The AAVSO DSLR Observing Manual

AAVSO
49 Bay State Road
Cambridge, MA 02138
email: aavso@aavso.org

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Foreword

This manual is a basic introduction and guide to using a DSLR camera to make variable star observations. The target audience is first-time beginner to intermediate level DSLR observers, although many advanced observers may find the content contained herein useful.

The AAVSO DSLR Observing Manual was inspired by the great interest in DSLR photometry witnessed during the AAVSO's Citizen Sky program. Consumer-grade imaging devices are rapidly evolving, so we have elected to write this manual to be as general as possible and move the software and camera-specific topics to the AAVSO DSLR forums. If you find an area where this document could use improvement, please let us know. Please send any feedback or suggestions to aavso@aavso.org.

In earlier versions of this manual, most of the content was written during the third Citizen Sky workshop during March 22-24, 2013 at the AAVSO. The persons responsible for creation of most of the content in those chapters are:

Chapter 1 (Introduction): Colin Littlefield, Paul Norris, Richard (Doc) Kinne, Matthew Templeton
Chapter 2 (Equipment overview): Roger Pieri, Rebecca Jackson, Michael Brewster, Matthew Templeton
Chapter 3 (Software overview): Mark Blackford, Heinz-Bernd Eggenstein, Martin Connors, Ian Doktor
Chapters 4 & 5 (Image acquisition and processing): Robert Buchheim, Donald Collins, Tim Hager, Bob Manske, Matthew Templeton
Chapter 6 (Transformation): Brian Kloppenborg, Arne Henden
Chapter 7 (Observing program): Des Loughney, Mike Simonsen, Todd Brown
Various figures: Paul Valleli

The current version retains much of this material but has been revised and extended.

Many thanks go to Arne Henden, Rebecca Turner, Brian Kloppenborg, Matthew Templeton, and Elizabeth Waagen for their editorial and other contributions to the first edition of this Manual.

Clear skies, and Good Observing!

Mark Blackford
AAVSO Member, Observer, and Volunteer

American Association of Variable Star Observers
Cambridge, Massachusetts
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Chapter 1: Introduction

1.1 Prologue

You're out jogging one night in your usual park. It's dark, but you know the area well, so you don't have a fear of running into anything. Tonight turns out to be different, though. As you jog you notice someone just off the path with a camera on a tripod. Strangely, you notice that both her gaze and her camera are pointed up, right up to the sky above. You glance up at the sky as you jog past seeing just the brightest points of light in your light-polluted sky. What could she be doing? In this case, the woman, who is a High School history teacher by day, is performing measurements on the brightness of certain stars, data that will be of use and interest to professional astronomers. She's one of a growing breed of people called "citizen scientists." This manual will show you how you can participate as well.

Most of us with a passing interest in astronomy has read an astronomy magazine every so often and seen the stunning photos that grace their pages. Most of these pictures are taken with cameras attached to guided telescopes and heavily processed to make them look as good as they do. That is the realm of astrophotography. This manual will take you in a different direction. Here we're going to take a look at how you can record scientifically valuable photographs to measure the brightness of variable stars — stars whose brightness change over time. The goal of this manual is to guide you through the process of using the same DSLR camera that you use for general photography to contribute scientific quality data to the astronomical community.

1.2 Target audience

The AAVSO's DSLR photometry manual is meant for anyone with an interest in using DSLR cameras to measure the brightness of variable stars. Most of the information in this book is written with the first-time observer in mind, but provide high-level details that even the more advanced observer may find interesting.

Amateur astronomers may find that measurement of variable stars adds a new dimension to your hobby. It is a real treat to see your own measurements build up the "light curve" of a star's changing brightness! Variable stars are also fine targets for student research. Some projects are appropriate for high-school level science projects; others can engage college undergrads with observational and analytical challenges.

1.3 The what, why, and how of DSLR photometry

Photometry is the science of measuring how bright a particular object in the sky is. At first blush, this might not seem like a particularly thrilling subject, but it is actually a dynamic field in which amateurs can play a key role. Although there are many types of objects for which photometry is important, this manual concentrates on variable stars because stellar photometry is one of the easiest fields to learn and in which to contribute valuable measurements.

1.3.1 What are variable stars and why do we observe them?

Stars can change in brightness due to the physical processes happening inside, on, or near the star. By carefully observing this variability, it is possible to learn a great deal of information about the star and, more generally, astrophysical phenomena. In a very real sense, therefore, variable stars are like physics laboratories. The same fundamental physical processes that operate here on Earth – gravity, fluid mechanics, light and heat, chemistry, nuclear physics, and so on – operate exactly the same way all over the universe. By watching how stars change over time, we can learn why they change.

Although many stellar variations cannot be reliably detected from the ground due to absorption or distortion by the atmosphere, there are still hundreds of classes of variable stars observable from the ground, each with a few to several thousand known members. For example, stars may change in size, shape or temperature over time (pulsating variables), they may undergo rapid changes in light due to physical processes around the star (eruptive variables), or they may be eclipsed by stars or planets in orbit around them (eclipsing binaries and exoplanets). The key is that something is physically happening to the star itself or in its immediate vicinity. (You may see a star twinkle in the sky, but that variation is due solely to the Earth's atmosphere and is completely unrelated to the star itself.)

See https://www.aavso.org/types-variables for an extensive list of variable types used in the AAVSO Variable Star Index (VSX).

Different kinds of stars vary on different timescales. Some stars may take weeks, months, or years to undergo detectable changes. Others take days, hours, minutes, seconds or even less. Some stars vary regularly, and we can see patterns in the variations that repeat over time. Other stars undergo chaotic changes that we can never predict exactly. Some stars vary the same way for centuries, while others – like supernovae – may flare up briefly and then disappear, never to be seen again.

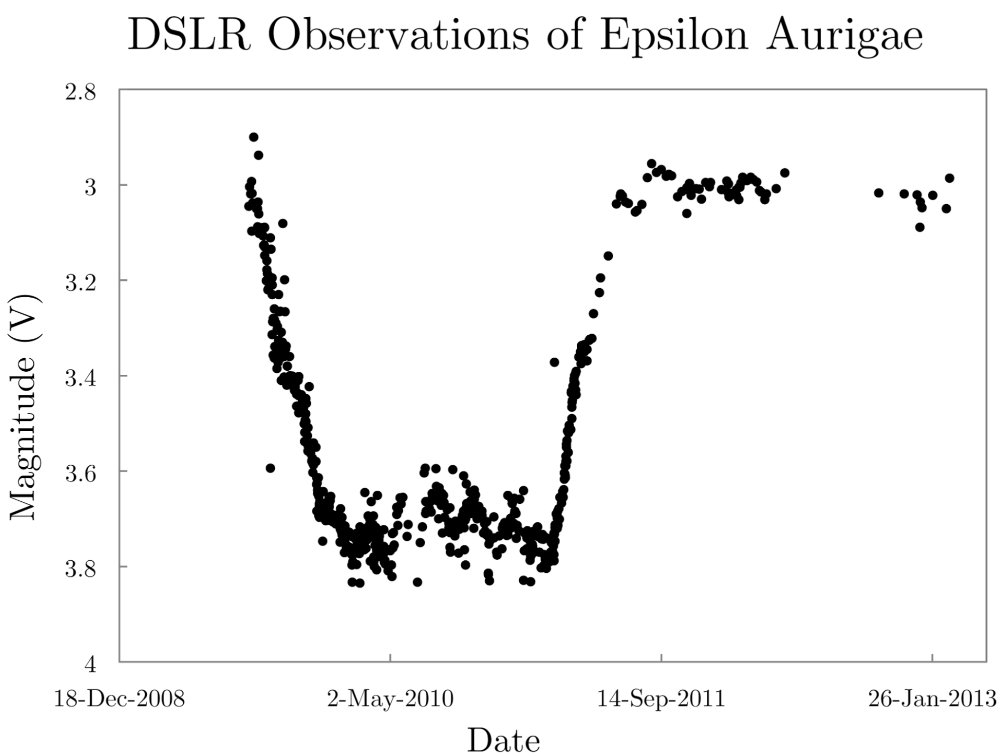


Figure 1.1. DSLR observations of epsilon Aurigae during its 2009-2011 eclipse. Each data point on this plot was contributed by an amateur astronomer.

Variable stars also have a range of apparent brightness (how bright they appear to us) as well as a range of intrinsic luminosities (how much light they actually give emit). A star may be intrinsically luminous, but if it is thousands of light years away, it will appear faint. Variables also have a range of amplitudes—how much their brightness changes over time. Some variable stars can vary by ten magnitudes or more, which is a factor of ten thousand in brightness, a huge change! Some variables vary by a millimagnitude (mmag), or even less, and their variations may be impossible for you to detect. There are many stars in between, and there's no shortage of targets that you'll be able to do productive work on, regardless of your equipment. With this manual, you'll learn how to use your DSLR to obtain valuable scientific measurements and report your findings so they can be used for scientific research.

So how do amateurs fit into this picture? Professional astronomers use photometry extensively, but because they have only limited observing time they frequently depend on amateur astronomers to perform photometry on interesting objects for them. As a result, your observations provide the raw material which powers scientific inquiry. Scientists can speculate endlessly about why things appear and behave the way they do, but ultimately, those hypotheses must be tested in order to productively advance our scientific understanding. If you give researchers reliable data, they can make accurate models to describe how the universe works, and our understanding improves and expands. For example, amateurs used off-the-shelf DSLR cameras to regularly monitor the brightness of epsilon Aurigae, a notoriously enigmatic binary system, as it underwent a long-awaited eclipse between 2009 and 2011 (see Figure 1.1). Thanks to the work of these amateurs, professional astronomers received a wealth of useful data from which they were able to glean new insights into this fascinating binary.

1.3.2 How do we do DSLR photometry?

Fundamentally, DSLR photometry is a simple process: After properly configuring your camera you take a series of special exposures (called bias, darks and flats) that are used in later analysis. After this, the camera is pointed skyward and a series of long (10+ second) exposures are taken of a particular area of the sky. These images are processed using specialized software to obtain instrumental magnitudes (brightness estimates as measured by the camera). Instrumental magnitudes are then calibrated to agree with magnitudes of known constant stars in the images against which any variable stars can be measured. There are several steps along the way which are explained in greater detail in later chapters.

Figure 1.2. A typical DSLR camera mounted on a tripod.

1.4 Visual vs. DSLR vs. CCD observing

Before the invention of electronic sensors and photographic equipment, astronomers had only their own eyes for estimating the brightness of stars. Although this technique is ancient, it is still widely practiced and remains useful for observing certain types of variable stars, especially those which are relatively bright and which have large variations in brightness. In addition, with visual estimates, there is no need for expensive, complex equipment, making it a highly economical method of variable star observing. However, visual estimates are prone to error due to the color sensitivity of the human eye, age of the observer, experience in making visual measurements, and possible bias. As a result, it is often difficult to detect subtle brightness variations visually, and different observers will often disagree as to the exact brightness of a variable star by as much as several tenths of a magnitude. The *AAVSO Manual for Visual Observing of Variable Stars* details the process of making visual observations of variable stars.

With the advent of affordable, high-quality DSLR cameras, citizen scientists are no longer limited to making visual estimates of variable stars. With DSLR observations, it is possible to compensate for certain effects, such as star color, which frequently thwart accurate visual estimates of a star. DSLR users can detect exceptionally subtle variations in brightness and reliably compare their estimates with those of other electronic observers – but only if they carefully follow proper procedures, particularly those outlined in this manual.

Another option is to use a CCD camera and filter wheel (containing several photometric filters) attached to a telescope. At a superficial level, CCD photometry is similar to DSLR photometry. Professional astronomers use CCDs because they offer potentially superior image quality and versatility, but good CCDs tend to be significantly more expensive than DSLRs and have a steeper learning curve, too. In terms of cost effectiveness, DSLRs will generally offer much better value than CCDs. The AAVSO has published a comprehensive guide to CCD photometry and its use in variable star observing.

1.5 Are you ready? (Prerequisites)

Before getting started with DSLR photometry you need to have some experience with your camera. You should:

- Know how to operate your camera. In particular, be able to set the image format to RAW (CR2, NEF, etc.), shut off additional image-processing options, turn off auto focus, manually adjust focus, and mount your camera onto a tripod, piggy back on top, or at the prime focus, of a telescope.
- Have a good working knowledge of computers and be able to install software on your machine.
- Highly recommended, but not required: have some experience making visual variable star estimates.

Visual experience will teach you how to identify fields, how color affects estimates (important later when we discuss filters), the behavior of a star's light curve, how to submit data, and perhaps most importantly – patience! Also, visual observing is usually quite fun and addictive, so practice will help make sure you enjoy variable star observing. After all, for most of us this is a hobby right?

Download a copy of the AAVSO's excellent *Manual for Visual Observing of Variable Stars* and become familiar with it. Select some well observed binocular variables and follow them regularly for a month or two, comparing your estimates with those of other observers.

DSLR Observing has many facets in common with visual observing. Each facet you gain experience with visually is one less you have to learn before reaching your main goal of DSLR photometry.

1.6 Expectations

In general, this manual will focus on the aspects of observing variable stars with DSLR cameras. Although we use the word “DSLR” extensively throughout this text, we are using it to refer to a general class of camera that is suitable for conducting photometric observations. Recently, many point-and-shoot cameras have started to support several features that are required for doing astronomical photometry. Hence, the text discussed here may be applicable to your camera, even if it is not a DSLR.

In this manual we focus on variable stars because stars are among the easiest objects to measure. The techniques you learn are applicable to a wider range of objects (like exoplanet transits, and active galactic nuclei), but they may not be as accessible without a more substantial investment. With a few exceptions, we won't go into the details about how a DSLR works or how to operate any specific model of camera. Also, please realize that the techniques used in DSLR photometry are similar, but not identical to astrophotography. In particular, de-focusing in DSLR photometry will result in blurry images that are not pretty to look at, but are scientifically valuable.

Not this…. This!

Figure 1.3. What you should, and should not, expect to see in DSLR photometry. **Left panel:** spectacular image of eta Carinae nebula central region (ESO 2.2m telescope at La Silla Observatory in Chile).
Right panel: wider field of view image of same region, 20 sec exposure with 80 mm f6 refractor and Canon 600D DSLR, green channel image. (Mark Blackford)

It is the goal of this manual to demystify the process of obtaining scientific-quality photometry with DSLR cameras. Many amateur astronomers are unnecessarily intimidated by photometry's supposedly steep learning curve, and with DSLRs, it is possible to start taking useful data almost immediately. Although it is true that obtaining good photometric data requires careful analysis and attention to detail, photometry is a field which is readily accessible to amateur astronomers who lack a technical background. Enthusiasm, patience, and good technique, rather than in-depth mathematical or scientific aptitude, are all that is required.

> ***"I feel it is my duty to warn others...that they approach the observing of variable stars with the utmost caution. It is easy to become an addict, and as usual, the longer the indulgence is continued the more difficult it becomes to make a clean break and go back to a normal life." Leslie C. Peltier (1900-1980)***

References

***AAVSO Visual Observing Manual*: http://www.aavso.org/visual-observing-manual**
***AAVSO Guide to CCD Photometry*: http://www.aavso.org/ccd-photometry-guide**

Chapter 2: Equipment Overview

DSLR cameras provide an economical way to become involved in digital photometry. In terms of hardware, there are fundamentally three things that are required: a lens or telescope to collect and focus star light, a camera capable of providing images in an unprocessed format, and some sort of mount to stabilize the camera during long exposures. These devices can be as simple as a suitable point-and-shoot camera on a fence post, or as elaborate as a professional-grade camera mounted at the prime focus of a telescope. Prior to discussing how one conducts the observations and reduces the data, it is best to first understand exactly what equipment is required for DSLR photometry. We will be discussing each of these three components in detail. But first some physical aspects of these cameras will be described so that you may better understand what happens when you adjust various camera settings.

2.1 What is a DSLR?

“A digital single-lens reflex camera (also called a digital SLR or DSLR) is a digital camera combining the optics and the mechanisms of a single-lens reflex camera with a digital imaging sensor, as opposed to photographic film. The reflex design scheme is the primary difference between a DSLR and other digital cameras. In the reflex design, light travels through the lens, then to a mirror that alternates to send the image to either the viewfinder or the image sensor. The alternative would be to have a viewfinder with its own lens, hence the term "single lens" for this design. By using only one lens, the viewfinder presents an image that will not perceptibly differ from what is captured by the camera's sensor.” (Wikipedia)

Recently, point-and-shoot cameras have started to support features that are required for astronomical photometry. Hence, this manual may be applicable to your camera, even if it is not explicitly a DSLR.

As illustrated in Figure 2.1, a DSLR camera is made from an ensemble of optical and electronic components that are needed for capturing images. Many modern DSLR cameras also come with a plethora of settings and in-camera software processing options, most of which are not useful or downright detrimental for astronomical photometry.

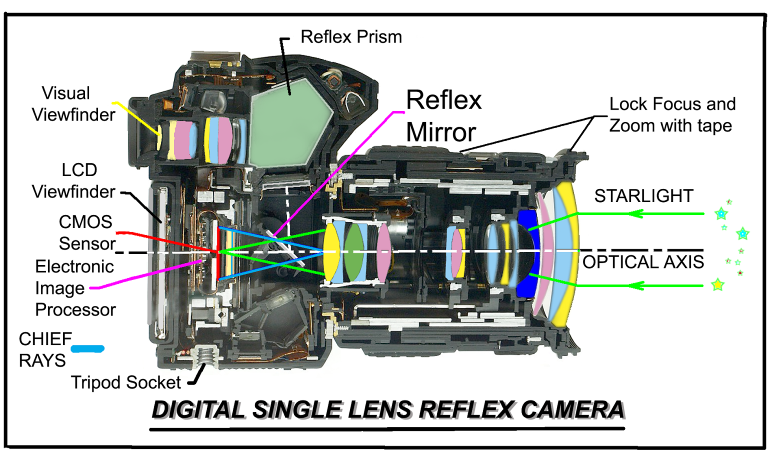


Figure 2.1. A cutaway of a DSLR camera showing the various components involved.

All DSLR cameras on the market today have CMOS (Complementary Metal Oxide Semiconductor) sensors, so we will concentrate on this type of device. For a discussion of CCD camera technology, please see the *AAVSO Guide to CCD Photometry*. Cameras with Foveon detectors (which have three color-specific layers of pixels instead of a single plane of different colored pixels) are not often seen. If you wish to know more about them, please ask on the AAVSO DSLR Photometry forum.

2.1.1 Optical path

The camera consists of a lens attached to the front of the camera body, a shutter, several large filters, a microlens array, additional filters, and a detector. The optical components in which we are most interested are shown schematically in Figure 2.2. The first optical component is the lens. Its primary purpose is to project and focus an image onto the sensor. Behind the lens is the f-stop diaphragm. This determines the total aperture, or light gathering surface, of the lens. These components are typically contained within the lens body itself.

Within the camera body, the first element encountered is typically the shutter. The purpose of the shutter is to control the amount of light entering the camera.

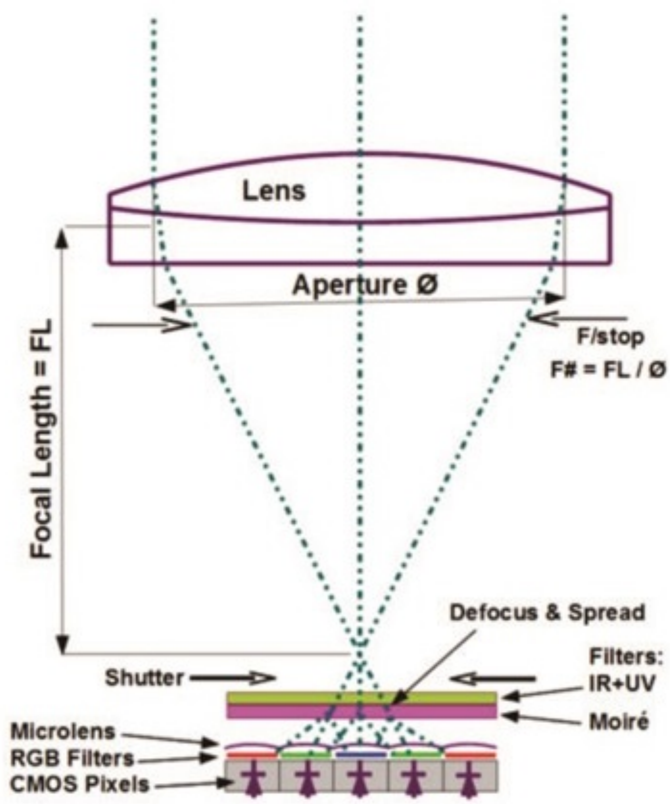


Figure 2.2. Typical DSLR optical layout with a CMOS detector and RGB Bayer array. (Roger Pieri)

Behind the shutter are a series of filters that perform several functions, including:

- IR dye that reduces excess sensitivity to deep red and Infrared light
- IR cut (dielectric filter) that eliminates Infrared light above 700 nm
- UV cut (dielectric filter) that eliminates Ultraviolet light below 400 nm
- low-pass filter that spreads the light to reduce the Moiré interference pattern caused by the Bayer structure (slightly reduces the resolution, and reduces the undersampling issue in photometry)

Behind these filters and immediately in front of the detector, a microlens array (cemented onto the detector) focuses the light falling on each pixel into the most sensitive part of it, improving the filling factor of the pixel to a level approaching 100%.

2.1.2 CMOS detectors

DSLR CMOS detectors have a color filter array, often referred to as a Bayer array, (see Figure 2.3) of red, green, and blue (hereafter RGB) pixels. There are usually two sets of green pixels. The RGB filters are produced by depositing different pigments directly on the top surface of each pixel of the CMOS sensor and cannot be cleaned or removed. Each pixel is therefore sensitive only to its own color of light.

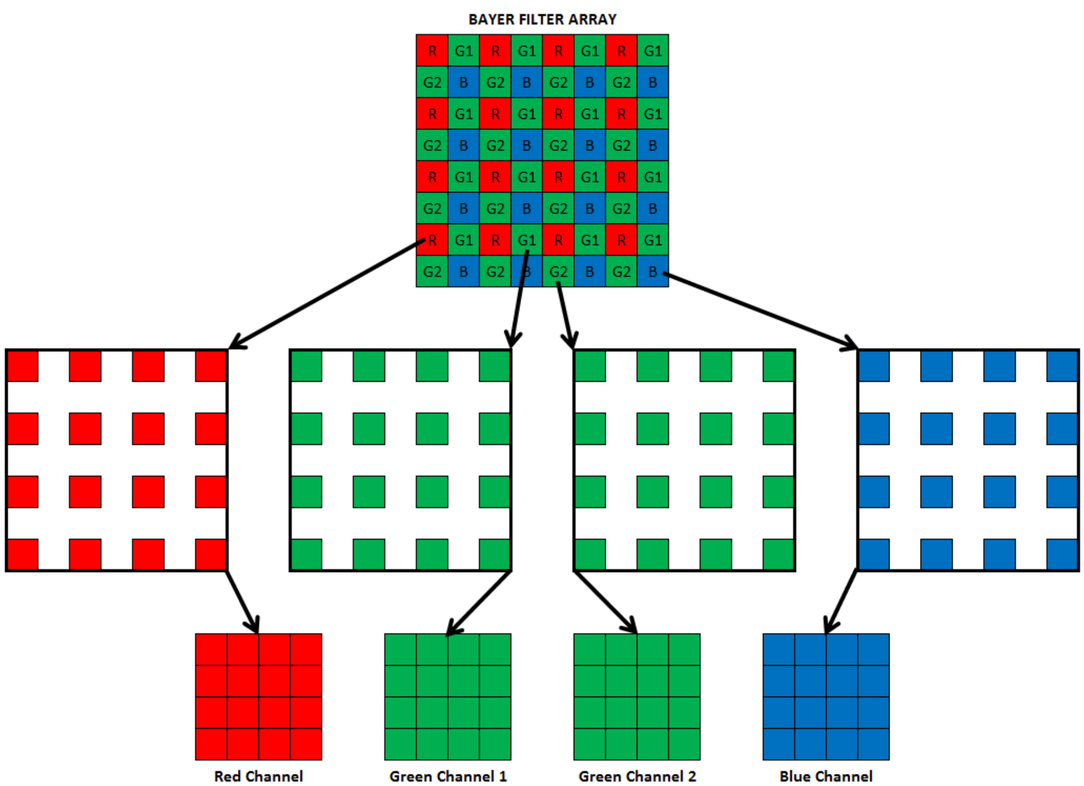
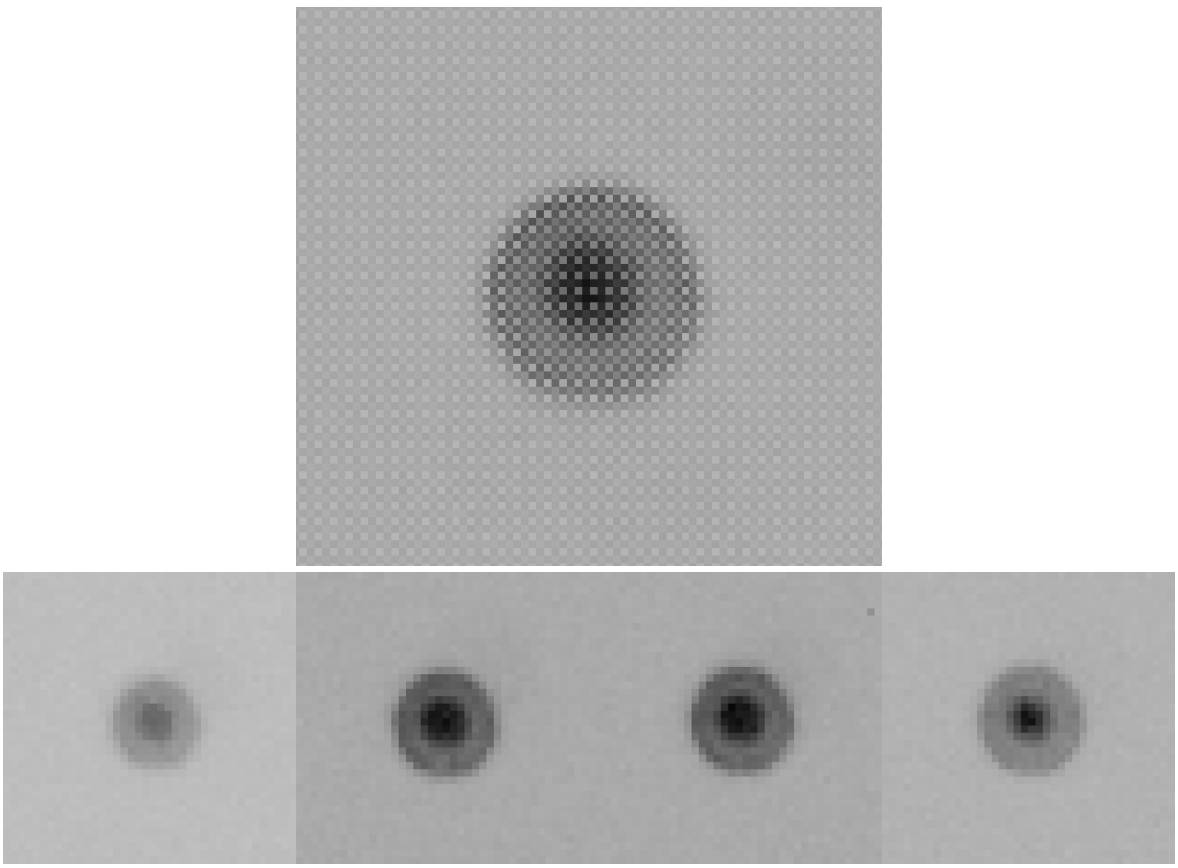


Figure 2.3. **Top:** Schematic showing a typical Bayer matrix color filter arrangement. **Middle:** Each color channel can be extracted separately using appropriate software, note gaps between pixels. **Bottom:** Each channel is usually displayed with dimensions half that of the original RAW image, an exception is AIP4Win where the missing pixels are filled in using interpolation algorithms. (Mark Blackford)

The specific order of colors may vary between camera manufacturers so it is important to determine which color channel in your DSLR corresponds to red, which to blue, and which to green.

Traditionally in DSLR photometry only the Green channels are used to estimate Johnson V band magnitudes. However, this ignores information contained in the Red and Blue channels which, in many situations, can be used to accurately measure stellar magnitudes in Johnson B and Cousins R bands, respectively. We will return to this topic in greater detail in later chapters.

It is important to note that RAW DSLR images are greyscale, not color images. The top panel of Figure 2.4 is an enlarged section of a RAW image of an out of focus star showing individual pixels and the checkerboard pattern of intensity resulting from the Bayer filter array. Below are images of the individual color channels extracted from the RAW image.



Red Channel Green Channel 1 Green Channel 2 Blue Channel

Figure 2.4. Top: magnified view of an out of focus star in a RAW DSLR image showing monochrome checkerboard pattern due to the Bayer filter array. **Bottom:** Individual color channels extracted from the RAW image. (Mark Blackford)

The voltage increase of a single photoelectric event is quite small; hence the accumulated voltage on the capacitor is similarly tiny. In order for this signal to be read, it is first passed through an amplifier before being processed by an analog-to-digital converter (ADC). The gain setting of the amplifier determines the "ISO" (a measurement of the sensitivity of the detector) that matches the signal to the fixed range of the converter. The ADU (analog to digital units) output of the ADC is proportional to the number of electrons collected by the photodiode of each pixel. When saved as a RAW data file, these ADU values are the fundamental information used in DSLR photometry. This discussion is continued in greater detail in Section 2.4.

A schematic representation of CMOS detector electronics is shown in Figure 2.5. The sensor itself is made from a silicon chip onto which the CMOS circuitry is etched. The photon-sensitive element in each pixel is a photodiode (or a MOS photogate). These devices operate by the photoelectric effect, in which a photon impacting the detector generates an electron-hole pair. Due to the construction of the photodiode, the electron is quickly moved out of the bulk material and pushed onto a nearby capacitor. At the beginning of an exposure, this capacitor is reset and its voltage read. During the exposure, each impacting photon results in a slight decrease in charge on the capacitor. At the end of the exposure, the voltage on the capacitor is read a second time.

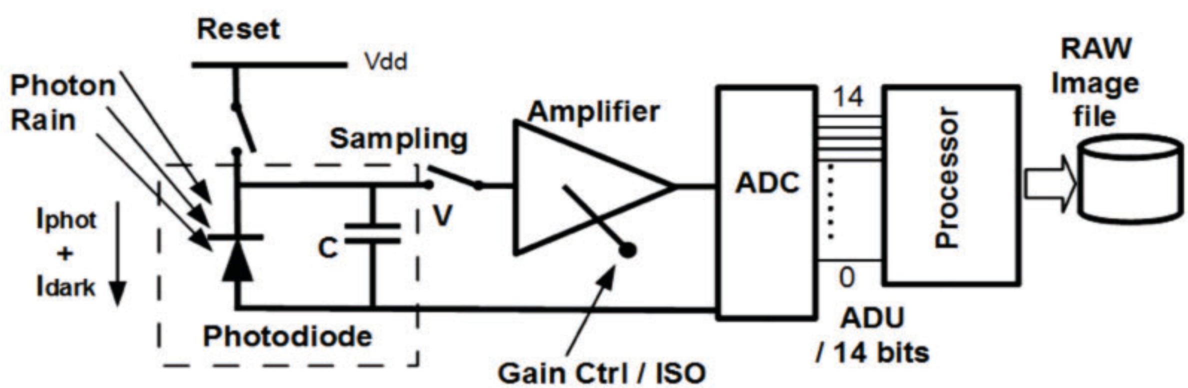


Figure 2.5. Schematic representation of the components of a CMOS detector. (Roger Pieri)

The most common DSLR camera sensor size is APS-C, which is 14.9 x 22.4 mm, but other formats also exist in cameras that may be used for photometry: the 4/3 system (13 x 17.3), the 1" format of some hybrids (8.8 x 13.2), the 1/1.7" used in "expert" DSC (5.7 x 7.6). The "full frame" format (24 x 36 mm) also exists, but it is not so common, relatively expensive and subject to greater vignetting problems.

2.1.3 DSLR camera features to avoid for photometry

Modern DSLR cameras have a plethora of additional functions, most of which are not useful and can even be harmful for photometric measurements. Foremost, JPEG images should never be used in astronomical photometry. To generate a JPEG image, the RAW ADU values from the detector are processed to convert the image into a non-linear sRGB color space (absolutely non-photometric) and then compresses it into a JPEG file. The non-linearity and compression lead to a significant degradation of data precision (from ~14000 levels of brightness to a maximum of 256 levels) that prohibits precise flux measurement.

Some cameras have a de-noising or image enhancement function that modifies the underlying data, possibly corrupting the photometric data in the process. Functions that measure the illumination of a scene, and autofocus, are nearly useless for stellar photometry. The "live view" magnification function (5x, 10x, etc.) is useful to focus/defocus on a bright star, but the viewfinder (possibly with a right-angle adapter) is often more useful when framing the desired sky area.

2.2 Lenses and telescopes

The first step in doing DSLR photometry is getting light into the camera. Starlight must be focused on the sensor either by a lens directly mounted on the camera or by attaching the camera to a telescope. A typical assortment of DSLR lenses is shown in Figure 2.6.

Figure 2.6. Various DSLR lenses. (Paul Valleli)

The lens is the first element of the photometric chain. Lenses can be generally described by two properties: aperture and focal length. The aperture area determines how many photons may enter the optical system within a fixed period of time. Larger apertures (smaller f-numbers) collect more light and permit fainter targets to be observed. The focal length determines the magnification of the image. When combined with the size of the detector, the focal length determines the field of view (FOV, the angular extent of the sky your camera can record) of the instrument.

The FOV needs to be large enough to include a good set of comparison stars in addition to the target star. A short focal length lens has a wide FOV, thus it is well-suited for measuring bright variables (bright comparison stars are generally farther apart than faint ones), and for capturing many stars simultaneously for bulk analysis. The longer the focal length of the lens, the more "zoomed in" you are, that is, you see a smaller area of the sky but in greater detail. Thus, for fainter stars, a longer focal length lens or a telescope is needed. At a given f-stop (f-stop is a setting that determines the area of the aperture) the sky background level is the same for all focal lengths, but the aperture surface and the resulting numbers of photons reaching the detector are proportional to the square of that focal length. Therefore, zooming in strongly increases your ability to measure fainter stars because the SNR (signal-to-noise ratio) over the sky background shot noise (more on those in Chapter 4) improves a lot.

What lens should you use? There are two approaches to deciding. The first is to use the lens that you have, and select targets that are compatible with your camera/lens. There are plenty of stars needing attention, so almost any lens/camera combination can be put to good use. The second approach is to decide upon a particular star or project, and acquire a lens/camera setup that is a good match to the needs of the chosen project. In either case, your choice of equipment will be a balancing act between several lens parameters. These parameters include field of view, aperture size, focal length, limiting magnitude, and achievable exposure duration.

Almost all DSLR variable-star projects use "differential photometry", in which the brightness of the target variable star is compared to the brightness of a nearby star of known constant brightness – a "comparison star". In order for this to work, both the target and the comparison star need to be in the same image field of view, and the comparison star should be roughly the same brightness as your target. If your target is bright (say, a naked-eye star), then most likely you'll need a FOV of several degrees (or more – maybe 10 to 30 degrees) in order to capture a comparable-brightness comp star in the same image as your target. A wide FOV implies a short focal length, which in turn is nicely compatible with the standard lenses that come with most DSLR camera kits.

