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

L. Lindegren

Lund Observatory, Box 43, S-22100 Lund, Sweden

1. INTRODUCTION

During this Workshop concepts have been described by which spaceborne optical interferometry can be employed to gather highly accurate fundamental data (astrometry, photometry, possibly also spectral data and radial velocities) for very many stars. The most ambitious such concept proposed to date is GAIA (Lindegren & Perryman 1995), which was taken as a starting point for the discussions of this session. The performance of the baseline concept can be summarised in a few key numbers: (1) astrometric accuracy about 10 μarcsec at $V = 15$ mag; (2) limiting magnitude $V = 15$–16; (3) number of stars $\sim 50\,10^6$; (4) wavelength region 350–700 nm, with precision photometry in several colour bands.

Although the science that can be done with GAIA is overwhelmingly rich, good scientific arguments can be found for an even higher accuracy and fainter limiting magnitude, or the possibility to observe in crowded fields or in a different wavelength region. For the present discussion we should consider the material prerequisites for an improvement in these and other areas, especially in view of current or foreseeable technological developments. On a more fundamental level we should also try to identify the technologically most critical aspects of a future mission, in order that relevant studies can be initiated in time.

At the beginning of the session certain key questions were put forward for discussion:

- Is it possible to design and manufacture a Fizeau interferometer with a 1° field of view? What are the requirements in terms of alignment and position control of the various elements (mirrors, focal plane assembly)?

- Laser gauging will probably be required both for the active control of the mirrors and for baseline monitoring. What are the requirements, prospects, and complexities of such metrology systems?

- What are the prospects for further enhancements in terms of limiting magnitude (towards 17–18 mag in the interferometric mode), observation in crowded fields, and sub-μas accuracy on bright stars?

- Correction for stellar aberration to 1 μas requires that the satellite velocity vector is known, with respect to the solar system barycentre, to a few mm/s. Is this a serious problem?

- If science demands that the astrometry should be made (also) in the near-IR or IR region, what are the consequences in terms of available detectors and their performance, resolution, and relations to the visual wavelengths?

- Can existing or future detectors be applied to 'direct fringe detection' in GAIA, resulting in a more efficient instrument?

- What are the research and development areas most relevant for spaceborne interferometric astrometry?

The first question is addressed in the contributions by Loiseau & Shaklan (1995) and Shaklan (1995) to these proceedings. The present session focussed on possible enhancements of the baseline detection method and on requirements for orbit determination and attitude perturbations. Questions of metrology requirements and data rates were also taken up. Finally a few areas were identified where additional input or studies were deemed especially desirable.

2. IMPROVING THE DETECTION METHOD

The baseline detection method currently proposed for GAIA (in the coherent, i.e., interferometric mode) is to use modulating phase grids whose periods are matched to the fringes, and CCD detectors to record the modulated light intensity by accumulating a 'light curve' in pixel memory (Lindegren & Perryman 1995, Høg 1995a). While this method is considered feasible with existing technology and sufficient for the targetted accuracy, it does not optimally use the positional information contained in the fringe images. Its main weaknesses are: (a) that the fringe-to-grid matching requires restricting the wavelength band to $\Delta\lambda/\lambda \simeq 0.25$ by means of filters; and (b) that the field lenslets necessary to image the entrance pupils on the pixel memory introduce 'subfields' of (currently) several hundred arcsec^2, in which the star signals are mixed, thus making it difficult to observe in crowded regions or to extend the magnitude limit beyond $V = 16$. Ideally, these disadvantages could be completely eliminated by means of a detector combining high spatial and temporal resolution with a modest energy resolution, thus allowing space interferometry to reach the fundamental limit set by the wave/particle nature of light. While the superconducting detector system described by Perryman & Peacock (1995) may provide the ultimate solution, the performance could also be improved in the context of conventional detectors, namely by the use of dispersed fringes and/or direct fringe detection. These techniques were extensively discussed in this session.

