LUNAR ECLIPSE ASTROPHOTOGRAPHY

for better photography of an amazing lunar event

CONTENTS

INTRODUCTION

Lunar eclipses are events that occur approximately once every six months as the Moon passes through Earth's shadow. At the Moon's distance from Earth, Earth's shadow is approximately four times the Moon's size. The Moon's shadow at Earth's distance is much smaller, measured on the scale of several kilometers instead of thousands of kilometers. Because of this, solar eclipses are fairly short events whereas lunar eclipses can last several hours.

Lunar eclipses can be frustrating to photograph, even if one has already mastered photographing the moon under normal circumstances (also covered in this guide). This is because during a total lunar eclipse the Moon can easily dim by over a factor of 10,000 in brightness which messes up metering, exposure lengths, and gets into the realm where tracking the movement of the moon over a longer exposure becomes a problem.

The purpose of this guide is to give practical advice on (a) photographing a lunar eclipse, and (b) processing the photographs in a way to bring out the most detail with the least amount of image noise. This guide is also geared towards photographing a *total lunar eclipse* rather than a *partial* or *penumbral* eclipse. However, since the Moon will show these other types during a total eclipse, this guide can be used to photograph any lunar eclipse.

It is recommended that you go out and test these techniques to learn the limits of your equipment and software *before* a lunar eclipse event so that you have the basics figured out already, you are experienced with your equipment and photographing the moon under normal circumstances, and you are not struggling during the event to determine proper settings.

It is highly recommended that you read this guide straight-through and use the different sections as a reference *only once you are familiar with it in its entirety*. This is mainly because different pieces of information are introduced at different times and not necessarily in a completely linear manner (for example, the last section "Additional Photographing / Processing Tip: Image Arithmetic" contains information that you should use in both the photographing and processing sections).

SOME TERMS EXPLAINED

Photography/Camera Terms

<u>Aperture</u>: Aperture is the opening through which light enters at the front of the camera lens. Modern lenses have generally a 5-8 blade system that is used to shrink or expand the aperture within the limits of the physical size of the lens itself. An "open" aperture has a low *f*/number and lets in the most light. A "stopped down" or "closed" aperture has a high *f*/number and decreases the amount of light. Every change in 3 *f*/numbers is "1 stop."

<u>Focus</u>: Focus is when an object is not "fuzzy" but sharp and crisp. Almost all camera lenses (Zeiss being a notable exception) have auto-focus capabilities, but they require a reasonable amount of contrast in the scene to find the proper focus. For the moon, many camera systems cannot automatically focus, and so manual focus is necessary.

ISO: This is the digital equivalent of film "speed." It is a digital gain which will increase or decrease the intensity of the image recorded on a CCD or CMOS detector. ISO does *not* actually increase nor decrease the amount of light that the detector receives, just how much it is multiplied by in the final image. Because of this, any increased ISO will increase the brightness in the final image, but it will also increase the amount of noise, since noise is amplified along with the signal.

Shutter Speed: This is the length of time that the shutter is open and lets light in through the camera to be recorded. This is generally synonymous with exposure length.

Saturated: Your camera's detector works like millions of tiny buckets that hold bits of light. Each bucket can only hold so much before it becomes full. At that point, adding more light to the bucket won't change anything. When this happens, it is called "saturated." The bucket - pixel - will appear completely white in your final photograph.

Moon Terms

Full Moon: This is a lunar phase when Earth is between the Sun and Moon and we see the completely lit side. This is the only time when a lunar eclipse can happen.

New Moon: This is a lunar phase when the moon is between the Sun and Earth and we see the unlit side. This is the only time when a solar eclipse can happen.

Phase: The amount of "fullness" that the moon appears to have as seen from Earth. A crescent phase is less than half full, a gibbous is when it is more than half full. A waxing moon is when it is getting more full, and a waning moon is when it is getting less full. A first quarter moon is when it is a waxing half moon, and a third quarter moon is when it is a waning half moon.

Eclipse Terms

First Contact: The Moon's limb first enters Earth's shadow.

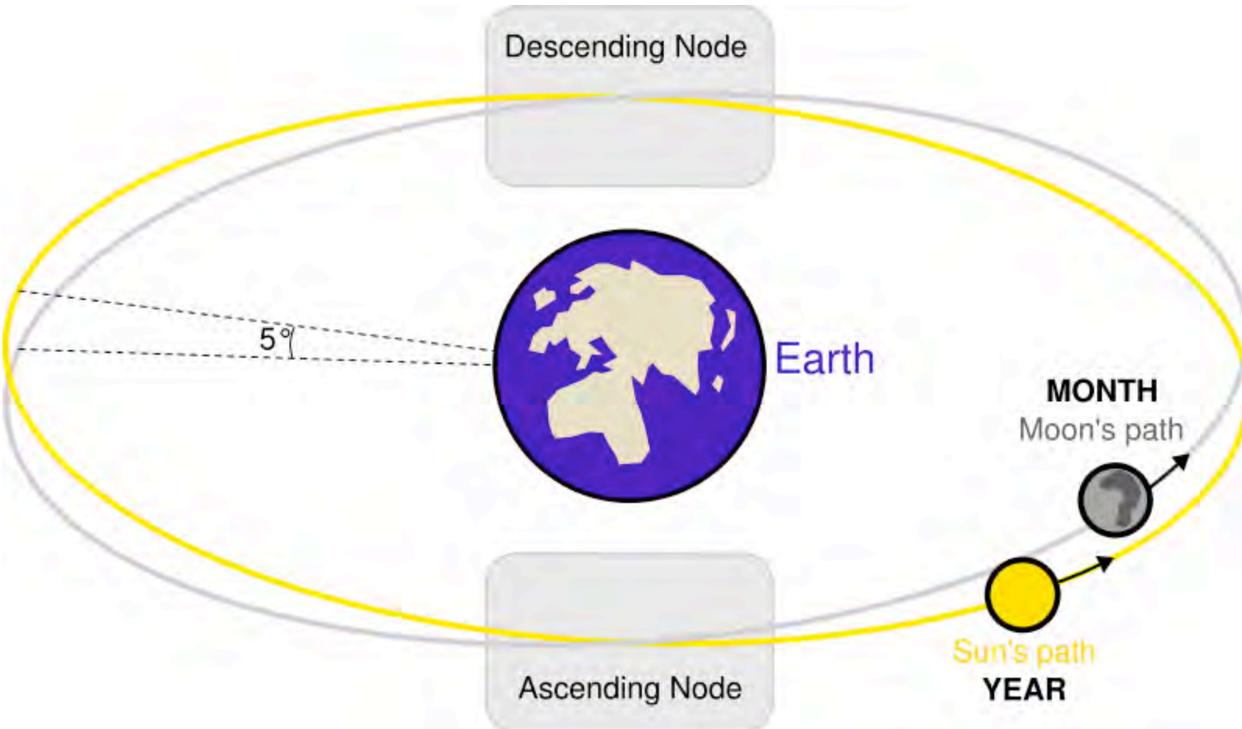
Penumbra: Literally, "almost shadow." Earth casts a circular shadow into space, and that shadow has an outer ring and an inner circle. The outer ring is called the "penumbra." If you were to stand within the penumbra, you would observe Earth blocking part of the sun. From your point of view, you would see a partial solar eclipse. When the moon is in the penumbra, it will appear to darken slightly as seen from Earth.

