REVIEW OF FOCUSING & FOCUSING MASKS

by H.R. Suiter

During the focusing operation a number of things happen more or less automatically. Typically, one relies on eye-hand coordination to move from a defocused image on one side to an equally defocused image on the other side of focus. Splitting the difference, the hand comes to a reasonable compromise position in-between. Lastly, most eyes are capable of focus accommodation to fine tune from the compromise position. As long as the apparent position of the image is within about 300 mm to 1 m away from the eye, the resulting focus locks-on comfortably. This demands an accommodation of 3 diopters, a situation that prevails until middle age, where loss of near-focus goes by the name *presbyopia*, or "old-sightedness." When one exceeds 45 or 50, or if cataract surgery has been performed, even visual observers can use a little help.

What we've already noted for visual observers goes with even greater emphasis for cameras. Cameras have zero accommodative power. They have to rely on geometric or diffraction depth-of-focus (DOF), whichever is greater.[1]

Geometric DOF

Look at Figure 1, which depicts the geometry used to calculate the geometric depth of focus. The little square viewed from the side is a single pixel. Note by equal triangles, *f*/D = DOF/B, where B is the size of the maximum tolerable circular blur. It is common to define the maximum B as the pixel period P.

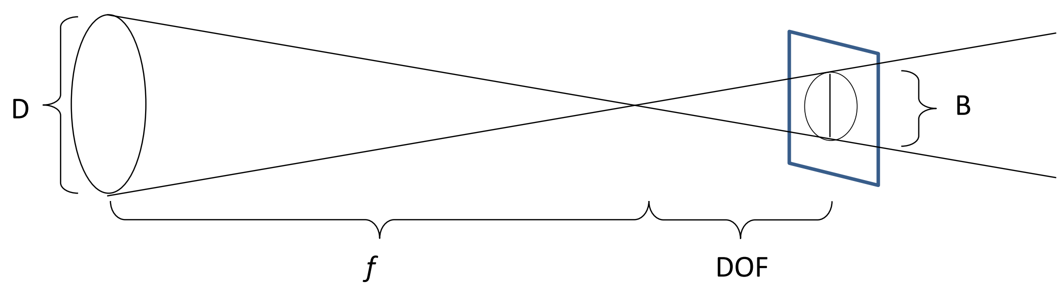

Figure 1. Method used to calculate the size of geometric blur.

Note that *f*/D = F, or the aperture ratio. Thus, for DOF much less than *f* :

$$DOF = F\,B \sim F\,P \qquad (1)$$

If the aperture ratio is the middling value of 8 (halfway from the typical *f*/6 Newtonian and *f*/10 Schmidt-Cassegrainian) and the pixel period is 10 μm, then one side of the DOF is 80 μm. If we envision the tolerated error in focus on the other side of the pixel, we get another defocus the same size.

Diffraction DOF

Using an expression from Appendix E of Ref. 2, and setting the tolerance to 1/4 wavelength, one gets the equivalent expression to Eq. 1, only for diffraction instead of geometry. It doesn't involve pixel period.

$$DOF = 2\,F^2\,\lambda \qquad (2)$$

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[1] Sometime "DOF" is used to denote the closely related "depth of field," which is derived from using the thin-lens equation to calculate the corresponding focus conjugates of the distant view.

[2] H.R. Suiter, *Star Testing Astronomical Telescopes, 2nd Ed.*, p. 372, Willmann-Bell, 1994-2009.

For the same *f*/8 aperture ratio and the color yellow-green, we get DOF = 128(550) nm =70.4 µm, or basically the same value. This happy convergence relies somewhat on luck, however. Faster aperture ratios are dominated by the geometric DOF and slower apertures tend toward the diffraction DOF.

Notice that *both* sides of the DOF for the *f*/8, 10 µm-pitch pixel add up to only about 160 µm, or $1/6^{th}$ mm (0.0065 inch). Small as it is, that is huge compared to an *f*/2.5 Schmidt camera that I used a long time ago. The actual focal-plane resolution with some emulsions was somewhere around 200 line-pairs/mm, so it had to be focused within 0.001 inch.

Let's look at a focusing sequence and see what can be made of it. Using a monochromatic Fourier transform model written in Matlab,[3] one can generate the sequence for a perfect circular pupil in Figure 2.[4] Contrast has been manipulated but still a hint of the dimming of illumination that comes with defocus has been allowed to show through.

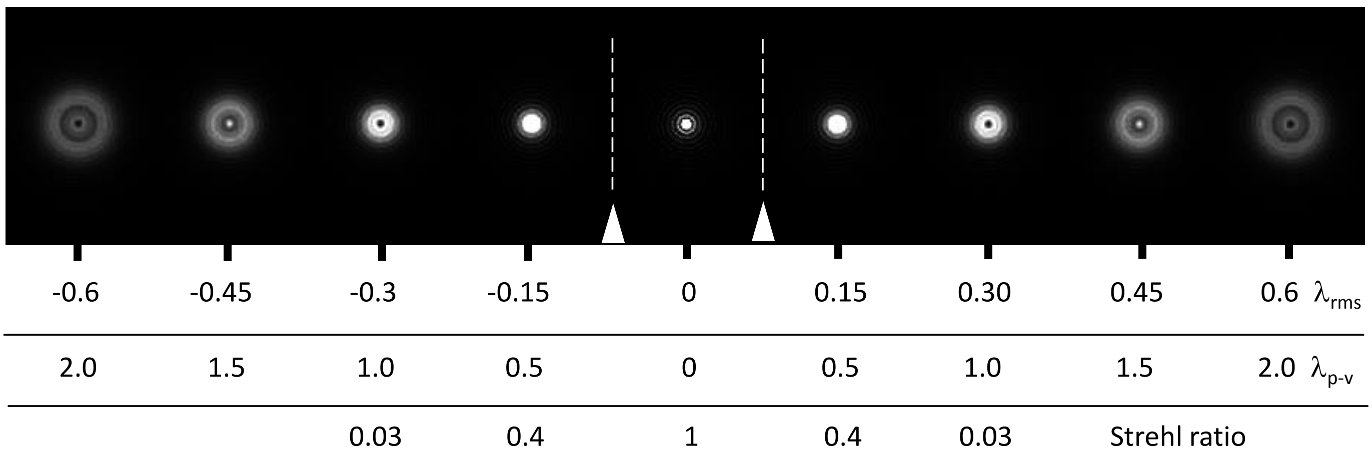

Figure 2. Diffraction patterns for a perfect unobstructed circular pupil.
Three different label strips are applied at the bottom.

We are trying to focus within the region denoted by ±0.075 wavelengths RMS (root mean square) phase change from center to edge, which is roughly equivalent in the case of defocus to ±1/4 wavelength P-V, and a Strehl ratio drop to 0.8 (the tolerated zone is marked by isosceles triangles and dotted lines). It is this Strehl ratio of 0.8 that is the classical definition of "diffraction limited."

The Strehl label shows just how badly the image falls apart with defocus. Actually, the calculation of the Strehl ratio itself is based on an approximation[5] that becomes uncertain when Strehl ratio is much below 0.1, but you may be certain that you don't want your optics defocused that far. I haven't even labeled it out to the edges. This diagram is calculated out to two wavelengths defocused, which is farther than used for the rest of the diagrams below. I wanted to show the way most of us focus. For our *f*/8 example, the left side of the sequence to the right side is about 1.1 mm. We wiggle the focuser and try to decide its center.

