# The Hitch-hiker's Guide to AAVSO Photoelectric Photometry (PEP)

**Version 2.0**
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Tom Calderwood

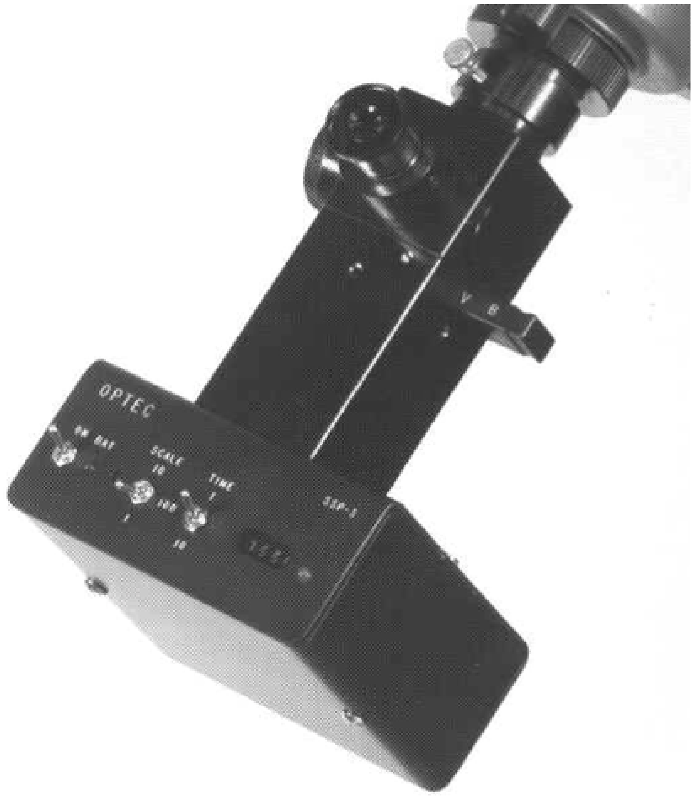
*High quality photometry of bright, astrophysically interesting stars.*

The AAVSO photoelectric section was founded in the late 1970s. We use old-school technology, but we can get superior results on bright stars. Compared to imaging systems, our equipment is fundamentally simpler to calibrate and operate, and data reduction is straightforward. What we lack in sensitivity, we make up for in quality. With properly chosen targets and careful technique, we remain a viable research group.

This document is a work-in-progress, representing my best understanding of PEP as practiced at AAVSO. It lacks the polish of other AAVSO manuals, but I think you will find it entertaining reading. The content lies somewhere in between a cookbook and a reference book. I will try to provide a wide, but not too deep overview of the equipment and practice of photometry with single-channel photometers. I will fudge on the details, occasionally, in the service of clarity.

Readers should also check out the Optec photometer manuals on-line. See Appendix B, where you will also find pointers to more advanced works on photometry, that will hopefully be less intimidating after digesting this guide.

# Tool of the Trade




Optec SSP3 Photometer © Optec Corporation

## Revision history

| | |
|---|---|
| 17 January 2017 | First general release |
| 28 May 2020 | Release 2.0. Some equations fixed, some material simplified, less-important stuff removed. Another revision expected in 2021. |


## Acknowledgements

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# A Day in the Life of a “PEPPER”

As twilight descends, PEP observers ready their equipment. Scope covers removed, dew heaters energized, mounts powered up, red lights switched on, and the list of the night's targets laid out. The photometer will be turned on and the whole optical system allowed to reach thermal equilibrium. Snacks and beverages appropriate to the season are arranged within easy reach.

As the sky darkens, the pepper looks up to judge the conditions. Are lots of dim stars visible? That indicates good transparency. Highly desirable. Are the stars high in the sky twinkling? That indicates poor seeing. Highly undesirable. Might thin clouds have crept in? Has a neighbor turned on an objectionable light? The pepper will keep track all night. The Moon may be up, but that is not necessarily a problem, nor is moderate light pollution.

When full darkness arrives, the work begins. The telescope is brought to the first target and readings are taken. The photometer gives numbers called *counts* that indicate the light intensity. The counts appear on an LED display and are written down, along with the time (alternatively, a computer might log the data automatically). The process for measuring one variable star involves comparing its brightness against that of a reference star, and the telescope will be swung back and forth between the two stars for twenty or thirty minutes. During this procedure, the pepper will actually *look* at the stars in a special eyepiece, centering them in the field, and those stars will become familiar friends over the observing season. *Yes, that's R Lyra, noticeably orange. And there's Castor, a double.* The pepper will develop an intimacy with the stars that eludes observers who use cameras.

With one star completed, the pepper moves on to others—as many as suit time, pleasure, and conditions. Perhaps a long-period variable, perhaps an eclipsing binary, a pulsating star, or a supergiant on the road to supernova. The pepper may be following these stars because they’re too bright for imagers. Just as sensitive professional observatories must relinquish bright novae and supernovae to smaller amateur instruments, so typical amateur imaging systems have difficulty with stars about magnitude 7 and brighter. That doesn't mean peppers don't go fainter, but there is a “sweet spot” in the brightness scale that we pretty much have to ourselves.

When the night's work was done, the pepper closed up shop and got some sleep. But in the morning, there is more to do. The counts and times recorded in the dark were only raw data. They must now be *reduced* to a standard form that astronomers can use. The pepper enters the information into a program, a spreadsheet, or a web form to perform the reduction. The counts associated with the variable star and its reference are turned into a magnitude, along with an estimate of the uncertainty of the measurement. These values are the fruit of the observations.

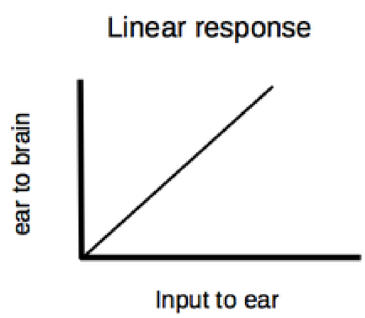
The collected magnitudes of the prior night are then uploaded into the AAVSO database. The pepper may compare them against other recent data, noting any serious discrepancies that might indicate a problem. Many stars vary in a gratifying pattern, and the pepper will experience the satisfaction of filling out the “light curve” as the season progresses.

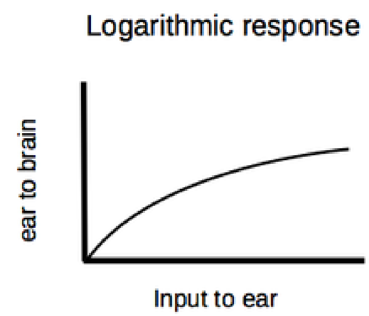
Satiated by fresh data and fresh coffee, the pepper then checks the forecast for the next clear night...

# Chapter 1 — Background

## 1.1 The Magnitude System

We owe magnitude measures to the astronomers in ancient Greece. With their naked eyes, they divided stars into six numerical ranks of brightness, with magnitude one being brightest and six dimmest. This was the start of the trouble: as the stars got dimmer their numerical magnitudes got larger instead of smaller. The other problem was that the Greeks didn't understand how the eye responds to light of different intensities. They assumed the eye was *linear*, that when it told the brain that light A was twice as bright as light B, that meant that A really was twice the physical brightness. Not so. Human senses tend to be *logarithmic* or nearly so. Hearing works this way, and that's what allows us to distinguish such a huge range of sound intensity. As a sound level rises, the ear compresses the signal before feeding it to the brain. Below are diagrams illustrating the difference between linear response and logarithmic response.




The signal from a “linear” ear that could detect a cricket would blow the brain to bits if it heard an air horn. Logarithmic response lets the ear and brain get along over that wide range, and the eye/brain link works the same way. The Greeks thought of their magnitudes as six levels of linearly increasing brightness. If the brightness of a magnitude six star was *b*, then magnitude five brightness was *2b,* magnitude four was *3b,* and so on, the brightness increasing by the addition of *b* with each step. This meant stars of the top magnitude were six times brighter than those at the bottom (see table, below). But, in fact, magnitude one was 100 times brighter than magnitude six, and each step increased the brightness by a multiplication of about 2.512 ($2.512^5 = 100$). A big difference.

| **Magnitude —>** | **6** | **5** | **4** | **3** | **2** | **1** |
|---|---|---|---|---|---|---|
| Linear-magnitude brightness | b | 2·b | 3·b | 4·b | 5·b | 6·b |
| Logarithmic-magnitude brightness | b | 2.51·b | 6.31·b | 15.85·b | 39.82·b | 100·b |

Magnitude to brightness conversion

Actually, the Greek magnitude system did not exactly fit a 100x scale—what we use today is a modern refinement that also includes stars of zero and negative magnitudes. It uses fractional magnitudes and goes far fainter than human vision. The point to remember is that our photometers measure brightness, but we convert brightness to magnitude to do our data analysis, a transformation that has benefits.

Photometrists must work with three kinds of magnitude. The *instrumental* magnitude, “m”, is what we measure from the ground. This value is affected by absorption of light in the air. The *extra-atmospheric* or *extinction-corrected* magnitude, “m0”, is m with an adjustment for the estimated extinction (m0 is always brighter than m). Finally, there is *standard* magnitude, “M”, that is an adjusted extra-atmospheric magnitude. This refinement accounts for the non-uniform color sensitivity of different instruments. It can either dim or brighten the m0 value. If two observers properly color-calibrate their instruments, and properly estimate extinction during data collection, their standard magnitudes should be apples-to-apples comparable (the magnitudes in star catalogs are standard magnitudes).

Note: you will see the word “millimags” bandied about as a unit of measurement. A milli-magnitude is 0.001 magnitudes, a convenient unit for small values.

## 1.2 Time and Date

The civil calendar is not a very convenient time base for recording long-term astronomical data. It is divided into irregular months (with leap years thrown in) and there was a discontinuity when we switched from the Julian to Gregorian calendar. Instead, astronomers use *Julian Date* (JD) to mark time. JD 0 is the first of January, 4713 BCE, and the Julian days are numbered consecutively from then. As of this writing, seven decimal digits are needed to express a Julian Date (eg: 2457477). For convenience, we sometimes use *Reduced Julian Date* (RJD), that omits the first two digits of JD. There are no “Julian hours” or minutes: fractions of a JD are expressed as a decimal.

The Julian Day begins at the International Date Line, but in planning and recording our nightly observations, we use Universal Time (UT or UTC), which is referenced to the Greenwich meridian. UT is twelve hours behind “Julian time,” meaning that the Julian day advances at noon UT. There is a handy AAVSO utility for converting back and forth between Julian Day and civil day/time. For observers in the western hemisphere, JD typically stays the same during one night.[1]

## 1.3 Star Identifiers

Generally, the twenty-four brightest stars in a constellation are identified by Greek letters, with α the brightest and ω the dimmest. After that, they are designated by lower-case (a, b, c, ...z), then upper-case (A, B, C,…Q) Latin letters. This is the “Bayer” system. Variable stars within this range are known by the Bayer identifier. Post-Bayer variable star designations, which are not in order of brightness, begin with R, going to Z, then go to double-character designations, like SU. The two-letter identifications proceed in a strange pattern, which we need not go into here. Suffice it to say that all the letter combinations amount to 334 designations. Beyond this, the variables in a constellation are known as V335, V336, V337, etc. There are also “NSV” designations. NSV

1 There is also Heliocentric Julian Date (HJD) that is referenced to the position of the sun rather than the earth.

stands for New Catalog of Variable and Suspected Variable Stars, a list not ordered by constellation.[2]

Various star catalogs made over the years assigned only numbers to stars, and the prefix of the catalog is given with the number. The numbering system generally proceeds in order of Right Ascension. Below are catalogs you may encounter.

| Catalog | Prefix |
|---|---|
| Henry Draper | HD |
| Hipparcos | HIP |
| Bright Star (Yale) | HR (or BS) |
| Smithsonian Astrophysical Observatory | SAO |
| Bonner Durchmusterung | BD |

## 1.4 Photometric Bands

Your stereo system may have tone controls to boost or cut the treble, midrange, or bass portions of the audio. These controls are *filters*. Imagine what you could do with very extreme filters. If you were listening to an orchestra concert and cut the treble and midrange deeply, you could, in principle, listen to just the notes from the double-bass players and exclude the other instruments. The filters allow you to select specific information from a broad spectrum of input. We use filters in photometry for just this reason: different bands of color provide unique data about what is going on in a star. No one has devised an optical filter that can boost a desired range of color—our filters only cut out what we prefer to ignore. Filters come in groups known as *systems*. The most common is the *Johnson* system, developed by Johnson and Morgan in the 1950s. The primary filters are U, B, and V. The U filter rejects visible light, permitting near-ultraviolet light to pass through. The B filter transmits blue light, and the V filter roughly passes the human "visual" color response in green. Johnson also defined an R filter for red light, and an I filter for red beyond human vision. There are many other color systems in use, but for AAVSO PEP we chiefly use Johnson in B and V, and the R and I filters defined in the *Cousins* system.[3] The color range that a filter lets through is known as its *passband*.

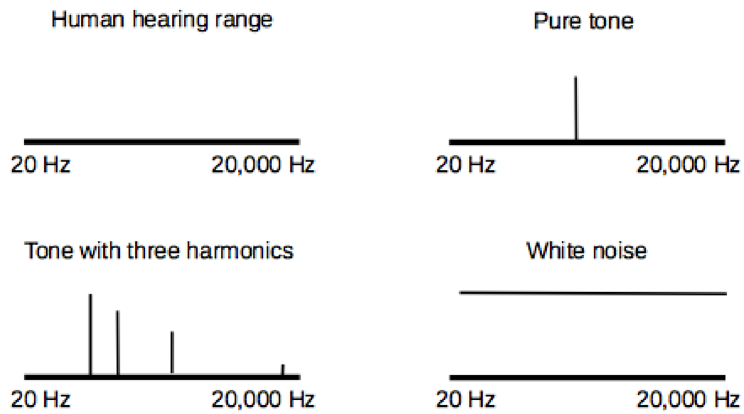
Instrumental, extra-atmospheric, and standard magnitudes in a particular filter band are denoted using the letter of the band. E.g.: v, v0, and V for the V filter; b, b0, and B for the B filter.

