Chapter two
The Basics of Design

It isn't possible to go into much detail about structural design without covering some basics of science and engineering. The most important part of the material I am going to go over here is covered in the introductory chapter or two of any physics textbook, or in a mechanical engineering class called Statics. In the course of our wander through the subjects we need, we will touch on Statics, Dynamics, the science of Materials, Heat Transfer or Thermodynamics, and the study of Deformable Bodies, or how real things deform under load.

Static means “at rest”, and the word is used many places in science. Electrostatics is devoted to the study of electrical charges that aren't moving, Hydrostatics to pressures in non-moving fluids, and so on. Statics is used to study the motion of bodies that are not accelerating; that is, motionless or moving with constant velocity (I'll explain those words a lot more precisely later). We will use statics a lot in analyzing our mounts.

Dynamics is also a word used many places, and means “moving”. Dynamics is the study of bodies that are accelerating. Most telescope mounts aren't designed to do this for long periods, but we do need a concept or two from this area as well. It comes into play in analysis of vibration.

Materials science is a relatively new science. Perched on the boundary of science and engineering, it is a blend of physics, chemistry and mechanical engineering. It is devoted to creating desired properties in a material by manipulating its composition and processing. For example, you would process steel very differently for use as a bell or a car bumper. Material science offers us the opportunity to choose the properties we want in the place we need them, or create a custom material of our own for our use in the mount.

Deformable Bodies, often called Strength of Materials, is the first class where student engineers deal with the fact that in the real world things bend, droop, sag, expand or shrink. This can be a complex subject, but there are some really important ideas we need out of this one.

Thermodynamics is concerned with heat flow in materials. This can also be a complex subject, but we won't need much of it. Perhaps we can use this to solve once and for all the age-old debate over what color a telescope should be.

Finally, we will look at the role of experimentation in design. Paper design results can be very good, but don't always work in the real world. You may have heard people say, with a derisive tone, that a design “looked good on paper” but was a flop. Sometimes reality has a few tricks in store for us.

Math and Terminology

Although much of the material here can be explained without math, and I will try to do that as much as possible, real design can't be done without some math. It may surprise you to know that all that you really need is a foundation in high school algebra, and the ability to punch the keys on a calculator that includes trigonometric functions like sine and cosine. Although engineering school is very analytical, and math beyond Calculus is required, most engineers don't use calculus in their day-to-day practice. The calculus is most useful in helping you understand the way that formulas are derived, and is not necessary if you merely need to use the formulas. In any case, remember that the purpose of math in science is to simplify the real world, and allow us to model it better. That said, let's get going!

In much of our work, we will be concerned with *forces* on a mount. What do we mean by the word force? Depending on how you like it, we can state it in words or as a simple mathematical relationship. Let's go with words first. The best definition of a force probably still comes from the first person to give it the modern definition; Sir Isaac Newton stated it in his "Principia" (1686) as his first law of motion. It is usually phrased today as,

> *"A body at rest tends to stay at rest, or a body in uniform linear motion [i.e., in a straight line at constant velocity] tends to stay in uniform linear motion, unless it is acted upon by an outside force".*

A force causes change in velocity, and we call this change *acceleration*. Mathematically we state this as:

$$\vec{F} = m \cdot \vec{a} \qquad \textbf{1}$$

where **F** and **a** are the force and acceleration (I'll get to the arrows in a minute...), while the m represents the mass. Mass is a measure of the amount of matter in an object and is not weight. As an amateur astronomer, you are undoubtedly aware that weight depends on gravitational acceleration and varies from planet to planet.

Forces have both a magnitude, a measure of how big they are, and a direction. For example, all weights have the direction "downward", toward the center of the earth. Conveniently, there is something in mathematics that also has the characteristic of possessing a magnitude and direction. This is called a *vector*, and the arrows above the terms in the equation are common notation for a vector. Another common method of denoting that a letter represents a vector is to print the letter in **bold** type, as in the above paragraph. I will use both notations, typically referring to the vector with an arrow in equations, but in bold face type when describing it.

Vectors can be used to describe many common things. Velocity, the rate of change of position with time, is a vector. Speed is not a vector. A velocity would be stated as 60 mph north, while the speed is just given as 60 mph. Acceleration is the rate of change of velocity with time, and is also a vector, as we've stated already.

Airplanes stay in the sky because their weight vector is precisely balanced by the lift vector caused by air flow over their wings. A very common and important example of vectors is found analyzing springs. When you press or pull on a spring, you exert a force on it, and it responds with a restoring force proportional to its compression or extension. The relationship is nicely linear and simple:

$$\vec{F} = -k \cdot \vec{x} \qquad \textbf{2}$$

where **x** is the displacement and k is the so-called spring constant, which depends on the particular spring. The minus sign is because the restoring force is in the opposite direction to the displacement. This equation is known as Hooke's Law.

Few telescope mounts are designed with springs as main structural component, at least as you or I would recognize them. Let me just say in passing that to a vibration control engineer, *everything* in the world is a spring!

Since vectors model forces so well, you might think that they can tell us something about how forces combine. This is indeed the case. We can add vectors graphically like in figure 1, by placing them nose to tail:

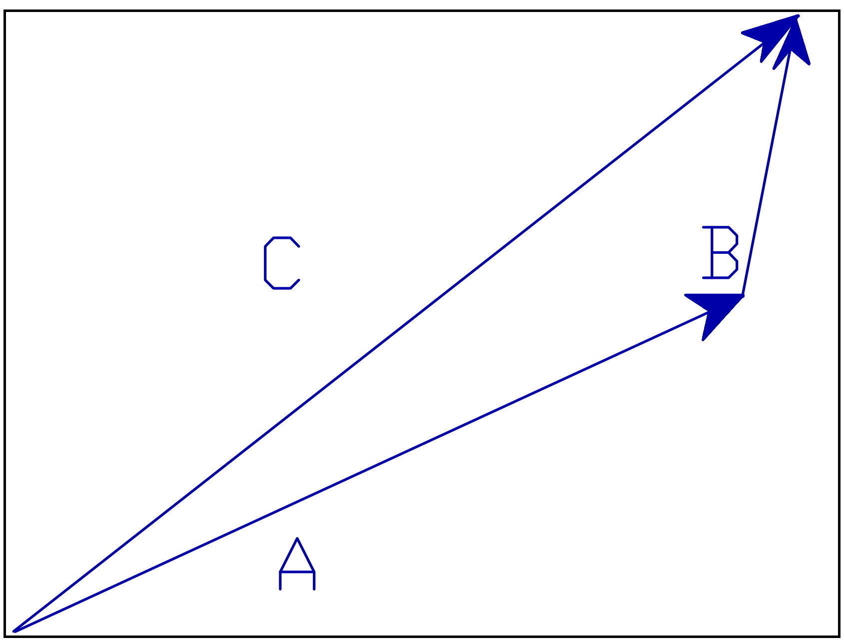

Figure 1 Graphical vector addition

Here, we see that the head of vector **A** is moved to the tail of vector **B** and the resultant drawn from the tail of **A** to the head of **B**. Notationally, we write it as simple addition:

$$\vec{C} = \vec{A} + \vec{B}$$

The two vectors don't have to be exactly in this orientation to add them. We can slide them all over the place, as long as we maintain their magnitude and direction. Of course, you have to be a pretty good draftsman to do this with any accuracy; that's why I don't like this method. Thankfully, there is a very easy way to handle the problem without resorting to drawing pictures at all (or at least without drafting instruments and a table).