2.1. Use of Dispersed Fringes

Fringe dispersion would overcome the bandwidth limitation mentioned above by recording the fringes (or the modulations produced after a grid) simultaneously in several spectral channels. Several ideas related to this concept were discussed in particular by Y. Rabbia, F. Vakili and J. Noordam.

Y. Rabbia suggested two lines of thought for possible improvements. (1) In the set-up where the pupils are imaged on the CCD behind the grid, there is some freedom to use idle pixels to accommodate a spectrum at modest resolution. A possible way to tackle this is to form a 'channelled spectrum', where the linearly varying Optical Path Difference (OPD) between the two pupils produce a different modulation period in each spectral channel. Recording of the sliding fringe pattern along the spectrum will require on-board processing. (2) Since the field pixels should ideally remain untouched and dedicated to spatial resolution, a more attractive approach might be to use another dimension where spectral information is potentially available, such as the OPD space; in principle this amounts to using Fourier spectroscopy for the spectral encoding. The problem here is to find a way to introduce a controlled OPD since, in a Fizeau interferometer, the OPD is already taken out by the motion of the image across the field.

F. Vakili recalled the generic principle of a Courtès polychromator, whereby the stars are imaged on a grating, and the entrance pupil of the telescope is used as a slit; an array of field lenses then produces a series of images in different colours (Vakili & Percheron 1991; Coutès 1995). If this could be incorporated into the GAIA scheme it would be possible to do without filters, with a substantial gain in the number of useful photons. However, it is not clear how a dispersive element could be introduced into a Fizeau interferometer.

J. Noordam outlined an idea to operate GAIA as a Michelson interferometer, using some 10^5 optical fibres to couple the telescopes point-by-point in their focal planes. The fibre lengths would have to be carefully matched to produce the correct delay for each point in the field of view. Fringe dispersion would be required to increase the acceptable field angle of each fibre pair to several arcseconds.

Fascinating as these ideas are, it appears that they have not yet reached sufficient maturity to be included in a revised baseline design for GAIA. The participants were nevertheless encouraged to continue thinking about clever ways to make better use of the photons.

2.2. Direct Fringe Detection

Perhaps the most promising route towards improved performance would be to dispense with the modulating grid and put the detector directly in the focal plane. The most obvious solution would be to use a CCD operated in the Time Delayed Integration (TDI) mode, electronically following the optical image across the chip. Independent of detector type and operation mode, there must be sufficient spatial resolution to distinguish individual fringes. Contributions by Daigne (1995), Gai et al. (1995) and Høg (1995b) were directly or indirectly concerned with this idea. According to the sampling theorem, at least two samples (pixels) per fringe period are required to reconstruct the signal, but in practice some 4 to 6 pixels per period would be needed in order not to reduce significantly the visibility (and consequently the signal-to-noise ratio and the precision of the phase determination). At a focal-to-baseline ratio of $F/B = 4.8$, as in the current GAIA design, and an effective wavelength of 550 nm, this corresponds to a pixel size of 0.44–0.66 μm, clearly rather small for conventional CCD technique.

The requirement on linear size can be relaxed in exactly three different ways: (1) by increasing the F/B ratio, primarily by increasing the focal length F (in order not to lose resolution); (2) by increasing the effective wavelength; and (3) by allowing fewer pixels per fringe period. It is not unlikely that a total factor of 3–5 could result for a revised design compatible with the present envelope, operated at a slightly longer effective wavelength and with a reasonable sampling of the fringes. Both the increased wavelength and the reduced sampling rate would of course by themselves degrade the precision, so it remains to be seen whether the benefits of direct fringe detection would outweigh these factors. Moreover, it is not clear if even a pixel size of $\simeq 2$ μm is feasible, especially in the near infrared.