## 1.5 Response Curves

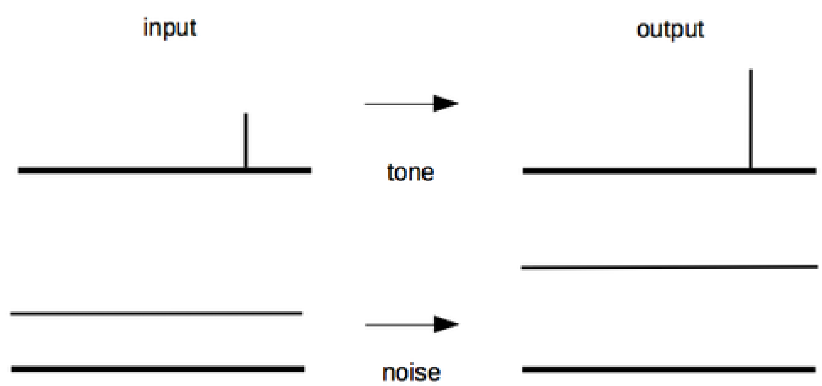
When I was growing up in the 1970s, quality stereo equipment was becoming readily available to the masses. A good amplifier might have a distortion specification of +/-3 decibels from 20 to 20,000 Hertz (Hz), which

2 Beware of an ambiguity in certain star designations where the spelled-out Greek character matches a two letter variable prefix. The notorious example is μ Cep. If one queries online programs for "mu Cep," one gets results for MU Cep (both are variables). The same problem exists for η (nu). The usual disambiguation is to append a period after mu or nu ("mu." and "nu.") to indicate the Greek character. In the database of PEP stars, an alternate solution was used: insertion of 'i' in the prefix ("miu" and "niu").
3 The SSP3 cannot realistically make use of U band.

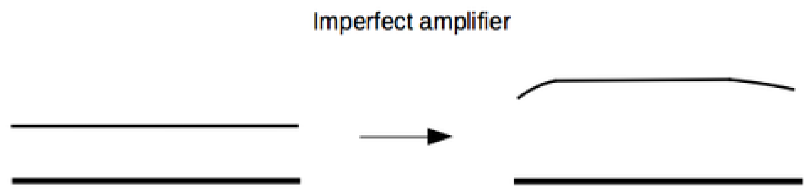
roughly covers the range of human hearing. To visualize audio, we use spectrum diagrams, which show the intensity of sound at each frequency (below). A pure electronic tone consists of a single spike. A musical instrument like the flute produces a fundamental tone plus harmonics, or overtones, of decreasing intensity. An orchestra in action would have a vast forest of tones. At the extreme, white noise consists of sound at every frequency.



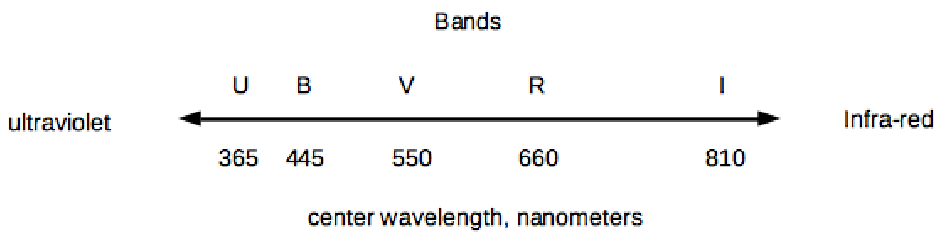

An ideal amplifier will take the input sounds and do nothing but magnify them uniformly from 20 through 20,000 Hz. In other words, the output spectrum is identical to the input spectrum, only at a higher intensity.



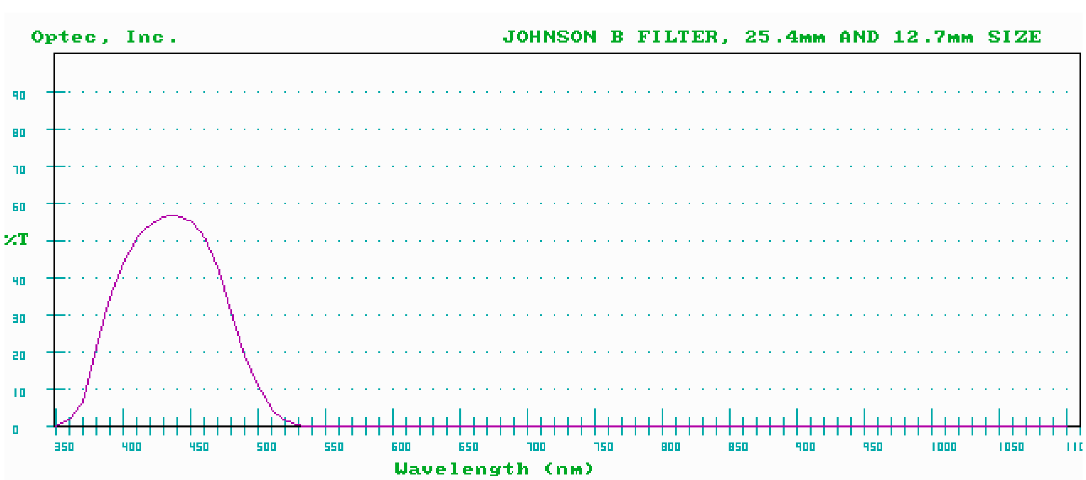

The ideal amplifier has a *flat response* over its operating range, as you can see by comparing the white noise inputs and outputs. Of course, no amplifier is perfect. It may work very well in its frequency mid-range, but suffer at the extremes. Below, our bass and treble lose a bit.




In optical systems, we have similar concerns about response, though we deal in attenuation, not amplification. Any spectrum can be characterized in terms of frequency, as above, or in wavelength. Optical frequencies are huge, inconvenient to describe in Hertz units. Instead, we use wavelengths, usually measured in nanometers (nm).

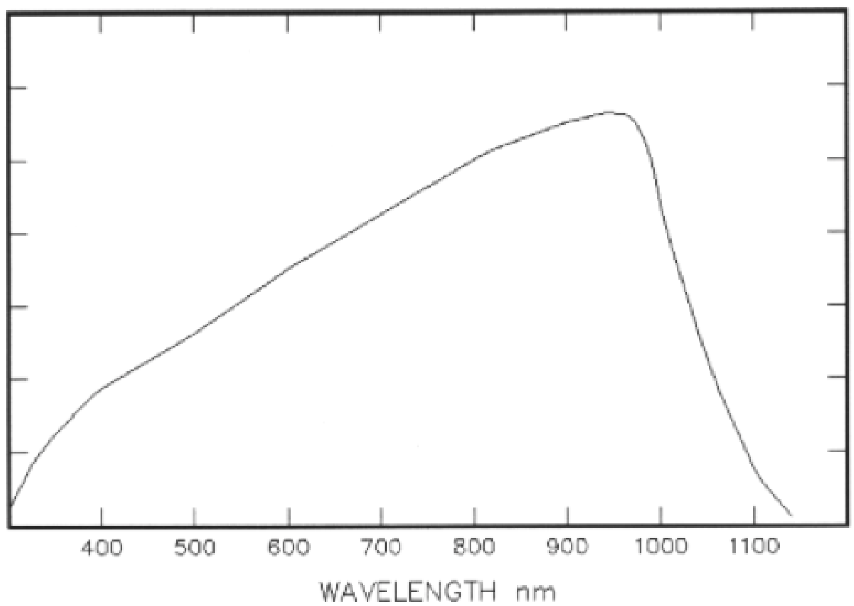



One might hope that the B, V, R, and I filters would exhibit flat response within their passbands, but they do not. Below is the response curve for the “old” B filter from Optec. Not only does the filter fail to sharply chop off at each side, its peak efficiency is only about 55%. This is not a criticism—Johnson's filters were not perfect either.




B filter transmission © Optec corp.

Filtering is a very tricky business, even in audio, and flat response curves are not to be had. But the situation is worse than it looks. Our telescope, filter, and sensor form a chain, and each component has its own response curve. The telescope curve is very nearly flat, but not perfectly so. It will transmit different wavelengths of light with slightly different efficiencies. The sensor in our photometer also lacks a flat response, being more sensitive at some wavelengths than others. If we think of these pieces as filters, that each transmit different fractions of the incoming light, we get a total response of scope% · filter% · sensor% at every wavelength.




SSP3 sensor response curve © Optec corp.

We needn't dwell on the details of all this, but remember that the sensitivity of our measurements, in any band, is affected by the combined efficiency of the whole photometric chain.

## 1.6 Single Channel Photometry

A photometer is nothing but a scientific-grade light meter. At the moment, the PEP group is using Optec SSP photometers almost exclusively. These are what are known as Direct Current, or DC photometers. The other category of photometer is the pulse-counting, or photon-counting type. The difference is this: when a photon arrives at a “counting” style photometer, the sensor puts out an electronic pulse. This pulse goes to a counter, which is allowed to accumulate over a period known as the *integration time*. The final count reflects the number of photons. In a DC photometer, the arriving photons are not registered individually. They produce a continuous current that is proportional to the number of photons. In the olden days, this current was fed into a chart recorder. The chart pen would deflect according to the strength of the current, and a measurement was called a *deflection*. The SSP photometers use additional electronics to turn the current into counts, but these are not photon counts. The term “deflection” still gets used by some writers, but it becomes confusing. I will banish it from this note and introduce *sample* in its place. A sample is a set of consecutive ten-second integrations (usually three), averaged to produce one value.

While an camera has millions of pixels, a single channel photometer has only one honking-big pixel. This pixel is much larger than the size of a star image. As a consequence, when we aim the photometer at a star, it also sees a bit of sky around the star. This presents a complication, because the sky is not perfectly dark. Earth's atmosphere glows, even on the darkest night. Furthermore, stars that are too dim to see can contribute light within the field of view of the sensor. We call all this light *sky background*, and it contaminates the measurement we make of the target star. To correct for it, every sample on the star is accompanied by a second sample on the sky near the star. When we report counts for the star, we subtract these *sky counts* from the *star+sky counts* to get a *net count*. This procedure is not perfect, but, with care, it works well.

Like most AAVSO observers, we in PEP practice the art of *differential photometry*. That is, we establish the magnitude of a variable star by comparing it against a (hopefully) constant star having a (hopefully) reliably magnitude. Variable stars in the PEP program each have an assigned “comparison” star. Use of the same comparison improves the internal consistency among multiple observers. It should be noted, here, that photometry can be a squirrelly business—studying starlight through the atmosphere poses inevitable problems. Every measurement is subject to perturbations, and truly good reference magnitudes are established by expert observers averaging many observations.

The typical PEP observing sequence interleaves samples of the variable (or “program”) star with samples of the comparison: comp...var...comp...var...comp...var...comp, the telescope being moved back and forth.[4] Each variable sample is referenced against the average of the two comparison samples that bracket it. Having three samples of the variable not only gives us a more reliable result than a single sample, it allows us to compute a statistical error, or uncertainty, for the observation sequence as a whole.

As noted above, our DC photometers produce counts that are proportional to the number of photons received during an integration. If $p$ photons arrive, we will have a count of $k \cdot p$, where $k$ is a constant for our photometer. The complete reduction of counts to magnitude will be left to another section, but suffice it to say that we will take the logarithm of the counts, so that the magnitude will be of the form $\log(k \cdot p)$. If we get $p_v$ photons from the variable and $p_c$ photons from the comparison, then the magnitude difference, $\Delta M$, will be of the form $\log(k \cdot p_v) - \log(k \cdot p_c)$. If we have a reliable magnitude $M_c$ for the comparison, then the magnitude of the variable will be $M_c + \Delta M$. That is fine for me and my photometer, but what about you? Your photometer will have a slightly different value of $k$. Doesn't that mean our instruments operate on different “scales,” like Fahrenheit and Celcius? How can we reconcile our results? The mathematics of logarithms comes to the rescue: $\log(k \cdot p)$ can be re-written as $\log(k) + \log(p)$. This means that the differential magnitude formula can be simplified as follows:

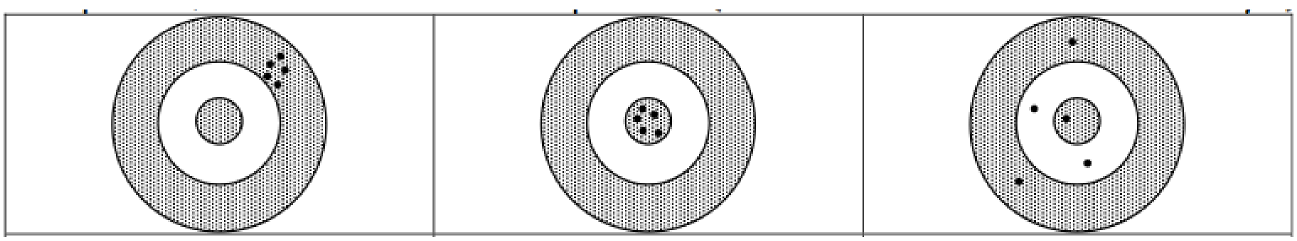
$$
\begin{aligned}
\Delta M &= \log(k \cdot p_v) - \log(k \cdot p_c) \quad \text{becomes} \\
&= (\log(k) + \log(p_v)) - (\log(k) + \log(p_c)) \quad \text{[expanding the logarithms]} \\
&= (\log(k) - \log(k)) + (\log(p_v) - \log(p_c)) \quad \text{[re-arranging terms]} \\
&= \log(p_v) - \log(p_c) \quad \text{[canceling terms]}
\end{aligned}
$$

4 Covered in detail in chapter 2.

My differential magnitude is independent of *k,* and so is yours. We can compare them directly. This independence applies to all multiplicative factors that affect our respective counts. If your scope aperture is bigger than mine, your photon counts will be higher by a factor. If your filter has a 10% higher transmission efficiency, your counts will be higher. Likewise if your sensor has 5% greater sensitivity, or your integration timer runs 3% slower. All these considerations drop away when we compare stars differentially on a logarithmic scale.

