STELLAR PHOTOMETER

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Stellar photometer

The stellar photometer is an instrument attached to a telescope that allows us to measure the luminosity of celestial objects, for example, stars. Before the use of CCD cameras for photometry, photometers were the most widely used professional instruments for measuring the brightness of stars.

There are basically two types of photometers: photoelectric ones in which a solid state detector based on the photoelectric effect is used, and those in which the detector is a photomultiplier tube.

Photometers are instruments rarely used by amateurs, which are mostly declined by the use of CCD cameras for photometry. As a photometric instrument it has some advantages over CCDs, for example in the measurement of bright stars, high-speed photometry, etc. The main drawback is that it is more difficult to measure weak stars and more complex to automate measurements.

At amateur level, it is possible to find second-hand photometers from the manufacturer Optec, specifically the SSP-3 model for a price of around 150€. This device is a manually operated photoelectric photometer. There is a superior model, called the second generation SSP-3a, in which measurements can be automatically recorded via a serial port connected to a computer. However, this equipment is not easy find second-hand and new has a price of about 1500€, or if we talk about the model that includes the automation of the filter about 1800€. Optec manufactures a version with photomultiplier tube, the SSP-5 model, in its initial version with manual operation, and currently available with data output and optionally with filter automation. This equipment is twice the price of the equivalent SSP-3 models.

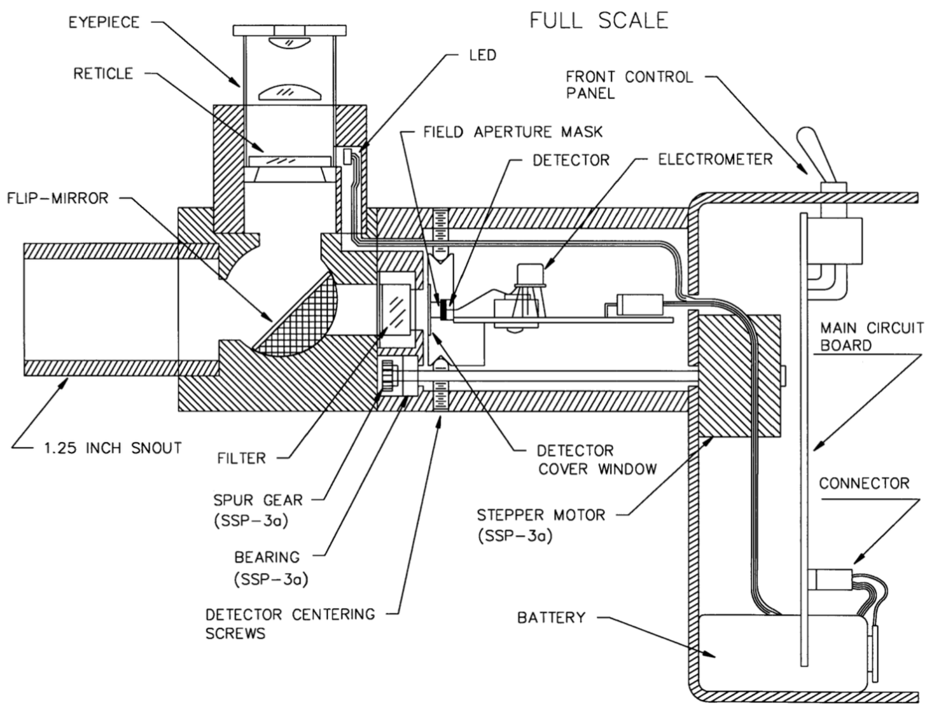
My goal is to manufacture a photometer with the following features:

- Based on photomultiplier, which allows measuring stars weaker than those based on photoelectric detectors.
- With full automation:
    - o Data output for computer connection
    - o Integrated camera centering system
    - o Automated switching from star-center to metering mode
    - o Automated filter selection system

But before explaining the solution, I will briefly explain how a photometer works, for example, the non-automated basic model SSP-3. The equipment has a robust and compact aluminium body, a construction thanks to which you can find second-hand equipment in perfect condition: it is almost indestructible. The body of the photometer houses a mirror that can be rotated to operate in two positions. The first at 45 degrees deflects the light towards an eyepiece that allows the star to be center thanks to a lighted circle marked in the center so that, when the star is inside the circle, it can be considered to be correctly centered. The second position, at 0 degrees, allows the light to pass into an aperture mask behind which is the solid state sensor. The adjustment of the elements of the equipment (eyepiece and diaphragm assembly with sensor) is made at the factory so that if we have previously centered the star with the mirror at 45º, when the mirror is rotated at 0º the star light passes through the aperture mask and all the light falls on the sensor. The eyepiece is factory set with a screw that fixes it in such a position that if we see the star in focus with the mirror at 45º, when the mirror is set to 0º the focus is exactly on the sensor. The metal part that fixes the opening mask and the sensor has four screws for its centering. From the sensor, there is an electronic that allows the received signal to be amplified and converted into pulses for counting. The equipment also has a filter holder housing, which in the first generation version of the equipment allows three filters: V, B and U.

Optical Modifications

The diagram below is from the SSP-3 manual. Please note that only in the SSP-3a version is the gear and motor system for filter automation available. In my case, the SSP-3 I started from was not the 'a' version and therefore did not have a filter automation system.



The solution adopted for the photometer to be built is the following:

- Starting from a first generation SSP-3 photometer
- Use only the mechanical elements of the photometer:
    - o Body
    - o Mirror with its turning system
    - o Metal part containing the opening mask
    - o Filter holder with corresponding filters
- It will not be used:
    - o The back box of the photometer housing the electronics, connectors, switches, display, etc.
    - o Electrometer plate and amplifier electronics plate, pulse converter, etc.
    - o The eyepiece as such, although one of its lenses will be used.

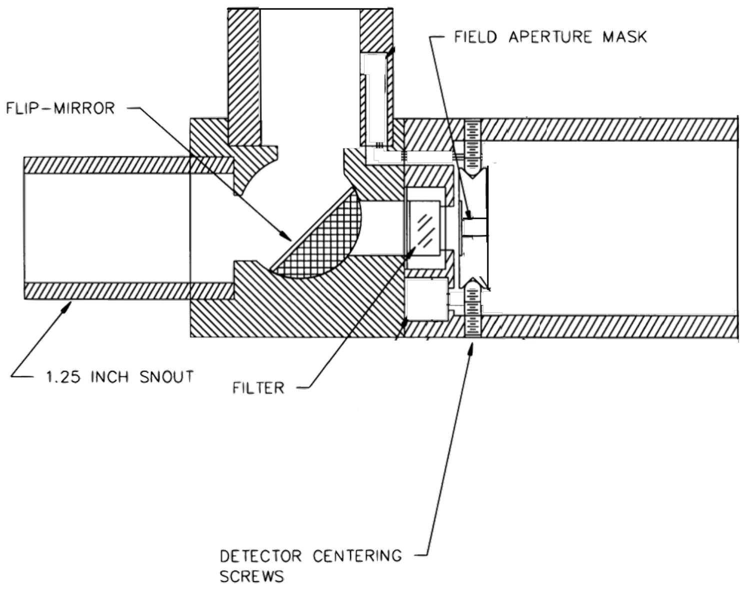
The body of the SSP-3 photometer is of excellent construction and will make it easier for us to build the equipment to get to the desired photometer, but we need to make some changes, which are basically the following:

- Remove the rear aluminum housing for electronics
- Remove the electronics and cables
- Remove the light LED from the reticle and the cable
- Remove the eyepiece, which we will disassemble to reuse a lens.
- We will disassemble the metal piece containing the opening mask and the sensor by removing the four screws that fix it to the photometer body.

Of all the elements that are removed, all can be thrown away except the metal piece that contains the opening mask and the sensor, and the eyepiece, from which we will take advantage of one of its lenses.

We'll start by removing the sensor. In fact, the sensor makes the metal part completely opaque and prevents light from reaching the photomultiplier that we will place. To do this, carefully remove the sensor that is firmly attached to the part. The only way is to break the sensor, and in the operation if we are lucky the opening mask will be undamaged. Otherwise, we will have to get an aperture of the size we want, in my case the diameter of 1mm is suitable for the type of measurements I will make, later on we will explain how it affects the mask and the focal of the telescope.

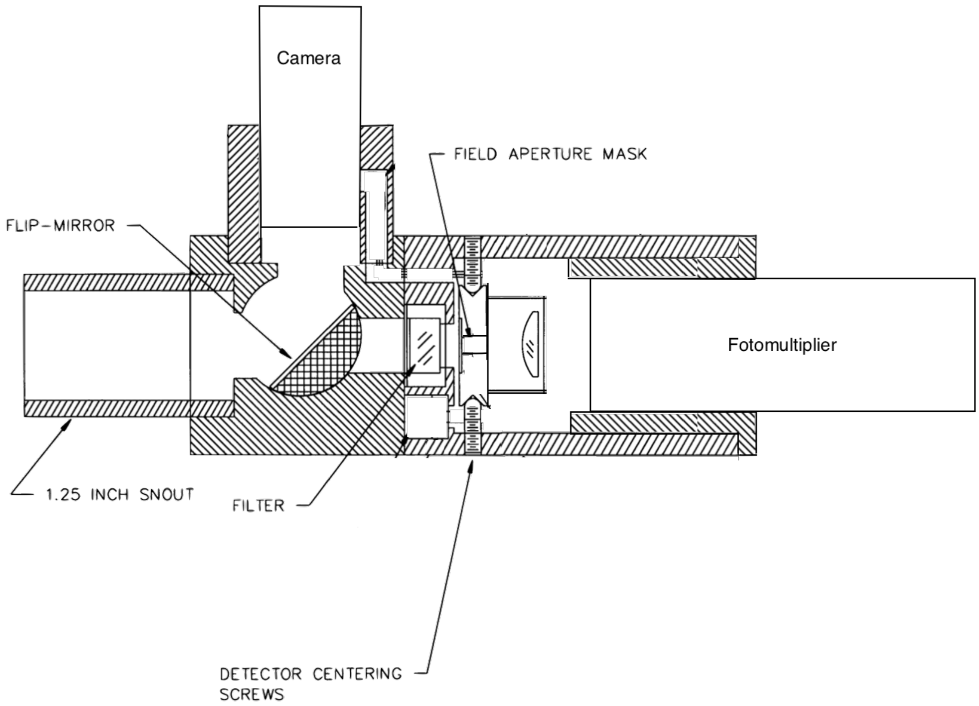
Once these operations have been carried out, we are left with the useful elements of the photometer and the result will be as shown in the following diagram:



From here we need to add elements for the photometer we want to use:

- Instead of the eyepiece, we will place a CCD camera that will allow us to automate the process of centering the star. In my case I used a Starlight Xpress Lodestar X2, perfectly suitable for this purpose because it has the same diameter as an eyepiece and because of its high sensitivity. As will be explained later, this camera's main mission is to automate the process of centering the star, and depending on the focal length of the telescope it can also be used for the correct positioning of the telescope.
- We will add two motors, one to automate the mirror rotation and the other to automate the filter selection. These steps will be described below. It will require a small electronic for control from the computer.
- We'll add a Fabry lens behind the opening mask. This lens will be obtained from the eyepiece that came with the equipment.
- We'll add a piece for the photomultiplier coupling.
- And finally, all that is left to do is to add the photomultiplier itself and carry out the process of adjusting the elements.

