The Spectro point spread function for GAIA

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GAIA-CUO-094 18 September 2001

Abstract. We discuss the point spread function for the Spectro instrument based on realistic effects of the time delayed integration, transverse image motion and pixelization, but assuming rather small wave front errors. Stars brighter than 10 mag, which will saturate the CCD, may be observed photometrically using the image wings, but the central wavelengths will be slightly shifted towards red.

Keywords: PSF – Spectro

1. Introduction

The point spread function, PSF, for the Astro instruments has been discussed by Lindegren (1998) and Lattanzi et al. (1998).

Knowledge of the PSF is important for many design considerations, e.g. the sampling of the images. Here we focus on the possibilities for doing photometry of stars which are so bright that the image is saturated in the centre, by using the wings of the PSF. The possibility to use the wings for calibrating the magnitude scale, has been discussed by Høg (2001). The presentation given here is based on an internal technical report by Fabricius & Lindegren (2000).

2. From diffraction image to PSF

The intensity of the monochromatic diffraction image from a square aperture, as for Spectro, is given by the expression

$$I = \frac{\sin^2(\pi x D_x/\lambda)}{(\pi x D_x/\lambda)^2} \frac{\sin^2(\pi y D_y/\lambda)}{(\pi y D_y/\lambda)^2}, \tag{1}$$

where x, y are angular coordinates in the focal plane and D_x, D_y are the dimensions of the aperture. A cut along the x–axis is shown in Figure 1 for a long and a short wavelength for the Spectro instrument. The full width of the central peak is close to one pixel for red light and less than half a pixel for blue light.

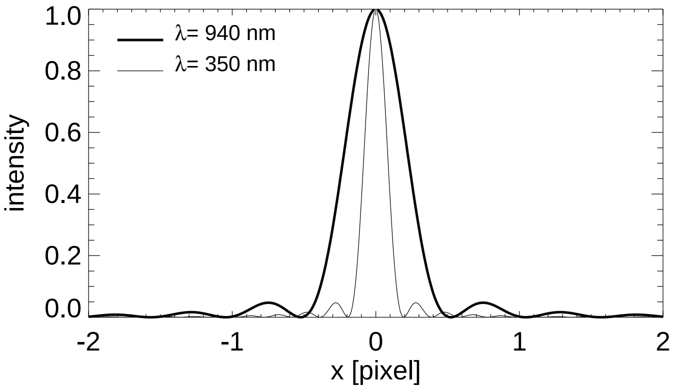

Figure 1. A cut through the monochromatic diffraction image for Spectro for two different wavelengths. The pixel size is 10μm or 500 mas

To derive the PSF, the spectral distribution of the detected light must be taken into account, as well as the smearing introduced by the time delayed integration, TDI, and the drift of the star in the transverse direction due to the spin axis motion. On top, a considerable smearing is introduced by the pixelization because of the large pixels. The least predictable contribution comes from the optical aberrations, which depend on the polishing errors of the mirrors and the stability of the optical system. The aberrations can be expressed in terms of wave front errors.

2.1. WAVE FRONT ERROR

An example of realistic wave front errors for the Astro instrument has been provided by Matra Marconi Space for 15 different points in the focal plane. In each point, the rms wave front error is around 45 nm. The highest value, about 100 nm, is reached in one of the corners (point 15). No similar set of examples are available for Spectro. Instead we have used the values for Astro (point 15), but restricted to the size of the Spectro aperture. The resulting errors are about three times smaller than for Astro, but cannot be expected to be realistic in the very wide Spectro field.

For the design of the Spectro optical system, a set of spot diagrams were computed (Matra, 1999) for a two degree field, but presently a four degree field is foreseen, and although the spot diagrams for the central part are satisfactory, they do not represent the whole field.

