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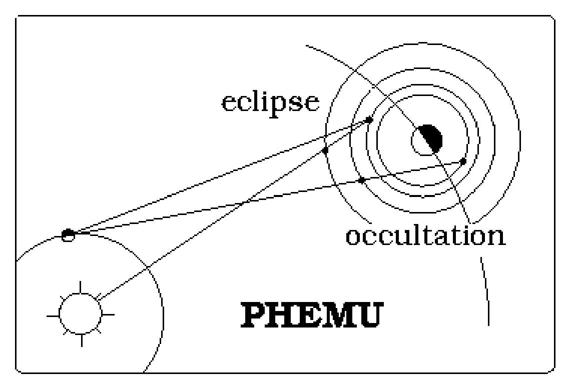

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THE OBSERVATION OF THE MUTUAL PHENOMENA WITH A CCD CAMERA

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1. Introduction

The CCD detector are more and more used in astronomy by the professionals as by the amateurs. The photometric applications being already classic, this note aims at explaining in detail the precautions to be taken to realize a good photometric calibration of a CCD camera. The observation of the mutual phenomena bring however, specific problems which we shall explore. We shall also see that the techniques of treatment of image allow to increase the number of observable phenomena by comparison to the photometric observations. One can so observe phenomena close to the limb of Jupiter or during twilight. The first observations of mutual phenomena with cooled CCD cameras took place during the campaign PHEMU91 and showed all the interest of this type of observation (one will refer to the catalog PHEMU91 on the server of IMCCE to have examples of lightcurves obtained with CCD (http://www.imcce.fr).

2. Calibration of a CCD camera

<u>a) How a CCD detector works</u>

An elementary explanation of the functioning of a CCD detector is necessary in order to understand the purpose of calibrations. A CCD is a matrix of photoelements: by photoelectric effect, certain number of the incidental photons is transformed into electrons. In every element electrons are stored. When the integration is ended one moves electric charges to on the edges of the target of the CCD pixel by pixel. The packages of electric charges "went out" so one by one of the matrix. One measures then the tension of release of every pixel, which is proportional to the electric charges, i.e. to the light received by each pixel. An analogue to digital converter allows then to quantify this value.

<u>b) Photometric calibration</u>

The transformation of the light into electric charges is obviously the more delicate part of the acquisition.

Offset map:
The first problem is that all the electrons do not result necessarily from a transformation consecutive to the catch of an electron. Indeed the simple thermic excitement produces free electrons. It is so necessary to quantify this production which is variable from a pixel to another one because of the manufacturing defects. The most effective method consists in acquiring a series of poses realized in the same conditions of exposure time, temperature as in the recording, but in the total darkness. One puts here in evidence one of the crucial points of a good observation CCD which is the necessity of a good thermal regulation of the target. One can make the average of a dozen such images to decrease the effects of the noise of reading. The correction of the thermic noise is made then simply by removing this "offset map" from every acquired image. One will note that in the absence of any thermic electron, the CCD always produces an output signal different of zero. This variable value from a pixel to the other one is called the electronic offset.
Finally with this method, the map which one measures represents the sum the maps of thermic noise and electronic offset. One realizes so these two corrections at one time. Afterward we will speak only about offset map.

Flat Field:
The second problem is that the quantum return on every pixel is not constant. It is so necessary to have a map of sensibility of the detector. For that, it is necessary to enlighten the CCD with a calibrated light. If we suppose that the response of the target is linear (what is very close to the reality), an uniform light can be enough. One makes a map of sensibility of the matrix by making the average of a dozen images to decrease the problems connected to the noise of reading. For the correction of an image, one divides every pixel of the image by the corresponding pixel of the image of the Flat Field of uniform light (denoted FF in the following and PLU in french) and one multiplies by the mean value of its FF to preserve the dynamics. It is necessary to realize one FF for each used filter, furthermore as the conditions of observations change each night (temperature, dusts), it is necessary to realize one FF each night of observation.
The problems do not end here! Photons coming from the Galilean satellites passed through various optics which have convoluted the signal. The method most often used is to make FF for the whole system of acquisition; one needs then an uniform source in the infinity. It is not simple to realize! This problem is not yet suitably resolved today. The least bad is certainly to use the sky background during twilight by paying well attention to the problem of undesirable light. Some observers use a white screen placed inside the dome. Besides these problems, it is necessary to realize one FF for each filter and for each night of observation: the conditions of observation may vary from day to day (temperature, dusts...).

