

Observing

CCD Observing Manual

1.0 Introduction

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1.1 Target Audience

The CCD Observing Manual is meant for anyone with an interest in using CCDs to make variable star estimates. Most of the information is written with the beginner and intermediate CCD observer in mind. However, even the most advanced CCD observer will probably find some information useful. CCD Photometry has been called an *art* by some because of all the intricate details involved in getting a good result. Art and science both have one thing in common: neither has experts.

If you have any questions we encourage you to [contact us](#) or check out our [further reading and linkage](#) section.

1.2 CCD vs. Visual Observing

Ah, the debate of champions. After years of debate on the [AAVSO Discussion Group](#) a general consensus has emerged. CCD and visual variable star astronomy are *collaborative* and not *competing* endeavours. Each brings their own strengths and weaknesses to the table:

	Strengths	Weaknesses
Visual	<ul style="list-style-type: none"> • Quick • Easier (less fuss) • Less equipment/Less expensive 	<ul style="list-style-type: none"> • Cannot go as faint • Less precision
CCD	<ul style="list-style-type: none"> • Better accuracy • More accepted by scientific community (if filtered) • Can go much fainter • Can be automated 	<ul style="list-style-type: none"> • Time consuming • Complicated • More equipment/Expensive

The most successful observing programs in the AAVSO combine the capabilities of both programs. For example, the [eclipsing binary committee](#) routinely uses visual observers to follow an EB to get a general idea for the time of minima. Then the CCD observers schedule a night where they can refine that time. Also, for [cataclysmic](#) and [long period](#) variables visual observers

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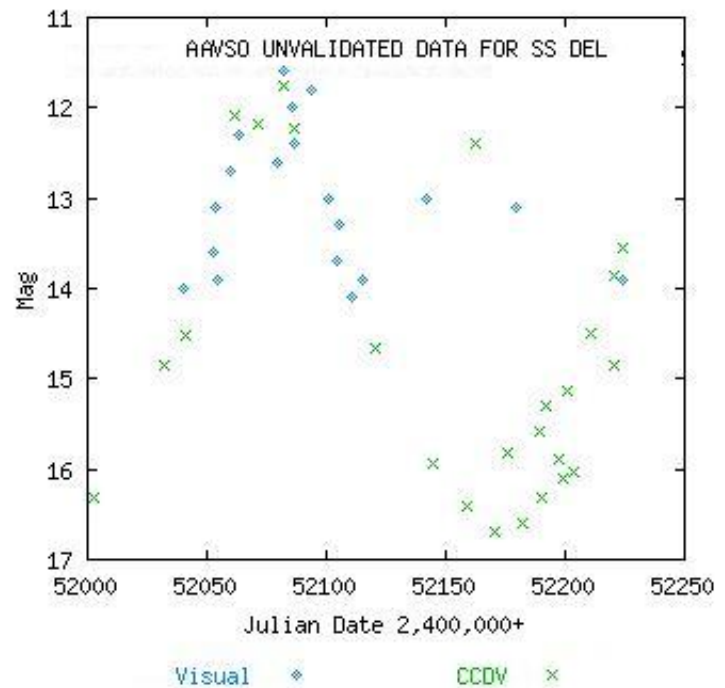
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will observe the star while it is bright (above mag 14.5 usually) and then the CCD observers will take over while it is faint. When the star gets bright again, it is handed back off to the visual observers. In these ways, both groups can cooperate and get the most out of their observing program.

To the right is a light curve of [SS Del](#). You can see how the visual observers took over near maxima (brighter than mag 14) and the CCD observers took over near minima (below mag 14). This is a great example of cooperation to build a terrific light curve.

If you are currently a visual observer and are happy with your current program then there is no need to invest the time and money for CCD work. Only consider CCD work if there are specific programs that you would like to participate in that require the unique benefits of the CCD, or if you are a lover of technology and would just enjoy the challenge it presents. Remember the goal here: to have fun and collect real data for the [scientific community](#). Both can be achieved by CCD and visual observing programs.



1.3. Are You Ready? (Prerequisites)

Before getting started you should have some experience with your CCD camera. You should:

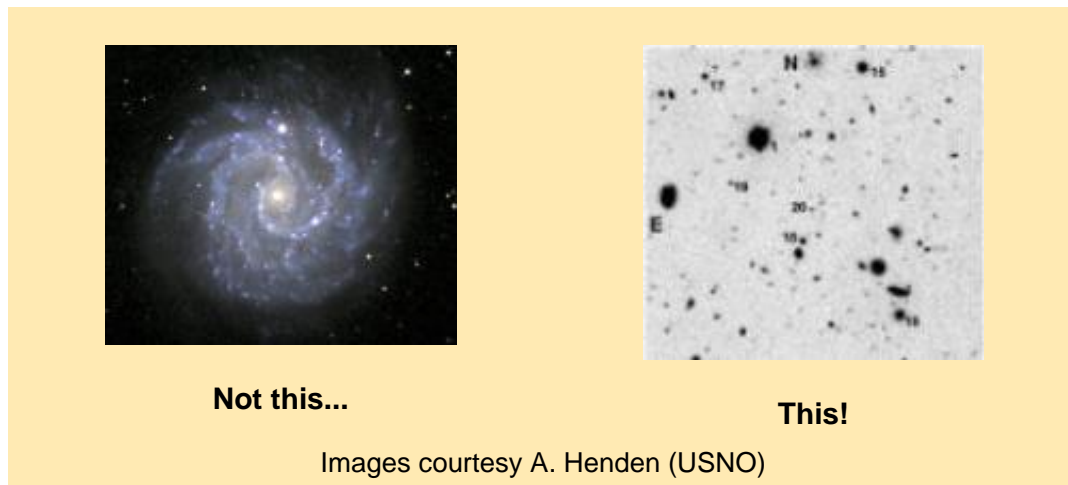
- Know how CCD cameras operate (well depth, shutter types, linearity, etc.)
- Have basic experience using your CCD camera
- Have good working knowledge of [computers](#) (especially regarding processing data and txt files)
- Highly recommended but not required: Have some experience doing *visual* variable star estimates.

The last item can save you a lot of time. "An ounce of prevention is worth a pound of cure". In general, for every visual variable star estimate you will probably end up saving yourself ten times that amount of time in your CCD learning curve. Try to make at least one hundred visual variable star estimates. Pull out some [binocular variables](#) and just follow them once a week for a month. If you haven't already, get a copy and become familiar with the excellent [Manual For Visual Observing of Variable Stars](#).

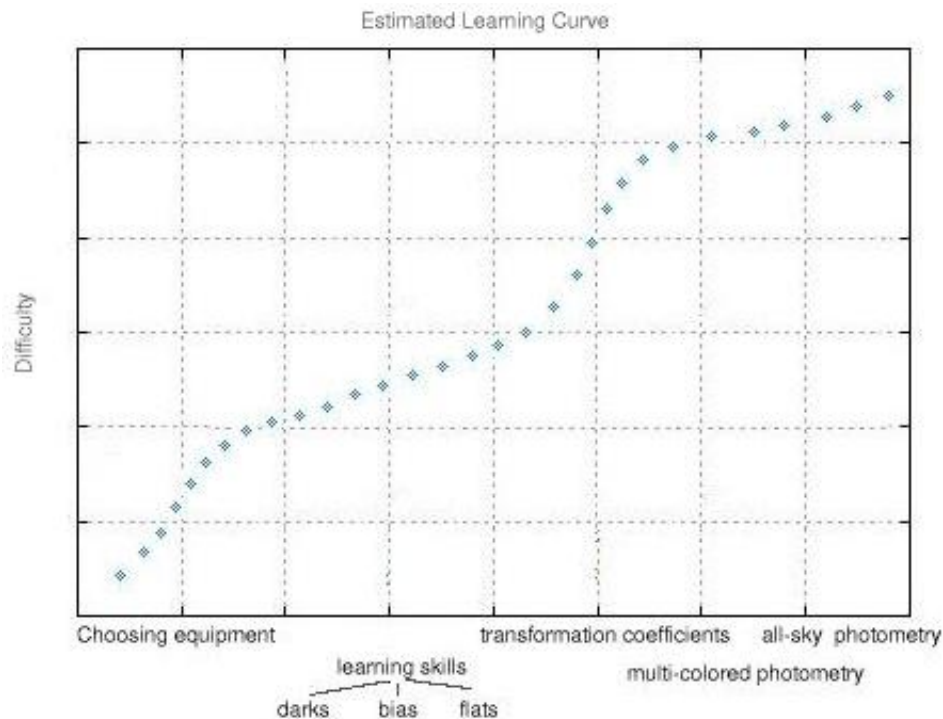
This experience will be key to teaching you how to identify fields, how color affects estimates (important later when we get into [filters](#)), the behaviour of a star's light curve, how to submit data, and perhaps most importantly - patience! Also, visual observing is usually quite fun and addictive, so practice will help make sure you enjoy variable star observing. After all, for most of us this is a hobby right? CCD Observing has many facets to it. Each one of these areas you gain experience with is one less area you have to be concerned with while learning CCD observing. Get the basics out of the way now so you can focus on the hard stuff later.

1.4 Expectations

In general, this manual will focus on aspects of CCD observing specific to variable star photometry. With a few exceptions, we won't go into the details about how a CCD works, how to cool it, etc. Also, variable stars are usually just dots in the image so you won't find any help here in taking pretty pictures. (Although to some of us an image of a mag 17 CV in outburst is awful pretty!)



You are starting out on a very long journey, be prepared and patient! The good news is that you can start taking useful data almost immediately! However, you'll find the learning curve very long and at some times steep. Below is a general estimate of the learning curve you'll go through:



Obviously it is impossible to predict your personal experience so this graph should be taken tongue-in-cheek. However, the core idea is sound. In the beginning you'll find that [choosing equipment](#) is a pretty daunting task. But once that is done you will settle down into a steady routine of making observations and slowly improving your accuracy. After you have mastered the basics such as [dark](#), [bias](#), and [flat fielding](#) then it gets pretty tricky in the world of

[transformation coefficients](#) and [all-sky photometry](#).

Take your time along this curve and stop at any point you want. Some people, for example, find that messing with transformation coefficients isn't worth the extra amount of effort so they settle for photometric accuracy of 0.2 mag or so. This is still accurate enough to do good work. To determine how far you want to go you should compare the goals (and requirements) of your [observing program](#) against the amount of work you want to put into it.

In some cases it can take years of experience before a new observer can master transformation coefficients and get their [error](#) to the 0.01 mag plateau. So remember to take your time, have fun, and bite off only as much as you can chew!

1.5 Why CCD's?

The two main reasons why CCDs are great for variable star observing is because they are more accurate and more sensitive than the human eye. Additionally, you can archive and automate your observations. Below is a summary of a few of these advantages:

Sensitivity

With a CCD you can see objects much fainter than is possible visually. For example, a 10" telescope with a Starlight Xpress MX916 CCD can get to mag 16 in 2 minutes in light-polluted, mag 4 suburban skies. With a visual telescope you would likely need 16-20 inches of aperture along with crystal clear and dark skies away from the city.

Accuracy

The linear nature of a CCD means that when proper procedures are carefully followed the [photometry](#) can be very accurate. In general, the accuracy of your result is in direct response to the amount of work you put into the observation. CCDs can easily and quickly get to an accuracy of .2-.3 magnitude. With just a little bit of work you can get that to 0.1. With a little more, you can get to .05. Finally, if you are prepared for a lot of work you may be able to get to 0.01 accuracy. With each level of accuracy is more work along with restrictions on what you can observe.

Most visual observers can get to 0.2-0.3 mag accuracy if they are very experienced. However, when the data is combined with other observers the scatter and accuracy of the light curve suffers tremendously. Scatter can be as high as 1.5-2 mags! CCD observers, however, use [professionally standardized filters](#) to make their observations. This makes the bandpass for each CCD observation very similar to each other, meaning that the combined accuracy can be up to .01mag. This is one reason why the scientific community prefers CCD over visual data. The professionals use the same type of filters so they can easily combine their data with that from amateurs.

Archiving

CCD data is recorded digitally by a computer so it can be easily archived. These archives can be sent to others for further review, the data can be recalibrated at a later date (Ex: if the sequence is changed), and any questions that arise over the data can be answered.

Automation

Advanced CCD observers can automate their observations to make better use of their observing time. For example, one observer may set an observing plan to image 5 objects all night long while they are asleep. Then all the observer needs to do is wake up a little early to

turn off the system and can reduce the data at a later date (such as a cloudy night). Automation isn't easy though, and depends largely on the quality of your mount.

Fun Factor

Let's face it, when the temperature is 10 degrees outside and the wind is blowing, wouldn't you rather be inside a heated room than [freezing your lips](#) to the telescope? Also, some of us are real techheads who love the technology and the challenge of data reduction. For those brave souls, CCD observing is a real treat!