## 1.7 The Sinkhole

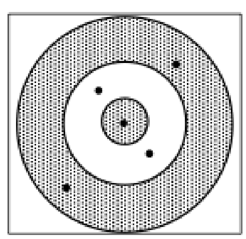
Much photometric ink has been spilled on the distinction between *accuracy* and *precision,* the main source of trouble being that the former term has an ingrained colloquial meaning that is different from its technical usage. There is also the question as to whether you are discussing a single measurement, or a group of measurements. The latter situation is usually illustrated with the infamous "target diagrams:"



precise, not accurate | precise and accurate | imprecise and inaccurate

*images: haystack.mit.edu*

On the left, we have an archer who is precise, but not very accurate. His arrows landed in a tight group, but they missed the center by a wide margin. Moving right, we have an archer who is both precise and accurate, with a tight group on the bullseye. Rightmost, we have an archer who is neither precise nor accurate. Below, we have an archer who might be described as accurate but not precise:



the average is accurate

He certainly is not precise, but one can argue that his *average* has high accuracy, in that the mean (x,y) location of his five arrows is right on the money. If his objective was to *locate* the center of the target by the average of his shots, he did very well. However, he still would get a low score in the competition.

Another perspective on accuracy and precision was offered by Arne Henden:

*It is pretty safe to say that the average CCD observer has very good precision, but pretty poor accuracy. What this means is that the uncertainty from point-to-point in, say, a time series, is excellent. That is why so many observers are able to detect an exoplanet transit (millimagnitude depths) … where the peak-to-peak amplitude may only be a few hundredths of a magnitude. Compare one observer to another observer for the same object and the same night, and you might see far larger separation between the mean levels of the two time series—the "accuracy" part.*

There is a useful distinction in this description: precision defined in terms of the *uncertainty* of the measurements. Every measurement, even a digital one, has some level of uncertainty. So does an averaged group of measurements. Our fourth archer, from a measurement perspective, had high accuracy but also high uncertainty. The second archer had high accuracy and low uncertainty.

In some quarters, there is an effort to sidestep problems with the word "accuracy" by substituting a new word, *trueness*. Trueness is the metric for how close the measured value is to the True value. In the PEP vision I proposed, I deliberately stayed away from both accuracy and precision so as not to drag readers into the sinkhole too early. The vision may now be rephrased as *Highly-true, minimally-uncertain photometry of bright, astrophysically interesting stars.* This is what we mean by "high quality." A practical upshot is that if you and I take photometry of the same target at the same time, our results ought to agree, within our mutual uncertainties, and not because our uncertainties are large.

## 1.8 Our Mascot: Count von Count of Sesame Street

*"The Count loves counting; he will count anything and everything, regardless of size, amount, or how much annoyance he is causing the other characters. For instance, he once prevented Ernie from answering a telephone because he wanted to continue counting the number of rings..."* - Wikipedia

*image: wikipedia.org*

*One...Two...Three...Ahahahaha!!*

# Chapter 2 — Observing

## 2.1 Scopes and mounts

At base level, a PEP observer needs a telescope with a tracking mount, a photometer, and at least one photometric filter. The optical tube almost needs to be cassegrain, though a compact refractor is usable. The Optec photometers weigh about 2.5 pounds—you don't want them at the front end of a Newtonian. Likewise, the photometer will turn a long refractor into an amazing pendulum that is no fun to balance. In either case, the photometer, which has a right-angle eyepiece you must look through, would swing all over creation as the tube is moved around the sky.

Your mount, surprisingly, need not be equatorial. We will aim the photometer so that the target star is dead-center in the field of view. This means we don't care about the field rotation that affects altitude-azimuth mounts. The mount *does* need to track the sky automatically and well. A GOTO mount is not strictly necessary, but it makes a big difference in the ease of operation. If you plan to operate a GOTO mount strictly with a hand-control, be sure that the controller supports "user defined objects." Life without this is an incredible headache because the star catalogs in the controllers will not have all the stars you need, or will not have them easily accessible for the back-and-forth pointing we use.

If you plan to operate your mount via a computer, there should be no difficulty configuring user objects, and it will be easier to command slewing than with a hand controller. But you'll still use the handpad for fine positioning and you need slow speed adjustments that really work. I once bought a mount that advertised a wonderful range of slew speeds, but it turned out that the two slowest were unusable, causing endless problems.

If your mount is not computerized, it is essential that the manual slow motion controls work very smoothly, without backlash. A further consideration involves fork (or half-fork) mounts. The photometer sticks out a long way from the back end of the optical tube, and it will hit the base of the mount if you try to swing it between the tines of the fork. If you operate the mount in alt-az mode, a considerable portion of the sky near the zenith will likely be inaccessible. On an old Meade LX-200, you can only get to about 65° altitude. Of course, you can wait for objects to sink to a lower elevation, but sometimes you really want to shoot straight up. If you operate in equatorial mode, some parts of the sky will still be out of reach, but you can aim overhead.

German equatorial mounts are fine, unless they are tripod-mounted and the photometer case hits the legs. Finally, your GOTO mount need not have perfect slewing. However, it is important for slew errors to be reasonably *predictable*. When you first slew to your program or comparison star, you want to know where it is likely to be relative to the center of the field. If your desired star is not remarkable in color or brightness, you may find yourself having to choose among possibilities, and end up taking data on the wrong one.

Above all, act carefully if buying a new telescope or mount. Ask an experienced observer if it is really suited to your needs.[5]

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5 A final word on scopes: you don't need expensive, super-corrected optics. We work right on the optical axis, where aberrations are at a minimum. Increased aperture does more good than a tighter point-spread function.

## 2.2 Photometers and filters


Generation 1 SSP3 Generation 2 SSP5

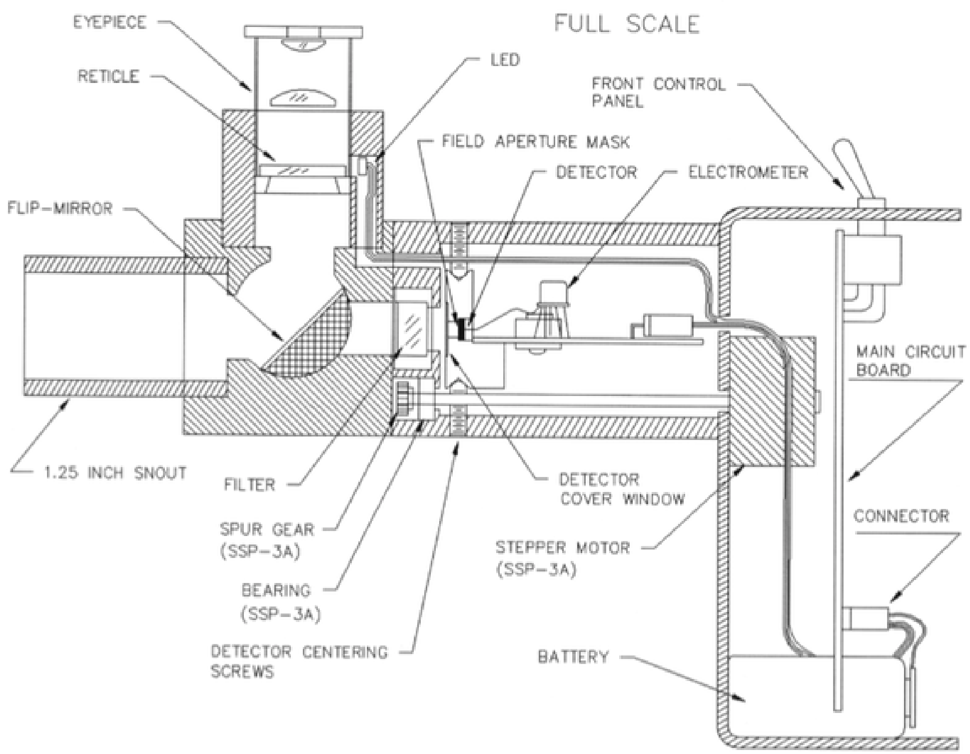
Your choice for a photometer will likely be an SSP3 or SSP5 by Optec (http://optecinc.com). They are available new and used, "Generation 1" or "Generation 2," and with or without motorized filter switching. Only Generation 2 models are still manufactured. These are computerized and have some definite advantages. The Generation 1 models, however, can be bought cheap on the used market. The going rate for a Gen. 1 SSP3 is about $200+shipping (circa 2015). You may have to be patient for one to appear on eBay or AstroMart, but the devices are out there. If you are new to handling scientific instruments, you probably want to start with an SSP3. These photometers are almost indestructible. I've dropped them four feet onto concrete and had them survive. The SSP5 is more delicate, and if it suffered the same treatment you might be out hundreds of dollars for a new photomultiplier tube. The trade-off is that the SSP5 can see much fainter stars. Of course, it costs more to buy in the first place. Another attraction of the model 3 is that it can be operated off of an internal 9V battery.[6] Downloadable manuals for the SSPs are available on the Optec web site.

The Gen. 1 photometers have a four-digit LED display that shows the counts, and the operator would manually record the numbers. Gen. 2 can either display those counts, or send them to a computer for automatic logging. An advantage here is that the computerized log will handle counts as high as 65535, whereas the on-board display can only go to 9999 (but see Appendix F). If you are observing a var/comp pair where one star is way brighter than the other, the bright star might overflow the display. Either generation might be fitted with a motor for switching among filters, making it an "A" model (SSP3A/SSP5A). Unmotorized models have a sliding metal bar with mounting holes for two filters. You push-in/pull-out the "slider" to effect a filter change. Motorized

6 A rechargeable 200mAh battery can be used, though I have had trouble with degradation in nickel-hydride cells. Alkaline batteries may fail in cold weather.

models have space for at least six filters in the slider. Optec sells a control/acquisition/reduction program, SSPDataQ for use with the Generation 2 photometers. It runs only on Windows, and communicates over an RS-232 link. The Gen. 2 data protocol is not complicated. You could write your own software package to control it. Also, Gen. 1 photometers can be upgraded to Gen. 2 at reasonable cost.

The physical packages for the SSP3 and SSP5 are almost identical. They have a 1.25" snout that slides into a conventional focuser. The forward rectangular box contains the optical bench, and the box at the rear has the processing electronics. A Gen. 1 SSP3 is illustrated below.




Generation 1 SSP3, © Optec corp.

The sensitivity of the SSP3 is such that you will want at least an eight-inch telescope to have a reasonable selection of targets (ten-inch if you want to do B band). Stars in the PEP program are usually bright, but there's no sense artificially limiting your choices. The SSP5 can go about five magnitudes fainter than the SSP3 (or seven magnitudes if you buy the extended-sensitivity photomultiplier), hence its attraction for experienced observers.

When outfitting your photometer, you will want at least a V band filter, and your next choice should be B band.[7] If you are buying a used photometer that has been sitting around for years, plan to buy new filters (over time, the cement that holds the layers of colored glass in the old filters together deteriorates and becomes cloudy). Optec has ceased making its own filter "sandwiches" and is buying filters of different manufacture from Chroma Technology. The Chroma filters are thinner and transmit more light. Photometric filters are not cheap,

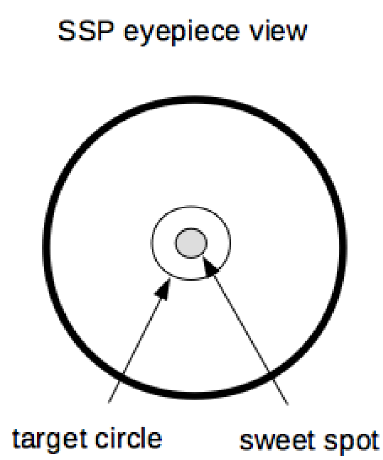
7 If you have enough aperture.

so buy what you will actually use.[8] If you use the manual filter sliders, have the filters mounted in the color pairs you will need. If you are going to do both BV and VI photometry projects, get two sliders and put BV in one and VI on the other. Old sliders will have B in the right position, V in the left, so that when the slider is pushed all the way in, the B filter is in the optical path. Optec has since reversed this convention. If you prefer to have your short-wavelength filter on the right, as I do, you need to specify that when ordering.

Don't clean your filters (or telescope objective) unless you need to. Your system may need re-calibration after such maintenance. There are four screws that adjust the X-Y position of the sensor, and one or two screws that lock the eyepiece in place. Don't fool with those, or your target reticle may not be centered properly.

## 2.3 Basic operation

The SSP devices have a flip mirror. The mirror directs light to the eyepiece, or flips out of the way so light falls on the sensor. You start with the eyepiece, slewing the scope to put your star in the center of the target circle. The eyepiece has a once inch focal length, so with an 8” F/10 SCT you are working at a magnification of 80x. At this power, the field of view is about 24 arcmin in diameter, and the target circle perhaps 1.5 arcmin. The detector sweet spot is the central 35% of the target (by radius). At the rim of the circle, sensitivity may fall to 0. As you begin to experiment with centering a star, you will notice that your left/right/up/down eye position makes a difference, shifting the apparent location of the star in the circle. You'll get used to this, and gradually learn to keep proper eye alignment (keep the whole field stop of the eyepiece in view, if possible). Though I am nearsighted, I don't wear my glasses when making observations. I usually focus the photometer with my glasses on, and then remove them, improving the eye relief.

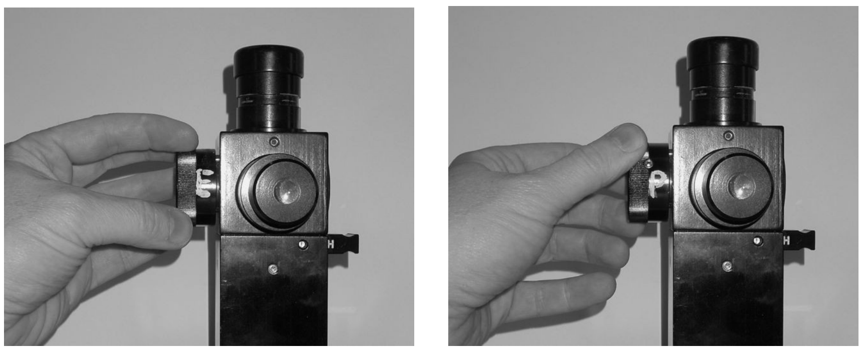



Once the star is well-centered, the flip mirror knob is turned (I have put white letters “E” and “P” [“eyepiece,” “photometer”] on the knob so it is easy to tell the position in the dark). A series of three integrations can now be

8 The standard SSP5 has zero response in R and I bands, but the extended-sensitivity version will work in R. There are caveats regarding the R and U filters (see section 3.5 on Transformation).