It should be noted that the optimal wavelength, in terms of a balance between optical resolution and number of photons, depends much on the energy spectrum of representative targets. Thus, science may also be a driver for increasing the operational wavelength depending on the emphasis on different kinds of targets.

3. ORBIT AND ATTITUDE REQUIREMENTS

Astrometric observations are conventionally referred to an observer at rest with respect to the solar system barycentre by performing a Lorentz transformation (usually called 'correction for stellar aberration'). After this it is possible to compare observations made at different times in order to compute, for instance, the parallax. The size of the correction is of the order of v/c, where v is the barycentric velocity of the observer and c the speed of light. In order to compute the correction to within 1 μas ($5\,10^{-12}$ rad) we need to know the barycentric velocity vector of GAIA to within 1.5 mm/s. Such a requirement is appropriate even if the targetted accuracy is 10 μas, because systematic error sources should be kept well below the latter value, which may in fact be surpassed for bright stars.

The satellite velocity vector is determined in two steps: firstly, the velocity with respect to the Earth is obtained by fitting the geocentric orbital parameters to (mainly) range or doppler measurements; secondly, the geocentric velocity is transformed to the barycentric frame by adding the Earth velocity from a standard solar system ephemeris. The whole procedure must be carried out in a general-relativistic framework, the details of which need not concern us now.

W. Flury thought that the geocentric velocity could be determined *a posteriori* to a few mm/s without great difficulty, even for libration point orbits (Earth-Moon L_4,

L_5 or Sun-Earth L_1, L_2; Flury 1995) where the GPS system cannot be used. At first this may seem surprising, but it should be noted that 1.5 mm/s corresponds to 1 km over 10 days, perhaps representing the shortest timescale of significant interplanetary perturbations.

A similar argument applies to the accuracy of the Earth ephemeris, where radar range measurements among the inner planets are at least accurate to a few km. The Viking Lander range data (good to ~ 7 m) have provided extremely accurate ephemerides for Earth and Mars; for example, their inertial mean motions are known to better than 0.15 mas/yr (Williams & Standish 1989), or 4 μm/s in linear velocity, with other elements known to a corresponding accuracy. Of more concern is the relative orientation of the planetary ephemeris frame with respect to the extragalactic VLBI frame (ICRS), to which the GAIA observations will be tied by direct observation of radio-optical quasars. The present uncertainty of the relative orientation of the two frames is 3 mas (Folkner et al. 1994), representing a (highly systematic) error of 0.4 mm/s in the Earth's velocity vector in the VLBI frame.

In summary it appears that existing orbit determination techniques and solar system ephemerides are adequate, or at least very nearly so, for global astrometry down to the 1 μas level.

A short discussion on requirements for attitude smoothness was prompted by the previous contribution by Høg (1995c). Although the requirements have not been quantified, it appears that careful consideration should be given to the exterior design of the satellite with a view to minimise perturbing torques.

4. CONCLUSIONS: AREAS FOR STUDY

At the end of the session certain areas were identified where additional input or studies were considered useful, or even important for the further development of the GAIA concept. They are described in the following subsections.

4.1. Detectors

Direct fringe detection, if proved feasible, would bring about a very significant improvement of GAIA in terms of accuracy, limiting magnitude and ability to observe in crowded fields. This possibility, which mainly depends on detector technology, should consequently be pursued with high priority. Since it would also have a profound impact on the design, calibration and operation of the instrument, as well as on the on-board computing, telemetry rates, and scientific data processing, such a study should be initiated at the earliest possible stage. Of particular relevance is the question whether CCD techniques can be adapted to direct fringe detection. Physical limitations on the smallest useful pixel width need to be addressed, especially at the long wavelength limit.

However, the study should more generally address the prospects of high performance, high spatial and/or temporal resolution detectors, also in view of other improvements of the baseline detection method. The end result should be a clear indication of the most promising detection method for GAIA and possible requirements for further technological development.

