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ASTROMETRY AT MICRO-ARCSEC RESOLUTION: OPTICAL DESIGN ASPECTS AND TECHNOLOGY ISSUES.

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ABSTRACT *- After the success of the ESA mission Hipparcos, space is considered as the "final frontier" for astrometry. The Agency is supporting an industrial study aimed to the assessment of some critical aspects of the GAIA mission, a concept for* 10^{-5} *arcsec global astrometry. The paper focuses on design aspects of the interferometric optical module of the payload to allow an active control option. This is, with the metrology subsystem, the most demanding module of the design under development by our team. The results obtained from optical simulations are quite encouraging. Today, micro-arcsec global astrometry based on interferometry appears less daunting and closer to implementation than before.*

1 - INTRODUCTION

Gaia is a concept that has emerged as the new ESA initiative in space astrometry. It will be competing for the Interferometric Cornerstone-class mission recommended by the Survey Committee and adopted by the Agency as part of its *Horizon 2000 Plus* program of scientific satellites.

In January 1997, ESA initiated the activities of the industrial study named APLT/AMTS with Alenia Aerospazio (ALS) as prime contractor. This study focuses on the design of large-field interferometric optics and its active control system based on highly accurate linear laser metrology. GAIA is the primary reference mission of the study.
In September 1997, the Agency has also started a GAIA System Study with MATRA as prime contractor with the goal of assessing the overall feasibility of the GAIA concept and its cost envelope. With the extension given to the ALS contract, the two studies will proceed in parallel for most of 1998. Exchange of results and/or specifications are foreseen through the Agency, with obvious benefits for the quality and the level of detail of the final technical reports

The primary goal of GAIA is to measure positions, annual proper motions, and trigonometric parallaxes (distances) to 10 μarcses rms down to a limiting magnitude of V=15 and possibly fainter ([Lind 96], and references therein). Likewise Hipparcos, GAIA will continuously map the whole sky but, differently from its predecessor, will measure *all* objects down to its survey magnitude limit

1.1 - Global astrometry and phase interferometry

The measurement principle is based, like for Hipparcos, upon the simultaneous observation of two fields separated by a sufficiently large angle lying on a great circle. These two line-of-sights (LOSs) form the so called basic angle (BA) and could be imaged by two different telescope units or by a beam combiner (BC) which multiplexes the two beams into one entering a single imaging optics. Regardless the number of telescopes used, the individual GAIA telescope unit is actually a small Fizeau-like interferometer with a baseline which, in our configuration, is ~2.5m. Critical for GAIA is the accurate measurement of the phase of the interferometric fringes (as opposed to the more common visibility measurements) and of the BA. Accurate phase measurements impose near ideal matching between optics and focal plane (FPA) detectors. These are operated in TDI mode to cope with a scanning satellite surveying the entire celestial sphere.

To illustrate the essential role played by interferometry in a global astrometry mission like GAIA we start with simple, first principle, considerations. One expects that the accuracy of any optimal location process increases with the decreasing angular size of a Point Spread Function (PSF) which depends, in turn, on the size of the main aperture of a given optical system: the larger this aperture the smaller the PSF angular size, the higher the location accuracy (more details in [Lind 78] and [Gai 97]).
The ideal (no aberrations) fringe pattern $I_\lambda(s)$ (PSF) generated by a pupil comprised of two circular sub-apertures separated by the baseline vector **B** joining the sub-aperture centered at P1 to the other centered at P2 is

$$I_\lambda(\mathbf{s}) = 2b(d^2\pi/4)^2 f_\lambda \left[\frac{2J_1(\frac{\pi dt}{\lambda})}{\frac{\pi dt}{\lambda}} \right]^2 [1+\cos(k\mathbf{B}\cdot(\mathbf{s}-\mathbf{u}'))]$$