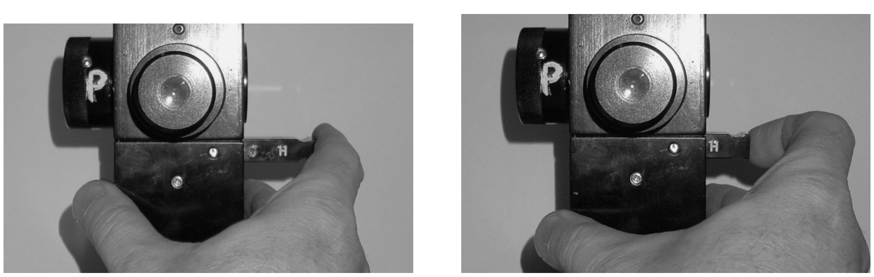
taken, but there is a catch: the integration timer is not synchronized to the mirror flip. Integration is actually happening all the time. Every ten seconds the counter is reset, regardless of the position of the mirror. Therefore, the first count you get after flipping the mirror is almost certainly not a full integration, and must be discarded (while an integration is taking place, the display will show the results of the prior integration). Generation 1 photometers have an LED to the right of the display. Except in early models, when the display updates, the light flashes, which is handy if the current and prior counts are the same.

Unless conditions are exceptional, the values you get for the three integrations will vary somewhat. I like to see the highest reading no more than about 1% above the lowest (assuming modest “dark” counts[9]). If the numbers are dancing around, you have bad sky conditions or bad tracking, the latter indicated by values going down, down, down. It should be obvious that you don't want to manhandle the flip knob: be gentle. Same with the filter slider:



Flipping the mirror: use the fingers, not the wrist

Move slider out: pull with thumb and forefinger, push with index finger



Move slider in: squeeze between thumb and forefinger

9 Dark counts are what you get with the mirror in the “eyepiece” position. They are set with an adjustment described below.

If your manipulations vibrate the scope a little, that's ok (let it settle), but a jolt will put you off target. As you take your second or third integrations on a star, note if the counts are close to those of the first integration. A mismatch indicates a centering error or changing sky conditions. It cannot be overemphasized to pay attention to the counts and not simply log them. They are your key diagnostic for problems. If your counts are 10,000 or more, the aforementioned LED will come on and stay on. On a Gen. 2 unit, the alphanumeric display will say “OVER.”

Having got your star sample, flip the mirror and pan nearby for a sky sample. At a minimum, get the star outside of the target circle by one-half circle diameter. This is not always sufficient. If your star is very bright, scattered light in the optics may contaminate the field of view beyond the circle. If you suspect this, keep moving the scope further off the star until your counts minimize. Obviously, keep the circle away from any other stars, and don't forget to flip the mirror again afterward! You want counts from the sky, not the inside of the photometer case. If you can't seem to get consistent sky counts, there might be a dim star lurking below visibility in your background area—try checking a star chart.

Taking samples will seem awkward at first, but you will eventually develop a rhythm for the process. This is why I like my short-wavelength filter in the same position for all of my sliders—it's part of the pattern.

## 2.4 Setting the gain and integration time

The output of the SSP sensor is fed into an amplifier, which has three gain settings. If I am working with very bright stars, I use a gain of 1x, otherwise I use 10x. My feeling is that 100x is just magnifying the noise along with the star signal, and I don't use it. I see the gain setting as just a way to prevent count overflows, not a means to extract more information on dim stars. At 100x, my own SSP3 at room temperature has dark counts that change by fifty or even more in a ten-second integration. If you are only getting about 1000 net counts at that gain, internal noise is giving you a 5% variation in star readings before considering any sky effects. In principle, you could use different gain settings for the variable and the comparison to deal with a wide brightness range between the two stars. Be *very* careful about this. You cannot assume that the ratio between gain settings is exactly 10:1.

One second integrations are not useful on account of scintillation, an atmospheric effect that causes short-term fluctuations in brightness. Stick to ten seconds. If you have a Gen. 2 photometer, you can use five second integrations to prevent overflow, but take twice as many integrations so you still get a total of 30 seconds for a sample.

In preparation for taking data, there is an adjustment that must be made for Gen. 1 photometers while the mirror is set for the eyepiece. The photometer has an “offset,” which sets a floor for integration counts. The internal noise of the device generates some counts even with no light. These “dark” counts usually decline with temperature, and while we want to minimize them, we don't want our display to underflow (go blank) as the night gets colder. The offset is adjusted so that there will always be some counts at any integration/gain combination we expect to use that night. There is a little hole to the right of the on/off switch with a screw. Turn the screw clockwise to reduce the dark counts, or counterclockwise to increase. You want to adjust the offset so that all your star readings will be at least several hundred.[10]

## 2.5 The standard sequence

We have already touched on the usual order for taking samples, with program the star bracketed by the comparison. The complete sequence, omitting sky samples, is as follows:

1. Comparison sample #1
2. Variable sample #1
3. Comparison #2
4. Variable #2
5. Comparison #3
6. Variable #3
7. Comparison #4
8. Check star
9. Comparison #5

The sampling data could be recorded in the following format:

10 In the SSP circuitry, linearity suffers at low counts.

| Target | Time | Integration 1 | Integration 2 | Integration 3 | mean |
|---|---|---|---|---|---|
| Comparison #1 | | | | | |
| Comp Sky | | | | | |
| Variable #1 | | | | | |
| Var Sky | | | | | |
| Comparison #2 | | | | | |
| Comp Sky | | | | | |
| Variable #2 | | | | | |
| Var Sky | | | | | |
| Comparison #3 | | | | | |
| Comp Sky | | | | | |
| Variable #3 | | | | | |
| Var Sky | | | | | |
| Comparison #4 | | | | | |
| Comp Sky | | | | | |
| Check Star | | | | | |
| Check Sky | | | | | |
| Comparison #5 | | | | | |
| Comp Sky | | | | | |

The "check star" is a safety precaution. We only sample it once, so the measurement is not hugely reliable. However, if the observed check magnitude is seriously out of whack, we need to look for problems. The check is also useful for detecting variation in the assumed-constant comp star. Since each star sample is accompanied by a sky sample, a total of eighteen samples are taken. In a single color, this takes about twenty minutes. The integration means would be calculated the next day, not during data acquisition, but if you are keeping a paper record of the counts, it makes sense to put these means on the same sheet as the integrations. The sample start time need only be recorded to the minute, and it is not actually necessary to record the time of sky samples.

This sequence has proven effective, but it is not carved in stone. If you have two variables close together that use the same comp/check, you could do the following:

1. Comparison #1
2. Variable A #1
3. Variable B #1
4. Comparison #2
5. Variable A #2
6. Variable B #2
7. etc.

But don't push it too far. As the star samples get further apart in space and time, the reliability of the results can suffer. It should also be said that the three-integration pattern could be expanded to four or even five, but I wouldn't use two. Multiple integrations help smooth out variations caused by the atmosphere.

When you are doing two-color photometry, the star and sky must each be sampled with both filters. Rather than sampling star & sky in filter 1, then star & sky in filter 2, there is a more efficient pattern (here in B and V):

1. B band star
2. shift filter
3. V band star
4. move to sky
5. V band sky
6. B band sky
7. shift filter (for next star)

This involves only one star-to-sky motion per target.

## 2.6 Skies: the good, the bad, and the ugly

Our enemies in the pursuit of good photometry are wind, turbulence, heat, light pollution, aerosols, and water vapor. Wind shakes the equipment, turbulence and heat convection shift and distort the light, light pollution gives us photons we don't want, and aerosols and water absorb the photons we do want. It's a tough life, not even considering clouds (imaging observers can actually tolerate a bit of thin cloud cover, but we can't). If what you see in the eyepiece looks bad, wait and hope for improvement.

For the good results on dim stars, you need transparent skies. During the day, note how low-down the sky stays really blue. Look for jet traffic: if the contrails stretch from horizon to horizon, there's lots of water vapor in the sky. If you observe near a nighttime flight corridor, remember that those same contrails can float right in front of your stars.

All-in-all, watch the counts.

## 2.7 Tricks of the trade

For a two-color observations, you nominally center a target star, flip the mirror, take a sample, flip the mirror again to check that the star is still centered, shift to the second filter, flip the mirror, take a sample, flip the mirror yet again to verify centering, shift to a sky position, flip the mirror, take the first sky sample, flip the mirror and check that you have not drifted onto a star, yadda, yadda, yadda. I don't do that. I center the star, sample in the first color, slide the filter and sample in the second color. Then I pan away from the star and take the sky samples. Familiarity with my star fields inform me that a certain-length pan will take me to a clear area. This is part of the "rhythm." Once you become used to what the counts (including sky counts) are expected to be, there is no need to re-confirm your pointing if the values are well behaved.

## 2.8 Extra notes on the SSP5

The SSP5 has a slightly different optical configuration. In front the PMT,[11] there is a "Fabry" lens that spreads the incoming light beam. As a consequence, the SSP5 does not have such a restricted sweet spot—it has full sensitivity over a wide area of the target circle.

Get in the habit of flipping the mirror to "eyepiece" before you move the telescope from one star to another: you might accidentally sweep across a bright star in between. You also might mistakenly command a slew that points at the moon or a terrestrial light. Yes, there is a safety circuit, but you don't want to power-cycle the photometer to reset it. Turn the photometer off right away when you finish observing, lest you turn on a bright light nearby as you close up shop for the night. And on the control panel of my SSP5, I put a big letter "E" to remind me to set the mirror to eyepiece before turning the unit on.

Optec used to sell two different V filters. The V filter for the SSP3 has always been a bandpass filter, allowing a window of transmission. There was once a second type of V filter used in SSP5s having the standard PMT. This PMT cannot detect anything redwards of V band, so the filter did not block the spectrum in that region. It was a lowpass filter that only cut off bluewards of the V band. You cannot use this filter in an SSP3! SSP5s with an extended-sensitivity PMT in my SSP5 must also use a bandpass V filter.

11 Photo-Multipiler vacuum Tube.

# Chapter 3 — Data Reduction

## 3.1 Software

I am aware of four different approaches for reducing AAVSO PEP data:

1. AAVSO PEPObs (V band only)
2. SSPDataQ from Jerry Persha/Optec
3. Homebrew spreadsheets
4. Homebrew programs

Most people seem to prefer spreadsheets, and we now have a version for BVI reductions. I hate spreadsheets and wanted elaborate reduction capabilities, so I wrote my own program. PEPObs has the advantage that it is available as an Internet web page, and so requires no special software on the user's computer (Appendix A). Choose the reduction package that is most convenient for you. Just be aware that different tools will give slightly different answers.[12] If I must make exacting comparisons among the results from different observers, I obtain the raw data and re-reduce them all through a single tool. In section 3.5, I go into the details of reduction, which are good to know, even if you don't write your own tool.

## 3.2 Data management

If you have a productive career as a photometrist, you will end up collecting a lot of observations. Early on, it is important to develop a strategy to keep your data organized. If you store data on a computer, don't fall into the trap of giving all your files cryptic names and dumping them into a single directory. There are various ways to structure your personal archive. At the top level, you might break it up by calendar year, or perhaps by variable type (eclipsers, pulsators, etc.), or maybe reverse those two levels of stratification. I presently have top-level directories for each star. My filenames for individual observations are of the form <star_id>_<telescope>_<RJD>_<bands>, where RJD has an integer and fractional part, eg: p_cyg_TC9_57424.810_BV. I observe with more than one telescope, hence, its inclusion in the file name.

## 3.3 Observational honesty

We want the data we report to be free of "opinions"—judgement calls by the observer. Human expectations are not always in line with reality, and our magnitudes are supposed to represent reality. Human factors *do* creep in, however, and we must manage them responsibly. For instance, what if I complete a standard sequence on a star, only to find that I forgot a sky sample along the way? Do I just throw away my data, or try to estimate the

12 You may hear statements like, "This tool uses the method of chapter 4 in Henden and Kaitchuck." That characterization is fine so far as it goes, but keep in mind that chapter 4 of H&K is not a software functional specification—it does not define an algorithm. Various programmers can read chapter 4 and come up with different implementations. Also, authors may use different approximations in their calculations.

background counts? If my background has been consistent over the other samples, I have no problem using an average background in place of the missing one, but I would put a note with the observation that there was an estimate involved. What if a hot integration slipped through when I was not looking, only to be found during reduction? If integrations have been stable, I would drop the offender and make a note in the observation record.

A consideration to make when making a call about a reduction: will the magnitude need to stand on its own, or is it to be evaluated as part of a larger group? For instance, if we are fitting a line to several magnitude readings, we need not be too worried about a small bias in one of them.

The questions around ratty data can become a philosophical conundrum. If the sky looks bad and I choose not to observe, there is nothing to report. But if I go ahead and try to collect data, am I right to exclude them from some larger analysis because they are of poor quality? In principle, it seems I should report everything, but crummy data may only muddy the story. One needs to be careful about excluding poor results just because they don't agree with expectations.

## 3.4 Avoiding embarrassment

When you submit data to AAVSO, or any other organization, look at your numbers. *Do they make sense?* Some hilariously bad results get reported when people don't perform simple quality control. Just because the computer tells you a value doesn't make it right. If you find problems with your reported observations, delete them and upload fixed versions.

