The AAVSO
Guide to CCD Photometry

Preface

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The *AAVSO Guide to CCD Photometry* has existed in a number of different forms since AAVSO observers first began using CCD cameras in the 1990s. Since that time there has been a dramatic increase in the amount of CCD-acquired data, and these data account for more than 80 percent of all data submitted to the AAVSO per year as of the 2011 fiscal year. The decreasing cost and increasing usability of consumer-grade CCD systems are leading to this increase, and we expect the amount of CCD data to increase further with time.

The ease with which "data" can be obtained and extracted from a CCD system does not necessarily indicate the ease with which science can be done with that data. This version of the *AAVSO Guide to CCD Photometry* represents a complete rewriting of the CCD manual with the ultimate goal not being data but science. While this will still cover elementary use of CCDs and reduction of data, the material will be presented with the aim of helping you generate data that will be as scientifically useful as possible. The AAVSO is renewing its emphasis on scientific value of data rather than raw quantity of data, and CCD observers will need to adapt to this shift as much as visual or other observers do. Ultimately, the scientific utility of your data is of far higher importance than quantity, depth, or Annual Totals.

This manual is intended to serve beginner and intermediate CCD observers who want to use their equipment to obtain photometry of variable stars that is of the highest quality possible. It is possible to take photometric data with a small telescope and CCD camera that equal the quality of data taken with professional observatories, and there is in principle no difference between data taken by an amateur observer and data taken by a professional. We aim to reduce those differences even further by helping you take the best data possible. We'll tell you how to get data out the back end of your system, but we'll also explain why and how to do this the right way.

The Manual will always be a work in progress, and we depend on the community to help us develop and document best practices in CCD observing. You may find things in this document that are out of date or unclear. Please give us feedback as to what works for you and what doesn't.

Please send any feedback or suggestions to aavso@aavso.org.

Clear skies,

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Chapter I: So, you want to be a photometrist?

If you own or have access to a telescope with a CCD camera, you can use them to obtain scientifically useful variable star data. The AAVSO supports several different observing modes, with CCD observing and visual observing (with the aided or unaided eye) being the two most popular. Both kinds of observing have strengths and weaknesses, and each has its place in variable star astronomy. This manual is intended to help a novice observer become a better CCD photometrist. This is critical for our mission, because the quality of data we receive from the observers impacts the quality of science that researchers will do with it. A CCD camera is capable of obtaining very good variable star data, and like most scientific instruments, it is also capable of obtaining very **bad** data. We want to help you aim for and produce **good data**.

Our CCD observer community is drawn from a number of different populations. Some former (and current) visual observers made the leap to CCD observing. Some people who used CCDs for astro-imaging wanted to do more than create "pretty pictures". Some people may use remote or shared facilities to obtain astronomical observations and want to maximize their value. Some people may have come across an article on variable star observing and thought *hey, that sounds cool!* They may have taken the leap directly into CCD observing.

For the sake of simplicity, this Guide will assume you have a passing knowledge of astronomy – you should know for example how stars move across the sky during a night and what astronomical coordinates are (like Right Ascension and Declination), and what the magnitude of a star means. We will also assume that you have already learned enough about how to set up and operate your telescope, how to connect your CCD camera to a computer, and how to use the software that came with the camera and telescope to operate them. At this stage, you should at least be able to turn on your telescope, point it to a field in the sky or have the telescope point itself, and take an image with the camera. If you've taken a picture of a star field, cluster, nebula, or galaxy with your telescope that you're reasonably satisfied with, you're all set with what you need to know. If you're just starting out with a new instrument, learn the basics of how to operate it and have some fun first. Get a good feel for how the telescope works, and – especially – how to use it to take images that track properly.

Along with this you should be comfortable with the software that came with your telescope, or at least have a copy of the software manuals. Most commercial CCD software will have everything you need to at least process your images to scientific usability. Later in the manual we'll talk about how to extract data from those images, and that can be done with most commercial CCD software packages, or with the AAVSO's own *VPhot* software. More on that later.

In general, you do not need to be a mathematician, an engineer, or an astrophysicist to obtain good data. Some knowledge of mathematics including algebra and trigonometry *will* be assumed – many of the calculations required for CCD photometry can be automated with spreadsheet software, but a basic understanding of math is required so

that you understand what goes into that spreadsheet and what comes out. There will be equations here, and you *will* need to know some of them.

Finally, I'll assume that you have an interest in both variable stars and taking good quality scientific data. Familiarity with variable stars before you start doing CCD observing would be great, at least at the level of knowing what a variable star is in comparison to a non-variable star, but you can learn as you go along, and we'll cover the basics of what "variable star photometry" is and why we do it in the next chapter. Many of our best CCD observers got their start as visual observers, so don't be afraid to pick up this guide's sister publication, the *AAVSO Manual for Visual Observing of Variable Stars*.

Note that "taking good data" may involve making some mistakes and (crucially) learning from them. Taking **very** good data is complicated, and it requires some effort. It's easy to get bad data from a CCD; it's fairly easy (or at least straightforward) to get good data. It's harder to get *great* data whether you're an amateur or a professional, but we're confident that you *can* do it if the circumstances allow; otherwise we wouldn't be writing this. It's ok to make mistakes, but if you learn from them, you'll be on your way to collecting good data.

Photometry

When we "observe" a variable star, we mean that we're measuring the amount of light that the star appears to give off at a given moment. We repeat that measurement over and over, making the measurement as often as we need to completely track all of the variations. If our measurements are consistent and accurate, we can then make physical models that try to explain why the light changed the way we measured it. Your task as a variable star observer is to make good measurements so that researchers can make good models. The better your data, the better their models. The process of measuring the light from a star is called **photometry**, and a person who does this is a *photometrist*. We're hoping you'll become one, and a good one at that, once you work through this *Guide*.

There are a number of details about how you make that measurement that can improve researchers' chances of making realistic models, and not all of those details will be relevant to you. You can take excellent data for some stars just by pointing your telescope at the target, taking one or more images, and processing the images with simple methods. That's *not* how the majority of stars are observed effectively, but it is possible sometimes. Most of the time you'll be using your camera to take one or more images of a star on a single night, and then revisiting that star over and over again over time. You might even spend many hours a night on just one star, taking images over and over again, as quickly as you can. You may use one or more *filters* to measure light with well-defined wavelengths. You will even spend time measuring specially selected *non-variable stars* to better *calibrate* your observations. All of these and more are involved in turning your observations into useful data.

Photometry is the measurement of starlight intensity by any means. While this guide will teach you how to do photometry with a CCD, a CCD isn't the only instrument capable of

doing this, and your ultimate goal isn't to be a "good CCD observer", it's to be a good *photometrist who is using a CCD camera*. There's a difference. Just about anybody can saw a piece of wood in half, but that doesn't make you a carpenter. A CCD camera will produce a bunch of numbers that get turned into another set of numbers inside your computer, and perhaps another set of numbers in your analysis software, spreadsheet, and so on. That doesn't make it photometry. Don't focus on the technology, focus on the purpose. Your goal isn't to produce *numbers*; it's to produce *knowledge* that may lead to *understanding*. We'll show you why and how, starting now.

Chapter II: Variable Stars: The What, Why, and How of Measuring Them

What are you measuring with photometry?

Variable stars are stars whose light varies measurably due to physical processes inside, on, or around the star. There are hundreds of classes of variable star, and each represents a different way that a star can vary. Stars may change in size, shape or temperature over time (pulsators), they may undergo rapid changes in light due to physical processes around the star (accretors and eruptives), or they may be eclipsed by stars or planets in orbit around them (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 to the Earth's atmosphere. Variable stars vary all on their own, independent of anything happening here on Earth.

Different kinds of stars vary on different timescales. Some stars may take weeks, months, or years to undergo changes that we can detect. Others take days, hours, minutes, seconds or much 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.

Variable stars also have a range of apparent brightnesses (how bright they appear to us) as well as a range of intrinsic luminosities (how much light they actually give off). A star may be intrinsically luminous, but if it is thousands of light years away, it will appear to be faint. Variables also have a range of amplitudes, that is how much their light changes over time. Some variable stars can vary by ten magnitudes or more, which is a factor of ten thousand in flux, a huge change! Some variable stars vary by a millimagnitude, 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 the size of your telescope.

Why are you doing photometry?

