CALIBRATING THE MEDIUM BAND PHOTOMETER USING SPIKES

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ABSTRACT

The option of using the diffraction spikes of bright stars for calibrating the Medium Band Photometer is rediscussed using realistic models of the PSF. The conclusion is that the steepness and asymmetries mean that this method cannot stand alone, and the use of gates to assist the measurements should be studied.

Key words: Gaia; Photometry; Techniques: photometric.

1. INTRODUCTION

The linearity of CCDs only holds for a certain range of signals. For bright sources the response is reduced, and for the brightest stars (brighter than 10 – 12 mag, perhaps) saturation sets in and no photometry can be made. Not only the bright stars but also the very faintest stars will suffer from systematic errors, so ways must be found to calibrate the magnitude scale.

The diffraction spikes in the Gaia telescopes are generated by the rectangular entrance pupil. Since the light meets no obscuration (e.g., not a secondary mirror), thanks to the off-axis telescope design, the form of the spikes can be well computed.

In the diffraction spikes the intensity is much weaker than in the central image, and it has therefore been suggested that they might be useful not only for observations of the brightest stars, but also for calibrating the magnitude scale.

We show here that the spikes will give important contributions to the calibration, but we must also include other methods using gates and high resolution sampling.

2. THE MEDIUM BAND PHOTOMETER

The focal plane of the MBP is shown in Figure 1, with a red and blue field. Each field is divided in ten CCDs (not shown) with separate medium band filters.

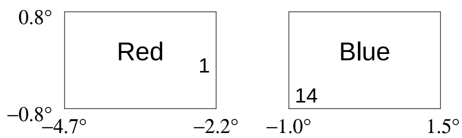

Figure 1. The layout of the MBP focal plane with the red and blue field. The points referred to as ‘1’ and ‘14’ are indicated.

EADS Astrium has calculated monochromatic optical point spread functions for three different wavelengths and for three different points in each field. In order to determine the effective PSFs, we have included the effects of:

- pixel size;
- distortion;
- four phase, time delayed integration;
- attitude rate errors along scan;
- across scan motion; and
- charge diffusion.

Two examples of the resulting effective PSF are shown in Figures 2 and 3. The value indicated by the contours is the fraction of the total signal contained in one pixel. The figures also show the larger, observing windows, WM3, WM5, and WM7 consisting of 3, 5, and 7 patches respectively. Each patch is four pixels across scan and 10 pixels along scan. A detailed description of the sampling, including specialized windows for calibration, was recently given in a report by Høg (2004a), along with a summary (Høg 2004b).

3. CALIBRATING THE SPIKES

For all observations, we must know the usual calibrations for variations of the CCD response as a function of time and wavelength, different for each CCD chip and pixel column. We must also know how the signal depends on

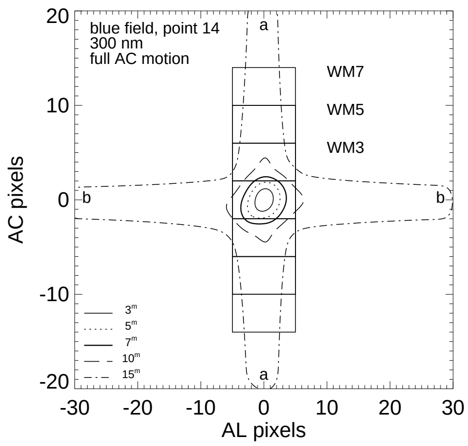

Figure 2. The monochromatic PSF at 300 nm for point 14 of the blue field. The current sampling scheme for the spikes is indicated, They contain three and seven patches respectively.