## 3.5 Gory details of reduction

### 3.5.1 Instrumental magnitudes

Having acquired counts from our photometer, what is the conversion to magnitude? We already know that it involves taking a logarithm, and since magnitudes go in the opposite direction of brightness, we must introduce a negative factor somewhere. Further, we want the magnitude to decrease by 5 for a 100x increase in brightness. The formula, then, is

$$m = -2.5 \cdot \log_{10}(\text{counts})$$

This is equivalent to $-5/2 \cdot \log_{10}(\text{counts})$, or $\log_{10}(\text{counts}^{-5/2})$. Let's verify the formula: call the instrumental magnitude of some star $m_1 = \log(c^{-5/2})$. Consider what happens when c increases by a factor of 100. The new magnitude, $m_2$ =

$$\log((100c)^{-5/2}) = \log(100^{-5/2} \cdot c^{-5/2}) = \log((10^2)^{-5/2} \cdot c^{-5/2}) = \log(10^{-5} \cdot c^{-5/2}) = \log(10^{-5}) + \log(c^{-5/2}) = -5 + \log(c^{-5/2}) = -5 + m_1$$

Our star is five magnitudes brighter. Q.E.D. Remember that the 2.5 factor is actually 2.5, *not* 2.512 rounded down.

Because of the properties of logarithms, the differential magnitude between the variable and comparison can be expressed two ways:

$$\Delta m = m_{var} - m_{comp} = -2.5 \cdot \log(counts_{var}/counts_{comp})$$

### 3.5.2 First-order extinction

First-order extinction is the simplest correction applied in the reduction process. The Earth's atmosphere attenuates starlight, and the more atmosphere through which the light passes, the more attenuation. When collecting data, the variable and comparison stars, though typically close together, are at slightly different altitudes. We compensate for the extinction difference. The quantity of atmosphere is measured in “airmass” units, and the symbol for the value is “X.” Straight overhead is an airmass of one. At thirty degrees elevation, the airmass is two, and it quickly rises as you go lower. To compute the correction, you need two numbers: the differential airmass between variable and comparison ($\Delta X$ = var airmass - comp airmass), and the extinction coefficient, kappa ($k'$)[13], in units of magnitudes per unit airmass. Note that $\Delta X$ can be positive or negative. The differential extinction is $\Delta X \cdot k'$, and this value is subtracted from the instrumental magnitude. In V band, this quantity is usually quite small.

### 3.5.3 Color contrast

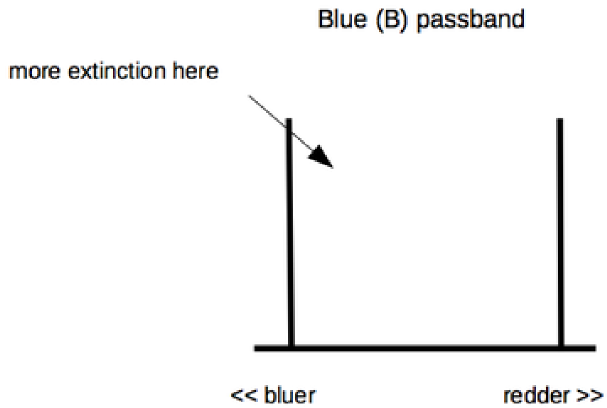
Before proceeding further, we must introduce the concept of color contrast, based on *color index*. A star's color index is the difference in standard magnitudes in two passbands. The most common index is B-V, the B magnitude minus the V magnitude. A reddish star will have a bright V magnitude (relative to B), and B-V will be positive. A bluish star will have a bright B magnitude, and B-V will be negative. The difference in indexes, $\Delta(B-V) = (B-V)_{var} - (B-V)_{comp}$, gives the color contrast between variable and comparison. Values of $\Delta(B-V)$ near zero indicate stars with very similar color. A positive $\Delta(B-V)$ indicates the variable is reddish relative to the comparison. Color contrast can be expressed both in terms of standard magnitudes, B&V, or instrumental magnitudes, b&v. These two contrast values are usually very close, but they are not the same, and they have different uses.

### 3.5.4 Second-order extinction in B band

In the blue part of the spectrum, extinction increases rapidly as the wavelength shortens. In B, we see an effect caused by measurably different levels of extinction within the passband. At the short-wavelength end, light will experience more attenuation than at the long-wavelength end.

---

13 Well, kappa *prime*. Extinction, $k$, is formally divided into a color-insensitive part, $k'$, and a color-sensitive part, $k''$, with the total extinction $k = k' + k''$. For first-order extinction, $k''$ is zero.



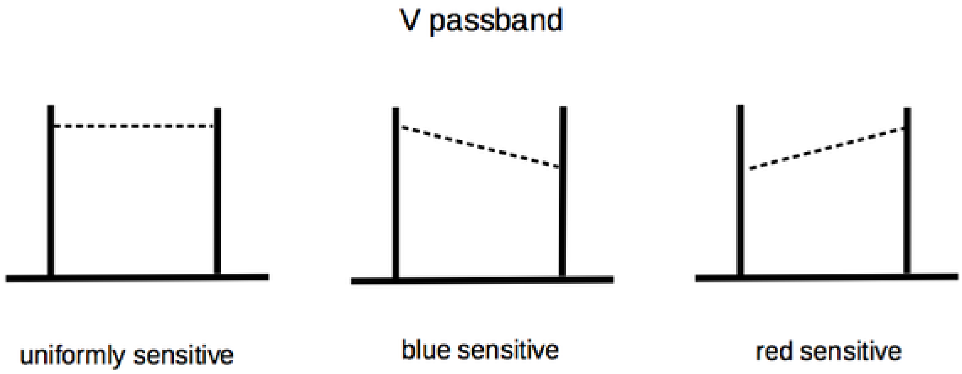

This means that at a given altitude, a star with an excess of blue light will suffer more extinction than a star with an excess of red light. If our variable and comparison have different color indexes, this will affect our results. Second-order extinction is quantified as $k''_B \cdot X \cdot (b\text{-}v)$. The differential correction can be approximated as $k''_B \cdot X_{mean} \cdot \Delta(b\text{-}v)$,[14] where the first term is the second-order extinction coefficient, and the second is the average of the variable and comp airmasses. This extinction is subtracted from the instrumental magnitude. Here, we use the instrumental color contrast, rather than the standard contrast. This is because the process for measuring $k''$ takes place in instrumental magnitudes.

Common $k''_B$ values are in the range -0.02 to -0.04, according to the books, but I have seen -0.052 in my own instrument. Second order extinction can be substantial. For example, if $k''_B = -0.03$, $X_{mean} = 1.5$, and $\Delta(b\text{-}v) = 0.500$, the correction will be +0.022. Second order extinction in V, R, and I is negligible, and U band is its own strange world.

### 3.5.6 Transformation

No two combinations of scope/filter/sensor are identical. In particular, every system has different sensitivity to color across the spectrum of a given passband. Hence, your instrumental results for a star will differ from those of everyone else. As an example, consider the (exaggerated) spectral sensitivities illustrated below. At left is a system with uniform spectral sensitivity; at center, a system with more sensitivity at the blue end of the V passband; at right, a system with more sensitivity in the red. In general, measurements by these systems will not agree. Transformation adjusts your instrument to the "standard system," whose data points are comparable for all observers.

14 Assumes the two stars are fairly close together.




To effect transformation in V and B bands, we need coefficients $\varepsilon_v$ and $\varepsilon_b$, known as “epsilon-V” and “epsilon-B”.[15] The transformation adjustment is epsilon · Δ(B-V), a value added to the instrumental magnitude. For an SSP3, $\varepsilon_V$ tends to be around -0.05 (though I have seen much lower). Thus, for Δ(B-V)= 0.500, the transformation adjustment is -0.025.

To think about this, imagine that I have the blue-sensitive system. First, consider that my variable and comp have the same B-V. This means that they are equally affected by my non-uniform color response, so a differential comparison of the two will be unaffected (the V transformation is $\varepsilon_v \cdot 0$). Now consider my variable to be bluer than the comparison, so that Δ(B-V) < 0. My comp has a comparative excess of red, and that red light will suffer in my response curve, making the comp appear dim relative to the variable. If my comp is dim, that makes the variable appear brighter than it really is. With the $\varepsilon_V$ and color contrast values both less than zero, the transformation value added to the instrumental magnitude will be positive, making the standard magnitude of the variable dimmer.

Note that the “old” Optec R filter does not transform well to the standard system, and the U filter will not transform at all.

### 3.5.7 Complete magnitude reduction formulae

We can now state the formula for converting instrumental magnitudes to standard magnitudes.

**standard magnitude = instrumental magnitude - extinction(s) + transformation**

$$V = v - k'_V \cdot \Delta X + \varepsilon_V \cdot \Delta(B\text{-}V)$$

$$B = b - k'_B \cdot \Delta X - k''_B \cdot X_{mean} \cdot \Delta(b\text{-}v) + \varepsilon_B \cdot \Delta(B\text{-}V)$$

15 I am going to skip the “mu” coefficient (μ) used to transform the B-V color index.

### 3.5.8 Airmass computation

To a first approximation, the airmass of a star at altitude *a* above the horizon is 1/sin(*a*) or cosecant(*a*). A gory algorithm for computing airmass from RA/Dec and your location and time is given in Appendix G.[16]

### 3.5.9 Time of observation

When we report a time for the whole observation, which took place over many minutes, we typically choose the time of the second variable sample. This is the “middle” of the sequence (not counting the check star). Alternately, one could use the average times of the first and fourth comparison samples. Given our low time-resolution, the exact value is not a big deal. However, you should record your individual sample times at consistent points: e.g.: at the beginning of the first integration or end of the last integration.

### 3.5.10 Metadata (data about the data)

How do metadata affect the reduction of your results? They don't, but they are important when someone comes along later and tries to evaluate your data. Metadata also help observers detect problems in their own reductions (*Oops, wrong extinction coefficient…*). Observation records in the AAVSO archive contain fields for only a limited amount of metadata, so we must encode any additional information in the “notes” section. The recommended format is <keyword>=<value>, with such pairs separated by the Unix pipe character, '|'. We avoid using apostrophes and quotation marks, which make for complications when parsing the comments with shellscripts. The challenge with metadata is to include enough without going overboard. Appendix C has the PEP metadata definitions.

### 3.5.11 Reference magnitudes

If you observe the PEP program stars, the comp and check stars are specified in a file on our web site. Reference V magnitudes for the comparison and check stars are given in the file, and B-V are given for both the variable and comp. If you expand to other filter bands, or other stars, you need a reliable source for magnitudes. In the case of B band, we can compute the comp B magnitude from the information in the database. We are given V and B-V, hence, the B magnitude is (B-V) + V.

Beyond B band, we must look elsewhere for reference data. It should be pointed out that there is no documentation for where the database magnitudes actually came from. When we bring more star magnitudes into the PEP ecosystem, we should be careful about their origins. A convenient source of magnitudes is the SIMBAD website, but I only use it for casual inquiries. A better choice is the General Catalog of Photometric Data, from which most PEP program magnitudes seem to have been drawn. The GCPD contents have been submitted to a vetting process that seems reasonably thorough and consistent. A drawback is that the index only works with HD star designations, and not HR or SAO numbers, which are common in the PEP database. I think we should avoid introducing any new HR/SAO identifiers into the mix.

16 If you ever run across the term *zenith angle*, that is the star’s angular distance from the zenith, not its altitude.

As a general rule, we want to draw magnitudes in all bands from the same source for a given comparison, and we want the color index, whether B-V or V-I, etc., of the comparison to be close to that of the variable, so as to minimize transformation problems. If you use a comparison magnitude that is not traceable to a chart ID, you *must* include that magnitude the metadata.

As regards star coordinates, I would like to propose that we limit precision of right ascension to the tenth of a second, and declination to the arcsecond (eg: 13h 42m 20.5s, 33d 15m 42s). Extra digits, though rife in the PEP database, are of no practical value.

### 3.5.12 AAVSO extended file format

If you are reducing your own data, you will need to produce an AAVSO-standard text file that can be uploaded via WebObs. The format definition is available on the AAVSO website. Read the file definition carefully. The comparison and check star magnitudes are *instrumental*, not standard. If you are using reference magnitudes from the PEP database, the chart will be "PEP." The definition for TRANS is out-of-date (we don't use Landolt fields). Put "YES" in the transform field if you transform.

# Chapter 4 — A Quick Digression on Statistics

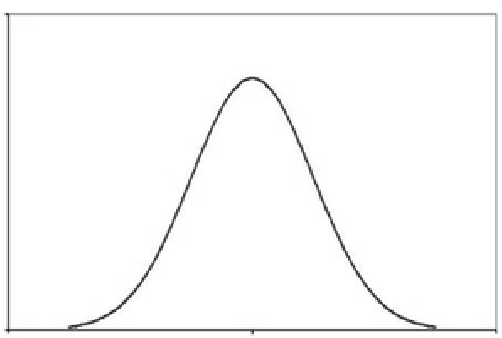
## 4.1 Precision

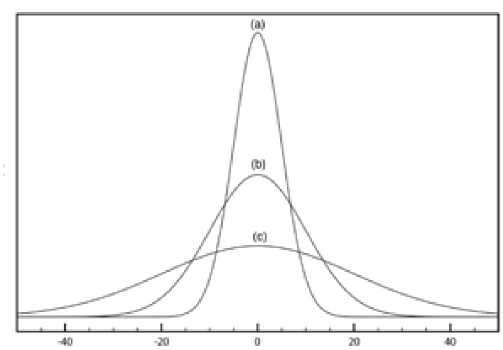
No measurement is exact. The joke about astronomy is that observations that agree within a factor of two of theory are doing well. In photometry, we can do better than that, but we must work at it. Measurements are affected by problems both random and systematic. We call these problems *errors*. A systematic error is introduced when:

- We have dew on the optics
- Our tracking slips
- Counts are recorded incorrectly
- We use the wrong comparison star
- Time or date are noted wrong

and a dozen other things. We strive to eliminate systematic errors by good habits and operating the equipment alertly. Random errors cannot be eliminated, but statistical techniques let us manage them.

