Sky survey and photometry by the GAIA satellite*

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Abstract

GAIA is designed as a scanning satellite to collect data for high-precision astrometry with standard errors of 10 μarcsec of positions, parallaxes and annual proper motions for stars brighter than $V =$ 15 mag, and sub-milliarcsec precision for all stars brighter than $V =$ 20 mag. Multi-colour photometry will be obtained for these about one billion stars.

An overview of the GAIA mission with respect to multi-colour photometry of stars is given. The detection of supernovae and solar system objects, and the possiblity for surface photometry are mentioned. An appendix on GAIA mapping and photometry contains the three sections: samples and patches, precision of aperture photometry, mapping and photometry.

1 Introduction

The GAIA satellite is being studied as candidate for an ESA cornerstone mission to be launched about 2009. The overall design and the scientific goals of the mission are presented by Lindegren (1998). The present paper focuses on the design and performance with respect to multi-colour photometry.

The measurements are obtained with CCDs in time-delay integration (TDI or drift-scanning), a concept introduced for an astrometric and photometric satellite by Høg (1993). Three separate, but rigidly connected

*This paper is an updated and much extended version of Høg et al. (1998a).

telescopes are scanning along the same great circle during a slow spinning of the satellite with three hours per revolution. During a five year mission any area of the sky will cross the field-of-view of each telescope about a hundred times, following a revolving scanning law similar to that of Hipparcos (ESA 1997).

The use of separate telescopes, unlike in Hipparcos where two areas on the sky were superposed in one focal plane, is a great advantage for the identification of the observed objects. The resulting problem for accurate astrometry of achieving a stable basic angle between the fields of the two astrometric telescopes has obtained a satisfactory solution (Lindegren 1998).

The sky images collected by the large CCD mosaics contain very much data, but only a minor part contains useful information. If everything were read-out from the CCDs most of it would be on the sky background and be dominated by the readnoise since the integration time is only about 1 s per CCD. Only the interesting parts of the sky will therefore be read out and the rest be flushed more quickly during the reading process, and thus be skipped entirely. This leaves more time for reading the useful information, resulting in less readnoise per unit sky area (cf. Sect. 7.2.2).

Our considerations have shown (see SAG_CUO_44) that the amount of data can thus be reduced by at least a factor thousand. When this is done it appears that the resulting telemetry rate is feasible for GAIA so that no severe constraint on telemetry rate exists anymore.

Two possibilities for defining the interesting sky areas have been considered. The use of an input catalogue of about 100 million stars, or of spots on the sky, selected for their astrometric and astrophysical interest could limit the transmission to cover only areas around these stars. But no surveys exist that could be used as basis for a meaningful selection of the stars, especially since GAIA can measure stars as faint as 20th magnitude, and with high angular resolution of about 100 mas.

The other possibility, the one finally chosen, is to detect stars as they enter the field-of-view, determine their position, magnitude and signal-to-noise ratio (SNR), and, if the SNR exceeds a certain limit, to collect data around such stars during the remaining part of the field crossing. The serious objection to this approach was that data should then be transmitted for all the one billion stars brighter than 20th mag, ten times more stars than originally envisaged for the GAIA mission. The resulting data rate seemed again to be prohibitive, but this problem has been solved by recent development of transmission techniques, allowing for GAIA an average rate about 1 Megabit per second.

GAIA measurement will thus be determined only by a detection when an object enters a field-of-view, not by any prior knowledge of objects, even if they have been previously observed by the satellite. The on-ground data base containing the measurements will however be able to access or collect all available measurements of any required star or sky area for the purposes of data reduction. Stars near the detection limit will not be observed during all transits.

It is imperative that GAIA collects photometric data in addition to the astrometric in order to correct the astrometric observations for possible chromatic effects in the instrument depending on the colour of the stars. Multi-colour photometry is also required to classify all stars for use in the various astrophysical applications. Radial velocities for the stars brighter than 17th mag supplement the GAIA results for use in kinematic studies.

Astrometric information and broad-band photometry is collected by the two astrometric telescopes pointing at a basic angle of 106 deg from each other and having rectangular apertures of 1.7×0.7 m^2. Narrow-band photometry is obtained in the spectrometric telescope with aperture of 0.75×0.7 m^2, which also collects radial-velocity data (Lindegren 1998).

2 Detection and photometry

The focal plane arrangement of the astrometric telescopes is indicated in Fig. 1, covering an area of about 0.5 deg^2 with CCDs. Stars are detected by immediate on-board analysis of data from the astrometric sky mapper (ASM) with four CCDs (ASM0-3). ASM0 with very short integration time is suited for the detection of very bright stars. The ASM1 is the main CCD for the detection of stars. ASM2 is redundant, i.e., not used in normal operation, but kept as replacement if another one should fail. ASM3 provides a refined analysis of the objects detected in ASM1. The double analysis is important to provide a sharp cut limiting magnitude, and to ensure that a detection from a cosmic ray hit is not used to generate useless data by observation during the remaining field crossing. Stars of, e.g., magnitude $I = 20$ are detected with a probability of 0.9. The detection of solar system objects and nebulae is also foreseen, as discussed in Sections 3 and 5, respectively.

Two-dimensional positions of stars in the focal plane coordinate system are obtained from the ASMs. They are required for the determination of the satellite scan velocities and the data taking in the subsequent field

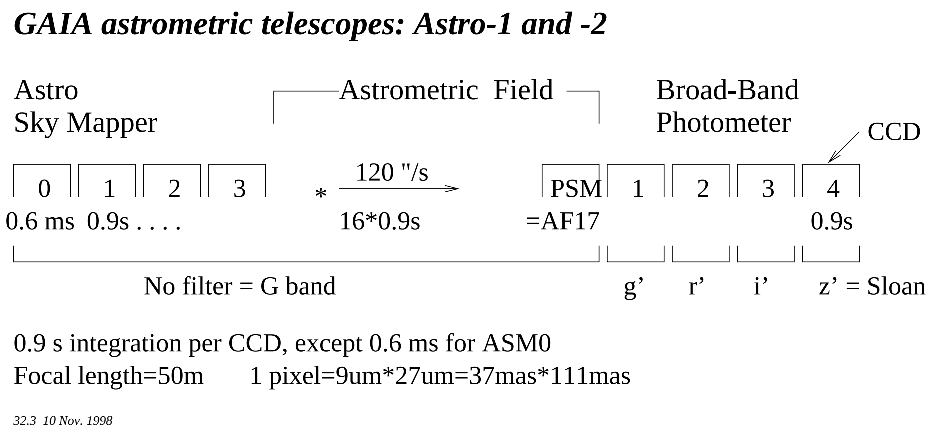

Figure 1: *One of the focal planes of the two astrometric telescopes, Astro-1 and Astro-2, with CCDs integrating over 0.9 s. The 4+1+4 CCDs of the astro sky mapper (ASM), the photo sky mapper (PSM=AF17), and broad-band photometer (BBP) are shown. The first 16 CCDs of the astrometric field (AF) are indicated. Stars are detected in the astro sky mapper and then measured astrometrically 16 times. The PSM shall collect samples for a mapping of the surrounding of the detected star within a radius of 1 arcsec. Photometry is obtained through colour filters in the BBP giving four-colour photometry in each of the two astrometric telescopes.*

crossing. The positions are also used for the reconstruction of the satellite attitude by means of reference stars with known celestial positions, both in orbit and on the ground during the data reduction.

The CCDs are read in samples of a size matched to the specific scientific purpose (see Fig. 2) taking into account that a large sample means a great reduction of the read-out noise per unit area which is the dominating noise source for faint objects, far larger than that of the diffuse sky background. The size and form of the sample shall also ensure that the data transmitted to ground have the maximum scientific content per bit, this leads to the rectangular form matching the Airy disk in the ASM, and the one-dimensional samples used in the astrometric field (AF), including the photo sky mapper (PSM), and in the broad-band photometer (BBP).

The data collected from the PSM (without filter) and from the BBP cover an area of about 3 arcsec^2 centred on each object. These one-dimensional scans are obtained at different position angles in the course of the mission. A superposition (stacking) of the data from the many observations per object will allow a two-dimensional mapping of the sky area, which is important for double stars, quasars and cores of galaxies (cf. Sections 5 and 7.3).

