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Beish, J. D. (1999). "Windows International Mars Patrol Astronomical Calculator WIMP," The Digital Lens: Newsletter of the Association of Lunar and Planetary Observers Computing Section, http://www.m2c3.com/alpocs/tdl1999/wimpinfo10031999/WIMP.html

Beish, J. D., (2000). "Discrete Topographic and Orographic Clouds of Mars," Association of Lunar and Planetary Observers Internet Web Page: The Mars Section, http://www.lpl.arizona.edu/~rhill/alpo/marstuff/discrete.htm

Beish, J. D. (2000). "A German Equatorial Mount for the Planetary Telescope," The Digital Lens: Newsletter of the Association of Lunar and Planetary Observers Computing Section, http://www.m2c3.com/alpocs/tdl2000/mountmath05222000/mount.htm

Beish, J. D. (2000). "Martian Volcanoes on HST Images," Association of Lunar and Planetary Observers Internet Web Page: The Mars Section, http://www.lpl.arizona.edu/~rhill/alpo/marstuff/VOLCANO.htm

Beish, J. D. (2000). "Measuring Celestial Dimensions with Micrometers," The Digital Lens: Newsletter of the Association of Lunar and Planetary Observers Computing Section, http://www.m2c3.com/alpocs/tdl2000/celestialdimensions01232000/celestial_dimensions.htm

Beish, J. D. (2000). "Nuts and Bolts of Computing the Ephemeris - Part Four," The Digital Lens: Newsletter of the Association of Lunar and Planetary Observers Computing Section, http://www.m2c3.com/alpocs/tdl1999/nutsbolts08301999/TDL-4.html

Beish, J.D. (2000). "Practical Calculations for the Newtonian Secondary Mirror," The Digital Lens: Newsletter of the Association of Lunar and Planetary Observers Computing Section, http://www.m2c3.com/alpocs/tdl2000/telescopemath06202000/field1.htm

Beish, J. D. (2000). "Some of the 'Astronomical Seeing' Scales," The Digital Lens: Newsletter of the Association of Lunar and Planetary

Design a German Equatorial Mount for the Planetary Telescope

Jeff Beish,

Association of Lunar and Planetary Observers (A.L.P.O.)

INTRODUCTION

After a question from a planetary observer/telescope maker was posed to me concerning telescope mounts a reference came to mind that may interest other telescope makers. Fred Tretta published a paper in the Riverside Telescope Makers Conference at 1980 that detailed the mathematical treatment of this fascinating subject [***Tretta***, 1980]. Several other related articles will be referred in this paper.

Many of our colleagues build their own observing equipment or redesign and modify existing telescopes to make them more stable for high powered observing. There are several caveats and debatable aspects of telescope mount design that will be discussed in the next section

There is nothing more frustrating than a shaky mount that poorly tracks the planet you are studying. For those who photograph or use CCD cameras the tracking and alignment of the telescope mount is even more important, as important as good optics. To keep a magnified image of an extended object in place during exposures the planetary telescope must be at least ten times more stable than one used for deep sky photography and hundreds of time better than for visual observing.

BASIC CONSIDERATIONS

Generally, a planetary observer desires a permanent mounted or roll around telescope where portability is not paramount. To keep you telescope from moving about at the slightest touch or oscillating in the wind the mount must be massive and very strong. Rigidity of the mounting parts of the telescope, as well as materials that can take a lot of stress, is desirable for mounts. Also, good dampening is important to quickly absorb and dissipate oscillations that may be induced into the mount.

The only materials available to the amateur for practical use is aluminum and steel. Other types of materials, such as titanium, stainless steel, hardened aluminum, and special hardened polymers are expensive and hard to work with. Generally, ordinary steel is more desirable than aluminum, even though aluminum is lighter than steel. Steel is stronger and nearly as stiff as aluminum, an important consideration for dampening. However, if one uses aluminum then they must increase the diameter of the shaft because the *modules of elasticity* of steel is three times that of aluminum. This also requires larger bearings and must be added into the cost of the system.

