

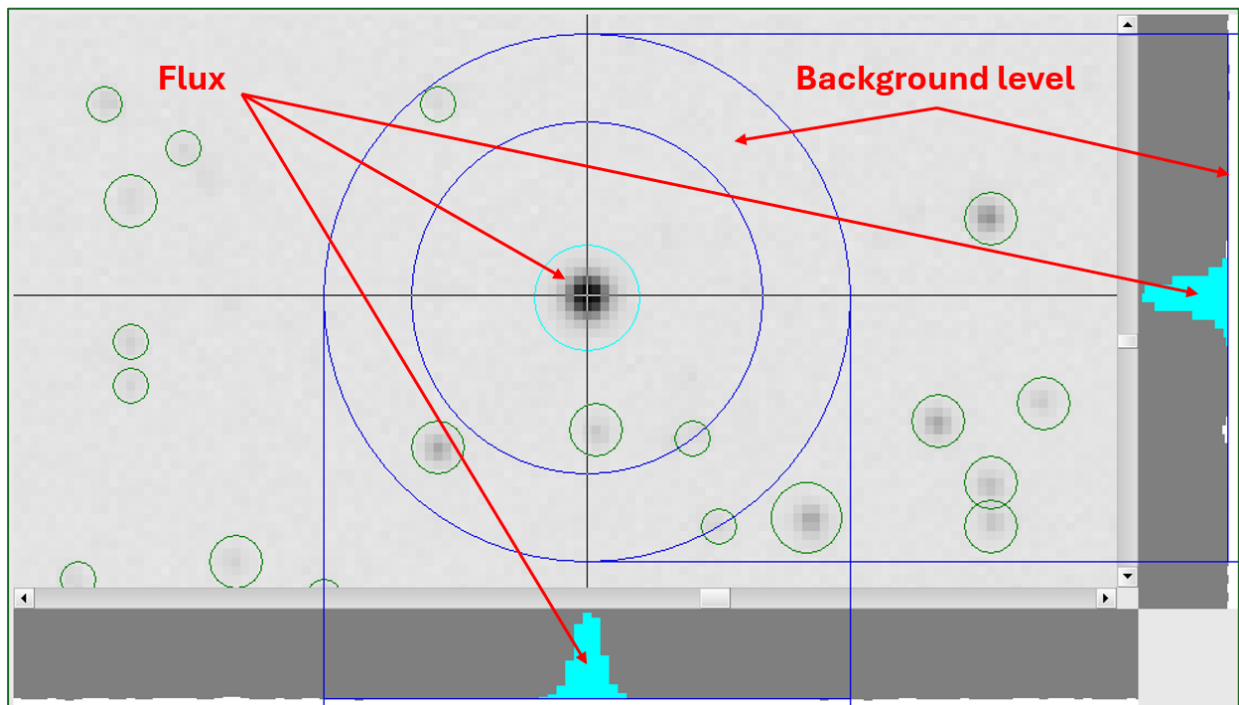
## A short introduction to photometry

The main task of photometry is to measure **flux** of astronomical objects and its changes in time. It represents amount of light captured from each object (star, galaxy, asteroid, comet, etc.) within the image and it's calculated as a sum of values (ADU<sup>1</sup> counts) of all pixels belonging to the particular object. This means pixels positioned within a defined circle (**photometric aperture**) centered around the star's centroid.

### Remark:

For simplicity, we will call the measured object **variable star** or just a **variable** from now on, as the recording of brightness changes of variable stars is the most typical application of photometry. Also, such stars are often marked with an abbreviation **VAR**. However, let's keep in mind that everything explained here is also valid for other astronomical objects like asteroids, novae, supernovae, etc.

However, ADU values of each pixel do represent not only the amount of light captured from the variable star, but also the light from the sky background (natural background as well as light pollution) and by sensor bias. It is the task for photometric software to determine the background value and subtract it from each pixel, so the measured flux corresponds only to light coming directly from the object.



To achieve the best possible estimation of the background value, it is not determined globally for the image, but individually for each measured object. Notice the three circles around the star in the figure above. The smallest, cyan, one represents the photometric aperture. The two larger blue circles define the area, known as **background ring**, which is used for calculating the background value.