Since the PSM observes without filter, stars brighter than $I = 23$ mag within 1 arcsec from the central star can be detected by stacking the about 100 scans from the mission (cf. Sect. 7.2.1).

Broad-band colour filters, four of the five Sloan colours $g'r'i'z'$ (Fukugita et al. 1996) will be selected in order to reach the faintest stars. These four colour bands divide the entire range from 400 nm to the sensitivity limit of the CCD at about 1000 nm into four essentially non-overlapping pass bands. The separation wavelengths are 550, 700, and 850 nm. The ultraviolet band, u', is also being considered but this would require a CCD with ultraviolet sensitivity, whereas all the other CCDs in the astrometric telescopes will be chosen with an enhanced red sensitivity in order to obtain the most accurate astrometry of the Galaxy's predominantly faint red stars. An ultraviolet band will however be included in the narrow-band photometer (NBP) of the spectrometric telescope (cf. Fig. 4).

The resulting four-colour photometry will have a precision of, e.g., about 0.03 mag in the i' band at $I = 20$ mag for all spectral types, according to present estimates (see Fig. 3).

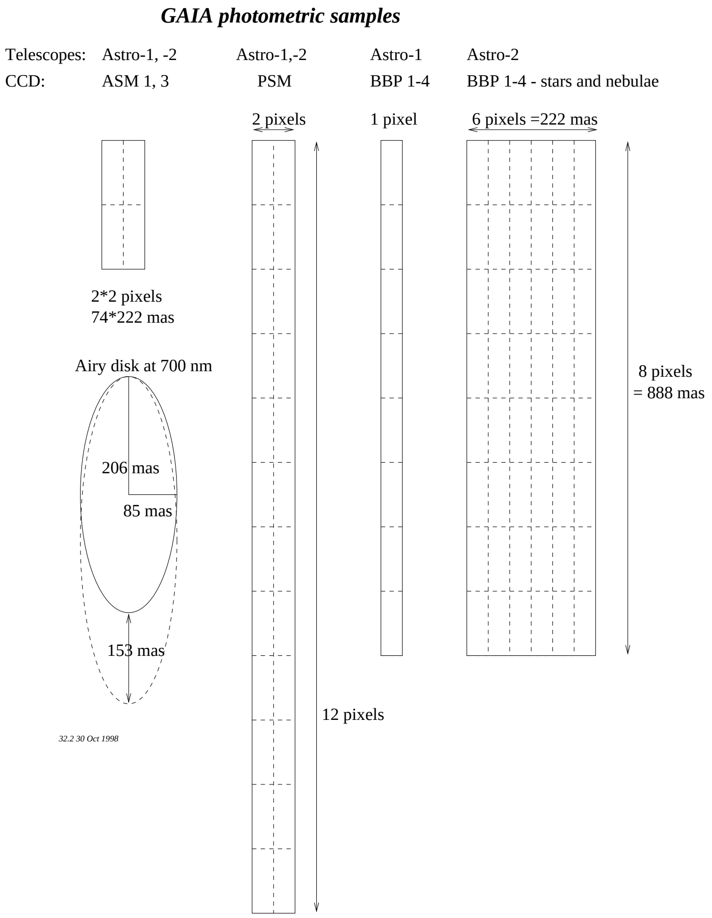

Figure 2: *The proposed samples of the astro sky mapper (upper left), the photo sky mapper (PSM), and the broad-band photometer (right). The Airy disk of the astrometric telescopes is shown as solid ellipse, while the dashed ellipse shows the elongation due to the maximum value of cross-scan motion of the image during 0.9 s integration time. The narrow samples of one pixel width along scan will give a resolution about 50 mas. The broad sample for the BBP in the Astro-2 telescope will give a resolution about 200 mas, and corresponding less read-out noise. The choice of samples must be guided by the scientifically desirable resolution and the resulting readnoise, thus optimizing the total scientific results from GAIA within certain constraints. The permitted telemetry rate does not appear as a severe constraint for the proposed sampling.*

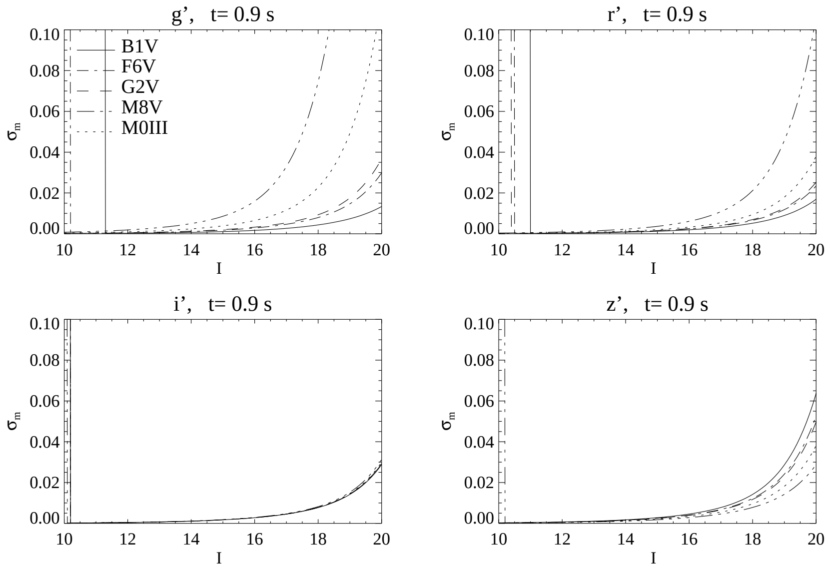

Figure 3: *Precision of broad-band photometer in four bands of the Sloan photometric system. Average of 100 observations, integration time t, the vertical lines indicate saturation of the CCD at bright stars. Saturation is assumed at* 500 000 *e- in the serial register.*

3 Detection of supernovae and solar system objects

The position of objects detected in the ASM is obtained relative to the focal plane coordinate system. These positions can be converted to celestial coordinates by means of a calibrated satellite attitude and calibrated instrument parameters. Preliminary calibrations are obtained from observations of reference stars with known positions, and are subsequently refined by means of the observations in the part of the field dedicated to astrometry (see Fig. 1 and Lindegren 1998). This calibration is required in the construction of the final catalogue of objects, including identification of repeated observations of the same object and improvements by the astrometric measurements in the field. The identification process will then show that some objects have not been observed before, because they could be solar system objects (which are moving), or new objects like variable stars.

It can be shown from the information in Jørgensen et al. (1997) that thousands of supernovae could be detected in this way. Hundreds of tidal disruptions of stars at super-massive black holes in galaxies could also be detected, if these events are as bright and frequent as expected (Rees 1997). The data reduction system should contain a 'quick-look' facility, using preliminary calibration parameters. This would allow the detection of such events, and their distinction from solar system objects, within a few hours of the observation so that ground based follow-up of the light variation and spectrum can be initiated.

4 Narrow-band photometry

The spectrometric telescope on GAIA is used for obtaining radial velocities in one part of the focal plane and narrow-band photometry in another part, each part having an area about 1 deg^2. The focal plane of the narrow-band photometer contains the spectrometric sky mapper in which stars are detected and measured as in the sky mapper of the astrometric telescopes. Stars exceeding a given SNR limit are then followed for data collection in the remaining part of the fields.