If your target is faint, then you want to balance two approaches to achieving a high-signal image. You can take a long exposure, or you can use a lens with a large aperture. Doubling the exposure doubles the number of photons that you collect (other things being equal), but this can be a problematic approach as you move to fainter targets. You might be able to capture a nice high SNR image of a naked-eye star (5th mag, say) in a 10-second exposure using your standard 50-mm f1.4 lens. But for the same SNR a 10th-magnitude star (which provides only 1/100th as many photons per second) would require a 1000-second exposure (nearly 17 minutes), which means that you need to accurately follow the sky's rotation for that long exposure, which also raises a host of other challenges.

A 50-mm f1.4 standard lens has a collecting aperture diameter of about 35 mm– not very large! By mating your camera to a telescope, you can achieve a huge increase in collecting aperture. For example, a modest 6-inch aperture telescope will provide 18 times the collecting area of a standard 50-mm f1.4 lens, thereby extending your magnitude limit significantly. Of course, the telescope is likely to have a fairly long focal length (say 30 to 60 inches), and hence provide quite a narrow FOV. This means that you are not likely to have a bright star within the FOV (but there's a good chance that you'll have a few faint – say, 10th magnitude – comparison stars, which is what you need for a 10th-mag target). The narrow FOV implies the need for a good tracking mount.

So, there is a role for everything from standard lenses (bright stars), to telephoto lenses (fainter targets with appropriate comp stars within a few degrees), and telescopes (faint targets with one or two comp stars within the narrow field of view).

Knowing the lens focal length and the size of the sensor in your camera (see your camera manual), you can determine the field of view from Table 2.1 or equation 2.1. This equation is an approximation which is appropriate for APS-C sized sensors used with lenses of focal lengths 50mm or greater.

FOV (degrees) = 57 x sensor size (mm) / focal length (mm) [Eq. 2.1]

A convenient way to directly determine the field of view of a star field image is to use the Astrometry.net webpage to perform a blind plate solve (i.e. identify stars in the image and determine FOV without the user providing any information other than the image itself). Currently DSLR RAW images are not suitable so you first have to convert the image to JPEG, GIF, PNG or FITS format.

Go to the upload page at http://nova.astrometry.net/upload . Click "Choose File" button then navigate to your converted image and select it. Click on the "Upload" button (it may take a while depending on the file size and your internet speed). After a few seconds the webpage will change to the status page. The plate solve process may take anywhere from a few seconds to several minutes. Click on the "Go to results page" link to display the results of plate solve process (Figure 2.7). Listed on the right are image center coordinates, field of view size, pixel scale and orientation.

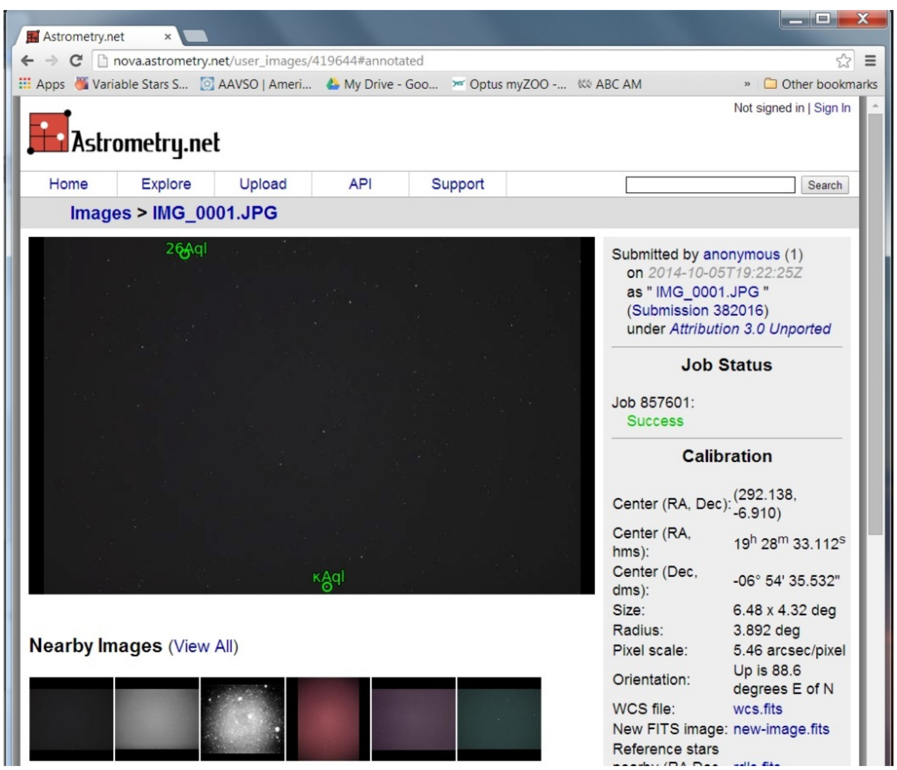


Figure 2.7. Astrometry.net Results page showing image center coordinates and field of view determined from a star field image using a blind plate solve routine. (Mark Blackford)

Figure 2.8 shows the familiar constellation Orion and illustrates how the area of sky captured by a DSLR depends on the focal length of the lens used.

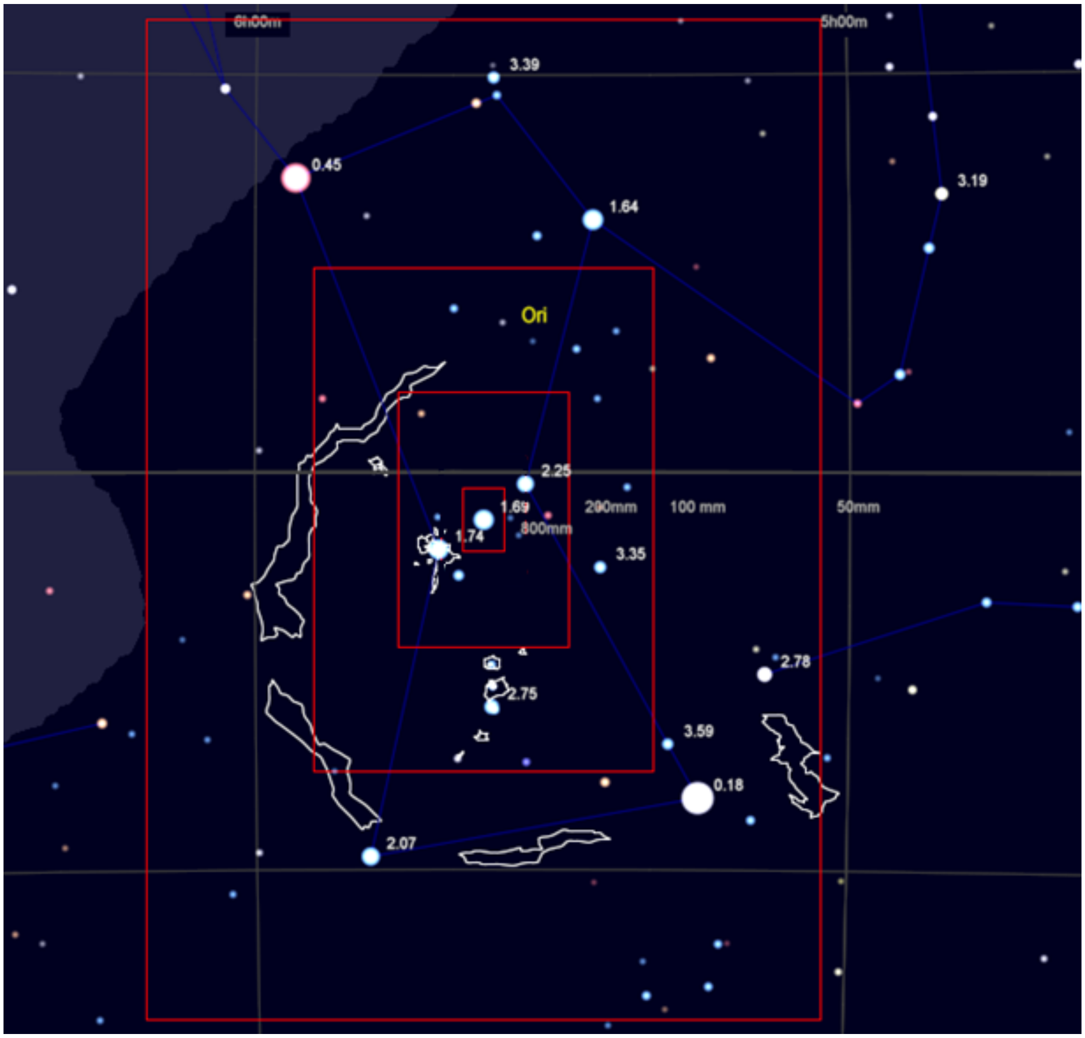


Figure 2.8. Field of view of an APS-C sensor-equipped system at several focal lengths. (Roger Pieri)

Table 2.2 shows the area of aperture at f/4 for the focal lengths and sensor types in Table 2.1. The enormous range of photon flux as a function of FOV and sensor size can clearly be seen. Thus, the f-stop determines the ability of each configuration to access and measure a large range of magnitudes.

Table 2.1. Example of focal length needed to cover a given FOV for typical sensor sizes. Blue cells: very expensive lenses, better to use a telescope connected to the camera body. (Roger Pieri)

All dimensions in mm	**APS-C** **14.9 x 22.3**	**4/3 System** **13 x 17.3**	**1" System** **8.8 x 13.2**	**1 / 1.7"** **5.7 x 7.6**	**1 / 2.3"** **4.6 x 6.1**	**Full Frame** **24 x 36**
FOV width deg.	**W/H=1.5 Foc.Length**	**W/H=1.33 Foc.Length**	**W/H=1.5 Foc.Length**	**W/H=1.33 Foc.Length**	**W/H=1.33 Foc.Length**	**W/H=1.5 Foc.Length**
64	18	14	11	6	5	29
48	25	19	15	9	7	40
32	39	30	23	13	11	63
24	52	41	31	188	14	85
16	79	62	47	27	22	128
8	159	124	94	54	44	257
4	319	248	189	---	---	515
2	639	496	378	---	---	1031

Table 2.2. Area of aperture at f/4 for focal lengths and sensor types shown in Table 2.1. (Roger Pieri)

All dimensions in mm	**APS-C** **14.9 x 22.3**	**4/3 System** **13 x 17.3**	**1" Format** **8.8 x 13.2**	**1 / 1.7"** **5.7 x 7.6**	**1 / 2.3"** **4.6 x 6.1**	**Full Frame** **24 x 36**
FOV width deg.	**W/H=1.5 Aperture mm²**	**W/H=1.33 Aperture mm²**	**W/H=1.5 Aperture mm²**	**W/H=1.33 Aperture mm²**	**W/H=1.33 Aperture mm²**	**W/H=1.5 Aperture mm²**
64	16	9	5	2	1	41
48	31	19	11	4	2	80
32	74	45	26	9	6	193
24	135	81	47	16	10	352
16	309	186	108	36	23	805
8	1248	751	437	145	93	3253
4	5004	3012	1753	---	---	13042
2	20030	12055	7018	---	---	52200

Blue cells: as in Table 2.1

The camera lens must be able to be focused manually; autofocus will not work when aiming at the stars. For aesthetic astrophotos, stars are focused into tight points, but for DSLR photometry, it is necessary to defocus to spread the light over a larger region of the sensor to ensure adequate sampling in each of the color channels. Don't be tempted to use sharp focus in attempting to capture very faint targets because this will introduce artefacts as discussed in Section 5.5.

The only exception is when imaging through a telescope with focal length long enough to produce focused star images with Full Width at Half Maximum intensity of 8 pixels or more.

Bright targets can be defocused more to allow longer exposure time that would otherwise result in saturated pixels.

Many DSLR cameras come equipped with standard kit zoom lenses like the 18-55mm f5 lens in Figure 2.6. These types of lenses are relatively slow (i.e. large f-numbers) and of poor optical quality when used at the widest aperture setting. They may perform adequately when stopped down, but generally it is recommended that they not be used for photometry.

High quality (and therefore relatively expensive) zoom lenses are suitable for DSLR photometry if care is taken to avoid zoom and focus creep which may occur when pointing high in the sky. If the zoom lens changes focal length over the course of an observing session, the focus will shift and saturation or blending of nearby stars may occur, and astrometry and image stacking can be more difficult. The shift could be due either to an environmental effect such as temperature change or a physical effect such as the weight of the lens itself as the target moves from low to high elevation. Tape can be used to prevent the focal length from shifting.

Fixed focal length lenses are recommended for DSLR photometry as they generally have higher quality optics and faster f-number than similarly priced zoom lenses of comparable focal length.

2.3 Tripods and mounts

The camera needs to be attached to some kind of mount in order to obtain images of good quality; a hand-held camera will not provide enough stability to take data-quality images. There are a number of ways to mount a camera, with a fixed tripod being the simplest and least expensive. It is also possible to mount a camera equipped with a lens on an equatorial mount – a mount that follows the movement of the sky – or to attach (or "piggy-back") a camera onto a telescope that's on an equatorial mount. Doing so has the benefit of letting your camera point at exactly the same location in space as it moves across the sky during the night. Finally, you can also attach a digital camera to a telescope focuser, in essence turning the telescope itself into a lens for the camera. Which of these you use is a matter of personal preference and resources. While you can obtain good quality data with any of these mounts, your choice of mount will define what objects you can observe, and how you observe them.

Below, we describe the most common types of mounts.

2.3.1 Tripod or other fixed mount

A tripod consists of a standardized mounting point to which cameras or other optical instruments can be attached. Your camera likely has a small threaded hole at the bottom into which a screw on the tripod head can be inserted. It provides a way to keep the camera fixed and pointed at exactly the same place in the sky, without being subject to motion (like the small movements of your hands and arms). The limitation is that the stars move across the sky during the course of a night due to the Earth's rotation. This is acceptable, but will limit the exposure times that you can use so that stars are not trailed beyond the limits that your software can measure.

2.3.2 Equatorial mount

An equatorial mount makes use of motorized axes to compensate for earth's rotation thus keeping a target within the FOV of the camera for extended periods of time. . Such a mount typically replaces the fixed head of a tripod. Equatorial mounts are often used with telescopes, enabling them to track the movement of the sky and follow the same object in space during the course of the night without having to constantly adjust the telescope by hand. Instead of a telescope, a digital camera and lens can be attached directly to such a mount. Equatorial mounts have additional requirements: you need a power source to drive the mount, and you need to polar align the mount with the North or South Celestial Pole so that it can track properly. In principle, a well-aligned equatorial mount allows you to use longer exposure times than a fixed tripod can. Doing so will let you observe fainter stars, because the longer your exposure time, the more light you can collect. Table 2.4 gives sample exposure details for driven mounts.

2.3.3 Piggy-back mount

A "piggy-back" mount simply attaches the camera and lens to an existing optical instrument, most commonly a telescope on an equatorial mount. Note that the telescope is not used to provide light to the camera, but simply as a mounting point for the camera and lens. In this case, your main concern is how to attach your camera to your instrument rather than to a mount. Some telescopes have mounting hardware readily available (either standard with the telescope or available commercially) but others may require that you design and create your own mounting hardware. In any case, the main requirements are that the camera is securely and safely attached to the telescope, and that it remains in place without slipping or shifting as the telescope moves. You should also be aware that adding a camera to a telescope will change the weight balance of the mount, and may therefore require that you rebalance your equatorial mount.

2.3.4. Small RA motorized units

Small devices specific for DSLR cameras also exist. They do not have a Declination axis but only a motorized Right Ascension axis that follows the sky. The camera with its lens is mounted on this platform using a ball head fixture. The assembly can be pointed to any direction in the sky and then follows it. This device has no tripod of its own and is normally affixed onto a sturdy enough photo tripod. This solution works well for a couple of minutes of exposure with a lens, not a telescope. The cost is much lower than a good level equatorial mount and the equipment is light, much easier to transport and set up. A very low cost solution would be to build a traditional “barn-door” mount. It is made from two plywood plates joined with a door hinge controlled by a screw which is either rotated by hand or using a small motor/reducer. The camera is mounted on one of the plates via a ball head fixture. The hinge axis is pointed to the North (South) Celestial Pole. One final solution is to use an entry level equatorial mount like an EQ1 and equip it with a stepper motor which should be suitable for 60-90 second exposures with a 200-mm focal length lens. Overall cost should be about $200 US. This assembly is light, very easy to transport, and can be set up in a couple of minutes.

2.3.5. Motorized Computer controlled Alt-Az mount

A number of commercial suppliers offer excellent motorized computer controlled Alt-Az mounts that would be suitable for DSLR photometry through short to medium focal length lenses. These mounts allow easy target acquisition and tracking after a simple initial alignment process. Field rotation will limit the useful exposure time to probably less than a minute, depending on the target declination, but still significantly longer than with a non-tracking mount.

2.3.6. Caveat

Any of these mounts will allow you to take good scientific data, but using an non-tracking mount – either a tripod mount or an equatorial mount without drive or good polar alignment – will require that you take shorter exposures, usually less than 5-20 seconds (Table 2.3). This is because the sky will rotate slightly across the field of view of your camera during exposures, resulting in trailed images. If the trails are too long, the extra background pixels in the photometric aperture will increase the noise and lower the SNR (signal-to-noise ratio). However, some photometry software packages provide an elongated measurement aperture that could fit the trail and provide superior results if the star is bright enough. Another limit of long trails (or defocus) is the risk of blending of stars, in particular if a short focal length is used.

The next section will provide guidelines for exposure times based upon your camera optics and also whether you are using a fixed mount without tracking or equatorial mount with tracking.

2.4 Camera settings

2.4.1 Manual mode

There are many camera settings on your DSLR, most of which you will not be using. There are also many different cameras, so you will need to reference your manual to find the following settings, many of them through a series of menus. Your goal is to simplify the camera, turn off all the bells and whistles, and collect just the raw image. Your first step is to turn the mode dial to “M” to acquire manual control over the exposure time and f-stop, described below.

2.4.2 f-stop

The next step is to choose an appropriate f-stop. The f-stop is a number equal to the focal length of the lens divided by the diameter of the aperture, the opening that lets light into the camera. The lower the f-stop, the more light gets in, but sometimes there are lens defects that can be minimized by avoiding the lowest f-stop. As a general rule you want to collect more light, so you want your f-stop to be a small number, such as f/2 or f/4. If you go above f/7, you have probably stopped it down too much.

2.4.3 ISO

The ISO setting on your camera determines the amplification of the sensor output. Higher ISO is helpful when imaging faint stars, but with a bright star, high ISO increases the risk of saturation, which occurs when a sensor pixel receives more photons than it can accurately count. On the other hand, a low ISO number avoids the saturation problem and allows for a wider range of brightness to be measured. An ISO of 100 to 200 is typically recommended for bright stars. Higher ISO may be necessary for fainter stars, depending on the aperture, exposure time, and number of pixels illuminated by the starlight.

As mentioned above, the ADU output of the ADC is proportional to the number of electrons collected by the photodiode of each pixel. The calibration factor e/ADU is inversely proportional to the ISO number. For most common APS-C DSLR cameras having a 14-bit ADC, the ideal calibration factor of one electron per ADU is reached between ISO 100 and 300, depending on the pixel size. Below that ISO range, the finest data increment (quantization) is 1 bit on the ADC for several detected electrons, thus sensitivity is lost. This quantization regime allows higher possible photometric accuracy and dynamic range under a high flux regime (where the capacitor can be filled by electrons), but the detectability is limited to a couple of electrons. In modern cameras, the output of the converter is typically a 14-bit value, which may include some coding shift (e.g., 1024 or 2048 for Canon cameras). Thus, out of the 16384 possible values represented by a 14-bit number, only approximately 14000 are usable. At ISO 400 and above, the ADC output will record every electron collected by the photodiode. Thus, the total number of electrons readable is altered (proportionally to the ISO number) by the way the possible dynamic range and SNR are altered. Figure 2.9 shows electron linearity and saturation for the Canon 450D Green channel at various ISO settings.

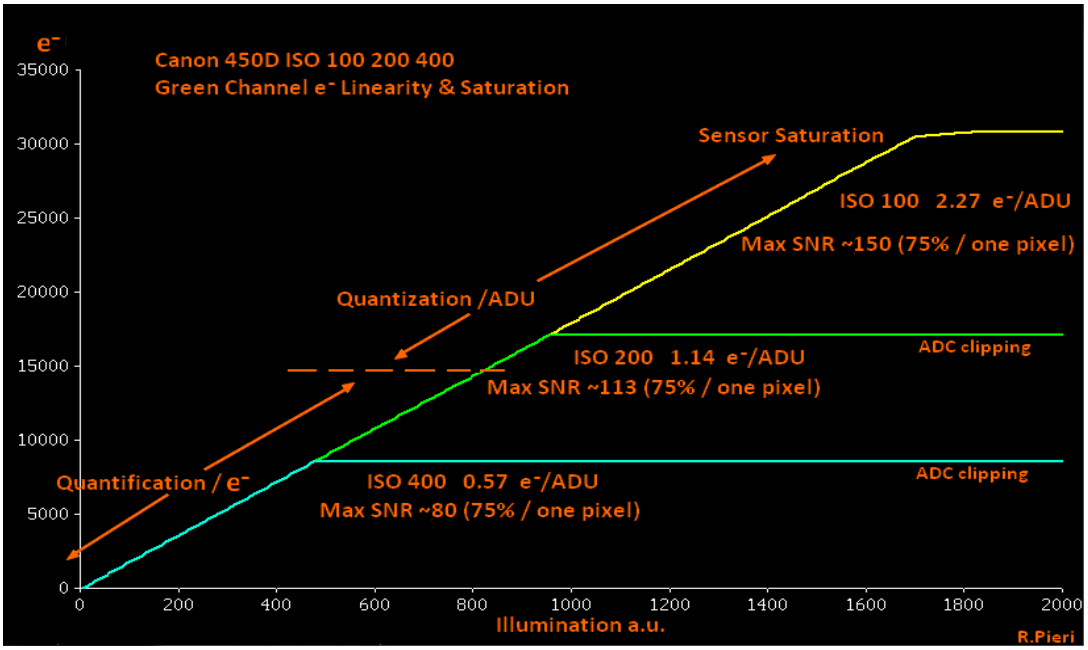


Figure 2.9. Electron linearity and saturation for Canon 450D Green channel at several ISO settings. (Roger Pieri)

To this point we have assumed that only stellar photons are measured by the camera, but this is in fact an oversimplification. The RAW output measured as ADU is proportional to the photon count of the star, plus sky background, plus several sources of noise. The noise comes from intrinsic fluctuations of the source, scintillation of the atmosphere, and the camera's own electronic circuitry. In particular, some of the ADU measured are in fact dark current caused by thermally generated electrons in the photodiode. Most of the time, the contribution of dark current can be mitigated by taking a series of dark frames (images where no light is permitted to enter the system) that will be subtracted from the RAW output. Random amplification noise and shot noise from the mean dark current also contribute to the measured signal. These terms are discussed in Chapter 4.

2.4.4 Exposure time

Now you will set the exposure time so that you can take photos at least several seconds long. The amount of time you choose will depend on several factors, such as the brightness of the star, the f-stop, the ISO setting, and whether you wish to avoid star trailing. If the star is faint, you need to expose long enough to measure the brightness accurately. If the star is bright, a long exposure risks saturation. Since a lower f-stop allows in more light, a lower f-stop also allows a shorter exposure. As the ISO setting is lowered, the required exposure time increases. If your camera is mounted on a tripod, your exposure times are limited to about 5-20 seconds (Table 2.3) to avoid having long star trails. If your camera is on a driven mount, you can go up to about 60 seconds before worrying about the background brightness of the sky or the accuracy of the drive. For long exposures, you may need to set the exposure time to "BULB" and use a cable release to operate the shutter. You might choose to take multiple images of identical exposure time and combine them in a software process called stacking. The combined exposure of stacked images should total at least 60 seconds to properly average the variability of the signal due to atmospheric scintillation, commonly observed as twinkling. This integration time is a function of the level of photometric accuracy desired for the observation, the sky "seeing," and the aperture of the instrument. The scintillation is strong with small aperture and gets weaker when the aperture increases. It is another effect of "seeing", the turbulence of the atmosphere.

Tables 2.3 and 2.4 on the next page list estimates of the faintest magnitude reachable under an excellent sky using different optics at maximum aperture. These are calculated with the assumptions that the camera is pointed at the zenith, 400 ISO setting, without and with RA drive. The corresponding exposure time and saturation level are provided for a photometric aperture of 25 pixels at ISO 400 and 100. A much larger dynamic range can be reached using a larger defocus.

It should be noted that, although stars may be recorded in an image at the indicated limiting magnitude, their signal to noise ratio (SNR) would be extremely low. Photometry of such stars is subject to large errors and should only be attempted if longer exposures or larger aperture instruments are not available. Stacking several images will improve SNR at the expense of time resolution.

2.4.5 File format

DSLR cameras offer a variety of file formats. The one required for photometry is RAW, which records directly what the sensor has detected and includes no processing or compression by the camera. The file extension used by Canon for RAW files is .CR2, Nikon uses .NEF. Consult the manual if your camera is from another manufacturer. RAW requires an enormous amount of memory storage, but all of this information is necessary for accurate photometry.

While JPG is a more common format for photographers, it does not preserve the information the universe has laboriously delivered to your camera sensor. It is recommended to avoid the combined RAW+JPG mode that exists in many DSLR cameras. The JPG output requires a lot of work for the processor (noise reduction, various camera internal corrections, de-Bayer, sRGB conversion, etc.). It uses a lot of battery power and generates heat that increases dark noise.

There are a number of other settings on your camera that are undesirable in photometry. Any function that involves the camera processing the image, such as noise reduction, must be avoided. You will also want to turn down the LCD brightness (even switch it off) to maintain your night vision and your battery life. The authors of this guide cannot know all the settings that may be available on your camera, but when in doubt, choose the one that sounds like it will not do anything fancy.

Table 2.3. Suggested exposure times for fixed tripod (non-tracking) mount. (Roger Pieri)

Optics type	FL mm	F-stop	Aperture Size mm²	Max* Exposure	Limiting Mag	Sat. Mag	Sat. Mag	FOV** deg
Zoom 18-55mm f3.5-5.6	55	5.6	76	20 s	8	5.1	3.7	15.3 x 22.8
Zoom 70-300mm f4-5.6	70	4	240	16 s	9	6.2	4.8	12 x 18
Tele 200mm f4	200	4	1963	5.5 s	10	7.3	5.9	4.24 x 6.36
Zoom 70-300mm f4-5.6	300	5.6	2254	3.7 s	10	7.1	5.7	2.8 x 4.2
Refractor 400mm f5	400	5	5026	2.7 s	10.5	7.6	6.2	2.1 x 3.2

* Trail of 15 pixels of 5.2 microns at declination 0 deg. Averaging of star scintillation typically needs a total of 60 s integration, so several images should be stacked or averaged to reach a 60 s series. Making several series (5 or more) enables a reasonable statistical analysis; it is important to optimize the settings.
** APS-C size sensor
"FL" is the Focal Length.
"Limiting Mag" is the faintest star magnitude measurable with an instrumental uncertainty of 0.05 mag in a photometric aperture of at least 25 pixels, in one image. Depending the sky condition overall uncertainty would be higher.
"Sat. Mag" is the magnitude at which at least one pixel reaches 75% of the saturation level.

Table 2.4. Exposure examples for a tracking mount. (Roger Pieri)

Optics type	FL mm	F-stop	Aperture Size mm²	Max* Exposure	Limiting Mag	Sat. Mag ISO 400	Sat. Mag ISO 100	FOV** deg
Tele 200mm f4	200	4	1963	60 s	13	9.9	8.5	4.24 x 6.36
Zoom 70-300mm f4-5.6	300	5.6	2254	60 s	13	10	8.6	2.8 x 4.2
Refractor 400mm	400	5	5026	60 s	14	10.9	9.5	2.1 x 3.2
Newton 800 mm f4	800	4	31416	60 s	16	12.9	11.5	1 x 1.6

Notes as in Table 2.3

Chapter 3: Software Overview

After your imaging device, computers and software are the most important components in DSLR photometry. Many aspects of planning observations, acquiring and calibrating images, measuring, analyzing, and reporting results are aided by the use of appropriate software. There are a number of free and commercial options available, with new offerings coming to the market occasionally. Some perform multiple tasks while others are more specialized. No one package does everything so you will probably end up using a small suite of programs, each dedicated to a specific task within your workflow.

Because software is constantly changing, this manual does not provide guidance for any single software package. Instead, we provide a high-level overview of the features you need, probably want, and might be able to use within a photometric reduction suite. Tutorials for several popular photometry software packages are available on AAVSO's website (www.aavso.org/dslr-observing-manual).

3.1 Minimum requirements for DSLR photometry software

When considering software for DSLR photometry, there are four key components that the software must perform: open RAW images, apply bias/dark/flat frames, extract individual color channels, and perform photometric analysis. There is no single "correct" program to use, and you may find yourself using several programs to do these steps. In the next few paragraphs we discuss each one of these steps in greater detail.

3.1.1 Support for the RAW format of your camera

As described in the previous chapter, in order to extract accurate photometric measurements from your images, it is imperative that the raw data values recorded by the camera remain unaltered by any built-in processing. Consequently, your photometry software must be able to read and manipulate the RAW format which your camera produces. There is no universal RAW format: Canon uses CRW and CR2 files whereas Nikon uses NEF files. Other camera manufacturers have their own formats.

When shopping for software (or a new camera), keep in mind that when a new camera is released, it may take several weeks to months before processing and photometry software is updated to read the new RAW format. You should verify that support for your camera is present by consulting the software publisher's website.

3.1.2 Integrated image calibration (bias, dark, flat frame corrections)

As will be explained in the next chapter, a series of calibration images must be taken in addition to your science images. These bias, dark, and flat images characterize constant offsets, unequal illumination caused by your optics, and hot pixels (or other imperfections) in your camera's detector. To obtain an accurate estimate of the intensity of the stars, these effects must be removed. Thus, your software must not only read and display the images, but also apply these calibration frames to your science images.

3.1.3 Extraction of individual color channels

As described in the previous chapter, the Bayer color filter array on DSLR sensors allows red, green and blue information to be recorded simultaneously in the same image. Each color is said to be in a separate channel or plane. Your photometry software must be able to separate RAW images into individual red, green, and blue images. There are actually two green channels and some software, e.g., AIP4Win, combines them into one image. Other software, e.g., MaxIm DL, treats each green channel separately. At present most software only extracts one color channel at a time, so it may be necessary to repeat the extraction process if all three colors are of interest.

Many of the popular photometry programs include the capability to extract color channels from RAW image files (e.g., MuniWin, IRIS, AIP4Win, MaxIm DL). With these, you can use a single program to extract the color channel, perform image calibration, and perform photometric analysis. A few popular photometry programs do not handle DSLR RAW image files (e.g., MPO Canopus, VPhot), or do not have the capability to extract individual color channels. If you like the photometry tools in one of these programs, then you'll first have to extract then convert the single-color image to the FITS format that MPO Canopus and VPhot require.

Most programs produce extracted color images that are smaller than the RAW image (e.g., 5200 x 3460 pixel RAW image will result in a 2600 x 1730 pixel extracted image). AIP4Win, however, interpolates how much red, green and blue light would have fallen on each pixel in the image. It does this by looking at, for instance, the surrounding green pixels and interpolating how much green light should have fallen on the red and blue pixels. Thus extracted images are the same size as the RAW image. Several interpolation methods are available and it is important to select the bi-linear option for greatest accuracy.

Note: Depending on which software you use, color channels may need to be extracted prior to calibration. It is very important not to mix the calibration frames for different color planes.

3.1.4 Photometric analysis

Photometric analysis is the measurement of the intensity of star light collected by the detector during an exposure. The most common approach in software typically used by amateurs is call aperture photometry, and this is the only technique discussed in this manual. Details are given in Chapter 5, but essentially aperture photometry measures two parameters for each target and comparison star. The first is the total intensity in a small circular aperture centered on the star, called the measurement aperture. This total will include photons from the star, plus photons from sky-glow. The second parameter is the average intensity per pixel in a region containing no stars called the sky annulus, also centered on the star but larger in radius than the measurement aperture (see Figure 5.3). From these the software can calculate the sky background-corrected intensity of each star. Many programs allow this procedure to be batch processed (see topics below on batch processing and scripting) which will greatly simplify and speed up the analysis if multiple images are to be measured.

3.2 Useful software features

The following are some additional features found in some photometry software which you'll find make image processing much more efficient. None are required, but they will make your work easier.

3.2.1 Batch processing of images

To remove the drudgery of manually processing each image individually, most DSLR observers will want to process whole batches of images in one go. Depending on your acquisition technique and target star properties, you might need to record dozens or hundreds of images of the same field, as well as multiple calibration frames. Processing that many files one by one will quickly ruin the fun of DSLR photometry. Batch processing performs repetitive calibration and measurement operations on a series of files.

3.2.2 Scripting

Even better than batch processing, scripting allows you to combine several operations in a configurable workflow. Some software packages define a simple 'programming language' to let the user write scripts (e.g., IRIS), others use a Graphical User Interface (GUI) to define the workflow interactively and then apply it to sets of files (e.g., Fitswork). This is an advanced feature that is only offered by some software, especially those that are also used by professional astronomers. Beginners should not worry too much about scripting and work out their workflows manually first, but experienced observers will find this feature very helpful to boost productivity and avoid the frustration of performing some trivial tasks over and over again. When initially selecting a software package, you may wish to make sure you have the possibility to later use scripting, although initially you will likely not use it while learning.

3.2.3 Alignment and Stacking

An effective way to improve the Signal-to-Noise Ratio (SNR) of your images and/or reach fainter targets is to align and stack (i.e., add together or average) images. Many photometry software packages can align and stack photos although the step-by-step procedure will be slightly different. In general the software will first register each image by identifying several stars common to each. In the alignment phase the images are then rotated and moved to ensure the registered stars in subsequent images are aligned. The stacking phase then calculates median or average values of each pixel from the images in the stack. The final image is the result of these stacked pixel values.

The noise portion of the content of each pixel is not constant but fluctuates around a mean value and may change from one image to the next. By stacking images, the signal-to-noise ratio tends to improve. This is because addition of several measurements results in both the signal and the noise increasing in absolute terms, but the noise, being random, increasing more slowly than the signal. For regions in the stacked image with no stars the result will be pixel values close to a constant sky background level (close to zero for short exposures from a dark site) and scatter reduced compared to the individual images. In the case of stars the pixels will not change much from one image to another so the result of the alignment and stacking process will reduce the noise while leaving any stars mostly unchanged.

3.2.4 Computer control of focusing and image acquisition

Image acquisition can be controlled by software when the camera is connected to a computer via USB cable (normally used for downloading images from the camera's memory card). Canon provides the EOS Utility program with their DSLR's. Other camera manufacturers should provide similar software, either free or at an additional cost. Third-party software is also available, i.e. BackyardEOS, BackyardNIKON and MaxIm DL.

Such software greatly facilitates framing of the target, setting an appropriate amount of defocus and exposure duration. You can quickly check framing of target and comparison stars by acquiring an image and displaying it on the computer. If necessary, camera pointing can be adjusted before the science images are captured. The image can also be measured to ensure stars of interest are not over or underexposed, and exposure duration adjusted accordingly.

Autofocus will not work on the night-time sky and must be turned off. In fact, for photometry the image needs to be slightly defocused (see Image Acquisition chapter). Setting the lens to the infinity (∞) marker is unlikely to be suitable either, especially if you are using a zoom lens. Manual focusing can be particularly time consuming and frustrating so software control is desirable. BackyardEOS is one program that does this with Canon electronic lenses. Other software may be available for specific cameras.

