Sampling in Astro
of bright stars and double stars

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Abstract

We discuss sampling for astrometry and photometry in the Astro telescopes. Astrometry of bright stars should make use of the cross-scan spikes. Sampling of the spikes is specified for all stars with $2 < G < 12$ mag at the expense of 3 per cent more telemetry from the astrometric fields. The advantages are higher astrometric accuracy, better mapping of double stars, avoiding selectable gate phases on the CCDs, and the onboard control becomes simpler. Astrometry and photometry of narrow double stars require larger sampling windows and about onboard detection of duplicity. Larger windows for all stars with $G < 16$ mag are specified at the total cost of 13 per cent more telemetry from the astrometric fields. Onboard detection of duplicity may then only be needed for fainter stars resulting in perhaps 10 per cent increase of telemetry, but the benefit of such detection is being discussed. Larger windows are also specified for broad-band photometry, resulting in the same relative increase of telemetry of about 20 per cent in total for astrometry and photometry in Astro. A strategy for onboard allocation of windows for single and double stars is proposed. A strategy for transmission of data in suitable blocks is also proposed.

1 Introduction

Use of the diffraction spikes for the calibration of medium-band photometry in the Spectro telescope has been discussed in GAIA-CUO-091 [7]. We shall here discuss the spikes in the Astro telescopes and show how they can be used for astrometry of the bright stars from $G = 2$ to 12 mag which latter magnitude is where the CCD becomes saturated. We shall specify a sampling which at the same time is sufficient for all narrow double stars with $G < 16$ mag. A similar sampling is specified for the broad-band photometer (BBP).

Strategies for onboard allocation of windows to single and double stars, and for transmission of data are proposed

The following description is focussed on the new design, i.e. CUO-100, Issue #3, but the description of CUO-100, Issue #2 is partly retained here for the sake of easy comparison, and also because some of its features (e.g. the alternating centering) may still be of interest even though they are abandoned in Issue #3.

1.1 CUO-100, Issue #2

The following changes or additions have been made since Issue #1.

1. Extension of the magnitude range to $G = 2.0$. An astrometric error from photon noise about 2.0 μas for $G = 2$ to 12 mag is expected. (Minor changes of the numbers in Tables 1 and 2 by more accurate calculations.)

2. Virtual extension of windows in AF to 16 pixels along scan instead of 12 by alternation of centering (see Figs. 1b and 5a).

3. Window allocation for double stars is improved (see Figs. 5b,c,d and Sect. 5). A strategy for onboard allocation of windows for single and double stars is proposed.

Table 1: Astrometric errors with the sampling proposed in Issue #2 of CUO-100; the errors with the sampling in Issue #3 will generally be smaller than given in Column 7. The columns contain G: magnitude; A_G: required attenuation if the CCD pixel saturates at $G = 12.0$ mag; y_{sat}: ordinate of the uppermost saturated pixel (see the scale at left in Fig. 1b); y_{max}: the maximum non-saturated interval of the given window; F_1: fraction of total flux in this interval; F_e: total counts per CCD in the interval; σ_{ph}: resulting photon noise error; y_{min}: the minimum non-saturated interval of the given window; the resulting flux and astrometric error from photon noise. The total astrometric error is $\sigma_{tot} = \sqrt{\sigma_{ph}^2 + 1.4^2}$.

G	A_G	y_{sat}	y_{max}	F_1	F_e	σ_{ph}	y_{min}	F_1	F_e	σ_{ph}
mag	mag	pix	pix	1	1000e-	μas	pix	1	1000e-	μas
2	10	45					W0: 48-56	.0007	3717	0.8
3	9	26	W0: 28-56	.0037	7810	0.5	W1: 28-32	.0009	1900	1.0
4	8	16	W1: 16-32	59	4965	.6	W1: 20-32	36	3029	0.8
5	7	11	W1: 12-32	99	3316	.8	W2: 16-20	23	770	1.6
6	6	7	W2: 8-20	142	1894	.8	W2: 12-20	63	840	1.6
7	5	4	W2: 4-20	376	2000	1.0	W3: 6-12	158	839	1.6
8	4	3	W3: 4-12	313	661	1.8	W3: 4-12	313	661	1.8
9	3	2	W3: 2-12	789	664	1.7	W4: 4-8	234	197	3.2
10	2	1.5	W4: 2-8	710	238	2.9	W4: 2-8	710	238	2.9
11	1	1	W4: 1-8	.2245	300	2.6	W4: 2-8	.0710	95	4.6
12	0	–	W5: 0-4	.9501	505	2.0	W5: 0-4	.9501	505	2.0

4. Calibration of the filter passbands is proposed in Sect. 6 besides of the previously discussed calibration of the magnitude scale.

5. A strategy for transmission of data in suitable blocks is proposed in Sect. 8.1.

6. The strategies for window allocation and data transmission came naturally during the design of the new sampling, almost as necessary consequences and fully consistent with the new proposed sampling. The strategies were thus designed from scratch, without consulting any documents from the simulation working group, and in this manner we have perhaps a good basis for coming discussions.

1.2 CUO-100, Issue #3

The following changes or additions have been made since Issue #2.

1. The patches now always contain 16 samples, thus the alternating centering is dropped for the sake of simplicity.

2. The total number of patches for stars brighter than 12 mag has been changed from 5+5 to 3+3, and all samples now have the same size of 4 pixels across scan.

3. The 3 patches above or below centre are placed at a distance of Y pixels from the centre where Y is derived directly from the counts in ASM1 on the vertical spikes.

4. The total cost of these changes is 3 per cent extra telemetry for the astrometric fields compared to Issue #2, cf. the last lines of Tables 3 and 4.