For the sake of simplicity we assume that **B** lies on the X axis and the focal plane (FP) on the X-Y plane. The vector **s**, measured in radians, spans the FP; the unit vector **u'** represents the direction on the sky (positive toward the optical system) of a given source within the FOV of the Fizeau interferometer (see below). The other quantities in this expression for $I_\lambda(\mathbf{s})$ are t, the norm of the vector difference **s** - **u'**, d the diameter of the two sub-apertures, λ a generic operational wavelength, k the wave number, and b a normalization constant. The pure diffraction term, defining the Airy disk, is as usual given in terms of J_1, the Bessel function of first order.
In the absence of aberrations the interferometric PSF is space invariant. Also, the diffraction term does not depend on the interferometer baseline **B**. Therefore, the Airy disk is insensitive to small changes in **B**, while the phase of the fringe pattern is extremely sensitive to such perturbations. Suppose **u'** represents a point-like object on the optical axis (Z axis), then for the nominal baseline it is $\mathbf{B} \bullet (\mathbf{s} - \mathbf{u}') = \mathbf{B} \bullet \mathbf{s} - \mathbf{B} \bullet \mathbf{u}' = \mathbf{B} \bullet \mathbf{s}$, and the modulation term has a maximum at $\mathbf{s} = 0$. Suppose now that the baseline is tilted in the X-Z plane of a small angle γ, then $\mathbf{B} \bullet \mathbf{s} - \mathbf{B} \bullet \mathbf{u}' = \mathbf{B} \bullet \mathbf{s} - B\gamma$, which is not zero for $\mathbf{s} = 0$. The zero-phase point on the FP is now at $B_x s_x = -B\gamma$, i.e., it has changed by approximately the same amount as the small baseline tilt. Therefore, a tilt of $\gamma \sim 5 \times 10^{-11}$ rad (~ 10 μarcsec) of the baseline generates an angular error on the sky of a similar amount. Such a small baseline rotation corresponds to a linear shift of ~ 150 picometers (pm) in the Z-axis direction of one

sub-aperture with respect to the other! This is why it is a necessity to address very high accuracy metrology when discussing the interferometric implementation of GAIA [Gai 97b]

2 - BASIC REQUIREMENTS ON OPTICS AND OPTICAL SYSTEM

In order to achieve the measurement accuracy of the GAIA mission, quite stringent constraints are imposed on the optics

a) simultaneous measurements along two viewing directions separated by a wide angle to improve on great circle rigidity, i.e., to minimize systematic errors in the angular separation of targets in the two fields which, in the case of a single field-of-view (FOV) successively observing the regions along the great circle, are likely to be introduced by attitude and configuration perturbations.

b) large single FOV This is needed for two distinct and equally important reasons The first is to provide exposure time sufficiently long for each target (this is the transit time of a target across the scanning FOV) The second reason is to ensure a non negligible superposition between the sky strips covered in subsequent revolutions and therefore strengthening the mathematical relations among targets over the whole great circle region. Long exposure times translates into a requirement for the size of the along-scan FOV, while sufficiently large overlap regions between two successive scans call for large across-scan field;

c) system stability And this involves both the optical configuration (which concerns us here) and the smooth motion of the satellite, as both will contribute errors to the targets positions. In principle, some of those errors can be recovered from the observations themselves, but only up to some degree and under sufficient regularity assumptions. It is interesting to note that optical instabilities introduces field-dependent errors, while attitude effects mostly generate *common-mode* effects;

d) low distortion and residual aberrations, which should in any case be calibrated to provide the required measure of distance among targets over the FOV (and eventually over the whole sky), are even more critical for the elementary measure, because of the time-delay integration (TDI) mode of the focal plane detectors they are clocked at a given rate (possibly different for each chip), but PSF variations and apparent speed modifications induced by local optical scale changes may build up during the integration, resulting in a loss of visibility of the final fringe pattern

The actual values allocated to each parameter depend on the implementation concept and mission profile under evaluation. Therefore, in the baseline design described in [Lind 96], the stringent metrological requirement related to the targeted mission accuracy, and derived in section 1 from first principles, are transferred directly to the three-dimensional placement of each component of each independent telescope This is due to the potential variation of the line-of-sight (LOS) of a telescope induced by each discrepancy with respect to the nominal configuration, which is immediately reflected in a change of the basic angle between the LOSs of the two telescopes, and in the distance among targets in the two FOVs.