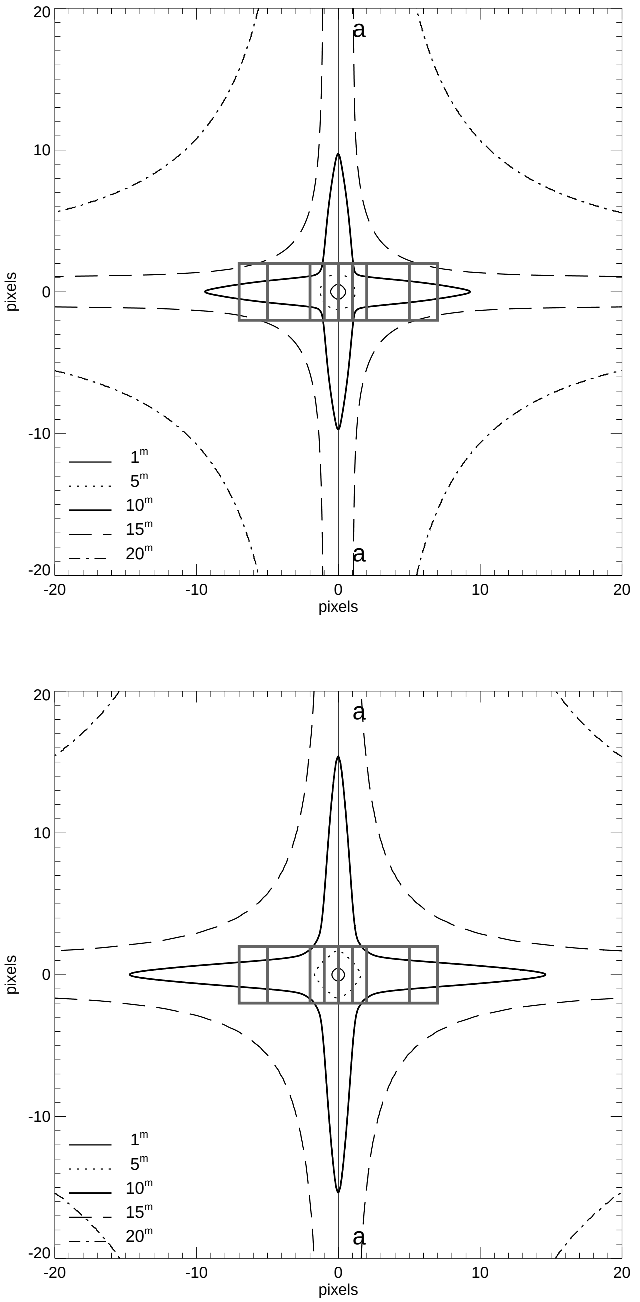

Figure 2. The psf at 350 nm (top) and 940 nm (bottom). The contours show which fraction of the light falls in an area of one pixel. The proposed sampling of the central part of the image is indicated

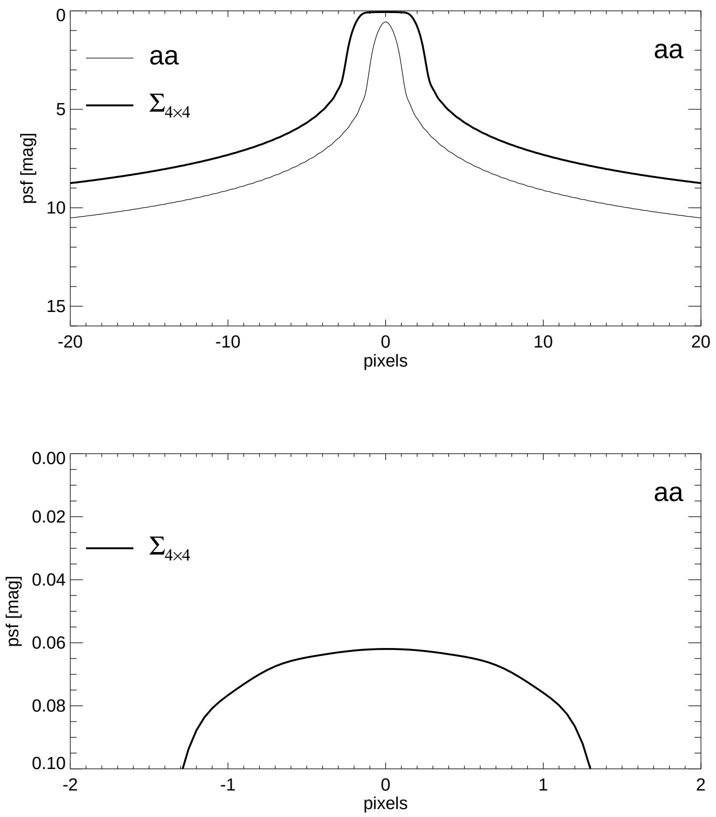

Figure 3. A cut through the 940 nm psf along the line aa. The thick line shows the running sum of 4 by 4 pixels. The bottom panel provides a magnification

2.2. Spectro PSFs

The fortran program by Lindegren (1998) for the Astro PSF, was adapted to the Spectro aperture and pixel size. The typical transverse motion of the star was assumed to be one pixel also in Spectro, because both the pixel size and integration time is about 3 times larger than for Astro. The smearing due to the TDI was again set to one pixel.