We can represent the magnitude and direction of any vector as a sum of vector *components*. Let's consider a vector in a plane and give it a magnitude 5 and direction 37 degrees measured clockwise from the + X axis.

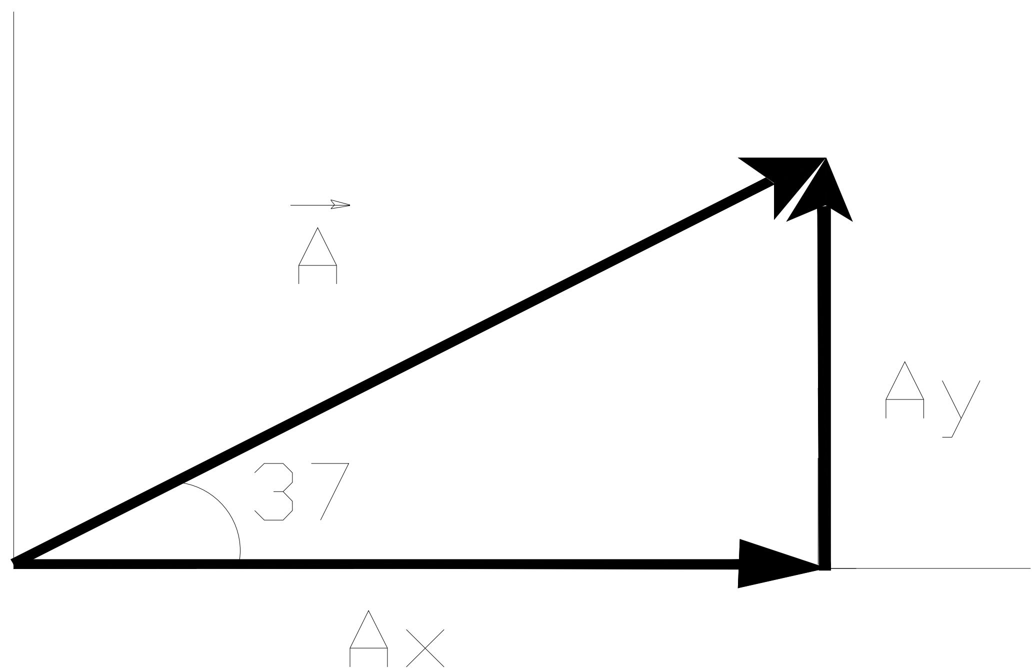

Figure 2 Vector Components

You can see clearly that from the standpoint of graphical addition, **A** = **Ax** + **Ay** because of the nose to tail relationship of the two components. In fact, component **Ay** could have been drawn on the y axis or anywhere else as long as its line of action remains perpendicular to the line of action of **Ax**.

Now some of you are probably saying something like "big deal! We've replaced a vector we knew everything about and replaced it with 2 others we know nothing about". In fact, we know everything we need to know about **Ax** and **Ay** if we use a little trigonometry. By definitions in a right angle triangle, the components are:

$$\vec{Ax} = \vec{A} \cdot \cos(37) \quad \textbf{4}$$

$$\vec{Ay} = \vec{A} \cdot \sin(37) \quad \textbf{5}$$

I want to stress that these are the definitions for using sine and cosine. The three most useful trigonometric functions, in terms of figure two are:

$$\sin\theta = \frac{A_y}{A} \quad \textbf{6}$$

$$\cos\theta = \frac{A_x}{A} \quad \textbf{7}$$

and

$$\tan\theta = \frac{A_y}{A_x} \quad \textbf{8}$$

Getting back to the figure, I could have put the axes in any orientation, and the obvious choice is with one axis parallel to **A** so that there is only one component involved. Since we do this to add a bunch of vectors, we usually only simplify one vector out of the bunch and it doesn't do much for us. It is handy in some applications, though.

To add the vectors then, we add their components in the x and y directions, keeping the terms separate. For example, let's assume we have a hoist system consisting of two ropes to support a mirror blank as seen in Figure 3. The two ropes each have 100 pounds of pull in them, 60 degrees <u>to the vertical</u>. What is the total pull in the vertical direction?

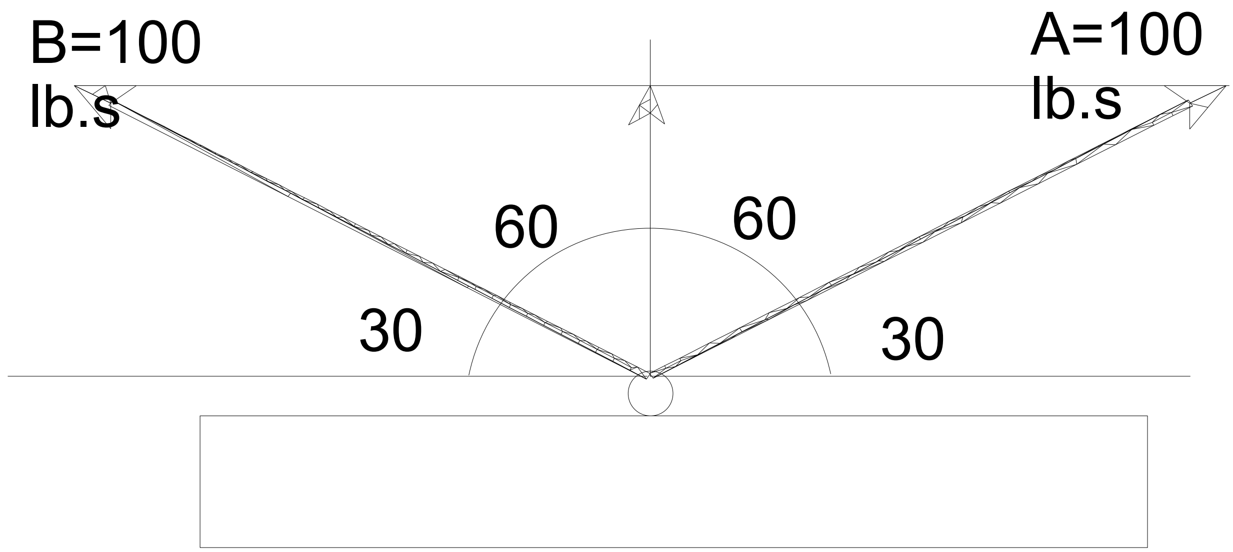

Figure 3 - Two Ropes supporting a mirror blank

To solve this, we make up a table of components and add them:

$$\vec{A} = 100\cos(30)\,\vec{x} + 100\cdot\sin(30)\,\vec{y} \qquad \textbf{9}$$

$$\vec{B} = 100\cdot\cos(150)\,\vec{x} + 100\cdot\sin(150)\,\vec{y} \qquad \textbf{10}$$

