Telescope Performance: Refractors versus Everybody Else

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I own a good-sized Schmidt-Cassegrain -- a 14-inch (35 cm) Celestron 14 -- and a substantial high-end refractor -- a 1987 Astro-Physics 6-inch (15 cm) f/8 triplet. I have spent a fair amount of time over the last several years comparing the ability to show detail of telescopes like these, and have heard much discussion on the matter. Some of the debate was acrimonious, and some confused. Yet with care taken not to oversimplify matters, I believe we can understand the relative performance of such different instruments, and learn why not everyone perceives it the same way, perhaps even without using too much mathematics in the process.

Comparisons commonly use calculated data about image sharpness. It is relatively easy to make such calculations. Unfortunately, what is easiest to do -- and therefore often done -- requires oversimplifying the optics, the seeing, the targets observed, and the observers themselves.

Optics are oversimplified by assuming that they are perfect. Performance calculations most often deal with perfect optics of an assumed diameter, perhaps with a central obstruction. Real telescopes have optical errors, but perhaps the calculators can be forgiven for not always dealing with them: After all, there is only one kind of perfection, but there are a vast number of errors and combinations of errors, perhaps too many for comprehensive treatment. (Though some authors do a more comprehensive treatment; Suiter's book has many examples.)

Seeing is also often considered perfect. It is as if there were no atmosphere between the observer and the object in view. Yet real seeing is not so pleasant, and moreover, it can vary dramatically from place to place and from moment to moment.

The targets for which calculations are made are usually simple and stylized; they are test patterns composed of regular parallel stripes, alternating black and white, of equal widths. The stripes are not sharp edged: The centers of the black ones are solid black, and the centers of the white ones are bright white, but the brightness varies smoothly in between. (In mathematical terms, the brightness variation is a sine wave -- actually, a sine wave plus enough of a constant so that the value of the wave does not drop below zero.) Yet real astronomical objects do not look like test patterns -- they are used only because they make the mathematics of the analysis easier. Indeed, if you ever see an astronomical object that does look like such a test pattern, the folks at the SETI institute would probably like you to give them a call pretty soon.

The observers are simplified because they are tacitly assumed to be interested only in the results for perfect telescopes looking at stylized test patterns in perfect seeing. Alas, we're not, and what's more, few of us know how to apply such results to real optics, conditions and targets.

The calculation generally made is, how crisp do those test-pattern stripes look through a telescope? With stripes a particular distance apart, and a telescope of specific aperture and central obstruction, do they still look sharp and intense? Or are the blacks a little milky and the whites a little murky? Or are they starting to fade out, as if you were looking at a zebra that had been rolling in the dirt? Or are they gone entirely, so that the entire field is a uniform shade of gray? The relative contrast between the stripes as seen and the stripes as they were created, is called the modulation transfer function, and a common calculation is to figure out how it changes as the stripes get closer together or farther apart, with the details of the telescope unchanged.

With the simplifications that I have mentioned, the behavior of the modulation transfer function is pretty intuitive. When the stripes are far enough apart, your telescope -- any telescope -- will be just loafing; it will show them with as much contrast as they had when they were drawn. When they are too close together, even the best telescope can't see them at all: For any telescope, there is a stripe separation below which the entire field grays out, and no trace of stripes can be seen. The contrast varies smoothly and regularly between those extremes. It doesn't go from sharp stripes to uniform gray all of a sudden; rather, as the stripes get closer and closer together they start looking murkier and murkier, and finally blur together and become indistinguishable from one another.

With perfect optics and perfect seeing, a large-aperture telescope can see the stripes better than a small one. When the stripes are wide enough apart for both telescopes to be loafing, they both see an equally high contrast, but as the stripes get narrower and closer, they look grayer sooner in the small telescope, and vanish from view in the small telescope while they can still be seen in the larger one. In that sense, aperture has a theoretical guarantee of winning.

Let's add some less than perfect optics to the system now. My Celestron 14 is pretty good, but its optics are not nearly as well fabricated as the ones in my six-inch refractor, and they have a big central obstruction, too. What difference does all that make?

When the optical defects in the large telescope are no worse than those seen for typical commercial instruments, the effect is that the modulation transfer function for the large telescope sags in the middle. When the stripes are wide apart, the telescope is still loafing, even with its imperfections, so it still shows them well. And when the stripes get too narrow and too close together for the small telescope, the big one will likely still show them, though they might not show up as well as if its optics were perfect. But optical defects can reduce the contrast of the big telescope in for separations where the small telescope can still see the stripes, so much that the small, perfect telescope will have better contrast than the big, imperfect one. A central obstruction on the big telescope has a similar effect. The stripe separation at which it is easiest for this to happen is very roughly at a value a few times the resolving power of the small telescope -- at wider separations, both telescopes are loafing, and at narrower ones, the small one doesn't have much of a chance against the big one.

To understand the effect of seeing, imagine that we use fancy instruments to make a "snapshot" of what the seeing does to the incoming wavefronts of light at a particular, fixed, moment in time. We could then take our data to a professional optician and have a thin sheet of glass made with exactly the same wavefront errors figured into it. Putting that sheet of glass in front of our telescopes, in perfect seeing, would duplicate the effect of seeing at the moment the snapshot was taken. We have thus shown that seeing is an optical defect like any other, and we already know what optical defects do, so we are done with seeing, right?

