Chapter one
Introduction

New telescope makers seem to be overwhelmed by the requirements for their optical surfaces. As a natural outgrowth of the quest for optical perfection and errors of less than 1/10 wavelength of light, a lot of ATMs come to believe that the optics are all that matter in a telescope. Gatherings of ATMs tend to turn into discussions of contrast, modulation transfer functions, central obstruction percentages, and the appearances of airy disks.

While the optics are certainly important and no telescope can be better than its optics, it's also true that no optics can be better than their supporting structure. It is simple fact that the best optics in the world can be rendered useless by a careless or inadequate mechanical design. If you have ever had the misfortune of using a mount that is wobbly, vibrates incessantly, or sways in the gentlest breezes, then you have seen the problem.

This is not a new problem, nor a new statement about it. The first ATM I ever spoke with was a professor of Physics and Astronomy who was in the process of putting a 24" telescope into operation at a remote site. His advice to me was that it was always easy to come up with optics. Someone's aunt Matilda always seemed to have a mirror that was handed down to them and stuck away in an attic. The hard part was mounting the optics in a useable telescope. In the early days of telescope making, the problem was addressed by making mounts into massive monsters. Automobile axles were pressed into service, as were lathe heads, engine blocks, and any other large chunk of metal they could find. There seems to have almost been a competition of sorts to see who could use the largest mass of metal in their mount. I suggest that this is wrong.

The last 100 years have seen the same revolutionary changes in mechanical design engineering as in all other fields of engineering. A great deal of these have been due to new materials that offer tremendous gains in performance. But just as many changes have been due to computer-enhanced analysis of designs that allow engineers to see which parts of a design are most critical and how to reinforce them for optimum performance.

A strong motivating force behind these improvements in mechanical engineering has been the development of space flight. Hardware weight is critical in space-based applications. It costs tens of thousands of dollars per pound to put a payload into orbit. A pound saved in the weight of a rocket can translate into several pounds of payload into orbit because the rocket must lift that pound, plus the fuel to lift it, and at some point the rocket’s payload is exceeded. Many innovative techniques were developed for processing alloys in these applications, as well as new techniques for designing structural components. New materials were also developed, and there are now rockets and missiles with composite skins. Graphite fiber reinforced plastics have replaced metal in these uses.

The aviation industry was quick to embrace these developments. Commercial aviation is concerned with shaving a percent or two off the weight of the airframe; 10% would be a major advance and a new aircraft being even one percent overweight can doom that model to second-tier status. The famous Voyager plane that flew around the world without refueling was largely made of composite materials. Many sport planes are now constructed from foam and fiberglass composites. Innovative military aircraft such as the F-117A Stealth fighter, F22 Raptor and the B2 bomber utilize a lot of composites in their construction. Boeing has recently committed to a composite air liner, the 787, which will be the first commercial air liner made primarily from composites.

It should come as no surprise that these changes have made their way into the design of astronomical research instruments. For reasons that will become apparent as we go along, weight is the enemy in telescope design. The largest telescope in the world on a conventional equatorial mount is the 530 ton, 5 meter (200") Hale telescope on Mt. Palomar, while the largest single mirror telescopes in the world are currently in the 8m class. The Hale is generally considered to be the largest example of an equatorial mount that will ever be built.

Much of the research work being done in the field of large optical telescopes centers on methods of reducing the weight of the primary mirrors. For many years, the largest single mirror telescope in the world was the Bol'shoi Teleskop Azimutal'nyi in the Russian Caucasus Mountains. It is reported that the first Russian 6 m mirror broke under its own weight while being cast and turned into a mirror. Today, several single piece telescope mirrors over 8m in diameter exist with larger mirrors in the works. None of these mirrors are “full thickness”/full weight (note: in the early days of glass mirror making someone proposed the ideal ratio of diameter to thickness is 6:1, so that a 6” mirror is 1” thick, and so on; this has become known as “full thickness”). In this respect, the Hale telescope was way ahead of its time. Large triangles and cylinders where no glass would be cast were molded into the blank, thus making the blank much lighter than a solid blank would have been.

