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Photometric and imaging performance

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Abstract

Three topics within GAIA photometry have been selected for discussion here. (1) The sampling scheme of the CCDs has been tuned to serve the various purposes: detection of stars, astrometry, broad- and medium-band photometry, and imaging of a small area around each detected star, but the tuning may not yet be optimal. (2) The calibration of CCD sensitivity is critical since we aim for millimagnitude accuracy, the spikes of the diffraction image are suited for an accurate calibration of the magnitude scale, and for extending the range of astrometry and photometry to very bright stars. (3) Finally the various photometric filter systems are illustrated.

1 INTRODUCTION

The multi-colour photometry with GAIA shall serve astrometric and astrophysical purposes. The broad-band photometry in four or five bands of wavelength in the focal planes of the two Astro telescopes shall especially give the spectral energy distribution of each star or quasar with an accuracy sufficient for the correction of chromaticity errors in the astrometry (see [3]). This photometry is also useful for astrophysical purposes. Astrophysical information for most of the one billion objects observed by GAIA would be missing unless it is provided by GAIA. Therefore all objects will obtain broad-band photometry in Astro and medium-band photometry in the Spectro telescope, *cf.* the bands in Sect. 4.

An overview of GAIA photometry is given in various sections of [1] and [2], and some was presented at the meeting. The following sections go in more detail on some topics and introduce new possibilities, but they are basically consistent with these texts. Three topics of GAIA photometry have been selected here: The sampling scheme of the CCDs in Sect. 2, the photometric calibration and measurement of bright stars and double stars in Sect. 3, and an overview of the relevant photometric systems in Sect. 4. A fourth topic has been discussed recently in [4] : Multi-colour photometry with GAIA of the diffuse sky background.

2 SAMPLING AND IMAGING

The CCDs of GAIA integrate the light from stars and background in time delayed integration, TDI mode, synchronized with the scanning motion of the satellite. At the angular rotation speed of 120 arcsec/s this results in 0.86 s integration time per CCD in the two Astro telescope fields and about 3 s per CCD in the Spectro field, *cf.* Section 3 of [1] for details. An average star will cross one of the Astro fields 67 times during a five year mission and the Spectro field 100 times.

All point sources, mostly stars, are detected if they are brighter than a given limit using the read out from the whole area of the first CCD in the Astro and Spectro telescopes, *i.e.* respectively the first Astro sky mapper, ASM1 (not shown in Fig. 1) and the Spectro sky mapper, SSM. In the following CCDs only a window or patch centred on the position of the detected star is read out for analysis on-board and/or transmission to ground. This means that about 99.9 per cent of the pixels can be skipped since most of the sky contains no stars, even with a detection limit of $G = 20$ mag. This gives a lower read out noise and much less data to be transmitted to ground.

The G magnitude is measured with no filter so that the whole CCD sensitivity range is utilized. This applies for all CCDs except those in the broad-band photometer, BBP, and the medium-band photometer, MBP, and the G magnitude is nearly equal to the V magnitude for most stars, *cf.* Sect. 6.4.2 of [1].

The charge content of the pixels is read out from the serial register of the CCD in samples where the charges of several pixels have been added or 'binned'. The sampling or binning in the GAIA telescopes is shown in Fig. 1. The sampling is identical to that in Fig. 3.7 of [1], except that a smaller sample is proposed in Astro-2 for multi-colour photometry of galaxies according to [5], and an error in the drawing of the SSM has been corrected.

The patch of 25 samples from the third Astro sky mapper, ASM3, covers an area somewhat larger than the Airy disk. About 130 such patches for each detected star will result from a five year mission. Analysed together they will provide a mapping or imaging in a field of 1 arcsec diameter as indicated in the lower right of the figure.

