OPTICAL DESIGN OF GAIA

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ABSTRACT

The optical design is discussed for the GAIA astrometric satellite project of the European Space Agency. A Gregory-type telescope with a focal length of 60 m is presented, and the usefulness of dispersed interferometric fringes is discussed. A payload with four interferometers is proposed and presently called GAIA95C. It contains two Hipparcos-type beam combiners and telescopes with 2 m diameter giving direct imaging onto a focal plane assembly of CCDs suited for astrometry and 10-colour photometry.

Key words: space astrometry; GAIA; optical system.

1. INTRODUCTION

The basic aim for designers of the GAIA satellite payload is to place the most performing instrument inside the available volume of the Ariane 5 launcher, i.e. a cylinder of 4.2 m diameter and 3.02 m length. GAIA is planned as a scanning satellite similar to Hipparcos, rotating about the axis of the cylinder with a speed of approximately 120 arcsec/s while the spin axis revolves slowly, in about two months, in a cone around the direction to the Sun. The satellite spin gives the stars a slow motion across a field in which one-dimensional astrometric measurements of high precision along a great circle will be obtained. At least two directions of view separated by a very constant angle are required, but it is still open whether this 'basic angle' shall be realized by a Hipparcos-type beam combiner, as we propose in Section 4, or by two or three separate telescopes whose relative angles are monitored (or controlled) as originally proposed for GAIA by Lindegren & Perryman (1995).

The best scientific performance with respect to astrometry and photometry is wanted. The main driver in the design is astrometry where a precision and accuracy of 10 microarcsec must be achieved. Faint stars of 18–20 mag should be reached, though with less accuracy, in order to observe significant tracers of Galactic structure in the crucial parts of the Galaxy (see Perryman, Lindegren & Turon 1997 and Gilmore & Høg 1995). Also dense fields must be observable for the same reasons. It has been clear for some time that a Fizeau interferometer is the best option for achieving this goal.

A large number of features must be optimized in the design of a satellite. In the present paper the attention shall be focussed on the critical parameters of the interferometer (in Section 2), on the possibility to use dispersed fringes (in Section 3), and on the entire telescope design and optical assembly (in Section 4).

2. FIZEAU INTERFEROMETER

The interferometer must be of the Fizeau type in order to obtain a field of significant size with ideal (i.e. diffraction-limited) imaging; a Michelson interferometer cannot provide this. Postponing the question of the telescope design until Section 4, we can here discuss the basic parameters of the interferometer as illustrated in Figure 1.

The entrance pupil of the interferometer consists of two entrance windows of identical shape and size placed in front of a telescope. The light through the pupil will create a diffraction image in the focal plane of size and shape defined by the size and shape of each window. This diffraction image will contain a number of $2B/b$ fringes due to interference of light from the two windows.

In the illustrated case where the pupil ratio is $b/B = 0.50$, four fringes result. The zero-order fringe contains 50 per cent of the light, two first-order fringes each contain 20.2 per cent, and the rest of the light is contained mainly in the higher uneven orders (not shown in Figure 1). The higher even orders are suppressed, as seen in the two 'half-fringes' of second order inside the Airy disk, thus making the total of four fringes, as given by the expression $2B/b$.

The shape of the window is here chosen to be rectangular, mainly because the discussion is simplified through the simpler resulting formulae, as indicated in the Figure for the size of the Airy disk and the fringe period. Circular or oval windows may later be