The choice of photometric system is subject to discussion, with the 7-colour Strömvil system (Straižys et al. 1997) being a candidate. The seven bands of about FWHM=20 nm are located at 350, 374, 411, 467, 516, 547, and 656 nm. The very narrow Strömgren Hβ band cannot be included because too long integration times would be required, but the Vilnius band

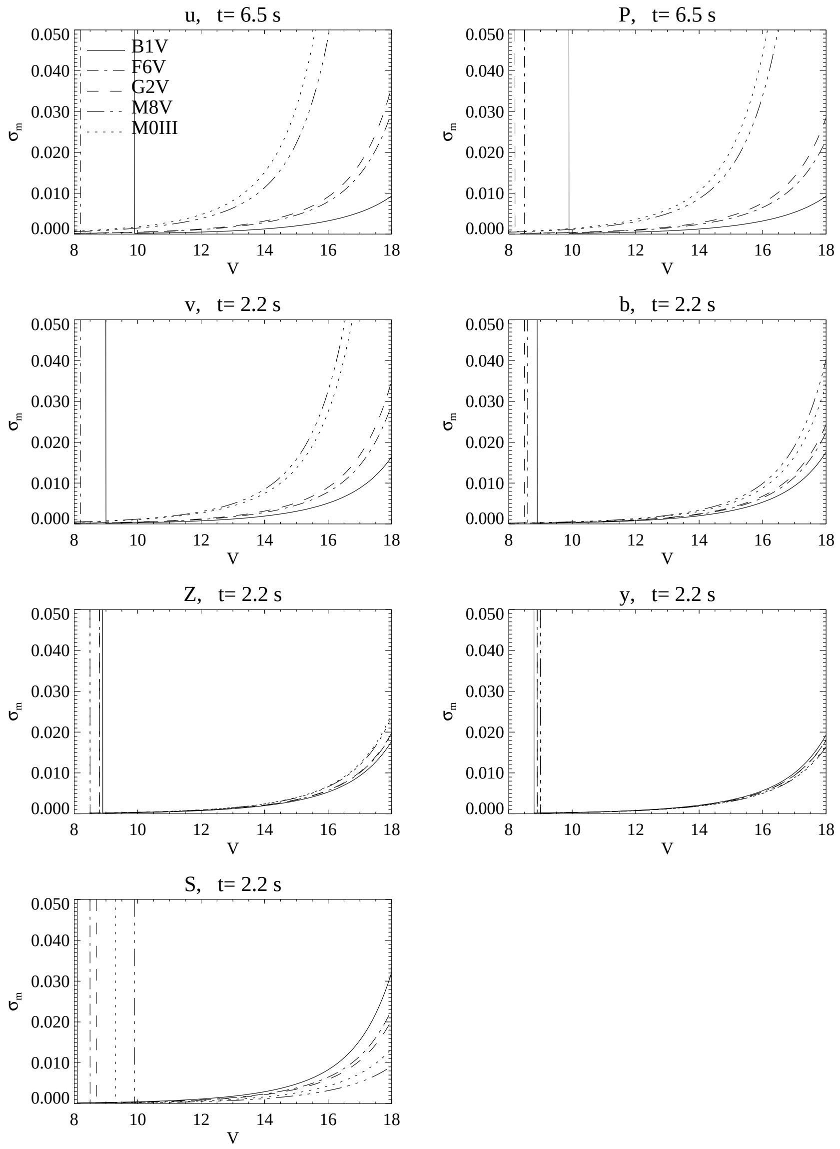

Figure 4: *Precision of narrow-band photometer (NBP) in the seven-band Strömvil photometric system. Average of 100 observations, integration time t, the vertical lines indicate saturation of the CCD at bright stars. Saturation is assumed at* 500 000 *e- in the serial register.*

at the Balmer jump, 374 nm, is supposed to replace Hβ for luminosity classification. The ultraviolet band can be included here, but not in the astrometric telescopes, since a CCD with sensitivity in the ultraviolet is preferred. The resulting photometry would obtain a precision of 0.005 mag for a G star in the y-band at $V = 16$ mag (see Fig. 4), and a limiting magnitude about $V = 18 - 19$ is foreseen.

If colour indices in the Strömvil system are measured with the accuracy of ± 0.01 mag (1% photometry), then the following accuracy of the determined physical parameters is expected, according to Straižys (1998).

- spectral class: ± 0.8 subclass
- temperature: from ± 2000 K for hot stars to ± 200 K for cool stars
- absolute magnitude M_V:
  ± 0.4 - 0.6 mag for luminosity V-III stars
  ± 0.8 - 0.9 mag for supergiants of all types
- surface gravity log g: ± 0.5 dex on average
- metallicity [Fe/H]: ± 0.15 - 0.2 dex
- colour excess E(B-V): ± 0.02 - 0.03 mag
- interstellar extinction A_V: ± 0.1 mag
- distance d: ± 25 % for luminosity V-III stars

The classification is single-valued everywhere in the HR diagram (from B to M type stars) within the listed error limits. Most of the peculiar stars (Be, Herbig Ae/Be, T Tauri type, Ap, Bp, Am, F–G–K subdwarfs, G–K metal deficient giants, carbon-rich stars, white dwarfs, many types of unresolved binaries, etc.) will be recognized. Only about 5 % of the unresolvable binaries will be misclassified. For Population II stars the M_V and [Fe/H] will be less accurate than given above.

In case of lower accuracy of the photometry, when the errors are larger than ± 0.01 mag, the classification accuracy will be somewhat lower, but many types of stars can be recognized even at ± 0.04 mag errors.

More recently, Knude & Kaltcheva (1998) have obtained an accuracy in M_V of ± 0.3 - 0.4 mag for A-F supergiants by means only of *uvby* photometry and no $H\beta$, and using Hipparcos parallaxes for calibration.

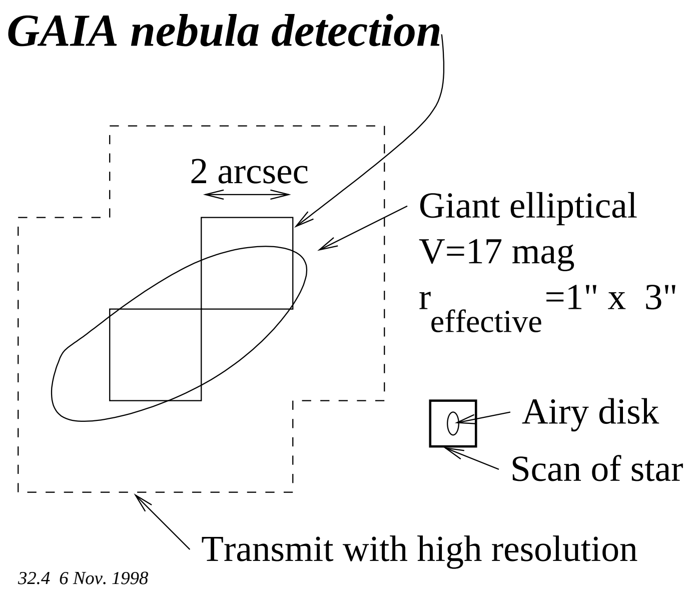

Figure 5: *Detection of excess surface brightness due to the presence of a galaxy and transmission of high resolution data from a surrounding area.*

5 Surface photometry

The determination of the surface brightness of the sky is crucial for the derivation of magnitude and SNR for the stars. This is simply called 'background' determination and several different backgrounds must be determined. A 'local' background within an arcsecond of the star is required for star detection. It is considered to determine it as the trimmed median value of all samples in such an area. This method should be sufficiently reliable because the diffraction images are fairly well separated at 20 mag and even beyond, also in high density regions as, e.g., Baade's Window. This is expected due to the very small diffraction image (see Figs. 2 and 5) and the short exposure time of 0.9 s, unlike most astronomical CCD images.

The background should also be determined in all small square areas of 2×2 arcsec^2 (see Fig. 5) from the ASM1 samples. From these background values, obtained as trimmed medians, a 'global' background is determined as median or mean of the preceding several degrees of scan. An excess brightness in a small square over the global background could be significantly detected at the level of about $\mu I = 20$ mag/arcsec^2. The samples in such squares and suitable surroundings (see Fig. 5) should be transmitted.

An analysis on the ground with superposition of the many observations of each area would give a reliable photometry in the four colours (BBP) at high angular resolution. Normal galaxies with $I \sim 18$ mag could be measured out to the effective radius, and many Galactic nebulosities.