5. The mapping with AF17 and A2BBP is discussed in a separate Sect. 3.4

6. Physical double stars obtain a separate Sect. 4.3.

7. The window allocation is improved in Sect. 5.

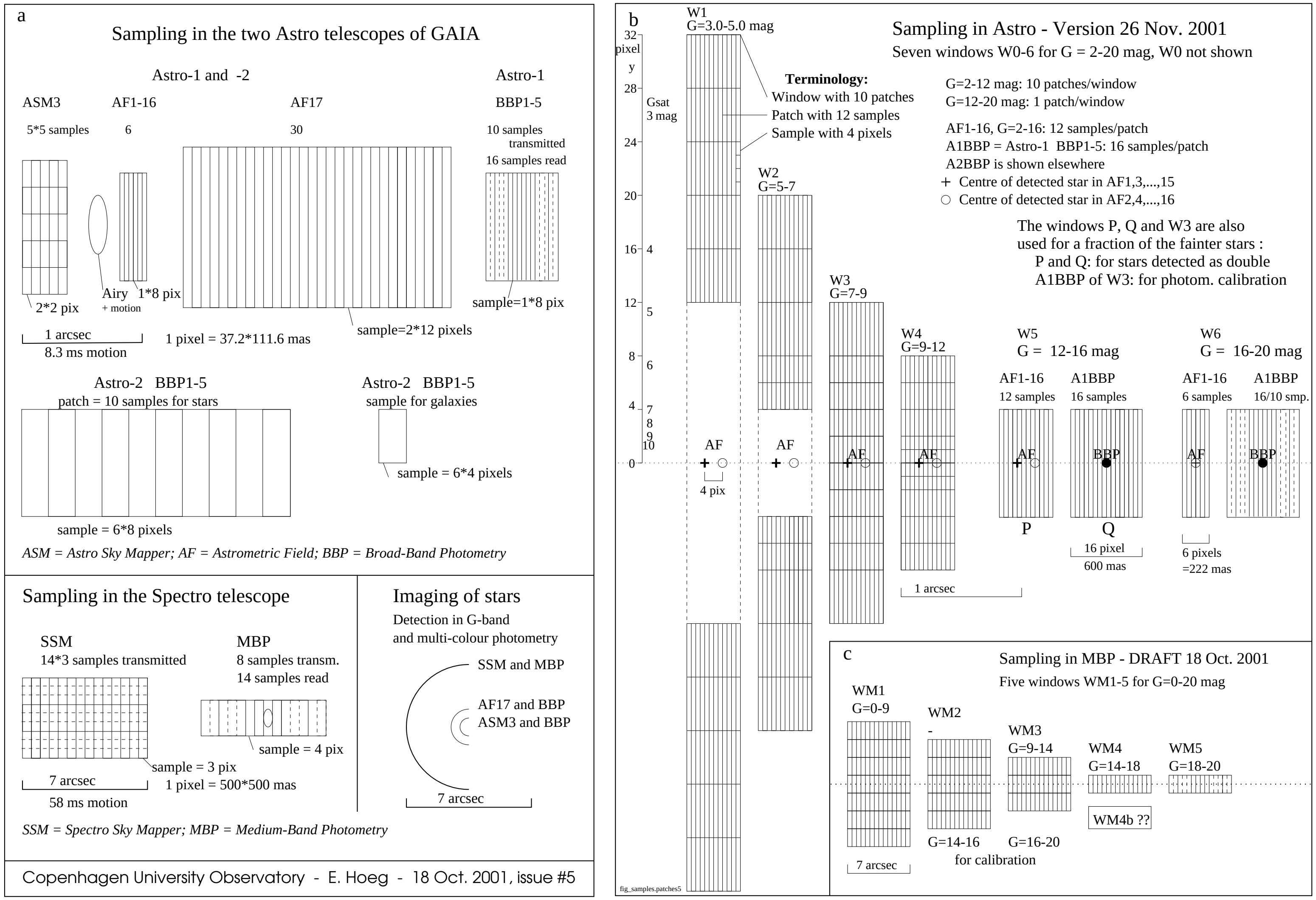

Figure 1: Sampling in the focal planes of GAIA as proposed in Issue #2 of CUO-100. **a:** Sampling in Astro and Spectro according to the GAIA baseline. **b:** Sampling for Astro proposed in CUO-100.2 for the benefit of bright stars and double stars. **c:** Draft of sampling in the medium-band photometer, to be discussed in another report.

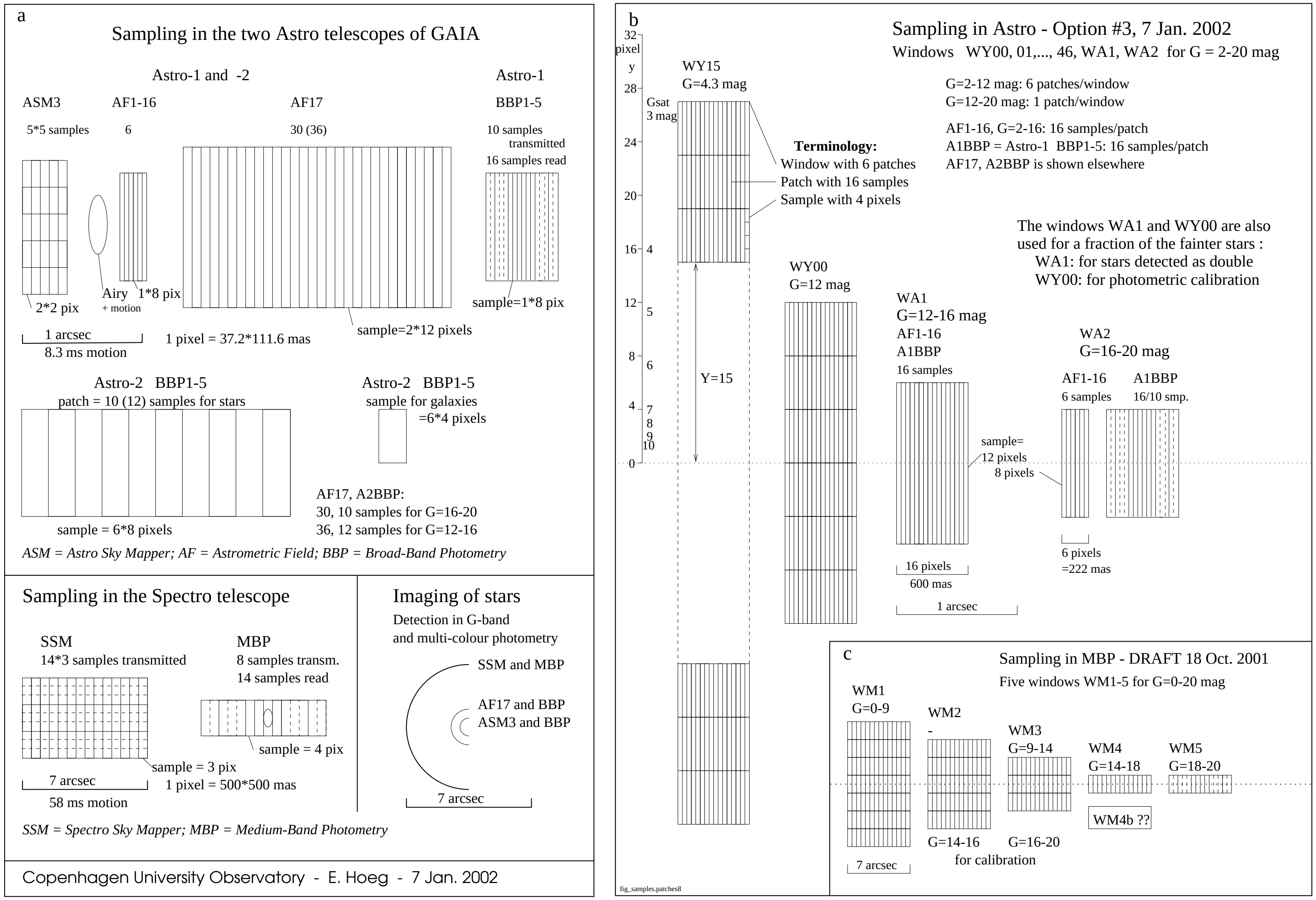

Figure 2: Sampling in the focal planes of GAIA as proposed in Issue #3 of CUO-100. **a:** Sampling in Astro and Spectro according to the GAIA baseline. **b:** Sampling for Astro proposed in this report for the benefit of bright stars and double stars. **c:** Draft of sampling in the medium-band photometer, to be discussed in another report.