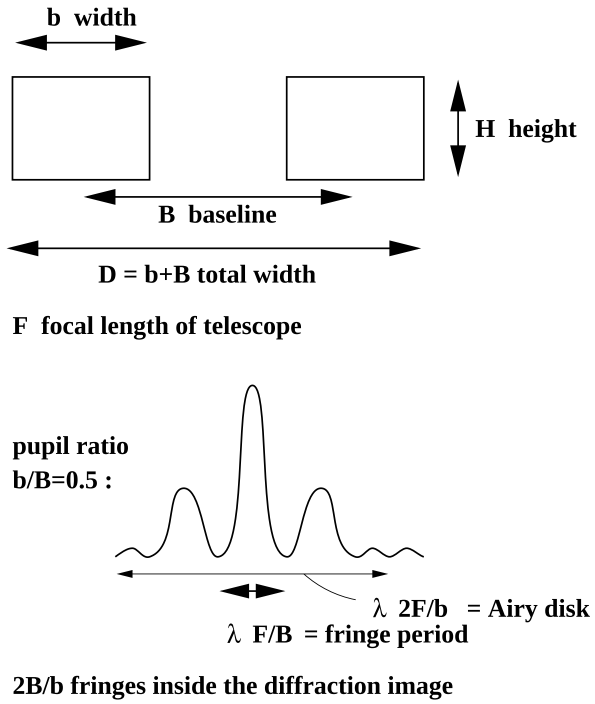

Figure 1. Aperture geometry of an interferometer. The resulting fringes inside the diffraction image are shown for the pupil ratio b/B=0.5. This ratio gives the best astrometric precision for a given value of the total width D=B+b.

chosen for ease of manufacturing, without an essential degradation of the performance.

The pupil ratio $b/B = 0.50$ is appropriate for two reasons. It has been shown by Høg, Fabricius & Makarov (1997) that for a given value of total width $D = b+B$ this ratio gives the smallest astrometric standard error for the location of the monochromatic image, affected by poissonian noise from the photon counts. If a telescope design for GAIA with given D is available which gives diffraction limited performance in a large field, it will generally do so for any value of b, so that no good reason exists for choosing a smaller value for the pupil ratio than 0.50.

Another reason for this choice is that a larger fraction of the light (90 per cent) is concentrated in the inner three fringes than for any smaller value of the ratio. The light from a star is polychromatic with most of the light inside an interval of 400 nm and this gives a considerable smearing (widening) of all fringes, proportional to the order of the fringe, according to the fringe period being $\lambda F/B$. The widening of fringes decreases the astrometric precision, without affecting the photometric precision. This decrease of astrometric precision can be avoided by the fringe dispersion, discussed in Section 2, but this has its own costs.

The standard error for the location of an image for a rectangular pupil of width b is given (in radians) by:

$$\sigma_N = \frac{\lambda}{1.155\pi b\sqrt{N}} \tag{1}$$

(see Lindegren 1978 or Høg, Fabricius & Makarov 1997) where N is the total number of collected photons, assuming zero background counts.

The standard error for an interferometer along the direction of the baseline B is:

$$\sigma_N = \frac{\lambda}{2\pi B\sqrt{N}}. \tag{2}$$

where N is proportional to bH (see Figure 1). The real measurement error will be larger, for instance due to undersampling of the image, background counts, and perhaps optical aberrations.

The designer thus has to minimize σ_N by optimal choice of B, b, H, with $b/B = 0.5$. This requires the design of a telescope with a large field in order to maximize the integration time of the scanning satellite and hence N, the number of collected photons.

The final choice of pupil ratio may be different from 0.5 since background and readout noise have not been taken into account in the above discussion, neither have such practical considerations as vignetting and optical manufacturing.

