

Photometric Accuracy of the Optical Monitor

Igor Antokhin (antokhin@astro.ulg.ac.be)

Institut d'Astrophysique et de Géophysique, Université de Liège

January 2001

Abstract

Various factors which may influence photometric accuracy of the data obtained with the Optical Monitor are analysed. It is shown that the most likely source of the photometric errors for the bright stars (brighter than $\sim 14^m$ in V) is the pixel-to-pixel sensitivity variations of the CCD not accounted for in the current reduction procedure. For the fainter stars the primary source of errors is the straylight features. Depending on the source brightness, they may influence the photometric magnitude even if they are so faint themselves that they cannot be detected visually.

1 Observational data

For the field EXO 0748-67 we have 5 exposures in the V filter in rev. 17, 37, 40, and 44 (2 exposures). This allows for the consistency check between the exposures. Namely, we can compare the typical standard deviations for various stellar magnitudes, obtained from a single frame, with the scatter of the magnitudes themselves from frame to frame. The comparison is shown in Fig.1.

The plot shows all stars in the field which were measured at least 4 times¹. Every star is represented by 2 dots: the filled and the open ones. The x-coordinate of both dots is the average magnitude of a given star over the frames in which it was measured. The filled dot represents the average value of the star's standard deviations obtained in these frames. I call these deviations "internal" errors as they are obtained from individual frames and are mainly determined by the poisson errors of the stellar and the background count rates. The open dot represents an estimate of the standard deviation based on the magnitudes of the star in different frames (I call it the "external" error):

$$\sigma^{ext} = \sum_{i=1}^n (mag_i - \langle mag \rangle)^2 / (n - 1)$$

It is important to note that in Fig.1 the internal errors are the errors of the RAW magnitudes while the external ones are calculated from the magnitudes CORRECTED for the coincidence loss (c.l.). One might think that the internal errors should be corrected to account for the error propagation while applying the c.l. correction formula. The reason why I did not do this for this plot, will become evident below. For now I just note that for the faint stars below say $\sim 15^m$ the difference is not important as their fluxes are in the linear part of the CCD dynamic range.

3 evident features (problems) can be readily seen in Fig.1:

1. For the bright stars ($< 14^m$), σ^{ext} is larger than 1% and clearly exceeds the error which would be expected from the poisson noise for these stars.
2. For the other stars, the scatter of the σ^{ext} values seems to be too large, even despite the fact that we usually have only 4 measurements per star.
3. The median of the open dots goes HIGHER than the median of the filled dots.

We need to understand the reasons for these features.

¹For most stars, there were 4 measurements: some fainter stars were not identified in all frames, some were rejected from some frames due to the severe straylight, in the rev. 44 one of Rudi-5 windows is absent etc...

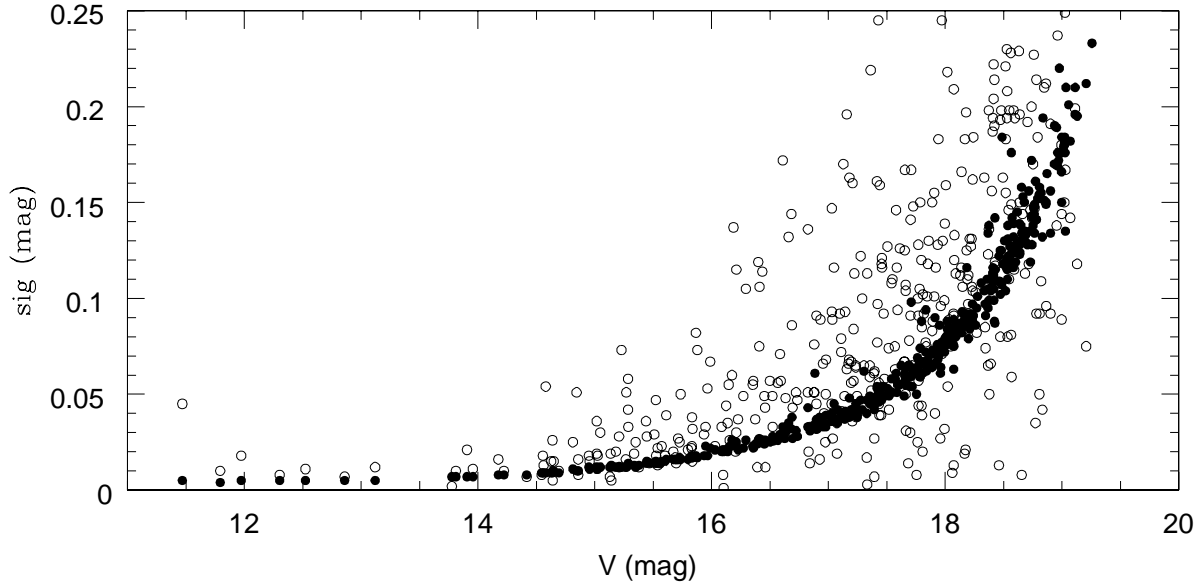


Figure 1: Observational data for the 5 V exposures of the EXO 0748-67 field. Filled dots: $\langle \sigma^{int} \rangle$, open dots: σ^{ext} .