When we thrice measure the magnitude of a star, we have *sampled* its magnitude three times. What is the character of this sample? We model our measurements as a normal, or Gaussian distribution around the "true" magnitude of the star. The normal distribution is illustrated below:






images: cpp.edu chemwiki.ucdvis.edu

If the true measurement would be at the center, we can expect actual measurements to be distributed around it in proportion to the height of the curve (left). Normal distributions can have different levels of scatter (right). A normal distribution is characterized by its *standard of deviation,* $\sigma$ ("sigma"). In the right-hand diagram, the tall curve has a small $\sigma$, whereas the squat curve has a large $\sigma$. If we were making a distribution curve for the heights of a collection of 100 men—a distribution expected to be Gaussian—we could measure all the individuals and compute the $\sigma$ of that group as:

$$\sigma = \sqrt{\frac{\sum_n (h_i - h_{mean})^2}{n}}$$

Where $h_{mean}$ is the average height, and the $h_i$ values are heights of individuals

We could also *estimate* σ by measuring only some of the men. In this case, the formula becomes:

$$\sigma_{est} = \sqrt{\frac{\sum_k (h_i - h_{mean})^2}{k-1}}$$

Where k<n, and $h_{mean}$ is the mean of only k measurements

We divide by k-1 because the estimate based on k is likely too small. This is known as the *unbiased* sample standard deviation.[17] Our three measurements of a star's magnitude are regarded as a subset of an infinite collection of possible measurements. The precision of our subset is given by dividing the estimated σ by the square root of the number of samples. It is the *standard deviation of the (sample) mean* (SDOM).

$$\sigma_{mean} = \sqrt{\frac{\sum_n (h_i - h_{mean})^2}{n \cdot (n-1)}}$$

This formula is closely related to that for *standard error*, and as n gets large the two converge.[18] This is the error, or uncertainty, that we report with our observations. We expect a 68% chance that the true magnitude is within +/- SDOM of our measured value. This "one-σ" estimate is, thus, not very good. If we double the SDOM, we have a two σ-estimate that has a 95% chance of success. In the interest of full disclosure, the normal distribution is just a model for our measurements. It only truly applies if they are fully independent, and ours are not. Why? Each differential magnitude is based upon two comparison star samples. The "after" comparison sample for the first variable sample is reused as the "before" sample to compute the second variable sample. Also, any statistic computed on just three points cannot be tremendously robust.

By contrast, the photon-counting photometrists, including CCD observers, base their precision on the *Poisson* distribution. You will hear them talking about *signal to noise ratios* (SNR or S/N). A S/N of 100 means a one-σ precision of 0.01 magnitude. In general, their precision is 1/(S/N). It is also true that their data are not strictly Poisson in nature. We, like they, are working with *models* of reality because the models are mathematically tractable.

A side note: you may see references elsewhere to "One-Percent Photometry." That is photometry at the level of 0.01 magnitudes.

---

17 The biased standard deviation uses k as the divisor.

18 The standard error formula uses $n^2$ as a divisor. For our purposes, it significantly underestimates the error.

## 4.2 Fitting

The uncertainty calculation gives us a handle on the interpretation of a single measurement, but we must sometimes evaluate groups of measurements, as when establishing extinction or transformation coefficients. How do we cope with the combined errors in a collection of points? This question was resolved as part of the first high-quality mapping project ever undertaken: the survey of France in the years after the revolution. The metric system was then being established, and the length of the meter depended upon the circumference of the earth. Mechanical surveying equipment had reached a new level of sophistication at that time, but the scientists in charge of reducing the survey data knew that there would still be significant random errors involved. In particular, two-dimensional data points that ought to lie on a perfectly straight line would not be expected to do so. How was the true equation of the line to be determined from the noisy data? The solution, proposed by Adrien-Marie Legendre in 1805, was *least squares fitting*.

A line is determined by two parameters, a slope, m and an intercept, b ($y = m \cdot x + b$). For a hypothetical line, the "goodness" of its match to the data would be expressed as the sum of the squares of the y distances to each point from that line. So if we had n points of the form ($x_i$, $y_i$), the sum of the squared distances from our hypothetical line would be:

$$\sum_n (y_i - (m \cdot x_i + b))^2$$

If we can select m and b so that this sum is minimized, we will have "fit" the best line to the data. With some help from calculus, this is easily done, and any calculator with Linear Regression functions will do it. In spreadsheet programs, this is a linear "trend line." It may also be called the *Best Fit Straight Line* (BFSL).

## 4.3 Weighted averaging

If we want to compute the mean of multiple measurements of the same quantity, we will want to ascribe the more "weight" to measurements having low uncertainties. For instance, it is best to determine our epsilons based on more than one night's data, and each night's reduction has its own associated error. For a collection of n (value, error) pairs, the computations are:

$$\text{weighted mean} = \sum_n (val_i/err_i^2) \,/\, \sum_n (1/err_i^2)$$

$$\text{weighted error} = 1 \,/\, \sqrt{\sum_n (1/err_i^2)}$$

# Chapter 5 — Calibration

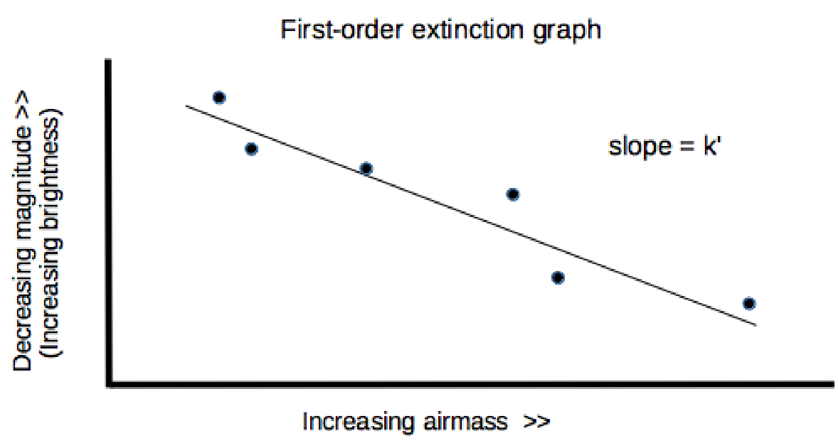
Having introduced the factors needed to reduce our data, we can go into detail about calibration observations. These are performed to establish coefficients for first-order extinction, second-order extinction, and transformation.

## 5.1 First-order extinction

There are three sources for $k'$:

1. Follow the instrumental magnitude of one star over a range of airmass during the night.
2. For several standard stars at different airmasses, compare the instrumental magnitudes against their standard magnitudes ("Hardie method"). This is done in a brief period.
3. Assume a fixed or seasonal value.[19]

For methods 1 and 2, you are creating a graph of the sort below.




If we will be out for an extended observing run, the single-star/large-range method may be convenient. First thing in the evening, you would take samples on a star that is either high in the sky, or low in the east. Over the course of the night, sample the star as it changes altitude, and once more before you finish. If you will be observing only part of the night, be sure the star you choose for extinction will cover a reasonable range of altitude. Ideally, you want samples—I like to have at least five—over an even distribution of airmasses. This means that you sample your extinction star more often when it is lower. A simple approximation for airmass is 1/sin(altitude). Henden & Kaitchuck (see Appendix B) provides lists of standard extinction stars for northern and southern hemisphere observers. These are fairly bright stars with a B-V color index close to 0. To reduce the extinction measurements, you plot the instrumental magnitudes against airmass, and fit a line to the points, the

19 A common value for sea level extinction is 0.25. B band tends to be about 0.13 higher.

slope of the line being *k*'. Because magnitudes *decrease* as brightness increases, the slope of the above line, in magnitudes per unit airmass, is actually positive.

The disadvantage of the above method is that one needs to be taking data for an extended period, and for the extinction to stay fairly constant during that time. For some observing sites, the latter constraint is a significant problem. Most observers who face this difficulty compute a coefficient separately for every star they observe, based upon the change in extinction of the comp star during the standard sequence. I don't like this method. The twenty or thirty minute duration of the sequence will not place the comp at a significant range of airmasses, leading to noisy results. One can argue that when the star is high in the sky, the differential extinction will be quite small, so the noise is unimportant, and when the star is lower, the airmass range will improve and the noise will go down. I'm still not sure that this approach is any better than just randomly picking an extinction correction between 0 and 4 millimags (in V band), or, with more sophistication, selecting a value from 0 to 4 based upon the amount of differential airmass. In any event, the comparison star almost certainly has a nonzero B-V, introducing the possibility of a skewed estimate of the first-order B extinction.

I typically use the “Hardie” method for measuring extinction, which takes fifteen minutes or less. It depends on having reliable magnitudes in both of your filter bands for a selection of stars that are at a variety of altitudes. I use the H&K first-order extinction stars. The Hardie method is described in Astronomical Techniques, chapter 8. I have pre-selected sets of stars for each month of the year. If my observing run takes place early in the night, I can use the set for the preceding month, and if up very late, use the set for the following month. If I am running for a very long time, I might use sets from two months at different times, just to check for consistency during the night. With the Hardie method, one cannot just plot the instrumental magnitudes, for each extinction star is of different brightness. Instead, one plots the *difference* between the standard and instrumental magnitudes (V-v) against airmass. The fitted line, again, gives the extinction coefficient.

Regardless of the method you use, it is dangerous to perform the fitting calculation without generating a plot and actually looking at it. An aberrant data point can skew the results, and it may be necessary to drop one or more values. A crummy collection of points may indicate unstable extinction that night. Even a crude diagram will suffice for this safety check.

## 5.2 Transformation (the easy way)

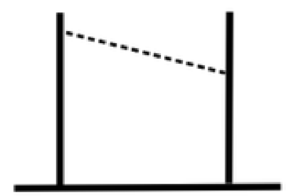
There are three methods to determine the epsilons:

1. Blue/red star pair
2. All-sky (multiple stars, range of colors)
3. Cluster (ditto)

Epsilons are usually established only once a year but preferably based on multiple observing runs.

What, exactly, is the purpose of transformation? In differential photometry, we measure the difference in instrumental magnitudes between two stars, $\Delta v$. That difference is unlikely to match the difference established by a “standard” photometer. In the Johnson photometric system, the results from his photometer *are* the standard. His response curve, like ours, is not flat, but we use his results as the anchor for own our work. Transformation, then, is an adjustment to our $\Delta v$ so that it matches the $\Delta V$ of Johnson; or, so that $\Delta V$ - ($\Delta v$ + transform) = 0.

Let's return to our response curve of the blue-sensitive photometer:



blue sensitive

To establish the V transformation, we will measure the instrumental magnitude difference between a bluish star and a reddish star. $\Delta V$-$\Delta v$ is the shortfall (or excess) of measured difference, where $\Delta V = V_{blue} - V_{red}$, and $\Delta v = v_{blue} - v_{red}$. Looking at the response curve, we see that a star rich in blue light will fare well, but a red-heavy star will lose, in comparison, a significant fraction of its brightness. Since $v_{red}$ will be more positive (dimmer) than it should be, $\Delta v$ will be too negative, and $\Delta V - \Delta v$ will be greater than zero. The transformation, which is added to $\Delta v$ during reduction, must, therefore, be negative.

For any given pair of stars, the amount of transformation will depend on the color contrast: less contrast = less transformation. Therefore, we normalize our measured shortfall/excess by dividing it by the color contrast, to give us a coefficient of transformation, $e_V$:

$$\varepsilon_V = (\Delta V - \Delta v)/\Delta(B-V) \quad (*)$$

When we apply transformation to a variable/comparison combination, the correction will be $\varepsilon_V \cdot \Delta(B-V)$.

So this seems simple, in practice: measure a blue/red pair. Well, not so fast—I was loose with terminology. We actually need to measure $\Delta v0$, the extinction-corrected instrumental magnitude, not $\Delta v$. Anytime we throw extinction into the mix we are adding a complication that is best avoided. The solution has been to find blue/red pairs that are very close together. When such a pair is near transit, the extinction for the two stars is very nearly the same. Since the extinction corrected magnitudes are $v_{blue} - k'_V \cdot X$ and $v_{red} - k'_V \cdot X$, the corrected differential magnitude is:

$$(v_{blue} - k' \cdot X) - (v_{red} - k' \cdot X) = (v_{blue} - v_{red}) - (k' \cdot X - k' \cdot X) = v_{blue} - v_{red}.$$

The extinction drops out. Unfortunately, bright blue/red pairs are hard to come by. The AAVSO PEP webpages list a total of 12 in both hemispheres, but the Aquarius and Pegasus pairs have been deprecated as unreliable, and Andromeda is questionable.

The transformation observation of a pair is an extension of the standard sequence, but with no check star. The blue star is treated as the variable, and the red as the comparison. Instead of three variable star samples, we take seven, bracketed by eight comparison samples. The mean $\Delta v$ so obtained is used in formula (*). We take seven samples because we want this measurement to be very reliable, and it is customary to compute the standard deviation of the differential magnitudes to quantify their consistency. Clearly, we want good skies for this measurement, but we do not need ideal transparency. What we need is *consistent* transparency during the sequence. The AAVSO procedure calls for conducting the sequence within one hour of transit for the pair. This minimizes differential extinction. For pairs that transit at low airmass you can push the time envelope.

The formula for $\varepsilon_B$ is very similar to that for $\varepsilon_V$, needing only a correction for second-order extinction:

$$e_B = (\Delta B - \Delta b + X \cdot k''_B \cdot \Delta(b-v))/\Delta(B-V)$$

Which means that you must measure second-order extinction before reducing an $e_B$ sequence (you can still collect the $e_B$ data beforehand). Some people use a fixed estimate of $k''_B$ to get around this.

## 5.3 Transformation (the hard way)

As noted, above, blue/red pairs are hard to find, and good calibration is dependent on high-quality reference magnitudes. Further, we want $\Delta$(B-V) to be large, and we also want $\Delta b$ and $\Delta v$ to be large. Satisfying all these conditions is not easy. Our alternative is an *all-sky* calibration. Here, we sample multiple standard stars of varying B-V, which usually requires us to make the measurements over a large portion of the sky. These measurements must be corrected for first-order extinction, and therein lies the rub. If your skies are not uniformly transparent in space and time, proper extinction correction may not be possible.

