GAIA: GLOBAL ASTROMETRIC INTERFEROMETER FOR ASTROPHYSICS

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ABSTRACT

GAIA is a concept for an astrometric interferometer studied as a possible cornerstone mission within the European Space Agency's scientific programme Horizon 2000 Plus. It is envisaged to consist of two to four wide-field optical interferometers with baselines of a few metres contained in a single payload and operated in a continuously scanning mode. The target astrometric accuracy is 10 microarcsec or better for the positions, parallaxes and annual proper motions of many millions of stars, to be supplemented with spectrophotometric measurements and (possibly) radial velocities provided by on-board instrumentation. Primary scientific objectives are in the fields of galactic research, stellar physics and detection of planetary systems. The presentation is an outline of the technical concept of GAIA in the light of on-going studies.

Key words: GAIA; space astrometry; interferometry.

1. WHY ASTROMETRIC INTERFEROMETRY?

The Hipparcos project was a first step in the large-scale acquisition of astrometric data from space. It demonstrated that space conditions are ideal for the very accurate measurement of *large* angles, and hence for the establishment of *absolute* trigonometric parallaxes and an optical *reference frame* virtually free of the geometrical distortions and magnitude effects afflicting all previous such systems constructed from the ground. This was made possible through a general approach, in which all considerations of hardware and operational design, instrument calibrations, observing programme and data reductions were subordinated to a single goal: that of achieving the highest possible global accuracy. The success of the mission brought attention to the exceptional scientific potential of future space astrometry programmes reaching well into the microarcsec accuracy domain (Kovalevsky & Turon 1991).

A natural extension of the global scanning technique used by Hipparcos would be to employ interferometry to enhance resolution and hence the astrometric accuracy. In fact, astrometry appears to be a most attractive and rewarding first application of optical or near-infrared interferometry in space. This follows from a combination of several factors: Wide-angle measurements are in essence one-dimensional and consequently well suited for the simplest type of interferometer, using a single baseline providing high angular resolution in one direction only. The scant *uv* coverage provided by a single baseline is no serious problem in view of the relatively low complexity of stellar objects. Moreover, while the resolution of an imaging interferometer is limited by λ/B, the wavelength divided by the baselength, the limiting accuracy for astrometry is some $N^{1/2}$ times smaller, if N is the number of photons detected on the object. Thus, as Hipparcos has proved, high astrometric accuracy can indeed be achieved with a modest-size instrument. In contrast, high-resolution imaging cannot do without much longer baselines, and also a good *uv* coverage requiring several baselines and severely limiting the throughput. Finally, it should be noted that high-resolution imaging through the atmosphere is a very active research area, holding considerable promise for the future, while the frontier of global optical astrometry must, by all accounts, remain in space.

Based on such considerations, GAIA was proposed (Lindegren et al. 1993, Lindegren & Perryman 1996) as a concept for a cornerstone mission within the European Space Agency's 'Horizon 2000 Plus' scientific programme. An interferometric observatory was subsequently identified as one of the three cornerstones of this programme. Assuming that an appropriate target accuracy can be demonstrated, it has been recommended that such an interferometric mission should be dedicated to astrometry (Battrick 1994). GAIA is now studied by ESA as one of two candidates for the interferometric observatory.

GAIA will observe of the order of 30 to 300 million objects with an astrometric accuracy of 5 to 20 μas (microarcsec) and with a completeness limit of $V = 15$ or fainter. The astrometric observations will be complemented with accurate multi-colour, multi-epoch photometry suitable for temperature, luminosity and metallicity classification, and possibly also with radial-velocity observations (Favata & Perryman 1997). The scientific objectives cover an extremely wide range of topics in stellar physics, galactic structure and dynamics, detection of planetary systems and brown dwarfs, extragalactic astrophysics and general relativity (Perryman et al. 1997).

2. FEATURES OF THE GAIA CONCEPT

The specific features of the GAIA concept which we believe are essential for achieving this very high accuracy for a very large number of stars can be summarised in the following points.

Wide-angle connections: Building a rigid reference frame over the whole sky requires direct connection of objects in widely (1–2 rad) separated regions of the sky. For Hipparcos this was achieved with the beam combiner, a two-part mirror splitting the telescope aperture to create two viewing directions, separated by the 'basic angle' of 58°, and a superposition of the corresponding fields of view in the focal plane. A similar arrangement, using a beam combiner in front of an interferometer, could be used for GAIA. Alternatively, there could be two separate interferometers with baselines set at a fixed angle to each other. In either case the resulting basic angle must be controlled or monitored to microarcsec precision on all time scales up to a few hours.

