Turn the focus slightly back and forth while examining a star at high power, and even minor flaws in your telescope will be revealed. Use the computer-generated comparison images on the next few pages to judge what you see. *Sky & Telescope* photographs by Chuck Baker.

Star-Test Your Telescope

"I'M GOING to tell you a little-known fact," begins Harold Richard Suiter in his new book, *Star Testing Astronomical Telescopes.** "Telescopes are easy to test."

It's true. The hard part for most amateurs has been finding out exactly how to do it.

Optical quality has been a top concern among telescope buyers especially in the last nine years, ever since (according to folk wisdom) many poor telescopes were rushed through production in time for Comet Halley. Debates have raged about various manufacturers' quality control, as well as about how good a telescope actually needs to be. But there hasn't been much hard information to guide the winds of opinion.

That may be about to change. Amateurs have long known, at least in a vague way, about the star test. Many know that a telescope's quality can be judged by comparing how a star's diffraction pattern looks a little outside and a little inside of focus. But here too myth and confusion abound. Now, at last, Suiter has analyzed the star test in book-length thoroughness. He presents a bounty of information and instructions in a clear, practical manner never before available.

For estimating spherical aberration, you need a central obstruction that covers 33 percent of your objective's diameter. A paper disk can fill the bill.

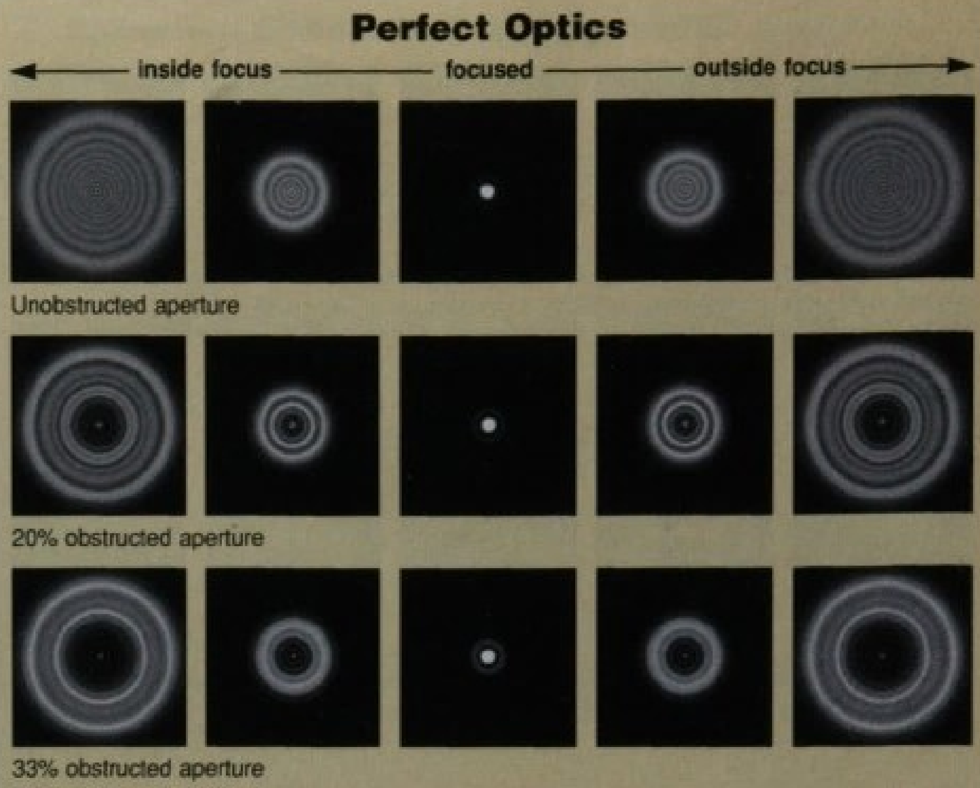
Computers made this work possible. The main reason amateurs have had so much trouble with the star test is a lack of clear illustrations showing what to look for. The tiny, shimmering diffraction pattern of a star at very high power is almost impossible to photograph and hard to draw accurately. The standard illustration guiding amateur star testers has been a single plate published by H. Dennis Taylor in, amazingly, 1891. It has been copied and recopied so many times in the last century that current reproductions are all but unreadable. Couldn't someone could do better than this?