The above considerations led our team to reconsider a winning concept of the Hipparcos mission, i.e., the Beam Combiner (BC), initially discarded because a suitable allocation did not seem to be feasible In this approach, the implementation of a base angle between two LOSs is obtained by means of a small number of optical components (flat mirrors), therefore factoring out most of the critical

requirements to a simple system (as discussed in section 3), separated from the interferometric telescope unit (ITU), acting as a wide field imaging light collector fed by the combined beam.
The ITU requirements are significantly relaxed from the stringent (picometer) values to the less challenging (nm or μm) range required by the interferometric conditions (cophasing). The actual value of the basic angle is, as already mentioned, nearly irrelevant, although its stability is mandatory (the actual value is a by-product of the astrometric data reduction); with the BC we propose, the range of values achievable for the basic angle is roughly between ~ 40° and ~ 80°.
The FOV required is larger than 0.6° in each direction; our current design has a useful FOV of ~0.7° x 0.7°, and work is in progress to further increase the coherent FOV (especially in the along-scan direction) and reduce distortion, presently still above the required 10^{-4}. Such value is deduced from the acceptable degradation of the fringe pattern over an integration time of 0.2 s, as from the baseline mission concept: any improvement allowing for longer exposures will result in significant gain on both scientific and engineering aspects, providing more accurate measurements on fainter targets and a reduction of the raw data throughput. To this purpose, satellite attitude requirements must be strengthened accordingly: the driver is again to limit the degradation of the fringe pattern, and the value resulting for the stability of the scan velocity vector is within a few milliarcsec/s.
In is worth noticing that current optical configurations and system modeling provide values quite close to the basic mission requirements, and further improvements are under way.

3 - DESIGN ASPECTS OF THE INTERFEROMETRIC MODULE

3.1 - Optical configuration for the ITU

A possible optical configuration for GAIA is shown in Fig.1. It has been derived by modifying the Korsch-type design developed by Aerospatiale (see [Thom 97]), in such a way as to allow the integration of the beam combiner on the same optical bench, and to decrease the original field distortion.

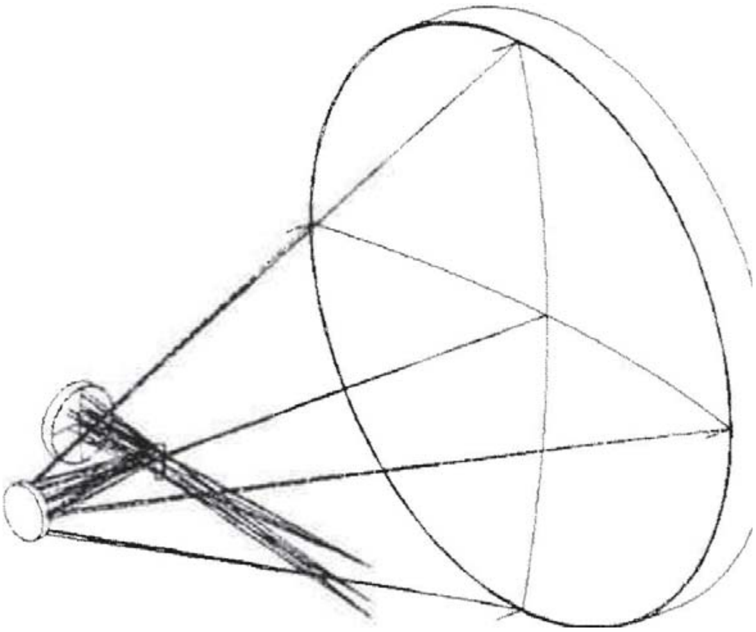

Fig.1 - Possible optical configuration for the GAIA ITU. The monolithic primary (3.15m in diameter) is shown. The two sub-apertures are on the plane defined by the following mirrors

The main design parameters of the unit are: baseline = 2.55 m, equivalent focal length = 40 m, primary mirrors diameter = 60 cm, secondary mirror diameter = 30 cm, tertiary mirror diameter = 25 cm, quaternary mirror diameter = 40 cm.
The spot diagrams, the distortion map, and an example of the interferometric PSF (fringe pattern) generated with this configuration are shown in Fig.s 2, 3, and 4, respectively.