The actual appearance of the star is not as rock-hard as in the sequence. Atmospheric turbulence causes the tight patterns to jump around and they may be too bright near focus. That leads to the next trick used in focusing by experienced observers. Use dimmer stars. A threshold star can be forced to vanish with a little defocus. Bringing it to its brightest aspect, it will be close to focus.

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[3] Suiter, p. 344.

[4] Even though all of these patterns are calculated for one color and depicted in black-and-white, there is little to be learned from doing a "pretty" full-color calculation. I calculate one color pattern later, where it does matter.

[5] V.N. Mahajan, *Jour. Opt. Soc. Amer. 72* (9) 1992.

MASKING

By masking off some of the aperture, one hopes to convert some of the radiometric (or "brightness") information into easily recognized geometric information. The ideal situation would be one that did not require rocking of the focuser, but displays the defocus in a single image.

A simple-minded way of attempting this is to imagine the rays originating from an off-axis circular pupil. Such a mask mimics an off-axis pupil, and so would hardly be expected to provide any additional geometric detail. In addition, it would have about 9 times the diffraction DOF appearing in Eq. 2 above.

But what happens if we duplicate the hole on the other side, as in Figure 3? At the focus, we would see only an enlarged spot. It seems apparent that we can use this to measure defocus only if the two apertures begin to break apart inside the focus tolerance defined for the whole aperture. This is by no means guaranteed because of diffraction spreading of the spot.

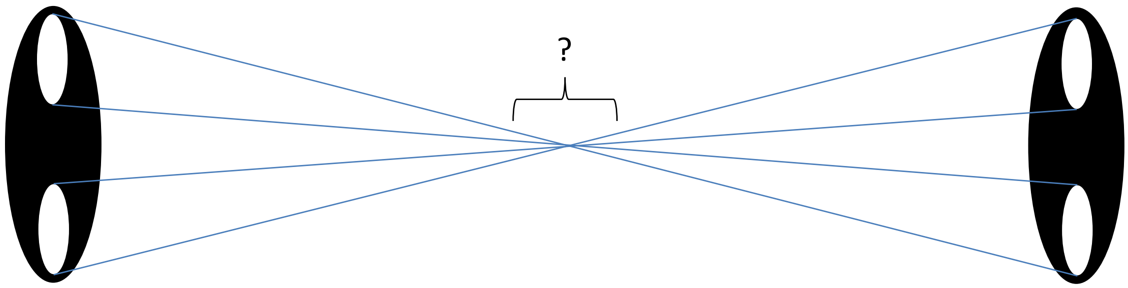

Figure 3. A crossing mask resembling two large holes in the Hartmann test.

Using the Fourier transform diffraction model in the Appendix, we calculate the behavior of this crossing in Figure 4. Let's unpack this image to reveal all of its information. First of all, the desired full-aperture pattern is seen to the right side of the mask. Next is a set of puffed-up diffraction patterns, with the Strehl-ratio tolerance edged by narrow white triangles. The duality of the pattern becomes obvious at a RMS deviation of 0.15 wavelengths (i.e., Strehl ratio = 0.4) and even more obvious at RMS deviation of 0.225. The patterns are crossed by interference lines, which are real effects and not pixelization, but different colors mix these somewhat.

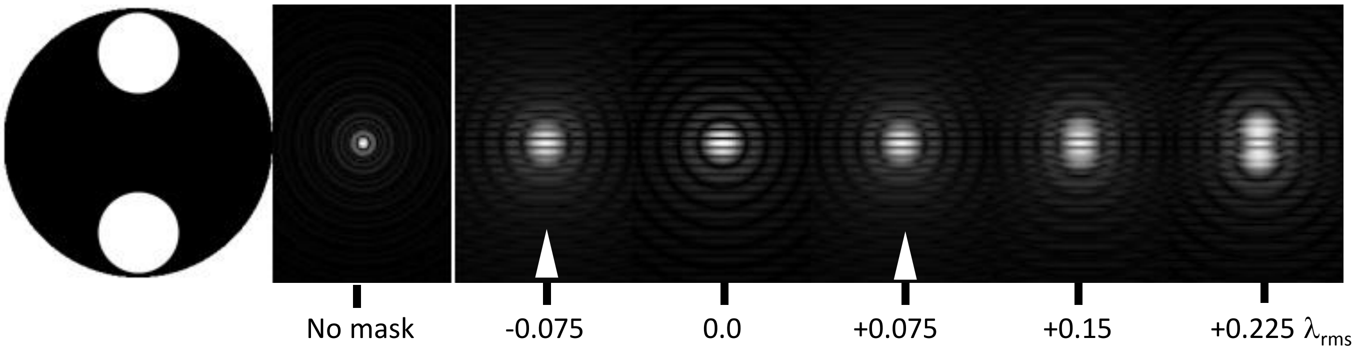

Figure 4. A two-holed focusing mask, called by some a Hartmann mask, and by others a Scheiner disk.
The Strehl-ratio ≅ 0.8 limits are indicated by triangles. Intensity = Io + 3.7 magnitudes.

This mask is fine for focusing a photographic instrument if you can read a position scale. When I first made one of these masks (in 1979), observing buddy John Kerns and I were using it on the Perkins Observatory's 16-inch *f*/2.5 Schmidt camera (*f* ~ 1 m) where the focuser read off in thousandths of an inch.[6] The tube was made of plain steel, and expanded or contracted with temperature. Most times – if the telescope hadn't been disturbed – we just

[6] This instrument has since been moved to Lowell Observatory near Flagstaff AZ where the film/plate-holder focus has been swapped for a digital one (presumably wrapped piecewise around a sphere or field-flattened).

took the proper focus from a pre-measured chart, and tried an exposure with this "book" setting. When focus seemed to unpredictably shift, we would take a series of likely exposures, with John changing the focus micrometer by 0.001 inch and deliberately bumping the guiding paddle between exposures. My job was up at the end of the tube gently covering the aperture instead of flipping the shutter doors. After passing through the region where focus was probably contained, we would take the plate inside and develop it in a tray. By selecting the two images resembling a clear and equal split on both sides, we would divide the total difference by two to estimate the best focus. Plotting the micrometer value on the temperature chart would show if focus had wandered from the predicted value. We had to be extremely careful to always change the focuser in the same direction, because of the gear slop in this (or any) system.

This method is unlikely to give a very good focus by eyeball. Trying to adjust within the slightly oval appearance of ± 0.075 waves RMS is very difficult to do, and the observer is often reduced to rocking the focuser to greater distances again. It is slightly better than no mask at all because it does display duality if defocused far enough, but the advantage is slight.

A three-holed version of this mask became available commercially a number of years ago. Its advantage over the two-holed version is not apparent, other than the questionable advantage to the maker of greater likelihood of patent protection. A theoretical description using the same model results in Figure 5. The image displays only subtle variations even out to a RMS deviation of 0.15, and even then any differences are difficult to see. The fact that I can no longer find this mask sold on the web, I take as additional evidence that it didn't work very well. It seems to have been modified by the seller to a variant of the Bahtinov mask to which I will discuss later.