Continuous scanning: This permits simple operation and very efficient utilisation of the observing time: no complex scheduling, nor overhead time for re-pointing etc. are required. A scanning law similar to that of Hipparcos also maintains a geometry with respect to the Sun which is as simple as possible, a considerable advantage for the detection and elimination of thermal perturbations.

Use of circle closure condition: The scanning should complete a full revolution (spin) of the instrument in a few hours. Closure conditions on the scanned great circle allow accurate determination of the most critical geometrical instrument parameters with a time resolution corresponding to this spin period: the basic angle, scale value, field orientations and large-scale field distortions. This does not mean that 'great-circle reductions' (as used in the Hipparcos data reductions) are needed, but that the global reductions permit such parameters to be modelled with this resolution.

Wide-field observations: A continuous scanning law admits no flexibility as to the distribution of observing time to different objects. While some areas of the sky are more frequently scanned than others, the mean observing time per object is completely determined by the total effective mission time and the solid area of sky occupied by the detectors. To obtain sufficient ($\gtrsim 1000$ s) observing time on any given object a field diameter of up to a degree may be required.

Simultaneous multi-object capacity: The previous condition of sufficient time per object can only be realised with a capacity for truly simultaneous observation of *all* the programme objects which happen to be within the detector solid angle at a given time. For instance, with 10^8 objects on the programme and 1 deg^2 detector solid angle, on the average 2400 objects must be observed in parallel.

Redundancy of observations: Hipparcos typically achieved some 20–25 distinct epochs of observation per object, not counting successive scans with nearly identical geometry. This gave sufficient redundancy for an adequate treatment of single stars (requiring five astrometric parameters per object) and simple cases of astrometric binaries (7 to 9 parameters); in favourable cases object models with up to 15 parameters could be used. With the higher resolution and accuracy of GAIA, a very large proportion of the programme stars will exhibit duplicity or multiplicity, very often coupled with significant orbital motion, variability, etc. To successfully cope with this increased complexity of the targets, appropriate redundancy of observations and diversity of scanning directions must be ensured through the choice of scanning law and mission length.

Multi-colour photometry: Even all-reflective instruments are chromatic at the level of a fraction of the size of the diffraction image, due to the wavelength dependence of diffraction. Adequate calibration of chromatic effects requires knowledge of the spectral composition of every object. For GAIA, it is likely that a single colour index will not be sufficient. Multi-colour photometry, covering at least the whole spectral range used for astrometry, must therefore be an integral part of the mission. The chosen photometric system should of course at the same time be optimised for its astrophysical uses.

Global reduction: The observations of all the programme stars are reduced together, in principle on an equal basis. Thus all the stars contribute to the determination of the reference frame and to the calibration of the instrument, and the adjustment of all the unknowns is part of a single minimisation process. This approach contrasts with the possible use of a smaller subset of high-accuracy targets for the definition of the reference frame, an alternative which is rejected because *a priori* selection of such targets would be very difficult and lead to a less robust system. Of course, problematic objects must be iteratively isolated, so that their modelisation errors do not corrupt the reference frame and calibrations.

3. TECHNICAL ISSUES

The required large field of view can only be achieved in a Fizeau-type interferometer, where pathlength equalisation is maintained throughout the field in a manner equivalent to a single big telescope. Important hardware constraints for GAIA derive from the requirement of a non-deployable payload compatible with the Ariane 5 launcher envelope (4.5 m diameter, 5–6 m height). In practice this implies a maximum interferometer baselength of about 2.5 m. Apertures of at least 0.5 m diameter are required to reach sufficiently faint stars. Depending on the detection system equivalent focal lengths of more than 50 m may be necessary. Two to four such interferometers, possibly using beam combiners to achieve stable basic angles between them, can be stacked in a cylindrical payload.

The satellite spins with a period of about three hours about the cylinder axis, perpendicular to the interferometer baselines. The spin axis precesses around the direction to the Sun in a revolving scanning law, resulting in multiple sky coverage every year. A mission length of five years is foreseen both in view of the resulting high astrometric accuracy, especially for the proper motions, and for the much improved ability to cope with complex objects and to detect planetary and brown dwarf companions with periods of several years.

Details of the optical system, detection system, data acquisition and other critical aspects of the mission have been discussed in a number of papers; see for example the proceedings of the RGO-ESA Workshop *Future Possibilities for Astrometry in Space* (Perryman & van Leeuwen 1995) and several contributions to the present symposium (Bertinetto et al. 1997, Cecconi et al. 1997a, 1997b, Høg et al. 1997, Makarov 1997, Pace 1997, Scholz & Bastian 1997). Among the many technical aspects considered, a few issues have emerged as particularly important at the present state of development; they are briefly described hereafter.