Variable stars are interesting for a number of different reasons, but ultimately we study them because they're like physics laboratories. We can't go and touch a star or change it in some way to study it, but if we can understand how the light from variable stars changes, we can learn more about how the universe works. The same fundamental physical processes that operate here on Earth – gravity, fluid mechanics, light and heat, chemistry, and nuclear physics – operate exactly the same way all over the universe. By watching *how* stars change over time, we can learn *why they change*. What you're doing with your observations is providing the raw material that powers scientific inquiry. Scientists can speculate endlessly about why things appear and behave the way they do, but ultimately those hypotheses have to be tested in order to productively advance our scientific understanding. That's where observing comes in, and it's where you have the

greatest chance of making a valuable contribution to variable star science. If you give researchers valid and accurate data, they can make accurate models for how the universe works, and our understanding increases and improves. Conversely, if they have bad data, those scientists may make bad models, which can mislead us and hinder progress in the field.
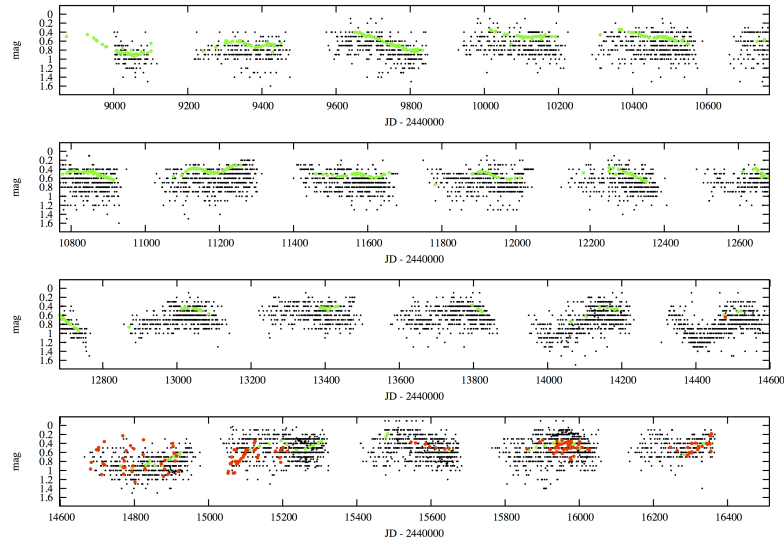
Lightcurve of Betelgeuse (alpha Ori) from the AAVSO International Database. Black points, visual observations; green points PEP V observations; red points, CCD/DSLR V points. Note that in general the CCD scatter is far higher than that of PEP, comparable almost to visual data. Alpha Ori is an extremely difficult target for CCD photometry because it is so bright.

As for the broader question of why variable stars are interesting, variable stars often tell us more than what a specific star is doing at a given time. They can also tell us something about the circumstances under which stars form, how they spend their lives, and how they eventually evolve and die. Learning more about what stars are and why they behave the way they do gives us a more complete picture of the universe that we live in both in the present and over cosmic timescales, from planets and stars to galaxies and beyond. That's ultimately what all of variable star astronomy is about.

In this document we'll concern ourselves mainly with variability at optical wavelengths -- light with wavelengths observable with the human eye -- but keep in mind that there are any number of stars that are variable at wavelengths of light from radio waves up to X-rays and gamma rays. Often stars are variable at optical and other wavelengths of light, and even in the optical spectrum, some changes may appear different at different wavelengths. That's a key thing to remember, especially for doing CCD photometry: often we're not only interested in how much the overall amount of light is changing but in the properties of that light variation as a function of wavelength. Knowing both the overall change and the wavelength dependence may help us understand the underlying physics of what's happening to the star, which is ultimately what we're after in variable

star astronomy. Later in this guide we'll spend a lot of time talking about how we can measure (or at least constrain) the spectral properties of the stars we observe. By doing so, we have a much more comprehensive picture of how and why some stars vary.

How do we perform photometry?

The details of that question are going to form the bulk of this guide that follows, but in brief, you will use a piece of electronic equipment -- a charged-coupled device or "CCD" camera -- to measure the number of photons that your telescope receives from a variable star along with a set of known "comparison stars" observed at the same time. You'll take those numbers along with some additional calibration data that you'll obtain, to turn your measure of the number of photons into a physical measure of the brightness of a star at one moment in time. By repeating that measurement over and over again, you can measure how the light from the star changes over time. That's the essence of photometry, regardless of what equipment you're using to make the measurements, but it's worthwhile taking a moment to explain what's happening inside the camera when it's exposed to light.
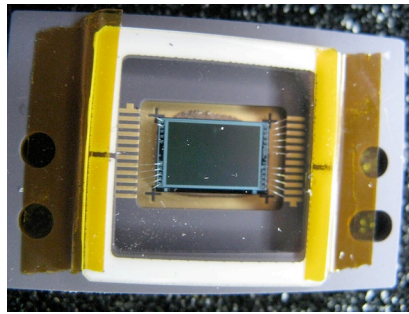
An (older) example of a CCD chip. The detector area is the gray rectangle in the middle. Note the wiring at the edges; the chip is read out through the wiring, which is connected to an analog-to-digital converter within the camera. (Courtesy Arne Henden)

A CCD camera has at its heart a semiconductor wafer (like silicon) that's been divided into a large number of electrically charged, isolated squares that we call "pixels". This is referred to as a "CCD chip". When the chip is exposed to light, photons strike each pixel and release electrons via the photoelectric effect. Each pixel and its associated electronic gates act like a small capacitor, collecting these electrons from the silicon pixels as the light strikes them. Each pixel is wired to a central processor, and the charge that collects in each pixel accumulates until the chip is "read out" by the camera's electronics. During readout, the central processor measures the collected charge on each pixel. This is an analog voltage that is converted (using an analog-to-digital converter) into a digital number. What gets passed from the CCD chip into your computer is the *position* of the pixel on the chip and a digital representation of the *amount of charge it held* at the time of readout. This is what creates the *image* that comes out of your system.

What also makes the image useful for variable star astronomy is that the image is also tagged in some way (typically in the image header) with the *time* it was taken. So at this point you have most of what you'll want -- *a measurement of light at a specific moment in*

time -- to do "photometry". However, this is just the first step. There are several more important things to do in between opening the shutter on your camera and getting a final set of numbers -- a time, a magnitude, and an uncertainty for each measurement -- primarily involving how the counting of electrons by your CCD chip relates to a physical quantity like the amount of light emitted by a star at a certain wavelength. This calibration step is a long but straightforward process that transforms that CCD data into physical information about the star.

The calibration process will involve measuring
- the noise inherent in your camera's electronics
- the peculiarities of your telescope's optics, from aperture to CCD chip
- the wavelength response of your system -- how different wavelengths of light are registered, and eventually
- the wavelength response of the atmosphere through which you observed.

Each of these steps will be covered later in this manual, but for now, realize there is more to doing photometry of variable stars beyond making a single observation. The procedure for taking calibration data for your variable star observing will eventually become routine, but we'll explain what you have to take and why soon.

The key point to take from this chapter is that the goal of photometry isn't the numbers that come out of the CCD camera and your data processing, it's the *science* that you can do with the number. In order to do science, that number has to represent something physically meaningful, and has to be presented in a way that is useful for rigorous scientific analysis. That's where we're aiming with this manual.

In the next chapter, we'll cover the very basics of what equipment and software you'll need before you can start doing CCD photometry. Every telescope, mount, and CCD camera manufacturer will have its own peculiarities, but there's enough overlap in what they do that we'll cover what you should have when you go out to the observatory for a night of variable star photometry. Many of the parameters of your system are relevant to what you'll be able to observe effectively to get good data. You won't be able to obtain good data for every variable star in the sky with any single system, regardless of its size or cost. However, there will be many objects that can be observed easily and effectively no matter what you have -- just realize you should figure out what those objects are *before* you get to the telescope.

Chapter III: Equipment and Software Overview

Since you are using this Guide, it is assumed that you already have a telescope, mount, CCD camera and all the associated equipment needed to do photometry. Therefore, there is no point in describing what equipment you should get, but rather how to make the most of the system you have. There are many different types of telescopes, CCD cameras, and software packages. In this chapter, we mainly want to explain the things that all will have in common, and what will generally be required to get good data from any system. You should consider this chapter as being less about doing photometry, and more about the critical step of **preparing** for photometry *before* you get out to your observatory and start observing.