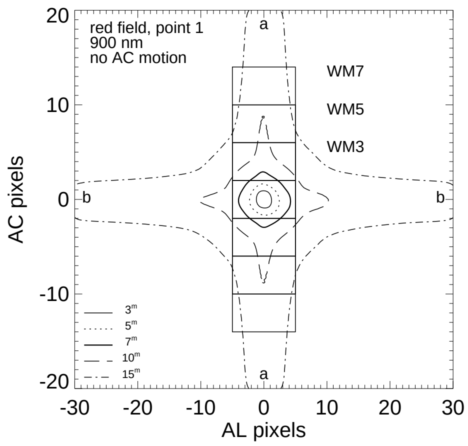

Figure 3. The monochromatic PSF at 900 nm for point 1 of the red field.

the precise position of the star in the observing window, and on the across scan motion of the star during the transit, due to the precession of the scan axis.

For normal observations of the central image, the window size has been chosen to keep each of these effects below some 0.01 – 0.02 mag, giving good hope for correcting them through calibrations.

Further from the centre, in the spikes, the same effects must of course also be calibrated, but the amplitudes of the errors will be much higher and the detailed calibrations therefore much more demanding. In addition, chromatic effects which are very small in the centre, are quite important in the spikes as discussed below.

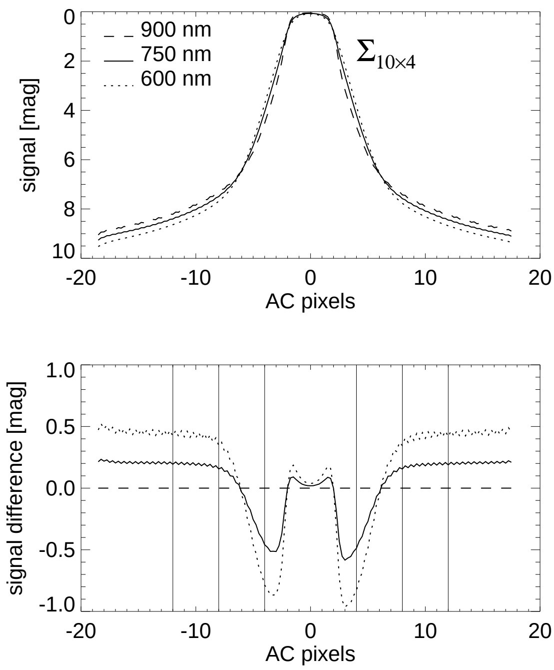

Figure 4. The upper panel shows the fraction of the signal contained in a 10 by 4 pixels patch for three different wavelengths at point 1 of the red field, as a function of the across scan position of the patch. The lower panel shows the differences with respect to the reddest wavelength.

3.1. Chromatic Effects

Figure 4 shows the fraction of the signal contained in a patch of 10 $\times$ 4 pixels, as a function of the across scan (AC) position of the patch relative to the star. The PSFs are for point 1 of the red field, and for wavelengths of 600, 750, and 900 nm. When the star is more than 1 – 2 pixels away from the centre in the across scan direction, the signal drops very steeply but at a slightly different rate at the three different wavelengths. The lower panel of the figure shows the differences of the three PSFs relative to the reddest PSF. Far from the centre the signal is expected to be proportional to the wavelength and the differences should approach stable values of 0.20 and 0.44 mag respectively, which is just what we see in the figure. *This means that the effective filter system is different when we use the spikes as compared to using the central image.* We also notice that conditions are fairly stable when the patch is at least 8 pixels from the centre, whereas the outer patches of the WM3 window situated only 4 pixels from the centre will see yet another filter system which even changes quickly with the precise across scan position.

This wavelength dependence can in principle be used to calibrate the central wavelength of each filter and thus show the change during the mission. The effect appears from Figure 5 to be about 2 mmag/nm at 600 nm which may be sufficient for a calibration when use is made of the millions of photometric observations made with the WM5 and WM7 windows.