6 Conclusions

At the present stage of studies (October 1998) the following results from the sky mappers and photometers are expected in a five year GAIA mission. GAIA will obtain a complete astrometric and photometric survey of a billion stars and compact objects brighter than $I = 20$ mag, including solar system objects, quasars, the cores of some galaxies, and stars in globular clusters. Multi-colour photometry of all the objects and their immediate surrounding will be obtained as a necessary support for the astrophysical applications and for the accurate astrometric analysis. The stars brighter than $I = 23$ mag can be detected within 1 arcsec of the stars detected in the ASM, and four-colour Sloan photometry can be obtained for most of them. The detection and measurement of nebulosities in this small map of 3 arcsec^2 has not yet been investigated.

Surface photometry at high angular resolution will be obtained in four colours for the central parts of all bright galaxies and Galactic nebulosities.

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7 Appendix: Mapping and photometry

The samples read from the CCDs and transmitted to ground have been described in connection with Fig. 2. It has also been mentioned that an area within 1 arcsec from each detected star is covered with measurements. But it was not specified how many samples would be transmitted. The present ideas are described below and illustrated in Figs. 6 and 7, and may be referred to as the October'98 baseline for sampling. They result from a long development described in numerous reports SAG_CUO_nn and discussed in the GAIA SAG. This baseline is subject to further optimization as may result from simulations of GAIA observations. It is also subject to further discussions in the SAG, but no alternative has been proposed.

Here follow three sections with more details: samples and patches, precision of aperture photometry, and mapping and photometry.

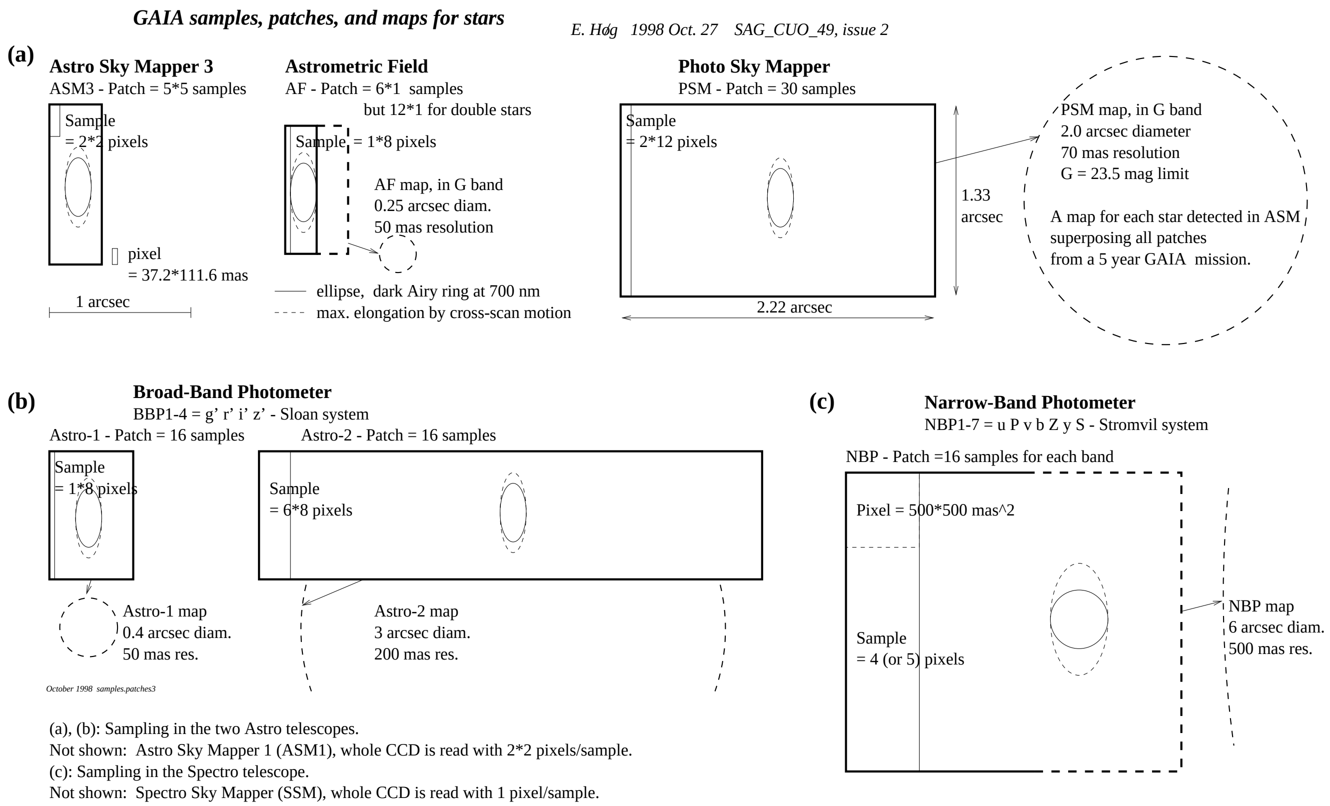

Figure 6: *Samples, patches, and maps for stars. All these patches except those from the ASM3 are transmitted to the ground.*

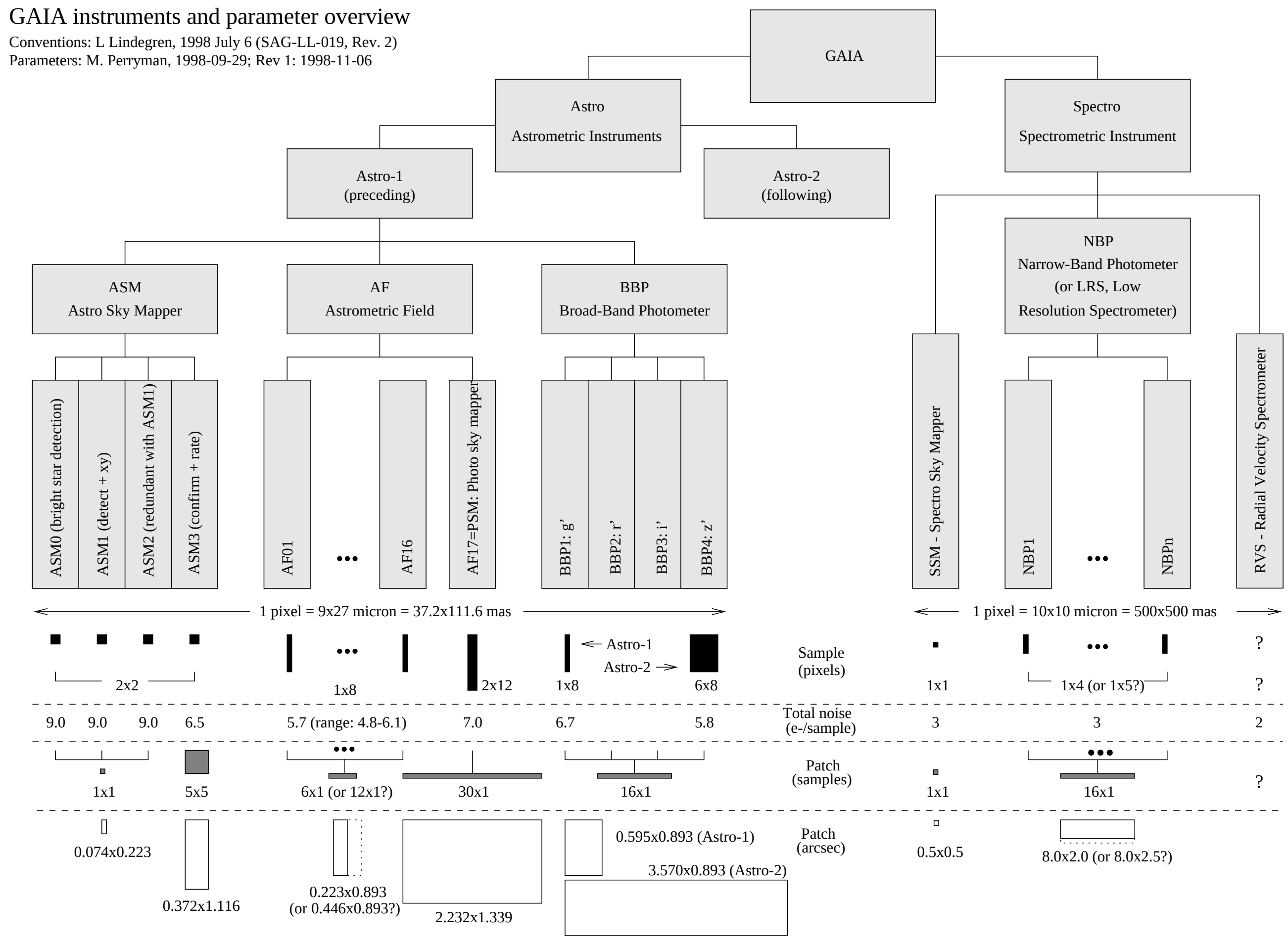

Figure 7: GAIA instrument and parameter overview (Courtesy L. Lindegren and M. Perryman).