Table 2: Fraction F of total flux from the star above y and below $-y$ taken together, in accordance with Fig. 4.

y [pixel]	0	1	2	3	4	5	6	7	8	9	10	12
F [0.0001]	10000	2510	975	679	499	408	344	298	265	238	217	186
y [pixel]	16	20	24	28	32	36	40	44	48	52	56	
F [0.0001]	146	123	107	96	87	80	74	70	66	62	59	

2 Bright stars

The present GAIA baseline design is described in the Gaia Study Report [3], called GSR hereafter. The astrometric accuracy as function of V magnitude is shown in Fig. 3.14. The detector saturation level in the astrometric field is reached at about $V = 11.6$ mag for a G2V star. The standard error increases towards fainter magnitudes governed by photon noise.

The astrometric error remains almost constant in Fig. 3.14 at about 2.7 microarcsec for brighter magnitudes up to $V = 3$ mag. This is obtained by the use of shorter integration times than the standard 0.86 s so that saturation is just about reached for all brighter magnitudes. Implementation is done by a number of selectable gate phases on each CCD. The gate phase is selected according to the G magnitude observed in the ASM. This means that all other stars on the CCD will also obtain the shorter integration time. As a result the surrounding area of a bright star will suffer from a shorter integration, corresponding to about 1 s scan or 120 arcsec, and the same across the scan. Stars in this area will therefore get rather poor observations due to the shorter integration.

If the spikes are used for the bright stars as proposed below, the gates become superfluous, the complication of selecting them and the non-uniform integration of the surrounding area will disappear. Furthermore, the feasibility of the selectable gates has not been assured.

2.1 Detector saturation

We shall in this report speak of the detector saturation level as the GSR does. But this needs closer consideration when we get the expected report from A. Holland about CCDs (see [5]). What really matters is the level up to which the counts are useable for astrometry which requires a certain degree of linearity. When non-linearity starts the standard error of the CCD reading N becomes larger than $\sqrt{N}$, and the correction for non-linearity of the observed PSF becomes difficult.

We believe however that such considerations could only change the proposed sampling in Fig. 2b with respect to the separation Y, to be defined in Sect. 3.3.

In Sect. 3.75 of the GSR the expected full-well capacity is given as 250 000 e- for the CCDs in Astro (the CCDs in Spectro are different). This is a conservative assumption since 400 000 e- could well be assumed according to Holland [5].

The G magnitude where pixel-saturation starts is derived from Fig. 3b. The attenuation along the vertical spike is given, showing, e.g., that the central pixel contains a flux 2.0 mag fainter than the total flux of the star. Assuming a pixel saturation at $G = 12.0$ mag we give in Table 1 and on the left scale in Figs. 1b and 2b the ordinate $y_{\rm sat}$ at which saturation ends at the given magnitude. The required attenuation $A_{\rm G} = 12 - G$ is also given in the table.

We note however that these assumptions in the GSR on pixel saturation are not up to date. The total flux at $G = 12$ mag is 531 000 e-. This gives a maximum at the centre which is 2 mag fainter, i.e. 84 000 e- per pixel. Thus, saturation comes only at 1.2 mag brighter stars.

This implies that the central pixel will not be saturated at $G = 11$ and perhaps not at $G = 10$, as assumed in Table 1, and that $\sigma_{\rm ph}$ will come close to 2.0 μas. This also implies that all limits for the windows for bright stars could be shifted towards 1.2 mag brighter, and even more if Holland's expected 400 000 e- hold. This should be verified in the coming industrial studies.

Table 3: Proposed sampling in Option #2 for the astrometric field and the resulting telemetry. Telemetry for the BBP is specified in Sect. 6. The columns contain $n_{\rm smp}$: Number of samples in the window; G: magnitude interval; $N_{\rm st}$: number of stars on the sky in the interval; $N_{\rm smp}$: total number of samples during the mission ($N_{\rm smp} = 133 \times 16\ n_{\rm smp} N_{\rm st}$). Two different sets of magnitude intervals are shown: one (as in Fig. 1b) giving 10 per cent more telemetry than the baseline design (Fig. 1a), the other 23 per cent more, without yet accounting for onboard detection of duplicity (see Sect. 4).

$n_{\rm smp}$	G mag	$N_{\rm st}$ 10^6	$N_{\rm smp}$ 10^9	G mag	$N_{\rm st}$ 10^6	$N_{\rm smp}$ 10^9	Note
1x6	2-20	1035	13160				Baseline design
10x12	2-9	0.12	30	2-9	0.12	30	
10x12	9-12	2.3	587	9-13	6.0	1526	
1x12	12-16	58	1481	13-17	114	2900	
1x6	16-20	975	12400	17-20	915	11640	
	2-20	1035	14498	2-20	1035	16096	Total
			+10			+23	Relative to baseline

Table 4: Proposed sampling in Option #3 for the astrometric field and the resulting telemetry. Telemetry for the BBP is specified in Sect. 6. The columns contain $n_{\rm smp}$: Number of samples in the window; G: magnitude interval; $N_{\rm st}$: number of stars on the sky in the interval; $N_{\rm smp}$: total number of samples during the mission ($N_{\rm smp} = 133 \times 16\ n_{\rm smp} N_{\rm st}$). Two different sets of magnitude intervals are shown: one (as in Fig. 2b) giving 13 per cent more telemetry than the baseline design (Fig. 2a), the other 27 per cent more, without yet accounting for onboard detection of duplicity (see Sect. 4).

$n_{\rm smp}$	G mag	$N_{\rm st}$ 10^6	$N_{\rm smp}$ 10^9	G mag	$N_{\rm st}$ 10^6	$N_{\rm smp}$ 10^9	Note
1x6	2-20	1035	13160				Baseline design
6x16	2-9	0.12	24	2-9	0.12	24	
6x16	9-12	2.3	470	9-13	6.0	1221	
1x16	12-16	58	1975	13-17	114	3867	
1x6	16-20	975	12400	17-20	915	11640	
	2-20	1035	14869	2-20	1035	16752	Total
			+13 %			+27 %	Relative to baseline

end of centerline

3 Windows and sampling

The sampling in the GAIA baseline is shown in Fig. 2a. We propose in Fig. 2b a new sampling for the astrometric field and the BBP of Astro-1, with sampling in 49 different windows between $G = 2.0$ and 20.0 mag. The new sampling in the BBP applies only to Astro-1 while the sampling with large samples in Astro-2 remains as shown in Fig. 2a.

We apply a terminology indicated at the upper left in Fig. 2b. A *sample* is usually the accumulated charge in a one-dimensional set of pixels across scan. But the set of pixels in a sample is sometimes two-dimensional as in ASM3, AF17, and BBP of the Astro telescope in Fig. 2a. In all cases a sample is a single number when transmitted to ground.

A *transmitted sample* may be identical with a *readout sample* from a CCD with one-dimensional binning as in AF1-16, or with two-dimensional binning as in ASM3 and AF17. But a transmitted sample may also be obtained by addition onboard of several read samples as in Astro-1 BBP1-5 for the faintest group of stars, or in SSM and MBP where the readout samples are indicated by dashed lines.

A *patch* is a one-dimensional set of samples along scan. A *window* is (as in the GAIA Study Report) the complete set of samples transmitted from a CCD for a given star consisting of one or more patches. It is noted that a patch in previous terminology could be two-dimensional and was equivalent to what we now call a window. In the new terminology for instance the SSM window in Fig. 2a consists of 3 patches, each containing 14 samples.