2 Obvious potential explanations which could be checked from the analysis of the data themselves

2.1 Global change in the CCD sensitivity with time

This was the first possible explanation which came to my mind. Recall that the magnitudes used in the plot are the absolute magnitudes calculated according to

$$mag = -2.5 \lg flux + 18.1071, \quad (1)$$

where 18.1071 is the current zero point in the V filter and $flux$ is the stellar flux measured within the aperture with the radius $R=6''$. If the global sensitivity is changing with time, $flux$ may vary from frame to frame. To check this assumption I calculated the differential magnitudes choosing one star (the same in all frames) in every frame as a reference. With 2 different reference stars (of $12^m.5$ and 15^m) the results were identical to those shown in Fig.1.

2.2 Large-scale variability of the sensitivity over the CCD

This was suggested at the last Jan 2001 calibration meeting. Currently the flat field is assumed to be equal to 1 so if two frames are shifted relative to each other, this might cause the increased scatter in σ^{ext} .

To check this assumption I compared two frames obtained during the rev. 44. They have exactly the same positional angle and their relative shift is equal to only $1''.5$. However, for these 2 frames, the scatter in the magnitude differences also greatly exceeds the internal error. This rules out the large scale sensitivity variations as a potential explanation.

2.3 Mod8 fixed noise

This was also suggested at the last cal. meeting. The idea was that if i.e. the sky annulus is too narrow and includes a small number of pixels, the fixed noise might increase the error of the background, resulting in the increased error in the magnitudes of the faint stars.

However, the sky annulus used in the analysis, while being rather narrow (to avoid the straylight problem as much as possible), still covers about 100 pixels. The inner and outer radii of the sky annulus are $R_1=7$, $R_2=9$ pixels. Here and below I always refer 2x2 binned subpixels as “pixels”. The star aperture $R=6$ pix covers 113 pixels and apparently effectively averages the mod8 noise.

Nevertheless, to check this assumption, I measured the background and its error for different sky annuli with R_2 up to 20 pixels (corresponding to the area of 1102 pixels), in a straylight-free region of a frame. There was no decrease in the background standard deviation while using larger annuli.

3 Numerical simulations: the basic algorithm

At this point, I decided to write a program which would simulate the whole observing and data reduction process. The algorithm of the simulations was as follows:

1. Create the average fluxes of about 550 artificial “stars” ranging from $0.04 \text{ counts/s/aperture}^2$ to $500 \text{ counts/s/aperture}$, which corresponds to the magnitudes varying from $21^m.6$ to $11^m.4$. The individual average fluxes were distributed within this interval so as to approximately represent the magnitude distribution in the real data.
2. For every “star”, add the average background to its average flux, multiply the sum by the exposure time and generate 4 random poisson numbers with the above sum as the average. In the data I have, the background level is equal to $\sim 1.3 \div 2.0 \text{ counts/s/aperture}$ and is slightly changing across the field. This was accounted for, but is not really important. The exposure time T_{exp} was assumed to be equal to 1000 sec. Then, generate 4 random numbers for the background of a given star. This gives me 4 artificial frames containing the infalling count numbers for the set of stars and their backgrounds.
3. Assuming the constant framerate $FT = 0.01 \text{ s}$ and the dead fraction $DF = 0.02$, divide the above count numbers by T_{exp} to get the count rates and apply the inversion of the c.l. correction formula to these rates:

$$cts_raw = \frac{1 - e^{-cts_true \cdot FT \cdot (1 - DF)}}{FT} \quad (2)$$

This way, we get the RAW measured count rates for the stars and the background.

4. Process the obtained raw count rates in the same way we do it in the data reduction, i.e. apply the c.l. correction formula

$$cts_corr = -\frac{\ln(1 - cts_raw \cdot FT)}{FT(1 - DF)}, \quad (3)$$

to both stellar flux and the background, subtract the background and calculate the magnitude according to (1). The internal error (the error of the RAW magnitude in a given frame) is calculated as

$$\sigma^{int}(mag_raw) = \frac{2.5}{\ln(10)} \frac{\sqrt{\sigma^2(cts_raw) + \sigma^2(cts_bg_raw)}}{cts_raw - cts_bg_raw} \quad (4)$$

where $\sigma^2(cts_raw) = cts_raw/T_{exp}$ (same for the background). This formula follows from the assumption of the poisson distribution of the *measured* stellar (cts_raw) and background (cts_bg_raw)

²For the $R=6$ pix aperture.

count rates and directly corresponds to the error estimates made by the standard photometric programs like *daophot*. As the magnitudes themselves are corrected by applying (3) to the raw count rates, the error of the *corrected* magnitude will be different. It can be calculated using the above formula, but with $\sigma(cts_raw)$ and $\sigma(cts_bg_raw)$ replaced by:

$$\sigma(cts_corr) = \frac{\sigma(cts_raw)}{(1 - cts_raw \cdot FT)(1 - DF)}, \quad (5)$$

according to the propagation of the error in (3).

