

# The AAVSO

## Guide to CCD Photometry

Version 1.1



**AAVSO**  
49 Bay State Road  
Cambridge, MA 02138  
Phone: +1 617 354-0484  
Email: [aavso@aavso.org](mailto:aavso@aavso.org)

Copyright 2014 AAVSO  
ISBN 978-1-939538-10-9

## Table of contents

<b>Preface</b>	<b>4</b>
<b>Acknowledgements</b>	<b>5</b>
<b>Chapter 1: So, you want to be a photometrist?</b>	<b>6</b>
<b>Chapter 2: Variable stars – The what, why, and how of photometry</b>	<b>9</b>
<b>Chapter 3: Equipment and software overview</b>	<b>13</b>
Telescope and mount	13
CCD camera	14
<i>InfoBox 3.1 – How to determine the linearity of your camera</i>	16
Filters	21
Computer and software	22
Charts	24
<b>Chapter 4: Image acquisition &amp; processing</b>	<b>27</b>
Making calibration images	27
<i>InfoBox 4.1 – Quick Guide to Making Calibration Images</i>	27
<i>InfoBox 4.2 – Taking Twilight Flats</i>	31
Science image acquisition	31
Special cases	34
<i>InfoBox 4.3 – Scintillation</i>	35
<i>InfoBox 4.4 – Estimating Airmass</i>	36
Image inspection	37
<b>Chapter 5: Photometry - measuring images</b>	<b>41</b>
Check your images	42
Identify the stars	42
<i>InfoBox 5.1 – The PSF Plot</i>	43
Set the aperture	44
Choose the check and comparison stars	45
Measure the magnitudes	46
<i>InfoBox 5.2 – A note about magnitudes</i>	47
Determine the uncertainty	48

<b>Chapter 6: Transforming your data</b>	<b>51</b>
General overview and assumptions	52
Determining your transformation coefficients	52
Applying the transformation coefficients	59
<b>Chapter 7: Photometry and science</b>	<b>62</b>
Photometry and filters	62
Time considerations: variability timescales, exposure times, and cadence	64
<b>Appendix A: What is starlight?</b>	<b>69</b>
<b>Appendix B: Why and how stars radiate</b>	<b>71</b>
<b>Appendix C: Submitting observations to the AAVSO</b>	<b>75</b>
<b>Appendix D: Observer resources</b>	<b>81</b>
<b>Index</b>	<b>82</b>

## Preface

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 now account for more than 80 percent of all data submitted to the AAVSO per 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 *generating data but enabling 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 the scientific value of data rather than the quantity of data submitted, 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 how much of it you collect.

This guide 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 so that your *data* provide researchers with useful *information*.

The *Guide* 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](mailto:aavso@aavso.org).

Clear skies,

Sara Beck, *AAVSO Technical Assistant, Science Team*

Arne Henden, *AAVSO Director Emeritus*

Matthew Templeton, *AAVSO Science Director*

## Acknowledgements

The AAVSO and the authors of this Guide would like to express their sincere thanks and appreciation to the following people who have contributed in some way to this publication:

For their time and programming skills in creating the transformation tools:

Gordon Myers

Richard Sabo

George Silvis

For help, encouragement, and valuable feedback:

Dave Cowall

Tim Crawford

Blake Crosby

Thibault de France

Allan Hollander

Robert Jenkins

Ken Menzies

John O'Neill

Sebastián Otero

Miguel Rodrigues

Phil Sullivan

Gary Walker

First published (Version 1.0): September 2014

Version 1.1: February 2015

- March 3, 2015: update to Chapter 6
- January 11, 2016: minor wording change to “*Deciding how many images to make*”, Chapter 4, page 33.
- February 9, 2016: minor wording change to “*Submitting Observations to the AAVSO*”, Appendix C, page 78.
- February 26, 2016: corrected and replaced plots in “*InfoBox 3.1 - How to determine the linearity of your camera*”, Chapter 3, page 16.

## Chapter 1: 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 guide 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 astrophotography. 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 *I want to try that!* 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 *Guide* 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. You will need to develop the habit of examining your results carefully, and assessing whether they make sense every time you submit an observation.

Finally, we'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, and we encourage everyone to pick up this guide's sister publication, the *AAVSO Manual for Visual Observing of Variable Stars*.

Note that obtaining “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 brightness changed in that manner. 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 again and 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. Nearly everyone can saw a piece of wood in half, but that doesn't make them a carpenter. A CCD camera will produce 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. Those numbers aren't photometry unless the process of doing this is correct. 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 2: 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 many 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 exist with 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* — 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 innumerable variables 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.

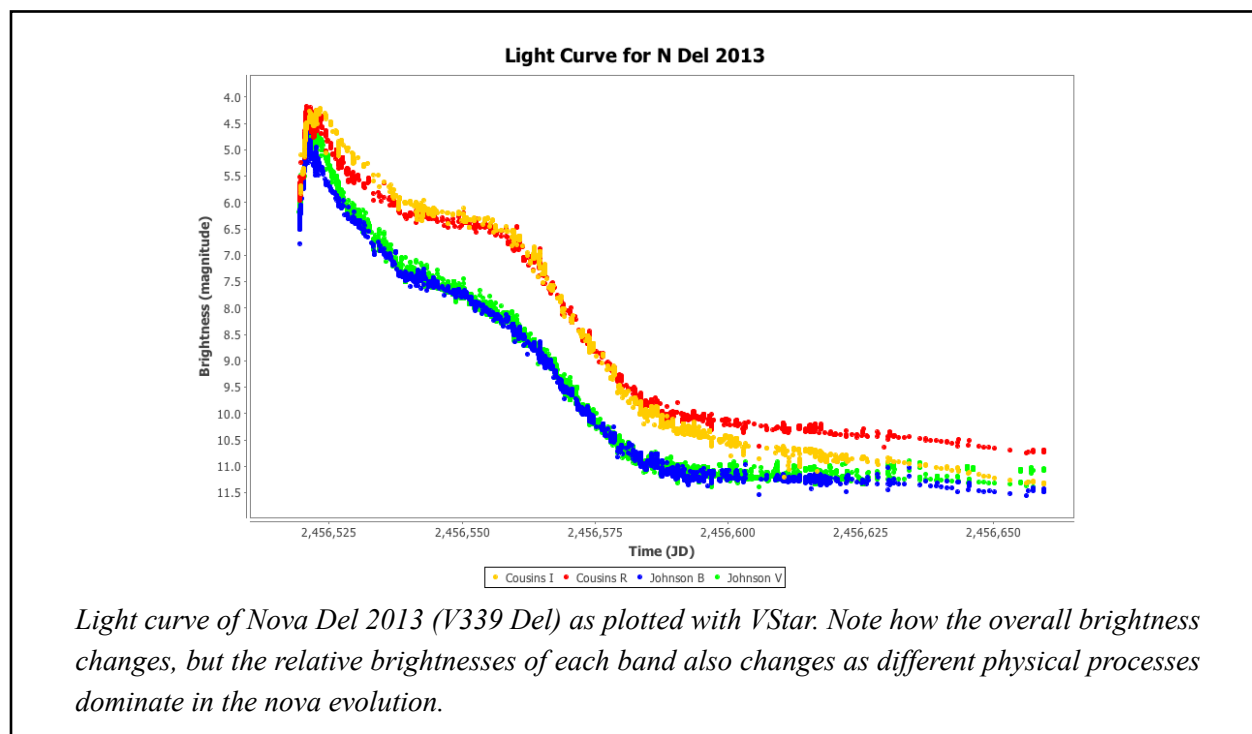
*Why are you doing photometry?*

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 a variable star changes, we can learn more about how the universe works. The same fundamental physical processes that operate here on Earth — gravity, fluid mechanics, electromagnetism, 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.

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, providing insights on everything 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.

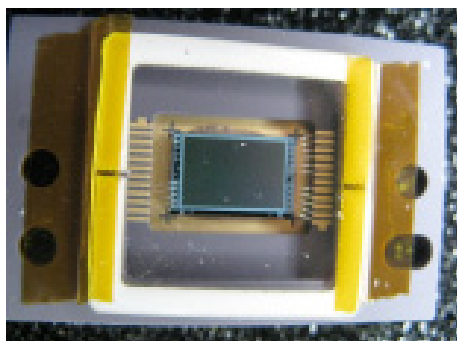


Knowing both the overall change and the wavelength dependence may help us understand the underlying physics of what's happening to the star, which is ultimately what we're after in variable star astronomy. Later in this guide we'll spend some time talking about how we can measure (or at least constrain) 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 calibrated, 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.

A CCD camera has at its heart a semiconductor wafer (made out of 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 into a digital number using an analog-to-digital converter. What is sent 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.



*An example of an (older) 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)*

What 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 at a certain wavelength that the star emits. 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 guide, but for now, realize there is more to doing photometry of variable stars beyond making a single observation. The calibration data you'll take for your variable star observing will eventually become routine, but we'll explain what you have to take and why.

The key point to take away 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 those numbers. In order to do science, your results have to represent something physically meaningful, and have to be presented in a way that is useful for rigorous scientific analysis. That's our goal, and that's where we're aiming with this guide.

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 3: 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

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 is needed. In general, the simpler the optical systems the better. If at all possible, try to avoid adding a focal reducer (which can cause vignetting) 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.



*Two of the AAVSONet telescopes: BSM-Hamren, 65mm Astro-Tech AT-65EDQ (right) and Coker 30, a 30cm Meade LX-200GPS (above).*

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 more than 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.

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 both for longer exposures and time-series runs.

Finally, there is the question of having an observatory to house your equipment. Although not absolutely essential for getting good data, some sort of permanent mount (with a way to protect it from the elements) will save you a lot of time and frustration setting up and breaking down all of the equipment each night. Even a good, sturdy watertight box on rollers that you can put over your mount, will save hours of setup and alignment time each observing session. With a more substantial structure, you will feel comfortable leaving your CCD camera and computer attached and ready for use. There are many solutions and they don't have to be expensive.



*Roll-off roof shed*



*BSM-HQ's housing*

## **CCD camera**

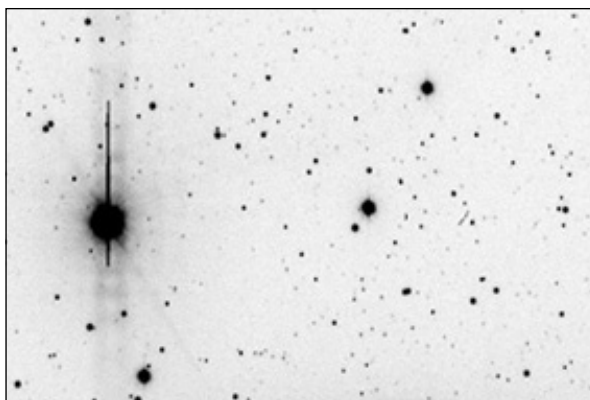
CCD cameras range widely in quality, complexity, and cost, but most can be used quite successfully for photometry. The important thing is that you should get to know your camera well in order to get the most out of it. Then you can use what you know set up your observing program appropriately.

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

### *Linearity and well depth*

Pixels in your CCD camera respond in a linear way to photons: one photon equals  $X$  counts, where  $X$  is a constant (defined by the *gain*) 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 this amount—called the “full well depth”—in any pixel on your chip, any extra photons striking that pixel will generate electrons that 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”.

Some CCD cameras are designed with an “anti-blooming gate” (ABG) to prevent this from happening by siphoning off the spill-over electrons before they contaminate adjacent pixels. 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.



*Reversed color image showing “blooming”*

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 limit is so you can prevent it from happening to your target or comparison stars.

See the *InfoBox* on page 16 for instructions on how to find the linearity of your camera.

### *Chip problems*

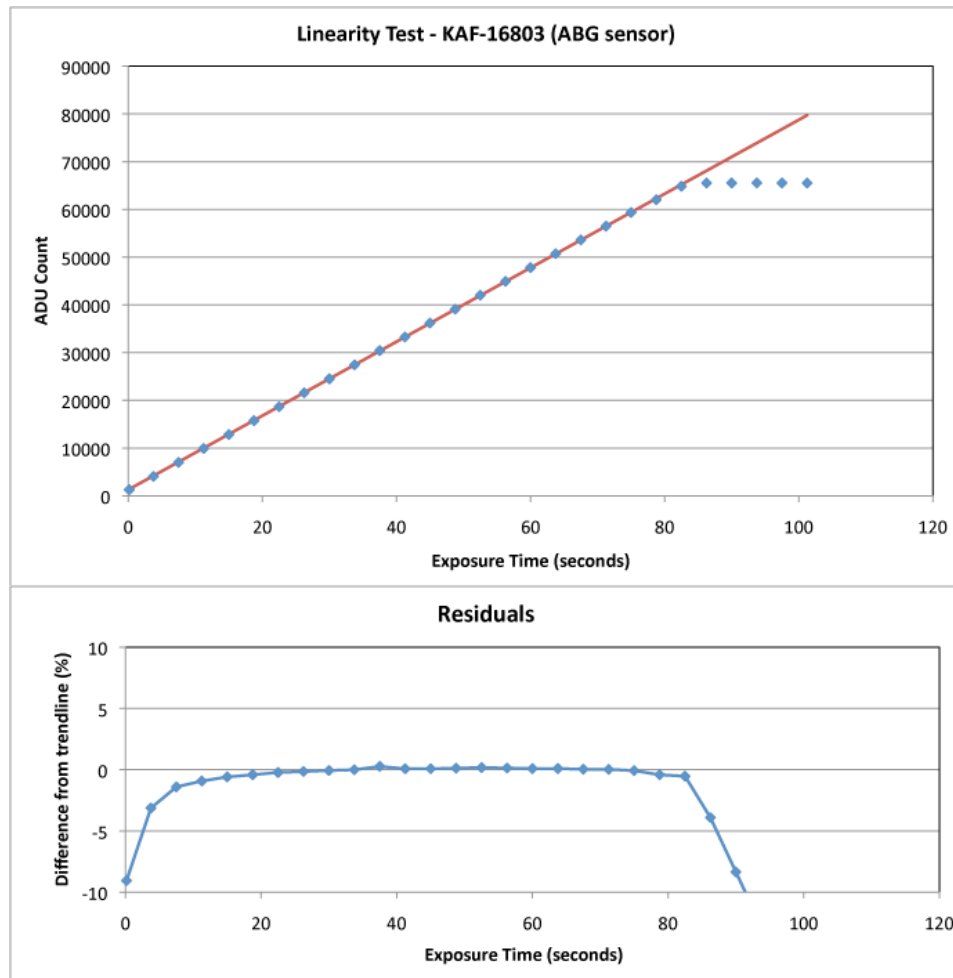
CCD chips can sometimes have (or develop over time) problems such as “hot pixels”, “blocked columns” or other defects. Finding such defects does not usually mean you have to toss it out and buy a new camera! Most defects are not a problem at all and will not affect the quality of your photometry as long as they can be avoided.



*InfoBox 3.1 – How to determine the linearity of your camera*

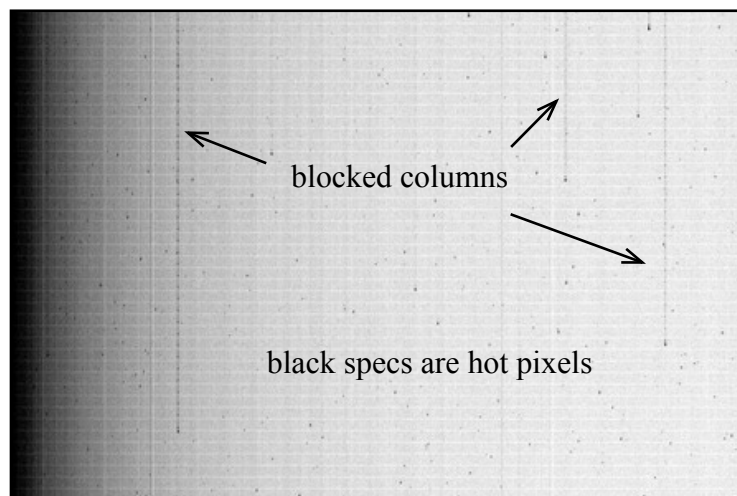
1. Set up a light source by illuminating a white screen. (It does not to be perfectly uniform, just stable).
2. Point the telescope at the screen and adjust the brightness until a 10 second exposure will result in a mean central region ADU count of 10,000.
3. Take a series of images where the exposure 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 one or two more exposures between each 10-second one through straight sections of the plot, then at even more frequent intervals in places of interest of the plot — e.g. where it begins to curve at either end or in any other non-linear section(s).

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.





One way to avoid problems caused by chip defects would be to inspect a few of 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. Also, since CCD chips degrade with time, it would be a good idea to repeat this exercise at least once each year. Having that information at your fingertips as you point your telescope at the field you are imaging will better help you to avoid using any bad areas to measure stars of interest to you.



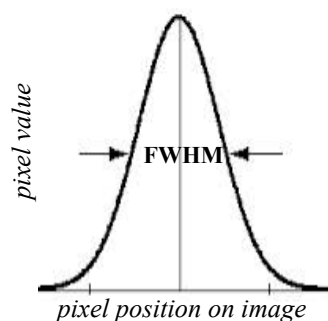
*Reversed image of a bias frame showing blocked columns and hot pixels.*

### *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.

### 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. Ideal images of point sources made by optics have an intensity pattern called an *Airy disk*. However, in practice the light from stars (generally considered to be a point source) has to pass through the Earth's atmosphere which diffuses and expands the pattern. The dot which represents the image of a star on your CCD image is called a *seeing disk* because the seeing conditions have a profound effect on the intensity of the light. In order to measure the intensity 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 seeing disk 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.

So how do you know if your system gives proper sampling of the seeing disk? The answer is simple. All you have to do is measure it directly. Just take a well-focused image of any random star field close to the zenith. Most CCD software has a tool for measuring the characteristics of a single star image, including the size (i.e. FWHM) of the seeing disk expressed in pixels. This is your system's sampling of the star image.

Measure several stars around the center of the image that have a good SNR but are not saturated. This may vary a bit across the image because of seeing effects and optical aberrations. It may also change over time as the seeing (scintillation) changes. **You are just looking for an approximate number of 2–3 pixels per FWHM.**

Often, achieving this goal 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. If you are averaging a FWHM of less than 2 pixels, you are probably *under-sampling*. If the FWHM of your seeing disk is more than 3 pixels in diameter, you may be *over-sampling*. Either situation could pose problems for the accuracy of your photometry, though under-sampling is much worse than over-sampling. Fortunately, there are things you can do to remedy the situation.