Wrong. Remember that our "snapshot" represents seeing which affects both telescopes, not just one of them. We have to consider whether it affects them both the same way, or differently. And there is no precise answer, for there are different kinds of seeing. For example, suppose the seeing contained only little swirls and eddies, all much smaller than either telescope. The effect of these eddies would be to roughen the wavefront as it passed through them, and the scale of the roughness would be much smaller than either aperture. The wavefront would have the kind of irregularities that telescope makers call "lemon peel" or "dog-biscuit", and the roughness would affect both telescopes similarly.

On the other hand, suppose the seeing consisted solely of huge swirls of air, much larger than either telescope, so that the wavefront change seen by either was a smooth, linear deformation. In that circumstance, the total wavefront variation due to seeing seen by the C-14 would be larger than that seen by the six-inch refractor, in the proportion fourteen to six. The C-14 would be much more adversely affected by the seeing that the smaller instrument. Interim kinds of seeing are also clearly possible, and what actually occurs is almost certainly a combination of irregularities of many different scales.

Remember also, that the last few paragraphs of analysis are solely for a single, static snapshot. Seeing changes rapidly, however, and sometimes there are moments of clarity amid minutes of chaos. Only the observer can decide how long it is worth waiting for a good moment, and factor that consideration into the decision of which telescope is best to use. One person might prefer the six-inch refractor because in many seeing conditions, it gives views that are on the average less affected by seeing than does the C-14. Another observer on the same night might prefer to wait patiently at the eyepiece of the larger instrument, seeking a moment when its greater aperture would show more detail.

The point about real targets deserves careful thought. There is a common myth that telescopes cannot see detail smaller than the diameter of their Airy discs. That's not true -- it's not even close -- if it were, the only star we could see would be the Sun. Telescopes can see high contrast detail that is smaller than their resolution limit -- and stars are a good example -- but it looks to the observer like lower-contrast detail of larger size. Thus when we look at stars, we see Airy discs, which are much larger than the stars' actual sizes, and therefore do not have nearly as high a surface brightness.

Another simple experiment may illustrate the point. Go outside by day, and find some telephone poles on a long street. Pick a particular wire passing over your head, and look at it. Let your eyes follow the wire as it extends into the distance, and notice how the view changes. For me, when the wire is close up, I see it with noticeable width, and darkly black -- a tangible high-contrast line drawn against the sky. As the wire gets further and further away, it gets narrower, but stays black, at least for a while. But after a certain distance, it narrows no further: The image I see holds constant width, but starts to get grayer. Where the wire finally fades from sight, the image is still the same width, but it has become so pale a gray that it fades into the sky. What is happening is that the wire has become much narrower in angular width than my eye can resolve, and my eye is widening the narrow, dark line into a wider, gray blur -- the black of the line diluted with lots of skylight. A telescope will do the same thing to linear detail, and will also widen small, high-contrast spots into larger, low-contrast ones.

What do changes in optics and seeing do to real views? The key is to realize that it is possible to express any image mathematically as a sum of the regular test patterns we have been talking about, using patterns with lines of different widths, running in different directions. Having done so, one determines finds the modulation transfer function for each test pattern in turn, applies it, and adds the results back up to get the modified image. The individual test patterns of which the image is composed are called its angular frequency components, and those of you who are familiar with the relevant mathematics will recognize that I am talking about a Fourier transform of the image. (Don't panic -- I promise not to explain it.)

Doing the Fourier transform of a real image is a lot of work, and sometimes the results are surprising. Thus the important point is not to prejudge the matter: For a particular image, the telescope that will win is the one that has a high modulation transfer function at the angular frequencies -- the line separations -- where the image has strong frequency components. With perfect optics and good seeing, the big telescope will win all the time, but if there are line spacings for which the smaller telescope performs better than the big one, whether because it has better-crafted optics or because the seeing treats it more gently, then there may well be objects, with strong frequency components for those same line spacings, for which the smaller telescope gives a better view. Note that because seeing is involved, whether such objects exist, and what they are, may vary from heartbeat to heartbeat.

In conclusion, here are my present personal opinions as to when I should use my Celestron 14 Schmidt-Cassegrain and when I should use my 6-inch Astro-Physics triplet refractor.

For public star parties, with a long line of people waiting for a view of the Moon or a planet: Use the 6-inch -- in all but superb seeing, it will give a steadier and more aesthetically pleasing view.

For double stars: Use the C-14, and wait for moments of good seeing.

For deep-sky work -- looking at faint fuzzies: The C-14 wins across the board, on grounds of greater light collecting ability.

For chasing down subtle shading in the clouds of Venus, and possibly for surface markings on Mercury: Use the 6-inch -- this detail is fairly wide, and is low-contrast.

For the Moon: This is an interesting case. Most of the detail is relatively high contrast, so I think the C-14 shows more detail, but the 6-inch's ability to show low-contrast differences well may create a more aesthetic view, so the telescope to use for public work or casual viewing may be different than the one die-hard lunies will want. Be prepared to wait for the seeing to settle with the C-14.

For the other planets: I think there is no clear winner. I suspect there are features on most of the planets for which the C-14 does best, and others for which the 6-inch is superior in many common kinds of seeing.

Bibliography:

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