### Hint:

It is no exception that there are no other stars in the background ring, especially in the star-poor sky regions. On the other hand, it is virtually impossible to define a background ring, so it does not contain any other star in star-rich regions within the Milky Way. SIPS of course excludes such stars from the background value calculations, but sometimes a dim star remains undetected and thus its light affects

<sup>1</sup> The abbreviation ADU means Analog-to-Digital converter Unit. It is a number returned from A/D Converter when the charge accumulated in each pixel is digitized.

the background value. Also, some other artifacts, like for instance bright star diffraction spikes, may affect the background value. So, especially for dense star fields, it is highly recommended to set the **Use robust mean for background** option in the **Photometry parameters** dialog box (see the [Photometry calculation](#) for details).

Since human's perception of brightness is not linear (we are able to see a really huge range of brightness), astronomers start using a nonlinear unit as well. This logarithmic brightness unit is called **Magnitude** and it is defined in such a way that a **100-times brighter** object (with 100-times greater flux) differs **by 5 magnitudes**. The magnitude scale is also defined as negative, i.e., a lower magnitude value means brighter object. So, the object with Magnitude 1 less is  $\sqrt[5]{100} = 2.5119$  times brighter.

## Instrumental magnitude

Based on the definition above, we can calculate the **instrumental** magnitude  $Mag_I$  from flux  $F$  using the following equation:

$$Mag_I = -2.5 \cdot \log_{10}(F)$$

It strongly depends on the instruments used (telescope and camera; thus, the name), exposure time, and other parameters. Naturally, the flux accumulated by a small lens and low sensitivity camera will be much smaller than a flux from large telescope and premium high sensitivity camera.

Unfortunately, the flux also varies with the weather conditions, object altitude above horizon, and other conditions. So, instrumental magnitude alone is not useful as the influence of these effects often overshadows the intrinsic brightness changes of the variable star, which we want to measure.

Remark:

This is why neither SIPS **Photometry** nor **Astrometry** tools work directly with instrumental magnitudes.

## Relative magnitude

To eliminate flux variations with other causes than the real object brightness changes, another **comparison star** is used as a brightness reference. It is assumed that all factors influencing the variable star flux also affect the comparison star in the same way. Thanks to logarithmic magnitude scale, the **comparison star instrumental magnitude** is just subtracted from **variable star instrumental magnitude** to obtain variable star relative magnitude  $Mag_R$ .

$$Mag_R = -2.5 \cdot \log_{10}(F_V) - (-2.5 \cdot \log_{10}(F_C))$$

This can be simplified to the **Pogson equation**,

$$Mag_R = -2.5 \cdot \log_{10}\left(\frac{F_V}{F_C}\right),$$

which bypasses the need to calculate the intermediate instrumental magnitudes and uses directly the fluxes.

The uncertainty of relative magnitude can be defined as follows:

$$\sigma_{Mag} = \frac{2.5}{\ln(10)} \cdot \sqrt{\left(\frac{\sigma_V}{F_V}\right)^2 + \left(\frac{\sigma_C}{F_C}\right)^2}$$

Unfortunately, using the variable and comparison star flux ratio does not eliminate all unwanted effects. Different colors are absorbed differently by our atmosphere; red light is less absorbed than blue one (this is why the sky is blue as well as why Sun or Moon close to the horizon appear redder). So, if the variable and comparison star colors are different, their fluxes vary with changing airmass over the observing session differently, and thus their ratio changes as well. This effect (different extinction ratio) significantly affects the relative magnitude.

The very effective way to eliminate (or at least suppress) this effect is choosing variable and comparison stars with the same color. Extinction is then the same for both stars.

Using a filter to limit the range of wavelengths also limits this effect. Unfortunately, it would be necessary to use a very narrow-band filter to eliminate it completely and such filters are not used in research applications for various reasons. Standard photometric filter passbands widths are tens, or even more than a hundred nanometers, and different star colors still affect the flux ratio.

## Absolute magnitude

The relative magnitude gives no idea how the object is “really” bright, as it depends on the brightness of the used comparison star. Thanks to the logarithmic nature of the magnitudes, there is no natural zero point like “zero brightness”. A reference zero point (a star with brightness 0 Mag) is then chosen as a part of some absolute magnitude standard.