Umbra: Literally, "shadow." This is the inner circle of Earth's shadow. If you were to stand in the penumbra, you would see a total solar eclipse. When the moon is in the umbra, it will appear to darken significantly, and it will also turn a bloody, ruddy red.

The Science of Lunar Eclipses - What Is Going On

Orbital Information

Earth orbits the Sun once in approximately 365.25 days. For all intents and purposes, the Earth orbits the Sun in the same plane year after year. The Moon orbits Earth once every 29.53 days. It also orbits in a plane, but that plane is tilted relative to Earth's orbital plane by 5.1°. That means the Moon will *only* be in the same plane as the Earth and Sun two times in a lunar orbit (called "nodes"). These crossing points are, more often than not, *not* lined up so that the Sun, Earth, and Moon form a straight line.



This is illustrated in the picture above. It shows the Sun's path *relative to Earth* as a yellow line. The Moon's path is illustrated as a grey line. These can be thought of as the paths of these two objects through Earth's sky. The Moon will make one full revolution in 29.53 days, whereas the Sun will take the 365.25 days. Unless the two bodies are at the same nodal point at the same time, there will *not* be an eclipse.

Remember, this diagram is *not* meant to imply the Sun orbits Earth. Think of it more as illustrating the Sun's and Moon's paths through Earth's sky throughout the year.

When Earth, the Sun, and Moon all form a straight line in space, Earth will witness either a solar eclipse or a lunar eclipse, depending upon the order of alignment. If the Moon comes directly between the Sun and Earth, we will have a solar eclipse (the Sun is eclipsed by the Moon), and if Earth comes directly between the Sun and Moon, we will see a lunar eclipse.

Since the Sun-Earth-Moon system must line up exactly in order to produce an eclipse, eclipses are more likely to be "partial," meaning that the Moon's (in the case of a solar eclipse) or the Earth's (in the case of a lunar eclipse) body only covers part of the Sun, as seen from the other object. To help visualize this effect, close one eye, and hold your hand at arm's length towards a light bulb. Partially block the bulb. That is a partial eclipse. Now completely cover the bulb. That is a total eclipse. Your hand can be in many more places to get a partial eclipse than a total eclipse.

The reason I address both types of eclipses - lunar and solar - is that it is sometimes easier to think of different parts of a lunar eclipse by thinking of its analogue as a solar eclipse. After all, a lunar eclipse seen from Earth is the same event as a solar eclipse as seen from the Moon.

Stages of a Lunar Eclipse

A lunar eclipse has 6 main "contact" points (as defined by NASA) that define the main stages:

- P1 - Initial stage of contact, when the Moon *first* enters Earth's penumbra.
- U1 - Initial stage of contact with Earth's umbra. You will generally not see any change in the moon with your eye until this stage.
- U2 - Entire moon is within Earth's umbra. This is called "Totality."
- U3 - Moon's limb begins to exit Earth's umbra, moving into the penumbra.
- U4 - Moon's limb emerges from Earth's penumbra. Past this stage, the moon will not look much different to your eye.
- P2 - Entire moon is outside of Earth's shadow, ending the eclipse.

This makes listing times easier for websites, but for my purposes, I usually think of the eclipse as having 5 stages: No eclipse, penumbral eclipse, umbral eclipse, penumbral eclipse, and finally no eclipse. You can have part of the Moon in one stage and another part in another, so perhaps NASA's terminology is easier to understand. That is up to you.

Earth's penumbral shadow is approximately four the diameter of the full Moon. Because of its large size, *if* the Moon takes the longest path through the center (the moon is *exactly* on a node), the entire eclipse (P1 through P2) can last upwards of 6 hours. Earth's umbral shadow is approximately twice the diameter of the full Moon, and the umbral eclipse (often referred to as "totality" when the entire Moon is within Earth's umbra) can last up to 3 hours.

In practicality, most lunar eclipses are shorter than this idealized 6 hour time.

Why You Can See the Moon During a Total Eclipse and Why It Is Red

If the Moon is completely within Earth's shadow such that the Sun is completely blocked from sending light on its surface, then the question may be asked, why you can see it at all? The reason lies in Earth's atmosphere.

Earth's atmosphere acts like a lens, bending light that passes through it. Even though the solid part of Earth is blocking the Sun completely, the atmosphere can still bend light around the Earth, allowing the Moon to remain visible.

As the atmosphere bends the light, it also filters the light and it does not treat all colors equally. It preferentially will scatter shorter-wavelength light - bluer light - which is why the sky appears blue during the day. It will still scatter longer-wavelength light - red light - but much less than it will scatter the bluer light.

The more atmosphere the light passes through, the more the longer wavelengths (redder light) will also be scattered, which is why sunsets are red. After passing around Earth's disk to reach the Moon during a total lunar eclipse, the Sun's light has passed through *a lot* of Earth's atmosphere, filtering out most of the bluer colors and leaving only a little bit of red light left to reflect off the Moon, giving the lunar eclipse its red colors.

Equipment Needed/Recommended to Photograph a Lunar Eclipse

1. Camera with Manual Settings

At the very least, you will need a camera with which you can *manually* set the exposure length, aperture, focus, and ISO.

Manual focus is a must because, unless you are using a long telephoto lens (300 mm equivalent or longer, probably), your camera will likely not be able to automatically focus on the Moon. It will focus in and out and never find where the proper focus point really is. In addition, if you simply focus at "infinity" or "∞" as marked on the lens, it still will not be at the proper focus point because there is some degree of play built into the lens to compensate for changes in temperature, focal distance, and other variable factors. Often, you will need to manually find the proper focus point and you will not be able to rely upon your camera's auto-focus nor even the markings on an SLR camera's lens.

Manual exposure length (AKA shutter speed) and aperture go hand-in-hand for my purposes in this guide because they both control how much light will be recorded by the camera's detector. A longer exposure length or a wider aperture (lower *f*/number) will give you the same effect - more light. A shorter exposure length or a smaller aperture (higher *f*/number) will give you the same effect as well - less light. You need to be able to set these manually because your camera will otherwise likely over-expose any image of the moon (unless you rely upon spot-metering, which is not addressed in this guide).

A camera determines the exposure and aperture by taking a reading of how much light is in the field of view - an *average* over the *entire* field (again, unless you're spot-metering). If the image in the camera's field of view is of a mostly dark sky with a small circle of white (the Moon), then the *average* of the entire field is fairly dark. The camera will then interpret this average dark scene as needing a long exposure so that the *average* light recorded will be a neutral 50% intensity. In actuality, you want the night sky to be nearly black and the Moon to be properly exposed, requiring a shorter exposure than your camera thinks is necessary.