*What should I do if my system is under-sampling?*

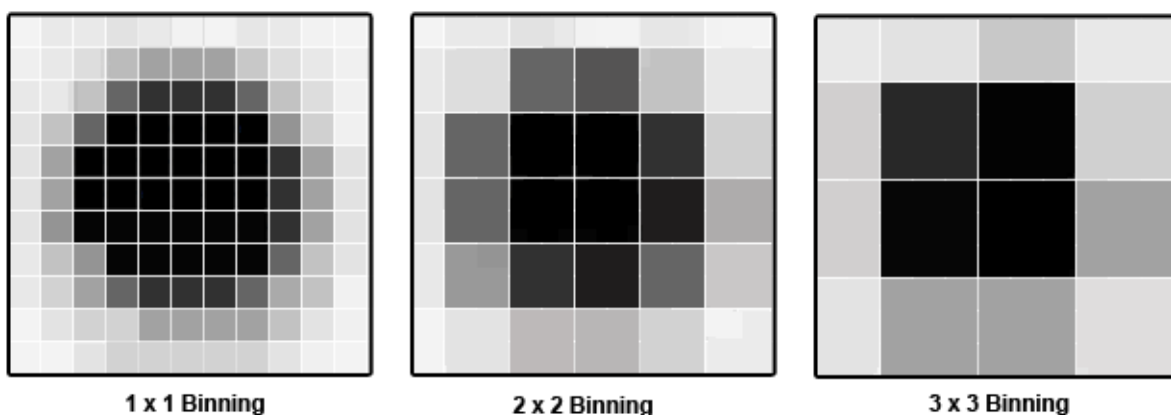
The goal here is to try to increase the size of the seeing disks on your image. One option would be to **defocus your telescope a bit, then increase the exposure time**. If you have to defocus, then be very careful that other nearby stars are not close enough to affect the photometry. Also try to create flat frames (see the next section) that are defocused to the same degree and always take your images with the same amount of defocusing (which can be very tricky!). You might find that adding a good-quality focal extender or Barlow could also help the situation somewhat.

*What should I do if my system is over-sampling?*

First of all, check the focus and make sure that the seeing disks are as small as possible. If the FWHM 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. Another option to consider is binning your results.

## Binning

Binning is something you can do to increase 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. If you do a linearity test (as described on page 16) you should ensure that you run this test using the same level of binning that you will use for your science frames. Your calibration frames must also be binned to the same degree. *It is not recommended to bin groups larger than 2x2 pixels.*



## Image Scale (or CCD Resolution)

Another piece of information it would be useful to know about your system is image scale or resolution. The image scale of your system can be computed using this equation:

$$\text{Image scale} = (\text{CCD pixel size} / \text{focal length}) \times 206.265$$

(image scale 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 times the aperture.

Knowing the image scale of your system is handy for figuring out how the seeing conditions are in your location on any given night. Simply use this equation:

$$\text{Seeing} = \text{Image scale} * \text{FWHM}$$

Generally in most suburban locations, seeing averages between 3 and 4 arcsec, but it certainly varies from location to location and could be better or worse on any given night.

## Field of View

Knowing the field of view (FOV) of your system ahead of time is essential to helping you find the exact area of the sky you wish to image. It is also a good idea to check it against a star chart or your planetarium software to see if your field is indeed large enough to contain the variable star you wish to image as well as all the comparison stars you will need for the photometry at the same time. If it isn't, you may find yourself having to compensate by adjusting the effective focal length of your system.

To calculate the FOV you will have with your system, use the image scale computed above, along with your detector size in pixels:

$$\text{FOV} = (\text{image scale} \times \text{width}) \text{ by } (\text{image scale} \times \text{height})$$

*(FOV in arcsec, image scale in arcsec/pixel, height & width of the chip in pixels)*

Below are two examples of systems using the same CCD camera :

*CCD Camera:* SBIG ST402 (KAF-0402 chip), Chip Size =  $765 \times 510$  pixels

**Example 1:**

*Telescope:* Takahashi refractor, Image scale = 3.5 arcsec/pixel (low resolution)

FOV = Height:  $3.5 \text{ arcsec/pixel} \times 765 \text{ pixels} = 2677 \text{ arcsec}$

Width:  $3.5 \text{ arcsec/pixel} \times 510 = 1785 \text{ arcsec}$

**44'  $\times$  30'**

**Example 2:**

*Telescope:* Celestron 11" SCT, Image scale = 0.66 arcsec/pixel (high resolution)

FOV = Height:  $0.66 \text{ arcsec/pixel} \times 765 \text{ pixels} = 505 \text{ arcsec}$

Width:  $0.66 \text{ arcsec/pixel} \times 510 = 337 \text{ arcsec}$

**8.4'  $\times$  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 away 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 be valuable—and is sometimes required—but they are a trade-off in terms of work. Less signal gets to your camera, so your exposure times are longer. However, you—and the researchers 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 three cases where unfiltered observations are useful: when the source is known to have a neutral color - where all wavelengths are equally bright (typically in hotter objects like CVs in outburst), when the object is very faint, and simply detecting the source has great value (as in gamma ray bursts) or where period-determination is the overriding scientific goal.

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 I, Cousins R and Johnson U in that order. “Johnson” and “Cousins” simply denote standard filter band passes developed by Harold Johnson and Alan Cousins respectively.

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 the manufacturer's instructions.

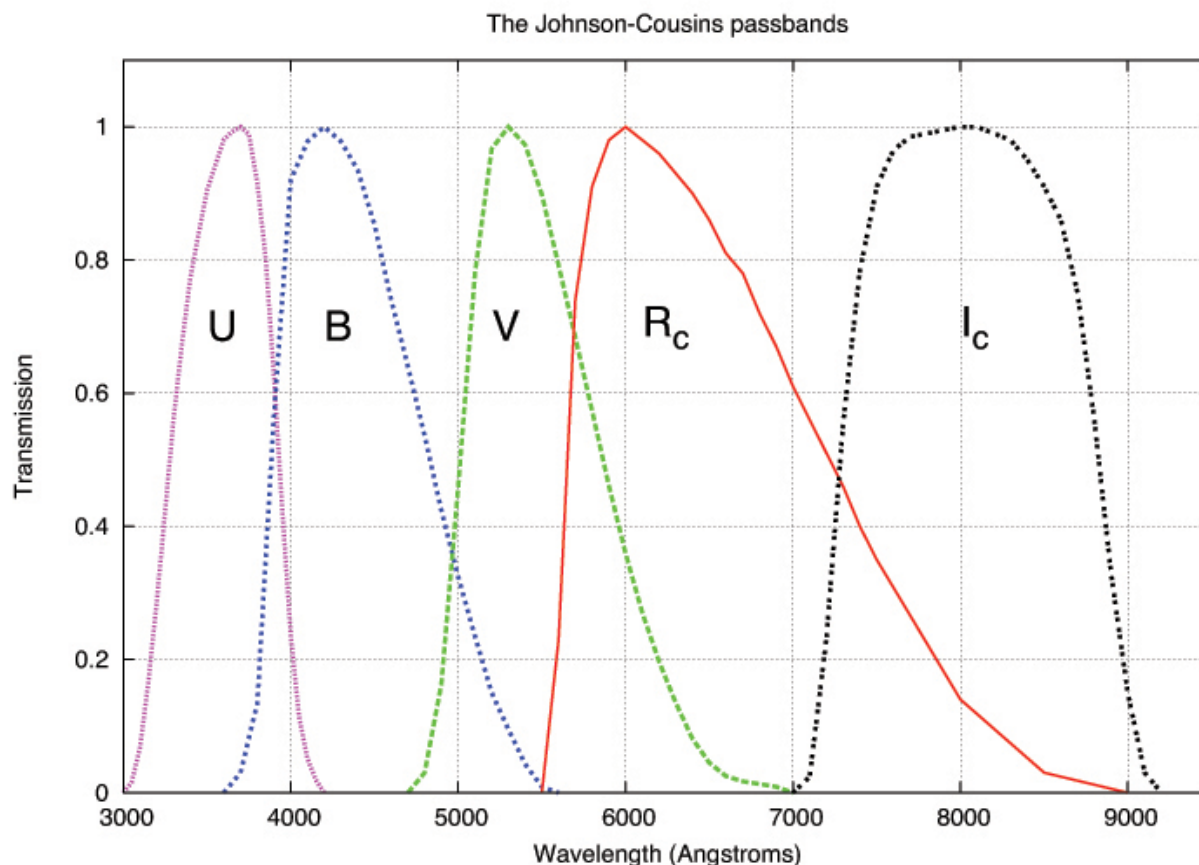


Figure 3.1 – Plot of transmission versus wavelength in each of Johnson–Cousins filters.  
(courtesy of Michael Richmond, RIT)

## 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. Since you will be spending more time at the computer than at your telescope, it is important that you choose software that you can be comfortable with and that you spend the time getting to know it well. 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 most popular software packages include:

- AIP4Win
- AstroArt
- CCDOps
- FotoDif (Spanish language software)
- IRAF
- LesvePhotometry
- MaxIm DL
- MPO Canopus
- VPhot

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 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 images you create with your CCD camera will be saved in the FITS file format. FITS (Flexible Image Transport System) is the standard method of storing scientific images into computer-readable files, and is supported by all software packages. A useful feature of the FITS format is that information about the image (such as target name, time of exposure, etc.) can be stored in a human-readable format along with the image itself.

Another 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 it from another source such as a broadcast time signal like WWV in the USA or the equivalent in other parts of the world. There is also software available to check and correct your system’s time drift. Either way, it is important that you update your computer’s clock often 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 very short period of time. This may not seem like much, but for measuring short-term variations in some stars, or doing occultation work, it could make a critical 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 begin accruing lots of images that will consume a lot of storage space on your computer. You should decide how you will handle this in an organized manner *before* you start. Everyone makes mistakes or misses problems with images once in awhile, and it is not uncommon for observers to find a processing error, a comparison star sequence change, or some other reason to retrieve images from the past. Therefore, 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 in your files:

- Nightly logs containing notes on what is being observed, weather, the moon phase, 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 East to the left, 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 to see 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 likely 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.

*Would you like a standard field chart?* – You may find this option useful when you are preparing to image a standard field for the purpose of computing your transformation coefficients. Selection of this option means that comparison star labels will be omitted from all but the “standard stars”. See Chapter 6 for more on transformation.

Figure 3.2 – The AAVSO's Variable Star Plotter (VSP) with the CCD-specific options enlarged.

### Variable Star Plotter (VSP)

#### VARIABLE STAR PLOTTER

**WHAT IS THIS?**

The Variable Star Plotter (VSP) is the AAVSO's online chart plotting program that dynamically plots star charts for any location on the sky, or for any named object, currently in the Variable Star Index (VSI). By creating charts this way, every chart utilizes the most current data available. Through the use of unique Chart IDs generated by the Variable Star Plotter, one user can plot a chart, and another user in different part of the world can plot an identical chart by simply using the same Chart ID. The Variable Star Plotter is the tool you should use to create any chart that you would like to use.

**WHAT CAN I DO?**

By entering an object name or its coordinates on the sky, the Variable Star Plotter can produce a star chart for that object or location, and tailor it to your specific observing requirements. Many different parameters are adjustable via this interface, allowing you to get the perfect chart for the job. Customizable field of view, print resolution, magnitude limit, and orientation can be set for any chart plotted, or these values can be auto-assigned by selecting from one of the legacy chart scales familiar to many of our long-time observers. The charts produced by this tool include comparison star sequences for visual magnitude estimations.

**HOW CAN I GET HELP?**

For detailed instructions on using VSP, consult the [Help Guide](#). We also provide a [S&T method API](#) for embedding charts in your website or custom software. If you need further assistance, you can email us at [avso@aaavso.org](mailto:avso@aaavso.org).

#### PLOT A QUICK CHART...

**WHAT IS THE NAME, DESIGNATION, OR ALID OF THE OBJECT?**  
*Required if no coordinates are provided below*

MR UMa

**CHOOSE A PREDEFINED CHART SCALE**  
*A is larger, slower; G is smaller, faster.*

G

**CHOOSE A CHART ORIENTATION**

☐ Visual ☐ Reversed ☒ CCD

**DO YOU WANT A CHART OR A LIST OF FIELD PHOTOMETRY?**

☒ Chart ☐ Photometry Table

**PLOT CHART**

#### ADVANCED OPTIONS

**DO YOU HAVE A CHART ID?**  
*A Chart ID will allow you to reproduce prior charts*

**PLOT ON COORDINATES**  
*Required if no name is provided above*

RIGHT ASCENSION  
 DECLINATION

**WHAT WILL THE TITLE FOR THIS CHART BE?**  
*Displayed at the top-center of the chart*

**WHAT COMMENTS SHOULD BE DISPLAYED ON THE CHART?**  
*Displayed beneath the chart star field*

**MISCELLANEOUS OPTIONS**

7.5 FIELD OF VIEW \*  
20.5 MAGNITUDE LIMIT \*  
75 RESOLUTION \*

**WHAT NORTH-SOUTH ORIENTATION WOULD YOU LIKE?**

☒ North Up ☐ North Down

**WHAT EAST-WEST ORIENTATION WOULD YOU LIKE?**

☐ East Right ☒ East Left

**WOULD YOU LIKE TO DISPLAY A DSS IMAGE ON THE CHART?**  
*If Yes, retrieves and displays an image from the Digitized Sky Survey*

☐ No ☒ Yes

**WHAT OTHER VARIABLE STARS SHOULD BE MARKED?**

☒ None ☐ GCVS only ☐ All

**WOULD YOU LIKE ALL MAGNITUDE LABELS TO HAVE LINES?**  
*If Yes, this will force lines to be drawn from all magnitude labels to the stars*

☒ No ☐ Yes

**HOW WOULD YOU LIKE THE OUTPUT?**  
*If HTML, headers/footers and other extra information will be shown*

☒ HTML ☐ Printable

**WOULD YOU LIKE A BINOCULAR CHART?**  
*Binocular charts omit comparison star labels not useful for binocular viewing.*

☒ No ☐ Yes

**WOULD YOU LIKE A STANDARD FIELD CHART?**  
*Standard field charts omit comparison star labels not included in the standard field.*

☒ No ☐ Yes

**RESET ALL** **PLOT CHART**

**CHOOSE A CHART ORIENTATION**

☐ Visual ☐ Reversed ☒ CCD

**DO YOU WANT A CHART OR A LIST OF FIELD PHOTOMETRY?**

☐ Chart ☒ Photometry Table

**WOULD YOU LIKE TO DISPLAY A DSS IMAGE ON THE CHART?**  
*If Yes, retrieves and displays an image from the Digitized Sky Survey*

☐ No ☒ Yes

**WOULD YOU LIKE A STANDARD FIELD CHART?**  
*Standard field charts omit comparison star labels not included in the standard field.*

☒ No ☐ Yes

## Chapter 4: 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 instrumental signal. 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 your software 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.

#### *InfoBox 4.1 – 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  $\sim 1/2$  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 a 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 the Master Bias from each, then median–combine them all together to create a Master Dark.

##### **Flat Frames**

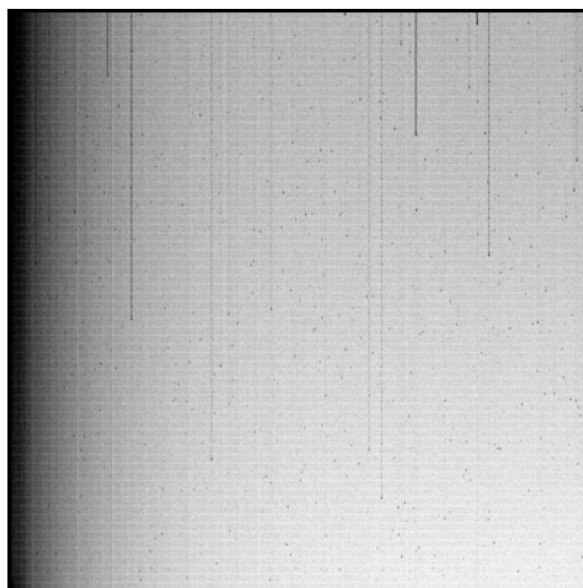
- Take images of a uniform light source or the twilight sky.
- Ensure that focus is good and the same as that of science images.
- Exposure time should result in about half of the full well depth.
- Take 10 or more images for each filter, average (or median combine) them together, then subtract the Master 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 (or the shortest exposure possible with your system) without allowing any light into your camera. Since the bias frames you take will be averaged together to create a "Master Bias", it is necessary to take a lot of them so that any random noise will be smoothed out. Using only a small number of noisy bias frames could actually introduce more error into your science images than it removes!



*Negative image of a bias frame*

All of your calibration and science frames must be taken with the same temperature setting and as low as practical for your location and time of year. Set the camera cooler to a temperature it can reach using no more than 80% 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 rises enough that you can no longer regulate the CCD temperature, or a change is made to your system's electronics path.

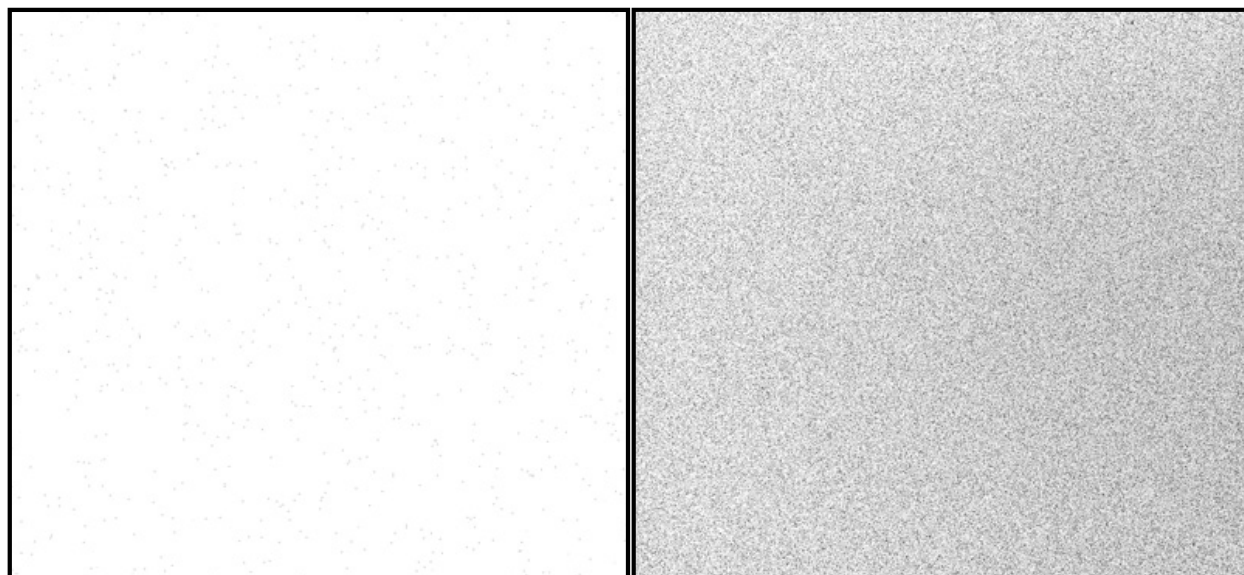
## Dark Frames

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. As with bias frames, you must take new darks any time something changes with your electronic equipment (such as using a new computer, different wiring, etc.)