So, we can think about absolute magnitude<sup>2</sup> as a relative magnitude but related to a chosen reference point (zero-magnitude star). While it is practically impossible to always select a zero-magnitude comparison star, it is also not necessary. If we know the absolute magnitude of the comparison star, we can get the absolute magnitude of the variable star simply by adding the comparison star absolute magnitude to the measured relative magnitude of the variable star. However, there are some caveats in this thinking.

In general, star flux varies with wavelength depending on the star temperature (stars mostly follow the Planck’s law of black body radiation). Also, sensor sensitivity in different wavelengths differs, as well as optics and atmosphere transparency etc. This is why the term “absolute magnitude” without specification of the color (photometric system—wavelength interval defined by a standard photometric filter) is only a vague term. It is useful to give a general idea about celestial object brightness, e.g. during public lectures, but it is not used in research at all.

Remark:

While the dimmest stars visible by naked eye brightness is approx. 6 Mag, Vega is 0 Mag, Sirius (brightest star except Sun) -1.5 Mag, Jupiter can reach around -2.5 Mag, Venus -4.5 Mag, full Moon -12.5, and Sun even -26.7 Mag.

Otherwise, color is important when talking about absolute magnitudes. For instance, cold red stars are several times brighter in red light compared to blue light. And similarly, a white dwarf can be many times brighter in blue compared to a brightness in red color.

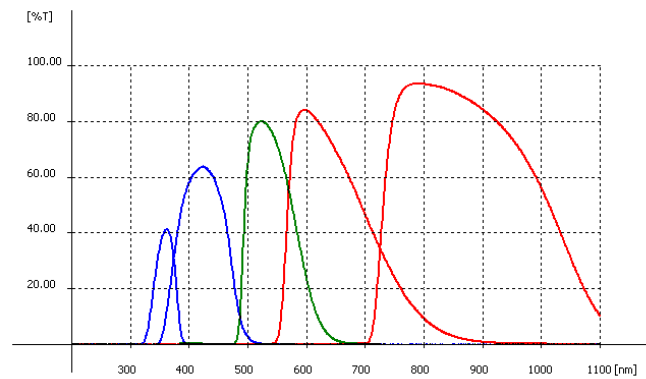
Astronomers defined several photometric standards over time. Such standards are always associated with a set of filters, defining a passband (a range of wavelengths).

### Johnson-Cousins standard

Johnson-Cousins is one of the oldest and still widely used photometric systems. It consists of 5 filters denoted U (ultra-violet), B (blue), V (visual), R (red), and I (infra-red). The passbands are illustrated on the image below:

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<sup>2</sup> The “absolute magnitude” here means magnitude related to some standard photometric system, not a magnitude expressing object brightness in the 10 parsecs distance.



#### Remark:

The UBV filters were introduced by Johnson and Morgan in the 1950s, but their filters for red and infra-red colors were not consistent and poorly reproducible. Only later Cousins (in the 1970s and 1980s) redefined these filters, which is why the last two filters are sometimes denoted  $R_C$  and  $I_C$ .

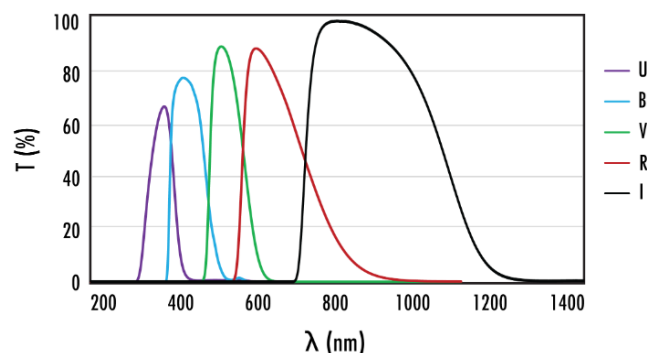
These filters are created by adding metal-oxide dopants directly into the glass, as the technology of manufacturing filters using thin interference layers was not available these times. This caused several disadvantages of the UBVRI set:

- Peak transparency is well below 100%, it reaches only ~40% in the case of U filter. So, using these filters wastes precious light.
- The passband edges are not very sharply defined and individual passbands significantly overlap, which negatively affects physical interpretation of observations.