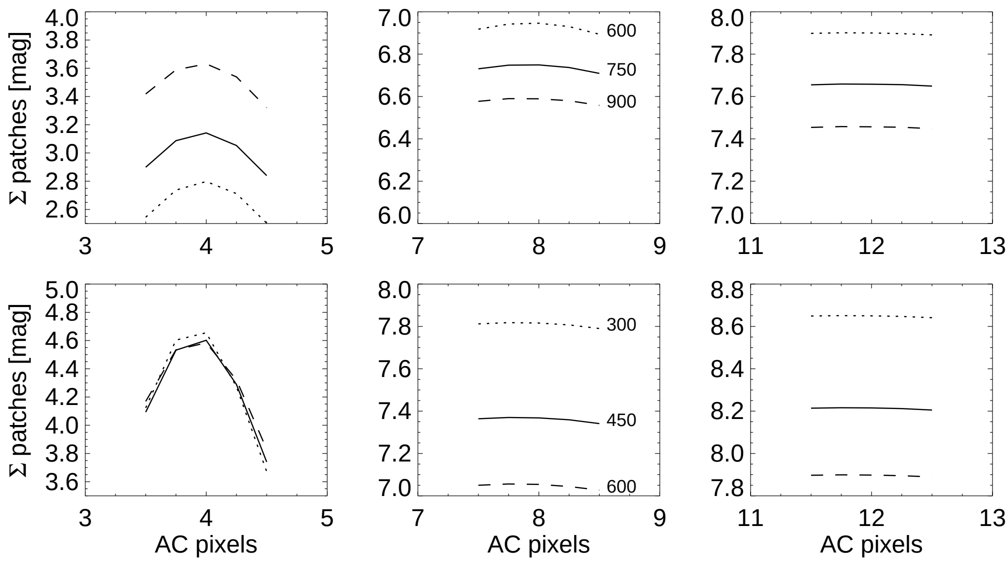

Figure 5. The variation of the combined signal of two patches, symmetrically situated in the window, with the across scan position of one of the patches. When the star is off-centre, the signal is brighter. The upper panels are for point 1 in the red field, whereas the lower panels are for point 14 of the blue field.

3.2. Saturation of Pixels

For stars brighter than about 12 mag the pixels near the centre of a star may be saturated which happens when a pixel contains more than about 100 000 electrons. The anti-blooming of the CCD prevents the excess electrons from affecting the neighbouring pixels. A sample of 4 pixels in the central patch cannot be used for photometry if even one pixel in it is saturated.

Three methods are available to deal with saturation which may even be used in combination: 1) A shorter integration time may be activated by means of one of the gates in a CCD. If this is done when a bright star arrives, saturation may be avoided. 2) The samples with saturated pixels are not used, but only the samples before or after, i.e. the outer $4 + 4$ or $3 + 3$ samples in a patch of 10 samples. 3) Full pixel resolution is provided in the central 10×12 pixel part of the WM3, WM5, WM7 windows, resulting in windows called WMP3, WMP5, WMP7. Such WMPn windows could be used for all bright stars and for some fainter ones for the sake of calibration. The central part will then contain 10×12 samples and the small samples of one pixel size will be unsaturated closer to the centre of a star than the larger samples would be and can therefore better be used for measurement of the star or for calibration.

3.3. Decentering

The signal in the outer patches of the WM3, WM5, and WM7 windows depends steeply on the exact across scan position of the star. The simplest way to reduce the steepness is to add the signals from corresponding upper and lower patches. This means adding the patch at $+4$ pixels to the one at -4 pixel, adding the ones at $+8$ and at -8, etc. The resulting attenuation as a function of the across scan position of the star is shown in Figure 5 for two points in the focal plane.

The patches at 8 and 12 pixels are quite well behaved with variations of a few hundredths of a magnitude when the star is centred within 0.5 pixels as will nearly always be the case. The problematic patches are the ones at $+4$ and -4, where the combined signal varies several tenths of a magnitude, sometimes even a whole magnitude, when the star moves from the centre to 0.5 pixels from the centre. Clearly these latter patches, i.e., window WM3, will be difficult to use for high accuracy photometry, but the WMP3 window with full pixel resolution will be better.

