The Whiz Wheel
Astro-imaging Exposure Calculator

INTRODUCTION

The *Whiz Wheel* is an astro-imaging exposure calculator for both emulsion photography and electronic imaging. It can be used with various types of digital cameras such as CCD cameras, web cams and video cameras.

The late Gordon Patterson, of Saskatoon, Saskatchewan, came up with the initial idea for a calculator around 1975. The version you now hold is the latest in a line of exposure calculators that has evolved to meet the demands of amateur astronomers. For this latest version, it was necessary to expand the use of the *Whiz Wheel* to the realm of digital cameras. The lure of instant assessment and gratification are helping them dominate the market. This calculator can be used with cameras for both terrestrial and astronomical targets.

Just about every type of astronomical object is represented on the *Whiz Wheel*. Stars are not included because they are point sources, where all the light is concentrated into a tiny spot. Only objects that will show a discernible size in your image can have a reliable exposure time calculated. The Sun is a special case because it virtually always requires the use of very dense filters to image it—more on the use of filters later.

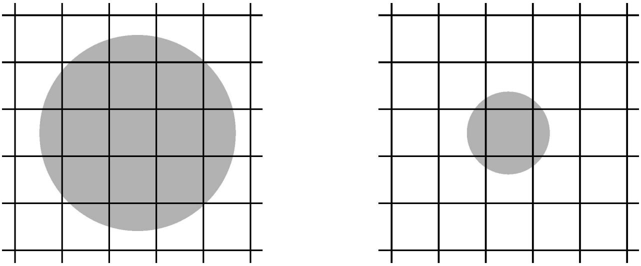
At first sight the *Whiz Wheel* is rather daunting. If you are too young to have used slide rules, this will be especially true. But read on. Soon you will be a pro at its use. You will find it really is as simple as “1-2-3”!

This pamphlet assumes you have a working knowledge of basic photography and astronomy, including the concepts and interrelationships of f/stops, film speed ratings, magnitudes, etc. Photographing the heavens can be as simple as attaching your camera to a tripod and snapping away at the crescent Moon, or as difficult as obtaining a sharp photo of Saturn or a good exposure of a dim nebula. We have to work within many constraints while astro-imaging. One cannot move in closer or change the viewing angle, nor can we throw more light on the subject if the object is too faint for our liking. For these and other reasons, the astro-imager’s arsenal of tools and techniques is necessarily varied. We hope that this *Whiz Wheel* will be one of those handy tools in your bag of tricks. It doesn’t even require batteries!

When engaging in a technically demanding activity, it helps to have a good understanding of the fundamentals. Some of what follows is a cursory look at the factors that determine the observed properties of astronomical objects. After this we describe the *Whiz Wheel’s* scales. If you prefer, you can cut to the chase and first read the section, “Using the *Whiz Wheel*”, then come back to the other sections at your leisure.

FACTORS THAT DETERMINE BRIGHTNESS

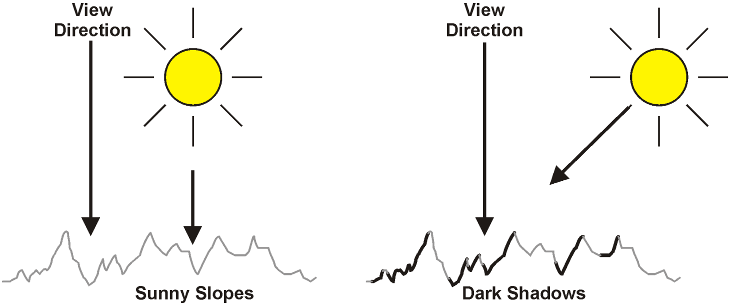
When imaging nonstellar objects it is the brightness per unit surface area that matters, not the total brightness. Surface brightness is commonly given as magnitudes per square arc second (mag/arcsec^2) or per square arc minute. A planet's distance from the Sun and its albedo, or reflectance, fundamentally determines its surface brightness. Because the brightness of a non self-luminous object varies inversely with the square of the distance from its light source, a small change in distance will cause a noticeable change in brightness. Increasing the Earth-planet distance will reduce its apparent surface area and thus reduce its apparent brightness. However this has no effect on the surface brightness.



Total brightness changes with size, but brightness per square remains the same.

Mercury has the most eccentric orbit of any planet but Pluto. Its distance from the Sun varies enough to cause a 2.3-fold change in total brightness (0.9 magnitude). The other planets, with their less elliptical orbits, exhibit a much smaller range of about 0.1 to 0.4 magnitudes.