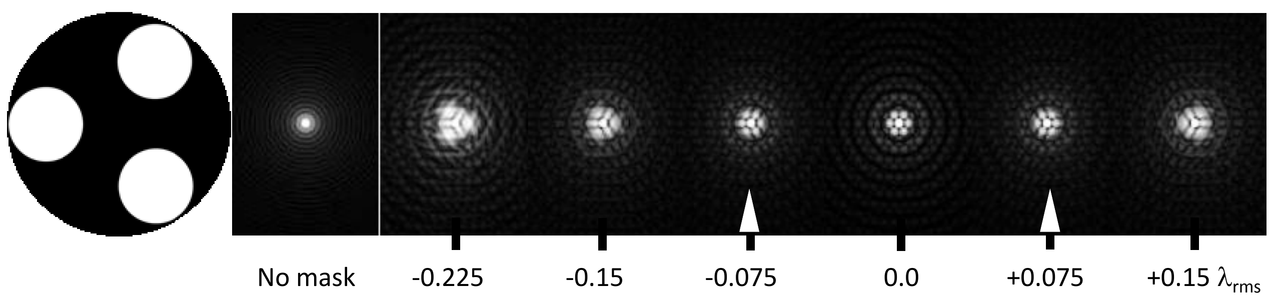

Figure 5. Three-holed version of the Hartmann/Scheiner mask. Strehl ratio = 0.8 indicated by triangles. I = Io + 2.4 mag

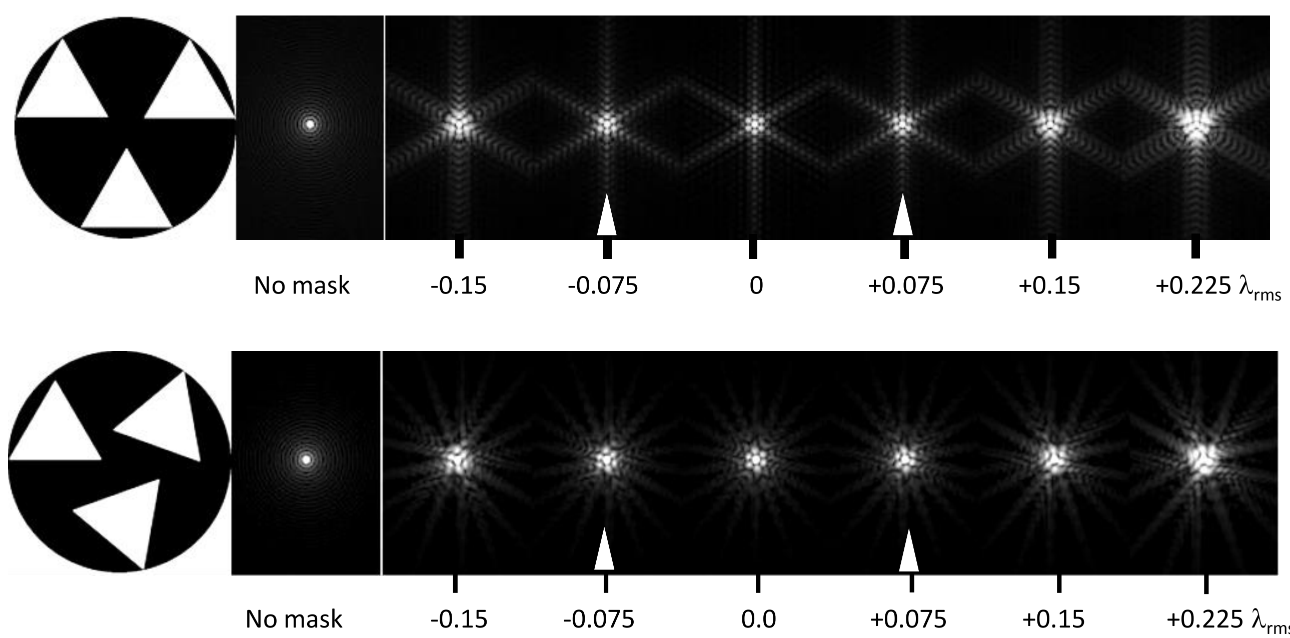

Figure 6. Two triangular three-hole patterns. Strehl ratio = 0.8 indicated by triangles. I = Io +2.7 mag

Another version of this three-holed mask exists in making the holes triangular, either aligned or in the case of some masks I've seen, skewed (see Figure 6).

These do show a slight improvement on Fig. 5 performance of the triple round-hole mask. There are more diffraction artifacts in the form of spikes, but they do not move much and may be viewed as only incidental. The aligned mask seems somewhat superior in that it more easily displays a mirror reflection beyond RMS focus deviation of 0.15. The skewed one is a hopeless jumble.

A two-holed mask can be designed to provide a distinct diffraction artifact very close to focus. It is a crossed pattern that is balanced left-to-right only at focus, with oppositely directed protrusions even at RMS deviation = ±0.075. I first saw it at Ref. 7, but the Bahtinov forum group also mentioned it. See Figure 7. The exact shape of the two rectangles may be adjusted for tuning the appearance of the focused pattern.

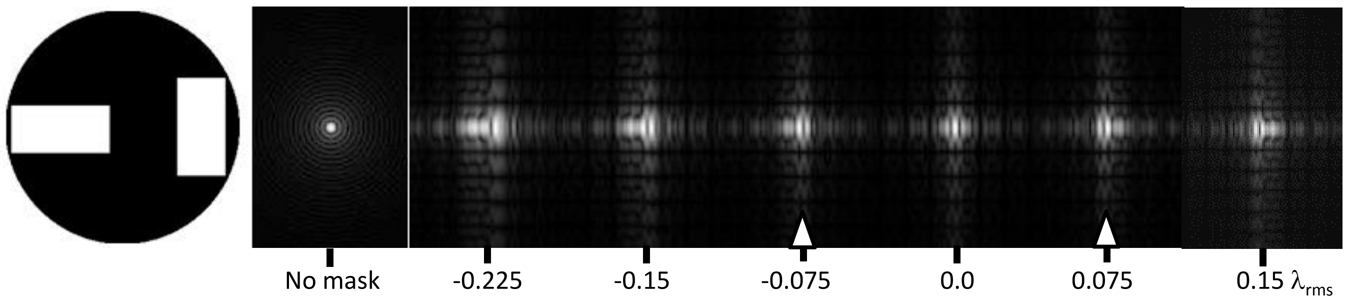

Figure 7. An easily-made center crossing mask. I = Io +3.3 mag

BAHTINOV-TYPE MASKS

Just now becoming commonly known to the U.S. amateur, but long known in Russia is the Bahtinov mask.[8] It was invented by Pavel Bahtinov[9] at least as far back as 2005, and possibly earlier. It is a bilateral pattern designed to induce desired diffraction artifacts. It has two important features:

1. It has more edges cut into it, so the amount of spike diffraction is greater.
2. It is periodic and covers much of the aperture, so the diffracted light appears concentrated into compact side images.

Feature #2 is important and is often neglected by those who write about the mask. In the astronomy forum of reference 8, Bahtinov comments that the balance of first-order spots were a lucky discovery. Most subsequent people, particularly Western adherents, have been overly enamored of the spikes, which seem to move across the image. Relying on spikes severely reduces the number of acceptable stars you can use as focusing targets (at least visually). Concentrate rather on the first-order diffraction spots.

