1 Telescope and Observing Fundamentals

This chapter will discuss the fundamentals of telescopes and observing which are independent of the telescope type or, as in the case of the contrast of a telescope image, dependent on aspects of the telescope design. Later sections in the chapter will discuss the effects of the atmosphere on image quality due to the 'atmospheric seeing' and the faintness of stars that can be seen due to its 'transparency'. The final sections will give details as to how the stars are charted and named on the celestial sphere and how time, relating to both the Earth (Universal Time) and the stars (sidereal time) are determined.

There is one problem that can cause some confusion: the mixing of two units of length: millimetres and inches. Quite a number of US and Russian telescopes have their apertures defined in inches, and the two common focusers have diameters of 1¼ and 2 inches. However, the focal lengths of telescopes and eyepieces are always specified in millimetres, as are the apertures of more recent US, Japanese and European telescopes. In this book I have used the unit which is appropriate and have not tried to convert inches into millimetres when, for example, referring to a 9.25-inch Schmidt-Cassegrain telescope. In calculations and where no specific telescope is referred to, millimetres are always used.

1.1 Telescope Basics

Focal Ratio

A telescope tube assembly will have an objective of a given diameter, D, and have a focal length F. The ratio of the two, F / D, is called the focal ratio, f (Figure 1.1). Typical focal ratios range from 4 to 15. It is easier to design an optical system with a larger focal ratio, so telescopes whose focal ratios are towards the lower end may need more complex – and hence expensive – optical designs or, as in the case of a Newtonian telescope with a short focal ratio, additional corrector lenses.

Cambridge University Press
978-1-107-61960-9 - An Amateur's Guide to Observing and Imaging the Heavens
Ian Morison
Excerpt
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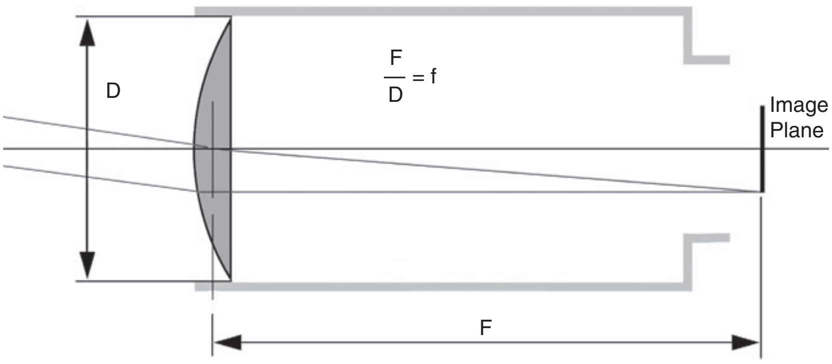

Figure 1.1 The definition of *f*, the focal ratio of a telescope.

Telescope Magnification

The magnification is given by F/f_e, where f_e is the focal length of the eyepiece. For example, when a 13-mm eyepiece is used with my 820-mm refractor, the magnification is 820/13 = 63. It is often thought that the prime purpose of a telescope is to give very high magnifications, but the highest useful magnification is limited theoretically by the objective diameter (which defines its resolution) and practically by the 'seeing' (Section 1.5) at the time. This relates to the turbulence in the atmosphere above the telescope and usually limits the effective resolution to 2–3 arc seconds. (An arc second is 1/3,600th of a degree.)

The eye has a resolution of about 1 arc minute (60 arc seconds) in daylight. But this is reduced when the pupil is fully dilated for night viewing to perhaps 2 arc minutes. So, supposing that the effective resolution of the observed image is 2 arc seconds, a magnification of just 60 will bring this up to 2 arc minutes. However, for many objects, spreading the light out over a greater area on the retina can help, so higher magnifications are useful, but it is very rare – perhaps under superb seeing conditions – that magnifications of more than 200 will enable one to see more. There is a rule of thumb that the magnification used with a telescope should not exceed ×50 per inch of aperture (or twice the aperture in millimetres) so, for example, a 6-inch (150-mm) telescope would not be expected to work well at magnifications greater than 300.