(Note that the 150 degrees is the sum of the 60 +60 +30 from the positive x axis).

$$\vec{A} = 86.6\,\vec{x} + 50\cdot\vec{y} \qquad \textbf{11}$$

$$\vec{B} = -86.6\cdot\vec{x} + 50\cdot\vec{y} \qquad \textbf{12}$$

$$\text{Total} = 0\text{lbs}\cdot\vec{x} + 100\text{lbs}\cdot\vec{y} \qquad \textbf{13}$$

There are a couple of things to notice here. First off, note that using the cosine of 150 degrees automatically made the **x** component of vector **B** negative. Second, the vector notation used for **x** and **y** is because the two components are still vectors. This is a sticky point, and you can just write the x and y values in columns. As long as you remember that they are separate things, and don't add x's and y's, you're okay. You'll notice that due to the symmetry of the problem, the two ropes each contribute half of the 100 pound vertical pull, but the pulls in the horizontal direction cancel each other out, doing nothing to lift the blank while tiring out the people pulling on them!

How many components do you need? A vector in three dimensions can be represented by three components, one each in the x, y and z directions. Even though we are dealing with three dimensional mounts, we can often get by with two dimensional vectors, since the force or motion in the third direction is of no concern.

Vector subtraction is carried out the same way. As with any numbers:

$$A - B = A + (-B) \qquad \textbf{14}$$

and the key to subtraction is multiplying one vector by (-1). This changes the sign of the components so that you can now add them. (It also reverses the direction of the original vector). Of course, this is the same as saying:

$$\vec{A} - \vec{B} = (Ax - Bx) + (Ay - By) \qquad \textbf{15}$$

II. Statics

We'll spend a lot of time here, not so much because the material is very hard, but because it may be very new to you and there are a lot of fundamentals to cover. Mathematically, all of statics reduces to two equations:

$$\sum \vec{F} = 0 \qquad \sum \vec{\Gamma} = 0 \qquad \textbf{16}$$

Stated in words, the sum of the forces acting on a body is zero, and the sum of all the torques acting on a body is zero. The Greek letter gamma, Γ, is commonly used to represent torque, but you can substitute a **T** any time you see it, if you'd like. From Newton's first law, the linear and angular acceleration are zero. The thing we're looking at is either at rest, or moving in a straight line at constant velocity.

A torque is a force applied at some distance from a point of rotation. If you're familiar with torque wrenches from work on a car or something else, you'll remember that torques are expressed in inch-pounds, foot-pounds or Newton-meters. This is because we multiply the force times the perpendicular distance from the pivot point.

Before we get into solving problems in statics, we need another of Newton's laws from his Principia. Newton's third law states that for every action there is an equal and opposite reaction. More precisely,

> *Whenever one body exerts a force on another, the second always exerts on the first a force that is equal in magnitude, opposite in direction, and has the same line of action.*

Newton's third law means that when you place a two pound book on a table, the table presses back up on the book with precisely two pounds of force. If you instantaneously remove the book, the table instantaneously stops pushing up. Smart table! Furthermore, this is a real force not something we've made up, because if there was no force balancing the weight of the book, the book would start accelerating.

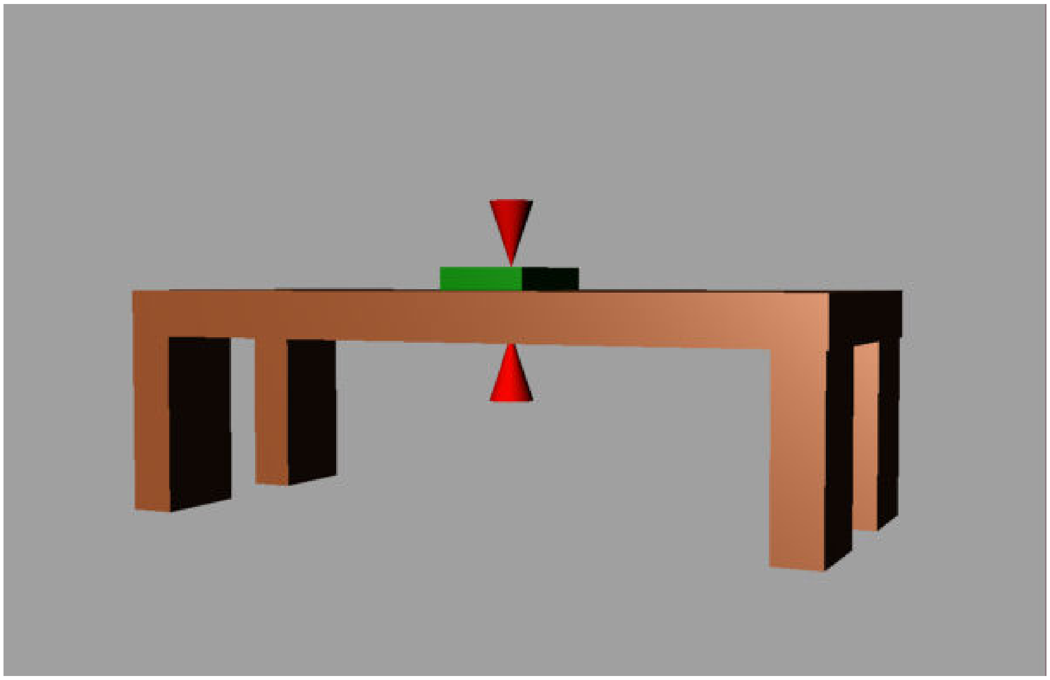
Figure 4 – A book on a table illustrates Newton's third law.

Let's look at the example of the book on the table. We represent this in a diagram as shown in Figure 4. The downward pointing red arrow represents the weight of the book. The upward pointing red arrow is the reaction force that the table exerts on the book. This is an example of a free-body diagram, a simple way of showing the forces involved in a system we are trying to analyze. A properly drawn free-body diagram is the first step in performing analysis, and can simplify the process a lot.