Although we are going to describe the process step by step, here is a simplified outline of where we want to go, ignoring for the moment the part of the engines and indicating only the optical part, which will help to follow the explanations.



In the diagram, it can be seen that the modifications to the optical system consist of placing a CCD camera instead of the eyepiece to automate the centering process, adding a Fabry lens after the opening that we obtain from the eyepiece itself, and placing a piece to adapt the diameter of the back of the metal body to the diameter of the photomultiplier used. The photomultiplier to be used is tubular with an optical window at one end of the tube.

The functioning of the whole is as follows: when the mirror is 45º, the image is obtained on the camera, which we will use to centeR the star; when the mirror is at 0º, the image is projected on the aperture mask that will allow only the light of the star and the surrounding sky to pass through, which will affect the Fabry lens and project a small circle on the optical window of the photomultiplier to measure the light of the star. The camera should be adjusted so that when the image is in focus, it is still focused on the aperture mask when the mirror allows light to pass through, keeping in mind that this adjustment must be made with the presence of the filters as they change focus.

Camera

The camera used as mentioned above is a Starlight Xpress Lodestar X2. It has the advantage of having the same outer diameter as the eyepiece, so it fits perfectly in place of the eyepiece. In addition, it has a suitable back focus so that the focus can be adjusted to match the image when the mirror is at 45° with the focus on the aperture mask when the mirror is at 0°.

In the camera image, we will not only get the star we want to measure centered, but we will also have a surrounding star field. The camera does not have a large CCD, and the field of view will also depend on the focal length of the telescope. This image obtained can be interesting to achieve not only to center the star but also to make the positioning of the telescope using some suitable software such as PinPoint. In my particular case, with a C11 telescope the resulting focal length is more than 3m and the image has too small a field of view, which limits its usefulness for positioning the telescope.

Aperture mask

The aperture mask is essential to ensure that the light from the star we are measuring reaches the photomultiplier and not that of all the surrounding stars. In reality, we will never receive only the light from the star but also from the surrounding sky, as it is impossible to isolate only the star.

Both the focal length of the telescope and the diameter of the aperture mask will determine the angular diameter of the portion of the sky that reaches the photomultiplier.

The formula for determining the angular diameter is:

D=d*20626/Focal

Focal: focal point of the telescope in cm
d: diameter of the opening mask in mm
D: angular diameter in arcs of seconds

In my case the focal length with the Celestron C11 at primary focus is Focal=3135mm, so the angular diameter through the aperture mask of d=1mm is D=65 arcs of a second.

What is the correct value? The criterion is to obtain the minimum possible value that guarantees that we are able to keep the star within the field of view set by D for the duration of the measurement, which will normally be no more than 60 seconds. Therefore, the key is the adjustment we have made for the centering of the star (i.e. that once centered in the camera, it is effectively centered in the mask) and the accuracy of the mount during tracking. The 65 seconds of arc in my case is a correct value because I can keep it centered without any problem. Perhaps you should try with a 0.5mm mask and see if with 33 arcs of seconds it also behaves properly, for the moment I have not done this test because it is quite tedious as it requires removing the mask holder and replace the mask and recalibrate all the equipment.

The reason why it is good to have a field through the mask as little as possible is that when we measure a star we measure not only the light it emits, but also the light from the surrounding sky. The luminosity of the surrounding sky will determine the weakest magnitude we are able to measure. That is to say, if for example the light received from the bottom of the sky without any star is equivalent to that of a star of eleventh magnitude, we will hardly be able to measure a weaker star of magnitude 11, and we will be limited below this magnitude to the noise signal ratio since the measured value must be subtracted from that of the bottom of the sky. Details of these values will be given in later sections with the photometer after completion.

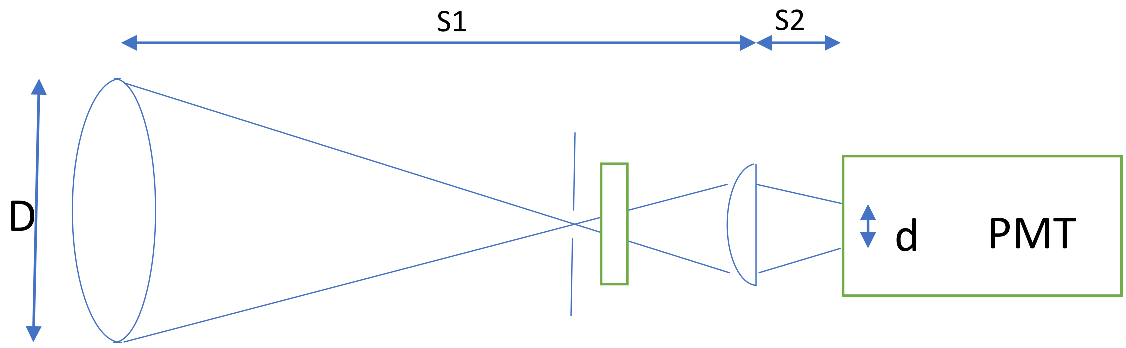
Lens Fabry

The Fabry lens is a very important element in the optical construction of the instrument. In principle, it seems that no optics are needed after the aperture mask, as the focal length is very large and therefore the angle of the cone of the image is very small, and all the light will reach the optical window of the photomultiplier, which is itself very wide (of the order of 20mm). It could therefore be thought that all the light that passes through the mask will reach the photomultiplier in its entirety and it will be able to measure correctly. In fact, it is true that all the light will reach the photomultiplier, but there is one aspect that we have not taken into account and that will reduce the accuracy of the measurements.

The photomultiplier has an optical window behind which is the photocathode, which is where the light hits and triggers the emission of photons that will generate the measurement. But the photocathode does not have an identical sensitivity over its entire surface, so the small oscillations of the telescope by the tracking itself or for any other reason such as wind, etc., will produce a variability in the measure that will reduce precision. We solve this problem with the Fabry lens.

The Fabry lens fulfills the objective of ensuring that the image of the telescope's primary mirror is projected onto the photocathode, so that the movement of the point of incidence of the star on the surface of the photocathode is minimized in order to avoid changes in the measurement due to irregularities in the surface itself.

The optical scheme of what we want is represented below, where D is the diameter of the primary mirror and d the image it projects on the surface of the photomultiplier. We will calculate how far we have to place the photomultiplier of the lens (S2) and with what diameter the image is projected (it will have to be smaller than the photomultiplier window).



The Fabry lens is a flat convex lens, and since the SSP-3 eyepiece is a Ramsden type, we will use the larger of the two lenses it is made of. Ramsden eyepieces are designed with two convex flat lenses of equal focal length and separated from each other by 2/3 of the focal length of each lens. The focal of the eyepiece is ¾ of the focal of each lens. Since the focal length of the eyepiece is 25mm according to the SSP-3 specifications, we deduce that the focal length of each lens is approximately 33mm.

From the equation of the lenses, the following must be observed in the optical scheme:

$1/S1+1/S2=1/F$
$S1/S2=D/d$

F being the focal length of the Fabry lens, D being the diameter of the primary mirror and d being the diameter of the image formed by the lens on the photocathode.

As D is much larger than d, S1 is also much larger than S2 and with a value of approximately a f (telescope focal), so we have to have very approximately S2 be F.

Therefore: $f/F=D/d$

From here, we get that $d=D*F/f$ and in my case:

$d=280*33/3135$ which gives us a diameter of about 3mm

In short: with the Fabry lens of the SSP-3 eyepiece placed about 33mm from the photocathode, we get a 3mm image that will hardly move despite the small oscillations of the telescope during the measurement, so the irregularities of the photocathode surface will not generate noise in the measurement.

To use the lens of the eyepiece, disassemble it and use the larger of the two lenses together with the tube in which it is supported and fix the assembly with glue to the piece that supports the opening, so that the flat part of the lens will be towards the photomultiplier.

Photomultiplier

The photomultiplier is a highly sensitive optical detector. Its operation is based on the fact that the photons that hit the photocathode generate electrons due to the photoelectric effect that are accelerated towards electrodes thanks to an electric field generated in the device. The device has a series of stages in which the electrons initially generated multiply until they generate a current that responds in a very linear way to the number of incident photons. In short, with a photomultiplier we can count the incident photons, although logically their efficiency is not 100%, so the photons counted will be a fraction of the incidents, and this parameter will give us the efficiency of the detector.

The main characteristics of this type of optical detector that interests us are the high sensitivity, linearity, without saturation problems and great speed of response.

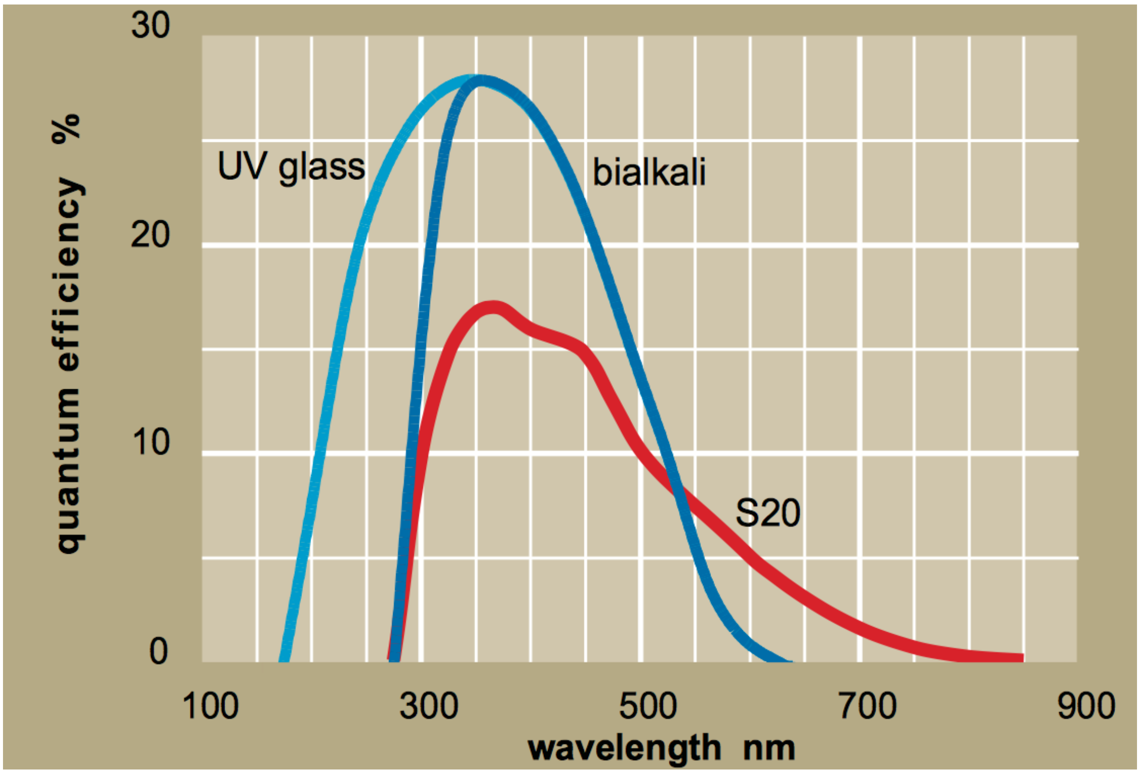
Photomultipliers were widely used in astronomical photometry until the advent of CCD cameras. With a CCD camera, we can measure hundreds of stars at once, perform differential photometry using stars of similar magnitude in the captured image, and measure very weak stars. However, the photometer outperforms the CCD in measuring variability in bright stars, in measuring events that occur over short periods of time such as hides, very short period variables, flashes, etc. Much comparative information on CCD and photometer is found in the literature on photometry and it is usually concluded that light curves with photometer are more accurate than with CCD.