#### Bessel (Johnson-Bessel) standard

The low peak transparency of Johnson filters, particularly in the U and B passbands, lead to an effort to modernize the UBVRI filter set. The modification, known as Bessel or Johnson/Bessel filter set, primarily focused on increasing the peak transparency.

While the Bessel approximation of the UBVRI passbands can in theory reach 100% peak transparency, in reality such filters are virtually impossible to manufacture, and the peak transparency is lower. But still, the Bessel filters offer significant gains in transparency, which results in lower exposure times and/or better S/N of captured images.

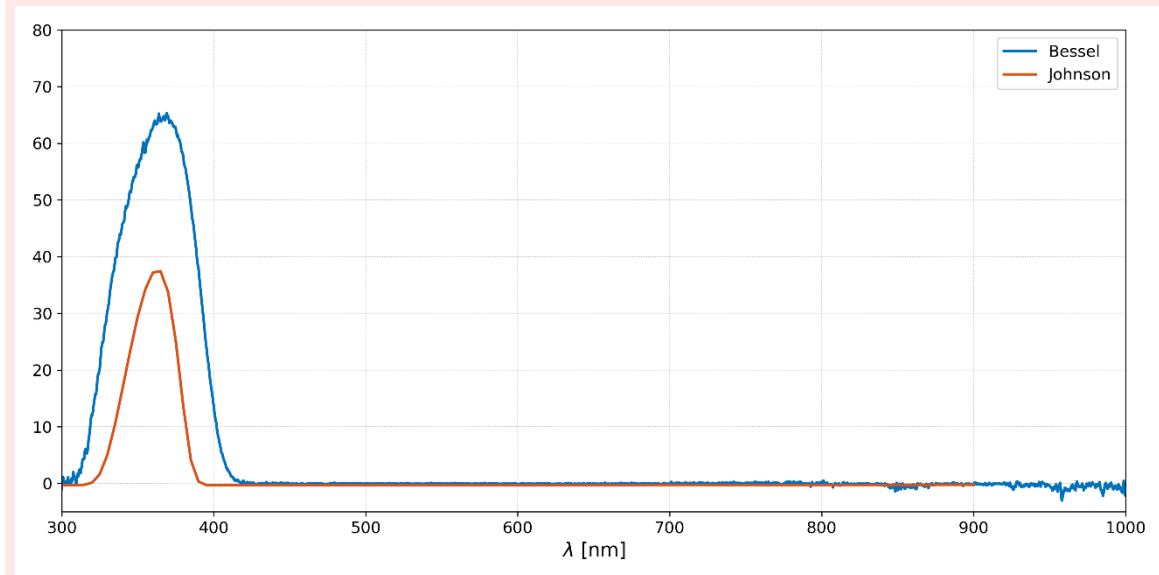


Unfortunately, the Bessel filter variants do not differ only by peak transparency, but also by passband ranges. So, Johnson-Cousins and Bessel magnitudes are not directly exchangeable, it is necessary to perform magnitude transformations between these two systems. E.g., the Landolt fields UBVRI magnitudes are Johnson-Cousins, not Bessel ones.

#### Warning:

Many filter manufacturers now offer Bessel filter variants instead of traditional Johnson-Cousins filters. But only some of these manufacturers properly mark these filters as Bessel ones, sometimes the filters are named just “UBVRI photometric filters” or even “Johnson-Cousins UBVRI filters” without mentioning they are the Bessel variants.

For example, consider the difference between the Johnson and Bessel U filters:



The integral signal passing through the Bessel U is several times greater compared to Johnson U, but also the spectral range of the Bessel U is significantly wider.

#### Sloan standard

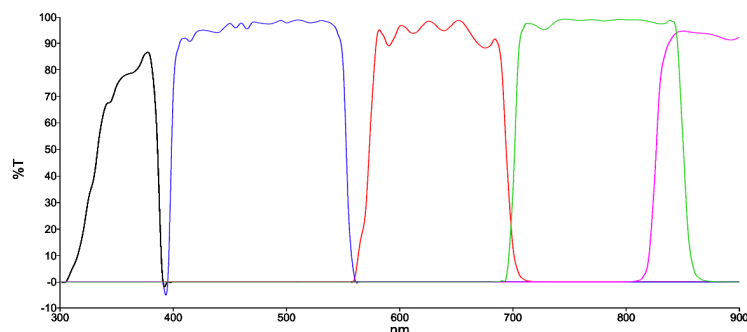
The Sloan Foundation Telescope at the Apache Point Observatory, used to perform the Sloan Digital Sky Survey (SDSS), rejected the aging UBVRI filters and introduced modern set of filters with well-defined passband edges and high transparency within the passband. The filters, abbreviated u, g, r, i, and z, are made from colored glass substrates and interference layers.