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2.0 Equipment

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An unknown speaker at the first AAVSO CCD workshop said, "*Calculate the expense of all the required equipment, multiply that by three, and that is what the final cost will be.*"

2.1 Telescope

Purchasing a telescope is a big step. A telescope should be chosen with your entire observing program in mind. Don't just purchase a telescope based solely on CCD requirements unless you plan to never use it visually. Also remember to take into account things like portability and size.

External links for telescope purchasing advice:

- [Buying a Telescope: Suggestions for Newcomers](#)
(formerly the sci.astro.amateur Telescope Buyer's FAQ)
- [Scopereviews.com](#)
- [Cloudynights.com](#)
- [Telescope Buyer's Guide](#)

(The AAVSO does not endorse any of these links or any brand of telescope)

When it comes to CCDs, the most important features in a telescope you want to consider are:

- **Aperture:** This one is easy. The larger the aperture - the fainter you can go. However, remember that with CCDs modest sized telescopes can do a lot of work. The vast majority of stars in the AAVSO program are mag 16 or brighter, so purchasing a "light cannon" isn't required. However, we do have some programs which need large aperture ([High Energy Network](#), I'm looking in your general direction...). Note that bigger aperture has the downside of smaller FOV (for same f-ratio).



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- **Field of View:** CCDs are notorious about having small field of views (although this is changing as technology progresses). Small fields of view make it hard to get the comp stars in the same field as the variable. It also can make it frustratingly difficult to find the object. The smaller the f-ratio the better.
- **The Mount:** This is crucial. The mount's ability to find the object ("goto") and the tracking will profoundly affect your observing experience. Also consider the setup time. A mount that isn't very accurate, takes forever to align, and tracks poorly will leave you so frustrated that you may lose interest in the hobby. If possible, do not skimp on the mount. Equatorials are a must because alt-az mounts cause field rotation during medium and long exposures, which destroys photometric accuracy.

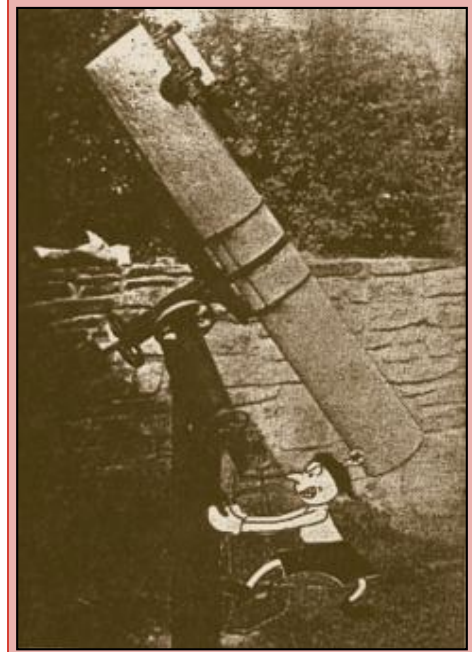


Fig. 1. The gremlin can't shake the mount of Mr. Ruiz' telescope. ([about the gremlins](#))

The simpler the optical system the better. Stay away from focal reducers and anything else that can cause vignetting unless you *really* know what you are doing. Also stay away from color corrected systems and in general anything that adds a nonuniform effect to the field or changes the natural color of the incoming starlight. Celestron's Fastar system cannot be used for photometry. Also watch out for poor baffling because it can create ghost images that look like stars in your final image.



Warning Signs

Don't worry too much. Most telescopes are great with CCDs. Small scopes have rich fields of view and large ones can go as deep as some professional scopes. Find a scope that you will enjoy. It needs to fit your budget and be easy to setup and use. Remember what [Clint Ford](#) said, "*The best scope for you is the one you use the most.*"

No Telescope? No Problem!

It is possible to use a CCD for photometry without a telescope. Simply attach a 35mm camera lense to the CCD (usually with a T-adapter) and aim at the sky. You still need to use a proper [filter](#), though. There are many bright variables that are very red so have scatter in their light curves. These would be ideal targets for such a system.

Best Advice

The **absolutely, positively, best advice** you can follow when purchasing a telescope is to talk to people in your local [astronomy club](#). Spend some time looking through their scopes, ask for anecdotes and advice, seek out the CCD observers and see what they use. However, remember that most club members won't know anything about photometry so seek out those with photometric experience.

2.2 CCD Camera

The best CCD camera for you depends, like the telescope, a lot on your personal situation. You need to consider the cost, your observing goals, your telescope, and then of course the reputation of various manufacturers and models.

For More Information

[CCD Equipment Basics](#) from Starizona

Observing Goals

Do you plan on *only* doing variable star photometry or do you also want to use your camera to also take pretty pictures, hunt for asteroids, etc? For pretty pictures, [binning](#) and [antiblooming](#) can be a big help, but both are not recommended in the world of photometry. Also, resolution is important for pretty pictures but it isn't in photometry. Here we are going to give you advice regarding photometry only. If you plan to use your camera for other targets then seek the advice of groups in that area of interest and choose a good "middle-ground" camera.

What Are You Looking At?

First, get a feel for what [observing programs](#) interest you and read up on them. There may be different features on a CCD that will help in some programs. For example, if you are going to do a lot of [supernovae hunting](#) or [GRB work](#) then you will want a camera with a wide field of view. If you are doing studies of [bright LPVs](#) then you will want a camera with a good dynamic range and large well depth.

Sampling & Pixel Size (Telescope compatibility)

One of the most important things you need to consider when purchasing a CCD is its pixel size. For most consumer (front-illuminated) chips you want to spread the FWHM of the star across 2 pixels of the CCD for optimal photometry according to "[Astronomical Image Processing](#)" by Richard Berry & James Burnell. This will help you optimize your signal to noise ratio and improve accuracy. To get the best FWHM you will need to determine how much of the sky will fall on a single pixel of your CCD camera. This means making a calculation concerning the telescope's aperture, f-ratio, and the size and number of the CCD chip's pixels.

Full-Width Half-What?

FWHM stands for "Full-Width Half-Maximum" and is basically the size of the star on the chip. The size is chosen by counting pixels that are filled to 1/2 the dynamic range between the background and the brightest (fullest) pixel in the star's image. Most software will determine this for you and we'll discuss it in more detail in the [Photometry](#) section.

To determine the amount of sky that will fall on the pixel use this formula:

$$\text{Sky} = (206.265/Y) * X \quad (\text{if focal length is millimeters})$$

$$\text{Sky} = (8.12/Y) * X \quad (\text{if focal length is inches})$$

Where **X** is the pixel size of the CCD chip in microns and **Y** is the focal length of the telescope in millimeters. Example: A 10" f/10 telescope (2540mm focal length) and a CCD with the Sony ICX 083 chip (11.6 X 11.2 micron pixels = 11.4 avg) will give 0.9 arc second per pixel. To see how much sky will fit on the entire CCD we just multiply that by the size of the array (752x582). In general, 1 arc second per pixel would be too small. However, by binning the chip you can double, triple, or quadruple the pixel size. So by triple binning we would get a pixel size of almost 3 arc seconds.

Here is a calculator we created to do the calculation for you:

Telescope aperture:

F-ratio: f/ Pixel Size: microns.

Size of array: X (optional, only if you want full field of view calculated)

Pixels vs. "Seeing"

For most amateurs living in suburbia seeing conditions limit your telescope's resolution to between 3 and 4 arc seconds, although it may be smaller for those in great locations or on days of exceptionally good seeing. What you want to do is come up with a telescope + ccd system that will spread this seeing out over 2-3 pixels. **Example:** If you get seeing conditions on average of 3 arc seconds, you will want a telescope that puts 1.5 arc seconds on each pixel so that the FWHM of the star will cover 2 pixels in your final image. This is called *sampling*.

Binning

This is also where binning can help. If your conditions are so bad one night that your seeing blurs the star across 4 pixels, you can do 2x2 sampling to get it back down to 2 pixels. Binning refers to the combining of a group of adjacent pixels into one large pixel. 2x2 binning, for example, takes an array of 4 pixels and makes them act as 1. The downside to this for photometry is that some of the starlight will be landing on the gates dividing the pixels and will be lost. This causes a slight hit in accuracy so binning should be avoided when possible.

More help:

- o [Telescope Optics & Pixel Size](#) from Apogee
- o [Starizona's Pixel Calculator](#) This online tool lets you mix and match between different telescope and camera systems.
- o [WhatUSee](#): Field of View calculator (windows)

Antiblooming (ABG)

The "[anti-blooming gate](#)" is a feature on some CCDs to prevent electrons from leaking from one pixel to another. This happens when a star is bright enough to "saturate" the pixels on the camera, filling up the wells. What is left over "leaks" onto adjacent pixels. This causes spikes and other artifacts in the image. ABG mitigates this effect by putting "gates" between the pixels. However, this can destroy linearity of the chip and your photometric accuracy will go along with it.

It is highly recommended that you purchase a camera without ABG. Many manufacturers sell cameras with ABG removed or else have documentation on how you can remove it yourself (if you are brave and mechanically inclined). Another advantage to not having ABG is your CCD sensitivity will be greater.

However, if you end up with ABG in your camera all is not lost. In that case, a good rule of thumb is to limit your pixel saturation to 50% of your well depth. Most cameras with ABG stay linear in this range. For example, most 16 bit cameras stay linear to 32,000 units or less per pixel. Your [software](#) will be able to tell you the saturation of a pixel and your CCD documentation will tell you the well depth of your pixels.

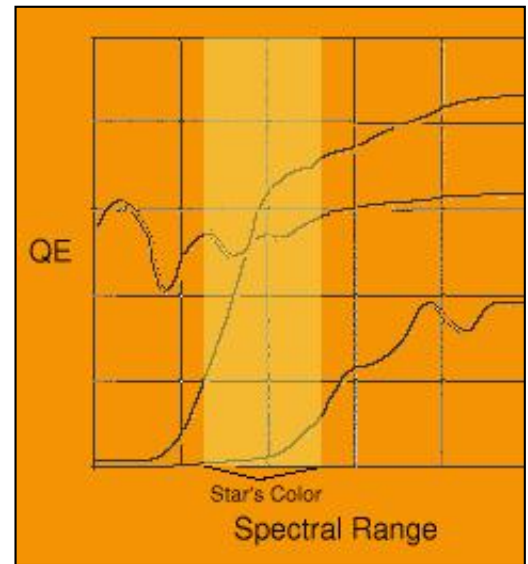
2.3 Filters

Different models of CCD chips have different spectral responses. Because of this, it is vital that one use proper photometric filters when observing variable stars.

Take a look at the diagram on the right. The 3 lines represent the spectral response of 3 popular CCD chips. The highlighted area represents the passband of a photometric filter.

Notice how each CCD chip has a different spectral response in the region of the star's light in the filter's passband. If each user imaged the star unfiltered they would all get wildly different magnitudes!

But don't think that using filters is a bad thing. In fact, this is one of the strengths of CCDs. When you use a filter you equalize the passbands of various CCDs. This means that your data can be added to other CCD observations without the scatter that visual observations have (because visual observations are unfiltered).

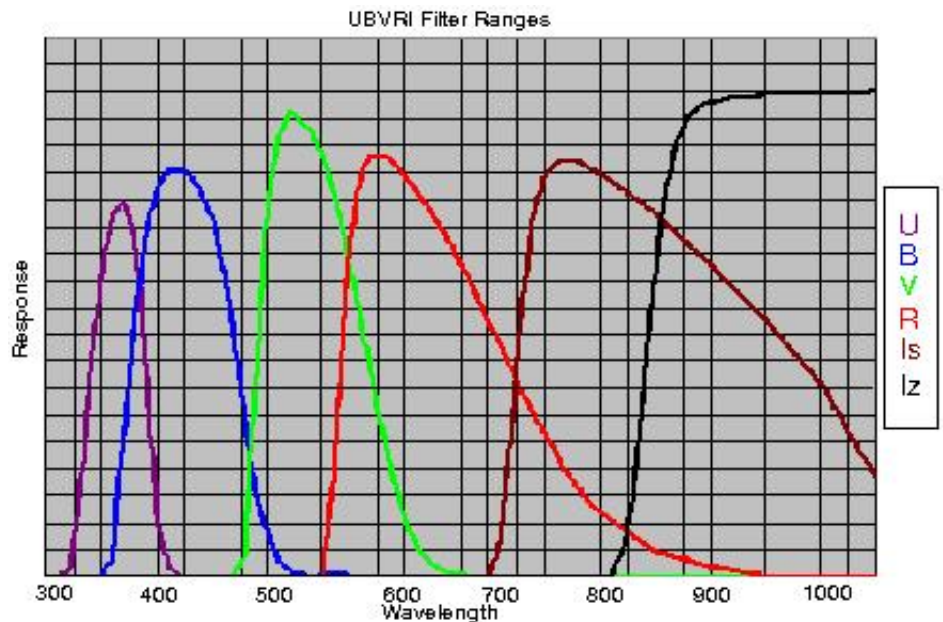


The standard filters most often used for photometric work are:

- **Johnson U** (U): This is in the near ultraviolet range. Very few consumer level CCDs are sensitive in this range.
- **Johnson B** (B or Bu): This is the **blue** range. Cataclysmic variables (CV's) tend to be bright in B, especially when in outburst.
- **Johnson V** (V): This is close to what the human eye sees so the V stands for Visual. It is roughly centered in the **green**.
- **Cousins R** (R or Rc): This is **red**. Mira's are bright in R.
- **Cousins I** (I, Iz or Ic): This is very near infrared. The human eye cannot see this portion of the spectrum so an Ic filter may look opaque when held up to the light. There are many I bands (Is, Iz...) but Ic is the most common.