Method to be followed to calibrate a CCD camera:
In summary, here is the method of photometric reduction:
1: Realize a dozen images of the sky in the twilight. To have a sky background as constant as possible, it will be necessary to point the telescope contrary to the Sun and at an important height above the horizon. Indeed verify that no pixel is saturated and that the average level of the image is equal or superior in the middle of the dynamics of the detector.
2: Realize a dozen images in the same conditions of temperature and of time exposure but in the total darkness.
3: Calculate the Flat Field. For that, make the sum the thorough images of sky, then the average of the offset maps. Remove then from the sum of N FF, N time the average of the offsets.
4: Just after the observation of the phenomenon, make an offset map in the same conditions of recording as those of the observation (in particular in case of windows, keep the same windows for this map).
5: Finally for every image of the phenomenon it will be necessary to remove the offset map, to multiply by the mean value of the FF, then to divide this image by the FF (1).

$$\mathbf{I}\,(x,y) = (\, \mathbf{I}_{raw}(x,y) - \mathbf{I}_{offset}(x,y)\,)^{*}\, \mathbf{I}_{FFaverage} / \,\mathbf{I}_{FF}(x,y) \quad (1)$$

we will suppose that the response of the CCD detector is linear. In case of intensified cameras for which the gain function is unknown, it will be necessary to determine a reciprocity function as described in paragraph 4 of the Technical Note n°4.

3. Calculation of the light flux of an object

We shall suppose now that the radiometric corrections are realized, i.e. that the intensity of every pixel is proportional to the photonsreceived. It is now necessary to isolate satellites on the image and to calculate their light flux.

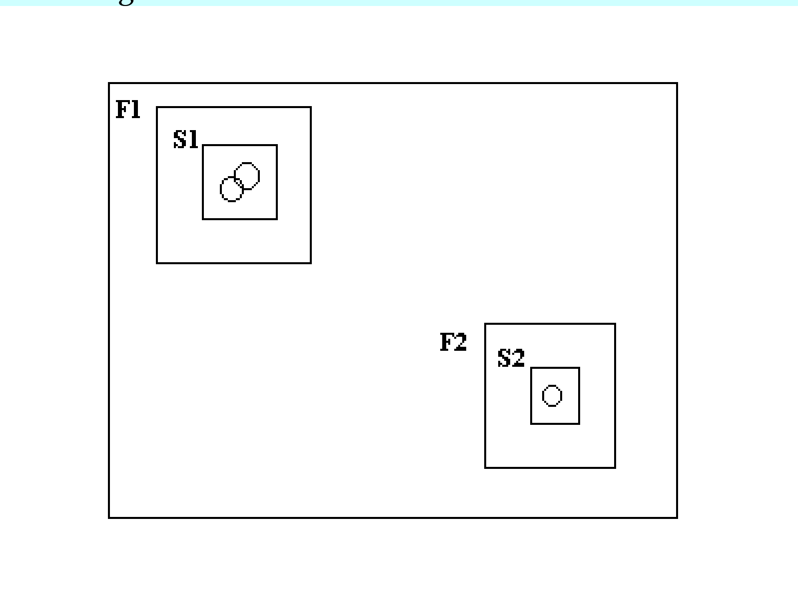
a) Simulation of the diaphragm of a photometre

When the sky background is uniform (that is for example if the satellites are far from the limb of Jupiter), the simplest is to simulate a photometre. It is enough so to calculate the sum pixels situated inside a window centred on a satellite (this window can be squared or circular). One will note S1 this sum and N1 the number of pixels. We will make the same calculation for a larger window. One will have then F1 and M1. We will calculate the sky background on the outer part of the second window (2). The light flux of the satellite is then calculated on the first window (3).

