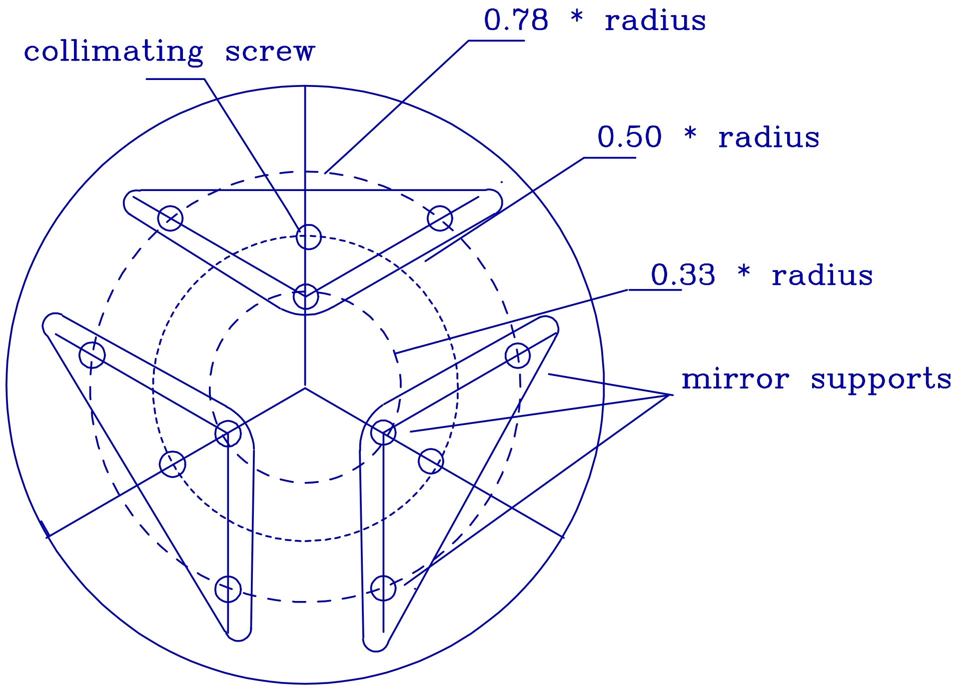

Figure 2 - Nine Point Cell With Support Points Optimized by FEA

Commercially made cells like this are often made of two pieces of cast aluminum or other metal. The back piece accepts bolts to hold the cell in the OTA and has its own bolts for collimating the optics. These are typically about 1/4-20 bolts surrounded by springs that together allow a push-pull action where tightening the collimating bolts pulls the two pieces together and loosening the bolt allows the spring to force them apart.

The strength of these springs is not critical, but you do want to scale them to the weight of the mirror. They should support the full weight of the mirror without collapsing completely. If each spring would collapse 1/2 inch under the weight of the mirror then three springs would collapse 1/6 inch. A 15 pound mirror would want springs with a spring constant of about 30 pounds/inch or so and it should be able to compress no more than 1/2 inch before it reaches its limit. A spring with a collapsible length of 1/2 inch would compress 1/6 inch due to the weight and then be adjustable for 1/3 inch which is the remainder of the 1/2 inch. This is plenty of adjustment range. You would hardly notice, though, if the springs compressed 1/4 inch or 1/8 inch and the travel was reduced or enlarged.

The mirror is not clamped at its edge, but is simply restrained from falling out of the cell by small metal clips bent over the front surface. The front contact is as small as practical and lined with cork or something else that is soft and non-marring. They barely touch the surface and are there as a precaution against the mirror tipping forward. The clips are set to about .008" or 0.2 mm from the mirror side; this is about the thickness of a playing card. A lateral shift of the mirror by these few mils is the least damaging thing that can happen to the image.

One of the outcomes of the FEM analysis of mirror cells is that there is no particular reason to stick to numbers of supports that are multiples of three, such as this nine point cell, or the popular 18 or 27 point cells. Five point cells are just as valid as three or nine point cells, as are pretty much any number of supports you desire. Another interesting result is that a central support can be helpful. Such cells are still rather experimental, and I don't have design data on them, while the data for more "conventional" cells is widely available, and will give results that are not far off.

Many ATMs have designed mirror cells with David Chandler's program Cell.exe. http://www.davidchandler.com/cell.htm David Lewis' analysis of the nine point cells produced this way is that they are very close to optimum – at least for thicker mirrors. Again, as the mirror gets thinner, shear forces become more important and the support points may need to move. If you're contemplating something like a 16" by 0.75" thick mirror, you should check with PLOP's results to make sure your cell design will not cause optical problems.

Twelve Point Cells

Twelve point cells are new in telescope design and don't appear in any of the historical literature. PLOP analysis has given rise to these cells. The situation is complex because there is not a single standard way of designing 12 point cells. A good place to start reading about this is:
http://www.atmsite.org/contrib/Holm/Plop_optimized_cells/12PointCells/index.html

A good all-around start is the design shown in Figure 3. This approach introduces the concept of a whiffletree. A whiffletree (a term borrowed from horse-drawn carriages) is the cross bar that connects the bars that hold the support points (shown here as hollow circles). The whiffletree centerpoint can be the collimation adjustment, although it doesn't have to be. The junctions where the whiffletree bars join the support point bars must be compliant and allow them to pivot. This is how the load is equalized across the support points.

The whiffletrees are **0.595 * Radius**, so in a 10" mirror they'd be 2.975 inches long. The supports for the mirror support points are **0.484 * Radius**; 2.420" long in this 10" mirror. The collimation points are on a ring at **0.535* Radius**, and this puts the inner supports at **0.325*Radius** and the outer supports at **0.730*Radius**. This cell would be tricky to build to high accuracy. There are other cells on the above mentioned web site that might be easier to build. The dimensions of this cell were derived from a figure on that site. ***Don't build a cell based on this figure!*** It is just there to show a representative approach.