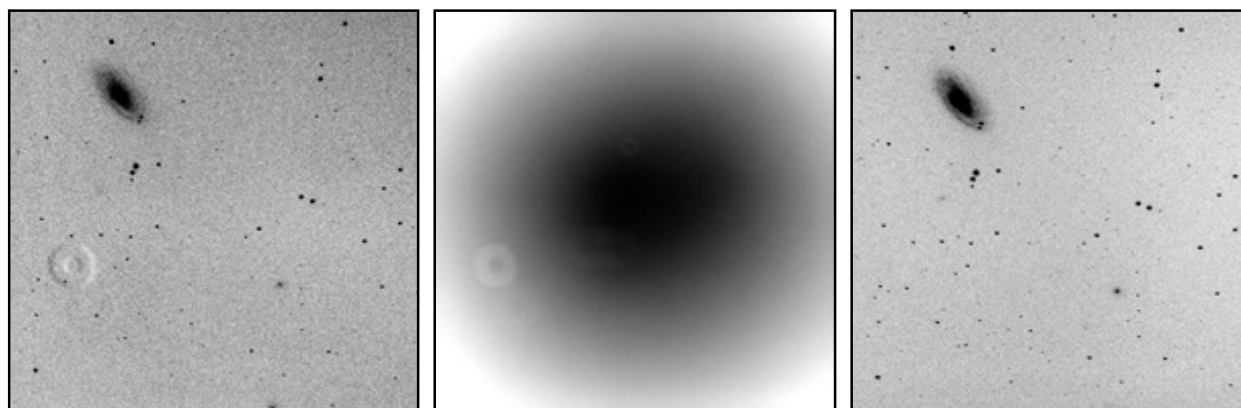


*10-second dark frame  
(negative image)*

*300-second dark frame  
(negative image)*

## 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 flattened 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 InfoBox 4.2*). 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 your science frames, 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 15).

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. Use the Master Dark with an exposure time that is equal to or longer than that of the flat.

You can use the set of Master Flats just created for more than one observing session, but it is good practice to make new ones at least every month. 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.

#### ***InfoBox 4.2 – 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  $5^{\circ}$  - $7^{\circ}$  below the horizon in the evening or ending when the sun is  $5^{\circ}$  - $7^{\circ}$  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.** Consider placing a white T-shirt over the end of your telescope to further diffuse light from any stars that get imaged.
- 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  $\frac{1}{2}$  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 of the filters when it is a bit darker.

### **Science Image Acquisition**

Now that you have a set of calibration frames to work with, its 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 cold a temperature 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 80% (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 earlier, 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 guide!), you should always use photometric filters except for rare cases where the science requirements call for unfiltered observations. 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 which 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 21) for more on this.

### *Choosing exposure times*

The exposure time you select for each image depends on a number of factors including the brightness of the variable at the time, which filter you are using, the quality of your telescope's drive mechanism, and whether or not you are guiding. In general, you should use the longest exposure time appropriate for both overall brightness and timescale of the variation you wish to measure. 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 analog to digital units or ADUs (see the section on determining linearity, page 16). 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 and minimum "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 possible frustration in the future.

Keep in mind that a star image can saturate long 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.
- Very long exposures are best broken into several shorter exposures. The longer the exposure, the more chance there is that your image could be spoiled by drive abnormalities, a passing satellite, cosmic ray hits, passing cloud, etc. The shorter images can be stacked to improve the SNR.
- Never take exposures of less than 3 seconds, and preferably never less than 10 seconds — especially 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 nearly always 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 especially 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 at least three images in each filter, process them separately, average the resulting magnitudes (actually, the fluxes should be averaged before converting to a magnitude, but in most cases the difference is insignificant), 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” (see page 64). 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 20).
- 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. This may include a guide scope or camera and its own software if you have them installed in your system.
- 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*

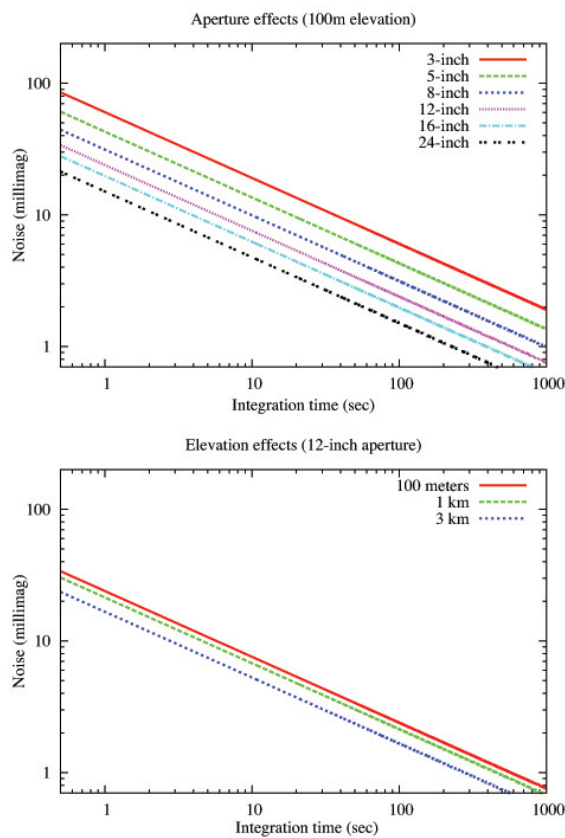
Bright stars pose a special problem for photometrists. In order to avoid saturation of your star image, you will want to use a short exposure time. However, in addition to possible issues caused by the shutter opening and closing, very short exposure images can suffer more from scintillation effects than longer ones where the "twinkling" is averaged out over a longer period of time. To avoid such problems, it is recommended that you never take exposures of less than 10 seconds duration. When you reach the point where you cannot take a short enough exposure to avoid saturation, 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. (Note that you will need to retake flats if you do!)
- Try using a photometric blue (B) filter instead of 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 Ic-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.

In any case, where you have to use very short exposure times to avoid saturation, you should consider taking multiple images and then combining them into a single measure if the star varies slowly enough. This will help lessen the impact of scintillation.

#### InfoBox 4.3 – Scintillation



Scintillation is caused by refraction of starlight by individual turbulent cells in the atmosphere. The stars scintillate on both short and long timescales, but the amplitudes of changes on short timescales are larger. Scintillation has been measured experimentally (see *Young 1967*) and the noise effects on a signal can be approximated as a function of the telescope aperture, the exposure time, the airmass, and the elevation of the telescope site. This graph shows the effects of aperture (top) and site elevation (bottom) on the scintillation noise as a function of exposure time using Young's equation (assuming  $S_0=0.09$ , airmass=1.5). Larger telescope apertures serve to average over more small turbulent cells, so the noise effects in large aperture telescopes are greatly reduced. Radu Corlan's website has useful tables of scintillation effects, available at:

<http://astro.corlan.net/gcx/scint.txt>.

#### 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 as a result.

### *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 amounts of extinction 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 for an object directly overhead is 1 and the airmass for something on the horizon is very large.

#### ***InfoBox 4.4 – Estimating airmass***

Airmass (X) can be approximated using this formula:

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

Where  $\theta$  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.)

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

When you submit your data to the AAVSO, it is desirable for you to include the airmass for each observation. If your photometry software does not calculate it for you or you can not get the airmass from your planetarium software, you could estimate the zenith angle of your target and compute it yourself (*see InfoBox 4.4*).

## **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, but 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.

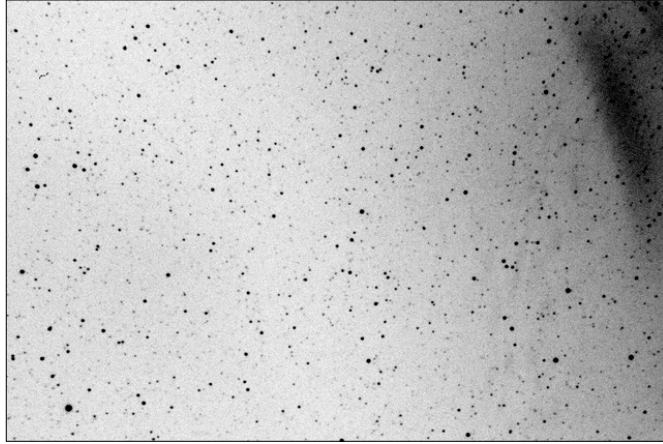
The next few pages contain a list of common image problems and how they manifest themselves. Examples of images with these problems can be found on pages 38–40.

### *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 brightest center of the star. It would be a good idea to do this for the target star as well as for the check star and all the comparison stars you plan to use. If the ADU count for any of them gets close to or exceeds the “full–well depth” of your camera, then that star is saturated and should not be included in any measurements. It is perfectly OK to use other un–saturated stars in the field as long as they aren’t affected by blooming spikes from any star that is saturated.

### *Filter problems*

The filter wheel inside your CCD camera is a fairly delicate piece of equipment. Sometimes the filter wheel can get “stuck” causing it either not to turn at all or to rotate only half–way into position. A filter stuck part–way will often obscure the stars in part of your image. If the filter wheel 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!



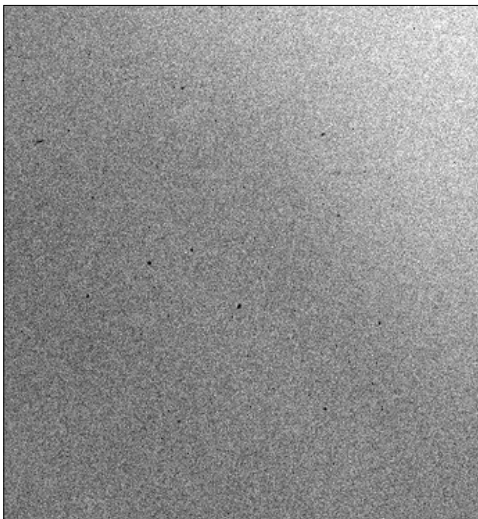
*Negative image showing the effect of scattered light from the Moon in the upper right corner.*

### *Scattered light*

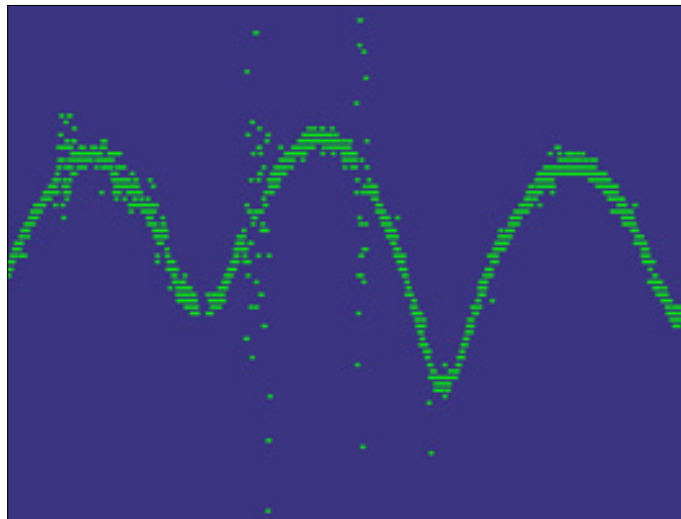
Reflections off the inside of your telescope tube or other optical elements can cause bright areas, rings or double star images that could affect your results. This is particularly evident when the moon is up or there are bright stars or planets near the field you are imaging.

### *Atmospheric problems*

When you are setting up your equipment for a night of imaging, take a few moments to study the sky! Record what you see — especially if there are clouds about — and make notes about the seeing conditions and transparency. As it is difficult to see thin cloud in a very dark sky, you should consider recording what you see when it is still twilight or during dawn.



*Clouds in negative image*



*Light curve of VW Cep showing the effect of clouds*

It isn't always easy to detect the effect of thin cloud in your images, but later on as you study the results of your photometry and suspect that something could be wrong, your notes may come in very handy. In rare cases, a thin, uniform cloud may affect your target star and the comparison stars you are using to the same degree, and due to the way differential photometry works, the effect will be cancelled out. However, this is rarely the case so you should look at the results of your measurements during questionable weather conditions with a great deal of skepticism.

### *Cosmic rays*

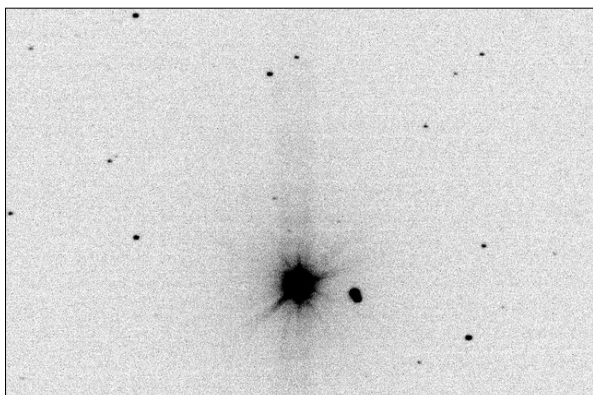
It is not unusual for you to see the effect of cosmic ray hits on your images especially if you are observing from a higher-altitude location. These will manifest themselves as small streaks, curls or small, sharp (1–3 pixel) bright spots on your images. They are random and generally do not pose a problem. 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.

### *Airplanes/satellites/meteors*

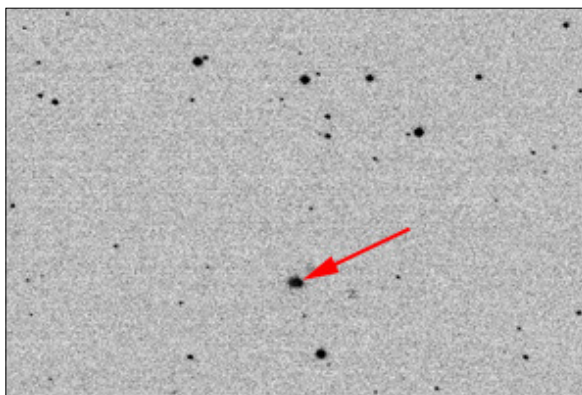
Much as with cosmic rays, airplane, meteor and satellite trails which pass through your image are not a problem as long as they aren't too close to a star you are measuring. If you are unlucky enough for this to happen, you may have to choose other comparison stars or skip using this image altogether.

### *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 a ghost if it looks like a fuzzy patch and gradually fades with each subsequent image. Generally these artifacts

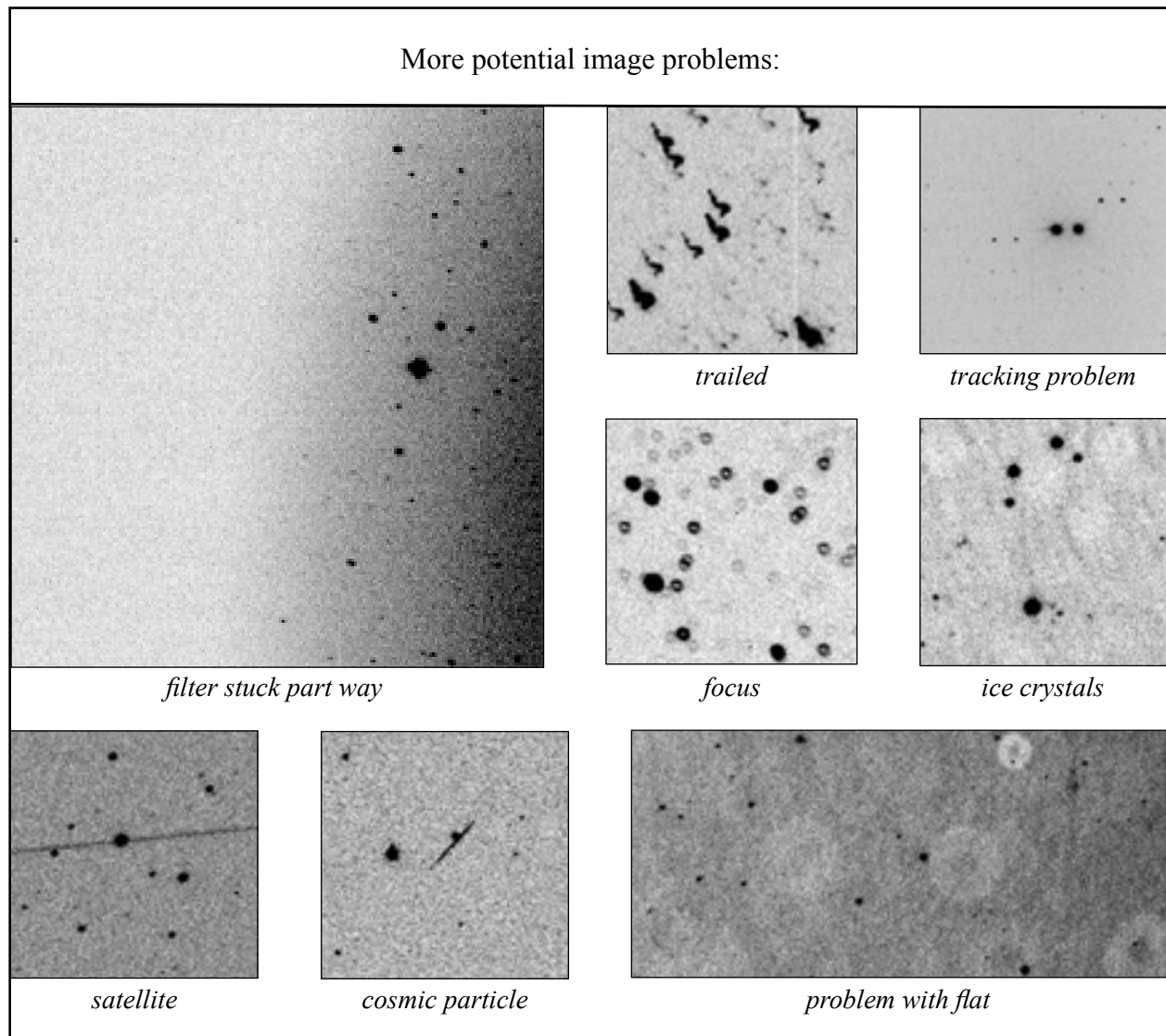


*Negative image showing the bright star DY Eri*



*Next image taken showing a “ghost” of DY Eri in a different field*

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-band) filter. To avoid them, 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.





## Chapter 5: Photometry – measuring images

Now that you have a set of carefully calibrated CCD images, it is time to measure the brightness of the stars you have captured. This is the process known as *photometry*. As with image acquisition and calibration, there is software available to do most of the hard work, but it is important that you understand it and use it properly or your results may not be scientifically useful.

Since there are a variety of software packages available, including the AAVSO's own photometry program – VPhot, this guide will not attempt to delve into specifics of how to use any particular program. Instead it will focus on concepts and techniques common to all of them, which will help you to produce good data.

*What is differential photometry?*

There are two kinds of photometry that are commonly done in astronomy:

- differential photometry – in which the magnitude you derive for the variable star is compared to the magnitude you derive for stars of known brightness in the near field at the same time, so that a “standardized magnitude” for the variable can be determined.
- all-sky photometry – a more complicated procedure in which the star magnitudes are derived directly using the results of nightly calibration of your system and current atmospheric conditions using a set of standard stars outside the field-of-view.

Only differential photometry will be covered in this guide because it is far easier and yields excellent results. It is also much more forgiving when observing conditions are not ideal. For example, if a thin cloud passes through your field of view when you are taking an image, chances are good that it will affect the magnitude of the comparison stars you measure as much as it will affect the magnitude of the target star. The magnitude *difference* between them will therefore be nearly the same and your results may be unaffected.