Telescope and Mount

BSM – California

W30

Most telescopes can work well with CCDs. Smaller telescopes like the AAVSOnet's Bright Star Monitor (BSM, a refractor) are good for imaging brighter stars. Larger diameter telescopes help you go for the fainter variables where increased light-gathering power is needed. In general, the simpler the optical systems the better. Try to avoid adding anything like a focal reducer (which can cause vignetting), color correction systems, or anything that adds a non-uniform effect to the field. Note that some types of telescopes (Newtonians for example) may have issues like coma that will naturally distort stellar images off axis, and this effect will need to be considered when performing photometry.

One of the difficulties of using a CCD is that the field of view is much smaller than what you may be used to without the camera. In general, the smaller the f/ratio (focal length/aperture) of the telescope, the larger the field of view, which makes finding the field and trying to capture all the comparison stars in the same frame a little easier. You can adjust this for an existing telescope by using a focal reducer, but as mentioned above,

doing so has the potential to cause other problems.

It is also important that you try to reduce stray light entering the system. This is generally more of a problem with reflectors. Take your camera off and look through the end of your telescope at the night sky. Look for reflections or glints of light off any of the internal surfaces. If you see anything but the stars out the end of the telescope, your camera will pick that up as well and will affect your images. You should consider trying to find a way to eliminate that stray light either with paint or by adding some flocking material to the inside of the tube.

Finally, having a good mount for your telescope is absolutely essential to success. Equatorials are a must because alt-azimuth mounts cause field rotation during medium and long exposures, which is very difficult to compensate for. Whether you have a German equatorial mount (GEM) or a fork mount is a case of personal preference but both will work fine. It is important, however, that they be well–aligned and track accurately. It will save you a lot of time and frustration if they also help you find the target field with GoTo controls or will allow your computer to take you to the field. Auto-guiders are not essential, but helpful for longer exposures.
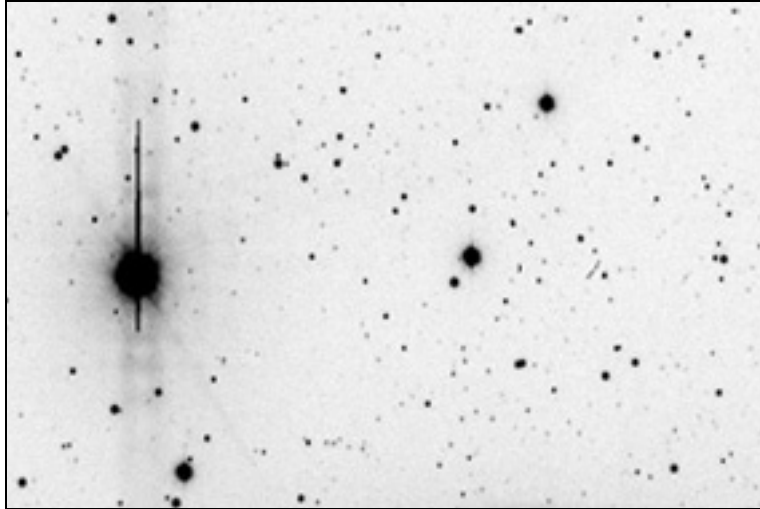
CCD Camera

CCD cameras range widely in quality, complexity, and cost, but most can be used quite successfully for photometry. The important thing is that you should get to know your camera well in order to get the most out of it. Then you can use what you know set up your observing program appropriately.

Here are some things that your should think about with regard to your camera:

Linearity and well depth

Pixels in your CCD camera respond in a linear way to photons: 1 photon equals X counts, where X is constant up to a point. One of the most important things to know about the CCD chip in your camera is that each pixel can handle only a certain amount of light and still give you an accurate readout. If you exceed the "full well depth" of any pixel on your chip, any extra photons striking that pixel will spill out and contaminate other pixels creating an effect called "blooming" in which spikes appear to come vertically up and down out of the saturated pixel. Before you reach that point, the response of the pixels to photons may also change, becoming "non-linear".

Reversed color image showing "blooming"

Some CCD cameras are designed with something called an "anti-blooming gate" (ABG) to prevent this from happening by putting a wall between the pixels to prevent spill-over. This is great for keeping unsightly spikes out of your pretty galaxy photos, but it can be bad for photometry because it can destroy the linearity of your chip and give you inaccurate results.

Fortunately, you can still use a camera with ABG as long as you know its limitations and don't exceed them. Even if you don't have an ABG camera it is still important to know your camera's saturation limits. What isn't so obvious is that pixels can saturate or your chip could become non-linear well before blooming occurs. You have to know what this point is so you can prevent it from happening to your target or comparison stars.

*How to determine the linearity of your camera*

1. Set up a light source by illuminating a white screen. (It does not need to be perfectly uniform, just stable).
2. Point the telescope at the screen and adjust the brightness until a 10 second exposure will result in a mean central region ADU count of 10,000.
3. Take a series of images where the exposure time increases in 10 second increments (i.e. 10, 20, 30, 40, etc.) until it obviously saturates.
4. Plot the exposure time versus mean central region ADU count.
5. Take more exposures closer together at places of interest on the curve (where it begins to curve at the top or isn't linear in other places).

   From this plot you should be able to determine at what count your camera saturates and if there is any non-linear behavior along the way.
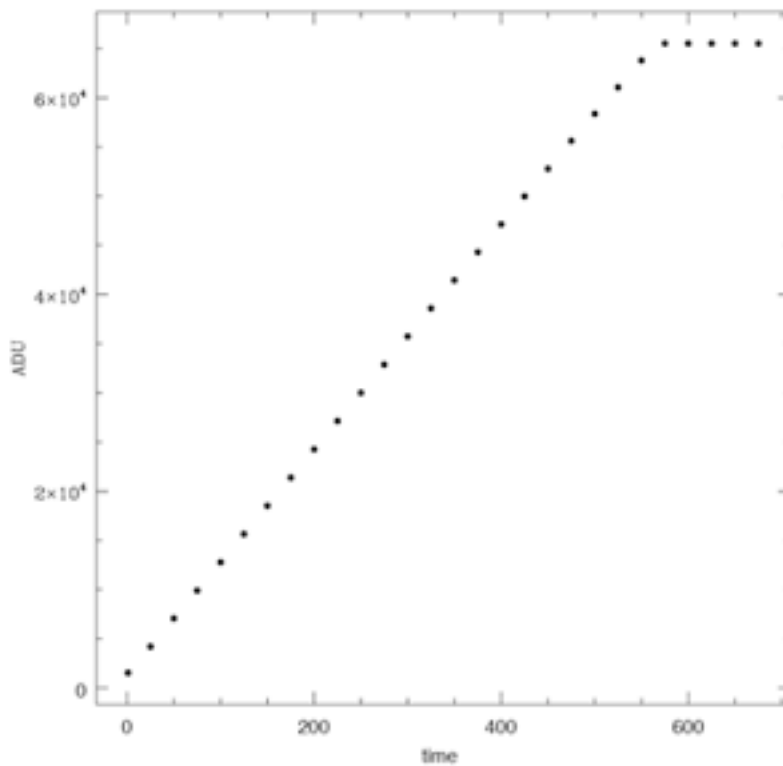
Chip problems

CCD chips can sometimes have problems such as "hot pixels", "blocked columns" or other defects. Finding such defects does not usually mean you have to toss it out and buy a new camera! Most defects are not a problem at all and will not affect the quality of your photometry as long as they can be avoided.
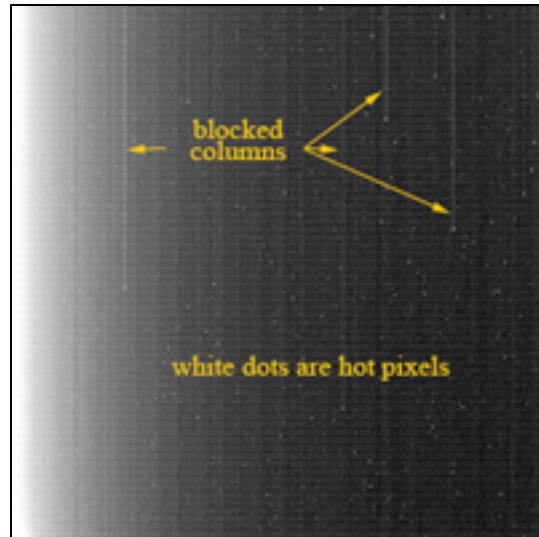
Bias frame from K35 showing
blocked columns and hot pixels

One way to do this would be to inspect a few your images carefully and note what you see. You can draw a rough sketch of the defects on the image and include the plate coordinates for each. Having that information at your fingertips as you point your telescope at the field you are imaging will better help you to avoid any bad areas.