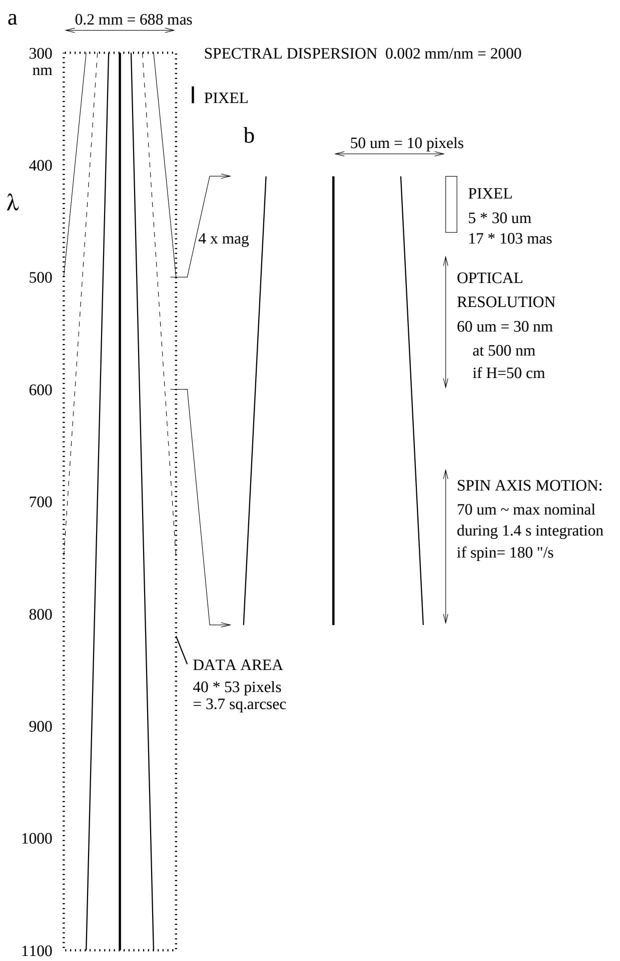

Figure 2. Dispersed fringes, assuming F=60 m, B=1.0 m, b=0.5 m. (a) The fringes in the sensitivity range of CCDs, (b) optical and spectral resolution, and smearing due to the spin axis motion.

Table 1. Two telescope units each with two interferometers with 100 cm baseline using dispersed fringes, 5 year mission. Predicted standard errors due to photon noise in astrometry and photometry for a G0 star (see Section 3). The effects of, e.g., background, readout noise and undersampling are included. Units: mas = milliarcsec, and 10 nm for the 8 central wavelengths given to the right in line #3.

	Astrometry		Photometry [millimagnitude]								
V	par.	p.m.	W	u	P	v	b	Z	y	S	I
mag	mas	mas/year		35	37	41	47	52	55	66	81
12	0.003	0.002	0.1	1	1	1	1	1	1	1	1
14	0.008	0.005	0.2	3	2	2	1	1	1	1	1
16	0.022	0.013	0.6	7	6	4	3	3	3	3	1
18	0.068	0.040	1.6	24	20	12	9	8	8	9	3
20	0.302	0.177	6.3	70	60	30	25	20	20	20	9

3. DISPERSED FRINGES

The polychromatic diffraction image with fringes may be dispersed into a spectrum along the direction of the fringes. The result is shown in Figure 2, assuming a constant dispersion of 0.002 mm/nm = 2000. This may be achieved by a glass prism in a collimated beam of the imaging telescope, with the refracting edge of the prism parallel to the baseline. Such a prism generally introduces a geometric field distortion which must be taken into account.

The dispersed fringes, especially the three fringes of zero and first order containing 90 per cent of the light, may be measured by a CCD as the spectra drift across with constant speed. Time delayed integration (TDI) in about one second of integration can be obtained. An analysis of the data area of about 4 arcsec^2, indicated in Figure 2, would provide an astrometric measurement in horizontal direction (along scan) and a spectrophotometric measurement in the vertical direction. Since the star light at any one point is nearly monochromatic the disturbing widening of fringes is thus avoided.

The astrometric and photometric performance of such a system has been studied by Høg, Fabricius & Makarov (1997). The result is shown in Table 1 which is based on the following assumptions: two telescope units, each with a Hipparcos-type beam combiner and two interferometers with baseline B = 100 cm, b = 50 cm, H = 50 cm; a readout noise of 1 e$^-$ per pixel which by far dominates over any reasonable assumptions about sky background and scattered light; a focal length of 60 m and pixels of 5×30 μm^2, as shown in Figure 2; an angular area of the CCD detectors for each telescope of 0.10 deg^2; present day quantum efficiency of CCDs (see Straizys & Høg 1995, Table 2); and a mission length of five years.

A method to achieve the low readout noise of 1 e$^-$ per pixel by co-addition is proposed by Høg, Fabricius & Makarov (1997). But even with this (optimistic) assumption the readout noise remains significant at the faint magnitudes. An ideal readout noise of zero would decrease the astrometric errors given in Table 1 by 5, 20 and 40 per cent at V = 16, 18 and 20 mag, respectively.