BackyardEOS also automates image acquisition, as do other programs. This is particularly useful when multiple images of one field are required for later stacking or to record relatively rapidly varying stars, e.g., eclipsing binaries. The software can be programmed to obtain a set number of images at specified time intervals.

MaxIm DL is a powerful acquisition and analysis package popular with CCD and DSLR imagers alike. However, unlike most other acquisition software, MaxIm DL saves images in FITS format [see section 3.2.6], not the camera's native RAW format. This is not a problem as FITS is the usual input file format for photometry software.

3.2.5 Automatic plate solving (astrometry)

Plate solving is the process of automatically identifying the stars detectable in an image, by cross-referencing with a star catalog. If you have prepared your observation session by looking at finder charts first (as you should), you will soon learn how to identify the target and comparison stars manually without the help of automatic plate solving. But for some advanced techniques like automatic photometry, or when you think you notice a change of brightness in one of the stars in your field that might not even be part of your original observing program, plate solving can be useful. Some advanced packages like MPO Canopus (http://www.minorplanetobserver.com/MPOSoftware/MPOCanopus.htm) even use this to automatically identify variable stars (or asteroids etc.). A web-based solution is astrometry.net, which also offers standalone (Linux) software which you may download and use locally.

3.2.6 Converting images to FITS format

The "Flexible Image Transport System" (FITS) is an open standard for images (and some other astronomical data sets like tabular information) and is very popular in the astronomy community. It allows lossless storage (the stored file contain all the information that was present in the original RAW image file) which is essential for photometry. Recall that JPG is a compressed file format, and it is not lossless. Because FITS is supported by practically all serious astronomy software, it is a very good choice when you want to exchange image data between different software packages. Another big advantage of the FITS format is that it allows storage of image metadata (e.g., time of observation, observation location, duration of exposure, field coordinates in the sky, etc.) in a standardized way that software can understand. Also, for archiving your images, FITS is the best choice. There are, however, several sub formats of FITS and you might have to experiment a bit to find a common sub format supported by all of your favorite software.

Fitswork (http://www.fitswork.de/software/softw_en.php) can batch convert RAW files to FITS format and it even supports some scripting functionality.

3.2.7 Differential extinction and transformation corrections

As will be explained in greater detail in Chapter 6, for the most accurate results it is necessary to apply two corrections to our measured magnitudes. The first corrects for the effects of differential atmospheric extinction caused by different path lengths of starlight through the atmosphere when the field of view is relatively large and the star's elevation is relatively low. This situation often arises in DSLR photometry with camera lenses. Stars in the part of the frame closer to the horizon experience more extinction than stars closer to the zenith and this can skew our magnitude estimate of the target variable.

The second correction is called transformation and is necessary because filters and CMOS sensors in DSLR cameras do not have the same spectral transmission function or spectral response function as the standard astronomical filters and CCD cameras. Transformation is the process of transforming the measured instrumental magnitude to a standard astronomical magnitude, e.g., DSLR green channel magnitude to Johnson V magnitude.

Most photometry programs do not perform these tasks; AAVSO's VPhot does facilitate transformation correction but as yet does not allow extinction correction. Normally these corrections would be performed in a spreadsheet.

3.2.8 Report generation and web submission

Observations should be submitted to the AAVSO International Database via the WebObs site (http://www.aavso.org/webobs). Several photometry packages (e.g., AIP4Win, MaxIm DL, VPhot, and MPO Canopus) can generate suitable text file reports.

Alternatively, observations may be recorded in a suitably formatted spreadsheet for subsequent uploading to WebObs (http://www.aavso.org/aavsoextended-file-format).

3.2.9 Time Synchronization

Manually setting the camera date and time with reference to a radio time signal at the beginning of the observing session is usually sufficient when observing longer period variables. In other situations accurate time stamping of images is important, e.g., time series of eclipsing binary stars to determine the precise time of minimum light. Canon cameras, and presumably others, can be configured to synchronize with the computer clock when attached via USB cable. The computer clock can be automatically synchronized at regular intervals with an internet time server. Many modern operating systems automatically perform this task; however, dedicated software such as Dimension 4 (http://www.thinkman.com/) can be used. Software control of the DSLR (Section 3.2.4) allows a convenient way to ensure the camera clock is correctly set prior to acquiring each image.

3.3 Software capability comparison chart

The most common software solutions used for variable star observing are Windows or Linux based. Four common photometry software packages are compared in Table 3.1 below. Note: There are several versions of MaxIm DL available. In order to do DSLR photometry you will need the MaxIm DL Pro version. Features and prices were applicable in early 2013.

Table 3.1. Software Comparison Chart.

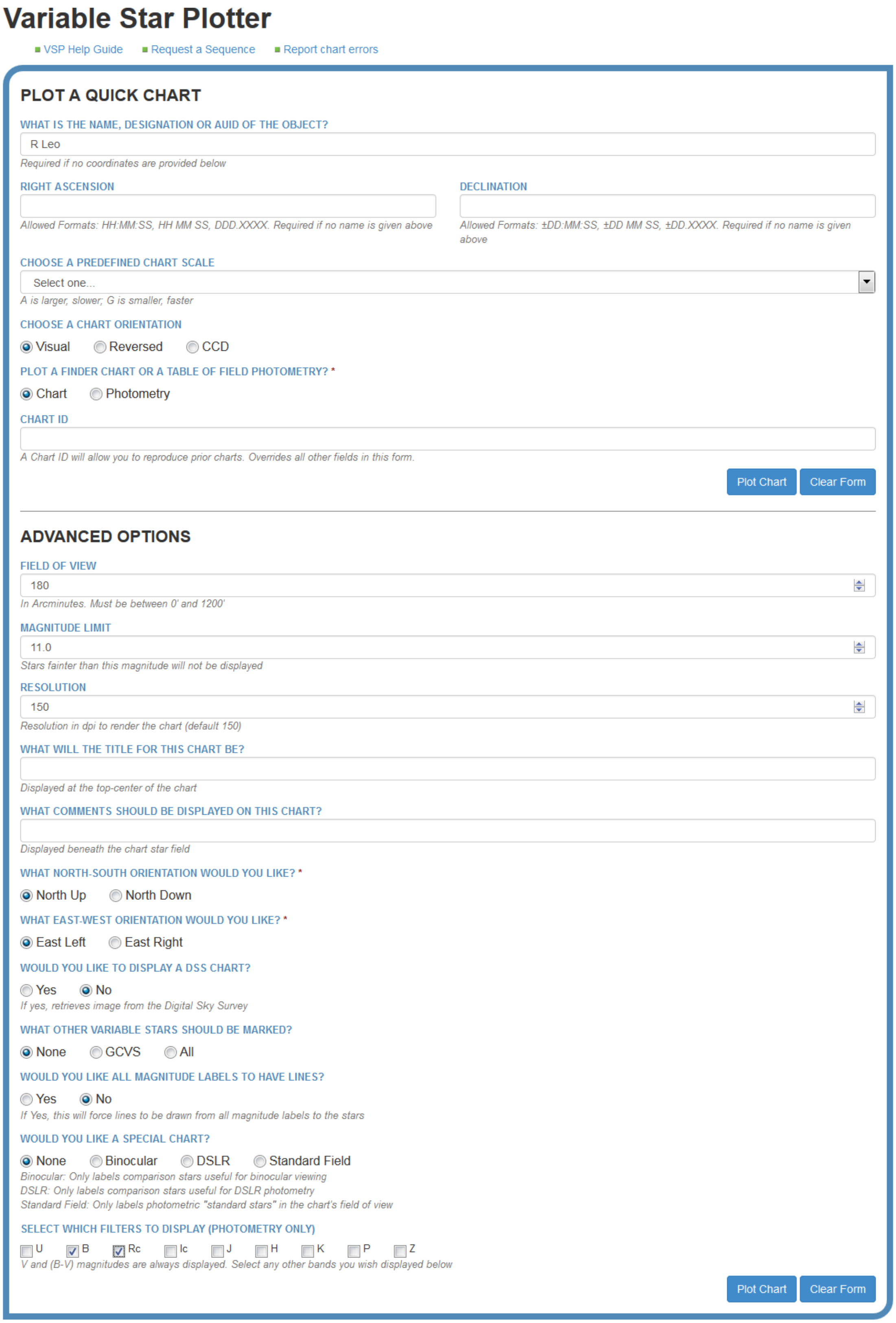
Features	**IRIS**[4]	**Muniwin**[5]	**AIP4WIN**[6]	**MaxIm DL Pro**[7]
Photometric Analysis	√	√	√	√
Use RAW Images	√	√[1]	√	√
Apply Bias, Dark & Flat Frames	√	√	√	√
Color Separation	√	√	√	√
Batch Processing	√	√	√	√
Alignment & Stacking	√		√	√
Camera Acquisition Display	√			√
Focus & Camera Control	√			√
Convert to FITS	√	√	√	√
Scripting	√	√		√
Telescope & Mount Control	√			√
Plate Solving	√		√	√
Report Generation			√	√
Cost	Free	Free	$99[2]	$499[3]

Notes:
1) Limited formats supported; contact the author regarding your camera (Muniwin website).
2) The $99 cost includes the book *The Handbook of Astronomical Image Processing*.
3) Only the MaxIm DL Pro and Suite will have all the features required for DSLR photometry.
4) http://www.astrosurf.com/buil/us/iris/iris.htm
5) http://c-munipack.sourceforge.net/
6) http://www.willbell.com/aip/Index.htm
7) http://www.cyanogen.com/maxim_main.php

3.4 Other useful software

3.4.1 Star charts and planetarium software

Printed star charts, or electronic charts displayed on a digital device, are useful for locating the region of sky to be imaged. Charts which identify target variable and comparison stars can be generated online with the AAVSO "Variable Star Plotter" (http://www.aavso.org/vsp). Figure 3.1, shows the VSP data entry page; see the VSP Help Guide link at the top of the page for detailed instructions.



Variable Star Plotter

- VSP Help Guide
- Request a Sequence
- Report chart errors

PLOT A QUICK CHART

WHAT IS THE NAME, DESIGNATION OR AUID OF THE OBJECT?

R Leo

Required if no coordinates are provided below

RIGHT ASCENSION

Allowed Formats: HH:MM:SS, HH MM SS, DDD.XXXX. Required if no name is given above

DECLINATION

Allowed Formats: ±DD:MM:SS, ±DD MM SS, ±DD.XXXX. Required if no name is given above

CHOOSE A PREDEFINED CHART SCALE

Select one...

A is larger, slower; G is smaller, faster

CHOOSE A CHART ORIENTATION

(•) Visual ( ) Reversed ( ) CCD

PLOT A FINDER CHART OR A TABLE OF FIELD PHOTOMETRY? *

(•) Chart ( ) Photometry

CHART ID

A Chart ID will allow you to reproduce prior charts. Overrides all other fields in this form.

Plot Chart | Clear Form

ADVANCED OPTIONS

FIELD OF VIEW

180

In Arcminutes. Must be between 0' and 1200'

MAGNITUDE LIMIT

11.0

Stars fainter than this magnitude will not be displayed

RESOLUTION

150

Resolution in dpi to render the chart (default 150)

WHAT WILL THE TITLE FOR THIS CHART BE?

Displayed at the top-center of the chart

WHAT COMMENTS SHOULD BE DISPLAYED ON THIS CHART?

Displayed beneath the chart star field

WHAT NORTH-SOUTH ORIENTATION WOULD YOU LIKE? *

(•) North Up ( ) North Down

WHAT EAST-WEST ORIENTATION WOULD YOU LIKE? *

(•) East Left ( ) East Right

WOULD YOU LIKE TO DISPLAY A DSS CHART?

( ) Yes (•) No

If yes, retrieves image from the Digital Sky Survey

WHAT OTHER VARIABLE STARS SHOULD BE MARKED?

(•) None ( ) GCVS ( ) All

WOULD YOU LIKE ALL MAGNITUDE LABELS TO HAVE LINES?

( ) Yes (•) No

If Yes, this will force lines to be drawn from all magnitude labels to the stars

WOULD YOU LIKE A SPECIAL CHART?

(•) None ( ) Binocular ( ) DSLR ( ) Standard Field

Binocular: Only labels comparison stars useful for binocular viewing
DSLR: Only labels comparison stars useful for DSLR photometry
Standard Field: Only labels photometric "standard stars" in the chart's field of view

SELECT WHICH FILTERS TO DISPLAY (PHOTOMETRY ONLY)

[ ] U [x] B [x] Rc [ ] Ic [ ] J [ ] H [ ] K [ ] P [ ] Z

V and (B-V) magnitudes are always displayed. Select any other bands you wish displayed below

Plot Chart | Clear Form

Figure 3.1. Variable Star Plotter (VSP) data entry webpage. (Mark Blackford)

The resulting chart has the variable star plotted in the middle, Figure 3.2. When setting up and focusing, these charts are useful to verify that the variable is well placed in your images. The magnitudes of some adjacent stars are also indicated, and you should ensure that some of magnitudes similar to your target star are included in the field of view, so that they can be used as comparison stars in the photometric reduction. Magnitudes are labeled without decimal points (which may be confused with the symbol for a faint star), so a magnitude 7.1 star would be labeled 71.

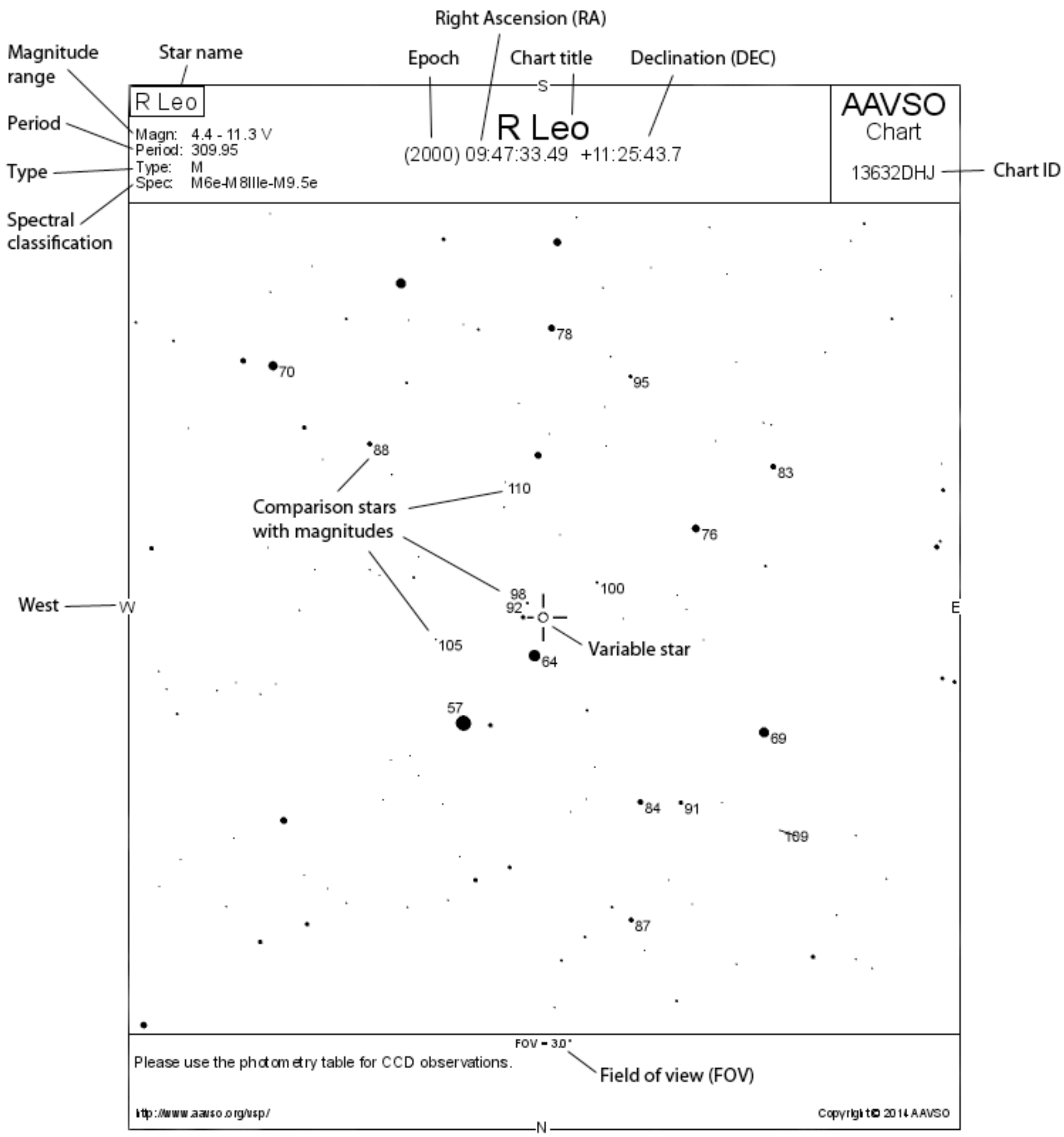


Figure 3.2. Variable Star Plotter chart of the field around the variable R Leo, with explanations of the information displayed on the chart. (AAVSO)

Comparison star magnitudes on VSP charts are given to one decimal place only. This is generally fine for visual observers but not adequate for DSLR analysis. Select the “Photometry Table” option on VSP to produce a detailed list of comparison stars for the field. Magnitudes and estimated error are given to 3 decimal places.

If you are using a well-aligned equatorial mount, the coordinates of the star supplied on the chart can help you to move quickly to the proper star field.

If you are using simply a tripod, a chart showing more of the sky may be useful to you in aiming your camera. Paper charts showing large areas of the sky, or sky atlases, can be used for this. However, planetarium software is more convenient because the displayed chart can be resized and oriented to match your imaging system and targets easily searched for and centered. Many planetarium packages can also control a telescope mount (see “Telescope and/or mount control” below). There are numerous free and commercial options available such as Stellarium, Cartes du Ciel, and TheSky. Some planetarium software for mobile devices can detect the direction you are pointing toward and adjust the view automatically to show stars in that direction, which can be very convenient.

One point to bear in mind when using software is that the variable star may be shown at a different brightness than you will see it on your observing night, specifically because it is variable!

3.4.2 Mount control

Many telescope mounts with “GoTo” capabilities can be controlled using software on your computer. These types of mounts often come with drivers or communication protocols that are understood by planetarium software, like Stellarium or TheSky. There are at least two major advantages to mount control via software. One is that a “target” may be easily located in the first place (provided it is visible in the sky at the time). A second is that a tracking mount will allow a camera to stay pointing at the same target, to compensate for the rotation of the Earth. This allows longer exposures and permits fainter stars to be detected. Ideally, the camera should be mounted on an equatorial mount, but many GoTo mounts are altazimuth mounts, which are easier to set up and are readily controlled by computer. Strictly speaking, use of an altazimuth mount (without an expensive camera rotator) causes the image to rotate slightly. Most software that process sequences of images can compensate for this, and for short exposures it isn’t a serious issue within individual images.

Chapter 4. Image Acquisition

4.1 Acquisition overview

DSLR photometry is, in principle, a very simple process: take images of the sky, calibrate them, extract photometric data, reduce the data to magnitudes, and submit your measurements for long-term archiving. The image acquisition step is fundamentally the most important of these processes for if the input data is of poor quality, so too will be the final product.

In this chapter we dive into the details of the preparatory work you should do before snapping your first data set, how to take calibration frames, how to find your star field in a tiny viewfinder, how to acquire images and assess their quality, and finally some tricks of the trade from experienced DSLR photometrists.

4.2 Preparatory work

4.2.1 Notebooks

Perhaps one of the most important aspects of doing science is keeping good records of what you have done. This may sound like an overly simplified concept, but a logbook of your observing setup and sessions will not only help you identify problems with your data or observing procedures, but also let other experimenters duplicate your experiment should the need arise.

At a minimum, your records should indicate the date and time of your images, the targets on which science data are being taken, the weather conditions, and anything that goes wrong during your observing session. It is also a good idea to periodically note the temperature, humidity, and sky conditions as these can alter the quality of your images. Don't forget to note anything unusual about the session or your equipment. Is your neighbor's garage light on tonight when it wasn't on last night? Did you run out of power halfway through an imaging session and change batteries?

4.2.2 Observing location, mounts, and camera controls

As with any observing session, most of the work is done in the dark. You should find a location from which to observe that is free from obstructions both in the sky and on the ground. Whether you are using a tripod or a telescope mount, familiarize yourself with the location and operation of its controls and features which might be useful. For example, how do your tripod's legs extend? How does the leg bracing lock? How do the stops/breaks work on the head? Does the head feature a quick release platform? Try attaching your camera to the mount in the daylight and reaching extreme locations (e.g., zenith) to verify that nothing interferes with pointing, could get tangled, or unintentionally damaged during your session.

Concerning your camera, you should be able to find and use all of the following controls:

- Focus and zoom rings
- Manual focus (e.g., turn off auto focus)
- Image stabilization switch (turn to off)
- Exposure time
- F-stop
- ISO setting
- Image save type (set to RAW)

4.2.3 Camera power

Perhaps one of the most obscure “gotchas” in DSLR photometry happens when the camera either loses power or the battery gets too low. Some observers in the past reported that their DSLRs background noise increased dramatically as the battery charge decreased or after the battery was changed. This does not appear to be an issue with newer cameras, but is something to keep in mind if you are using equipment more than a few years old. If you plan on doing long observing sessions (i.e., near the length of time that your battery lasts), it would be advisable to use external power or have a second battery on hand if external power is not practical at your observing location.

4.2.4 Finder Charts

Locating a variable star and its comparison stars without a good-quality finder chart is often an exercise in futility, so be sure to bring one with you into the field. It is often particularly helpful to bring finder charts which have different fields of view, especially with fields of view which are larger than that of the camera. See Section 3.5.1.

4.2.5 Observing plan

A good observing session starts with a well-defined plan. We suggest creating a checklist of the actions required to obtain scientific quality images, especially if you are just starting out with DSLR photometry. What fields do you intend to observe? Location of comparison stars relative to the target (finder charts help). What camera settings will be required? How many images are needed? These items should all be recorded in your observing logbook which may be paper or electronic.

4.3 Noise sources and systematic bias

One might expect all pixels in an image to have exactly the same ADU value if the camera is illuminated by a completely even light source. However, this is never the case. The detected signal is impacted by several factors including vignetting by the lens or telescope, pixel-to-pixel sensitivity variations in the sensor, dust on various optical surfaces, counting statistics due to random arrival times of photons, and electronic noise generated in the camera.

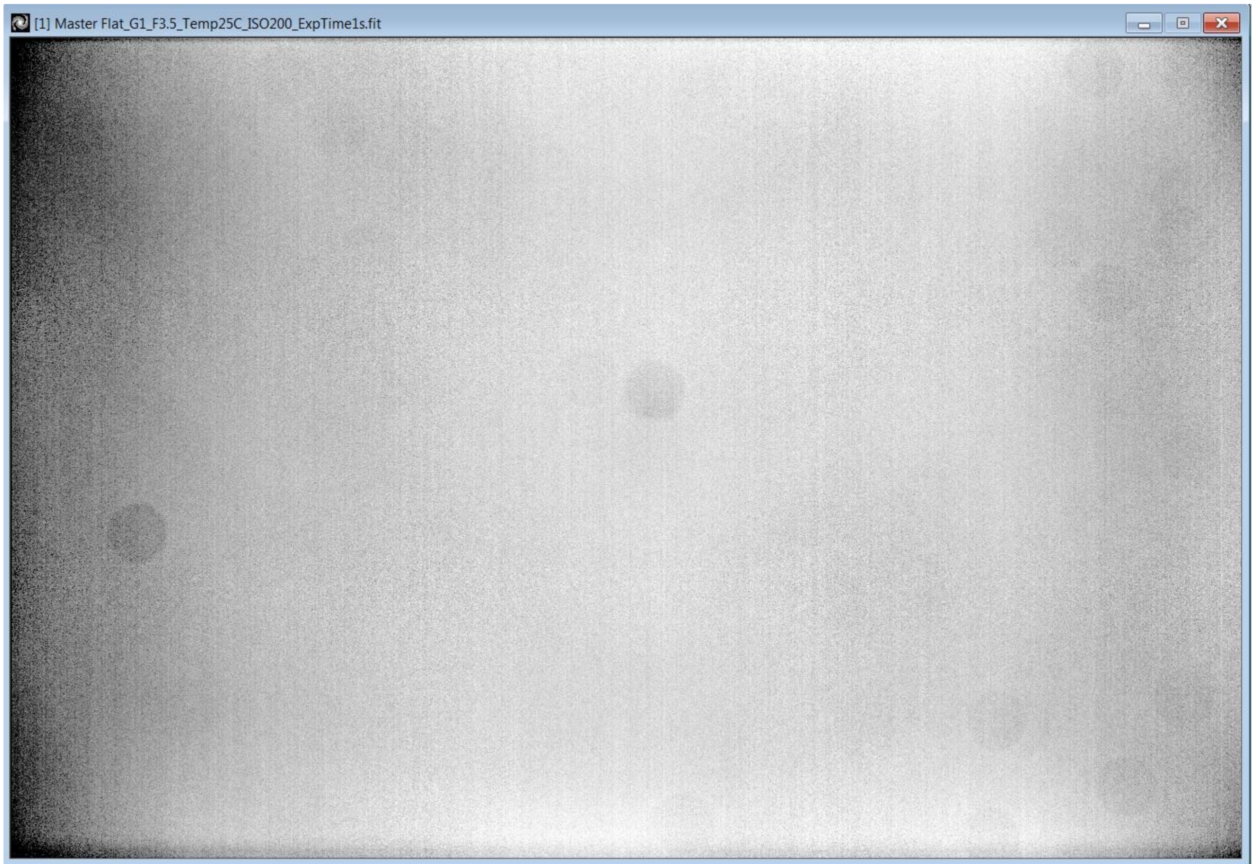


Figure 4.1. A highly-stretched image of an evenly illuminated light box. (Mark Blackford)

In Figure 4.1 we can see several of the aforementioned artifacts. The circular splotches are caused by dust on the optics, the reduced intensity in the corners is due to vignetting, and the vertical and horizontal lines are due to pixel sensitivity variations and electronic noise. Although not obvious to the eye, these artifacts are also present in science images and should be removed before photometry is undertaken.

To properly account for these effects, you must take a series of calibration frames and perform a number of mathematical operations on your science frames including subtraction of bias and dark frames to remove the fixed-component noise and division of the resulting image by a flat frame to remove the effects of vignetting and pixel-to-pixel sensitivity variations as well as dust shadows. Details on how to perform these operations can be found in your photometry software's manual. This section provides a detailed explanation of the various artifacts these calibration steps attempt to mitigate. For further reading, we refer the reader to the *Handbook of Astronomical Image Processing* by Berry and Burnell (Willman-Bell Publishers), or similar online sources.

4.3.1 Random Noise

The artifact easiest to understand in images is random noise. Random noise is totally independent from pixel-to-pixel noise, and from image to image. In each picture the pattern of random noise is different. The grainy aspect of images (Figure 4.2) taken at high ISO is due to this noise which generates a positive or negative error in our magnitude measurement.

There are two principal sources of random noise in DSLR images. The first is Johnson-Nyquist noise. This noise is generated in the camera electronics and is caused by thermal agitation of electrons. This is often referred to as “read noise.” The second source of noise is shot noise, which is related to the number of photons, N, detected and arises from the statistical nature of photon emission at the source. Shot noise is simply the square root of the number of photons detected.

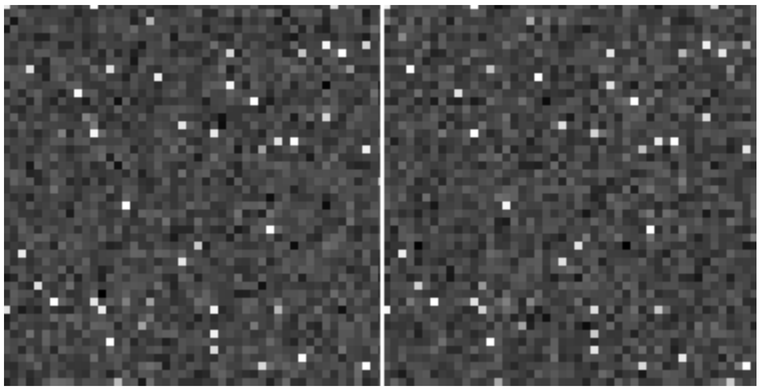


Figure 4.2. Two 120-second exposures, ISO 400, 20°C, same block of pixels from the raw images. Bright pixels are impulses of dark current and are the same in both images. The grainy background is random noise and is different in each image. (Roger Pieri)

Random noise is present in calibration images as well as science images and cannot be eliminated. The only way to reduce its impact is to increase the signal (photons) by using longer exposures, either in a single long shot or by "stacking" (adding) several shorter images if there is a risk of saturation.

Many cameras have built-in software filters which reduce the visibility of this noise in images. Although useful in everyday photography, such filters alter the original data in the image and should not be used in photometry. Thus any on-camera noise reduction options must be disabled when performing photometry.

4.3.2 Fixed Pattern Noise (FPN)

Contrary to Johnson-Nyquist and shot noise, fixed pattern noise (FPN) is not random; it is due to technological defects of a permanent nature. When particular pixels are affected by such defects they form a pattern which is repeatable from image to image. Unlike random noise, FPN can be characterized and removed during the image calibration process.

There are several types of fixed pattern noise including bias and systematic offsets, dead or hot pixels, dark current, and dark current impulses. In the next few paragraphs we describe each of these in greater detail.

4.3.3 Bias and Systematic Offset

A bias is a tiny shift of the black level of each pixel, often linked to the row/column organization of the pixels. It can be either uniform across all pixels, or form strips at the black level of images (see Figure 4.3). The amplitude is extremely low in present sensors, usually only a few ADU.

Note: There are similar defect patterns (strips) in DSLR images that are not repeatable from image to image, and cannot be removed by image calibration. This is usually due to spurious signals induced by the digital electronic circuits into the highly sensitive analog electronics. However, they are at very low ADU levels and not too much of a problem.

Some cameras have a systematic offset by design. This is a perfectly determined shift of the coding of the black level into the image file. It's often 1024 or 2048 ADUs in modern cameras. This offset provides for the possibility to record negative values of the noise and some black level drift. This feature is important for photometric processing because it needs to be subtracted before any non-additive mathematical operations, like flat frame correction, are applied.

Bias and systematic offsets are present in all science and calibration images. They are removed by subtraction of a master bias frame (discussed later in this chapter).

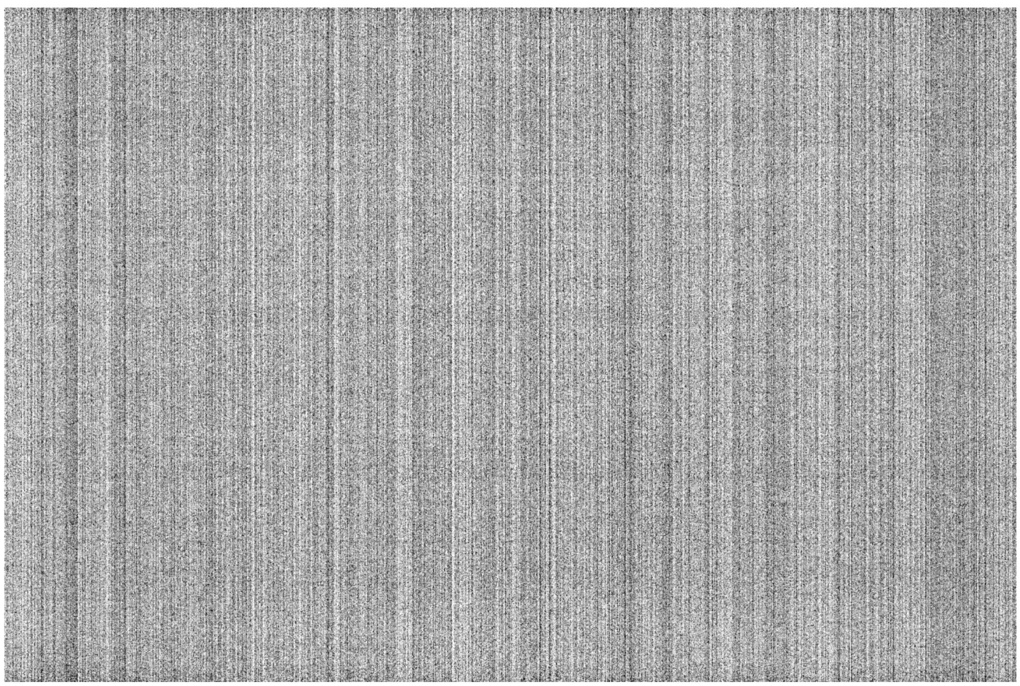


Figure 4.3. Highly-stretched master bias frame showing fixed pattern noise with amplitude of a few of ADUs (ISO 200). This image has both a uniform offset from 0 ADU and strips linked to row/column organization of the addressing electronics. (Mark Blackford)

4.3.4 Dead and Hot Pixels

Dead and hot pixels are pixels which are not functioning properly. Dead pixels don't respond to light and usually have ADU values near the systematic offset level. Hot pixels have too much dark current (see below) and high ADU values compared with normal pixels in the image. They are defects of the sensor, normally some are tolerated at the periphery of the sensor, but there should be none or very few in the center area.

The pattern of defective pixels is repeatable from image to image and can be corrected by first recording their coordinates in a file (called a defect map) then replacing the ADU values of these pixels in science and calibration images with a value interpolated from surrounding normal pixels. This corrective process is applied before any other calibration steps.

Hot pixels are detected in dark images and dead pixels in flats. The ADU threshold set by the user determines which pixels are included. At ISO 100 a threshold of 500~1000 ADU above black level of a dark image is a good starting point. Consult your photometry software manual for the precise method of creating a defect map.

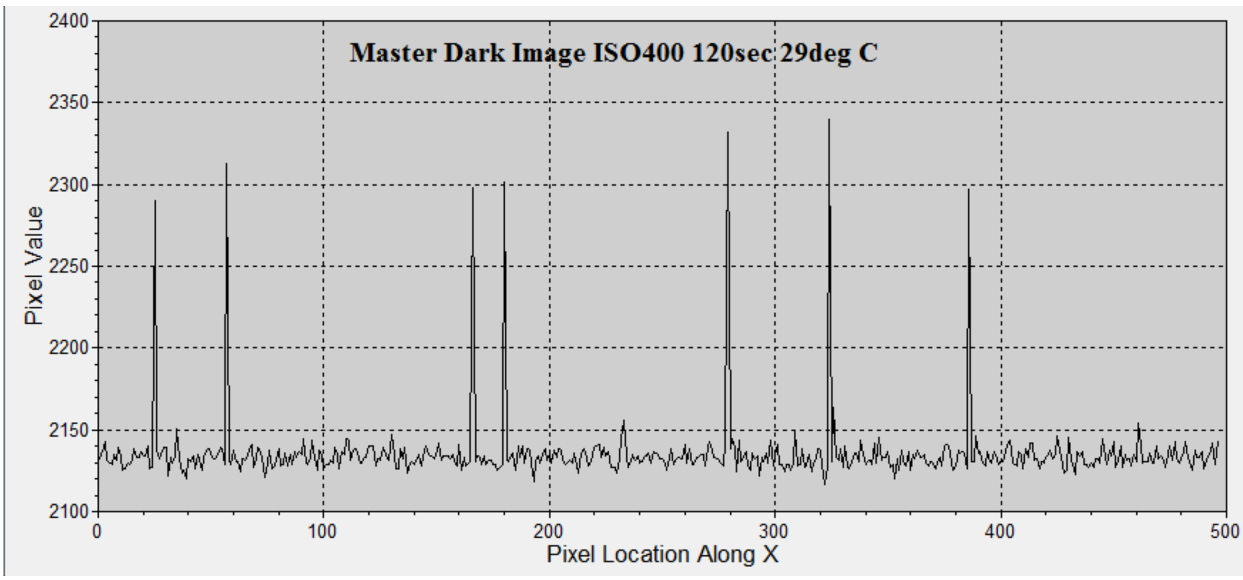


Figure 4.4. Line profile showing ADU values along an approximately 500-pixel section of a long exposure image. The fluctuations around ~2140 counts (ADU) are due to random noise. The prominent spikes are hot pixels. (Mark Blackford)

The defect map process is very effective, takes very little processing time and doesn't cost observation time to prepare the file. If it is available in your photometry software it is recommended that it be used. Defect maps can be used for several months. Its validity is limited by the aging process of the sensor.