Resolution and Field of View

Your camera and telescope work together to define the resolution and field of view (FOV) you can expect from your system. It is important to quantify these and design an observing program that takes advantage of the strengths of your setup.

Resolution and sampling

When you inspect the image of a star, you will notice that it is made up of a group of pixels, with some brighter ones near the center and some dimmer ones surrounding it. In order to measure the size of an image like this when it doesn't have sharp edges, scientists use the term, "Full-Width, Half-Maximum" (FWHM). This is defined as the number of pixels that are filled to one-half the dynamic range between the background and the brightest (fullest) pixel in the star's image.

In order to get the best results you can out of your photometry, you should strive to *sample* such that the FWHM of your star images is spread across two to three pixels. This will help to optimize the signal to noise ratio (SNR) and improve the accuracy of your measurements. Often, this won't be feasible or even possible, given that it is highly dependent on the seeing conditions and limitations of your equipment, but you may be able to tweak it a little.

To get an idea of what you can expect from your system in practice, use this expression:

$$\textbf{FWHM}_{\textbf{expected}} = \textbf{seeing/resolution}$$
(FWHM in pixels, seeing in arcsec, resolution in arcsec/pixel)

Generally in most suburban locations, seeing averages between 3 and 4 arcsec, but it could be better or worse on any given night. Once you have made some images, you can calculate the seeing yourself by reversing the equation (Seeing = $FWHM_{measured}$ x Resolution)

In theory, the resolution your system can achieve is expressed by this equation:

$$\textbf{resolution = (CCD pixel size/focal length) x 206.265}$$
(resolution in arcsec/pixel, CCD pixel size in microns, focal length in millimeters)

You should be able to get the CCD pixel size from the manufacturer's specifications on your camera. The focal length of your telescope can also be expressed as f/ratio x aperture.

Using these two equations, you can get an idea as to the size of a star's image produced by your system, which you can then compare to your goal of 2 to 3 pixels.

Here are two examples from Sara's observatory that puts it all together:

> **Using this equipment:**
> *CCD Camera:* SBIG ST402 (KAF-0402 chip), Pixel Size*:* 9 x 9 microns
> *Telescope:* Takahashi refractor, Focal length: 530mm
> *Seeing:* 3 arcsec
>
> **You can calculate:**
> Resolution = (9 microns ÷ 530 mm) x 206.265 ≈ **3.5 arcsec/pixel**
> $FWHM_{expected}$ = 3 arcsec ÷ 3.5 arcsec/pixel ≈ **.85 pixels**

Analysis: In this case, if your assumptions abut seeing are correct, the star image will be less than the size of one pixel or .85 pixels. This is considered *under-sampling*. Check your image and determine the FWHM. If it is indeed less than one pixel, then you might consider doing something to increase the size of the image. One option would be to defocus your telescope a bit, then increase the exposure time. If you have to defocus, then be very careful that other nearby stars are not close enough to affect the photometry. Also be sure that you create flat frames (see the next section) that are defocused to the same degree.

Another example:

> **Using this equipment:**
> *CCD Camera*: (same as above)
> *Telescope:* Celestron 11" SCT, Focal ratio: f/10, Aperture: 11"
> *Seeing*: 4 arcsec
>
> **You can calculate:**
> Focal length = 10 x (11" x 25.4"/mm) = 2794 mm
> Resolution = (9 microns ÷ 2794 mm) x 206.265 ≈ **.66 arcsec/pixel**
> $FWHM_{expected}$ = 4 arcsec ÷ .66 arcsec/pixel ≈ **6 pixels**

Analysis: In this case, you are *over-sampling* your image a bit. If the FWHM of the star images is greater than six pixels, you might consider using a focal reducer. Not only would it reduce your pixel size by decreasing the focal length, but it would also give you a larger field of view.

Binning

Another way to handle a problem with over-sampling, as in the above example, is through binning. Binning is something you can do to reduce your effective pixel size by grouping pixels together. Your software can be set up to sample (or bin) a group of 2 pixels by 2 pixels to make those four pixels act as one. There is a tradeoff, however. Resolution will be lost, so you have to be sure that star images have not blurred together with other nearby stars. Also if one of the four pixels in the group is saturated, the accuracy of the photometry will suffer. *It is not recommended to bin groups larger than 2x2 pixels.*

1 x 1 Binning   2 x 2 Binning   3 x 3 Binning
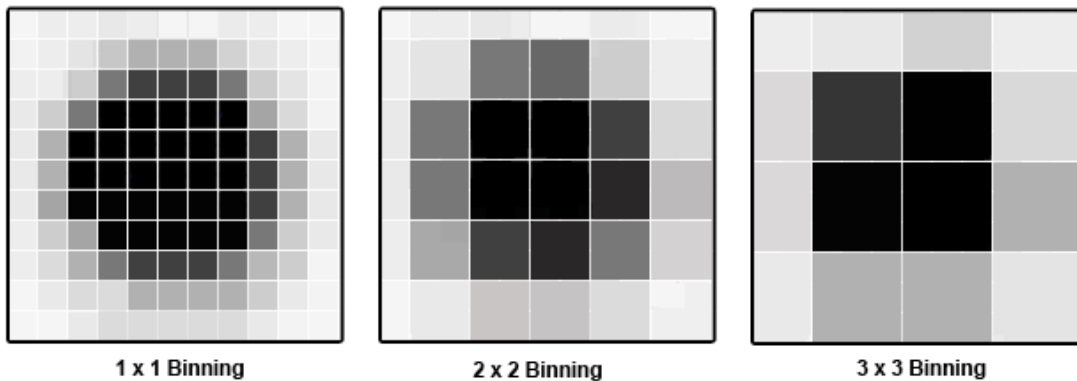
Field of View

To calculate the field of view (FOV) you will get with your system, use the resolution computed above, along with your detector size in pixels:

FOV = (resolution x width) by (resolution x height)
(FOV in arcsec, resolution in arcsec/pixel, height & width of the chip in pixels)

Using the two examples from above (with the same camera):

CCD Camera: SBIG ST402 (KAF-0402 chip), Chip Size = 756 x 510 pixels

Example 1:
Telescope: Takahashi refractor, Resolution = 3.5 arcsec/pixel (low resolution)

FOV = Height: 3.5 arcsec/pixel * 756 pixels = 2646 arcsec
       Width: 3.5 arcsec/pixel * 510 = 1785 arcsec
       44' x 30'

Example 2:
Telescope: Celestron 11" SCT, Resolution = .66 arcsec/pixel (high resolution)

FOV = Height: .66 arcsec/pixel * 756 pixels = 499 arcsec
       Width: .66 arcsec/pixel * 510 = 337 arcsec
       8.3' x 5.6'

Good photometry can be performed on images regardless of whether your FOV is large or small. Having a large FOV is good for bright stars and targets having comparison stars that could be a bit farther from the variable. A system with a smaller FOV is good for fainter stars or resolving stars in more crowded fields.

Filters

Many CCD camera systems will include some option to place filters of various kinds into the beam path between the telescope and the CCD detector. In photometry, filters limit the wavelength range of data coming into the detector at a given time. This gives you the ability to measure the spectrum of a source at well-defined points, providing more physical information about the emission. In one sense, filtered photometry is like (very) low resolution spectroscopy. This can provide additional physical information about the object that you're observing, and in general can increase the usefulness of your observations. Using filters can valuable -- and is sometimes required -- but they're a trade-off in terms of work. Less signal gets to your camera, so your exposure times are longer, BUT you and the astronomers using your data will learn more physical information about the stars as a result.

Properly reduced, your observations will relate better to those of other observers when you use standard photometric filters. The reason is that each CCD chip model has a slightly different spectral response. Without a filter, your observations could possibly still be useful for period analysis but the magnitudes you derive may be unphysical and differ greatly from those of other observers. Not only will the results reflect the qualities of your particular CCD chip, but the fact that you are imaging the entire spectrum of a star at once means that your observations could be many magnitudes brighter than what was seen visually or imaged with a V filter. There are typically two cases where unfiltered observations can and should be made: when the source is known to have a neutral color, where all wavelengths are equally bright (typically in hotter objects like CVs in outburst), or when the object is very faint, and simply detecting the source has great value (as in gamma ray bursts).