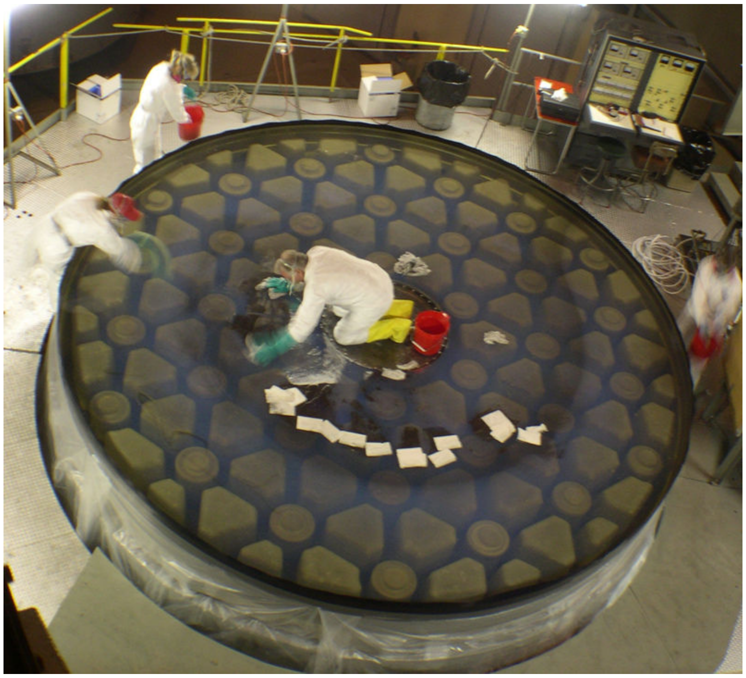

Figure 1 - Workers prepare the 200" Hale mirror for aluminizing. Note the cut-corner triangles and cylinders where there is no glass, seen through the surface.

There are two schools of thought in the construction of these giant telescopes; breaking the mirror into small segments, and making the single mirror lighter. The 10 meter diameter Keck telescopes on Mauna Kea in Hawaii exemplify the first approach; they are designed around 36 hexagonal tile mirrors, with the tiles held in place and positioned by the precise alignment of mechanical positioners behind the tiles. The second approach is exemplified by Roger Angel and his group at the University of Arizona who have developed a method for spin casting large lightweight mirrors. The mirrors produced with this method have honeycombed backs consisting of ribs reinforcing the mirror surface to prevent it from sagging, and the result is much lighter than a solid mirror of the same size. The spin casting technique allows them to produce very short focal length mirrors with less grinding and waste of glass, thereby making the resulting telescope shorter as well as lighter. The “brute force” technique for producing lightweight, full-sized mirrors is to produce a very thin mirror. Since a thin mirror will not be able to hold its surface accuracy against the pull of gravity, the telescope must control its surface accuracy by active control of the mirror mount. This is the approach taken for the 8.2 m ESO Very Large Telescope, with the enormous blank cast by Schott Glasswerke of Germany and made into a mirror at REOSC in France.