#### Remark:

It is an interesting fact, that the SDSS “z” passband was not defined by a real filter, but just by the decreasing sensitivity of the used detectors.

However, for use with other telescopes and cameras than the original Sloan Digital Sky Survey camera, the slightly modified standard was created. To distinguish the modified standard from the original one, letters marking individual filters are suffixed with an apostrophe (the modified Sloan standard filters are denoted u', g', r', i', and z'). Filters following this standard are now commercially available.

The modified Sloan passbands are illustrated on the image below:



It is worth noting that virtually entire visible light 400-700 nm is covered with just two Sloan g' and r' filters. Also, peak transparency of these filters approaches 100% so using them does not unnecessarily waste precious light.

### Glass standard

The Glass<sup>3</sup> JHK filters cover infra-red part of the electromagnetic spectrum. Individual filters are centered around 1.2 μm, 1.6 μm, and 2.2 μm. However, except for the recently introduced (but still prohibitively expensive) SWIR sensor-based cameras, these wavelengths are not reachable by amateurs and SIPS supports them only for completeness.

Remark:

As usual, there are many modifications of this standard and many sky surveys used slightly modified filters (e.g., 2MASS) and it is usually necessary to apply transformations to convert magnitudes among them.

### Absolute magnitude and Landolt fields

Since comparison stars with precisely defined magnitudes and appropriate color indices are not guaranteed in the field of interest, a bit more complex but also more general procedure leading to absolute magnitudes was introduced. It is based on flux-to-magnitude transformation, calibrated on so-called **Landolt fields**—areas uniformly distributed around celestial equator, so some Landolt fields are always available for observation. Stars within Landolt fields have very precisely measured absolute magnitudes. Originally, UBVRI magnitudes were available, now also u'g'r'i'z' magnitudes are added. The purpose of these fields is to calibrate the observing setup (telescope, camera, filters), which means determining of transformation function terms, which then allows to calculate absolute magnitude just from observed fluxes.

The transformation function could be like this:

$$Mag = -2.5 \cdot \log_{10}(F_V) + q + c_1 \cdot CI + e_1 \cdot AM$$

Where:

- $F_V$ : measured object flux
- $q$ : offset
- $c_1$ : the first-order color coefficient
- $CI$ : the star color index (e.g., Johnson B – V magnitudes)
- $e_1$ : the first-order extinction coefficient
- $AM$ : air mass

Free parameters  $q$ ,  $c_1$ , and  $e_1$  are typically determined by fitting the above function on fluxes from images of one Landolt standard field.

As mentioned above, the measured flux strongly varies with airmass (object height above horizon) as well as with weather conditions. So, best results require calibrating of the transformation function each night (or even several times during night if the weather conditions significantly change).

More complex transformation functions may be used to better eliminate unwanted effects and enhance precision, like for instance higher-order polynomials representing color dependence:

$$Mag = -2.5 \cdot \log_{10}(F_V) + q + c_1 \cdot CI + c_2 \cdot CI^2 + e_1 \cdot AM$$

Also, a different color system may be used (Sloan g'–r' can be used instead of B–V if Sloan filters are used), multiple color indexes can be used at once (Sloan g'–r' and r'–i' in one equation), etc.

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<sup>3</sup> Refers to an infrared astronomer Ian Stewart Glass, not a material from which the filters are made.

## Ensemble photometry

Relative magnitudes suit many scientific tasks well: determining of the minimum or transit time, period analysis, identification and characterization of the multiple star systems, ... This is why the SIPS Photometry tool was originally designed with only relative magnitudes in mind. Also, converting magnitudes to some absolute photometric system is time consuming procedure; it requires capturing some Landolt field in addition to target object, data must be excessively processed, at least if the process is not automated and only general tools (like Excel) are used.