Important note: Defect replacement should only be performed if you are heavily oversampled. If a defect occurs in a star profile, you are making assumptions as to what the proper interpolated value might be, and those assumptions will fail if adjacent pixels differ much in intensity.

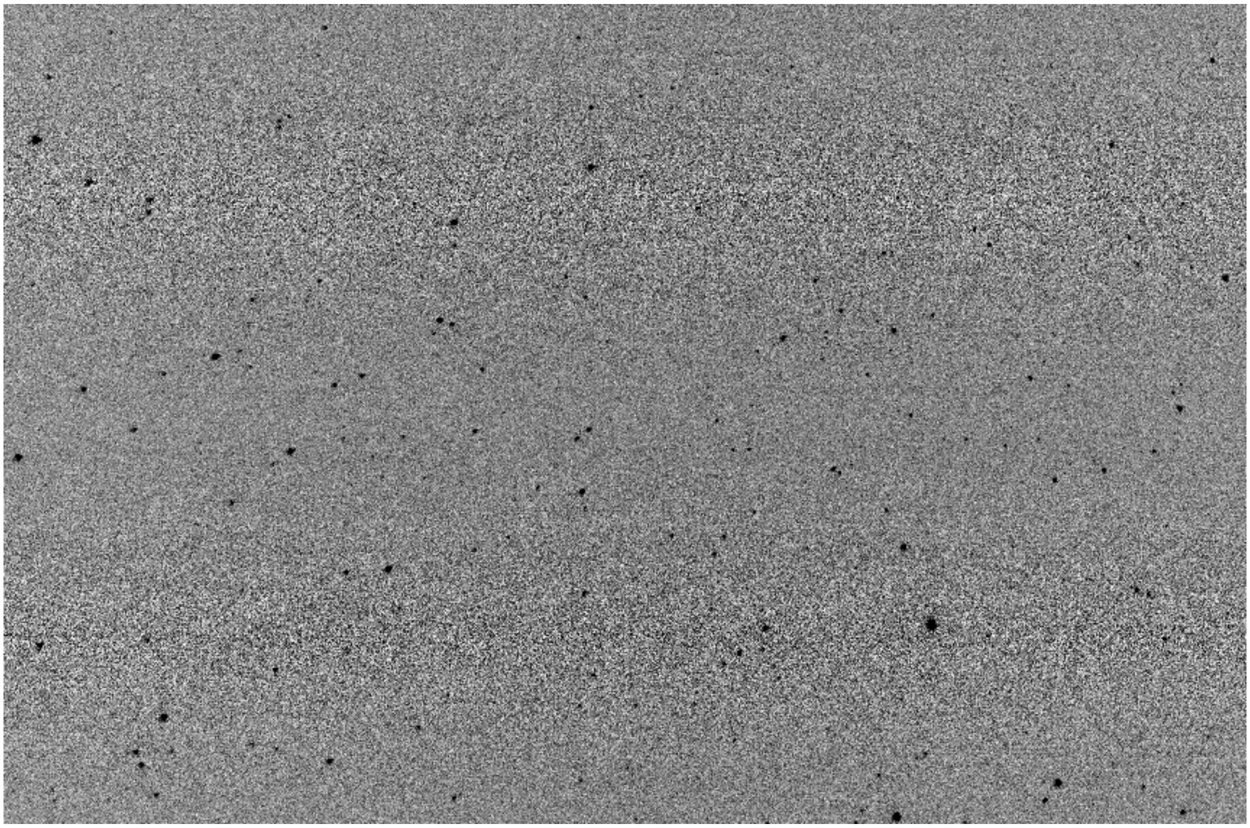


Figure 4.5. Horizontal strips or banding may occur in DSLR images. These strips are normally at a very low level (a couple of ADU) and are caused by noise in the analog circuits of the sensor prior to the ADC. There are algorithms to eliminate these artifacts, but they are not common in astronomical software. Properly applied background subtraction tends to mitigate this source of noise. (Roger Pieri)

4.3.5 Dark current and dark impulses

4.3.5.1 Normal Dark Current

In CMOS image sensors the photodiode works under an inverse polarization mode. That means a positive voltage is applied to the cathode relative to the anode. The current from the source is blocked. The remaining current is due to electrons liberated by the photons falling on the photodiode. But there is another tiny current that also exists in any diode, the inverse current, which is a kind of leakage of the blocking mode. This signal is small, about 0.1-1.0 electron per second, and results in a small increase of the output ADU level of the pixel.

The normal inverse current is fixed by the design of the sensor and all pixels have the same positive shift due to it. The corresponding accumulation of electrons in the pixel is proportional to the exposure time. This results in some elevation of the global black level (more or less like the sky background). In fact this is not visible in our images as it is compensated by the DSLR electronics. The only effect remaining is the corresponding shot noise, which increases the random noise level of long exposures.

The inverse current of diodes is also very sensitive to the temperature of the diode. It typically doubles every 5 to 10°C. Therefore the electron charge increase is proportional to the exposure time and an exponential function of the temperature of the sensor. Although the CMOS sensor itself often generates very little heat (i.e., has a low power dissipation), the camera's processor will elevate the ambient temperature of the camera. Typically a camera will warm by 10°C after about one hour of use, much less than CCD cameras that require cooling. Normal dark current is less of an issue for DSLR than CCD.

4.3.5.2 Dark Current Impulses

DSLR astrophotography is frequently plagued by a few (~3%) deviant pixels that have significantly higher dark current than normal. These deviant pixels appear much brighter in the image and are often called hot pixels or "dark impulses" (e.g., the bright pixels in Figure 4.2). Dark impulses are not measurable in very short exposures because they are just below the random noise range of most recent DSLR cameras; however, they become an issue in longer exposures.

Although dark impulses are a truly annoying anomaly in astrophotography, they have less of an impact in photometry where the light is (intentionally) dispersed over a few hundred pixels. Background subtraction and stacking/averaging also reduces the impact of dark impulses.

4.3.6 Master Calibration Frames

Often overlooked, the creation of master calibration frames (which we advocate later in this chapter) also introduces some additional random noise into the science images. To minimize this extra noise we use master bias, dark and flat frames made from at least 16 individual frames, but the more the better. Image signal scales linearly with the number of frames but random noise scales with the square root of the number of frames so signal-to-noise ratio (SNR) improves as more frames are added.

4.4 Calibration frames (bias, darks, and flats)

4.4.1 Bias Frames

4.4.1.1 Classical Bias Correction

Fixed pattern noise due to bias and any systematic offset are usually removed from science images by subtracting a master bias image. The master is made by stacking a number of shots taken in absolute dark, of very short exposure, at the ISO value used for the science images.

Bias frames can be collected at any time because sensor temperature and focus setting are not important. Cloudy nights are ideal for preparing master bias frames. Set the shutter speed to the shortest available on your DSLR (typically 1/4000th second), ensure no light reaches the sensor (lens cap on, viewfinder blocked, darkened room) then record at least 16 or as many as several hundred images. Consult your software manual for instructions on how to prepare the master bias from these individual frames.
A separate master bias frame should be made for each ISO setting used for science images. They can be used for months. The limit is the possible aging of the electronics.

4.4.1.2 Artificial Bias Correction

Subtraction of a master bias frame inevitably adds some amount of random noise (even when several hundred individual bias frames are used to construct the master frame). Instead, some people subtract an artificial image in which all pixels have the same value as the systematic offset, i.e., 1024 or 2048 ADU. This has the effect of removing the systematic offset from science and calibration images without adding extra random noise, but at the expense of retaining the FPN due to bias.

4.4.2 Dark Frames

There are several approaches to dark correction. The choice as to which to use will depend on the specific characteristics of the images being calibrated and the options available in your photometry software.

4.4.2.1 No Dark Correction

Images recorded with exposure times less than 30 seconds in cool ambient temperatures may not show significant dark current or dark impulses. This is usually the case for flat frames where exposures are typically only a few seconds. In this situation dark correction is not necessary and in fact would add random noise without significantly improving photometric precision. It would be wise to check your camera's own characteristics under various temperature and exposure settings before adopting the no dark correction option.

A simple test is to process a series of images with and without a dark correction; if the differences are just a few millimagnitude it means hot pixels are not a problem. A few mmag could easily be due to the added random noise from the master dark correction process.

4.4.2.2 In-camera Dark Correction

Many DSLRs have an option for in-camera long exposure noise reduction. Immediately after taking a science image the camera automatically records another with exactly the same exposure but without opening the shutter. The second image is subtracted from the first before saving the corrected image file to memory card or computer. Neither the original science nor the dark images are saved.

In principle this seems like a good idea, however, in practice it is not. The camera will use one dark image per one science image, thus the random noise added is much greater than a master dark frame (this is mitigated somewhat if you will be stacking several science images). More importantly, half of the observing time is spent taking dark frames so the number of science images is greatly reduced. The one advantage of this in-camera process is that the temperature of both images will be very similar, but this is not sufficient compensation for the disadvantages.

In general, in-camera long exposure noise reduction and other such options should be disabled.

4.4.2.3 Classical Dark Correction

In the classical process at least 16 dark images are recorded during the observing session, under the same settings and conditions as the science images (ISO, exposure time, temperature). Any possible leak of light into the camera must be eliminated (viewfinder covered and lens cap on). A master dark frame is then made using these individual dark frames. Consult your photometry software for specific steps.

It is difficult to make a set of dark images with the same dark impulse level as the science images because the sensor temperature of the DSLR is not stabilized. To mitigate this issue, some people collect half the dark images before starting the science images and the other half afterwards. This tends to bracket the temperature range science images are recorded under and can lead to improved dark correction.

Classical dark correction is the recommended approach for DSLR photometry.

4.4.2.4 Exposure-scaled Dark Correction

You may need to use different exposure times for different targets depending on their brightness. With classical dark correction it would be necessary to create a master dark frame for each exposure time used, at the cost of extra time spent recording individual dark frames.

Some photometry packages have an option for scaling a long exposure master dark frame so that it can be used for dark correction of shorter exposure science frames. This can work reasonably well with CCD camera with fixed point temperature regulation.

However, Canon and Nikon DSLR cameras apply some processing to reduce the effect of dark current even in RAW images. The effect is that variance in dark images increases as the exposure time increases, as expected, but the mean pixel value does not increase linearly; instead it remains within a few ADU of the offset value. Therefore exposure-scaled dark correction is not recommended for Canon and Nikon RAW images. Other camera brands may or may not be suitable; users are advised to test their camera's dark current behavior before adopting an exposure-scaled dark correction strategy (see Appendix A).

4.4.2.5 Optimized Dark Correction

A more sophisticated procedure available in several photometry packages (e.g., IRIS and MaxIm DL) scales the master dark frame to minimize RMS noise of the final image. This procedure can accommodate temperature differences between the dark and science frames, even changing sensor temperature throughout the observing session.

Again, optimized dark correction is not recommended for Canon or Nikon RAW images for the same reasons stated in section 4.4.2.4 above.

4.4.3 Flat Field Correction

Flat field frames are images of an evenly illuminated source which reveal asymmetries or artifacts in your camera's optical setup. Unlike dark correction, flat field correction is mandatory for all images intended for photometry. Flat field images must be recorded with the camera and telescope/lens in the same configuration (focus, f-stop, ISO, etc.) used for the science images. Exposure times must be adjusted to avoid saturation.

Finding or making such an evenly illuminated source is surprisingly difficult and has led to many, shall we say, interesting online forum discussions and at AAVSO conferences. Thus we cannot (and dare not) advocate one particular technique. Before presenting a few popular options, we offer a few general words of advice.

Care should be taken to ensure that each of the RGB channels receive sufficient intensity in each image. Ideally this should be about ⅔ of the maximum ADU value of your camera. Most DSLR cameras available since about 2008 have 14 bit analog to digital converters with maximum ADU values of 2^{14} = 16384 ADU. Older DSLR models often had 12 bit ADC units with maximum ADU values of 2^{12} = 4096 ADU. Check your camera's maximum ADU value by measuring the pixel values of an over exposed image.

Flat frame exposures are typically only a few seconds long so there is no appreciable dark current; however bias and offset signals are still present and need to be removed in the calibration process. Your photometry software should handle this process.

Because flats are supposed to be images of a uniformly illuminated source, they will correct for any vignetting and pixel-to-pixel sensitivity variations that are present (provided the camera and telescope/lens configuration is not altered). However, dust shadows may change due to movement of dust on the optical surfaces and changes in focus settings. To minimize this effect, disable any ultrasonic cleaning options on your camera. Flat frames should be prepared regularly, but not necessarily every night if no refocusing or other changes have been made.

As with all calibration steps, flat field correction adds noise to the calibrated image. To minimize the amount of noise added the master flat images are made from multiple flat frames. You should aim for at least 16, more if time allows. Your photometry software will have an option for making a master flat frame from individual frames using either average or median combine routines. The median option is usually preferred because star images in individual sky flats or cosmic ray traces will not adversely affect the master flat frame.

No matter which method you adopt you should perform the tests outlined in Appendix B to check for uniform illumination of the light source.

4.4.3.1 Twilight Sky Flats

When photographing through a telescope the field of view is usually small enough that images of a cloudless twilight sky (which is reasonably uniform on the scale of a degree or so) can be used as flat field frames. There is limited time in which to record sky flats during evening and morning twilight, and it may be necessary to vary the duration of each frame to ensure adequate exposure as light levels change.

If you are making twilight sky flats, it is best to turn your telescope's tracking off, so that any star images in your images will be trailed to different positions on each flat frame; the "median combine" (rather than "averaging") option in your photometry software will eliminate them from your master flat.

For fields of view greater than a degree acquired with standard or telephoto lens, indirect lighting techniques must be used.

4.4.3.2 Dome Flats

A flat target such as a piece of mat board illuminated by the twilight sky or diffuse artificial lighting can be suitable. Make sure that the target board more than fills the entire image.

4.4.3.3 Light Box Flats

Alternatively, a light box can be constructed and placed in front of the camera lens for acquiring flat field images. These allow control over illumination levels and can be used at any time, instead of having to wait for suitable twilight conditions. Instructions for light box construction are readily available on the internet. One simple but effective design is described in the *Handbook of Astronomical Image Processing* by Richard Berry and James Burnell.

4.4.3.4 Electroluminescent Panel Flats

In recent years electroluminescent (EL) panels have become readily available and some people have successfully used these for flat field imaging. They are less bulky than traditional light boxes and easier to use in the field, but can be relatively expensive. The uniformity of illumination of some EL panels have been less than ideal for photometry so the user is encouraged to check theirs as shown in Appendix B.

4.4.3.5 Computer monitor flats

A computer monitor may provide a suitably uniform illumination source for preparation of flats. Display a white screen (a blank Word document perhaps) and place several sheets of white paper between the screen and camera lens to reduce intensity and diffuse the light. Exposures should be several seconds to minimize effects of screen refresh flickering.

Not all monitors are suitable. Some have uneven intensity across the screen or have viewing angle intensity variations. Some people have reported poor results when using short focal length lenses.

4.5 ISO and exposure times

If there were a top 10 list of DSLR photometry questions, then those involving exposure times, ISO settings, and ensuring images are of photometric quality would certainly occupy the top slots. Picking these settings requires thoughtful consideration of both your camera's noise characteristics and the science objective you wish to accomplish. In this section we explain the careful tradeoff between sensitivity and precision and provide a few guidelines for optimal settings.

4.5.1 ISO setting, quantization error, and dynamic range

Selecting the right ISO setting is choosing between two evils. As discussed in Chapter 2, the ISO setting simply adjusts the gain on the amplifier used to read out pixel values. One might expect a high ISO setting to be ideal for photometry, but this is not always the case. At high ISO, the camera will show fainter sources, but this will amplify not only the starlight, but also the noise. Additionally, a high ISO will reduce the camera's dynamic range (the range of brightness contained in an image). Thus high ISOs limit the range of magnitude differences your camera will be able to detect.

Conversely, at low ISO values, small differences in electric charge will be assigned the same value by the ADC, thus the precision of the detector is lost. The latter situation is called "quantization error". Quantization error can be easily illustrated in a non-technical fashion with the following image of a clear, blue sky at a beach (see Figure 4.6). We know from everyday experience that the brightness of a clear sky varies smoothly along a gradient. However, if a camera cannot detect subtle variations in brightness, it will produce a strange-looking image in which the sky has a "stair-step" appearance, as is the case with the image in Figure 4.6.

Figure 4.6. The sky in this image is split into discrete intervals due to quantization error.

This artifact is more than just ugly. In the context of DSLR photometry, it also degrades the photometric value of the image. The beach image should use hundreds of different intensities to represent the sky, but here, it only uses five, which is why the sky is divided into five unrealistic-looking zones. (In fact, quantization error occurs at high ISO as well, but in that case it occurs because your gain is so high that the addition of one electron means multiple ADU steps.)

ISO setting of 200 or 400 should achieve a good balance between precision and noise, with lower ISO values (e.g., 100) better for brighter stars. Thus if your science topic will involve a wide range of magnitudes, you should probably stick to the low end of this range. Likewise, if you are observing a field with many stars of similar magnitude, a higher ISO setting may be acceptable, as long as the higher ISO setting does not saturate the stars.

4.5.2 Exposure time, saturation, and non-linearity

With photometry, one must be careful to ensure images are of photometric quality. It is crucial that the observer be able to set an appropriate exposure to avoid problems with saturation and non-linearity.

Understanding the concept of linearity requires a brief, minimally technical digression into how DSLRs detect light. When light strikes a pixel in the sensor, it creates an electric charge in the pixel which is proportional to the intensity of the light. Thus, if star A is 2 times brighter than star B, it should generate an electric charge twice as great in the pixels that it shines on. However, there is a maximum amount of charge that any one pixel can hold. Once a pixel reaches this limit, it cannot hold any additional charge, so any additional photons will not produce a corresponding increase in the charge held by that pixel. This is called saturation. In a sense, once saturated, a pixel has become "blind" for the remainder of the exposure and will no longer have a linear response to light. This does not harm the camera, but it does mean that it is impossible to obtain meaningful photometry of the saturated star. Photometry of non-saturated stars in that image will not be affected. In practice, it is absolutely essential to ensure that neither the target star nor any of the comparison and check stars is saturated.

Closely related to saturation is the concept of non-linearity. Normally, when light from a constant source falls onto a pixel, there will be a direct linear relationship between the exposure time (plotted on the x-axis) and the electric charge (the intensity, plotted on the y-axis). For example, doubling the exposure time should double the intensity at a given pixel. However, for CCD-type detectors, as pixels approach saturation, the formerly linear relationship will become non-linear. With a nearly saturated star image, for example, increasing the exposure time by 10% might result in only a 5% increase in charge (rather than the expected 10%). Non-linearity is even more dangerous in photometry than saturation because it is less obvious to detect. Testing your camera's linearity is a useful exercise, see Appendix E for details.

Why should anyone care about saturation and non-linearity? Photometry rests upon the presumption that there is a direct, linear relationship between how bright a star appears in an image and its actual brightness. Once a pixel loses its linear response to light, this assumption breaks down because the electric charges held by non-linear/saturated pixels do not correspond with the true brightness of a star. In Figure 4.7, Star A is one magnitude brighter than Star B, but once star A becomes saturated, the differential magnitude goes from -1 toward 0, even though neither star has varied in true brightness. Knowing the ADU value at which your camera begins to saturate is therefore important.

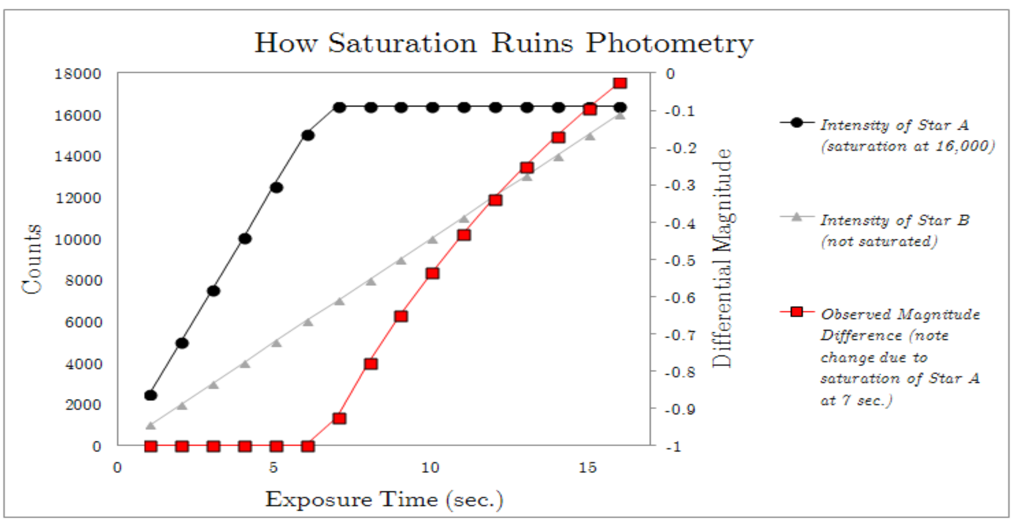


Figure 4.7. The assumption that a star's brightness is linearly related to measured counts is violated once the star begins to saturate the detector as shown here for Star A.

The easiest way to avoid issues with saturation is to simply keep the maximum intensity for the target, check and comparison stars below 75% of the maximum value for your camera. If you have an older 12-bit camera, the maximum intensity is 2^{12} or 4096 counts, so you would need to keep the intensity below about 3100 counts to be safe. For a 14-bit camera, 12300 counts would be a safe cutoff. These numbers are very conservative but allow for changes in observing conditions, such as seeing or transparency, that might push a star into saturation.

Picking ISO settings and exposure times can be a time consuming process. You should refer to Tables 2.3 and 2.4 in Chapter 2 for some starting guidelines Your first few evenings of DSLR photometry may be best spent getting a feel for the best camera settings for targets that interest you.

4.6 Finding and framing the field

At first this is one of the most frustrating parts of the learning curve, especially if you are using a tripod. This is also where experience conducting visual observations really pays off. The same problems you have finding a field visually apply to DSLR photometry. The difference is that your field of view will be smaller. Here are a few recommendations:

- Learn to use star charts to find fields visually and/or with binoculars.
- Practice on easy-to-find and frame fields.
- Locate the nearest bright star to your target area. Use it for rough alignment.
- Looking through a camera that is pointing high in the sky is difficult for many people. Consider purchasing a right-angle finder for the camera.
- Purchase a red dot finder that attaches to your camera's flash hot shoe.
  Take one test exposure and examine it on your camera. Use your camera's zoom-in feature to identify asterisms which may help you with further alignment.

4.7 Acquiring science data and tricks of the trade

Before we bring this chapter to a close, we want to reiterate a few of the main points to help you have a productive observing run with good (i.e., scientifically useful) results.

When taking science data, be sure to:

- Set your camera to RAW format (e.g., Nikon's .nef or .nrw and Canon's .cr2 or .crw).
- Verify the camera's date and time is set correctly. If at all possible, set the camera to UTC rather than leaving it on local time. If you must leave the camera on local time, make sure it is as accurate and precise as possible (preferably to the closest second), and clearly note the difference between the camera time and UTC in your log.
- Defocus the stars slightly to the point that they are round and occupy several pixels. Stars should be round and fully filled. If they start to look like doughnuts, you've gone too far. Star images can be quite different on either side of focus. Experiment to determine if under or over focus is best for your lens.
- Use the live-view feature to check focus and field framing, but shut it off when not needed. The ambient heat from the display may increase noise on the sensor, the generated light may diminish your night vision, and may needlessly increase your power consumption, especially if you're using batteries.
- Take the images in a low ISO setting (typically 200-400). Although higher ISO levels are more sensitive, they suffer from a loss of precision (dynamic range).
- Shut off any noise reduction or built-in image-processing options in your camera.

- Shut off any ultrasonic/automatic optics cleaning options in your camera.
- Practice operating your camera indoors before taking it outside in the dark.
- Stick to a small set of ISO and f/number settings to minimize calibration frame sets.
- Set colour balance to “daylight”, although it should not affect RAW images.

Chapter 5: Image Processing and Assessment

5.1 Overview

This chapter will generically describe how to translate your science images into accurate photometry, a calibrated measurement of the brightness of a variable star at a specific moment in time. The major steps in the process after image acquisition are (1) checking that all of your calibration and science images are suitable for photometry, (2) applying calibration frames, optionally co-registering and stacking images to increase SNR, (3) extracting the individual RGB channels from the image(s), (4) performing aperture photometry on the target and comparison stars, and (5) performing final quality checks. Please note that steps 2 and 3 depend on the capabilities of your photometry software and may need to be reversed.

Before we get started, we will assume that you've followed the instructions for acquiring images in Chapter 4, and have a full set of calibration frames in addition to your science images. To summarize, make sure you have the following:

- A set of bias frames, from which a Master Bias frame will be made (least 16 and preferably many more)
- A set of dark frames, from which a Master Dark frame will be made (least 16 and preferably many more)
- A set of flat frames, from which a Master Flat frame will be made (least 16 and preferably many more)
- All of your science frames

We'll assume that when you took your science and calibration frames, you used appropriate exposure times that provide sufficient signal but avoid saturation of stars of interest. As part of this chapter you'll check that this is indeed the case, but we won't otherwise discuss how to acquire images here.

Testing camera linearity should be done before you start taking data regularly — you'll likely do it once for each camera that you use and then keep notes on the results for future observing runs. You should also do the tests outlined in Appendices A and B to examine the noise characteristics of your camera, and to assess whether you have suitably "flat" flat frames.

5.2 Processing preliminaries and image assessment

Prior to reducing any data, it is best to spot-check a few images to ensure they are suitable for photometry. The very first thing to do should be straightforward: check that the images have the correct image type and header information.

5.2.1 Image header

Before recording images, you selected the camera settings that you intended to use (exposure duration, ISO setting, color balance setting, file type, f/number, etc.). Examine the header of an image and confirm that you did, indeed, get what you intended. (It is not unknown to intend to use f/4, but in the cold, dark, and late night inadvertently use another value entirely.)

5.2.2 Original image format

Confirm that your original image was "RAW" format (the file extension is usually *.CR2 for Canon cameras, and *.NEF for Nikon cameras). You cannot do useful photometry with the compressed "JPEG" file format (*.jpg). Your image-processing software may convert the RAW file to a FITS format image. This is expected, and is a full-fidelity conversion that retains all of the information in the original image.

5.2.3 Image date and time

Confirm that the timestamp on your image header appears to be correct. The raw image should have a timestamp that accurately records the time the image was taken. Beware of errors in setting your camera's clock, daylight saving time, and date change at midnight.

Most cameras record the time that the shutter was triggered, i.e., the start of the image. Your photometry program may adjust the image time, or add another keyword, so that the time recorded in the header of the calibrated image is the midpoint of the exposure;

$$T_{midpoint} = T_{start} + 0.5*T_{exposure} \qquad \text{[Eq. 5.1]}$$

Most photometry programs also attempt to translate the image time into UT (Universal Time) based on information that you've given the program about your time zone. It is worthwhile to double check that this has been done correctly, at least the first few times that you use the program, to make sure that the recorded image time in UT is correct.

Most programs also calculate the Julian Date that corresponds to the mid-point of the image. This is the preferred time system when submitting photometry results to AAVSO. Again, it is worthwhile checking that this is done correctly the first few times you use the program, or if you change any time-related settings in the software or in your camera.

5.3 Application of calibration frames, stacking and binning

Calibration is required to correct vignetting and dust shadows, uneven pixel sensitivity and various sources of noise. The master calibration frames must be applied in the following order to ensure systematic effects are properly removed:

1. Create master bias, dark and flat frames
2. Subtract master bias from master dark and master flat, and all science frames.
3. Subtract master dark from all science frames, (but not from master flat since flat exposures are usually only a few seconds therefore dark correction is not necessary).
4. Divide the normalized master flat into all science frames.

Your photometry software will have a built-in method for making master frames and applying them to the science frames. In simple language, both bias and dark frames are subtracted from an image (because the effects of bias and dark current are added background in a signal), and so the software will subtract the counts in each pixel in a bias or dark frame from the corresponding pixel in the frame to which the correction is being applied.

Flat fielding, on the other hand, is a multiplicative correction, because differences in field illumination cause a fraction of the mean flux to be transmitted per unit time, and the fraction varies with position in the focal plane. The software will normalize the flat field so that the mean pixel value is 1.000, and then divide each science frame pixel value by the corresponding flat field normalized value. As an example, if a given pixel in a flat field is 97% of the mean value, you divide that pixel in the science frame by 0.97. Again, your software should do all of this behind the scenes; typically you will only need to tell the software the names of the bias, dark, and flat frames, and then follow whatever instructions are provided by your software to apply each correction.

5.3.1 Alignment and stacking

For most DSLR photometry projects, the target stars are of sufficient brightness that they easily register on each exposure, however, in some cases (e.g., faint targets) it may be necessary to first align and then stack several images to increase the effective SNR of the target. Most photometry software has some functionality to perform these operations (almost) automatically. For DSLR RAW images it is important to first separate the RGB color channels from each image before aligning and stacking the single color images, otherwise mixing of color channels may occur.

There are several methods of aligning individual frames, some of which produce cosmetically appealing star images but can degrade the photometric information. When aligning photometry images your software should use full pixel steps or a linear intensity interpolation method for sub-pixel shifts.

Similarly there are several methods of stacking the aligned frames. Median stacking is recommended for photometry because transient events such as satellite trails or cosmic ray strikes affecting one or a few individual frames will not adversely affect the final stacked image.

If you do stack, be sure to examine the resulting images critically. Verify that the individual frames are correctly aligned and examine the header of the image to verify that the timestamp makes sense. It should be automatically adjusted to the mean time of the group of images.

5.3.2 Binning

Like stacking, binning is an optional procedure. Binning combines the signal in several adjacent pixels to create an image that is smaller in size, but with slightly higher SNR in the resulting image. Most photometry software has this functionality built-in, but not all software properly accounts for the Bayer array nature of DSLR data. This could lead to mixing of data from adjacent R, G and B pixels thereby making the binned image useless for photometry. Check your software's documentation prior to binning, and understand what it is doing to avoid unwanted behavior.

To avoid these issues first separate the RGB color channels from each image (Section 5.4) before binning.

5.4 RGB color separation (extraction)

As discussed in chapter 2, DSLR cameras have an array of red, green and blue filters overlaying the individual sensor pixels, each pixel having just one of the color filters. This fixed pattern, called a Bayer array, is a fundamental property of DSLR cameras. For photometric analysis, it is necessary to extract the individual color channel images and work with them one color at a time. Frequently only the green channel is used in DSLR photometry because it most closely corresponds to the astronomical V filter. However, useful photometry can also be carried out on the R and B channels.

The process of separating green pixels from red and blue pixels is sometimes called "debayering", however this isn't quite correct. Debayering (or demosaicing) refers to the process of producing a color image (each pixel having ADU values for R, G and B) from information encoded in a greyscale RAW image. We want to separate the R, G and B color channels from the original RAW greyscale image, a process called color separation. The resulting images are also greyscale.

Many photometry programs are able to extract individual color channels from RAW images, although the procedure may be different for each program. For example, AIP4Win extracts both green channels and present them as a unified image of the same size as the initial image. Conversely, MaxIm DL extracts each green channel separately. The best procedure is to extract both green channels, average them together, and perform photometry on the resulting image. Be sure to verify that the target and comp star are not saturating in the original or resulting image.

Color separation may be performed before or after image calibration. It does not matter which order you choose so long as all data (calibration frames and science frames) are treated identically.

5.5 Post-calibration assessment

Now that you've recorded and calibrated images as described above, it is important to critically examine a few frames to make sure they are suitable for photometry. Below is a list of things to check. Each photometry program has specific instructions for how to interrogate images in order to accomplish this assessment.

5.5.1 The size and shape of star images

Generally photometry software expects round or only slightly elliptical star images. Excessive elongation (trailing) would require larger measurement apertures which introduces more noise. When using a non-tracking mount exposures need to be kept short enough to minimize trailing. A sturdy mount will minimize vibration-induced image artifacts (wiggles).

Your photometry software should be able to show the intensity-profile of star images as a graph. The profile should not be too narrow or too wide. The width of a star profile is described by its Full-Width-at-Half-Maximum (FWHM) value (for a detailed description see the Wikipedia page at http://en.wikipedia.org/wiki/Full_width_at_half_maximum). FWHM of stars on RAW images (before calibration and channel splitting) should be no less than about 8-10 pixels. This is to ensure that the star image is well-sampled in all four color channels.

Consider the following thought experiment. If focus was sharp enough, all light from a star would fall on just one pixel, perhaps red. Surrounding green and blue pixels would record no intensity from the star. Photometry from such an image would falsely indicate the star is bright in red wavelengths but very dim in blue and green. In practice, focused star images are not single points of light, instead they have a circularly symmetric (approximately) Gaussian distribution of intensity from a bright core, fading rapidly to background levels within a few pixels (Figure 5.1). Most of the star's light would fall on a single pixel but some intensity will be recorded in surrounding pixels. Photometry of the image would indicate excess brightness in the color of the central pixel and decreased brightness in the colors of surrounding pixels.

If the star's image drifts across the sensor over time due to imperfect tracking the central peak will move across many pixels. Therefore relative brightness in each color will change depending on the color of the pixel that the centroid falls on. Figure 5.2 shows measured BVR magnitudes of nova Centauri 2013 (V1369 Cen) from a too-tightly focused time series recorded on February 12th, 2014. The B and R light curves show oscillations due to drift and periodic error in the mount's RA drive. The V light curve shows only a very low amplitude oscillation because the two green channels are averaged together, almost cancelling out their individual oscillations.