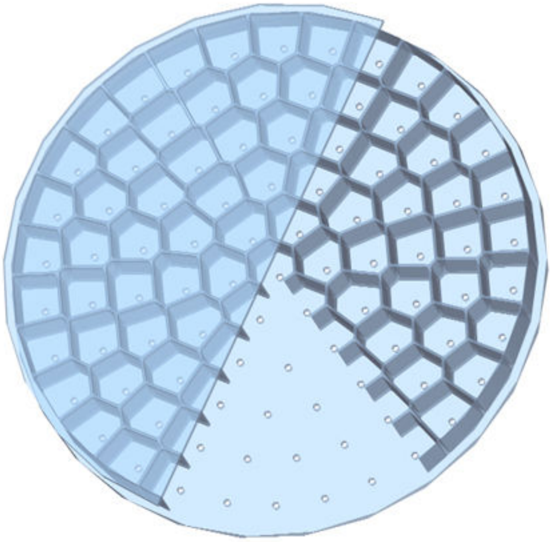

Figure 2 - A Hextek^{TM} fused lightweight mirror blank. - Courtesy Hextek^{TM}

Figure 2 shows a lightweight, fused glass mirror blank produced by Hextek, a spin-off of the University of Arizona mirror lab. There has been some amateur work with fused glass mirrors like this, honeycomb-backed mirrors, and other even more exotic technologies, but such techniques are generally beyond most amateurs. I present them to show the lengths that telescope designers are going to in order to reduce weight. If you are willing to go to the expense of making a mirror lighter by using a honeycombed, or egg-crate mirror, then you are undoubtedly interested in the ways that mechanical design can help you take weight out of your telescope. Most amateurs interested in saving weight on the mirror simply use a thin blank, defined as one with a thickness less than 1/6 of its diameter.

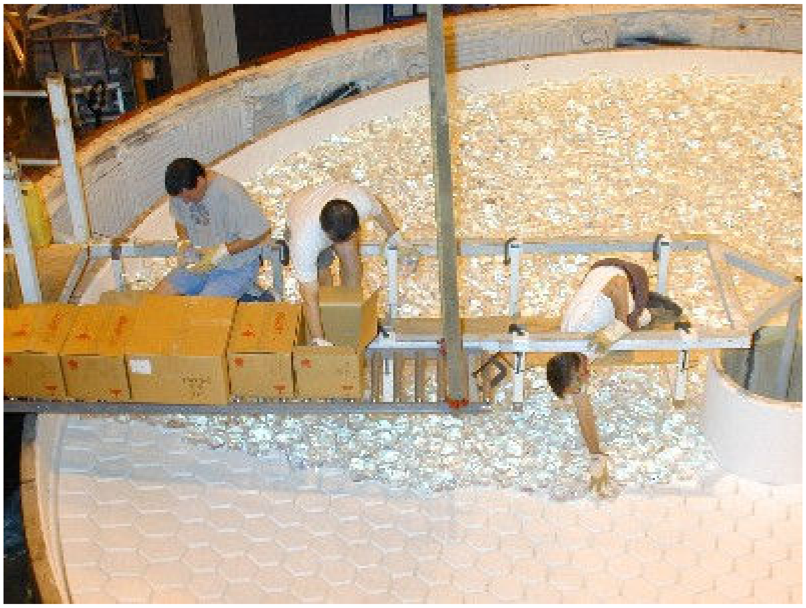

Figure 3 University of Arizona Mirror Lab workers load glass into a telescope mirror mold prior to melting and spin-casting.

Form Follows Function – and Other Laws of Design

It has been said that one of the hallmarks of good design is that “Form Follows Function”. That is; something is shaped in such a way as to naturally perform its function. For example, a sports car is aerodynamically shaped to reduce drag, and has a low center of gravity to assist high speed cornering, while a sports utility vehicle has a higher center of gravity to clear the larger obstacles commonly found off-road. It won't corner as well as the sports car, but the sports car will rip apart its underside on a moderately sized rock. As another example, a supersonic fighter like an F-16 is shaped completely differently than a sub-sonic plane like an air transport passenger liner. The fighter must handle high G loads, be extremely maneuverable, deliver weapons to a hostile environment, and bring its pilot home alive. In trade for this, it may require massive amounts of maintenance work. The passenger liner handles much lighter acceleration loads, and its biggest design criteria is to deliver a load of passengers in relative comfort with high reliability. It will be expected to work with much less maintenance.

Telescopes and their mounts also must meet this standard. Since Galileo started using telescopes for astronomy almost 400 years ago, many brilliant innovators have addressed the two main design problems telescopes face: keeping the optics aligned for proper performance, and tracking the object under study for long periods. But the first workers had access to only the materials and techniques of their day, and no history of experiments that tried and succeeded, or that tried and failed. In that sense, we are able to do the things we do today because we stand on the shoulders of our predecessors. Throughout this book, I'll show examples of early approaches to the problems of telescope mount design. I hope it helps you to see the way the problems have been addressed in the past because in a very real sense, we truly do “stand on the shoulders of giants”.