If you only set the camera to manually select either the shutter *or* aperture, it will try to compensate by setting the other automatically and still over-expose the moon. I recommend choosing a wide aperture, perhaps ⅔ to 1⅔ *f*/stops (2 to 5 "changes") smaller than your maximum (that is where the lens is usually sharpest), and then only adjust the exposure length. A good website to check for *your* lens' sharpest aperture is `http://www.photozone.de/all-tests`.

An alternate way to think about shutter speed and aperture is to think about it in terms of EV, or "Exposure Value." EV is defined as:

$$\mathrm{EV} = \log_2\left(\text{aperture}^2 / \text{shutter speed}\right)$$

EV is useful because it is ISO-independent, and it combines aperture and shutter speed into one term to easily show how much light reaches the camera sensor. Also, objects can be defined as having a certain EV of brightness. For example, the "sunny 16 rule" is defined as an aperture of *f*/16 and a shutter speed of $1/100^{\text{th}}$ second for an ISO 100 to properly expose a sun-lit scene which has an EV15. In a cloudy scene, the highlights may have an exposure of either *f*/11 at $1/100^{\text{th}}$ of a second, or *f*/16 at $1/50^{\text{th}}$ of a second, which corresponds with EV14. If you increase the ISO by one stop (such as from ISO 200 to ISO 100), you must make a corresponding 1 EV decrease to compensate.

The full moon is approximately EV15 according to Wikipedia; however, I have found it - on average - to be closer to EV12-EV13 (why this is the case is addressed in the "How to Photograph the Moon" section). Thus, if your sharpest aperture is *f*/8, then your shutter speed should be 1/120-sec (if EV13). (Note that this is covered again and in more depth in the "How to Photograph the Moon" section.)

Besides aperture and shutter speed, manual ISO is also important, again for the reason mentioned above: Your camera may try to compensate with your manual exposure by increasing the ISO to give a brighter picture. You do not want this. The lower the ISO, the less noisy the end image will be, so you should try to set this to the lowest ISO you can and work from there. In terms of EV, you need to divide your shutter speed by any change in ISO (so if you go from ISO 100 to ISO 200, that is a factor of 2 or a 1 stop change, so divide your shutter speed by 2 to increase the exposure value by 1 stop get the same amount of light).

Remember, though: ISO does *NOT* change how much light the sensor receives, only how much it amplifies the signal of the light when recording the image. Due to this being a strictly electronic process (or chemical in the case of film), any *noise will also be magnified*.

Finally, if your camera has RAW capability then you should be photographing in RAW mode. JPEG adds compression which negatively affects image quality, starting with the blue channel and dark areas of the picture (not something you want in a dark image!).

2. Tripod

Though a tripod is not necessary for the very first phases of the eclipse, but it will become necessary as the Moon embeds itself further within Earth's shadow. In the beginning of the eclipse, you will probably find yourself taking exposures of ~1/120-sec. However, during totality, your exposures may lengthen to several seconds, or possibly over a minute. It is humanly impossible to hold a camera still for this length of time.

However, you should use a tripod for the duration of the eclipse because (1) you do not have to manually re-locate the Moon between photos very much, and (2) it will allow you to take longer exposures without any concern of camera shake; depending upon how steady your hands are, this may actually be a necessary piece of equipment. Invest in a tripod and you will be thankful! Another piece of equipment that will be helpful is a wireless remote/trigger or cable release so the camera does not shake when you press the shutter release to take the photo.

3. Telephoto Lens

Although any length lens can photograph the moon, the longer the lens, the more detail you will be able to capture simply because it will appear larger in the picture. Note that, if you are using a non-SLR, I recommend *not* using the "digital zoom" as this has nothing to do with optics and gives you the same (but often worse) image you would get when manually resizing in Photoshop or other image editing software.

Ideally for imaging, you want your subject to fill the entire field of view of the lens to give you the maximum final resolution. The Moon averages ~30' (or ½°). A lens that gives this field of view vertically is approximately a 2700 mm equivalent (divide by any crop factor your camera body may introduce, such as 1.6x on the Canon Digital Rebel series, so a 1700 mm lens would work in that case). As stated above, though, this is the theoretical *maximum* length you would ever want to use for a single-image shot, and it does not mean you cannot use a shorter lens, such as a 1000 mm, 500 mm, 300 mm, 200 mm, 100 mm, or even 50 mm. This will simply give you a smaller moon with less detail in the final image.

4. Mount that Tracks the Sky

The moon moves from East to West, just like the Sun and stars appear to move, though its rate is ever-so-slightly less than other objects'. This motion is not significant when photographing a full Moon as you can take relatively short exposures and so will not capture its movement. However, the longer your lens and the slower your exposure, the more this motion plays a role.

When I use an 800 mm lens (~1300 mm equivalent) to photograph the Moon, I can see motion within 1 second. With a 300 mm lens (~500 mm equivalent), I see motion within 5-10 seconds. This is, therefore, really a non-issue when just photographing the moon normally, and only becomes important when photographing earthshine or eclipses. It is also fairly easy to calculate how fast the moon will move across your camera's sensor (see Appendix B).

Since part of the purpose of this guide is to explain how to photograph eclipses, you *will* need a mount that tracks the sky for some of the darker parts of the eclipse - the U2 contact up to the U3 contact. These necessitate a much longer exposure (last eclipse, I was using ISO 100 (I should have increased this) and exposures at f/12 of 75 seconds and the Moon was still barely visible).

Finding a Suitable Location

This is a short section because there is really no magic in finding a suitable outdoors location. Just make sure you can see the Moon. If you cannot see the Moon, move to a different location. If there are bright lights in the area that interfere with your view, move to a different location. If the Moon moves behind a tree, move so you can see it. The best places are away from bright lights, sheltered from the wind, and at a high altitude (like on top of a mountain).

If the confusion about finding a suitable location is more about the final product - having the phases of the eclipse arcing over a cityscape or landscape - then go to this guide's section entitled "Putting It All Together - The Final Product."

How to Photograph the Moon: Out of Eclipse, Any Phase

This section is the most important to photographing a lunar eclipse, even though it covers how to photograph the moon more generally. This is also the longest section. If you can master this, and if you understand what is going on, then photographing the actual eclipse will be significantly easier. You will want to focus on firmly establishing yourself as being able to photograph the full moon after reading this section, since lunar eclipses can *only* happen during a full moon.

The steps to do this are (1) set up your equipment, (2) make sure it is working right, (3) determine your basic exposure settings, and (4) focus properly. So go ahead and do 1-2.

Steps 3 and 4 are somewhat iterative - you will need to determine your exposure so that you can focus. Then go back and make sure your exposure is still correct, and then if you have changed it, you will want to verify your focus is still correct.

When determining your exposure settings, remember that the three main things that determine how much light is recorded are (1) shutter speed / exposure length, (2) aperture, and (3) ISO (remember that shutter speed and aperture can be collectively referred to in the EV measurement).