From my point of view there is another reason to value the photometer with photomultiplier with respect to cameras: the type of information processing requires a greater physical understanding of what is being measured, it is necessary to perform calculations that allow a better understanding of the physical concepts that are related to astronomical photometry. With the photomultiplier-based photometer we are counting photons and from this data and bearing in mind physical and astronomical concepts the interpretation of the data is more interesting.

In my case, I used a photomultiplier that I already had and had previously used for experiments (https://www.observatorio-majadahonda.com/blank-z32cy). The detector used is Sens Tech's P30USB with Bialkali type photocathode. The detector is perfectly formatted for integration into the body of the SSP-3, and has the following features that make it suitable for the photometer:

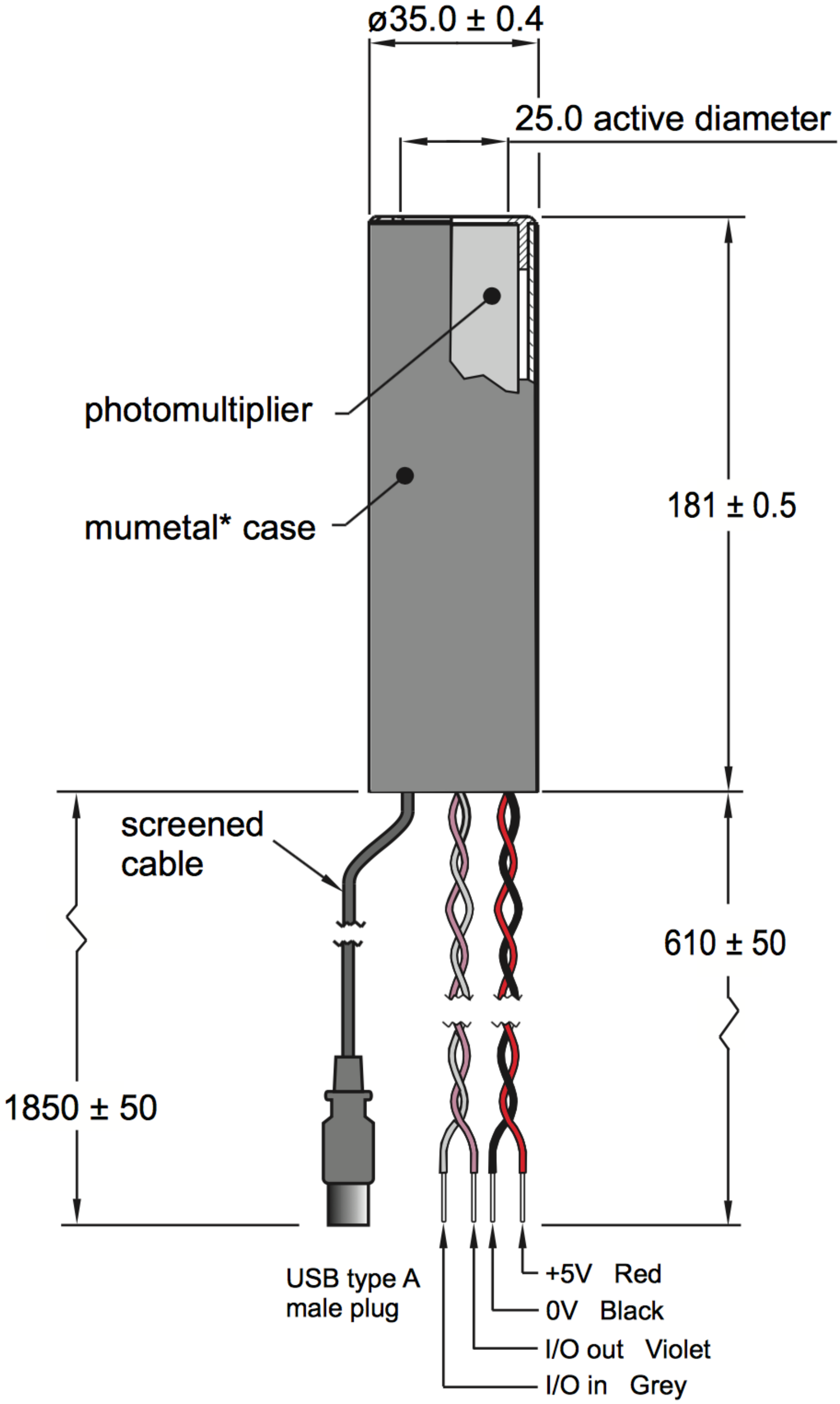
- Tubular format of 35mm diameter with the optical window at one end of the tube.
- It does not require the use of high voltage, as the high voltage source required in photomultipliers for electron acceleration is integrated. The detector is powered at 5VDC.
- The data output is via USB, so the automation of measurement capture is very easy. The manufacturer provides an ActiveX control for the implementation of a software that allows us to count received photons.
- Automatic dead time correction (effect that occurs with measurements of very high photon number values).
- Counting capacity up to 100MHz

The wavelength-dependent quantum efficiency curve is shown below:



We can mention two snags from this detector:

- Low quantum efficiency for red, which will affect us especially when choosing comparison stars, we will explain later.
- The temperature range determined by the manufacturer is from +5°C. However, I have not observed any operational or precision differences with measurements at temperatures in the observatory between 0ºC and 5ºC.

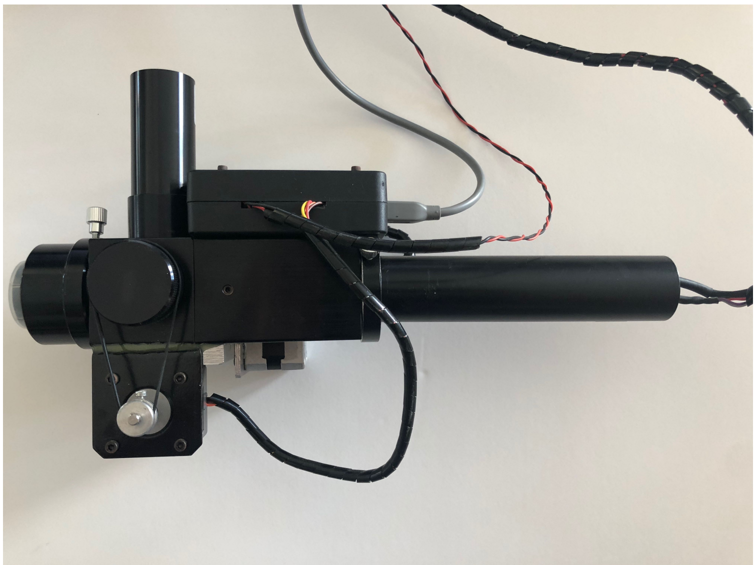

ø35.0 ± 0.4
25.0 active diameter
photomultiplier
mumetal* case
181 ± 0.5
screened
cable
610 ± 50
1850 ± 50
USB type A
male plug
+5V Red
0V Black
I/O out Violet
I/O in Grey

Constructive details

The following picture shows the photometer installed on a C11 following a MoonLite focuser.

You can see how the body of the SSP-3 has been replaced by the Starlight Xpress Lodestar X2 camera.

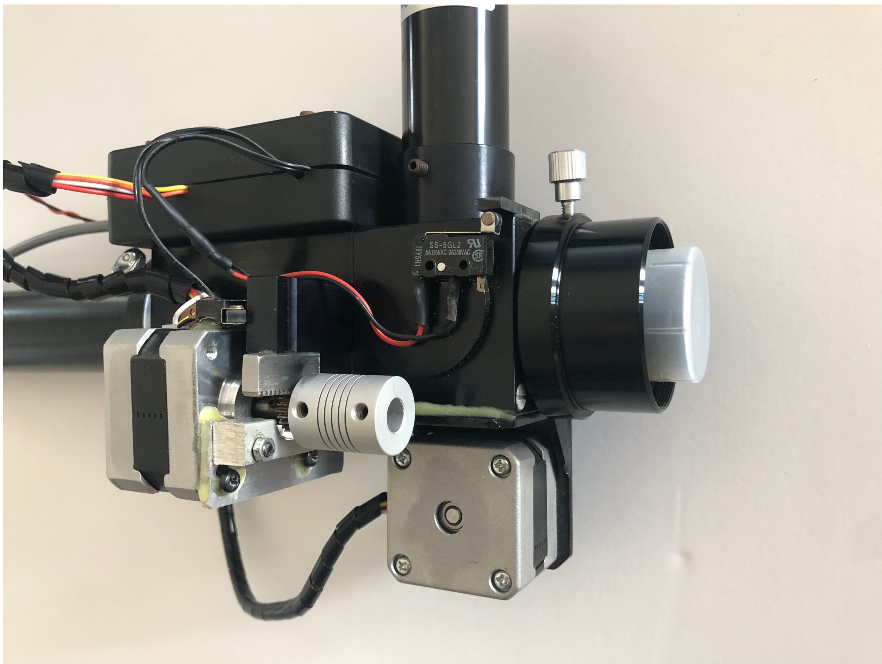
At the bottom you can see how a stepper motor is attached to the mirror, which controls the rotation of the mirror by a simple rubber belt drive.