Planets whose visible surface is soil or rock — as opposed to clouds — can vary in apparent surface brightness quite a bit due to the *phase effect*. This is determined by the angle at which the Sun illuminates the planet's surface and the viewing angle from Earth. This is important for the Moon and Mercury as they go through their range of phases. It also pertains to a lesser extent to Mars, which can appear gibbous at quadrature.



Surface appears darker with sunlight from the side.

The phase effect results in the surface brightness always being greatest at full phase. The planets beyond Mars are so distant that they always appear at virtually full phase. Moreover, they are cloud covered anyway.

Aurorae, comets, nebulae and distant galaxies often exhibit a large range of brightness across their surfaces, depending on their intrinsic luminosity and the thickness of material along a given line of sight. For such objects there will often be no single perfect exposure — the exposure you choose will depend on which aspect you want to show best.

The light from our distant targets is attenuated and blurred by our atmosphere. The amount of this attenuation depends on the amounts of water vapor, dust and pollutants, and on the angle of entry through the atmosphere. The lower the object appears in our sky, the longer the path length through the atmosphere and therefore the greater the attenuation. The blurring effect, called astronomical seeing, is also worse near the horizon. It can turn a star from a point of light into a churning blob several arc seconds across.

THE WHIZ WHEEL SCALES

The four basic elements of the photographic equation are written as:

$$\textit{exposure time} = \textit{focal ratio}^2 / (\textit{film speed} \times \textit{object surface brightness})$$

These elements are incorporated in the circular slide rule as four logarithmic scales printed on three moveable disks. Unlike object brightness in the photographic equation, which is based on factors of two, on the *Whiz Wheel* object brightness is scaled as astronomical magnitudes, where one magnitude is a change in brightness by a factor of 2.512. For all scales, one full turn around the circle spans 20 photographic stops, or 15 magnitudes, or a brightness range of one million.

The three disks correspond to:
outer disk - exposure time, with corrections for reciprocity failure (film only),
inner disk - object surface brightness information, and
middle yellow disk - film speed and focal ratio.

The clear plastic sector is the cursor and attenuation scale. All these are discussed separately below.

Outer Disk

The outer (largest) disk shows exposure times from $^1/_{1000}$ to 1000 seconds (16.7 minutes). There are several phenomena that will affect your exposure:

- reciprocity failure (for film),
- atmospheric extinction, and
- filter factor (if filters are used).

For digital cameras reciprocity failure can be ignored. Most photographic films suffer from reciprocity failure when exposure times exceed about one second.

The inner half of the outer disk shows exposure times corrected for three reciprocity failure rates. For interested users, the formula for calculating these is:

$$T_{corr} = (T_{calc} + 1)^{1/p} - 1$$

T_{corr} = the corrected exposure (seconds);
T_{calc} = the exposure (seconds) determined from the photographic equation; and
p = Schwarzschild factor. It is 1 when reciprocity failure is negligible and we use the times on the outermost scale. As reciprocity failure worsens for slower to faster films (p = 0.9, 0.8 or 0.7, respectively), we use the exposures on the inner annulus of the outer disk.

The exposure times corrected for reciprocity failure are positioned with the corresponding “p” factor labels (values for p = 0.8 run along the dotted line). As a rule of thumb, the “p” factors and their corresponding film speed ranges are approximately: ISO < 200 ⇒ p=0.9; ISO between 200 and 800 ⇒ p=0.8; and for ISO > 800 ⇒ p=0.7. These recommendations are not cast in stone, as temperature affects reciprocity failure (cold will lessen, or improve it), and variations are often found even within a manufacturer’s line of same-speed films. Exposures longer than 60 seconds on the reciprocity failure-corrected scales are indicated in minutes.

An insidious side effect of reciprocity failure is to be found in many color films; the red-, green-, and blue-sensitive emulsions often have slightly different reciprocity failure rates, resulting in a color shift during very long exposures. Reciprocity failure is one of the biggest unknown variables to deal with in long exposure photography, especially when exposing to the sky fog limit. Here is where experience with your favorite films comes in.

Digital cameras made for terrestrial imaging suffer virtually no exposure dependent effects when imaging celestial objects and they are designed to compensate for the response of the camera’s CCD to different colors. This makes imaging both easier and more predictable with CCDs than photographic film.