Consider a simple Dobsonian again (Figure 5). The tube weighs 30 pounds, including the mirror, cell, tube, focuser and the rest. How much force is on the box's side bearings? The first thing we do is state the one thing of which we are certain:

$$\sum \vec{F} = 0$$

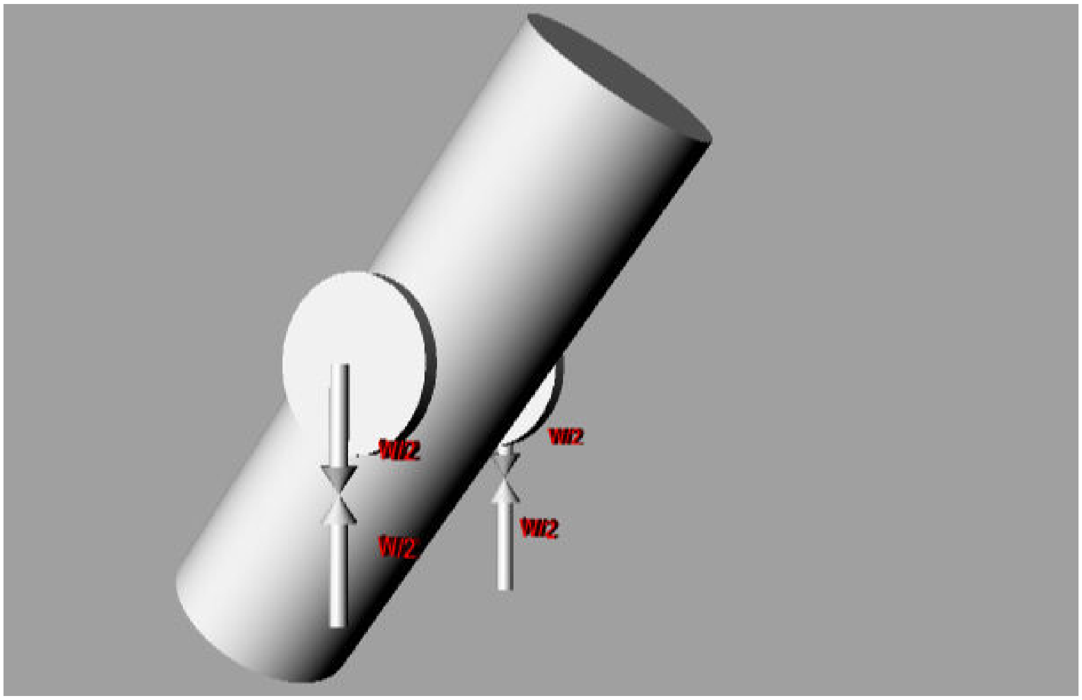

Figure 5 - The force on each bearing is W/2

The only force pushing down is the weight of the scope, 30 pounds. What is the force on each side? Since the total force is 30 lbs., that must be divided between the two bearings. The force on each side must be half of 30, or 15 pounds. Note that if this scope was not vertical there are x and y components of the weight and the force would not necessarily be the same 15 pounds on each bearing.

In doing this analysis, we have summed the forces in the vertical (usually taken as Y) direction. In other words we have said:

$$\sum \vec{F}_y = 0 \qquad \textbf{18}$$

Where the F_y denotes forces in the y direction. We can do this because the sum of the forces in any direction must be zero or the object would be accelerating in that direction.

We solve this as follows:

$$\sum \vec{F}_y = 0 \qquad \textbf{19}$$

Now the sum of forces is written as:

$$\vec{Fr} - \vec{W} = 0 \quad \textbf{20}$$

We say this because the upward reaction force is usually taken to be positive while the weight's direction is down or negative. If you solve this by adding the weight to both sides you obtain:

$$\vec{Fr} = \vec{W} \quad \textbf{21}$$

This says the reaction force equals the weight.

$$\vec{Fr} = 30 \quad \textbf{22}$$

Since the reaction force comes from two bearings:

$$2\,f_b = f_r \quad \textbf{23}$$

$$f_b = 15\ lb.s \quad \textbf{24}$$

When two bodies are arranged so that one is exerting a force on the other, the reaction force that the “pushed on” body exerts back on the first perpendicular to their contacting surfaces is called the *normal force*. We distinguish this force because it has an important role in determining the friction force.

The friction force, f, is determined by the normal force and a coefficient of friction that depends on the materials involved. Since the normal force is the contact force between the two bodies, the greater the contact force, the greater the friction. The normal force isn't always just the weight; if you put something on a block and lift one end of the block up, the object slides easier. I'll get back to this in a few minutes. The description for friction is:

$$\vec{F} = k \cdot \vec{N} \quad \textbf{25}$$

The coefficient of friction, k, is always greater than 0 and typically less than 1; the lower the value the smaller the friction force. For example, a 10 pound weight on a level surface that had a coefficient of friction equal to 0.2 would offer 2 pounds of friction resistance when pushed or pulled.

Friction is unique in that it always has the same direction in any problem, the direction that opposes motion. If you try to push a block to the right across a table, the friction force opposes you by pushing to the left. If you try to push to the left, it opposes you by pushing to the right. Of course, this is our everyday experience with friction.

There are actually two coefficients of friction for any material pair: static and kinetic (moving). Static friction is always a larger value, and it takes a small increment over the static friction force to get the objects moving. The common term engineers use for this is “stick-tion”; considerable engineering effort has gone into ways to minimize the extra force beyond the static friction value required to move something.

Ways to minimize the sticking include using a high frequency vibration to break the sticking – this is probably not a good idea with your telescope, so you want to choose a pair of materials with minimal stick-tion. Once motion begins, the static friction k is replaced by the smaller kinetic friction k, and the object will move easily. Exactly what happens to the body once motion starts depends on the pair of materials, and we'll come back to this in a little while.

Some values for coefficients of friction are in table 1:

Material Pair	Static	Kinetic
Teflon/nylon	0.055	0.050
Teflon/Formica	0.105	0.083
Teflon/aluminum	0.12	0.095
Teflon/PVC	0.13	0.13
nylon/aluminum	0.13	0.125
nylon/Formica	0.20	0.19
PVC/Formica	0.25	0.17
PVC/plywood	0.28	0.23
felt/Formica	0.23	0.22
felt/aluminum	0.31	0.31
plywood/Formica	0.37	0.20
plywood/particle board	0.45	0.30

TABLE 1: Some coefficients of friction for materials used in telescope making. From Berry, 1980. Kinetic friction measured at 1 mm/sec.

Going back to our Dobsonian, how much friction the scope experiences also depends on where the bearing pads are located. The rocker base, for example, has the full weight of the tube assembly and bearing box on it. Assume that the box weighs another 15 pounds, so that the force on the pads is the total of both weights, 45 pounds. Then the friction force experienced is:
(assuming Teflon on Formica).

$$f = 0.105 * 45 = 4.73\ lb.s \qquad \mathbf{26}$$

What if the telescope is not sitting on perfectly level ground – or it's an equatorial bearing? Consider an inclined plane (**Figure 6**). In this geometry, the normal force is not the same as the weight. The trick to seeing how the forces are calculated is to note that the triangle formed by the plane is similar to the one formed by the weight **W** and its components Wx and Wy. The component of the weight that makes the block slide to the right down the plane is:

$$\vec{Wx} = \vec{W}\cdot\sin(\alpha) \quad \textbf{27}$$

and the component pushing on the plane is:

$$\vec{Wy} = -\vec{W}\cdot\cos(\alpha) \quad \textbf{28}$$

(minus sign because the component points in the negative Y direction). The normal force has this magnitude and opposite direction. In both of the equations and the figure, the Greek letter alpha, **α**, represents the angle.