Here are the steps involved with performing differential photometry on your images:

1. Check your images
2. Identify the stars
3. Set the aperture
4. Choose the check and comparison stars
5. Measure the magnitudes
6. Determine the uncertainty

## 1. Check your images

Although you might have done this before, a visual inspection of each image can save a lot of time and frustration. Look for clouds, airplane or satellite trails or cosmic ray hits that could contaminate any of the stars (both the target and comparisons) you wish to measure. If you've taken a set of time-series images of the same field, you can examine them all in sequence to look for changes over time.

Double-check all of the stars you are measuring to be sure that none of them are saturated. Remember that just because you may not see blooming from a star in your image, doesn't mean that it can't be saturated. One way to see if a star image is saturated or not is to examine a point spread function (psf) plot of the star's brightness profile (see sidebar). If it looks like the top of the curve is flat, chances are good that the star has saturated the detector and there will be no way to derive a good magnitude for it. If you have not yet determined the linearity of your camera it would be a good idea to do so (see Chapter 3, page 16). With practice, you will get a feel for the best exposure time to use for your images based on a star's magnitude and the filter you are using.

Examples of some of the problems you might see when inspecting your images are shown on page 40.

## 2. Identify the stars

Study your images carefully — especially in crowded fields or in cases where the stars you wish to measure are very faint. It is not uncommon for a close companion or nearby star to be confused with the variable star you wish to measure, particularly when the companion is brighter. A large-scale (zoomed in) chart should always be consulted when you are imaging a field that is new to you so you can make sure that there are no hidden surprises, and you observe and analyze the right star.

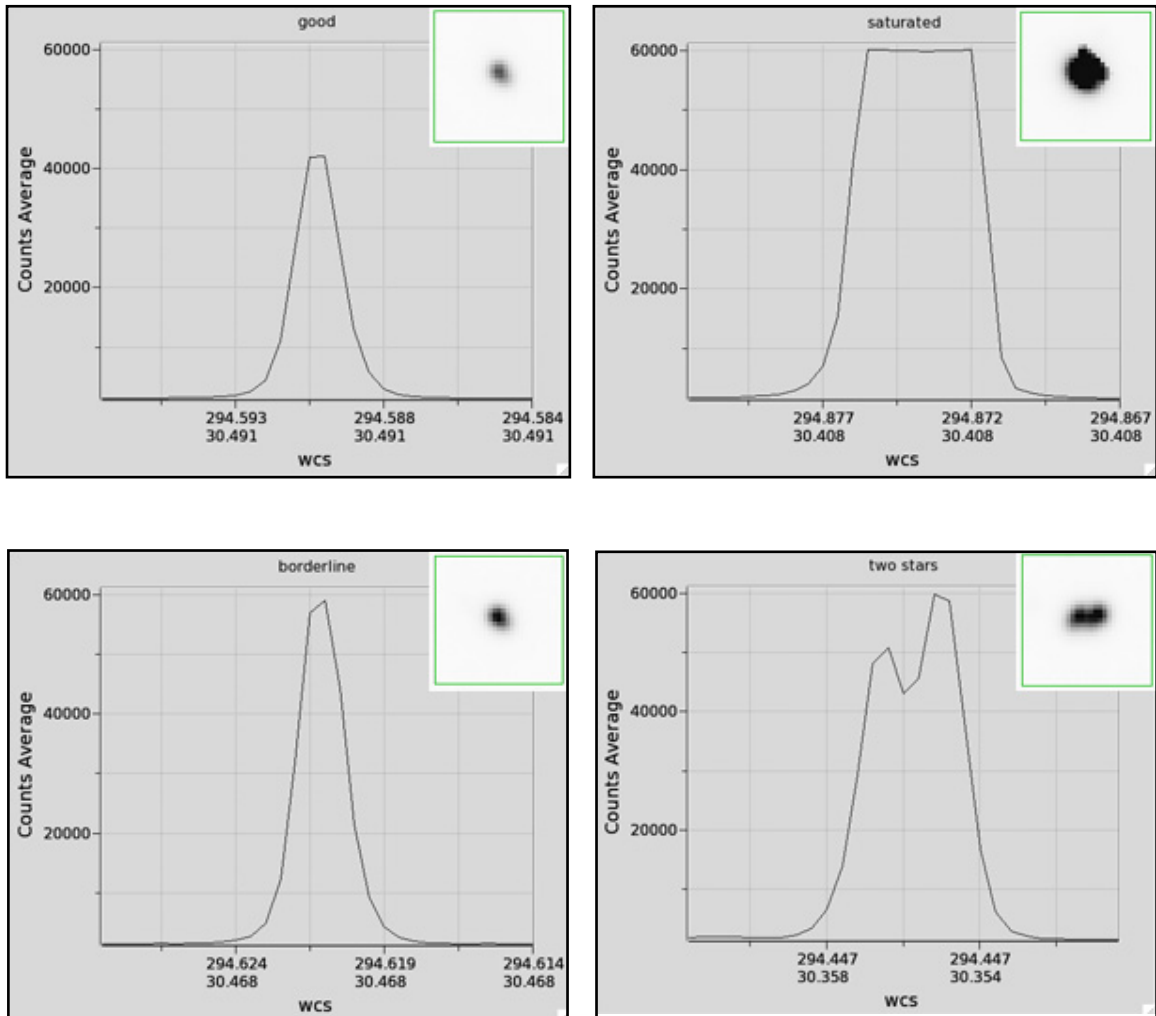
Depending on which software package you use, star identification will either be done automatically or you will have to do it yourself using your charts. In either case, it is important to check to be sure that the variable and comparison stars are correctly identified. Astrometry software is good but not perfect! It can be thrown off by defects in your images or misidentify stars with close companions.

If your software does not import comparison star sequence information from the AAVSO, you will have to do this yourself. The best way to get the information you need is to use the AAVSO Variable Star Plotter (VSP) to make a chart and get a Photometry Table. Using the chart, you can identify the comparison stars and record the published magnitudes for each filter color in the appropriate places. Using a DSS image in your chart can also be very helpful.

### InfoBox 5.1 – The PSF Plot

Your photometry software should provide a way for you to make a point spread function (psf) plot of a selected star from your image. Generally this will be a two– or three– dimensional plot of the ADU count for each pixel versus a cross–section or radial cut through the star as seen on your image.

Such a plot can be very useful in determining whether a star in your image is saturated or perhaps blended with another star. Below are some sample psf plots (created using DS9) along with a close–up of the star being measured from the image.



### 3. Set the aperture

Strictly speaking, photometry is simply the measurement of the amount of light energy received per unit time. In this guide, we will concern ourselves only with the method known as *aperture photometry*, so named because we measure the strength of light in little circles or apertures, centered on individual stars in our image.

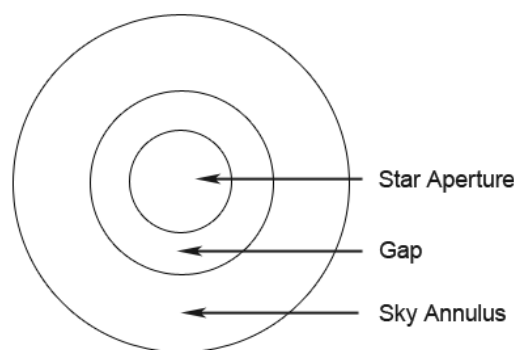
Two other ways in which photometry can be performed include *point spread function (PSF) fitting* and *image subtraction*. These techniques are useful for making measurements in very crowded fields but since both are very complicated and are rarely included in commercial CCD software packages, they will not be covered here.

The aperture is comprised of three parts as seen in the diagram:

*Star aperture (or Measuring aperture)* – this is the innermost circle, which surrounds the star you are measuring.

*Gap* – this is simply a space between the signal circle and the sky annulus.

*Sky annulus* – the outer ring that is used to capture information about the sky background.



The software package you use will probably create these circles automatically as soon as your image is loaded. However, you should have some control over the size of the each ring and may need to make small adjustments to suit your image or avoid problems. One important rule to remember is that *you must use the same sized set of rings for every star in the same image*.

Here are some other suggestions and guidelines regarding the size of the aperture rings:

- The diameter of the star aperture should be 3 to 4 times the rough average FWHM of all the stars you wish to measure. Your software should provide a way for you to determine the FWHM. (FWHM, or “full-width at half-maximum” is defined in Chapter 3, page 17.)
- Make sure it looks like the brightest star you are planning to measure fits completely within the star aperture. If the aperture is too small it won’t measure the star completely. If the aperture is too large, you increase the chance of including other faint stars in it.
- The diameter of the inner circle of the sky annulus should be about 5 times the average FWHM (or about 10 pixels across).
- Adjust the outer ring of the sky annulus if necessary. A bigger sky annulus yields better signal-to-noise ratio (SNR) but it is good to avoid field stars if you can.

- If there is no way to avoid “contamination” from field stars in the sky annulus, don’t panic! Your software may be able to remove their contribution automatically; consult your software manual to see if and how this is done.

#### **4. 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 (B-V) 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?

## 5. Measure the magnitude

In most modern software, with the entry or acquisition of comparison star data, a click of your mouse will provide you with the magnitude of your target. It is good, however, to understand what is going on within your software to accomplish this (especially if you have older software that is not as automatic).

The first step the software takes is to measure the *instrumental magnitude*. This is simply a number related to the count of the photons (or ADUs) captured within the aperture. By subtracting the instrumental magnitude of a comparison star from the instrumental magnitude of the target star, you get what is known as a *differential magnitude*. Here is the formula:

$$\Delta v = v_{\text{measured}} - c_{\text{measured}}$$

Where  $\Delta v$  is the differential magnitude,  $v_{\text{measured}}$  is the instrumental magnitude of the variable star and  $c_{\text{measured}}$  is the instrumental magnitude you just measured of the comparison star.

In order to make your observations more useful to the scientific community, you now need to convert from a differential magnitude to a *standardized magnitude* by adding to it the published magnitude of the comparison star like this:

$$V = \Delta v + C_{\text{published}}$$

Nearly all software packages available today, will allow you to perform what is known as *ensemble photometry*. What this does is to compare one-by-one the variable star with each comparison star you selected. Using the equations above it will then compute the standardized magnitude of the target star based on each comparison star and return the results as a weighted average of all these

values. You are left with one standardized magnitude for your target star, which is generally less error-prone than it would be if only one comparison star was used. If it seems like one of the comparison stars in the ensemble is noisy or has a problem which is adversely affecting your results, try removing it from the ensemble and re-compute the average again.

Please note that we are using the convention that lower-case letters stand for instrumental magnitudes, upper-case, italicized letters (like *V*) are for standardized magnitudes, and non-italicized upper-case letters are for magnitudes which have been *transformed*. We'll explain transformation in the next section, but to summarize quickly: you may have taken an image with a standard Johnson V-filter, but you must perform some additional calculations to place your measured “v” magnitude onto the Johnson V system with the highest accuracy. We'll show you how in Chapter 6.

### ***InfoBox 5.2 – A note about magnitudes***

The magnitude system dates from the second century BCE, and is attributed to the Greek astronomer Hipparchus. It is a logarithmic system where brighter stars are assigned smaller magnitudes. The system was developed to classify naked-eye stars, but has been adapted in the telescopic age to measure optical brightness for many kinds of astronomical objects. There is a direct relation between magnitudes and fluxes: five magnitudes difference in brightness corresponds to a multiplicative factor of 100 difference in flux, meaning that each magnitude corresponds to a factor of approximately 2.5 in flux. Because the magnitude scale is logarithmic, ratios of fluxes can be expressed as differences in magnitudes. The relative difference in magnitudes between two objects with different measured fluxes can be obtained with the following equation:

$$\text{mag}_1 - \text{mag}_2 = -2.5 \log_{10} (\text{flux}_1 / \text{flux}_2)$$

For a longer discussion, see the AAVSO website: <http://www.aavso.org/magnitude>

Your software will probably convert measured fluxes (number of ADU within your measurement aperture) to instrumental magnitudes for you, but be aware that it may use arbitrary zero-points for these instrumental magnitudes. This may lead to strange-looking (but otherwise perfectly legitimate) instrumental magnitudes like “-12.567”. Such instrumental magnitudes are fine as long as *all of the stars are measured with the same instrumental zero-point*. This is because the zero points cancel each other out when differential magnitudes are calculated.

## 6. Determine the uncertainty

The magnitudes that you measure only provide part of the information of your observation. Every legitimate piece of scientific data comes not only with a measurement, but also with an *uncertainty*, which tells the researcher who uses your data how well constrained your measurement is. Therefore, it's important that you accurately calculate and submit the uncertainty in your magnitudes along with the magnitude itself.

Your measurement uncertainty will contain both a *random* component and a *systematic* one. Random noise includes things such as photon noise (which is proportional to the square root of the number of photons your camera receives), and thermal noise in your CCD detector. These noise sources need to be characterized, but very little can be done to reduce them, and they put a lower limit on your uncertainty. Systematic uncertainties are related to your instrumentation, and can include things such as the way that your measurement apertures influence your output magnitudes, or whether you have uncertainties or errors in your flat fields or in the magnitudes you use in your comparison star values. We will not go into a detailed discussion of the theory of uncertainties here, but we recommend the AAVSO's CHOICE course *Uncertainty about Uncertainties* and the accompanying notes by Aaron Price for further discussion. We'll simply limit ourselves to *how* to do this.

The easiest but not ideal way is to let your CCD software do the work. Most CCD software will either return an uncertainty in magnitudes or will tell you the signal-to-noise ratio (SNR or S/N). A handy approximation is to assume that the uncertainty in magnitudes is  $1/\text{SNR}$ , so that a stated SNR of 50 yields an uncertainty of 0.02 magnitudes. The reason we say this is not ideal is (a) the SNR will be calculated just for each image that you measure, and will not tell you anything about noise from non-photometric conditions for example, and (b) you have to trust that the software is doing this correctly. Most software *now* does a reasonable job of doing this, but historically that was not always the case for all software. As always, look at your results and see if they make sense.

Beyond that first method, there is no one best way to calculate uncertainties, but it depends on what and how you plan to observe. If you're making multiple measurements of a star during a single night (e.g. a time series run), you can use the variations observed in either your variable or your comparison and check stars to estimate the total photometric uncertainty. There are two choices here. If you know the variable isn't changing in brightness on short timescales (a Mira star, for example), then you can calculate the magnitude of the variable on each frame, and then calculate the standard deviation of those measures of the variable to give you the uncertainty. (Note: ideally, for a slowly varying star, you would go a step further and combine all of the measures of the variable made on a single night into one magnitude instead of submitting the entire time series.) If the variable does change on short timescales (a cataclysmic variable, for example), then you should



instead obtain the uncertainty from multiple measures of your comparison or check stars instead. In all cases, you compute the uncertainty using the equation for the standard deviation,  $\sigma$ :

$$\sigma = ( (\Sigma(x_i - x)^2) / (N-1) )^{1/2}$$

where  $x_i$  are the individual magnitudes,  $x$  is the average magnitude, and  $N$  is the total number of measures being averaged. You would then report  $\sigma$  as your uncertainty. Note that if you are using the standard deviation of a comparison or check star for this test, you should use one that has similar brightness to the variable.

If instead you only take one image per filter of a given field, you're limited to calculating uncertainties based on the information contained in this one image. For the case of a faint star, *you must use the CCD equation*:

$$S/N = N_{star} / (N_{star} + n(N_{sky} + N_{dark} + (N_{readnoise})^2) )^{1/2}$$

where  $N$  is the number of photons received from each of star, sky, dark current, and the readnoise of the CCD, and  $n$  is the number of pixels in your measurement aperture. Although this may look complicated, it is simply a modification of the case where you're measuring the uncertainty due just to photon noise. To see this, imagine that  $N_{star}$  is much larger than any of the other terms. In that case, the CCD equation approaches the limit of the square root of the number of photons received.

Note two things here. First, note that  $N$  in the above equation is the number of photons, rather than the number of ADU, which is what your CCD measures. This introduces a slight modification to the equation for ADU which includes the *gain*,  $G$ :

$$S/N = N_{ADU} \times G / ( (N_{ADU} \times G) + n_{pix} \times ( (N_{ADU,sky} \times G) + N_{dark} + (N_{r.n.})^2 ) )^{1/2}$$

Second, note conveniently that *you can use the SNR value from your software instead of the full CCD equation* to estimate the uncertainty in the case of a star whose brightness is well above both the sky background and readnoise.

The next best option with single-image photometry is the case where you have multiple comparison stars available in the frame. In this case, you can measure all of the comparison stars along with the variable, calculate the magnitude of the variable obtained using each of the comparisons, and then calculate the standard deviation of all of these magnitudes. This will take into account the intrinsic uncertainties in both the variable and the comparison stars.

The CCD equation is universal, but is also somewhat involved to calculate, since you have to measure all of these things individually, and it doesn't provide information about other sources of uncertainty beyond what was present in that specific image, such as sky conditions. However, with a single image, it's the best you can do and you should use it, especially in the case where you're working with faint stars and lower S/N.

## Chapter 6: Transforming your data

### *Why is transformation necessary?*

The AAVSO International Database is composed of data collected from many different observers, at different times, from around the globe. The beauty of such a system is that it allows all interested observers to contribute to the archive, thus it has a great deal of potential to expand the duration and breadth of coverage for the target stars. Unlike data collected through surveys, which can experience coverage gaps due to bad weather conditions, equipment failures or discontinuation of funding, the AAVSO approach reduces the effect of such problems. On the other hand, the fact that each observer is using different equipment and procedures can introduce offsets which makes it difficult to reconcile from one observer to another.

Assuming that the procedures outlined in this guide have been followed carefully, and no mistakes have been made along the way, the largest remaining differences between measurements reported by two different observers looking at the same star with the same filter at the same time is likely caused by differences in the color response of each observer's equipment. Each telescope, filter and CCD combination has its own unique characteristics, which, depending on the color of the star being measured and the filters used, can result in magnitude differences of anywhere from several hundredths of a magnitude to several tenths of a magnitude from one observer to another. Even two photometric filters purchased from the same vendor will have a slightly different spectral response that will affect your measurements!

By transforming your data to a standard system, these differences can be greatly reduced if not eliminated. This will have the effect of not only bringing your observations more in line with those of other observers who have transformed their data, but it will make the whole database more scientifically useful. It is the goal of the AAVSO to get all CCD observers to transform their data as a matter of course.

### *How do I transform my data?*

There are two parts to the process of transforming your data. The first is to determine your transformation coefficients. The second is to apply these coefficients to your observations.

At first, you may find the whole process a little daunting and certainly there has been much confusion and little guidance available in the past. With this guide, the AAVSO hopes to change this by explaining the process clearly and by covering only the simplest, most straightforward cases. By following this procedure, you will achieve most if not all of the corrections necessary to convert your data to the standard system. If you wish to delve deeper, please check out the references listed at the end of this guide.

## General overview and assumptions

For the sake of simplicity and to be consistent with other material given in this guide, the explanation that follows assumes that you are performing differential aperture photometry. The magnitudes you derive and ultimately include in your report to the AAVSO are differential magnitudes, that is to say, they are derived by measuring the difference in brightness between the variable and a comparison star.