Inner Disk

The inner disk shows the range in surface brightness of most types of astronomical objects. The surface brightness scale around the disk’s edge is based on the astronomical magnitude scale.

Because a number of very bright and very faint subjects are included on the *Whiz Wheel*, the surface brightness scale extends over a factor of about 200 million, or more than two turns around the circle. This overlap necessitates tripling some of the brightness values on the scale.

Numbering on the scale begins at magnitude -10, which is just a little fainter than the surface brightness of the Sun (-0.58). This is near to but not associated with Mars. It ends more than two turns later at +22, at the brightness of a dark sky.

There are a series of shaded, nested arcs on the inner disk. These are the surface brightness ranges for most types of celestial objects. Each end of most arcs is labeled with the corresponding surface brightness in mag/arcsec^2.

The Moon's surface brightness on each day between new and full moon is plotted with the segmented arc. This brightness is the average for the illuminated surface, which can vary by a factor of two between the bright highlands and the darker mare.

The entire arc for Mercury would be longer than that of the Moon, except that we are more concerned with its brightness during the limited periods of best visibility around greatest elongation (the dashed line at the middle of the segment).

The deep sky object arc is really a series of overlapping arcs, with each class of object dimming in the direction of the arrows right down to the sky fog limit. The same is true for some comet features, their brightness being similar to deep sky objects.

The penumbra of a lunar eclipse is not represented because it is mostly only a bit dimmer than the full Moon itself, and only gets significantly darker very close to the umbra where the brightness drops rapidly. The brightness of the Earth's umbral shadow (as seen during deep lunar eclipses) can vary quite a bit depending on what is happening in Earth's atmosphere, hence the long arc.

The earthshine brightness range is given for the period between one and four days before and after new Moon. Earthshine is brighter closer to new Moon.

Results obtained using any of these surface brightness values will give image densities on film comparable to a metered exposure of a subject with an average reflectance of 18%. For certain objects you may want to give a bit more or less exposure for aesthetic reasons. Earthshine is a case in point where you might like your image to more resemble the visual appearance, and also minimize overexposure of the bright crescent by shortening the exposure. The opposite is the case with Venus, where some overexposure will more faithfully depict its nearly blinding brilliance. Some otherwise faint subjects, deep sky objects in particular, can contain much brighter areas than the average values given here. An example would be the nucleus and bright knots in the spiral arms of an otherwise dim face-on galaxy.

Middle Yellow Disk

The middle yellow disk contains two scales: focal ratio on the outside and film speed on the inside. The focal ratio scale ranges from f/1.0 to f/1000, and this scale's index pointer (labeled "f/#") is located on the outer disk at the exposure time of $^{1}/_{100}$ second. Film speeds are located on the inner circle, and its index pointer (labeled "ISO") is on the inner disk at the surface brightness value of 9.2. Film speeds range from ISO 1 to ISO 100,000.

There is no published ISO speed rating for digital cameras, but this can be determined experimentally (see the section *CCD Effective Speed*).

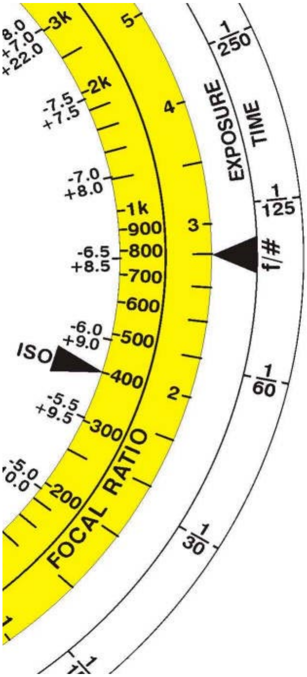
Clear Plastic Sector

This sector carries the cursor and an attenuation scale calibrated in magnitudes. The basic cursor is at 0 magnitudes of attenuation. The attenuation may be due to optical filters or attenuation by our atmosphere. This range should be sufficient for the use of most filters and atmospheric effects. Intermediate values of attenuation may be interpolated.

