MISSION CRITICAL ASPECTS FOR A FUTURE SPACE ASTROMETRY MISSION: SUMMARY OF THE PARALLEL DISCUSSION SESSION

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INTRODUCTION

This paper is a summary of the discussions which generated and developed during two parallel sessions devoted to the analysis of critical issues, both scientific and technological, raised by the possibility of doing space interferometry for μarcsec absolute astrometry. The GAIA concept (Lindegren & Perryman 1994) was assumed as the *baseline* mission design.

Efforts concentrated on feasible ways, both in view of present technology or foreseeable developments thereof, to deal with those metrology, attitude control, fringe measurement, and optical aspects which would allow GAIA to address the largest possible spectrum of crucial problems of 21st century astrophysics. Direct fringe detection is identified as a concrete possibility to improve the astrometric precision by a factor of two, and on-board attitude control appears demanding but feasible. Finally, picometer metrology remains the most challenging task ahead.

The possibility of directly charting distances and motions of the stars outside our solar neighborhood and all the way to the far end of the Milky Way and beyond has been the dream of generations of astrometrists. Now that Hipparcos has demonstrated the possibility of accurate space-borne global astrometry, and space interferometry promises the ultimate in angular measurements, the opportunity to lead an ancient science into the realm of 21st century astrophysics is before us!

Such an opportunity has recently become a concept for a Cornerstone space mission within the ESA Horizon 2000+ program (Lindegren & Perryman 1994). This concept, named GAIA, was adopted as the *working baseline* for discussion during the two parallel sessions devoted to mission critical aspects.

GAIA will achieve its scientific goals by an Hipparcos-like survey of the sky with astrometric accuracy of 10 μarcsec for stars down to $V = 15 - 16$ mag. This two-orders-of-magnitude improvement over Hipparcos astrometry requires the operation of a 3-m baseline, fully controlled (passively or actively) Fizeau-type 'diluted' optical interferometer.

Other critical areas, some of which were already identified in the report by Lindegren & Perryman (1994), are the operational wavelength (and bandwidth) of the interferometer and the attitude, metrology, and detection subsystems.

The two mission critical aspects parallel sessions focused on these topics. In preparation, I had solicited certain introductory presentations, intented to stimulate both critical and creative thinking which might result in improvements to the mission baseline design. I owe a great deal of gratitude to the following colleagues for their work in preparing such contributions: C. Burrows (1995), S. Casertano (1995), F. Donati (1995), and S. Shaklan.

The next section is concerned with issues related to mission parameters and scientific goals and, in particular, with the implications of going into the near-infrared. The next sections deal directly with some of the most challenging technological issues raised by the GAIA concept. The grounds covered naturally reflect the interests and the competences of the people who participated in our sessions. The last section focuses on those areas which either require better understanding or are deemed essential for further improving upon the baseline design, so as to make GAIA a stronger mission.

Other critical aspects came up during the discussions but could not recive proper attention: the daunting complexity of the data reduction; issues related to the telemetry rates and the amount of on-board computing power; the selection of the most suitable orbit (geostationary, at the Lagrangian point L5 of the Earth-Moon system, etc.) in connection with the demanding requirement of mm/sec precision on the satellite velocity. More on these topics can be found in Flury & Rodriguez-Canabal (1995) and Lindegren (1995).

Finally, I wish to mention very briefly that, in addition to the astrometric measurements, a key complement to the GAIA concept is the acquisition of precise multicolour photometry (to 0.01 mag or better) for a complete spectral classification including luminosity class. Detailed discussions of this requirement and its significance for the astrophysical exploitation of the GAIA results can be found elsewhere in these Proceedings.

2. MISSION PARAMETERS AND SCIENCE

Mission critical aspects are not necessarily technological in nature. Science, when leading to a technically feasible concept, should always be considered the driver. Important science, which might have not been considered at earlier stages of mission development and would make the overall scientific return sensibly stronger, should become a *critical* aspect; and newer designs should try to accomodate the required technical modifications.

