SCIENCE AND TECHNOLOGY: TRADE-OFFS IN THE DESIGN OF A FUTURE ASTROMETRY MISSION

S. Casertano

ESA/STScI, 3700 San Martin Drive, Baltimore, MD 21218, USA

ABSTRACT

Optimizing the science capabilities of a future astrometric mission requires a careful scrutiny of detailed design choices. Among the key areas are scanning law, wavelength coverage, detection strategy, baseline tolerance, and mission length. The impact of each on various classes of science projects is discussed, with an approximate indication of their relative priority and of possible trade-offs.

Key words: space astrometry, GAIA

1. WHERE ARE THE TRADE-OFFS?

An astrometric mission designed to reach an accuracy of at least 10 μas at $V = 16$ mag or fainter, such as that presented in the baseline GAIA concept (Lindegren & Perryman 1995), will enable substantial scientific advances in many different areas of astrophysics. The topics, discussed in numerous presentations in this meeting, range from solar system asteroids to gravitational wave detection, from the search for planets to the dynamics of the Milky Way, from star clusters to AGNs. Obviously, such a diverse set of scientific goals—and the many specific projects that can be defined within each group—will have different requirements in terms of magnitude, accuracy, spectral coverage, time sampling, density of targets in the sky, and so on. Ideally, it would be desirable to optimize all of these parameters simultanously. However, limits such as spacecraft size and weight, total cost, technology limitations, and so on will limit the improvements that can be made, and choices will have to be made which will benefit some science areas rather than others.

The purpose of this presentation is to identify a number of such choices and to illustrate the impact they might have on the expected science returns. The discussion will adopt the baseline GAIA concept as a starting point. Global parameters such as mirror size, baseline length, number of interferometers, and field of view are not addressed explicitly, since they are largely determined by stiff external constraints (weight/size and financial) which are either fixed or not yet clear enough. However, should the possibility arise to have, for example, larger mirrors at the expense of the third interferometer, then such a trade-off must be considered in the same vein.

It is very likely that choices that now seem crucial will become less significant because of technological improvements, and on the other hand, possibilities now hard to envision will be made relevant. The goal here is not only to open the discussion on some items that may become relevant, but especially to illustrate the need for the scientific community to look at all aspects of the mission in order to enable *informed* choices as early as possible.

In order to make the discussion more manageable, this presentation focuses on a small number of *technical* and *scientific* mission parameters, and on how they interact with one another. The scientific mission parameters will in turn impact various science areas in different degrees. This is where trade-offs will likely occur; more effort should be expended wherever the *incremental* science benefits are largest, within the constraints of technical feasibility, cost, development time, and so on.

The technical mission parameters considered are:
(a) the scanning law, closely tied to the spin rate;
(b) the wavelength range for coherent mode imaging;
(c) the fringe detection strategy (direct vs. indirect, via grid modulation);
(d) the baseline tolerance, i.e., the accuracy with which the relative positions of the interferometer baselines is controlled and/or measured (probably via laser metrology);
(e) the mission length.

The scientific capabilities of the mission are characterized by the following science parameters:
(1) the limiting magnitude for fringe detection;
(2) the astrometric accuracy, both for bright and faint objects;
(3) the time sampling of the position of individual stars;
(4) the spectral energy distribution of feasible targets;
(5) the confusion limit, i.e., the ability to observe crowded fields.

Some of these are very important to specific science areas; for example, high astrometric accuracy for bright stars is crucial for planetary detection. In the following, each of the science parameters will be considered in turn, by illustrating briefly the consequences of the possible choices of mission parameters and discussing which science areas are more sensitive to each. In the end, a set of possible complementary choices will emerge; the purpose is not to advocate that particular set of choices, but rather to illustrate the process by which rational choices can be made. Many areas need to be studied in detail before technical feasibility, cost, and trade-offs can be discussed in a more realistic manner.