7.1 Samples and patches

A sample sometimes means a *sample-area*, i.e. an area on the sky corresponding to one or more electronically integrated pixels as, e.g., shown in Fig. 2. A sample also means the *sample-value* of this area, i.e. the charge in units of electrons [e-] obtained from reading the sample-area from the CCD. Thus a sample-value is obtained from the A/D converter of the amplifier at the serial register of the CCD. It is not obtained as the sum of smaller sample-values.

The GAIA instrument and sampling has been illustrated in SAG_LL_019, revision of 1998-11-06, included here as Fig 7. This figure and Fig. 6 show the October'98 baseline.

A patch means a set of samples, covering a certain small area of the sky. It may be two-dimensional as for ASM3, or one-dimensional as for the other fields shown in Fig. 6.

The following two sections describe the samples and patches, and the transmission to ground for each CCD in the sequence of time as a star crosses each focal plane. The samples thus obtained for a star are collected in each focal plane. A suitable compression is carried out before transmission to ground.

7.1.1 Astro-1 and -2 telescopes

ASM0: All samples of the CCD are read with 2×2 pixels/sample and are used for the detection processes related to very bright stars.

No samples are transmitted to ground, but the CCD row number, time, position on CCD, flux of the detected star, and the SNR limit used.

ASM1: All samples of the CCD are read with 2×2 pixels/sample and are used for the detection processes related to stars and nebulae.

No samples are transmitted to ground, but the CCD row number, time, position on CCD, flux of the detected star, and the SNR limit used.

Values for the sky background around the star are determined, e.g. by the trimmed median of samples in squares of 2×2 arcsec shown in Fig. 5. The transmission of background values is being discussed.

ASM2: This CCD is only used as replacement in case one of the other ASMs should fail.

ASM3: A patch of 5×5 samples (2×2 pixels/sample) is read at the position calculated for a star detected in ASM1. The patch is used for the refined estimation of the position on the CCD and amplitude (flux) of a star detected in ASM1. The scan speeds along and across scan are estimated using the positions from ASM1 and 3. These estimated values are used onboard and are transmitted to ground, including the SNR limit used, but the patch itself is not transmitted.

AF1-16: A patch of 6 samples (1×8 pixels/sample) is normally collected per star per CCD and is transmitted to ground. But a larger patch is required for double stars, e.g. 12 samples/patch. The size shall be defined by analysis of the patch in ASM3.

PSM = AF17: A patch of 30 samples (2×12 pixels/sample) is collected per star and is transmitted to ground.

BBP: A patch of 16 samples is proposed per star per CCD to be transmitted to ground. The amplitude of the star and the background around it shall be derived by onground analysis. The 16 samples in Astro-1 cover a rather small area before and after the star which may seem too small to derive an accurate background value. But it should be taken into account that the presence of disturbing stars or nebulosities will be known from analysis of the PSM patches. The background around each star is obtained in a larger area from the observations in Astro-2. and this value may also be used in the analysis of Astro-1 observations.

An excess surface brightness detected in ASM1 indicates the presence of a galaxy or nebula. In that case the normal patches for detected stars are not collected in the Astro-2 instrument, at least for a part of the mission. Instead a two-dimensional set of samples, also of size 6×8 pixels, is transmitted for a certain area.

7.1.2 Spectro telescope

Detection and measurement in the Spectro telescope have been discussed so far only for stars. But nebulosities may also be an interesting subject because the Strömvil system includes seven intermediate width bands, and especially bands in the UV and on Hα.

SSM: Transmission to ground of the datation, position, and amplitude of detected stars, and the SNR limit applied.

NBP: A patch of 16 samples is proposed per star per CCD to be transmitted to ground.

The radial velocity instrument is not discussed here. But we propose to place a dichroic mirror of size 2.0×1.0 degree^2 in front of the focus with the radial velocity spectrograph and utilize the reflected light with $\lambda < 700$ nm for NBP. The transmitted light besides of the spectrograph should be used infrared band photometry.

7.1.3 Results of PSM data analysis

The purpose of the PSM is to detect fainter stars and other objects around all stars detected in the ASM in order to estimate and even correct for their disturbance on the central star.

The PSM data from the entire mission for any star detected in ASM will be subject to an astrometric and photometric analysis described in Sect. 7.2. The basic arguments and expected results are given here.

The along scan width of 2 pixels gives a sufficient resolution for the mapping of a 1 arcsec radius circle centred on a given object, and the lower resolution only reduces the astrometric and photometric precision slightly compared with 1 pixel width. The advantage is less read-out noise to affect the astrometry and photometry of the faint stars, and less data to transmit.

The height of about 12 pixels/sample is required in order to cover the whole mapping area with sufficient number of scans in different orientations.

It has been shown by simulations that a star of $I = 23$ mag can be detected from 100 stacked patches, if it is situated within 1 arcsec of a star detected in the ASM. Four-colour photometry of most of these stars is obtained by analysis of the corresponding BBP patches in Astro-1 and Astro-2 (cf. Table 2).

Table 1. Number of objects brighter than a given limit in an area of 3 arcsec^2.

Position	Objects	Limit		N3	Source
b=5 deg, <l>	stars	I=20.0	V=21.5	0.030	SAG_LL_012
	stars	23.0	V=25.5	0.15	
Baade's window	stars	I=20		0.65	SAG_LL_013
	stars	21		2.0	
	stars	22		5.8	
	stars	23		18	
b>15 deg	galaxies	I=23		0.008	SAG_ML_3 1997

Table 1 contains the number of various kinds of objects in various parts of the sky in the area of 3 arcsec^2 covered by the PSM. It shows that the patch has the proper dimensions to map an area of that size in all parts of the sky. It shows, for instance, that the use of a two-dimensional distribution of shorter samples in the cross-scan direction is not required to cope with the highest star densities, considering the penalty of higher readnoise per unit area when a larger number of samples has to be read and be taken into account in the image analysis.

The average star density for a field at $b = 5$ deg for $I < 20.0$ and $I < 23.0$ mag is only 0.030 and 0.15 star per 3 arcsec^2, respectively.

Baade's window has the highest star density in the sky, according to SAG_LL_013, even higher than the LMC or the galactic centre. Some globular clusters do have a higher star density at their centres than Baade's window, but the outer areas of all globular cluster can be measured by GAIA. This is true from the point of view of angular resolution, but the present design of GAIA assumes an average star density of 14 300 star/deg^2 and a maximum of 155 000. This latter density corresponds to all stars with $V < 19.7$ mag at the Galactic centre, according to the density model in SAG_LL_012. The implications for the electronic design of accepting a higher density must be further studied (cf. Sect. 7.2.1 and 7.2.2).

The average density of stars with, e.g., $I < 22.0$ mag in Baade's window is 5.8 stars per 3 arcsec^2. The density of about 6 stars could probably be handled in the analysis of the PSM patches. This may be concluded from the along scan width of the star image about 0.2 arcsec, compared with the 2.0 arcsec scan length implying that the stars will disturb each other only moderately in each scan. The background will be affected by the fainter stars, but could still be coped with.

The frequency of external galaxies away from the zone-of-avoidance is only 0.008 galaxies per 3 arcsec^2 and therefore constitute no problem for the typical faint star measurement.

The possibility of nebula detection in the PSM remains to be investigated.

7.2 Precision of aperture photometry

The following contains general formulae for the standard errors related to CCD aperture photometry (based on CUO_26). The PSF photometry is briefly mentioned for comparison purposes, but formulae are given in Sect. 7.3. We will speak of the photometry of a star, but the formulae are valid for the photometry of any signal or excess brightness inside a given area, called the aperture, over that of a certain sky background.