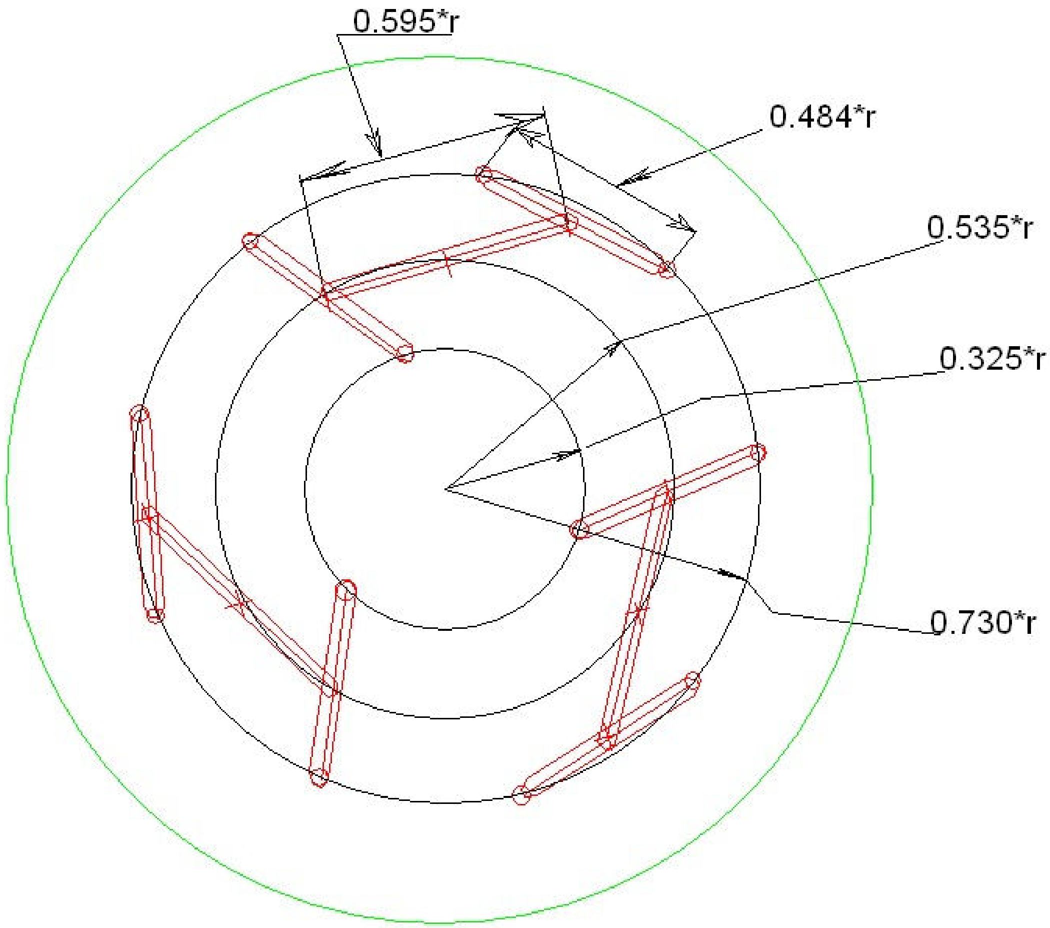

Figure 3 – Prototype 12 Point Cell

Eighteen Point Cells

The most popular type of cell for larger mirrors has 18 points; an 18 point cell will support mirrors in the sizes up to around 35 – 40 inches. Figure three shows the essentials of an 18 point cell as viewed from the rear. Here you see the whiffletree bars supporting two triangles, with all supports compliant.

The result from FEM analysis of 18 point cells is somewhat more complicated. There are no ideal radii for the support points that will work over all focal lengths and all diameter mirrors similar to the results presented for three and nine point supports.

According to David Lewis' analysis, a good compromise is for the inner supports to be at **0.378*Radius** and the outer supports at **0.764*Radius**. The caveats are as follows: this configuration will work for a moderate focal length mirror up to a 29.5" mirror (750 mm). Error is increasing rapidly with increasing diameter; as the diameter doubles from 300mm to 600mm, the error goes up by a factor of seven.

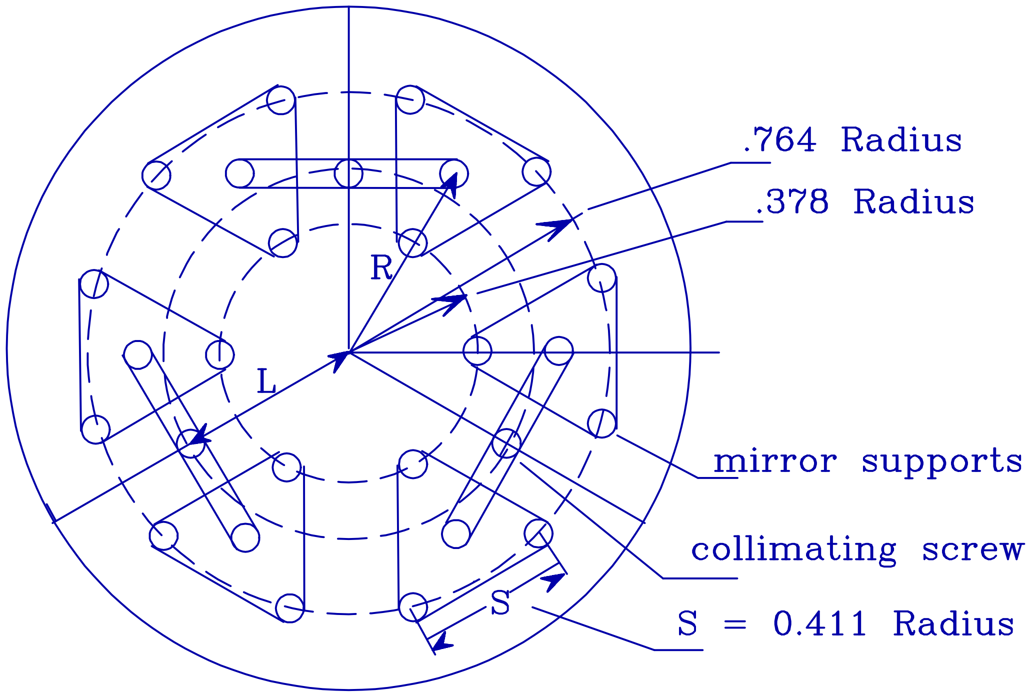

Figure 4 - An 18 Support Point Cell

How do you handle a larger mirror? As diameter goes up from 500mm (19.7") to 900 mm (35.4") the inner support should vary smoothly from **.380*Radius** up to **.386*Radius**, while the outer support should vary from **.775*Radius** up to **.811*Radius**. But that's not the complete story. As the focal length decreases, the points need to be moved differently, shifting farther out from the center of the mirror as f ratio gets shorter. Again, this is primarily the problem of the large, fast, thin mirror.

The dimensions of the cell can be worked out with some tedious trigonometry. The outer support ring contains 12 supports, spaced every 30 degrees around the mirror. The inner ring has six supports, spaced every 60 degrees. The triangles are equilateral, with distance between supports equal to **0.411*Radius**. The support points for the triangles are located at **0.615*Radius** from the center, the dimension labeled **R** in the drawing. The collimation bolts are located at the centers of the bars that join the triangles, and are at **.533*Radius,** the dimension labeled **L** in the drawing. The support bars are the same length as the radius to the support bolts, or **0.615*Radius** long.

More complex cells are found in the literature. The next most common size has 27 support points, and will support amateur scopes up to the largest sizes amateurs are building. The analysis of these cells with Finite Element Method modeling promises to revolutionize the designs of the cells we use.

If you are working on a thin mirror telescope, you should look into the FEM programs that ATM's have been using. Dave Lewis' website is at: http://www.davidlewistoronto.com/plop/ Here you'll find information on what the program does and how to use it. For some results you might be able to use as is, go here: http://www.davidlewistoronto.com/plop/design.htm

I'm Confused. How Many Support Points Do I Need?

