THE ONE TRUE WAY TO COLLIMATE A NEWTONIAN REFLECTOR TELESCOPE

by

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Keeping a Newtonian reflector in proper collimation is necessary in order to observe sharp, coma-free star images. The "faster" the mirror, i.e., the lower its focal ratio (of focal length to diameter), the more important it is to collimate the telescope as accurately as possible.

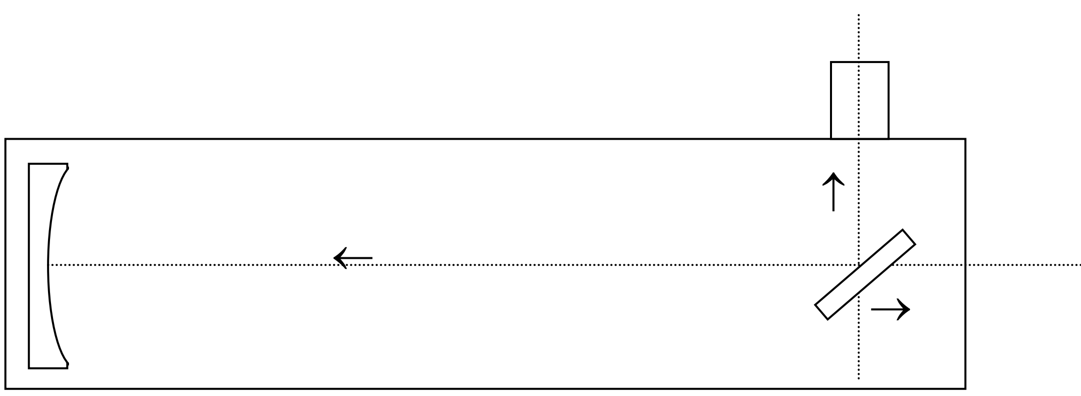
The main symptom that your telescope is "out of collimation" is the inability to bring stars into sharp focus from one side of the field to the other at the same time. In extreme cases, star images may look like tiny comets which turn inside out with the "coma" facing the other way as the focuser is run in and out. It's a dead giveaway when the optimum focus is different from one side of the field to the other.

Many different collimation methods are in use. A few of them are variations on the One True Method. Most methods are false, and only lead to an approximate collimation at best. Long-focus (f/10) and medium-focus (f/6 – f/7) telescopes are so forgiving of poor collimation that most amateur astronomers are satisfied with almost any method. However, the owner of a fast (f/4 – f/5) Newtonian soon discovers that what seemed to work for the old f/8 is no longer adequate.

The One True Method is actually easier to understand and carry out than many of the compromise methods, some of which require several cycles of "iteration" (backtracking) before settling on an approximate result.

Only three steps are required to collimate a Newtonian perfectly:

1. Make the optical axis of the primary mirror coincident with the axis of the telescope tube;
2. Make the optical axis of the eyepiece holder perpendicular to the telescope tube; and
3. Position the surface of the diagonal mirror at the intersection of these two axes, and at a 45° angle to each axis.



Steps 1 and 2 may be done in either order, but once they have been accomplished, those adjustments must not be tampered with while carrying out Step 3. **Warning:** Any so-called collimation method which calls for adjusting the primary mirror **last** is most likely an inaccurate compromise!

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The purpose of Steps 1 and 2 is to get the optical axes of the mirror and the eyepiece at right angles to each other. The telescope tube is merely a convenient frame of reference for this operation. If the 90° angle between the axes is not achieved, then the "central ray" from a star to your eye will not strike the mirror or enter the eyepiece squarely (or both), causing coma and other aberrations.

There are many ways for carrying out each of the three steps. Several which actually work will be discussed in the following pages.

Step 1: Make the optical axis of the primary mirror coincident with the axis of the telescope tube.

It is assumed that the mirror has been figured symmetrically, i.e., its optical axis passes through its physical center. It is also assumed that the mirror (in its cell) is physically centered in the telescope tube. Measure to be sure; shim or adjust if necessary.