These formulae are convenient to use during instrument design and they give standard errors very similar to those obtained from simulations.

The use of analytical formulae has the advantage over simulations that the relative importance of the various error source is more easily seen, especially Eq. (11) is instructive, more so than Eq. (7).

Definitions and assumptions:

t	:	integration time [s]
S	:	star signal or flux (during t), unit is [e-]
P	:	number of counts in the aperture [e-]
PSF	:	point spread function of a star
n_s	:	number of samples in the 'aperture' for the star
n_b	:	number of samples used to estimate the background
b	:	sky background per sample [e-]
σ_b	:	standard error of estimated sky background [e-]
r	:	total readnoise per sample (rms) [e-]
R	:	signal-to-noise ratio, SNR
$n_{\rm obs}$	:	number of observations, i.e., superposed sky patches

In aperture photometry the counts from stellar flux plus background, P, is estimated as the sum of n_s samples centred on the star

$$P = S + n_s b \tag{1}$$

The number of samples should be large enough to include the wings of the PSF, allthough a small correction for the wings could be applied if the PSF and the star location are well known, and if the background is uniform (see Sect. 7.3.3). Aperture photometry is therefore suited for bright stars where the background is relatively less important than for faint stars.

The variance of P obtained in aperture photometry is

$$\sigma_P^2 = P + n_s\, r^2 = S + n_s\, b + n_s\, r^2 \tag{2}$$

since P is assumed to have basically a Poisson distribution with the variance P to which is added the Gaussian readnoise contribution from n_s samples.

The sky background b is estimated, e.g. by a mean or median method, from a number of n_b samples near to, or surrounding, the star. This number should be equal to or a few times n_s, so that the error of the estimated b is small compared to the error of P.

The signal estimate is obtained from the observed P and b as

$$S = P - n_s\, b \tag{3}$$

Its variance is accordingly

$$\sigma_S^2 = \sigma_P^2 + (n_s\, \sigma_b)^2 \tag{4}$$

The signal-to-noise ratio of a signal S is generally defined as the ratio

$$R = S/\sigma_S \tag{5}$$

We thus obtain a formula for prediction of performance:

$$R = S/\sqrt{S + n_s\, b + n_s\, r^2 + (n_s\, \sigma_b)^2} \tag{6}$$

If n_{obs} observed sky patches of the same star are superposed the resulting SNR is obtained from Eq.(6) by multiplication with $\sqrt{n_{\mathrm{obs}}}$.

The standard error in aperture photometry of an estimated magnitude m from one observation is

$$\sigma_m = 1.086/R = 1.086\sqrt{S + n_s b + n_s r^2 + (n_s \sigma_b)^2}/S \qquad [\mathrm{mag}] \tag{7}$$

The background b must be estimated from samples close to the star in order to be representative, since we really want to know the background contribution to the samples containing the star (see Sect. 7.3.3). It does not help very much to determine the background from a much larger number of samples than n_s. This is evident from the factor $(1 + n_s/n_b)$ in Eq. (11).

The background value may be estimated as the median or the mean value of n_b samples. The median value has less sensitivity to the presence of disturbing stars than the mean, i.e. its bias is smaller in case of a disturbed background, but its standard error in case of white noise is larger than that of the mean.

The standard error of an estimated median background is, according to ESA SP-1200, Volume 1, Equation 1.3.15

$$\sigma_{b.med} = \sqrt{\pi/2}\, \sigma_{b1}/\sqrt{n_b} \tag{8}$$

where n_b is the number of samples and σ_{b1} is the standard error of the single sample value. This is valid in case of pure Gaussian noise, as when the readnoise dominates.

The background may alternatively be estimated by a mean value which is, however, reliable only for a very low density of stars

$$\sigma_{b.mean} = \sigma_{b1}/\sqrt{n_b} \tag{9}$$

where

$$\sigma_{b1} = \sqrt{b + r^2} \tag{10}$$

Equations (7) and (10) are based on the assumption that the counts from star and sky background have a Poisson distribution and that the readnoise has a Gaussian distribution. Introducing (9) and (10) in (7) gives a formula valid only at star densities where disturbing stars can be neglected

$$\sigma_m = 1.086\sqrt{S + n_s(b + r^2)(1 + n_s/n_b)} \ / \ (S\sqrt{n_{\rm obs}}) \tag{11}$$

This formula has been used in estimates from CUO, e.g. in CUO_37, 38 from where the Figs. 3 and 5 are taken, and where a margin factor 1.2 was applied to all errors.

The influence from disturbing stars is generally small for GAIA photometry due to the short integration time t and the direct imaging with high angular resolution. Disturbing stars in the samples containing the star or in those used for the background may partly be taken into account by means of the knowledge of the presence of these stars, especially obtained by the photometric sky mapper (PSM).

The influence of disturbing stars is less in PSF photometry because fewer samples are used and because of proper weighting. Since also the influence of the background is smaller, PSF photometry is preferred for faint stars. Nevertheless, estimates of the precision of aperture photometry can be representative for PSF photometry. A comparison of the estimates from simulations of PSF photometry (in CUO_42, 43) showed only 10 per cent smaller standard errors than the estimates by the present formulae for aperture photometry.

An accurate knowledge of the PSF is required for an accurate photometry. This should be possible to obtain with the very stable optical system of GAIA. But for bright stars where millimag precision is wanted both aperture and PSF photometry should be computed.

Finally, the standard error of R is

$$\sigma_R = 1 - 0.5 \ R^2/S. \tag{12}$$

The location of a star has the approximate standard error

$$\sigma_{\rm xy} = \sigma_{\rm PSF}/R \tag{13}$$

where $\sigma_{\rm PSF}$ is the standard deviation of a Gaussian fit to the PSF in respectively x or y directions, if the global PSF is two-dimensional. This follows from the location error of $\sigma_g/\sqrt{N}$ for a pure Gaussian with the sigma σ_g, containing N electrons, and without background.

Table 2. Photometric standard errors for the average of n_obs=100 observations in the Astro and Spectro telescopes.
Spectral type G2V, V-Ic=0.72, V-G=0.24 mag.
Sky background uV=21.0 mag/arcsec^2 and Sp.T.=G2V.
Count rates from SAG_LL_021.
Only photon noise and total RON for star and background are included in the standard errors.

			(1)	(2)	(3)	(4)	(5)	(6)
			AF	PSM	BBP	BBP	NBP	NBP
		Band	G	G	i'	i'	y	y
V	I							
mag	mag		mmag	mmag	mmag	mmag	mmag	mmag
17.0	16.3		1	1	3	3	8	7
18.0	17.3		2	2	6	5	15	14
19.0	18.3		4	4	12	9	33	27
20.0	19.3		8	8	27	20	76	60
21.0	20.3		17	16	65	45	183	143
22.0	21.3		40	37	159	109	-	-
23.0	22.3		97	90	396	268	-	-

Sample =	1*8	2*12	1*8	6*8	1*4	1*4	[pixel]
Sample area =	.033	.100	.033	.199	1.00	1.00	[arcsec^2]
V=15.0: S1=	43830	43830	11670	11670	765	765	[e-/s]
Integr. t=	0.90	0.90	0.90	0.90	2.2	2.2	[s]
V=15.0: S=	39447	39447	10503	10503	1683	1683	[e-]
n_s=	6	3	6	3	3	3	
Backgr: uV=	21.0	21.0	21.0	21.0	21.0	21.0	[mag/as^2]
Backgr: b=	5.2	15.7	1.4	8.3	6.7	6.7	[e-]
Total RON: r=	5.7	7.0	6.7	5.8	4.5	3.0	[e-]
sg_b1=	6.1	8.0	6.8	6.5	5.2	4.0	[e-]
n_b=	6	3	6	3	6	6	
sg_b.mean=	2.5	4.6	2.8	3.8	2.1	1.6	[e-]
n_s-term=	452	388	539	252	122	72	[e-]
V_b=	19.8	20.0	18.2	19.0	17.8	18.4	[mag]

7.2.1 The dominance of readnoise

We will estimate the precision to be expected for broad-band and narrow-band photometry by means of the preceding formulae for aperture photometry. This is a simple and reliable method of estimation, but it does of course not imply that the final GAIA photometry will be obtained by aperture photometry.