Some people use non-photometric filters for their observations. The problem with these is that they are non-standard and it is difficult (if not impossible) to convert your results to the standard system. You will not be able to use the published magnitudes of the comparison or check stars - which are usually given using the standard colors - or compare your results with those of other observers.

If you use only one filter, the best choice would be Johnson V. This is because magnitudes obtained from images made with this filter most closely mimic observations made visually. If you wish to use a second filter, the next most useful is Johnson B followed by Cousins R, Cousins I, and Johnson U in that order. "Johnson" and "Cousins" simply denote standard systems developed by those individuals.

Since filters tend to degrade over time, it is important to inspect your filters annually, make new calibration images frequently (see next chapter) and clean them using manufacturer's instructions.

Computer and Software

Since you most likely will be spending more time working with your data at the computer than actually taking images at the telescope, it is important that you have some basic computer skills. You should also understand the software you are using very thoroughly; not only how to use it, but the basics of what it does. Taking some time to learn how to use your software correctly will quickly pay off.

There are many good software packages available and some perform several or all of the functions listed below. The AAVSO does not endorse any of them in particular and this Guide will not attempt to explain how to use them. What you choose depends on personal preference and compatibility with your system. In most cases, you can download trial versions so you can do some research before buying. It can also be useful to discuss the choices with other observers to learn about the strengths and weaknesses of each product.

Some of the popular software packages include:
- ✦ AIP4Win
- ✦ AstroArt
- ✦ CCD Soft
- ✦ MaxIm DL
- ✦ Mira
- ✦ MPO Canopus
- ✦ VPhot
- ✦ IRAF

Here are the functions that you will need software to perform:

- ✦ CCD interface – controlling the CCD camera itself, selecting filters, making exposures. Often, your CCD camera will come with its own imaging software.
- ✦ Data reduction – processing images, applying calibration frames.
- ✦ Astrometry – also known as "plate solving" to find the actual RA and Dec position of each of your target stars.
- ✦ Photometry - To do brightness measurements and create an AAVSO report in the proper format.

Obviously, you will need to have a computer available to run this software. There are no fixed requirements here but Windows is the most commonly used operating system. Some of the software packages mentioned above will only run on Windows machines and there may not be a Mac or Linux version available. It is also helpful to have plenty of USB ports as you will need one to run your camera along with any other peripherals you may use.

The other necessary function for a computer is to keep accurate time. If you have internet access at your observing site, you can get accurate time from the USNO Master Clock (http://tycho.usno.navy.mil/simpletime.html). Otherwise, you may have to get time from another source such as GPS or a broadcast time signal like WWV. Either way, it is important that you update your computer's clock to show the most accurate time possible since this is the time which will eventually end up in the .fits header of your images. Without frequent updates, your computer's built-in timekeeper could be off by several seconds (if not more) in a short period of time. This may not seem like much, but for measuring short-term variations in some stars, it could make a big difference in the usefulness of your data.

The other important function of a computer is for data storage and archiving. As you will soon discover, it won't take long for you to start accruing lots of images that will consume a lot of storage space on your computer. It would be a good idea to decide how you will handle this in an organized manner before you start. Since it is not uncommon for you to find a processing error or some other reason to retrieve images from the past, it is essential that your files are complete and organized so you can find what you need as easily as possible.

These are the things you should keep:
- Nightly logs containing notes on what is being observed, weather, etc.
- Calibration images
- Nightly raw images
- Calibrated images (flat field and dark subtracted images)
- Logs of observations
- Notes regarding processing

Charts

Using proper variable star charts is an important part of any variable star observing program and the AAVSO has created an online tool to make this easy for you. You can find the "Variable Star Plotter" (VSP) along with links to help pages on the AAVSO website here: http://www.aavso.org/vsp.

Some of the options you might find helpful for CCD observing in particular include the following:

Choose a chart orientation – selecting the CCD option will create a chart with North up and West to the right, much as your camera should see it.

Do you want a chart or list of field photometry? – You may choose to plot a chart or simply a table of field photometry. It is recommended that you use both. The photometry table will be useful as you select comparison stars to use since it gives position, color, and magnitude information using different filters. The comments field is also useful as it alerts you to possible problems or things to watch out for when using a comparison star.

It is also important that you plot a chart of the part of the sky you are imaging so you can use it to check that you have identified the field correctly. Inspect the chart very carefully and if necessary, create a large scale (zoomed in) chart, so that you can use it to check for close companion stars near the variable or any of the comparison stars you plan to use.

The AAVSO comparison star sequences have been carefully chosen and calibrated so please use them! Using non-AAVSO sequences does not necessarily mean that your data will be useless, but it probably won't compare well with observations made by others in the AAVSO International Database.

Many software packages (like VPhot) already include AAVSO comparison star information so you won't need to type it in, but you should still check to be sure it is not out-of-date. Revisions, updates and new sequences are being produced all the time – largely as a result of requests from observers.

Would you like to display a DSS image on the chart? – This option will overlay an image from the Digitized Sky Survey on your chart. This can also help with field identification as it shows the stars in a way that more closely resembles what you will see coming from your camera.
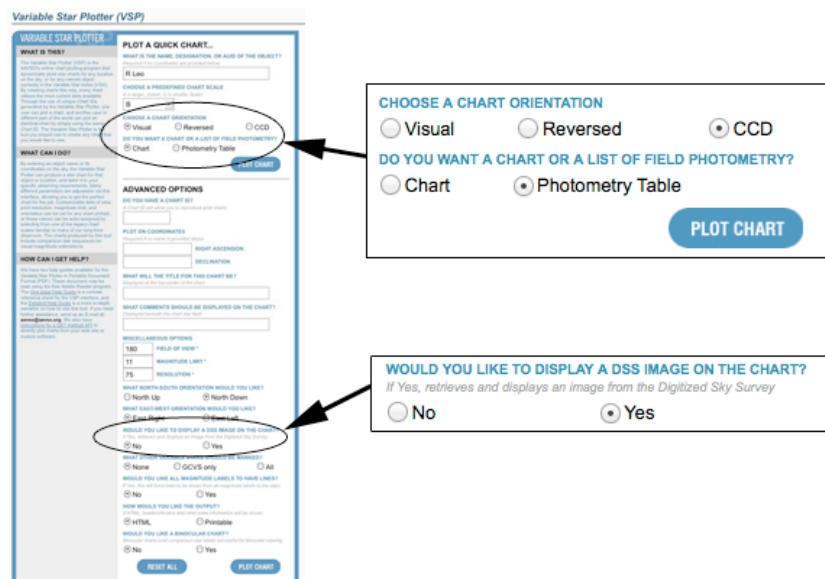
The AAVSO's Variable Star Plotter (VSP) with the CCD-specific options enlarged.

Chapter IV: Image Acquisition & Processing

Making Calibration Images

One of the keys to collecting scientifically useful data is calibrating your images properly. It is important that the data or "science images" accurately represent the signal from the stars. Sources of non-astrophysical signal should be quantified and removed wherever possible so that they do not contaminate your data.

Fortunately, there is a straightforward way to do this by taking special kinds of images that capture the effects of different kinds of noise. You may find that your photographic imaging software will be a big help with this and does most of the work for you. Just be sure to specify what kind of calibration frames you are taking in each case so that it will know what to do with them later when they are being combined. In most cases, the only other decisions you will have to make as you set up your imaging program relate to exposure times, the number of images to make, and what filter is selected.

Quick Guide to Making Calibration Images

All of the calibration frames should be done at the same temperature as that of the science images. Allow your camera cooler to run for ~ ½ hour to settle down before taking images.

Bias Frames
- Should be done in the dark with shutter closed and/or lens cap on.
- Exposure time should be zero seconds (or shortest possible).
- Take 100 images and average them together to create Master Bias.

Dark Frames
- Should be done in the dark with shutter closed and/or lens cap on.
- Exposure time should be the same (or longer) as for your science images.
- Take 20 or more images, subtract Master Bias from each, then **median combine** them all together to create Master Dark.

Flat Frames
- Take images of a uniform light source or the twilight sky.
- Ensure that focus is good and the same as that of science images.
- Exposure time should result in not more than ½ of the full well depth.
- Take 10 or more images for each filter, average (or median combine) them together, then subtract the Master Dark and Master Bias to create a Master Flat.

