A SMALL INTERFEROMETER IN SPACE FOR GLOBAL ASTROMETRY: THE GAIA CONCEPT

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Abstract. We present a concept for a scanning interferometer for global (wide-angle) astrometry from space. The GAIA concept has been proposed for the European Space Agency's long-term scientific programme. It consists of three Fizeau-type interferometers with 2.5 m baselines, set at large and fixed angles to each other. Complete utilization of the instrument's resolution and sensitivity requires a new type of photon-counting detector, combining very high spatial and temporal resolution. An array of superconducting tunnel junctions (STJ) may ultimately provide this capability. Pending this development we describe a focal-plane configuration for GAIA using existing technology in the form of a modulating grid and CCD detectors. We estimate that 50 million stars brighter than $V = 15.5$ could be observed on the 10 to 20 microarcsec accuracy level. In addition, high-precision multi-colour, multi-epoch photometry is obtained for all objects.

1. Introduction

The highly successful Hipparcos mission has demonstrated that a small, dedicated astrometry satellite can perform wide-angle measurements over the whole sky with an accuracy ultimately determined by instrument reso-

E. Høg and P. K. Seidelmann (eds.),
Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, 337–344.

lution and photon noise. The capacity to produce large quantities of high-quality data can be derived from a combination of a few simple ideas:

- use of two viewing directions, separated by a large angle, connecting all parts of the sky in a few steps;
- one-dimensional angular measurements along the great circle through the viewing directions;
- continuous scanning and observation of all programme stars as they pass over the fields of view, while maintaining a constant geometry with respect to the sun;
- determination of critical instrument parameters from the closure conditions on each complete rotation (few hours), making long-term instrument stability quite uncritical;
- positions, proper motions and parallaxes ideally solved in a single global solution together with all instrument and attitude parameters.

These ideas appear to be equally valid for a future space astrometry mission aiming at accurate wide-angle astrometry for very many stars. Indeed, they are the basis for at least two proposals submitted to the European Space Agency since 1993, the Roemer project (and subsequently Roemer+; see Høg, 1994) and GAIA (Lindegren et al., 1994). Both aim at sub-milliarcsec astrometry and multi-colour, multi-epoch photometry for many millions of stars.

The target accuracy for GAIA is 20 μas for the positions, parallaxes and annual proper motions of all compact optical objects brighter than $V = 15$–16, or some 50 million stars and a significant number of extragalactic sources. In order to achieve this accuracy we propose to use a fixed configuration of small optical interferometers of a few metres baseline.

2. Scientific Objectives

A full survey of the scientific capabilities of an instrument like GAIA is clearly beyond the scope of this paper. The following few examples are mostly drawn from existing reviews (e.g., Kovalevsky & Turon, 1992, Ridgway, 1993, and the report of the ESA Interferometry Review Panel under the chairmanship of Dr. C. Dainty).

Stellar luminosities: Direct luminosity estimates are based exclusively on trigonometric parallaxes. At the 20 μas accuracy level the parallax method would reach to 5 kpc with a relative precision of 10%, or to 10 kpc with 20% precision. For the first time this would provide an extensive network of distance measurements throughout a significant part of our Galaxy, including the galactic centre, spiral arms, the halo, and the bulge. The volume would include numerous representatives of the rarer but evolutionary important classes of objects, such as the most massive stars, novae and nova-like variables, central stars of planetary nebulae, Cepheids, and RR Lyrae stars.

Planetary Detection: The detection of non-linear photocentric motions in the paths of nearby stars due to planetary companions has been extensively studied for example as part of NASA's TOPS (Towards Other Planetary Systems) programme. At 20 μas mission accuracy, GAIA would be able to detect Jupiter-mass planets with an orbital period smaller than the mission duration out to distances of 100 pc, while correspondingly smaller planets could be detected for very nearby stars. In principle all 50 million stars could be screened for possible signatures of planetary or brown dwarf companions, providing a complete census to well-defined and uniform detection limits.

Binary Systems: A rich variety of astrophysical phenomena in interacting binary systems could be addressed with very accurate astrometric data, including questions about accretion rates, precursors, mass distributions, and kinematic behaviour. For binary systems in general, GAIA would provide a vast statistical material for systems with angular separations greater than 1 mas, in many cases including orbital parameters and component masses.

Clusters: Studies of open clusters are important for numerous reasons, mostly because they represent a co-eval population of stars with well-defined initial chemical compositions. Some 20 open clusters are considered to lie within about 400 pc, sufficient to provide individual distances to better than 1% accuracy with GAIA. Ages of *globular clusters* have indicated a possible discrepancy with the age of the Universe derived from present estimates of H_0 and Ω. Direct distances are needed for an absolute determination of ages, and GAIA would provide sufficient accuracy to resolve the age conflict.