2.1. Operational Wavelengths

Possible trade-offs between mission parameters and science are addressed in Casertano (1995). The discussion focused on the implications of shifting the operational wavelength toward the near-infrared. An operational wavelength in the 2-μm region (K band) would greatly increase access to the galactic plane and the Bulge regions. However, the K-magnitude astrometric error, $\sigma_a \sim \lambda_K / \sqrt{(N_K)}$, where N_K is the number of photons, is ~ 4 times that in V. The energy distribution of normal stars is such that the equivalent increase in the number of infrared photons needed (a factor of 16) to maintain astrometric precision is achieved only for extreme (intrinsic) V–K colours (spectral types later than M5). The astrometric accuracy of typical (G–K) stars would be lowered to some 40-80 μarcsec, although this is probably suitable for many of the Galactic dynamics problems. This science would then compete with that requiring the highest accuracy (i.e., planetary search around solar-type stars).

If the metrology were to support photon noise limited astrometry of bright objects, for example, then it would be better to stay with a visual operational bandpass, and move near-infrared detectors to the incoherent area of the focal plane. If metrology better than 50 pm should prove infeasible, then infrared operational passbands should be reconsidered.

Angular resolution degrades as well, and this could add to the problem of confusion in denser fields. However, near-infrared fringe systems are fully resolved for separations of about 1 arcsec, and this should still be sufficient resolution given a reasonable limiting sensitivity of a 2μm survey. Also, further help would come from the possibility of direct fringe detection, which is in principle easier (at least in terms of pixel size) at longer wavelength.

Detector technology is likely to pose limits in the possible implementation of a near-infrared option. K-band (or J-band, at ~ 1 μm) detectors have different properties (directly accessible pixels, fast read-out, etc.) from the more familiar CCDs; also, their technology is not as well developed as that of CCDs (i.e., larger pixels and smaller arrays, higher read-out noise). Using the reddest wavelengths accessible to CCD detectors, i.e., Cousins I at ~ 800 μm, might then result in the best compromise.

2.2. Gravitational 'noise'

Burrows (1995) discussed the possibility that for any given survey star there is a $\sim 50\%$ chance that its direction is gravitationally bent by a faint star anywhere close to the line of sight. Also, because of the peculiar motions within the Galaxy, this berturbation is not static, but has a characteristic time scale of ~ 20 years. Therefore, the effect would add fictitious motions to the intrinsic, astrophysically relevant, ones. The actual likelihood of this general relativity event is a strong function of the survey limiting magnitude, targets spectral type, and the local stellar density throughout the Galaxy. Thus, detailed calculations are necessary to establish precisely the role of such gravitational 'noise'.

3. OPTICS

Discussion on optical design, modeling, and tolerancing followed presentations by Shaklan and Burrows (1995).

3.1. Residual Aberrations

A monochromatic investigation of fringe visibility as a function of distance from the field centre (Loiseau & Shaklan 1995) has shown that residual distortion in the current optical design generates a phase shift of 1.5 fringe period at the field edge ($\sim 0.6^\circ$). The introduction of a finite bandpass will probably show that this phase shift is also wavelength dependent, similar to the *chromaticity* effect in Hipparcos. Dealing with this effect implies reducing the field of view or, alternatively, calibrating it. Calibration of the chromatic phase shift would add an important operational requirement to the needs for GAIA mutlicolour photometry.

3.2. Design Improvements

Some efforts should be devoted to investigating the possibility of a co-planar design, in which *two* interferometers, at the given angle, would share the same optical bench. This has the potential to alleviate one of the two most demanding metrology issues, i.e., that of controlling the angles between two interferometers (see below). Sketches of possible configurations were attempted, but none appear to be practicable at the moment.

3.3. Modeling

Optical modeling appears much more demanding than it was for the Hipparcos mission. In particular, more sophisticated codes are required to characterize the sensitivity of the design to residual aberrations (c.f., the above discussion on field distortion induced fringe phase shift). Also, optical modeling will have to include the focal plane assembly. In the case of the baseline concept, this end-to-end modeling will guide the optimization of the placement of stops and masks before the detectors to eliminate unwanted (unmodulated) light, thus increasing the signal-to-noise ratio of phase determination.

More importantly, inclusion of the focal plane assembly will lead to the metric requirements for the grids mosaic (ruling errors and flatness). These appear such that it would be necessary to resort to accurate in-flight calibrations. Monitoring of the initial calibration would then be included within the data reduction, like in the Hipparcos mission.

Finally, the optical system can no longer be considered isolated from the rest of the structure, and *residual* environmental disturbances must also be included in the modeling. This coupling is indispensable for finding the best means to control these interactions between mechanical structure and optics.