1. **Set your ISO to its *lowest* setting** (this will probably be 100 or 200).
2. Set your aperture to its *largest* setting, which is the *lowest f*/number. Then increase the *f*/number by about 1-2 stops (remember, this is based upon a "sweet spot" of sharpness in most lenses). This will **usually be about *f*/8**.
3. Experiment with shutter speed until the moon is exposed properly. Use your *f*/number and an EV13 for the full Moon *as a starting point*. The following table should help:

f/number	1.4	2.0	2.8	4.0	4.5	5.0	5.6	8.0	14.0
Shutter Speed	1/4000	1/2000	1/1000	1/500	1/400	1/320	1/250	1/120	1/40

The above table should only be used *as a guide*, especially because the moon's brightness will vary depending upon its position in the sky, its phase, atmospheric turbulence, and particles and pollution in the air. If the moon is *not* full, you will need to *increase* the exposure length because there will be less light from it. I have found that thin crescent phases are approximately 10% the brightness of the full moon (so at *f*/8, you may need 1/10th - 1/15th sec. exposure).

An example: With an *f*/14 aperture on a 900 mm (1440 mm equivalent) lens, an exposure of around 1/120-sec properly exposed the full moon for me. That corresponds to EV14.5, and this was when the moon was near its highest point in the sky.

Another example: When using a 480 mm equivalent lens at *f*/5.6, an exposure of around 1/250- to 1/320-sec properly exposed the full moon a few months earlier.

Note that in these examples, the focal length has nothing to do with the exposure length, I just mention it for completeness' sake.

Take a Test Photo

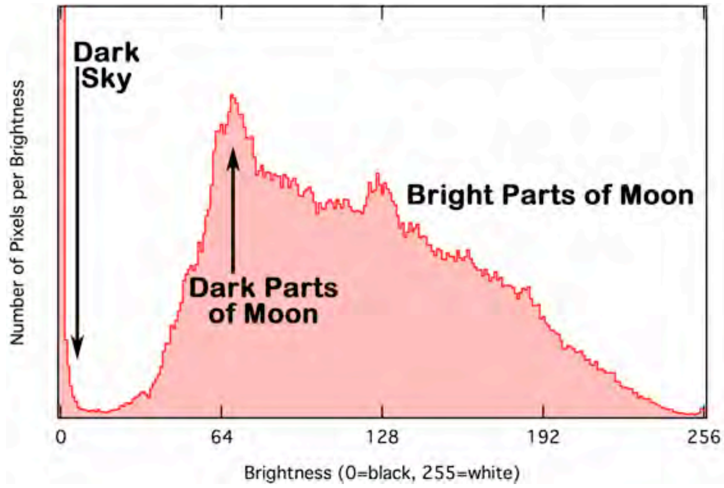
If the Moon appears too black/dark with your shutter speed, decrease the speed to allow more light in. If the Moon appears all white/bright with your shutter speed, increase the speed to allow in less light.

This is where using the Histogram feature on your camera helps. The Histogram is a graph telling you where most of the recorded light falls. If the Histogram peaks towards the left side, this means that most of the pixels in the image are dark. If the Histogram peaks towards the right side, then the opposite is true. Ideally, you want it to peak in the middle. But, unless the Moon fills the entire field of view of the image, this will not happen because the night sky will dominate the scene.

Therefore, most of the pixels will be fairly dark, up against the left side of the Histogram. However, there should be a peak in the brighter part of the Histogram (the right side) - this is the Moon. You want that peak to be somewhere in the middle of the Histogram. You do not ever want it to truncate prematurely against either side.

Further explanation of Histograms is not the purpose of this guide. For more information, many people recommend this webpage: `http://www.luminous-landscape.com/tutorials/understanding-series/understanding-histograms.shtml` .

The image below shows an example full moon and its annotated histogram next to it.



If you are finding that you need very slow shutter speeds at this point (such as 1/30-sec or longer *if* the moon is *more than* half full), then double-check your aperture and make sure that it is mostly open (you are using a small *f*/number). If you are finding you need really fast shutter speeds (such as 1/300-sec or faster), then double-check the ISO to make sure it is not too high.

Now, Focus, and Shoot the Moon!

To focus, set the manual focus at infinity, or if you have an SLR, then set it as far "past" infinity as you can. Take a picture. Either look at it on the camera's LCD screen (zoomed in), or at the image on a computer. It will probably be out of focus. Now - just a little at a time - change the focus in the other direction, and take another picture. Continue this process until the picture you take is in focus (or in focus enough for your purposes).

For me, this used to be the longest part of setting up and it can be a pain. But it is a very necessary step … you would not want to spend 5 hours out in the cold photographing the moon and come back and look at out-of-focus blobs. If you are photographing for a long time, you should also check the images periodically throughout the night to ensure the focus has not changed due to temperature, focus creep, or accidentally bumping the lens.

An alternative method that can be used on newer cameras involves the "Live View" feature - something that has been on Point & Shoot cameras for much longer than dSLRs. This is where you can view the field on the camera's LCD screen as opposed to through the viewfinder. On many of these, you can even zoom in to see finer details. Using the Live View, you can refine your focus much more easily and much more quickly -- it usually takes me about 10 seconds as opposed to several minutes. You may find it easier to refine your focus by looking at a bright star as opposed to the moon, getting the star to be a point instead of a big ball or doughnut.

Now that the lens is in focus, double-check the exposure Histogram to make sure your exposure settings are still alright, and adjust accordingly if they are not.

Now for the most important part: *Write down your settings!* These are your baseline settings and you can use them as a starting point for all other lunar photography. I usually make a detailed log of all my settings along with details of the night (how clear the sky was, any significant light pollution, etc.) and also any processing details in order to use as reference for future photography.

HOW TO PHOTOGRAPH THE MOON: DURING PARTIAL UMBRAL ECLIPSE

I am not covering how to photograph a penumbral eclipse *per se* because the beginning part of the penumbral eclipse really does not affect the appearance of the Moon. The Moon needs to be about 50% or more within Earth's penumbral shadow before you start to see a change, where a small part of the leading edge (towards Earth's East horizon) of the Moon will noticeably darken. At this point, photograph as you would the normal full Moon.

As the Moon continues to embed itself within Earth's shadow, you will start to notice that your Histogram of exposure is shifting to the left, indicating the Moon is getting fainter. You should adjust your exposure length accordingly, making it longer.

As the Moon reaches the U1 contact, that initial darkened corner will appear to go almost completely black. I recommend taking exposures of 2 lengths at this point - one to properly expose the brighter, penumbral section, and one to properly expose the darker, umbral section. In my experience, this requires a factor of about 100x difference in shutter speed (between 7-8 EV difference). So if, while just before the U1 contact you are taking 1/15-sec exposures, you should now be taking 1/15-sec and ~6-8-second exposures, the latter to properly expose the part covered by Earth's umbral shadow.