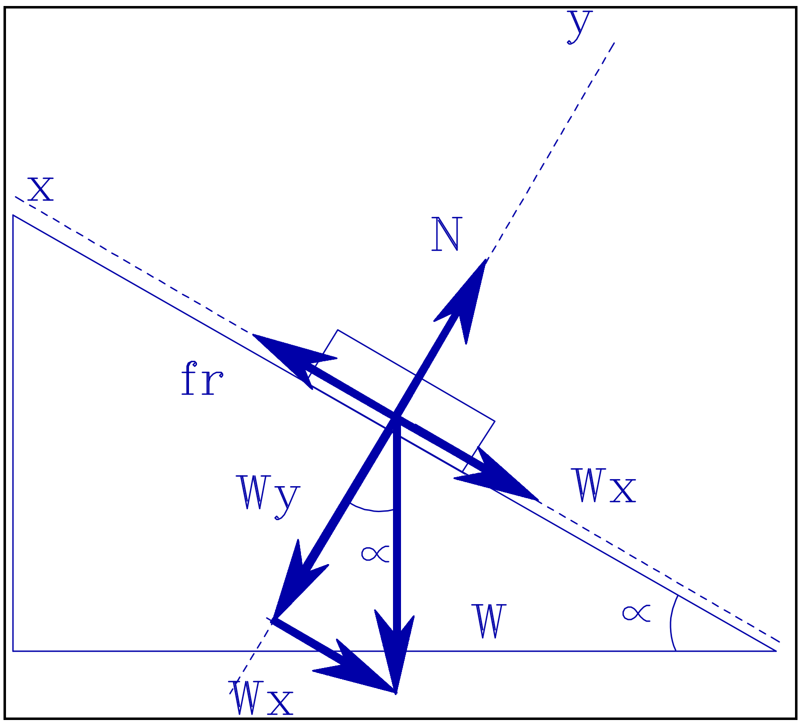

Figure 6 In the inclined plane, the normal force is not the weight, but the weight modified by the angle.

In the case of the inclined plane, the body will slide down the plane if the component of weight down the plane is greater than the static friction:

$$\vec{Wx} \geq fi \quad \textbf{29}$$

or:

$$\vec{W}\cdot\sin(\alpha) \geq k\cdot\vec{W}\cdot\cos(\alpha) \quad \textbf{30}$$

Note that this says:

$$\frac{\vec{W}\cdot\sin(\alpha)}{\vec{W}\cdot\cos(\alpha)} = \tan(\alpha) \geq k \quad \textbf{31}$$

or the block will slip if the tangent of the angle is greater than the coefficient of friction.

If they are exactly equal, the block will slide down the plane with constant velocity (a statics problem) once it starts moving. If the component of weight down the plane is greater than the friction force, it will accelerate down the plane (a dynamics problem). In practice, if the acceleration is small or short-lived, we may not care much.

The inclined plane is important in physics and engineering, and we'll see this geometry in many other places. The German Equatorial has geometrical aspects analyzed by similarity to an inclined plane.

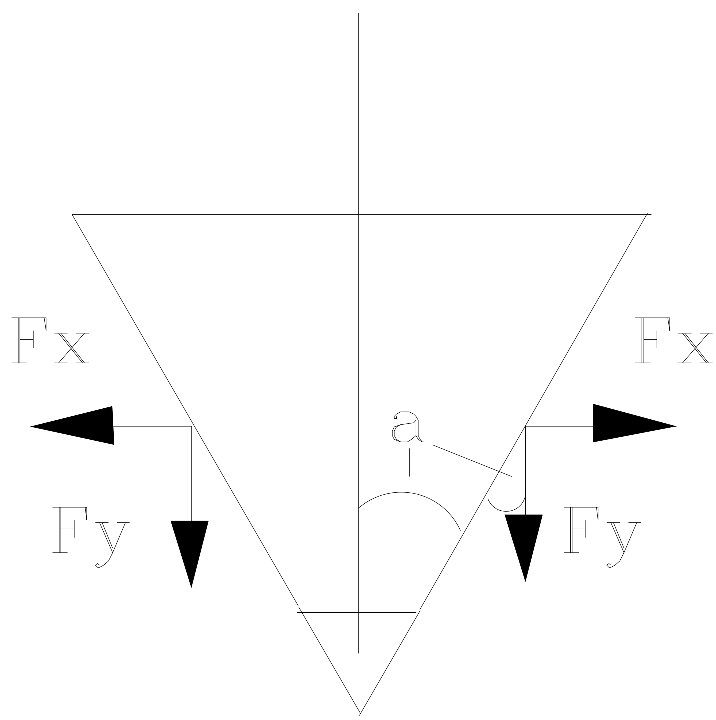

Figure 7 - A Vee Block

In contrast to an inclined plane, is a Vee block. Figure 7 shows a Vee block in cross section across the long axis of the block. It should be obvious by examining the figure that the components along the X axis cancel out. Gravity is acting downward in this diagram, so the normal force comes from the components in the Y direction. Each side presents a force of **W/2***sin(a) so that the total force is:

$$\vec{F} = \frac{\vec{W}}{\mathrm{Sin}(\alpha)} = \vec{W}\cdot\csc(\alpha) \qquad 32$$

This says that the force is inversely proportional to the sine of the included angle. The other function, cosecant, is another way of saying 1/sin. Since the sine has a value that approaches zero as the angle approaches zero, we see that the normal force, and hence friction, go up as the angle approaches 0 degrees (that is, as the walls go to vertical). Mathematically, friction approaches infinity.

The force diagram for circular Dobsonian side bearings is the same as for a Vee block, and the force triangle is shown on the right in **Figure 8**. The first thing to notice is that the weight is evenly divided on the two pads, so each pad has a weight of **W**/2 on it. The geometry is a little tricky here. The 60 degree angle at the top of the triangle (on the upper right in the figure) is one angle of a triangle. The angle where the normal force hits the Teflon pad is always 90 degrees. This is drawn as the heavy "y" arrow. That means the other angle, the one we care about, is 30 degrees. This is the angle used in the Vee block derivation – it's always 90 minus the angle that the pad is from the vertical. The friction force on each block is then **W***k**/(**2*sin(30)**)**, or for both bearings, **W***k**/(**sin(30)**)**.

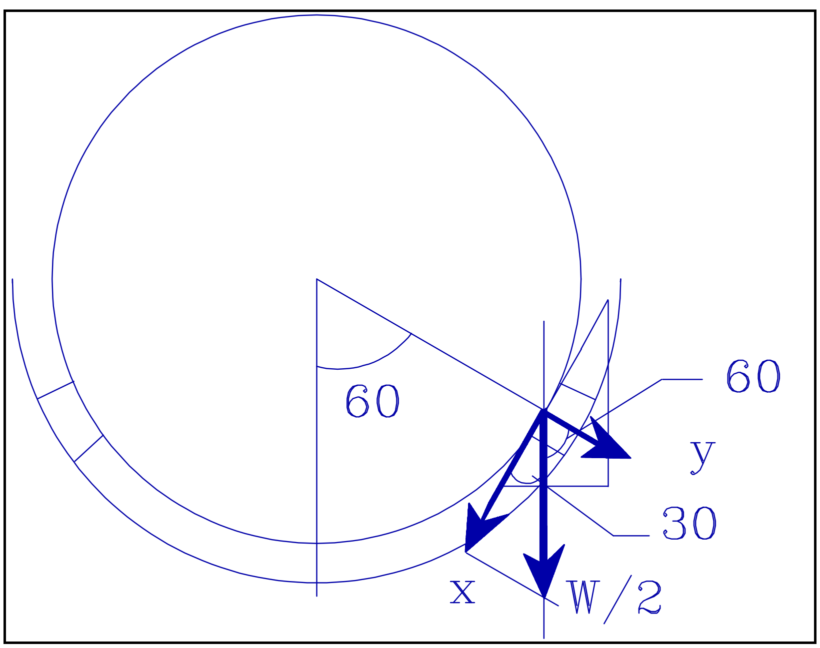

Figure 8

In general, as the angle with respect to horizontal goes up, and the pads go up the sides, the normal force increases, and with it, the friction increases. If your assembled telescope moves too easily in elevation, move the friction pads higher.