USING THE *WHIZ WHEEL*

To use:

1) *Turn the yellow disk to align your imaging system's f/number with the "f/#" index on the outer disk.*
2) *Turn the inner disk to align the "ISO" index with your film's speed rating (or effective ISO of an electronic detector) on the yellow disk.*
3) *Place the long line on the clear plastic sector over your subject or its surface brightness on the inner disk.*
4) *Under the same cursor line indicating your subject, read the exposure time on the outer disk. (If you need to compensate for filter/atmospheric attenuation, read the next section.)*



If the f/stop and ISO rating of the film or electronic detector remain the same, exposure times for any other subject can be scanned very quickly. Be aware that being a circular slide rule, the *Whiz Wheel* doesn't have built-in stops. In some situations your calculated exposure time will be outside the printed range. You must then either extrapolate, or change one or both of the f/ratio and ISO rating to get a reasonable exposure time. Trying to find exposure times for outlandish combinations will only give nonsensical results. Don't try to get the result of using ISO 25 film with an f/15 telescope for faint galaxy photography!

Example

Suppose you wish to get some good photos of one of those rare auroral displays (i.e. the northern and southern lights). Your camera is already loaded with the ISO 400 film you were using for constellation photos. That trusty 28 mm wide-angle lens would be a good choice, allowing you to frame the aurora with some interesting foreground objects. To keep the exposures as short as possible and better capture the quickly changing features, you will use the lens wide open at f/2.8. What would be a good starting exposure?

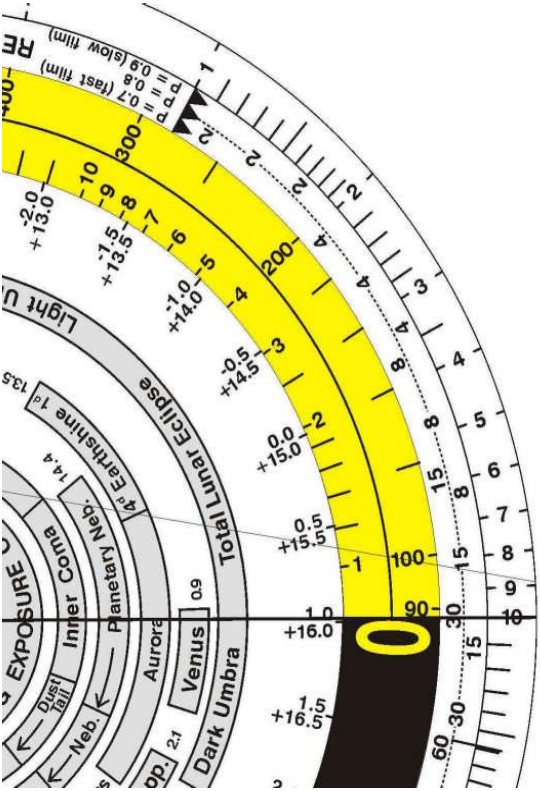
Begin by setting the lens aperture, or f/ratio, on the yellow disk. Rotate the disk until “2.8” is located at the “f/#.” index. Next, set the ISO by rotating the innermost disk until the “ISO” index points to “400” on the inner edge of the yellow disk.

Now, hold the three disks firmly in place while you move the clear plastic sector until the long cursor line is over the aurora arc, in this case about the middle of the arc.

The recommended exposure of 10 seconds is read along the outermost edge of the assembly, but as this is longer than one second, reciprocity failure should be taken into account. Assuming a “p-factor” of 0.8 for our 400 ISO film, we now read a corrected exposure of about 20 seconds on the middle scale of the three reciprocity failure correction circles (the dotted line).

As in all astro-photography, it is wise to bracket your exposures by at least one full stop over and under to ensure getting an optimum image, especially if you are unsure of the subject brightness or if the image will be particularly valuable to you.

Centering on our computed time of 20 seconds, a range of exposures that should guarantee a decent image of that aurora would be 5, 10, 20, 40 and 80 seconds. If you were using slide film you might even want to bracket at half-stop intervals because of its narrower exposure latitude than that of print film. With experience you will find that you can keep the bracketing of exposure times to a minimum.



To calculate an exposure time for the Sun, it is necessary to include the effect of filters, which is discussed in the next section.

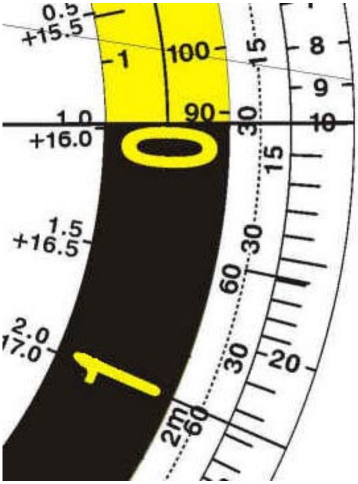
CORRECTING FOR THE ATMOSPHERE AND FILTERS

On the back of the *Whiz Wheel* is a table (**Altitude/Attenuation/Filter Factor**) indicating the brightness loss with altitude above the true horizon due to absorption and scattering in our atmosphere. It lists the corresponding altitude, in degrees, for each 10 percent of light loss. To correct for atmospheric attenuation, find the exposure for the undimmed subject, and then read the new exposure under the appropriate attenuation index on the clear plastic sector.