Suiter tried a few years ago, but he was frustrated by the inability of artists to portray the diffraction patterns accurately. He decided that the only way would be to computer-generate the patterns from optical theory, then import them into a graphics file that could go to a printing

*Available for $24.95 from Sky Publishing Corp.

plate untouched by human hands.

The job was slow. Each frame on these pages and in the book took up to 2½ hours of computation time on a 50-MHz 486. "I kept the computer hot for three months," Suiter says. The result is impressive. The book displays with perfect clarity all the star-test comparison images you'll ever need, illustrating all kinds of telescope aberrations in their pure forms.



The star test in three perfect telescopes. As you turn the focus knob from inside to outside of sharpest focus (left to right in all illustrations), a star's diffraction pattern at high power should look the same on both sides of focus. Note that a central obstruction, such as a secondary mirror, not only adds a dark central shadow to the out-of-focus patterns but also adds complexity to their ring structure. Interestingly, a central obstruction smaller than about 20 percent has essentially no effect on *focused* images compared to zero obstruction, at least in high-quality scopes. Illustrations are not to scale; the in-focus diffraction pattern has been magnified several times in all cases for clarity. All star-test images are by H. R. Suiter and copyright 1994 Willmann-Bell, Inc.

HOW TO TEST

Take the telescope out in early evening and leave it long enough to cool to the temperature of the surrounding air — as much as two hours, or even more. This will eliminate most optical problems arising from thermal effects inside the telescope.

Aim at a fairly bright star nearly overhead, center it in a very high power eyepiece, and get it focused. Use a strong yellow or green eyepiece filter if you have one. Such a filter, which isolates one color near the eye's peak spectral response, is *essential* for testing a refractor, including an apochromat, or other color-corrected telescope (unless you are testing for chromatic effects specifically). A color filter also helps to clarify the test patterns in a reflector.

Ideally, if the air is calm, you will see a tiny, bright disk of light surrounded by one or two thin, fainter rings. This is the telescope's diffraction pattern for a point source of light, its fundamental resolution limit — the smallest detail the telescope can ever show. The angular size of the diffraction pattern is inescapably set by the size of the aperture and the wave nature of light.

Now turn the focuser very slightly. The star image will enlarge and grow internal rings. They should be round. Turn the focuser back the other way. As the pattern enlarges on the other side of sharp focus, it should look exactly the same as it did on the first side.

If it does, you have an unusually superb telescope and can quit right now. A perfect star test means the optical system is much better than what's often meant by "diffraction limited": having no more than ¼ wave of error measured peak-to-valley on the wavefront. (The effects of various amounts of wavefront error on planet images are explored in the companion article beginning on page 90.)

The illustration above shows the star test being done on three perfect telescopes in perfect atmospheric seeing. As you read from left to right, the focuser is being turned from inside focus (nearer the objective) to the outside. The top row displays the patterns in a telescope with no central obstruction, such as a refractor. The lower two rows are for telescopes with secondary mirrors that block 20 and 33 percent of the objective's diameter, respectively. Note that for each instrument, the images are exactly alike at equal distances on either side of focus.

Almost never do conditions allow you to see the patterns so clearly. Atmospheric turbulence, or "seeing," usually makes them shimmer, break apart, or fuzz over. Suiter's top test patterns on the next page display the effect of poor to average seeing, quality 5 on W. H. Pickering's widely used scale of 1 to 10. Clearly, atmospheric turbulence usually overwhelms the minor telescopic defects that the star test is capable of revealing in good conditions. The better the seeing, the easier and more sensitive the star test becomes.

But even on a bad night you can try a simple trick to see how excellent optics should behave. Cut a 1- to 2-inch round hole in a piece of thin cardboard and attach it over the front of the scope (off-center if you have a reflector). Aim at a very bright star. This new, smaller aperture will make the diffraction pattern larger, mask optical aberrations, and penetrate poor seeing better. Watch as you turn the focus slightly in and out. Now you know what you want the full aperture to show.