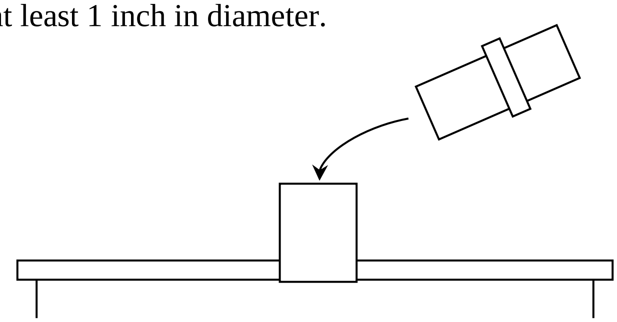
For all methods, it is first necessary to paint a tiny dot on the exact center of the mirror. (This will not affect its performance, since this area is in the "shadow" of the diagonal.) Remove the primary mirror from the telescope. (It is not necessary to remove the mirror from its cell.) If necessary, clean the mirror using an approved procedure. Make a circular piece of cardboard, such as poster board or a manila file folder, the same diameter as the mirror. Use a compass, then cut out the circle. Use the compass point to enlarge the hole in the center slightly. Carefully lay the cardboard on the mirror. If necessary, cut notches where the mirror clips touch the face of the mirror. Then use a toothpick to apply a tiny drop of dark paint through the hole onto the mirror.

Optional: Some of the methods also require a larger "target" to be applied to the mirror; now is a good time to do it. As soon as the paint has dried thoroughly, attach a circular "gummed reinforcement", commonly used to prevent the holes in notebook paper from tearing, to the center of the mirror, centered on the paint spot. Replace the mirror in the telescope.

Low-tech method: Remove the diagonal or move it over to the side of the tube. Aim the telescope nearly horizontal or slightly upwards, so that it is convenient to look down the tube. Have an assistant turn the mirror-adjusting screws until the reflection of your eye is centered on the dot on the mirror **and** in the circular outline of the end of the tube. This is sufficient for high-f/ telescopes.

Medium-tech method: The improvement here is the use of a cardboard mask with a hole in the center to make sure you are positioning your eye at the center of the end of the telescope tube. Make a circular cardboard mask to fit over the end of the tube. Use a compass as before, but then use a hole punch, cork borer, or other device to make a ¼-inch hole in the center. Cut two V-shaped notches on opposite edges of the circle in order to admit enough light to see the spot on the mirror. After removing the diagonal, tape the disk to the end of the tube. Look through the central hole while an assistant turns the mirror-adjusting screws until the reflection of the hole is centered on the dot on the mirror. This is considerably more accurate than trying to hold your head in the right place.

High-tech method: Instead of the cardboard peep-hole used in the medium-tech method, build a sturdy cap for the end of the telescope, using aluminum, plywood, or heavy Plexiglas. As above, cut out some large notches to facilitate viewing the *underside* of the cover with a small inexpensive dental mirror, which is easily obtainable at a large general merchandise retailer (e.g., Wal-Mart). On the *exact* center of the end cap, mount an eyepiece holder or a 2-inch-long piece of 1¼-inch I.D. tubing. Enlarge the center hole to at least 1 inch in diameter.



Insert a laser collimating device (commercial or home-made) all the way into the eyepiece holder on the end cap. (The laser should have attached to its "business end" a disk of white paper or cardboard, with a central hole just large enough for the beam to pass through.) With the diagonal removed and the cap assembly in place, adjust the laser, the eyepiece holder, or the entire cap until the laser beam falls on the exact center of the mirror. Use the dental mirror to observe where the reflected beam strikes the white target. Adjust the mirror screws until the reflected beam retraces the exact path of the incident beam, back into the hole.