Now, the whole procedure may seem meaningless, as in the step 4 I simply reverse what I did in the step 3. However, the purpose of the simulation was not to check the scatter introduced by the small number of frames. For that, I would simply generate 4 random numbers and compare the estimated sigma with the known sigma of the poisson process. The goals of the simulations were:

- (i) to compare the errors estimated according to (4) (including these errors after their correction for the c.l effects (5)) to the true poisson errors. Equation (4) assumes that the RAW count numbers are driven from a poisson distribution, while for the bright stars they are NOT.
- (ii) the algorithm above assumes the perfect detector in the sense that it does not introduce any noise. It was clear that the results of the simulations would not agree with the observed data. So the more important second goal was to try to find the source(s) of the detector noise (and include it into the simulations) which would account for the observed features.

4 Simulation results

4.1 The basic algorithm

In Fig.2a the results of the simulations with the basic algorithm are shown. While the scatter of the external errors for the fainter stars is rather large, it clearly does not account for the observed picture. First, it is still smaller than the observed one. Second, it is symmetric relative to the internal errors (which is not surprising). To demonstrate that the scatter is indeed related to the small number of simulated frames, I repeated the simulations with the number of frames equal to 500. The resulting plot is shown in Fig.2b.

Now, it is interesting to look at the brighter stars. In Fig.3a the left part of the bottom plot from Fig.2 is shown with the y-axis scale increased. I show the simulations made for 500 frames to make the effect more evident. Clearly, the internal error of the RAW magnitude systematically exceeds the true poisson error for stars brighter than $\sim 14^m$. This is because, as I said before, this error is calculated in the assumption that the RAW fluxes have poisson distribution. In fact, for the bright stars, coincidence losses make the distribution non-poisson and the brighter the star, the *narrower* is the distribution of its raw flux compared to the poisson one. In the extreme case of a star for which we count one event during every frametime period, the probability distribution for the RAW flux will be a δ -function equal to 1 at $x = 1/FT$ and 0 elsewhere, with its standard deviation equal to zero. However, if one assumes that the measured flux is driven from a poisson distribution he/she would estimate the deviation as $\sqrt{1/FT}$.

If someone would “believe” in an error estimate for the RAW magnitude of a bright star made in this way, he/she would naturally want to adjust the error for the effects of the coincidence loss. However, this estimate will be meaningless with respect of the true poisson error of the star, for the initial estimate of the RAW magnitude error is already wrong. This is demonstrated in the Fig.3b, in which the filled dots show the internal errors corrected for the c.l.

This is a simple stuff but I thought I should mention it. If an observer uses a general photometric package like *daophot* to reduce the OM frames, the errors will be calculated by the package in an assumption of the poisson distribution of the RAW count numbers.

4.2 Local sensitivity variations (LSVs)

Returning to the problem with the large observed errors of the bright stars, I must note that it is further amplified by the fact that apparently the internal errors shown in Fig.1 are overestimated. That makes