Your software will also make it easy for you to average images together and apply your calibration frames to your data frames. Depending on which software package you are using, the steps of averaging frames together or subtracting one from another could be automatic or almost automatic. It is important to know the basics of how your software works and what choices you may have to make in the process.

The idea behind calibration images is that they should be used to standardize your data images without distorting the good signal in any way, making them more representative of the light received from the source without being modified by the response of your system.

Bias Frames

Your CCD camera and its electronics have intrinsic noise that adds signal to every image you take, regardless of the exposure times. *Bias frames* are used to compensate for read-out noise, interference from your computer and other electronic noise. They will also remove any constant signal applied to your CCD output by your camera's hardware. Bias frames are created by taking zero-second exposures without allowing any light into your camera.
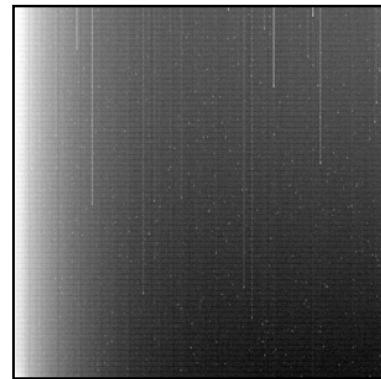
W30 Bias Frame

Each bias image will consist of both underlying bias variations in the image and a random noise component. You're interested in just the underlying bias variations, so you take multiple bias frames in hope of averaging out the noise. Your final "Master Bias" frame will be an average of all of these biases, and it is necessary to take a lot of them so that any random noise will be smoothed out. It's not excessive to take 50 to 100 bias frames at this point. Using only a small number of noisy bias frames could actually introduce more error into your science images than it removes!

As with all calibration frames, it is important to take biases with the temperature setting as low as practical for your location and time of year, and at the same temperature as you use for your science images. Set the camera cooler to a temperature it can reach using no more than about 90% of its cooling capacity and let it work for about half an hour or until the temperature of the camera stabilizes.

Once you have created a Master Bias you should be able to use it until either the ambient temperature changes significantly or a change is made to your system.

Dark Frames

The thermal motions of electrons within the chip slowly generate signals in proportion to the exposure time, not because they're exposed to optical light, but because these thermal electrons have a chance to pile up in each pixel over time. *Dark frames* are designed to quantify "dark current" or thermal noise in the CCD chip so it can be subtracted from the data images. "Hot pixels" can generally be controlled with good temperature regulation and will diminish as the temperature of the chip goes down.

To make dark frames, ensure that there is no light entering your camera, and take images having the same or longer exposure time than you will need for your science images. The reason you should not use dark frames with a shorter exposure time than your science image is that if your software has to "scale them up" to account for a longer exposure, the hot pixels could saturate which would negatively impact the end result.

As with the bias frames, the more images you make, the better, since your software will average all of your dark frames together once the Master Bias is subtracted from each. It is a good idea to inspect your darks for cosmic ray hits and remove any bad ones before they are averaged. Your software should tell you how to do this.

One suggestion is to make all of your bias and dark images on cloudy nights and store them in a "library" organized by temperature and exposure time. You must take new darks any time something changes with your electronic equipment (such as using a new computer, different wiring, etc.)


W30 – 10 second dark frame
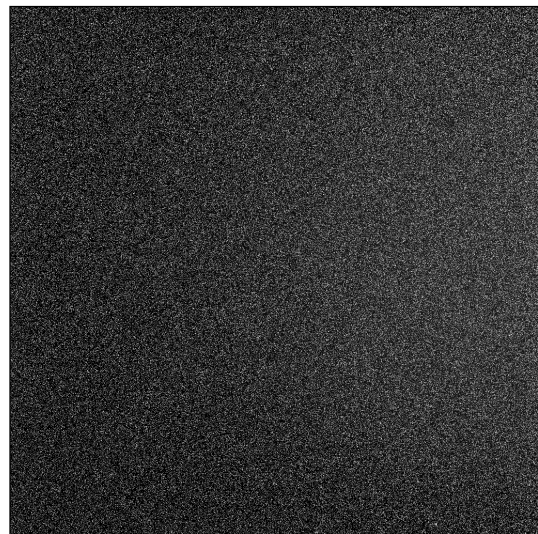
W30 – 300 second dark frame

Flat Frames

The purpose of a flat frame is to create an image which, when applied to your science image, will compensate for problems in the light path through your telescope to the CCD chip. Such things as dust on optical surfaces, reflections from baffles, and poorly aligned optics can all cause gradients in the amount of light that gets through your system. By taking images of a uniform light source, many of these gradients can be recorded and quantified so that their effect can be removed from the science image just as the bias and dark frames remove other kinds of noise.
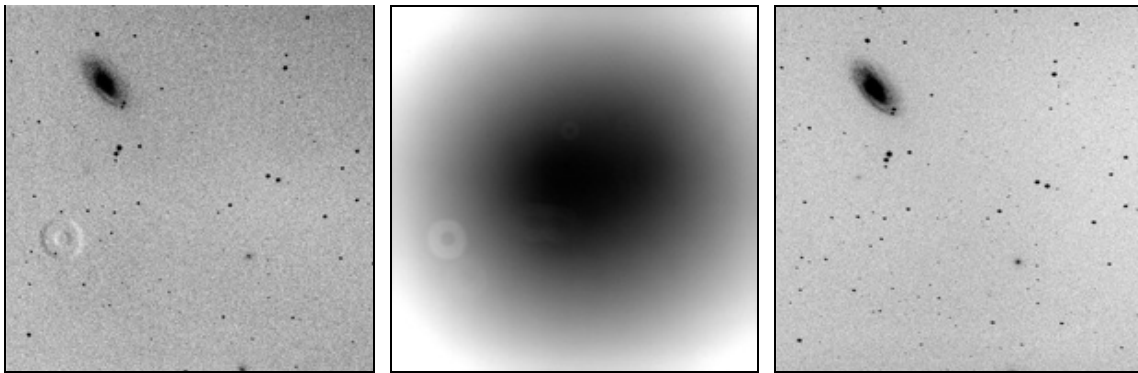
Improperly flatted image showing effect of dust speck   *V-Flat with dust*   *Image with flat applied*

The hardest part about taking flats is coming up with the "uniform light source". Many people use commercial or home-built light boxes or a uniformly illuminated white surface inside the dome or against the wall of their observatory. Another popular procedure is to use the sky itself at morning or evening twilight (see sidebar). In either case, it is important that the source be uniform, otherwise the images taken will not accurately reflect the problems in your light path, but the problems in your light source!

To take flat frames, ensure that the temperature of your camera is stable and the same as the temperature used for your bias and dark frames. The focus should be set to that used for stars, otherwise your "dust donuts" will not match what is affecting the science images.

Exposure times will vary with each filter unless you can adjust the brightness of your light source to compensate for the differences. The goal is to expose your CCD to one-half of the full well depth of the pixels (this is explained in the section on equipment, page 14).

Take at least 10 images for each filter. If your light source is the twilight sky, ask your software to "median combine" your flats together for each filter to remove any stars that may have been included, otherwise average them. A Master Flat for each filter will be created when the Master Dark is subtracted. If you have a choice, use the Master Dark with the closest, but longer exposure time for each flat.

You can use the set of Master Flats just created for more than one observing session, but make new ones at least every week. Dust has a way of getting into everything, no matter how hard you try to keep it out! If anything changes in your optical train (such as adding a focal reducer, replacing a filter, or removing or rotating your camera) you must create new Master Flats.

Taking Twilight Flats

Using the sky itself is the easiest (and least expensive) way to create good flat frames. However, it is not fool proof! By following the suggestions below, you should be able to avoid the major pitfalls.

- ✦ Use the approximately 20-30 minute window, starting when the sun is 5° - 7° below the horizon in the evening or ending when the sun is 5°-7° below the horizon in the morning.
- ✦ Point your telescope toward the zenith.
- ✦ **Move your telescope between frames so that stars don't wind up in the same place on any two frames.**
- ✦ Avoid imaging the Milky Way region because too many stars will be captured.
- ✦ Don't take flats when there is a bright moon or clouds in the sky.
- ✦ Pick an exposure time for each filter which will result in ½ full well but not less than 3 seconds or more than 30 seconds.
- ✦ Make flats for the B filter (if used) during the brightest period and the rest when it is a bit darker.
- ✦ Median combine images instead of averaging them to remove signal from stars.