For a somewhat more sensitive version of this test, insert the laser into a Barlow lens, then insert both into the eyepiece holder on the end cap. (The Barlow lens should also be fitted with a white paper target which has a hole for the beam to come out through.) The laser beam will now be spread out over a larger area of the mirror than before. Make sure it is aimed roughly at the center; exact aiming is not necessary. Now, an image of the gummed reinforcement will be projected onto the target attached to the Barlow lens. Fine-adjust the mirror screws until the "life-saver" image is centered around the beam hole in the target.

Now that the primary mirror is exactly aligned with the tube, it must **not** be adjusted again during the collimation procedure, no matter what anyone tells you!

Step 2: Make the optical axis of the eyepiece holder perpendicular to the telescope tube.

The goal in this step is to make the eyepiece holder aim at a spot on the exact opposite side of the tube. Most procedures tell you to mark the spot by measuring in the same distance from the end of the tube as the center of the eyepiece holder. Not only is this distance hard to measure, but the procedure assumes the end of the tube has been cut perfectly square! Here's a more accurate way: Make an eyepiece-holder "target" by cutting out a perfectly rectangular piece of poster board or flexible cardboard; its short ends should be about the same length as the diameter of the tube, and the long sides about 3½ times that length. With the diagonal still removed, slide the rolled-up cardboard into the end of the tube. Unroll it until it is snugly fitted around the inside of the tube, with its ends slightly overlapped. Mark the overlap with a sharp pencil. Take the cardboard out and cut it about a mm longer than the mark would seem to indicate. Test-fit the cardboard inside the tube again: it should fit snugly with no wobble and no overlap; trim if necessary.

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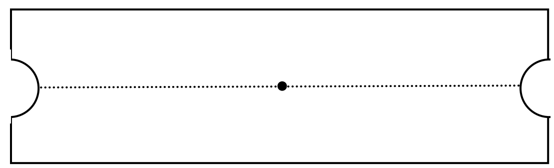
Remove the cardboard again, and draw an exact center-line along the "inside" surface. Mark the exact center of this line. (This spot will mark the location of the target.) Poke a hole through the cardboard at this point, just large enough to insert a toothpick. Next, make a cut-out for the eyepiece-holder's draw tube: Measure its outer diameter, and draw a circle that size on the cardboard, half on one end and half on the other (on the center line, of course). Cut out the semi-circles.



Put the cardboard back in the tube again, with the hole fitted around the focuser's draw tube, which should be protruding slightly into the telescope tube. Make sure that the cardboard is positioned snugly and accurately. Finally, apply a tiny drop of white paint through the target hole onto the inside of the telescope tube. If the tube is flock-lined, scrape off a small area for the spot to be painted on.

Now you're ready to make sure the eyepiece holder is perpendicular to the mirror's optical axis.

Low-tech method: Make (or purchase) a "sighting tube", a dummy eyepiece (without lenses) which lets you sight through pinholes or inscribed rings to see exactly where it is aimed. Put it into the eyepiece holder, and see if it is aimed at the white paint spot on the far side of the tube. If so, you're very lucky! If not, you'll have to file or shim the base of the focuser until it does point to the spot. Make sure it stays aimed properly as you rack the focuser in and out. If not, try to tighten the slop out of the mechanism, or invest in a better focuser.

Medium/high-tech method: Same as above, but use the laser collimator (without the Barlow lens) to shoot a beam from the eyepiece holder to the paint spot on the far side. Shim or file the base of the focuser if necessary.

At this point, you have made the optical axis of the eyepiece focuser exactly perpendicular to the optical axis of the primary mirror, which runs down the exact center of the telescope tube. Promise you won't fiddle with either of those adjustments while you position the diagonal!

Step 3: Position the surface of the diagonal mirror at the intersection of the two optical axes, and at a 45° angle to each axis.