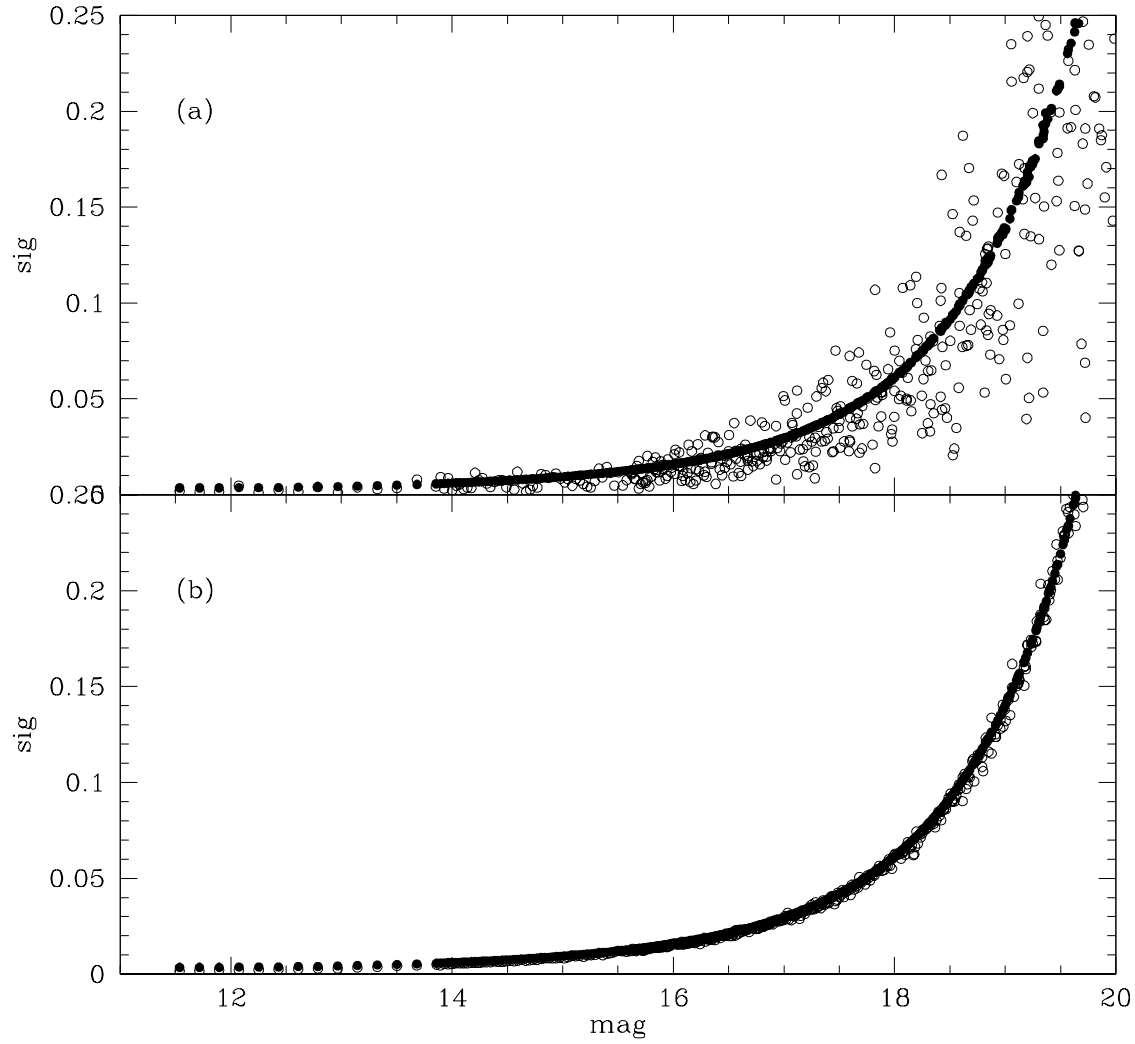


Figure 2: Simulations, the basic algorithm (i.e. pure poisson noise in the data, no noise introduced by the detector). The meaning of the symbols is the same as in Fig.1. (a) 4 artificial frames; (b) 500 artificial frames.

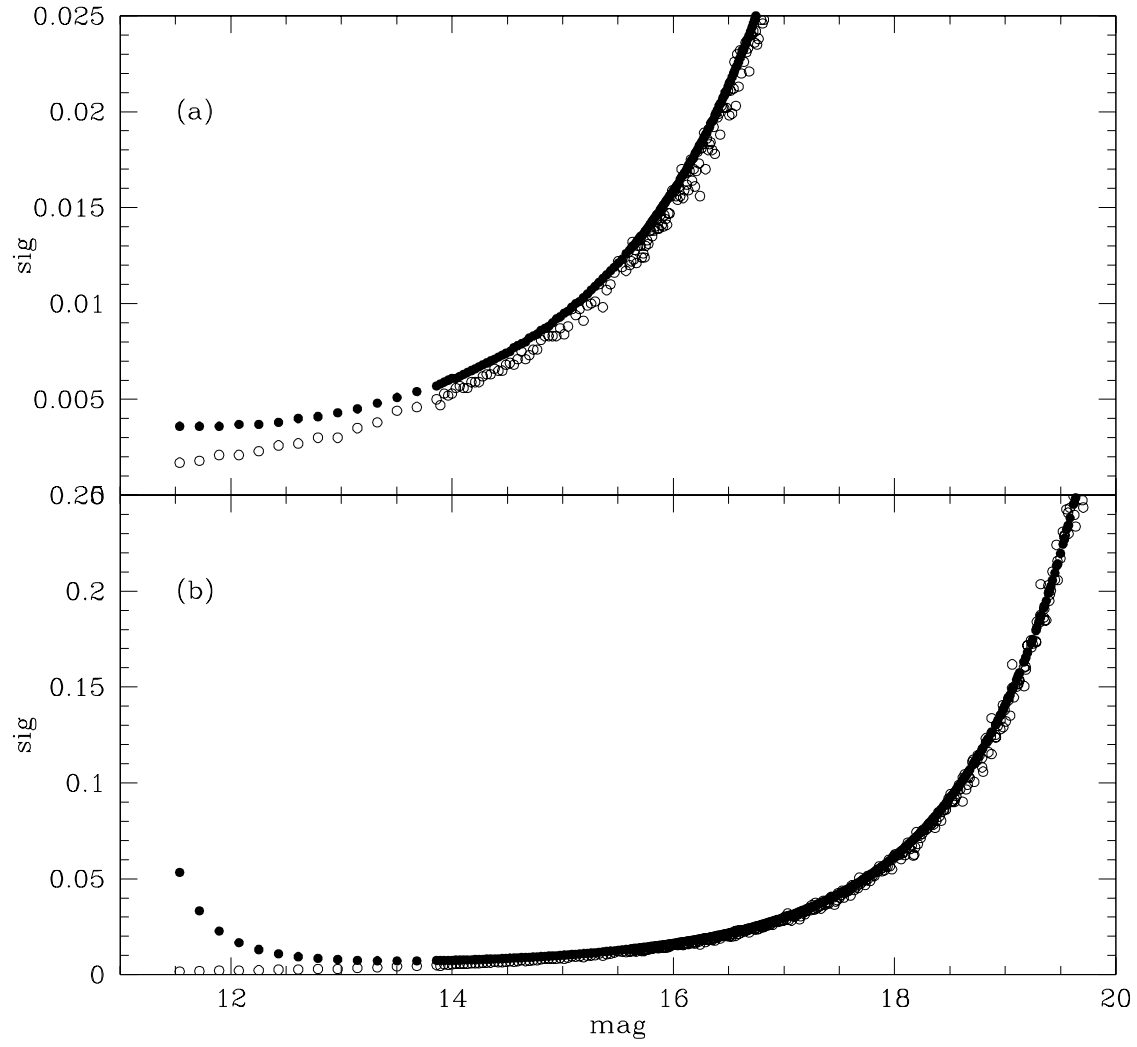


Figure 3: Simulations, the basic algorithm. 500 artificial frames. (a) the same as in Fig.2b; (b) the same as in Fig.2b but the internal errors are corrected according to (5).