If one desires the same strength using a material other than steel they must calculate the equivalent diameter and find the nearest bearing size. Also, if you don't have a couple of steel shafts laying around then you must consider the difference in cost in the materials you wish to use.

TYPICAL INSTRUMENT FOR IMAGING

A typical planetary telescope might be a 12.5" f/7 Newtonian. This example will be discussed here as our instrument for CCD imaging and photography. The telescope is 8 feet long and focuser is 66 inches from the axis point of gravity along the tube assembly. CCD technology is used in this discussion instead regular photography because the image scale is smaller and CCD chips are usually much smaller than a frame of film. Exposures are shorter and it is more susceptible to telescope movement than film.

Let's say you have a couple two-foot long, 1.5-inch steel shafts laying around and are curious as to the equivalent strength and weight of using aluminum shafts. So, the way to find how much the 1.5-inch steel shaft will bend or flex under a load and compare it to an aluminum shaft. First we dig out some mechanical equations. Two dimensions are involved here, bending and torque. Engineers of often refer to the two quantities to describe these two as: *linear deflection* and *tortional deflection* [***Tretta***, 1980].

First, we find the moment of inertia (**I**) of the shaft to use in the equation for the deflection on the shaft with a given weight [***Albrecht,*** 1989]:

(1) $I = \pi D4 / 64$, where π is 3.14159 and **D** is diameter of shaft. It would be 0.2485 for the 1.5-inch shaft.

The simple equation for linear deflection (Δ) of a cantilever is: $\Delta = WL3 / 3EI$, where **W** is the weight of the load, **L** the length of the shaft, and **E** is the modulus of elasticity. The **E** for steel is 30 x 106 and aluminum is 10 x 106 (See Figure 2).

However, our shaft is mounted in bearings and is subject to two deflections, 1) in the part of the shaft extending out from the top bearing and 2) in the part between the bearings. So, we must conjure up a little more complex equation:

(2) $\Delta = WCp2\ (2Cp + 3Lp) / 6EI$, where **Cp** is the shaft extended beyond

Lets say your telescope tube and saddle weighs 100 pounds and the bearing are separated by 12 inches, with 4 inches extended beyond the top bearing of the polar axis and the center of weight is at the end of the 4 inch extension.(**Cp**). Now:

$$\Delta = [100 \times 42\ (2 \times 4 + 3 \times 12)] / 6 \times 30 \times 106 \times 0.2485 = 0.00157\text{" } (0.04\text{mm})$$

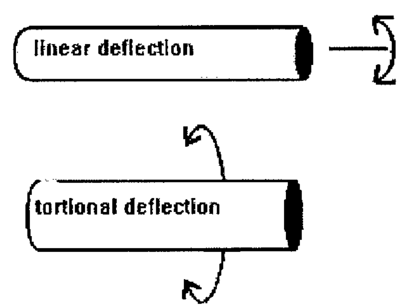

Figure 1. Simple illustration of the two elements to consider when selecting shaft sizes, *linear deflection*and *tortional deflection.*

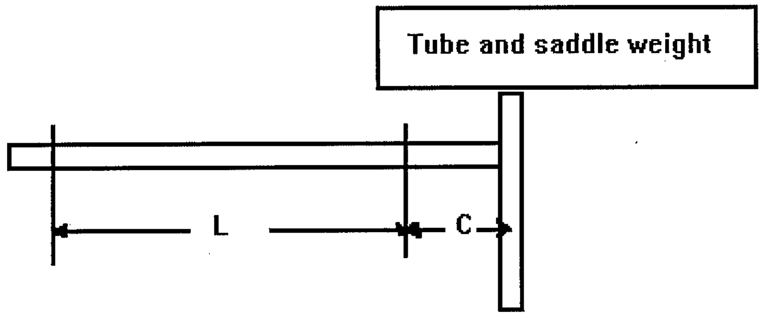

Figure 2. Simplified drawing of polar axis shaft with declination axis and telescope tube and saddle weight loading the shaft. Linear deflection results in shaft between bearings (**Lp**) and overhanging shaft (**Cp**).