3.4. Tolerancing

Tolerances to linear displacements within the optical system (piston errors) do not appear very demanding. For an operational wavelength of ~600 nm and a bandpass width of ~100 nm, displacements smaller than ~ 10 nm of the M2+focal plane assembly block (M2 represents the two secondary mirrors) relative to the block made of the two primary (M1) and the two tertiary (M3) mirrors would maintain the ΔOPD below λ/100 (*fringe stability* criteria). Indeed, the requirements on the GAIA metrology system (see below) from baseline and basic angles (angles among the three interferometers) control call for nanometer accuracy. Tilt errors can also shift the fringe system on the focal plane assembly, which would translate directly into a direction error. Ray-tracing techniques should provide a first, relatively inexpensive, assessment of tilt tolerancing (Cecconi & Lattanzi 1995).

4. FRINGE DETECTION

The issue of direct fringe detection was extensively discussed with particular attention to realistic approaches for achieving direct fringe detection on time scales useful to GAIA (Gai et al. 1995; see also Høg 1995b, Lindegren 1995).

4.1. Potential Benefits

The benefits of this possibility were already recognized in Lindegren & Perryman (1994): better efficiency (fainter magnitudes), substantial improvement of the astrometric accuracy (by a factor of 3), better performance in crowded fields (fringe patterns of stars separated by some 0.2 arcsec would be fully resolved), and diminished sensitivity to 'spoiler' stars. In particular, at the 10 μarcsec level, unresolved faint stars would affect astrometric accuracy of $V = 15$ mag target objects. In principle, a 23 mag star provides enough photons ($\sim 10^{-3}$ those of the 15 mag target) to shift the photocentre by $\sim 10^{-3}$ fringes, which is comparable with the astrometric accuracy to be achieved. In reality, the astrometric error is sensitive to variations in the S/N ratio, making the magnitude limit to spoiler stars somewhat brighter. A simple calculation shows that only spoilers brighter than $V \simeq 19$ mag would significantly degrade ($\geq 0.01\%$) the astrometric error of the target. Therefore, the actual situation would not be as bad as photon ratios would indicate, but it remains an area of concern, considering that spoilers density is higher in regions of primary importance for GAIA (galactic plane, globular and open clusters, etc.).

4.2. Technology

The technological challenge for direct fringe detection with CCDs or near-infrared devices is primarily linear size of the pixels along the high resolution (interferometric) dimension; proper sampling of the fringe pattern requires pixels smaller than 1 μm (see below). It was noted that this value is comparable with the operational wavelength, an aspect that should be carefully investigated in terms of processes which might decrease detector efficiency, e.g., quantum and pixels cross-talk effects. Although VLSI techniques to work at the sub-μm level have been announced, the above requirement can be relaxed, for example, by increasing the interferometer equivalent focal length. Another possibility is that of operating the interferometer at near-infrared wavelengths, as discussed in sec. 2, with the caviat that the technology is , in this case, somewhat less mature compared to CCD detectors. Also, increasing the wavelength would not change the potentially critical ratio of pixel size to wavelength.

4.3. Sub-optimal Sampling

Yet another possibility is that of combining *non-optimal* pixels and *resampling* techniques to achieve sub-pixel resolution (Gai et al. 1995). The possibility of resampling comes in naturally in GAIA, as a smoothly scanning satellite is continuosly changing the direction of its optical axis. At 550 nm, the central fringe is ~40 mas, i.e., ~4 μm. Optimal sampling calls for pixels of ≤0.6 μm, while undersampling begins at approximately the Nyquist limit of ~ 2 pixels per resolution element (the FWHM of a fringe), i.e., ~1μm pixels. At two pixels per (total) fringe, i.e., pixels of 20 mas, and using a simple total average technique to recover the fringe from the undersampled data, the loss in astrometric accuracy is only a factor of 1.4 compared to the ideal (optimal sampling) case (Gai et al. 1995). Therefore, it appears that undersampled direct fringe detection could improve astrometric accuracy by a factor of 2 upon GAIA's baseline design. No fundamental problems with technological issues were identified, and details on possible implementations discussed (Gai et al. 1995; Høg 1995b).

5. METROLOGY

This is probably the most challenging technological aspect of the GAIA concept and an area where ESA should invest adequately as soon as possible. The OSI (JPL) and POINTS (CFA, Cambridge) groups have demonstrated one dimensional picometer metrology. Although these results were achieved in controlled laboratory settings, and mantained for short periods of time and for small relative distances only, they still represent a crucial step forward toward the demonstration of picometer metrology for μarcsec astrometry.