There are a couple of parameters in the classic Bahtinov mask, the pitch or periodicity of the cuttings, and the angle between the two tilted regions. The masks that seem to be made most commonly has a period of about 2 cm and an angle of 30 to 40 degrees. One such commercial mask appears as it was processed by the Matlab model in Figure 8, and the first-order image is marked by yellow ovals. Focus is best when the three first-order images are balanced.

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[7] http://www.astro-photos.net/fokussieren.html in German. This site is undated, but is likely to be old, as it neglects the Bahtinov mask until a note is tacked on at the end. Use Google Translate, or just skip the text and view the pictures, which are largely self-explanatory.

[8] https://astronomy.ru/forum/index.php/topic,10421.0.html

[9] Google transliterates it: "Bakhtinov," but I continue with the common spelling.

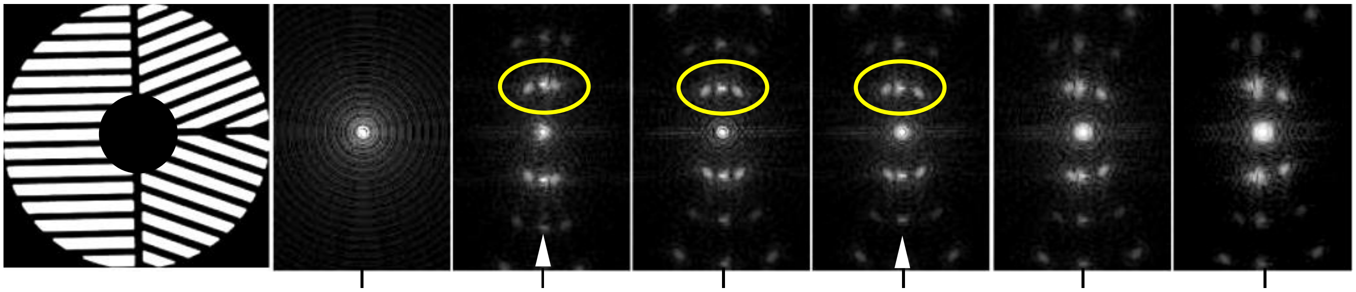

Figure 8. A commercial-type Bahtinov mask. Concentrate on the yellow ovals for focus information. I = Io + 1.4 mag

Hand-cutting smooth-edged strips in a stiff piece of plastic or cardboard is difficult. Is there any other way of performing this operation at home? I found that as long as I was willing to tolerate a little less transmission and some extraneous diffraction structure, I could make a mask out of three pieces of rectilinear *plastic mesh*. I could not locate a readily available mesh with period as large as the 1 or 2 cm of the Bahtinov masks I have seen on the web, so I lessened the angle between the two tilted portions. I made this a 1/7-inch period mesh with an angle of 10 degrees. After observing that the 10° mask spots are a bit tight. I made another on the same frame at 20°.

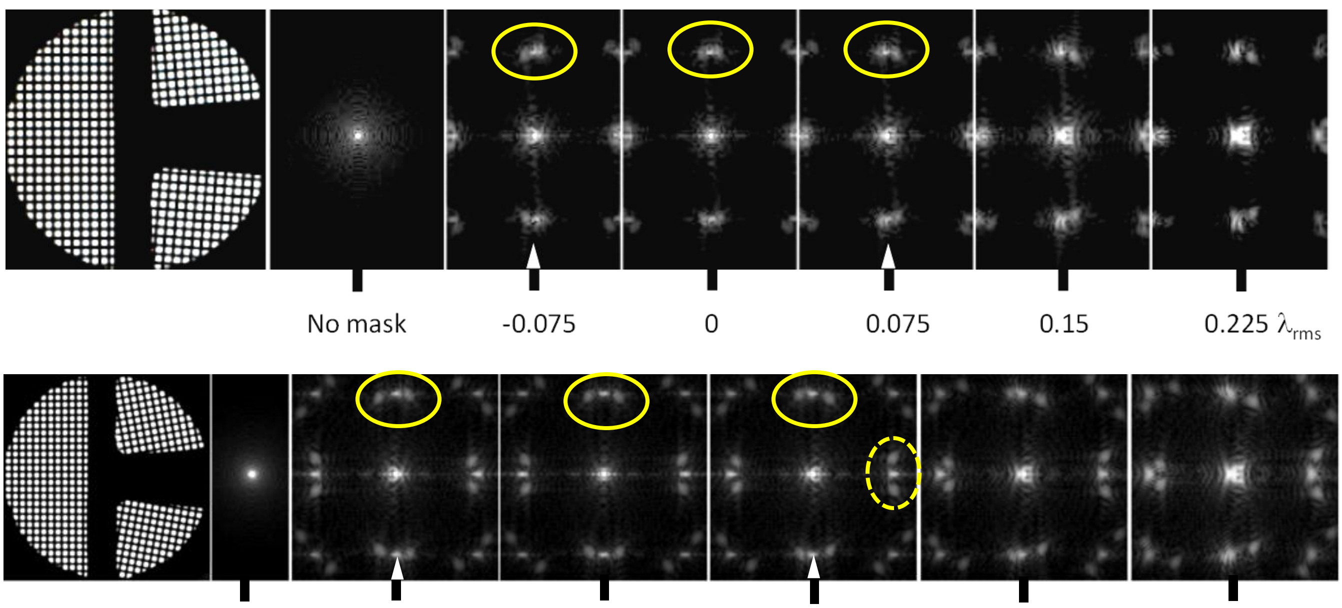

Figure 9. Bahtinov masks made by cutting out pieces of "plastic canvas" mesh: (top: 10°, bottom: 20°) I = Io + 3.1 mag. The solid ovals circle the part of the pattern that shows the imbalance of defocusing. The dotted line points out an internal check at 90° to the main pattern. If these dots are not balanced perfectly, then the mask has been assembled with an error.

The mesh mask works acceptably if directed toward somewhat brighter stars. It diminishes the central star by another 1.5 magnitudes beyond the intensity reduction of the 1-dimensional grating. Only the up-and-down direction parallel to the central bar displays the Bahtinov behavior of off-center spots. Far from being a work around, this extra structure has a purpose. If the mask has been made with side regions placed at the wrong angles, it shows itself as an imbalance of the diffraction structure at 90 degrees to the main defocusing pattern.

The next mask will make more sense if one remembers the spots are smeared into stubby spectra. On the same 2006 Russian astronomy forum used to discuss the Bahtinov mask (and about the fourth page down), Andrei Oleshko suggested putting bars of one spatial frequency on half of the mask and a different spatial frequency on the other. The bars remain parallel; one doesn't need to tilt them. The result is modeled in Figure 10.

Remember, each of these off-axis spots is smeared into a spectrum. Thus, the blue end of the outer spot may be just outside (or on top of) the red end of the inner spot. If one adjusts the spatial frequencies of the mask just right, interesting color mixes might arise from the spectral overlap. Even if there is no color mixing, consider the significant misalignment of the spots right over the ±0.075 DOF tolerance.