That is a mighty small deflection. But, lets see what that does to a magnified planetary on your brand new CCD camera chip. Using a standard planetary CCD setup the chip may be 2.64 mm (0.104 inch) square. Now lets say each pixel on the chip is 14 microns (14 millionths of a meter) square. Using an 88-inch focal length in the telescope above, the CCD camera has 0.04 arcsec per pixel resolution. Then you have Ganymede centered on the chip magnified up to 0.5 mm, a very high magnification for that little moon for sure. Now, a breeze comes up and moves your telescope with a half pound force on the upper tube. How much does that translate to linear deflection and how much does that effect the movement of the telescope tube (moment arm)?

Well, the deflection of a telescope with 0.5 pound wind force is:

$$\Delta = [0.5 \times 42\ (2 \times 4 + 3 \times 12)] / 6 \times 30 \times 106 \times 0.2485 = 0.000008'' \ (0.0002 \text{ mm})$$

Wow, that is not very much. Usually we just round things off to the nearest 10th of an inch! But, what does that tiny bit do to our image if Ganymede?

We now have to consider what the tiny deflection of 0.0002 mm (α) at the shaft translates to at the focuser, a long way down the telescope tube from the center of axis! If the distance (**Df**) from the center of the axis, or center of gravity, is 5.5 feet (1676 mm) , then the focal plane at the camera chip will move:

$$\text{CCDm} = \text{Df} \tan \alpha = 1676 \tan 0.0002 = 0.006 \text{ mm}$$

The half millimeter image of Ganymede would then occupy a group of 36 pixels (each pixel is 14 microns), so a movement of 0.006 mm would not scatter the image outside the 0.5 millimeter area very far.

So, if the above exercise results in an acceptable error then we must look at the other deflection, ***torque***. This deflection produces more movement at the camera and can be found by:

$$\textbf{(3)} \qquad \delta = 584 \text{ TL} / 0.038\text{XE},$$

where **T** = WCd , or twisting force. **Cd** is the distance from the center of the torque axis to the weight, **L** is the distance from the drive gear or restrained end of the shaft to the weight, **E** modulus of elasticity, and **X** = **D4** for the solid shaft (See Figure 3).

So, the shaft distance (**L**) is 12 plus 4 inches or 16 inches to the weight, **Cd** is from the shaft to the center of the telescope tube weight, say 12 inches:, **T** becomes 0.5 pounds x 12 or 6 inch/pounds, and **D4** = 5.0625.

$$\delta = (584 \times 6 \times 16) / (0.038 \times 5.06 \times 30 \times 106) = 0.010 \text{ radians}$$

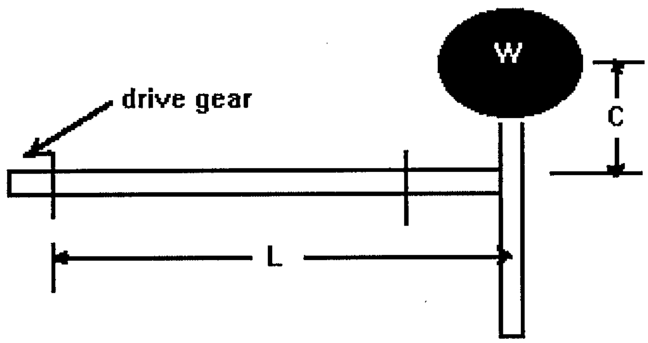

Figure 3. Simplified drawing of polar axis shaft with declination axis and telescope tube pointed up. Counterweight (not shown) and balances tube and saddle weight. Tortional deflection results when external force causes unbalance to tube and saddle and twists polar shaft (**L**). Overhang of tube and saddle (**Cd**) from center if polar axis.