Galactic Dynamics: The huge number of stars and the impressive accuracy of proper motions and parallaxes would totally revolutionise dynamical studies of our Galaxy. Considerable advances would be possible in our understanding of the structure and motions within the spiral arms, the disc and the outer halo. Questions related to the existence and amount of dark matter could be addressed by direct measurements of the distribution and kinematics of stars in the solar neighbourhood and of the rotation curve beyond the Sun.

Proper Motions of the Magellanic Clouds and AGN's: Proper motions for large numbers of stars in LMC/SMC would clarify the dynamical behaviour of these systems, and in particular whether they are gravitationally bound to our Galaxy. Further out, the nuclei of active galaxies are sufficiently point-like that their relative proper motions may be measurable. An astrometric programme reaching 15–16 mag would include a number of

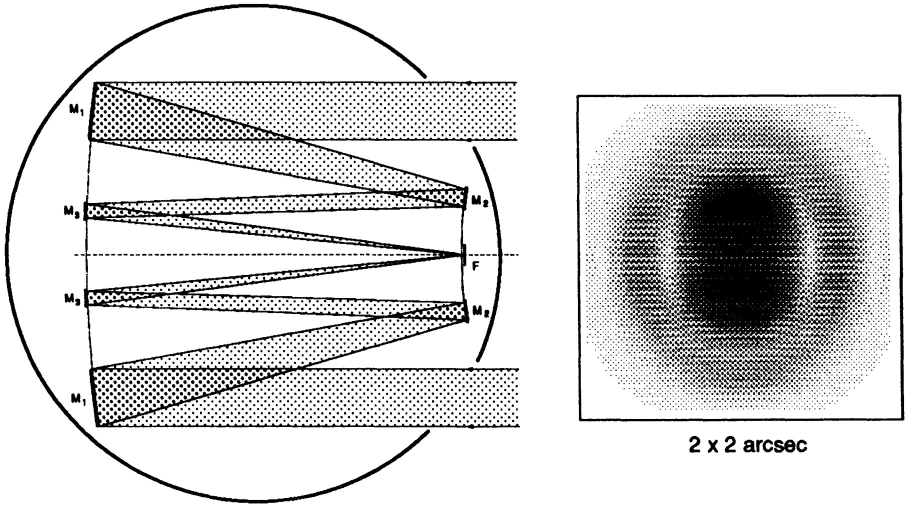

Figure 1. Optical layout of one of the Fizeau interferometers. The two pupils are 0.5 m in diameter and the baseline (distance between the pupil centres) is 2.5 m. The total width is 3.0 m and the focal length 11.5 m. A three-mirror design provides a diffraction-limited field of nearly 1°. The envelope (of 4.3 m diameter) indicates how the interferometer may fit into the Ariane 5 shroud. The focal surface (F) is conveniently located near the envelope to allow cooling of the detectors. To the right an example of the calculated diffraction image at field angle 0.31°, showing the Airy disk modulated by Young's fringes.

quasars allowing a direct tie of the stellar proper motions to the extragalactic (inertial) reference frame, which is critical for dynamical interpretation of the motions.

General Relativity: The gravitational light bending at right angle to the sun is about 4 mas. This quantity has been measured by Hipparcos to 1% accuracy. At the much higher precision offered by GAIA such measurements start to become interesting as a means to discriminate between General Relativity and alternative theories.

For all kinds of studies involving stellar distances, access to *absolute* parallaxes is essential. Direct determination of absolute parallaxes requires wide-angle astrometry, utilizing the different parallax factors in different parts of the sky. Wide-angle measurements are also necessary to build a distortion-free and rigid system of coordinates and proper motions over the whole sky, which is critical for all dynamical studies of large-scale motions. In order to take full advantage of the space environment it is thus essential that a future space mission aims at *global* astrometry rather than narrow-field measurements.

3. The GAIA Concept

A possible optical configuration for the GAIA concept consists of three mechanically connected Fizeau interferometers, each with two 50 cm apertures on a 2.5 m baseline (Fig. 1). Continuous scanning, as opposed to a pointing instrument, requires a large field ($\sim 1^\circ$ diameter) in order to accumulate sufficient observing time on each object, and hence to reach faint objects. All objects within the field of view can be observed simultaneously, resulting in extremely high efficiency in terms of the astrometric yield. The large field can only be realized with a Fizeau-type interferometer, where the two primary mirror elements (M_1 in Fig. 1) are parts of an imaginary single primary surface.