Moments and Torques

Anyone who has opened a door knows that the friction in the hinges is not the only force to overcome. Want a demonstration? Next time you're at a door with an automatic closing device, the kind that pushes back gently as you open it, try pushing halfway out to the handle, or even closer to the hinge. A lot harder isn't it?

What you are doing when you push on the door is generating a torque about the hinges. Again, *torque* is defined as the force applied multiplied times the perpendicular distance to the pivot point. Notationally:

$$\vec{\Gamma} = \vec{F} \cdot l \qquad \textbf{33}$$

Looking down from the top of a door, we create the free body diagram shown in **Figure 9**. The large circle on the left represents the hinge. With the force applied at the handle we get:

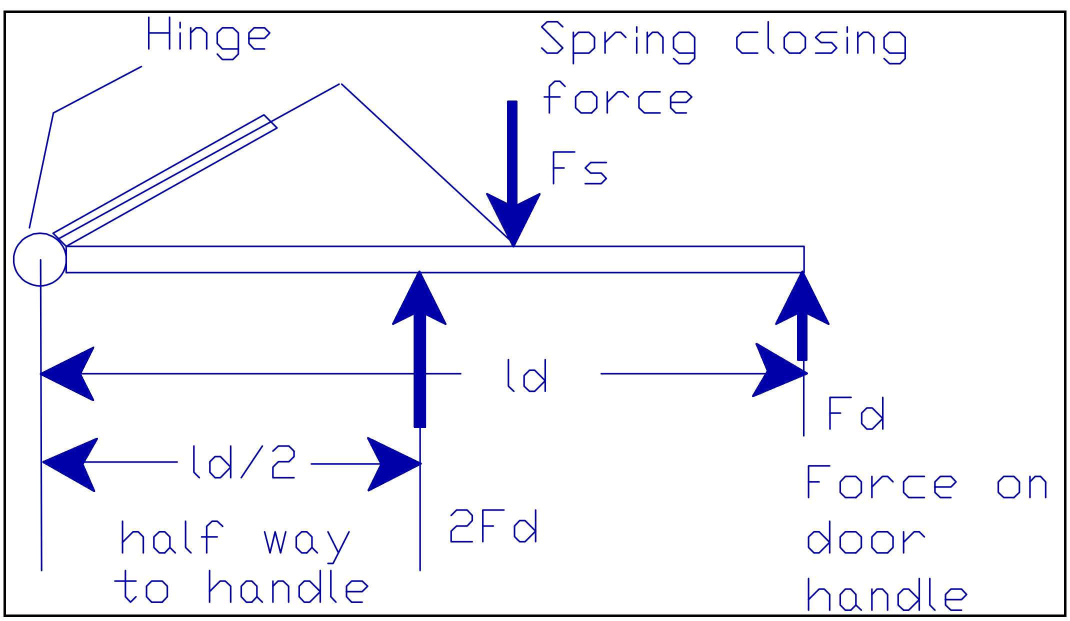

Figure 9 Top view of a door with the forces on it.

$$\sum \vec{\Gamma} = 0 \qquad \textbf{34}$$

$$\vec{f_s} \cdot l_s = \vec{f_d} \cdot l_d \quad (35)$$

I hope you see that to generate the same value of torque at half the distance ($l_d/2$), we need twice the force ($2\mathbf{f}_d$). What's true for doors is true for Dobsonians, and it's the torques that really determine how the mount feels.

In Figure 10 we see our typical Dobsonian again, with the distances marked for the lines of action of the forces. We ordinarily push these scopes near the eyepiece, so the forces are shown from there to the center of the mount. Using the value of friction we found earlier, we can solve for the force required to move the scope. First, we'll look at the rotation of the azimuth bearing, the ground board.

$$\vec{f_r} \cdot r_p = \vec{f} \cdot L \quad (36)$$

This says that the friction force ($\mathbf{f}_r$)times the radius from the center of the bearing to the friction pad (r_p) equals the force required to push the telescope (**F)** times the distance from the point where we push to the center of the bearing (L).