As the Moon slips further into the umbral shadow, you will find you need to take increasingly longer exposures (again, base this upon how bright it looks in the LCD screen / computer, and/or on the exposure Histogram; or, see the section at the end on Image Arithmetic).

This is also the point of the night where you may find the requisite exposure length is such that you capture the Moon's motion through the sky *if* you are not using a mount to track its movement. To compensate, you can start to increase the ISO and open the aperture completely. The resulting photograph will be a little noisier and a little blurrier, but that is better than having the Moon look like an arc of light due to its motion if you don't have a proper mount.

Note that during this entire "transition" phase through the penumbral to umbral eclipse, it may behoove you to take a few different shutter speeds around a given setting for each photograph. This will give you a few different options when processing the photographs, especially if you are not using your camera's RAW setting. Note that the different shutter speeds can be executed semi-automatically via a camera's "auto bracketing," which is sometimes abbreviated as AEB. Check your camera's manual to determine if you have this feature and how to use it if you do.

HOW TO PHOTOGRAPH THE MOON: DURING TOTALITY

Totality begins at contact U2 and ends at U3. It is when the Moon is completely within Earth's shadow and it will turn a deep rusty red color. The illumination, however, will be asymmetric, part of the moon appearing brighter than the other part, with a brightness gradient going across the entire surface. This is because part of the Moon will *always* be a little closer to the edge of the umbral shadow than the rest of the Moon, so it will appear a little lighter.

When I photographed the lunar eclipse of August 2007, totality lasted about an hour and I took 12 images (1 set of photos every 5 minutes). When I finished processing them, it was pretty neat to see the lighter limb of the Moon rotate nearly 180°, from the part that was the last to come into the umbral shadow to the part that was the first to exit. My point in this anecdote is that while you can just take one photograph during totality and call it a night, there is more going on that you can photograph.

I found my exposure length during totality going from 1/125-sec originally (when the Moon was not in Earth's shadow) to 30-sec just after U2 to 75-sec during mid-totality, when the Moon was darkest. Granted, I was using a fixed f/16 aperture lens, and I completely forgot about changing the ISO, but this represents over a factor of 10,000 change in brightness. This also presents practical problems with any tripod that does not track the sky (or the Moon) because a minute-long exposure is bound to show motion. Except for increasing the ISO even further which will result in noise that you may not consider tolerable, I would recommend resigning yourself to taking several shorter exposures and then adding them or averaging them together (see the section "Additional Photographing / Processing Tip: Image Arithmetic").

Otherwise, during totality, there is no need to take different length exposures for each "phase" - as during P1-U1 and U3-U4 - because the entire Moon is relatively in uniform brightness. For this reason, the partial umbral eclipse is probably the most difficult to both photograph well and to process to a final product that you enjoy.

How to Process the Photographs: What to Avoid

These photographs can be processed normally, as you would any other photograph. However, there are a few main tips - or pet-peeves of mine to avoid - that I would like to address.

Pushing the Contrast Too High

Do not try to enhance the contrast too much. The Moon (normally) appears black and white. Therefore, it is very tempting to alter the Levels, Contrast, or the Curves such that it makes the lunar mare (the dark parts) appear almost black and the highlands (the bright parts) appear almost white. But this is *not* what the Moon really looks like! It does not look like that to your eye and it does not look like that to your camera, so you should not try to make it look like that on your screen. In reality, the reflectivity of these regions vary by a factor of around 2-3.

Claiming to Use the "Sunny 16" or "Looney 11" Rule

Don't!

Okay, now that that's out of the way … the "Sunny 16" rule for photography is a rule-of-thumb approach on how to set your exposure settings (shutter, aperture, ISO) for a bright, sun-lit scene, and properly expose it. The claim goes, "The moon is brightly lit by the sun, so you should follow the 'Sunny 16' rule!"

This is true, the moon is lit by the sun (and a bit by Earth, but that's a different issue). However, the reflectivity of the lunar surface is around 8-10% … the reflectivity of Earth is generally 30-90%, with asphalt being the closest lunar analogue with a reflectivity of around 5-10%.

Consequently, if you use the "Sunny 16" rule, you will under-expose the moon, or at the very least not take advantage of the full dynamic range of your camera.

There is similar reasoning with the "Looney 11" rule, though it states, "Well, the 'Sunny 16' rule will under-expose the moon 'cause the moon's dark, so let's increase the aperture size and just modify the 'Sunny 16' to make it the 'Looney 11,' so you set your aperture to *f*/11."

While this modification will get you a decent exposure, it completely ignores where your lens is sharpest. Most lenses are sharpest around *f*/8, and the sharpness dramatically decreases for larger apertures. Since the moon is relatively small and the atmosphere can be very blurry, you want to take maximum advantage of your optics and *choose the aperture that's sharpest, not one that has a whimsical catch-phrase!*

Going for Super-High-Resolution When the Sky Won't Allow It

I'll be among the first to admit that I've been guilty of this: Claiming that I have a lunar image that's 7200 pixels across that's super-high-resolution. While this may be practically true - I may have an image of the moon that's 7200 pixels across, it completely ignores the practicalities of photographing through Earth's atmosphere.

Earth's atmosphere is turbulent. It moves around, and it moves in different directions at different elevations within the atmosphere. This is what makes stars "twinkle." The ability to resolve - see fine details - objects through Earth's atmosphere is defined by the term "seeing."

From the ground, the average site on Earth will have a seeing of about 1 arcsecond. There are 60 arcseconds in 1 arcminute, and there are 60 arcminutes in 1 degree. In other words, the moon, being about ½° across, is about 1800 arcseconds across ($0.5 \cdot 60 \cdot 60 = 1800$). This means that from an average location on Earth, even if the image that comes off your camera has the moon being 4000 pixels across, you do not have 4000 pixel's-worth of detail. So, you should decrease the resolution in your photo-editing software of choice.

There are of course exceptions. The best astronomical viewing sites are in deserts on top of mountains (Arizona, Hawai'i, Chili, etc.). At these sites, the best seeing is around 0.1 arcseconds, so you could theoretically get up to 18,000 pixels across of detail. Average seeing at these sites is more like 0.3-0.5 arcseconds, 3600-6000 pixels. And then on the other side, there are really bad locations. Here in Boulder, where we get turbulent air coming off the Rocky Mountains, seeing averages 2-3 arcseconds, limiting the usable resolution to 600-900 pixels across.

Note that there are ways to figure out the seeing in your location on a given night by photographing a bright star, but that is beyond the scope of this guide. Additionally, there are techniques to help mitigate the atmospheric distortion (image stacking), but that is also beyond the scope of this guide.

The take-home message here is that all because your camera may spit out an image at very high resolution, that does not mean that it is usable. Actually look at the image to see how many pixels across a feature appears, and then down-sample (reduce the image size) until that is closer to 1-2 pixels.