Preliminary studies indicate that this instrument could yield positions, parallaxes and annual motions to the level of 20 microarcsec at $V = 15$, and possibly down to a few microarcsec at $V = 10$. A mission length of 5 years should be targetted, especially in view of the very much improved ability to detect planetary companions and measure orbital binaries with periods of a few years. The limiting magnitude will be around $V = 16$, as set mainly by background light and confusion from other stars in the detector subfields (see below). No pre-selection of programme stars is required; the instrument would simply observe all objects above a given threshold.

3.1. DETECTORS

Exploitation of the full information at the fringe frequency by means of a detector (CCD) directly at the focal surface would require a prohibitively large number of pixels. This requirement, and the corresponding tolerances on the detector performances, can be relaxed dramatically with the inclusion of a modulating element, resulting in a data collection somewhat analogous to that employed with Hipparcos.

In this concept the focal surface is covered by a grid containing a large number of slits parallel to the interference fringes of the stellar images. The grid period must match the fringe spacing $\lambda_{\rm eff}/L$, where $L = 2.5$ m is the interferometer baseline, so that the transmitted light is modulated as the star images move across the grid (Fig. 2a). The phase of the detected modulated signal provides the positional information (star image relative to the grid), while the amplitude contains photometric information. A much improved efficiency can be obtained with a completely transparent 'phase grid' (Fig. 2b), in which the phase or delay of the light is modulated instead of the amplitude, e.g., by means of a corrugated grid surface.

An integrated 'light curve' of the modulation can be recorded by a CCD in which the electric charges generated by the photons are shifted back and forth synchronized with the modulation. Alternatively, arrays

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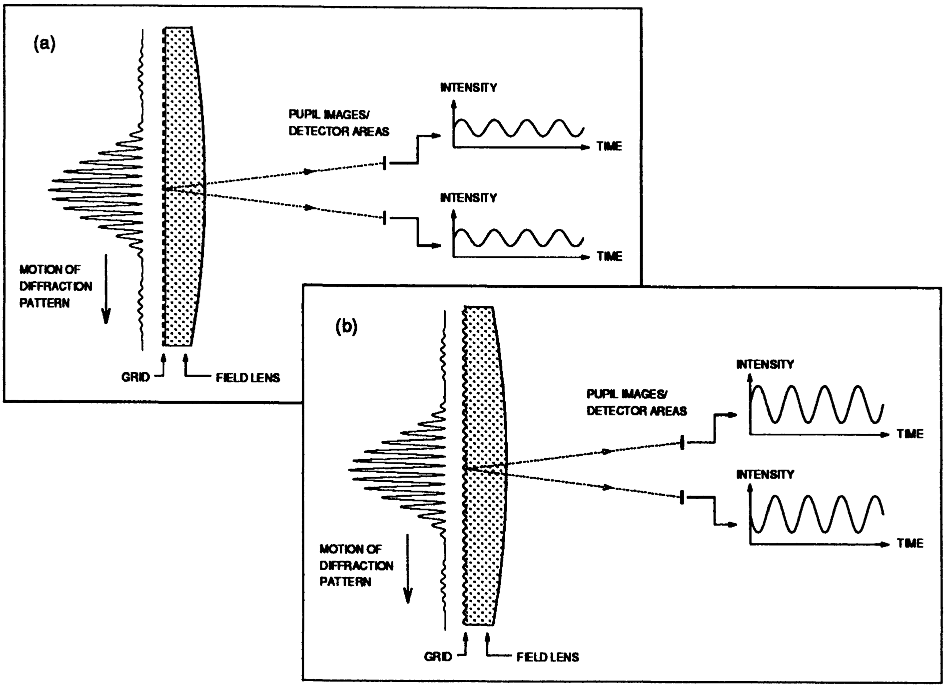

Figure 2. Interaction of the diffraction image with (a) an amplitude grid consisting of parallel slits having a period matching the interference fringes, and (b) a phase grid modulating the phase of the transmitted light. The phase grid gives more light on the detector and a stronger modulation, with the two pupil images modulated in anti-phase.

of photon-counting avalanche photodiodes (APD) could be used. These are characterized by high quantum efficiency, high time resolution, a large dynamic range, and a wide wavelength response, all of which are important qualities for the present application.