4.2. Metrology

The need for control and monitoring of optical elements and interferometer baselines can be summarised by the following two requirements: (1) For each interferometer, the individual mirrors must be correctly positioned with respect to the underlying 3 m telescope in order to achieve fringes over the whole field of view. This requirement should be roughly the same as for a diffraction limited telescope, i.e., in the 10–20 nm range for the relative mirror positions. (2) The angle between the two interferometer baselines should not vary by more than a few microarcsec over a complete spin period (3 hours); more precisely, larger variations are allowed provided they can be either monitored or predicted from other (such as thermal) data to a corresponding precision. The zero point and long-term drift of the baseline angle are of no consequence to the mission accuracy. The requirement in terms of linear displacements is in the 20–50 pm range. This applies equally to all short-term changes affecting the field distortions at the few microarcsec level.

The short-term stability achievable by passive means should be examined in relation to realistic structures, materials and thermal control systems. If passive control is not sufficient, it is likely that a fairly sophisticated metrology system will be needed to monitor the relative baseline orientations. From this system it should also be possible to derive the necessary information for the alignment of each interferometer in order to obtain fringes. Experiences from the POINTS and OSI projects suggest that the required precision can indeed be reached by laser gauging, but its application to GAIA requires a dedicated study.

4.3. Orbit and Attitude

The feasibility of orbital velocity determination to a few mm/s, in all three axis, needs to be studied. Modelisation errors in the effects of solar radiation pressure, solar wind, and attitude control may be the limiting factor and must therefore be considered in the study.

Requirements in terms of the actual attitude (absolute pointing, rotation rates and accelerations), real-time and *a posteriori* attitude knowledge need to be quantified. From this, the acceptable level of perturbing torques may be derived and consideration given to the exterior design of the satellite. This must however be balanced against a number of other (probably conflicting) requirements derived, for instance, from solar power considerations and the need to establish a thermally stable environment for the instrument, e.g., by means of deployable structures keeping the payload in permanent shade.

REFERENCES

Courtès, G., 1995, in G. Comte & M. Marcelin (eds.), IAU Colloq. 149, *Basic principles in spectro-imaging*, ASP Conf. Series Vol. 71, p. 1

Daigne, G., 1995, *Direct fringe detection and sampling of the diffraction pattern*, ESA SP–379, this volume

Flury, W., 1995, *Orbit options for an interferometric astrometry mission*, ESA SP–379, this volume

Folkner, W.M., Charlot, P., Finger, M.H., Williams, J.G., Sovers, O.J., Newhall, XX, Standish, E.M., 1994, Astron. Astrophys. 287, 279

Gai, M., Lattanzi, M.G., Casertano, S., Guarnieri, M.D., 1995, *Non-conventional detector applications for direct focal plane coverage*, ESA SP–379, this volume

Høg, E., 1995a, *Some designs of the GAIA detector system*, ESA SP–379, this volume

Høg, E., 1995b, *Some mission options and a photometric system*, ESA SP–379, this volume

Høg, E., 1995c, *Astrometric satellite with sunshield*, ESA SP–379, this volume

Lindegren, L., Perryman, M.A.C., 1995, *The GAIA concept*, ESA SP–379, this volume

Loiseau, S., Shaklan, S., 1995, *Analysis of an astrometric Fizeau interferometer for GAIA*, ESA SP–379, this volume

Perryman, M.A.C., Peacock, A., 1995, *A superconducting detector system for GAIA*, ESA SP–379, this volume

Shaklan, S., 1995, *End-to-end modeling of high precision astrometric telescopes*, ESA SP–379, this volume

Vakili, F., Percheron, I., 1991, in J.M. Beckers & F. Merkle (eds.), ESO Conf., *High-resolution imaging by interferometry II*, part II, p. 1247

Williams, J.G., Standish, E.M., 1989, in J. Kovalevsky, I.I. Mueller & B. Kołaczek (eds.), *Reference Frames*, Kluwer, p. 67