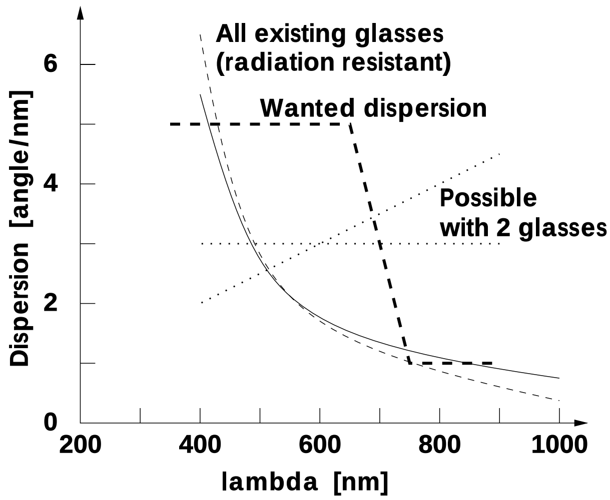

Figure 3. Design of a prism for dispersion of fringes. Existing optical glasses leave only little flexibility for the design.

3.1. Design of Prism

The design of a suitable prism for the dispersion has been studied. The dispersion of available radiation resistant glasses varies in the interval shown by the dashed and solid curves in Figure 3. These include calcium fluoride, fused silica and 16 glasses available from Schott. A prism of only one glass would give a spectrum with dispersion quickly increasing towards the blue end. It is possible by combination of two glasses to obtain a dispersion as function of wavelength in the range between the two dotted lines. The one with constant dispersion (horizontal line) could thus be used to obtain spectra as in Figure 2, although the dispersion would sharply increase at shorter than 400 nm.

The actual resolution in the measured spectrum is determined by three contributions: the vertical length of the pixel which in Figure 2 has been chosen to be negligible compared with the two other contributions, the optical resolution width and the spin axis motion. Taken together, the actual resolution width would be increasing with wavelength if the optical