Photometric filters can usually be purchased from the same vendor that sells you the CCD. The most popular manufacturers are [Optec](#) and [Schuler](#) (via Astrovid). Prices can range from around \$50 to \$150 per filter.

When using a system with a low f-ratio telescope you may want to get 48mm filters instead of the standard 1.25" filters to account for vignetting at the edges of the filter.



Start With V.

To start off, you only need to purchase the V filter. The is the most common filter used and for most stars in the AAVSO program it is all you will need. Among the complications you run into with the other filters is that most AAVSO charts only list V mags (or close approximations) so it can be difficult to find appropriate comp stars for the other filters. Only use other filters when your observing program specifically requires it.

Some suppliers call their filter sets various combinations of Johnson, Cousins and Kron. They all have the same V response and the alternate names refer to the designation of filters other than the V filter in their series. The filter is different from a Tri-color (RGB) green filter, in that it is more narrow in bandwidth and centered at a different wavelength. The proper filter response is sometimes referred to as a "Bessell" response which refers back to a paper by [Mike Bessell](#), who published curves on filters in the [IAU Colloquium 136 on Stellar Photometry](#).

Anecdote: One of the authors spent hours one night trying to get a flat field using an I filter. Frustrated and dejected, he gave up only to realize a week later that the light source he was using was flourescent, which doesn't radiate IR!

IR Blocking

When using one of the standard UBVRI filters you don't need to worry about using an IR Blocking filter since they are built into the standards for those filters.

Unfiltered Observations

Unfiltered CCD observations are not very useful to the AAVSO. In fact, it is almost preferable to do visual work instead of unfiltered CCD work because at least the human eye (the "Mark I Eyeball") has a somewhat similar spectral response when compared to unfiltered CCDs. Unfiltered CCD observations can be really off. For example, an unfiltered CCD obs of a red mag 10 star could show up as mag 3 because of leaks of red light in the CCD. With that said, there are a *few* observing programs where unfiltered observations are acceptable, but never assume it unless you have checked with the AAVSO first.

2.4 Computers & Software

Hardware

CCDs do not tend to require powerful computers. However, some new USB and TCP-IP supported CCD systems may require newer machines with USB ports and properly configured ethernet cards. You should have a good working knowledge of computers before you purchase a CCD. In fact, the more you know about computer "stuff" the easier CCD work will be. Especially useful is knowledge about spreadsheets, databases, and some basic scripting skills. You will likely spend more time manipulating your data on the computer than actually taking the images. The more you know - the more you can automate. Some of the tasks are tedious and can be made bearable through scripting.

Windows PCs are the dominant platform for CCD systems (surprise). However, some Macintosh systems do exist (SBIG sells a Macintosh adapter for most of their line of CCDs) and the new Macintosh OS X architecture is based on UNIX which opens the door for UNIX-based CCD programs. Speaking of which, support for CCDs under Linux has grown measurably in recent years. Almost any commercial CCD camera will have Linux drivers available (usually third party and free). However, using Linux or a Macintosh to drive a CCD system should be attempted only by those who are thoroughly familiar with their operating system.

Regarding monitors, if you have a very large CCD chip, make sure the monitor and video card can support the image resolution your chip will supply. If it doesn't, you may find yourself scrolling madly or shrinking images.

Software

CCD software can be broken into two large categories: **CCD Interfaces** and **Data Reduction**. The first category consists of software that actually controls the CCD during the observing session. The second category is made up of programs that specialize in manipulating the data after it has been recorded. Most CCDs will come with a program that controls the camera well but doesn't do much in the realm of data reduction or telescope control. You can either use this software to control the camera and another software package to reduce the data or you can spend a little more and find a program that will do both.

Here are some links for some of the most popular software currently available:

- [AIP4Win](#) | [Support Group](#)
- [MaximDL](#) | [Support Group](#)
- [AstroArt](#) | [Support Group](#)
- [Mira](#)
- [IRAF](#) and [Pyraf](#) (a python-based front end to IRAF)



(The AAVSO does not endorse any of these links or software packages)

Most professionals (and many advanced amateurs) use IRAF, a free program distributed by National Radio Astronomy Observatory (NRAO). It is a very powerful and flexible collection of CCD control and reduction packages. Right now it runs on most UNIX platforms, including Macintosh OS X. However, it can be a challenge to learn and should only be attempted by those familiar with UNIX. If you have Perl, Python, Tcl, or other kind of scripting skills then using IRAF will be much easier.

Choosing the software will be a little like choosing the telescope. You need to consider your hardware requirements (does it support your CCD model and telescope mount? Does it run on your operating system?), cost, and ease of use. For the latter, look for trial

versions and, as with the telescope, ask friends about the software they prefer to use. If possible, spend an observing session or two with the friend and let them teach you the ropes. Finally, lots of online support exists for most programs (usually in the form of e-mail discussion groups).

Be Comfortable With Computers

One last thing to remember is that CCD observing is computer intensive. Computer skills are usually the prerequisite lacked most often by new observers. Please make sure you are comfortable using computers before adding CCDs to your hobby. Many observers e-mail us daunted and frustrated by the amount of tedious work they must put in to reduce and format their data. CCD manufacturers don't advertise that! The highway of CCD observing is littered with debris from folks who got frustrated with the technical requirements and threw their equipment out the window. Be patient and jump in when the time is right.

Here are a sample of some things you will need to know or learn:

- How to troubleshoot a bad connection to your camera. (i.e. is it a broken serial port? cable too long? temperature too high?)
- The difference between various file formats? (especially RTF, TXT and other ASCII formats)
- Can you manipulate text data?

CCDs generates *huge* amounts of data. You need to be able to manipulate the data to get it into a format [acceptable by the AAVSO](#) and the scientific community. Recently it has gotten easier as CCD photometry packages have begun putting in data export features into their software. This formatted data can often be [uploaded to the AAVSO](#) with little or know editing by the observer.

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3.0 CCD Camera Skills

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3.1 Calibration Overview

A raw CCD image contains a ton of data. Some of it is good (signal) while some of it you don't want (noise). It is the Zen-like balance between signal and noise that will determine the accuracy of your measurements.

Signal

The signal in your system is the starlight itself and nothing else. Those photons that left the stars tens to billions of years ago land on your CCD chip and are converted into electrons. These electrons are counted and then displayed on your screen and stored on your computer in binary form. The trip from CCD to monitor is a dirty one.

Unwanted Signal

The unwanted signal in the system mostly comes from the sky (cosmic rays), the telescope (vignetting, reflections), the CCD chip (dust donuts, hot pixels, dark current), the CCD charge-detection node (read-out noise), and the computer (timing).

Calibration to the Rescue

Calibration is the combat itself between signal and unwanted signal (some people call this noise but by its strictest definition it isn't - you could also call it bias or unwanted effects). Through calibration you can mitigate the effects of each of those sources of unwanted signal. Sometimes you can merely diminish it (read-out noise) and sometimes you can completely eliminate it (cosmic rays). Calibration can be a very tedious and time consuming process. It is also one of the areas of CCD observing where experience helps out the most. In the beginning you may be a poor calibrator. No problem! As time goes on you'll get better and find the best calibration system for you.

Do the Calibration Shuffle

There are three important calibration routines that all CCD observers should be familiar with. *Bias Frames* help compensate for read-out noise and interference from the computer. *Dark frames* compensate for the thermal properties of the CCD chip and *Flat frames* compensate for noise in the light path. All three are combined to give you the best calibration possible.

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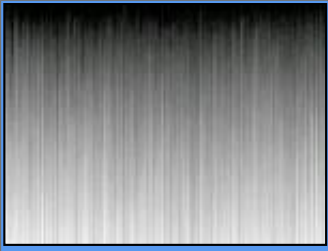



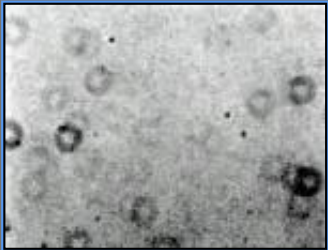

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	Frame	Data	RX And value
Bias			10.0 +/- .4 Vmag
Dark			10.2 +/- .1 Vmag
Flat			10.25 +/- .05 Vmag

The above illustration is a completely arbitrary example of what *could* happen during a calibration procedure for an image of [RX And](#). Notice how the magnitude estimate becomes more precise and the error drops after each step in the procedure. [Error estimation](#) is actually far more complicated and discussed in [another section](#). But this gives you a general idea of what the various frames look like and their impact on the final image and data reduction.

$$\text{Calibrated} = (\text{Raw} - \text{Bias} - \text{Dark}) / \text{Master Flat}$$

$$\text{Master Flat} = (\text{Raw} - \text{Dark}) / \text{Flat}$$

3.2 Calibration Trifecta: Bias Frames

The first step in calibration is to prepare a *bias frame*. A bias frame is basically an image taken with the shutter disabled. The image will consist only of read-out noise and noise caused by interference of the computer. What a bias frame does is set the [zero point](#) of the CCD output and the pixel scales to the same value. This makes the final image more accurate since the zero points are equal and no nonlinear pixel values exist.



Bias frames will have very little signal in a modern quick-read-out healthy CCD camera (larger and older cameras will have more signal). They will have virtually no effect on the visual description of the image (astrophotographers rarely bother with bias frames). In fact, you may find that the bias value changes by less than one ADU per pixel (your [software](#) will be able to determine this). In that case you should take the average value of all the pixels in the frame and apply that average to every pixel. What this does is correct for statistical "accidents".

A bias frame will also take into account thermal current that collects while the frame is being downloaded to your computer.

Note: If one uses darks that are the same duration as the light frames, bias calibration is unnecessary because it is included in the dark data. Bias frames are only required if one intends to scale their darks.

Taking Bias Frames

Not all CCDs can take pure bias frames. Some CCDs just are not designed to take an exposure without using the shutter. In those cases you can simply skip the bias frame and go straight to the [dark frame](#) (which will include some of the same data as the bias frames) or you can make a pseudo-bias by taking an exposure with the shutter at the shortest possible exposure length and your system completely blocked of any light.

If your camera can take a bias frame, it is likely already setup in your software. A bias frame is a 0 second exposure. After you take it, inspect it for artifacts. In theory, the field should be uniform. But in reality you'll notice some changes in amplitude. If you notice any patterns, they were likely caused by a spurious noise source (computer CPU chip, home electrical surge, etc.). Take a number of bias frames and determine whether you are operating in a "noisy" environment or not.

The more bias frames you take, the better the result. The readout noise in the bias frame will decrease by the square root of the number of frames you take. In very sensitive cameras you may want to take as many as 50 frames! A good rule of thumb is to take as many bias frames as you take [darks](#).

If you found that you are working in a noisy environment then you should *median combine* your bias frames, otherwise *average* your frames together to make a *master bias*.

3.3 Calibration Trifecta: Dark Frames

A *dark frame* measures the thermal readout of your CCD, a.k.a. its temperature. A dark frame is an exposure where the shutter is opened but no light is allowed to hit it so it only measures the energy from the CCD itself (dark current). This is normally done by placing a dust cap on the telescope and then covering it with a blanket, cloth, or something opaque to light. Darks also compensate for *hot pixels*, which are defects in the CCD chip that makes pixels look like they are permanently "on" or "lit". **Darks are very easy to take and are the most important calibration step** so there is no reason not to take darks.



Taking Darks

The [Handbook of Astronomical Image Processing](#) recommends the "Image-Times-Five" rule. The more dark frames you take, the more accurate the frame and the lower the noise. For a sample of 100 electrons, the uncertainty is 10%, for 10,000 it is 1%. A good rule of thumb is to make sure the total exposure time of all your dark frames equals five times that of the image you are calibrating. So if you are taking a 2 minute image, you can do five 2-minute darks or ten 1-minute darks.

This is where your [bias frame](#) comes in. The dark frame also contains readout noise. Readout noise does not scale over time, so your dark frame right now is unscalable. That is a pain if you plan to take exposures of different lengths during your observing session because then you must take a ton of dark frames to match the integration time (times five!) of each image. If you could yank the readout noise then the dark frame only consists of thermal noise, which *is* scaleable. So let's do it! All you need to do is subtract the master bias frame from each dark frame you took. It's that simple.



10-minute amplifier glow (electroluminescence). Older CCDs suffer from this effect which can be removed with a dark frame.