Table 2 gives the precision as function of V magnitude, followed by all relevant assumptions about sample size, count rates etc. Most of it is selfexplanatory since the notation is in accordance with the preceding section. The sky background is assumed to have a surface brightness of $\mu V = 21.0$ mag/arcsec^2. This is about one magnitude brighter than the average sky in order to obtain a conservative estimate. Several per cent of the sky in low latitude areas are even brighter. The central parts of galaxies are also brighter, but these parts cover only a very small part of the total sky area, e.g. about 0.1 per cent for galaxies with $I < 18$ mag.

The values of readnoise, r or RON, are taken from Fig. 7. This figure gives the total readnoise per sample, assuming that up to 2 800 000 stars/deg^2 has to be read in the Astro telescopes. These total RON values include the electric noise and they are: ASM0 and 1: 9.0, ASM3: 6.5, AF: 5.7, PSM: 7.0, BBP in Astro-1: 6.7, BBP in Astro-2: 5.8.

From Table 2 appears in all cases that the standard error of one sample, σ_{b1} given by Eq. (10), is only a little larger than r, showing that the readnoise dominates over the sky background. Columns 3 or 4 for i' cannot directly be compared with Fig. 3 because 3×8 pixels/sample, $r = 4.5$ and $n_s = 3, n_b = 6$ were assumed for the figure.

The readnoise for the Spectro instrument in Fig. 7 is assumed to be 3.0 e- for the SSM and NBP. In Table 2 the assumptions of 4.5 and 3.0 are made (Columns 5 and 6) in order to illustrate the effect of decreased readnoise. The precision values in Column 5 multiplied by the margin factor 1.2 agree as expected with the plot for y in Fig. 4 where $r = 4.5$ was assumed.

The relative effect of the star signal, S, and the n_s-term in Eq. (11) is of interest, therefore the value of the latter term is given in the table. The magnitude V_b at which the two terms are equal is also given. At this magnitude the standard errors would decrease by a factor $\sqrt{2}$ if background and readnoise were negligible. At fainter magnitudes the improvement would be even larger.

Improvement in this direction is possible by way of the three parameters n_s, r, n_b. Decreasing n_s is best achieved by performing PSF photometry, but the effective value of n_s in PSF photometry would probably be only about 20 per cent smaller than the value assumed in the table.

The readnoise is discussed in the following section.

Table 3a. Precision for maximum star density 800 000 stars/deg^2. Otherwise as Table 2.

			(1)	(2)	(3)	(4)	
			AF	PSM	BBP	BBP	
		Band	G	G	i'	i'	
V	I						
20.0	19.3		8	7	23	19	
21.0	20.3		16	15	55	43	
22.0	21.3		35	33	134	103	
23.0	22.3		85	79	334	254	
Backgr:		b=	5.2	15.7	1.4	8.3	[e-]
RON:		r=	4.8	5.7	5.6	5.4	[e-]
		sg_b1=	5.3	6.9	5.7	6.1	[e-]
		n_s-term=	339	289	393	225	[e-]
		V_b=	20.2	20.3	18.6	19.2	[mag]

Table 3b. Precision for maximum star density 200 000 stars/deg^2.

20.0	19.3		7	7	21	18	
21.0	20.3		15	14	48	44	
22.0	21.3		35	30	117	95	
23.0	22.3		83	71	289	233	
Backgr:		b=	5.2	15.7	1.4	8.3	[e-]
RON:		r=	4.7	4.8	4.8	4.8	[e-]
		sg_b1=	5.2	6.2	4.9	5.6	[e-]
		n_s-term=	327	232	293	138	[e-]
		V_b=	20.2	20.6	18.9	19.7	[mag]

Improvement is finally possible by an increase of n_b but the effect is not very strong because of its position in the bracket $(1 + n_s/n_b)$. The improvement for broad-band photometry if n_b were doubled, from the value $n_b = n_s$ as in the table to the value $n_b = 2\,n_s$ would mean only 7 per cent smaller standard errors at V_{b}.

7.2.2 Maximum star density and readnoise

The values of readnoise for the Astro instrument may be decreased if the requirement for measuring 2 800 000 stars/deg^2 is relaxed, which would result in more accurate broad-band photometry. Only a small fraction of the sky has such a high star density and the penalty for photometry of faint stars all over the sky is considerable.

Two cost and hardware reasons also exist for requiring only a lower maximum star density. The cost of onboard handling of more than the present maximum of 155 000 stars/deg^2 is not negligible, and the thermal design depends on this number in the following way. The present satellite hardware design assumes that the same number of samples is read in each CCD independent of the star density since this will result in a constant power dissipation. This is important for the thermal stability of the instrument which is designed to be $\pm$ 30 microkelvin. Some dummy samples not belonging to any star are therefore usually read but not used further.

It might be better to design the reading frequencies for a star density of for instance 1 000 000 or even lower and to increase the SNR detection limit for data collection in the AF and BBP fields when too many star are detected on a CCD of the ASM. The information from ASM1 and ASM3 about a detected star should still be transmitted for the normal lower SNR limit for the sake of statistical completeness. At least 6 samples should always be collected from the PSM in order to determine the coordinate along scan. This coordinate could be compared with that from the ASM in order to decide whether the object is moving, i.e. a solar system object.

The readnoise could be very effectively decreased by the use of a reading frequency adapted to the number of patches to be read, but at the cost of complexity.

The effect of adopting lower reading frequencies is shown in Table 3 where the values of readnoise, as calculated by M. Perryman, for the maximum star densities of 800 000 and 200 000 star/deg^2 have been used. The decrease in readnoise from Table 2 is seen to be significant, but the readnoise is still dominating over the sky background. (The value of r for the AF is not consistent with that in Table 2, cf. Fig. 7.)

The improvement is most easily seen in Table 4 containing only the line for V = 22.0 mag from each table. The largest relative improvement is obtained in Column 3, i.e. for the high resolution measurement of i' in Astro-1, which is in accordance with the bright value of V_b.

Table 4. Precision for V=22.0 for various maximum star densities.

V	I		(1)	(2)	(3)	(4)	
			AF	PSM	BBP	BBP	Maximum density
		Band	G	G	i'	i'	
mag	mag		mmag	mmag	mmag	mmag	stars/deg^2
22.0	21.3		40	37	159	109	2 800 000
22.0	21.3		35	33	134	103	800 000
22.0	21.3		35	30	117	95	200 000

7.3 Mapping and photometry

The samples of a one-dimensional patch may be analyzed in various ways to obtain astrometry and/or photometry. A patch may be analyzed alone giving epoch astrometry and/or photometry of an object. We assume here that the astrometric calibration, i.e. the satellite attitude and the geometric parameters of the focal plane are available from a previous calibration process.

Several patches may be analyzed together to get, e.g., mission averages if the whole mission is used. When mission averages of the astrometric parameters are known it is possible to return to the individual patches in order to derive epoch photometry.

Depending on the stars and application considered, the relevant astrometric star parameters are either the two position coordinates in the ICRS reference system, or the five parameters, including position, parallax and proper motion components, or even additional orbital parameters of double stars. The important thing is that astrometry must come first, and then be followed by photometry.

Thus, the astrometric parameters and the stellar flux in several colour bands may be derived as mission averages from all the patches belonging to a given star.

For the final photometry the calibration and the astrometric parameters must be known, but the photometry does not require the highest accuracy.

Probably an overall accuracy of 10 mas per patch would be sufficient, i.e. 0.3 pixel width, which will be available early in the mission.

7.3.1 Epoch astrometry and photometry

If each one-dimensional patch is analyzed separately one may speak of epoch astrometry and photometry. Such astrometry would be one-dimensional since only a position component along scan could be derived, called the w coordinate and being measured relative to some point on the sky inside or near the patch. The coordinate across scan is called z.