Science Image Acquisition

Now that you have a set of calibration frames to work with, it is time to start collecting images of actual variable stars. There are several factors to consider as you create these images.

Temperature setting

The temperature of your camera should be set to as cool as possible to reduce dark current. If you use a thermoelectrically cooled camera, set the temperature to the coldest temperature it can reach using a power level of no more than about 90% (so that there is still a little reserve power for cooling if needed). Give the camera about 30 minutes to stabilize before you start taking images. As mentioned above, your calibration images should be created using the same temperature setting as your science images.

In summer time, if you have to operate your camera warm, choose targets needing shorter exposure times to reduce dark current.

Use of filters

In order to produce data that can be easily understood by users (which is the goal of this work), you should always use photometric filters. Unfiltered data or data taken with non-standard filters is of limited use since the color of the star and your system's response to that color will likely be very different from one observer to another. Such data can be used for timing of events such as the minima of an eclipsing binary, but it won't accurately describe reality in a way that others can repeat. It is far better to collect your data using one or more of the standard photometric filters. See the section on filters in Equipment (page 17) for more on this.

Choosing exposure times

The exposure time you select for each image depends on the brightness of the variable at the time and which filter you are using. The most critical aspect of choosing an appropriate exposure time for a given filter is not to "saturate" the image of the variable or any of the comparison stars. Doing so will give you a false reading of the star's brightness which will result in worthless data.

To avoid this problem, it is important to start by knowing the saturation point of your camera as measured in ADUs (see the section on determining Linearity). Once you know what the upper limit is, take some "practice" images of stars of known brightness using different exposure times. By inspecting the images and using your software tools to measure the number of ADUs in the star's image you will be able to determine the point at which the star saturates. From this information, you can establish the maximum "safe" exposure time for each magnitude star you are likely to image. You can then save your findings as exposure time versus star magnitude for each filter in a table for future reference. This will save you a lot of time and probably frustration in the future.

Keep in mind that a star image can saturate well before it "blooms" (i.e. you see vertical spikes coming out of it)!

Here are some other useful tips related to choosing exposure times:

✦ If you are uncertain as to the exposure time to use on a new target, always err on the side of a shorter exposure.
✦ Long exposures are best broken into many shorter exposures. The images can be stacked to improve the S/N ratio.
✦ Never take exposures of less than 3 seconds if your camera has a bladed shutter. Anything shorter will cause the shutter opening and closing to affect the photometric data.
✦ Realize that different filters will often require different exposure times, not only because of filter throughput and CCD response, but because the star may emit much less light in one band than another. This is often true of bluer filters, particularly when observing red stars.

Deciding how many images to make

The first step in deciding how many images to make of each target star in your program is to determine what is appropriate for that particular star or class of stars. For example, if you are imaging a Mira-type star having a period on the order of many months or a year, then it makes no sense to submit more than about one observation per week for that star. In this case, you should create just three images in each filter, process them separately, average the resulting magnitudes, and submit just one averaged observation in each filter as a group to the AAVSO.

"Time series" observing runs in which hundreds of images are made of one star over the course of an evening should be reserved for stars which are actually doing something in the astrophysical sense over that short a time scale.

More information on this subject is covered in the section of this Guide on "Photometry and Science". The point here is that in order to do good science, an appropriate cadence of observations is important and it is something you should consider carefully as you set up an observing run. Too many observations of some kinds of stars in too short a time can distort a light curve and waste your time. Too few observations of other stars can render your data less valuable.

Finding the field

Because of the typically small field of view of a CCD camera, you may have more than a little trouble finding the field of the variable you would like to image. Here are some

suggestions and tips:

- ✦ Know the field of view of your system. Suggestions on how to figure this out are given in the Equipment section of this handbook (page 15).
- ✦ Make sure that your telescope is well aligned before you start. Go to an obvious bright star first, get it into the center of the field of view and re-sync your alignment. It's a good idea to use a V or B filter when you do this to reduce the chance of getting a "ghost image" of the bright star on your next exposure.
- ✦ Print out VSP charts of different scales and use them to help you check asterisms to verify that you are pointing at the star you think you are. You may wish to use the DSS image overlay option on VSP. Take your time and get it right!
- ✦ Use chart software (such as *Guide*, *The Sky*, etc.) that you can customize to match your view in size and limiting magnitude. Overlay a frame on the star map to show your camera's field of view.
- ✦ Use software to control the pointing of your telescope if it is more accurate than using the GoTo controls.
- ✦ Try to place the target star in the center of the field of view and ensure that your comparison stars are also in the same frame.

**Special cases and other issues**

Bright stars

Bright stars pose a special problem for photometrists. In order to avoid saturation of your star image, you will want to use a short exposure time. However, very short exposure images can suffer more from scintillation effects than longer ones where the "twinkling" is averaged out over a longer period of time. You might even reach the point with very bright stars where you cannot take a short enough exposure to avoid saturation. In this case, you may wish to try one or more of the following techniques:

• Use an aperture mask on the end of your telescope to reduce the amount of incoming light getting to your camera.
• Try using a photometric blue (B) filter along with a visual (V) filter. Not only does the filter itself reduce the amount of light reaching your camera, but CCDs are less sensitive to the B-band than V- or R, or I-bands.
• Defocus the image a little. This spreads the light out over several pixels, thereby allowing you to increase the exposure time before saturation occurs.

Crowded fields

Inexperienced observers should avoid imaging fields in which the stars are very close together. The reason is that it is very difficult to do accurate photometry when stars are touching or overlapping each other. Data containing the combined measurement of two stars is generally of very little use. In order to separate the two stars, you must use mathematical techniques such as point spread function (PSF) fitting which is beyond the scope of this Guide.

The one exception to this guideline is when the nearby star has 1% or less of the counts of the target star throughout the range of the variable. In this case, it would be OK to use the combined magnitudes of the variable and the nearby star. However, in crowded fields, this is rarely the case. Worse, variables with large ranges (like Miras) may be much brighter than the nearby star at maximum, but fainter at minimum. This case often leads to confusion of the two by observers, and the AAVSO archives have a number of "flat-bottomed" light curves because of this.
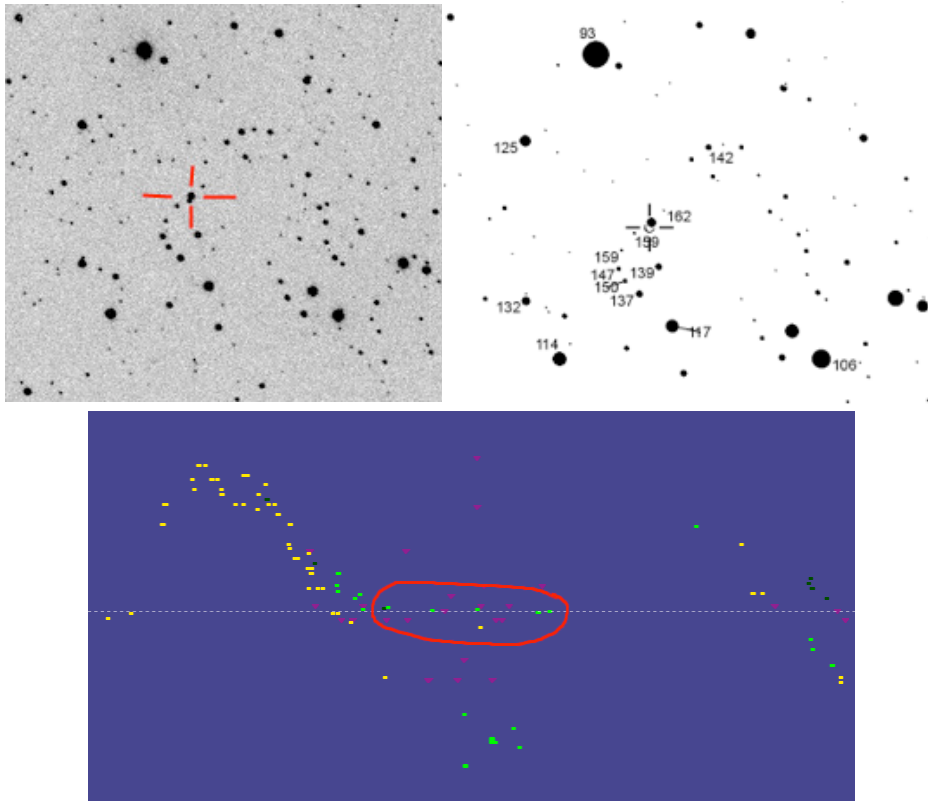
Close companions. Top left: actual image of ST Aurigae with variable in the crosshairs. Top right: AAVSO chart of ST Aurigae -- note the star adjacent to the variable. Bottom: light curve of ST Aurigae -- note the green points circled in red. These are incorrect positives where the observer mistakenly photometered the companion star rather than the variable itself.