That same half pound wind force now translates to 0.010 x 1676 mm or 17mm! However, the image only oscillates 0.57 seconds of arc in the field on the 2.64 mm CCD chip or nearly 15 pixels (arctan 0.010 radians = 0.57 arcsec). A large amount considering Ganymede is only around 1.5 arcsec!

In practice the planetary observer will not permit wind to reach a level that interferes with the photography or imaging. Winds would probably be in to order of a half pound or so. But, the wind can cause the upper end of a telescope move about and oscillate. For a good discussion of the effects of wind on telescopes see the [***Berry***, 1980], reference below.

So, run the numbers through the above equations using an aluminum shaft, only substitute 30×10^6 with the **E** for aluminum or 10×10^6. By increasing the shaft diameter to 2 inches ($D^4 = 16$) the above equations would result in the following, from equations (1), (2), and (3):

$$I = 3.14159 \times 24 / 64 = 0.7854$$

$$\Delta = [0.5 \times 42 \, (2 \times 4 + 3 \times 12)] / 6 \times 30 \times 106 \times 0.7854 = 0.000008'' \; (0.0002 \text{ mm})$$

$$\delta = (584 \times 6 \times 16) / (0.038 \times 16 \times 30 \times 106) = 0.003 \text{ radians}$$

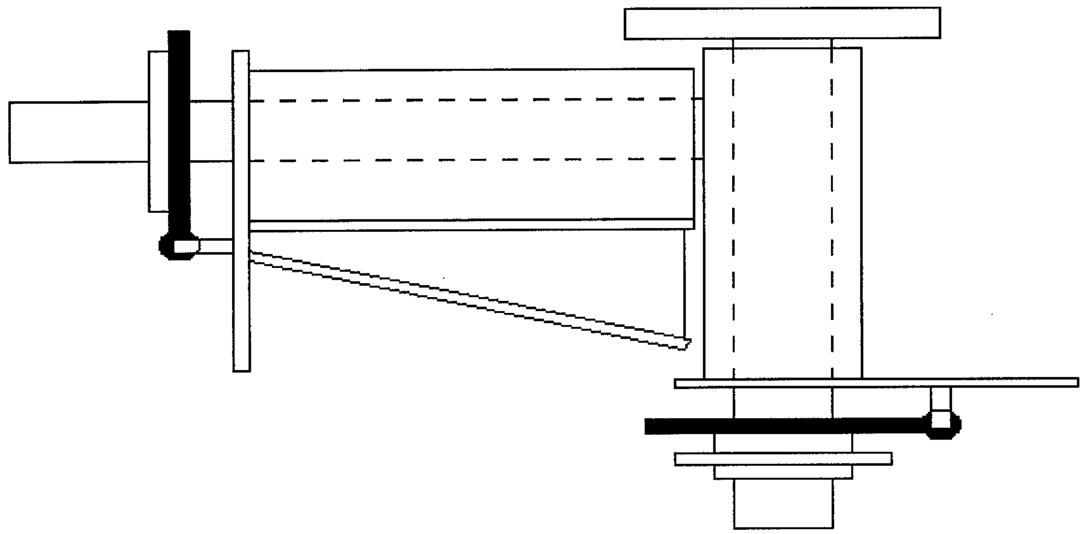

Figure 4. Schematic drawing of an optimized German equatorial mount with large shafts, short bearing distances, and short distance from point of weight to polar axis. Axis gearing shown in solid blocks and dashed lines indicate shafts in housings.

The half pound wind force now translates to 0.003 x 1676 mm or 5 mm, but the real angular displacement is 0.18 arcsec, only 4 or 5 pixels on the CCD chip. Magnifying the image of this little 1.5 arcsec Ganymede to 0.5-mm an effective focal length would need to be around 69 meters! A 41-cm telescope with an effective focal ratio of f/169 would project Ganymede to a half millimeter on the typical CCD camera chip. Well, if you don't believe this is possible, then Don Parker published an image of Ganymede he made using his 41-cm Newtonian and LYNXX PC camera and he lives on the windy coast line of South Florida [***Parker,*** 1995].