Using an Über-High ISO and Über-Fast Shutter Speed

I got into an argument with a guy once on a certain photography forum. He claimed that if you can get decent results with ISO 1600 and a shutter speed of around 1/2,000th sec, then why not use it? He was recommending this to a beginner who was trying to figure out how to photograph the moon and no one had yet recommended this guide (until I posted).

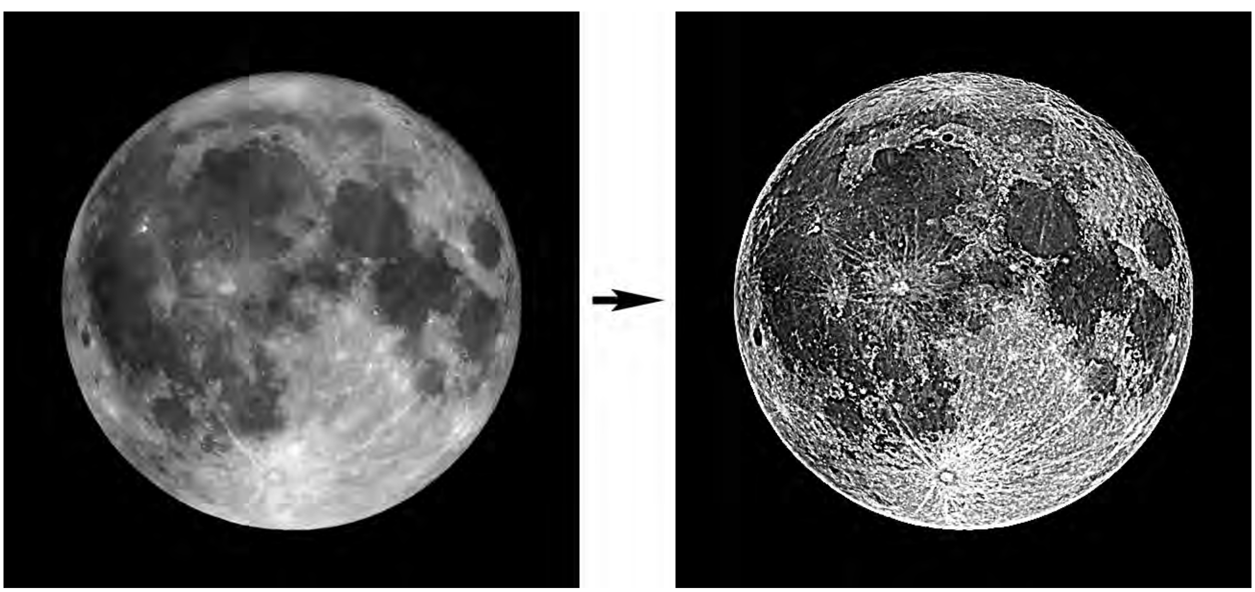
I explained to the poster that there was absolutely no good reason to be using such a large ISO. The difference in shutter speeds of 1/2000 versus 1/100 in terms of camera shake or the motion of the moon is completely negligible. And I really don't care what camera you're using - as of 2010, pushing any camera to ISO 1600 is going to introduce noticeable noise. The other guy argued that you can always lower it later on.

So I pointed out two reasons. First, if the guy is trying to take his first decent photograph of the moon, then he should start out with "good form" and use a low ISO. Second, I argued that if he got a good exposure with such a high ISO, the image would still not look as good as it could have if he had used a lower ISO. It would look grainy and have significant color noise.

Sharpening

Do not over-sharpen. I cannot emphasize this enough. Over-sharpening an image will result in a blob-like moon that looks like it was painted in oil or water colors. If you feel you must sharpen, then please pay close attention to what you are doing. Do not choose too large of a pixel radius over which to sharpen. Do it sparingly.

Below is an example of an over-sharpened moon, taken from the image I used above. The one on the left was sharpened with the Unsharp Mask filter. And this is not a Straw Man argument - I have seen people do this.



HOW TO PROCESS THE PHOTOGRAPHS: PARTIAL UMBRAL ECLIPSE

This phase of the eclipse is the most difficult of the three, the reason being the huge difference in brightness from the umbral shadow to the penumbral shadow. For your faster exposures, you have the penumbral part properly exposed but the part of the Moon in the umbral shadow is probably black. In your slower exposures, the darkest portions are now a ruddy red, but the penumbral part is saturated (completely white).

In the end, it comes down to a personal preference and how much processing in Photoshop you want to do. For the most basic processing, you can do your fast exposures and your slow exposures separately and choose one or the other - or even both - to keep, depending upon what your final display will be (see the "Putting it All Together - The Final Product" section).

An alternative that is "fake," but which the average Joe will not know is fake, is to use your longer exposures in combination with your shorter ones:

1. Use the slower exposure that properly shows the part in the umbral shadow. Process them such that the part in total eclipse is fairly dark, but that it is still easy to see details (image 1 below).
2. In a new Layer, paste one of your first images from the night (Moon completely out of Earth's shadow) over top. Set the Blending Mode to "Multiply," and lower the Opacity to around 40% (image 2 below). You will probably have to shift the top Moon image a little bit because the Moon will have wobbled a little and features will not nicely line up. It is more important to have the features that overlap in the umbral shadow to be aligned properly. This will have the added effect of giving more detail in the umbral part.

   This should now give you detail in the saturated penumbral shadow section that is fairly subtle, but remember that it is really bright so all you want is a subtle hint of what is there (remember, there is up to 13 EV difference between the penumbral and umbral shadow).
3. There will also probably be glare from the saturated part causing a glow. If you wish to remove it, you can do so by using the Elliptical selection Marquee to select a circle around the disk of the Moon (hold the Shift key to make it a perfect circle), Invert the selection (not the colors), and then fill the new selection with black. I usually do this in a new layer so that I can remove the mask easily if I want to (image 3 below).

How to Process the Photographs: Totality

This is the same as the "Out of Eclipse" processing - unless you are going for the advanced technique discussed in the "Additional Photographing / Processing Tip: Image Arithmetic" section … which is left to that section.

I have personally found that I need to adjust the Levels a bit more here (in Photoshop, I set my blacks around 25 and white at 255 for most of my images during the last eclipse). I have also found a need to adjust the Curves a little more during totality in order to bring out some of the features (I generally had 3 points along the curves at (35, 30), (125, 110), and (220, 220)). Remember, though, keep it subtle. Try to bring out the detail and contrast, but do not make it look fake.

Do *not* take the above values as gospel because your exposures will be different from mine, and so you will need to make your own judgement on adjustments. I mention these numbers only as a possible guide and to make you aware of them as something to try to play with when processing your images.

Putting it All Together - The Final Product

This is entirely up to you. As an academic, I generally do a simple montage of the eclipse, as shown in the image below. I list the time and show the image, and have it in an even grid. I was a little artistic in the montage shown below in my design of a graphic to illustrate the mountains, and I used a fancy font for the title. Because the Moon set behind the mountains while eclipsed, I was able to get a very cool photo of that event, shown as the last actual moon image in the montage below.