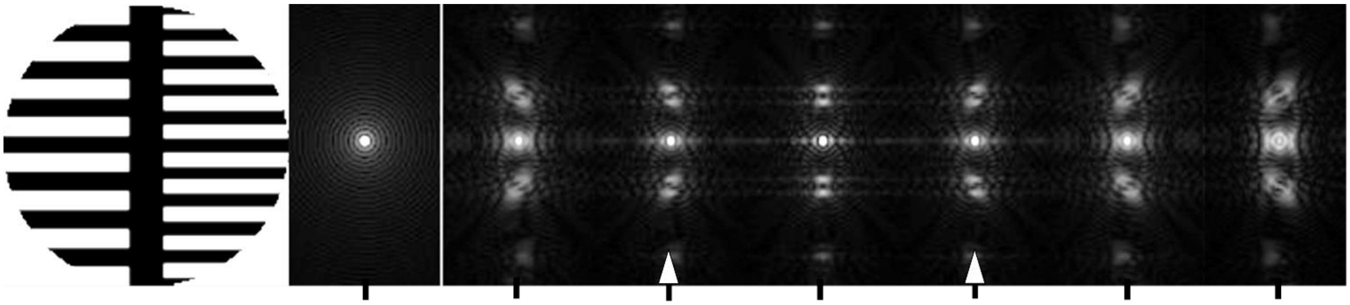

Figure 10. One dimensional two-spatial-frequency mask in only one color. I = Io +1.8 mag

It was said in a footnote at the beginning of this article that little point of going through the additional effort to simulate a color image. Nevertheless, it should be done once for this particular mask to demonstrate the alignment of the spectra. I made one of these out of 5-count and 7-count plastic canvas mesh (described later in the "Making" section), and took an image as input to the model. The results are shown in Figure 11 for spectral values taken at a difference of about 20 percent between red and blue. This spread simulates the response of the photopic visual spectrum. Labeling is somewhat different because the RMS wavefront deviation varies for blue and red. This model is only for three colors and weighting variables are involved. Nevertheless, in actual use it demonstrates the modeled behavior surprisingly well. In fact, I could watch the spectra wiggle left and right between inside and outside focus as the air turbulence cells swept over the aperture. Notice how the sideways spectra of the mesh are useless for focusing, but still serve to check the construction of the mask.

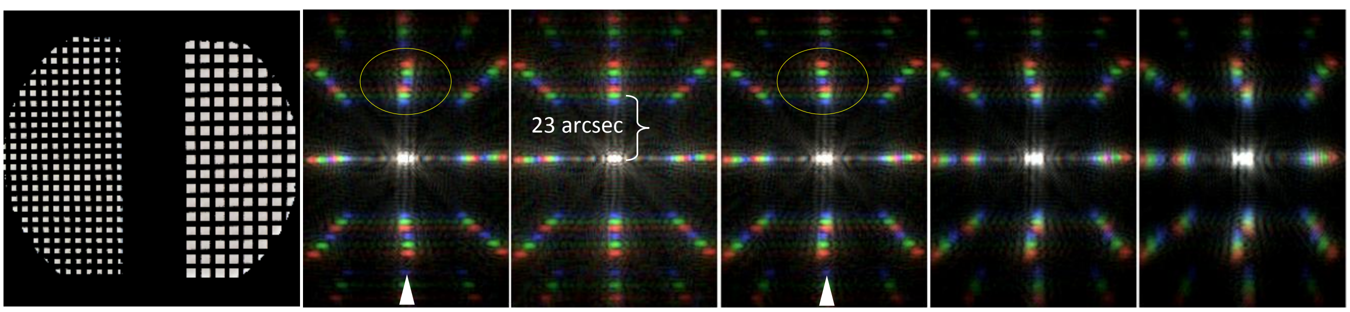

Figure 11. Oleshko mask.[10] Three colors are modeled with a 7-count mesh set next to a 5-count. The aperture is 100 mm. Actual spectra are smoother and less spotty. I = Io +3.3 mag

This focus tool seems to be very sensitive. However, it requires more effort to manufacture a specially designed mask to arbitrary user specifications. I estimate that optimum coarser period is required to have 60% to 80% the spacing of the finer one. I used the 5 per inch and 7 per inch spatial frequencies of the plastic canvas only because they seemed to be about right and existed ready-made. This mask certainly deserves more investigation.

There was some material on both the German website and the same Russian astronomy forum that discussed Bahtinov masks about Y-shaped masks. These are just Bahtinov masks without periodicity and without much transmission either. Because of the lack of multiple periods, they tend toward focusing on very bright stars with the spike alone. Figure 12 shows an example displayed with especially low contrast so the diffraction spike will show. The "spray nozzle" is a configuration that I designed to transmit more light in the zeroth order. Y-shaped

[10] http://www.oleshko.net.ru/notes/focusmask.shtml (get fundamental site in translated Chrome browser, and drill down on sidebar)

masks will work acceptably as long as the target is bright enough (visually) or is taken with a longer exposure (photographically). If star is too dim, the user struggles to see the spike.

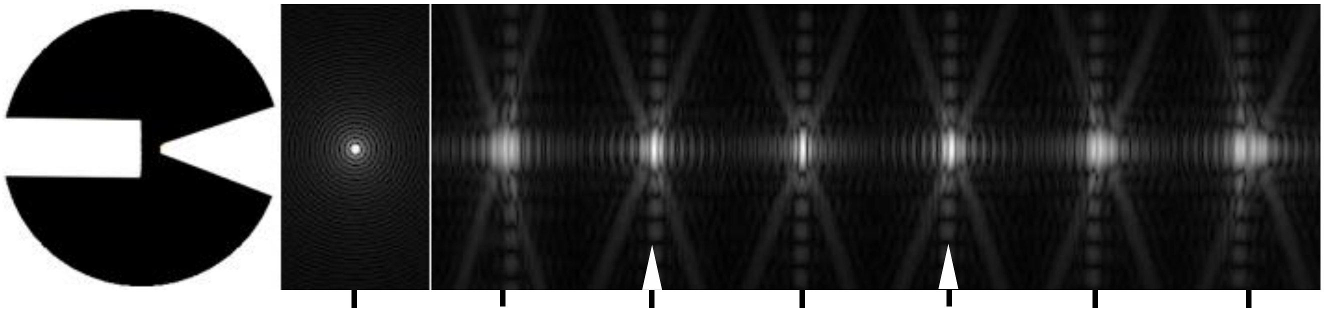

Figure 12. "Spray nozzle" mask produces just spikes. First-order spots don't show as well. I = Io + 3.2 mag

GRATING PERIOD

We can calculate the radius of the mesh diffraction by looking at Figure 13. Each diffraction grating location corresponds to the same phase in the next period if the delay is exactly nλ, where n = 0, 1, 2 etc.

Here P is the grating period, λ is wavelength, and θ is the angle of the diffraction phenomenon. You can slide the triangle anywhere in the opening and if the short end is equal to $n\lambda$, it is still a maximum. Let's choose n = 1 and calculate the angle of diversion.

$$\theta = cos^{-1}(n\lambda/P) \cong n\lambda/P \text{ for small angles.} \quad (3)$$

so $\theta = \lambda/P$ = 0.00056[mm] /20 [mm] =2.8e-5 radian → 5.8 arcseconds. Thus, if Figure 8 has a 20 mm period, the little ovals are 5.8 arcseconds from the center of the pattern. That is about twice the separation of each of the epsilon Lyrae double-star components, so it is a bit too small to see the first-order spots at prime focus. Many high-end refractors have a Bahtinov mask included with about a 1-cm slit period. The first order of a 1-cm period is at 11.6 arcseconds; this is larger than the spacing of coarse hand-cut masks, but still difficult to see in the presence of pixel sampling.[11] Such coarse masks must be intended only to produce spikes, because the spots are too close.