Imaging in an area about 2 arcsec diameter can be obtained with the patches from the CCD # 17 in the astrometric field, AF17. This imaging is obtained in white light, *i.e.* the whole sensitivity range of the CCD. The final analysis can assume that the positions of patches on the sky is known with sub-milliarcsec accuracy since a global astrometric and photometric analysis will be carried out, *cf.* Sect. 3.2. This is the reason why stars as faint as $G = 23$ mag can be detected, which is important because they could disturb the photometry and astrometry of the central star. When these stars are detected they can be taken into account either for a correction or rejection of the main star. All these stars will obtain broad-band photometry with the patches from Astro-1 and Astro-2.

It is noted that the 16 samples in Astro-1 BBP1-4, the four CCDs for broad-band photometry, are read out with 8 pixels length across scan as indicated in the figure. Before transmission the outer 10 samples are reduced to 4 samples by numerical addition of 2 or 3 samples, *cf.* Sect. 3.2.

The samples in the Spectro telescope are shown at lower left. All pixels in the CCD of the SSM are read out and the samples are used for the detection. The 14×9 samples in a patch centred on the detected star are reduced to the 14×3 samples by additions as indicated in the figure. The 100 patches per star during the mission will be used for an imaging of an area of 7 arcsec diameter. Again, stars about $G = 23$ mag can be detected, and they can obtain medium-band photometry. The angular resolution will be about 0.5 arcsec, not as high as in the Astro telescopes.

2.1 Optimization

The sampling shown in the figure is a compromise between the wish to get the best possible angular resolution and astrometric and photometric accuracy, and the contraints of read out noise and transmission rate. The development of the scheme during two years of the GAIA study is documented in about twenty technical reports from Copenhagen University Observatory, cited in [1]. This optimization was done mainly by simple considerations, it should be