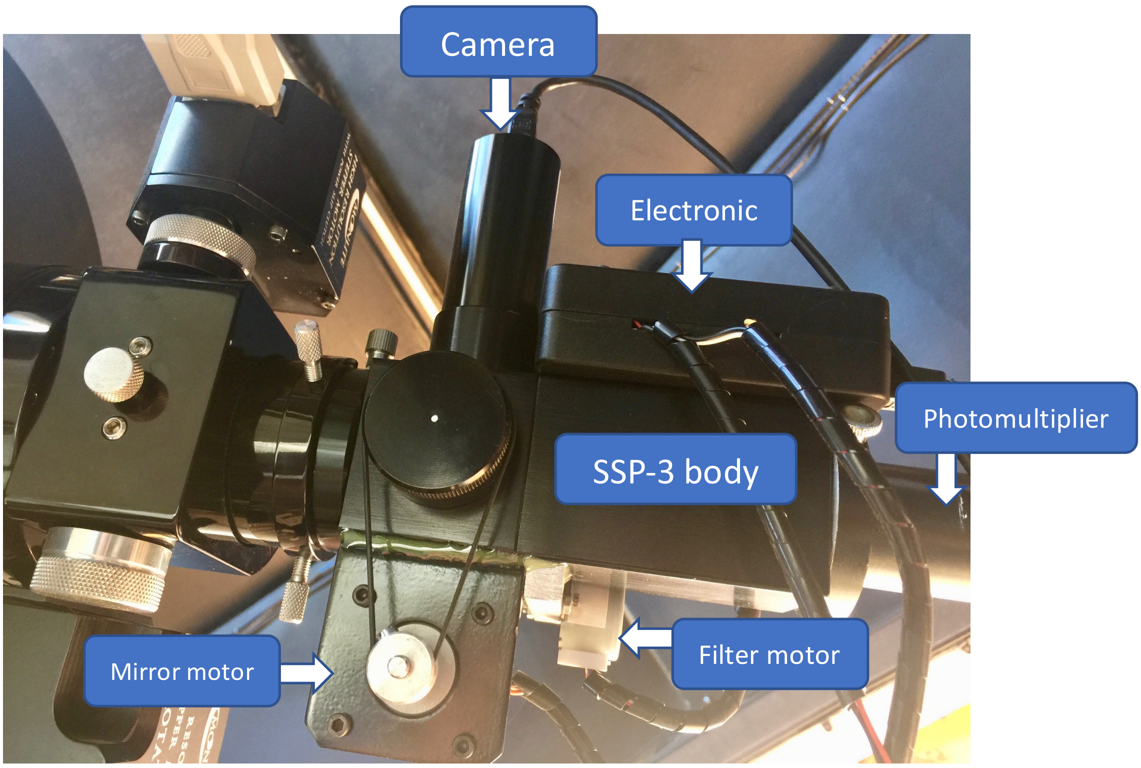
A box containing the stepper motor control electronics, the aforementioned mirror control electronics and the filter control electronics, as well as the digital inputs of the limit switches for detecting the position of the mirror and the filters, is attached to the body of the SSP-3.

The photomultiplier is attached to the back of the SSP-3 using a aluminum custom turned part to adapt the inside diameter of the SSP-3 to that of the photomultiplier.

In the following picture, you can see the stepper motor that controls the movement of the filter and the limit switches to detect the correct position of the mirror and the filter.



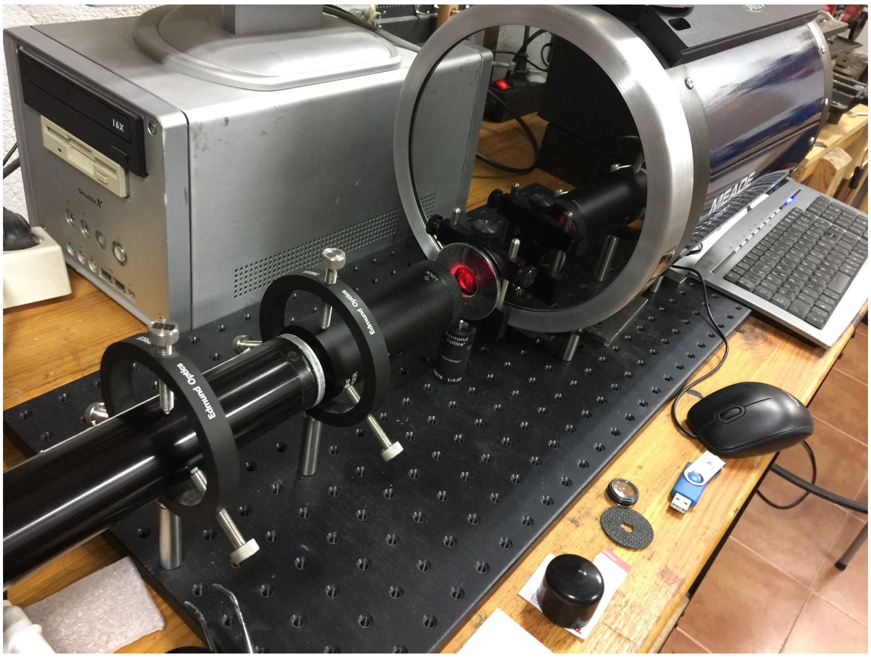
A photo below shows the elements that make up the photometer with labels to identify each element of the system:



Mechanical adjustment of the photometer

For the adjustment of the instrument, it is mounted on a bench by aligning a laser with an LX200 tube and the photometer.

The laser is magnified with a beam expander and attenuated with a neutral density filter and a sun filter attached to the telescope aperture.



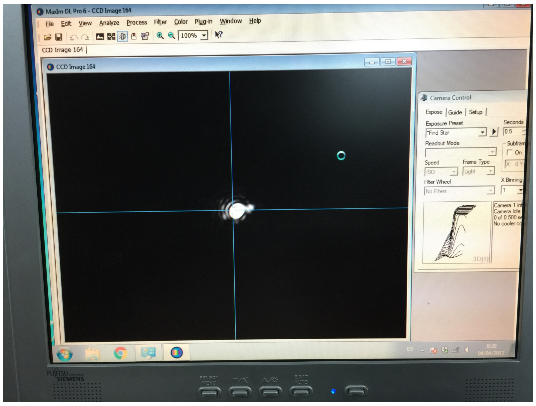
Attached to the telescope with a manual focuser, the photometer is placed without the photomultiplier.

The process of mechanical adjustment consists of making the laser focused and centered on the camera with the mirror at 45º, and the laser focused on the aperture mask with the mirror at 0º.

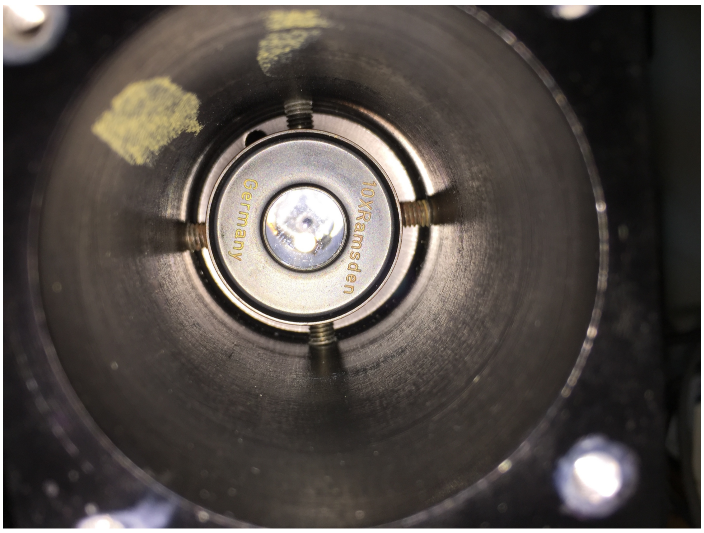
It is a tedious process that we can do by iteration and we must play with:

- The focus of the telescope
- The position of the camera in its housing that can zoom in and out of the mirror.
- The opening mask is centered using the four screws on the body of the SSP-3.

The photo shows the laser point centered and focused on the camera.

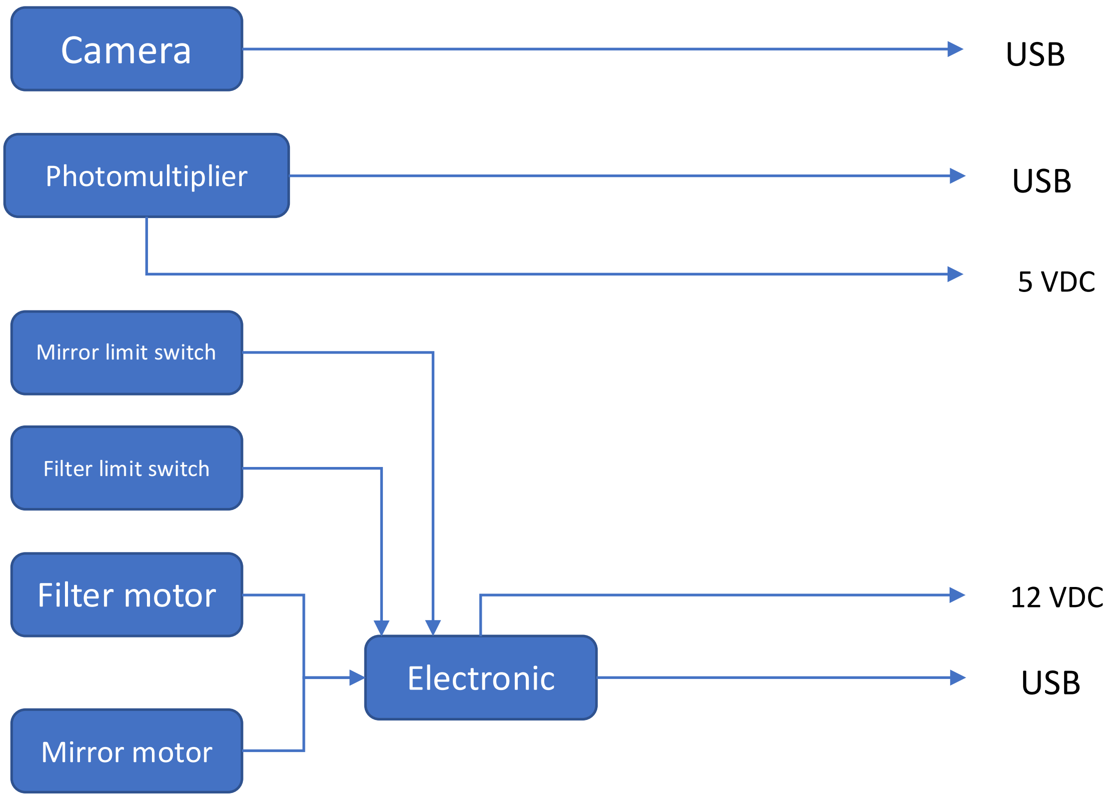


The adjustment screws of the aperture mask attached to the Fabry lens are shown (off-center assembly in the picture before adjustment).



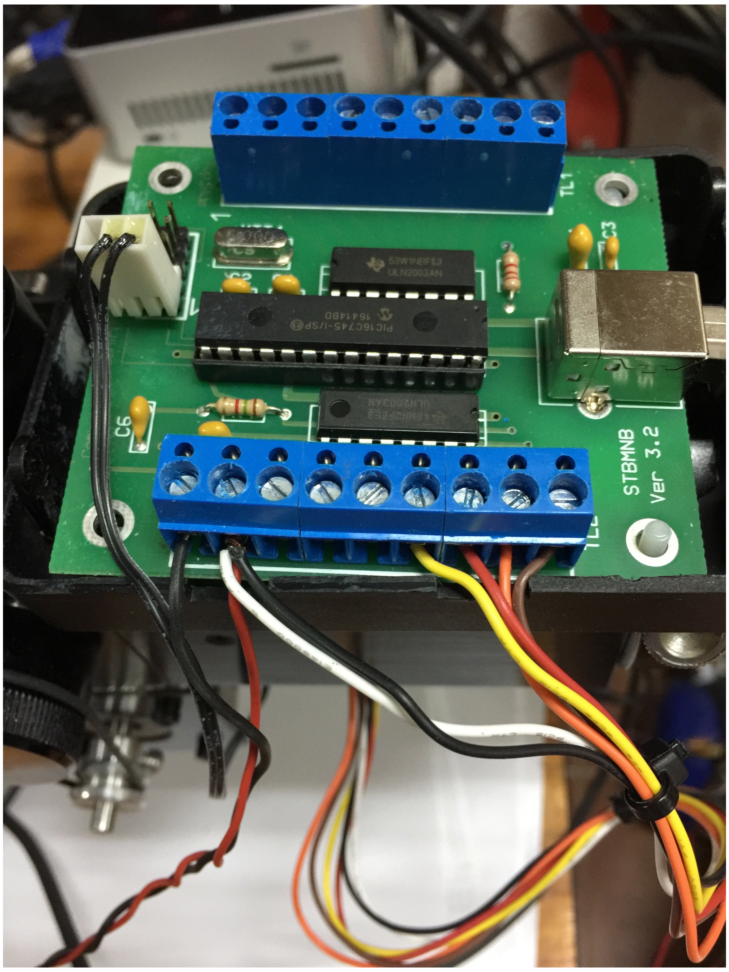
Checking the photometer elements

All elements of the photometer are controlled via USB. The following is a functional connection diagram:



Electronics

The stepper motors are controlled via an electronic Stepper Bee board (https://www.pc-control.co.uk/stepperbee_info.htm) which allows two stepper motors to be connected, has digital inputs for connecting the limit switches and can be controlled via USB. The picture shows the plate with the connections.