As seen in sec.3 above, the metrology discussed for the internal alignment of the interferometric optics appears moderate requiring accuracies of only ~ 10 nm. Also, another important strength of the mission is the concept of a *scanning* satellite, i.e., the same stars are reobserved during several successive scans on time scales of 2-3 hours. Therefore berturbations of typical time scales above the scan period will be dealt with at the data reduction level by enforcing closure on the numerous repeated observations. Over shorter periods, the metrology system will, likewise the Attitude Control subsystem (see below), have to cope with substantially more difficult requirements.

5.1. Critical Aspects

The metrology critical aspects that were discussed are the control of the baseline between the two M1 mirrors (baseline error), and of the relative angles of the three interferometers. An astrometric accuracy of 10μm requires that the baseline equivalent error be maintained below ~ 50 pm. This value should not be interpreted just as the distance between the two 55-cm apertures; it should be read as the total error on the three-dimensional orientation of the baseline relative to a system of local fiducial points (which are part of the metrology system).

Errors on the interferometers angles transform directly into angular errors on the sky. However, in the case of the base angles there is the possibility of using the third interferometer to acquire intra-scan 'closure' informations by demanding, for example, that the sum of the angles between interferometers 1 and 2, and 2 and 3 adds up to the angle between 1 and 3 (LePoole, private communication). Furthermore, as mentioned before, a co-planar design could, if feasible, improve the base angle stabilty.

Strictly related to the development of gauging systems capable of picometer accuracy is the definition of an optimal strategy that would best utilize those high precision measurements for controlling the interferometers over time scales shorter than the spin period. One possibility is the implementation of an *active*, closed-loop, design. An active metrology system would have the advantage of keeping the optical system within specifications at all times, but its requirements and/or associated costs may reveal themselves prohibitive. Also, although such a system would certainly be critical for a *pointed* imaging telescope, this is not necessarily the case for an astrometric survey satellite. Alternative to active control is an open-loop, *passive*, system whose main purpose would be that of sampling, with the required accuracy and frequency, the status of the optical elements and, possibly, of the focal plane assembly (see below). In this case, the metrology data would be read in at the time of data reduction and used to *correct* the science data. This would probably require sophisticated modeling to assure the necessary astrometric accuracy.

5.2. Focal Plane Assembly Metrology

The metrology of the focal plane assembly is certainly as important as that of the optical system. In particular, the local metric should be known, and stable, to better than $\sim$ 500 pm, and the flatness to match the flat focal plane (in the currect design) should be better than $\sim$20 arcsec. It is difficult to believe that these numbers can be turned into manifacturing or implementation requirements for focal planes with mosaics of modulating grids, as is the case of the baseline design, or of CCDs, as it would be for the direct fringe detection hypothesis. Therefore, it would appear necessary to resort to sophisticated ground-based calibration plans, but, quite possibly, only in-orbit calibrations will be able to provide the necessary accuracy. This task might result into a major undertaking; as such, it should not be underestimated and considered early on during mission development. Stability of the initial calibration over periods shorter than $\sim$ one spin axis revolution would have to become a design requirement, while all critical systems should 'self-calibrate', via closure equations, over longer periods.

6. ATTITUDE DETERMINATION AND CONTROL

Most of the second session was devoted to the problem of attitude restitution and control. The account presented by Donati (1995) concentrated on the requirements for the baseline concept, and the discussion that followed tried to extrapolate some of those requirements to a mission implementation with direct fringe detection.

The two most important astrometric error sources related to spacecraft attitude are (a) along-scan *jitter*, and (b) imperfect knowledge of the *actual spin rate*. The objective of the on-board attitude determination and control system is to maintain those errors to a sufficiently small level compared to *photon noise*.

6.1. Jitter

The along scan jitter can be seen as the high frequency contribution to the blurring of the fringe system during the sampling time, i.e., the integration time for the elementary science measurement. In other words, jitter does not affect the fringe centre as such, it adds to the error budget of its estimation. In the baseline design, the basic integration time is the crossing time of a subfield during which the elementary time series in encoded, $\sim$0.2 sec. Therefore, to add 'coherently' the information from all of the subfield crossings, the total power of jitter frequences $\geq$ 10 Hz should be contained within, say, $\sim$ 1 mas. In the simplest implementation scheme proposed for direct fringe detection, the basic integration time is the time for recording, on a single CCD operated in drift scanning mode and with sufficiently high signal-to-noise, one of the 10 *undersampled* fringe patterns necessary for an accurate reconstruction of the actual pattern. [Each of the 10 CCDs covering the focal plane contributes an undersampled fringe pattern with a relative shift of 1 mas.] The time of this elementary process is therefore $\sim$ 3 sec; however, it should be possible to read the undersampled fringe every $\sim$ 0.5 sec, or 6 times per chip (Gai et al. 1995), thus reducing the requirement on jitter to values in all similar to the baseline case.

