Sky survey and photometry by the GAIA satellite*

E. Høg, C. Fabricius, J. Knude, V.V. Makarov
Copenhagen University Observatory
Juliane Maries Vej 30, DK-2100 Copenhagen Ø

23 July 1998 – Final version = SAG_CUO_41

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 in this volume by Lindegren (1998). The present paper focuses on the design and performance with respect to multi-colour photometry.

GAIA is designed as a scanning satellite to collect data for high-precision astrometry (10μarcsec) and photometry of a billion stars. 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 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 too much data to be all transmitted to the ground. A reduction by at least a factor thousand is required. Two possibilities have been considered. The use of an

*Presentation at the International Spring Meeting of the Astronomische Gesellshaft in Gotha, May 11–15, 1998

input catalogue of about 100 million stars, or 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 only at 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. 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 measurements of any given sky area for the purposes of data reduction.

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. A multicolour 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).

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). It has two parts, the second part (ASM2) providing 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

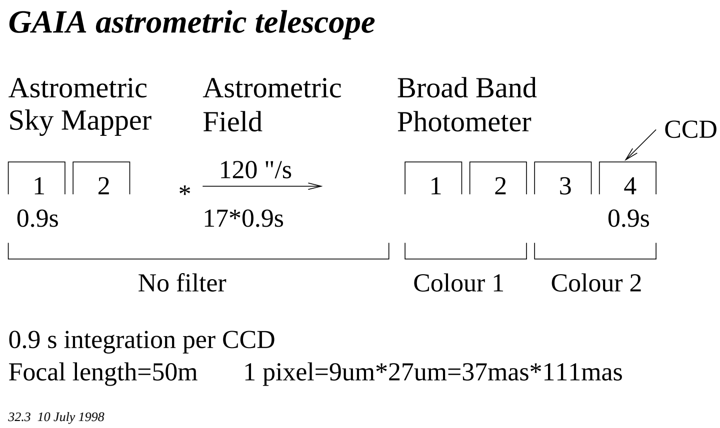

Figure 1: *One of the focal planes of the two astrometric telescopes with CCDs integrating always 0.9 s. The 2+4 CCDs of the astrometric sky mapper (ASM) and broad-band photometer (BBP) are shown, and the 17 CCDs of the astrometric field are indicated. Stars are detected in the astrometric sky mapper and then measured astrometrically 17 times. Photometry is obtained through colour filters in the BBP giving four-colour photometry from the two astrometric telescopes.*

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.

Two-dimensional positions in the focal plane coordinate system is obtained from the ASMs. They are required for the determination of the satellite scan velocities and the data taking in the subsequent field 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, thus the form matching the Airy disk in the ASM and the one-dimensional sample used in the broad-band photometer (BBP).

The data collected from the BBP cover an area of about 1 arcsec^2 centred on each star. These one-dimensional scans are obtained at different position angles in the course of the mission. A superposition of the data from the many