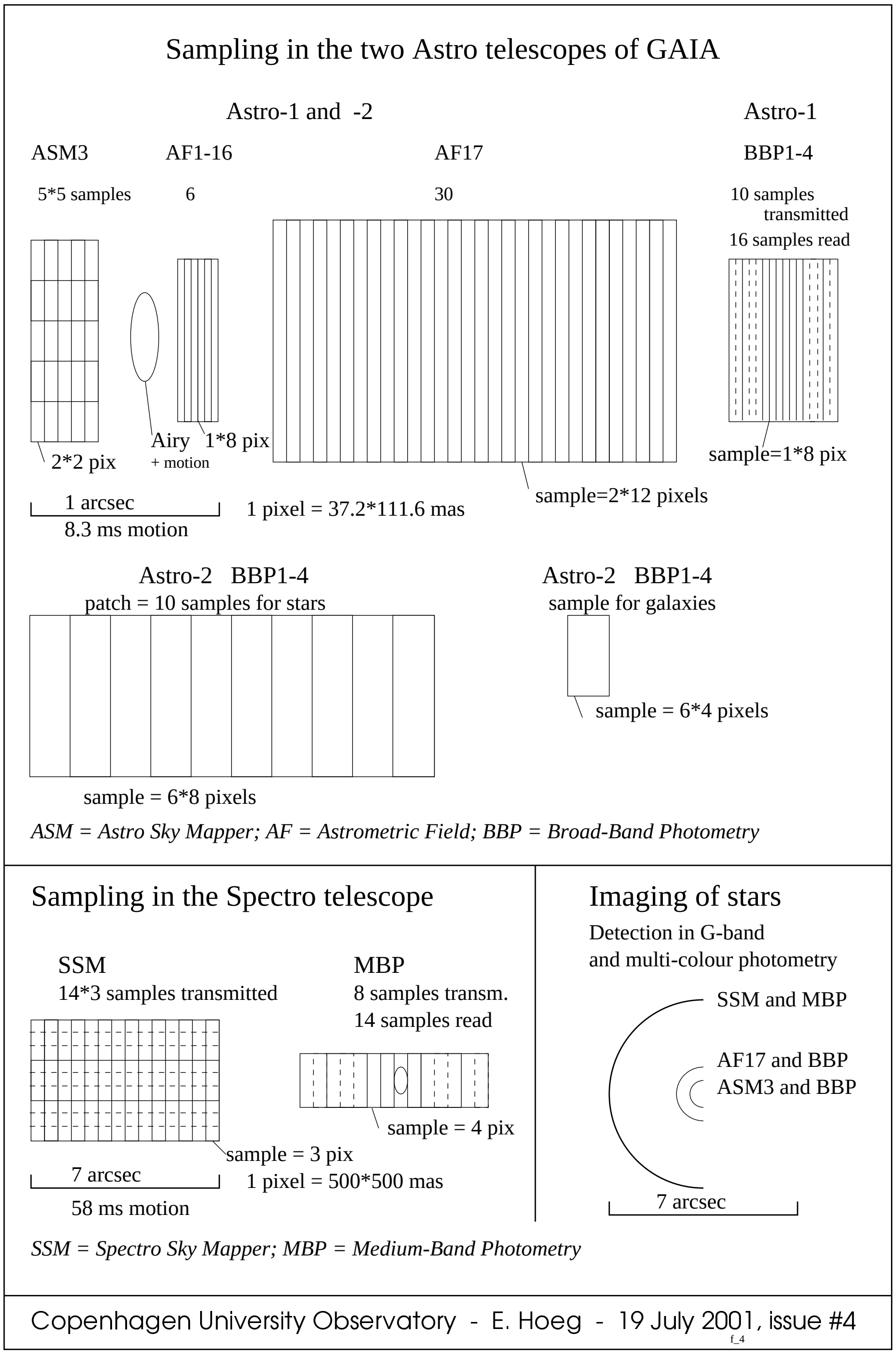

Fig. 1. Sampling in the Astro and Spectro telescopes. The patches of samples are obtained from left to right, chronologically as a star crosses the field of view, but the star is at a fixed position in each patch. The sampling is identical to that in Fig. 3.7 of [1], except that a smaller sample is shown here in Astro-2 for broad-band photometry of galaxies, according to the results in [5].

verified and possibly improved during the preparation phase of GAIA, e.g. by simulations of double and multiple stars. The mathematical formulation of the data analysis in [6] is a good starting point, though the detection of disturbing stars by means of ASM3, AF17 and SSM has not yet been implemented.

An optimization on difficult cases of, e.g., very high star density, must not endanger the performance on the vast majority of objects, which are in fact single or double stars in a nearly empty sky. The difficult high-density areas cover perhaps so small a fraction of the sky that they could be observed by ground- or space-based instruments with a smaller field pointed for longer integration time. All instruments have certain limitations, even GAIA, but GAIA performs well at star densities up to 2 million stars per square degree brighter than $G = 20$ mag, *cf.* Fig. 6.6 in [1]. The imaging performance on extended sources, e.g. quasars, compact galaxies, or in star forming regions deserves especial attention. An optimization of the sampling must take into account in a balanced way the whole scientific case of GAIA described in the 100 pages Sect. 1 of [1].

3 CALIBRATION OF SENSITIVITY

The internal photometric calibration is discussed in Section 7.5 of [1] where it is shown that a calibration with sub-millimag accuracy should be possible. The calibration is not done from observations of ‘standard stars’, *i.e.* stars with accurately known magnitudes and/or colour indices in some well-defined photometric system. Such standards will almost exclusively be used to define the overall zero points of the various magnitudes scales. Most of the calibration is done by means of anonymous stars, distinguished only by their (presumed, and eventually confirmed) constancy from one transit to the next, and that they are generally well-behaved, e.g. not obviously double. Thus, literally millions of suitable calibration stars are available scattered over the whole sky. The transits of the same constant calibration star across two different CCDs, or along two different pixel columns on the same CCD, produces a condition equation relating to the photometric responses of the two CCDs or columns.

The response of a CCD is not constant and not a linear function of the stellar flux. It varies with the position of the star on the CCD, and from one CCD to another, and it varies with time during the mission. It can also vary with the immediately preceding history, for instance if a very bright star has recently crossed the same part of the CCD, but this short-term after-effect is not discussed here. Nor is the effect of cosmic rays or blemishes.