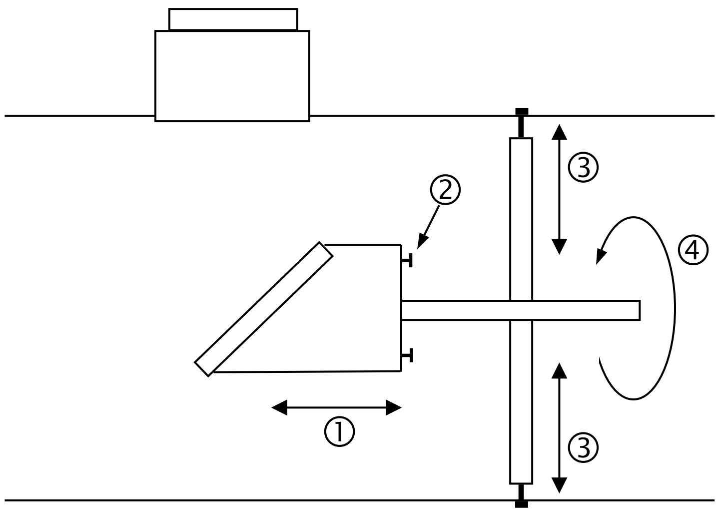
When the diagonal is properly positioned, it should appear circular rather than elliptical (**if** it is a true ellipse with its major axis longer than its minor axis by a factor of $\sqrt{2}$ or 1.414). Furthermore, its circular image must be centered in the eyepiece draw tube, and the reflection of the primary mirror and the diagonal's reflection in the primary mirror must all be concentric. And don't forget: you have to achieve all of this **only** by positioning the diagonal, without touching the primary mirror or focuser adjustments!

(Determining the proper size of the diagonal is a different subject altogether; it is assumed here that you will continue to use the diagonal you already have.)

If you study the drawing of the Newtonian system on page 1, you will see that the front (reflective) surface of the diagonal must lie at the point where the optical axes of the primary mirror and of the eyepiece focuser intersect, in a plane that is tilted 45° to these axes. If this is done, the optical system is in perfect alignment and no coma or aberrations will be introduced. However, the diagonal's position *along* this plane is as yet undefined, and will be specified later for optimum results.

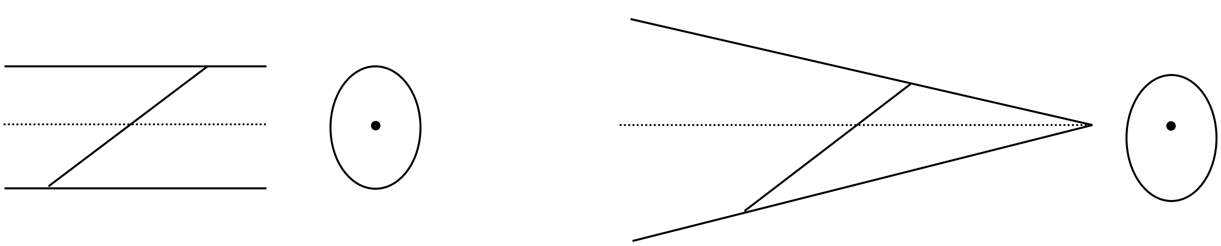
A diagonal holder should have four types of adjustments:

1. The mirror may be moved along the axis of the tube, varying its distance from the primary mirror.
2. The mirror may be aimed by three adjustment screws.
3. The mirror may be moved across the tube, varying its distance from the focuser. (On many spider assemblies, this adjustment can only be done by using washers to shim the points where the vanes attach to the tube.)
4. The mirror may be rotated around the long axis of the tube.



