A NEW OPTICAL CONFIGURATION PROPOSED FOR GAIA

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ABSTRACT

The baseline optical configurations proposed for the Global Astrometric Interferometer for Astrophysics (GAIA) have an effective focal length of ≈12 m (Perryman & Lindegren 1994, Shacklan & Loiseau 1995) appropriate for image location on the focal plane via a modulating grid. To allow direct fringe detection, an effective focal length of 25–30 m is required to sample properly the white interferometric fringes with improved state of the art CCDs. Alternative optical configurations of the GAIA interferometer subject to the requirement above and therefore suitable for direct fringedetection were investigated. In particular, a 4-mirror and 4-reflection (4M/4R) configuration was designed and analysed. This configuration realizes an effective focal length of 25 m due to the introduction of one aspheric surface; this appears sufficient to match the sampling requirement of the fringes which calls for ≈2.5 μm pixels.

Key words: space interferometry; GAIA, optical design.

1. INTRODUCTION

The Global Astrometric Interferometer for Astrophysics (GAIA) has been proposed by Lindegren & Perryman (1994) for high precision astrometric measurements on about 50 millions of stars, and it is now the new ESA initiative in space astrometry. At the moment, the baseline optical configurations for GAIA (Lindegren & Perryman 1994, Shaklan & Loiseau 1995, Shaklan & Loiseau 1996, Rigoni 1996, Cecconi 1996) are characterized by a relatively short effective focal length, ≃11.5 m; this is too small for properly sampling fringes with pixels manufacturable in the near future (≈ 2.5μm pixel size). Therefore, a new configuration was searched for a longer effective focal length ≥25m.

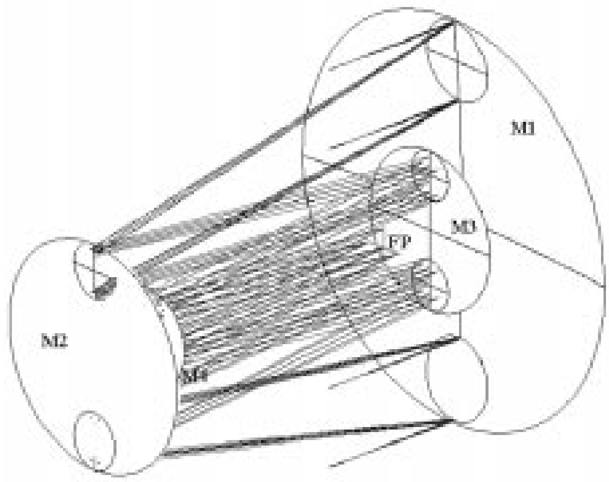

Figure 1. Layout of the 4M/4R optical configuration with an effective focal length of 25 m. The apertures of the interferometer are obtained by properly limiting the used area of the corresponding monolithic mirror.

2. SEARCHING FOR A NEW CONFIGURATION

The CODE V ray-tracer program was utilized in the search for a new optical configuration for GAIA. Table 1 lists the parameters used as specifications of the new configuration. Rays were entered only in that outer ring of the full entrance pupil defined by the two apertures of the interferometer. Spot size rms and optical path difference rms were both included in the merit function to be maximized.

Table 1. Optical specifications for the new GAIA configuration.

Baseline	2.4 m
diameter of single main aperture	60 cm
Diffraction-limited field of view	$\oslash \approx 1^o$
Effective focal length	25 m

With only three reflections, even with aspherics, it was not possible to achieve a diffraction-limited configuration. A 4M/4R diffraction-limited solution, with three conics and one aspheric, was found to have the required effective focal length. Its layout is sketched in Figure 1, while Table 2 lists its optical prescriptions.

The theoretical full-pupil Airy disk diameter is $\approx 5.7\mu$m at 550 nm. Full-pupil spots have to be compared with such a value to verify the diffraction-limited condition over the field of view analysed. In Figure 2 the spots are shown as they appear at the best focal plane (where the rms spot diameters are minimal) and on two defocused planes ($\pm 10\mu$m from the best focal plane). Given this criterion, the configuration is not diffraction-limited at 0.54^o off-axis. However, the instrument under study is an interferometer with two apertures. Therefore, only the rays entering them are significant in the generation of the spots (interferometric spots). But to what can they be compared? The monolithic Airy spot criteria is