3.1. Wavelength Region

The original concept foresaw a wavelength coverage roughly optimised for unreddened solar-type stars and the region of maximum quantum efficiency for standard CCD detectors, or ∼ 350–800 nm. However, a very strong scientific case can be made for an instrument optimised towards longer wavelengths, especially for studies of the Galaxy (Gilmore & Høg 1995). Most luminous kinematic tracers are intrinsically red stars, and combined with the strong interstellar reddening in the disk and inner region of the Galaxy this gives a considerable advantage in the near infrared relative to the optical region. Going into the thermal infrared is on the other hand technologically unrealistic and probably scientifically unnecessary. A tentative conclusion is that GAIA should be astrometrically optimised for the longest wavelengths compatible with conventional CCD technique, where good quantum efficiency and low thermal noise can be achieved, i.e. towards $\lambda \sim 900$ nm.

3.2. Direct Fringe Detection

Another feature of the original proposal, as described e.g. in Lindegren & Perryman (1996), was the use of a modulating grid to encode the position of the interference fringes. This eliminated the need for a detector with very high spatial resolution. A considerable disadvantage was the necessity to integrate light in ‘subfields’ of a few hundred square arcsec, causing a relatively bright limiting magnitude ($V \sim 16$) in the interferometric mode, and confusion problems in crowded areas. By contrast, ‘direct fringe detection’, using a detector with sufficient spatial and temporal resolution to record the complete fringe pattern as it moves across the focal plane, was hypothesised as the ideal solution in terms of accuracy, limiting magnitude, and ability to observe in crowded fields, but was at the time considered technically less realistic. The basic problem was the very large number of pixels required in the scanning direction, of the order of $2\text{–}5\times10^5$ for the targeted accuracy.

Several recent developments make us more confident that direct fringe detection may be achieved by means of CCD detectors operated in the time-delayed integration (TDI) mode: fewer pixels per fringe period may be required than originally anticipated; small pixel sizes may be technically feasible with adequate performance; optical solutions permitting long focal lengths exist; operation in the near-infrared relaxes the need for spatial resolution. Inevitably, each of these factors results in some loss of accuracy or sensitivity compared with the hypothetical ideal detector, but this may in the end be outweighed by the inherently higher precision of the technique, by less complex technology and greatly enhanced scientific potential.

3.3. Fringe Dispersion

The use of direct fringe detection on a two-dimensional detector opens the possibility to use also fringe dispersion to improve fringe contrast (and hence astrometric precision) and, at the same time, provide low-resolution spectrophotometric data on the targets. Dispersed fringes could be produced by means of an objective prism or aperture grating inserted at an intermediate pupil. The dispersion is perpendicular to the scan direction, i.e. along the fringes, which are spread out in a fan-shaped pattern (Høg et al. 1997).

A cross-section of the fringe pattern along the scan thus gives a quasi-monochromatic (small $\Delta\lambda/\lambda$) interferogram of high contrast, which is favourable for the astrometric precision. However, spreading out the fringe pattern over a larger area also increases the contributions from sky background and readout noise and results in more crowding of the images. For faint stars, and especially in dense fields, these disadvantages may prove to be severe. Moreover, the introduction of a prism could have a serious impact on the optical stability. Thus, if scientific emphasis is put on the observation of faint stars and in crowded regions, fringe dispersion is probably not the preferred choice. On the other hand, without fringe dispersion the necessary multi-wavelength photometry must be realised through filters, with a corresponding loss of photons and precision.

3.4. Beam Combiner

The global measurement principle calls for the use of a large ‘basic angle’ between different viewing directions and the means to control or monitor this angle to microarcsec precision over all time scales up to several hours. In the original proposal there were three stacked interferometers (A, B, C), each defining its own viewing direction, and the relative orientations of the three interferometer baselines were controlled by internal laser metrology. Three interferometers were required for redundancy and could be operated in any of the four configurations: ABC (nominal), AB, BC, or AC. By the use of a common base plate for two interferometers, the metrological control of a pair such as AB or BC may be relatively straightforward (if complex), while AC is probably much more difficult. In any case the relative positions and orientations of a large number of mirrors need to be controlled.