6.2. Spin Velocity

The other source of error comes from the uncertainty on the predicted value of the along-scan velocity of the fringe pattern. This error *directly* affects the location of the fringe centre, which would impose an unrealistic μarcsec requirement on the along-scan attitude. In the following I assume that, thanks to Hipparcos-like full-sphere solutions, the attitude can be improved by at least a factor of 10, and a tolerable ratio of attitude to astrometric errors is $\sim$ 100. Therefore, similarly for the baseline concept and the direct fringe detection option, it appears reasonable to require that the error on the scan speed be <50 mas/sec. Two causes contribute to this error: imperfect knowledge of the spin velocity as such and an artificial along-scan component induced by small rotations around the optical axis. As just discussed, the 'pure' along-scan component should be kept below 50 mas/sec. As for the other component, an error, ϵ_ω, on the angular velocity around the optical axis will 'project' as $\sim \xi\ \epsilon_\omega + \epsilon_\omega^2$, where ξ ($\leq 0.5^\circ$) is the distance (in rad) from field centre, on the spin axis. The ϵ_ω^2 is negligible, while the ξ-dependent term requires that ϵ_ω <5 arcsec/sec (Donati 1995).

Methods for the on-board determination of the attitude were also discussed. Besides the 'traditional' ways directly or indirectly linked to the Hipparcos mission (Donati 1995), new devices, as optical gyroscopes based on the Sagnac effect, should be considered for *monitoring* the spin velocity. Morover, improved spacecraft designs (shapes) might be able to further reduce the attitude requirements (Høg 1995a; Donati 1995).

7. WHAT LIES AHEAD?

In this summary section, the above considerations are used to define a prioritized list of studies that should be initiated or further pursued. As the views of the discussion group that participated in the two mission critical aspects sessions might be different from those expressed by the other groups, the following recommendations should be seen as expression of partial understanding of the many implications of a GAIA-like mission. Hopefully, the weighted synthesis of all of the good ideas discussed in this workshop, and in the parallel sessions in particular, will result in an improved mission concept.

7.1. Direct Fringe Detection

The possibility of direct fringe detection promises, if proved feasible, an improvement of a factor of ~ 2 to the baseline design. Some of the methods presented during the workshop should be further developed and a serious effort should be put into planning (including work elements and costing) for a technological study which would lead to a more complete mission concept in the shortest amount of time (this should explicitely involve interested CCD manufacturing companies).

7.2. Metrology

Definition and development of a metrology system, including the control strategy, for GAIA are urgent. ESA should start a major activity in this field which foresees prototype hardware and laboratory testing, and close relations with the POINTS/OSI groups should be maintained and/or established. However, a reliable long-term development program, phased in with the evolution of the astrometric mission, requires the establishment of solid european competences in high accuracy metrology. For the time being, a significant step forward could be accomplished with relatively small resources through software simulations of adequate complexity. Metrology of the focal plane assembly should be part of these efforts.

7.3. Attitude

The attitude requirements appear demanding but possible. However, devices for 50 mas/sec accuracy on the scan speed are not yet available and therefore the necessary developments should be quickly identified. Possibilities are the new optical gyroscopes, or the use of the third interferometer. The mission would also benefit from new thrusters for a smoother implementation of the scanning law.

7.4. Optics

Optical design appears well established, but accurate modeling, to include polichromatic tolerancing, coupling with mechanical structures, and the focal plane assembly, should be further pursued. Alternative optical configurations, like the same-bench two-interferometer idea, should receive further attention. A longer equivalent focal length would help the focal plane sampling; this might still be worth doing even if it might require a reduction of the field of view.

7.5. Calibrations

Calibration plans, to include both ground-based and in-orbit, should be developed soon after deciding on the design of the most important subsystems. Particular attention should be given to the detailed calibration of the focal plane assembly. Simulation efforts would be greatly beneficial to this aspect.

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