The Exit Pupil Diameter and Its Effects

There can be a problem when using very high or very low magnifications. If you hold up a telescope or pair of binoculars towards the sky or a bright wall, the eye lens of the eyepiece will show an illuminated circle. This circle is called the 'exit pupil' and is the column of light that leaves the telescope to enter your eye (Figure 1.2). Its diameter is simply given by the diameter of the aperture divided by the magnification. There are problems if this is too small, such as using a very high magnification with a small-aperture telescope when 'floaters' within the eye can become very obvious or when

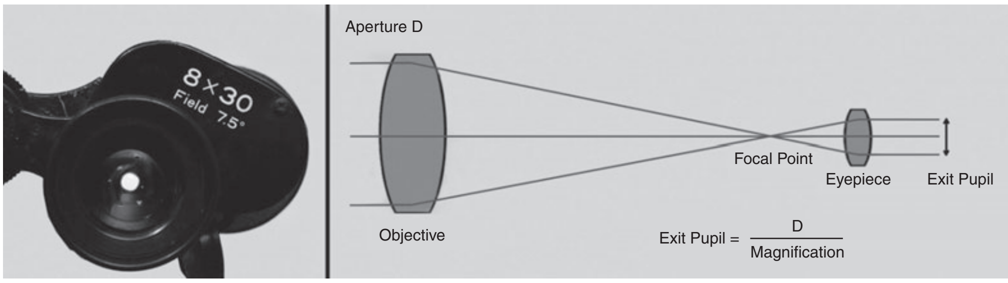

Figure 1.2 The definition of the exit pupil of a telescope or binocular.

it is too big, as then, if the exit pupil is greater than the diameter of the iris, not all the light collected by the telescope will enter the eye and the effective diameter of the telescope will be reduced. Young people have a fully dilated iris of ~7 mm but, as we age, this reduces to ~5 mm. My 80-mm refractor has a focal length of 550 mm so, if I use my 40-mm Paragon eyepiece, I will get a magnification of 13.75 and hence an exit pupil of 5.8 mm. As a result, not all of the light collected by the telescope will enter my ~5-mm pupil and the effective diameter of my telescope is reduced to 70 mm. To get the very best out of my telescope I would need to use a 35-mm eyepiece, which would give a magnification of 15.7 and an exit pupil of 5.1 mm.

In the same way as the resolution of a camera lens tends to peak and then fall off as the aperture is reduced, so the eye will give its maximum resolution when not all the aperture of the eye's lens is in use. Studies indicate that this is when the effective aperture of the eye is about 1.5–2 mm in diameter. The eye's effective aperture when used with a telescope is *not* the diameter of the dilated pupil, but the diameter of the telescope's exit pupil. You may well find that, when you are observing a planet, a particular eyepiece might give you the clearest image. It is then quite likely that the telescope/eyepiece combination is giving an exit pupil around this diameter.

Field of View

Finding the field of view of an eyepiece when used with a given telescope is a little more complex. If one looks through an eyepiece at the open sky, one sees a white circular aperture whose size is limited by what is called the 'field stop' of the eyepiece. This aperture defines what is called the 'apparent' field of view of the eyepiece. For simple three-element eyepieces this might be just 40 degrees but, in the case of complex wide-field eyepieces, can exceed 100 degrees. If you know the apparent field of view, then simply dividing this by the magnification will give an approximate actual field of view. The eyepiece with a 13-mm focal length referred to earlier has an apparent field of view of 68 degrees so, given the magnification of 63, will have a true field of view of just slightly more than 1 degree when used with a scope of 820-mm focal length – very nice to view the Moon surrounded and contrasted against a black sky. A second way is to measure the diameter of the field stop with a ruler; 18 mm in this case. The true field is then given by multiplying the ratio of the field stop divided by the focal length (18/820 = 0.22) by 57.3 (the number of degrees in a radian) to give 1.26 degrees. I suspect that this is a more accurate result. A third way is to observe a star close to the celestial equator and time how long it takes to cross from one side of the field of view to the other when the telescope is not tracking. This time in seconds is divided by 86,164 (the number of seconds in a sidereal day) and multiplied by 360 to give the actual field of view in degrees.