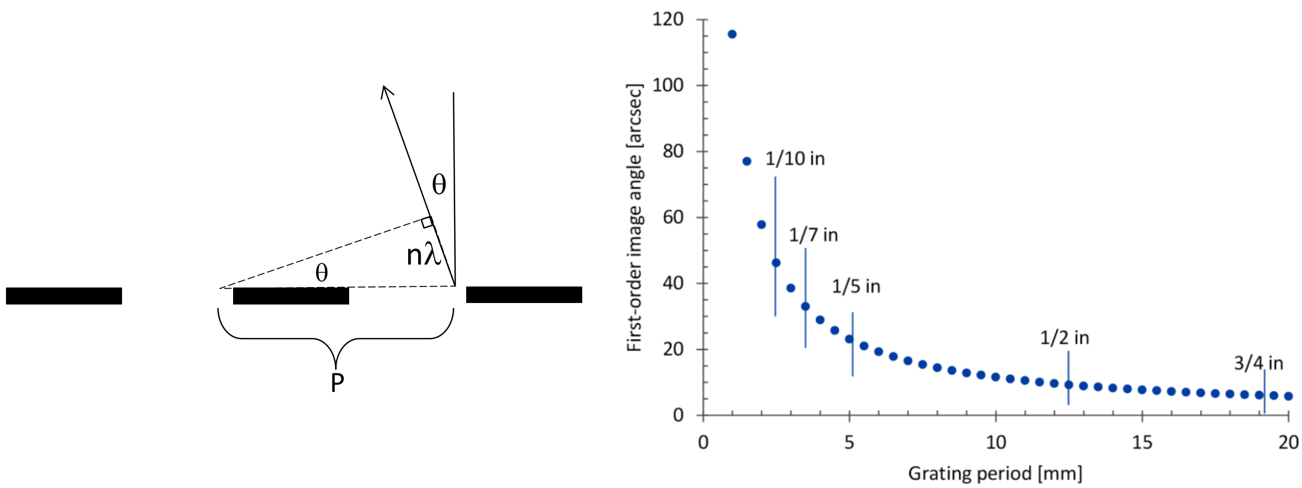

Figure 13. Geometry of a diffraction grating and angle to first-order image using a central wavelength of 560 nm.

[11] For example, a 125-mm *f*/7 astrograph has an image scale of 0.24 arcsec/µm; thus, each 10 µm pixel covers 2.4 arcsec.

My small plastic canvas mesh had 1/7-inch periods = 3.6 mm. The yellow-green wavelength divided by the period is 0.00056[mm]/3.6 mm, so the first dots appear at 32 arcseconds or 1/2 arcmin from the center of the pattern. That is somewhat larger than the radius of the planet Jupiter when it is closest to the Earth, so the pattern still requires high magnification.

MAKING AN EASY PLASTIC-MESH BAHTINOV

Of course, the definition of "easy" varies among people. Let's say this is fairly easy for any telescope maker or hands-on amateur astronomer to make at home. More importantly, it's inexpensive and quick. If you don't like the mask, you can make another. First of all, measure your aperture and tube. Buy a set of small nylon screws and nuts; make them one inch or longer. We want nylon because it offers loose mounting grips with no risk of scratching the tube or optics. If you can remove the dewcap easily, pull it off. My Maksutov’s dewcap is attached to the end of the tube loosely and hangs on the scope like a slightly tilted hat. If I were to try to suspend a mask way out at the end, it would not be centered on the aperture.

Go to a crafts store and obtain a few sheets of black 7-count plastic canvas. The particular sample appearing in Figure 14 has the good characteristic of square holes. Alternatives plastic meshes can be envisioned and could be made, such as some sort of plastic outside an array of circular holes. Spikes would be suppressed in that configuration, although the side-spots would still be visible. Some plastic canvas makers sell a 5-count mesh, always clear or translucent,[12] but it is harder to find. If you don't already have it, obtain some good sturdy packing tape.

The backing sheet for the little Maksutov's mask was 1.5-mm thick cardboard. If you are making a mask for a larger telescope, you may want a thicker board for stiffness, but don't overdo this. This mask will probably not be your final one. When you are satisfied with the design you can make a finished, more permanent version. With a thinner board I could still use a paper punch to make the holes (blue circles) for the mounting posts.

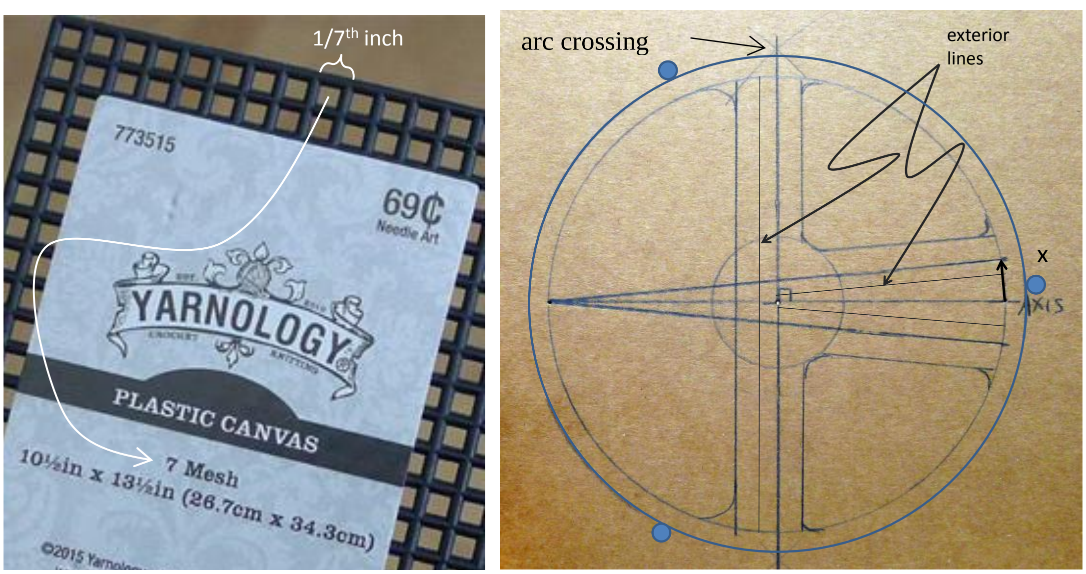

Figure 14. (L) Example crafts plastic canvas with a 7 per inch period. (R) Layout diagram for the 10-degree pattern

Lay it out like the Figure 14(R) example. I have two circles, one at the diameter of the tube, and the second the diameter of the aperture. Draw an axis line through the left edge of the aperture and the center. Use Euclidean compass methods to construct a perpendicular line using as compass centers each end of the axis line where it

[12] The translucent mesh would damage the effectiveness of a focusing mask only slightly. Any light that comes through the mask is so diffuse that it is hard to see and focus. It is largely beyond the field of view.

crosses either the tube or the aperture circle. Figure 14(R) uses the aperture circle. See the little arc-crossings; connect them.