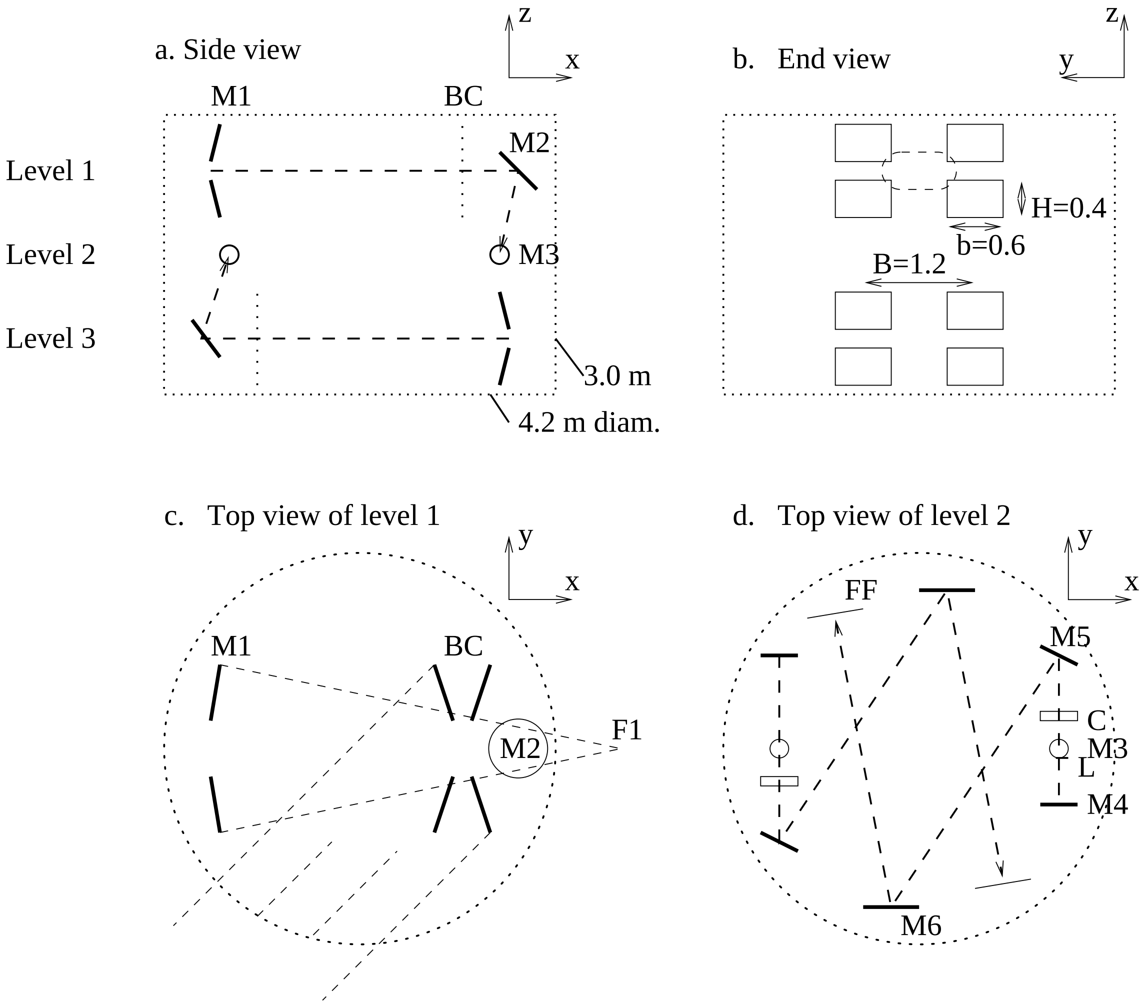

Figure 4. Optical layout of GAIA95C with four interferometers inside the Ariane 5 envelope. (a) Two telescopes with Hipparcos-type beam combiners (BC) and main mirrors (M1) of 2 m diameter (in levels 1 and 3) form images onto the focal planes (FF) in level 2, (b) entrance pupils of the four interferometers, (c) top view of the upper telescope, (d) view of the beams folded by the flat mirrors M3, M5 and M6. L is a lens system at the primary focus. The Gregory secondary mirror, M4, and the corrector plate, C, constitute an inverted Schmidt telescope.

resolution were the most significant of the three contributions. It will be variable with time if the spin axis motion is a significant contribution since it varies along a great circle scan.

With spectrophotometry it is in principle possible to measure any number of wavelength bands and of any width. In practice the finite resolution sets limits, and it has been shown that most of the astrophysical information may be found in fairly few bands. From an astrophysical point of view it is therefore desirable and adequate for most classification purposes to measure photometrically in the 7 bands of 'intermediate' width 30–40 nm situated from 350–660 nm (see Table 1).

The Cousins' red band I at 810 nm has a width of 140 nm, therefore a smaller dispersion is required there. But such a 'wanted' dispersion (dashed broken line) cannot be achieved with existing glasses. The result is that the spectrum of each star becomes longer than wanted, so that more confusion of sources is encountered. The spectrum of a star is however not as long as the data area of 800 nm indicated in Figure 2. Since most of the light in any spectrum is contained within 400 nm the real instantaneous field of view for any star is about 2 arcsec^2, according to Figure 2.

3.2. Preliminary Conclusion

Dispersion of fringes offers a number of advantages (see Høg, Fabricius & Makarov 1997) compared with the photometry through glass or interference filters as proposed by Lindegren & Perryman (1995). The disadvantages of dispersed fringes compared to direct imaging can however not be neglected: more confusion of sources; more disturbance from readout noise; a larger number of pixels to be read and analysed. The choice is not obvious and requires an analysis with more specific designs and mission requirements.

4. TELESCOPE DESIGN

After the preceding specification of the optical requirements in terms of baseline, aperture pupil, focal length and field size, it is appropriate to describe a telescope assembly fitting into the Ariane 5 envelope, and a corresponding focal plane assembly of CCDs. We consider a telescope combining the light from two interferometers viewing in two directions via a Hipparcos-type beam combiner, but the same type of telescope might be used in two separate telescopes whose angle would be monitored by metrology. The pupil ratio is always $b/B = 0.50$.