Thus, the CCD is here assumed to have a slowly varying and non-linear response. The sensitivity is essentially a one-dimensional function of the cross-scan position on the CCD since the other dimension is integrated by the TDI motion across the CCD.

Defining I : observed count rate, and m : calibrated apparent magnitude, we have by definition

$$m = f - 2.5 \log I \tag{3.1}$$

where f is the calibration function to be determined for each band.

We furthermore define j : number of the spectral band, k : number of CCD for the given spectral band, y : cross-scan coordinate on the CCD, and t : epoch of the observation. Photometric calibration then means to determine the functions $g(j,k,y,t;m)$ and $\Delta g(j,m)$ in the equation

$$f = g(j,k,y,t;m) + \Delta g(j,m) \tag{3.2}$$

This requires iterations since the calibrated magnitude m appears as argument on the right hand side. Each iteration requires two steps, the first is to determine or improve the g function by use of the constant calibration stars in intervals of perhaps 1 mag size. In each of these intervals the constant stars will be used to derive the function $g(j,k,y,t;m)$. These functions must be derived for the central part of the stellar images and for the spikes as sampled by the patches described in the following section.

The second step is to determine or improve the function $\Delta g(j,m)$ by means of the spikes. The final iterated g function used in Eq. 3.2 will correct an observed count rate of a constant star to a magnitude which is independent of the time of observation and of where in the focal plane the observation took place. The Δg function will correct for an error of the magnitude scale.

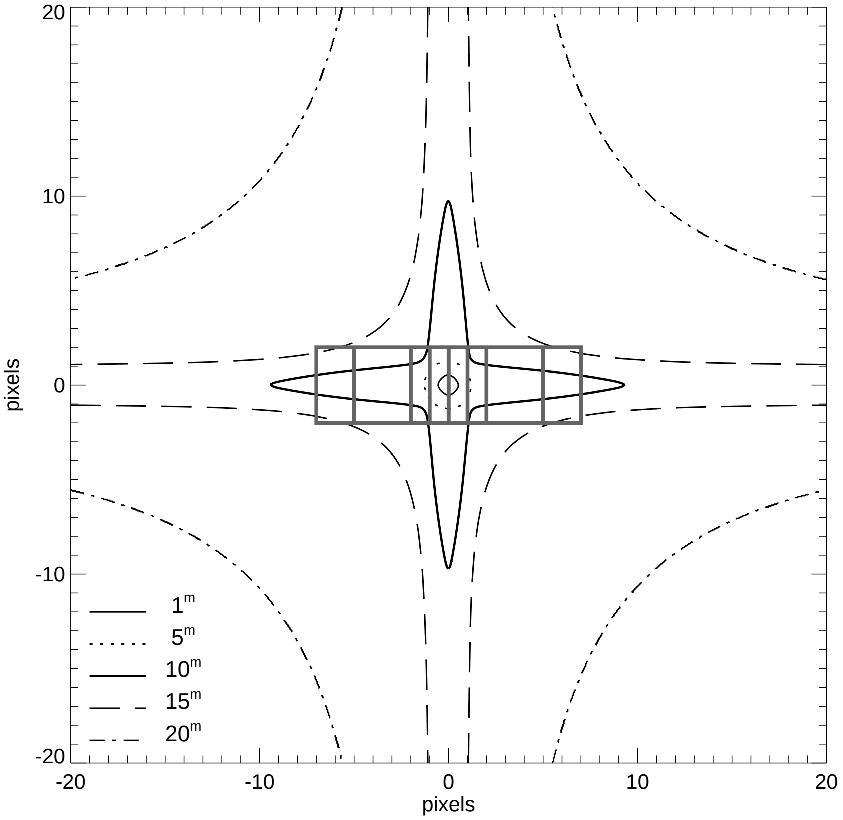

Fig. 2. The PSF in the Spectro telescope at 350 nm for a 40 nm (FWHM) filter (see [7]). The transverse motion of the star and the TDI smearing have been taken into account, curves of equal attenuation in [mag] are shown. The patch of 8 transmitted samples is indicated.