the discrepancy even stronger. We certainly need some source of additional noise to explain the observed picture. At this point I thought about the pixel-to-pixel sensitivity variations of the CCD. While the size of the physical pixel is equal to 4 arcsec and our aperture has the radius $R=6$ arcsec (i.e. not much larger than the size of the physical pixel), changes in the local sensitivity may cause the additional noise. Recall, however, that we have two frames separated by as little as 1.5 arcsec and yet the scatter of the magnitudes between these two frames still large. This would imply, if we adopt the hypothesis, that the local changes in the sensitivity of the physical pixels are somehow translated into the changes of the sensitivity of the virtual pixels. From the current local flat field image sent me by Bob Shirey, it is not clear what would be the possible amplitude of such variations, for the statistics of this image is extremely poor³. However, I could simply *assume* some level of the additional noise introduced by this effect and incorporate it into the simulations. So I did.

Fig.4 shows the effect of the inclusion of the LSVs. For the upper plot, every *cts_raw* and *cts_bg_raw* was multiplied by a random gaussian number with the average equal to 1 and the standard deviation equal to 0.01, which means 1% effect of the LSV *on the fluxes/backgrounds measured within $R = 6$ arcsec aperture*. The bottom plot shows the same simulation but with the standard deviation of the LSV equal to 0.004.

Thus, the effect of the LSV on the measured count rates equal to 0.4% is apparently sufficient to explain the observed magnitude errors of the bright stars. Note the increase of the errors toward the brighter limit. This is of course the result of the error propagation when the c.l. correction is applied. We even have a slight similar tendency in our observed data in Fig.1 (though it is only based on a couple of data points...). I would like to stress it out, however, that the agreement between the simulations and the data does NOT prove that the LSVs are indeed the reason for the observed behaviour. In fact, ANY additional noise will cause the same effect.

4.3 Straylight

While the LSVs seem to be a good candidate for the explanation of the bright star errors, they do not solve the problems 2 and 3 mentioned in the 1st section of the report. As I thought about it I realized that as long as two frames are not shifted relative to each other (so the large scale CCD sensitivity variations are not important), ANY additional noise within the detector would only increase the scatter but preserve its symmetry relative to the internal errors curve. This is because the average value of any such noise signal would be constant.

To made the distribution of the open dots asymmetrical, we need something which average level is changing from frame to frame. The straylight is the perfect candidate to this role. Indeed, its count rate is not constant and depends on the particular configuration of the stars in the field observed. Let's assume that within a given frame we have some additional straylight within the stellar aperture but not in the background annulus. Let the count rate of the straylight be *cts_sl* (I won't bother with the c.l. correction assuming that the count rate is low). Then, without knowing anything else, we would estimate the internal error according to (4), just replacing $\sigma^2(cts_raw) = cts_raw/T_{exp}$ by $\sigma^2(cts_raw) = (cts_raw + cts_sl)/T_{exp}$. But in fact an additional error should be added under the square root equal to $\sigma^2(cts_sl_0)$, the error of the straylight average count rate.

Straylight will of course change the internal errors as well. But the point is that the true error will always be higher than the internal one and will manifest itself in the distribution of the external errors.

Of course, changes of the average straylight count rate from one frame to another do not have to be gaussian; they are most likely not. Nevertheless, to simulate the effect of the straylight, I assumed that its average count rate is distributed according to the gaussian law (actually, I also tried the uniform distribution, which gave me qualitatively the same results). The modification of the algorithm consisted in *adding* a random gaussian number with the average equal to zero and standard deviation equal to 0.4 *counts/s/aperture* to the *cts_raw*. Setting the average to zero emulates different possible combinations of the straylight features: stronger/weaker straylight in the background annulus compared to the flux within the stellar aperture. The results of the simulations are shown in Fig.5. In this simulation, the LSV effects are turned off.

³The latest flat field has better statistics so it is worth applying the flat field correction to see whether the scatter would decrease. This is to be done in the near future.