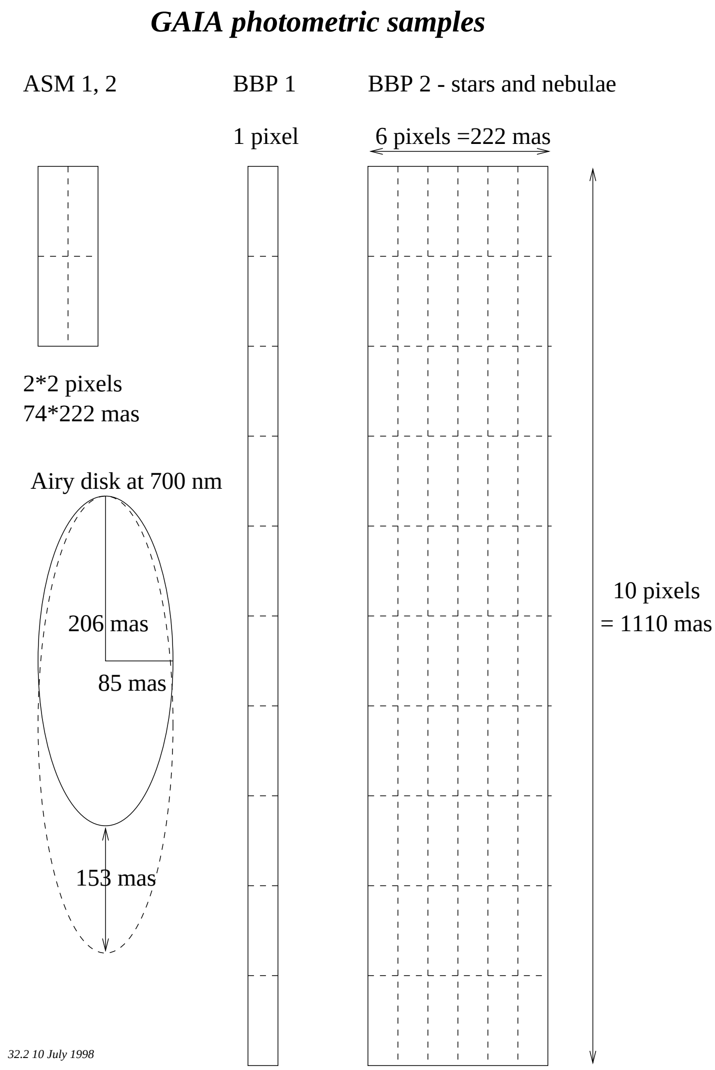

Figure 2: *The proposed samples of the astrometric sky mapper (upper left) and the broad-band photometer (right) compared with the Airy disk of the astrometric telescopes. The samples for BBP1 and BBP2 will give a resolution of about 100 and 200 mas, respectively. The choice of samples must be a compromise between the scientifically desirable resolution, the resulting readnoise, and the permitted telemetry rate, thus optimizing the total scientific results from GAIA within certain constraints.*

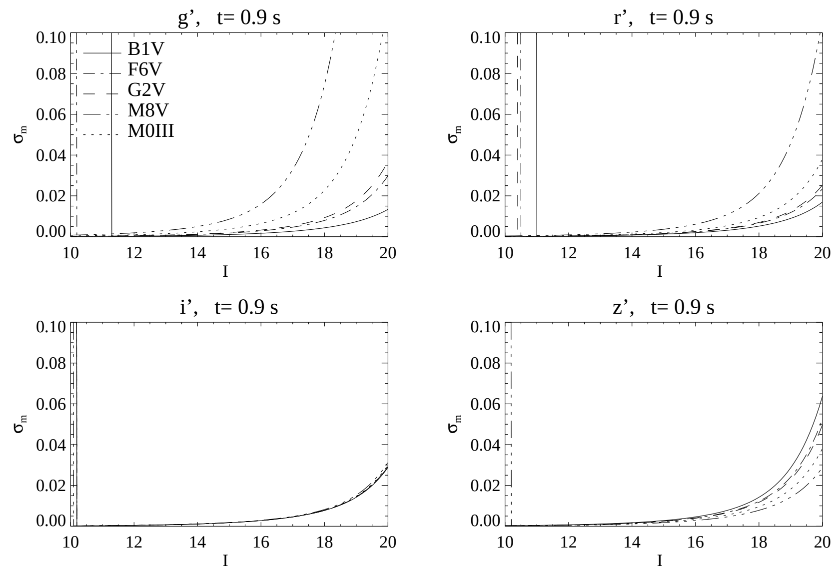

Figure 3: *Precision of broad-band photometer in four bands of the Sloan photometric system. Average of 100 observations, integration time t, the vertical lines indicate saturation of the CCD at bright stars.*

observations per star will allow a two-dimensional mapping of the sky area, not only of the star, which is important for double stars, quasars and cores of galaxies.

Broad-band colour filters, e.g. the four 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. An ultraviolet band cannot be included because CCDs with enhanced red sensitivity will be chosen for the astrometric telescopes 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 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).

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 moving solar system objects, 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.

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 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,