OTHER MECHANICAL CONSIDERATIONS

Shaft size is not the only important factor in mount stability. Distance between bearings play an important role in both linear and torsional deflections. After the telescope tube design and saddle have been optimized for strength and weight, one must begin design on the mount and acquire the materials. If you are like most telescope makers you have a favorite junk yard or other TM friends with plenty of junk laying around not in use.

If one were to consider temperature effects of steel and aluminum they will find that aluminum expands and contracts about twice as much as steel. An aluminum shaft in steel bearings will tighten and loosen as the ambient temperatures change, causing some slop in the system at times.

From the discussions above we can now concentrate on the elements the designer has control over; 1) distance between bearings of each axis, and 2) distance from the top bearing of each axis to the point where the weight loads that particular shaft. That is, the distance **C**, as can be seen in figure 2, and distance **C** in figure 3. The overhang from the top bearing of the polar axis shaft to the declination axis housing should be as short as possible. The telescope tube should be as close to the polar axis as possible without hitting the driver gear or its housing.

Using the discussion above a mount was designed for a 16-inch f/5 Newtonian with an seven foot tube. The tube is an eight inch thick rolled aluminum tube, 18 inches in diameter. The weight of the tube, mirror and cell and other components weigh in at 180 pounds. The requirement is to provide a stable instrument for CCD imaging in 10 to 15 MPH winds with a calculated error in position of 0.24 to 0.54 arcsec!

At our favorite junk yard, near the air port, we found a two 3-inch hardened steel shafts, four 3-inch I.D. tapered bearings, and a length of 5-inch steel water pipe to use as the axis housings. Two 14-inch lengths of the pipe were cut and the inside of each end was machined to fit the bearing race and were pressed in to place. The polar shaft and a steel block was threaded then the end of the shaft was welded in place to the block. Holes were made in the block to attach the polar shaft to the declination housing. The block also provided the stop to hold the tapered bearing in place. A steel plate and side supports were welded the declination housing.

The declination shaft assembly was made the same except the block was larger and was used to attach to the saddle. Each previously cut and machined shaft was snugly fitted in the bearing inside races and placed with bearings in the housings. Each shaft had been threaded to accept a ring to tighten or snug up the bearings with the housing. Both shafts were machined down to fit a 2-inch drive gear clutch assembly. The gear end of the declination shaft was threaded and a longer shaft was attached for the counterweight (See Figures 4 and 5). The next step is to weld plates and brackets to the polar housing to attach this "equatorial head" to a pier of some sorts.

THE PIER

The pier is the foundation to the entire telescope system and can be a primary source of instability in the telescope mounts. It is often over looked by many and they use a simple rule is that the larger and heavier the better. However, two weak points mounts can be the point at which the equatorial head meets the pedestal (*wedge*) and the point at which the wedge is the coupled to the pier can nullify the advantages of a large pier.

The pier must attach to the equatorial head with a wedge that aligned with the latitude the particular observer is located. While is may be possible to weld together a steel wedge at the exact angle, it should never the less have some way to make small adjustments in azimuth and polar angle. Even the best made mounts will move about from seasonal temperature changes or just medal fatigue after years of use.

As seen in figure 6, the pedestal or wedge is made from two 1/2-inch 9" x 12" steel plates welded together with triangular wedges. The wedge assembly is attached to the pier using three welded steel tabs and 3/8-inch bolts. The wedge is closely aligned to the North, but can be fine adjusted with an eccentric screw for polar adjustment.

SADDLE

The telescope tube assembly is usually attached to the mount by the saddle and can be a source of stability problems that are hard to find. Since this interfaces the tube to the mount it must be made to dampen out vibrations from both eternal and internal forces, and to provide a strong platform for the tube. In the examples above, the 16-inch f/5 Newtonian has an eight foot long tube and requires a fairly long saddle.