For example, if you measure two stars of true equal brightness in the bandpass of a standard filter, you will derive two different measured magnitudes for these stars with your own system if the two stars are not equal in color. Our goal will be to transform these measurements to a *standard system*, such that the resulting magnitudes you report will be the same.

In order to make this transformation to a standard system, you need to know two things: the color of the stars you are measuring — known as *differential instrumental color* — and the effect of that color on the differential magnitude you obtained — the *differential instrumental magnitude*.

By relating the differential instrumental color to the *differential true color* of standard stars for which the colors have been very carefully determined, you will be able to come up with a term called a *color transform*. In a similar way, by relating the differential instrumental magnitude to the *true differential magnitude* of this same set of standard stars you can derive a *magnitude transform*. Applying these two transforms to observations you make of variable stars where the color and magnitude is not accurately known will enable you to “correct” your measurements and convert them to a standard system which in theory can be matched by fellow observers.

In astronomy, the color of a star (or color index) is generally expressed as the difference in magnitude resulting from measurements made with two different filter colors. You can do this with different combinations of filters, but since the most widely used measure is b-v (i.e. the magnitude as measured using a Johnson B filter minus the magnitude as measured using a Johnson V filter), it will be assumed that you have these two color filters at least. As you will see later, there is a way in which you can transform your data even if you have only one photometric filter, but generally your results will be better if you have at least two. If you use more than two filters, you will need to come up with color and magnitude transformation coefficients for each of them.

## Determining your transformation coefficients

### *Step 1 – Image a standard field and calibrate the images*

The first step in determining your transformation coefficients is to image a “Standard Field” using each of your filters. Standard fields are star fields for which the magnitudes of selected stars are

known very precisely in several colors. For your convenience, the AAVSO has prepared standard sequences for six star clusters, which were selected on the basis of several factors including their range of colors and quantity of stars that will conveniently fit into one CCD image.

***Table 6.1 – Standard clusters***

<b>Name</b>	<b>RA</b>	<b>Dec</b>	<b>Mag Range</b>	<b>Diameter(arc min)</b>
NGC 1252	03:10:49	-57:46:00	8 – 15	300+
M67	08:51:18	+11:48:00	7 – 16	74
NGC 3532	11:05:39	-58:45:12	8 – 13.5	30
Coma Star Cluster	12:22:30	+25:51:00	5 – 10	450
M11	18:51:05	-06:16:12	8.5 – 17	20
NGC 7790	23:58:23	+61:12:25	10 – 20	7

You can produce a chart for one of these fields using the AAVSO Variable Star Plotter (VSP) by typing in the RA and Dec of the cluster you wish to image and selecting the FOV and limiting magnitude appropriate to your system, as you would with any other chart. Be sure also to select “Yes” to the question, “Would you like a standard field chart?” This should result in a chart similar to the one in Figure 6.1 on the next page. You may also wish to print out the associated Photometry Table containing the published magnitudes of all the Standard stars, which will come in handy if your software does not load the comparison star photometry for you (see Figure 6.2, page 55).

Now use the same good practices you would follow with any imaging. Try to image the clusters when they are high in the sky and set your exposure time so that you can get as many counts as reasonable without saturating the brighter stars. Take several images with each filter and stack them to increase the SNR. Then calibrate your images with bias, darks and flat frames.

To minimize the effects of spurious problems or atmospheric effects, it is a good idea to repeat the entire process of imaging the standard field and computing your coefficients over several nights. Your results from each of the nights can then be averaged together to get one better set of coefficients.

### ***Step 2 – Measure the images to obtain instrumental magnitudes***

Using your photometry software, measure as many stars as you can to obtain their instrumental magnitudes. There is no need to select a specific target star or check star. As with any crowded field, be careful not to measure any stars that are so close together that their images are “blended.” Also be very careful with star identification and in the case of multiple stars with the same identifier, check the RA and Dec to be sure you know which is which.

Figure 6.1 – M67 chart

This sample chart was produced using the AAVSO's Variable Star Plotter (VSP) using the RA and Dec for M67 given in Table 6.1 with a FOV of 15' and magnitude limit of 13.8. The stars circled in red were used in the example given in this Guide.

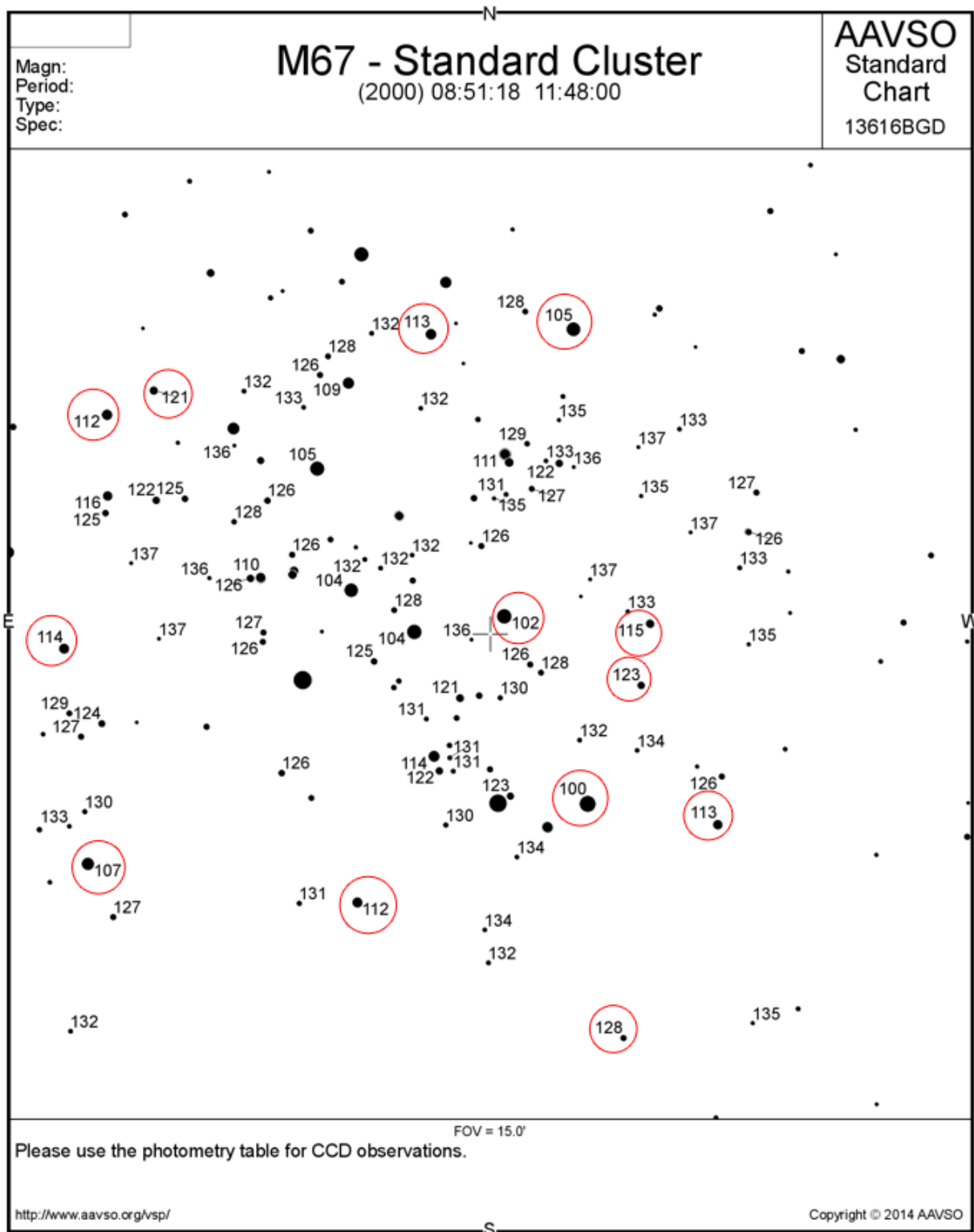


Figure 6.2 – M67 photometry table

This is an *excerpt* of the photometry table associated with the chart in Figure 6.1 showing the 10 brightest stars used for computing the transformation coefficients in the example. They are the same stars as those circled on the chart.

## Variable Star Plotter (VSP)

■ Printable Version ■ Return & Replot

### Field Photometry From the AAVSO Variable Star Database

Data includes all comparison stars within 0.12500° of RA: 08:51:18 (132.82500) & Decl.: 11:48:00 (11.80000).

AUID	RA.	Dec.	Label	U	B	V	B-V	Rc	Ic	J	H	K	Comments
000-BLG-879	8:51:11.82 [132.79926d]	11:45:21.7 [11.75602d]	100	-	9.978 (0.050) <sup>10</sup>	10.040 (0.029) <sup>10</sup>	-0.062 (0.058)	10.059 (0.040) <sup>10</sup>	10.086 (0.049) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-886	8:51:17.12 [132.82133d]	11:48:16.4 [11.80455d]	102	12.915 (0.038) <sup>10</sup>	11.553 (0.023) <sup>10</sup>	10.289 (0.016) <sup>10</sup>	1.264 (0.028)	9.626 (0.021) <sup>10</sup>	9.063 (0.027) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-887	8:51:22.83 [132.84512d]	11:48:02 [11.80056d]	104	12.583 (0.031) <sup>10</sup>	11.562 (0.018) <sup>10</sup>	10.453 (0.014) <sup>10</sup>	1.109 (0.023)	9.886 (0.016) <sup>10</sup>	9.386 (0.020) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-888	8:51:26.87 [132.86194d]	11:48:40.7 [11.81131d]	104	11.118 (0.022) <sup>10</sup>	11.064 (0.016) <sup>10</sup>	10.489 (0.013) <sup>10</sup>	0.575 (0.021)	10.149 (0.015) <sup>10</sup>	9.822 (0.021) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-890	8:51:29.01 [132.87090d]	11:50:33.3 [11.84260d]	105	12.703 (0.030) <sup>10</sup>	11.656 (0.018) <sup>10</sup>	10.533 (0.012) <sup>10</sup>	1.123 (0.022)	9.952 (0.014) <sup>10</sup>	9.438 (0.017) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-889	8:51:12.71 [132.80298d]	11:52:42.6 [11.87850d]	105	12.620 (0.032) <sup>10</sup>	11.617 (0.023) <sup>10</sup>	10.524 (0.016) <sup>10</sup>	1.093 (0.028)	9.961 (0.020) <sup>10</sup>	9.471 (0.022) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-891	8:51:43.58 [132.93156d]	11:44:26.7 [11.74076d]	107	13.003 (0.029) <sup>10</sup>	11.898 (0.019) <sup>10</sup>	10.763 (0.016) <sup>10</sup>	1.135 (0.025)	10.185 (0.020) <sup>10</sup>	9.657 (0.023) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-892	8:51:27.04 [132.86266d]	11:51:52.8 [11.86467d]	109	11.117 (0.030) <sup>10</sup>	11.042 (0.021) <sup>10</sup>	10.946 (0.019) <sup>10</sup>	0.096 (0.028)	10.902 (0.022) <sup>10</sup>	10.844 (0.024) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-893	8:51:32.62 [132.88593d]	11:48:52.3 [11.81454d]	110	11.416 (0.027) <sup>10</sup>	11.283 (0.019) <sup>10</sup>	11.064 (0.017) <sup>10</sup>	0.219 (0.025)	10.948 (0.020) <sup>10</sup>	10.820 (0.024) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-894	8:51:17.07 [132.82111d]	11:50:46.7 [11.84630d]	111	13.192 (0.029) <sup>10</sup>	12.221 (0.018) <sup>10</sup>	11.132 (0.014) <sup>10</sup>	1.089 (0.023)	10.560 (0.017) <sup>10</sup>	10.059 (0.021) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-895	8:51:26.46 [132.86024d]	11:43:51 [11.73083d]	112	11.474 (0.027) <sup>10</sup>	11.391 (0.019) <sup>10</sup>	11.263 (0.016) <sup>10</sup>	0.128 (0.025)	11.215 (0.017) <sup>10</sup>	11.146 (0.023) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-896	8:51:42.39 [132.92662d]	11:51:23.3 [11.85648d]	112	13.307 (0.032) <sup>10</sup>	12.342 (0.016) <sup>10</sup>	11.266 (0.012) <sup>10</sup>	1.076 (0.020)	10.697 (0.016) <sup>10</sup>	10.187 (0.020) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-897	8:51:21.78 [132.84074d]	11:52:38.1 [11.87724d]	113	12.060 (0.025) <sup>10</sup>	11.911 (0.020) <sup>10</sup>	11.305 (0.013) <sup>10</sup>	0.606 (0.024)	10.945 (0.018) <sup>10</sup>	10.609 (0.020) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-898	8:51:03.54 [132.76474d]	11:45:03 [11.75083d]	113	11.727 (0.028) <sup>10</sup>	11.604 (0.020) <sup>10</sup>	11.314 (0.017) <sup>10</sup>	0.290 (0.026)	11.149 (0.021) <sup>10</sup>	10.988 (0.025) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-899	8:51:21.59 [132.83995d]	11:46:06.4 [11.76845d]	114	13.463 (0.031) <sup>10</sup>	12.500 (0.017) <sup>10</sup>	11.427 (0.014) <sup>10</sup>	1.073 (0.022)	10.867 (0.016) <sup>10</sup>	10.376 (0.020) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-900	8:51:45.10 [132.93793d]	11:47:46.2 [11.79617d]	114	13.451 (0.026) <sup>10</sup>	12.546 (0.016) <sup>10</sup>	11.494 (0.011) <sup>10</sup>	1.052 (0.019)	10.941 (0.014) <sup>10</sup>	10.442 (0.017) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-901	8:51:07.84 [132.78265d]	11:48:09.5 [11.80264d]	115	11.912 (0.025) <sup>10</sup>	11.949 (0.017) <sup>10</sup>	11.544 (0.014) <sup>10</sup>	0.405 (0.022)	11.293 (0.017) <sup>10</sup>	11.050 (0.021) <sup>10</sup>	-	-	-	STD_FIELD
000-BLG-902	8:51:42.37 [132.92653d]	11:50:07.9 [11.83554d]	116	13.599 (0.029) <sup>10</sup>	12.686 (0.017) <sup>10</sup>	11.636 (0.012) <sup>10</sup>	1.050 (0.021)	11.081 (0.015) <sup>10</sup>	10.580 (0.020) <sup>10</sup>	-	-	-	STD_FIELD

### Step 3 – Compute the transformation coefficients

AAVSO volunteers have developed software tools to assist you with both computing transformation coefficients and the next step — applying the coefficient to transform your data (*see <http://www.aavso.org/transform>* to download the programs and read useful information about them). In order to understand the principles, this guide uses the “spreadsheet method” so that you can see what is being done more clearly.

The easiest way to explain the process of transforming your data is to give an example using real data. This will enable you to see how it works without getting into a lot of theory and messy equations. You can then substitute your own data into the appropriate tables and derive your own results.

In the example that follows, it has been assumed that you are following the most common practice and imaging in just two colors – Johnson B and Johnson V. For simplicity, just 13 stars in the standard field of M67 were measured. In reality, it is better to include more like 30–50 stars covering a wide range of colors. Our sample data has been entered in the columns marked “My Data”. In all cases, the instrumental magnitudes you obtain are given in lower case letters while the Standard (published) magnitudes are given in upper case letters. Your goal is to compute one color transform ( $T_{bv}$ ) and two magnitude transforms ( $T_{b_{bv}}$  and  $T_{v_{bv}}$ ) from this data set.

Start by entering the identifier(s) of each star you measured along with its instrumental magnitude from images made using each filter you use. Add the published magnitudes of the same stars for each color:

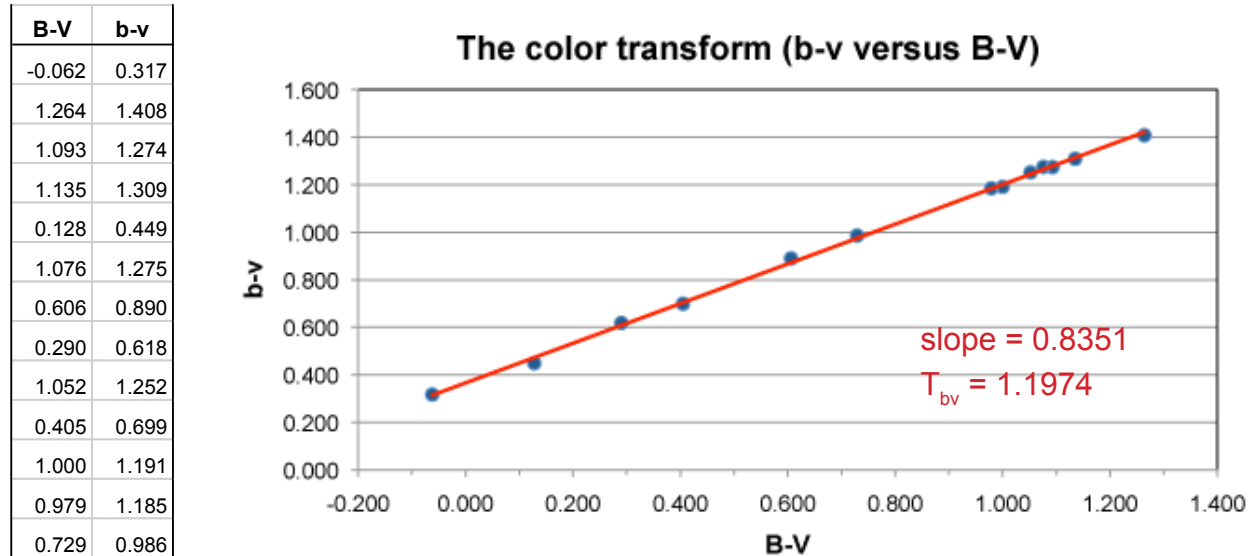
Table 6.2 – Sample data for M67

M67		My Data (inst. mags)			Standard Data		
Star ID	AUID	b	v	i	B	V	I
100	000-BLG-879	-7.981	-8.298	-7.501	9.978	10.040	10.086
102	000-BLG-886	-6.575	-7.983	-8.462	11.553	10.289	9.063
105	000-BLG-889	-6.487	-7.761	-8.102	11.617	10.524	9.471
107	000-BLG-891	-6.194	-7.503	-7.866	11.898	10.763	9.657
112	000-BLG-895	-6.591	-7.040	-6.421	11.391	11.263	11.146
112	000-BLG-896	-5.725	-7.000	-7.337	12.342	11.266	10.187
113	000-BLG-897	-6.111	-7.001	-6.960	11.911	11.305	10.609
113	000-BLG-898	-6.364	-6.982	-6.562	11.604	11.314	10.988
114	000-BLG-900	-5.511	-6.763	-7.072	12.546	11.494	10.442
115	000-BLG-901	-6.054	-6.753	-6.493	11.949	11.544	11.050
121	000-BLG-904	-4.929	-6.120	-6.400	13.138	12.138	11.122
123	000-BLG-908	-4.709	-5.894	-6.121	13.359	12.380	11.409
128	000-BLG-929	-4.508	-5.494	-5.497	13.541	12.812	12.033



Next, create the plot used to determine the color transform by plotting the instrumental color ( $b-v$ ) versus the Standard color index ( $B-V$ ). The advantage of actually plotting your data is that you can see how your observations fit the line and remove outliers so they will not negatively impact your results.