As the CCD temperature changes during the night, the dark current will adjust. Except in extreme circumstances, you do not need to take darks for each image. A good rule of thumb is to take your dark frames in the middle of the observing session. Another plan is to take some of the darks at the beginning, some in the middle, and some at the end.

For each image remember to subtract the bias. Inspect each frame to make sure that cosmic ray events do not contaminate them. They will appear as a bright spot on your dark frame. It depends on altitude, physical size of the CCD chip, and exposure time but in general expect about 1 cosmic ray event every few minutes of exposure time. When you have a bunch of darks, average them together to create a *master dark*. (You can skip the cosmic ray inspection by *median* combining at least 3 frames instead of averaging them; but then your final dark will have slightly more noise.)

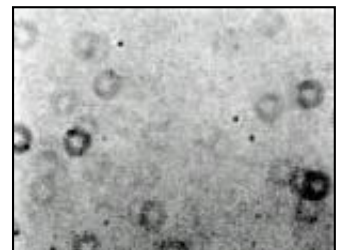
Tip: It is possible to create a *library* of dark frames for different temperatures and operating environments. Some people will create them once a month (during the full moon downtime perhaps?) or once a week. However, these dark frames will never be as good as ones you take during the observing session. Experiment with your own system and see how a library of darks affects your final [error](#) and then decide whether the savings in hassle is worth it for your current project.

Now you have 2/3 of the calibration process completed. Some observers will quit there. If you have carefully made your master dark frames and done everything else correctly it is possible to get to 0.03 mag accuracy in your photometry.¹ For most AAVSO [observing projects](#) this is all the accuracy you need.

For those who want to really push their accuracy, [here is a tip for how to take low noise dark frames](#) from Ron Zissell.

3.4 Calibration Trifecta: Flat Frames

For the absolute highest quality photometry flat frames must be used to calibrate your image. A flat frame compensates for obstructions, reflections, and other problems in the light path. This is the path light travels from the time it enters the telescope to the moment it strikes the CCD chip. Dust on optical surfaces, reflections from baffles or poorly aligned optics, vignetting, and other noise sources can interfere with your final data.

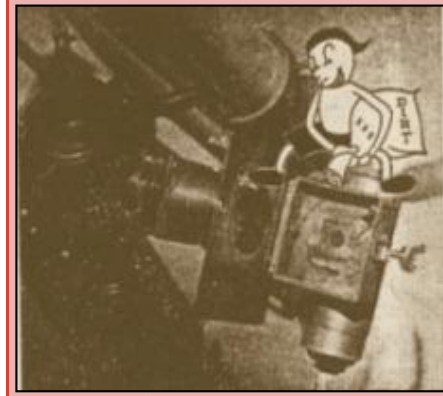


Flat fielding is the most difficult calibration routine you will have to deal with. There are many things to watch out for and many ways to do it. In fact, some people call it an *art* because it is so intricate and there are so many creative ways you can do it. The key is to be patient and realize that your first few flats will likely not turn out well. Take your time and with experience you'll be

able to *master the master flat!*

The Concept

A flat field is a picture of what's wrong with your system in regards to light. (This is an oversimplification but bear with us here..) You will see dust donuts, light gradients, reflections, and more (right). Now that you have an image of what is bad, you take an image of the star. *That* image is an image with good (star) and bad (noise). You remove the flat field from the image and you are left with only the good. Trim the fat, so to speak.



The free

passage of light through the small aperture can be seriously impaired by dirt and dust. ([about the gremlins](#))

Taking Flats

The first thing you have to do is take *flat darks*. These are [dark frames](#) taken to be applied to the flats. So you want to match the integration time with that of your flat, not that of your final image. These darks will be separate from your image calibration darks. Other than that, the procedure is exactly the same as [above](#).

The goal is to take an image of a uniform light source (the "flat" field). So the first thing you need is that uniform light source. This is the most difficult part of taking flats. The good news is that once you find a uniform light source that works you can use it forever. There is no fool-proof method of creating the uniform field. How you do it will likely depend on your physical location, mechanical ability (handyman factor) and your level of patience! Here are some of the most popular light sources for flat fields:

- **Domes:** Shining a light on the underside of the roof of a closed dome.
- **Twilight:** For about 15 minutes at dusk and dawn a photometric sky can be a uniform blue.
- **Lightboxes:** These are boxes with a light bulb inside that fit on the outside of the telescope's central opening.
- **T-Shirts!:** All sorts of creative ideas have been used to create uniform fields from white cotten t-shirts to film screens to the sides of houses. The limit is your imagination.

Usually the light source will be a dimmable bulb so that the light can be adjusted for the [filter](#) you are shooting through. Different filters transmit different amounts of white light so what may be a good source for a V filter may be a weak source for an R filter. If you don't have a dimmable bulb you can adjust the image exposure time, but then you need to take a new set of flats. (This can get complicated pretty quickly!) The light source should be reflected off uniform surfaces before entering some type of diffusing screen. For example, you may want to shine a light on a [white poster board](#) which reflects it to a piece of translucent plastic before going into the telescope. The more times you reflect the light, the more uniform the field will be.

Once you have a uniform field, expose your CCD to about 1/2 of the full well depth of your pixels. Take at least 16 flat field images, this is the lowest number required in order to avoid adding noise to your final calibrated image. For .01 mag accuracy photometry keep your signal to noise ratio to 500:1 or better. The exposure time will differ based on what filter you are using since each will pass a different fraction of the light source.

Every time you change an element in the light path, such as removing a filter, you change the

light path so you have to take new flats. So you can't take a flat with a **V** filter, then take it off and put on an **R**. When you do that the V filter flats should be discarded. (If you are using a high quality filter wheel then you can do all the flats at once since their orientation in the light path will be the same when the filter wheel changes it.)

Applying Flats

1. Average all your flats
2. Average or median combine all your darks made specifically for the flats
3. Subtract the averaged dark from the averaged flat

What you have left is your *master flat*. Congratulations! This flat will be good as long as you don't change anything in the optical configuration of your system.

Now you can begin taking data (images). Divide the flat into each image after you have dark subtracted it. Most software programs have a way of automatically doing this. Now your images are fully calibrated.

Rejoice!

- [Starting out in Photometry Part 2: Flat Frames](#) from [CCD Views](#): Good description of a flat field learning process, setup and routine

3.5 Finding the Field

At first this can be one of the most frustrating parts of the [learning curve](#). It is also an area where visual observing experience really begins to pay off. The same problems you have with finding the field visually exist with CCD. The difference is that your field of view will be **a lot** smaller.

Recommendations:

- **Alignment:** Don't skimp on your alignment procedures.
- **Chart Masks:** Draw a circle on a sheet of plastic indicating the field of view of your CCD and then block out anything outside that field of view. Use this mask on your [charts](#). Make one for d, e, and f-scale charts.
- **Use Big Charts:** Your field of view may fit within an f-scale chart, but bring d and e-scale charts with you while observing. This way if your mount doesn't put you within the f chart you can find yourself on the e or d charts. If the e and d charts don't go faint enough, print out a copy of the field using the [DSS](#).
- [Learn to read the charts](#)

3.6 Image Integration Style

It is perfectly acceptable to coregister and then stack (a.k.a combine, sum, average) images to improve your signal to noise ratio. However, don't perform any nonlinear calculations on the field as this will destroy the photometry. One advantage to doing a median combine is that you can remove cosmic rays that way, but you do take a hit in your signal to noise ratio.

3.7 Tricks of the Trade

Here are some notes and general rules of thumb from some experienced observers:

- Don't expose for less than a few seconds. Anything shorter will cause the shutter to

affect photometric data (the speed of the shutter opening and closing will affect the amount of light that falls on pixels depending on where the pixels are located in reference to the rest position of the shutter).

- Plug in your camera first when you begin setting up for the night so that it can reach a temperature equilibrium by the time you are ready to take darks. Most modern consumer cameras need 15-30 minutes to stabilize.
- Outside temperature and humidity can affect dark frames quite a bit. Experiment to determine how many degrees of a temperature change your system will handle before you need to take a new set of darks.
- Keep careful written records of seeing conditions, photometry results, how many darks and flats you took, etc. This will come in handy later when you are reducing data. Remember data reduction may take place days or weeks after you took the image when many vital details may have been forgotten.
- Practice, practice, practice. And don't forget to enjoy yourself.
- [Tips on Starting an Observing Program](#) (from CCD Views): Includes details on optimizing your observing session
- Develop a personal convention for naming your files so that you'll know what they are without opening them or consulting your notes. This will reduce your observing log burden and speed-up analysis. (For example, 0072AP160.fit could mean file #007, source 2002AP, bin 1, 60-second exposure. One observer recommends using the naming scheme: yyyy.mm.dd Object (filter, exposure time) (details) .fit Sorting these files by name will result in time dependent scheme AND no file will be lost due to copying different files with identical file names.)

If you have any tips please [send them to us!](#)

¹: From Handbook of Astronomical Image Processing by Richard Berry and James Burnell, page 257.

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Observing

CCD Observing Manual

4.0 Photometry

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4.1 Introduction to Photometry

Photometry is the process of taking brightness estimates of stars in the sky. Some call it an *art* and some others even call it *black magic* because it can be quite challenging and confusing. But don't let that scare you, it is also very fun. Variable stars are addictive. When you have been following the same star for a long amount of time it can almost seem like part of the family. You expect certain activity, and when it acts up, you get concerned! Photometry is definitely a challenge, but it is a worthy one and a unique area of science where amateur help is not only needed but required.

There are many different methods to photometry. Each has different requirements and results. In general, the more work you put in the more accurate your data will be. So what needs to be done is a comparison of the methods with the level of accuracy you need for your [observing program](#).

4.2 Differential

Differential photometry is the easiest to learn. It is quite similar to visual observing in that you get the variable star (**V**) in the same field as your comparison ("comp") star (**C**) and you estimate the difference between the known (C) star and the unknown (V) star. An additional check star (**K**), whose magnitude is known, is compared with the comp star to make sure it also does not vary. Differential photometry looks something like this:

Estimate = V - C as long as known K - C equals observed K-C.

The limit to differential photometry is that you must have a comp and check star in the same CCD field of view as the variable. This usually means using a [star chart](#) made by the AAVSO. Also, your final magnitude estimate is subject to errors in the estimates of the comp star. The strengths include the cancelling out of air mass and atmospheric disturbances, which is one reason why differential photometry is easier than [all sky](#).

Note: Some [software](#) products use more than one comp star to make the estimate. They do it in a number of ways but in general it makes your photometry more complicated but also may make it a bit more accurate. [Click here for an AAVSO Discussion Group post on the topic.](#)

Variable Star
Centroid: 95.24, 66.36
Star-Sky: 54831.8
Sky Bkgrd: 3200.1
V - C = -0.744 Mag

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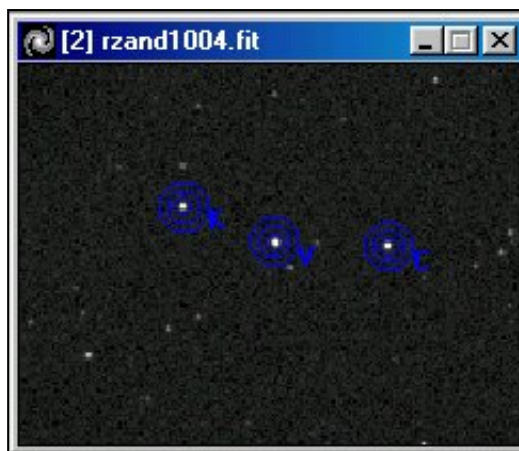
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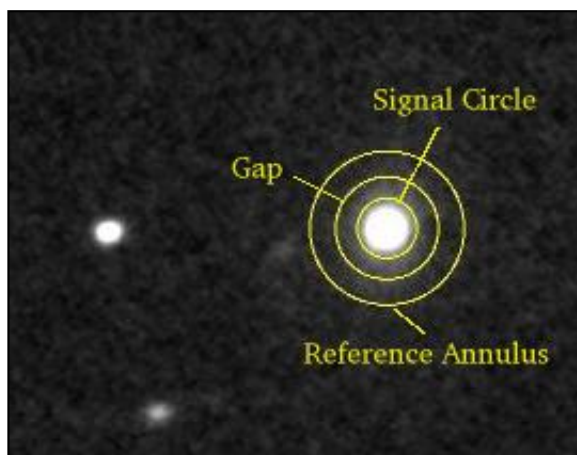
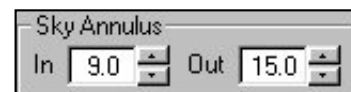
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Aperture Photometry

In differential photometry, *apertures* (a.k.a. annuli) are selected around the variable, comp, and check stars. In each aperture are 2 or 3 circles. The inner circle's size is adjusted to fit around the star itself. The outer circles are adjusted to include background light but not light from any neighboring stars. The software then calculates the average sky value for the outer circles and for the inner circle. The outer (sky) value is subtracted from the inner (star) value. This also happens for the comp and the check star. The resulting star values are compared to get the final values for the image.