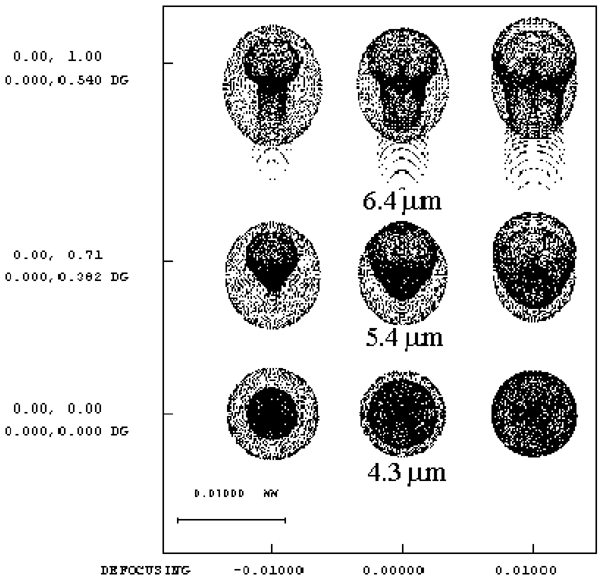

Figure 2. Full pupil spots at best focus for field angles of 0.0^o, 0.38^o and 0.54^o (center column). The spots in the two lateral columns are for two focal positions displaced by $\pm 10\mu m$ from best focus.

Table 2. Optical prescriptions of the 25 m effective focal length configuration obtained after the optimization process. z is the vertex coordinate of the monolithic surface, R is the radius of curvature, K is the conical constant and A4 is the fourth-order aspheric term.

Surf.	R (mm)	K	A4	z (mm)
M1	-14371.6	-1.778	-	-3426.0
M2	-14201.0	-17.975	-	3122.4
M3	-2928320.9	1.078e7	-	-2640.5
M4	-11313.6	-0.32e18	-.26e-11	2212.2
FP	∞	-	-	Best Focus

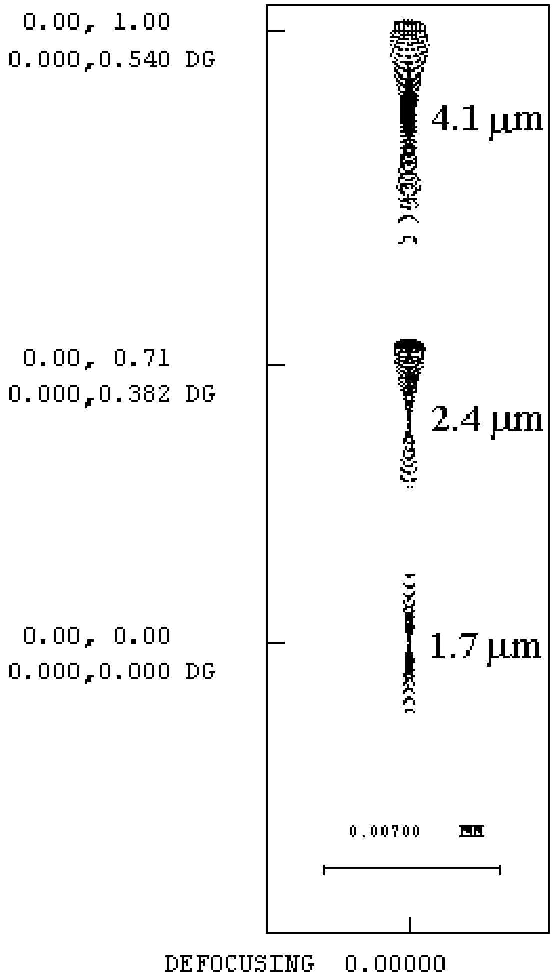

Figure 3. Interferometric spots for field angles 0.0^o, 0.38^o and 0.54^o at best focal plane.

not of help here; we can oly say that the smaller the rms diameters of the interferometric spots (see Figure 3) the better the corresponding fringes, but this is not a quantitative criteria.

Therefore, to verify the diffraction-limited condition of the interferometer within the specified field of view, fringe visibilities were computed. In Figure 4 we show the PSF's (fringes) corresponding to the angles 0.0^o, 0.38^o and 0.54^o from the optical axis, in the yz-plane. The values of their monochromatic (550nm) visibilities (V's) are also shown.

Visibility was computed taking into account the approximate formula $V^2/2 \simeq I_2/I_1$ where I_1 and I_2 are the total energies at, respectively, low and high frequencies in the power spectrum domain. An interferometric system can be considered diffraction-limited when its visibilities are larger than 0.8. The values reported in Figure 4 appear very good; and they remain above the $V = 0.8$ criteria after multiplying them by a factor $\sim$0.9, which closely approximate the effect of the finite spectral bandwidth utilized with the actual interferometer ($\sim$100 nm centered at 550 nm).