4.1. Gregory Telescope Systems

The proposed telescope is of the Gregory type, consisting of a concave primary mirror focusing the light in an intermediate focus. This image is reimaged by a concave (Gregory) mirror onto the final focal plane. A very long effective focal length may be obtained by a suitable magnification through the Gregory mirror which then acts almost as a collimator. The basic curvatures and relative positions of the mirrors are specified completely by the focal lengths of the two mirrors (F1, Fg), and the effective focal length (F). Proper folding by means of flat mirrors is required in order to contain the system inside the available volume and so that the best optical performance is achieved.

A system of this kind with baseline 1 m and F=60 m was described by Høg, Fabricius & Makarov (1997) and has been called GAIA95 because the concept was first described in an internal report in 1995. It was an aplanatic Gregory system and contained a lens in the intermediate focus to compensate the large field curvature. Detailed optical calculations showed however that the diffraction-limited field would be too small for GAIA.

Another system was later proposed (GAIA95B) with $B = 1$ m, $F = 60$ m, $F1 = 4.0$ m and $Fg = 1.275$ m. The Gregory system was modified into an inverted Schmidt system. Detailed optical calculations showed that good performance would be obtained with a lens system of three lenses of silica at the primary focus. Diffraction limited imaging in a field of at least 0.5 deg diameter and a field distortion of 0.015 per cent was achieved in a preliminary optimization.

The present proposal (GAIA95C) shown in Figure 4, has B=1.2 m, F=60 m, F1=4.3 m, Fg=0.540 m and the Gregory system is an inverted Schmidt. Detailed optical calculations have not yet been carried out, but the experience from GAIA95B indicates that a similar performance can be achieved. No fringe dispersion is assumed here, but in principle a prism could be inserted in the nearly parallel beam near the Schmidt corrector.

The largest diffraction limited field for given values of B and F is obtained when F1/B and Fg are as large as possible. The first value can hardly be increased in the available volume, but it is possible to increase Fg by adding a flat folding mirror M7.

4.2. Optical Assembly

The optical assembly in Figure 4 consists of two beam combiners (BC) in the levels 1 and 3, each connected with a Gregory-type telescope (M1, L, M4, C) where L is a lens system and C is the corrector plate. Each system is folded by flat mirrors (M2, M3, M5, M6) leading to a final focal plane (FF) in level 2. The entrance pupils of the four interferometers are shown in Figure 4b.

The big mirrors BC and M1 are shown as if they each consisted only of the four reflective optical surfaces, but this does not prejudice any practical form of manufacture or assembly. All the smaller mirrors are thought to be monolithic.

A basic angle of the beam combiners about 95 degrees, but different for the two systems, is indicated. An even larger angle would perhaps facilitate the telescope baffling.

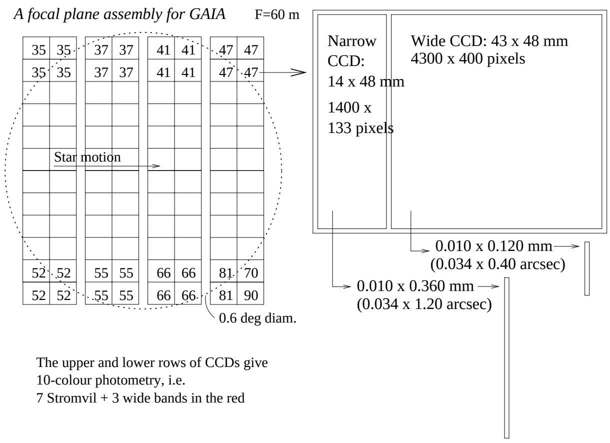

Figure 5. Focal plane assembly of CCDs. Direct imaging of the fringes is assumed, without fringe dispersion. Stars move horizontally from left to right.

4.3. Focal Plane Assembly

The original GAIA proposal by Lindegren & Perryman (1995) contained a telescope with 12 m focal length and a detection system with a modulating grid. This involved an instantaneous field of view of 300 arcsec^2 so that stars fainter than about $V = 16$ mag could not be observed due to confusion of the signal with other faint stars. The authors pointed out the great potential advantages of direct detection of the fringes by a CCD, but a telescope with the required long focal length to match the size of available CCD pixels was not yet known. The design of a CCD detector system for the modulating grid was discussed by Høg (1995) at the RGO-ESA Workshop at Cambridge in 1995, showing a number of difficulties with no obviously viable solutions.