Near horizon

Observations made low on the horizon should also be avoided. Observe objects only when the airmass is less than 2.5 (or altitude > ~23°). When light from a star has to pass through a thicker cross-section of the earth's atmosphere, its brightness is diminished. This is known as attenuation or atmospheric extinction. It is possible to apply corrections to your data to make up for this, but it gets complicated since the rate of attenuation changes rapidly as you near the horizon. The effect also differs depending on the color of the stars you are measuring. At some point, you will need to apply different extinction coefficients to every star even in the same field of view. The seeing also gets worse as you get closer to the horizon.

The thickness of the atmosphere is quantified in terms of airmass. Airmass is defined as the length of the path that light takes as it passes through the atmosphere as related to the length of the shortest possible path – straight up. Thus, the airmass of something directly overhead is 1 and the airmass for something on the horizon is infinity.

Airmass (X) can be approximated using this formula:

$$X = 1/\cos(\theta)$$

Where θ is the zenith angle or the angle of the object you are imaging as measured from directly overhead. (Zenith angle = 0° directly overhead and 90° on the horizon.)

Altitude (angle above horizon)	Zenith angle (angle from overhead)	Airmass
90°	0°	1.00
60°	30°	1.15
30°	60°	2.00
23°	**67°**	**2.56**
20°	70°	2.92
10°	80°	5.76

Image Inspection

Before you begin measuring your images, it is important that you perform at least one round of quality control by inspecting them visually. In doing this, you will be made aware of potential problems with your system or procedures as well as conditions outside of your control which may affect your final results. In some cases, you can still use the

images in others you cannot. Either way, it will save you a lot of trouble later on when you try to figure out why an observation is so different from the rest.

Below is a list of common image problems and how they manifest themselves.

Saturation

Stars that are much too bright for the exposure time often suffer "blooming". It is important to note, however, that a star's image can be saturated well before you see any blooming. To see if a star has saturated, check its ADU count in the darkest center of the star. If this number exceeds the "full-well depth" of your camera, then it is saturated and that star should not be included in any measurements. It is perfectly OK to use other stars in the field as long as they aren't affected by the image of the star that is saturated.

Filter problems

The filter wheel inside your CCD camera is a fairly delicate piece of equipment. Sometimes they can get "stuck" causing it either not to turn at all or to rotate only half-way into position. A part-way stuck filter will often obscure the stars in part of your image. If the filter does not turn at all, you may think you are imaging in a certain color when you aren't. This may be harder to detect until after you perform your photometry and see how the magnitudes of the stars you measured compare with the magnitudes you derived from another color filter. If something doesn't make sense, go back and check it!
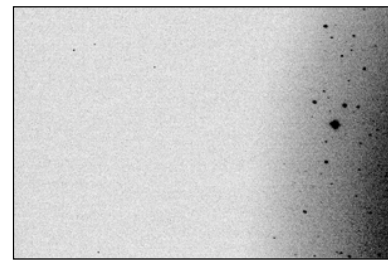
Image taken with the filter stuck between two settings

Scattered light

Reflections off the inside of your telescope tube or other optical elements can cause bright areas, rings or double star images that could affect your results. This is particularly evident when the moon is up or there are bright stars or planets near the field you are imaging.

Scattered light from the Moon in upper right corner

Atmospheric

When you are setting up your equipment for a night of imaging, take a few moments to study the sky! If you think that clouds may be lurking or there is a hint of cirrus around, chances are, they will wind up influencing your images. It isn't always easy to detect thin cloud in your images, but if you suspect that some was present, make a note of that and study the results of your photometry very carefully. In theory, a cloud that affects your target star would also affect the comparison stars you are using and due to the way differential photometry works, the effect will be cancelled out. However, this is not always the case so you should look at the results of your measurements with skepticism.
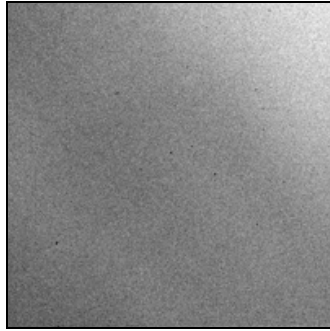
Clouds in image
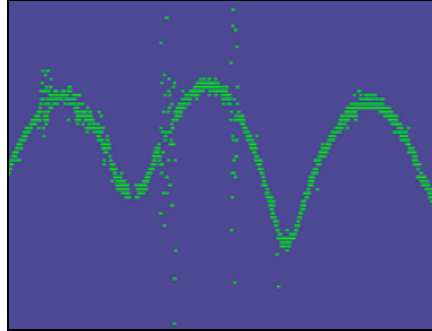
*Light curve of VW Cep showing the effect of clouds*

Cosmic rays

It is not unusual for you to see the effect of cosmic ray hits on your images especially if you are observing from a higher-altitude location. These will manifest themselves as small streaks, curls or small, sharp (1-3 pixel) bright spots on your images. They are random and generally do not pose a problem. If however, one should happen to land in the signal circle or the sky annulus of a star you are measuring, the effect might be noticeable.
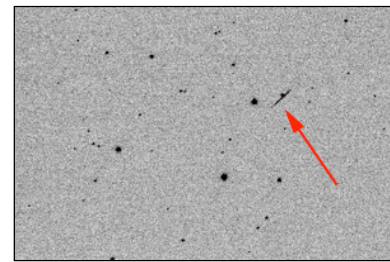
A cosmic ray hit

*Airplanes/satellites/meteors*

Much as with cosmic rays, airplane, meteor and satellite trails which pass through your image are not a problem as long as they aren't too close to a star you are measuring. If you are unlucky enough for this to happen, you may have to choose other comparison stars or skip using this image altogether.
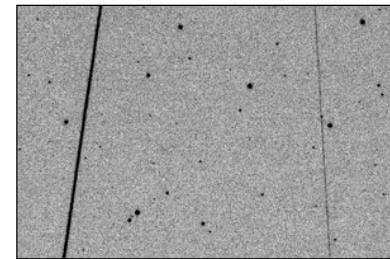

Two objects pass through this image

Ghosts (residual bulk images or RBIs)

Due to the way the chip works in your CCD camera, if you image something bright, it is possible for you to get a "ghost" of that same object on the next image you take. You can tell it is an ghost if it looks like a fuzzy patch and gradually fades with each subsequent image. Generally these artifacts are not a problem unless they interfere with a star you are trying to measure or confuse you as to the identification of the field. They are more prevalent with images taken using a red (e.g. Rc or Ic) filter. To remove them when they occur, try warming up your CCD and waiting few minutes for the image to "bleed". When you cool your camera down again, it should be gone. Another possible option is to keep any bright objects near the edge of your field of view so the ghost is unlikely to affect anything.
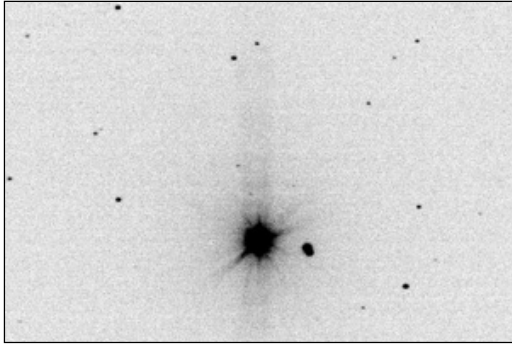
Image showing the bright star DY Eri
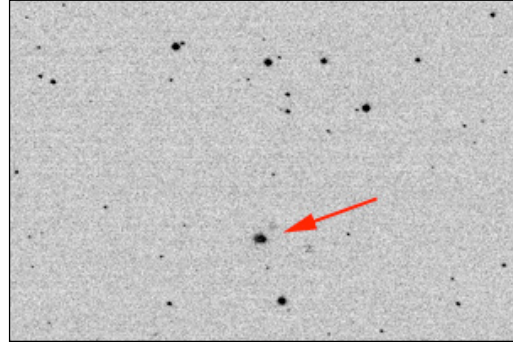
Next image taken showing a "ghost" of DY Eri