Light-Gathering Power

Larger-diameter objectives collect more light, so enabling one to see fainter objects. To explore this further we need to understand the concept of apparent magnitude. The Greek astronomer Hipparchus placed the stars into six magnitude groups: the brightest in magnitude 1 and the faintest in magnitude 6. Quantitative measurements have since shown that the first-magnitude stars were about 100 times brighter than the sixth-magnitude stars, and this was made a definition. The magnitude scale is logarithmic, so that a fifth-magnitude star will be some factor (say, Z) brighter than a sixth. In the same way, a fourth-magnitude star will be *the same factor Z* times brighter than a fifth-magnitude star. Thus a fourth-magnitude star will be $Z \times Z$ times brighter than a sixth-magnitude star, and so a first-magnitude star will be $Z \times Z \times Z \times Z \times Z$ times brighter than a sixth-magnitude star. But this brightness ratio has been defined as 100, so Z must be the fifth root of 100 = 2.52.

It was found that some stars were brighter than this – given 'zeroth' magnitude – and some even brighter still when the magnitude scale becomes negative, with, for example, Sirius at magnitude −1.5. The planets can be even brighter, with Venus reaching magnitude –4.7.

Let us take a real example to see how this determines what we might be able to see with a pair of 40-mm-aperture binoculars. With our dark-adapted eyes observing at site with no light pollution and a transparent sky, we might be able to see a sixth-magnitude star. If we assume that our eye has a pupil of diameter 6 mm we can see that the binoculars have a diameter 6.6 times greater. They will thus collect $(6.6)^2$, or ~44, times more light.

Now an increase in collecting area of 2.52 times would allow one to see 1 magnitude fainter stars, an increase of in area of 6.35 (2.52 × 2.52) times, 2 magnitudes fainter. Continuing, a 16 times increase in aperture should show stars 3 magnitudes fainter, a 40 times increase 4 magnitudes fainter and (by definition) a 100 times increase 5 magnitudes fainter. So, with our binoculars collecting 44 times more light, we should be able to see stars slightly fainter than 6 + 4 magnitudes – slightly more than 10th magnitude.

It is worth noticing that I specified a site with little light pollution and transparent skies – everyone will have noticed that from a given site when the atmosphere is very clear we can see far fainter stars. The transparency of the atmosphere has a double effect, as not only will the atmosphere, if somewhat 'hazy', reduce the light that we receive from the stars, but it will also scatter back far more light pollution, making it even harder to see the stars. This is discussed in greater detail in Section 1.5.

Books often give a table of the 'limiting magnitude' that a scope of a given aperture can observe. I would rather give a table of what I call the 'magnitude gain' of a telescope, which I think is far more useful and relates directly to the observing conditions. Note the magnitude of the faintest star that you can observe in the direction in which you wish to observe (which takes into account your eyesight, the sky transparency, light pollution and elevation) and simply add the appropriate telescope gain to find the faintest-magnitude star that you should be able to observe in that direction.

75 mm	4.5	90 mm	4.9	102 mm	5.2	114 mm	5.9
130 mm	6.3	150 mm	6.7	180 mm	7.1	200 mm	7.4

Under perfect conditions towards the zenith, a young eye might be able to spot a star with a magnitude of 6.5. If this is added to the magnitudes just given, one gets what is called the 'limiting magnitude' of a telescope, which, in the case of a 150-mm scope, would be ~13.2. Faint stars, which would not be seen using a low magnification under light-polluted skies, will become more apparent if the magnification is increased by using eyepieces of shorter focal length as, with increased magnification, the brightness of the sky background is reduced but that of the stars is not. This increases the contrast between them and the sky and enables stars perhaps 1–2 magnitudes fainter to be seen.

The Resolution of a Telescope

The detail in an image viewed by a telescope is theoretically limited by its resolution, which increases with telescope aperture. (But, as mentioned earlier, this is usually limited by the atmosphere.) The resolution of a scope of given aperture can be measured experimentally by, for example, observing when the two stars of a close double can just be split. This approach gave rise to the empirical 'Dawes limit' proposed by W. R. Dawes and gives the resolution, in arc seconds, as $R = 4.56/D$, where D is in inches, or $R = 116/D$, where D is in millimetres. For a scope of aperture 100 mm this gives 1.16 arc seconds.

The image of a star under perfect observing conditions and when one is using a telescope such as a refractor which has an unobstructed aperture is in the form of a central disk – called the 'Airy disk' – which contains 84% of the light surrounded by a number of concentric rings of decreasing intensity. The whole is called the 'Airy pattern' (Figure 1.3). This is the result of the diffraction of light as it passes through the telescope aperture.