The plate is housed in a commercial plastic box that has been modified so that it rests correctly on the upper part of the body of the SSP-3 (oval opening and hole shown in the image on the right of the photo) and has a cable outlet. Plastic hexagonal turrets have been attached to fix the plate to the box.

One of the advantages of this control board is that it is supplied by the manufacturer with a DLL that allows it to be used to develop the control software for the operations associated with the motors: mirror rotation and filter selection.

Counting photons

Once we have the photometer mounted, we will give a physical sense to the measurements, and for them we ask ourselves:

1. How many photons per second pass through the telescope aperture from a star of a given magnitude?

2. How many of the photons passing through the aperture are actually detected by the photometer?

To answer the first question, we will consider that we are using a photometric filter V in the photometer.

According to the Johnson-Morgan-Cousins filter system, the number of photons emitted by a star of magnitude V=0 is:

10^8 per second, square meter and nanometer

Starting from the relationship between magnitude and emitted flux for two stars of magnitude m1 and m2, with fluxes F1 and F2 respectively:

$m1 - m2 = -2.5 * \log (F1/F2)$

or the equivalent expression in number of photons emitted:

$m1 - m2 = -2.5 * \log (N1/N2)$

We consider the star 1 the one that is measuring you and the star 2 the one of magnitude V=0 of which we know the emitted flux or its equivalent in number of photons:

$m - 0 = -2.5 * \log(N/10^8)$

From where $N = 10^8 * 10^{(m/-2.5)}$ in s^{-1} m^{-2} nm^{-1}

Then total N for a radio telescope R of aperture will give us:

$N = PI*R^2*86*QE*10^{(8-m/2.5)}$ (1)

Being:
- PI the pi constant
- R the diameter in meters of the telescope aperture. In my case, a C11, taking into account the central obstruction of the secondary mirror R is 0.0925 m.
- 86 in nm band pass for filter V
- QE is the quantum efficiency of the entire optical system, including the telescope, together with the detector.
- m the magnitude of the star

This expression allows us to empirically calculate the optical efficiency of the system from the measurement of a star of known magnitude. To do this we will choose a star with a magnitude similar in V to B and we will measure it when it is in a position close to the zenith. To the resulting value we will subtract the measurement of the bottom of the sky without a star. If the star is not at the zenith, it will be necessary to make an adjustment according to the air mass of its position at the time of measurement (this will be explained in detail later).

$QE=N/(PI*R^2*86*10^{(8-(m+C)/2,5)}$

Where C has been added as atmospheric factor correction according to the "air mass" at the time of measurement.

For example, for a star of magnitude V=4.8, we obtain a photon net count (star measurement minus sky bottom measurement) of 197685 photons per second.

We apply the formula and we get:

QE=197685/(3.1416*0.0925^2*86*10^(8-(4.81+0.2556)/2.5)=0.0908

The value of 0.2556 is the value calculated (see below for how) to correct atmospheric extinction. It should be noted here that a star with magnitude V similar to magnitude B has been selected for the measurements in order to simplify the necessary corrections, given that in addition to making the correction for atmospheric extinction it is necessary to make the correction for color, due to the different sensitivity of the detector depending on the wavelength.

The obtained value is of an efficiency of approximately 9%, that is, the telescope and photometer set including the photomultiplier detects 9 out of every 100 photons that pass through the telescope aperture. If we repeat the calculation for filter B we will obtain a value slightly higher than triple, given the higher efficiency of the bialkali detector for filter B frequency.

Having this data is important because we can use it for the inverse process, that is, we can calculate the magnitude of a star from the number of photons we detect.

To do this, clear m from the formula (1) and obtain:

m=2.5*(8-log(N)/(QE*PI*R^2*86) (2)

This formula will give us a value m of the measured magnitude (instrumental magnitude) and we will need to adjust it to its correct magnitude according to parameters such as atmospheric extinction and the spectral color of the star.

In practice, this calculated magnitude will not be used as a correct measure of the magnitude, but it will help us to have a very approximate value and make decisions in the automated process, for example if we detect that there is an excessive difference between the measured value and the expected value.

The technique to be used for accurate measurement is differential photometry as explained below.

Limits of magnitude

Now that we can relate magnitude to the photon count, we can set the magnitude limits of the stars we can measure.

For bright stars, the value to be taken into account is the maximum count allowed by the photometer in a single reading, which according to the photometer manual is 6.7108.863. According to the formula of the previous section, a star of magnitude 0 for example would give us a count of about 17.000.000 photons per second, which implies that we would have to accumulate photons count at most in an interval of about 4s. As will be explained in the next section, the readings are taken by accumulating 2s intervals so there is no limitation for very bright stars. This is an important advantage over CCD photometry, where there are saturation problems.

For weak stars, the limit is in the quantum efficiency of the system that will determine the number of photons received and in the signal-to-noise ratio, which will depend on the accumulation time of the measurement and the quality of the sky. For example, with a magnitude 13 star we would receive about 100 photons per second and with a magnitude 11 star we would receive about 800 per second. I've run tests with magnitude 11 and the result is good in clear skies.

With stars weaker than magnitude 11, it is possible to make astrometric measurements, such as occultation's, but it is difficult to obtain precise values of photometric measurements due to the low signal-to-noise ratio we will obtain.

In short, with this equipment we can measure from stars of magnitude 0 to stars of magnitude 11, reaching this limit with very dark skies.

Measuring the sky bottom

As mentioned above, measurements with the photometer require measuring the star and then measuring the bottom of the sky in the star area, so that the result of the star's luminosity will be the net value resulting from subtracting both measurements.

In practice, the measurement of the sky bottom is done by moving the telescope to an area close to the star of which we are measuring where there are no stars or they are very weak so that they do not affect the measurement (for example magnitude>16).

This measurement of the sky bottom is essential to obtain the correct measurement of the star, but also the number of photons received will indicate the quality of the sky, at least in those that refer to darkness.

The level of darkness can be measured in magnitude per arc of a second squared and is a data that we can calculate from the received photons, since we can convert the number of photons into magnitude, and we can calculate the area of the field of view determined by the aperture mask of the diaphragm.

As explained above, the angular diameter of the field of view for a 3135mm focal length and a 1mm aperture mask is 65 seconds of arcs.

We first calculate the magnitude based on the photons received per second of arc squared, i.e. we apply the formula of photon to magnitude conversion, but previously divide the number of photons by the area in seconds of arc squared: pi*(65/2)^2.

For example, if measuring the sky background, we receive 1500 photons, the result will be 19.18 mag/arcosec^2. It is a result compatible with the levels of light pollution in the urban area in which the observatory is located.

In practice, the values measured at my observatory in Majadahonda (Madrid) range from about 1500 photons/s on a dark night (19.18 mag/arcosec^2), to about 5000 photons/s on a full moon night (17.87 mag/arcsec^2).

How long to measure

The number of photons received per second is proportional to the brightness of the star. If for a given star we receive, for example 100.000 photons in one second, it would seem reasonable to think that there is no reason to measure more than one second or even that a measurement for a fraction of a second would be sufficient. However, this is not the case and here we will explain the reasons and the criteria to carry out an accumulation of photons received during a certain time interval in order to carry out a correct measurement.

The underlying reason why we must perform the measurement by accumulating photons received over a period of time is related to the accuracy of the measurement.

In terrestrial photometry, an excellent objective is to achieve an error in terms of magnitude of +-0.001, which is equivalent to an accuracy of 1 per 1000 in the photon count.

Let us see that we can indeed refer indistinctly to uncertainty in the magnitude or in the number of photons measured. For example, where n is the number of photons received with an uncertainty of 1 per 1000:

Uncertainty of m = -2.5*log((n+-n/1000)/n) = -2.5*log(1+-1/1000) =+- 0.001

In practice, and with an amateur equipment, achieving an uncertainty in the magnitude of 0.001 is a really good data, and in practice I have been able to verify that with the equipment and techniques described in this document we can obtain precisions between 0.003 and 0.001, and in some cases better than 0.001.

When we talk about the error due to the dispersion of the data, we are referring to the standard error, that is, the standard deviation of the mean.

The main causes of scattering in the photon count to be considered are two:

- The Possion noise, which is proportional to the square root of the number of events, i.e. the number of photons counted. To get a noise of 0.001, we need to count at least 10^6 photons:

For 10^6 photons we estimate a noise of square root of 10^6 = 10^3 which gives us an estimated error of 10^3/10^6 = 0.001

The way to accumulate the sufficient number of photons so that the error due to the Poisson distribution is within the value we want is to measure for a sufficient interval of time.

For example, if our star is of magnitude 5, we will receive with my equipment about 200.000 photons per second, so we will need 5 seconds of integration for an indetermination of 0.001 magnitudes as far as Poisson is concerned.

If the star is very bright, the Poisson distribution will not have much bearing on the accuracy of the measurement, but if the star is weak, we will have to take it into account.

In my case, I usually do 40s integrations. To get a Poisson error of 0.001 I need to accumulate N photons so that sqr(N)/N=0.001, so N=10^6 in the 40s, which means receiving 25000 photons per second. According to formula (1) this is true for a star of magnitude 7 or less. To measure stars weaker than magnitude 7, you should increase the integration time based on this criterion.

- The next aspect to keep in mind is scintillation. The standard deviation due to scintillation depends on the diameter of the telescope, the air mass, the wavelength, and the integration time.

  The diameter of the telescope is fixed, the wavelength will be determined by the filter and therefore the factors we will have to look at are:

  - Air mass: whenever possible, we will try to take measurements when the star is as close to the zenith as possible. In my case, I set a lower limit, so I don't take measurements below 30º of altitude.
  - Integration period. The longer we accumulate the incident photon count, the less impact the error will have due to scintillation.

  Suppose we are measuring a star bright enough that we do not need to consider Poisson's error. The next aspect is to calculate the integration period so that the scintillation keeps the expected theoretical error below the desired 0.001.

  The dependence of the integration time on the standard deviation due to scintillation is on the form:

  S=beta/sqr(t), where in beta we reflect the impact of the other factors that we are not going to consider here.