An all-sky or cluster calibration for $\varepsilon_V$ is illustrated below.[20] For standard stars of varying color, the difference between the standard and extinction-corrected instrumental magnitudes is plotted versus their standard color index. This measures the gap between standard and instrumental magnitudes as a function of color index, which should be linear. Epsilon is the slope of the fitted line. A cluster calibration, which uses stars in a single open cluster, has the advantage of not needing the first-order extinction correction,[21] making it more reliable (you should do this near transit, like the red/blue pairs). The problem is that calibration stars in the "standard" clusters are too dim for the SSP3, unless you have a monster telescope.

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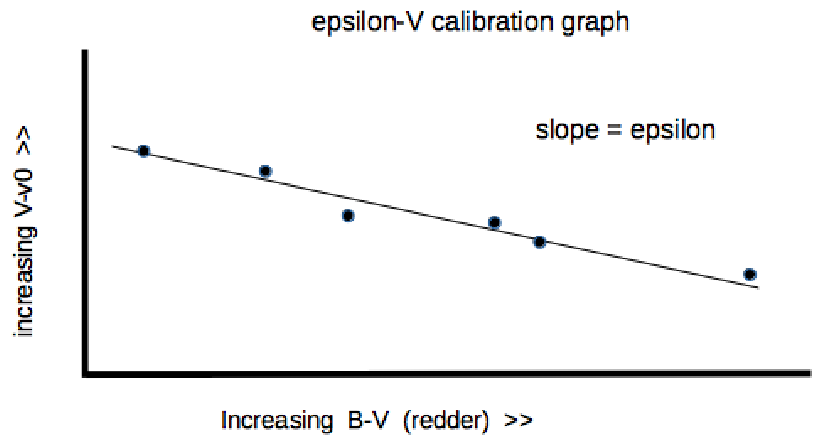
20 For $\varepsilon_B$, the vertical axis becomes B-b0.

21 Second-order correction still applies.

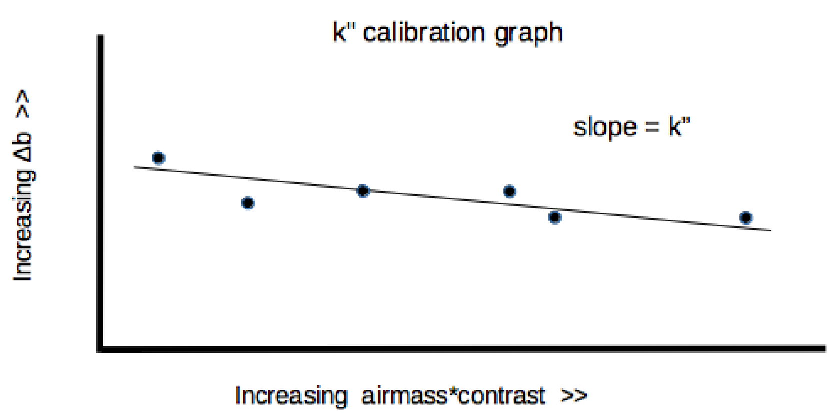



In the case of a star pair calibration, you are effectively doing the above fitting operation with just two points. Hence, it is important that the standard magnitudes be very reliable and the stars be as different in B-V as possible. For B and V bands, we really don't need the all-sky technique–the good red/blue pairs work fine.[22]

## 5.4 Second-order extinction

For calibrating second-order extinction, we return to the red/blue pairs. Instead of observing near transit, we follow a pair from high in the sky to low (or vice versa). Like first-order extinction, we want the observations reasonably evenly-spaced in airmass, and to cover as wide a range in airmass as is feasible. If your pair transits near an airmass of 1.0, you could sample them at X=1.2, 1.4, 1.6, 1.8, 2.0, and 2.2, which will come at decreasing time intervals (if the stars are setting). Your latitude, the declination of the pair, and your horizon will determine the range over which you can sample.

The coefficient is determined yearly, by plotting the instrumental B difference, $\Delta b$, versus the product of airmass and contrast, $X \cdot \Delta(b-v)$. As the airmass increases, the difference will decrease (the blue star will get redder, and the red star will not change much). k" is the slope of the line fitted to the data points.




22 ΔI values are being established for I band calibration.

# Chapter 6 – War Stories

If you stick at the photometry business, you will eventually find yourself trying to untangle mysteries in the observational data of yourself and others. I want to at least touch on some factors that come into play in these investigations. “Debugging” differential photometry requires thinking about measurement problems in a new way.

For starters, every reduced magnitude is based upon measurements of two stars, not one. A magnitude problem could be caused by trouble with either measurement, or both. A latent problem could be hidden when errors cancel out, only to emerge with different targets. Let's consider variable *Var* and comparison *Comp,* where *Var* is brighter than *Comp*. The differential magnitude $\Delta M = M_V - M_C$ will be negative.

| Magnitude: | 4.0 | 3.0 | 2.0 | 1.0 | 0.0 | -1.0 | -2.0 |
|---|---|---|---|---|---|---|---|
| | | | \| | | \| | | |
| | | | *Comp* | | *Var* | | |

$$\Delta M = M_V - M_C = 0.0 - 2.0 = -2.0$$

If we make a “hot” measurement of *Var*, one that is too bright, $M_V$ moves further to the right on our scale, and $\Delta M$ becomes more negative. This makes our reduced magnitude, $M_C + \Delta M$, more negative, brighter. But if our measurement of *Comp* is hot, the $M_C$ moves closer to $M_V$, and $\Delta M$ becomes less negative. Our reduced *Var* magnitude will become dimmer, not brighter. Conversely, “cold” measurements will have the opposite effects. As an exercise, try swapping the relative positions of *Var* and *Comp* on the magnitude scale.

What might cause a hot measurement? An example: In 2014 I started taking B band data for the first time. One of my targets was CH Cygnus. This star was also being followed by Jerry Persha, inventor of the SSP devices. I was alarmed to see that my B band magnitudes were about 0.25 brighter than his—a very large amount—but my V magnitudes agreed well. I reduce my data with a homegrown program, so I first assumed that I had a software bug. But I couldn't find any problem with the B band code, and, furthermore, my check star magnitudes were reasonable. Jerry used the same Optec filters as I did, so filter problems did not seem to be an explanation, but he suggested that I might have a “red leak” in my B filter. A filter leak allows light from outside the intended passband to reach the sensor. This will make the star appear brighter. A quick check on the catalog magnitudes of CH Cyg in increasingly red bands (left-to-right) showed:

| **B** | **V** | **I** | **J** | **H** |
|---|---|---|---|---|
| **8.77** | **7.08** | **5.345** | **0.76** | **-0.35** |

(J and H are actually near-infrared). The clue here is the huge difference between B and J: J is eight magnitudes brighter. If the blue filter were letting even a little of that light through, we could have trouble. But why wouldn't Jerry have this same problem with his filter? The answer was that he had a leak, too, but his photometer couldn't *see* it. Jerry uses an SSP5, the photomultiplier-based photometer. The photomultiplier tube was insensitive to light redder than the R band. I had an SSP3, which uses a photodiode sensor that, in principle, might detect the J band light. But how to prove this? The solution was some inventive filter-swapping by Jim Kay between an SSP3 and a near-infrared SSP4. The two-step process worked as follows: first, the JH filters from the SSP4 were installed in the SSP3, and the SSP3 pointed at an IR-bright star. Jim confirmed that J band light was getting detected by the SSP3 sensor, even though such light was outside the nominal wavelength range of the device. Next, Jim put the BV filters on the SSP4, and confirmed that it could detect light through the B filter. The SSP4 photodiode is definitely not sensitive to B band, so near-IR must have been leaking through it. (Optec has now come out with a new B filter). Optec never saw this leak in quality-control testing, because the range of wavelengths to which the B filters were subjected did not extend to the near-IR. Observers had not noticed it because so few stars have such a huge IR excess. My check star did not have the excess, so it was unaffected.

This kind of detective story is not uncommon, and it illustrates the thought process needed to explain aberrant readings—particularly the need to think about your photometry rig as a *system* of interacting components. Other leak stories exist in the photometric history books. An interesting one took place during Nova Delphinus 2013, where certain observers where getting hot magnitudes in V band. In PEP-land, we use Optec filters almost exclusively, but the CCD observers buy their filters from a variety of sources. Each manufacturer's filters will have slightly different characteristics, compounding the difficulty of making everyone's measurements agree. In this case, the V filters from one vendor had a passband that extended too far into the red. We don't demand that all filters have identical cutoffs—that's one of the reasons for transformation. But just to the red side of V band is the location of the hydrogen-alpha emission line that was a strong radiator in the nova. Broad-band photometry does not cope well with emission lines. A proper V filter will not pass that line, but the suspect filters had such a long tail on the red side that some of the Hα was sneaking through.

# Afterword

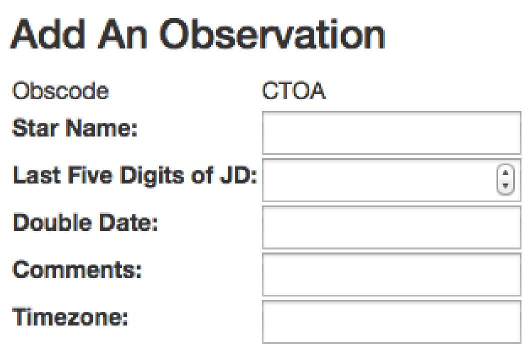
Early in the life of the PEP group, science advisor Dr. John Percy penned some words of wisdom for the participants. Below is a sampling that is just as relevant today:

> *Choose a program which fits your equipment, site, ability, and time available.*
>
> *There are definite advantages to working with a group on an established program or campaign. You get more feedback that way.*
>
> *Photoelectric photometry should be enjoyable as well as satisfying. Don't forget what the word "amateur" means.*

Watch the Counts!
Tom

# Appendix A: PEPObs

Raw V band observations can be processed on the AAVSO website go through a reduction tool accessed through the WebObs page. You are presented with a form in which to enter star identification, date and time, and samples. The “Double Date” is the pair of evening/morning civil dates for the night in question. This field is not parsed for format, it is just a note that may later be used by AAVSO staff if there is a later question about the correct date. The “Comment” field will be included in the data record stored for your observation. Your observer code is automatically populated (you must be logged-in on the AAVSO site to submit data). This tool only works for stars in the PEP database.



**Add An Observation**

Obscode CTOA

**Star Name:**

**Last Five Digits of JD:**

**Double Date:**

**Comments:**

**Timezone:**

The form then continues with a series of cryptically-numbered lines, each having a time, count, and gain.

| Time | Target | Deflection | Gain |
|---|---|---|---|
| 4:25 | 3 | 1000 | 10 |
| 0:00 | 4 | 20 | 10 |
| 4:27 | 1 | 800 | 10 |
| 0:00 | 4 | 23 | 10 |
| 4:28 | 3 | 1004 | 10 |
| 0:00 | 4 | 21 | 10 |
| 4:29 | 1 | 799 | 10 |
| 0:00 | 4 | 18 | 10 |
| 4:30 | 3 | 1010 | 10 |
| 0:0 | 4 | 22 | 10 |
| 4:32 | 1 | 812 | 10 |
| 0:00 | 4 | 24 | 10 |
| 4:33 | 3 | 1007 | 10 |
| 0:00 | 4 | 22 | 10 |
| 4:35 | 2 | 750 | 10 |
| 4:36 | 4 | 26 | 10 |
| 4:37 | 3 | 1002 | 10 |
| 0:00 | 4 | 25 | 10 |

Add this observation to the report

The numbers refer to the following pattern: 3=comparison, 4=sky, 1=variable, 2=check. The sky samples are implicitly associated with the immediately-preceding star samples, and the time associated with a sky sample is not used. The time format is hh:mm. Sample counts are entered as integers, so you will round your average of three integrations. When you "Add" the observation, some consistency checks are performed, and, if passed, the observation is added to a list at page top:

## Current Report

| Star Name | JD | Magnitude |
|---|---|---|
| ALF ORI | 2457456.6870 | 4.289 |

Submit this report

You can then enter data for more stars, or submit what you have.

There are bugs in WebPEP. The most serious is that it calculates sidereal time incorrectly (fast by 8 minutes, as I recall). Another: if you succeed in collecting some *very* consistent samples, WebPEP can report an error of 0.

# Appendix B: References

**Publications:**

*Photoelectric Photometry of Variable Stars,* 2nd edition, Hall & Genet; especially chapters 9-14. Readily available on the used market; Willmann-Bell still has some new copies. Fairly approachable. Spills a lot of ink on pulse-counting.

*Astronomical Photometry*, 2nd edition, Henden & Kaitchuck; especially chapter 4 and appendices G, H. More technical and still in print. Like Hall & Genet, it spends a lot of time discussing pulse counting systems.

*Software for Photometric Astronomy*, Ghedini. Harder to find. Willmann-Bell still has it.

*Astronomical Techniques*, various authors; see chapter 8 on PEP reductions by Hardie. Long out of print, but available at the Internet Archive (http://archive.org).

A word of caution as you start exploring outside of this document: historically, photometrists have worked a lot with V, B-V, and U-B in place of V, B, and U. This had certain advantages, but required different math (eg: the transformation coefficient for B-V is mu (μ), and for U-B is psi (ψ)).