3.1 PSF of Astro

The point spread function at a point in the astrometric field is shown in Fig. 3. The point 09 has been chosen, according to the example given in GAIA-LL-025 [9], at the upper left corner which has the worst wave-front error (WFE), but this error is so small that it has no implications for the following discussion. The effects of TDI motion along scan and of a typical cross-scan motion of 1 pixel per CCD due to the scanning law are taken into account.

3.2 Design of windows in Issue #2

The sampling in seven intervals of magnitude (see Fig. 1b) is designed to cope with bright stars, double stars, and photometric calibration in a reasonably economic manner with respect to telemetry as explained in this and following sections.

The windows of sampling are sufficiently large in the cross-scan direction to contain enough of the spikes for bright stars. The windows are large enough along scan, 12 pixels in the AF and 16 in the BBP, to contain narrow double stars down to $G = 16$. For fainter stars the GSR baseline sampling is maintained. The sampling is designed so that the telemetry is only increased by 10 per cent which should be acceptable in view of the great advantages. The telemetry for astrometry is specified in Table 3, and that for the BBP in Sect. 6.

The windows for the AF have a width of 12 pixels and the centering changes from one CCD to the next for $G < 16$ mag so that a length of 16 pixels along scan is in fact covered. This is illustrated in Fig. 5a and the advantage for double stars is discussed in Sect. 5.

The cross-scan width of the windows is designed by means of the thin curve in Fig. 3b. The curve shows a change of attenuation by 9.0 mag from 2.0 mag at the centre to 11.0 mag at 26 pixels from the centre, which means that the upper and the lower patch in the window W1 contain unsaturated pixels for $G = 3$ mag. The total flux in these two patches, F_e, and the resulting photon statistical astrometric error σ_{ph} is given in the second line of Table 1.

It is noted that the window W0 is not shown in Fig. 1b for lack of space, but it is similar to W1 with separations at y =24, 28, 32, 40, 48, 56. This window covers the interval $G = 2.0$ to 3.0 mag containing about 123 stars on the entire sky.

The central part of the three brightest windows, W0, W1 and W2, are omitted because the patches are saturated and therefore considered to be useless. This view could change when we analyse with a continuous CCD response, but the windows proposed here should probably be maintained, for two reasons. The astrometric accuracy is ample as σ_{ph} in Table 1 shows, and it is practical to have the same number of 10 patches per window for

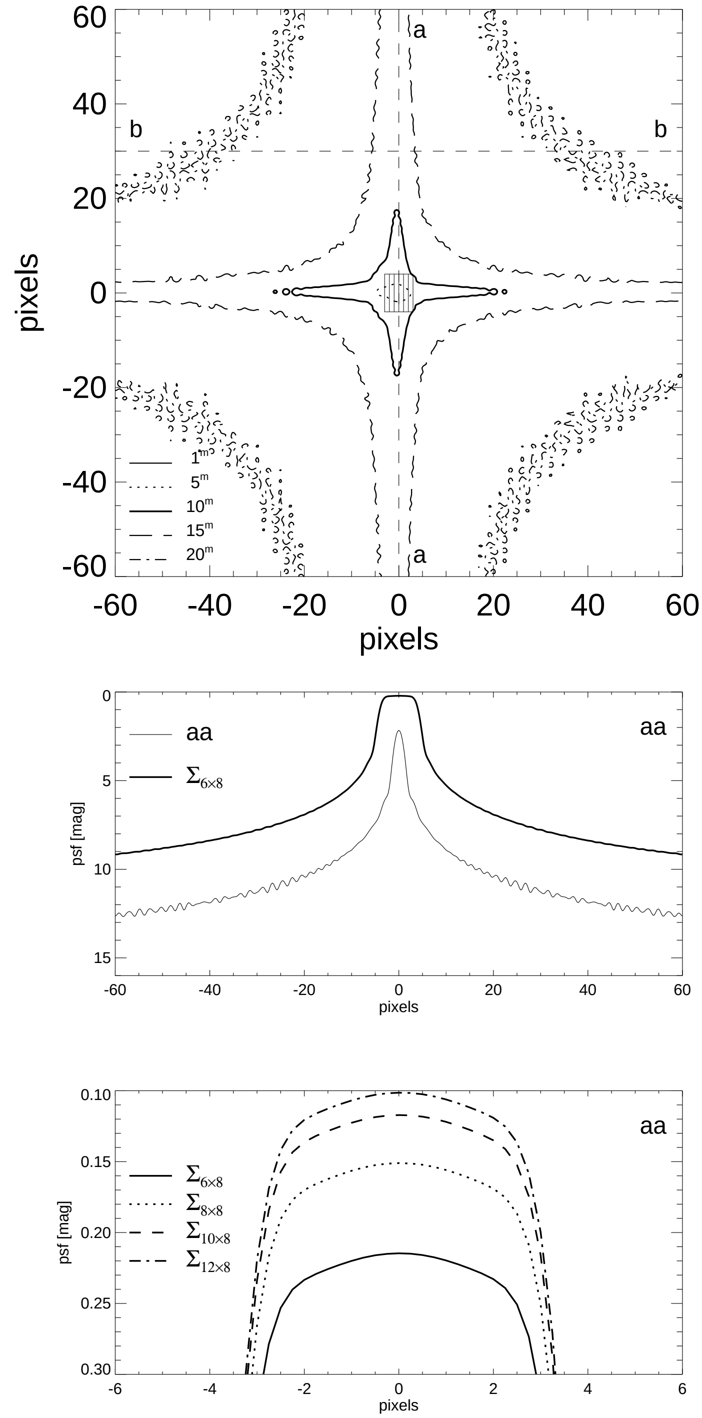

Figure 3: The PSF at the upper left corner of the astrometric field for a star with $V - I =$ 1.0 mag. From top, **a**: The PSF, note that the innermost (dotted) curve is for the attenuation of 5 mag. **b**: Attenuation along the vertical spike (aa), thin curve is for one pixel, fat curve for the light integrated over an area of 6x8 pixels, i.e. the central 6 samples of the patch. **c**: A magnification of the central part of the attenuation curve above, including also areas of 8x8, 10x8 and 12x8 pixels.