3.1 The spikes

The rectangular entrance pupil of the GAIA telescopes creates diffraction images of the stars with spikes which can be used in the calibration process. Circular pupils would have been unsuited for this purpose. An example of a point-spread-function is shown in Fig. 2. We propose to use the vertical spikes for calibration purposes, but not the horizontal ones since

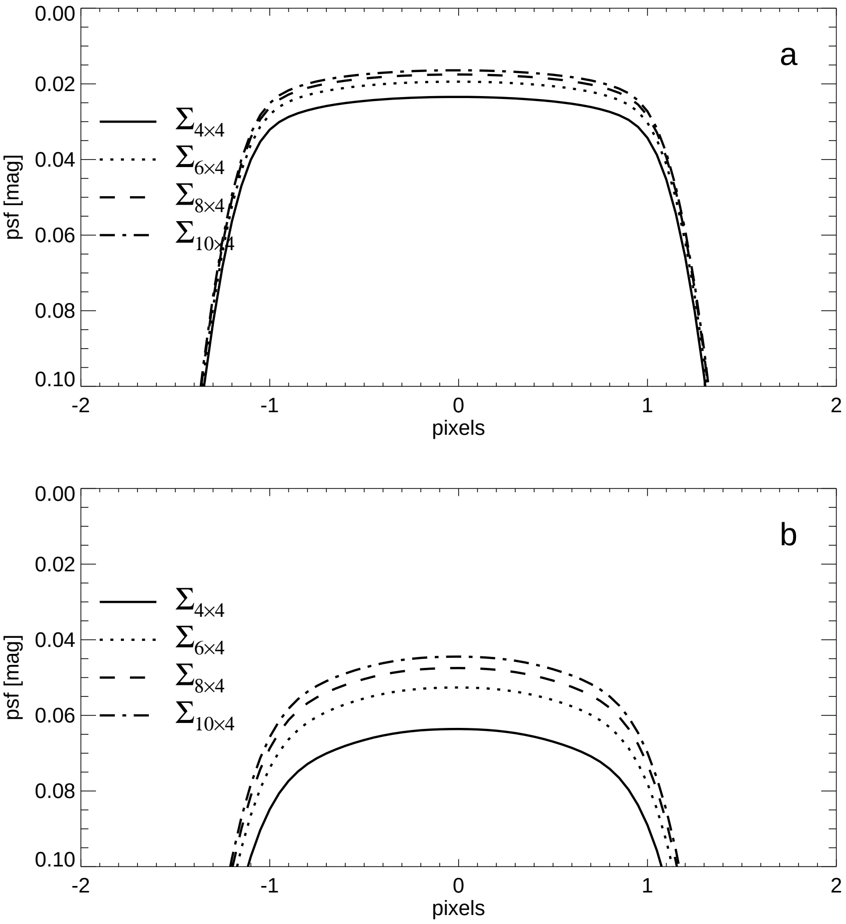

Fig. 3. The running sum through the PSF when sampled by $n \times 4$ pixels, versus the vertical offset of the image from the centre of the patch. Central wavelength and width in [nm] of the filter band are in (a): 350, 40, and in (b): 940, 20. It appears, e.g., in (a) that 0.025 mag, *i.e.* $\simeq 2.5$ per cent of the light of a centred image at 350 nm falls outside the four central samples covering 4×4 pixels. This fraction is 0.065 mag at 940 nm according to (b).

the trailing spike can be affected by a bright central part. The profile along a horizontal line anywhere in the central image or in the vertical spike has the same form. Such profiles differ only by a shift of a certain magnitude which can be theoretically calculated from the entrance pupil, focal length, transmission of the filter, and CCD sensitivity. Naturally, the final calculation of the PSF must be based on a verification using comparison with real GAIA data to improve the theoretical formulae for this calculation.

It is possible to use photometry of the spikes to determine the calibration functions $\Delta g(j, m)$ if the spikes are sufficiently sampled, and a realistic scheme is proposed here. The stars need not be constant for this part of the calibration but they should not be double. The vertical spikes are also useful for astrometry of bright stars, which is mainly relevant in the Astro tescopes.