Although steel and aluminum are stiff, they tend to dampen out slowly as compared to wood or fiberglass. A saddle made mostly of wood provides excellent dampening and is durable when preserved with paint or other coatings. Saddles with a steel or aluminum base with wooden cradle is a very good combination for a saddle. The weak link in the chain here is the connection between the declination shaft and the saddle. Here is where you can use a large steel or aluminum block to provide a solid support for the saddle and surface for the shaft.

EFFECTS OF WIND ON TELESCOPES

Wind is probably the one element in our design criteria that we should concentrate on most. Richard Berry gave a good talk at R.T.M.C. in 1980 on the effects of wind on Dobsonian telescopes and presented the table shown below (Table I) [***Berry***, 1980].

From the table and equation **(4)** you can figure the amount of force on the exposed portion of your telescope tube, say 3 feet of the upper end of the 18-inch diameter tube, where the square area is 4.5 square feet. Then apply this force as the weight **(Wf)** in the calculations for deflections in the above. In the equation the constant **S** is 0.7 for a cylinder and 2.0 for a square tube:

$$\text{(4)} \qquad Wf = Fc \times S \times Ta$$

For a typical South Florida sea breeze, for a wind of 5 to 10 MPH, find Ta from Table I:

$$Wf = 0.26 \times 0.7 \times 4.5 = 0.8 \text{ pounds force}$$

Quite a force from a fairly mild breeze. Consider this same wind on a square tube. That would yield 2.3 pounds! A wind shield is highly recommended!

Table I. Wind factors as they relate to square area of telescope tube exposed to wind. Table extracted from paper presented by Richard Berry at the 1980 R.T.M.C.

Wind	Fc
mi/hr	lbs/ft2
5	0.06
10	0.26
15	0.58
20	1.02
25	1.60
30	2.30

Also, the frequency of the vibrations caused by wind flowing in the front and down the tube can be approximated by: 0.3 x velocity (mi/hr) / D (diameter in feet). In the example for the 16-inch f/5 telescope above it would try to oscillate at:

2Hz = (0.3 x 10) / 1.5

2Hz per second would be the natural tendency of the oscillations with a 0.8 pound force applied. The amount of difference in image displacement would be about 0.001 arcsec in this telescope with a mount with 3-inch steel shafts.

WEIGHING THE MOUNT

To find the weight of your steel shaft you first find the square area of the shaft and multiply that times the density of material. In the example, a steel shaft 24 inches long and 1.5-inches in diameter will have an squarė area of :

(5) We = πr2 x L = 3.14159 x 0.752 x 24 = 42.4 square inches

The density of steel is 0.283, so: 0.283 x 42.4 = 12 pounds

How about those lead counter weights. The density of lead is 0.411. Most counterweights are either cast iron or molded lead and are usually thin cylinders. Use equation **(4)** for predicting the weight of the counterweights.

For example, you need to balance the one hundred pound telescope and saddle, so you might place a hundred pound lead weight at the same distance at the opposite end of the declination shaft. You have a discarded two pound coffee can so that would be a good mold to pour the lead in. Before you begin remember to leave a hole in the weight for the shaft!

A wood dowel with the same diameter as the shaft works fine. If the can is 6 inches in diameter and 9 inches tall, find the weight if the can if filled with lead (The density of lead is 0.411):

Vcan = 3.14 x 32 x 9 = 254.5 sq. in. x 0.411 = 104.6 lb

Vhole = 3.14 x 0.752 x 9 = 15.9 sq. in x 0.411 = 6.5 lb

or, 104.6 - 6.5 = 98 pounds!

In practice the bearing and shaft housing for the declination axis is usually 12 to 14 inches long, so the counterweight has to be further down the shaft to clear the housing and have enough room for small adjustments. We do not want too far away from the center of axis, so, we could use two thirds of the counterweight (66 lb) at 18 inches down the declination shaft to produce the same inch/pounds.