The 'Rayleigh criterion' states that a telescope can resolve two stars when the peak of one star's diffraction pattern falls into the first minima of the other (Figure 1.4). This gives a somewhat lower resolution limit than that defined by Dawes, as in the Raleigh criterion there is a drop of ~26% in brightness between the two peaks whereas in the case of the Dawes limit the drop is only 5%. The angular separation between the centre of the Airy disk and the first minima of the Airy pattern is given, in radians (1 radian = 57.3 degrees), by $1.22\ \lambda/D$, where λ is the wavelength of the

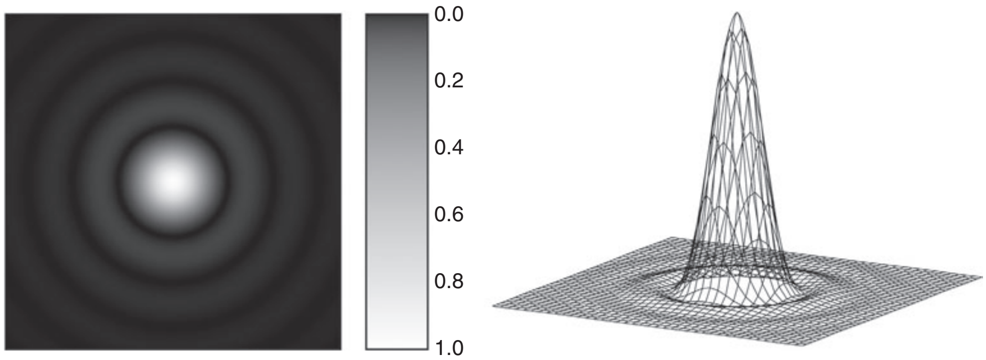

Figure 1.3 The Airy pattern shown (*left*) as a greyscale pattern and (*right*) as a 3D plot. (Image: Wikimedia Commons)

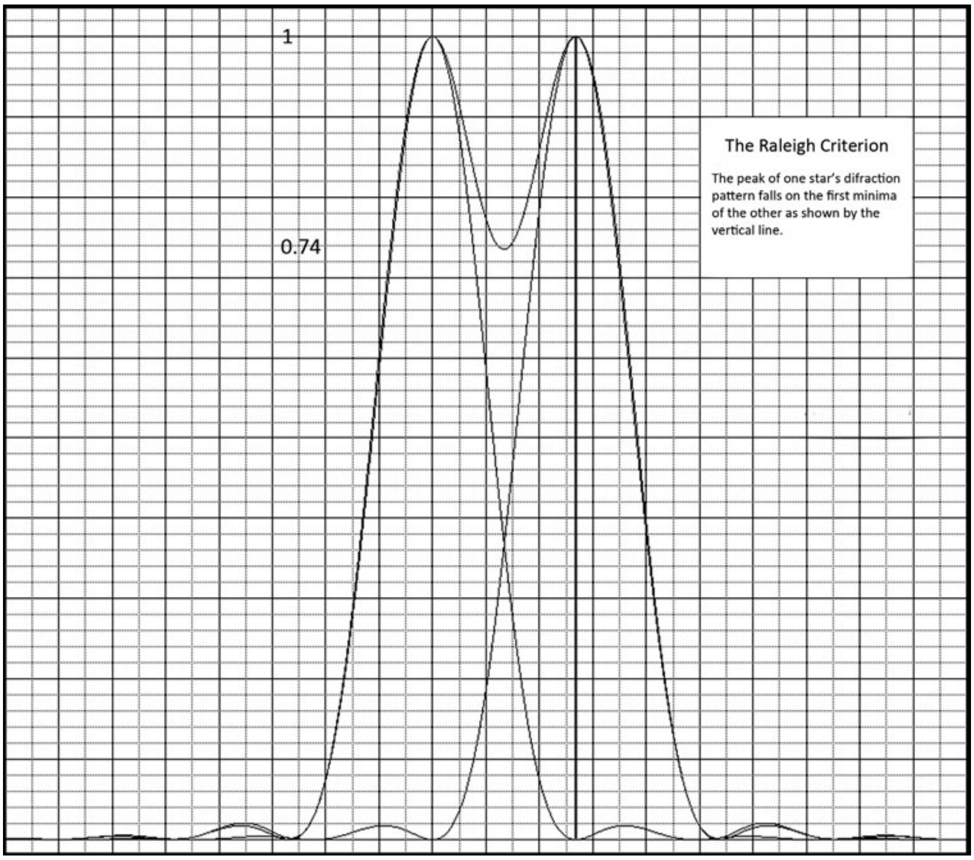

Figure 1.4 The Rayleigh criterion.