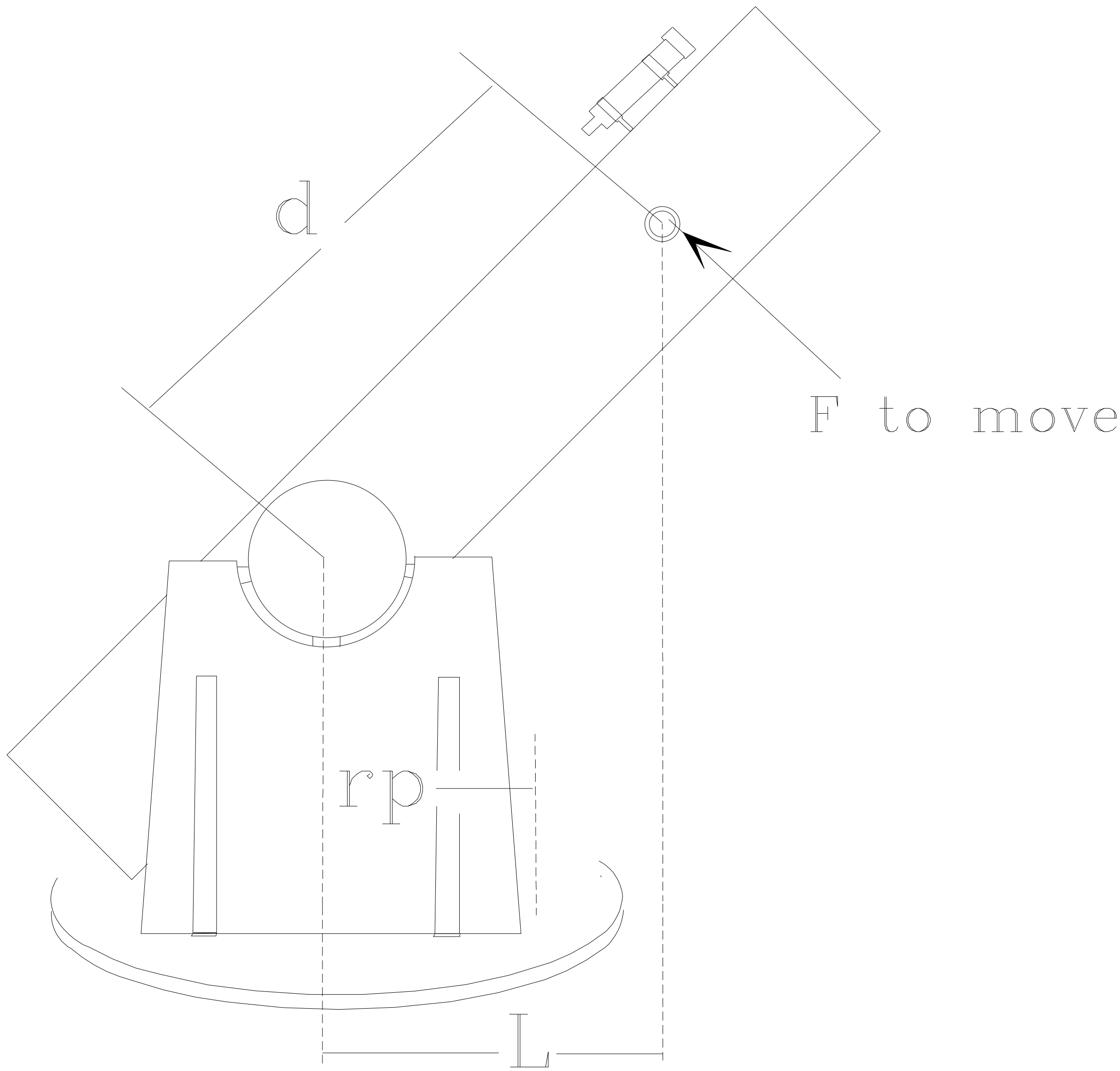

Figure 10 - Torques on a Dobsonian

Rearranging, we find that the force required to move the ‘scope is as shown in equation 37.

$$\frac{\vec{fr} \cdot rp}{L} = \vec{f} \qquad \textbf{37}$$

Now, L may not be obvious from the drawing, but is obtained from the same simple trig that gives us vector components. If the distance from the eyepiece (where we are pushing) to the center of the bearing disk is **d**, then **L = d*cos(alt)**, the altitude angle measured from the horizontal. Now that means that the force required to rotate the mount in azimuth varies with the angle of the object being viewed, and indeed it does. How do you design for this? Typically by choosing a median value or one representative of the way you intend to use your scope: 45^o is common because the seeing is usually impaired as you go significantly lower than that.

Let's see some representative numbers so that I can show something important about units. Let **d**=30 inches and put the scope at 45^o so that **L=d*cos(alt)** or **L=30(.707) =21.21** inches. If the azimuth bearings are on an 18 inch diameter circle, **Rp**=9 inches. Then:

$$F = \frac{4.73\cdot lbs\cdot(9\cdot in)}{21.21\cdot in} = 2.01\cdot lbs \qquad \mathbf{38}$$

So a push of 2 pounds is required to move the scope about the azimuth axis.

The units of torque are force times length. I've used pounds and inches in this example, but I could have used any units as long as I used the same kind on both sides of the equation. What is important is that you can check your manipulations by carrying the units and verifying that the result is in the units you expect. Here, we were looking for units of force (pounds) and that's what we found when inches divided out of the top and bottom of the fraction.

The force on the altitude bearing is comparatively easy to calculate. That's because the distance from the eyepiece to the middle of the bearing is constant at all tube angles. There are four contact points (two on each side); each one gets one fourth of the weight of the telescope. The total friction force is:

$$f_r = k(4\frac{W}{4\sin 30}) = \frac{kW}{\sin 30} \qquad \mathbf{40}$$

$$f_f = .105(\frac{30}{0.5}) \qquad \mathbf{41}$$

$$= 6.30\ lb.s \qquad \mathbf{39}$$

The force required to move the scope in elevation (assuming 8 inch bearings) is then:

$$\vec{F} = \frac{(6.30\cdot lbs)\cdot(4\cdot in)}{30\cdot in} = 0.84\cdot lbs = 13.4\cdot oz \qquad \mathbf{42}$$

Thus 13.4 additional ounces will cause the telescope to slip and move in altitude.

Step back a second and look at what we've just shown. This starts with a balanced tube assembly that is not moving. We then calculated the force required to equal the static friction, knowing that to overcome this friction requires just a “smidgen” more.

What if we don't like that number? We plan to use an eyepiece that will add an additional pound (more than the current eyepiece). What do we do? There are several things that we can change (engineers refer to do this as having several degrees of freedom). For example, we can choose materials with a greater coefficient of friction. Instead of the Teflon/Formica pair, we could use a nylon pad and Formica. This will virtually double the friction to 12 pounds, and the force required to move the scope to 1.6 pounds. There are many options, but changing materials will typically give you around a 4:1 range of change.

Moving the pads farther apart will increase the normal force and thereby the friction. The minimum separation is usually recommended to be 30^o from the vertical, or 60^o apart. The increase is the ratio of cosec 60 to cosec 30, or 1.73:1 and the force to cause slippage goes up by the same ratio. Likewise, increasing the diameter of the bearing will increase the torque. Going from an 8" bearing to a 10" size will increase the force by a factor of (5/4) -- or (new diameter)/(old diameter) -- from 13.4 ounces to 16.8 ounces. Of course, you could also increase the weight of the telescope, but most of us consider that a last resort. A Velcro strip on the tube and some coins in a small sack that will stick to it is a common counterweight, added as needed. Some ATM’s have resorted to springs to increase the counterweight force.

What's the best thing to do? Generally, it's to make the bearings larger. The problem with changing materials is that certain materials – Teflon and textured Formica –have been shown to work best in a properly loaded mount. The problem with changing the angle of the pads is that there really isn't much freedom here. You can only spread them so far (or move them so much closer together) before you get problems with the bearing becoming unstable as you push on the scope. At some point, the scope will want to push off the bearings, or wedge in place. There is a price for this modification that you need to consider, though: the scope will take more of a push to get it moving when you aren't using the heavier eyepiece. Of course, if we had too much friction we could do the same sorts of things to decrease the force required to move the scope.

How much friction is right? To some extent that depends on your preferences. To some extent it depends on the size of the telescope; users seem to expect a bigger telescope to require a bigger push. The preferred range is about 1.5 to 4 pounds, although the upper end can go higher if the resulting motion is smooth.

Finally, some concerns about the materials used in the Dobsonian mount. The Teflon used in the classical design has a characteristic called cold flow. That means if you clamp a piece under pressure at room temperature, it will flow or deform to relieve the pressure. Pressure has the units of force/area, so each pad should have an area that keeps pressure in the range of 10 to 30 pounds per square inch. For instance, the base pads in our sample mount will each support 15 pounds, and several writers have reported 15 psi as the optimum value. A one square inch pad is ideal here.

The Teflon/Formica combination has been extensively investigated because a properly designed mount has a feeling described as “buttery”. As you push on the scope, the motion is an easy gliding action. The result feels like it's sliding on butter. The reasons for this are that the proper loading minimizes the stick-tion effect mentioned before, and that the combination displays a coefficient of kinetic friction that varies with the velocity of motion. If you keep the Teflon loaded near 15 psi, you will get this desirable effect.