Figure 6.3 – Plotting the color transform



Note that a least square fit trend line was added and its slope computed to be 0.8351 in this example. Since the color transform is defined as the inverse of this slope or  $1/0.8351$ ,  $T_{bv} = 1.1974$ .

To compute the B and V magnitude transforms, start with the same data as in Table 6.2, but this time plot the difference between the standard magnitude and the instrumental magnitude ( $B-b$ ) or ( $V-v$ ) versus the standard color index ( $B-V$ ) as shown:

Figure 6.4 – Plotting the B-magnitude transform

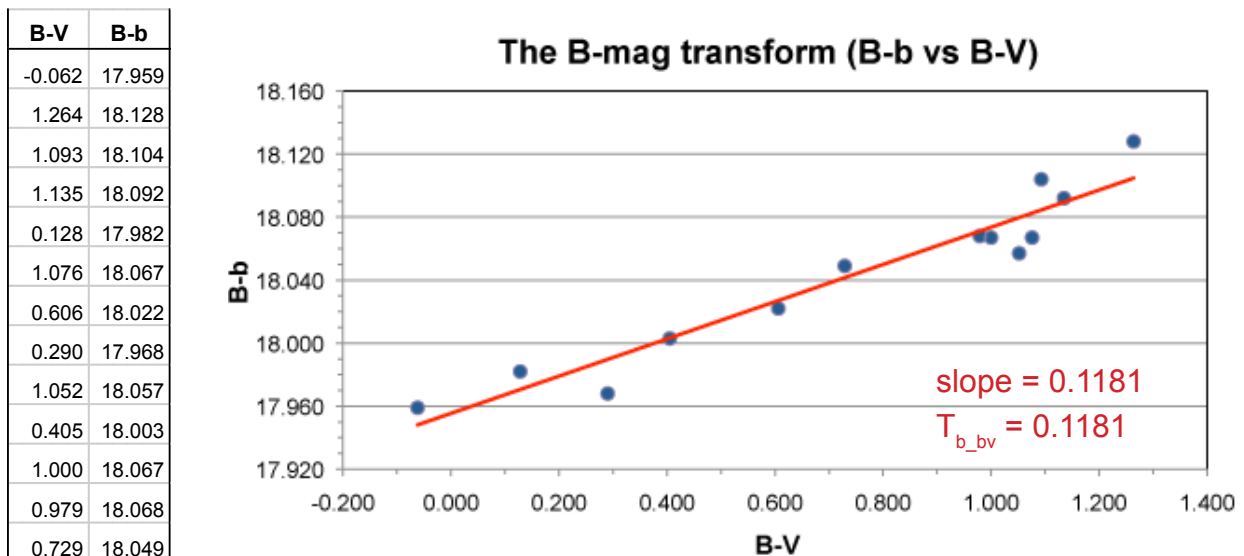
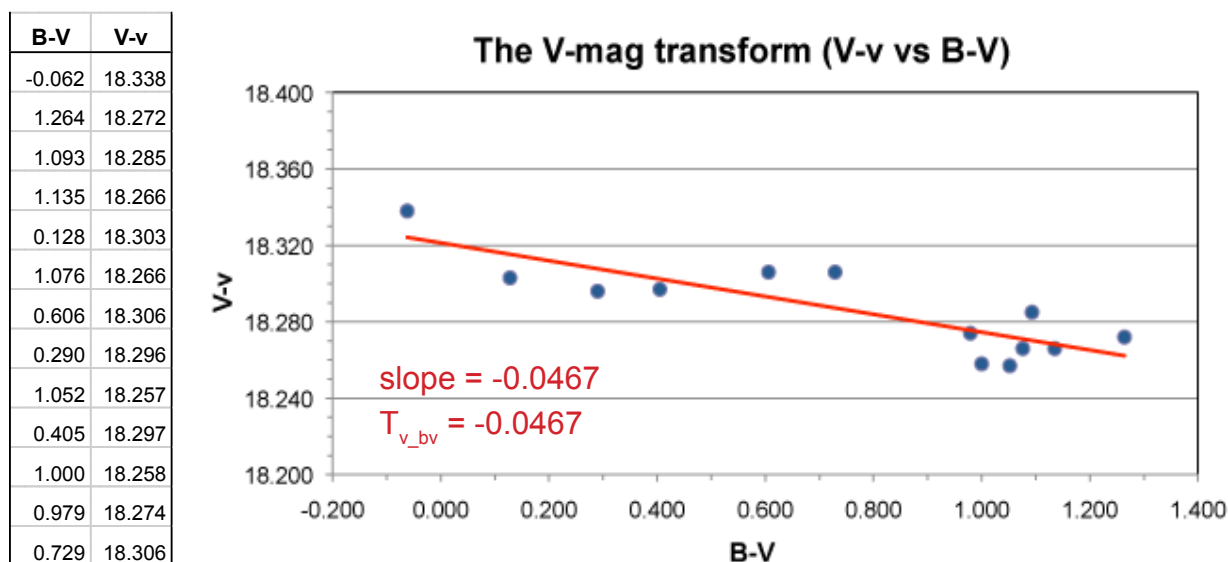


Figure 6.5 – Plotting the V–magnitude transform



You might wonder why we bother to create plots for each of the transforms when the least–squares fit and slope can be computed without them. The answer is that with a plot, it is easy for you to pick out any points that are outliers and exclude them from the computation.

*What happens if I want to use more than two colors or a different set of colors?*

Depending on the filter set you use, you may find that you need to find transformation coefficients for your system using an Ic– or Rc–band or some other filter. These would be computed in much the same way as the B and V coefficients described previously.

For example, if you have an Ic–band filter in addition to the B– and V– band ones, you will need to calculate two more coefficients:

$$T_{vi} = 1/\text{slope of the plot for v-i versus V-I}$$

$$T_{i\_vi} = \text{slope of the plot for I-i versus V-I}$$

Similarly if you have a BVR filter set you would need to add these coefficients instead:

$$T_{vr} = 1/\text{slope of the plot for v-r versus V-R}$$

$$T_{r\_vr} = \text{slope of the plot for R-r versus V-R}$$

There is also more than one way to calculate the same coefficients using different colors, which you might find useful. For example, if you are imaging a very red star (like a Mira) which happens

to be too faint at minimum to detect using a B–filter, and you have an Ic or Rc filter available, you could use one of these combinations to compute the V magnitude transform:

$$T_{v_{vi}} = \text{slope of the plot for V-v versus V-I}$$

or

$$T_{v_{vr}} = \text{slope of the plot for V-v versus V-R}$$

*How often must I compute my transformation coefficients?*

Transformation coefficients should be computed at least once a year, but if you change anything in your optical train (replacing a filter, adding a field flattener, etc) you will have to compute your coefficients again.

### **Applying the transformation coefficients**

Now that you have computed your transformation coefficients, it is time to use these coefficients to transform real target data to the standard system. For the sake of simplicity, it is assumed that you are using just one comparison star and not an “ensemble” of comparison stars. Note: Transforming observations that were derived using an ensemble of comparison stars is an advanced technique which depends on how the ensemble was calculated. As such, it is best left to software packages.

The basic equation is here:

$$V_{var} = \Delta V + T_{v_{bv}} * \Delta(B-V) + V_{comp}$$

... and here is an explanation of each term:

- $\Delta V$  is the instrumental magnitude of the variable minus the instrumental magnitude of the comparison star or  $V_{var} - V_{comp}$
- $V_{comp}$  is the published V–magnitude of the comparison star
- $T_{v_{bv}}$  is the V–magnitude coefficient you just calculated
- $\Delta(B-V)$  is the difference in the standard color of the variable versus the standard color of the comparison star. This should be computed using the formula:

$$\Delta(B-V) = T_{bv} * \Delta(b-v)$$

In other words, you can derive  $\Delta(B-V)$  by multiplying your color transform by the measured color difference between the variable and comparison star,  $\Delta(b-v)$ . Of course, this assumes that you

actually made images of the target star using both a B filter and a V filter. If for example, you were only able to create an image in one color, it is possible to substitute the published B-V values for the variable and comparison stars (if they exist) for the measured ones in the above equation. Please note that this method is prone to error since in many cases, the color of a variable star may change.

As before, it is easier to understand what is going on using an example based on actual data. Here is some sample data (the instrumental magnitudes are given):

Variable: measured		Comp: measured		Comp: published	
b	v	b	v	B	V
-6.223	-7.855	-6.202	-7.109	11.779	11.166

... and the B and V transformation coefficients computed earlier:

$T_{bv} = 1.1974$ $T_{b_{bv}} = 0.1181$ $T_{v_{bv}} = -0.0467$
--

Start by computing  $\Delta(b-v)$  with the equation:

$$\Delta(b-v) = (b-v)_{var} - (b-v)_{comp}$$

$$(b-v)_{var} = -6.223 - (-7.855) = 1.632$$

$$(b-v)_{comp} = -6.202 - (-7.109) = 0.907$$

$$\Delta(b-v) = 1.632 - 0.907$$

$$\Delta(b-v) = 0.725$$

Now multiply this result by the color transform to get  $\Delta(B-V)$ :

$$\Delta(B-V) = T_{bv} * \Delta(b-v)$$

$$\Delta(B-V) = 1.1974 * 0.725$$

$$\Delta(B-V) = 0.868$$

Compute  $\Delta v$  with:

$$\Delta v = v_{var} - v_{comp}$$

$$\Delta v = -7.855 - (-7.109)$$

$$\Delta v = -0.746$$

Putting it all together:

$$V_{\text{var}} = \Delta v + T_{v_{\text{bv}}} * \Delta(B-V) + V_{\text{comp}}$$

$$V_{\text{var}} = -0.746 + (-0.0467 * 0.868) + 11.166$$

$$V_{\text{var}} = 10.379$$

Just for comparison, the un-transformed magnitude would be simply:

$$V_{\text{var}} = \Delta v + V_{\text{comp}}$$

$$V_{\text{var}} = -0.746 + 11.166$$

$$V_{\text{var}} = 10.420 \text{ (untransformed)}$$

Transforming your B measurement would be done in a similar way using this equation:

$$B_{\text{var}} = \Delta b + T_{b_{\text{bv}}} * \Delta(B-V) + B_{\text{comp}}$$

where ...

$$\Delta b = b_{\text{var}} - b_{\text{comp}}$$

$T_{b_{\text{bv}}}$  = your B magnitude coefficient

$\Delta(B-V)$  is the same as above

$B_{\text{comp}}$  is the published B magnitude of the comparison star

To test your understanding, try working through the example to compute  $B_{\text{var}}$  using the same sample data as before. You should arrive at a this result:

$$B_{\text{var}} = 11.861$$

This is the long-hand way to perform a two-filter transform. It makes the process easy to understand, but it is not necessarily the best way to proceed. To reduce error and improve your results, you will want to use just two coefficients — in this case just  $T_{b_{\text{bv}}}$  and  $T_{v_{\text{bv}}}$  — for a two-filter system. Unfortunately, the algebra gets very messy very quickly. That is why we recommend using a tool like TransformApplier (<http://www.aavso.org/transformapplier>) to help you with this process.

## Chapter 7: Photometry and science

The first six chapters of this guide give you everything you need to make variable star observations with a CCD that may be useful for science. Most of the requirements, procedures, observing and analysis techniques are outlined there, and you are ready to start observing. This chapter is intended to give you some additional astronomical background that will aid you in planning and executing observations on your own that are more likely to yield scientifically useful results. In many cases, an observing campaign requested by the AAVSO or other organization will tell you exactly what observations they want and why; here we want to give you background on general principles that should guide your observing techniques. You can consider Chapter 7 an “extra”, but you should at least read through it to see how we at the AAVSO think your observations should be made. In particular we want to focus on two things: (1) why filtered and transformed observations are useful, and (2) what to think about when forming an observing plan for specific classes of variables, including filter use, observing cadence, and exposure times.

Before we go further, “step zero” of your observing process should be to consult the AAVSO website to see what resources we have for observers, and what stars we’re asking for data on. As an example, the AAVSO (and several other variable star organizations) run Observing Campaigns where data are requested on specific stars at specific times. There are also many perennial targets for which data are always needed, so there will be no shortage of targets for you. We won’t cover which specific stars to observe here in the *Guide*, because there are too many that are worthy of observers’ time — it’s worth a book just for that topic alone. Just keep in mind that you can be selective of what targets you explore to improve how likely it is that your data will be used by researchers. The exception is when you yourself are the researcher, and you have a well-defined, novel research question that you want to answer with your observations, but that is also a topic for an entirely different guide.

### Photometry and filters

Before you start, you may want to read Appendices A and B of this *Guide* that cover some physical background on light, and how stars radiate. The simplest thing to take away from that discussion is that starlight contains more information than how much of it arrives at your telescope at a given moment, and that you can learn more by making observations with standardized filters than by simply taking an unfiltered image. Photometric filters have well-defined wavelength cutoffs and transmission properties, and they were designed to closely approximate a standard system, such as the Johnson–Cousins or Sloan system bandpasses. If you measure starlight through one of these filters, you are making a measurement not of the total amount of light that comes in, but the total amount of light within a wavelength range defined by the bandpass of the filter.

Filtered photometry may provide very useful astrophysical information. Stars with different physical properties (like temperature or chemical composition) will have unique spectral characteristics as measured in each of these filter systems. For example, a star of spectral type “A” will have a spectrum such that if you obtain calibrated measures of the star in Johnson B and V, the difference in those calibrated magnitudes will be close to 0.0. Stated in a more familiar way, the (B-V) color of an A-star is close to zero. That was set by definition — it was how the magnitude systems were defined in the first place in the Johnson system. The (B-V) color of a G-type star, cooler than an A-type star, will be somewhere around +0.7 — the calibrated B-band magnitude of that star will be 0.7 magnitudes fainter than the V-band magnitude. Spectral types for stars are based in large part on their temperatures, which in turn are reflected in how their spectra appear. More importantly, if you obtain a set of calibrated photometry for a given star, you can then compare those colors against known spectral calibrations to determine the approximate spectral types of your stars. Precise spectral typing is more complicated (and usually involves taking spectra), but photometric colors can give you some useful information about the properties of stars. One obvious example that we won’t go into here is the color-magnitude diagram, where the magnitudes and colors of stars in clusters lie on very well-defined locations on this diagram, and these locations correspond to different evolutionary stages like the main sequence and red giant branch.

Things get even more interesting for variable stars, because their colors can change while their overall light varies. Remember that colors may correspond in part to the temperature of a star. We also know that some stars change temperature during the course of their variations. A pulsating star like a Cepheid or RR Lyrae can change by 1,000 K or more during a pulsation cycle, and it so happens that this temperature shift results in a substantial change in color, especially in (B-V). So you’ll see a few things if you perform calibrated multifilter photometry of a Cepheid. First, you’ll see the V-band light curve will have a different amplitude than the B-band curve (and may even have a slightly different shape and phase). Second, because of the difference between V and B, you’ll see that the color curve — a plot of (B-V) versus time — is also variable. This is useful information in Cepheids, because it’s a good way of showing (for example) during what part of the light curve the star is hottest. You’ll find similar examples in other classes of variables whose temperature changes during their variation, dwarf novae being a good example; they go into outburst because their accretion disks transition to a hot, bright state that temporarily overwhelms the light coming from the cooler, redder secondary star. There are also some other physical processes that can cause color changes, obscuration by dust being one example. Dust preferentially scatters bluer wavelengths of light out of the line of sight, making the underlying star appear redder than it otherwise would. Dust is one reason some long-period variables and R Coronae Borealis stars appear very red.

So why is all of this relevant to variable star photometry? Note that we used the word “calibrated” many times in the discussion above. When spectral standards were created, they were done so us-

ing very well-defined filters and equipment whose properties are measured and understood. They were also established in such a way that atmospheric extinction was calibrated and removed from the measurements. Your filters, your equipment, and your observing conditions will almost never match those of the observers who created the spectral standards that defined the various properties of stars. Thus, if you obtain a “V magnitude” and a “B magnitude” for a star without calibrating your filters and equipment or determining the atmospheric extinction, they will be different than those of the known standards. You might measure the (B-V) color of the G-type star mentioned above and find that it’s +0.8 instead of +0.7, and that of the A-type star is +0.05 instead of 0.0. That’s why you have to determine your transformation coefficients using well-defined standards: you’re determining the corrections that you need to apply to your data so that your measurements are on the same system as those of agreed-upon standards. In that way, your magnitudes can be most easily compared to everyone else’s magnitudes. It isn’t that your magnitudes are “wrong” — it’s that they’re different. But the problem is then how to understand data from many different observers, all of whom are different. Ultimately your data will be a lot more useful if you can minimize the differences between your magnitudes and standard magnitudes. That is why we spend so much time asking people to transform their data.

### **Time considerations: variability timescales, exposure times, and cadence**

If you’ve been a variable star observer for awhile, you’re probably aware that different stars vary in different ways. Some stars can vary with timescales of seconds or minutes (like some cataclysmic variables) while others may change over weeks, months, or years. Some stars may even show both kinds of variability. This is something you need to keep in mind when deciding how to observe a given star. If you have many different variable types in your observing program, you almost certainly don’t want to use the same method for every star. The three primary things to keep in mind are:

1. You must be able to obtain useful signal to noise with an exposure time that’s less than the timescale of variation.
2. You will need to average multiple observations of bright stars where the integration time is very short (ten seconds or less) due to scintillation.
3. You should not over-observe a star whose timescale of variation is very long, nor under-observe a star whose timescale is very short.

Point (1) above is mainly a concern for stars that have very fast variations and are intrinsically faint. The classic example of this is the orbital light curve or superhump of a short-period cataclysmic variable. There are a number of CVs whose orbital periods are 90 minutes or less, but which



are also very faint. The trick is to figure out how to balance signal-to-noise requirements with the requirement that your exposure time doesn't smear out any interesting rapid variations.

Point (2) is a common concern for those instrumental observers working at the bright end, brighter than 7th or 8th magnitude for many typical SCT+CCD systems. Scintillation is a rapid change in intensity of starlight caused by inhomogeneities in Earth's atmosphere. There's nothing you can do to avoid it, only to average out its effects. The atmospheric eddies responsible for scintillation have a broad distribution in sizes, and is worst (a) with small apertures and (b) short timescales. We'll assume that you can't arbitrarily increase your aperture size, so the only corrective method you can use is to make multiple measures and average them. You'll likely see rms errors on the order of a few to several hundredths of a magnitude when your exposure times are ten seconds or less. If the stars you're observing vary on much longer timescales than your exposure time (Miras and other bright giants being classic examples), then you should absolutely take several exposures, measure the magnitudes, and submit the averaged magnitudes as your result. Submitting every frame's magnitude serves no scientific purpose.