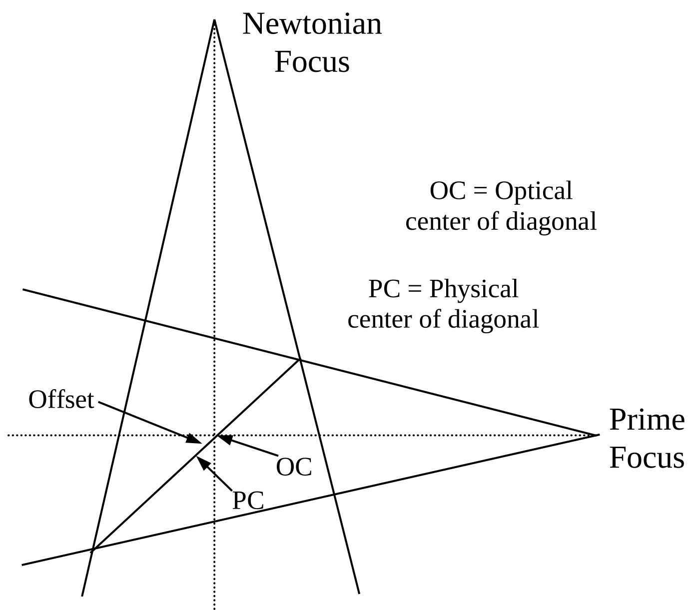
While the diagonal is out of the telescope, clean it if necessary. You will need to mark the physical center and the optical center of the diagonal, as explained below.

Theoretically, the optical center of the diagonal is not quite the same as its physical center, but is located along the major axis of the ellipse ***towards*** the eyepiece holder and the open end of the telescope tube, i.e., ***away from*** the primary mirror, as shown in the right-hand drawing below. As a result, when the diagonal is properly positioned, its ***physical center*** will appear to be displaced ***away from*** the focuser and ***towards*** the primary mirror. This is known as the "diagonal offset".



In the figures on the left, it can be seen that a slice through a **cylinder** at a 45° angle produces an ellipse, whose center lies on the axis of the cylinder. However, if we slice through a **cone** at the same angle, as shown at the right, an identical ellipse is produced (i.e., the ratio of the major axis to the minor axis is $\sqrt{2}$ or 1.414 to 1), but the center of the ellipse does **not** coincide with the axis of the cone. This is because a larger portion of the ellipse is needed to "fill" the larger side of the cone, while a smaller part of the ellipse occupies the smaller side of the cone.

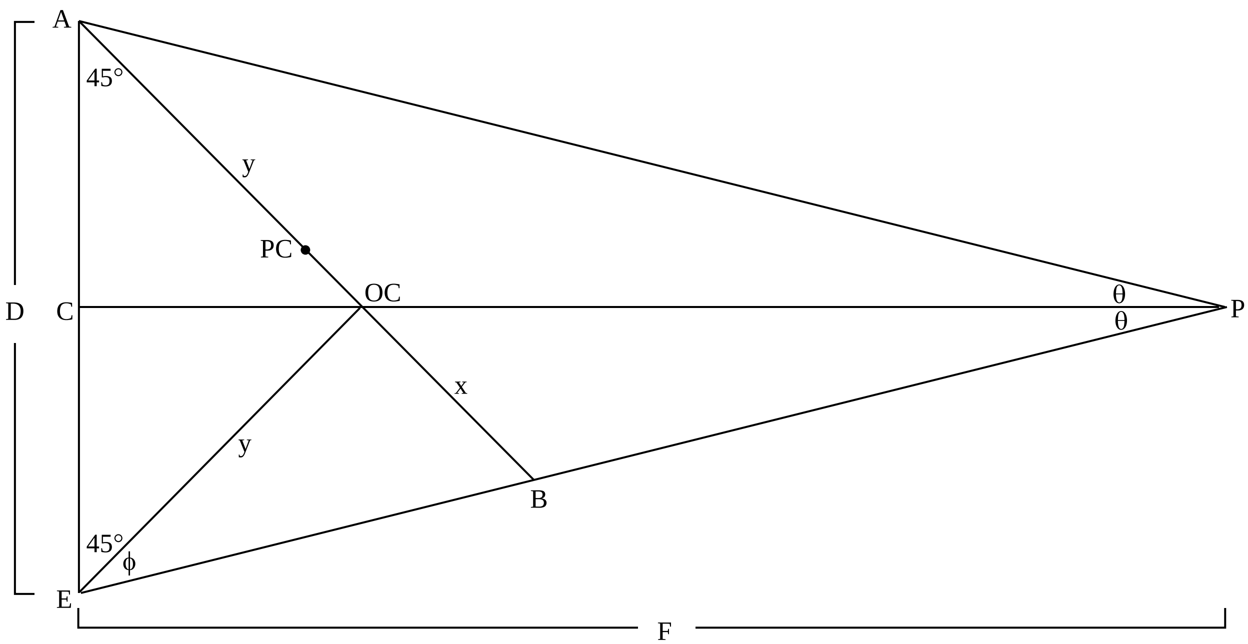
In a Newtonian telescope, a cone is generated by the rays of light reflected off the primary mirror as they converge toward the focal point. Of course, this cone is diverted 90° by the diagonal mirror, so we are really dealing with **two** cones intersecting at a right angle. As a result, the correct place for the physical center of the diagonal is **not** at the intersection point of the optical axes of the two cones, but displaced **away from** the eyepiece holder and **towards** the primary mirror, so that the ellipse fits perfectly into **both** cones at the same time. In other words, the diagonal is still in the same plane, but slightly ***displaced*** **(offset)** along that plane, away from the focuser and towards the primary mirror.