3.4. Across Scan Motion

The precession of the telescope axis will cause an across scan motion of the star varying between 0 and 1.5 pixels during the transit of a CCD. Looking again at the combined patches, the signal varies no more than 0.05 mag for the patches at 8 and 12 pixels depending on the across scan motion, an effect that appears to be within reach of calibration. For the patches at 4 pixels the variation is in the order 0.15 – 0.20 mag, and will add to the complications of calibrating WM3 for stars where the central patch contains saturated pixels.

4. THE MAGNITUDE SCALE

Basically there are two ways of checking the magnitude scale using the spikes. One way is to use observed attenuations from the centre to the outer parts of the spikes and correct this attenuation to be the same for all stars. Another way is to use a pre-computed attenuation and adjust the observed attenuation to fit the computed. Both ways have advantages and disadvantages and must be used in combination.

Figure 6 gives a crude illustration of how to correct the magnitude scale for non linear behaviour in the bright (or faint) end using the observed attenuation. We assume that the central part of the response curve is linear, but in the bright end the response is reduced.

We select two points across scan, either both points are on the spikes, or one point is on the spikes and the other is at the centre. What matters is that the optical signal has a well defined magnitude difference, $\Delta \mathrm{m}$, between these two points independent of the magnitude of the star. As long as we are within the linear regime, as the case labeled 'A', this magnitude difference is also the observed difference. As we go brighter (case 'B'), we will observe a somewhat smaller magnitude difference because the brighter point now feels the diminished response. Knowing the value of $\Delta \mathrm{m}$ from case 'A' we can however correct the scale.

If we use the difference between the outer patches of WM5 and WM7, $\Delta \mathrm{m}$ will be 0.8 – 0.9 mag which is a bit small. The attenuation in these patches is as much as 7 – 9 mag, which means that only very bright stars (brighter than perhaps 10 mag) can contribute, and will only check the linearity in the range 15 – 18 mag.

The alternative is to use the central patch in combination with the outer patches of WM5. The magnitude difference is then 7 – 8 mag. Taking the observed attenuation, only a very narrow range of magnitudes just below saturation will contribute, and only a very small part of the response curve will be tested. In this case it is advantageous to use the pre-computed attenuation, which will allow us to test both the faintest and the brightest end of the scale, assuming that the intermediate part of the scale is indeed linear.

5. CONCLUSION

The WM3 window is most probably unsuited for calibrations, but combinations of WMP3 and the larger WMP5 and WMP7 windows will provide a calibration of the critical parts of the response curve.

For bright star observations the WMP3 windows and the gates must be used, and it must be studied how these observations can be utilized in the calibrations.

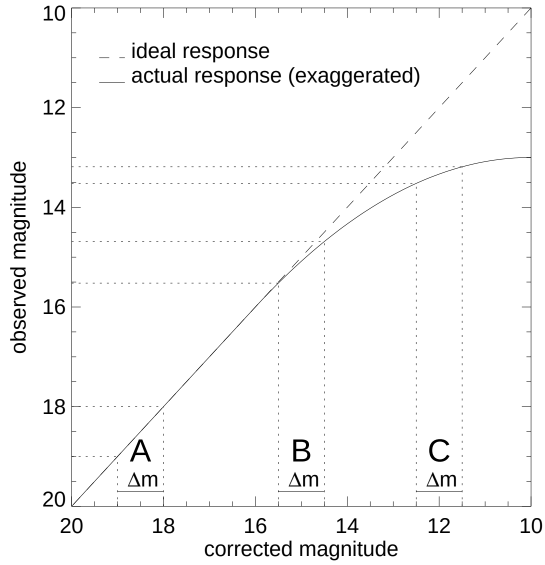

Figure 6. Determining the magnitude scale using observed differences. For a faint star (case A) the difference in signal from two points on the spikes is observed without scale errors. For a medium bright star (B), the same signal difference is observed slightly too small, and the bright end must be corrected. For a bright star (C) both ends must be corrected.

REFERENCES

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