**Manuals for the Optec photometers:**

*SSP3 Generation 1 Technical Manual*, Optec (http://archive.org)
*SSP3 Generation 2 Technical Manual*, Optec (http://optecinc.com/astronomy/catalog/ssp/index.htm)
*SSP5 Generation 2 Technical Manual*, Optec (http://optecinc.com/astronomy/catalog/ssp/index.htm)
(I can't find a manual for the Gen. 1 SSP5)

**Websites:**

https://gcpd.physics.muni.cz General Catalog of Photometric Data (GCPD)
One of the most reliable online sources of star magnitudes. R&I magnitudes in UBVRI system are Johnson.

http://simbad.u-strasbg.fr/simbad/sim-fbasic SIMBAD catalog
Has numerical information about a wide variety of astronomical objects with a flexible search interface.

https://www.aavso.org AAVSO home page

http://ssqdataq.com SSP data reduction software packages

# Appendix C: Metadata

PEP metadata are recorded in the “notes” of the AAVSO extended format photometry record. Different fields in the notes section are delimited by the ‘|’ character. Fields are of the form KEYWORD=<value> and no commas are allowed. Avoid using quotation marks and apostrophes. Aside from the COMMENT, values should not have spaces. Multiple fields within the COMMENT should be separated by a semicolon.

| | |
|---|---|
| SCOPE | optical tube used |
| SENSOR | photometer used |
| LOC | latitude/longitude of observer (to nearest degree) |
| INDEX | color index of reduction (BV, VI, etc) |
| K_B | first order extinction coefficient (here, in B band) |
| K_B_EST | estimated extinction |
| KK_B | second order extinction coefficient for B band (formerly KK_BV) |
| KK_B_EST | estimated second order extinction |
| TB_BV | transformation coefficient for B band in the BV index |
| TB_BV_EST | B transform when second order extinction is estimated |
| CREFMAG | comparison star magnitude |
| PROG | reduction program |
| DELTA | standard color contrast between variable and comparison |
| DELTA_EST | “estimated” delta (i.e.: a catalog value rather than a measurement) |
| COMMENT | observer comments, if appropriate (spaces allowed, delimit multiple comments with ';' |

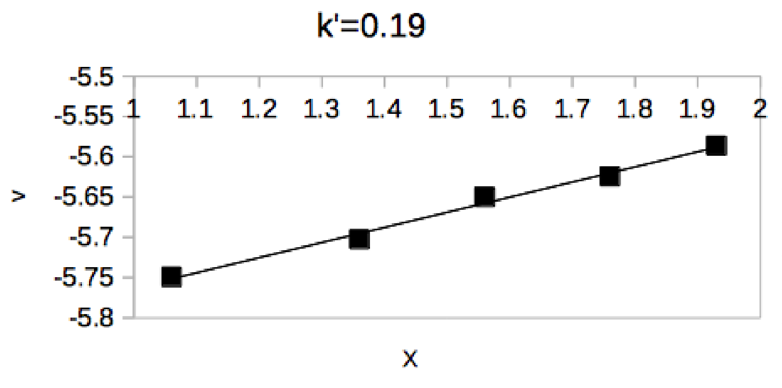
An example metadata section would be:

```
|SCOPE=10IN_SCT|SENSOR=SSP3|LOC=44N/131W|INDEX=BV|K_B=0.35|KK_B=-0.03|TB_BV=0.01|
DELTA=0.317|CREFMAG=7.22|PROG=TJC_PEP_5.0|COMMENT=POOR SEEING;HUMID|
```

# Appendix D: Extinction examples

Below are example reductions of first and second-order extinction data, beginning with the "simple" determination of first-order extinction. For a single star, we record the instrumental magnitude, $-2.5 \cdot \log_{10}$(net counts), at a range of airmasses during the night.[23] The extinction coefficient ($k'_V$ in this case) is the slope of the line fitted to instrumental magnitude versus airmass. The graph is here presented with the magnitude brightening in the negative y direction, so that the positive slope of the line is seen directly.

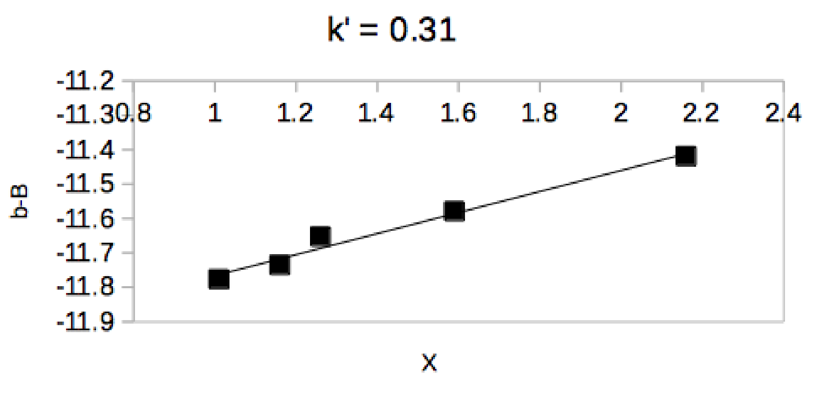
| X | v |
|---|---|
| 1.06 | -5.7493 |
| 1.36 | -5.7026 |
| 1.56 | -5.6500 |
| 1.76 | -5.6244 |
| 1.93 | -5.5865 |




Next, here are data for determining first-order B extinction via the "Hardie" method. A selection of stars having reliable standard magnitudes are observed in quick succession. They are chosen so as to span an airmass range of about 1.0. The stars, below, were taken from the list of Appendix A in Henden & Kaitchuck. This particular set is a bit imbalanced, having three stars at X<1.3, but it still illustrates the procedure. The value of $k'_B$ is the slope of the line fitted to the standard magnitude minus the instrumental magnitude (B-b) versus airmass.

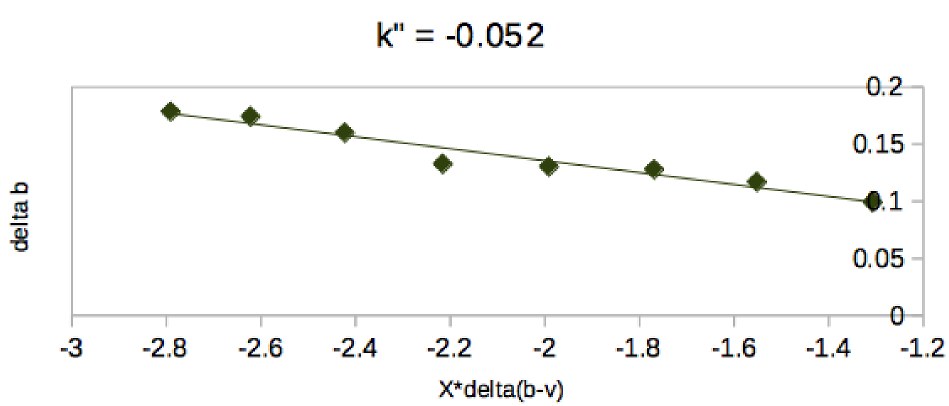
| **star** | **X** | **B** | **b** | **b-B** |
|---|---|---|---|---|
| lambda Per | 1.01 | 4.31 | -7.4667 | -11.7767 |
| 136 Tau | 1.16 | 4.59 | -7.1456 | -11.7356 |
| pi 2 Ori | 1.26 | 4.36 | -7.2930 | -11.6530 |
| phi Gem | 1.59 | 5.08 | -6.4993 | -11.5793 |
| gamma Cnc | 2.16 | 4.68 | -6.4993 | -11.4191 |

23 For B band, we would be careful to choose a star with B-V near 0 to avoid second-order extinction.




Finally, a second-order extinction reduction. Here, we observe a red/blue pair over a range of airmasses during the night. Magnitude deltas are in terms of the blue star minus the red star, so $\Delta b = Blue_b - Red_b$.[24] Note how Δb increases as the airmass increases. Both stars are losing light as extinction grows, but the blue star has a lot of light at the blue end of B band, where second-order kicks in, so its b magnitude dims (increases), faster, and $Blue_b - Red_b$ becomes more positive.

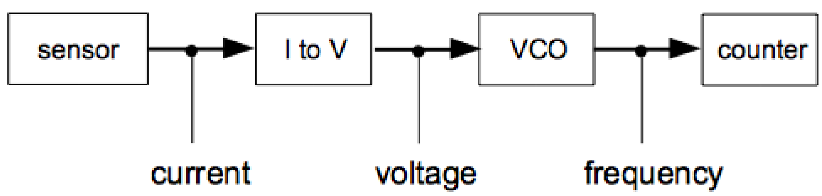
| X | Δb | Δv | Δ(b-v) | X · Δ(b-v) |
|---|---|---|---|---|
| 1.01 | 0.0991 | 1.3933 | -1.2942 | -1.3071 |
| 1.21 | 0.1169 | 1.3993 | -1.2824 | -1.5517 |
| 1.40 | 0.1278 | 1.3912 | -1.2634 | -1.7688 |
| 1.58 | 0.1302 | 1.3905 | -1.2603 | -1.9913 |
| 1.76 | 0.1326 | 1.3915 | -1.2589 | -2.2157 |
| 1.96 | 0.1599 | 1.3969 | -1.2360 | -2.4226 |
| 2.13 | 0.1740 | 1.4050 | -1.2310 | -2.6220 |
| 2.30 | 0.1783 | 1.3916 | -1.2133 | -2.7906 |




24 And Δ(b–v) = Δb–Δv.

# Appendix E: SSP electronics

All the SSP sensors generate currents. If we could count the individual electrons coming out we could actually generate photon statistics, but such is not the case. The current from the sensor is fed into a circuit that produces a voltage proportional to the current (current-to-voltage converter). In the olden days, this voltage got fed into the strip-chart recorder. In the SSP, this voltage is fed into a voltage-to-frequency converter (VFC).[25] This device puts out a train of electronic pulses, proportional in frequency to the voltage. The pulse train is fed into a counter. The output of the counter is copied to a buffer at the end of the integration time, and the counter is reset to 0. The contents of this buffer is what you see on the display. The pulse train runs continuously–independent of the counter circuit–and that is what you see on the analog output port, or on the "Pulse" test pin on the circuit board of a Generation 2 photometer. This means is that if you sample the pulse train yourself, it doesn't matter if the display overflows. The voltage-to-frequency circuit is nominally rated to 10kHz, which translates to 100,000 counts in ten seconds. However, bench tests have shown excellent results up to 14kHz. Care must be exercised for count rates below 1kHz: linearity suffers when ten-second counts drop below one thousand.




25 Also known as a voltage-controller-oscillator (VCO).

# Appendix F: Additional notes

a) When starting up in the evening, the photometer needs to stabilize, both thermally and electronically. Let the device come to ambient temperature before you put it to use. After you power it up, let it idle for ten minutes. Unless you are going to take a significant hiatus in data-collection during the night, leave the photometer on for the whole observing session.

b) I have seen a unit that had light leaks. I was using it under a dome that had red lights, and I noticed that my sky counts were elevated at times. It turned out that light was getting in through the eyepiece and reaching the sensor. The magnitude of the leak depended upon whether I was standing between the light and the photometer, casting a shadow. If you operate near a light source (eg: computer monitor) and you are seeing some inexplicable dark counts, try shielding the photometer case and see if the counts settle.

c) There is a phenomenon where the counts overshoot, then undershoot, then stabilize when switching from a bright star to a dim one. I have seen this on occasion, and so have others. What causes it, I do not know, but it is another reason to pay close attention to the counts. The workaround is to let a few integrations pass.

d) Airplane lights, satellites, and meteors can cause sudden increases in counts. Watch for them, and re-do suspect integrations. I once had to do photometry during a meteor shower, and got "hit" a few times.

e) The Generation 1 SSP3 is intended to run on an unregulated power supply of about 14 volts. In cold weather, a 12 volt supply may not suffice.

f) Although you get a 0-64K count range using computer logging, it is still possible to overflow on a bright star at a too-high gain. If you get a data set that has impossibly low counts for a bright target, this is what happened. Do not despair: add 65,536 to the low counts.

g) The Generation 1 display wraps around after 10,000 counts. Do not despair: the lower four digits are correct, merely add 10,000 or 20,000, etc. Use an integration time of 1 second to determine the unknown significant digit.

h) If your Generation 1 SSP3 display is completely blank with no overflow light, the unit is saturated (you're probably playing with it in daylight).

i) When looking through the eyepiece, you exhale on the photometer case. In cold weather, you will fog or frost-over the count display. Learn to breathe out of the side of your mouth in winter.

j) The weak link in Gen. 1 SSP hardware is the switches. The levers have no protection against impacts, and it is relatively easy to break them off. Replacement switches are hard to find, but we have a small stock of spares.

# Appendix G: Airmass computation

Below are my Python procedures for computing airmass. All angles (RA, Dec, latitude) are in radians. Universal Times are in minutes [0..1439), UT fractions are [0, 1).

```
# compute airmass from RA, Dec, location, and UT
def computeAirmass(ra, dec, julianDate, ut, longitude, latitude):
    # get sidereal time
    siderealTime = localSiderealTime(longitude,
                                     julianDate, ut/1440.0)

    # sidereal angle
    siderealHourAngle = siderealTime * 15.0 * degRad

    # compute hour angle
    meanHourAngle = siderealHourAngle - ra

    # sin of altitude
    sinAltitude =(math.sin(latitude)*math.sin(dec)) + \
        (math.cos(latitude)*math.cos(dec) * \
             math.cos(meanHourAngle))

    return sinAltitudeToAirmass(sinAltitude)


# compute local sidereal time
def localSiderealTime(longitude, julianDate, utDayFraction):

    # Oliver Montebruck's Practical Ephemeris Calculations (Springer Verlag 1987).
    # Greenwich Mean Sidereal Time (GMST) is the local sidereal time at
    # longitude 0.

    # GMST(in hours) = 6.656306 + 0.0657098242*(JD0-2445700.5) + 1.0027379093*UT

    # where JD0 is the Julian date at UT=0 (note JD0 will always end in .5 --
    # Julian days begin and end at UT noon).

    # The conversion to local sidereal time:
    # LST = MOD [(GMST - (degrees west of Greenwich)*(24/360)),24]

    greenwichST = 6.656306 + 0.0657098242*(julianDate-2445700) + \
        1.0027379094*(utDayFraction*24)

    siderealTime = greenwichST + (longitude/twoPi)*24

    # if we go over 24 hours, reduce to [0-23)
    if (siderealTime >= 24.0):
        siderealTime -= int(siderealTime/24.0)*24

    return siderealTime


# compute airmass from sine of altitude
def sinAltitudeToAirmass(sinAltitude):
    cosecant = 1/sinAltitude
    return cosecant - 0.0018167*(cosecant - 1) - 0.002875*(cosecant - 1)*(cosecant - 1) - \
        0.0008083*(cosecant - 1)*(cosecant - 1)*(cosecant - 1)
```