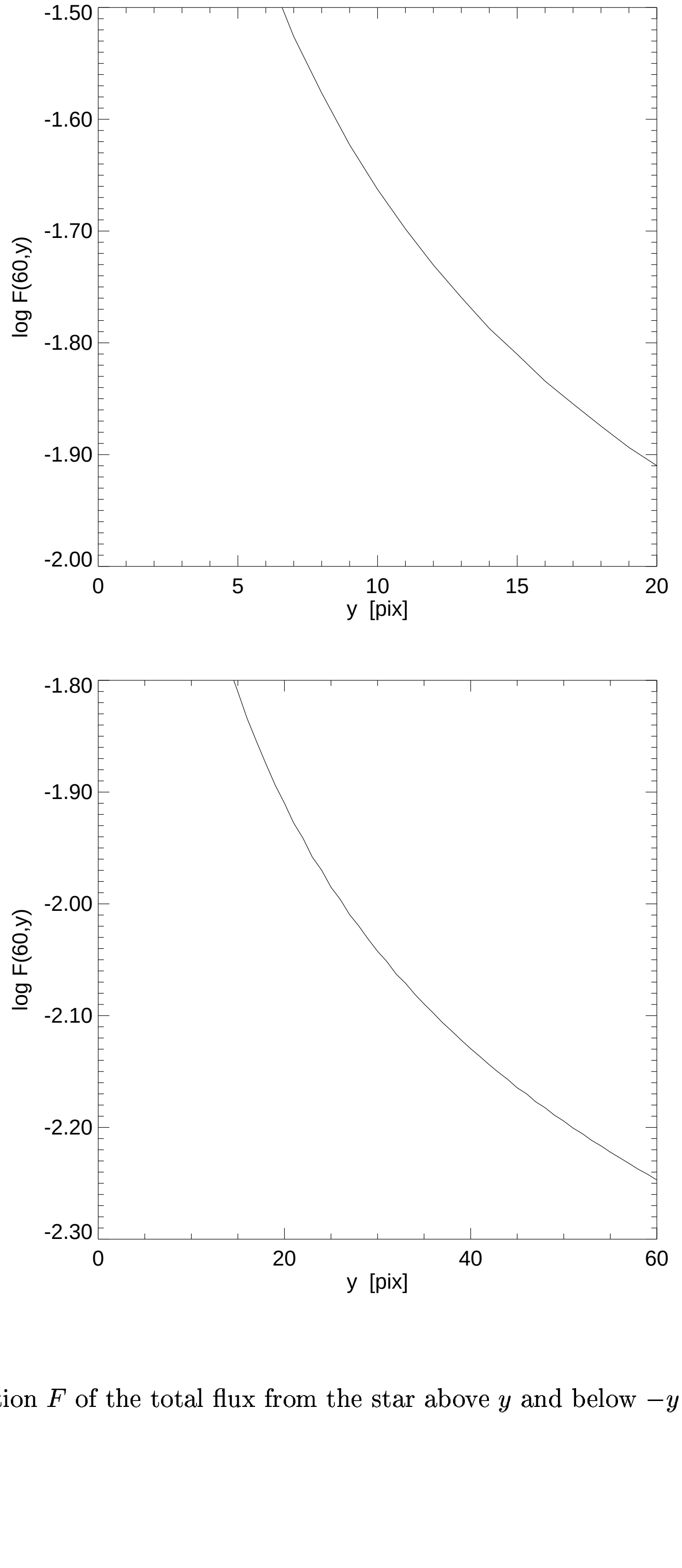

Figure 4: Fraction F of the total flux from the star above y and below $-y$ taken together.

all bright stars. The number of simultaneously read patches per CCD must at present not exceed 12 in the astrometric field according to Table 3.16 in the GSR.

The fluxes in Table 1 are computed by means of the values in Table 2 which are derived from Fig. 4. Table 1 gives a maximum and a minimum value for the photon error using two extreme assumptions for the available unsaturated patches. A star of $G = 5$ mag, e.g., may be measured in either of the windows W1 or W2 resulting in different useful fluxes.

Figure 3.14 of GSR shows a standard error of 2.5 μas at $V = 12$ mag. This includes 1.4 μas biases. Quadratic subtraction of this bias leaves an error due to photons of 2.0 μas. The total flux at $G = 12$ mag during the 0.86 s integration of a CCD is here assumed to be 531 000 e-. The photon statistical astrometric error is then $\sigma_{\rm ph} = \sqrt{531\,000/F_{\rm e}} \times 2.0$ μas given in Table 1. The assumed counts at $G = 17$ differs only insignificantly from the value 545 000 e- given in the GSR [3], Table 8.1.

It appears that a satisfactory astrometric error is obtained for all bright magnitudes, mostly better than that expected with selectable gates. The errors are larger than 2.0 μas for $G = 10$ and 11 but this problem should disappear when using realistic curves of CCD response instead of the saturation concept (see Sect 2.1).

A higher cross-scan resolution of 1, 2 or 4 pixels per patch is provided in the windows W0-4 and with several advantages. The compelling reason to have the higher resolution near the centre is the steep slope of the central parts of the PSF. If a pixel at the axis is saturated the sample to which it belongs will be useless, and also the patch. The high resolution at the axis is obviously an advantage for the measurement of double stars. It would not be an advantage to have high cross-scan resolution in the whole window, and it is prohibited by the maximum number of 12 patches per CCD in the GSR baseline.

3.3 Design of windows in Issue #3

We propose to transmit 3+3 patches for stars brighter than $G = 12$ as shown in Fig. 2b. The total number of patches for bright stars has been changed from 5+5 in CUO-100.2 to 3+3, and all samples now have the same size of 4 pixels across scan.

The separation Y is derived directly from the samples read in ASM1 on the vertical spikes such that no sample in the transmitted patches will exceed a given limit. This limit can be defined before launch based on the known linearity properties of the CCDs. It is noted that Y will depend not only G, but on G and $V - I$ for a given star. The derivation of Y directly from the ASM1 measurements is not based on any assumption of these stellar quantities.

The sampling with 49 different windows, WY00-46, WA1 and WA2, is designed to cope with bright stars, double stars, and photometric calibration in a reasonably economic manner with respect to telemetry as explained in this and following sections.

The windows of sampling are sufficiently large in the cross-scan direction to contain enough of the spikes for bright stars. The windows are large enough along scan, 16 pixels in the AF and the BBP, to contain narrow double stars down to $G = 16$. For fainter stars the GSR baseline sampling is maintained. The sampling implies that the telemetry is only increased by 13 per cent from the astrometric fields which should be acceptable in view of the great advantages. The telemetry for astrometry is specified in Table 4, and that for the BBP in Sect. 6.

The cross-scan width of the windows is designed by means of the thin curve in Fig. 3b similarly as in Issue #2. The resulting photon statistical astrometric error $\sigma_{\rm ph}$ will be smaller than given in the seventh column of Table 1 for $G = 10$ to 12 mag because a larger number of pixels across scan are taken, cf. Column 4. For brighter stars the error will be similar. More precise calculations of the astrometric error obtained with CUO-100.2 have been given by Arenou & Babusiaux in [1] and will hopefully be derived also for the present proposal.

The astrometric accuracy is good as $\sigma_{\rm ph}$ shows, and it is practical to have the same small number of 6 patches per window for all bright stars. The number of simultaneously read patches per CCD must at present not exceed 12 in the astrometric field according to Table 3.16 in the GSR.

3.4 Mapping around stars with AF17 and A2BBP

Any star may disturb the measurement of a main detected star if it affects the samples containing the main star. The astrometric disturbance d may be up to $d \simeq 0.25 \times r \times f$ where r is the flux ratio between the disturbing and the main star, and $f \simeq 2.2$ pixels = 80 mas is the FWHM of the sampled astrometric image. Thus

$$d \simeq r \times 20 \text{ mas}.$$

Such astrometric disturbances can be corrected if the positions, G magnitudes and colour indeces of both stars are known. For disturbing stars brighter than $G = 20$ the information is available from the AF1-16 and BBP data. It is the purpose of AF17 of Astro-1 and -2 (A1AF17 and A2AF17) and the BBP of Astro-2 (A2BBP) to provide the information for disturbing stars fainter than $G = 20$ and it has been shown that $G \sim 23$ mag may be detected and measured by accumulation of all the mission data. This means that the windows of AF17 and A2BBP have to cover an area beyond the cross-scan length of the samples in AF and BBP. This is achieved with respectively 30 and 10 samples for $G = 16-20$ and 36 and 12 samples for $G = 12 - 16$ mag (see Fig. 2a).