Now you have a set of concentric circles crossed by two perpendicular lines. Take half the angle you want to use between the tilted patterns, and figure out the length of the stubby arrow, denoted "x" in Fig. 14(R). The value was 8.8 mm for my angle, but as I've said above, later remade the split to be 20° rather than 10°. Connect the first tilted line, and measure x again. Now, go in the opposite direction and make another mark, matching it to the measurement rather than the theoretical value. It is more important to make this angle equal and opposite to the excursion on the other side than to match a value that you pulled from your hat. Geometric equality will make those first-order spots line up.

Next, scribe one or more "exterior" or "registration" lines parallel to the perpendicular and the two tilted lines. You may not need these, depending on details of your particular mask, but if you do you will be glad they exist. I could not simultaneously tape my meshes on (keeping the tape out of the optical path) and align them on the original lines, so I found them handy to perform registration of the mesh.

It is time to cut your holes. As is apparent from Figure 15(L), I was not precisely on the lines.

Finally, cut out your pieces of mesh, reserving the uncut, straight outer edges of the plastic for placing against the registration lines. While it is possible to see past a cut edge, the breakup of the line makes it more difficult. Start the mesh too large and work your way in, shaving a little off at a time. Try to remember that the tape must perform the following tasks:

a) cover the edge of the mesh,
b) stay out of the optical path, and
c) hold enough of the cardboard to remain attached.

Do not be surprised if you have to recut pieces of mesh a couple of times. Go back to Figure 14(L) and take comfort in the price in the corner of the label. That is why you were asked to obtain a few sheets.

The result in Figure 15(R) will appear from the bottom to be sloppy. It does not matter and will not show. After you have everything together, cut or punch the mounting holes.

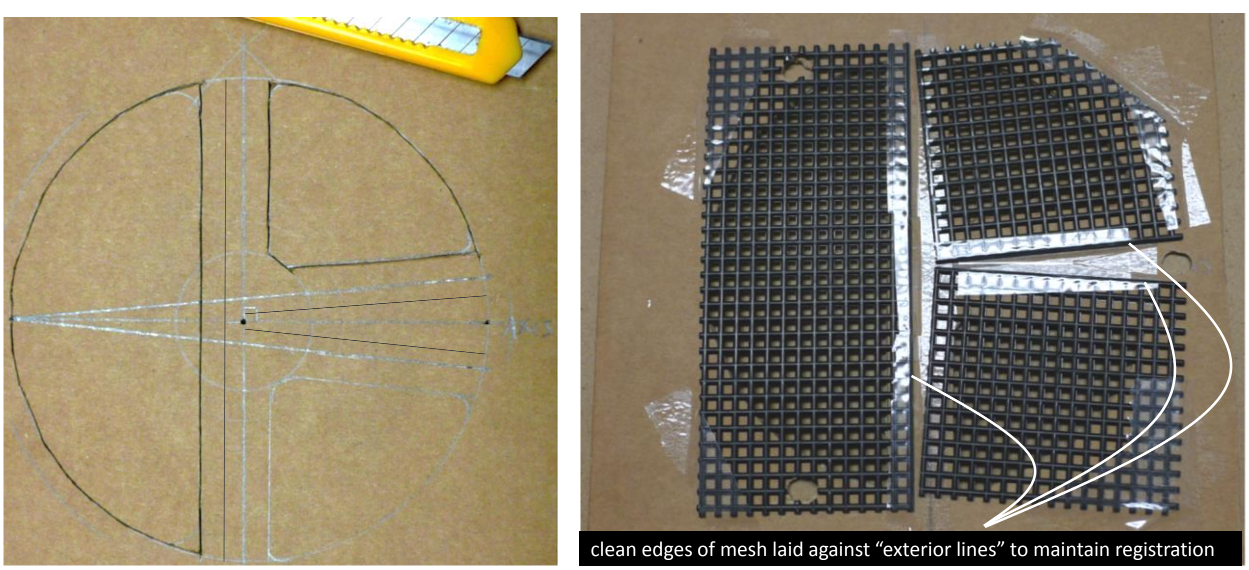

Figure 15. (L) Cutting out the holes. (R) The underside of the mesh Bahtinov.

Assembling the holder screws, we see the completed mesh Bahtinov from the front in Figure 16(L). The screws don't attach to anything on the telescope. They merely rest lightly on the outside of the tube. If the telescope is pointed anywhere above the horizon, the mask will remain on the front. Figure 16(M) is a photo I took against a uniformly-lit surface, and Fig. 16(R) is the same photo trimmed to 256x256 with the contrast greatly increased to feed to my model (for more information, see the Appendix posted under the Telescope Making section of www.bay-astronomers.org). Figure 9 is the theoretical performance of the actual mask photo of Figure 16. The action on the sky is very similar, except for spectral effects.

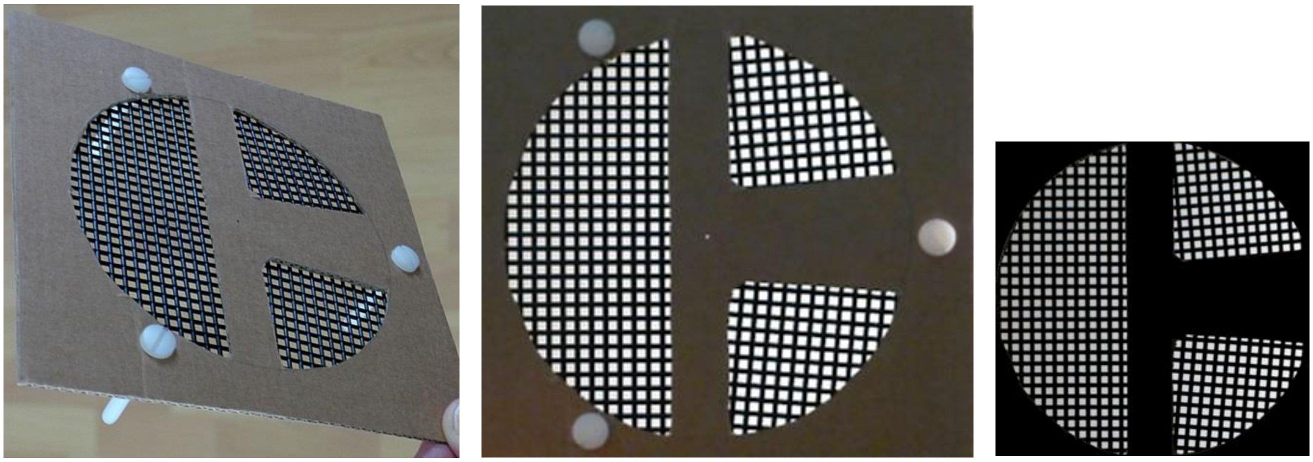

Figure 16. (L) The completed 10° mask, (M) Photograph of transmission, (R) Image prepared for model input.

Another trick that should be mentioned is the method of hiding the rough edge of a cutting, where that edge shape is intended to participate in the diffraction behavior we are looking for. No matter how one tries to smoothly cut a straight edge, the use of hand tools to slice the hole through the backing plate tends to produce rough surfaces that diffract in different directions. My answer is to merely cut a rough hole too large and cover the edge with a straight line. I cut strips from the edge of a plastic classroom folder to provide smooth edges in Figure 17(L). The use of side registration lines is helpful to maintain alignment here, too.