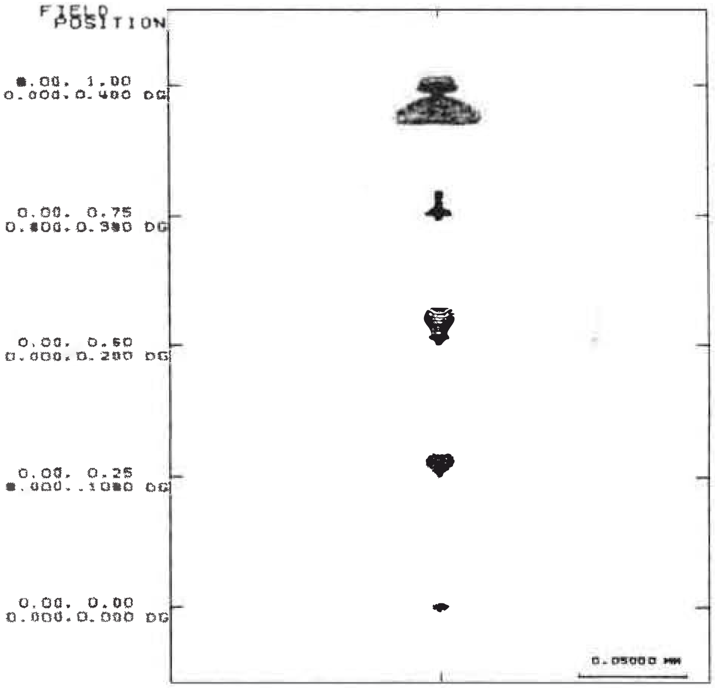

Fig.2. Spot diagram for the optical configuration in Fig.1. The top spot is for the field angle at (0°,0.4°) from the optical axis. The other spots are at (from top to bottom) (0°,0.3°), (0°,0.2°), (0°,0.1°), and on the optical axis, respectively. The length of the segment shown on the bottom right of the figure is 0.05 mm. This corresponds to ~0.26” at the scale of the ITU.

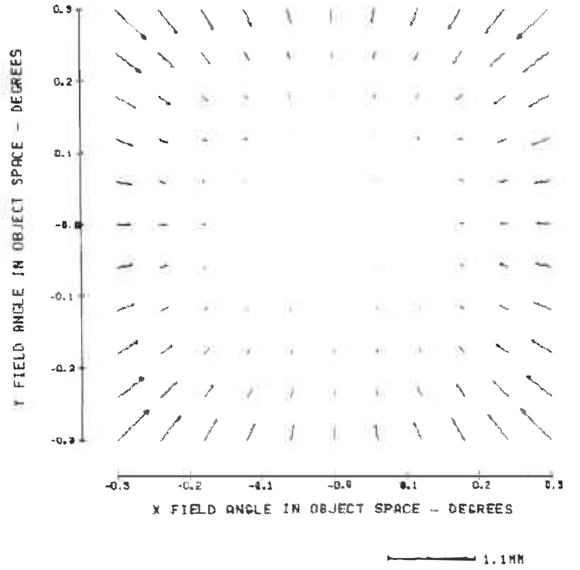

Fig.3. Distortion map. The vectors indicate the deviation from the gaussian focal plane as function of field angles in object space. Units are degrees on both axes. The length of the vectors measure the amount of distortion present. The length of the reference segment shown below the X-axis title is 1.1 mm.

Fig.4. Monochromatic fringe patters (at 750 nm) for an on-axis point-like source

3.2 - The beam combiner

The operating principle of the beam combiner is shown in Fig.5, while the possibility of accommodating the beam combiner elements on the same optical bench as that of the ITU is shown in Fig.6. The range of possible basic angles (BAs) that can be implemented with such a BC is between ~40° and ~ 80°