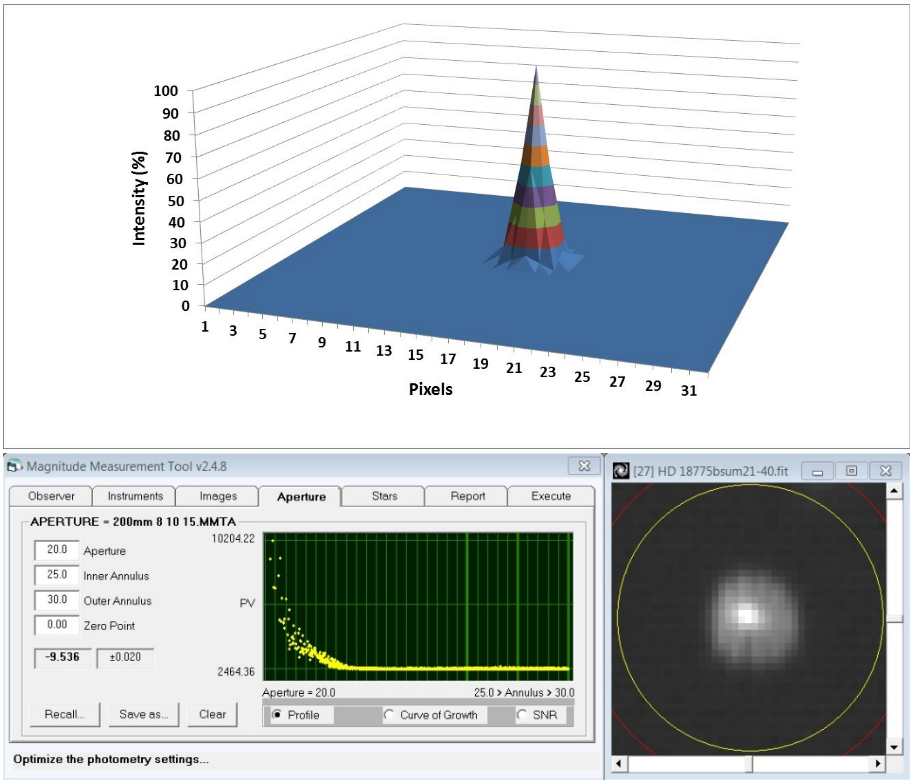


Figure 5.1. Top panel: synthetic Gaussian intensity distribution representing a sharply focused star image with FWHM = 2 pixels. **Bottom panel:** profile plot (left) showing the bright core and broad skirt of an insufficiently defocused star image (right). (Mark Blackford)

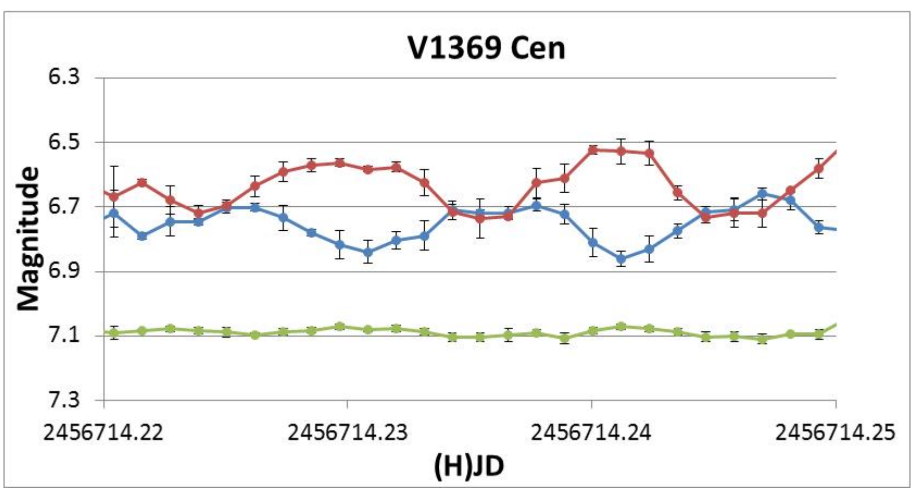


Figure 5.2. Nova Cen 2013 (V1369 Cen) light curves in B (blue line), V (green line) and R (red line) from images recorded with insufficient defocus. The oscillations are an artefact of the Bayer filter array, periodic error in the mount and drift due to imperfect polar alignment. (Mark Blackford)

Experimentation and simulation indicate star images should be defocused to at least 8 pixels FWHM to avoid under sampling problems (Variable Stars South Newsletter, January 2015, page 17).

Can your star images be too wide? In general, stars much larger than about 30 pixels may be difficult for photometry programs to handle. Also, as star images become broader, there is a higher risk that light from one star spreads into, and corrupts the brightness estimate of, its neighbors. So, check the FWHM of the target, comp, and check stars, and confirm that they are large enough to be well-sampled, and yet small enough to reliably place a photometric measuring aperture around the star to collect essentially all of its light. Pick a photometric measuring aperture that is appropriately sized for the stars to be measured.

Your photometric software may have a tool to test the effect of adjusting the aperture size on both the measured flux and signal-to-noise (for example, AIP4Win's MMT photometry tool). As a starting point, set the diameter ≈ 2.5-3 times the FWHM to begin doing reasonable photometry quickly, but note that for detailed work, there is some science to selecting the optimum measuring aperture (see Section 5.6.1).

5.5.2 Maximum ADU value and signal-to-noise ratio

The images of the target, comparison, and check stars must be bright enough to present a good signal-to-noise ratio, but not too bright that they are saturated. Place a photometric measuring aperture over each star (target, comp, and check) in turn, and examine two parameters: the maximum ADU value, and the signal-to-noise ratio. The maximum ADU value must be below the saturation point of your camera. If star images are saturated, then the only recourse is to re-take the images, after making an adjustment to reduce maximum ADU value. Possible adjustments include using a shorter exposure, selecting a smaller f-stop or using a slight greater de-focus to spread the star light over more pixels. Calibrated science images have a lower saturation ADU value than RAW images because the systematic offset (1024 or 2048 ADU) has been subtracted when bias correction was performed.

By the way, this requirement of staying within the saturation limit of your camera's chip is one of the most profound differences between taking images for "pretty pictures" of celestial objects and taking images for scientific measurements: the science images will generally appear bland and washed-out compared to the pretty pictures (which generally saturate stars in order to make the scene more visually pleasing).

5.5.3 Background star blending

If a background star that is so close to your target star (or comp or check) that it falls wholly or partly within the measurement aperture, the light from the background star will corrupt (or contaminate) the photometry. So, critically examine the region close to your target, comp and check stars for any background stars - even quite faint ones. Note the location of any potentially-interfering background stars, and try to select a measurement aperture diameter that will exclude them.

It is useful to consult a good planetarium program to see if there are any potentially-interfering background stars within about 5 magnitudes of the brightness of the target, comp or check stars. You may not be able to see them on your image, but if one is present, it will add light into the measuring aperture. The preferred approach to dealing with these is to keep them out of the measurement aperture. If that isn't practical, then note in your report the existence of the background star.

The problem of background star contamination will be more likely in the case of intentionally de-focused images. Also, use of a non-tracking mount may result in background star trails blending with the target star (or comp or check). Using shorter exposures and stacking them after calibration can recover the signal-to-noise ratio that was lost by using a short exposure.

5.5.4 Uniformity of the background

Examine the entire calibrated image for two subjective quality aspects: sky background flatness and cirrus. Stretch the image contrast to highlight very minor brightness differences, do you see evidence of dust donuts (the rings that show up on your image due to dust on preceding optical surfaces) or significant uncorrected vignetting (which would indicate that something went awry with your flat-fielding)? If this effect is apparent, and the ADU variation is greater than a few percent of your target/comp/check star peak pixel ADU count, then you should probably investigate the reason, and re-do your flat fielding.

The other image non-uniformity to look for is in the sky itself. Thin cirrus clouds and aircraft contrails that were not visible to your naked eye may show up as a pattern of changing sky-glow and transparency across your image. This effect is more likely to be seen, and be an issue, in wide-field images, such as those taken using standard camera lenses (e.g., focal lengths of less than a few hundred mm). With narrow-field images taken through a telescope, the FOV is likely to be so narrow that there is negligible variation in sky glow and extinction across the image.

Sometimes an image may contain an obvious artifact (plane lights or contrail, satellite, cirrus, etc.), but it doesn't come near any of the target, comp, or check stars. In this situation it is probably safe to ignore the artifact and measure the image anyway. If the problem is definitely thin cirrus, anticipate some related fluctuations in your photometry. Depending on the project, the presence of cirrus might require that you be aware of the effect and critically examine your resulting photometry in the light of the (now-known) inconstant sky conditions or — as a worst-case — set aside your images and try again the next night.

How many images should you examine? That depends to some degree on your observing program. If you are studying a star whose brightness changes very slowly (say a Mira star whose characteristic fluctuation time is several months), then you may be taking only a couple of images at one time during the night. In that case, critically examine one or two images. At the other extreme, suppose that you are studying an eclipsing binary whose period is a few hours. Then, you will be recording images every minute or so, all night long. During an all-night imaging session, all sorts of things can change in addition to your target star's brightness. So, select a few images to critically examine — some near the beginning of the evening, near the middle, and near the end of the observing session. If stars go out-of-focus over the course of the night, then your lens focus may be changing with pointing direction or temperature.

On your first few nights, and first few projects, by doing this critical image evaluation you will learn quite a bit about your camera and the settings and imaging choices that are most appropriate for your target star(s) and project. Keep a notebook with camera settings, lens used, and other factors, as well as notes on the resulting image quality. In short order, you will be able to zero in on the best set of parameters (especially exposure time) based on magnitudes of the target, comp and check stars, the lens or telescope used, and typical conditions at your observing site.

Now that the science images are calibrated, the next step is to measure the signal received from the target, check and comparison stars. How this is accomplished is detailed in Chapter 6.

Chapter 6: Photometry – From Measurement to Magnitude

There are several ways to perform photometry; two that you might read about are point-spread function (PSF) fitting and image subtraction, both of which are rarely included in commercial photometry analysis packages, but are used in the professional community. For example, you may come across mention of photometry being performed with a package called "DAOPHOT". This is a very powerful (but complicated) PSF-fitting package developed in the 1980's by Peter Stetson at the Dominion Astrophysical Observatory. The benefits of methods like these are that they work in crowded fields where images of the target star may be blended with nearby stars, or where it is difficult or impossible to measure the sky background without interference from nearby faint stars. Both of these methods are beyond the scope of this manual.

The method we will discuss is called aperture photometry and is by far the most common technique used by amateurs and professionals alike.

6.1 Aperture photometry

In aperture photometry three concentric circles are drawn around the target, check and comparison stars (Figure 6.1). The area within the inner circle is referred to as the measuring or measurement aperture. The space between the first and second circles is called the gap, and the area between the outer two circles is called the sky annulus, or sky aperture.

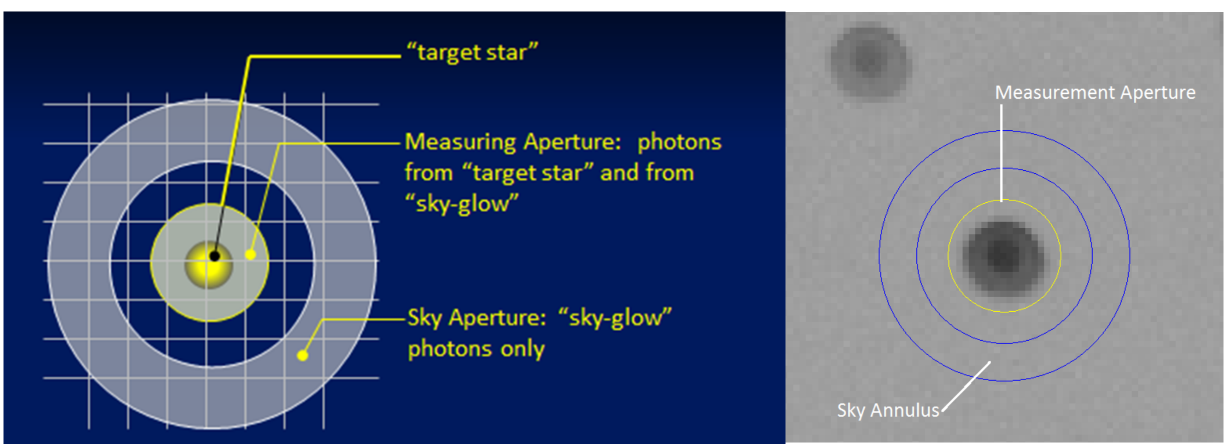


Figure 6.1. Left: Schematic and **Right:** enlarged portion of a calibrated and color extracted image showing measurement aperture and sky annulus positioned over the star to be measured. (Robert Buchheim and Mark Blackford)

Photometry software requires the user to specify the radii of the three circles and identify stars to be measured, usually by clicking on each star on a reference image. The program determines the centroid position (center of the star image) and draws the circles around the centroid.

For each star the program calculates total ADU count within the measurement aperture (which includes the star and sky background) and average pixel ADU value in the sky annulus, taking into account partial pixels where the square sensor pixels are bisected by the circular apertures (Figure 6.1 left). Because images are deliberately defocused, each star will occupy many pixels (Figure 6.1 right).

6.1.1 Selecting measurement aperture radius

The measurement aperture radius, usually defined in pixels, must be the same for all stars to be measured in the image. The radius is set so that it contains the vast majority of the signal from the star itself whilst minimizing the amount of signal coming from other sources like sky glow and background stars. A good method of selecting an appropriate aperture radius is to plot the intensity profile of the brightest star to be measured using tools usually found in photometry software (e.g. the Graph Window tool in MaxIm DL). Figure 6.2 shows the profile of the star in Figure 6.1, you can see that the star intensity drops to essentially the sky background level by radius 9 pixels; hence this is a suitable radius to choose.

It is important to graphically view the intensity profile and not just guess by looking at the displayed star image because the displayed intensity may be stretched to give a more pleasing image on the computer screen but give a false impression of the actual width of the star image.

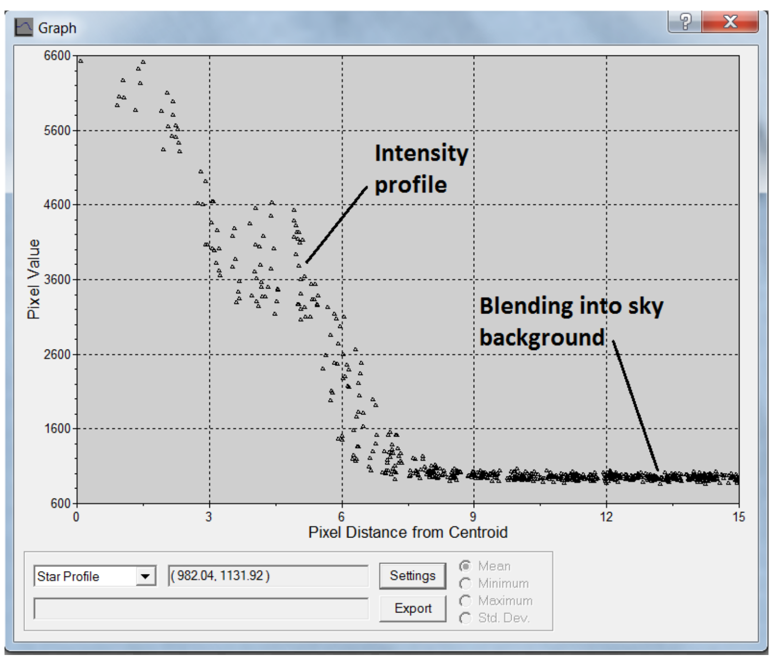


Figure 6.2. Graphical star profile of target star shown in Figure 6.1 using the Graph Window tool in MaxIm DL. (Mark Blackford)

If your photometry software cannot produce a graphical star profile, it should at least be able to determine the Full Width Half Maximum (FWHM) of the star image (see Figure 6.3 left panel). A useful rule of thumb is to set the aperture radius equal to 1.2 to 1.5 times the FWHM of the largest star image. It's better to err on the larger size if you use a non-tracking mount such as a simple camera tripod. As the measurement aperture radius is increased SNR first rises to a peak then falls off because no additional signal is collected from the star, but noise present in the extra pixels is added (Figure 6.3 right panel). Peak SNR correspond to radius of 6.5 pixels which is smaller than the 8.13 pixel FWHM and therefore a significant amount of star light is not collected. It is better to trade off a small amount of SNR for essentially complete collection of star light.

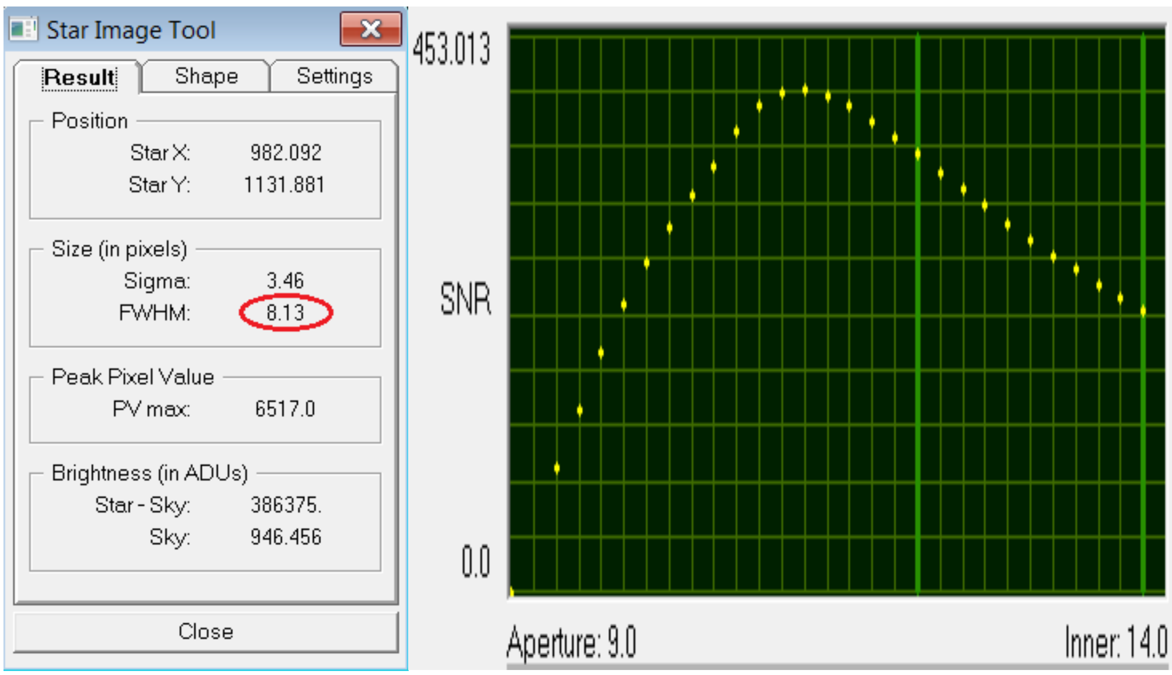


Figure 6.3. Left: Measured values of the target star shown in Figure 6.1 obtained using the Star Image Tool in AIP4Win. The measurement aperture radius was 9 pixels and the sky annulus radii were 14 and 20 pixels. **Right:** Signal to noise ratio as a function of measurement aperture radius, at 9 pixel radius SNR is ~360. (Mark Blackford)

6.1.2 Selecting the annulus size and position

The sky annulus is used to determine average pixel intensity of the sky background in the vicinity of the star being measured. The inner radius should be set several pixels larger than the measurement aperture to ensure any residual intensity from the star is completely excluded from the sky annulus. Since the sky background will be calculated from an average of a number of pixels in the annulus, a significant number of pixels should be included in the annulus. At a minimum it should contain the same number of pixels as the measurement aperture and preferably more. You can adjust this by changing the outer annulus radius.

Where possible, you should also try to avoid having too many background stars contained in the annulus. Most good photometric software will compensate for a few faint background stars but best practice is to avoid them if possible. Photometry software usually requires sky annulus radii to be the same for all stars to be measured in the image.

After defining measurement aperture and sky annulus radii the next step is to identify which stars in the calibrated image are to be measured. Photometry programs allow the selection of one or more target stars, one or more comparison stars, and one or more check stars in each image, and will perform all the relevant calculations. The output of aperture photometry is simply a count of how many ADU were generated by incoming photons from the stars being measured after subtraction of ADU counts due to sky glow. This value is called the star ADU.

6.2 Instrumental, differential and standardized magnitudes

6.2.1 Instrumental magnitudes

The traditional unit of stellar brightness is called magnitude which is a logarithmic scale, whereas star ADU values are a linear scale. Photometry software converts star ADU to instrumental magnitudes using the following equation:

$$\text{Instrumental Magnitude} = -2.5 \log_{10}(\text{star ADU}) \qquad \text{[Eq. 6.1]}$$

Instrumental magnitudes are specific to the camera and lens used to record images and the conditions under which they were recorded (e.g. exposure time, f-number, ISO, atmospheric conditions, etc.). They cannot be directly compared with instrumental magnitudes derived by other observers or even the same observer under different conditions. Furthermore, different photometry software may produce different instrumental magnitudes from exactly the same calibrated images because they use a different instrumental zero point. However, it is the magnitude difference between the comparison and variable stars that is important, not the absolute instrumental magnitude.

6.2.2 Differential magnitudes

Differential magnitude, Δmag, is calculated by subtracting the instrumental magnitude of the comparison star, $c_{measured}$, from the target variable star's instrumental magnitude, $v_{measured}$:

$$\Delta mag = v_{measured} - c_{measured} \qquad \text{[Eq. 6.2]}$$

In this manual instrumental magnitudes are denoted with lower case letters. Thus for the blue, green and red channels we have:

$$\Delta b = v_{measured\ b} - c_{measured\ b} \qquad \text{[Eq. 6.3]}$$
$$\Delta v = v_{measured\ g} - c_{measured\ g} \qquad \text{[Eq. 6.4]}$$
$$\Delta r = v_{measured\ r} - c_{measured\ r} \qquad \text{[Eq. 6.5]}$$

Δmag can also be determined directly from star ADU values:

$$\Delta mag = -2.5 \log_{10}(\text{star ADU}_{target}/\text{star ADU}_{comp}) \qquad \text{[Eq. 6.6]}$$

Obviously the differential magnitude depends on which comparison star was used, it is simply the brightness of the target relative to the constant comparison star. For some photometry projects this is sufficient, e.g. determining times of minimum of eclipsing binary stars, or the rotational period of asteroids.

6.2.3 Standardized magnitudes

However, other projects require the "actual" brightness of the target star, on a standard magnitude scale. For example, you may want to report that the target star was magnitude 8.45 at the time you observed it which can be directly compared with similar observations by other observers.

An additional step is required to determine the standardized magnitude. This is accomplished simply by adding the published catalog magnitude of the constant comparison star, $C_{catalog}$ to the measured differential magnitude:

$$\text{Standardized Mag} \approx \Delta mag + C_{catalog} \qquad \text{[Eq. 6.7]}$$

Italicized upper case letters denote standardized magnitudes, and non-italicized upper case letters denote catalog magnitudes. Thus for the blue, green and red channels we have:

$$B \approx \Delta b + C_{catalog\ B} \qquad \text{[Eq. 6.8]}$$
$$V \approx \Delta v + C_{catalog\ V} \qquad \text{[Eq. 6.9]}$$
$$R \approx \Delta r + C_{catalog\ R} \qquad \text{[Eq. 6.10]}$$

So, if you measure the target to be 0.40 magnitudes fainter than the comparison in the green channel and you know that the comparison catalog V magnitude is $C_{catalog\ V} = 8.05$, then you can report that the target star's standardized *V* magnitude is 8.45.

This observation is suitable for submission to AAVSO, to be included in their database of variable star observations. It should be identified as photometry in the "TG" filter if the green channel was used. "TG" indicates that the photometry represents measurements using only green pixels from a tri-color digital sensor, standardized using the catalog V-magnitude of the comp star. "TB" should be selected for magnitudes determined from the blue channel and catalog B magnitudes. "TR" should be selected for magnitudes determined from the red channel and catalog R magnitudes.

These filter designation are used on the AAVSO submission forms to distinguish DSLR (and one shot color CCD) photometry from several other filter systems.

TG, TB and TR magnitudes are valuable and useful contributions to the analysis of many short- and long-period variables, novae and supernovae.

Note that the ≈ symbol is used to denote that standardized magnitudes are only an approximation to true magnitudes. This is mainly because DSLR filters are not perfectly matched to the astronomical photometric filters used to define catalog magnitudes of comparison stars. The spectral response of your camera's blue, green and red filters are not exactly the same as Johnson B and V, and Cousins R bands, respectively, and no adjustment was made for these differences when calculating standardized magnitudes. See sections 6.4 and 6.5 for a detailed discussion of spectral response and how we can correct for filter differences.

Also, we have implicitly assumed that atmospheric extinction is the same for the target and comp stars. However, when using relatively wide field of view images, which are appropriate for many DSLR photometry projects, there is potential to have significant differential extinction across the image. Differential extinction is discussed further in section 6.5.

6.3 Comparison and check stars

We've used the terms comparison stars and check stars throughout this manual without fully explaining what they are, so let's address that now. Comparison stars are non-variable stars in the field of view of the target variable that have precisely measured magnitudes in one or more standard photometric bandpasses. They are used to produce standardized magnitudes of the target variable star as described in the preceding section. Check stars have exactly the same characteristics as comparisons stars, but they are treated in the same way as the target variable. Their role is to verify that the selected comparison star is indeed not variable.

Selection of suitable comparison and check stars is a crucial and involved process. The AAVSO has already prepared finder charts and photometry tables of comparison stars suitable for many variables; however you will inevitably come across targets for which no suitable comparisons have yet been compiled. In those cases you will need to either submit a request to the AAVSO Sequence Team (https://www.aavso.org/request-comparison-stars-variable-star-charts) or be prepared to do the work yourself. The following Section 6.3.1 is lifted directly from the AAVSO Guide to CCD Photometry Version 1.1, available from: https://www.aavso.org/ccd-photometry-guide.

6.3.1 Choose the check and comparison stars to use

This is a very important step because you will get different results depending on which comparison stars you use. In general, the more comparison stars you use, the better, since any errors or slight variability will be averaged out. However, it is important that you inspect the comparison stars you plan to use and select them with care to be sure that you have eliminated the ones that will give you worse results.

If at all possible, please use AAVSO comparison star sequences. Many software packages will allow you to load them automatically. If not, you can find the recommended comparison stars for each field by using the AAVSO chart plotting tool (VSP) and requesting output in the form of a "photometry table". The table will give you the position of each comparison star along with its magnitude and the magnitude error in each bandpass.

AAVSO sequences have been carefully designed to use stars for which magnitudes have been determined very accurately, are known not to vary or have close companions, and are of a color similar to the variable. The other advantage is that by using a standard set of comparison stars, your results should compare more favorably with those of other AAVSO observers when your data are combined in the AAVSO International Database. Researchers using your data will like that.

Here are some guidelines to follow when choosing which comparison stars to use:

- Try to select comparison stars close to the target and not near the edges of the image where they could be distorted.
- The comparison stars should be similar in color to each other, but not necessarily to the target star.
- Don't use red stars (many of which are themselves variable) or very blue stars. A good rule of thumb is to pick sequence stars that have (B-V) colors between +0.3 and +1.0, with (BV) of +0.7 being a good mean value. But do realize you will be limited to whatever stars appear in the field, and you may not have much of a choice.
- Pick comparison stars that are similar in magnitude to the target star.
- Be sure that none of the stars you select have companions.
- Choose comparison stars with a signal–to–noise ratio (SNR) of at least 100.
- Choose stars with similar magnitude errors, preferably all less than .01 – .02
- Ensure that none of the comparison stars you choose are near the saturation point in your image.

Check stars are important in that they can be used to determine if any of your comparison stars are varying or if other problems may exist with your image. A check star is simply a star of known brightness that doesn't vary which can be treated in the same way as you treat your target star. You should be able to compare the magnitude you determine for it with its published magnitude (in the same color) and the results should be very close. The check star should be as similar in color and magnitude as the variable as possible and it can be chosen from the list of available comparison stars in the same field as the target.

If you are processing several or many images taken of the same field on the same night (time series) it is a good idea to plot the magnitude of the check star versus time. If all goes well, the result should be a straight horizontal line. If your check star's magnitude varies, then something is wrong. Could a cloud have passed by when you weren't watching?

6.3.2 Where to find catalog magnitudes

If your target does not have an AAVSO chart or sequence, then a convenient source of standard magnitudes is the "Homogeneous Means in the UBV System (Mermilliod 1991)" database which is available on the web at VizieR (http://vizier.u-strasbg.fr/viz-bin/VizieR).

Enter "II/168/ubvmeans" in the Find Catalogs box, target coordinates or name in the search by position entry box and a search radius suitable for your image field of view; click "go". See Figure 6.4 for an example. The resulting output page shows all stars in that catalog within the specified search radius.

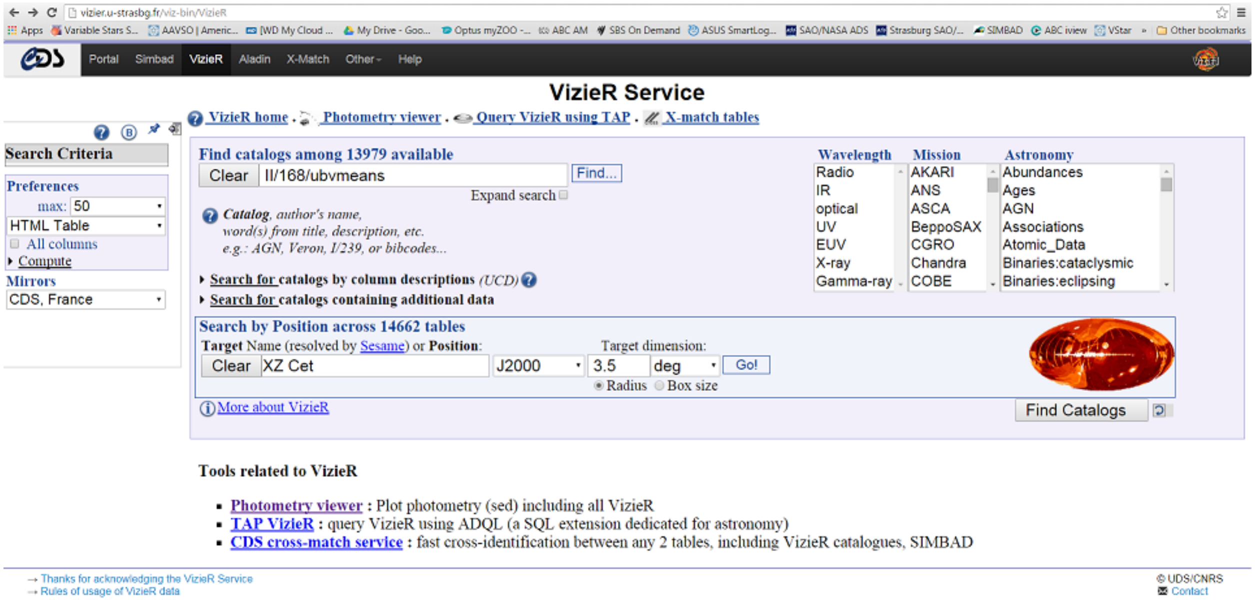


Figure 6.4. VizieR webpage showing example search of the Homogeneous Means in the UBV System (Mermilliod 1991) catalog for potential comparison stars around the anomalous Cepheid XZ Cet. (Mark Blackford)

Another very useful source is the AAVSO SeqPlot program (https://www.aavso.org/seqplot) which has photometric data from a number of catalogs including APASS, Tycho II and GCPD (General Catalog of Photometric Data). See Figure 6.5.

The choice of which catalog to use is not obvious. For DSLR photometry of stars brighter than about 10th magnitude the Tycho II, Homogeneous Means in the UBV System and the General Catalog of Photometric Data (GCPD) catalogs are probably the most appropriate.

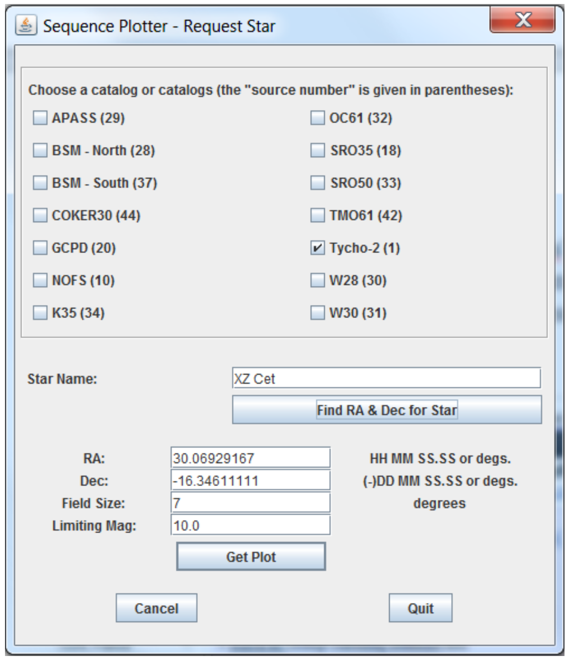


Figure 6.5. SeqPlot dialog box showing example search of the Tycho II catalog for potential comparison stars around the anomalous Cepheid XZ Cet. (Mark Blackford)

6.4 Spectral response of DSLR color channels

Astronomical photometry is simply the measurement of intensity in a specific part of the stellar spectrum. This is achieved by using filters that pass only a defined range of wavelengths through to the detector resulting in a defined spectral response for the particular photometric bandpass.

In order for different observers to compare results they need to use filters and detectors with the same spectral response. There will always be some difference between filters and detectors so astronomers use a technique called transformation to correct these (hopefully) small differences. We'll cover transformation in some detail later.

There are dozens of astronomical photometric filters covering the ultra violet, visible and infrared regions of the electromagnetic spectrum. Each designed to extract specific astrophysical information. The ones most relevant to us are the Johnson B and V and the Cousins R filters which are the most widely used ones in the part of the spectrum DSLR detectors are sensitive to.

Each DLSR color channel is sensitive to a specific range of wavelengths of light. This spectral response is determined by the spectral transmission efficiency of the lenses and filters in front of the CMOS detector (Figure 2.2) and the sensitivity of the detector itself to photons of different wavelengths.

However, DSLR's were not designed for photometry and their rgb filters are not well matched to the standard BVR filters. This means transformation requires much larger corrections, and some types of stars are not suitable for transformation at all. This is because their spectra contain strong emission or absorption lines that fall within the spectral response of, say, Johnson B filters but not within the spectral response of DSLR b filters. Such pathological stars also cause problems for conventional CCD photometry through photometric filters, but the effect is significantly worse for DSLR photometry.

Figure 6.6 shows standard photometric filter response curves at the top and DSLR rgb filter response curves at the bottom. Wavelength of peak sensitivity of the DSLR g filter closely matches that of the Johnson V filter but has a narrower bandpass. DSLR r and b filter bandpasses are also narrower than the corresponding astronomical filters and their peak sensitivities are much closer together. So the overall DSLR spectral response is more compressed than standard BVR filters.

Also shown are the positions of hydrogen beta and hydrogen alpha lines which are prominent features in the spectra of some stars. Clearly an unmodified DSLR camera is much less sensitive to H-alpha than a Cousins R filter, but more sensitive to H-beta than a Johnson B filter.

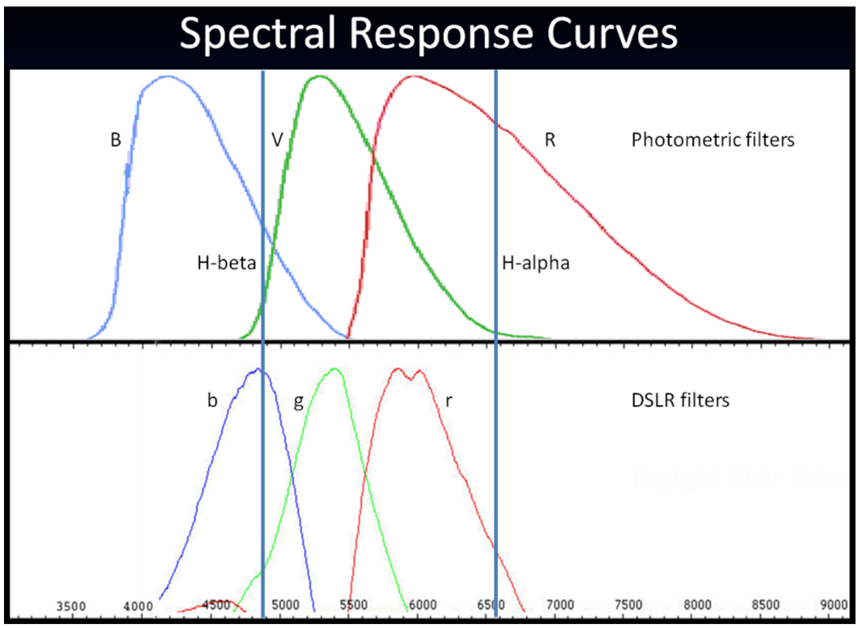


Figure 6.6. Top: Johnson B, Johnson V and Cousins R photometric response curves. **Bottom:** DSLR rgb channel response curves. (Mark Blackford)

Figure 6.7 shows a spectrum of V1369 Cen (nova Centauri 2013) displaying prominent emission lines including H-beta and H-alpha. The strength of these emission lines varied greatly as different physical processes became dominant throughout the evolution of the nova.