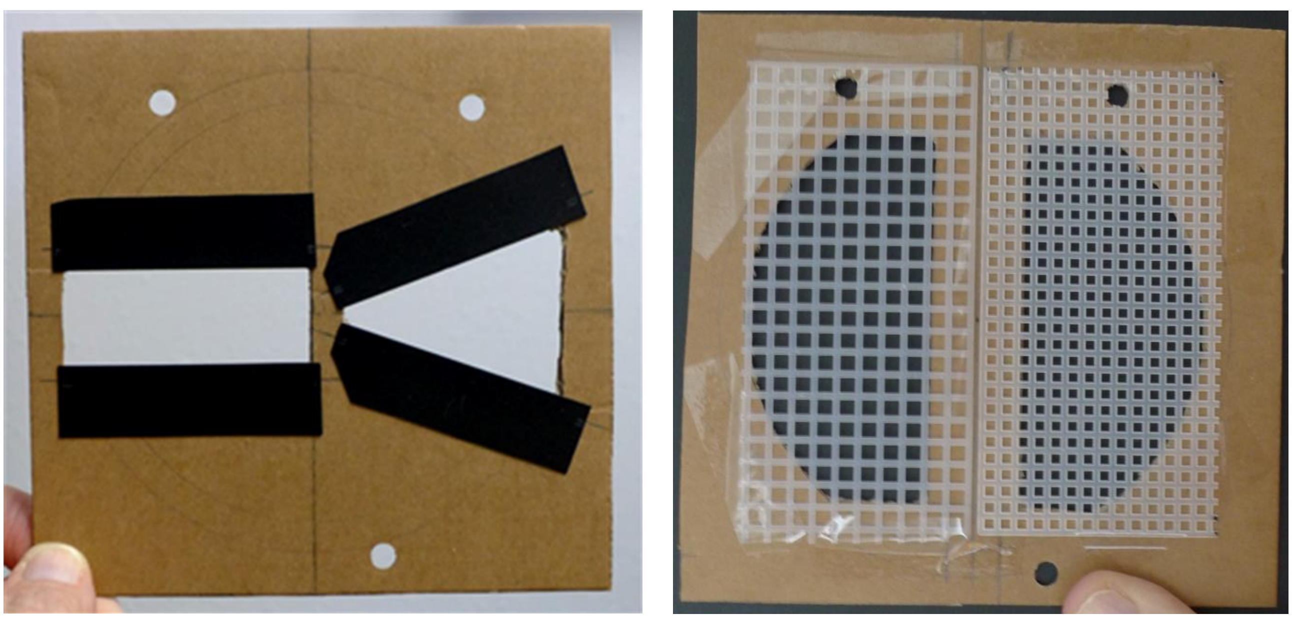

Figure 17. (L) Using straight pieces of plastic to hide the rough edges of hole cuttings (spray-nozzle mask).
(R) The two-frequency mesh mask is easy to align with only one reference line.

MECHANICS OF FOCUSING

Gear slop and other mechanical limitations in focusing have already been mentioned. For astrophotography, there is a discipline you have to get accustomed to. One direction of focus suspends the focusing barrel above a small gravitational fall, a kind of settling-in place. The other direction moves the focus in the direction where this fall has already taken place. To do focusing properly you have to learn which directions these are and always make your final focus from that direction where the focus is unlikely to shift randomly. (This effect is very common with rack and pinion or helix focusers but it is also seen in mirror-focusing catadioptrics.) Try to not move your optical tube much between the focusing on a bright star and the final view because you may shake the focus setting off its perch.

If your focusing tube can make a sort of lateral wiggle, you may not be able to focus critically at all. Try to obtain a kinematic-mount focuser, i.e., one that doesn't have too many bearing surfaces. A classic example of a kinematic bearing is the stiff four-legged bar-stool that seems to always rock on even the smoothest floor, whereas a 3-legged stool will sit firmly on the roughest ground. The Crayford focuser is formally kinematic (5 bearings, 6 degrees of freedom, leaving only the focusing direction movable), but so are other quality focusers.

Depending on your focuser, there may be a locking screw somewhere that prevents the eyepiece barrel from moving. If there is not, that is something that you should really add.[13] At the end of the focusing adjustment, tighten this screw and recheck the focus.

Get a motorized focuser, preferably one that reads out its position. My 10-inch is a pleasure to focus with a motorized focuser (it doesn't indicate position, though). I look into the eyepiece and can follow the changing focus without the tube shaking because the electronic control is attached to the focuser by a loose cord. Unless you are using a very slow optical system, you will find motorized focusing to be much easier.

And finally, remember that most tubes and optics expand and contract with temperature. There is a severe multiplier effect in Cassegrain-type instruments caused by the magnification of the secondary mirror. In the common Schmidt-Cassegrain (*f*/2 magnified to *f*/10) the focus shift inherent in the *f*/2 primary is multiplied by the magnification squared: 5x5 = 25. Keep checking focus as the temperature changes.

WHAT WE HAVE LEARNED IN THIS REVIEW

Focusing masks have been suggested (and sold) that do not perform well in modeling. While it is possible that they perform well in real life, they must do so by unusual mechanisms, not by the primary method of interference. In the straightforward diffraction theory of the model, they are not as sensitive as simple open-aperture focusing. For example, the classic two-hole Hartmann mask works only if there is a way of recording the individual numerical focus setting of each trial exposure.

The Bahtinov masks work fine, but it seems the commonest implementations have much too coarse a period for their most sensitive operating mode. This could be because most Bahtinov masks are hand-cut, or perhaps people using the models such as *Maskulator*[14] have been a bit too literal-minded. They confuse easy-to-model example masks with the actual best masks. Users should get out of the habit of looking for long spikes on greatly overexposed images (or super-bright stars) and learn to use Bahtinov masks where the greatest sensitivity lies – lining up those three first-order image smears to be as evenly spaced as Orion's Belt. For that sensitivity to be attained, the side-order images should be well-resolved by the pixel spacing. This requires careful selection and placement of the period and angle of the tilted arrays as well as focal plane sampling.

[13] Unfortunately, this is something we dare not try with internal-focusing catadioptrics.

[14] *Maskulator* was a program by Niels Noordhoek that calculated full-color simulations. Sadly, it no longer seem to work with all computers.

A common plastic canvas mesh has been introduced here as a way of avoiding difficult (or expensive) cutting operations. The mesh diminishes transmission, but its ease and adaptability more than makes up for the transmittance loss.

There seem to be some under-utilized masks that until now have been held back by difficulty of manufacture. In particular, the two-frequency mask of Andrei Oleshko, which appeared on about the 4th page of the same Russian astronomy forum as a common reference for the Bahtinov. The two meshes used in my example of Figure 17(R) worked very well for visual focusing on 100-mm Mak-Cass and also worked well for a later 10-inch example with motorized focuser (Figure 18). A mask that also deserves more investigation is the stubby cross-bar mask of Figure 7.

Figure 18. A 5-count coupled with a 7-count plastic mesh focusing mask on a 10-inch Newtonian in the Oleshko configuration.