Table 1.1 *The theoretical resolution in green light for a number of telescope apertures*

Aperture (mm)	Resolution (arc seconds)
102	1.35
150	0.92
200	0.69
300	0.46

light. (Both λ and *D* must be in the same units.) Using the wavelength of green light of 5.5×10^{-7} m, this gives a resolution, in arc seconds, of 138/*D*, where *D* is measured in millimetres. Thus, with a lens of aperture 100 mm, one gets a theoretical resolution of ~1.4 arc seconds. The resolution of some typical aperture telescopes is given in Table 1.1.

The form of the Airy pattern was first computed by George Biddell Airy and is a complex calculation but, interestingly, the approximate result can be simply derived from quantum theory. The Heisenberg uncertainty principle states that the more accurately one knows the position of an object (in this case a photon) the less well defined is its motion. If light passes through a slit of width *D* – which thus defines its position along one axis – the uncertainty principle shows that the light will have an angular spread along that direction given, in radians, by λ/D. However, in the case of a circular aperture, the light path is constrained in two axes, so increasing the angular spread and the size of the Airy disk will be correspondingly larger, hence the factor 1.22.

In the case of visual observing, the resolution is almost always limited by the atmosphere, but if the atmospheric seeing is excellent and very short exposures are made (in the form of a video sequence) and the best of these images are processed as described in Chapter 11, then the theoretical resolution *can* be obtained, as witnessed by the wonderful images of Jupiter taken by Damian Peach and others.

Curvature of Field

Ideally the image plane produced by a telescope would be flat. In practice, unless some corrective optics are included, the image plane is curved, with the outer parts of the image in focus slightly closer to the lens or mirror than the centre. The shorter the focal length of the telescope, the greater the effect. In visual observing, the eye is able to accommodate some curvature of field, and this is not too much of a problem, but when imaging is carried out with a large CCD array, the outer parts of the field may be out of focus. It is possible to purchase lens attachments, called field flatteners, that correct for this and some of the latest telescope designs, such as the

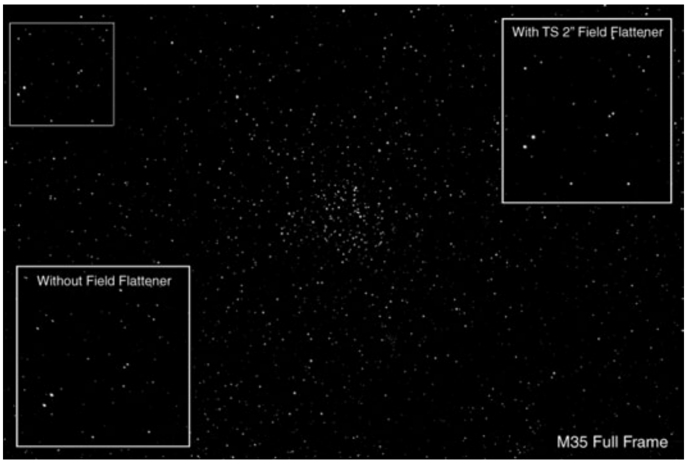

Figure 1.5 An image of the open cluster M35 taken with a Nikon D7000 DSLR with APSC sensor, with and without Telescop-Service 2-inch field flattener.

Celestron 'Edge HD' Schmidt-Cassegrains, incorporate them into the optical tube assembly. Figure 1.5 (and Plate 1.5 in colour) shows an image of the open cluster M35 taken with an 80-mm refractor and a Nikon D7000 DSLR with an APSC-size sensor. Insets show the field corner taken with, and without, the use of a Teleskop-Service 2-inch field flattener.

1.2 The Contrast in a Telescope Image

Image contrast is perhaps one of the key properties of a telescope and one which is particularly important when one is viewing the Moon and planets. It is a subject that is not too well understood, with erroneous statements often appearing in the astronomical press. The following two sections will, I hope, enable you to understand the various elements that come into play to determine what is termed the 'contrast' of an astronomical image. The approach that I believe gives the best understanding of the subject splits the discussion into two parts: firstly, that of the overall contrast of the image and, secondly, what I term the 'micro-contrast' of an image. I am not aware of any other author taking this approach, but I honestly believe that this is by far the best way of considering this very important aspect of telescope design.