Some random notes:

- Clouds and out of focused images are okay for differential photometry since they affect both the variable and the comp star the same but they may add some scatter/error to your estimates.
- If you do everything with care you can have an accuracy of 0.05 mag without taking [flats](#), however with flats differential photometry can get you to 0.015 mag.
- To increase precision setup your signal circle to [encompass 80% of the FWHM](#) to increase your [SNR](#).
- Sometimes the field may be very crowded and other stars will interfere with the sky annulus. Change the size of the gap annulus to remove the star from the sky annulus. ([example](#))

4.3 All Sky Photometry

All sky photometry uses comp stars that are more than a field of view away from the variable star. Because of this distance you must take into account extinction caused by the airmass you are looking into and many systematic variables. It is a complicated procedure but one worthy of mastering by those who want to get the absolutely most accurate photometry possible for fields without comparison stars. Also, all-sky photometry is very important for making new charts. If you feel you have mastered it then please contact our [chart making team](#) for a list of fields we need to be observed.

These are the equations we need to start All Sky BVRI photometry:

$$\begin{aligned} \mathbf{B-V} &= (\mathbf{b-v})\mathbf{T}_{bv} + \mathbf{K}_{bv} * \mathbf{X} + \mathbf{Z}_{bv} \\ \mathbf{V-R} &= (\mathbf{v-r})\mathbf{T}_{vr} + \mathbf{K}_{vr} * \mathbf{X} + \mathbf{Z}_{vr} \\ \mathbf{R-I} &= (\mathbf{r-i})\mathbf{T}_{ri} + \mathbf{K}_{ri} * \mathbf{X} + \mathbf{Z}_{ri} \\ \mathbf{V-I} &= (\mathbf{v-i})\mathbf{T}_{vi} + \mathbf{K}_{vi} * \mathbf{X} + \mathbf{Z}_{vi} \\ \mathbf{R} &= \quad \mathbf{r} \mathbf{T}_r + \mathbf{K}_r * \mathbf{X} + \mathbf{Z}_r \\ \mathbf{V} &= \quad \mathbf{v} \mathbf{T}_v + \mathbf{K}_v * \mathbf{X} + \mathbf{Z}_v \end{aligned}$$

Upper case BVRI implies Standard magnitudes,
Lower case bvri implies instrumental magnitudes.
T - are color transform coefficients
K - are atmospheric extinction coefficients
X - are the Air Mass terms.
Z - are zero point corrections

To avoid mistakes being introduced from exposures of different lengths, correct all instrumental magnitudes to the same exposure time.

If one chooses 10 seconds as the standard exposure for the night, one would correct all magnitudes by the following formula for even faint stars:

$$\mathbf{m(10)} = \mathbf{m(exp)} + \mathbf{2.50 \text{ LOG}(exp/10)}$$

An exposure (exp) of 20 seconds will produce instrumental magnitudes that appear 0.753 mag too bright relative to an exposure of 10 seconds.

$$\mathbf{m(10)} = \mathbf{m(20)} + \mathbf{2.50 \text{ LOG}(20/10)} = \mathbf{m(20)} + \mathbf{0.753}$$

The known quantities are the instrumental magnitudes, Standard magnitudes and Air Mass, X.

The unknown quantities are the Transformation coefficients **T**, Extinction coefficients **K**, and Zero point corrections **Z**.

One method of determining the three unknown coefficients in each equation would be to observe a number of stars at different altitudes and with a range of colors. Then do a Least Squares solution for the coefficients. Since some of the coefficients vary from night to night while others are fairly stable, it is better to determine the stable ones apart from the nightly ones.

4.4 Transformation Coefficients

First determine the T coefficients from a cluster such as [M67](#). M67 is an ancient open cluster with a number of well determined secondary standards with a range of color. It is compact

enough so that one can consider all the stars to be at the same Air Mass. This allows us to rewrite the [original equations](#) as :

$$\begin{aligned} B-V &= (b-v)T_{bv} + Q_{bv} \\ V-R &= (v-r)T_{vr} + Q_{vr} \\ R-I &= (r-i)T_{ri} + Q_{ri} \\ V-I &= (v-i)T_{vi} + Q_{vi} \\ R-r &= T_r(R-I) + Q_r \\ V-v &= T_v(V-R) + Q_v \end{aligned}$$

The extinction term is absorbed into the Zero point term since both are constants. As one takes the BVRI exposures in sequence, the cluster will be rising or setting, thus changing Air Mass.

To avoid this situation being significant, one can take the exposures in the order IRVBBVRI. The average of each color pair will center about the same air mass. Since the extinction is most for the shortest wavelength we keep the B images in the middle of the series.

Each of the revised equations has the form: $y = ax + b$

One can then plot the data. The slope will be the Transformation Coefficient. A Least Squares solution will give the slope and its uncertainty. The Q term is not of interest to us here.

In principle, the Y term should be the more uncertain and X term the better known quantity. In practice it makes little difference whether one plots Y vs X or X vs Y if one's photometry is done with some care to get the signal significantly above the noise.

$$\begin{aligned} (B-V) - (b-v)T_{bv} &= K_{bv} * X + Z_{bv} \\ (V-R) - (v-r)T_{vr} &= K_{vr} * X + Z_{vr} \\ (R-I) - (r-i)T_{ri} &= K_{ri} * X + Z_{ri} \\ (V-I) - (v-i)T_{vi} &= K_{vi} * X + Z_{vi} \\ R - r * T_r &= K_r * X + Z_r \\ V - v * T_v &= K_v * X + Z_v \end{aligned}$$

Again these equations have the form $y = ax + b$

One can observe one standard star as it rises or sets through a range of airmass and plot the Y, left hand side, vs the Air Mass, X. The slope will be the extinction coefficient K and the Y intercept at X=0 will be the Zero Point Z.

X can be given as the secant of the zenith distance angle, zd. This model implies a flat earth! At an altitude of 30 degrees the secant model will have an airmass in error of 0.005. A power series will give a better airmass as follows:

$$X = \sec(zd) - 0.0018167 * \text{Del} - 0.002875 * \text{Del}^2 - 0.0008083 * \text{DEL}^3$$

where Del = $\sec(zd) - 1.0$

Acknowledgements & More Help

Sections 3-5 of this page were written with help from Ron Zissell (ZRE), Doug West (WJD), and Bruce L. Gary (GBL).

Bruce also has an extensive web page available about how to determine your transformation coefficients. It goes into much more detail than this Manual and includes illustrations and examples.

- [CCD Transformation Equations](#) by Bruce Gary

A quicker method is to observe a number of stars at high and low altitude, being sure to include a range of colors too. These observations can be plotted as before and the extinction and zero point determined.

Excess sky signal is introduced here; but since most of the standard stars are brighter objects, this is not too objectionable.

Once the Transformation and Extinction Coefficients have been determined, one can insert the air mass and instrumental magnitudes from the unknown images into the first equations and tie them into the Standard BVRI magnitude system.

Transformation: If you apply transformation coefficients that are less than a year old then put: "Transform: Yes" in the Comments Explained portion of your observation (or click the appropriate box in WebObs & PCObs).

Zero Points

Zero points are one of the most difficult concepts to understand in photometry. Ron Zissell has written a discussion about zero points for [JAAVSO Vol. 26 No. 2](#). It is available below:

- [Zero point discussion in HTML](#)
- [PDF version](#)
- [Complete scanned article via ADS](#)

4.5 Pitfalls

- For All Sky photometry to work well, one must choose only the most stable and clear nights. One source of systematic error involves choosing the software aperture. One must be sure that the same fraction of each star's image is included in the software aperture. This is usually not a problem with a single image with many stars, however, over the entire sky, the seeing may vary with altitude and azimuth. At Ron Zissell's observatory located on the West edge of a college campus, the image size is larger looking to the East over the heated dorms and smaller looking West over a river valley. He must choose an aperture that is large enough to include all the light from the biggest image.
- One of the pitfalls that observers frequently have trouble with is understanding the difference between an *accurate* and a *precise* measurement. Richard Berry has written an excellent post to the [AAVSO Discussion Group](#) about this. [Click here to read it.](#)

4.6 Calculating Error

Introduction

Symantic Note of the Day: In everyday English, observers tend to use the term error to mean uncertainty. So here we define photometric error as measurement uncertainty.

"Uncertainty" includes the stochastic component (related to precision, which can be calculated using statistics) and the calibration component (related to systematic errors, that can only be estimated). At present, this manual explains how to include an "error" that is based only on the stochastic component. At a future date we hope to have a tutorial on how to determine the calibration component.

Reporting your photometric error/uncertainty to the AAVSO is a very important part of the observing process. When professionals are looking at your data they are much more likely to

respect the data if it includes an error term. Why? Consider as an example a professional who has a Target of Opportunity (TOO) observing project on a satellite. They need to observe U Gem when it goes into outburst (usually $V=13.5$). We receive an observation from one observer at 13.2 and another at 13.7. What does the astronomer do? If the observers submitted error then the astronomer would know which observation is more likely to be real.

Quick Start!

Simple error ranges can be computed in 2 easy ways:

- If your CCD software gives you [SNR](#), simply supply $1/\text{SNR}$ as your error estimate.
- If it does not give SNR, then use $1/\sqrt{\text{net_counts} \times \text{gain}}$

...where `net_counts` is the net counts of electrons which you can get from your software. This provides a first order approximation.

Tada!

This is only good for images where the star is bright and the background is dark. For other conditions or when you want a more precise error use this formula:

$$\text{SE} = 2.5 * \log_{10} (1 + 1/\text{SNR})$$

This gives a 1 sigma error. For a 2-sigma error, use $\text{SE}2 = 2.5 \log_{10} (1+2/\text{SNR})$

A derivative of the equation [is below](#).

Note: For bright stars the error you calculate may seem pretty small. That is because most of the error with bright star measurements is of *systemic* nature and not statistical. That is okay, we'll get to measuring systemic error soon enough.

Signal to Noise Ratio (SNR)

The signal-to-noise ratio (SNR) is a term that represents how much information you have from the measured object compared to how much information comes from other sources. It is a way to measure the confidence of your observation.

SNR is proportional to information; it is the ratio of signal to the uncertainty of that signal value.

The signal comes from the contribution of the star to the reading from the signal circle that encloses the star. Noise comes from uncertainty in both the [signal circle and sky annulus](#).

The uncertainty of the signal circle is proportional to the square-root of the number of pixels in the signal circle, whereas the uncertainty of the sky annulus is inversely proportional to the area of the sky annulus. Hence, SNR is maximum when the signal circle is small, but not smaller than the FWHM, and when the sky annulus is large.

What that means: For a perfect system SNR is maximum when the radius of the signal circle is $3/4$ FWHM. For a system with imperfect star shapes and imperfect tracking it is a good practice to use a radius twice FWHM. The sky annulus should be large for high SNR, but not so large as to include other stars or be affected by background gradients.

Most photometric software packages will calculate SNR for you. However, if they don't there are a few ways to do it manually:

$$\text{SNR} = \sqrt{C_{\text{net}}}$$

...where **Cnet** is the net number of electrons (counts multiplied by gain) from the star once the sky background has been subtracted. This is good for stars much brighter than background. Roughly speaking, 10,000 electrons gives a SNR of 100 which is approximately equivalent to an observational error of 0.01 magnitude. This equation is an over simplification of the formula for SNR. A more detailed discussion regarding calculation of the SNR can be found in the articles by Howell 1989 and Newberry 1991.

For Bright Stars

1. Calculate "Intensity" by doing the following:
 - o Calculate the average value per pixel of the sky annulus.
 - o Subtract this from all values per pixel within the signal circle.
 - o Sum these differences; call this Intensity.
2. SNR = square-root of Intensity

Consider a star to be "bright" when its intensity is three times the average level of the sky annulus. For other stars use the formula below.

The higher the SNR, the better your photometry will be. The easiest way to increase SNR is to stack many images. Collect images in groups of 3 to 5, and perform a median combine in order to remove cosmic ray defects that could give false photometry readings. Then average all your median combined images.

Stacking images preferentially increases the signal over the noise. The signal is summed but the noise increases only by the square root of the number of images you are adding. So the more images you stack, the better your SNR. Stacking 10 images increases signal by 10X while increasing noise by only ~3.2X!

For other ways to increase SNR see [Maximizing your SNR](#).

Going further...

For even better uncertainty, add the 1/SNR value to the standard deviation of your comparison/ check stars in quadrature.

$$\text{err} = \text{sqrt}((1/\text{SNR})^2 + \text{comp_stdev}^2)$$

A More Detailed Look at Error/Uncertainty

In this section we will look at the the basic definition that relates to errors, common sources of errors, and ways to reduce the errors in CCD photometry. By the end of this section you should have a good idea on how to quantify the photometric errors in your system.