At this point in the nova's evolution transformed DSLR R magnitudes were systematically dimmer by about 0.43 magnitudes than measurements made with CCD cameras through Cousins R filters. This was due to the intense H-alpha emission line, which the DSLR is less sensitive to.

On the other hand, transformed DSLR B and V magnitudes were systematically too bright by about 0.15 and 0.07 magnitudes, respectively, due mostly to the H-beta emission line (Figure 6.8).

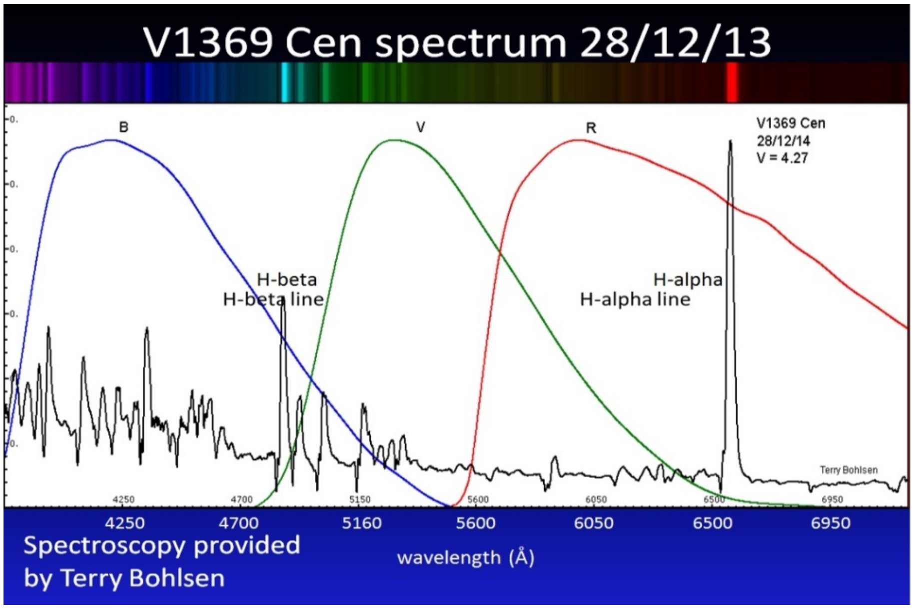


Figure 6.7. Spectrum of V1369 Cen (nova Centauri 2013) recorded some two weeks after peak brightness showing prominent H-alpha and H-beta emission lines. Superimposed are the Johnson B and V and Cousins R photometric filter response curves. (Terry Bohlsen and Mark Blackford)

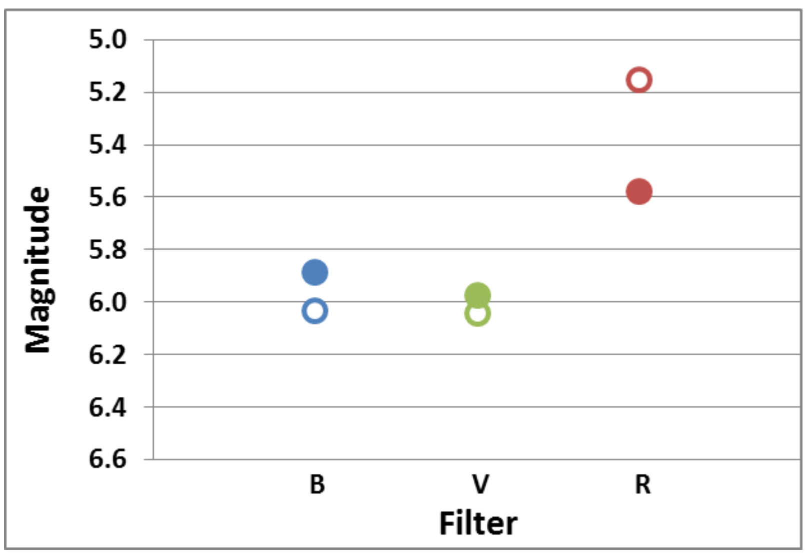


Figure 6.8. Comparison of DSLR (filled symbols) and CCD (empty symbols) observations of V1369 Cen (nova Centauri 2013) recorded nearly simultaneously. Blue, green and red data points represent Johnson B, Johnson V and Cousins R transformed observations, respectively. (Mark Blackford)

This is a very clear illustration of why DSLR instrumental magnitudes of certain types of stars (those with strong emission or absorption features) cannot and should not be transformed. By all means observe them but report the non-transformed magnitudes only.

So that's the bad news, but all is not lost for DSLR photometry. Many types of stars have spectra with more subdued spectral features and the overall spectrum shape is approximately blackbody-like. DSLR instrumental magnitudes from these stars can be very successfully transformed to the standard Johnson-Cousins photometric system.

Table 6.1 lists transformed BVR magnitudes of 15 photometric standard stars measured with a DSLR. The average of 30 measurements is shown in the columns headed "ave" and the standard deviation of those measurements is shown in the "stdev" columns. Columns labelled "delta" list differences between DSLR measured values and catalog values.

As you can see, transformed DSLR V magnitudes are all within 0.02 magnitudes of the catalog values and precision is below 10 millimags for all but the faintest stars. Accuracy and precision are only marginally poorer for B and R.

Table 6.1. BVR transformed DSLR observations of E1 Region standard stars (Menzies, J.W., Cousins, A.W.J., Banfield, R.M., & Laing, J.D. 1989, South African Astron. Obs. Circ., 13, 1). (Mark Blackford)

		B			V			R		
Star	ID	ave	stdev	delta	ave	stdev	delta	ave	stdev	delta
E130	HD 7706	7.763	0.011	-0.021	6.569	0.007	-0.011	5.939	0.010	-0.027
E142	HD 10167	7.003	0.011	0.008	6.672	0.007	0.007	6.487	0.015	0.018
E134	HD 8001	8.254	0.012	0.005	6.767	0.006	0.001	5.984	0.011	0.012
E121	HD 9733	7.829	0.011	0.013	6.921	0.006	0.004	6.445	0.011	0.018
E132	HD 8963	8.456	0.012	0.001	6.955	0.006	-0.006	6.175	0.012	0.003
E131	HD 10121	8.116	0.012	-0.023	6.964	0.007	-0.011	6.374	0.012	-0.030
E143	HD 8391	7.353	0.010	-0.006	7.023	0.007	-0.001	6.837	0.015	0.006
E104	HD 8305	7.799	0.013	-0.018	7.437	0.007	-0.018	7.228	0.018	-0.014
E170	HD 10101	8.609	0.016	0.008	7.576	0.009	-0.003	7.049	0.017	0.004
E101	HD 8977	7.798	0.012	0.007	7.710	0.008	0.006	7.670	0.021	0.004
E146	HD 7795	7.764	0.012	-0.007	7.849	0.009	-0.008	7.887	0.024	-0.012
E122	HD 7886	9.023	0.021	0.007	8.019	0.011	0.009	7.489	0.025	0.008
E109	HD 9403	8.727	0.022	0.022	8.206	0.011	0.019	7.913	0.034	0.017
E173	HD 9160	9.355	0.032	0.012	8.322	0.014	0.019	7.777	0.032	0.009
E102	HD 8382	8.659	0.029	0.009	8.449	0.020	0.005	8.335	0.051	0.017

So the take home messages are:

1) Stars with significant spectral emission or absorption lines are unsuitable for DSLR photometry if transformed magnitudes are required, but these pathological stars can be observed by DSLR if you report non-transformed magnitudes.
2) There are many types of stars that are suitable for transformed DSLR photometry.
3) All three DSLR color channels can be used for photometry.

6.5 Traditional extinction correction and transformation

As discussed in previous sections the effects of the imaging system spectral response and differential atmospheric extinction need to be corrected in order to achieve accurate magnitude measurements that can be compared with measurements made by other observers. In the following sections we will discuss corrections appropriate to two broad observing situations.

6.5.1 Narrow field of view or close to the zenith situation

In traditional CCD photometry differential extinction is assume to be negligible because the field of view when imaging through a medium to long focal length telescope is typically only a few tens of arc minutes. A DSLR imaging through the same telescope would have a similarly small field of view. Even when using telephoto camera lenses (where the field of view is several degrees or more), differential extinction is usually insignificant within about 30 degrees of the zenith. In such situations differential extinction may be safely ignored and traditional CCD photometry transformation corrections applied.

The AAVSO Guide to CCD Photometry provides a full description of the measurement and application of transformation coefficients from images of photometric standard star fields. Therefore in this manual we'll only summarize how these coefficients are applied to transform instrumental magnitudes to a standard magnitude system.

In DSLR photometry three colors are recorded simultaneously. Therefore, when differential extinction is negligible, the transformation equations are:

$$B_{var} = \Delta b + T_{b\_bv}*\Delta(B-V) + B_{comp} \qquad \text{[Eq. 6.11]}$$

$$V_{var} = \Delta v + T_{v\_bv}*\Delta(B-V) + V_{comp} \qquad \text{[Eq. 6.12]}$$

$$R_{var} = \Delta r + T_{r\_bv}*\Delta(B-V) + R_{comp} \qquad \text{[Eq. 6.13]}$$

$$\Delta(B-V) = T_{bv}*\Delta(b-v) \qquad \text{[Eq. 6.14]}$$

Where:

- B_{var}, V_{var} and R_{var} are transformed B,V and R magnitudes of the variable;
- Δb, Δv Δr are instrumental magnitudes of the variable minus the instrumental magnitudes of the comparison star (i.e. b_{var}- b_{comp} ,v_{var}- v_{comp} and r_{var}- r_{comp});
- T_{b_bv} , T_{v_bv} and T_{r_bv} are B, V and R magnitude transformation coefficients;
- $\Delta(B-V)$ is catalog B-V color index of the variable minus the catalog B-V color index of the comparison star;
- B_{comp}, V_{comp} and R_{comp} are comparison star catalog B, V and R magnitudes;
- T_{bv} is the B-V color transformation coefficient; and
- $\Delta(b-v)$ is the instrumental b-v color index of the variable minus the instrumental b-v color index of the comparison star.

Normal DSLR photometry practice has been to ignore the blue and red channels because their spectral responses were deemed to be too different from Johnson B and Cousins R. So only equation 6.12 was used, and Δ(B-V) was calculated from catalog B-V values for the variable and comparison stars. But this method does not take into account the fact that many variables change color over time, which would lead to systematic errors in the transformed magnitudes.

We saw in section 6.4 that for many stars DSLR b and r instrumental magnitudes can be successfully transformed to Johnson B and Cousins R. Equation 6.14 can therefore be used to determine Δ(B-V) from instrumental b and v magnitudes, and equations 6.11 and 6.13 used to transform b and r instrumental magnitudes.

To determine transformation coefficients we need to image a “Standard Field” containing many stars with precisely measured Johnson B, Johnson V and Cousins R magnitudes. The AAVSO Guide to CCD Photometry lists several standard clusters, some of which are suitable for wide field DSLR images. For southern hemisphere observers the Cousins E Regions at -45 degrees declination are also recommended. Figure 6.9 shows an image of M67 recorded with a Canon 600D DSLR and 80mm f6 refractor (field of view 2.67 x 1.78 degrees).

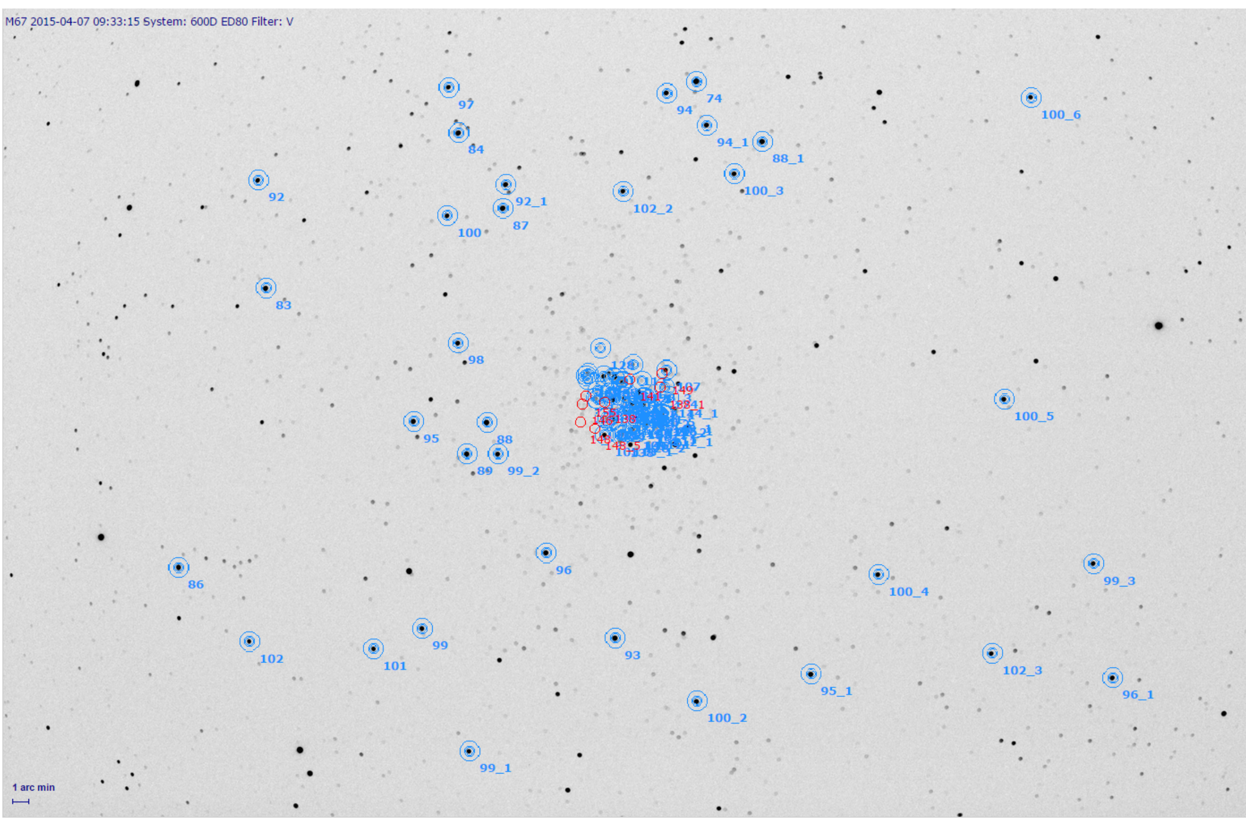


Figure 6.9. Star cluster M67 with standard stars indicated. The center of the cluster is too crowded at this image scale; however there are several dozen outlying standard stars suitable for determining transformation coefficients. (Mark Blackford)

After calibrating and extracting each color channel from the standard star field images we then measure instrumental magnitudes of all suitable standard stars. Equation 6.15 is used to calculate the color transformation coefficient, T_{bv}:

$$(b-v) = 1/T_{bv}*(B-V) + ZP_{bv} \qquad \text{[Eq. 6.15]}$$

Where (b-v) is the instrumental color, (B-V) is the catalog color and ZP_{bv} is an arbitrary zero point value. We plot (b-v) against (B-V) for each of the standard stars then least squares fit a straight line to the data points. T_{bv} is the inverse of the slope of the line.

The following Equations are used to calculate magnitude transformation coefficients:

$$(B-b) = T_{b\_bv}*(B-V) + ZP_b \qquad \text{[Eq. 6.16]}$$

$$(V-v) = T_{v\_bv}*(B-V) + ZP_v \qquad \text{[Eq. 6.17]}$$

$$(R-r) = T_{r\_bv}*(B-V) + ZP_r \qquad \text{[Eq. 6.18]}$$

Where (X-x) is the catalog magnitude minus the instrumental magnitude and other terms are defined above. For the green channel we plot (V-v) versus (B-V) for each of the standard stars then least squares fit a straight line to the data points. T_{v_bv} is the slope of the line. The other color transformation coefficients are determined in a similar manner. We now have all the information needed to determine transformed magnitudes of variable and check stars using equations 6.11 to 6.14.

The AAVSO Guide to CCD Photometry goes into greater detail of how to perform traditional CCD transformation. An alternative method will be presented in section 6.6 of this manual.

6.5.2 Wide field-of-view or close to horizon situation

One of the advantages of differential photometry is that as long as the target and comparison stars are close together in the sky, and not too close to the horizon, light from both stars passes through essentially the same amount of atmosphere (airmass), and therefore suffer essentially the same amount of scatter and absorption.

However, when a normal camera lens is used with a DSLR camera the field of view is fairly wide, easily several degrees and maybe larger than 30 degrees. For some projects involving bright stars, it is necessary to take advantage of this wide field of view, because your target and suitable comparison stars may be widely separated. If they are more than a few degrees apart and more than 30 degrees from the zenith, their light passes through different atmospheric path lengths, and hence the differential atmospheric extinction can be significant. The importance of this effect grows as (a) the separation between the two stars increases, and (b) the distance of one or both from the zenith increases. Note that we are ignoring another effect called second order extinction, which is dependent on the color of each star, but which is a much smaller effect than first order differential extinction.

In this situation, "transformation" must include the effect of spectral-response differences (as above) plus the effect of differential atmospheric extinction. This is done by adding one more term to the differential photometry equations:

$$B_{var} = -k_b*\Delta X + \Delta b + T_{b\_bv}*\Delta(B\text{-}V) + B_{comp} \qquad \text{[Eq. 6.19]}$$

$$V_{var} = -k_v*\Delta X + \Delta v + T_{v\_bv}*\Delta(B\text{-}V) + V_{comp} \qquad \text{[Eq. 6.20]}$$

$$R_{var} = -k_r*\Delta X + \Delta r + T_{r\_bv}*\Delta(B\text{-}V) + R_{comp} \qquad \text{[Eq. 6.21]}$$

Where:

- k_b, k_v and k_r are first order extinction coefficients (in magnitudes per airmass);
- ΔX is the airmass of the variable minus the airmass of the comparison star; and
- Other terms as defined above.

Airmass, X, is the path length that the star's light passes through the atmosphere on its way to the camera and is defined as X=1 at the zenith. For zenith angle ζ, the angle of the star from the zenith, less than 60 degrees airmass is approximated by $X = \sec(\zeta)$. Larger zenith angles require a more complicated calculation. Many photometric analysis programs will calculate airmass based on the observing location and time zone, image acquisition time, and equatorial coordinates of the star.

The traditional method of determining extinction coefficients involves imaging several standard stars at different times of the night, first when they are high in the sky (low airmass) and again later when low in the sky (high airmass) – or *vice versa*. We will not describe this method here; the interested reader is referred to Henden, A. A., and Kaitchuck, R. H. 1990, Astronomical Photometry, Willmann-Bell. Instead, an alternative method suitable for wide field DSLR photometry will be described in section 6.6.

6.6 Alternative extinction correction and transformation

In this section we present an alternative approach to extinction correction and transformation which was developed for the AAVSO Citizen Sky 2009-2011 epsilon Aurigae eclipse campaign (Kloppenborg et al., JAAVSO Volume 40, 2012). For simplicity, we will describe the technique as applied to the green channel, but it is equally applicable to blue and red channels.

Equation 6.17 can be extended to include the extinction correction term:

$$(V\text{-}v) = -k_v*X + T_{v\_bv}*(B\text{-}V) + ZP_v \qquad \text{[Eq. 6.22]}$$

This equation has the same functional form as a geometric plane in three dimensions:

$$z = Ax + By + C \qquad \text{[Eq. 6.23]}$$

If we assume that the instrumental magnitude, v, depends only on the right side of the above equation, then we may solve for the coefficients k_v, T_{v_bv}, and ZP_v, using a minimum of three comparison stars in the image. However, if one comparison star is “bad” (perhaps itself a variable, incorrectly identified, blended with a nearby star or its magnitude/airmass improperly calculated) the coefficients will be skewed. For this reason, 6 or more comparison stars are recommended to minimize the effect of a single “bad” comparison.

As Kloppenborg et al. explain, a least-squares fit of *n* calibration stars to the plane defined by equation 6.23 is found by solving for the coefficient matrix, X, in the following matrix expression, using the inverse of **A**:

$$\mathbf{AX} = \mathbf{B} \qquad \text{[Eq. 6.24]}$$

or fully formed:

$$\begin{bmatrix} \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i y_i & \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i y_i & \sum_{i=1}^{n} y_i^2 & \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} y_i & \sum_{i=1}^{n} 1 \end{bmatrix} \begin{bmatrix} -k_V \\ T_{V\_bv} \\ ZP_V \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} x_i z_i \\ \sum_{i=1}^{n} y_i z_i \\ \sum_{i=1}^{n} z_i \end{bmatrix} \qquad \text{[Eq. 6.25]}$$

But you don’t have to concern yourself with the details of matrix calculations, many spreadsheet programs and programming languages have suitable built-in routines. For example, the Reduction-Intermediate spreadsheet used by the AAVSO Citizen Sky project made use of the “LINEST” function in Excel.

The spreadsheet found here (under "Additional Material"): https://www.aavso.org/dslr-camera-photometry-guide allows analysis of instrumental magnitudes from blue and red channels in addition to the green channel. It also calculates the target’s (B-V) color index from its instrumental (b-v) color index using the comparison and check stars as calibration standards. The user can choose to apply:

1) No corrections (i.e. standardized magnitudes); or
2) Just transformation correction; or
3) Both extinction and transformation corrections.

Example data and instructions for using the spreadsheet are provided.

Standardized or transformed magnitudes from either spreadsheet are suitable for reporting to AAVSO.

See Appendix C for more details regarding atmospheric extinction.

6.7 Submitting your results

No scientific measurement has any value unless it is published so that it can be shared with the research community. "Publication" of most variable star photometric measurements means adding it to a well-known database, such as AAVSO's International Database (AID). Researchers then have access to your data, along with those of everyone else, by querying a particular star and timeframe. In order to be useful, your measurement must be accompanied by information that describes what it is, how it was derived, and other information related to its content and quality.

The AID data entry form is accessed from "WebObs (Submit/Search Data)" under the "Data" tab on the AAVSO's home page. You need to have an official AAVSO Observer Code and be logged in before data can be entered. Registration for an Observer Code (https://www.aavso.org/apps/register/) is free and open to everyone, not just AAVSO members.

Initially you'll use the "Submit Observations Individually" link on the WebObs page to enter a single observation at a time. Select "DSLR" from the "Choose Type of Observation" drop down list to display data entry fields required for this type of observation. Slightly different fields are displayed depending on which observation type is selected.

Figure 6.10 shows the entry form for an individual DSLR observation. The information requested by WebObs is probably self-explanatory, however the "More help…" link under each field provides further explanation if you are unsure.

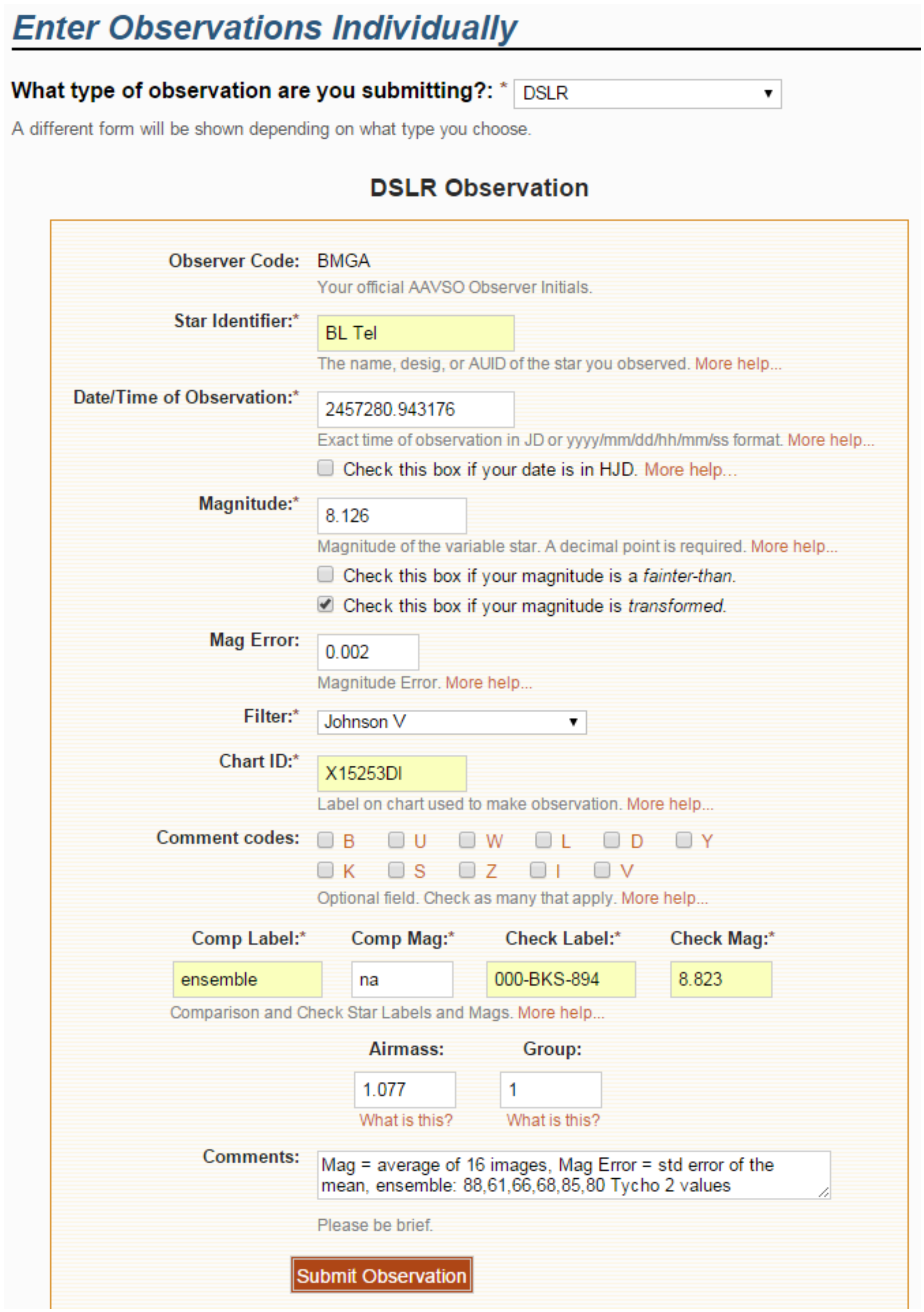
If you are submitting standardized magnitudes (i.e. non-transformed magnitudes) leave the "*transformed*" check box under the Magnitude field unchecked and select the appropriate "Tri-Color…" option from the Filter drop down list. For example select "Tri-Color Green" if the standardized magnitude was derived from green channel instrumental magnitudes.

For transformed observations (with or without extinction correction) be sure to check the "*transformed*" check box and select either Johnson B, Johnson V or Cousins R from the Filter drop down list, depending on which DSLR color channel was used.

When only one comparison star is used, as may be the case with traditional CCD reduction, you should enter instrumental magnitudes in the Comp Mag and Check Mag fields.

Enter "ensemble" in the Comp Label field and "na" in the Comp Mag field when an ensemble of comparison stars is used, as with the spreadsheets mentioned in section 6.6. In the Check Mag field enter the transformed (not instrumental) magnitude as calculated by the spreadsheet. In the Airmass field enter the calculated target star airmass at the time of the observation.

If submitting B, V, R magnitudes from an individual (or stacked) frame, indicate this by giving all three observations the same identifier in the Group data field. This helps in identifying that the magnitudes were obtained at the same time. The group identifier should be an integer number, identical for all observations in the group and unique for a given observer for a given star on a given Julian date.



Enter Observations Individually

What type of observation are you submitting?: * DSLR

A different form will be shown depending on what type you choose.

DSLR Observation

Observer Code: BMGA
Your official AAVSO Observer Initials.

Star Identifier:* BL Tel
The name, desig, or AUID of the star you observed. More help...

Date/Time of Observation:* 2457280.943176
Exact time of observation in JD or yyyy/mm/dd/hh/mm/ss format. More help...
Check this box if your date is in HJD. More help...

Magnitude:* 8.126
Magnitude of the variable star. A decimal point is required. More help...
Check this box if your magnitude is a *fainter-than*.
Check this box if your magnitude is *transformed*.

Mag Error: 0.002
Magnitude Error. More help...

Filter:* Johnson V

Chart ID:* X15253DI
Label on chart used to make observation. More help...

Comment codes: B U W L D Y K S Z I V
Optional field. Check as many that apply. More help...

Comp Label:*	Comp Mag:*	Check Label:*	Check Mag:*
ensemble	na	000-BKS-894	8.823

Comparison and Check Star Labels and Mags. More help...

Airmass:	Group:
1.077	1
What is this?	What is this?

Comments: Mag = average of 16 images, Mag Error = std error of the mean, ensemble: 88,61,66,68,85,80 Tycho 2 values
Please be brief.

Submit Observation

Figure 6.10. WebObs individual observation entry page with data fields required for DSLR observations. (Mark Blackford)

The Comments field can be used to identify stars used in the comparison ensemble and other relevant information, but is limited to 100 characters, including spaces and punctuation.

Carefully check your entries before pressing the Submit Observation button. WebObs has a facility to search for and edit entries if later you realize a submitted observation is incorrect.

The other method of submitting observations is more complex, and involves generating a file of observations rather than one at a time. The file must be in the AAVSO Extended File format (https://www.aavso.org/aavso-extended-file-format). Many software packages provide a compatible output called "AAVSO Extended Format", or similar. If you are using other photometry software or spreadsheets you'll have to generate a suitable text file yourself. Be sure that the "OBSTYPE" in that output file is set to DSLR. There is an option in WebObs to browse for your file and then upload it.

Finally, after submitting observations the Light Curve Generator (https://www.aavso.org/lcg) should be used to see how your data compare with those from other observers. It is fun watching a light curve being built in real time!

Chapter 7: Developing a DSLR Observing Program

One of the biggest challenges faced by a new observer is deciding which of the hundreds of thousands of known variable stars to observe. Where do you find lists or catalogs of stars? How do you decide which are appropriate for your instrument? How do you get charts showing the variable and surrounding stars, and how do you decide which to use as comparison stars?

The AAVSO Observers Section webpage (https://www.aavso.org/observers#sections) is an excellent place to start researching potential targets. There are numerous links to other resources, including those shown in Figure 7.1 which are particularly relevant to new observers.

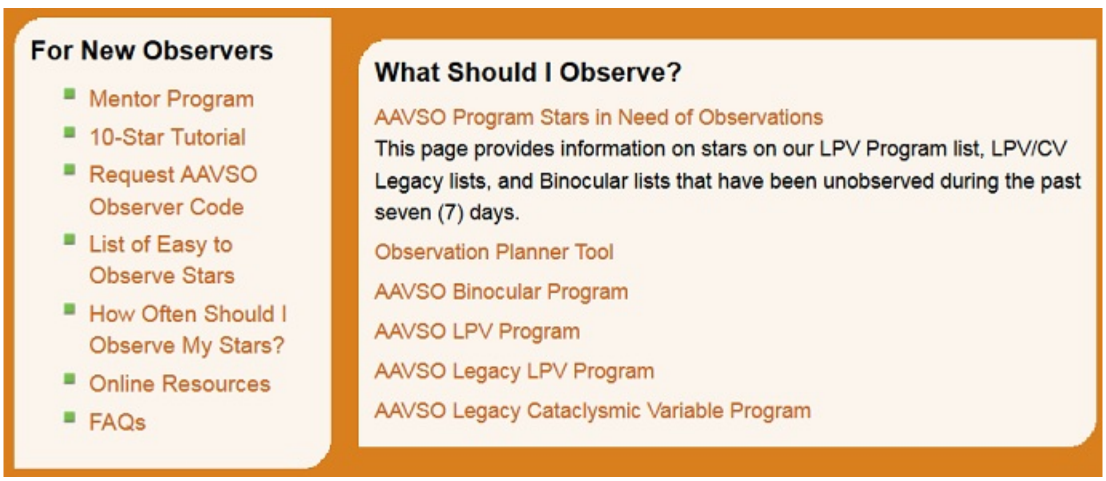


Figure 7.1. Part of AAVSO Observers Section webpage.

Stars in the AAVSO Binocular Program generally have magnitude ranges, finder charts and photometry tables suitable for DSLR photometry. Also check the various AAVSO Observing Sections, in particular the Eclipsing Variables, Short Period Pulsating Variables and Long Period Variables sections.

The Observation Planner Tool can be used to identify variables visible from your location on a particular night. Be sure to read through the instructions carefully to get the most from this tool and avoid choosing less appropriate targets.

In an effort to simplify that decision process, we've selected that we feel are a few good targets for newcomers. However, not all of them will be suitable for every observer.

7.1 Recommended Beginner Target Lists

The recommended beginner targets include 11 stars for northern observers and 10 stars for southern observers (Tables 7.1 and 7.2, respectively). They were selected based on a set of criteria we thought would make them useful as training stars. All have amplitude of variation greater than 0.3 magnitudes, except one small amplitude star, beta Cephei, included as a challenge. Most are quite bright, at least for part of their light curves, which should make it relatively easy to find and frame them in your camera field of view.

One target in the north and two in the south are about magnitude 8 or fainter at maximum so will require some effort to frame the image and attain reasonable SNR.

Most of these stars are also included in the AAVSO's visual observing Training Tutorials (available from https://www.aavso.org/10-star-training). These stars are indicated with superscript [2] in Tables 7.1 and 7.2. The 10-star tutorials include charts showing the entire constellation to help orient the observer and facilitate locating the variable. An example is shown in Figure 7.2 below. Numerical labels indicate comparison stars for visual observers; however they may not be suitable for DSLR observers. You should use Variable Star Plotter to generate an appropriate CCD chart and photometry table (see section 3.4.1).

All the stars listed are interesting and/or 'famous' and are of interest to professional astronomers. They all illustrate important stages in the evolution of stars. Mira was noted, in 1596, as the first variable star. Mu Cephei (mu is spelled miu in the table because that is the official international astronomical spelling of that Greek letter) is a large star in the final stages of evolution and soon to be a supernova. We consider that some of our recommended stars are suitable for high school and college projects and many have extensive references on the web that would be helpful for a student project.

Some of the stars have regular variation (such as the Cepheids and eclipsing binaries) and several have a cycle that is fully completed in less than five hours. A full cycle can therefore be recorded in a single observing session.

Table 7.1. Bright variable stars recommended for beginners in the Northern Hemisphere.