Calculation of the sky background: **Fond1 = (F1 - S1) / (M1 - N1)** **(2)**

Light flux of the satellite: **Flux1 = (S1 / N1) - Fond1** **(3)**

The only problem is to adjust the size of windows. It is not necessary to choose them too small because of the risk of losing a part of the object, nor too big what would add noise due to the too large part of sky. In practice it is necessary to make attempts, and to choose the combination which gives least variations onto the measures.



b) Use of a reference object for relative photometry

If a reference object is present in the field (generally another Galilean satellites, rarely a bright solar-type reference), we will calculate its light flux for each image. This flux is supposed to be a constant. If Flux2 is the light flux of the reference object S2, the light flux of the occulted or eclipsed satellite S1 will be:

Flux of satellite S1 = (Flux1 / Flux2) * FM2

where FM2 is the average flux of reference S2 , used in order to normalized the calculated flux of S1.

Then we obtain:

Flux of satellite S1 = ((S1/N1 - Fond1) / (S2/N2) - Fond2)) * FM2

This technique allows to observe events in difficult conditions: proximity of Jupiter (the background Fond1 and Fond2 may be very different), variation of the absorption or transit of light clouds (Flux1/Flux2 remains a constant), twilight (the sky background varies exponentially but is removed from each image). One will see the light curves corrected thanks to this method in paragraph 5. b) of the Technical Note n°6).

c) Adjustement of a gaussian curve

A second method consists in the adjustment of a mathematical profile of gaussian type (4). The total flux of the gaussian can be reckoned then simply (5).

$$\text{Gaussienne} \quad I(r) = I(0)\exp(-R^2/Â^2) \quad (4)$$

$$\text{Flux total} \quad \text{Flux} = Â^2\, I(0) \quad (5)$$

The function is fitted by a least-square method. However this method works well if the image of the satellite is big enough (width halfway up superior to 3 or 4 pixels). Furthermore if the images are good quality, as the visible diameter of satellites is not unimportant, the image of the satellite has necessarily no gaussian profile. This is particularly true for the image of two satellites in the course of a mutual occultation. This method, adapted well to stellar profiles is more complex and doubtless less successful than the simple photometric mleasurement of the total flux in a simulated diaphragm for the observation of the mutual phenomena.

4. Calculation of the light flux when the background sky is not uniform

It may occur that the sky background is not uniform. Indeed, the closeness of the limb of Jupiter, the figures of diffraction of the support of the secondary mirror or the twilight can perturb in a important way the uniformity of the sky background. The method of photometric measurement of the flux through a simulated diaphragm reaches here its limits. It is then necessary to adjust a mathematical surface on the sky background, then to remove it from the image to realize a synthetic flat background. As the photometric response of the CCD is linear, one can then use the previous methods. The adjusted surface is often a polynomial of degree 3. The observation of these "difficult" phenomena is certainly one of the big interests of the two-dimensional CCD observations.

5. Astrometry

For the occultations, one can also make an astrometric reduction to measure the relative positions of both satellites during the time when they approach one of the other one, and then when they go away. For this, it is necessary to observe for a long time before and after the phenomenon (45 minutes at least). Indeed, when satellites are very close, it is impossible to separate them. The cadence of acquisition can be reduced to 1 or 2 images per minute of time. To calculate the centre it is necessary to have a flat uniform sky background. So, as for the photometry to remove a synthetic background if needed. One can locate the satellite by taking into account only pixels above an equal level for example in the value of the background of sky more 4 - 5 times the standard deviation of the background noise. Once these pixels isolated, it is easy to calculate their centre of gravity or to adjust a gaussian surface.
The astrometric calibration is delicate. However the determination of the time of the minimum of distance between both satellites is possible without calibration. The minimum of distance can be calculated by adjusting the scale on the velocities of the satellites which are better known that the positions.
To have positions enough precise, the focal length the instrument should be at least 10 metres.