Another complication arises when imaging through filters, as light is *always* lost by some amount. Common photographic filters usually have a **filter factor** indicated on the filter or with its package. If it is not available, you can take a meter reading of a daytime scene with and without the filter to roughly determine the filter's light loss. The filter factor equals $2^{(\text{f/stop loss})}$. So for example, if your meter reading showed a 3-f/stop loss, the filter factor would be 2^3, or 8 (i.e. $^{1}/_{8}$ of the light is transmitted). This corresponds to about 2¼ magnitudes.

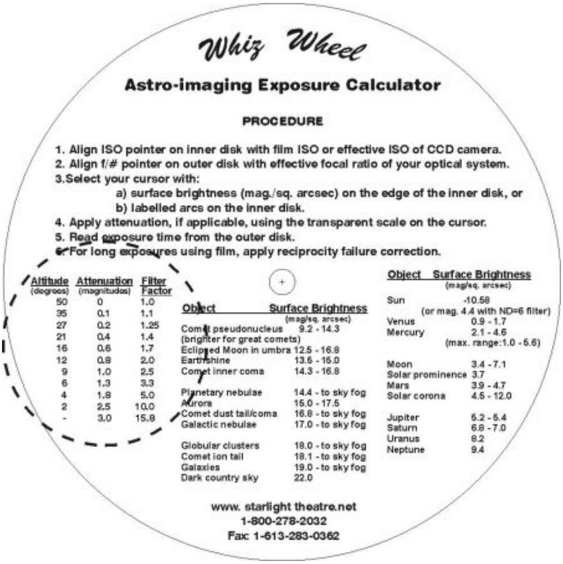
Some filters are rated by their *density*, which is the logarithm of the opacity. In other words, $10^{(\text{density value})}$ = the filter factor. A filter of density 2.0 blocks light by a factor of 10^2, or 100 (the filter factor) and therefore transmits $^{1}/_{100}$ the light. Keep in mind that store-bought thread-in neutral density filters are numbered by filter factor, *not* by the logarithm of the opacity.

Once the filter factor is determined, you can refer to the table on the back of the *Whiz Wheel* to read off the filter's attenuation in magnitudes.



Begin by setting the cursor (at 0-attenuation) as for non-filter work and then read the adjusted exposure under the appropriate attenuation index. Remember that when using film, if the new exposure is longer than one second compensate for reciprocity failure. Be aware that combinations of detector, filter and subject can alter the effective filter factor due to the spectral characteristics of each.

Keeping to our aurora example in the previous section, suppose you had a polarizing filter on your lens that was stuck and couldn't be removed, but you needed that wide angle shot for the right effect.



Whiz Wheel

Astro-imaging Exposure Calculator

PROCEDURE

1. Align ISO pointer on inner disk with film ISO or effective ISO of CCD camera.
2. Align f/# pointer on outer disk with effective focal ratio of your optical system.
3. Select your cursor with:
   a) surface brightness (mag./sq. arcsec) on the edge of the inner disk, or
   b) labelled arcs on the inner disk.
4. Apply attenuation, if applicable, using the transparent scale on the cursor.
5. Read exposure time from the outer disk.
6. For long exposures using film, apply reciprocity failure correction.

Altitude (degrees)	Attenuation (magnitudes)	Filter Factor
50	0	1.0
35	0.1	1.1
27	0.2	1.25
21	0.4	1.4
16	0.6	1.7
12	0.8	2.0
9	1.0	2.5
6	1.3	3.3
4	1.8	5.0
2	2.5	10.0
-	3.0	15.8

Object	Surface Brightness (mag/sq. arcsec)
Comet pseudonucleus (brighter for great comets)	9.2 - 14.3
Eclipsed Moon in umbra	12.5 - 16.8
Earthshine	13.6 - 16.0
Comet inner coma	14.3 - 16.8
Planetary nebulae	14.4 - to sky fog
Aurora	15.0 - 17.5
Comet dust tail/coma	16.8 - to sky fog
Galactic nebulae	17.0 - to sky fog
Globular clusters	18.0 - to sky fog
Comet ion tail	18.1 - to sky fog
Galaxies	19.0 - to sky fog
Dark country sky	22.0