It should be pointed out that if this "offset" of the diagonal is not performed, it will **not** introduce any coma or other aberrations, since the central rays are still being reflected at a perfect 90° angle. The only detrimental effect is a more pronounced falling-off of image brightness on one edge of the field compared to the other, due to the diagonal "missing" a portion of the light cone on that side. This is generally noticeable only in very fast optical systems. For slow mirrors, the light cone is so nearly cylindrical over short distances (i.e., from the leading to the trailing edge of the diagonal) that the required offset is negligible.

By the way, many sources imply that the offset is only in a direction away from the focuser (lateral), neglecting to mention that an equal offset towards the primary mirror (longitudinal) is also required, as can be seen in the diagram above. This is probably due to the fact that the need for the longitudinal offset is obvious when the diagonal is being centered in the draw tube.

Calculating the offset (Refer to the diagram below): D represents the diameter of the mirror, and F is its focal length. The reflected rays converge at P, the prime focus, forming a cone. A 45° diagonal, A·B, is inserted into the cone. The midpoint of line A·B (the major axis) is the physical center of the diagonal (PC), but clearly is not on the axis of the cone. The point on A·B which **is** on the optical axis is labeled OC (optical center). We are interested in computing the relative magnitude of x and y, the shorter and longer portions (respectively) of the major axis either side of the optical center.



Let θ be the angle subtended by half the mirror, as seen from the prime focus. We see that $\tan\theta = (C{\cdot}E) / (C{\cdot}P)$, which also equals (D/2) / F, which incidentally is 1 / 2f/, or the reciprocal of twice the focal ratio of the mirror. Since triangle P·C·E is a right triangle, angle P·E·C = 90° - θ. Part of this angle contains the 45° angle C·E·OC. Therefore, the remainder, ϕ, is equal to 45° - θ.

Now look at the smaller right triangle B·OC·E. Right away we see that $\tan\phi = x/y$, which is just what we need to know. $\tan\phi = \tan(45° - \theta) = (1 - \tan\theta) / (1 + \tan\theta) = (1 - D/2F) / (1 + D/2F)$.
Thus, the formula we need is $x/y = (1 - D/2F) / (1 + D/2F)$.

It is very useful to be able to calculate the diagonal offset in terms of the basic optical parameters of the telescope: the diameter (D) and focal length (F) of the primary mirror, and the major (long) axis of the diagonal (M).