Throughout this book, examples of early approaches to telescope design will be presented and discussed. Many of the designs will be familiar to you, although they may be implemented differently. For example, the earliest telescopes were made from rolled paper tubes, or from carefully cut slats of wood. As the instruments grew in size, the tubes evolved toward rolled sheet metal, and by the time the large refractor reached its peak in the 1890’s, the tubes had become riveted steel much like the buildings being constructed at the time. The early reflectors were made with metal mirrors. As the ability to silver glass was refined – and then replaced by the ability to aluminize glass – thus making large reflectors possible, the mechanical design likewise was refined. By the time the Hale telescope was constructed, experience with the Lick and Yerkes telescopes led the designers to realize what a truss would have to accomplish to make the 200 inch Hale successful.

The Four Laws of Telescope Design

Did you ever read Isaac Asimov’s robotics stories? Remember the Three Laws of Robotics? Before we get into the elements of design, let's look at the four laws of telescope design. The first law is the Foundation of the rest:

1.) **The telescope must not impair the image.** Stated another way, a telescope's mechanics must never impair its optics.

2.) **The telescope must be as light as possible**, so long as this does not violate the first law. This makes living with it easier in so many ways.

3.) **The telescope must be as stiff and strong as possible**, as long as this does not violate the preceding laws. Stiffness helps to raise resonant frequencies & make vibration easier to live with.

4.) **The telescope must reach thermal equilibrium as quickly as possible** as long as this does not violate the preceding laws. Thin mirrors help, as does a metal tube or truss, or a fan.

The Basics of Design

My purpose in writing this book is to present the fundamentals of the mechanical design of lightweight, strong, telescopes. To present anything beyond mere cookbook designs requires that I go into some depth in various topics from mechanical engineering and this will be the contents of the next couple of chapters. If you have studied high school physics, you can safely skip this material. This will not be in the depth required to make you into a structural engineer, but will be in sufficient depth to allow understanding. If you understand the material and analyses that I present, you will be well on the way to being able to design your own mount for your own applications.

For now, let me state some of the guiding principles of design. These will get more explanation and justification as we go along.

I. Keep the center of gravity over the support. At one extreme, a weight at the end of a rod acts like a low frequency tuning fork. Even if you can keep the mount from flexing excessively, it will be hard to make it stiff enough to not vibrate maddeningly.

II. Structural Components are stronger in compression or tension than in bending or torsion. In pure compression or tension (straight, end-on loading) even thin objects are remarkably strong. A design goal will be to make sure members are loaded along their axes. Not following rule #1 usually results in members being under bending load, and here you need a lot of strength.

III. Use triangles as building blocks. This simple rule can result in a lot of improvement. Triangles are simply much stronger than squares. How much stronger? According to tests published in Sky & Telescope[1], in a telescope tube made with 3/8" diameter steel rods, a triangle based tube was 100 times stronger than one based on rectangles. More interesting from my standpoint is that this means that a triangle-based tube made with 3/16" inch *hardwood dowels* was shown to be stronger than the rectangle-based tube made with 3/8" steel rods!

There is no magic here. The improvement comes from the fact that triangles will transfer loads into pure compression, while the rectangles can allow bending.

IV. Manage friction: it is either friend or foe. Friction is absolutely essential to the design of some mounts, notably the Dobsonian and its derivatives. Optimum friction forces have been empirically determined in these mounts. Too much friction and the scope won't move without a healthy push. Too little and the scope flops all over and won't support even small changes in weight, like the addition of a Barlow lens.

In other mounts friction makes it easier to use certain techniques, such as a motor drive with friction clutch. Or it can degrade performance, as in a bearing set intended to be free-wheeling. The point is that there is no reason to settle for what you get. The friction in your mount can be designed like any other parameter.

V. Manage vibration by design. Vibration is another thing we design to control. Vibration is a function of stiffness, weight, geometry, and material selection. Styrofoam makes a rotten bell! The specific vibration requirements for parts of a mount can be designed and tested for. Vibration in parts of a telescope and mount can be isolated from other parts with vibration isolation techniques used on aircraft and spacecraft, but with cheaper parts.

VI. Weight, strength and vibration resistance don't necessarily come together. I'm sure there are good mounts out there that are big and heavy. My point is that they don't always have to be. Furthermore, weight added haphazardly by the builder is just as likely to cause problems as solve them. I think we can show throughout this book that mounts can be surprisingly strong and steady while remaining remarkably light.