Object	Surface Brightness (mag/sq. arcsec)
Sun	-10.58 (or mag. 4.4 with ND=6 filter)
Venus	0.9 - 1.7
Mercury	2.1 - 4.6 (max. range:1.0 - 5.6)
Moon	3.4 - 7.1
Solar prominence	3.7
Mars	3.9 - 4.7
Solar corona	4.5 - 12.0
Jupiter	5.2 - 5.4
Saturn	6.8 - 7.0
Uranus	8.2
Neptune	9.4

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Assume the filter cuts the light transmission by half, or one f/stop, which would be a filter factor of 2. On the reverse side of the Whiz Wheel, we have an attenuation table. A filter factor of 2 corresponds to 0.8 magnitudes. Without moving anything on your wheel, the new exposure is now read under the estimated position for “0.8” on the clear cursor segment. The uncorrected exposure is 20 seconds, which is twice as long, or one f/stop longer, than without the filter. Correcting for reciprocity failure now gives a suggested exposure of about 45 seconds. As before, bracketing around this is wise.

The above procedure applies mostly to brighter subjects such as the Moon and planets, etc., which are brighter than about 14 mag/arcsec^2, and where there is sufficient contrast to ensure the exposure will not strongly record the sky background. Dimmer objects at low elevations will hardly be brighter than airglow, lingering twilight or light pollution. The added brightness and reduction of contrast may actually dictate that exposure times be somewhat *shortened*.

DIGITAL IMAGING

Long photographic exposures become crippled by reciprocity failure unless extraordinary measures are taken (i.e. gas hyper sensitization or cold emulsion photography). Digital (CCD) cameras are not subject to this phenomenon and the inherent efficiency by which they convert light energy into digital data makes them more effective than film for imaging many astronomical objects.

Entire books have been written about the techniques of digital imaging. This pamphlet will explain only how the *Whiz Wheel* can be used to estimate exposures of astronomical objects. There are two aspects of electronic imaging that affect the use of the *Whiz Wheel*: the detector’s effective ISO and, to a lesser extent, its spectral sensitivity.

There are no published effective ISO values for CCD detectors as there are for photographic films. Moreover, there can be a significant difference in the sensitivity between CCDs. Although some non-astronomical cameras allow users to select an ISO setting, this does not change the sensitivity of the camera's CCD. But once the sensitivity (effective ISO) has been determined, the results with the same camera will be repeatable.

CCDs are sensitive from the blue part of the visual spectrum to well into the near infrared (NIR). The blue sensitivity is often relatively low, but this is improving as new detectors are developed. Therefore, more than just the visual brightness should be included when judging the surface brightness of an object. The bolometric brightness is more useful than the visual brightness because it includes the brightness of an object over the entire spectrum. An exposure based on visual brightness may over expose the object unless filters are used to cut off the NIR hitting the CCD.

Most publications do not list the bolometric brightness, which includes the IR part of the spectrum, so some insights into the nature of the object may be necessary. Generally, objects that shine light (or reflect light) like our Sun (planets and solar-type stars) will include a relatively low amount of infrared light (3%). Objects shining with or reflecting cooler sources light (surface temperatures < 4000 K) will emit substantially more infrared light. In the case of reflection nebulae, particle size will also affect the amount of IR that is reflected. Small particles (size < wavelength) scatter little long wavelength light, hence their blue color. The IR light these particles emit is too far into the IR for common CCD cameras to detect.

CCD Effective Speed

The effective ISO of your digital camera depends on the physical design of your camera AND how stringent you are regarding image quality. What is sufficient for you may not be sufficient for someone else. The quality of an image depends on the signal to noise ratio (SNR). Generally, longer exposures have better SNR. To determine a reasonable exposure requires that you know the sensitivity of your CCD. Here is a method to determine its effective ISO.

1. *Take an image of an object with low contrast features and known surface brightness, ideally using an exposure time close to the best one.*
2. *Using image-processing software, quantitatively assess the image and, if necessary, scale the exposure so that the average intensity of the subject is about 75% of maximum.*
3. *Set your focal ratio with the f/# indicator, then place the cursor on the scaled exposure time on the outer circle. Be sure to correct for filter and atmospheric attenuation if applicable.*
4. *Rotate the inner disk so that the surface brightness for the object is under the cursor, then read off the effective ISO for your CCD.*

The characteristics of the CCD detectors in the digital cameras vary between models and manufacturers. However, the value you determine should not change for your camera. To remember your camera's effective ISO, write it on the back of the *Whiz Wheel*.