  In the case of the photometer described in this document, the typical value obtained from standard deviation in a night with dark skies for 2s integration is 0.005. Applying the formula, we get a beta of 0.007. From this data, what integration time is required for a standard deviation of 0.001?

t=(beta/S)^2=(0.007/0.001)^2=50s

In fact, the value I usually use is 40s of integration and in terms of magnitude uncertainty we can consider approximately +-0.001 magnitudes, which is fair value for the limits of an amateur observatory.

It should be noted that the error or uncertainty introduced by scintillation does not depend on the number of photons received and is therefore independent of the magnitude of the star. Once an integration period of 40s has been established according to the scintillation noise criterion, what is the magnitude limit to maintain the 0.001 uncertainty due to Poisson's statistical error?

sqr(N)/N=0.001 implies counting N=10^6 photons in 40s, which means 25000 photons per second, which corresponds with my equipment to a star of approximately magnitude 7.

As conclusions applicable to my equipment:

- For stars brighter than magnitude 7 and an integration period of 40s, both scintillation and Poisson noise are in a theoretical range of +-0.001 magnitudes.
- For stars weaker than magnitude 7 and an integration period of 40s, the scintillation noise remains at +-0.001 but the Poisson noise is higher and will increase the integration time.

These are the theoretical considerations, and in practice, the error of the measurements in these conditions (40s of integration, stars of magnitude 7 or brighter, at an altitude >60º, a clear night and with little moon) varies between 0.001 and 0.003 depending on the quality of the sky.

Error estimation

Undoubtedly, the measures we take are not perfect and if the process is not perfect, systematic and statistical mistakes will be made. But to be able to use the measures obtained, it is necessary to have an estimate of the error of the same.

As a measure of the error, we use the standard error calculated as the standard deviation of the mean as follows:

For a sample of n measurements, we calculate at standard deviation:

$$\sigma = \sqrt[2]{\frac{\sum_{i=1}^{n}(v_i - v_{mean)}}{n-1}}$$

where v_i is each measured value and v_{mean} the mean of the sample values.

From the standard deviation, we calculate the standard error:

$$SE = \frac{\sigma}{\sqrt[2]{n}}$$

In practice, how can we calculate this error? We can employ two strategies:

1. We group the values obtained in small groups and use for our study or data report the average value of each group associating an error calculated for the series.

   For example, considering groups of 3 measures:

$$V = \frac{1}{3} * (v_1 + v_2 + v_3)$$

$$SE_V = \sigma/\sqrt{3}$$

   The drawback of this way of operating is that we may be losing some of the information in the series. If the variable star has a long period of time, this will not be important, but if the star has a very short period of time, it should be borne in mind that the three averages will take several minutes (in the order of 4 per measurement with a single filter and 7 with two filters), which may affect the resolution of the series when calculating the period, for example.

2. In this second method we will calculate the standard error of an individual measurement. It may seem that this is not possible as we need a series to calculate the standard deviation. But it is possible thanks to a peculiarity of the photomultiplier software, which is that we can obtain the account data of photons subdivided into intervals. If we make integrations of 40s, we can have the total of received photons broken down into 20 sub measures of 2s.

In this way, we have a series and can calculate the standard error of an individual measurement such as:

$$SE = \sigma \; of \; measuremet \; of \; 2s/\sqrt{20}$$

With this technique, we can associate to each measurement an estimated error without the need to average measurements as in method 1 and lose resolution when we need it.

Reduction of measures

By measurement reduction we mean the processing required to obtain the correct magnitude data from the measurement of photons received during the integration period.

In the case of CCD the reduction requires extracting information from the photograph, while in the case of photometry with photometer, we directly obtain a value (photons in the case of photometer with photomultiplier) on which we have to perform certain operations.

The fundamental operations are:

- From the measurement of the number of photons received (n) of the star to be measured, calculate magnitude with the formula explained above using the formula m=-2.5*log(n*factor). The factor, as explained above, is obtained from the effective aperture, the filter band pass and the quantum efficiency of the instrument. Keep in mind that we are including the factor within the logarithm to give it a physical sense, but it can also be considered as a constant (called an instrumental constant) that can be obtained empirically:

  m instrumental=-2.5*log(n*factor)=-2.5*log(n)+Ci

(we indicate m instrumental because we have not yet obtained the magnitude of the star because some corrections have to be applied that are explained below)

- However, the correct value of n is not the photons in the star measurement, but we have to subtract the photons received by the background of the sky around the star. To do this, we focus on an area near the measuring star in which there are no stars in the field of view determined by the aperture mask or at least they are much smaller than the magnitude of the measuring star. The value of the instrumental magnitude is therefore

  m instrumental=-2.5*log((nstar-nsky) *factor)

- To convert the instrumental magnitude into the correct star magnitude, corrections are necessary for the following aspects:

  o The first is atmospheric extinction. Each measurement is made with the star at a different height in the sky, and therefore the light has to pass through a different amount of atmosphere that will produce an absorption. The extinction depends on the filter used, the amount of atmosphere that the light passes through (determined by the "air mass" parameter) and the behavior of the instrument itself (observatory, telescope, photometer). The way of calculating this impact is empirical as explained in the following sections and will determine the value of a coefficient that we will call the extinction coefficient that multiplied by the value of "air mass" will give us the correction in magnitude. The value of this parameter will have to be calculated for each filter we use.

  o The second is color correction. Since our instrument does not behave the same for each wavelength, a correction must be made to compensate for the different sensitivity depending on the colour of the star. The way this impact is calculated is also empirical and is explained in later sections. The value obtained is called epsilon which multiplied by the value of B-V (difference between the magnitude B and V of the star) will give us the correction in magnitude by color.

The formula we will use for the magnitude with the V filter is:

$$V = v - k'_v * X + \varepsilon_v * (B - V)$$

where v is the instrumental magnitude, k'_v is the first-order extinction coefficient for the filter V, X is the value of air mass, ε_v is the colour transformation coefficient for the filter V and B-V is the difference between the magnitude B and V of the star.

The formula for filter B:

$$B = b - k'_B * X - k''_B * X * (B - V) + \varepsilon_B * (B - V)$$

where b is the instrumental magnitude for the filter B, X is the value of air mass, k'_B is the first-order extinction coefficient for filter B, k''_B is the second order extinction coefficient for filter B, ε_B is the colour transformation coefficient for filter B, and B-V is the difference between the star magnitude B and V.

The following sections show how to obtain the following values for the filter V k'_v y ε_v. Similarly, they are obtained for filter B.

Calculation of $\boldsymbol{k'_v}$ and $\boldsymbol{k'_b}$

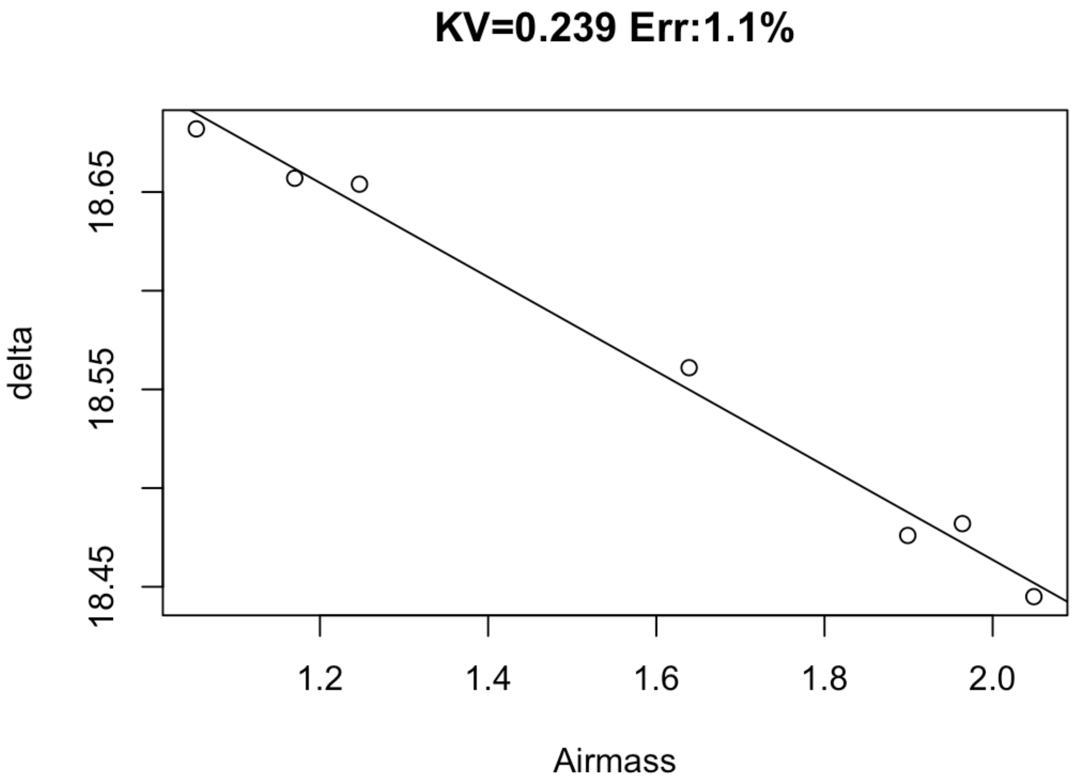
For obtaining k'_v we'll use an empirical method. We will use the "Northern First-Order Extintion Stars" catalogue in table A.1 of the book "Astronomical Photometry" by Henden & Kaitchuck. We will use photometric data from measurements of magnitude V for the list of such stars. They are stars with very small B-V values and are therefore suitable for not requiring colour transformation.

The procedure consists of measuring V for a series of stars in the catalogue and calculating for each measurement the difference between the V measured and the V measured in the catalogue, we will call this difference DeltaV. For this calculation, we will use the instrumental magnitude without any correction. Once we have these values, we represent in a graph on the Y axis the values of DeltaV and on the X axis the values of "air mass" at the moment of measurement and we calculate the line that best approximates the points of the graph using the technique of least squares: the slope of this line will give us the value we are looking for in k.

In the implementation of this procedure I have developed a script with the following methodology:

- Scroll through the list of all the stars in the catalogue to select the one that currently has an air mass close to 1.
- The V measurement is made by integrating for 40s.
- Search for the next star with an air mass greater than the previous measurement plus a small increment (for example 0.05) and repeat the process as many times as desired, for example 10 times.
- Using the data found, DeltaV is calculated for each measurement and finally the slope of the line that best approximates the points (DeltaV, Air Mass) is calculated.

For measurements, consider a clear night and analyze the deviation of the values obtained from the line that best fits. I have considered a value of 0.239 with a low error, as shown in the graph below:



For filter B the procedure is identical, obtaining a value of 0.364.