If you are building a telescope with a large mirror, you can have a lot of weight in the glass. Why make the telescope any heavier than it needs to be? Many of us live in suburban areas with less than ideal observing conditions. Isn't a lightweight telescope and mount easier to transport out to a dark-sky site?

Doing it right. The Dobsonian Mount

For the past couple of decades, the most popular mount for amateur telescopes, especially large aperture “light buckets”, has been the Dobsonian mount, developed by John Dobson of the San Francisco Sidewalk Astronomers. Let's look at one of these mounts in the light of what we've stated about mechanical design and examine it in some detail, while not going into mathematics quite yet.

Figure 4 shows a Dobsonian mount, in one of its embodiments. The tube here is square plywood, although concrete form tubes of heavy spiral wound paper are often used. The scope moves in two mutually perpendicular axes; elevation and azimuth. Most familiar camera tripods move this way, as do many moving things from military artillery guns to satellite TV antennas. Even our own heads are mounted on a two-axis mount. The azimuth bearing is formed from the large box that carries the telescope tube and the circular board underneath. One of these surfaces is covered with Formica or similar laminate. It slides against three or more pads of Teflon fastened to the other surface. Similarly the elevation bearing is formed by the large circular pieces on the side of the tube and by the matching semi-circular cutout in the bearing box. The circular bearings can be PVC pipe scraps from a plumbing job, wooden cutouts covered with aluminum strip or Formica, aluminum movie cans, or anything circular and appropriately sized. They also ride on Teflon bearings.

The moving parts of the mount, then, all depend on the friction between smooth materials like Formica and Teflon. In its best embodiments the movement of the telescope is “buttery” smooth, responding to the user's gentle push to find or stay on a target. In the case of the azimuth bearing, the friction can be controlled by the simple expedient of bolting the box and the ground board together and adjusting the tension in the bolt to provide the desired freedom of movement. The friction between the telescope elevation bearings and the Teflon pads on the bearing box depends largely on the weight of the tube assembly and can be controlled by manipulating the weight of the tube, choosing different materials for the bearings, changing the size or location of the bearings, or by a clamp that presses the elevation bearing onto the Teflon pad.