At full aperture you'll probably discover that the out-of-focus patterns are not quite the same on either side of focus. Don't panic; the telescope may still be very good. The star test is so sensitive that it will reveal tiny optical errors that have virtually no consequence in normal use, especially in average-quality atmospheric seeing.

But if the diffraction pattern is obviously very different on either side of focus, you've got a problem. Fortunately, the test will often enable you to diagnose and fix the problem on the spot.

Don't be too quick to judge a telescope harshly. Strange atmospheric and thermal effects come and go, so wait to see whether the problem persists on many nights under different conditions. If it does, and if the maker promised first-rate optics, you'll have a sound basis for complaint.

Here, then, are highlights from Suiter's field guide to optical aberrations.

DIAGNOSES AND PRESCRIPTIONS

Tube currents. First rule out currents of different-temperature air in and

Atmospheric Turbulence

The all-too-familiar effect of atmospheric seeing. These are five freeze-frames of simulated mediocre turbulence, quality 5 on the usual scale of 1 to 10 (aberrations about ½ wave peak to peak). The aperture's diameter is 20 percent obstructed.

Tube Current

The effect of warm air ducting along the inside upper wall of a tilted telescope tube, a common but temporary thermal problem.

Misalignment

The sign of poor collimation. Even though these patterns are asymmetric, they appear similar on both sides of focus. The lower a telescope's f/ratio, the more crucial collimation becomes; this is what a mere 6 arc minutes of misalignment looks like in a 10-inch f/4.5 reflector. The optical axis is to the right of the star image.

Pinched Mirror

A triangular deformity is a sign that the mirror is probably being squeezed in its cell. Loosen the mirror clips slightly to relieve the bending of the glass. Check for undue sideways stresses too.

around the telescope. The star test evaluates not just the objective lens or mirror but the entire optical system, including the air inside and in front of the scope.

Turn a bright star very far inside focus until it's a big, uniform disk. Do thin, wavy lines of bright and dark crawl or swirl across it? If so, you're looking at tube currents. They tend to move quickly in a reflector with its tube open to the breeze and very slowly in a closed-tube Schmidt-Cassegrain or refractor. To see a dramatic illustration of thermal currents, put your warm hand in front of the scope.

Often, warm air will chimney along the upper inside of a tilted tube. This produces a star test like that seen in the second row above. The dent and flare in the diffraction patterns will be aligned with the up-and-down direction across the tube front. To see which direction this is in the image, turn the star far out of focus, hold your hand in front of the aperture at the bottom edge, and see where it intrudes into the disk of light.

The cure for tube currents is simple: more cooling time. Good ventilation helps. In fact you can put a fan behind a reflector to blow the tube currents out.

Also, watch your surroundings. Don't observe over the roof of a warm house and don't set up the telescope on pavement, which absorbs solar heat all day and then produces plumes of warm air all night. Grass and bushes are a telescope's best surroundings.

Misalignment. This is one of the commonest and worst performance-killers. It's also usually the easiest to fix. Optical parts often get jarred slightly out of alignment in reflectors and, to a lesser extent, Schmidt-Cassegrains. The star test tells you how to tune up, or *collimate*, the telescope by turning adjustment screws to square up the optics. (Of course, the optics need to be at least roughly aligned beforehand.)

The series of star-test patterns depicted in the third row at left show the effect of misalignment. In focus, diffraction arcs spray to one side of the star. Outside of focus, the shadow of the secondary mirror (the dark area near the middle) is decentered. Note that, lopsided as it is, the pattern does look similar on both sides of focus. That's a sign that you've just got poor alignment, not poor optics.

Any reflector or Schmidt-Cassegrain should come with collimation instructions. The adjustment screws allow you to change the tilt of at least one mirror. This not only aligns the optics but moves the image. When collimating, you want to make the star move *toward its outward-flared side* (to the left in the test images). Recenter the star when you check after each adjustment. Centering the star in the field, like collimation itself, is especially critical in a reflector with a low f/number.