The longer samples in AF1-16 and A1BBP for the interval $G = 12 - 16$ is due to a preliminary proposal by Söderhjelm for the sake of double stars. It has been adopted here for the sake of an example showing the (acceptable) consequences for the design of windows for AF17 and A2BBP.

All analysis is done on the ground, and the final on-ground analysis will use all data in an integrated manner described elsewhere (see GSR Sect. 9.4.2 and Brown (2001) [2]). This implies that the astrometric effect of faint disturbing stars can be taken into account. An important byproduct is the photometry of the area itself, for instance if the detected point source is a quasar or a faint compact galaxy.

The samples for BBP in Astro-2 as shown in Fig. 2a give much lower angular resolution along scan than those in Astro-1, i.e. 6 pixels compared with 1 pixel. But this difference is less pronounced when the PSF is taken into account. The lower resolution means less readout noise which is quite significant for the faintest stars. The larger samples give coverage of a larger area around each star giving a better background determination which may perhaps be used in the reduction of the BBP from Astro-1.

4 Double and multiple stars

Double and multiple stars are measured in several ways by GAIA. An area centred on each detected star is mapped in on-ground analysis of various sets of GAIA data from the Astro and Spectro instruments with ASM3, AF17 and SSM in the G-band, and multicolour photometry is obtained by BBP and MBP data. This is indicated at lower right of Fig. 2a and described in GAIA-CUO-091 [7]. It includes astrometry and photometry of double star components if the resolution is adequate.

For stars brighter than $G = 12$ the AF17 data are not collected because they would not cover the large cross-scan window. But the data from windows of AF1-16 and BBP1-5 shall be used to make a mapping and photometry. This will include all disturbing stars of interest.

4.1 Stars brighter than $G = 12$ mag

The larger windows in AF1-16 and A1BBP for stars brighter than $G = 12$ imply possible disturbances from stars outside the area covered by AF17. This means that only stars brighter than $G = 20$ can be taken into account, and that the sampling of AF17 and A2BBP for these stars should be omitted.

But the data from windows of A1AF1-16, A2AF1-16 and BBP1-5 shall be used to make a mapping and photometry. This will include all disturbing stars of interest. Star may be detected from the AF1-16 data in each scan probably to a fainter magnitude than $G = 20$. But if such a faint star is not available from the other mission data from ASM detections, its position will only be accurate in the tangential direction relative to the main star. The radial position will be inaccurate due to the 4 pixel sample.

It should be kept in mind and be utilized that the GAIA telescopes offer the best resolution of double stars when the components happen to be in a 45 degree position angle, cf. the PSF in Fig. 3a. Especially the faint component in a pair with large magnitude difference may be found in these corners of the PSF.

Altogether, our preliminary considerations show that disturbing stars can be adequately taken into account with the proposed detections and measurements, but this deserves more detailed study.

4.2 Narrow double stars

The AF17 data will provide astrometry at a resolution of about 100 mas along scan, with about 4 times higher standard errors than for stars measured on the 16 CCDs in the main part of the astrometric field. Components with this separation of 100 mas and up to about 400 mas will also be measured by all CCDs with the proposed new sampling if the central star is brighter than $G = 16$ mag.

Across scan the sample size is normally 8 pixels=0.9 arcsec in order to collect most of the light from a star. In case of a double star a higher resolution across scan would be desirable, but if this were provided for all stars a much higher telemetry rate and a higher readout noise would result. The proposal in Fig. 2b provides a cross-scan sampling of 4 pixels=440 mas resolution for all stars brighter than $G = 12$ mag. A higher cross-scan resolution cannot be provided for fainter stars with an acceptable telemetry rate.

Along scan the length of a patch in AF is 6 pixels in the GAIA baseline, sufficient for good astrometry of single stars. A double star with 100 mas separation along scan, i.e. 3 pixels, would not be sufficiently covered by 6 pixels resulting in inferior measurement of the two components. The proposed patch has 16 pixel length. This will give good coverage for a separation of 10 pixels=370 mas if a system of equally bright components are centred on the window, but such components will be resolved in ASM and get separate windows.

If one component is much brighter this one will be centred on the assigned window. A faint component 5 pixels = 180 mas away will then be well covered. This width of window will be sufficient for most of the astrophysically interesting narrow double stars which can still be resolved in the final on-ground analysis.

It should be considered to apply the windows WA1 in Fig. 1b in Astro-1 also to stars fainter than $G = 16$ if they are detected as double in the ASM, but not resolved. This would result in 16 samples instead of 6 for astrometry of these stars. If e.g. 10 per cent are detected as double the additional telemetry would be 17 per cent on the telemetry for AF1-16 in Astro-1 for the faintest group. For the BBP 16 samples instead of 10 would, resulting in 6 per cent more telemetry for BBP in Astro-1 for these stars. This means altogether that 10 per cent detected double stars fainter than $G = 16$ mag increases the telemetry from AF1-16 and BBP in Astro-1 by about 15 per cent.

For stars brighter than $G = 16$ mag in the ASM we propose that no detection of duplicity is carried out by means of the ASM data since we believe that unresolved double stars are adequately taken care of by the window of 16 samples in the AF.

The window allocation for double stars resolved in the ASM, or for stars with unresolved duplicity detected in ASM, is discussed in Sect. 5.

4.3 Physical double stars

GAIAs performance for physical pairs has been studied by S. Söderhjelm (SS) and he has described his results in mails to us, most recently on 2001-12-13 and -14 and 2002-01-10. His studies are based on a model of the frequency of binaries as function of magnitude and magnitude difference, and on the sampling proposed in CUO-100.2.

For the stars fainter than $G = 16$ he concludes that a detection of duplicity in ASM can only catch a small fraction of physical pairs. This means that a larger window (12 or 16 pixels instead of 6) for the ASM duplicity detections is only rarely of importance. The detection capabilities are taken from the study by Makarov & Arenou [11] in CUO-80.

Thus, the detection of duplicity proposed above could be omitted which would be a nice simplification. But in a later mail SS revised his opinion saying that a window of 12x8 pixels is desirable for these stars. Thus further studies and confirmation is required.

For the stars between 12 and 16 mag SS finds that a window of 12x8 is adequate. He finds that even a faint companion to a 12 mag star is completely included, and therefore the primary position is not compromised. The sample of 12 pixels for these stars shown in Fig. 2b was based on another mail by SS, but it does no more seem to be needed. It is maintained in the figure for the sake of example.

Should be reduce the astrometric patch WA1 from 16 to 12 samples for 12-16 mag stars ? It would save 3.3 per cent on astrometric telemetry, but it would complicate the allocation of U2-windows if the AF and BBP have different lengths of patches.

5 Window allocation

The strategy for allocating windows after the detection in ASM should be very simple. We propose a *sequential strategy* based on the following principles.

1. No attempt should be made to judge which of the stars is more important because no good and simple strategy will be possible and because a rejected star will most probably get a fair number of observations from scans in other directions during the mission.

2. The allocation of windows should be carried out for each row of CCDs separately, based on the detections in the ASMs in a chronological list, the D-list. A window centered on a object in the D-list is called a U1-window.