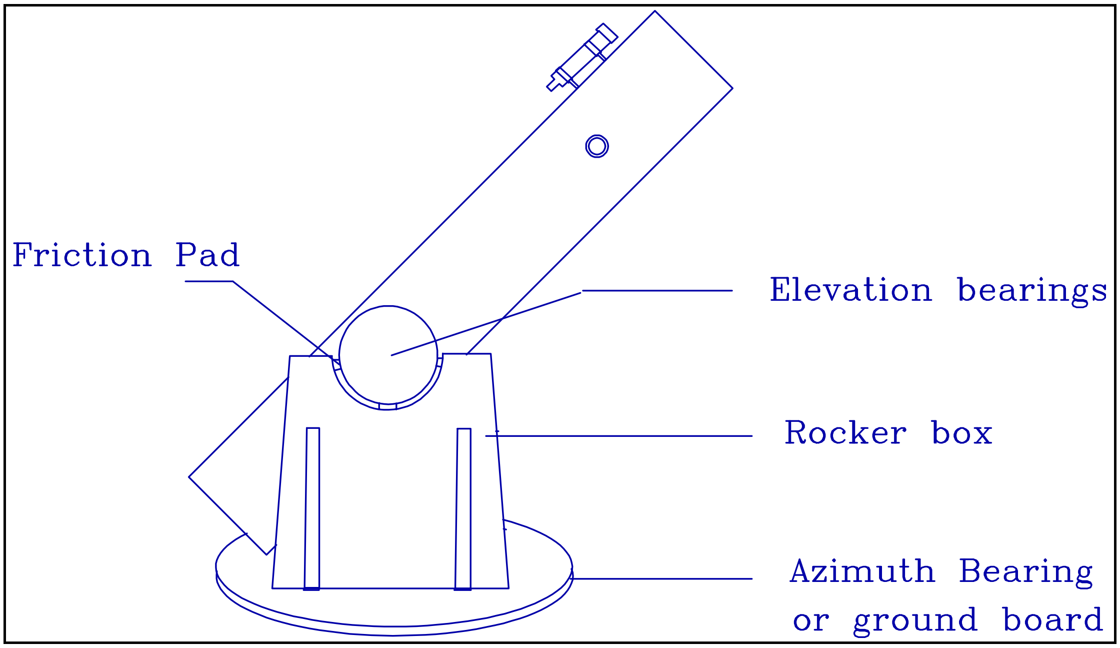

Figure 4 The Popular Dobsonian mount

The weight of the telescope is supported by the rocker box and the center of gravity of the telescope is centered exactly over these bearings. Hence, there is no bending moment and the box is in pure compression. The box itself is frequently made of plywood which offers the advantages of being strong in compression, and good at vibration damping. The bearing surfaces are large, which helps to manage the friction that controls all movement.

The altazimuth design itself allows the center of gravity to be well-placed as it is in these mounts. As will become apparent later, the “tipped-over” axis of the equatorial mount is at the heart of the design problems with equatorials.

The Dobsonian therefore complies with our design rules I, II, IV and V. This particular example doesn't use a triangle based tube, although many do, nor does it make an effort to make the mount particularly lightweight. Considering the ease with which one of these mounts can be put together, and how well it does the job of allowing a large mirror to get into the amateur's hands, these minor “sins” can be forgiven.

Refractors, too

All of the above requirements are just as valid for refractors as they are for reflectors like the one shown. Refractors can be, and are, mounted with Dobsonian-style mounts. They also have a reputation for being especially heavy.

There is nothing special about a refractor that requires it be heavier than a reflector. Simply, until very recently, refractors were long instruments, and this leads to two problems: first, the deformation (sag) in a given tube due to its own weight depends very strongly on its length, and second, a long tube presents more wind vane area to cause problems in the breeze. A six inch f15 refractor (a common f ratio) was over 90 inches long; even very strong materials will sag appreciably under their own weight in that length to diameter ratio. They therefore tended to be made from steel tubes; until recently, steel was the strongest material that an amateur could get, and steel tubes are quite heavy. The longer tubes generated more torque from windvaning when a breeze hit it, so the mounts were made larger and heavier in an attempt to resist this. A long refractor could be made lighter using techniques to be developed in this book. A short refractor, like the f4 or f5 instruments popular today, can utilize virtually any tube material.

The Basics of Telescope Mounts

Let's consider the basic problem involved in mounting a telescope. An object that you might be interested in observing can be at any point in the sky. To point at any spot, you need at least two, perpendicular axes which can be pointed in *any* orientation. If you have more axes, you can still point at any spot, but the mechanical complication makes this undesirable. With a single axis, you can only point to, at best, a single arc across the sky.