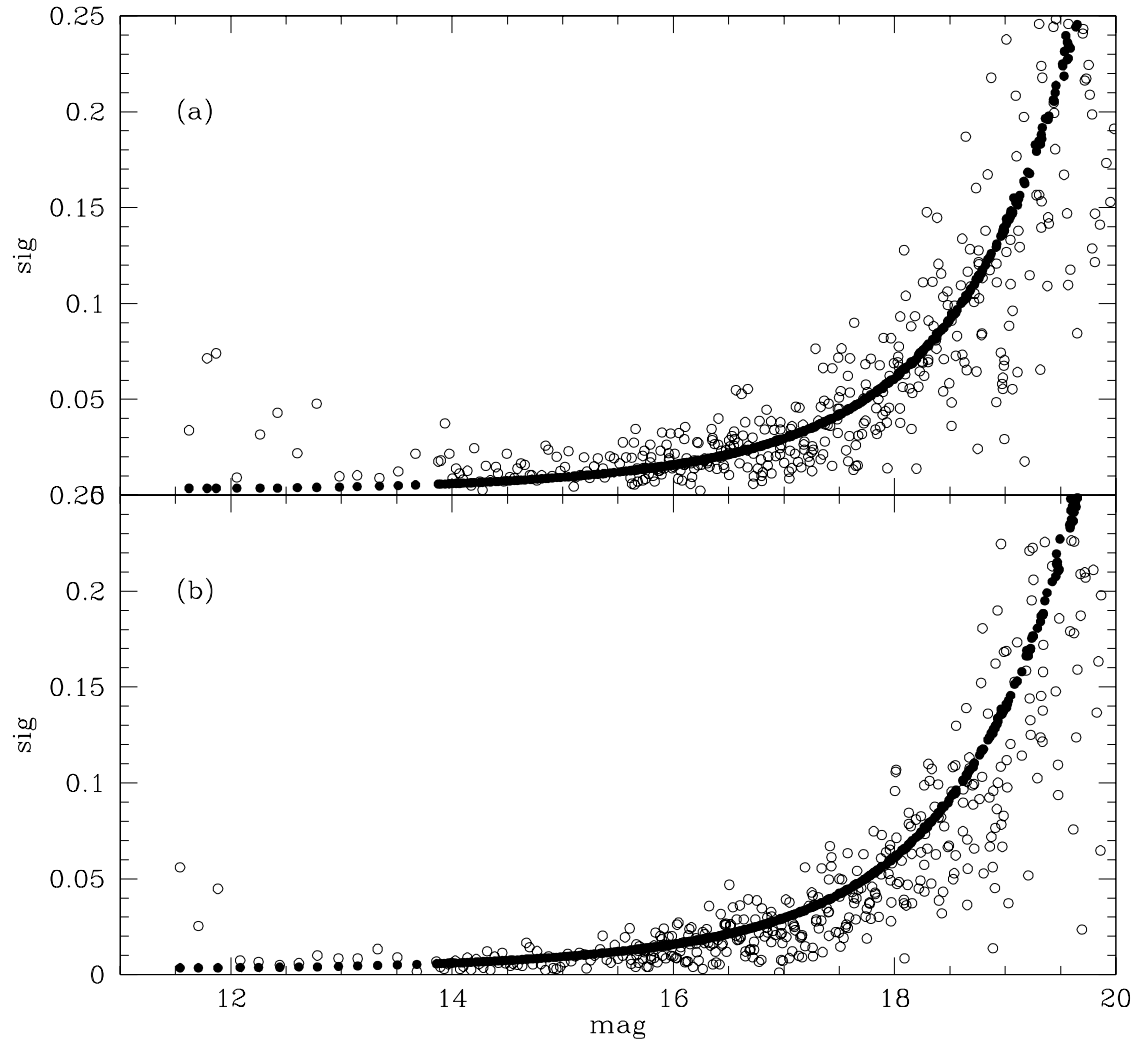


Figure 4: Simulations, LSV effect on the errors. 4 artificial frames. (a) the amplitude of the effect is 1%; (b) the amplitude of the effect is 0.4%.

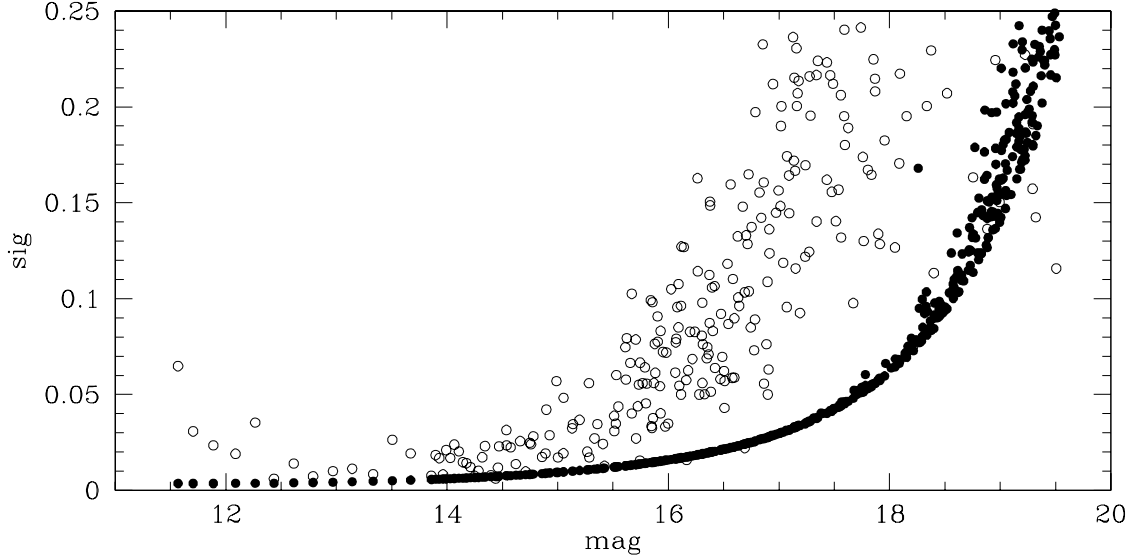


Figure 5: Simulations. Straylight effect on the errors. NO LSVs. 4 artificial frames. All stars are affected.