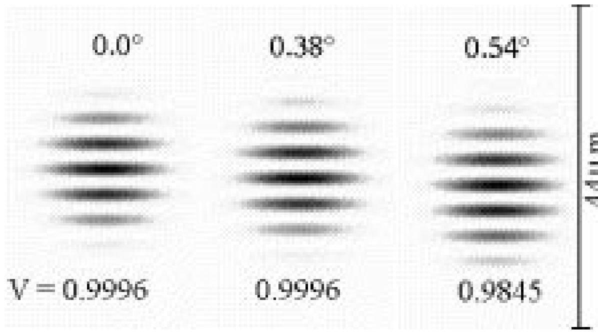

Figure 4. Fringes for 0.0°, 0.38° and 0.54° field angles (in the yz-plane) at best focal plane and their corresponding visibilities.

3. OPTO/MECHANICAL TOLERANCES

Any changes in shape and/or position of the nominal optical surfaces cause variations of the Point Spread Functions. That is, fringe visibilities and centroid coordinates (i.e., phases of centre fringe) are perturbed by any changes of the parameters in Table 2, which describe the nominal optical configuration found. A preliminary analysis of the opto/ mechanical tolerances was done on the new 4M/4R configuration.

Table 3 provides a synthetic summary of the results of this tolerancing work. The values under the heading *Coherence* represent the allowed maximum tilts or decenters (see caption of Table 3 for details) for good fringe visibility (V$\geq$ 90 per cent, i.e., good overlap of the two single-aperture Airy disks). The figures in third column are the permissible maximum deviations of the optical elements that will keep the fringe centroid within 1.2 nm of the nominal value; 1.2 nm corresponds to the required astrometric accuracy of $\sim$10 μarcsec.

Table 3. Tolerance values for the 4M/4R configuration. $\Delta\alpha$ is a tilt around the x-axis (normal to baseline). Δy is a decenter along the y-axis (baseline). z is the optical axis. Coherence corresponds to good contrast fringe patterns, while phasing to fringe centre shifts < 1.2 nm.

	Coherence	Phasing
M1 $\Delta\alpha$ (arcsec)	10^{-2}	1.5×10^{-5}
M2 $\Delta\alpha$ (arcsec)	10^{-1}	2.5×10^{-5}
M3 $\Delta\alpha$ (arcsec)	5×10^{-1}	4.5×10^{-5}
M4 $\Delta\alpha$ (arcsec)	5×10^{-1}	10^{-4}
M1 Δy (μm)	1	10^{-3}
M2 Δy (μm)	10	4×10^{-3}
M3 Δy (μm)	2×10^{3}	10^{-1}
M4 Δy (μm)	10^{2}	1

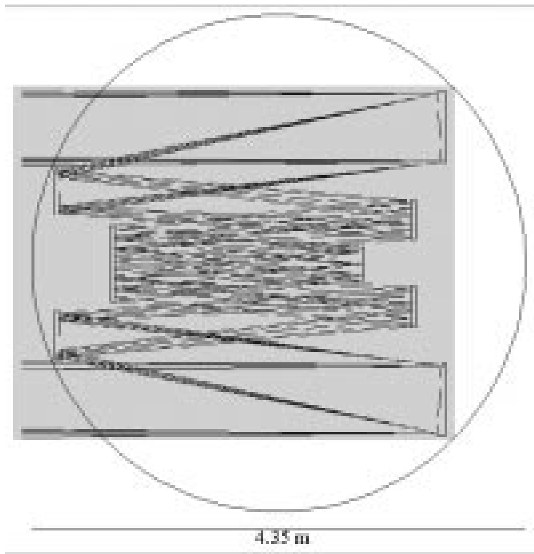

Figure 5. The new 4M/4R optical configuration found for GAIA is contained in ARIANE 5 envelope.

4. CONCLUSIONS

A new optical configuration with a longer effective focal length (of 25 m) than the baseline versions is now available for GAIA. The fringe width is $\approx$5.7μm at 550 nm, which might be sufficient already for direct fringe imaging on the focal plane. The configuration is contained in the Ariane 5 shroud (see Figure 5), is not vignetted, and has an interferometric diffraction-limited field of view of $\approx$1.0^o (diameter). Tolerances seem to require sub-nanometric metrology to measure/control the positions of all the mirrors with the necessary precision to ensure the required astrometric accuracy. Fringe visibility requires only nanometric metrology. Finally, the tolerancing analyis suggests that the mirrors more distant from the optical axis are those requiring more stringent metrology, confirming the opto/mechanical analysis made on the baseline 3M/3R options (Cecconi 1996, Cecconi et al. 1997).

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