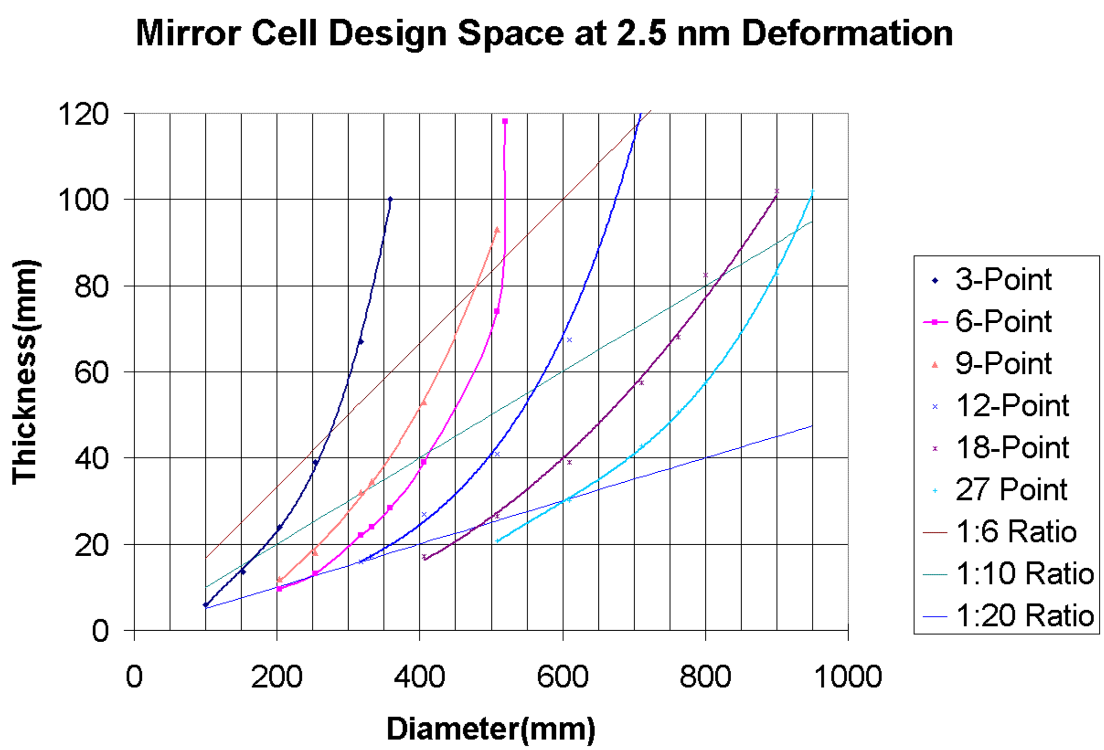

Figure 5 - Number of points vs diameter and thickness.

Confusion at this point is understandable. ATM Mark Holm has provided a graph to help you decide how many support points you need, seen in Figure 5. All points to the left of the curves show sizes that number of points is adequate to support. As was mentioned at the start of this section, if you are using a full thickness mirror (1:6 in this graph), in up to 250 mm sizes (10"), a 9 point cell will do. As the mirror gets larger and thinner, the number of required supports goes up. Mark now recommends using 6 point cells until they no longer work, then switching to 12 point cells, then 18 or 27 points. For example, the top-most diagonal line represents a "full thickness" (1:6) mirror. An 8" (200mm) mirror is supported with no problems by a 3 point cell. A 10" mirror (250mm) is just inside the 3 point line, showing a 3 point cell is adequate. A 9 point cell is adequate for a 1:6 mirror up to approximately 450mm, or 17.7", but if that 17" mirror is 1.7" thick (1:10), a 12 point cell, optimized by PLOP, is necessary.

As always in this sort of work, there are assumptions in there. Mark says, "I started with the assumption that the mirror and secondary have very fine figures and the cell should not noticeably degrade them. ATM's now have ready access to very well figured mirrors. Many homemade mirrors are quite good, and the standard of professional mirrors has risen essentially to perfection for the better firms. After estimating the degree of cell induced deformation that would not noticeably degrade the images from an essentially perfect mirror, I factored in another factor of two to allow for the effects of imperfect cell construction. That is something of a swag, but Jeff Anderson-Lee studied the case of 18 point cells and determined that reasonable construction tolerances could lead to a worsening of support of two to four times."

"My assumptions are more conservative than the ones David Lewis used for his recommendations for number of support points versus diameter and thickness. I won't argue which are more correct, but there is little reason to think that more conservative assumptions than mine are justified. In other words, you really don't need more support points than my graph shows."

If I haven't been clear enough on this, let me state it one more time: If you're designing a lightweight telescope around a thin mirror, you need to use PLOP. The web site home page is
http://www.atmsite.org/contrib/Holm/Plop_optimized_cells/index.html
and the FAQ is at
http://www.atmsite.org/contrib/Holm/Plop_optimized_cells/cellfaq.html On that web page, you'll find personal links to Mark Holm for more support in using PLOP.

Improving on the Mirror Cell

As will come as no surprise, there are good and bad cells out there. There have been a few ideas developed that bear separate mention. The ideas themselves don't necessarily make a cell excellent or trash, but they might make a cell easier or more fun to live with.

A. Push-Pull versus Spring-Loaded Collimation Bolts.

Robert Cox, in 1980, wrote that many of the ills of the current production run of mirror cells could be solved by throwing out the spring-loaded collimation bolts and substituting pairs of push-pull bolts. Cox's point, and it is valid, is that the force from the spring acts to help back out the collimation screws if the cell is subjected to shocks such as it would get being transported to a remote site. He further argues that a push-pull pair will put the bolts under tension and have the same effect as torquing them down. Lacking the ability to use a push-pull set, as is the case when modifying a commercial cell, he advocates using lock nuts on the screws to jam the adjustments in place.

The variable here is the quality of the machining in the cell. There are some very good ones, and some not-so-good ones. For convenience, I find it hard to beat a high quality machined cell with springs, and (given my lack of machine shop skills) my preference has been to buy them. Steer away from cells with wing nuts for adjustment. Anything that can be adjusted with finger pressure like that is much too loose. Adjustment should require a wrench.

B. Why 120° Between Collimation Screws?

I must confess to a weak spot about this: the action of collimation screws is never intuitive to me. The lines of action are 120 degrees apart and the everything else that I deal with in life doesn't move that way!

A few cells have appeared in the literature that use three collimating bolts set so the action is along mutually perpendicular lines. As shown in figure four, there are still only three bolts, but their arrangement allows the motion of the mirror to be more intuitive, at least to those of us who tend to think in rectilinear coordinates. One variant of this approach, built by Ed Stewart and shown in ATMJ #2, uses four pairs of push-pull bolts at the corners of a square. Eight bolts is a complex arrangement, but offers significant freedom in movement of the mirror surface.