Table 1. Sampling in the medium-band photometer of Spectro. N_p is the number of patches per star taken for the proposed percentage of stars. N_s is the resulting number of star transits for which spikes are sampled, compared with the number of transits without spikes given in the last line. The last three columns give the approximate attenuation in the patches on the spikes at 940 nm.

				Attenuation		
G mag	N_p patches	Percentage of stars	N_s 10^8 transits	#1	#2 mag	#3
0 - 9	7	100	0.1	5	7	8
9 - 14	3	100	12	5	-	-
14 - 16	5	0.5	0.5	5	7	-
16 - 20	3	0.05	0.5	5	-	-
12 - 20	1	100	without spikes: 1000	-	-	-

Stars are always observed by the patch shown in the figure giving 8 samples to be transmitted to ground. It is proposed for some stars to take two more patches, one below and one above that shown in the figure. The attenuation in each patch is about 5 mag at 940 nm compared to the central patch, according to [7]. With an attenuation of a factor 100 per patch, the two patches together give a standard error in astrometry and photometry which is $\sqrt{100/2} \simeq 7$ times higher than of the central patch. For shorter wavelengths the attenuation is higher and the factor correspondingly higher.

For bright stars it is proposed to take up to 3 pairs of patches on the spikes, *i.e.* 7 patches alltogether. The sampling proposed in Table 1 serves three purposes: the calibration of magnitude scale, the measurement of very bright stars where the central parts will be saturated, and the measurement of double stars with large magnitude difference where the faint component may be well sampled by the extra patches.

The resulting telemetry is obtained as $N_p \times N_s$. It thus appears that the proposed sampling would increase the telemetry from the medium-band photometry by about 4.0 per cent. It is useful for the various purposes of photometry to sample all stars to $G = 14$ mag with 3 patches as in the table, although for calibration it would be sufficient to go to 12 mag. Saturation sets in at $G \leq 12$ mag in the medium-band photometer according to Fig. 8.9 in [1]. With the proposed sampling and the attenuations given in the last columns of the table it should be possible to extend photometric measurements to $G = 3$ mag, and to calibrate the magnitudes from $G = 3$ to 23 mag.

A similar sampling should be introduced in the Astro instruments, perhaps with more than 7 patches for the brightest stars in order to obtain astrometry of them, even without the special CCD options for this purpose described in [1].

The patches on the spikes are always considered in pairs since the total flux in a pair is quite insensitive to a small decentering of the stellar image. This flux is shown in Fig. 3 versus offset of the image which will mostly be less than 0.5 pixel, and will never exceed 1 pixel. The offset will be known with milliarcsec accuracy at the final photometric reduction and can therefore be taken into account.

3.2 PSF and aperture photometry

The photometric data analysis is carried out on the ground as outlined in Sect. 9.4.2 of [1]. A 'local PSF fitting' is carried out on each of the patches, using the position of the star given by