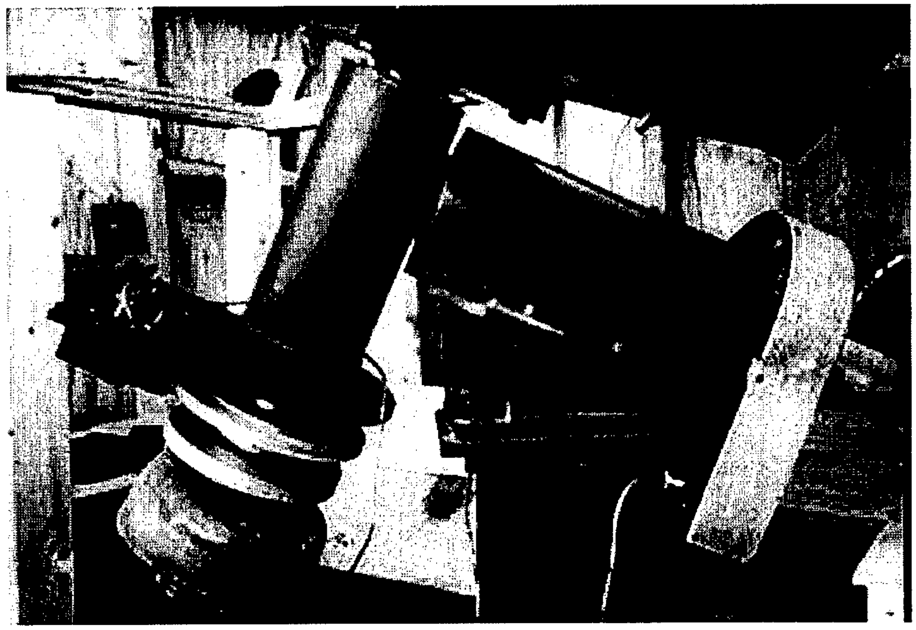

Figure 5. Photograph of author's German equatorial mount used for either a 12.5-inch f/7 or 16-inch f/7 telescope. Mount features 3.125-inch shaft diameters with three bearings per axis. Saddle is made from 3/4-inch AC plywood lined with 1/8-inch aluminum strips and screwed into place.

SUMMARY

1) The shafts must be of adequate cross-section to support the scope and guiding equipment without sagging or bending too much.

2) The mount should be "short coupled." That is, the distances from bearing supports to the payload should be as short as possible.

3) The RA and declination housings must be joined at an accurate right angle. Adjustment in preload is desirable.

4) The RA shaft should be in preloaded roller bearings to prevent any play.

5) The point at which the RA housing meets the pedestal should be thick and rigid.

6) The RA clockdrive should be 70% to 100% the diameter of he mirror. Any less will normally result in an erratic drive, and any more will not substantially improve your system. Your money is better spent on other parts of the mount.

7) The declination shaft should have preload adjustments on it to eliminate play.

8) The declination system should be electrically driven to avoid laying your hands on the mount to make corrections. Try a drive resolution of at least twice that of the RA drive.

REFERENCES

Albrecht, Richard E., "The Design of Telescope Structures - I," ***Sky and Telescope Magazine***, Vol. 77, No. 1, pp. 97-101, January 1989

Albrecht, Richard E., "The Design of Telescope Structures - II," ***Sky and Telescope Magazine***, Vol. 77, No. 2, pp. 210-214, February 1989

Berry, Richard, "How to Control Friction in a Dobsonian Telescope," ***R.T.M.C. Proceedings***, 1980.

Parker, D.C., "CCD Image of Jupiter's Moon Ganymede," ***Astronomy Magazine***, Vol. 23, No. 7, p. 106, July 1995.

Tretta, Fred, "An Analysis of Telescope Mounts," ***R.T.M.C. Proceedings***, 1980.

FURTHER READING

Brooks, John J., "Mechanical Considerations of Telescope Makers," ***Sky and Telescope Magazine***, Vol. 51, No. 6, pp. 423-428, June 1976.

Cox, Robert C., , "Temperature Effects on Mirror Cells," ***Sky and Telescope Magazine***, Vol. 46, No. 4, pp. 256-259, October 1973.

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