To see which screw to adjust, hold your hand in front of the telescope and move it around until its silhouette marks the outward-flared side of the out-of-focus star image. Slide your hand along the length of the tube to the mirror cell and twist the screw nearest your hand, or, if none seems well placed, the screw directly opposite your hand. If this makes the collimation worse, twist it the other way. You'll soon learn whether a clockwise or counterclockwise twist moves the star toward its flared side.

Mirror pinching. Sometimes a problem mirror is merely being bent by its holder. The three-lobed star-test pattern seen here is a sure sign that the three front clips are pressing on the edges of the mirror's front face. Take out the mirror cell, loosen the clips, slide a piece of paper between them and the glass, tighten the clips in place, and slide out the paper. The mirror should rattle ever so slightly against the clips.

A friend of mine bought a 10-inch Dobsonian that, he discovered, gave terrible images. The thin mirror was duct-taped to a hard plywood backing disk. He removed the mirror, covered the plywood with AstroTurf for softer, more even support, then tacked plastic lawn-edging material around the plywood; a lip on the plastic keeps the mirror from falling forward. Freed of its cruel stresses, the mirror sprang back to its original shape and proved to have been good all along.

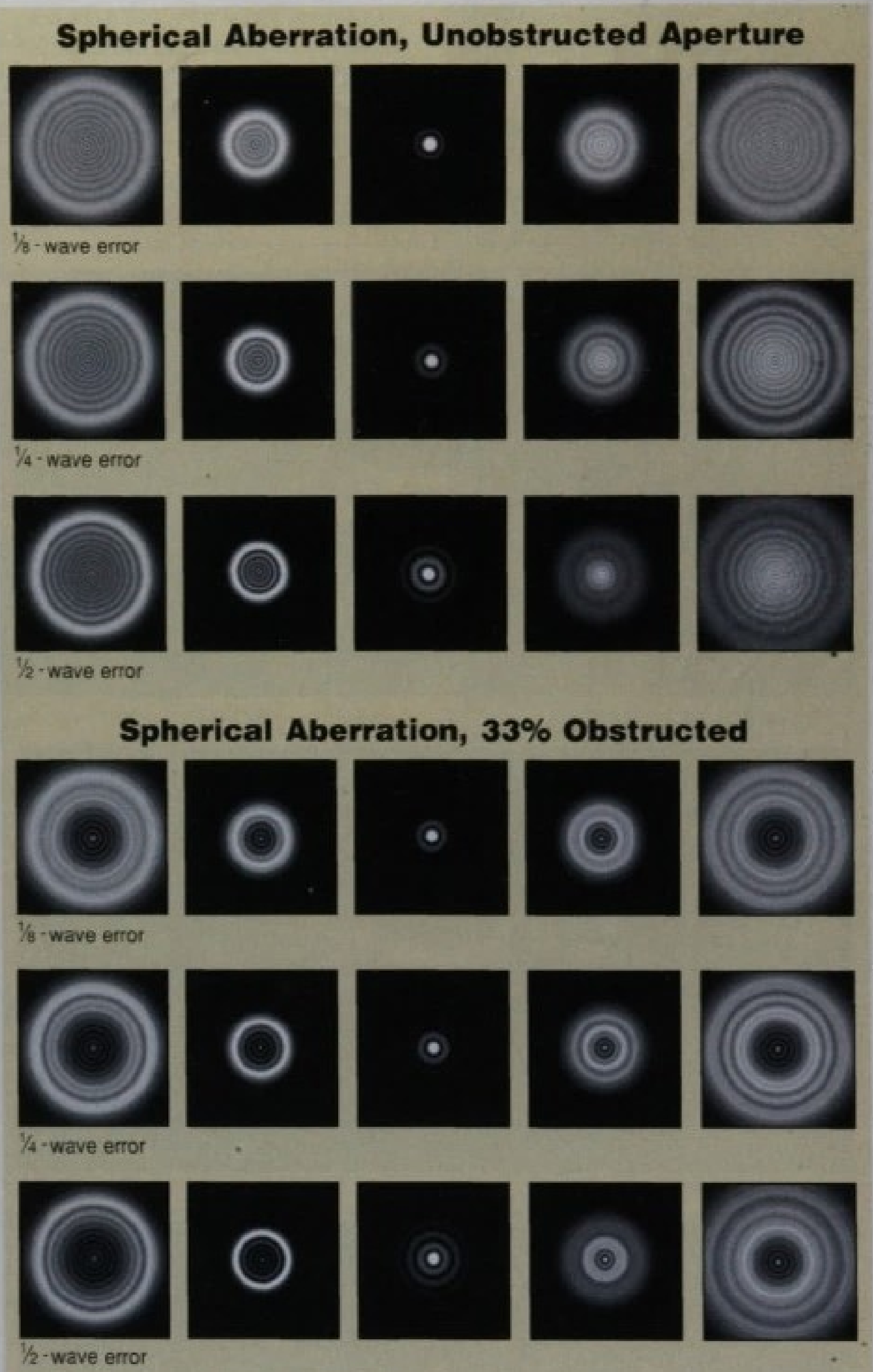
Spherical aberration. This is the commonest error on the glass itself. The two sets of figures at right show the effects of 1/8, 1/4, and 1/2 wave of spherical wavefront error. The top three rows are for an unobstructed telescope; the bottom three have a 33-percent-diameter aperture obstruction, typical of Schmidt-Cassegrains.