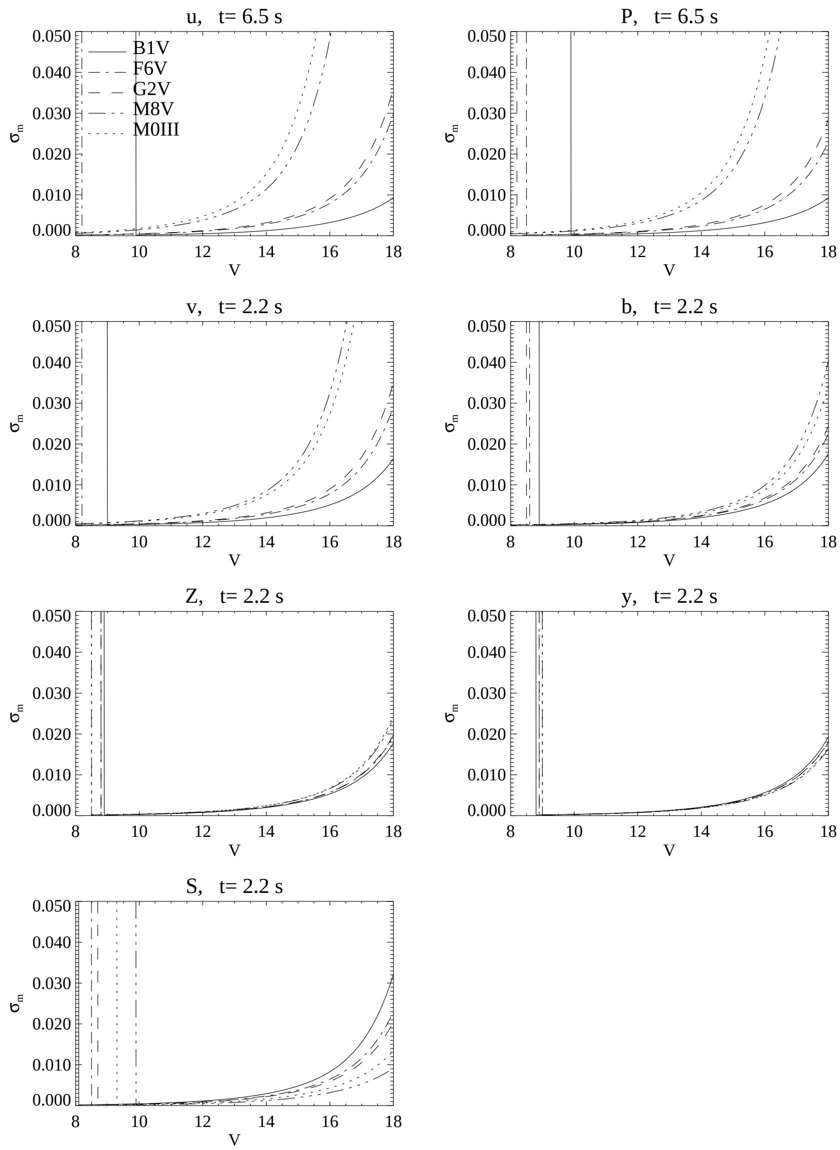

Figure 4: *Precision of narrow-band photometer in the seven-band Strömvil photometric system. Average of 100 observations, integration time t, the vertical lines indicate saturation of the CCD at bright stars.*

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 $V = 17$ 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
- 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.

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

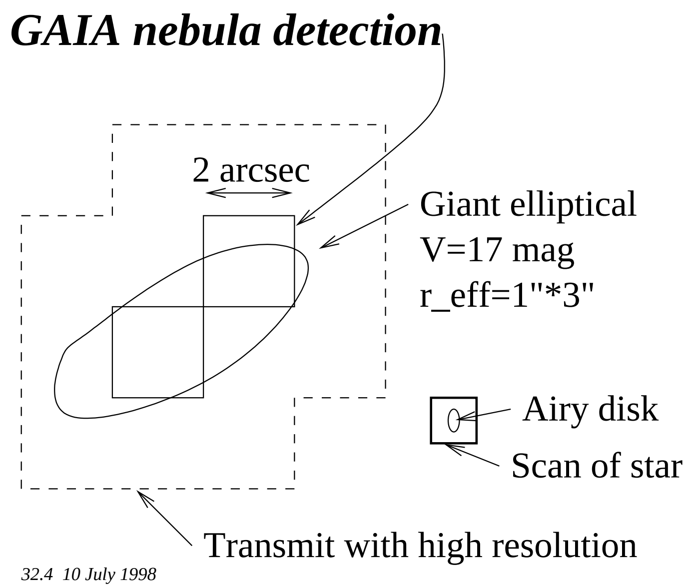

Figure 5: *Detection of excess surface brightness due to the presence of a galaxy and transmission of high resolution data from a surrounding area.*

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 be determined in all small square areas of 2×2 arcsec^2 (see Fig. 5) from the ASM1 samples. From these 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 their 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 white light (by the ASMs) and in the four colours (BBPs) at high angular resolution. Normal galaxies with $I \sim 18$ mag could be measured out to the effective radius, and many Galactic nebulosities.

Conclusions

At the present stage of studies (July 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.

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

References

[1] ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200

[2] Fukugita M., Ichikawa T., Gunn J.E., Doi M., Shimasaku K., Schneider D.P. 1996, Astron. J. 111 (4) 1748

[3] Høg E. 1993, IAU Symposium No. 156, I.I. Mueller and B. Kolaczek (eds.), p. 37

[4] Jørgensen H.E., Lipunov V.M., Panchenko I.E., Postnov K.A., Prokhorov M.E. 1997, Astroph. J. 486, 110

[5] Lindegren L. 1998, the present volume

[6] Rees M.J. 1997, In: Reviews in Modern Astronomy 10, R.E. Schielicke (Ed.), Astronomische Gesellschaft, Hamburg, 179

[7] Straižys V., Høg E., Davis Philip A.G. 1997, Proceedings of ESA Symposium 'Hipparcos - Venice'97', ESA SP-402, 761

[8] Straižys V. 1998, priv. comm.