I find the right angle alignment approach much more intuitive and plan to build one of these in the near future. I know of no commercial sources for amateur mirror cells with this alignment geometry.

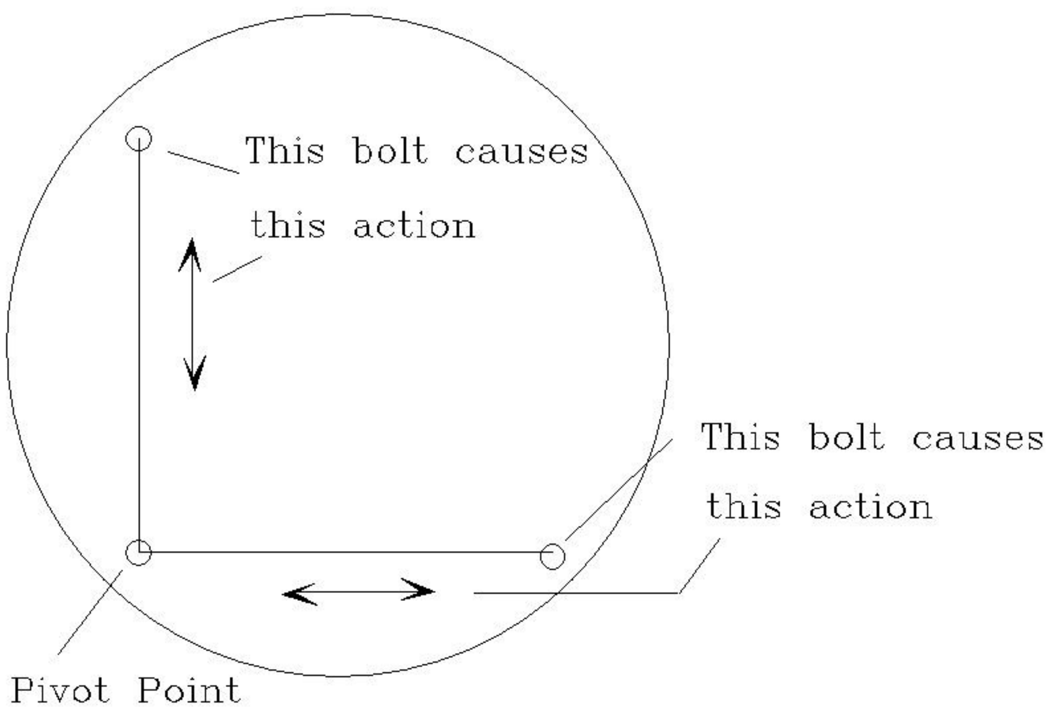

Figure 6 - Right Angle Collimation Adjustments Instead of 120°

II. Spiders and Secondary Cells

Spiders (not the kind that move into your tube when it sits around) get people's attention because they sit in the optical path. As almost all TMs realize, they are responsible for the characteristic spikes seen crossing brighter stars on our photographs. There are three main types of spider, and Figure 7 shows a sample of each type. The easiest to make and use is not suitable for larger telescopes, but fine for scopes up to 6".

Single Support. This type uses a single rod or vane that the secondary is glued to. A rod will vibrate at lower frequencies than a vane, and will sag more toward the primary. Both of these characteristics are undesirable. A vane (perhaps 1/16" aluminum or 1/8" wood) will sag less than a rod in the direction toward the mirror, but this only matters in an altazimuth mount with its constant load direction. In an equatorial, it will eventually be loaded in its weak direction and sag just as much (or more) than a rod. The secondary is bonded to a tab provided for it; in the case of the rod support it can be brazed on or bent out of the rod, in the case of the vane, the support is bonded on. RTV, again, works well here. This type is shown as figure 7a.

Bladed Spiders: These spiders (figure 7b) can be adjustable or non-adjustable (more precisely a one-time adjustable spider). The non-adjustable spider is typically made from three but maybe four thick vanes that hold the diagonal. Once the diagonal is put in place and the alignment is sure, the spider is glued in place with RTV or epoxy. The vanes are the same size as mentioned in the previous category, and made from wood or aluminum.

Adjustable spiders are built like the previous class, but are not bonded in place. Instead, they have adjustments to fine tune the position of the secondary in the tube. Most commercial spiders are of this type, and are made of thin metal blades that mount to the tube with screws or bolts that protrude through the wall. The diagonal holder can be adjusted forward and backward along the axis of the tube, and the entire assembly can be offset slightly. This is to allow the diagonal to be properly placed in faster telescopes, which need a slight offset of the diagonal.

If you don't want to buy one, you can make one as shown in figure 8. Start by cutting two equal lengths of 1/2" wide by 1/16" thick shop aluminum (sold at home improvement stores under various names -- see the Metal101 chapter). These are cut halfway through at their mid points so that they can be joined (in woodworking, this is called a cross lap joint). At the center of these, where the two pieces cross, a wood or cork disk 3/4 inch thick holds the two pieces of metal captive and keeps the joint from falling apart. The thickness isn't critical, and a thin plate can be screwed to the outward side of this circular piece to ensure that the metal arms don't fall out. The diagonal holder can be a simple piece of wood that matches the outline of the diagonal. Run a screw from this into the wood circle to hold it in place, or use a bolt as pivot rod around a screw hook in the wood disk. Another screw, this one from the back of the wood circle, through it and contacting the bottom of the diagonal holder, allows you to tip the diagonal forward; pulling it backward as you unscrew the adjustment. This is a good job for a small spring.

Curved Spiders. The last type of spider, shown as figure 7c., uses curved members to hold the secondary holder. This has been done to minimize the diffraction spikes that cause straight lines on photos. It is possible to buy spiders with curved blades, but they can be made from sheet metal or composite material. These spiders do reduce or eliminate the spikes that appear in the image, but the physics of the situation says that diffraction will occur with anything in the path, and the patterns seen during a star test are still degraded by diffraction. The degradation is just not as obvious in photographs.