As an alternative to this, a beam combiner may be used to achieve two viewing directions in a single interferometer. The beam combiner is a split mirror system placed in front of the interferometer, such that the basic angle is defined primarily by this device. The advantage is that the four plane mirrors of the beam combiner are much easier to control by metrology than the whole assembly of two (or three) interferometers. Disadvantages are that less space is available for the interferometer and that the superposition of fields gives a reduced target-to-background contrast and increased overlapping of images, and possibly also increased complexity of operation.

3.5. Data Rates and Target Selection

Reading out all the pixels of the large CCD mosaics in the focal planes, at a scanning rate of 120 arcsec s^{-1}, would give a total data rate of $\sim 10^{10}$ bits s^{-1}, some four orders of magnitude greater than realistic telemetry data rates in geostationary orbit (or L2 with Earth-pointing antenna). However, less than one per cent of the pixels are usefully employed at any given time. Thus, a reasonable data rate seems achievable if only small areas of a few arcsec^2 are read out around each target, and this is combined with a clever compression scheme possibly employing both lossy and lossless compression. Among the open issues are algorithms and performance of lossy compression, its cumulativity with lossless compression, requirements for on-board processing, and the mechanism for selecting target areas. From the viewpoint of data rates it is not realistic to observe *all* stars down to the actual limiting magnitude of GAIA, perhaps $V \sim 20$ or 21 (where accuracy could still be in the sub-milliarcsec range). Therefore, a statistical (random) selection of the fainter stars is probably desirable.

The target selection mechanism is related to the feasibility/desirability of using an input catalogue. The use of an input catalogue is perhaps the best way to ensure that each target is observed on every possible occasion, which is essential for good astrometric and photometric performance, while minimising the readout of empty pixels. However, it is not obvious if and how an input catalogue of sufficient completeness, resolution and dynamical range can be generated from ground-based surveys, particularly in the near infrared. Alternative solutions could be based on real-time detection of targets as they enter the field of view. If a random selection of the faint stars is required, the real-time detection must be combined with a memory mechanism ensuring that the same selection is made on all subsequent transits. Still another possibility could be to read all the pixels in randomly pre-selected (larger) areas of the sky.

4. STATUS OF ESA STUDIES

Two technology studies are in progress since January 1997 with Alenia Spazio as prime contractor. Originally formulated in a rather general framework (active pointing of large telescopes, and attitude measurement transfer systems, respectively), they do however directly address several key technological issues of GAIA: feasibility of direct fringe detection, attitude perturbations and attitude control, and the control of optical elements. They include the design and manufacturing of a laboratory testbed for validation of metrology and optics control systems. These studies are expected to finish in the second half of 1998.

An industrial ‘concept and technology study’ of GAIA will be conducted from September 1997 to the end of 1998. The overall objectives are to establish and study a feasible mission design, identify required technological developments, and define a cost-effective procurement approach. Study Manager at ESA is O. Pace (ESTEC). A GAIA Science Advisory Group has been set up by ESA, with currently seven external members from the astronomical community, to assist in defining a model payload for the industrial study. Towards the end of this study a comprehensive Science Report will be produced with the involvement of a wider scientific community. This report will be the basis for the future development of GAIA within the ESA scientific programme.

REFERENCES

Battrick, B., 1994, Horizon 2000 Plus: European Space Science in the 21st Century, ESA SP–1180

Bertinetto, F., Canuto, E., Cesare, S., Gai, M., Lattanzi, M.G., Mana, G., 1997, ESA SP–402, this volume

Cecconi, M., Gai, M., Lattanzi, M.G., 1997a, ESA SP–402, this volume

Cecconi, M., Rigoni, G., Bernacca, P.L., 1997b, ESA SP–402, this volume

Favata, F., Perryman, M.A.C., 1997, ESA SP–402, this volume

Gilmore, G., Høg, E., 1995, ESA SP–379, 95

Høg, E., Bastian, U., Seifert, W., 1997, ESA SP–402, this volume

Kovalevsky, J., Turon, C., 1991, Adv. Space Res., 11, 2(5)

Lindegren, L., Perryman, M.A.C., Bastian, U., et al., 1993, GAIA—Global Astrometric Interferometer for Astrophysics, proposal for a cornerstone mission concept submitted to ESA in October 1993

Lindegren, L., Perryman, M.A.C., 1996, A&AS, 116, 579

Makarov, V.V., 1997, ESA SP–402, this volume

Pace, O., 1997, ESA SP–402, this volume

Perryman, M.A.C., Lindegren, L., Turon, C., 1997, ESA SP–402, this volume

Perryman, M.A.C., van Leeuwen, F. (eds), 1995, Future Possibilities for Astrometry in Space, ESA SP–379

Scholz, R.-D., Bastian, U., 1997, ESA SP–402, this volume