Note the diagnostics to look for. On one side of focus, spherical aberration shows itself by a dark core, sharp diffraction rings, and a sharp, bright outer edge. On the other side of focus the image has a brighter core, fuzzier rings, and a hazier edge. If you're using an obstructed telescope, the central shadow is larger on the sharp-ringed side than the hazy-ringed side.

If a mirror is undercorrected (central part of the mirror too shallow), the sharp-ringed side is inside focus as illustrated. This is the most common situation. If the telescope is overcorrected (central zones too deep), the sharp-ringed side is outside focus. This was what users of the Hubble Space Telescope saw, to their horror, when they tested its focus after launch five years ago (*S&T:* October 1990, page 356).

Suiter offers a rough way to judge the spherical aberration you see. If your telescope is not already 33-percent obstructed, make it so by attaching a paper disk to the back of the secondary holder or suspending a disk on threads in front of the objective lens. Turn the focus very slightly one way, then the other. Look for the point on each side of focus where the dark central shadow first becomes visible. If it's twice as far from focus on one side as the other, you're looking at approximately 1/4 wave of peak-to-valley wavefront error.

Astigmatism is another common problem that's easy to recognize in the star test. Center the star in the field (as always) and check whether the out-of-focus patterns are slightly elliptical rather than round. If the telescope is astigmatic, the ellipse will change orientation by 90° when you pass through focus.



Spherical aberration is the simplest and probably most common optical error in telescopes. The star test is sensitive enough to reveal even a trace of it, much less than the ¼-wave aberration that many people allow while still calling a telescope "diffraction limited." In this article, aberrations are expressed as peak-to-valley deviations on the wavefront of the light as it reaches focus. This is twice the peak-to-valley error on the surface of a mirror itself, since a mirror's error is doubled on a reflected light wave. In other words, the top row of each group represents what are often called "1/16-wave optics" — and still the aberration is detectable in the star test!

Astigmatism can be caused by a poor cell bending the mirror. Check that the mirror is sitting evenly on all of its supports. Perhaps you can seat it by joggling it slightly.

If your own eyes are highly astigmatic, by all means wear your glasses! But mild astigmatism in your eyes won't show when you use high power, because the telescope's exit pupil will be so small. To be sure your eye isn't contributing to the image problem, rotate your head around the optical axis as you look. If the elongation does not follow your head around, you're okay in this respect. Now rotate the eyepiece; if the oval star image rotates with it, get a new eyepiece. Most eyepieces do show some astigmatism away from the field center; this has to be considered normal.

A common source of astigmatism in Newtonian reflectors is a slightly convex or concave secondary mirror. If the ellipse of the star image lines up with the telescope's tube, suspect the secondary.

Zones in telescope-making parlance are ring-shaped areas around the face of the objective that are too high or low. They show themselves best in the star test when you go a little farther out of focus than we've been looking so far. Zones are betrayed by rings of light and dark in the disk that, once again, differ on either side of focus. An example is at right, in the middle row.