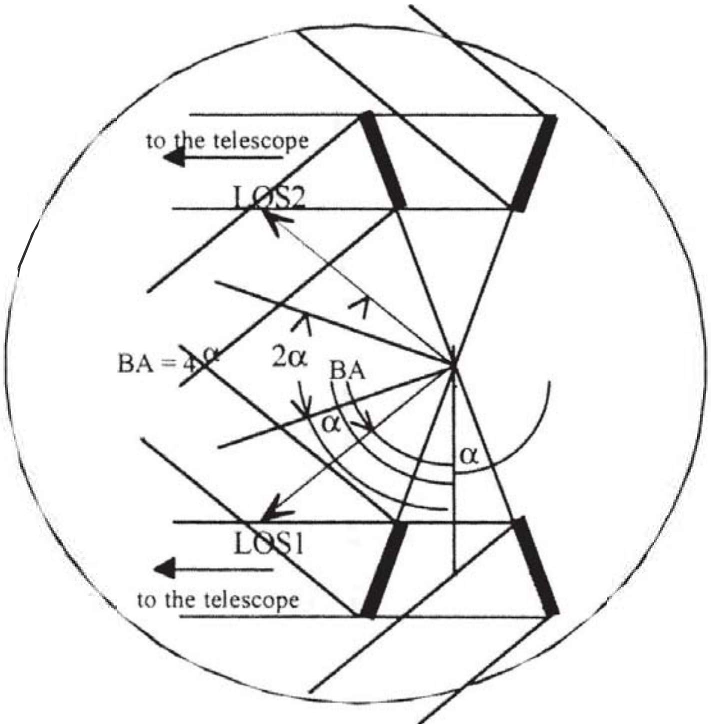

Fig.5. Operating principle of the beam combiner

As discussed earlier, the critical measurement in GAIA is the angle between two targets which appear in two different LOSs. If two independent ITUs are used to materialize the LOSs, then the three-dimensional positions of the optical elements of both telescopes must be kept within their nominal values to better than ~ 150 pm, as seen in section 1.1. The idea behind the BC is that of reducing such demanding requirements on a complex optical system like the ITU in Fig 1, and to shift such requirements to the degrees of freedom associated with the BC design of Fig 5, these are much easier to define and to implement into a physically sound laser metrology system made of a set of highly accurate linear measurements.

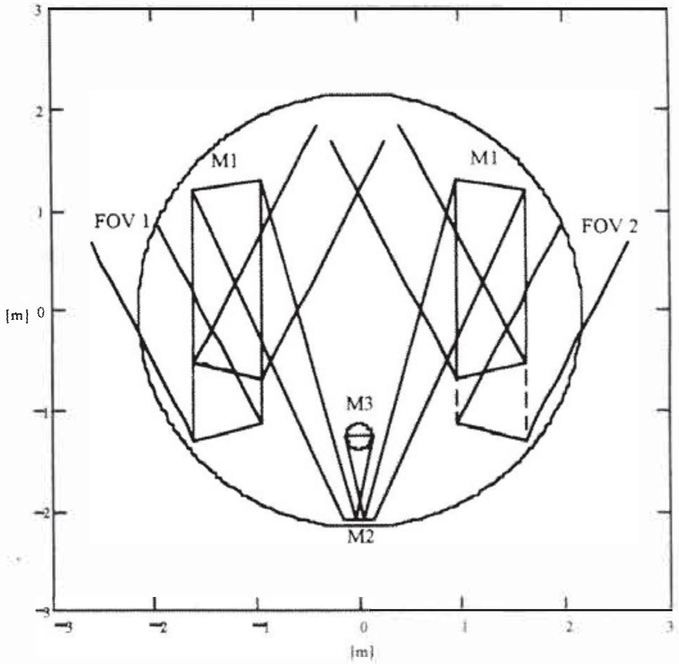

Fig.6. Beam combiner and interferometric telescope integrated on the same optical bench. The circle drawn around the ITU+BC combination represents the usable envelope of the Arianne 5 shroud. Units are meters on both axes.

3.3 - Tolerance analysis with the beam combiner

In what follows the Y-axis is in the high resolution direction, i.e., that of the baseline.
The tolerances given in the table below were computed for the displacements (Tx, Ty, Tz) and the rotations (Rx, Ry, Rz) of one of the two primary mirrors (the most critical optical element of the telescope). T_x is a displacement in the X-Y plane along the X-axis, and analogously for T_y and T_z. The rotation R_x is around the X-axis, i.e., one that generates a tilt of one of the two sub-apertures in the high resolution direction.

Effect	T_X [µm]	T_Y [µm]	T_Z [µm]	R_X [µrad]	R_Y [µrad]	R_Z [µrad]
contrast loss ≤ 9%	2.5	2.7	6.4	0.25	0.35	1.9
centroid shift ≤ 2 nm (with BC)	0.5	1.0	0.3	9.6×10^{-3}	3.2×10^{-2}	0.1

centroid shift ≤ 2 nm (without BC)	no effect	5×10^{-4}	5×10^{-4}	6×10^{-5}	no effect	no effect

From the numbers shown in the table, it is evident that the introduction of the BC has relaxed by more than two orders of magnitude the requirement on R_x, probably the most demanding degree of freedom of our ITU.

3.4 - Advantages introduced by the beam combiner

- Reduction of the most stringent requirements on the M1 mirror (T_Y, piston, α-tilt) by more than two orders of magnitude, at the cost of increasing to still acceptable level the requirements on T_X β-tilt, γ-tilt

- Sensible reduction of all the requirements on the M2, M3/M5, M4 mirrors; in particular it could be possible to avoid the control of the M3/M5 and M4 mirrors, if medium-term displacements are < 2 μm and the long-term ones < ~100 μm.

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