The spectral response of the telescope, including filter and detector, is here assumed to be rectangular, and variations of the stellar spectrum across the band are assumed to be of minor importance. Six monochromatic PSFs, each centered on one sixth of the rectangle, were added to produce the final, polychromatic PSF.

Figure 2 shows the resulting two dimensional PSF for a 40 nm wide filter at 350 nm and for a 20 nm wide filter at 940 nm. The displayed field of 40 by 40 pixels corresponds to a 20 by 20 arcsec square. The contours show the intensity in terms of the fraction of the total signal which would end up in a pixel centred on the contour. It is seen, that while the diffraction image in Figure 1 scales with the wavelength, the PSF does not grow in the same proportion. This is of course due to the smearing. At the centre, the currently proposed sampling of the image (cf. Fig 3.7 of ESA (2000)) is indicated. Figure 3 shows a cut through the 940 nm PSF along the line aa.

2.3. NON-SATURATED STARS

For most stars, a simple *aperture* photometry can be made, using, e.g., the central 4 by 4 pixels (Høg, 2001). The centering can of course only be done with integer pixel resolution and an error contribution from the sky mapper must be included in the centering error. Taking one pixel as worst case for the total offset, Figure 3 shows that we lose 0.02 mag as compared to a perfectly centered star. For shorter wavelengths the effect is smaller. In any case, the effect can be compensated when the offset is known. If the offset is 0.5 pix in y, and we require a magnitude error below 0.005 mag, we only need to know y within ± 0.2 pix.

2.4. BRIGHT STARS

Stars brighter than about 10 mag will saturate the central pixels or even columns. An obvious solution is to acquire additional patches above and below the normal patch. These patches should be sufficiently close to the centre, that the attenuation is not too big, and sufficiently far, that the PSF is not too steep. As judged from Figure 3, we can obtain attenuations down to about 10 mag, within 10 arcsec; making, in principle, almost any star observable.

If the PSF is steep, an uncertainty in the y–coordinate of the star will introduce an error in the magnitude. This can be largely compensated by using two patches, one above and one below the star, and taking the mean of the two magnitudes. If the patches are centred at $y = \pm y_p$ and the star is at $(x, y) = (0, 0)$, the attenuation can be read off Figure 3 both for the vertical cut, relevant for saturation considerations, and for the running sum, relevant for accuracy considerations. In reality the star will be offset from the centre, and the attenuation must vary slowly as a function of the star's location, for the scheme to work. Table I shows the range of attenuations for the running sum, using two patches, when the star is allowed any position within 1 pixel of the centre in both coordinates. Even for such large offsets, the attenuation

Table I. The range of attenuations when patches offset by y_p pixels are used

y_p	350 nm		940 nm	
pix	$\Delta m_{\min}$	$\Delta m_{\max}$	$\Delta m_{\min}$	$\Delta m_{\max}$
4	5.63	6.08	4.64	5.04
8	7.84	7.87	6.78	6.84
12	8.75	8.77	7.70	7.73
16	9.36	9.38	8.30	8.34
20	9.80	9.82	8.75	8.78

varies only little, except perhaps for $y_p = 4$ pix. If, however, we restrict the deviations to the still realistic 0.5 pixels, the attenuation varies only 0.07 mag. On ground, the spin axis attitude will be retrieved with an accuracy better than 1 mas (Matra, 1999). The position dependant part of the attenuation variation can then easily be corrected.

Using the wings, the bright stars will suffer from a fainter and redder signal. With $y_p = 4$ pix, a star of 10 mag will achieve a precision of a 14 mag star in the red and a 15 mag star in the blue, when two patches are used. The attenuation is 1 mag larger in the blue than in the red, a difference of 0.07 mag across a 40 nm filter, thus shifting its central wavelength about 0.6 nm towards red.

3. Conclusions

We conclude that reliable photometry can be obtained even for very bright stars with the Spectro instrument. There is, however, a need to make new simulations using more realistic wave front errors.

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