Now, if we recall that the straylight may affect *not all stars* we will get a *mixture* of two distributions which hopefully will resemble the observed picture. In Fig.6, the effect of the straylight is shown assuming that 30% of the stars are affected. Now, isn't it similar to Fig.1? Recall that the standard deviation of the straylight difference between the background and the stellar total count rates required to create this plot, is equal to $0.4 \text{ counts/s/aperture}$. This is about 5 times smaller than the typical background level and apparently cannot be detected by the visual inspection of the images.

One might argue that for those two frames obtained during the rev. 44, the straylight features must be identical as the shift between the frames is small. However, while the general patterns are indeed similar, there are clear differences in the straylight between these frames. The example is shown in Fig.7. Evidently, even slight change in the position of a star projected on the chamfer cause significant changes in the straylight pattern. Considering the low required amplitude of the straylight it is not surprising that these two frames still show significant scatter.

Finally, in Fig.8 I show the combined effect of the LSVs and the straylight. Note that from Fig.6 it might be concluded that the straylight effect alone without the LSV may explain the error behavior both for the bright and faint stars. This is exactly what I said before: whatever is the reason for the additional noise, it will affect the bright stars alike. Is there a way to discriminate between the two effects? Well, if we had a large number of observations of bright stars, then possibly yes. If the LSVs are not important, then there may be some bright stars – those not affected by the straylight (do such stars exist?) – which would have very small photometric errors. On the other hand, if the LSV is important, there will be no such stars. But we'd need A LOT of observations to check this, and it is certainly not worth the observing time. Another way to estimate the importance of the LSV is to accrue a highly accurate local flat field, apply it and check whether the errors are decreased. This will be done in the near future.

5 Conclusions

I will summarize what I learned from this study:

1. Estimates of the RAW magnitude errors made in the manner usual for the standard photometric packages (i.e., assuming the poisson distribution of the RAW count rates), give wrong results for the stars brighter than $\sim 14^m$. Correcting these estimates for the coincidence loss would give even

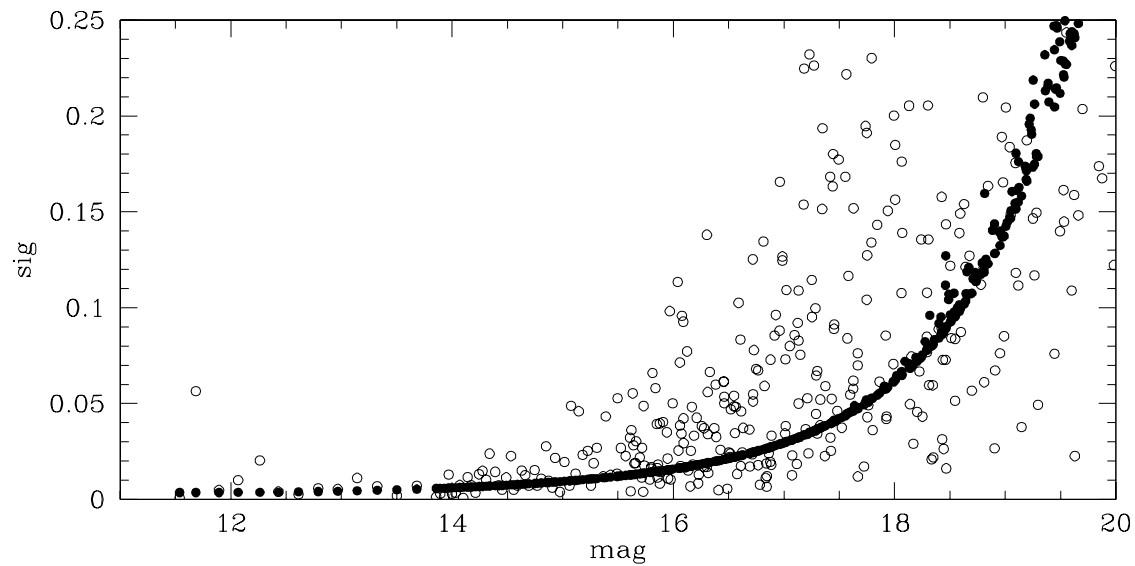


Figure 6: Simulations. Straylight effect on the errors. NO LSVs. 4 artificial frames. 30% of stars are affected.