Direct fringe detection was made possible with the GAIA95 system proposed later in 1995 by Høg, Fabricius & Makarov (1997). The last version of this system, GAIA95C mentioned in Section 4.1 has an instantaneous field of view of only 0.3 arcsec^2 with the following CCD system, i.e. one thousand times smaller than for the modulating grid. This means that stars as faint as 20 mag can be measured without significant disturbance from other (fainter) stars nearby in the field of view.

A focal plane assembly for GAIA with 96 CCD chips is proposed in Figure 5. Each CCD chip holds two CCDs, a narrow and a wide. They have the same width of pixels along scan (0.010 mm) but different heights, corresponding to 1.20 and 0.40 arcsec respectively. These ratios have been tailored to provide a large dynamic range of the system. This range is further extended towards bright stars by utilizing the attenuated light on the photometric CCDs for high precision astrometry.

The pixel width is twice as large as in Figure 2 which gives some loss of astrometric precision due to undersampling. But this loss is probably compensated by the higher quantum efficiency of wide pixels, which is one of several points to be studied.

The height of 120 μm for the pixels on the wide CCD is 1.6 times the optical resolution perpendicular to scan at 500 nm. A smearing by up to 60 μm during the 1.23 s integration time due to spin axis motion must be taken into account, corresponding to a spin rate of 120 arcsec/s.

In the image analysis usually 2 pixels should be added in vertical direction and pixels from about 4 fringes are of relevance, i.e. 11 pixels. Thus the instantaneous field of view is 11×2 pixels = 0.38×0.8 arcsec^2 = 0.30 arcsec^2. This approximate value may be used in estimates of the frequency of parasitic stars. Thus at $b = 0$ deg the number of stars with $V < 21.0$ mag in such an area is 0.0046 on the average, according to Allen (1973). With the use of a beam combiner this number is doubled. On the average sky the corresponding number is 0.0023 stars in the combined instantaneous field of view. These numbers would be multiplied by a factor 7 if fringe dispersion as in Figure 2 were used since the effective instantaneous field of view is then 2 arcsec^2 (see Section 3.1.)

Data from an area of about 3×3 arcsec should be transmitted to the ground in order to take into account the possible duplicity and the uncertainty of input position for the star. This latter uncertainty would be up to 0.4 arcsec (1σ) about the year 2015 for an input catalogue of very faint stars based on the presently or soon available large catalogues. This means 90×8 pixels per star from the wide CCD, and 90×3 pixels from the narrow CCD. This assumes that the area is not reduced as result of an on-board analysis. Such reduction of the area might endanger an analysis of unknown double stars, and it would be sensitive to disturbance by unknown components of stars, e.g. parasitic stars from the other field.

In some cases, e.g. known double or multiple stars, globular cluster and galaxies, the data should be transmitted from a larger area.

The assumptions made here imply that the CCDs must be read every 0.28 ms giving data from 183 million pixels per second from each of the two focal planes. The large compression required before transmission to the earth may be accomplished by use of an input catalogue, on-board signal analysis, and various compression algorithms.

A 10-colour photometry is proposed. The central wavelength (in unit of 10 nm) is given on the CCDs in Figure 5. These CCDs have been placed at the upper and lower extremes of the field in order that as many bands as possible are measured simultaneously in each field crossing which would be practical for the analysis of variable stars.

The bands are, as proposed by Straizys & Høg (1995), the 7 Stromvil bands of intermediate width (40 nm) placed from 350 to 660 nm. Then follows the Cousins' I at 810 nm and with 140 nm width. Two wide bands at 700 and 900 nm have been added in order to cover the whole spectrum as is required for the calibration and correction of astrometric chromaticity errors. The three wide bands have not been allocated as many CCDs as the seven Stromvil bands because their width ensure that they obtain sufficient signal.

In conclusion, the expected astrometric and photometric performances for the proposed GAIA95C system are similar to those of Table 1, but further studies must be made of the optical system, the influence of readout noise, etc.

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