A detector option considered in parallel with these conventional detectors is based on superconducting tunnel junctions (STJ). Development work going on in ESA suggests the possibility of photon counting in the optical, using the superconducting phenomenon. Such a superconducting camera (SUPERCAM) would comprise individual pixels, as for the CCD, but with parallel rather than serial readout. The potential advantages of this detector are its very high quantum efficiency over a broad wavelength range, very high time resolution, low noise, and an intrinsic wavelength resolution of the order of 10 nm. Disadvantages are its low operating temperature of around 1 K and the high data rate generated by a large array.

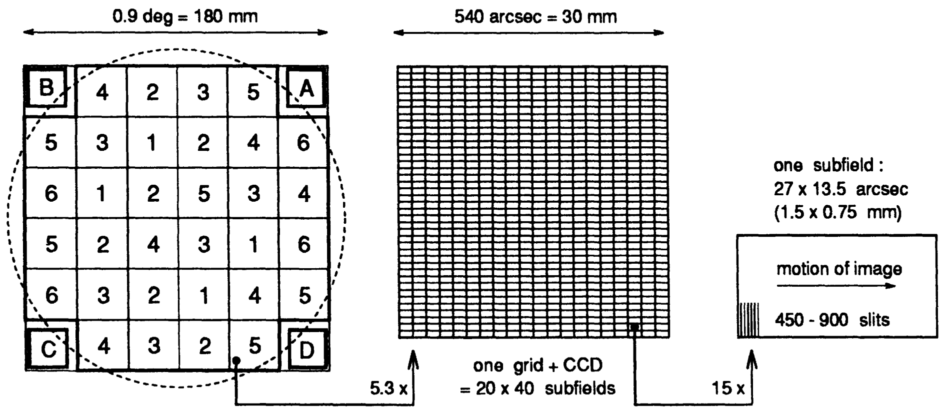

Figure 3. Focal-plane arrangement of grids and detectors. The one-degree field is divided in areas with different wavelength passbands (numbered 1 to 6 in the left diagram), each using its own CCD to record the light modulation. The areas are further divided into subfields of 27×13.5 arcsec^2. The field lens shown in Fig. 2 covers a single subfield. A–D are CCD detectors set directly in the focal surface and needed primarily for attitude determination (to ~ 2 mas) and active control of the mirrors. Additional CCDs around the central field may be used for lower-resolution astrometry and accurate photometry.

3.2. ARRANGEMENT OF GRIDS AND DETECTORS

With an observing programme of 50 million stars there are some 500–1000 objects in the field of view at any time. Ideally the modulated signal should be individually recorded for each of them. However, the light behind the grid is collected from the whole area covered by the field lens in Fig. 2. To avoid superposing the light curves of many stars, and also to reduce the background intensity level, the telescope field must be divided into a number of subfields, each equipped with its own small field lens and detector elements. Figure 3 indicates a possible focal plane arrangement. A subfield of 27×13.5 arcsec^2 gives an average background corresponding to $V \simeq 15.5$, increasing the photon statistical error by 50% at the faint limit. An array of 20×40 subfields defines an area of 9×9 arcmin^2, or 30×30 mm^2 in linear size, suitable for light registration by a single CCD.

All the subfields for a given CCD must use the same modulation frequency and hence the same grid period and the same effective wavelength. However, another CCD may use a different λ_{eff}. The optimum relative bandwidth per CCD is given by the ratio of aperture diameter to interferometer baseline, or ~ 0.2. The visible wavelength range could be covered with six overlapping wavelength bands, adding multicolour photometry as a natural part of the mission. The use of six different grid periods would also solve the phase ambiguity problem for the reconstruction of point images from the detector signal.

3.3. WIDE-ANGLE MEASUREMENTS

Two identical interferometers, with optical axes set at a large angle (1 to 2 rad) to each other and perpendicular to the spin axis, are required to bridge the long arcs in a sufficiently short time to overcome intrinsic variations of the instruments. For redundancy we propose to have three interferometers stacked on top of each other, any two of them being sufficient for the nominal mission goals. Using the 360° closure condition on every complete great-circle scan means that the astrometric results are very insensitive to all instrumental variations on time scales longer than a few hours. A crucial question is the actual requirement in terms of the short-term stability, in particular of the 'basic angle' between the two interferometer axes. Monitoring of short-term variations of the relative geometries of the two instruments by internal metrology is probably necessary.

4. Conclusion

There is a very strong scientific case for global optical astrometry at the 20 μas accuracy level. Such measurements cannot be obtained from the ground due to the atmosphere and partial sky coverage, but are well suited for a space mission using a free-flying satellite of moderate size. We consider that a small space interferometer dedicated to global astrometry, such as GAIA, would be a suitable candidate for implementation within ESA's 'Horizon 2000 Plus' programme.

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