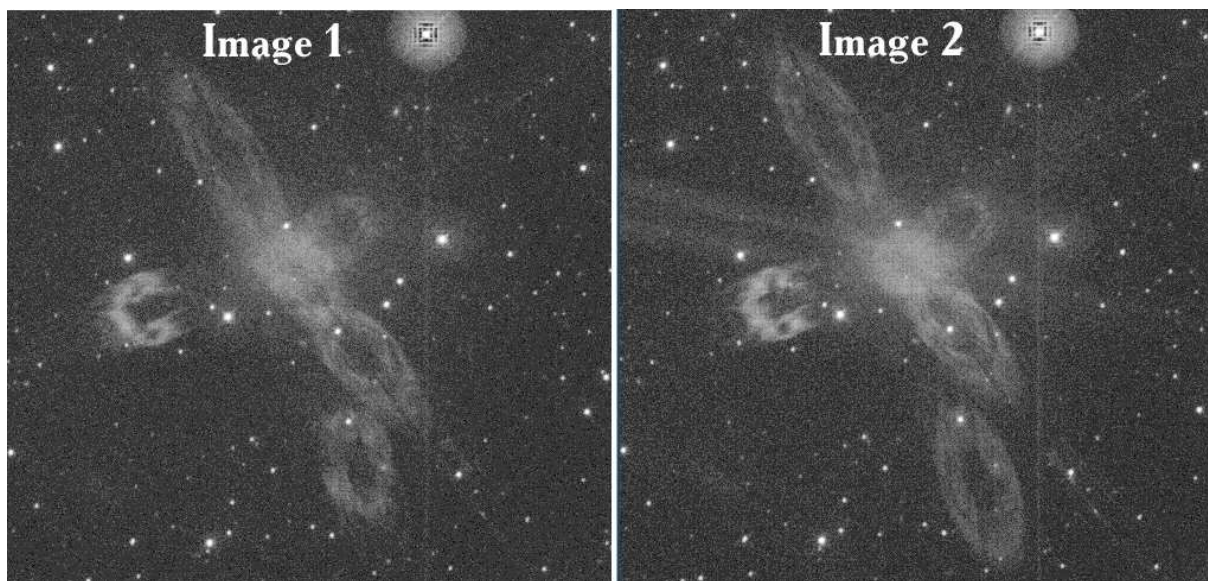


Figure 7: Images of the two frames in the V filter obtained during rev. 44.

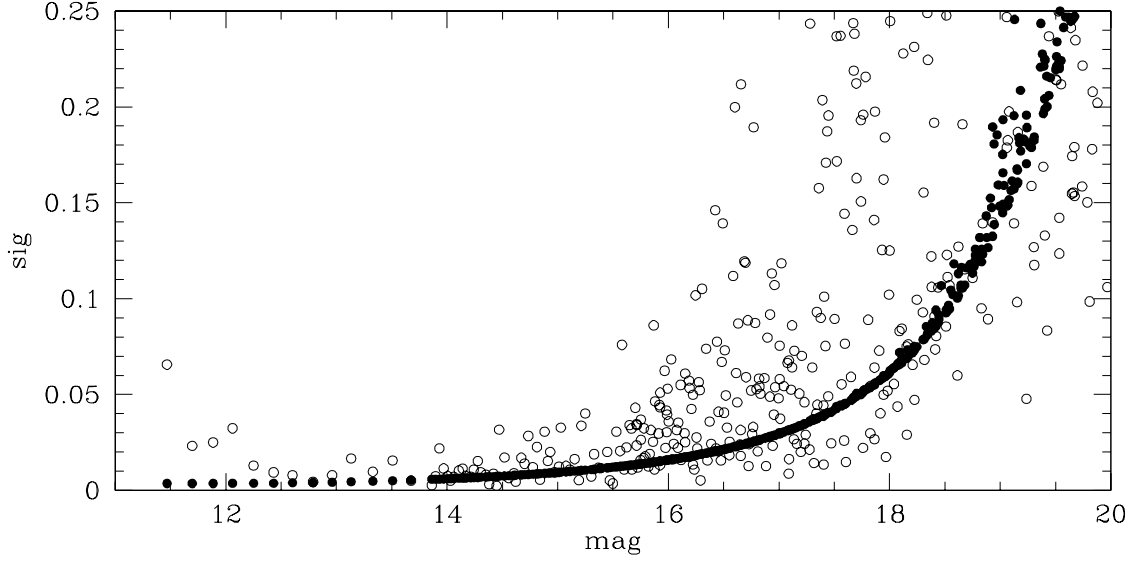


Figure 8: Simulations, Combined LSV and straylight effect on the errors. 4 artificial frames. The parameters for every effect are as before.

wronger numbers. Note, however, that, ironically, the behaviour of these corrected estimated errors is similar to what I finally got with all the effects introduced into the simulations. This is because we *overestimate* the error of the RAW count rate and in a sense this is equivalent to introducing some real additional noise and correctly accounting for it...

2. For the bright stars, the reason for the noise exceeding their poisson noise, may be related to the pixel to pixel sensitivity changes.
3. For the faint stars (the border between “bright” and “faint” stars is $\sim 14^m$) the effect which apparently explains the observed error scatter is the straylight. As a result of this scattered illumination, in Fig.1 we see a mixture of 2 distributions – one for the stars not affected by the straylight and the other one for the affected stars.
4. It is not clear whether the straylight effects alone may explain all observed features in Fig.1. However, as a matter of practical importance, it is possibly sufficient to say that the safe limit for the best magnitude accuracy is $0^m.01$. For the extremely bright stars (brighter than $\sim 12^m$) this limit may increase to $0^m.03 \div 0^m.05$ or even higher if $cts_raw \cdot FT$ is extremely close to 1..
5. I analysed observations in the V filter. While simulations are irrelevant to any particular filter, one can expect that in real data, the straylight effect would not be observed in the ultraviolet filters.