The fraction of the length of the diagonal from its bottom edge to the optical center (OC) is $x / (x+y)$. This is equivalent to $(x/y) / (1 + x/y)$. But x/y, as shown above, is $(1 - D/2F) / (1 + D/2F)$. For simplicity, if we substitute "z" for D/2F, we have $x/y = (1-z) / (1+z)$.

Then, the fraction of the diagonal to OC = $(1-z)/(1+z) / [1 + (1-z)/(1+z)]$. The actual distance is this fraction times the length of the diagonal, or $M * \{ (1-z)/(1+z) / [1 + (1-z)/(1+z)] \}$.

If we multiply the numerator and the denominator of the term in parentheses by 1+z, we obtain

$$OC = M * [(1-z) / [(1+z) + (1-z)], \text{ or } M * (1-z) / 2.$$

Substituting D/2F for z, we obtain $OC = M * (1 – D/2F) = M/2 – MD/4F$.

The diagonal offset = PC – OC. Since PC = M/2, i.e., the physical center is half-way along the diagonal, we now have **Offset** = M/2 – (M/2 – MD/4F) = **MD/4F**.

Thus, the diagonal offset is directly proportional to the diameter of the primary mirror and the length of the diagonal, and inversely proportional to the focal length of the mirror. In other words, the larger and faster the optical system, the more important it is to offset the diagonal properly. The two examples below will illustrate this principle.

We have just shown that the optical center of the diagonal needs to be displaced by a distance equal to DM/4F, where D and F are the diameter and focal length of the primary mirror, in consistent units, and M is the length of the major (longer) axis of the diagonal, preferably in millimeters.

Example A: Suppose we have a 10-inch mirror with a 41.5-inch focal length (f/4.15 focal ratio). The major axis of the diagonal is 93 mm. We calculate the offset = (10 in × 93 mm) / (4 × 41.5 in) = 5.6 mm. This is nearly a quarter of an inch, and should definitely be taken into account.

Example B: Now let's consider a 4.25-inch mirror with a 48-inch focal length (f/11.3 focal ratio). The major axis of the diagonal is 25 mm. We calculate the offset = (4.25 in × 25 mm) / (4 × 48 in) = 0.55 mm. This is only about one-tenth the amount of the "fast" system in Example A. This tiny offset may be ignored without any noticeable consequence.

Locate the physical center of the diagonal with a ruler. Make a tiny dot there, using an ultra-fine-point "Sharpie" or some such pen. Then, starting at the physical center, measure the calculated offset toward the eyepiece holder (away from the primary mirror) and place a slightly larger dot there. (This is the optical center.) If the offset distance is too hard to measure (e.g., less than a millimeter), it may be ignored without consequence.

Reinstall the diagonal assembly in the telescope. Using the "sighting tube" described in Step 2, position the diagonal longitudinally (Adjustment 1 on page 5) so that the marked **optical** center of the diagonal is centered as seen through the eyepiece holder. If the diagonal cannot be centered, the spider is skewed, and must be adjusted. You might have to ream out one or more of its mounting holes in order to achieve this important step.

The remaining steps serve to bring the diagonal to the correct lateral position in the telescope tube (adjustment 3), and to aim it exactly at the center of the primary mirror (adjustments 2 and 4). There are several ways to accomplish this.

Low-tech method: While looking through the eyepiece holder, use various combinations of the three adjustments described above (2, 3, and 4) to achieve perfect concentricity of the draw tube, the face of the diagonal (1 and 4), the reflection of the primary mirror in the diagonal (2), and the reflection of the diagonal in the primary mirror (3 and 2), pretty much in that order to minimize backtracking. Whatever you do, don't mess with the primary mirror or the focuser; they're already properly set!

Medium/high-tech method: Insert the laser collimator (without the Barlow lens) into the focuser. The beam should bounce off the diagonal at its optical center, not the physical center. (Use the dental mirror inserted through the front of the tube to get a good look at the diagonal.) The beam should then strike the center of the primary mirror, return to the same spot on the diagonal, and strike the center of the target in the focuser. Chances are, some adjustments will be necessary. Of the three remaining diagonal adjustments, the last is virtually independent, while the second and third are unfortunately interactive. However, an understanding of what each adjustment does will minimize backtracking.