Before discussing errors in CCD photometry we must understand the definitions of the mean, standard deviation, and the signal-to-noise ratio (SNR). If you measure the magnitude of a star five separate times you will get five different measurements. The average or *mean* will give you a more accurate estimate of the star's magnitude than any one single measurement. The average is calculated by summing all the measurements and dividing by the total number of them. In mathematical terms:

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$$

...where x_i are the values of the individual measurements and N is the total number of measurements. The summation sign is a mathematical symbol that simply means "the sum of x values from $i=1$ to N ." The next definition we need to be familiar with is the *standard deviation*. The standard deviation tells us the amount of dispersion (or spread or scatter) we should expect from a single measurement relative to the average. The mathematical formula for the standard deviation is:

$$\sigma_x = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2}$$

...where the Greek symbol sigma represents the standard deviation. In some texts, the standard deviation will be represented by s.d. Note that the standard deviation is always positive and has the same units as x_i . The average and standard deviation calculations are standard features in most spread sheet programs such as Microsoft Excel.

Two good references for a general discussion about the measurement of errors are: Henden and Kaitchuck 1982, and Lyons 1991.

Maximizing SNR

SNR can be improved by choosing the right sizes for the "signal circle" and "sky annulus."

Larger sky annulus areas are always better, except when it includes interfering stars or extends across an area where an imperfect flat field can have an effect.

There's an optimum size for the signal circle. Theoretically, the signal circle radius should be $\sim 0.8 * \text{FWHM}$. This assumes that a lot of things are text-book perfect. In the real world, a better choice would be:

"Signal Circle Radius = $1.5 * \text{FWHM}$ ".

The reason there's an optimum signal circle radius is that as the radius increases starting from zero the counts from the star increase in proportion to the number of pixels included in the circle whereas the noise from the signal circle total counts increases as the square-root of the number of pixels. For large signal circle radii the star's contribution to intensity does not increase with increasing radius whereas the the uncertainty of the total counts within the circle keep increasing in proportion to the square-root of the number of pixels. The radius where these two competing effects balance is the radius of 80 % of FWHM.

In choosing a signal circle radius consideration should be given to changes in FWHM throughout an observing session; the worst FWHM should be used: Signal Circle Radius = $1.5 * \text{FWHM}(\text{worst})$.

Sources of Error

There are several sources of error that creep into CCD measurements, such as, lack of color correction, not using a V band [filter](#), and a poor signal-to-noise ratio. Even with a V band filter CCD measurements will suffer from errors resulting from color differences between the comparison and variable star. This error can be removed by determination the instruments color

transformation coefficients and then transforming to the standard Johnson V band photometric system. This topic is covered in [section 4.4](#) of this manual.

Unfiltered photometric observations introduce another source of error similar to the lack of color correction. Since no CCD camera has a response that exactly replicates the standard V (or any other filter band) band, the wide band response of the camera measures flux from outside the desired wavelength region. For example, Mira variables are very red ($B-V > 1$), when using a red sensitive CCD camera they will appear to be much brighter than their actual V magnitude. The red sensitive camera and the star's intrinsic brightness at long wavelengths give a large error in V magnitude. This error can be minimized by using a V band filter.

The last source of error results from a low SNR. Figure 4.6.1 shows how the error increases as the magnitude increases. As the stars become fainter there are fewer photons for the camera to detect which results in a low signal for the camera to record. For a given exposure, the noise remains constant regardless if the star is bright or dim. Therefore, fainter stars have a lower SNR which leads to a larger difference in each individual measurement.

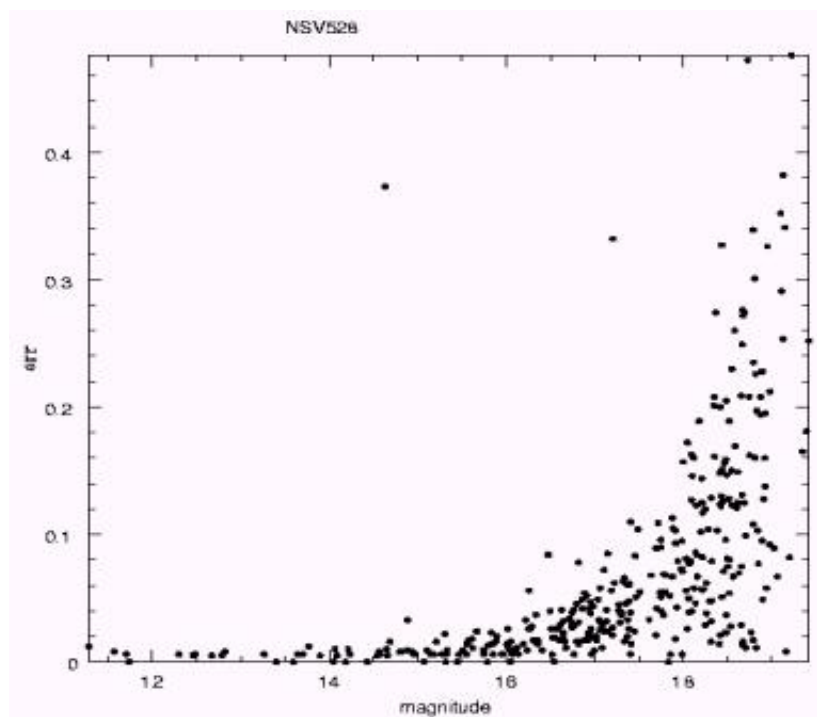


Figure 4.6.1 Graph showing the error in photometric measurements as it depends on the magnitude of the star. (graph provided courtesy of Arne Henden).

Once you are familiar with your camera and telescope the next step is to develop a scatter plot similar to figure 4.6.1. You can either make it error verse magnitude or more preferably, error verse SNR. To take the observations necessary for this plot refer to one of the standard calibration star fields in Martinez and Klotz 1997, Montgomery et.al. 1993, Romeo 1989 et.al., (<http://binaries.boulder.swri.edu/binaries/fields/ngc7790.html>). Once you have acquired a few images of a standard field, next reduce the magnitudes of the stars in the field. Choose one of the stars, preferably with $0 < (B-V) < 1$ and calculate the magnitude and SNR of as many stars in the field as possible. Your SNR values should range from greater than 100 to about 10. Now find the difference between the standard star magnitudes you calculated and the values listed in reference for that field. Next remove the minus sign from any of the error that were negative. At this point you should have a table that looks approximately like the following:

Table 4.6.1 The absolute error as a function of SNR

SNR	Abs(error)
5	0.66
10	0.36
20	0.20
30	0.14
40	0.11
50	0.09
60	0.07
70	0.07
80	0.06
90	0.05
100	0.05
110	0.04

Table 4.6.1 can be used to quantify your errors when reporting observations to the AAVSO. For example, you wouldn't report a measurement to an accuracy of 0.01 if your SNR was only 20. According to the table, your measurements shouldn't be reported to 0.01 magnitude accuracy unless your SNR is at least 90.

Example: Average and Standard Deviation

To determine the precision of the CCD camera, filter, and telescope combination, 13 V band differential photometric measurements were taken of the star SAO 69879 using SAO 69888 as a comparison star. The results are shown below.

8.548, 8.566, 8.559, 8.567, 8.522, 8.56, 8.553, 8.576, 8.595, 8.513, 8.548, and 8.572

Using the equations above, the average is 8.577 and the standard deviation is 0.022 magnitude. What this tells us is that the precision of a single measurement with SNR > 100 is approximately 0.02 magnitude. SAO 69888 and SAO 69879 are not standard stars with magnitudes known to 0.005 and transformation to the standard system was not performed. These measurements only provide the information about the precision of the measurement and not on the accuracy.

A Derivative of the SNR error equation

By Bruce Gary

Given: SNR

Definition of magnitude difference: $dM = -2.5 * \log(Y/Y_0)$, where log is logarithm to the base 10, Y and Y_0 are two brightness values (think of Y_0 as average magnitude solution)

Find: "magnitude SE" (standard error in magnitude units)

Solution:

SNR = Y_0/SE Where Y_0 = average intensity solution and SE is stochastic uncertainty (SE) of Y_0 solution. Adding and subtracting SE to and from Y_0 yields upper and lower Y-values

encompassing ~68% of the probability of finding the true solution (assumes Gaussian statistics).

These two Y-values, Y+ and Y-, are simply

$$Y+ = Y_0 + SE \text{ and } Y- = Y_0 - SE$$

Another way of writing these two Y-values is

$$Y+ = Y_0 + Y_0/SNR \text{ and } Y- = Y_0 - Y_0/SNR$$

This can be re-written $Y+ = Y_0 * (1 + 1/SNR)$ and $Y- = Y_0 * (1 - 1/SNR)$

Consider the ratios of these two Y-values to the average value:

$$Y+ / Y_0 = (1 + 1/SNR), \text{ and}$$

$$Y- / Y_0 = (1 - 1/SNR)$$

These ratios can be written as magnitude differences:

$$dM+ = -2.5 * \log (Y+/Y_0)$$

$$dM- = -2.5 * \log (Y-/Y_0)$$

Substituting the equations for Y+/Y₀ and Y-/Y₀ yields:

$$dM+ = -2.5 * \log (1 + 1/SNR)$$

$$dM- = -2.5 * \log (1 - 1/SNR)$$

"magnitude SE" = average of dM+ and dM- QED

Note 1: The + and - magnitude errors are different, the more so for smaller SNR. This is the way things are, and when SNR is large the two dM values can be averaged to give one SE. Hopefully AAVSO observers will always have large SNR, so that a simple average of the two dM values can be used. Whenever SNR <= 15 then the inequality of dM errors will exceed 22%. The value of dM+ will always exceed the absolute value of dM-.

Note 2: These errors, dM+ and dM-, are standard errors, or SE - also referred to as 1-sigma errors. This means that the truth has a 68% probability of existing within the range $Y_0 - SE$ and $Y_0 + SE$ (or $M_{avg} - dM-$ and $M_{avg} + dM+$). Of course, this assumes that calibration uncertainties are small compared to stochastic uncertainties.

Note 3: When using results obtained with the same instrument, the same "seeing," the same quantity of measurements, and the same analysis procedure (same annuli set for the photometry, same reference stars), whenever these same conditions apply, it is acceptable to ignore calibration uncertainties in order to monitor CHANGES in brightness. Clearly, each observer has different calibration offsets, and this is the reason it's difficult to combine observations from different observers to construct a light curve. It is much easier to construct a light curve from a single observer (provided that observer has sufficient data and adheres to the same analysis procedure). When observations are pooled from many observers either empirical offsets must be derived for each observer or each observer must present an estimated calibration uncertainty. The estimated calibration uncertainty should then be orthogonally added (square-root of the sum of squares) to the stochastic uncertainty, described above as dM- and dM+ before combining with other observations.