A completely different approach and one that I like but have not yet attempted, is more of a "time lapse" effect. The steps are as follows:

1. You first need a landscape or cityscape photograph taken at night (like the one shown below, used with permission). This can be photographed the same night or a different night at a different location. You then take your eclipse photos and process them.
2. Select each eclipsed Moon you want to use (by using the Elliptical Marquee), copy, and then paste into a new layer on your background image. It is not necessary to closely encircle the Moon as the black border will be removed later. Do any necessary re-sizing and re-positioning based upon how you want the composition to look.
3. For each eclipsed Moon layer, set the Blending Mode to "Screen." (You can also try "Lighten" and choose for yourself which look you prefer.) This will (among other things) remove pixels that are a *darker* color in the current layer than the layer below it.
4. You may find that there is still a "halo" around the Moon due to the pasting process. You can usually remove this by adjusting the Levels and Curves of the offending layer -- this will reduce the extent of the halo but increase its intensity in the remaining part. An alternative is to use the masking I suggested in the "How to Process the Photographs: Partial Umbral Eclipse."
5. You may now need to erase certain parts of an individual Moon to get it to "set behind" an object. You may also choose to airbrush in reflections off of water, if water is in your original land/cityscape photograph. There are many different ways to do this latter effect; one suggested method is to, in a new layer, use a white paintbrush, Hardness 0%, Layer Mode to "Overlay," paint in a reflection and adjust the layer's Opacity to suit your needs.

A third method I have seen is to arrange the eclipse phases in a circle or ellipse on a black background, or I have even seen "8," "∞," and "V" arrangements. There is really no limit here on how you can display the images. Once the photographs are taken, this part is where you make the composition completely your own, so try to think creatively!

I have steered clear of making a movie with my photos because the changes in brightness are extraordinarily difficult to portray with modern technology. You may notice this on my montage above, where the images in the second row (partial umbral eclipse phase) are brighter than the ones in the top row. But, if this does not bother you, then go ahead and see if you like the results.

One last tidbit to mention in this section: A total lunar eclipse is the *only* time when you can properly expose both the moon *and* stars in the same frame with the same exposure setting. Granted, it does depend upon how truly dark the lunar eclipse is (as this will change from eclipse to eclipse and location to location), but due to the dramatic dimming of the Moon, you can finally photograph the Moon and stars together.

Additional Photographing / Processing Tip: Image Arithmetic

The concept of "image arithmetic" is fairly easy to understand once you think of a photograph as just that - a *photo* (light) *graph* (picture). It is a map of the intensity of light at certain locations across the image. That intensity (in this digital age) is represented by a number. In an 8-bit image, that number is between 0 and 255. In a 16-bit image, it is between 0 and 65,535.

The motivation of image arithmetic is the following: Among other sources, noise is introduced into an image by the *counting statistics of photons*. This means that each "piece" of light (a photon) that hits the detector and is recorded is 1 count. But there is a fundamental uncertainty associated with counts. For digital detectors, which measure discrete "particles" of light, the uncertainty is the square-root of the counts recorded, written as $\sqrt{N}$. (This is known as Poisson Statistics, for those who are interested.) What this means in a practical sense is that if you record, say 100 counts, its uncertainty is ±10, or ±10%. But if you record 10,000 counts, the uncertainty there is ±100, or ±1%. More counts, or more intensity, equates to less noise.

The purpose of that digression is to emphasize that in astronomy, we want *as much light as possible* so that the noise is less. You can achieve this with longer shutter speeds and wider apertures; ISO will only increase the output of the detector, and the noise along with it. If we cannot take one long exposure to get more light, we get around it by taking several shorter exposures. So instead of taking one 60-second exposure of the Moon during totality, you can take 4 15-second exposures. Or 10 6-second exposures. One long exposure is easier to process, but if you are limited by the motion of the Moon or how much light you can record before your camera saturates, then this is a good substitute.

So now say you took 1/125-sec exposures of the non-eclipsed full Moon. You may argue that you had plenty of light, were not limited by the Moon's motion, and the image looks fine. But it still will contain noise. To suppress this noise, you can take multiple exposures (say, 5 or 10) and then instead of *adding* them to get a much brighter image, you can *average* them. Averaging multiple images together is the same as getting more light from a longer exposure (so less noise, as discussed above) but without making the overall image brighter.

You can use image arithmetic software to do this. IRAF and IDL are two expensive ones that I know of. Registax for Windows and Keith's Image Stacker for Mac are two free ones, but they lack the precise control and options that the more expensive ones provide. If you happen to have a scientific graphing and programming package, chances are you could write your own program to do this (I have done so myself in software called *Igor Pro*). Another option, and one that I think works incredibly well, is Photoshop.

Photoshop CS3 introduced a feature called "Smart Objects" which allows you to create a "Stack" of images. You can open several images at once and have it automatically create a Stack for you (File > Scripts > Load Files into Stack …), or you can manually put all your exposures into one file (in different layers) and convert them to a Smart Object (Layer > Smart Objects > Convert to Smart Object). Personally, I prefer to manually do this because I find there is a slight drift between exposures - even though I have use of a mount that tracks the sky. The automatic loading will attempt to auto-align the images if you click a checkbox, but I have found in previous versions that this is not very accurate, so use it at your own risk.

Once you have the photos in a Smart Object Stack, then you can tell Photoshop to take the Average of the Stack (Layer > Smart Objects > Stack Mode > Average). It is that easy. It may take awhile if your images are large and you do not have much RAM (I think it took me a total of 24 straight hours to process 40 moons with 5-10 shots each, though this was on a fairly old computer), but I believe you will find that the final average is much less noisy than any of the original images, especially if you are using a point-and-shoot camera.

If you would rather add several shorter exposures together to get one brighter exposure (such as if you followed my advice for totality and shot several shorter photographs), you can set the Stack Mode to "Sum." This is not as good as "Average" because you are summing the noise up instead of averaging it away, but it is better than a blurry image due to the Moon's motion.

If you have an earlier version of Photoshop (CS2 and earlier), then you will not have the Stack feature. Instead, you can use the much slower and more painful (speaking from experience) Image > Calculations … option. This will allow you to average two color channels from two images or layers at once. You will have to repeat this for all three (R, G, B) color channels, and it restricts you to having $N = 2^m$ images where m is an integer (so 2, 4, 8, 16, etc. total images). If you take 4 photos, you will have to average the color channels from image 1 and 2 together to get image A, then average 3 and 4 together to get image B, and then average all the channels for A and B to get the final image.

Copyright Notice

Thanks goes to the following people (or screen names) for advice in editing and content: Christopher Garber, Dennis Hammer, Alexander Blumenau, and timd346.