Don't be misled by the suspiciously uneven-looking rings you'll see in any telescope with a central obstruction, as shown on page 43. Again, you're looking for *differences* on either side of focus.

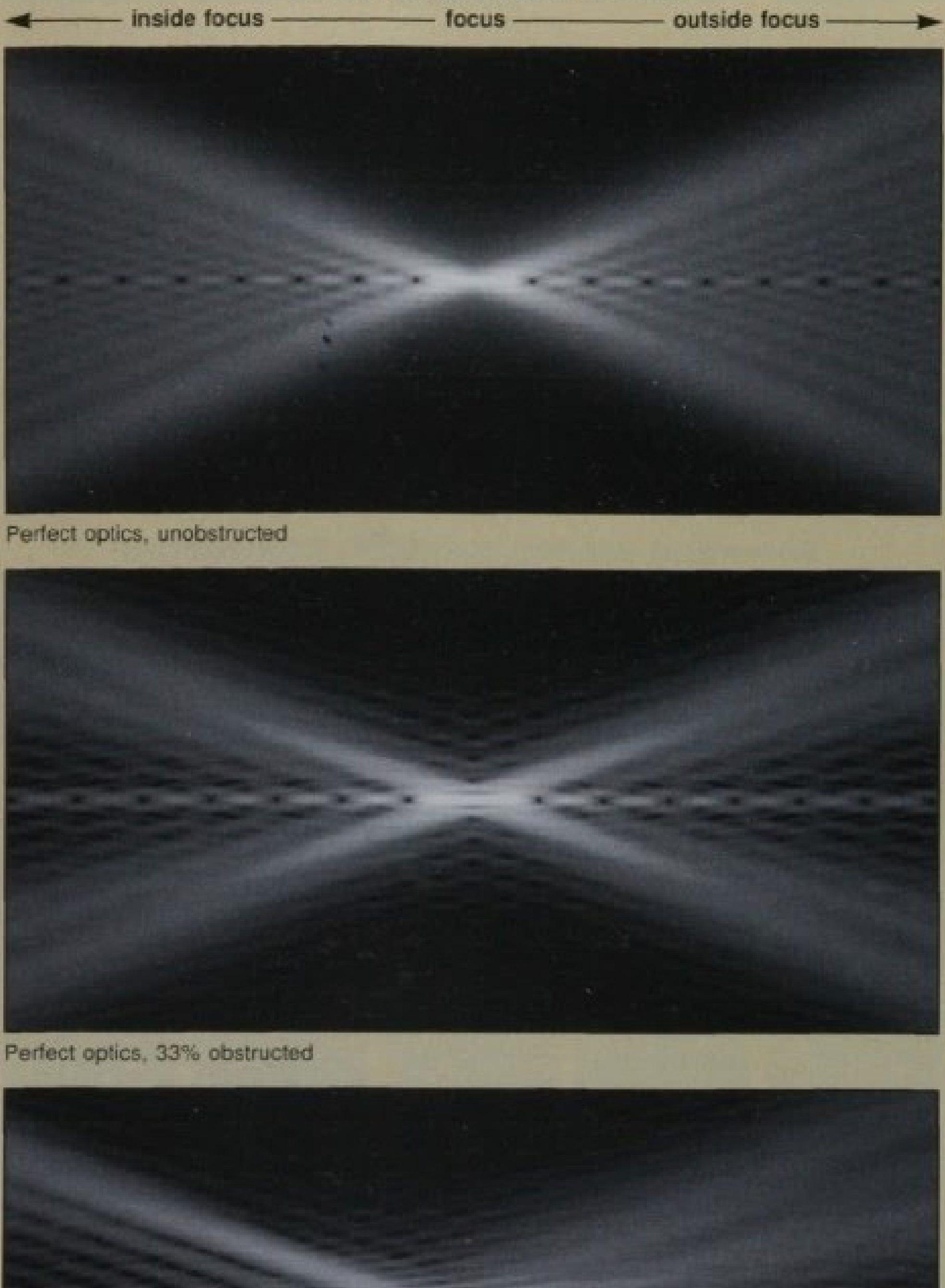
Turned-down edge is a long-standing woe of mirror makers. It's a special case of zone, limited to the outermost part of the mirror. As Suiter demonstrates, a turned edge is quite destructive to low-contrast images many arc seconds wide, such as views of the planets. It too shows best when you go rather far from focus in the star test. Look for sharp, contrasty diffraction rings outside of focus compared to hazy, flat rings and a very wide, hazy outer spray inside focus. This is a lot like what you see with the overcorrected variety of spherical aberration, except that the dark inner shadow (in an obstructed telescope) remains mostly unaffected.