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Observing

CCD Observing Manual

5.0 Observing Programs

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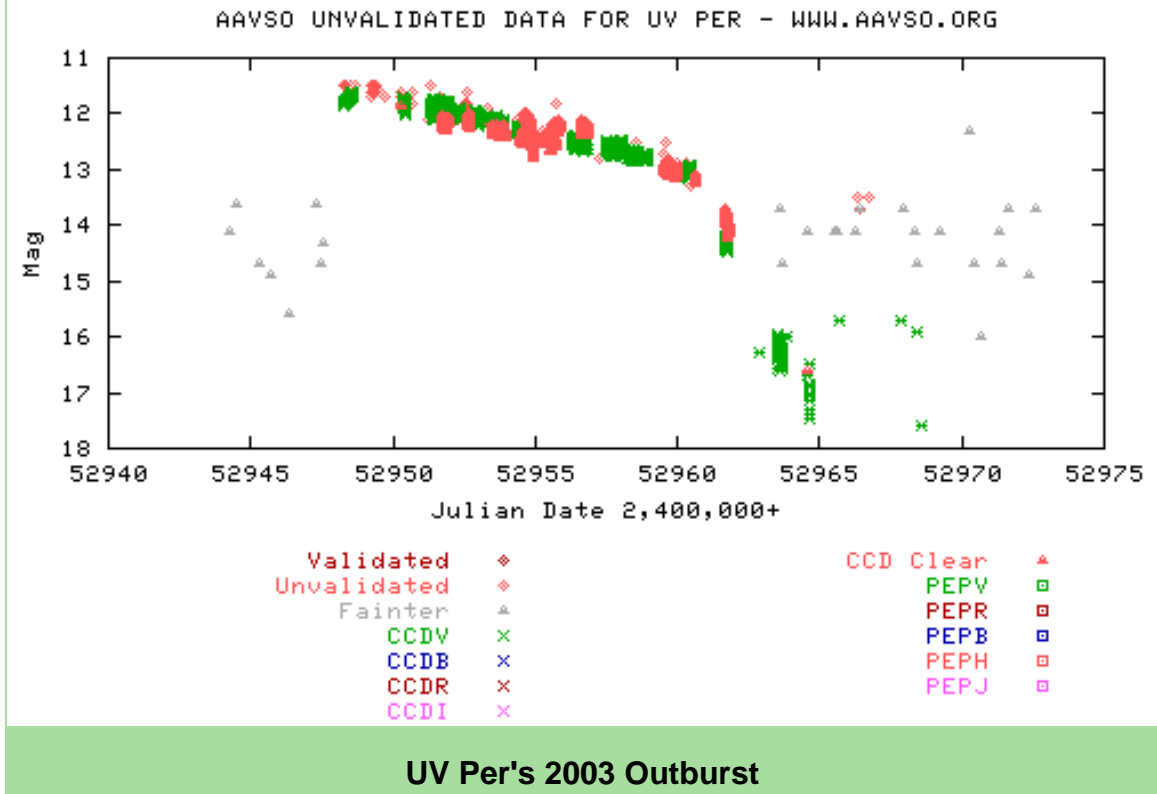
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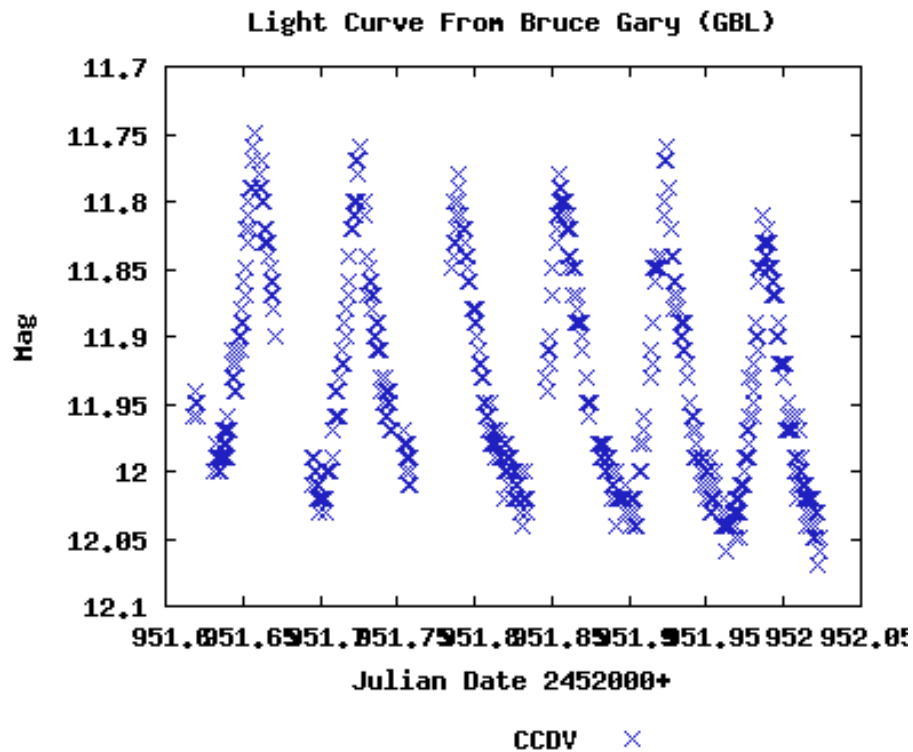
5.1 Cataclysmic Variables

[Cataclysmic variables](#) (CVs) are unpredictable stars. Their changes in brightness can be tiny (.01 mag) or steep (>6 mags!) and can occur every few minutes or every few decades.

Most CVs are monitored until they experience a sudden change in brightness, usually either an *outburst* or a *fade*. During this period of activity they are monitored closely for small variations in their light curve.

[Education: HOA](#)[Pick a star](#)[Create a light curve](#)[Recent Observations](#)[Find charts](#)

It is this second phase where CCD observers are especially needed. High resolution imaging of a star in outburst, for example, can discover *superhumps*. These superhumps can help determine the orbital period for the binary star and setup models for the system. Discoveries of previously unknown or changing superhump periods can be worthy of publication. However, you need very accurate photometry to detect superhumps in most systems, usually .01 mag accuracy.



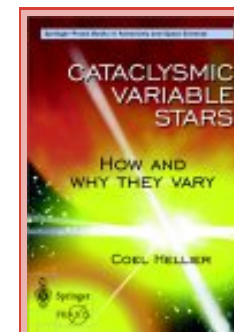
Example of superhumps detected by Bruce Gary (GBL). This data, combined with data from 18 other observers, refined UV Per's superhump period and measured it's evolution. It was published in [IBVS #5488](#).

CVs are a great opportunity for visual and CCD collaboration. Visual observers can monitor the CVs every night and then notify the CCD observers when they go into outburst. At that point the CCD observers can try to detect superhumps or other behavior.

CCD observers can also help by observing very faint CVs at quiescence. [CCD Views](#) has the following two articles about observing faint CVs:

- [Observing Faint CVs at Quiescence](#) (includes a list of recommended CVs)
- [More on Observing Faint CVs](#)

Also read [Cataclysmic Variables](#): A background on CVs from the [Manual for Visual Observing of Variable Stars](#).



[Cataclysmic Variable Stars: How and Why They Vary](#) is a recommended book for people interested in CVs. [Read our review from Eyepiece Views.](#)

5.2 Long Period Variables

Long Period Variables (LPVs) are red giants that have long periods. They are among the easiest targets for CCD observers since they don't need to be monitored every night and tend to be fairly bright. Because of this same reason, they also tend to be neglected by CCD observers who think we don't need any more data on them. On the contrary, LPV research is just as important as other fields of variable stars and the AAVSO receives more data requests for LPV data than any other type of variable star.

LPVs need to be observed only once a week. Since they tend to be red, using a [photometric filter](#) is a must. See the [Variable Star of the Month section on Miras](#) for more information.

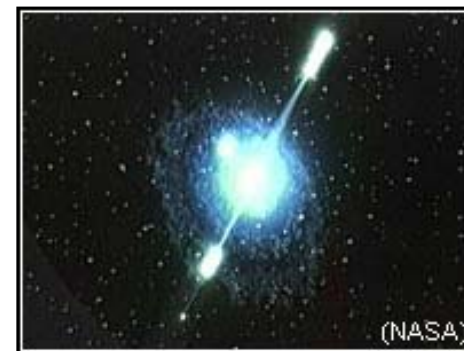
For a list of LPVs that are too faint for visual observers and are showing strange behavior check out [CCD Views](#).

Also read [Pulsating Variables](#): A background on LPVs, SRs and other pulsating variables from the [Manual for Visual Observing of Variable Stars](#).

5.3a Gamma Ray Bursts

The [AAVSO International High Energy Network](#) consists of a worldwide network of observers dedicated to searching for optical counterparts of gamma-ray bursts (GRBs) through a coordinated rapid response network.

What does this mean? They await word that a GRB has been detected (usually by satellite). When that word comes, they head to their telescopes and attempt to image the GRB using CCD cameras. Time is of the essence here and that is where the AAVSO GRB Network comes in.



Through a connection with the [GCN](#) at NASA's [Goddard Space Flight Center](#), notifications of recent GRB detections by orbiting satellites is distributed to the AAVSO. Our network takes these notices and distributes them, in turn, to our members based on a set of filters each observer specifies. The distribution method is primarily via e-mail, cell phone, and pager.

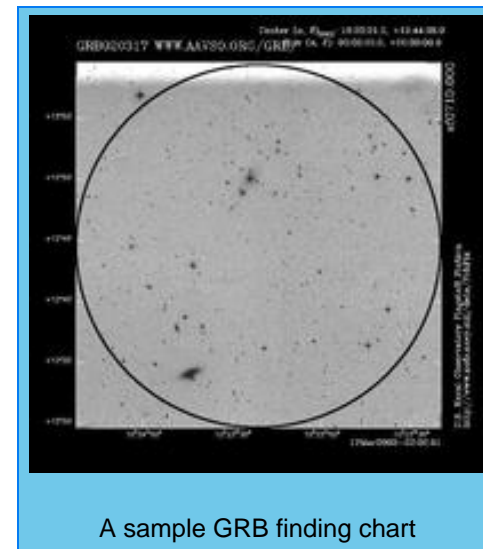
Satellite detects GRB -> Relay Station -> GCN@Goddard -> AAVSO HQ -> You!
then at AAVSO HQ:

Pagers Sounded -> Email Alerts Sent -> Charts Made & Placed Online -> Photometry Online

Depending upon the satellite that detected the GRB, the entire process can take from a few hours to a few *seconds*.

The speed of notification is key because most optical counterparts to GRBs discovered so far have been faint and very quickly became even fainter. The faster we react, the better chance we have of finding the counterpart and/or creating a light curve.

GRBs may hold one of the keys to better understanding our Universe. They are the most powerful explosions of energy yet discovered. They may be used as distance markers, glimpses into the early days of our universe, and much more. But none of this can happen unless we obtain more information on these strange events.



A sample GRB finding chart

Everything you need to know is available at the web site for the [AAVSO International High Energy Network](http://www.aavso.org/observing/programs/ccd/manual/5.shtml).

5.3b Blazars

The [AAVSO International High Energy Network](http://www.aavso.org/observing/programs/ccd/manual/5.shtml) is also observing Blazars in supports of the upcoming GLAST mission. Blazars are optically variable quasars with their jets pointed right at us. They vary on all timescales and at all wavelengths. They are observed in between GRB alerts. For more information visit our [blazar web pages](#).

Different CCD observing strategies are used with blazars. Since they vary so much campaigns of different lengths are devised. All objects are monitored monthly to set a baseline of behavior. Specific campaigns looking for intraday (timescales of 4, 8, or 12 weeks) and microvariability (resolution of several minutes for many days) are planned. In addition, when GLAST is launched blazar alerts will be issued similar to GRB alerts when the GLAST telescope is observing a blazar and detects a gamma ray burst from it.

5.3c Polars

The [AAVSO International High Energy Network](http://www.aavso.org/observing/programs/ccd/manual/5.shtml) is also observing magnetic cataclysmic variables, a.k.a "polars" or "AM Her stars". These are CVs with very strong magnetic fields that control the flow of material from one star to another. our observations of polars are in support of the XMM Newton mission. For more information visit our [polars web pages](#).

5.4 Eclipsing Binaries

The [Eclipsing Binary Committee](#) is a superb example of CCD and visual observers working together to do good science. The visual observers will follow a recently discovered or suspected eclipsing binary star (along with doing archival research) to try and determine a time of minimum. Then the CCD observers will refine that time and together they usually publish an [IBVS paper](#).

The [Eclipsing Binary Committee](#) can tell you what you need to do to observe and report data. They can also give you interesting targets and help coordinate observing programs if you would like to work with others.

5.5 Low Amplitude Stars

It is difficult for visual observers to record variations below a magnitude. CCD observers, on the other hand, can record variations down to the error level of their system. This makes CCD observations ideal for stars that may be bright but vary by small amplitudes. Such stars may be very red also, which increases visual scatter even more. If one wants to detect variations below 0.1 magnitude then precision photometry is essential.

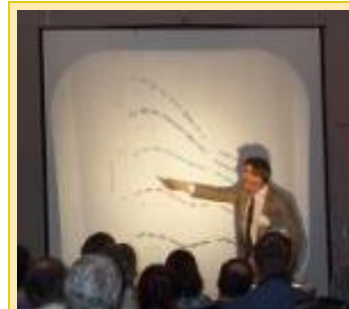
The [AAVSO PEP Committee](#) usually monitor the brighter of these stars (>10). CCD observers should follow the fainter stars (<10). Flare and flicker stars (such as [FU ORI](#)) also have small fluctuations in brightness which cannot be detected visually.

5.6 Supernovae/Novae Patrols

Most supernovae and novae patrols these days are done with automated systems. However, non-automated systems still have their place and discover tens of supernovae/novae per year. For novae, the key is to have a wide field of view. Many people will simply connect their CCD to a standard 35mm camera lens and then point at the sky along the galactic plane. For supernovae, the best method seems to be to select a group of galaxies to monitor and then image them as often as possible. In both cases, *blinking* the image will reveal new sources. Blinking is a term referring to flipping back and forth between two images of the same field. There are many programs that can help automate this process.

CCD observers can also help monitor previously discovered supernovae. Supernovae brighter than mag 14.5 usually are announced in an [Alert Notice](#). Fainter supernovae may be mentioned in the [News Flash](#) or [CCD Views](#) if there is some scientific interest in the object. Performing photometry of supernovae is very difficult because of the interference of the host galaxy, so be prepared for high error levels.

For more information consult the AAVSO [Supernovae Search Committee](#) and [Novae Search Committee](#) web pages.



[Dr. Robert Kirshner](#)

discusses a supernova lightcurve at the [90th Annual AAVSO Meeting](#). [Click here to listen to the guest lecture](#).

5.8 Variable Star Chart Calibration

This is a very challenging program for those who have mastered the art of [photometry](#). In order to make new [variable star charts](#) we need high quality photometry for the field. Believe it or not, no high quality (errors of .05 or less) photometric database exists for objects fainter than magnitude 10.5.