These can be made with two or more large hoops of metal that intersect at the

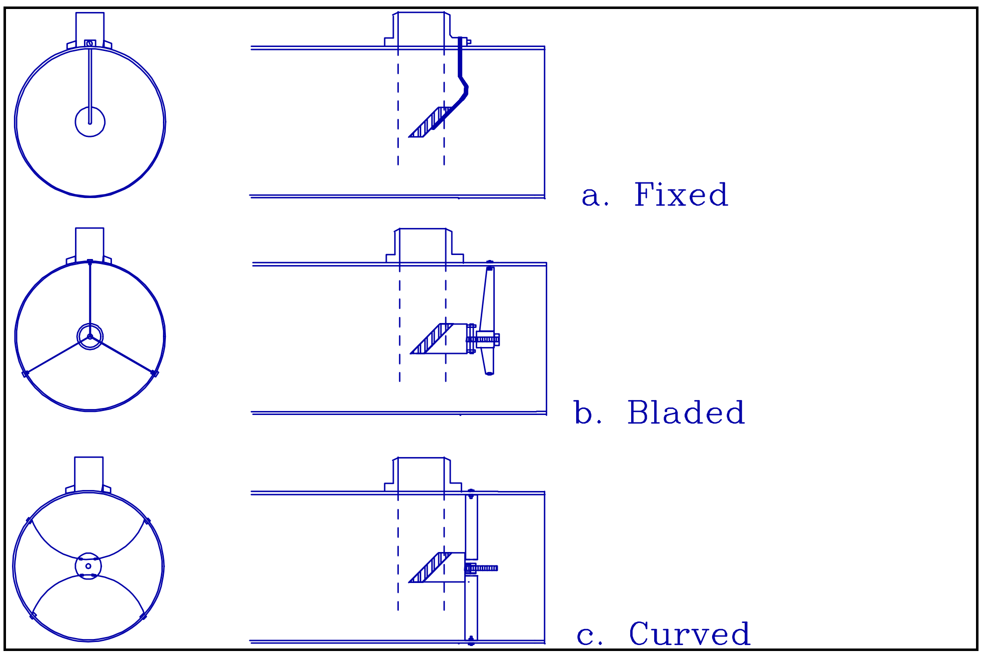

Figure 7 - The various forms of spiders.

center of the tube, where the diagonal holder is mounted.

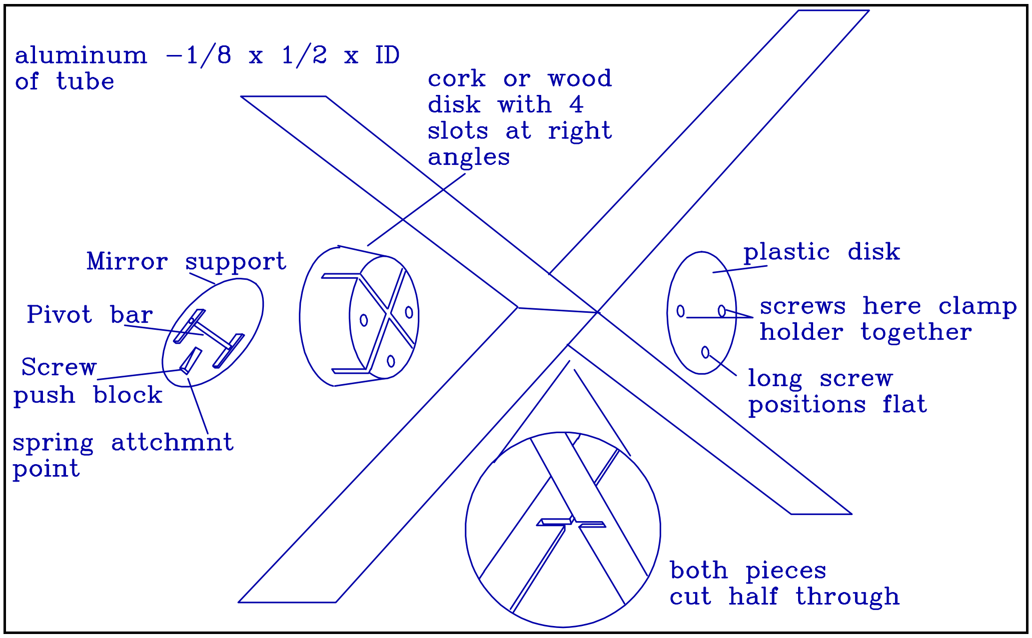

Figure 8 - A homemade spider.

A recent innovation is the **Wire Spider**. The Wire Spider was invented to achieve two goals: 1) minimize optical disturbances from thermal or diffraction effects, and 2) minimize weight. The Wire Spider is not currently available commercially, but is constructed from thin wire (approx .02”, 1mm or so) under tension to hold the spider in place. Furthermore, there are multiple ways to make a wire spider, from complex patterns that cross over to simpler straight wires replacing the vanes. The attached illustration, figure 9, may help clarify the idea. The wires cross midway out to the tube, and are anchored on the secondary holder with a wrap under the head of a screw or a screw eye. Similary, they can be attached at the tube with a screw eye. One builder even used the tuning mechanism from a guitar string to tension the wire!