When the w coordinate of an object is known the flux from the object may be estimated. The w coordinates of stars may be defined as locations where the cross-correlation between the point-spread function (PSF) and the series of samples have a significant maximum, i.e. the maximum cross-correlation method (MCC) for astrometry. Other location estimators may be considered and the methods to find the maximum should be discussed.

The subsequent flux estimation for stars may be carried out as simple aperture photometry or PSF photometry (cf. Sect. 7.3.3).

The final epoch photometry shall be based on astrometric calibration and astrometric star parameters derived in a separate processing.

7.3.2 Average photometry

When all astrometric calibrations and parameters of the stars are known it is possible to superpose or stack all patches from the mission for a given detected star, or perhaps a subset of patches for a given time interval, or separated in time according to a possible period. The position and orientation of all samples relative to a chosen celestial position inside the patches in the ICRS reference system will be available. The coordinates relative to this position are conventionally given as (x, y) with directions parallel to RA and Dec.

Sometimes it is more practical to use x, y coordinates relative to a point having the same parallax and proper motion as the main star in the patch, as has been used in Fig. 8.

Various possible ways to analyze such a set of patches may all be called 'mapping' because a map relates to two spatial coordinates, not only one coordinate as for epoch photometry from one patch.

One of the mapping techniques is a 'flux map' in x, y with a finer resolution than the width of a sample in which each picture element is the sum of the values of all samples containing that element. A flux map can be

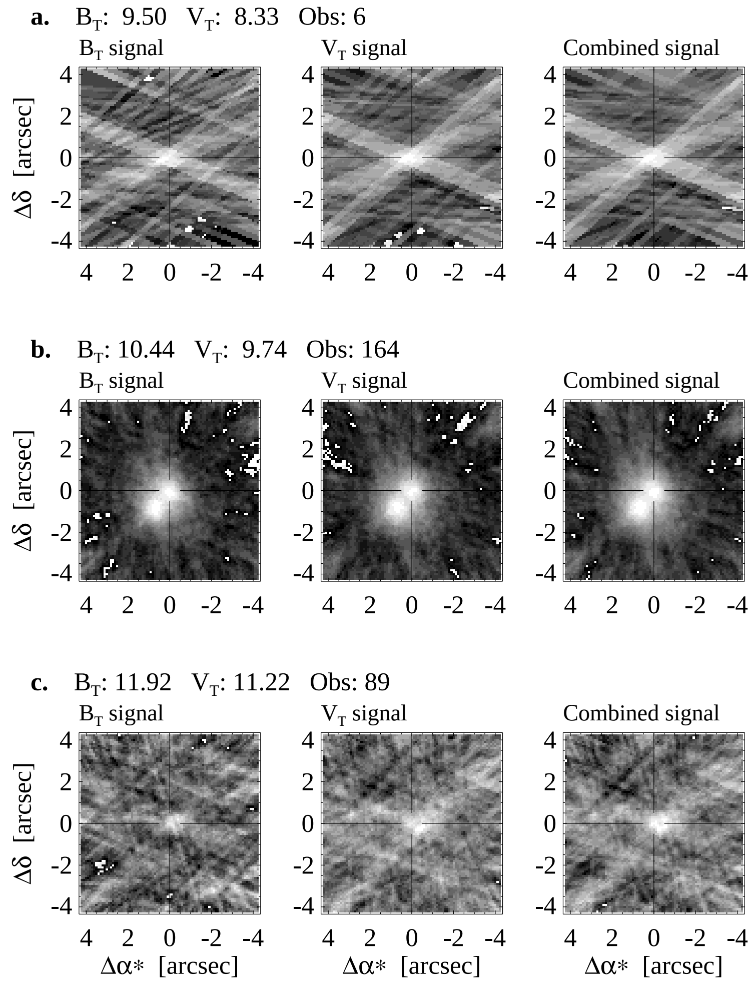

Figure 8: A flux map from the second Tycho data reduction. Superposition of photons in maps of 8×8 arcsec^2, centred on the predicted position. In the case of Tycho-2 the effects of known parallax and proper motion are included in the predicted positions. An offset from the centre thus determines a correction to the position given in the Tycho-2 input catalogue. (a) Only six observations were included in order to show the principle, therefore only a few position angles. (b) A double star with 1.2 arcsec separation and clearly resolved in 164 observations although the observed slit response function has FWHM = 1.0 arcsec. (c) A faint star, very faint in the B_T signal, but clearly detectable in the V_T and the combined signals.

displayed for visual inspection (cf. Høg et al. 1998b, Fig. 2, here shown as Fig 8). It will show stars and rather few traces of the original samples if the patches have many different orientations. A flux map is not required for astrometry and photometry of stars but can be of interest for unusual objects.

A flux map may also be constructed from two-dimensional patches. This is envisaged for the most interesting galaxies using the samples of 6×8 pixels transmitted from the BBP in Astro-2 if an excess surface brightness is detected in ASM1.

A photometric average may be obtained as simple aperture photometry by summing the amplitudes from simple aperture epoch photometry. Alternatively it may be obtained as PSF photometry by summing the amplitudes from PSF epoch photometry. The fluxes and amplitudes are linear quantities, and some epoch values for faint stars may be negative. Therefore conversion to a magnitude scale requires some caution. It is worth noting that none of the photometric values are censored, and that no photometric bias is therefore expected for such a reason. The only censoring takes place at the detection in the ASM.

7.3.3 PSF photometry

The point spread function (PSF) is a one-dimensional function in case of one-dimensional patches, and is obtained by convolution of the optical PSF with functions corresponding to the sample width, the TDI motion, and the mismatch of TDI motion with the velocity of the star image. This is called the 'global' PSF values if emphasis is required.

The global PSF for each observation epoch is placed at the known location of the star relative to the sequence of samples N_k, and the PSF value f_k corresponding to each sample is calculated. The global PSF should be normalized so that $\sum f_k = 1.0$ when the wings are completely included.

These values are then scaled to fit the observations corrected for background and with proper weighting. This gives the amplitude A which is an estimate of the stellar flux S due to the chosen normalization of the PSF.

For a more precise description we define:

N_k	:	the sample value with number k [e-]
f_k	:	value of the PSF corresponding to N_k
p_k	:	statistical weight assigned to the sample N_k
A	:	amplitude, flux estimated by PSF photometry [e-]
b	:	sky background per sample [e-]

The observation equation for epoch photometry is then

$$Af_k + \epsilon_k = N_k - b \tag{14}$$

and the solution is generally

$$A = \sum (N_k - b)p_k / \sum f_k p_k \tag{15}$$

The background b is obtained from the samples in the patch that are not disturbed by the detected star or any other small-scale object in the patch. This determination should therefore be iterated when more complete information of disturbing stars becomes available. Their images may then be subtracted before a new background value is determined or the disturbed samples may be rejected. Large-scale objects in the patch, for instance a part of a galaxy or nebulosity, will in principle contribute equally to all samples. Thus, due to the averaging only parts of the power spectrum of the background variations contribute to the accidental and systematic errors of the background value.

If the weights are chosen as $p_k = f_k$ the cross-correlation solution is obtained, other possible choices are weights giving the least squares or the maximum likelihood solutions.

We define the aperture, v, as a width corresponding to an integer number of samples. If the weights are $p_k = 1.0$ inside the width v and $= 0.0$ outside we obtain *corrected* aperture photometry. If the width is too small to contain the wings and if a realistic PSF is assumed Eq. (15) will give a correct amplitude, corrected for the loss of the wings.

Alternatively, we may define *simple* aperture photometry as the PSF photometry where the weight are those just defined and the (normalized) PSF is taken as $f_k = p_k/v$. Simple aperture photometry does not correct for lost wings. The formulae in Sect. 7.2 assume simple aperture photometry in the error estimates, but with no loss of flux from the wings.

Average photometry was defined in Sect. 7.3.2 and the Eqs. (14) and (15) can again be used if the proper PSF and b values are used for each patch. The samples N_k may thus belong to one epoch of observation or to any selection of epochs. The formulae remain valid even if only some of the observations at an epoch are used, but the result may then be less precise. It is also clear that the formulae can easily be generalized to apply a two-dimensional PSF if required.