Calculation of $\boldsymbol{\varepsilon_v}$ and $\boldsymbol{\varepsilon_b}$

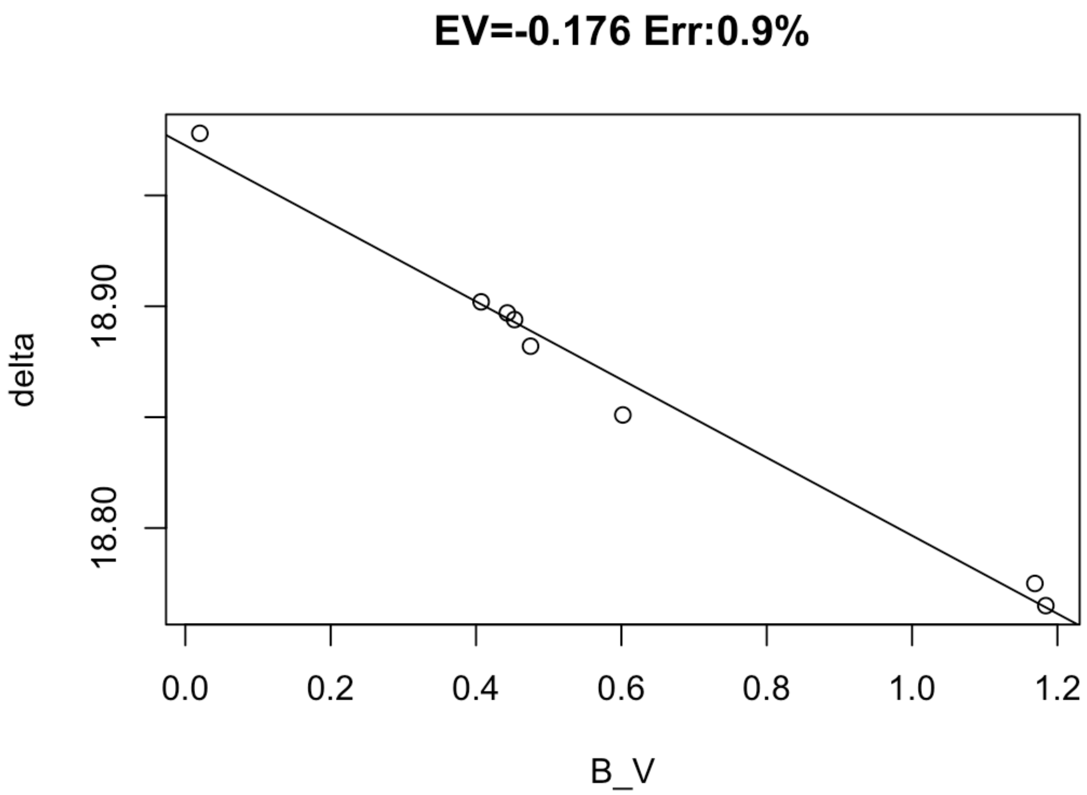
For obtaining ε_v we'll use an empirical method. We will use a standard catalogue of photometric values, specifically the one compiled by Brian Skiff and mentioned in the aavso.org PEP observation manual. In this catalogue we have a list of bright stars up to magnitude 7 with precise data of photometric values, from which we will use to calculate epsilon the values of V and B-V.

The procedure consists of measuring V for a series of stars in the catalogue and calculating for each measurement the difference between the V measured and the V measured in the catalogue, we will call this difference DeltaV. For this calculation, we will apply to the instrumental magnitude only the extinction correction. Once we have these values, we represent in a graph on the Y axis the values of DeltaV and on the X axis the values of B-V extracted from the catalogue and we calculate the line that best approximates the points of the graph by means of the technique of minimum squares: the slope of this line will give us the searched value of epsilon.

In the implementation of this procedure I have developed a script with the following methodology:

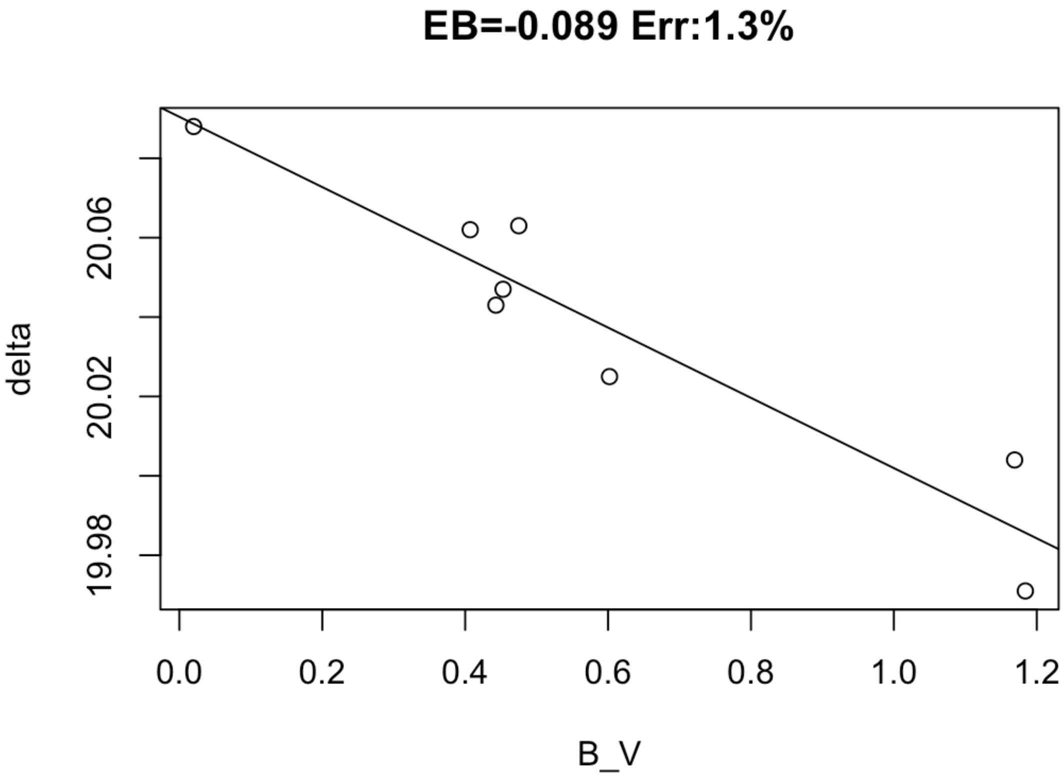
- The list of all the stars in the catalogue is scrolled through to select the one with the highest height at the start of the measurements.
- The V measurement is made by integrating for 40s.
- Search for the star closest to the previous measurement and repeat the process as many times as desired, for example 10 times.
- Using the data found, DeltaV is calculated for each measurement and finally the slope of the line that best approximates the points (DeltaV, B-V) is calculated.

The measurements made by this method give a value of -0.176 as shown in the following graph:



This is about three times higher than expected for a photometer like the SSP-3, but the fact is that the Bialkali detector photometer has an efficiency curve in relation to the narrowest wavelength and is much more inefficient at low frequencies (red), especially at 600nm and above.

Performing the same procedure for filter B gives a value of -0.089, as shown in the following graph:



Differential photometry

In the previous section, we have explained how we can obtain a magnitude value of a star by measuring the received photons focusing on the star, minus the photons received from the background of the sky and applying a formula that converts flow into magnitude along with the appropriate corrections depending on the instrument, the air mass of the star at the time of measurement and the color of the star. With this procedure, we obtain a value that we can call absolute magnitude.

However, the absolute magnitude is far from being a precise value due to factors such as the variation in the sky quality from one night to the next and during the night itself.

In very dark sky nights, the absolute magnitude values calculated as explained above do not differ by less than 1% from the expected value, but even this is not a sufficiently precise value to be used to measure small variations of magnitude. Our goal is to be able to measure variations in the order of 0.001 magnitudes and this requires much more precision.

In order to obtain accuracies of the order of milli-magnitude, we use differential photometry, which basically consists of measuring the star under study and a comparison star of which we know its magnitude consecutively. The comparison star should be close to the star we are measuring and have a similar magnitude and color.

The formula that we will use in differential photometry for measurements only with the V filter will be:

$$\Delta v_i = -2.5 * log10\left(\frac{count_{star(v)} - count_{sky(v)}}{count_{comp(v)} - count_{sky(v)}}\right)$$

$$\Delta v_{i0} = \Delta v_i - k'_v * \Delta X$$

$$\Delta(B - V) = Star_{B-V} - Comp_{B-V}$$

$$\Delta v = \Delta v_{i0} + \mathcal{E}_v * \Delta(B - V)$$

$$V = V_{comp} + \Delta v$$

Where Δv_i is the increase in instrumental v, Δv_{i0} is the increase of instrumental v corrected with the airmass variation between the star and the comparison.

In this case, since we only use a V filter, the following value is taken as the value

$\Delta(B-V)$ the difference B-V between the star to be measured and the comparison star according to the catalogue.

Since our parameters k_v' y ε_v are not accurate, to minimize the error of the corrections, we will try to make them ΔX is as small as possible (i.e. the stars are a little different, preferably less than a 1º) and we will try to ensure that $\Delta(B-V)$ is also as small as possible, i.e. that they are stars with similar colors.

When the measurements are made with V and B filters, we will apply these formulas:

$$\Delta v_i = -2.5 * log10(\frac{count_{star(v)} - count_{sky(v)}}{count_{comp(v)} - count_{sky(v)}})$$
$$\Delta v_{i0} = \Delta v_i - k'_v * \Delta X$$
$$\Delta b_i = -2.5 * log10(\frac{count_{star(b)} - count_{sky(b)}}{count_{comp(b)} - count_{sky(b)}})$$
$$\Delta b_{io} = \Delta b_i - k'_b * \Delta X$$

$$\mu = 1/(1 + \varepsilon_v - \varepsilon_b)$$

$$\Delta(B-V) = \mu * (\Delta b_{io} - \Delta v_{i0})$$

$$\Delta v = \Delta v_{io} + \varepsilon_v * \Delta(B-V)$$

$$V = Vcomp + \Delta v$$

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

Where Δv_i y Δb_i are the increase of instrumental v and b, Δv_{i0} y Δb_{io} are the instrumental v and b increments corrected by the airmass variation between the star to be measured and the comparison star.

In this case it is calculated $\Delta(B-V)$. We will use this method with both filters especially when $\Delta(B-V)$ is not known for example because it is variable.

Either with one or two filters, the measurements will be made with the following sequence:

$C_1V_1C_2V_2C_3V_{3\ldots}$

and group the stockings three by three as follows:

First measure: $C_1V_1C_2$
Second measure: $C_2V_2C_3$
Third measure: $C_3V_3C_4$

And so on and so forth. If we use both filters, for both the variable and the comparison star, we will make 2 measurements, one with each filter, resulting in a sequence of the type:

$C_{1vb}V_{1vb}C_{2vb}V_{2vb}C_{3vb}V_{3vb\ldots}$

It is being omitted to simplify the measurement of the sky, which must always be done after each measurement.

For a threesome $C_nV_nC_{n+1}$ we will use as the star's photon count value the measurement V_n but as the photon count value of the comparison star the average of C_n y C_{n+1}.

Two methods were described in the section on error estimation. Method 1 consists of calculating the standard error by grouping the measurements for example by three and this method is still valid for differential photometry where we will use for the mean and standard deviation the values resulting from the previous formula.

But method 2 gave us the standard error of the measurement of each star, not of the operation we do in differential photometry by subtracting the value of the previous and next comparison star from the measurement. In this case, if we start from the individual standard errors, we can calculate the standard error of the differential measurement as:

$$SE = \sqrt{SE_V^2 + SE_{C1}^2/2 + SE_{c2}^2/2}$$

Measurement automation

The instrument described in this document has two stepper motors:

- One for the rotation of the mirror that allows the light captured by the telescope to be directed towards the photometer or a camera.
- Other for filter selection V or B.