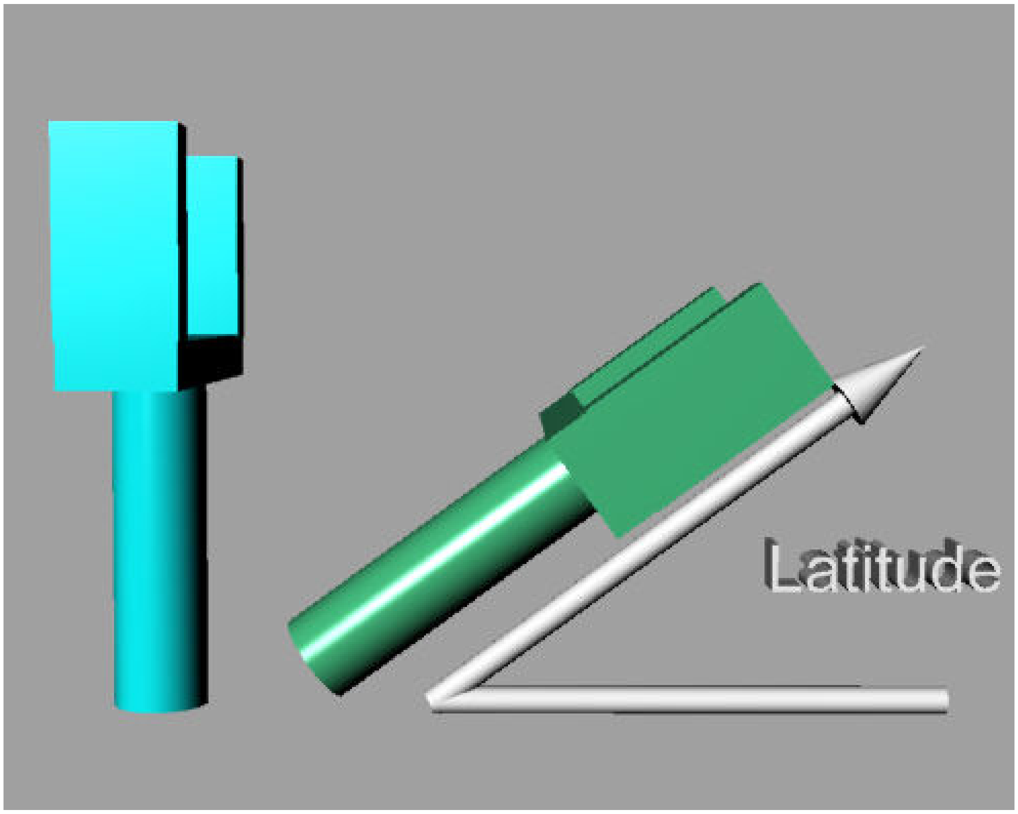

Figure 5 - Tilt an Alt-Az mount to make an equatorial

During the course of the night, celestial objects track across the sky from east to west. Objects close to the celestial pole, though, never rise or set, they simply circle the pole. If you were to carefully follow the motion of a star, for example, you would find that it rises at some point on the eastern horizon and tracks an arc, inclined by your latitude to your local vertical and horizontal, across the sky to the western horizon where it sets. If the telescope you were using had only local elevation and azimuth axes, like a Dobsonian or other altazimuth mount, you would find that you needed to continually adjust both axes to keep the object in the eyepiece. More subtle, but just as damaging to the photographer, is that the image in the telescope rotates during the course of its movement across the sky.

If you wanted to track the object in such a way that you could keep the object centered in the eyepiece while keeping it from rotating, you would try to mimic the geometry that causes its apparent motion. The object's motion is the same as the motion of a point on a globe rotating about the globe's axis, and you could re-create this motion by pointing one of your two axes at the pole that is above your horizon.

Figure 5 shows this graphically. The mount on the left is a simple altazimuth. If you could somehow tip it over so that the azimuth axis is inclined by your latitude angle, you'd find that the azimuth axis points at the pole, as in the mount on the right, and any celestial object that you pointed the telescope at would stay in view over the entire night. This, of course, is the principle of the equatorial mount and has been understood for almost 200 years; it is still a worthwhile thing to know about.

The equatorial has problems that come from this tipping over; in fact, all of the variations of the equatorial are attempts to overcome these problems. The biggest drawback is that the weight of the telescope in its cradle is positioned in a way that puts bending forces on the mount. As was mentioned in our second rule, this is the weakest loading for any structural member. Put another way, to handle a bending load adequately, the member has to have more material, which means it has more mass, and it is therefore heavier. Another problem is that structures loaded with bending forces have more vibration problems than structures loaded in compression.

You might ask if the equatorials have these problems, why are they still used? There isn't a simple answer to this question. For professional observatories, like the Keck telescopes or the MMT, the equatorial is undoubtedly obsolete. All of the new, giant telescopes will be altazimuth with computer driven motors to control the tracking of both axes and the rotation of the cameras or instruments. For the amateur, however, the equatorial still has a very large place. To begin with, it is still mechanically simpler to build an equatorial and track with one motor driving one axis than to build an altazimuth mount and track with two motors for visual use, or three for photographic use. Second, amateurs still carry telescopes out into the wilderness to find dark sky sites, and to photograph from chilly mountaintops; in such use, the low power requirements of a single motor on the equatorial are a definite help. Third, it is still easier to track an object for viewing at high powers with an equatorial than with the average altazimuth scope when the drive power is supplied by hand.