3. If a window is too close to the upper or lower edge of a CCD to be fully contained it must be omitted. Even more, all windows in the AF and BBP must be fully contained on the CCDs for any star. The maximum cross scan speed of 171 mas/s gives a motion of 2.9 arcsec during a full field transit and this is small compared with the vertical height of a CCD of at least 120 arcsec. The resulting rejection of partly observed stars is acceptable for the sake of simplicity.

4. The allocation should proceed in the strict sequence of the D-list for each ASM. This means that an allocation of a window should be final and not be subject to revision for the sake of any following allocation in the sequence.

5. If the attempted window for a given star appears to be in conflict with a previous allocation then we have the situation illustrated in Fig. 5b,c. U1 is always centered on an object in the D-list. One or more shifted windows, U2, U3 or U4, may then be allocated in addition to U1 as shown. If any of them is in conflict with previous allocation it must however be omitted.

6. A detection of unresolved duplicity in ASM from elongation of an image may be used to define two components, A and B, both to be entered in the D-list and for which windows are allocated as described here. But it appears from Sect. 4 that such duplicity detection is not recommended.

7. Windows U2-4 must border to U1 as shown in the figure, on all CCDs in the row, without gab or overlap as could be caused by rounding errors.

8. The U-points of allocated windows must be entered in a chronological list (the U-list) of allocations. The chronological sequence, i.e. the sequence along scan of the U-point, will facilitate the check of conflicts.

9. If an attempted window would be in conflict with more than one previous allocation it should be omitted.

10. Allocation is attempted for all detections in the ASM, in a strictly chronological sequence. (In CUO-100.2 a random choice of sequence was proposed for components of double, and especially multiple systems. But this is not recommended anymore.)

11. If an extended window (WY00-46) is required for A or B then only the window U2 can be added.

12. The window A17 is larger than the other AF and BBP windows and will more often conflict with a previous AF17. It might then be omitted without much harm just because it covers a large area which would probably be well covered anyway. Another strategy than omission would be to shift the AF17 vertically by the necessary amount, which is probably not worth the extra complication.

The extra telemetry implied by the windows in Fig. 5d is negligible. When the B component is in one of the two areas requiring three windows we encounter telemetry from one extra window. The two areas cover about

$$2 \times 12 \times 6 \text{ pixels} \;=\; 2 \times 0.44 \times 0.66 \text{ arcsec}^2 \;=\; 0.58 \text{ arcsec}^2.$$

The average density of stars brighter than $G = 20$ mag is 24 000 per sq.deg or 0.001 per area mentioned, i.e. the extra telemetry is 0.1 per cent. This only takes into account optical B components, not physically tied to A.

6 Broad-band photometry in Astro-1

The sampling of BBP in Astro-1 shown in Fig. 2b is matched to the sampling in the AF so that optimal high-resolution photometry is obtained for all single and double stars. This is important for astrophysical reasons, and it is even decisive for the astrometric reduction because of the expected astrometric chromaticity errors (see GAIA-CUO-096 [8] and GAIA-LL-039 [10]).

The patches in BBP are longer than in the AF for faint stars because a sky background must be measured for photometry while this is not needed for astrometry. The patches in BBP always have a length of 16 pixels along scan obtained by reading 16 samples from the CCD. For stars fainter that $G = 16$ mag the 16 samples are combined to 10 samples by on-board calculation (additions) before transmission in order to save telemetry, as indicated in the WA2-window of Fig. 2b. The outmost two samples on each side are intended for an unbiased background determination since they are less disturbed by e.g. an undetected duplicity of the main star than if three samples were taken taken together for transmission. This is more relevant in aperture photometry than in PSF photometry and this is why the read samples are combined for transmission as proposed in the figure.

Photometry is obtained in the BBP for several parts of the spikes which are not saturated. This may not be strictly required for the chromaticity corrections because the spectral composition of the light in any part of a spike may be computed from the BBP of just one good part of the spike using the computed PSF.

6.1 Photometric calibration in Astro-1

The BBP shall be calibrated by measurement of the spikes as described in Section 3 of GAIA-CUO-091 [7] for the medium-band photometry (MBP) in Spectro. The spikes contain information on the magnitude scale value because the PSF can be calculated from a well-known optical theory based on the known pupil, focal length, optical aberrations, spectral transmission profile, and colour index of the star. The only remaining photometric calibration is then a zero-point for every spectral band, a zero-point which should probably be tied to ground-based photometric standards. Thus, no sky-covering ground-based photometric standards of all magnitudes seem to be required, allthough they might be useful for the sake of verification.

The calibration may be done from data in the extended windows WY00-46 for stars brighter than $G = 12$. But the spikes for a star of $G = 12$ mag in the window marked WY00 will only reach $G = 17$ mag because the upper or lower sample is only about 5 mag fainter than the centre according to the curves in Fig. 3b. In order to calibrate the faintest stars of $G = 23$ mag detected in the surrounding of the main stars a fraction of faint star transits should be sampled with the WY00-window for the BBP.