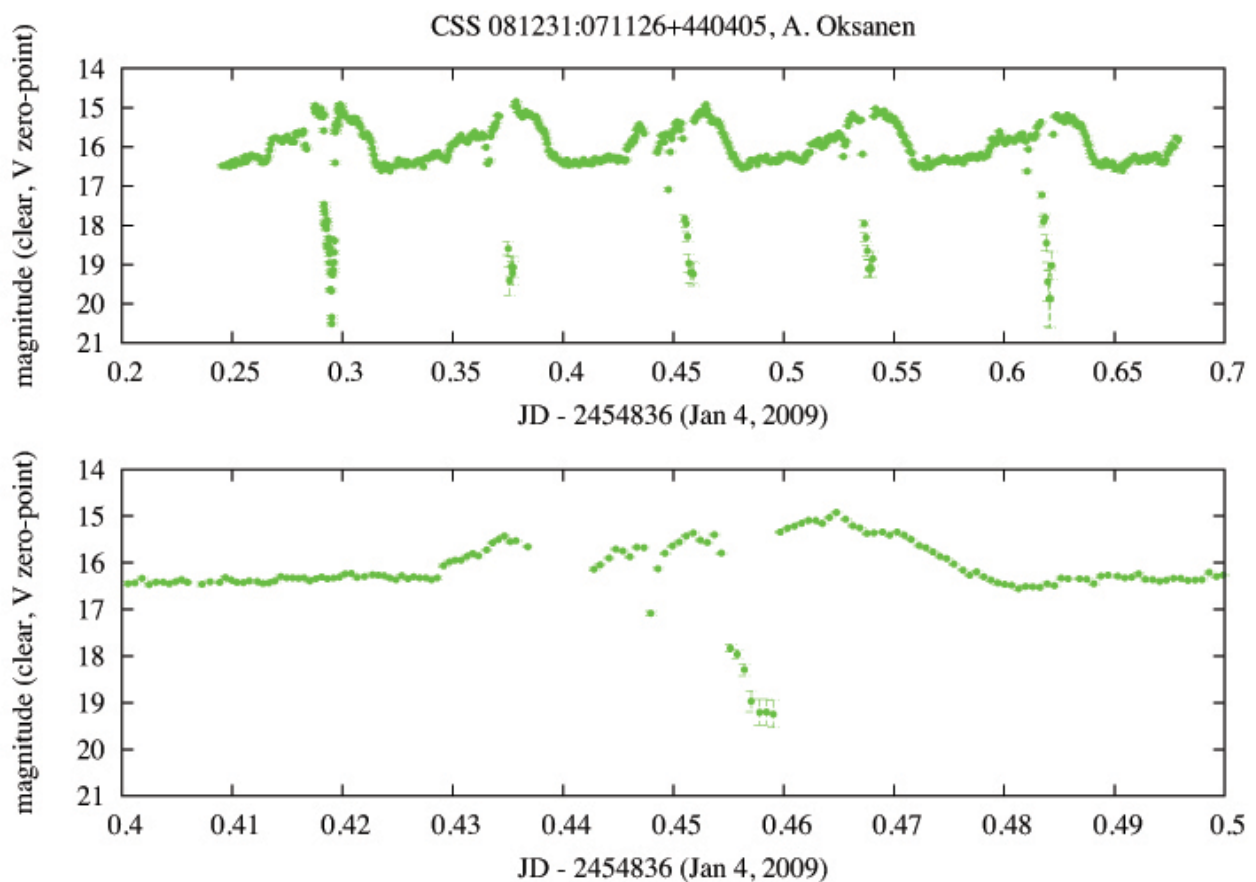
This leads naturally into point (3) on optimizing observing cadence. Different classes of variable stars vary on different timescales, from milliseconds to millennia. Your observations should be optimized to the type of variability you want to search for, and you should also realize that some kinds of variability may be beyond the reach of your equipment.

As an example, take the case of a slowly-varying star and lots of photons. Bright Miras in the AAVSO program are examples of these. Nearly all of the well-observed Miras in the AAVSO archives are easily measurable by CCD observers (with filters) throughout almost their entire range of variation; there are hundreds of Miras that spend most of their time brighter than  $V=14-15$ . The question then is how often to observe? The simple advice we give to visual observers — no more than once every 1–2 weeks — is equally good for CCD observers. A somewhat more sophisticated answer would be to take a few sets of observations — 3 or 4 exposures in each of your filters — on a single night, and then average together the resulting magnitudes in each filter. You'd then submit the averages rather than the individual magnitudes, and you'd submit them as groups of magnitudes so that a researcher would have not just magnitudes but colors. How often you should do that depends on the star, but in general for periodic stars it is good to have between 20 and 50 observations equally-spaced throughout the period of variation of the star. If the period is 500 days, that's one night every 10 days at most. If the period is 100 days, that's no more than once every two days (and should really never be more than once every 4–5 days).

Some observers don't do this, and there are some egregious examples in the AAVSO International Database where observers were doing intensive time series of a Mira as if it were a rapid variable. Those data are not technically wrong, but they are largely wasted effort, and for the most part aren't

useful for researchers in that form. [The only possible use of such data would be to look for rapid variations not typical of such stars, as might be caused by accretion onto an unseen companion.] Usually, an observer can make a more useful contribution if they take a few observation sets of one star, then move to take similar data on several other stars. There are plenty of variables in need of coverage, and a conscientious CCD observer could potentially create some wonderfully useful data sets for lots of stars.

Sometimes, you may encounter the exact opposite case — you may have a faint object that varies rapidly, and you're starved for photons (unless you have an enormous telescope). As an example of this case, look at one night's observations of the eclipsing polar CSS 081231:071126+440405 by AAVSO observer Arto Oksanen:



*Figure 7.1 – Unfiltered time series of an eclipsing AM Herculis–type cataclysmic variable. Note that the error bars are very small, and note also the number of times observations are made. The observing cadence is approximately one observation per minute, including both exposure and chip readout.*

These data were taken through a clear filter using a 0.4-meter (16-inch) telescope. When the star is between 15 and 17, the photometric uncertainties are around 0.015 to 0.02 magnitudes, which is well below the overall amplitude. Equally important is that the observing cadence is around one observation per minute. The orbital period of the star is just over 117 minutes, and so the observing cadence provides ample coverage throughout the orbital cycle. The result is that most of the orbital variations of this star are very well measured, and the overall light curve looks great.

The only time when it starts to be problematic is during the extremely short, deep eclipse, when the star goes below magnitude 20. First, the eclipse entry is extremely sharp — only a few seconds — so it isn't possible for an observing cadence of 1/minute to resolve that feature. Second, the eclipse is very deep — more than three magnitudes — so the eclipse causes the added problem of losing signal to noise. Uncertainties on the eclipse magnitudes approach 0.3 magnitudes, more than ten times larger than during the bright part of the orbit.

In this case, there's really nothing you can do to improve either temporal resolution or signal-to-noise during the eclipse — you're limited by the aperture of your telescope and the number of photons you're detecting, and there's no astrophysical reason to either shorten or lengthen exposure times. Shortening the exposures to improve temporal resolution would make the photometry too noisy to be useful, while longer exposures would simply smear out the eclipse leaving you with only a few data points during that interesting feature. This is an extreme case, but the number of interesting, faint stars like this is only going to increase as large-scale surveys like LSST begin finding new stars. For the more general case where you might have some options, simply be aware of the kind of variability you might see, and think ahead of time what your exposure times and cadence should be.

This is also a good example to raise the question of whether you are better off observing without a filter. Although we covered filters separately, they're relevant here to a discussion of timing because filters all lower your overall signal, and thus impact your exposure times and signal-to-noise; some filters may lower your signal so much that you can't make useful observations with them using your equipment. There are two principles to remember here:

- 1.) If the target is bright and you can get good signal to noise with an appropriate exposure time, you should always use filters. (Note that “good” will be defined by your project goals, but  $> 20$  is a reasonable value.)
- 2.) If the target has very red colors, you must use filters unless there is some overriding reason where unfiltered photometry is useful (e.g. transient searches and gamma-ray burst afterglows). If you cannot use a filter on a known red target, you are better off observing a different target.

In this case, the object is very faint at times (with eclipses below magnitude 20), so you are definitely photon-starved. The variations are also relatively rapid, so you want to keep them as short as possible. But the most important reason you can forgo using a filter is that this star is very blue like most cataclysmic variables. If you were to take a spectrum of this star, you'd find the continuum is relatively flat, and doesn't change very much with wavelength. In this case, broadband variations match variations measured through filters reasonably well, and unfiltered observations are a good compromise that gets you slightly higher signal to noise and/or shorter exposure times at the expense of spectral information that, in this case, isn't as important as the other information you get.

## Exceptions

Every rule has exceptions, and the guidelines for observing cadence and exposure time are no different. The most important thing to remember from the discussion above is that your exposure times have to be sufficient to detect the behavior you're searching for, and your observing cadence also has to match the timescales you want to cover. There may be research projects that look for behavior different from what is normally expected for a given variable star class. One example could be the discovery of an extrasolar planet transit in a longer period variable like an M- or K-giant. You might normally observe such a star once every several days, but a transit might vary on timescales of minutes to hours. You have to make observations with a much faster cadence in that case. In general such cases are rare, and usually happen when a star is already known to be special in some way (for example a Mira variable in a symbiotic system). You can certainly take high-cadence data to go exploring for interesting phenomena yourself, but realize those data will rarely be used as-is. You should consider examining your high-cadence data yourself offline, then averaging them and submitting the averaged data to the AAVSO archives rather than the individual points.

One more caution about Mira stars: do not make unfiltered observations of Miras, semiregulars, or other red variables in general. Unfiltered observations are really only suitable for "blue" stars (with B-V around 0.0). For red variables, your CCD is likely sensitive in the near-infrared, and red stars will be much brighter than you might expect them to be. You'll probably find occasional examples of someone reporting "CV" magnitudes for a Mira or semiregular star that are two or three magnitudes brighter than both visual data and filtered CCD data. Such observations really are wrong since the "CV" bandpass is very misleading to researchers. You might be tempted to observe very faint Mira stars without a filter in order to provide coverage at minimum, but the spectral properties of such data are so poorly constrained that they will not provide researchers with much useful information, and may actually cause more confusion than anything else. If you don't have filters for your CCD camera, you should avoid nearly all types of red variables, and restrict your work primarily to cataclysmic variables. Again, exceptions might be very faint transients like gamma-ray bursts.

## Appendix A: What is starlight?

There's much more information in starlight than how much of it there is and when you measure it. We ask CCD and other instrumental observers to use standard filters when doing photometry because filters allow you to measure both the amount of light, and its spectral distribution. The key physical property of light relevant here is the wavelength. Light is composed of *photons*, which are small bundles of electric and magnetic fields that travel through space at the same speed — the speed of light, *c*. These small bundles behave both like particles and waves, and since they are waves, they have a characteristic wavelength.

In optical light, the different *colors* you see correspond to light with different wavelengths. Red light has longer wavelengths than yellow light, which has longer wavelengths than green light, which has longer wavelengths than blue and violet light. All of the different colors of light observed together are called a *spectrum*. The visual spectrum is roughly composed of all light having wavelengths between 300 and 700 nanometers, from the violet to the red. There's more light beyond that range, too. Beyond the violet toward shorter wavelengths lie the ultraviolet, X-ray, and gamma-ray regions of the electromagnetic spectrum. Beyond the red toward longer wavelengths lie the infrared, microwave, and radio regions. We only define the visual spectrum this way because that's what the human eye is capable of seeing — our eyes aren't sensitive to light outside that range. Most normal stars emit the bulk of their light in the optical and infrared, and our own Sun emits the greatest amount of light around 500 nanometers, which appears green to our eyes.

A related quantity for each photon is its energy, which is also a function of wavelength. Specifically, the energy carried by a photon is inversely proportional to wavelength:

$$E = hc/\lambda$$

where *h* is Planck's constant, *c* is the speed of light, and  $\lambda$  is the wavelength. Note the inverse relationship with wavelength: shorter wavelength, blue photons have more energy than longer wavelength yellow photons, which have more energy than even longer wavelength red photons. The wavelengths of light that astrophysical sources emit are related to the total energy density of the system that's doing the emitting. A relatively cool star is unlikely to emit high-energy radiation *unless there are special sources of energy within the system*. Conversely, a hot star may be capable of emitting higher energy radiation, *but it also emit photons with lower energy*. (More on that in Appendix B.)

There is another property of light that we won't go into detail in this guide, and that is its *polarization*. Photons are bundles of electromagnetic radiation, where each particle consists of an oscillating electric and magnetic field. All photons received from a single source may be assumed traveling

The fields may oscillate in a single direction perpendicular to the direction of motion but with random orientation, or they may have a circular component to the oscillation (i.e., the photon is elliptically or circularly polarized). If the emitting source is polarized or if the light passes through a polarizing medium (like a dust cloud), there will be a preferential orientation for most photons you see. Circularly polarized light can also be created in environments or physical processes having strong magnetic fields.

Polarization can be measured with special filters, but it is a time-consuming process. We won't discuss it further, but be aware that it is another fundamental property of light that you observe.

Appendix B contains a brief discussion of radiative processes common in stellar astronomy, and how these can be described or explored using photometry.

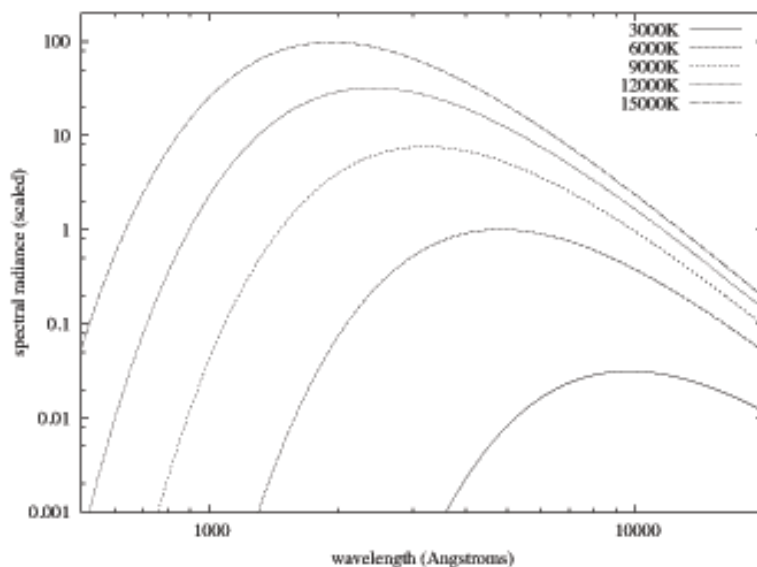
## Appendix B: Why and how stars radiate

Both the amount of light generated and the wavelength spectrum of light that an object like a star emits will depend on the physical properties of what's emitting the light. The spectrum of starlight is generally very complex on close examination, but the physics responsible for it can be broadly generalized into two processes: continuum emission, and line emission and absorption.

Continuum emission is any physical process that emits photons having a broad range of different wavelengths. As an example, think of the band of light that you see when you hold a prism in sunlight — you see several bands of color with red, orange, yellow, blue, indigo, and violet. All of those colors are present in sunlight at the same time, but you don't see them individually — the Sun simply looks white.

### Blackbody radiation

A special kind of continuum emission is blackbody radiation, emitted by all objects — any objects — with temperatures above absolute zero. The amount of light and the wavelength distribution of photons in the blackbody spectrum depend on one parameter: the temperature. The key things to remember are that if one star is hotter than another, (1) it will emit more light overall, and (2) the spectrum of light it emits will have more light at shorter wavelengths. If you have two stars whose physical sizes are the same and are the same distance away from us but one is at 10,000 K and the other at 5,000 K, the hotter star will be brighter (more light), and bluer (more emission at shorter wavelengths). Thus you can use starlight to take the temperature of a star without touching it — a neat trick! The equations describing blackbody radiation were worked out by Max Planck early in the 20th century, and you'll often see blackbody radiation referred to as *Planck radiation*.



*Figure B.1 – Black body spectra scaled to the peak spectral radiance of a blackbody at 6000 Kelvin. The Sun's effective temperature is about 5774 Kelvin. That of an A0 star is about 10,000 Kelvin, while that of an M star is below about 4000 Kelvin. Compare the bandpasses of filters shown in Figure 3.1 with the curves shown here.*

There are a few concepts related to blackbody radiation that are very useful in stellar astrophysics. First, Wien's Law is a simple equation that gives you the wavelength at which a black body emits the most light (i.e. the peak of the blackbody spectrum):

$$\lambda_{max} = b/T$$

where  $\lambda$  is the wavelength,  $T$  is the temperature of the blackbody, and  $b$  is a constant (known as *Wien's displacement constant*). You can derive this using the equation of a blackbody, and determining where the curve is maximum: you determine the temperature and wavelength at which the derivative is zero. This is a really handy equation, because it lets you roughly estimate the temperature of any blackbody-like object by simply measuring where the peak of its spectrum is. Many stars behave so similarly to blackbodies that this is straightforward to measure; where it breaks down are for stars that have such strong atomic or molecular absorption that their optical spectra don't match a blackbody very well. (This often happens for M stars whose spectra peak in the near-IR anyway.)

Another relation is the Stefan-Boltzmann Law, which provides a simple relationship between the energy flux per unit area from the surface of a black body and its temperature:

$$f_{bol} = \sigma T^4$$

where  $f_{bol}$  is the total energy flux per unit area,  $T$  is the temperature, and  $\sigma$  is a constant (the Stefan-Boltzmann constant). The hotter a blackbody gets, the more total energy it emits. Again, this yields another interesting astrophysical application. You may be able to estimate the effective temperature a star by some means (photometric, or spectroscopic). The total luminosity (the light emitted in all directions) by a blackbody is simply this quantity  $f_{bol}$  times the total surface area:  $4\pi R^2$ . Combining these two things, you get the interesting equation

$$L_{bol} = 4\pi R^2 \sigma T^4$$

There are a few potentially interesting quantities there, namely the luminosity (which can be tied into the distance to the star) and the radius of the star. This is important astrophysically; the luminosity of a star is proportional to both its effective temperature and to its radius. Spectral types also include *luminosity classes* from *dwarf* to *supergiant*. A star might have an effective temperature of 4000 K, but there will be a huge difference in luminosity depending on whether its radius is that of a dwarf star or a supergiant.



## Line emission and absorption

The second process, line emission and absorption, are two things caused by the same physical process — the emission or absorption of individual photons by atoms. Atoms are composed of nuclei (protons and neutrons) surrounded by electrons having very specific orbits. The orbits of these electrons correspond to specific energy levels. If an electron transitions from a higher energy level to a lower one, it will release the resulting energy difference as a photon with that energy. Since wavelength corresponds to energy, these electron transitions correspond to specific wavelengths of light. These wavelengths — or combinations of wavelengths — are unique to each atomic species. If you have a sample of hydrogen gas and excite it (say in a fluorescent tube), it will emit light at several discrete wavelengths corresponding to the electron energy levels of a hydrogen atom. Likewise if you have a sample of nitrogen, sodium, or neon gas (all common in fluorescent bulbs) they'll have different spectra. (This is why “neon signs” have different colors — they use different gases.)