The camera's main mission is to allow the automation of the star centering process to ensure that all the captured light passes through the aperture mask.

As explained in previous sections, the optimal use of the photometer requires a long focal length, more than 3000mm in my case, in order to minimize the light captured from the sky bottom and improve the accuracy of the measurements. But such a long focal length imposes a limitation and that is that aiming at the star is more complicated and requires a solid mount, of course equatorial, and a good setting in season. The camera mounted on the instrument is not suitable for aiming, as the field of view with such a large focal is very small, and for this reason a new camera has been installed in conjunction with a smaller focal tube, specifically 500mm, mounted on a piggyback on the C11.

In short, for the automation process we have the following elements:

- Equatorial mount EQ8
- 500mm focal tube with Starlight Xpress Lodestar X2 camera for aiming.
- C11 tube to which the photometer is attached to the primary photo
- Starlight Xpress Lodestar X2 camera attached to the photometer for star centering when the mirror of the photometer is at 45º.
- Photomultiplier attached to the photometer for measurement when the mirror is at 0º.

The set of elements is controlled by a script that will work under the ACP DC3 application and will do the following operations:

- **Precise pointing**: the first process is the pointing and for this the telescope is moved to the RA and DEC coordinates of the star to be measured and a photo is taken with the pointing camera (camera attached to the piggiback tube). With the obtained photo and the PinPoint tool, the position is resolved astrometrically and the telescope is moved to the correct position.
- **Turning the mirror to the centering camera position**: The mirror is rotated to the position that transfers light to the camera. This position is determined by reading a digital input connected to a limit switch.
- **Star centering**: A picture is taken with the aiming camera (camera attached to the photometer). The X,Y position of the brightest star in the field of view is calculated and X,Y is converted to displacement in RA and DEC. The telescope is moved until the star is centered, i.e. with a shift to the center of the telescope of less than a certain number of pixels (in my case 20). This is an iterative process.
- **Turning the mirror to the photomultiplier position**: the mirror is rotated until it reaches the position that allows all the light to pass towards the photomultiplier. This position is determined by reading a digital input connected to a limit switch.
- **Measurement of photons received from the star**: integration is performed by measuring accumulated photons in sub periods of 2s. This way of working allows us to calculate the standard deviation in real time and to interrupt the integration if it is excessive. The standard deviation takes very large values if for example the telescope is moved by a gust of wind and the star is deflected or if a cloud is passing by. In these cases the criterion adopted is to redo the integration after 30s.
- **Measurement of photons received from the sky surrounding the star**: without moving the mirror, the telescope is moved to an area near the star in which there are no stars with a brightness higher than magnitude 15, for

example, and the integration of the photon count is performed for a period equal to half that used to measure the star.

These steps must be carried out with both the variable star and the comparison star, and when working with several filters the steps are duplicated filter by filter.

For each measurement, the data from:

- Photons received from each star (for both the star under study and the comparison star) for the V filter and for the B filter if it is being used, with the standard error measured.
- Photons received from the sky bottom with each star and filter. The calculated mag/arcseg^2 data is recorded.
- The above formulas for differential photometry are applied
- The Air mass is recorded at the time of measurements.

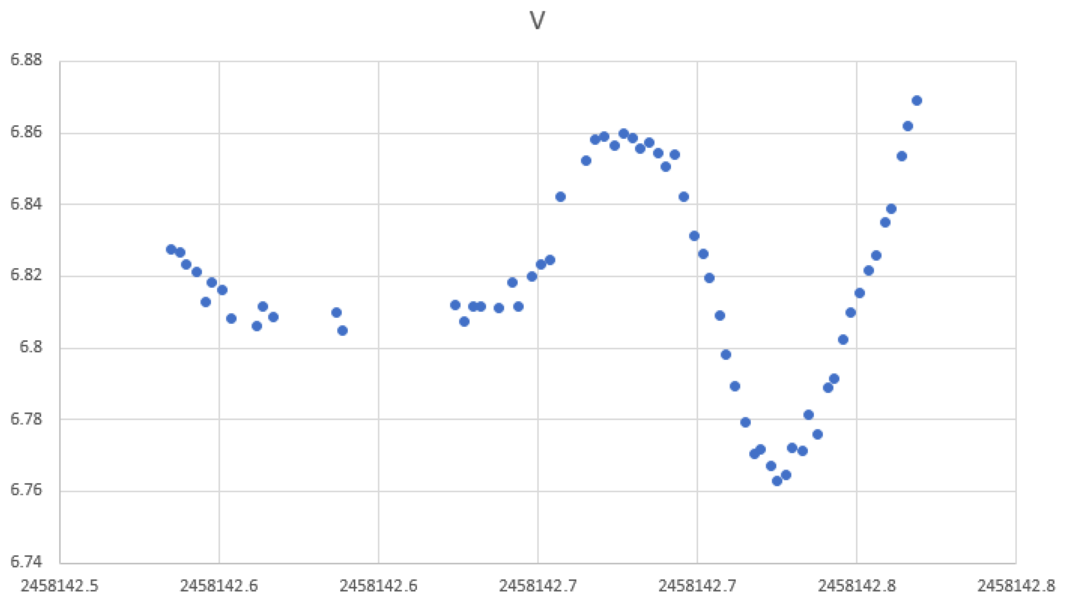
The resulting file is written as the night progresses, and already contains the reduced data, no further processing is required and this is an additional advantage of working with the photometer. As the measurements are already reduced, the data generated during the night can be represented graphically and if we are measuring a short period star we can see how the light curve is gradually shaped.

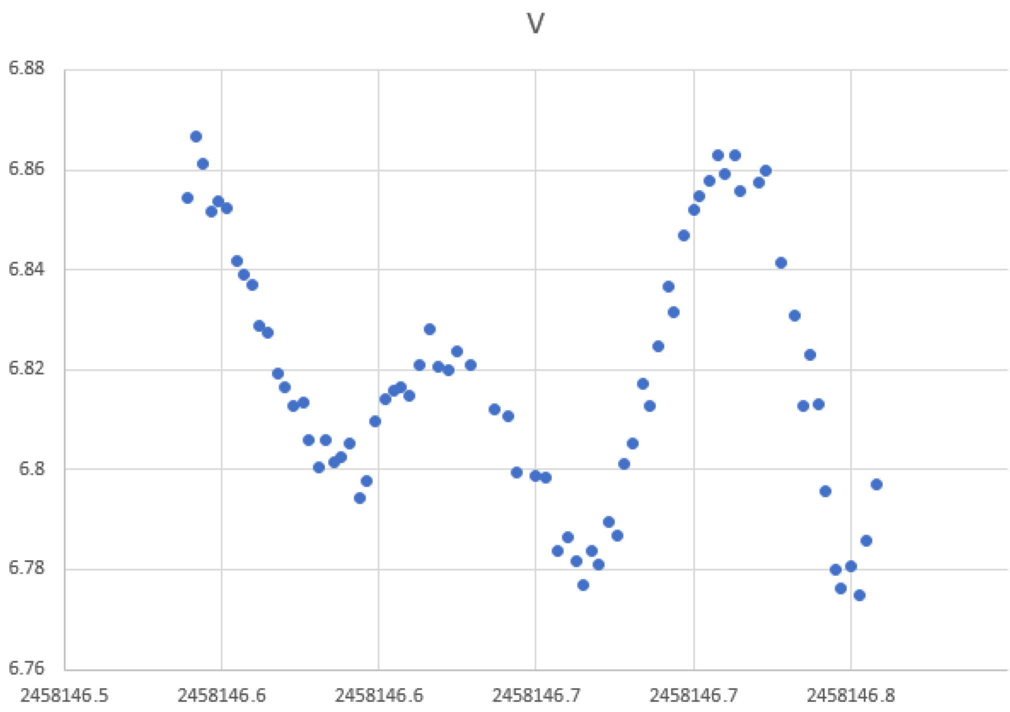
Results

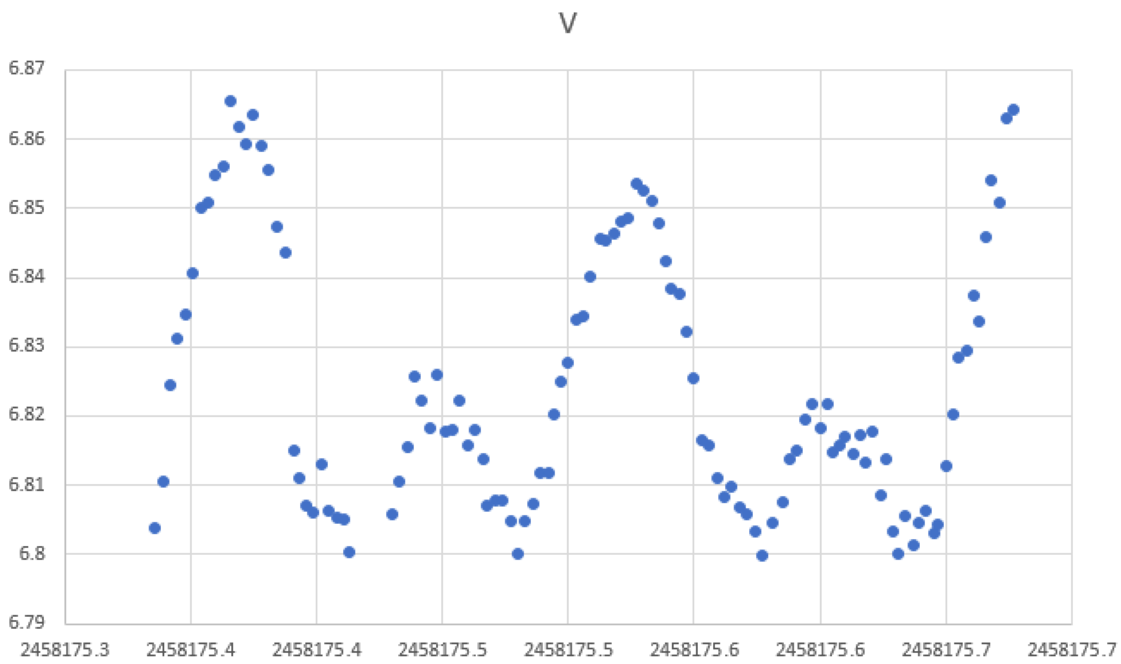
I am currently using the photometer to measure Delta Scuti bright stars.

The measurements are obtained with very acceptable uncertainty data considering that I use an 11" telescope and in urban environments: errors that vary depending on the quality of the night and the altitude of the star between 0.001 and 0.003 magnitudes, and in optimal conditions (stars near the zenith and excellent night) errors lower than 0.001.

The following is an example of the CO LYN star's curve of some nights, which seems to have a multi-periodic behavior:




V
6.88
6.86
6.84
6.82
6.8
6.78
6.76
2458146.5
2458146.6
2458146.6
2458146.7
2458146.7
2458146.8


V
6.87
6.86
6.85
6.84
6.83
6.82
6.81
6.8
6.79
2458175.3
2458175.4
2458175.4
2458175.5
2458175.5
2458175.6
2458175.6
2458175.7
2458175.7