Figure 6 shows a very sturdy example of a German equatorial carrying a large reflector. The tapered bearings will be shown later to help the vibration and deformation characteristics of this mount. **Figure 7** shows an example of an equatorially mounted large refractor. These are both examples of the German equatorial mount. **Figure 8** is the NGT-12.5 from JMI, a very well thought-out split ring equatorial mount for a 12.5” Newtonian.

The aim of this book is to go over the mechanical design of telescope mounts of all types, with emphasis on their mechanical characteristics – strength required, vibration resonance frequencies, and so on. I don’t intend to be a cookbook, or a catalog of designs to copy, rather a resource to use while designing your mount. I hope to allow you to choose a mount that is best for your needs. As we progress through the rest of this book, I’ll try to present photos of actual versions of the mounts being discussed.

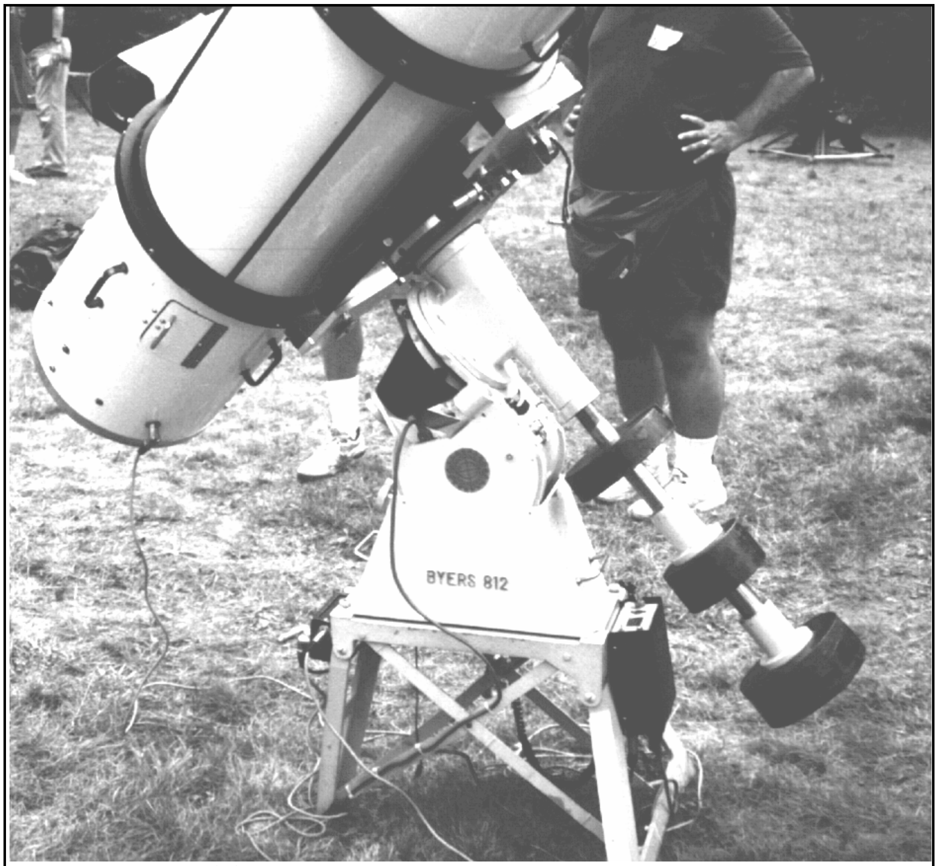

Figure 6 An Older Byers mount.

Figure 7 A Giant Refractor seen at Stellafane

Figure 8 The NGT-12.5, from Jim's Mobile, Inc.

References

1. "Structural Considerations for Telescope Makers", Gleanings for ATM's, Sky and Telescope, June 1976, pp. 423 - 428

2. Hextek, http://www.hextek.com/ Lightweight blanks based on fusing of glass tubes and plates.

3. Jim's Mobile, Inc., http://www.jimsmobile.com/ Producer of telescopes and accessories.