6. Method to be followed to observe the mutual phenomena

a) Dating the images

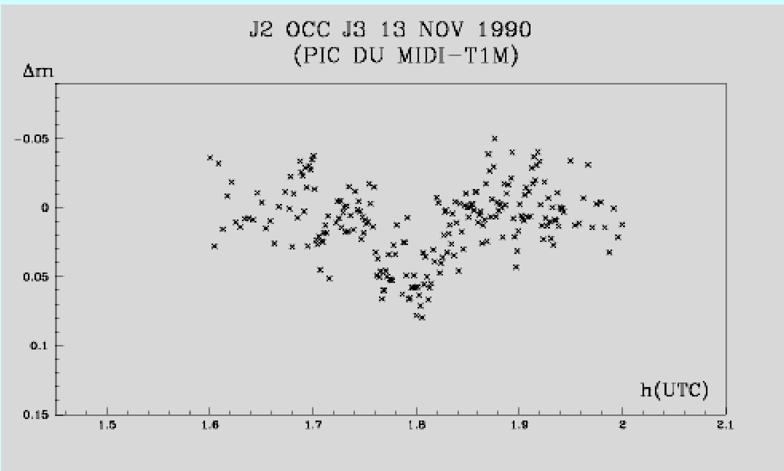
As for all the observations of phenomena, the knowledge of the time scale within an accuracy better than 0.1 second of time is necessary. Most of time, the internal clock of a computer is not confident. If using GPS time, be carful with the updating of your clock: no updating during the event! Just note the difference between your clock and the real UTC before and after the observation. If necessary, an interpolation will be made afterwards. Be sure also to know if the date of each image is the beginning or the end of the exposure. Note that the dtae of an image, is the date of the middle of the exposure.

b) Conditions of observation

It is important to have a large focal length (superior to 5 metres) so that the image of the satellite is distributed on several pixels. Indeed, there is between every pixels a not sensitive zone. If the image is too much concentrated, a large part of the light flux can be so lost in these zones. The change of position of the satellite from an image to the other one can then induce a strong noise in the flux. If one makes only of the photometry (and no astrometri by direct measurement of positions), it can be advantageous to put slightly out of focus the telescope.
The exposure time should be sufficient so that the flux is important. Indeed it is not enough to discover the satellite, it is necessary that the measure of the flux is most precise possible, so that the signal-to-noise ratio is important. The exposure time may be from several seconds if the phenomenon is not too short (more than 5 minutes). Attention also not to saturate the CCD. If one makes astrometric measures, a wide filter is interesting to decrease the chromatic aberrations. The CCD being usually sensitive in the red and the close infrared, a filter of type RG 695 Schott is adapted well. The global sensibility of the acquisition is only decreased by two.
To be able to compensate for the variations of transparency during the phenomenon, it is interesting to have a satellite not involved in the phenomenon on the image. It will then be necessary to apply a double window. The offset map and the Flat Field should be realized closer possible to the observation. The temperature of the CCD should be regulated as good as possible (in 0.1 °). In order to save the recording, one has the choice: either not to save the images (but by making measures of flux directly in real time) and to increase the speed of acquisition, or to save all the images and to make the reduction afterwards. As the exposure time will be usually superior to 1 second, the time for the saving of the image (about a tenth of second) is not dominating any more. The mutual phenomena being rare, it seems more careful to keep the images. On the other hand one can be limited by the size of the hard disk. It will be necessary to save then only a part of the image.

7. Interest and precision of the CCD observations CCD - Example

The observation of November 13, 1990 made with the telescope of 1 metre of the pic du Midi allows indeed to judge the precision of the photometric measures (cf. the catalog PHEMU91 on the server ftp://ftp.imcce.fr). We have used a filter RG 695 at the direct focus opened at F / 17. The phenomenon was of weak amplitude, however one can consider that the standard deviation of the measure is of the order of the hundredth of magnitude. The astrometric precision is of the order of the tenth of pixel by image.



8. Conclusion

One notices so that if the photometric calibrations is well done, the CCD observation is as precise as the photoelectric observations. This because an important part of the noise results from the sparkling of the sky. Numerous phenomena impossible to observe with a photometre become accessible with a CCD camera associated to a program of treatment of image. More, it is then possible to observe during daylight with infrared filters as filter I or K but a more powerful telescope is necessary.