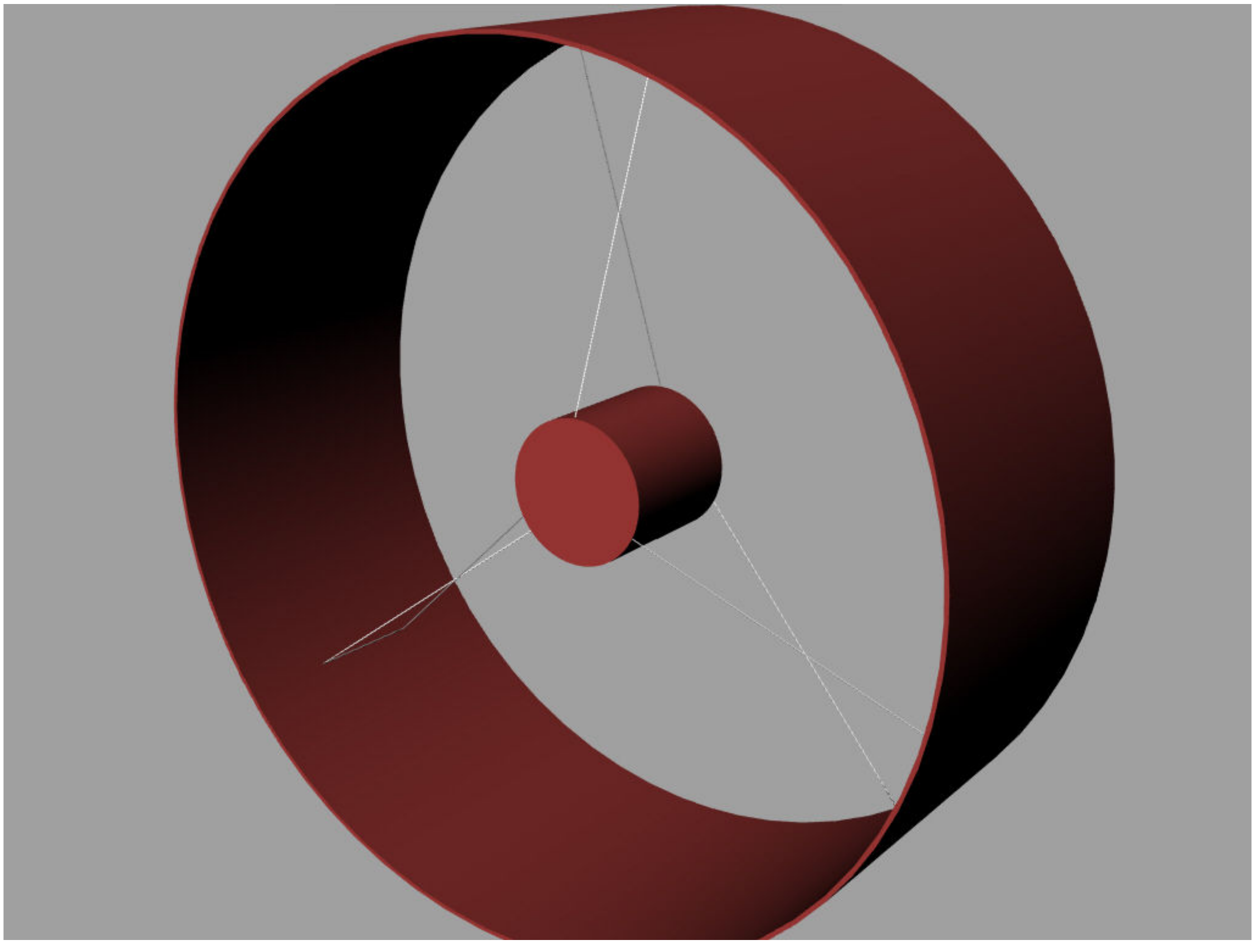

Figure 9 - A Wire Spider

III. Lens Cells

Lens cells are subject to the same sort of requirements that mirror cells are when it comes to aligning and holding position while not putting pressure on the objective. They have the additional complication of only being able to hold the lens by its outer edges. I should point out that since the support is entirely at the edge, the sophistication of the FEM-enhanced mirror cells is not available, yet the glass of a refractor is going to deform under its own weight just as a mirror does. This is yet another indication that the thickness of the glass does matter, and that the refinements of the mirror cells that we've just talked about are primarily important to those of us who are using larger, thin mirrors.

A typical lens cell is shown in cross section in figure 10. The lens sits on a metal lip in the cell that supports its weight. It is kept from slipping by the use of a compressible material between the glass and the walls of the cell. The lip that the lenses sit on is narrow, perhaps 1/16" (1.6mm) in typical amateur telescopes. You obviously want to minimize this surface, since it takes away aperture. The retaining cap that sits above the lens should not contact the front surface, but leave a gap like the .008 mentioned for mirror cells. This sort of cap is held on three small pins, like a bayonet mount light bulb (e.g., many car or flash light bulbs). Alternatively, many cells use a threaded retaining ring that screws into the cell until it rests just above the mirror surface.

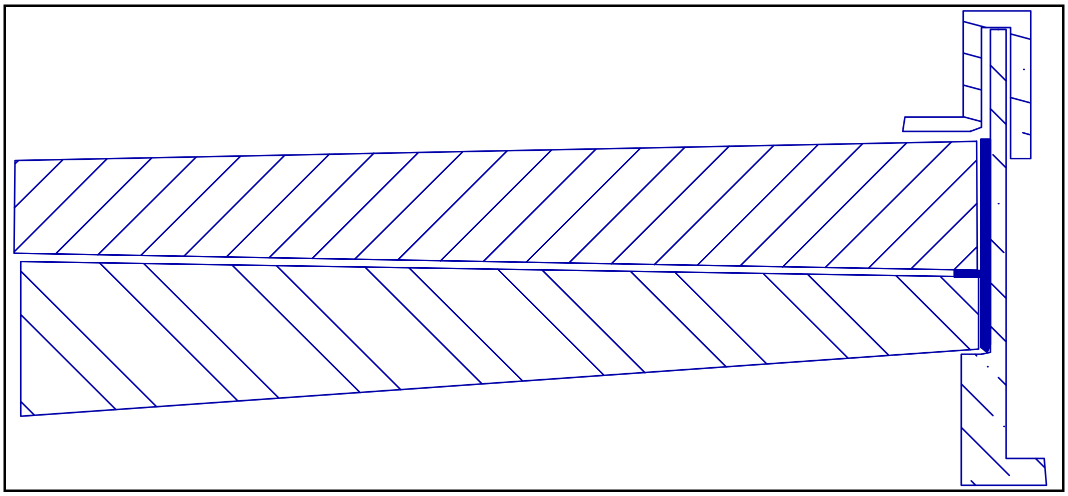

Figure 10 – Cross Section of a Lens Cell

The lens cell has to be mounted to the tube, and needs collimation adjustments. These goals are accomplished by three push-pull bolt pairs separated by 120^{o}, although you can certainly use four pairs separated by 90^{o} as shown for mirror cells above. One of each pair of screws passes through the cell into a mounting nut in the tube and pulls the two together, the adjacent bolt contacts a small metal tab and pushes them apart.

A serviceable cell can be made from plywood, oak, or other low-tech materials. In this sort of cell, two or more pieces of wood get circular cutouts for the lens. It is helpful if the bottom cell is slightly smaller than the lens to aid centering it in place, but this is not strictly necessary. The lens is placed in the cell, spaced equally from the wood all around its circumference by paper or playing cards, and then RTV is applied to bond it into place.

If you're afraid of squeezing RTV between the elements of the objective, you can put some tape at the places around the circumference where the RTV will be applied, or you can tape it completely. The RTV has to contact glass for a secure attachment, so only use a thin strip of tape to seal the air gap between the lenses. It is helpful if the wood is drilled through from the side to allow the tip of the RTV tube to get close to the lens. Apply the RTV and then walk away for 24 hours while it fully cures.

If you use a metal cell, be sure that the lens is loose enough to cause a perceptible rattle when you shake the cell. This is scary, but minute amounts of pressure on the lens can deform the image. If you use a compliant seal, like a rubber tape in the metal cell, you can still transmit enough pressure to the lens to distort the image. If you use RTV in a low tech cell, the RTV is compliant enough to eliminate this concern. If you perform a star test and see non-circular patterns inside and outside of focus, especially on a long focus refractor, suspect pressure before you suspect astigmatism.

IV. Focusers

With focusers, the issue is not mechanical strength or symmetry of loading, it's smoothness of operation and mechanical precision. Most of us have used the common rack and pinion style of focuser and often found it wanting in this area. The standard eyepiece size of 1¼ inch has the advantage of fitting well in a common plumbing store item: a sink drain tube, often made of chrome-plated brass, will accept the eyepiece with no metal working required. This allows the home worker to easily find materials that make acceptable focusers. If you enjoy precision work, especially with metal, this is an area to experiment in.

The simplest home made focuser is the friction type (see figure 11). In this type, a mounting block made from wood or plastic is cut for the eyepiece tube and then mounted to the telescope. The eyepiece tube is put through block, and if the friction is acceptable, you're done! If it is too loose, a pinching action can be added by splitting the block and putting a screw and nut through it that closes the split. This is adjusted once. If it is too tight, the hole in the block can be reamed out, or a lubricant, like a Teflon spray applied to the tube. Getting the fit to feel just right is the hard part, but for the cost of a sink drain tube and a small block of wood, you can make an acceptable focuser. If you are only going to use one eyepiece and only need to focus once, as in a finder scope, this is not a bad way to go.