The AAVSO needs good photometry for newly discovered objects (novae, supernovae, GRBs, etc.) and to update existing charts that have poor photometric data. In order to help us you will need to be able to perform [all-sky photometry](#) at the .01-.03 mag level. Our requirements are very strict because making a star chart is a serious business. If there is anything wrong with your data then every observation made with the new chart will be tainted.

If you feel you qualify or have further questions e-mail charts@aaavso.org.

5.8 Designing Your Own

Everyone has a favorite object, type of star, and/or method of observing. When designing a personal observing program think of what you can do with the CCD that visual or PEP observers cannot. Focus on those items to get the most out of your system. Also, be realistic with what you can do. For example, if you don't have the patience to take numerous careful flat and dark fields throughout the night then don't try to detect and report .01 mag variations in a star. Instead, go for an [LPV](#) program where .1 mag accuracy is enough.

You will probably find that as you become more experienced you will take a little from here and there and end up with a custom program. You can always send [feedback](#) to the AAVSO for help in planning a personal observing plan.

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6.1 Using Star Charts

The AAVSO has thousands of [variable star charts](#) available and [new ones](#) consistently being released. These charts have been continuously produced since the organization was founded in 1911. As such, the types and quality of the charts differ depending on when they were made. In general, all charts are intended as visual observing charts with errors to .1 visual accuracy. When CCD observing with these charts, use a [V filter](#) since V comes closest to the way things look visually. Record your observation to .1 accuracy.

Beginning in 2000, the AAVSO began publishing f-scale charts with data on them intended for CCD observers. These "CCD tables" usually included more details on the sequence used on the chart for visual observers. With these details (usually more accurately magnitude values and color indices) CCD observers can attempt to make estimates more accurately and in more color.

An example of one of these tables is seen to the right. The data from the table mostly comes from the source cited in the "Sequence:" field of the chart, located at the bottom of the image. However, this data can change. It can be revised or (more likely) improved by the astronomer who made the measurements. So be sure to consult the sequence source for the latest sequence data if you intend to work on a project that requires the most precise photometric data possible.

Comp	V	B-V
124	12.365	0.523
129	12.866	0.692
131	13.086	1.399
133	13.325	0.690
138	13.770	0.926
143	14.346	1.037
146	14.587	1.089
151	15.078	0.853
157	15.711	0.841
163	16.265	0.918
170	16.959	0.957
175	17.452	1.082

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6.2 Reporting Observations to the AAVSO

The AAVSO receives over 400,000 observations per year. Most of those are visual observations of just a few observations per star. CCD observers, however, can sometimes generate thousands of observations of one object per night. Submitting those one-by-one can be a problem so we have created special upload tools for CCD observers.

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Methods of Submitting Data

- [WebObs](#)
- [PCObs](#)
- [E-Mail](#)
- [Fax](#)
- [Postal Mail](#)

Method 1: Regular Observations

If you have made a few observations for a collection of different stars then it will be easier to submit them one-by-one just like a normal visual observation. Use WebObs, PCObs, or submit them via e-mail using the Official AAVSO Format.

Method 2: Batch Upload

If you have large amounts of data to upload, such as time series observations, then you should use the [WebObs](#) first.

The CCD Batch Upload Tool currently supports the formats made by AIP4Win, CBA, MaximDL and a generic 2 column format easily created with spread sheet programs.

Comment Codes, Comp Stars, & Charts

When you submit observations made with a CCD camera be sure to include the proper information about the filter used. If you did not use a filter put **CCD** in the *Comment Codes* field. For V use **CCDV**, B: **CCDB**, R: **CCDR**, and I: **CCDI**.

Also be sure to list your comparison stars ("comp stars") and the chart you used. This is especially important for CCD observers since your data can be very precise. If you are using a chart made by yourself or another organization put **K** in the *Comment Codes* field.

- [More information on the Official AAVSO Format](#)

Note: Tools such as [WebObs](#) and [PCObs](#) do the formatting for you so you don't have to know the Official AAVSO Format.

6.3 Using the MyNewsFlash System

The [MyNewsFlash](#) is a completely customizable and automated system to have variable star observations sent to you. It is a way to monitor your favorite stars or classes of stars and/or to be notified when something interesting is in outburst. The staff sometimes e-mails [Special MyNewsFlashes](#) when a specific object needs extra attention.

When starting out we recommend just to signup with all the default options checked. This will send you an e-mail once a day of CV's in outburst and all Special MyNewsFlash issues (usually ~1 per month). Then you can always go back and create more profiles or tweak yours to add new objects to the list.

6.4 Using the Alert Notice

The [AAVSO Alert Notice](#) is a more general alert that is issued when any information of significance needs to be rapidly distributed to the membership. Usually this involves novae, bright supernovae, request for observations from professionals and/or space-based telescopes, rare CV outbursts, and more.

The Alert Notice usually comes accompanied by charts used to observe the objects mentioned. Frequently a web page will be setup dedicated to the latest information and light curve from

those objects. Alert Notices are distributed via the [Web site](#), [e-mail](#), and postal mail for those who request it.

6.5 Using CCD Views

CCD Views is a publication of the [AAVSO CCD Committee](#). Its goal is to provide CCD observers with observing program ideas, hints and tips to make observing more fun and productive, and to provide feedback on observations submitted. CCD Views also routinely accepts submitted articles from AAVSO members and observers. It is a good general publication to read for ideas and background information. If you have specific questions about anything in CCD views [send it to the AAVSO](#) or post it to the [AAVSO Photometry Discussion Group](#).

CCD Views is distributed when circumstances warrant via the [Web site](#) and [e-mail](#).

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The logo for AAVSO, consisting of the letters 'AAVSO' in a white, sans-serif font, centered on a dark blue background.

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Observing

CCD Observing Manual

7.0 More Information & Administrivia

Observing

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[Photoelectric \(PEP\)](#)

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7.1 Discussion Groups

In 2003 a discussion group was created dedicated to variable star photometry. The [archives](#) are a rich source of material. If you have questions, whether introductory or advanced, consider posting them to this list. The membership are eager to help and the answer to your question will be archived for future new CCD observers. [Sign up here.](#)

Other Discussion Groups

- [AAVSO Discussion Group](#)
- [AAVSO High Energy Discussion Group](#)
- [Yahoo Groups Photometry & Astrometry Discussion Group](#)

7.2 Links

- [AAVSO CCD Committee](#)
- [MP3s and PowerPoint presentation](#) of CCD Workshop at 90th Annual Meeting of the AAVSO
- [AIP4Win Software Updates](#)
- [Dr Bill's Photometry Textbook](#): Free PDF download
- [Starizona's Guide to CCD Imaging](#)
- [Bruce Gary's CCD Observing Tips](#)

7.3 Publications & Papers

AAVSO Publications Covering CCDs

- [JAAVSO](#): Journal of the AAVSO
 - [Volume 20, Number 2](#): Special Edition Focused on CCD Technology (1991)
- [CCD Views](#)

Sky & Telescope magazine used to publish a magazine called "CCD Astronomy" in the 1990's. [You can order back issues through their web site.](#)

CCD Papers from JAAVSO 1980-2000

- [Asteroid Observations with CCDs](#) {S. J. Ratcliff} 21.6
- Calibration of Hipparcos Long-Period Variable Star Fields for Multi-CCD Data Reduction and Photometry Using MIRA (Abs.) {M. V. Newberry} 22.46
- CCD Data Reduction (Abs.) {S. B. Howell} 21.3
- CCD Imaging of Galaxies and Nebulae (Abs.) {R. W. Pogge} 21.11
- CCD Light Curves of Young, Low Mass Stars (Abs.) {J. Stauffer et al.} 21.14
- [CCD Observations of Short-Period Variables at Middlebury College](#) {S. J. Ratcliff, J. M. Collins} 21.16
- CCD Observations of Variable Stars (Abs.) {G. Emerson} 21.22
- CCD Photometry and Astrometry at Colgate University (Abs.) {T. J. Balonek} 21.14
- CCD Photometry at Wellesley College (Abs.) {P. J. Benson} 21.20
- CCD Photometry at Wesleyan University (Abs.) {W. Herbst et al.} 21.20
- CCD Photometry in the Context of the AAVSO Observing Program (Abs.) {J. A. Mattei} 21.13
- [CCD Photometry of IV Geminorum](#) {D. Gelch, P. J. Benson} 22.73
- CCD Photometry of the RR Lyrae Star AH Camelopardalis (Abs.) {H. A. Smith et al.} 21.64
- [CCD Photometry of the RR Lyrae Star SS Leonis](#) {A. L. Anderson et al.} 20.28
- [CCD Photometry of SN 1974G from Photographic Plates Using a Kodak DCS200 Camera](#) {V. Burkholder} 23.127
- [CCD Photometry of Variable Stars in a Sophomore-Level Astronomy Laboratory](#) {H. A. Smith} 22.35
- [CCD Photometry Results on Some Hipparcos Stars](#) {G. Walker} 23.1
- CCD Principles of Operation (Abs.) {W. Schempp} 21.2
- CCD Spectroscopy (Abs.) {R. M. Wagner} 21.12
- CCD System Issues (Abs.) {E. R. Craine} 21.2
- CCD Visual Estimates from the Starlight Xpress System (Abs.) {R. E. Royer, D. M. Phelps} 24.64
- [CCDs in an Educational Environment](#) {P. J. Benson} 20.150
- [Color CCD Observations](#) {S. B. Howell et al.} 22.2
- Differential Photometry and Light Curves (Abs.) {S. B. Howell} 21.11
- [Digital Imaging in the Introductory Astronomy Course](#) {L. A. Marschall, M. B. Hayden} 22.39
- [Exposure Nomographs](#) {R. E. Zissell} 24.26
- [Flat-Fielding for CCDs in AAVSO Observations, I](#) {G. P. Emerson, S. J. Little} 27.49
- [ICC CCD Camera Project: Motivation, Design and Status](#) {E. VanMatre} 22.22
- The Indiana Automated CCD Photometric Telescope: Software and Performance (Abs.) {R. K. Honeycutt et al.} 21.2
- [An Innovative Telescope Design for CCD Photometry](#) {J. E. F. Baruch} 19.90
- Introduction {J. A. Mattei} 21.1
- Introduction to the First AAVSO CCD Workshop {J. A. Mattei} 20.129
- [Introduction to Time-Series Photometry Using Charge-Coupled Devices](#) {S. B. Howell} 20.134
- [The Keck Northeast Astronomy Consortium's CCD Supernova Monitoring Project](#) {W. Herbst et al.} 21.48
- Laser Guide Star Imaged with a SpectraSource Lynxx CCD (Abs.) {J. W. Briggs} 21.21
- [Major Features of the CCD Photometry Software Data Acquisition Package and Reduction Package Distributed by Optec, Inc.](#) {J. Dickinson} 22.154
- [The Micro Observatory](#) (Abs.) {P. S. Leiker} 23.81
- [Obtaining Successful CCD Light Curves of Faint Cataclysmic Variables](#) {P. Szkody} 22.29
- Optimal Observatory Setup for CCD Photometric Observations of Extragalactic Supernovae (Abs.) {M. E. Motta} 27.82
- [Performance of Commercial CCD Cameras When Coupled to Small Telescopes \(3–12](#)

- [Inch](#) {G. Walker} 22.12
- Photometric Planetary Search (Abs.) {E. R. Craine} 21.12
- [Photometry with Charge-Coupled Devices: Characteristics and Applications](#) {G. H. East} 20.130
- A Program of Remote Use of a CCD-Equipped Professional-Grade Telescope by Students (Abs.) {C. Pennypacker} 22.46
- A Quickbasic Program for Doing Filter Transformation Coefficients for CCD Observers (Abs.) {G. Emerson, R. Demara} 27.81
- Real-World CCD Imaging with Small Telescopes (Abs.) {T. J. Balonek} 21.3
- A Review of Mass Storage Systems for CCD Imaging (Abs.) {J. R. Engel, E. R. Craine} 21.13
- [Searching for Novae: CCD Imagery or Photography?](#) {W. Liller} 27.44
- Shutter Mapping Correction for Short CCD Exposures {Ronald E. Zissell} 28.149
- [The Sky Over Crystal Lake](#) {G. S. Mumford} 20.157
- [Student Projects with CCDs](#) {P. J. Benson} 21.4
- Supernovae and CCDs (Abs.) {W. Herbst} 21.11
- Techniques for CCD Photometry of Superhumps During Superoutbursts of Dwarf Novae (Abs.) {G. Walker} 25.42
- Understanding the Signal-to-Noise Ratio: A Key to Better CCD Photometry (Abs.) {M. V. Newberry} 22.46
- [Using the Lynxx CCD Camera on a Small Telescope for Variable Star Observing](#) {G. P. Emerson, S. J. Little} 20.154
- [Variable Star Astronomy with a CCD Wide-Angle Lens System](#) {S. P. Cook} 24.122
- Variable Star CCD Light Curves and New Periods (Abs.) {P. J. Benson et al.} 22.87

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