The Overall Contrast of an Image

So what is meant by the overall contrast of an image? In an ideal world, the light that is recorded by a CCD camera of a particular feature in an image will have come only from the light emitted or reflected by that feature alone. This will rarely be the case. The lunar image at the left of Figure 1.6 is obviously of low contrast – the

Figure 1.6 A low-contrast (*left*) and high-contrast (*right*) image of the Moon.

blacks are grey, not black. In this case, the reason is that it was taken in twilight and so sky light was falling uniformly across the image. (By taking a sky image with the same exposure just to the left of the Moon and subtracting this from the lunar image removed much of this unwanted light and produced the image on the right, which has much higher contrast – quite a good tip! This is covered in Chapter 18.) However, after dark, there may well be light pollution spreading light into the image and, even with no light pollution, there will still be some 'air glow' reducing the contrast a little.

The overall image contrast (so that blacks are not as black as they should be) can also be reduced by factors in the design of the telescope being used. One often reads that reflecting telescopes give lower-contrast images than refractors, but one major reason for this statement no longer holds quite so true. A telescope mirror having a simple aluminium coating will reflect ~86% of the light falling upon it. As reflecting telescopes will have two mirrors, only ~75% of the light entering the telescope will reach the eye or camera. This will reduce the effective size of the telescope somewhat but not, in itself, reduce the contrast of the image. But what of the remaining 25%? Some of this light will be absorbed within the mirror coating, but a significant portion will be scattered and can fall anywhere within the image, so reducing its overall contrast. (If you shine a red laser beam at a mirror surface so that the reflected beam is away from your eyes, you will easily see where the beam meets the surface, thus showing that light is being scattered.) A major reason refractors give images with higher overall contrast than reflectors is that objective lenses may scatter only ~2% of the light passing through them.

This is why I believe that the high-reflectivity coatings that are now applied to many astronomical mirror surfaces are so important. With ~95% reflectivity, not only will they give somewhat brighter images but they will also greatly reduce the amount of scattered light, so improving the overall contrast. A high-reflectivity coating is well worth having even if at an additional cost: not only will the telescope perform better but a second advantage is that the mirror surface allows far less moisture to penetrate and is likely to last perhaps 25 years before it has to be re-coated. I have a 10-year-old Newtonian whose mirror was one of the first to be given a high-reflectivity coating and it still looks like new.

A second reason for reducing the overall contrast is that light scatters off the interior of the optical tube assembly. This is also why refractors can provide such high-contrast images, as a series of knife edge baffles reducing in size can be located within the optical tube to trap any scattered light. Matt-black flock coatings may also be used in both types of telescope to reduce this, and high-specification reflecting telescopes may also be equipped with a series of baffles mounted within the tube. If a reflecting telescope has a glass correcting element mounted at the front of the tube assembly, it is a good idea to use a dew shield (which extends the tube assembly outwards), not just to reduce the building up of dew on its surface but to prevent extraneous light from falling upon it. The best of these are also equipped with internal baffles. Even with a Newtonian, when extraneous light is a nuisance, an outward extension to the tube will help.

The overall design of the telescope will affect the overall contrast as well. It is impossible to beat a well-designed refractor, but Newtonian telescopes, where one observes across the tube assembly to the far wall, are almost as good. This also applies to the more complex Schmidt-Newtonians and Maksutov-Newtonians. My 150-mm Maksutov-Newtonian has a set of baffles immediately across from the focuser to prevent any light scattered off the tube walls from entering the field of view (Figure 1.7). Few standard Newtonians seem to be so equipped, and the application of some flocking opposite the focuser could well make a useful improvement.

The telescope designs that have the greatest problem with overall contrast are those where the light path exits through the primary mirror, as one is then looking up towards the sky. Such telescopes incorporate an internal baffle tube so that the incident light into the telescope is hidden by the secondary mirror and its support. This does involve some design compromises, as extending the baffling to increase the overall contrast may well restrict the light falling on the outer parts of the image – called 'vignetting'. Even so, extraneous light can still enter the baffle tube and be scattered into the image. Again, a dew shield will greatly help. Increasing the size of the circular secondary mirror support will also help, but this then has an impact on the second cause of reduced contrast within an image, which I term 'micro-contrast', as discussed in the next section.