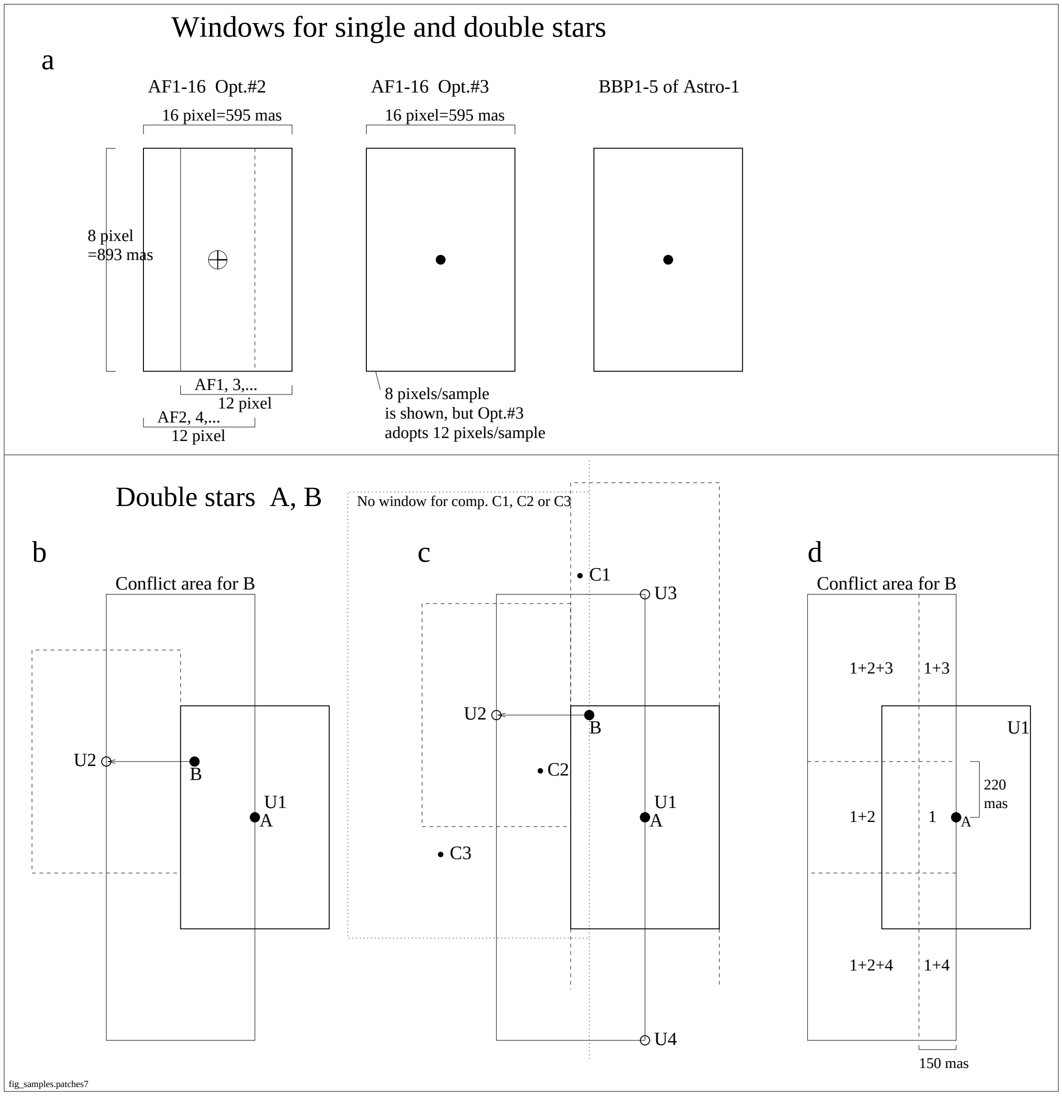

Figure 5: Windows for single and double stars. **a:** Option #2: Windows in AF have a width of 12 pixels and the centering changes from one CCD to the next so that a width of 16 pixels along scan is covered. BBP always covers 16 pixels. Option #3: Windows in AF and BBP always have a width of 16 pixels. **b:** Windows in AF and BBP for components A and B of a double star. In the "conflict area for B" a window centred on B would overlap with that for A. A centre at point U2 is therefore defined and the associated U2-window is added. **c:** A double star where two windows, U2 and U3, are added for the sake of component B. The dotted line indicates an area where a third component, e.g. C1, C2 or C3 would not get an additional window. **d:** Tentative division of the conflict area (dashed lines) showing which of the U1-U4 windows are required to cover a double star. (See more in Sect. 5).

A filter band calibration can also be performed which was not mentioned in GAIA-CUO-091. The central wavelength of a filter determines the slope of the spikes. Measurement of this slope throughout the mission can therefore be used to monitor the central wavelength of each filter in the BBP and MBP which may change due to aging. The possible accuracy should be estimated.

The width of the transmission profile cannot so easily be monitored because the effect of a change cannot be distinguished from a change of the central transmission. Only stellar spectra with distinct features within a filter band could be used for this purpose.

6.2 Telemetry for BBP in Astro-1

For calibration, a fraction of 0.5 per cent for $G = 12 - 16$ would be sufficient and only add 0.3 percent to BBP telemetry, as can be derived from the data in Table 1. About 0.04 percent of the $G = 16 - 20$ star transits would be sufficient and only add 0.3 per cent to the telemetry of BBP photometry. Thus alltogether 0.6 per cent is added to BBP telemetry from Astro-1 for the sake of photometric calibration.

The telemetry for the BBP resulting from our proposal will be about 10 per cent higher than from the GAIA baseline, namely the same percentage as for astrometry. This is the case if the number of 4 CCDs is maintained for BBP. With the proposed 5 CCDs in Fig. 1b another 25 per cent must be added, altogether 38 per cent should be added for Astro-1.

7 Broad-band photometry of galaxies in Astro-2

The photometry of stars with A2BBP is discussed in Sect. 3.4 and we shall here discuss photometry of galaxies.

The surface photometry of galaxies with A2BBP was discussed in IWG-OPM-003 of February 2000, [6]. Further scientific and technical evaluation is urgently required because a decision has to be taken soon whether surface photometry of galaxies shall be included in GAIA or not. Doubt about the scientific value of measuring one million galaxies has sometimes been raised in the SAG, and the telemetry for many more than one million is quite significant as shown in [6].

The samples for galaxies shown in the figure are half the size in the cross-scan direction as for stars, thus containing 6x4 pixels. This gives optimal resolution for BBP of galaxy photometry as shown by Vaccari & Høg (1999) [12]. This sample is therefore recommended instead of the 6x8 pixel sample in the GSR. The smaller sample will mean twice as much telemetry to cover the same area.

8 Concluding remarks

Astrometry and photometry in the Astro telescopes should apply the windows proposed here in order to improve the results for bright stars, double stars and for photometric calibration. This will require about 13 per cent more telemetry from the AF if no duplicity detection is made in ASM. The BBP in Astro-1 will require 38 per cent more telemetry if our sampling is adopted and the proposed 5 CCDs instead of 4.

Further studies are required.

1. A similar study as the present is planned for the MBP. A draft sampling is shown in Fig. 2c in accordance with the proposal in GAIA-CUO-096 [8].

2. Detection of duplicity from ASM1 and 3 data, cf. Sect. 4. What is the resolution of the normal detection ? Is detection of duplicity by elongation superfluous ?

3. Is the proposed measurement of disturbing stars sufficient for astrometry, cf. Sect. 4 ?

4. Is the detection of galaxies in ASM1 and subsequent photometry in A2BBP of sufficient scientific value considering the required telemetry ? A task definition study is required, cf. Sect. 7.

8.1 Data transmission strategy

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The telemetry rate required for the GAIA data, with or without the presently proposed additions, is about twice the rate provided by the antennas. Several ways to cope with this problem should be considered, and probably be applied in parallel. However, to transmit less data per star transit is hardly a good method from the scientific point of view, nor should the limiting magnitude in some areas be changed. It is better to provide a higher total telemetry bandwidth, perhaps by a second ground station which may be used when required or when available, for cost reasons thus not necessarily full time.

In any case with any realistic bandwidth a *data transmission strategy* must be defined, perhaps through an onboard handling with the following principles.

1. The data should be read and stored on board without selection of data.

2. The data should be stored in blocks for each of the three telescopes, and further divided in blocks corresponding to 1) all identification data (ID) and ASM data, 2) AF+BBP data for all stars in Astro-1 and -2 brighter than $G = 12$ mag, 3) AF+BBP data for the fainter stars, and 4) similarly for Spectro.

3. The ID+ASM data should include all detected stars, with a flagging whether they have in fact been allocated windows, and the D-list and the list of U-points. The U-list includes the information needed to reproduce the positions of the windows on all CCDs.

4. The blocks for ID+ASM and for the bright stars should always be transmitted and we assume that these stars are sufficient to allow on-ground attitude reconstruction of the required accuracy. The data for stars brighter than $G = 12$ mag constitute less than 3 per cent of the total for AF according to Column 4 of Table 4.

5. The blocks for the fainter stars should each cover no more than about 0.5 square degree in order to facilitate the following data selection strategy.

6. *Data selection strategy*: When it is realized that not all data onboard can be transmitted some of them must be selected, and some be overwritten/deleted. The selection of data blocks could be based on a priority system using 1) the known position on the sky of the onboard data sets, 2) the attitude requirements (which is perhaps fullfilled alone by the blocks of ID+ASM and bright stars), 3) a scientific priority for various areas, and 4) a knowledge of the number of observations already obtained for each area, including a quality measure for the expected astrometric parameters determination.

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