NORTHERN STARS					
Name	**Observing time**	**Magnitude Range**	**Type of Variable**	**Period (days)**	**Notes**
Z UMa	Year round	6.2 - 9.4	Semiregular variable	195.5	Can be observed every 5 days. You may need to change settings to take account of large change in magnitude.
delta Cep[2]	Year round	3.49 -4.36	Classical Cepheid	5.366266	Can be observed twice in one night or once before midnight. Famous historical variable star with a regular distinctive light curve. Report observations as del Cep.
Algol (beta Per) [2]	August to May	2.09 - 3.30	Eclipsing Binary	2.86736	Eclipse lasts about 8 hours. Measurements should be made for at least two hours each side of predicted minimum. 10 or more measurements needed for a reasonable light curve; these can be made every 15 minutes. Report observations as bet Per.
beta Lyr[2]	April to November	3.30 - 4.35	Eclipsing Binary	12.94061713	Semi-detached eclipsing star which means that it is in continuous eclipse. For most of its period one measurement per night is sufficient. Around primary minimum (a one-and-a-half day period) measurements can be made every hour. Report observations as bet Lyr.
miu Cep[1,2]	Year round	3.43 - 5.1	Semiregular variable	835	One measurement per night is sufficient. Report observations using spelling “miu” instead of “mu”.
eta Aql[2]	April to November	3.49 - 4.30	Classical Cepheid	7.1769	Can be observed twice in one night or once before midnight. Famous historical variable star with a regular distinctive light curve.
Mira[1] (omicron Cet)	August to February	2 - 10.1	Mira	331.96	Measureable for 100 days either side of maximum. Report observations as omi Cet.
R Lyr[1,2]	April to November	3.81 - 4.44	Semiregular variable	46:	One measurement per night is sufficient.
beta Cep	Year round	3.16 - 3.27	Beta Cephei pulsating variable	0.1904881	Has very small amplitude and will require 30 images to make a measurement in good sky conditions. Has a regular period and is continuously changing. An entire cycle can be measured in one session with measurements every 5 minutes. Report observations as bet Cep.
BE Lyn	October to April	8.57 - 8.97	High Amplitude Delta Scuti (HADS)	0.09586954	Has a short regular period which can be studied in one session with 10 measurements spaced 5 minutes apart.
V474 Mon	November to March	5.94 - 6.31	High Amplitude Delta Scuti (HADS)	0.136126	Has a short regular period which can be studied in one session with 10 measurements spaced 5 minutes apart.

[1] **Note:** This star is red, and untransformed DSLR magnitudes may be excessively bright.
[2] **Note:** Chart for this star exists in 10-star tutorial (northern stars)

Table 7.2. Bright variable stars recommended for beginners in the Southern Hemisphere.

SOUTHERN STARS					
Name	**Observing time**	**Magnitude Range**	**Type of Variable**	**Period (days)**	**Notes**
W Sgr[2]	March to October	4.29- 5.14	Classical Cepheid	7.59503	A triple system made up of the Cepheid, a close F5 dwarf, and a more distant A0 star.
kappa Pav[2]	April to November	3.91 - 4.78	W Virginis pulsating variable	9.083	By far the brightest example of a Population II (old) Cepheid. Low mass stars less luminous than classical Cepheids. Kappa Pavonis displays abrupt period changes. Continuous monitoring helps track them. Report observations as kap Pav.
beta Dor[2]	September to April	3.41 - 4.08	Classical Cepheid	9.8426	Only 0.1 mag. fainter than l Car and follows it in the ranking. Classical Cepheids are massive Population I (young) stars. Report observations as bet Dor.
l Car[2]	December to July	3.22 - 4.12	Classical Cepheid	35.562	The brightest Cepheid after Polaris in the sky, if we take apparent magnitude. Note that "l" is lower case L.
R Car[1,2]	December to August	3.9 - 10.5	Mira	307	Requires the use of several different settings to cover its entire range.
V Pup[2]	October to May	4.35 - 4.92	Eclipsing Binary	1.4544859	An eclipsing binary of the beta Lyrae type. Brightness changes are continuous due to the ellipsoidal shape of the components.
R Dor[1,2]	October to May	4.78 - 6.32	Semiregular variable	172	A semiregular star showing two maxima and strong amplitude changes from cycle to cycle. One of the largest stars with a diameter measured interferometrically from Earth.
zeta Phe[2]	July to February	3.94 - 4.42	Eclipsing Binary	1.6697671	An Algol-type eclipsing binary. You will find the star at maximum brightness most of the time, so catching an eclipse will require patience.
RY Lep	October to May	8.05 - 8.46	High Amplitude Delta Scuti (HADS)	0.2251475	An entire cycle can be measured in one session with measurements every 5 minutes.
RS Gru	June to January	7.94 - 8.48	High Amplitude Delta Scuti (HADS)	0.1470117	Has a short regular period which can be studied in one session with 10 measurements spaced 5 minutes apart.

[1] **Note:** This star is red, and untransformed DSLR magnitudes may be excessively bright.

[2] **Note:** Chart for this star exists in 11-star tutorial (southern stars).

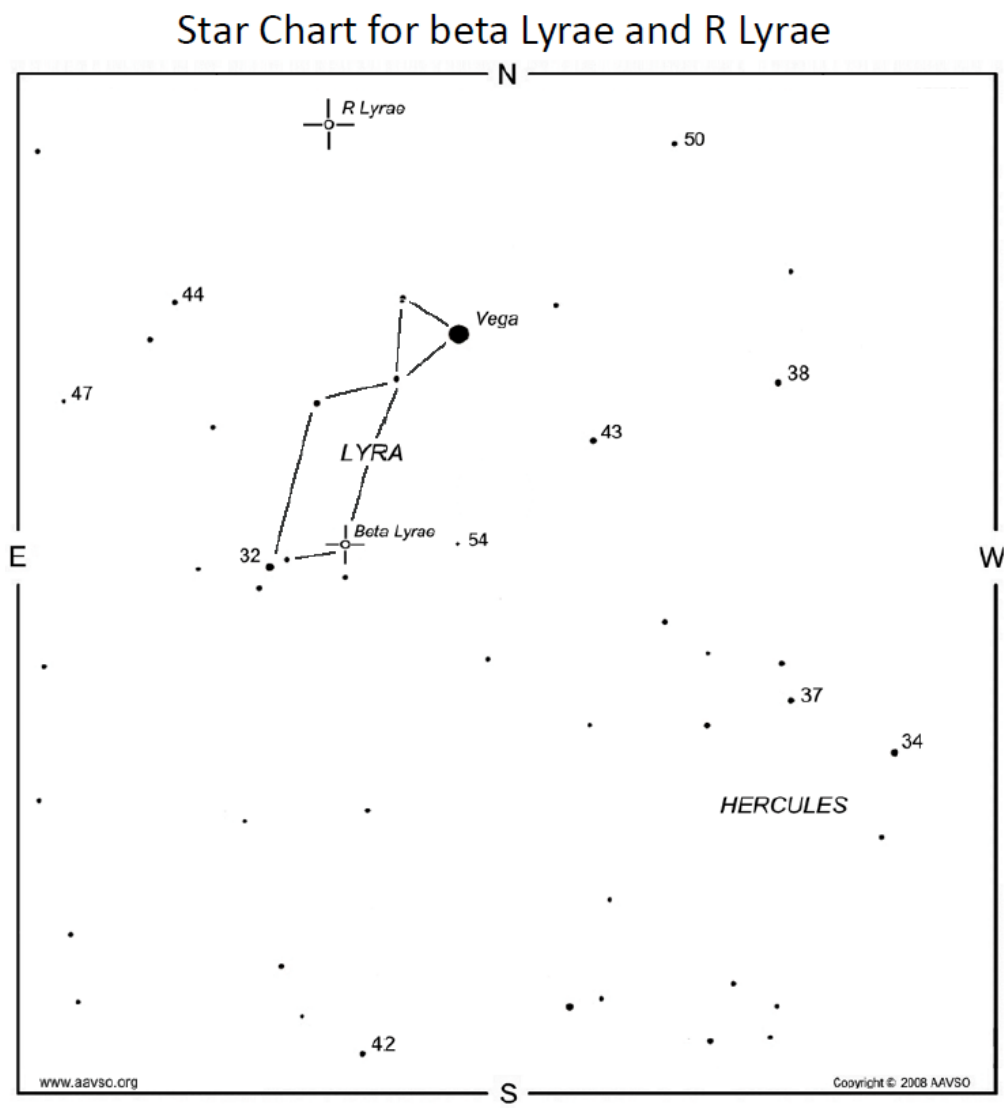


Figure 7.2. Finder chart for beta Lyrae and R Lyrae reproduced from the AAVSO's 10-Star Training Tutorial for northern visual observers. (AAVSO)

7.2 Deciding what to observe

Probably the two biggest factors influencing your choice of targets are your lens and mount. These and other equipment related topics were covered in Chapter 2. Other important considerations are your observing site (partially obscured view?), sky conditions (light pollution worse in particular directions?), how often you can observe, and how long you can stay out each session. Later, when you decide to expand your target list it would be wise to check out the observing programs and campaigns initiated, or recommended, by the AAVSO and other variable star organizations.

Above all, choose targets that interest you. If you don't think this is fun you won't do it for long. So what makes it fun for you? Is it the satisfaction of mastering the technical challenges? Is it the thrill of seeing a light curve take shape as observations are added over time? Is it being outside and in touch with the

Universe? Are there some stars you like to observe just for the fun of it? How serious do we need to be? Is any of this important? Can we take this seriously, contribute to science and still have fun? Absolutely! Believe it or not, this makes a difference. We want you to be successful, happy and productive. If DSLR photometry isn't fun for you, you'll soon lose interest.

7.2.1 Planning an observing session

A number of considerations contribute to planning an observing session. A major consideration is how long you have available for observing. You may have just one or two hours, or you may be able to observe all night. If only an hour or so then you will not be able to usefully observe an eclipsing binary - that will usually require measurements over four or more hours. But in one hour you may be able to observe five stars that only need one measurement per night. Remember, good practice is to record multiple images of each field from which an average magnitude can be calculated.

If you plan to observe several stars in a session make sure you carefully note any camera setting changes made as you move from one star to another. It is all too easy to forget to change or record settings when you are tired later in the night.

Targets should be high in the sky at the time you plan to observe them to minimize differential extinction effects. A good planetarium program is invaluable for checking this. You may need to relax this requirement when time critical observations are needed, e.g. novae or supernovae, when the target is not well placed in the sky.

If you are already a visual variable star observer you can, of course, choose to also conduct DSLR photometry of a favorite star by applying the principles in this manual.

7.2.2 Finder charts and comparison star charts with photometry tables

Locating a variable star is a learned skill. Up-to-date finder charts and photometry tables with well-determined magnitude sequences of comparison stars should be used (Section 3.4.1). Observers are urged to use such charts in order to avoid the conflict that can arise when magnitudes for the same comparison star are derived from different sets of charts. This could result in two different values of variation being recorded for the same variable star on the same night.

7.2.3 Ephemerides to predict when your subject star will be bright or faint

An ephemeris (plural: ephemerides; from the Greek word ἐφημερίς ephēmeris "diary", "journal") is a table of values that lists predicted times and dates of mid-primary eclipse of an eclipsing binary or maximum for pulsating stars (Cepheids and Miras). The ephemeris of stars on our recommended lists can be found in the AAVSO International Variable Star Index (VSX) http://www.aavso.org/vsx/. Enter the name of the star you want to observe, for example W Sgr, and click "search". The result page will have a link called "Ephemeris" on the right hand side of the line labeled "Epoch". Click on that link to display a window listing the next several maxima of this Cepheid variable. Note: the ephemeris will tell you the next several maxima for pulsating stars like Cepheids and primary minima for eclipsing binaries.

If the epoch and period in VSX have not been updated for many years the actual times of maxima/minima may not correspond closely to predicted times. This is a major reason for continuing observations of pulsating and eclipsing stars, to look for period changes which may be due to evolutionary changes or other stars orbiting the variable.

7.2.4 Weather report, humidity, dew point, temperature

Check the weather forecast for the night you plan to observe. There may be a promising evening but widespread faint wisps of cirrus, which become invisible when it is dark, can preclude good photometry. A DSLR camera is so sensitive that faint cirrus makes a big difference. Sometimes we have the pleasure of experiencing a transparent sky - cloud free, dust free and low humidity. Take full advantage of such a night, as they occur, in most parts of the world, all too rarely. Drop all personal/family/work/social commitments and get organized!

There are a number of astronomy specific websites and smartphone/tablet computer apps that provide additional information compared with general meteorological forecasts. Some nights start with good observing conditions but deteriorate as weather fronts pass through; others start cloudy only to clear up later. With some pre-planning you can take advantage of weather-limited sessions to make valuable observation. If prospects are good for the entire night you can prepare for a long time series of an eclipsing binary or high amplitude delta Scuti variable, if your mount is suitable. Time series imaging with a non-tracking mount would be extremely challenging, both in keeping the target and comparison stars well framed throughout the night and in measuring the images afterwards.

If fog is forecast your camera and lens may mist up. This may occur before the actual fog rolls in, so you have to plan your measurements to take place before the fog arrives. There can be dew on your camera without fog, so be alert to this happening, as it will ruin measurements. You can minimize the problem by transferring your set-up to a cool but drier environment (such as a garage) in between measurements. You can cover the camera in between measurements with a plastic bag, which preserves a drier environment.

If the ambient temperature is warmer or colder than your internal house temperature, it is advisable to put the camera outside for twenty minutes so that the camera and lens can thermally adjust.

If you live near the ocean be aware that condensation can be salty, which is very bad for the camera and lenses.

7.2.6 Sky conditions, phase of moon

Although a bright moon can have a significant impact on visual observations of variable stars, the effect on DSLR measurements is less severe. A bright moon has no effect on measurements in the part of the sky opposite the moon. Provided the camera lens has a hood, measurements are possible quite near to a bright moon so long no direct or reflected light from the moon enters the camera lens.

7.2.8 Non-variable star observing

An interesting and good night's work can be spent testing equipment and settings. Imaging standard star fields will allow you to determine transformation coefficients and test the accuracy and reproducibility of your measurements. Another worthwhile experiment is to check how signal to noise is improved when ten, twenty, or thirty images are stacked (or averaged) compared with a single image.

Before you attempt photometry of variable stars it is a very good scientific exercise to practice photometry on stars that do not vary. You can pick two close unvarying stars and measure the difference in brightness then compare your estimation of the difference with the catalog difference. You may find that using your first few clear nights for doing these exercises in DSLR photometry helps a lot when tackling your first variable stars.

This is a very good method of developing an understanding of your equipment. Experiment with changing the amount of defocus, length of exposure, ISO and f-stop. Work out which settings produce the most precise measurement.

Experiment with a pairs of stars that have a magnitude difference of over 0.5, a difference of around 0.2 and a difference of around 0.1. You may find that, for example, that you can only compare stars with a difference of 0.1 magnitudes when observing conditions are very good. With experience you should be able to reliably measure 0.01-0.02 magnitude variation of brighter stars.

Determine the brightest and dimmest stars for practical photometry with your lens and mount.

Choose pairs of stars with about the same color otherwise the difference you determine may not agree with catalog values despite the correctness of your settings and procedures.

7.3 Time to get started

In this manual we have presented in some detail how DSLR cameras may be used to monitor brightness changes of variable stars. For many types of variables DSLR measurements can be comparable with CCD photometry in terms of both precision and accuracy. DSLR's therefore provides a lower cost route for amateurs to hone their photometry skills and contribute valuable scientific data to the AAVSO International Database.

Now it's time to take your DSLR out under the stars and put into practice everything you've learned. Enjoy!

7.2.7 How often should I observe my program stars?

Tables 7.3 and 7.4 list recommended frequency of observation (cadence) for different types of variables.

Table 7.3. Observing cadence recommended for several classes of variable stars.

TYPE	DESCRIPTION	CADENCE (days)
Active Galaxies (AGN)	Active Galactic Nuclei. Optically variable extragalactic objects only included for historical reasons or observing campaigns. GCVS type GAL,BLLAC,QSO.	1
Gamma Cassiopeiae (GCAS)	Eruptive irregular variables of the γ Cassiopeiae type. These are rapidly rotating stars with mass outflow from their equatorial zones. The formation of equatorial rings or disks is accompanied by a temporary brightening or fading. Light amplitudes may reach 1.5 mag. in V.	5 - 10
Irregular	Slow irregular variables. The light variations of these stars show no evidence of periodicity, or any periodicity present is very poorly defined and appears only occasionally. Stars are often attributed to this type because of being insufficiently studied.	5 - 10
Miras (LPVs) period <300 days	o (omicron) Ceti-type (Mira) variables. These are long-period variable giants with light amplitudes from 2.5 to 11 mag. in V. Their periods lie in the range between 80 and 1000 days.	5 - 7
Miras (LPVs) period 300-400 days		7 - 10
Miras (LPVs) period >400 days		14
Novae (N)	Close binary systems with orbital periods from 0.05 to 230 days. One of the components of these systems is a hot white dwarf star that suddenly, during a time interval from one to several dozen or several hundred days, increases its brightness by 7-19 mag. in V, then returns gradually to its former brightness over several months, years, or decades.	1
R Coronae Borealis (RCB)	Variables of the R Coronae Borealis type. These are hydrogen-deficient, carbon- and helium-rich, high-luminosity stars belonging to the spectral types Bpe-C, which are simultaneously eruptive and pulsating variables. They show slow nonperiodic fadings by 1-9 mag. in V lasting from a month or more to several hundred days.	1
Recurrent Novae (NR)	Recurrent novae, which differ from typical novae by the fact that two or more outbursts (instead of a single one) separated by 10-80 years have been observed. Examples: T CrB, T Pyx.	1
RV Tauri (RV)	Variables of the RV Tauri type. These are radially pulsating supergiants. Light curves are characterized by the presence of double waves with alternating primary and secondary minima that can vary in depth so that primary minima may become secondary and vice versa. The complete light amplitude may reach 3-4 mag. in V. Periods between two adjacent primary minima (called formal periods) lie in the range 30-150 days.	2 - 5

Table 7.3. Continued

TYPE	DESCRIPTION	CADENCE (days)
S Doradus (SDOR)	Variables of the S Doradus type. These are eruptive, high-luminosity stars showing irregular light changes with amplitudes in the range 1-7 mag. in V. They belong to the brightest blue stars of their parent galaxies. As a rule, these stars are connected with diffuse nebulae and surrounded by expanding envelopes. Examples: P Cyg , η Car.	5 - 10
Supernovae (SNe)	Supernovae. Stars that increase, as a result of a final explosion, their brightnesses by 20 mag and more, then fade slowly. According to the light curve shape and the spectral features, supernovae are subdivided into types I and II.	1
Semiregular (SR, SRA, SRB, SRC)	Semiregular variables, which are giants or supergiants of intermediate and late spectral types showing noticeable periodicity in their light changes, accompanied or sometimes interrupted by various irregularities. Periods lie in the range from 20 to >2000 days, while the shapes of the light curves are rather different and variable, and the amplitudes may be from several hundredths to several magnitudes (usually 1-2 mag. in V)	5 - 10
Dwarf Novae (NL, UG, UGSS, UGSU, UGWZ, UGZ)	U Geminorum-type variables, or "dwarf novae". Close binary systems consisting of a dwarf or subgiant star that fills the volume of its inner Roche lobe and a white dwarf surrounded by an accretion disk. Orbital periods are in the range 0.05-0.5 days. From time to time the brightness of a system increases rapidly by several magnitudes (outburst) and, after an interval of from several days to a month or more, returns to the original state. According to the characteristics of the light changes, U Gem variables may be subdivided into three types: SS Cyg-type (UGSS), SU UMa-type (UGSU), and Z Cam-type (UGZ)	1
Young Stellar Objects (YSOs) active state	Young Stellar Objects. Variable pre-main sequence stars. May be T Tauri stars, UXors, FUors, or EXors.	1 or less
Young Stellar Objects (YSOs) inactive state		2 - 5
Symbiotics (ZAND)	Symbiotic variables of the Z Andromedae type. They are close binaries consisting of a hot star, a star of late type, and an extended envelope excited by the hot star's radiation. The combined brightness displays irregular variations with amplitudes up to 4 mag. in V.	1
Eclipsing binaries (EB)		1 per minute
High Amplitude delta Scuti (HADS)		1 per minute

Table 7.4. Observing cadence and timing precision recommended for several classes of variable stars.

TYPE OF STAR	OBSERVING FREQUENCY	REPORT JD TO
Cepheids	Every clear night	4 decimal places
Cataclysmic var.	Every clear night	4 decimal places
Mira variables	Once per week	1 decimal place
Semiregular	Once per week	1 decimal place
RV Tauri stars	Once per week	1 decimal place
Symbiotic stars*	Once per week	1 decimal place
R CrB* stars	During maximum once per week	1 decimal place
R CrB stars	During fadings every clear night	4 decimal places
Irregular variables	Once per week	1 decimal place
Suspected variables	Every clear night	4 decimal places
Flare stars	Continuously for 10 to 15 minutes for rare outbursts.	4 decimal places
Eclipsing binaries	Every 10 minutes during eclipse	4 decimal places
RR Lyrae stars	Every 10 minutes	4 decimal places

Note: Symbiotic stars and R CrB stars may experience possible small-magnitude, short-period variability. If you are interested in looking for this, then observations should be made every clear night and reported to 4 decimal places.

Appendix A: DSLR Camera Testing

This document is based on information in the following references:

1. *The Handbook of Astronomical Image Processing*, Second Ed., Richard Berry and James Burnell, Willmann-Bell, Richmond, VA.
2. *Profiling the Long-Exposure Performance of a Canon DSLR* published on Cloudy Nights by Craig Stark. A PDF of this and other interesting articles are available from:

http://www.stark-labs.com/craig/articles/articles.html

See Appendix E for information on DSLR sensor linearity testing.

We can determine several basic parameters of your DSLR camera from an easily recorded set of bias, dark and flat field images. These include the system gain, maximum ADU value (saturation value), full well capacity and read noise. You can also measure the temperature rise of your sensor as a long series of images is captured and determine how the noise level changes with temperature.

These measurements should be repeated at each ISO settings from 100 to 800, which are the only ones you should consider for photometry.

NOTE: Throughout this document reference is made to extracting one of the green colour planes. Some photometry software packages, e.g. MaxIm DL, allow you to extract the two green planes separately. Other software combines the two green planes into a single image, e.g. AIP4Win. If your software produces a single green image then you should use either the blue or red plane when measuring your camera's parameters. This is because a combined green image will have a smaller standard deviation compared with the individual green images, and therefore parameters derived from the standard deviation will be incorrect.

Maximum ADU value

Modern DSLR cameras have 14 bit analogue-to-digital converts (ADC) which nominally should give a maximum ADU value of $(2^{14} - 1) = 16383$. Some older cameras have a 12 bit ADC with nominal maximum ADU value of $(2^{12} - 1) = 4095$. However, in reality the true value will be somewhat smaller, and may be different at ISO 100 compared with higher ISO settings.

1. Record an over exposed Flat field frame
2. Measure the Maximum pixel value (it should be the same for all colour planes).

Results measured with a Canon 1100D:

ISO	Maximum ADU [ADU]
100	13584
200	15304
400	15303
800	15304

System Offset

Some cameras have a systematic offset by design. This is a perfectly determined shift of the coding of the black level into the image file. It's often 1024 or 2048 ADUs in 14 bit cameras, or 256 for older 12 bit cameras. This offset provides for the possibility to record negative values of the noise and some black level drift.

1. Record a bias frame with no light entering the camera (block view finder, lens cap on, room darkened) and the shortest exposure time your camera allows (e.g. 1/4000th sec).
2. Measure the median value of all pixels; this is the system offset value.

Results measured with a Canon 1100D:

ISO	System Offset [ADU]
100	2048
200	2048
400	2048
800	2048

System Gain (or Conversion Factor)

System gain has units of electrons per ADU (e^-/ADU) and describes the number of electrons required to change the intensity of a pixel by 1 Analogue to Digital Unit, the basic unit of change in a DSLR or CCD image. System gain should be the same in each colour plane but different for each ISO setting.

1. Record two flat frames at the same exposure time. Set the exposure so that the average pixel value is about ~2/3 of the maximum ADU value, and no pixels are saturated.
2. Extract one of the green planes from each flat field frame and save them as FG1 and FG2.
3. Add FG1 and FG2 together and measure the mean pixel value in an area near the center approximately 100 x 100 pixels in size. Note this value as $(\overline{FG1} + \overline{FG2})$
4. Subtract FG2 from FG1 then add 5000 (to ensure the resulting image does not have any negative pixel values).
5. Measure the standard deviation in an area near the center approximately 100 x 100 pixels in size. Note this value as $\sigma_{(FG1-FG2)}$.
6. Record two bias frames.
7. Extract one of the green planes from each of the bias frames and save them as BG1 and BG2.
8. Add BG1 and BG2 together and measure the mean pixel value in an area near the center approximately 100 x 100 pixels in size. Note this value as $(\overline{BG1} + \overline{BG2})$
9. Subtract BG2 from BG1 then add 5000 (to ensure the resulting image does not have any negative pixel values).
10. Measure the standard deviation in an area near the center approximately 100 x 100 pixels in size. Note this value as $\sigma_{(BG1-BG2)}$.

$$\text{System Gain} = \frac{(\overline{FG1} + \overline{FG2}) - (\overline{BG1} + \overline{BG2})}{\sigma^2_{(FG1-FG2)} - \sigma^2_{(BG1-BG2)}} \quad \text{[electron/ADU]}$$

Results measured with a Canon 1100D:

ISO	Gain [electron/ADU]
100	3.29
200	1.62
400	0.83
800	0.40

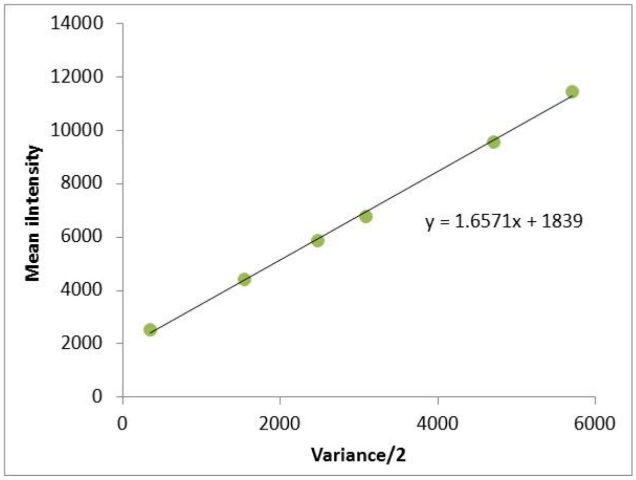
System Gain (Alternate Method)

This is a more involved but more robust method.

1. Record a series of flat field images, two at each of several exposure times. The longest exposure images should not exceed the maximum ADU value. The shortest exposure images should have mean ADU value at least a few hundred ADU above the system offset.
2. Extract one of the green planes from each of the flat field frames.
3. For one image in each pair measure the mean pixel value in an area near the center approximately 100 x 100 pixels in size. Note this value as $(\overline{FG1})$.
4. For each pair subtract FG2 from FG1 then add 5000 (to ensure the resulting image does not have any negative pixel values).
5. Measure the standard deviation in an area near the center approximately 100 x 100 pixels in size. Note this value as $\sigma_{(BG1\text{-}BG2)}$.
6. Calculate the variance by squaring $\sigma_{(BG1\text{-}BG2)}$ then divide by 2.
7. Plot the mean intensity as a function of variance/2
8. The slope of the line of best fit is the system gain at the ISO used. This should be very similar for each colour plane but different for each ISO setting.

An example with data from a Canon 1100D at ISO 200 is shown in the tables and plot below.

ISO 200 Pair	$(\overline{FG1})$	$\sigma_{(BG1\text{-}BG2)}$	$\frac{\sigma^2_{(BG1-BG2)}}{2}$
1	11437.569	106.809	5704.1
2	9576.640	96.978	4702.4
3	6786.631	78.522	3082.9
4	5861.261	70.304	2471.3
5	4426.033	55.426	1536.0
6	2514.221	26.337	346.8



System gain at each ISO setting from 100 to 800 is shown in the table below. These are very similar to the values obtained above.

ISO	Gain [electron/ADU]
100	3.41
200	1.66
400	0.84
800	0.40

Readout noise

The only source of noise in bias frames should be readout noise. Readout noise should be the same in each colour plane but will be different for each ISO setting.

1. Record two bias frames.
2. Extract one of the green planes from each of the bias frames and save them as BG1 and BG2.
3. Subtract BG2 from BG1 then add 5000 (to ensure the resulting image does not have any negative pixel values).
4. Measure the standard deviation of the resulting image. Note this value as $\sigma_{(BG1\text{-}BG2)}$.

$$\text{Readout noise} = \frac{\sigma_{(BG1-BG2)}}{\sqrt{2}} \text{ x gain [electrons r.m.s.]}$$

Results measured with a Canon 1100D:

ISO	Read Noise [electron]
100	23.7
200	12.5
400	7.0
800	3.1

Full Well Capacity

Full well capacity should be the same in each colour plane but will be different for each ISO setting. Actually the ISO 100 value is the true full well capacity, at higher ISO settings the measured value is the maximum number of electrons required to reach the maximum ADU value.

Full well capacity = (system gain) x (maximum ADU value) [electrons]

Results measured with a Canon 1100D:

ISO	Full Well Capacity [electron]
100	46376
200	25603
400	12787
800	6088

Dark Current

Measurements made so far are analogous to those used to characterize a CCD camera. Dark current, however, cannot be measured directly from DSLR images in the same way as for CCD images. For a CCD we would let the temperature stabilize then record a long exposure dark frame (D) of t seconds. From this we subtract a bias frame (B) then measure the average pixel value in a region near the center of the frame ($\overline{D-B}$). This value is multiplied by the gain to determine the average dark current:

$$\text{Dark current} = \frac{gain \times (\overline{D-B})}{t} \text{ [electrons/pixel/second]}$$

This number should always be positive and increase with CCD temperature. If temperature is stable, the total amount of electrons injected into each pixel by dark current will increase linearly with time.

RAW images recorded with Canon DSLR cameras, and possibly others, DO NOT exhibit the same dark current behavior. Using an example from a Canon 1100D at ISO 400 (Note: some photometry software adds an offset to master bias frames, MaxIm DL calls it a “pedestal”, so be careful to subtract this value when using a master bias in the calculation):

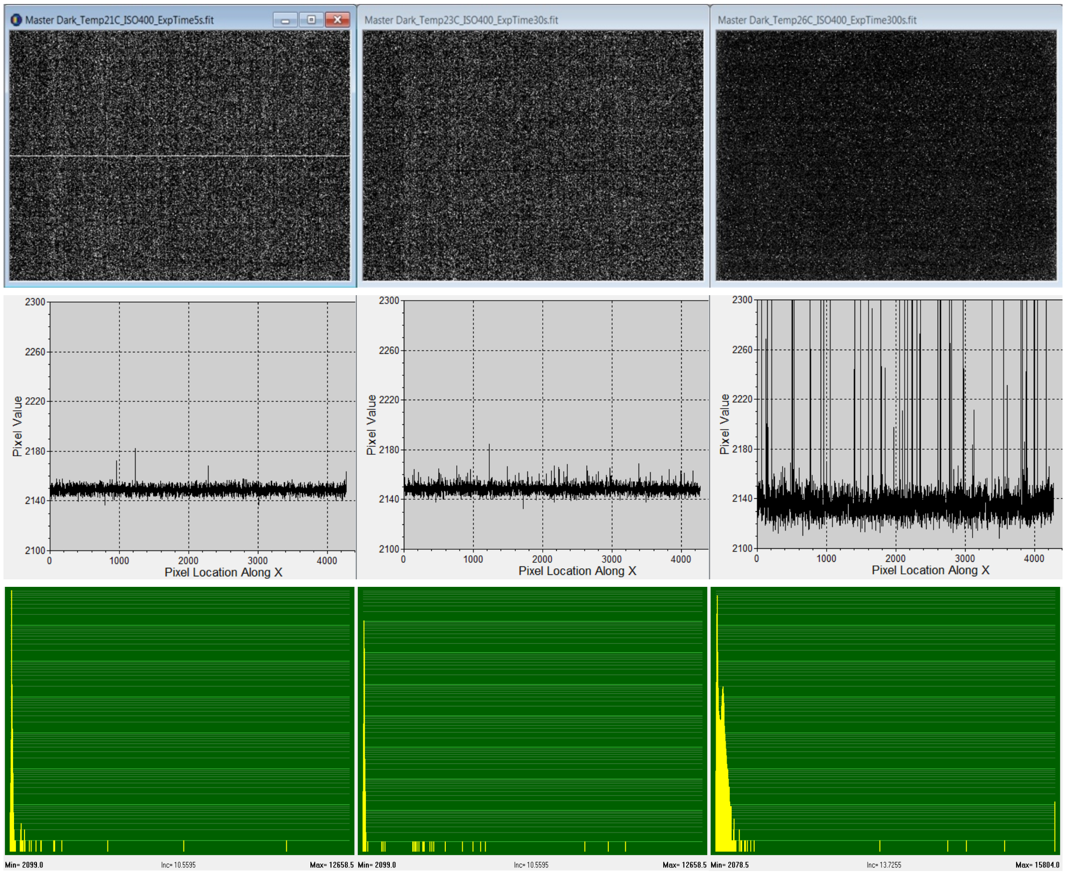
$$\text{Dark current} = \frac{(0.84 \times (2045.90 - (2148.117 - 100))}{60} = -0.042 \text{ [electrons/pixel/second]}$$

This is physically unrealistic. Craig Stark explored this behavior with an older Canon 450D (Rebel XSi). The variance in dark images increases as the exposure time increases, as expected. However, the mean pixel value does not increase linearly; instead it remained within a few ADU of the offset value. He concludes that even in a RAW image some processing has been done to reduce the effect of dark current. So how does this affect photometry with a DSLR camera? My current thoughts are:

1. Use dark frames of the same exposure and at the same temperature as the science frames
2. It may be better to use a dummy dark frame to avoid adding noise to the calibrated image
3. If a dummy dark frame is used it may be useful to apply a bad pixel map to reduce the effect of any hot or dead pixels

However, these conclusions need to be confirmed by further experimentation.

Canon 1100D ISO 400 master dark images, line profiles and histograms are shown below.



Top Left: 5sec 21^{o}C, **Top middle:** 30sec 23^{o}C, **Top right:** 300sec 26^{o}C.
Center: line profiles across the same row of pixels (shown on top left image) from the three master darks.
Bottom: Histograms from the three master darks. Pixel ADU value (intensity) is plotted on the horizontal axis and the number of pixels with that ADU value is shown on the vertical axis (logarithmic scale).

As seen in the line profiles, median pixel intensity is 2148 ADU for the 5sec and 30sec images, which represents the 2048 ADU systematic offset Canon imposes on RAW images plus an additional 100 ADU imposed by MaxIm DL. However the median pixel intensity of the 300sec image is only 2136 ADU. It appears Canon adjusts the systematic offset for longer exposures for some reason, even in RAW images. This will not adversely affect photometry from long exposure images, but dark correction during image calibration will be necessary to minimize the effect of additional dark current signal.

The vast majority of pixels in the 5sec and 30sec master dark images lie within the left-most peak of the histograms centered at 2148 ADU. These represent the distribution of random dark current noise.