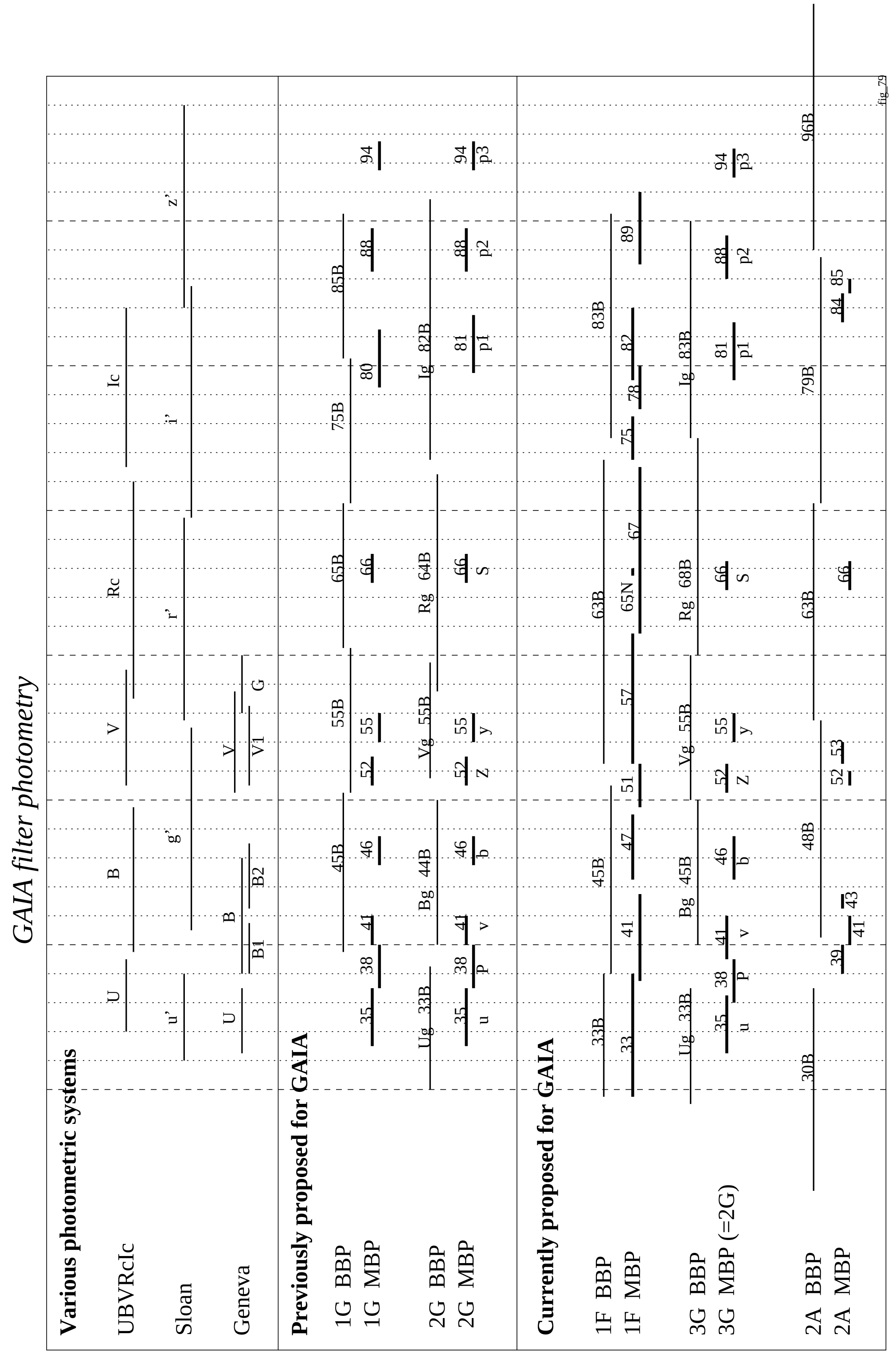

Fig. 4. Overview of photometric systems. Each band is shown with its width at half maximum (FWHM).