Appendix A

Here are a few websites that may also help:

- NASA's List of Lunar Eclipses:
  `http://sunearth.gsfc.nasa.gov/eclipse/lunar.html`
- Wikipedia's Page on Lunar Eclipses:
  `http://en.wikipedia.org/wiki/Lunar_Eclipse`
- Wikipedia's Page on Exposure Value:
  `http://en.wikipedia.org/wiki/Exposure_value`
- The Luminous Landscape's Page on Histograms:
  `http://www.luminous-landscape.com/tutorials/understanding-series/understanding-histograms.shtml`
- Online Photography Forum with Helpful Members:
  `http://www.thephotoforum.com`
- Online Astronomy Forum's Astrophotography Sub-Forum:
  `http://www.bautforum.com/astrophotography/`

APPENDIX B

Here is the fun stuff, the math to figure out how long you can leave the shutter open before the Moon will appear to move due to its motion through the sky.

To start off with, this will depend upon four main variables:

1. The number of vertical pixels your sensor has (the shorter dimension). You can do this with either dimension, but I will be using the shorter dimension.
2. The lens length you are using (and your camera's sensor size).
3. Your sensor's physical size in millimeters (or crop factor).
4. The number of pixels of motion that *you* consider acceptable.

Step 1: To start this problem, we need to know the Moon's rate of motion through the sky. *On average*, the Moon will rise 50 minutes *later* each night (the speed actually changes because the Moon's distance from Earth varies (look up Kepler's 1st and 2nd Laws)). This means it takes about 24 hrs 50 min to return to the same location, 360° away. Dividing these two:

$$\text{rate of motion} = \frac{360°}{24\text{ hr, }50\text{ sec}} = \frac{360°}{24.833\text{ hr}} \approx 14.497\ \frac{\text{degrees}}{\text{hr}}$$

The units I want to use, however, is arcsecond (arcsec, or ") per second (sec). There are 60 arcminutes per degree and 60 arcseconds per arcminute. Not coincidentally, there are 60 minutes in an hour and 60 seconds in a minute. Thus, the lunar rate of motion can also be expressed as 14.497 arcsec per sec.

Step 2: Now, we need to know the "plate scale" of your camera, which means how many pixels there are per unit of angular measurement. To start that, we need to know the field of view of your camera. This can be determined via trigonometry (and you can figure it out yourself if you would like), but the equation for *vertical* field of view (FOV) is:

$$\text{FOV} = \frac{360}{\pi}\tan^{-1}\left(\frac{\text{vertical sensor size in mm}}{2\cdot(\text{lens length})}\right)$$

The plate scale is simply the number of pixels per FOV:

$$\text{plate scale} = \frac{\text{pixels}}{\text{FOV}} = \frac{\text{pixels}}{\frac{360}{\pi}\tan^{-1}\left(\frac{\text{vertical sensor size in mm}}{2\cdot(\text{lens length})}\right)\cdot 3600}$$

The reason I multiplied the denominator by 3600 is to convert from degrees to arcsec. Note that you will get a slightly different plate scale if you use the horizontal size of your sensor; see the note at the end of this Appendix for more information.

Step 3: Finally, we can look at the units we have here. In Step 1, there are arcsec/sec. From Step 2, we have px/arcsec. We are interested in *number of pixels traveled in a given amount of time*, where time is represented by the variable *t*. Looking at the units, this is calculated from the following equation:

$$t = \frac{1}{\text{rate of motion}} \cdot \frac{\text{FOV}}{\text{pixels}}$$

That equation gives units of seconds on the left side, but units of seconds per pixel on the right. This is where item #4 above comes into play - how many pixels does it need to move before you consider it unacceptable? Therefore, our final equation is:

$$t = \left(\frac{1}{14.497}\frac{\text{sec}}{\text{arcsec}}\right) \cdot \left(\frac{\frac{360}{\pi}\tan^{-1}\left(\frac{\text{vertical sensor size in mm}}{2 \cdot (\text{lens length})}\right) \cdot 3600\text{ arcsec}}{\text{pixels}}\right) \cdot (\#\text{ px for blur})$$

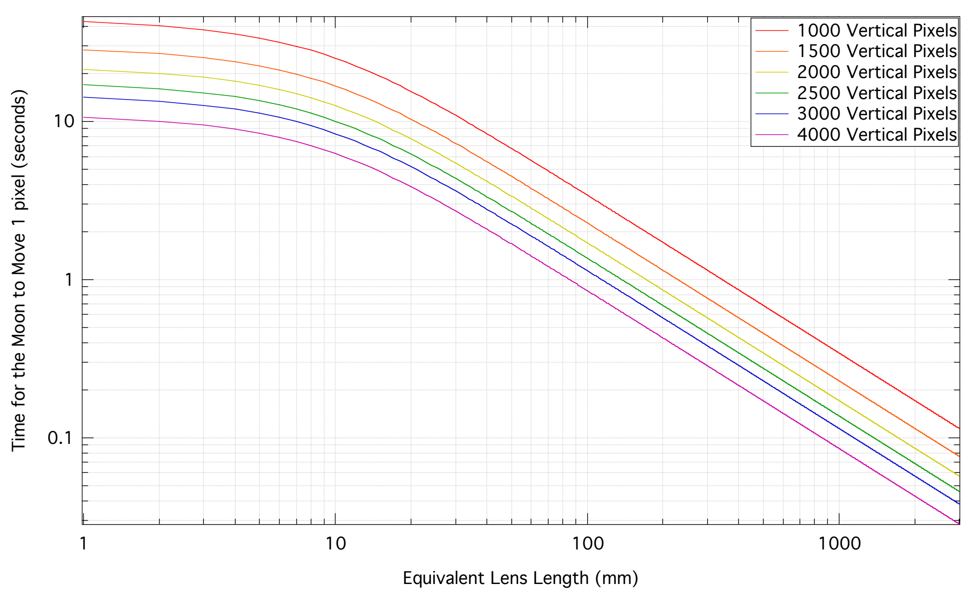
If you do not know how large your sensor is physically, you can substitute 24 mm for the vertical sensor size and divide by your camera's crop factor (e.g., 1.6 for the Canon Digital Rebels).

Plug In Numbers: This equation is in need of some simplification. Combining some of the values and units:

$$t = 28546 \cdot \tan^{-1}\left(\frac{\text{vertical sensor size in mm}}{2 \cdot (\text{lens length})}\right) \cdot \left(\frac{\#\text{ px for blur}}{\text{vertical sensor pixels}}\right) \text{ sec}$$

Now you can put in your own numbers. For example, my digital Rebel XT has 2304 px vertically, though my Canon 7D has 3456 px vertically, I consider a blur being 1 px or more, I usually use an 800 mm lens, and my sensor is about 14.8 mm vertically. Putting in those numbers, I will see 1 px of motion in only 0.1 seconds. If I were to use a much shorter 50 mm lens, I would see the motion in 1.8 seconds.

I am including a graph below of a range of sensor sizes and lens lengths for easy reference.



Note: You <u>will</u> get slightly different results if you use horizontal vs. vertical values. This is because the arctangent does not scale linearly, unlike the number of pixels. Consequently, these values are only approximate, and should be treated as accurate to within about a factor of 2 or 3.