First, see if the beam coming off the diagonal strikes the center of the mirror. If not, two adjustments (2 and 3) are possible. (Even if the beam *does* strike the center of the mirror, adjustments 2 and 3 may *still* need to be done.) In any event, adjust the aim (2) and/or lateral position (3) of the diagonal until the beam *does* fall on the center of the primary. With most spiders, aiming (2) is much easier than the lateral adjustment (3), which probably requires shimming the spider mountings with washers.

Then, see if the reflected beam coming back from the primary mirror falls onto the same spot on the diagonal. If so, go on to the fourth and final adjustment. If not, it's back to 2 and 3 again. If the returning beam strikes the diagonal too ***low*** (i.e., away from the focuser), it must be coming from too ***high*** a location; therefore, the diagonal needs to be moved laterally ***away from*** the focuser (3), and then re-aimed (2) so the beam once again strikes the center of the mirror. Keep making small adjustments until the beam strikes the center of the primary ***and*** returns to the same spot (the optical center) on the diagonal. Whatever you do, resist the temptation to "fix" things by re-aiming (i.e., ***mis***-aiming!) the primary mirror! If you do that, there won't be a right angle anywhere in your whole optical system!

Once this is done, all that's left to do is to rotate the diagonal (Adjustment 4) until the beam disappears back up the center hole in the target on the laser collimator. In fact, it is helpful when making the first three adjustments on the diagonal if it **is** misrotated slightly; this helps you see when the reflected beam is right next to the center of the hole, only a slight rotation away from perfection.

If large adjustments were necessary along the way, it wouldn't hurt to go through Step 3 (diagonal collimation) again in its entirety. This time, you might want to try it with the Barlow lens inserted.

Note that since the optical center of the diagonal was used, rather than its physical center, the necessary "offsets" have been taken care of automatically, and the field of view should be as uniformly illuminated as possible.

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The above procedures may seem like a lot of work, but most of it (including making the various tools) only needs to be done one time. It can safely be assumed that the drawtube will remain perpendicular to the telescope tube, and that the diagonal will stay in its correct lateral position, i.e., with its optical center on the optical axis of the primary mirror (and telescope tube). Consequently, an abbreviated method (see page 10) may be used confidently for all subsequent collimations.

Once the One True Method of collimation has been done, you know your telescope will be performing at its very best, and you don't have to waste countless hours "star-testing" the results, which is a euphemism for seeing just how badly misaligned your optical system is after an inferior collimation procedure.

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Relatively fast high-tech method, using a laser collimating device

Instead of tracing light rays as they enter the telescope, reflect off of the primary mirror, and are finally diverted into the eyepiece holder, this method reverses the process. Light rays are generated at the eyepiece holder and are used to aim the diagonal precisely at the center of the primary mirror; then the mirror is adjusted until those rays strike the center of the diagonal and are reflected back through the eyepiece holder.

It is assumed that the center of the primary mirror and the optical center of the diagonal mirror have been marked. Also, make sure that the optical center of the diagonal is still centered under the eyepiece holder, using the sighting tube as described previously. Alternatively, insert the laser collimator into the eyepiece holder, turn it on, and verify that the beam is striking the optical center of the diagonal, using the dental mirror to look at the surface of the diagonal.

Then, turn the diagonal's aiming screws (Adjustment 2) and its rotation (Adjustment 4) until the laser beam strikes the marked spot at the center of the primary mirror.

Finally, turn the primary mirror's adjustment screws until the laser beam strikes the optical center of the diagonal and disappears back into the center of the collimator.

If, for some reason, signs of poor collimation persist after completing this procedure, one of the assumptions on the previous page is no longer valid, and the longer method must be used.