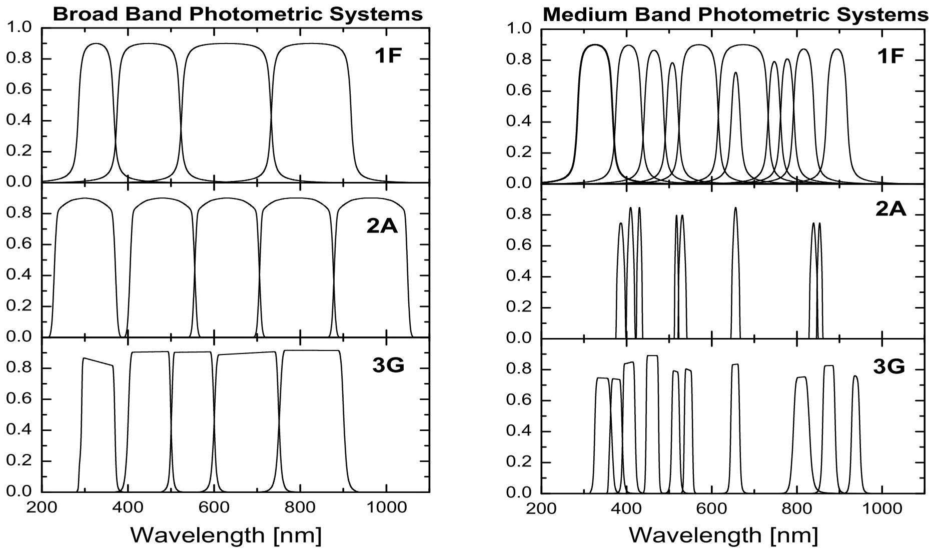

Fig. 5. The three proposed photometric systems for GAIA photometry. Further studies shall lead to one optimal system to be implemented on GAIA.

the star mapper. Such preliminary photometric data can be used for verification purposes and for scientific studies, e.g. of supernovae and other sudden events.

The final photometric analysis applies 'global PSF fitting' utilizing a known PSF, all astrometric information of the stars, and the satellite attitude so that only the magnitude of each star and the background is determined from the patches for the stars obtained during the mission. Also one or a few transits of a star may be analyzed in this way in order to obtain epoch photometry. A mathematical formulation is given in [6].

It should be noted that the term 'PSF fitting' used here differs from that used in, e.g., DAOPHOT processing where a functional form of the PSF is defined from well-exposed stars on the exposure, and is then used for other fainter stars on the same exposure to determine the flux and the position of the image.

In general, the fitting shall use the 10 or 8 transmitted samples for respectively BBP and MBP photometry as shown in Fig. 1. It is however possible to add, e.g., the central transmitted samples, except the two outer ones, into one new sample, and then make PSF fitting with three samples: the new one and the two outer ones. This is called 'aperture photometry'. The advantage of aperture photometry is that an uncertainty in the assumed PSF, for instance because the star is double, will have less effect on the photometric result because nearly all the star light is contained in the new central samples of the patches for all stars brighter than $G = 14$ mag according to Table 1. For bright stars the two outer samples will be sufficient for the background determination.

The curves in Fig. 3 are provided for discussion of the proper size of the two outer samples in the on-board compression. With the present sampling they each contain two samples read out from the CCD, leaving a central sample of 10×4 pixels for aperture photometry. The distance between the corresponding curve in the figure and that for 8×4 pixels is only 5 millimag at 940 nm (part *b* of the figure). This indicates that the proposed sampling is adequate.

The disadvantage of aperture photometry is that stars in the surroundings will affect the new central samples. This can at least partly be taken into account by means of the result from a previous PSF photometry, or the particular result may be flagged as disturbed, or it may be rejected from further use.

PSF and aperture photometry should be applied to all bright stars and can presumably give sub-millimag accuracies for many stars if they are relatively well-behaved, for instance not double.

4 PHOTOMETRIC SYSTEMS

The choice of filters for GAIA photometry is extremely important considering that GAIA multi-colour photometry will be the only astrophysical information available for most of the brightest one billion stars on the sky during the next perhaps fifty years. No other project on ground or in space could presumably compete with GAIA with respect to all-sky photometry. Thus GAIA photometry seems to be as unique as GAIA astrometry.

Figure 4 gives an overview of various photometric systems, $UBVR_cI_c$, Sloan, Geneva and the systems proposed for GAIA as of July 2001. At present three filter systems are proposed, shown in Fig. 5. The 1F system is the (provisional) baseline system described in [1]. The 2A and the 3G systems represent somewhat different basic ideas, and were proposed in respectively [8] and [9]. The medium bands in the 2G and 3G systems are identical and consist of three red bands plus the seven band Strömvil system which combines the Strömgren *uvby* and the Vilnius systems. The three systems in Fig. 5 are now being compared within the GAIA Photometry Working Group (see [10]) in order to derive an optimal system which can best serve the GAIA mission. The optimal system will probably have five broad and about ten medium bands.

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