The inverse of emission is absorption: if you have a photon of the right wavelength to excite an atom that has an allowed electron transition with just the right energy, the atom will absorb the photon. If you have a source of continuum emission (like the photosphere of a star) along with some gas that can absorb energy (like hydrogen, calcium, iron, or other elements in a star's atmosphere), the star's spectrum would look like a blackbody with some wavelengths reduced or missing. So when you take a spectrum of a star, you'll see mostly a continuum of light, but with dark bands appearing along the dispersion axis. The amount of absorption that you see depends on many different factors including the abundances of different atomic and molecular species, and the temperature of the star. A-type stars for example are defined as having the strongest absorption lines of hydrogen in their spectra. As another example, molecular absorption occurs in cool, M-type stars, and the kind of absorption you see depends on whether the star is richer in oxygen or carbon.

The astrophysics of radiation and radiative transfer is a very rich subject. Much of what was discussed above was laid out even before the golden age of quantum mechanics by the 19th century physicist Gustav Kirchhoff, and are summarized by Kirchhoff's three laws of radiation:

- 1) Hot, solid (or optically thick) objects emit a continuous spectrum.
- 2) A hot, optically thin gas emits light at discrete wavelengths characteristic of the chemical composition of the gas.
- 3) A continuous spectrum passing through a cool, optically thin gas will show absorption lines characteristic of the chemical composition of the gas (and at identical wavelengths to the emission lines that would appear if the gas were hot).

Kirchhoff outlined these rules in the 19th century, before atomic physics and quantum mechanics were understood. But for many cases of interest in variable star astronomy, these rules broadly describe everything you'll see, and the mathematical models of how light is created and how it propagates in a physical system are rooted in Kirchhoff's laws.

We won't cover spectral analysis in this manual, but it is possible to use observation and measurement of the strengths of spectral lines in a star to figure out what the star is made of. Atomic line measurement in the laboratory was and still is a major field in laboratory astrophysics. Absorption and emission lines will change their appearance in a complicated way that depends on relative abundances in the plasma, the temperature (and temperature structure when looking through a thin gas), and pressure. Some lines and groups of lines are so strong and prominent that they serve as proxies for the overall "metal abundance" (i.e. the abundance of everything except hydrogen and helium). In some cases, these can be so strong that they can even be detected in broad-band light, and thus can be detected with filtered photometry rather than spectroscopy.

### **Other processes**

There are other sources of radiation, including magnetic fields (especially important in active stars that generate X-rays), nuclear reactions, and radioactive decay (which power the interiors of stars and are also responsible for the energy that powers supernovae and their light evolution). Many variable stars will have multiple sources for radiation and absorption. As an example, the UV Ceti stars are low-mass, young dwarf M stars, usually very cool. These objects are generally very faint since their cool temperatures mean they radiate a relatively small amount of light, mostly in the red and infrared. However, they can also emit enormous amounts of blue, ultraviolet, X-ray, and even gamma-ray radiation in very short bursts due to magnetic reconnection events in their atmospheres analogous to solar flares on our own Sun. These stars are naturally very faint in blue, so when large flares occur, they may have enormous amplitudes in blue light, but relatively little in red. A bright flare may have a B-band amplitude of 3 or 4 magnitudes, but much less than a magnitude in R- or I-band.

The physics of radiation is one of the earliest courses a student in astronomy would take, and while it isn't required to be an observational astronomer, knowledge of radiative processes may provide you with some insight into what you're observing. One particularly useful book on the topic is George Rybicki and Alan Lightman's *Radiative Processes in Astrophysics*. A detailed reference on spectral lines and stellar spectra is David Gray's *The Observation and Analysis of Stellar Photospheres*.

## Appendix C: Submitting observations to the AAVSO

Submitting observations to the AAVSO — whether they were obtained visually, by using a CCD, a Photoelectric Photometer, a DSLR, or in some other way — is all done through use of the online tool WebObs (<http://www.aavso.org/webobs>).

You then must choose whether you wish to “Submit observations individually” or “Upload a file of observations”. If you have just a small number of observations then the individual option may be the easiest for you. If on the other hand, you are submitting a large number of CCD observations (either time-series or for many different stars), creating a file in “AAVSO Extended File Format” is definitely the better way to go. Fortunately, many of the photometry software packages in use today come with an option to export your results in the form of an AAVSO report — you simply need to upload it through WebObs. Should you have to create or tweak your own report, however, it is essential that you follow the format outlined in this Appendix. Even if you submit individual observations, you may find some of the field descriptions in the “Data” section helpful.

### **General information**

The “Extended Format” file must be a plain text (ASCII) type file. It is not case sensitive. There are two parts to the file; *Parameters* (or header information) and *Data*.

### **Parameters**

The Parameters are specified at the top of the file and are used to describe the data that follows. Parameters must begin with a pound/hash sign (#) at the start of the line. There are six specific parameters that the AAVSO requires you to include at the top of the file. Personal comments may also be added as long as they follow a pound/hash sign (#). These comments will be ignored by the software and will not be loaded into the database. However, they will be retained when the complete file is stored in the AAVSO permanent archives.

The six parameters that we require are:

```
#TYPE=Extended  
#OBSCODE=  
#SOFTWARE=  
#DELIM=  
#DATE=  
#OBSTYPE=
```

Here is an explanation of each:

- **TYPE:** Should always say “Extended” for this format.
- **OBSCODE:** The official AAVSO Observer Code for the observer, which was previously assigned by the AAVSO.
- **SOFTWARE:** Name and version of software used to create the format. If it is private software, put some type of description here. For example: “#SOFTWARE=AIP4Win Version 2.2”. This is limited to 30 characters.
- **DELIM:** The delimiter used to separate fields in the report. Any ASCII character or UNICODE number that corresponds to ASCII code 32–126 is acceptable as long as it is not used in any field. Suggested delimiters are: comma (,) semi-colon (;), exclamation point (!), and pipe (|). The only character that cannot be used are the pound/hash sign (#) and the “ ” (space). If you want to use a tab, use the word “tab” instead of an actual tab character. *Note:* Excel users who want to use a comma will have to type the word “comma” here instead of a “,”. Otherwise, Excel will export the field incorrectly.
- **DATE:** The format of the date used in the report. Times are midpoint of the observation. Convert all times from UT to one of the following formats:
  - JD: Julian Day (Ex: 2454101.7563)
  - HJD: Heliocentric Julian Day
  - EXCEL: the format created by Excel’s NOW() function (e.g. 12/31/2007 12:59:59 a.m. )
- **OBSTYPE:** The type of observation in the data file. It can be CCD, DSLR, PEP (for Photoelectric Photometry), or VISDIG (for *VIS*ual observations made from *DIG*ital images). If no obstype is specified, it is assumed to be CCD.

The OBSCODE and DATE parameters may also be included elsewhere in the data. Our data processing software will read these parameters and will expect all following data to adhere to them. (For example, you can add “#OBSCODE=TST01” to the report and all subsequent observations will be attributed to observer TST01.)

If you want to put a blank line between your parameter records and your data records, be sure to comment the line out with the pound/hash sign (#). WebObs will not accept a file with blank lines that are not commented out.

## Data

After the parameters, come the actual variable star observations. There should be one observation per line and the fields should be separated by the same character that is defined in the DELIM parameter field. If you do not have data for one of the optional fields, you must use “na” (not applicable) as a place holder. The list of fields are:

- **STARID:** The star’s identifier. It can be the AAVSO Designation, the AAVSO Name, or the AAVSO Unique Identifier (AUID), but NOT more than one of these. *(25 character limit)*
- **DATE:** The date and time of the observation, in the format specified in the DATE parameter. The AAVSO requires that you report the mid–point of the exposure time. If you stack images, this becomes more complicated so please add a note about how you have computed the exposure time in the NOTES field.
- **MAGNITUDE:** The magnitude of the observation. Prepend with < if a fainter–than. A decimal point is required (e.g. “9.0” rather than “9”).
- **MAGERR:** Photometric uncertainty associated with the variable star magnitude. If not available put “na”.
- **FILTER:** The filter used for the observation. This can be one of the following letters (in bold):
  - **U:** Johnson U
  - **B:** Johnson B
  - **V:** Johnson V
  - **R:** Cousins R (or Rc)
  - **I:** Cousins I (or Ic)
  - **J:** NIR 1.2 micron
  - **H:** NIR 1.6 micron
  - **K:** NIR 2.2 micron
  - **TG:** Green Filter (or Tri–color green). This is commonly known as the “green–channel” in a DSLR or color CCD camera. These observations use V–band comp star magnitudes.
  - **TB:** Blue Filter (or Tri–color blue). This is commonly known as the “blue–channel” in a DSLR or color CCD camera. These observations use B–band comp star magnitudes.
  - **TR:** Red Filter (or Tri–color red). This is commonly known as the “red–channel” in a DSLR or color CCD camera. These observations use R–band comp star magnitudes.
  - **CV:** Clear (unfiltered) using V–band comp star magnitudes (this is more common than CR)
  - **CR:** Clear (unfiltered) using R–band comp star magnitudes
  - **SZ:** Sloan z
  - **SU:** Sloan u
  - **SG:** Sloan g
  - **SR:** Sloan r

- **SI:** Sloan i
- **STU:** Stromgren u
- **STV:** Stromgren v
- **STB:** Stromgren b
- **STY:** Stromgren y
- **STHBW:** Stromgren Hbw
- **STHBN:** Stromgren Hbn
- **MA:** Optec Wing A
- **MB:** Optec Wing B
- **MI:** Optec Wing C

*Please note:* There are a few other (rarely used but legitimate) filters, which can be specified. If you are using a filter that is not listed here, please contact AAVSO HQ with as much information as possible about what you are using and we will let you know how to report it.

- **TRANS:** YES if transformed using the Landolt Standards or those fields that contain secondary standards as discussed in Chapter 6, or NO if not.
- **MTYPE:** Magnitude type. STD if standardized by utilizing the published magnitudes of the comparison stars or DIF if differential (uncommon). Differential means that the published magnitudes of the comparison stars were not used and only instrumental magnitudes are being reported. DIF requires the use of CNAME. Please note that use of the word “differential” in this case is not the same as saying you are doing “differential photometry”.
- **CNAME:** Comparison star name or label such as the chart label or the AUID for the comparison star used. If not present, use “na”. *(20 character limit)*
- **CMAG:** Instrumental magnitude of the comparison star. If not present, use “na”.
- **KNAME:** Check star name or label such as the chart label or AUID for the check star. If not present, use “na”. *(20 character limit)*
- **KMAG:** Instrumental magnitude of the check star. If not present, use “na”.
- **AIRMASS:** Airmass of observation. If not present, use “na”.
- **GROUP:** Grouping identifier (maximum 5 characters). It is used for grouping multiple observations together — usually an observation set that was taken through multiple filters. It makes it easier to retrieve all magnitudes from a given set in the database in case the researcher wanted to form color indices such as (B-V) with them. If you are just doing time series, or using the same filter for multiple stars, etc., set GROUP to “na.” For cases where you want to group observations, GROUP should be an integer, identical for all observations in a group, and unique for a given observer for a given star on a given Julian Date.
- **CHART:** Please use the sequence ID you will find in red at the bottom of the photometry table. If a non-AAVSO sequence was used, please describe it as clearly as possible. *(20 character limit)*.
- **NOTES:** Comments or notes about the observation. This field has a maximum length of 100 characters. If no comments, use “na”.

## Examples

Here is a simple report with multiple stars (the data used are not necessarily realistic!):

---

```
#TYPE=EXTENDED
#OBSCODE=TST01
#SOFTWARE=MAXIM DL 6.0
#DELIM=,
#DATE=JD
#OBSTYPE=CCD
#NAME,DATE,MAG,MERR,FILT,TRANS,MTYPE,CNAME,CMAG,KNAME,KMAG,AMASS,GROUP,CHART,
NOTES
SS CYG,2450702.1234,8.235,0.003,V,NO,STD,105,10.593,110,11.090,1.561,na,13577KCZ,outburst
V1668 CYG,2450702.1254,18.135,0.0180,V,NO,STD,105,10.594,110,10.994,1.563,na,3577KCZ,na
WY CYG,2450702.1274,14.258,0.004,V,NO,STD,105,10.594,110,10.896,1.564,na,13577KCZ,na
SS CYG,2450722.1294,10.935,0.006,V,NO,STD,105,10.592,110,10.793,1.567,na,13577KCZ,na
```

---

Note the existence of the #NAME, DATE... line in the above format. Since it is prepended with a #, it will be ignored by our software. Feel free to do this if it makes writing and reading the format easier for you.

Reporting ensemble photometry is permitted under this format. You need to pick one star (the check star) in addition to the target to be measured by the technique. The check star should not be included in the comparison–star ensemble. This star’s calculated magnitude should be put in the KMAG field, so that if the true magnitude of the check star is found to be different at a later date, a simple zeropoint offset can be added to your ensemble value. If ensemble is used, CNAME should be set to ENSEMBLE and CMAG should be set to “na”, as shown below.

---

```
#TYPE=EXTENDED
#OBSCODE=TST01
#SOFTWARE=IRAF 12.4
#DELIM=,
#DATE=JD
#NAME,DATE,MAG,MERR,FILT,TRANS,MTYPE,CNAME,CMAG,KNAME,KMAG,AMASS,GROUP,CHART,
NOTES
SS CYG,2450702.1234,11.235,0.003,B,NO,STD,ENSEMBLE,na,105,10.593,1.561,1,070613,na
SS CYG,2450702.1254,11.135,0.003,V,NO,STD,ENSEMBLE,na,105,10.492,1.563,1,070613,na
SS CYG,2450702.1274,11.035,0.003,R,NO,STD,ENSEMBLE,na,105,10.398,1.564,1,070613,na
SS CYG,2450702.1294,10.935,0.003,I,NO,STD,ENSEMBLE,na,105,10.295,1.567,1,070613,na
SS CYG,2450702.2234,11.244,0.003,B,NO,STD,ENSEMBLE,na,105,10.590,1.661,2,070613,na
SS CYG,2450702.2254,11.166,0.003,V,NO,STD,ENSEMBLE,na,105,10.497,1.663,2,070613,na
SS CYG,2450702.2274,11.030,0.003,R,NO,STD,ENSEMBLE,na,105,10.402,1.664,2,070613,na
SS CYG,2450702.2294,10.927,0.003,I,NO,STD,ENSEMBLE,na,105,10.292,1.667,2,070613,na
```

---

In this report, the ensemble solution gave 11.235, 11.135, 11.035 and 10.935 for the B, V, Rc, and Ic (respectively) magnitudes of SS Cyg for the first group, and 11.244, 11.116, 11.030 and 10.927 for the second group. The ensemble solution also gave 10.593, 10.492, 10.398, and 10.295 for the BVRcIc magnitudes of the check star for the first group.

## **After Submission**

Once you have submitted your observations to the AAVSO database, it is a good idea to take a look at the light curves of the stars you have observed using the Light Curve Generator (*LCG* – <http://www.aavso.org/lcg>) or VStar (<http://www.aavso.org/vstar-overview>) and see if you think that your data makes sense. If you find that your observations seem to be very different from those of other observers using similar equipment, it is important that you go back and check things against your observing notes or original images. Your observations may be correct while those of another observer or observers could have problems, but if you see a discrepancy, you should start by checking your own data again.

It is not uncommon for observers to make typographical errors resulting in the mislabeling of a star, reporting the wrong date or time, and mixing up the reported bands. If your report seems correct, go back and review your images. Could you have misidentified any of the stars, included a close companion in the aperture or saturated the target or any of the comparison stars?

If you do find a problem, you have the power to fix it. One of the other options available to you through WebObs is “Search for observations”. Using this search tool you should be able to narrow your search so that you can isolate the observation or observations with problems. Then you can either delete the observations and re-submit the corrected ones or edit the erroneous observation. Which option you choose depends on how many observations you have and the nature of the error.

One thing to note about the WebObs Search tool use is that by clicking the little unlabeled box in the left corner of the header row of the “Results” page, you can select all of the observations on that page which makes it much easier to delete a large group of observations rather than clicking on them one-by-one.

If you discover a problem with your data that would be very time consuming to correct, please do not hesitate to contact AAVSO Headquarters to ask for help. Alternatively, if you see something suspicious about another observer’s observations, you can report that to AAVSO HQ either through use of VStar, Zapper or an email describing what you see.



## Appendix D: Observer Resources

### Books

Berry, Richard, and James Burnell. *The Handbook of Astronomical Image Processing* (second edition). Willmann–Bell, Inc. 2005. ISBN 978–0943396828.

Budding, Edwin, and Osman Demircan. *Introduction to Astronomical Photometry* (second edition). Cambridge University Press, 2007. ISBN 978–0521885263.

Buchheim, Robert K. *The Sky is Your Laboratory*, Springer Science+Business Media, 2007. ISBN 978–0387718224.

Hall, Douglas S., and Russell M. Genet. *Photoelectric Photometry of Variable Stars – A Practical Guide for the Smaller Observatory* (second edition). Willman–Bell, Inc., 1988. ISBN 978–0943396194.

Henden, Arne A., and Ronald H. Kaitchuck. *Astronomical Photometry, A Text and Handbook for the Advanced Amateur and Professional Astronomer*. Willman–Bell, Inc., 1990. ISBN 978–0943396255.

Howell, Stephen B., *Handbook of CCD Astronomy* (second edition). Cambridge University Press, 2006. ISBN 978–0521617628.

Warner, Brian D., *A Practical Guide to Lightcurve Photometry and Analysis*. Springer Science+Business Media, 2006. ISBN 978–0387293653.

### Software

AIP4Win – [www.willbell.com/aip4win/AIP.htm](http://www.willbell.com/aip4win/AIP.htm)

AstroArt – [www.msb-astroart.com/](http://www.msb-astroart.com/)

CCDOps – [www.sbig.com/support/software/](http://www.sbig.com/support/software/)

FotoDif – [www.astrosurf.com/orodeno/fotodif/index.htm](http://www.astrosurf.com/orodeno/fotodif/index.htm) (in Spanish)

IRAF – <http://iraf.noao.edu/>

LesvePhotometry – [www.dppobservatory.net/AstroPrograms/Software4VSObservers.php](http://www.dppobservatory.net/AstroPrograms/Software4VSObservers.php)

MaxIm DL – [cyanogen.com/maxim\\_main.php](http://cyanogen.com/maxim_main.php)

MPO Canopus – [www.minorplanetobserver.com/MPOSoftware/MPOCanopus.htm](http://www.minorplanetobserver.com/MPOSoftware/MPOCanopus.htm)

VPhot – [www.aavso.org/vphot](http://www.aavso.org/vphot)

## Index

analog to digital unit (ADU)	32	ghosts	39
aperture setting	44	instrumental magnitude	46
airmass	36	linearity	15, 16
bias frames	28	point-spread function (PSF)	35, 43
binning	19	residual bulk image (RBI)	39
blooming	15	sampling	18
cadence	64	saturation	37
calibration	27	science frame (or science image)	31
CCD equation	49	scintillation	35
color index	52	signal-to-noise ratio (SNR)	18, 48
dark frames	29	software	22
differential magnitude	46	standard field	52
differential photometry	41	standardized magnitude	46
exposure time	32	transformation	51
extinction	36	uncertainty	48
flat frames	30	Variable Star Plotter (VSP)	24, 26
filters	21, 62	VPhot	23
full well depth	15	WebObs	75
full-width, half-maximum (FWHM)	17		