VIDEO IMAGING

One of the most frustrating problems we must deal with in lunar and planetary imaging is the blurring effect of our atmosphere. "Astronomical seeing" is caused by the mixing of relatively warm and cool pockets of air along our line of sight. We can minimize this by taking short exposures. Fortunately, the Moon and planets are bright enough so that relatively short exposures can be used. However, the random nature of "seeing" forces us to take many images in the hope that a few will be sharp.

The most efficient way to get these images is with video equipment, and then use commercial software to extract the best ones. But we still must use appropriate exposures to ensure that the images contain the optimal amount of information for subsequent processing.

Judging the exposure on a television monitor will not always work. The brightness and contrast of a TV screen can be adjusted to make us think the exposure is good. However, the exposure may not actually be the best.

In the same manner as outlined in the previous section, you can use the *Whiz Wheel* to determine the approximate ISO of your video system. Here's how.

Adjust the brightness, colour and contrast of a good quality television monitor so as to display a good rendering of a commercial broadcast. At the telescope, videotape an object with a limited range of surface brightness: a bright outer planet will be fine. Select an effective focal ratio or filter that will give a good image on your quality TV set — not the cheap monitor you carry into the field. Set the cursor, accounting for attenuation as appropriate, to $^1/_{60}$ second (or longer if you're using a time integration setting on your camera). Rotate the yellow disk to set the f/stop. Finally, rotate the inner disk until the subject appears under the cursor. The equivalent ISO is read off at the usual place.

With the effective ISO known, the *Whiz Wheel* will help you select a focal ratio and filter for optimal imaging in the future.

SOME FORMULAE

Definitions:

SB = surface brightness (mag/arcsec^2)
B = linear brightness value for brightness table
m = integrated visual magnitude (usually listed in catalogs)
A = area in arcsec^2

$SB = m + \log A / 0.4$
$mag/arcsec^2 = mag/arcmin^2 + 8.89$
$B = 2.512^{(9.256 - SB)}$
$SB = 9.256 - \log B / 0.4$

OBJECTS RANKED BY SURFACE BRIGHTNESS AND LINEAR BRIGHTNESS VALUE (B)

Object	Surface Brightness (mag/arcsec^2)	Brightness Value* (B)
Sun	-10.58	8.58x10^7
	(B=85.8 or 4.4 mag/sec^2 with ND=6 filter)	
Venus	0.9 - 1.7	2200 - 1050
Mercury	2.1 - 4.6	750 - 75
	(max. range: B=2000 - 29 ; mag/sec^2 =1.0 - 5.6)	
Moon	3.4 - 7.1	220 - 7
Solar prominences	3.7	160
Mars	3.9 - 4.7	138 - 66
Solar corona	4.5 - 12.0	80 - 0.08
Jupiter	5.2 - 5.4	42 - 35
Saturn	6.8 - 7.0	9.6 - 8.3
Uranus	8.2	2.6
Comet pseudo nucleus	9.2 - 14.3	1.0 - 0.01
	(This can be much brighter for the best comets)	
Neptune	9.4	0.88
Moon in umbra	12.5 - 16.8	0.05 - 0.001
Earthshine	13.5 - 15.0	0.02 - 0.005
Comet inner coma	14.3 - 16.8	0.01 - 0.001
Planetary nebulae	14.4 - to sky fog	0.009 - to sky fog
Aurora	15.0 - 17.5	0.005 - 0.0005
Comet dust tail/coma	16.8 - to sky fog	0.001 - to sky fog
Galactic nebulae	17.0 - to sky fog	0.0008 - to sky fog
Globular clusters**	18.0 - to sky fog	0.00032 - to sky fog
Comet ion tail	18.1 - to sky fog	0.0003 - to sky fog
Galaxies	19.0 - to sky fog	0.00013 - to sky fog
Dark country sky	22.0	0.000008

* The Brightness Value column lists the surface brightness on a linear scale.

** Technically these are not extended objects, as they are made of stars, but they can be treated as such when imaged with telescopes of less than about 1000 mm focal length and their stars are not resolved.

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