Helical focusers are typically low cost, and tend to be smoother than friction focusers. In this design, the eyepiece holder becomes a threaded barrel that turns in a larger diameter holding barrel. The outer barrel does not have to be fully threaded, but can simply use a small spring (like those in ball point pens) to press a small ball bearing against the threaded eyepiece holder. The focuser can then be held in place with a set screw. The problem with helical focusers is that the motion of the eyepiece holder is often not symmetrical around the center of the optical axis. This causes the image to rotate around the center of the field while you're focusing. At high magnifications the image can rotate outside the field of view, thus losing it before focusing. Since building one of these calls for the ability to cut metal threads, this design tends to be something homebuilders avoid.

The rack and pinion focuser can be built by the home builder without extensive metal working tools. A pinion and rack gear set can be bought from a gear supplier, or found in a scrap yard. The rack is then attached to the eyepiece tube with small metal screws, or by brazing it on, and the pinion attached to the outer barrel so that it engages the rack. The eyepiece tube needs to be held fairly tightly in the outer barrel so that it doesn't slide back into (or out of) the telescope when the focusing knob is released. This can result in too much friction, so the eyepiece tube is usually greased up pretty heavily. Even so, many of these focusers (including the commercially sold ones) tend to stick and slip, and don't work very smoothly. Another problem is that the tube tends to sag when it is racked fully out and loaded with a large eyepiece. This is because the eyepiece tube is not well supported by the housing.

Crayford focusers are the smoothest variety of focuser commercially available (figure 12). In this type of focuser, a focusing knob pushes the eyepiece tube against ball bearings mounted in two sets parallel to the axis of the eyepiece holder. This keeps the path of the eyepiece along a single straight path and makes it easy to focus without having the eyepiece holder stick or slip. If ball bearing sets are not available, the home builder can use a set of Teflon pads set at 90^{o} to each other (angle aluminum) with a rubber friction wheel to slide the eyepiece holder up and down.

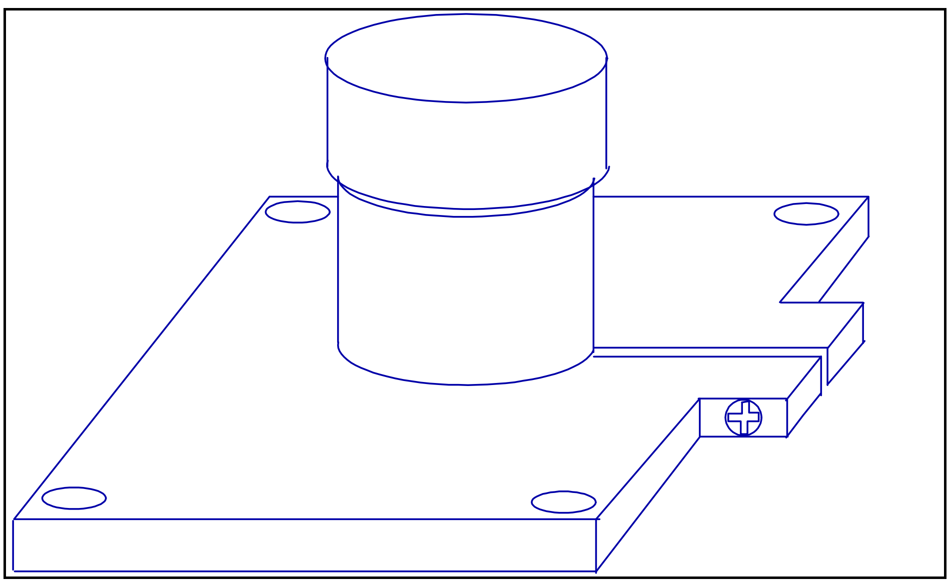

Figure 11 - The simplest type of homemade focuser, friction from a split board on a plumbing sink drain.

With the exception of the simplest friction-fit focusers, all focusers can be easily motorized. A motorized focuser will help minimize the amount of time focusing because you don't touch the telescope while focusing, and therefore don't cause as much vibration. In the case of rack and pinion or Crayford designs, a small DC motor can engage the focusing knob with a small rubber belt, or friction wheel. The direct approach, the one used by JMI in their Motofocusers, is to couple the motor directly to the shaft of the focuser by taking off one of the existing knobs.

The torque requirements for a motor in this type of use are very light, and any DC motor that runs off a convenient supply can be used. Motors are available from surplus sources, RC cars and other toys, as well as places like Edmund Scientific. A DC motor with a polarity reversal switch will run forward and backward, allowing you to adjust the focus easily.

A reasonable question is how fast the motor should be. Catalogs will often list many different motors at different prices. How much do we need to buy? This can be answered with a little arithmetic. The typical focuser has from 1 1/2 to 2 1/2 turns to run its full range. A rack and pinion focuser that I have on an early scope of mine takes 1 3/4 turn (1.75). If I want to run that entire range in one second, the speed is 1.75 revolutions per second (rps) or:

$$\frac{1.75rev}{\sec} x \frac{60\sec}{1\min} = 105rpm \quad (1)$$

If I drive the shaft of the focuser directly with the motor, this is the motor speed that will focus end-to-end in one second.

As in every other place we've looked, there are compromises here. A focuser that runs faster here will be harder to adjust precisely than one that runs slower. The best approach is to use two speeds, or even variable speed. A good alternative is a momentary contact switch that can be tapped gently to move the motor in pulses.

What if I have a motor that I want to use no matter what? As long as it's not extremely fast or slow, we can use it if we use a belt arrangement. If two wheels are driven by a belt, and the belt doesn't slip, they must have the same linear velocity at their outer edges. In chapter two, we said that the linear velocity is the angular velocity omega times the radius r. If I use the subscripts m for the motor and f for the focuser, saying that they are equal is the same as saying:

$$\omega_m r_m = \omega_f r_f \quad (2)$$

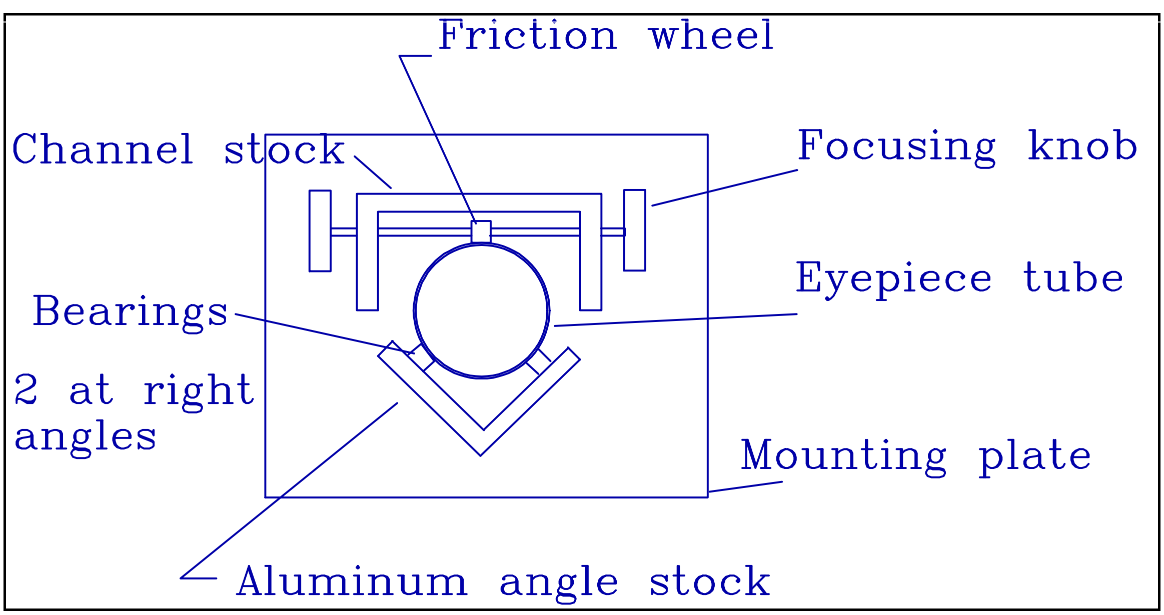

Figure 12 - The most advanced amateur focuser -- the Crayford

For example, let's say I have a 1000 rpm motor. I wrap a belt around its output shaft, 0.1" in diameter (radius 0.05"), and loop the belt around the focuser knob, 1" in diameter (r=0.5"). The speed seen by the focuser is:

$$\omega_f = \frac{\omega_m r_m}{r_f} = \frac{1000x.05}{0.5} = 100\ rpm \qquad \mathbf{3}$$

It can be seen from this that a faster motor can be used if we use a small drive wheel and a large focuser knob. The opposite is true also: a large drive wheel and small focuser knob will allow a slower motor to focus just as quickly.

As one last comment on the topic, I started this discussion with the statement that the belt doesn't slip. If it does, the transferred speed is slower than calculated. As a bonus, having a belt that slips will keep a higher torque motor from forcing the focuser into a bad position and possibly damaging it.

The “New Frontier” in focusers is adding computer feedback to focus under PC numerical control. Here, a small motor is controlled by a PC while a camera of some type (CCD or DSLR) takes exposures of a star. The program then acts to minimize the size of the focused star image.

Mounting Rings, Dovetail Plates and Other Things

The current emphasis on CCD and DSLR photography has created new interest in some subtle aspects of the various accessories that you can put on a mount and use to carry cameras, secondary telescopes, and other accessories. The problem here is that you want the relationship between the two parts of the mount, say your main OTA and a secondary guide scope, to stay constant. They can move as the night progresses, but they should move as a unit. This is referred to as “*differential flexure*” and even microinches of it can be a problem.

It should come as no surprise that the main concern here is stiffness. Stiffness is largely determined by geometry and material, and a very stiff component can weigh a small fraction of a what less stiff version weighs – or it can weigh substantially more, depending on how clever the designer is. For example, in Figure 13 the two mounting plates have the same area and essentially the same resistance to bending in the thin direction, but the one on the bottom has had much of its material removed and is therefore much lighter. This missing mass does change the properties of the plate, but the bending is set by the moment of inertia, largely a function of the area, not the amount of mass.

The stiffness needed applies to the fasteners used as well as the mounting plates themselves. Large fasteners are preferred.

Dovetail accessory rails have not been adopted for the Schmidt Cassegrain and photography sets because they are particularly strong, but because they have some self-aligning properties that make them easy to use. It's worth doing for your own telescope projects because there are so many options available if you want to use commercially available metal components. If you don't have your own metal milling capability, it's just makes sense to use systems that have been developed and tested extensively. In makes sense to adopt a common spacing for hardware, like the Meade LX200, or Celestron SCT spacing, so that these accessories are available if you need them. Of course, these two companies don't use the same spacing, so you might want to buy the accessories to determine where to drill your tube or mount!

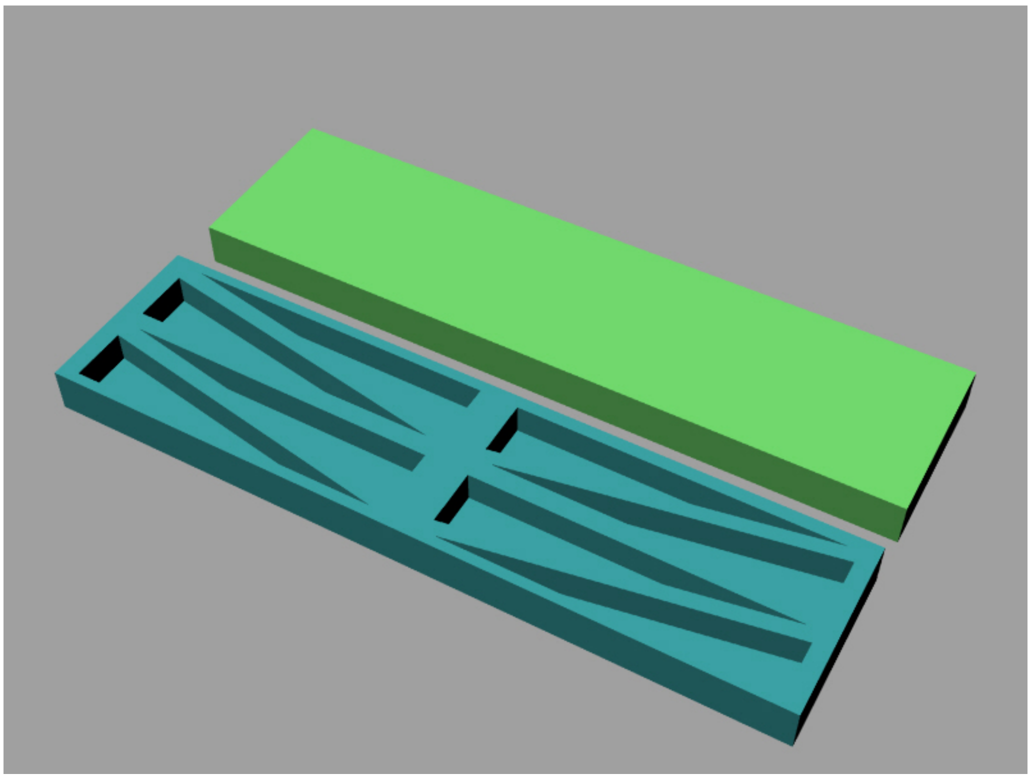

Figure 13 - Two mounting plates of the same overall size, but one is much lighter than the other.

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