Here comes the idea of **Ensemble photometry**<sup>4</sup>—obtaining absolute magnitudes using a transformation function **calibrated on every processed image**. No Landolt fields are used, but information about color index and magnitude in the used passband for many stars within each image must be known to allow calibration.

What's more, with enough calibration stars, the Ensemble photometry allows using of star position within the frame to enhance precision. Calculating with flux-to-magnitude transformation variations over a field of view helps compensate for missing or low-quality flat fielding, background gradients, etc.

Because Ensemble photometry is calibrated for each image, the extinction coefficient is not used:

$$Mag = -2.5 \cdot \log_{10}(F_V) + q + c_1 \cdot CI$$

- $F_V$ : measured flux
- $q$ : offset
- $c_1$ : the first-order color coefficient
- $CI$ : the star color index

The quality of transformation (absolute magnitude precision) depends on the reliability of star magnitudes used for calibration. Precision increases with number of stars used for calibration, many hundred or even thousand stars with known magnitudes lead to good results.

The Ensemble photometry in SIPS can use several transformation functions, differing in **color** and **spatial term orders**. Color term order can be in the range [1..2], spatial term order can be in the range [0..2] (spatial term order = 0 means star position within the image does not affect the transformation). The transformation with the higher order terms available looks like:

$$Mag = -2.5 \cdot \log_{10}(F_V) + q + c_1 \cdot CI + c_2 \cdot CI^2 + x_1 \cdot X + y_1 \cdot Y + x_2 \cdot X^2 + y_2 \cdot Y^2 + xy \cdot XY$$

Again, the  $F_V$  is the variable star flux and  $CI$  is its color index; but the transformation above uses also an object position within image  $X$  and  $Y$ . Free parameters are:

- $q$ : offset
- $c_1$ : first order color coefficient (mandatory)
- $c_2$ : second order color coefficient (optional)
- $x_1, y_1$ : first order spatial coefficients (optional)
- $x_2, y_2, xy$ : second order spatial coefficients (optional)

SIPS currently supports three color indexes:

- Johnson B – V
- Sloan  $g' - r'$
- Glass J – K

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<sup>4</sup> Sometimes the term “Ensemble photometry” is used for relative photometry using more than one comparison star (e.g., AAVSO protocol uses the term “ensemble” this way), do not confuse it with SIPS Ensemble photometry.

Color passband can be chosen from:

- Johnson-Cousins U, B, V, Rc, Ic
- Sloan u', g', r', i', z'
- Glass J, H, K

As explained earlier, an astrometry catalog, used for astrometry solution, must contain magnitudes for selected color index and passband. USNO catalogs, created from “red” and “blue” Palomar plates, do not contain standard magnitudes. UCAC5 catalog contains Gaia G magnitude, which unfortunately does not correspond to any standard passband, and Cousins R magnitude, which is not enough for ensemble photometry. So, UCAC4 is currently the only catalog containing magnitudes in many Johnson-Cousins and Sloan passbands available in SIPS.

As mentioned above, the ensemble photometry precision strongly depends on the number of available calibration stars within each image:

- If there are less than a few tens of stars, precision is very low.
- About a hundred calibration stars lead to moderate precision.
- Many hundreds or thousands of stars ensure that the precision is often better or equal to very best relative photometry.

In general, the ensemble photometry brings several pluses:

- + Measured object brightness is obtained directly in absolute magnitudes.
- + No comparison star(s) used; no need to carefully find non-variable, uncontaminated comparison stars with similar color.
- + Eliminates outliers caused by a comparison star (e.g., a satellite crossing the comparison star aperture etc.).
- + Same or better precision compared to instrumental magnitudes (with enough calibration stars).
- + Spatial dependence suppresses errors caused by VAR/CMP distance within image.

But it also brings some downsides:

- Astrometry reduction is obligatory.
- UCAC4 must be currently used as the primary astrometric catalog.
- Even in UCAC4, magnitudes in some color passbands are missing in some sky areas.
- A standard photometric filter, included in the UCAC4 catalog, must be used to capture images (unfiltered observations cannot be reliably processed).
- Enough stars within the field of view are necessary for proper calibration (a wide-field telescope/camera is a big advantage).