The best thing you can do for a turned edge is to mask it off. Experiment by laying a thin ring of cardboard or black construction paper on the outer ⅛ or ¼ inch of the mirror to reduce its aperture. If you're really sure of what you're doing, Suiter suggests painting out a bad edge by spinning the mirror on a lazy Susan while slowly, carefully, applying paint in from the edge with a fine brush. Don't mourn the loss of a little aperture. With a turned edge, you never had that aperture to begin with. It was just spraying light across a good image being formed by the rest of the mirror's area.

The blunt truth is that most mirrors would probably be better off with their outer ⅛ inch masked. According to Suiter, commercial mirrors tend to suffer from steep but narrow turned edges (the easiest to paint out), while amateurs make their mirrors with wider, shallower turned edges.

Roughness looks similar to poor atmospheric seeing, except that the seeing changes from instant to instant whereas roughness on the optics' surface stays put. Watch for irregular bright and dark spots that remain immobile through the seeing (and aren't due to slow-moving

Converging Light Beam



Here we are looking at right angles to beams of starlight as they converge to focus and emerge on the other side. All the round images in this article represent cross sections of beams like these. To see a profile of the changing diffraction rings as you turn the focuser from inside to outside of focus, slide a card from left to right across these diagrams and watch the patterns of light and dark change along its edge.

Astigmatism

Narrow Bad Zone

Turned-Down Edge

Astigmatism displays 90° asymmetry on either side of focus. *Zones* show up best in the star test far out of focus. The pattern in the second row was caused by a narrow zone (at 70 percent of the mirror's radius) of only ⅛-wave error on the wavefront (1/16 wave on a mirror's surface). *Turned edge* mimics overcorrection in the outer part of the pattern far from focus, but less so near the pattern's center.

tube currents). That's the sign of large-scale roughness, or "dog biscuit." You need a pretty bad case of it to show through even mild atmospheric turbulence. Roughness is particularly destructive to planetary images, as of course is poor seeing itself.

Those are just highlights of this long-overdue book. It quantifies almost all the effects it discusses, presents modulation-transfer functions indicating how they affect different types of observing (see page 90 of this issue), delves into diffraction theory, and yet is full of advice and experience from real-world amateurdom.

"Some may accuse me of trying to light a fire beneath manufacturers, but that is not my intent," writes Suiter. "My motivation is almost the reverse. Too long have manufacturers been forced to make inferior telescope optics because their customers buy . . . on price alone. What I'm doing is placing a reliable testing method in customers' hands. The star test will allow them to determine that Brand B, which costs a little more, *is indeed a better product* than Brand A. Manufacturers can return — with some relief, no doubt — to making quality optics, and their customers will be able to tell the difference."

A. M.

Star-Testing in Daylight

THE SUN'S reflection on a shiny sphere makes a fine "artificial star" that will be less troubled by atmospheric turbulence than a real star. You'll find that the air is steadiest in early morning over grass. To keep the test setup from introducing more than ¼ wave of spherical aberration on the wavefront, the artificial star must be more than $30(a/f)^2$ feet from the telescope, where a is the aperture in inches and f is the telescope's focal ratio (*S&T:* May 1991, page 528). A distance longer than this is preferable.

Small reflective balls make fainter but sharper "stars"; test on an image that is small enough to show crisp diffraction rings. Colored Christmas-tree ornaments can take the place of a color filter at the telescope.

Even better is a portable artificial star that you can set up indoors (if you have a long enough hallway) or outdoors at night. Richard Berry describes how to make one from common materials in the November 1992 issue, page 572.