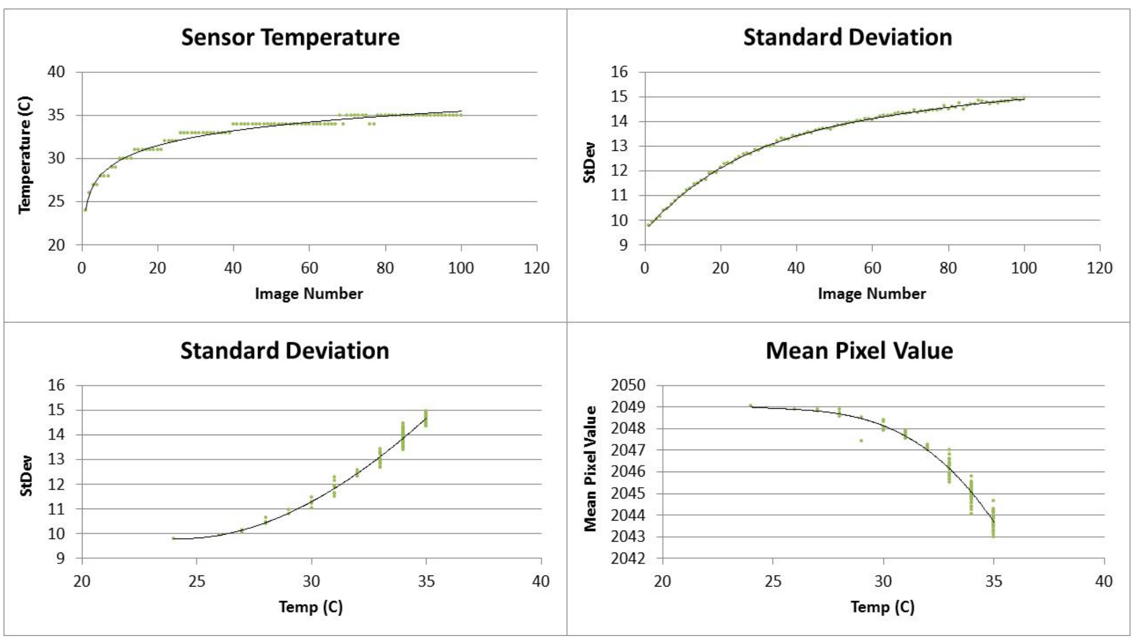
The 300sec frame also shows this peak, as well as a secondary peak ~200 ADU to its right which represents a slightly different population of pixels that have more dark current. The widths of these peaks will increase as the sensor's temperature rises. A small number of classical hot pixels (showing much higher dark response than the majority of pixels in the sensor) are to the right of the histograms.

Temperature stability

Standard DSLR cameras are not actively cooled like astronomical CCD cameras. The sensor temperature depends on ambient temperature and internally generated heat created by the camera's electronics. We can investigate the effect of this by recording a long series of dark frames. Sensor temperature is recorded in the EXIF information of the RAW image, but not all programs show this information. IrfanView is a freeware image viewer program (available from http://www.irfanview.com/) that shows all EXIF data.

1. Estimate your maximum expected science frame exposure, e.g. 8 sec for tripod mounted cameras or 60 seconds for tracking mounts.
2. Record 100 dark frames each with the exposure determined in step 1
3. Determine the mean pixel value, standard deviation and temperature of each dark frame
4. Plot sensor temperature as a function of image number
5. Plot standard deviation as a function of image number
6. Plot standard deviation as a function of sensor temperature
7. Plot mean pixel value as a function of sensor temperature
8. Plot mean pixel value as a function of image number

An example with 60 second dark frames from a Canon 1100D at ISO 400 is shown in the plots below:



The upper left plot shows sensor temperature rises rapidly at the beginning of the imaging sequence and approaches equilibrium after about 2 hours (100 images x (60 + 10) exposure plus download time). Higher temperature should result in higher dark current and larger standard deviation and this is borne out by the upper right and lower left plots. Higher dark current should also lead to increased mean pixel value as temperature increases, however the lower right plot clearly shows the opposite. As discussed in the Dark Current section above, Craig Stark attributes this anomaly to some internal processing by the camera to compensate for temperature changes, and this processing is even applied to RAW images.

Appendix B: Testing Flats for Uniform Illumination

No matter which flat field method is employed it is important to check how even the illumination is. A one percent variation in across the image can result in a measurement error of about 0.01 magnitudes.

An easy way to check illumination uniformity is to make master flat frames from two sets of images, the second set recorded after rotating the camera (or light box) by 90 degrees. Divide one master image by the other and measure pixel intensity (ADU values) across the diagonals of the resulting image (Figure B.1). There will be random fluctuations due to counting statistics but ideally there should be no systematic increase or decrease in intensity.

An example is shown in Figure B.2 where the uneven illumination was achieved by removing one of eight incandescent globes from the light box. The right graph shows 1% systematic variation along diagonal 1 (blue) and 0.2% along diagonal 2 (red). When all eight globes were used (left graph) systematic variation along diagonal 1 (blue) was less than 0.1% but along diagonal 2 (red) it increased slightly to 0.3%.

You should aim for less than 0.5% systematic variation in illumination across your master flat frames.

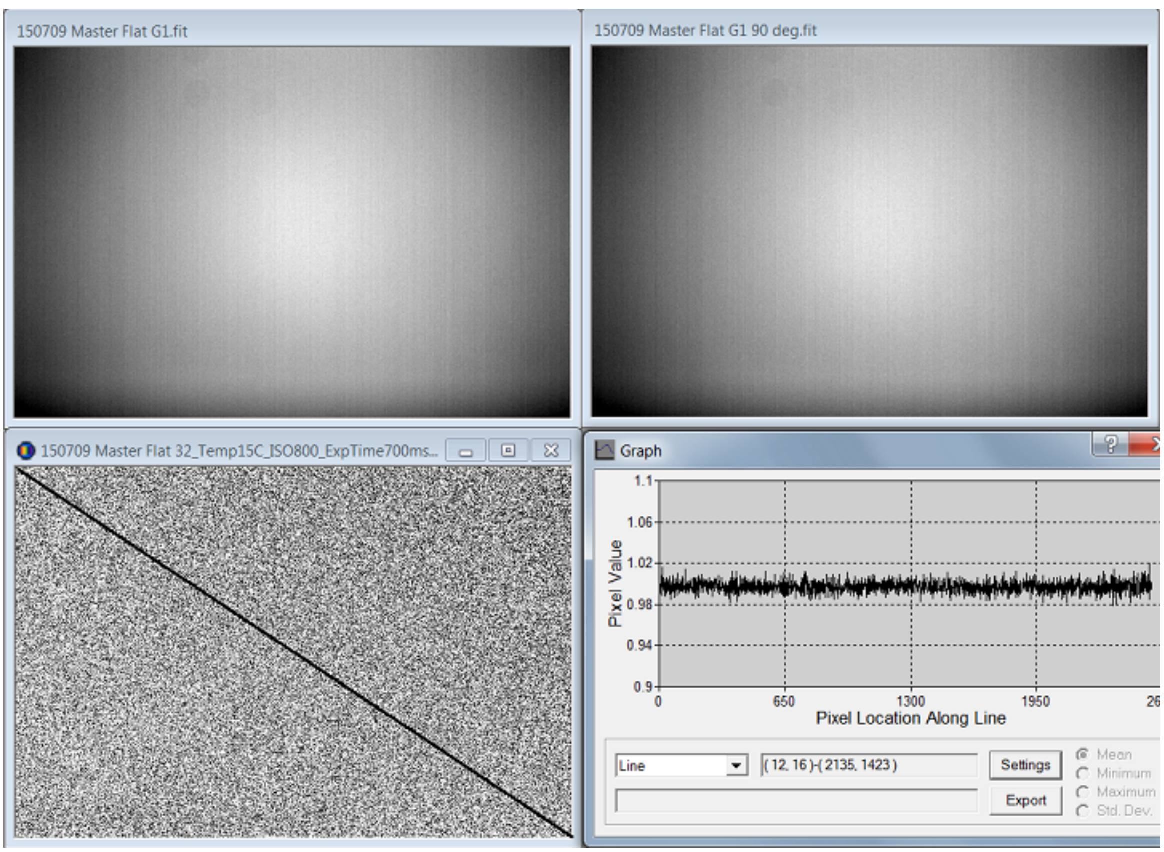


Figure B1. Green channel master flats recorded with camera rotated 0^{o} (top left panel) and 90^{o} (top right panel) with respect to the light box. Lower left panel shows the image resulting from dividing the first master flat by the second. Lower right panel shows intensity profile along the diagonal. (Mark Blackford)

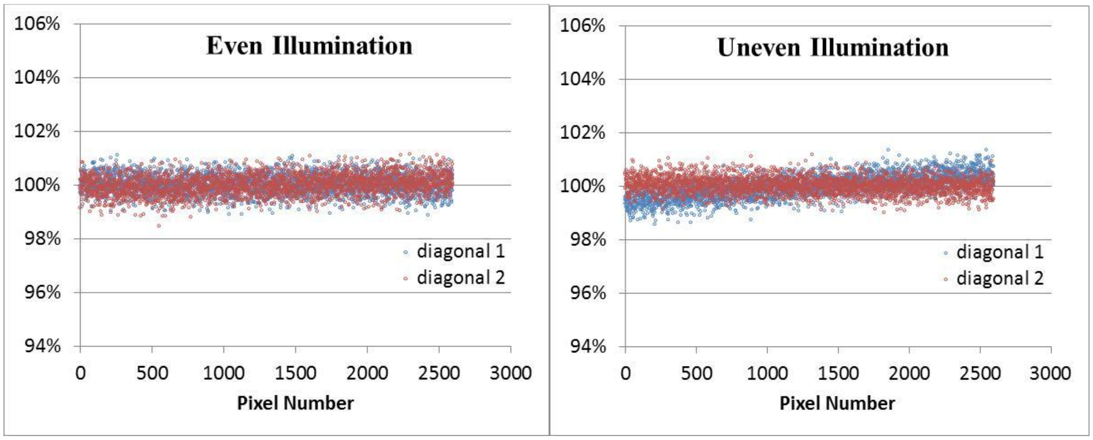


Figure B2. Line profiles obtained by dividing one master flat by a second master flat as described in the text. Left: result from an evenly illuminated light box. Right: result from an unevenly illuminated light box. (Mark Blackford)

Appendix C: Illustration of Primary, Secondary and Differential Atmospheric Extinction

(Adapted from an article by Mark Blackford in Variable Stars South Newsletter, October 2015)

With a few precautions CCD photometrists imaging through a medium to long focal length telescope can safely ignore the effects of atmospheric extinction. This is not always true for DSLR photometrists using a standard or telephoto lens where the relatively wide field of view can lead to significant differences in airmass across the image. This article will hopefully explain several aspects of extinction and quantify their effects on photometry for typical CCD/telescope and DSLR/lens scenarios.

Probably the most obvious effect of atmospheric extinction is dimming and reddening of the sun as it sets, but starlight is similarly affected. There are a number of factors involved including Rayleigh and aerosol scattering and molecular absorption, principally by ozone. For a normal atmosphere Rayleigh scattering from gas molecules dominates.

The amount of dimming is proportional to path length through the atmosphere (primary extinction). Shorter, i.e. bluer, wavelengths are dimmed more than longer wavelengths. Furthermore, the color index of the star also has a small additional effect on the amount of dimming (secondary extinction). In a wide field of view image stars nearer the horizon can have significantly greater airmass than stars further from the horizon, thus leading to different amounts of dimming (differential extinction). Below we illustrate each of these concepts using DSLR time series observations of non-variable stars.

Primary extinction

At the zenith (zenith angle, $\zeta = 0^{o}$) the path length of starlight through earth's atmosphere is defined as airmass $X = 1$. Airmass increases as ζ becomes larger, at first very slowly but more and more rapidly as a star approaches the horizon. Figure C1 shows the raw instrumental magnitude in each of the DSLR color channels for a non-variable star plotted as a function of time (top left panel) and as a function of airmass (top right panel). When seeing is steady and transparency remains constant throughout the night (a photometric night) measured instrumental magnitude will be a linear function of airmass, as shown in this plot.

To a first approximation the slope of the line is the primary extinction coefficient and is greatest at shorter (i.e. bluer) wavelengths. This is more easily seen in the bottom left panel of Figure C1 where instrumental magnitudes have been normalized to magnitude 0 at $X = 0$, i.e. above the atmosphere. We can see that even at the zenith the star has been dimmed by 0.181, 0.220 and 0.296 magnitude in the red, green and blue DSLR channels, respectively. Each filter has its own primary extinction coefficient which is a function of the effective wavelength of the filter. This results in the star's color indices becoming more positive, i.e. redder, as airmass increases (bottom right panel of Figure C1).

Primary extinction coefficients (denoted by k') can vary from night to night, even throughout a single night, as atmospheric conditions change. The principal cause is variation of aerosol content of the atmosphere, e.g. dust, smoke, water droplets, etc.

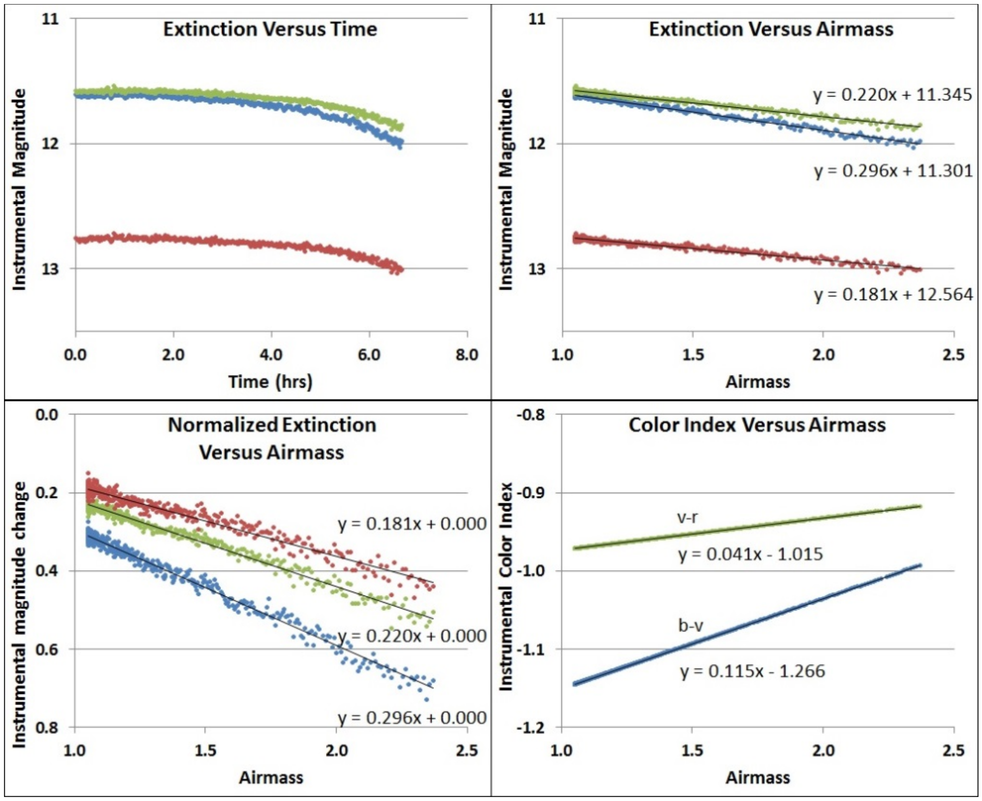


Figure C1. Top Left: Change in instrumental magnitude with time as a star moves from high in the sky to low elevation. Colors represent red, green and blue DSLR Channels. **Top Right:** Same data plotted as a function of airmass. **Bottom Left:** Same data as above, but normalized to magnitude 0 at airmass = 0, i.e. above the atmosphere. **Bottom Right:** Change in instrumental (b-v) and (v-r) color indices with increasing airmass. (Mark Blackford)

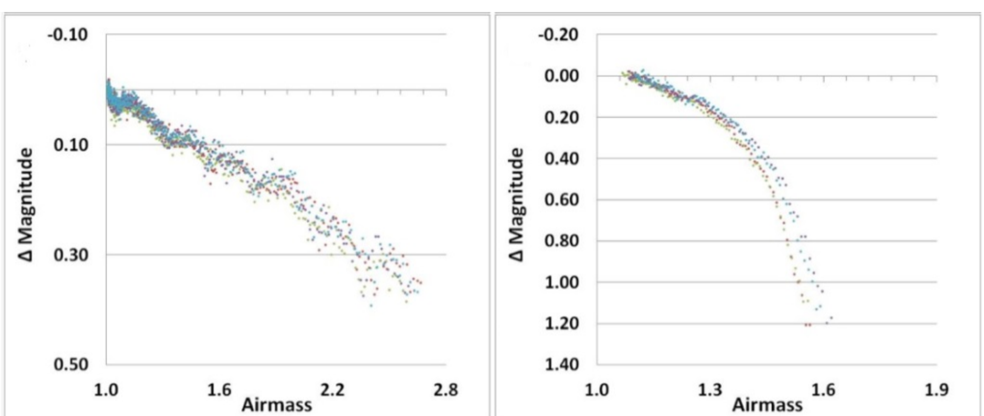


Figure C2. Normalized raw instrumental magnitude change plotted as a function of airmass for two nights with variable transparency. **Left:** Waves of thin cirrus cloud passing across the field throughout the session. **Right:** Steadily increasing extinction due to buildup of smoke haze. (Mark Blackford)

Figure C2 shows two examples of extinction on nights of variable transparency. The analyst needs to decide if small fluctuations are acceptable before applying extinction corrections. Differential photometry using uncorrected data from non-photometric nights may yield less accurate but still useful measurements.

Secondary extinction

Secondary extinction is a function of both airmass and color index of the star and is a consequence of the finite width of the spectral transmission curves of the broadband RGB filters in a DSLR, and CCD photometric filters.

Figure C3 shows the transmission curve of a DSLR green filter and generalized energy distribution curves for a blue and a red star. The blue star has relatively more intensity in the short wavelength side of the filter window compared to the red star. We know from the discussion above that shorter wavelengths suffer more dimming, so the blue star will dim slightly more than the red star. Different filters have their own specific secondary extinction coefficients.

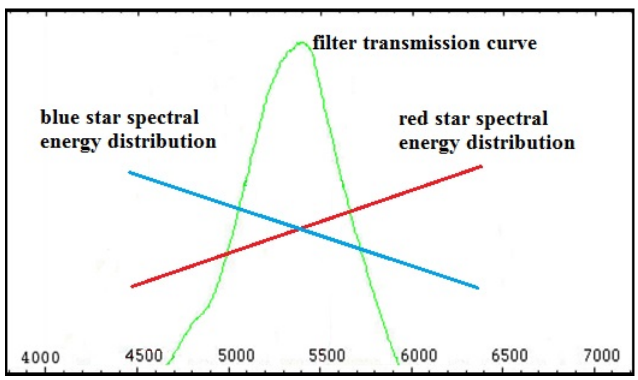


Figure C3. Schematic showing broadband filter transmission curve and energy distribution of a red and a blue star. (Mark Blackford)

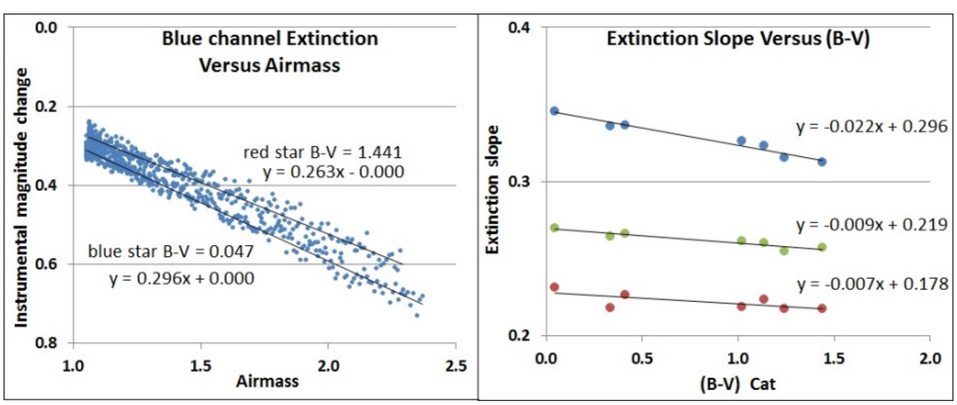


Figure C4. Left: Normalized blue channel extinction for a red and a blue star in the same time series of images showing different extinction rates (i.e. slopes). **Right:** Plot of extinction rates as a function of catalog (B-V) color index for each color channel. (Mark Blackford)

The left panel of Figure C4 plots normalized blue channel instrumental magnitudes for a red (B-V) = 1.441 and a blue (B-V) = 0.047 star plotted as a function of each stars individual airmass, measured from the same images. The difference in slope is the result of secondary extinction.

The right panel of Figure C4 plots the slope of instrumental magnitude versus airmass curves (extinction slope) as a function of (B-V) color index of 7 non-variable stars in the time series images. All three color channels show a small but definite dependence on color index, with the blue channel showing the largest effect. Secondary extinction coefficients are given by the slope of the lines and primary extinction coefficients by the y-intercept value.

Secondary extinction coefficients (denoted by k") should be relatively constant unless some aspect of the imaging system changes (filters, lenses, sensor, etc.).

Differential Airmass

If all stars of interest in an image had the same airmass and color index they would be dimmed by exactly the same amount by the atmosphere. Primary and secondary extinction would thus not be a problem. Narrow field of view photometry can approximate this situation if comparison stars with (B-V) values very close to that of the variable are chosen.

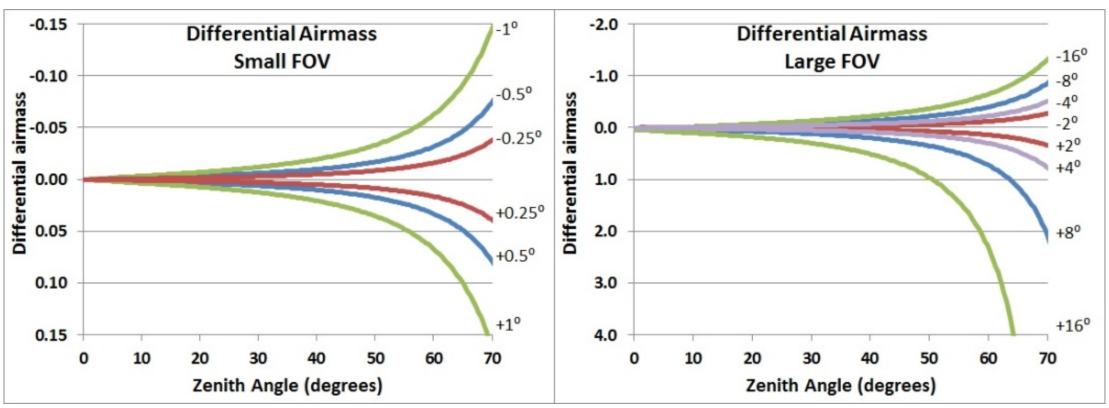


Figure C5. Left: Differential airmass as a function of star one zenith angle for typical telescope fields of view. **Right:** Same as above but for fields of view typical of camera lenses used for DSLR photometry. (Mark Blackford)

The left panel of Figure C5 shows the difference in airmass of two stars with separations indicated on the right hand side, plotted as a function of the zenith angle of the first star. Curves with positive labels indicate the second star is located west of the first star. Negative labels indicate the second star is east of the first star.

Differential airmass, ΔX, increases as the stars move from the zenith toward the horizon and amounts to only ~0.07 airmass for separation of 1° at ζ=60°. ΔX is even less for smaller separations typical of fields of view through medium to long focal length telescopes.

The situation is not so good for wide field of view images typical of DSLR photometry with standard or telephoto camera lenses, as shown in the right panel of Figure C5. For separation of $+16^{o}$ at $\zeta=60^{o}$ we have ΔX of ~2.5 airmass.

Differential Extinction - Bringing It All Together

So what does this all mean for DSLR photometry, how much effect does differential extinction have on instrumental magnitudes measured from wide field images?

1. Wide FOV situation

Let's take a typical case of a 100mm f.l. lens and APS-C sized sensor (14.9 x 22.3mm). The FOV will be 8.5^{o} by 12.7^{o}. If the target variable is at zenith angle 60^{0} and centered in the image then a comparison star could be up to 7^{0} away in one corner of the frame. From Figure C5 we can estimate maximum ΔX to be ~0.6 airmass for this scenario.

From Figure C4 we have the following primary extinction coefficients in each color channel:

$$K'_b = 0.296 \text{ mag/airmass}$$
$$K'_v = 0.219 \text{ mag/airmass}$$
$$K'_r = 0.178 \text{ mag/airmass}$$

Therefore differential primary extinction will be as much as:

$$\Delta'_b = 0.296 \times 0.6 = 0.178 \text{ mag}$$
$$\Delta'_v = 0.219 \times 0.6 = 0.131 \text{ mag}$$
$$\Delta'_r = 0.178 \times 0.6 = 0.107 \text{ mag}$$

Differential secondary extinction will be zero if both stars are the same color. However, if one of the stars has (B-V) = 1.100 and the other (B-V) = 0.600 then Δ(B-V) = 0.500.

From Figure C4 we have the following secondary extinction coefficients:

$$K''_b = 0.022 \text{ mag/airmass/}\Delta(B-V)$$
$$K''_v = 0.009 \text{ mag/airmass/}\Delta(B-V)$$
$$K''_r = 0.007 \text{ mag/airmass/}\Delta(B-V)$$

Thus differential secondary extinction will be as much as:

$$\Delta''_b = 0.022 \times 0.6 \times 0.500 = 0.007 \text{ mag}$$
$$\Delta''_v = 0.009 \times 0.6 \times 0.500 = 0.003 \text{ mag}$$
$$\Delta''_r = 0.007 \times 0.6 \times 0.500 = 0.002 \text{ mag}$$

Second order extinction has a much smaller influence than primary extinction.

Total differential extinction for this scenario on this particular night would be as much as 0.185, 0.134 and 0.109 magnitudes for the blue, green and red instrumental magnitudes, respectively. Clearly we need to correct for primary differential extinction at least.

2. Narrow FOV situation

Now let's consider a scenario where the variable and comparison star separation is 0.25^{o}, typical of telescopic CCD photometry. All other assumptions and extinction coefficients remain the same. From Figure C5 we estimate ΔX to be ~0.02.

Therefore differential primary extinction will be as much as:

$$\Delta'_b = 0.296 \times 0.02 = 0.006 \text{ mag}$$
$$\Delta'_v = 0.219 \times 0.02 = 0.004 \text{ mag}$$
$$\Delta'_r = 0.178 \times 0.02 = 0.004 \text{ mag}$$

Now let's consider differential secondary extinction:

$$\Delta''b = 0.022 \times 0.02 \times 0.500 = 0.00022 \text{ mag}$$
$$\Delta''v = 0.009 \times 0.02 \times 0.500 = 0.00009 \text{ mag}$$
$$\Delta''r = 0.007 \times 0.02 \times 0.500 = 0.00007 \text{ mag}$$

Differential secondary extinction is negligible and primary extinction correction is only necessary for photometry programs requiring the highest accuracy.

Summary

Differential extinction is not normally a problem for narrow field of view (<0.5^{o}) images if comparison stars have approximately the same color as the variable and they are not too close to the horizon. On the other hand, for wide field of view images typical of DSLR photometry differential extinction can be very significant, and must be corrected.

Appendix D: Star Images Inside and Outside of Focus

The figure below shows under-focus (inside focus) and over-focus (outside focus) star images recorded with a Canon 200mm F2.8L lens. The individual color channels have been separated, red at left, green 1 and green 2, then blue at right.

Red | Green 1 | Green 2 | Blue

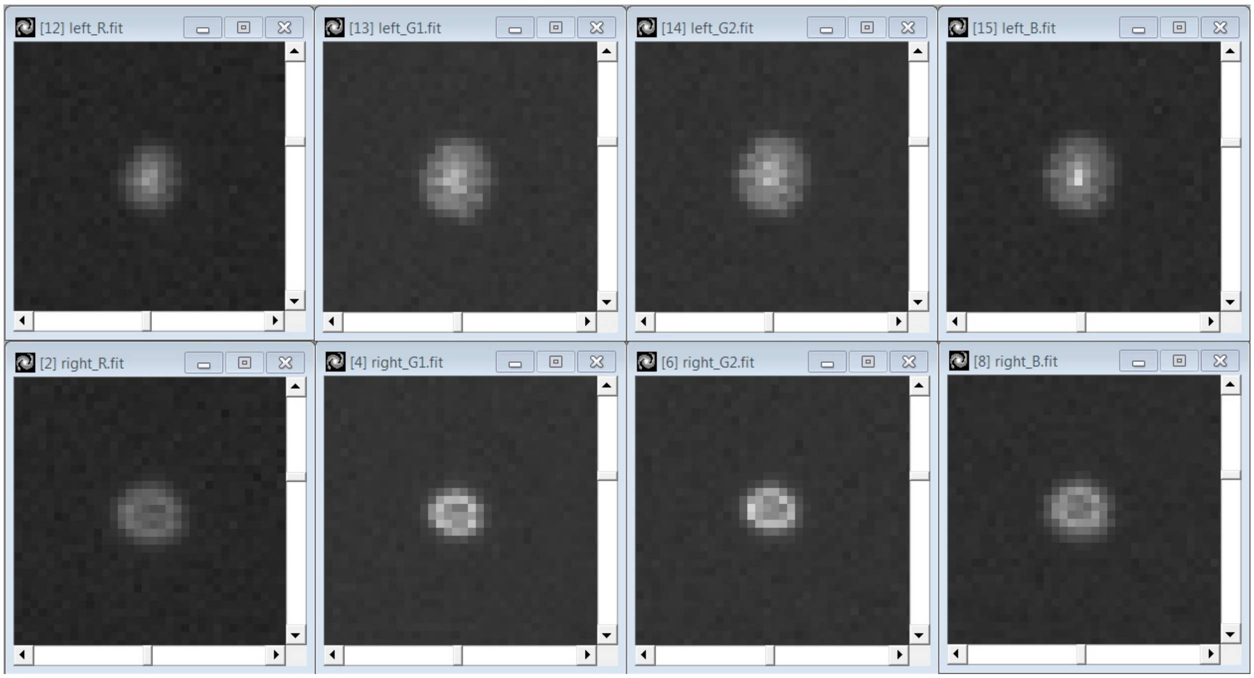


Figure D1: Shape of under focus (top row) and over focus (bottom row) star images recorded with a Canon 200mm F2.8L lens. (Mark Blackford)

Under-focus results in a bright central peak and broad skirt or halo, whereas over-focus results in a bright donut ring. Each color has slightly different size and sharpness.

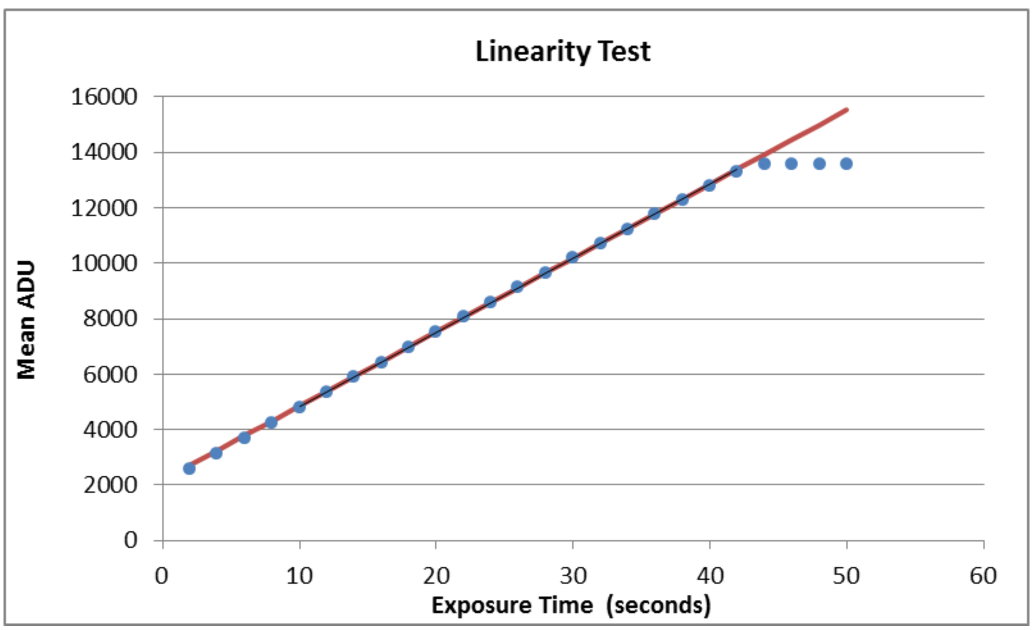
For photometry with this lens I find it is better to under-focus the star images and use an exposure length short enough to avoid saturating the central peak.

Other lens designs will have different under/over-focus behavior. You should test each lens you intend using to determine the appropriate focus setting for DSLR photometry.

Appendix E: Linearity Testing

The procedure outline here is a modification of one outlined in "InfoBox 3.1 – How to determine the linearity of your camera" in the AAVSO CCD Photometry Guide V1.1 (available for download from https://www.aavso.org/ccd-photometry-guide).

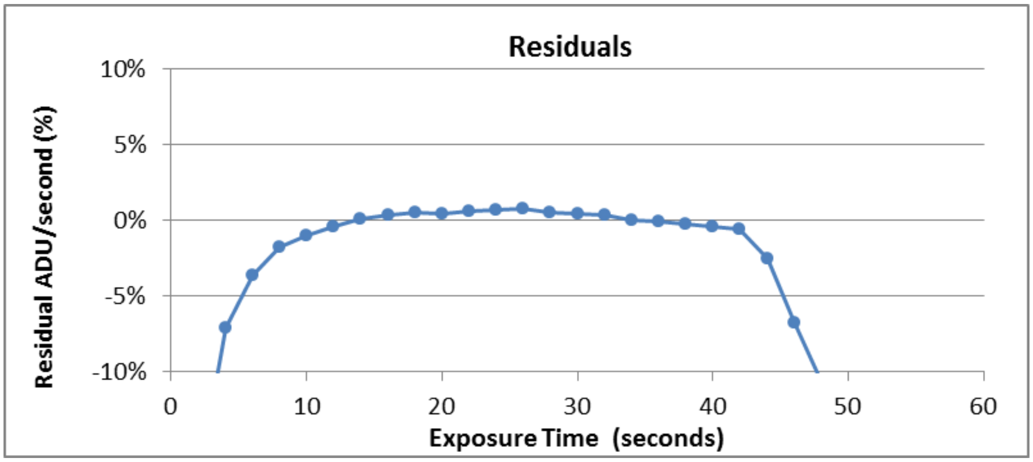
1. Set up a light source by illuminating a white screen. It does not need to be perfectly uniform, just stable. A light box or electro-luminescent panel with adjustable brightness would be ideal.
2. Set the camera to RAW and ISO 100.
3. Securely mount the camera so it points to exactly the same part of the screen throughout the exercise.
4. Adjust screen brightness and/or lens f-number until the green channel just starts to saturate in, say, a 40 second exposure.
5. Take a series of images where the exposure time increases from 2 seconds in 2 second increments (i.e. 2, 4, 6, 8, ..., etc.) until a few steps beyond saturation.
6. Repeat the sequence two more times so a total of three images are recorded at each exposure.
7. Measure the mean pixel ADU value in each image from exactly the same central region (say 200 x 200 pixels).
8. If your light source is stable the three measurements at each exposure time will be very similar. If not then your linearity test will not be valid.
5. Average the three measurements at each exposure and plot these as a function of exposure time. From this plot you will be able to determine at what count your camera saturates and if there is any non–linear behavior along the way. Saturation level for this DSLR at ISO 100 is about 13,500 ADU.



6. Now we calculate the data for another useful plot which shows more clearly any deviations from the ideal linear response. The y-axis intercept is 1896.7 in the example plot above. Subtract this value from the average ADU value at each exposure then divide by the exposure time in seconds. This is the count rate in ADU/second and should be constant if the light source is stable and the detector response is linear.
7. Next we select one point within the linear part of the plot above as a reference count rate, say 30 sec where count rate was 276.0 ADU/second. Subtract the reference count rate from the measured count

rate at each exposure time; this is the count rate residual. Now divide this residual by the reference count rate and format as percentage.

8. Plot the percentage count rate residual as a function of exposure time. The sensor linear region is where the residual is very close to 0% (between 10 and about 42 seconds in the plot below).



The negative deviation after 42 seconds is due to saturation. The negative deviation at exposure times less than 10 seconds is possibly due to the true shutter timing being slightly shorter than the set duration.
For this DSLR and illumination levels it would be safe to use exposure times between 10 and 42 seconds which correspond to 4,800 and 13,300 ADU, respectively.