Believe it or not, that's the meat of the subject of statics, “Five Minute University” style. Engineering students solve lots and lots of problems involving bizarre geometries. Of course, they are being prepared to handle anything from cranes and skyscrapers to miniature tools. We have more specialized things to study and there isn't much need for figuring obscure geometries.

So let’s now turn our attention to the subject of center of gravity. Intuitively, you know what this is: it's the imaginary point that behaves as the place where all the mass in a body is concentrated. It's the six inch mark on a perfect 12" ruler. We usually find the center of gravity of a telescope tube empirically by balancing it on a dowel or rod, but it is possible to calculate it from the data we have about the design. They certainly didn't find the balance point of the Keck telescope by balancing it on a rod!

To find the coordinates of the center of gravity (usually referred to as the CG, pronounced “see gee”) you mentally divide the body up into smaller sized slices or sub-bodies that you know the CG for and fill it into the following rather nasty looking equation:

$$x_{cog} = \frac{\sum x_i W_i}{\sum W} \qquad \textbf{43}$$

where x_{cog} is the x coordinate of the CG, x_i is the x coordinate of slice you are working with from some coordinate origin, W_i is the weight of that slice and W is the total weight of the body. To find y and z coordinates you use the same formula, substituting y or z for the x in the equation.

Another way of looking at the concept of the slices is to say that each slice is a single cross-section of the telescope. It will contain the mass of a component at the position of its CG. Say you have a mirror that weighs 10 pounds, and its center is 3 inches up the tube from the bottom. You would take a slice through the tube at 3 inches and say it weighs 10 pounds.

An example should help make this clearer.

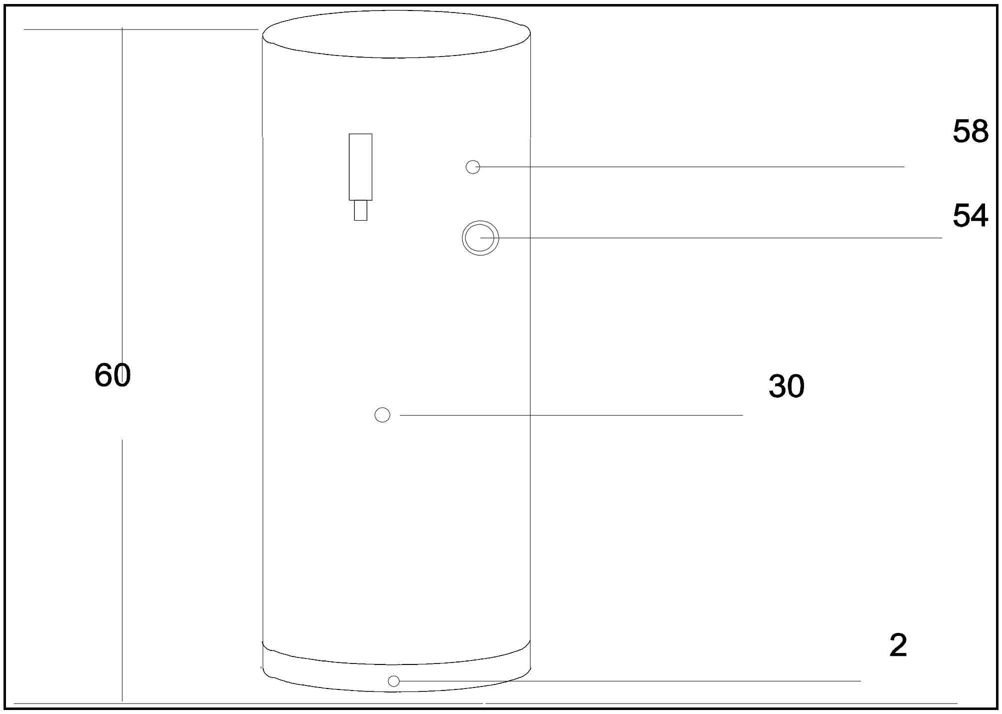

Figure 11 Finding the CG of the telescope tube.

First, we weigh of all the components or gather all of their specifications, and then make a table that includes the weights and how far up the tube they are.

Slice	Weight	x_i (inches)	x_i*W (in-lbs.)
Mirror	15 lbs.	2	30
tube	2 lbs.	30	60
Diag, spider, focuser	2 lbs.	54	108
Finder	3 lbs.	58	174
Total	22.00		372

We then divide the sum in the last column by the sum in the second, to get x_{cg} = 372 /22 or x_{cg} = 16.9 inches up from the bottom of the tube. I will leave it to you to prove to yourself that this is really the center of gravity. You can do this by summing the torques around the center of gravity. To do this, draw the tube turned over on its side so that all the weights point downward. Make all the torques on the left side of the COG negative distances from the CG and all of the torques on the right side positive distances. Multiply the weight times the distance, add them up and you will find that they add up to very close to exactly zero. The differences, if any, are due to using three significant figure accuracy.

There are assumptions buried in here, as there are in everything we do. What I have done is assume that the slices are one material of uniform density, i.e., that the weight in each slice is from only the component named. How good are these assumptions? Let's look at the bottom ring; it holds the mirror cell and mirror at 15 pounds. The two inches of the tube included with the mirror weigh 2/60 of two pounds or 1.1 ounce. The 15 pounds from the mirror in this slice is clearly much larger than the 1.1 ounce of tube. In the case of the focuser and spider, the two pounds dominates the weight of the tube by a factor of 32. The mass here, as in the finder scope and its holder, is clearly not centered in the tube, and this can cause rotation, even in a Dob. (in a Dobsonian, the movement of the CG off the centerline of the tube makes the apparent CG change with elevation angle).

How do you fix this? The finder and focuser clearly can not be in the center of the tube, and they are usually not opposite each other on the top and bottom of the tube's observing end. The most direct fix is to add a counterweight on the tube, radially opposite the heavy finder or focuser. This weight doesn't need to be at the same end of the tube and can be toward the bottom, helping to pull the CG down. This is not a problem with the typical Dobsonian, since the finders tend to be small and lightweight. If you're going to piggyback mount a second telescope on a large German equatorial, or SCT wedge mounted fork, you should consider the CG in 3 dimensions and try to keep it on the centerline of the tube.

Before we leave statics, I need to say that not everything we come upon can be solved by the principles of statics. There are such things as statically indeterminate problems which are found when the number of unknowns exceeds the number of equilibrium equations (summation of forces and torques about all three axes: six equations). This is an advanced concept, but you'll come across it if you do a lot of practice problems from books. "Real life" engineering solves these problems with computer models that break a structure up into small pieces and determine the loads and bending in every piece; these are called Finite Element Method, or FEM programs.

References and Further Reading

(In addition to the following, the interested reader can find many solved problems in the Schaum's Outline series of books from MacGraw-Hill. These are available in many public and college libraries, as well as larger bookstores and college bookstores.)

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