2. THE SCIENCE PARAMETERS

2.1 Limiting Magnitude

The limiting magnitude is perhaps the parameter that will affect most broadly the overall scientific capabilities of the instrument. While it is clear that great science can be obtained already at $V = 15$ mag, and the current GAIA concept calls for a limiting magnitude of $V = 16$ mag, a fainter limiting magnitude would benefit almost all science areas that can be addressed by an astrometric mission. The case for pushing the limiting magnitude further by one to three magnitudes has been made in a compelling way by Tucholke et al. (1995) globular clusters and dwarf spheroidals, by Platais et al. (1995) for open clusters, and by Gilmore & Høg (1995) for galactic dynamics.

Technical mission characteristics that affect limiting magnitude, aside from mirror size which is considered fixed, are: spin rate, wavelength range, and especially fringe detection strategy. If direct fringe detection were feasible, $V = 18$ mag or fainter can be reached comfortably within the current mission concept (Lindegren & Perryman 1995), without major changes to the wavelength coverage or to the spin rate and scanning law.

On the other hand, a significant slowing of the satellite spin rate will have to be accompanied by a change in the scanning law; the need to cover the whole sky several times per year leaves relatively little flexibility in the spin period, which probably cannot be increased beyond 10 hours (5 hours may be a more realistic limit). The corresponding gain would be at most about 0.5 mag.

Similarly, the limiting magnitude can be improved by observing a wider wavelength range than indicated in the baseline concept. However, this would lower significantly the astrometric accuracy because of the reduced fringe visibility; a rough estimate indicates that a gain of a few tenths of a magnitude would cause a 50% loss in accuracy.

As noted in the baseline concept, targets can be detected to $V \sim 18$ mag with incoherent mode imaging. The astrometric accuracy that can be obtained in this mode is likely to be satisfactory for some projects, such as the global dynamics of the Milky Way, but will not be adequate for the properties of open and globular clusters.

Mignard (1995) and Donati (1995) discuss the difficulties associated with the downlink data rate required by the baseline concept. Telemetry limitations may make it impossible to observe *all* objects down to $V = 18$ mag or so, and therefore preselection by means of an input catalog (Lasker et al. 1995) will probably be needed if this fainter limiting magnitude is achieved.

2.2. Astrometric Accuracy

Astrometric accuracy is a fundamental mission parameter and, in broad terms, it affects all of the planned science. For most scientific purposes, the accuracy that can be reached with the GAIA mission concept is fully adequate. However, a significant increase in accuracy would greatly benefit extragalactic science, especially for the Magellanic Clouds and dwarf spheroidals (Tucholke et al. 1995). Higher accuracy is required for gravitational wave detection (Fakir 1995) and would help the study of microlensing events (Miyamoto & Yoshii 1995). Even more significant is the impact that a higher accuracy for bright stars would have on planetary detection: the ability to reach the theoretical limiting accuracy due to photon statistics would enable detection of Jupiter-like planets around over a million stars, and of Earth-like planets around some tens of stars (Casertano et al. 1995).

Overall astrometric accuracy is limited by baseline errors (variations in the basic angle over short time scales) and photon statistics. The photon limit is sensitive to the wavelength range; for example, a shift to K band (2–2.5 μm) would decrease the accuracy expected for a G-type star by a factor of about 4. The accuracy would be recovered almost in full for very red (or heavily reddened) targets; this is discussed further in Section 2.4. However, the loss of a factor of several for most 'normal' stars may be enough to jeopardize the mission requirement of 10 μas at $V = 15$ mag.

Detection strategy also affects astrometric accuracy; although the actual numbers depend on the wavelength range and on technical aspects such as detector properties, it appears that direct fringe detection allows a gain of a factor 1.5–2 with respect to the use of a modulating grid. And, of course, a longer mission helps achieve a higher accuracy.

However, the ability to obtain the astrometric accuracy allowed by photon statistics is predicated upon the precision with which the relative positions of all optical elements can be monitored. A motion of one of the primary mirrors will result in an equivalent motion of the baseline of the interferometer to which it belongs, and therefore in a variation of the basic angle. Motions of the other mirrors will change the optical path difference, and thus also result in an effective variation of the basic angle. While long-period motions (over time scales comparable to the spin period) can be corrected for by using the relationships between interferometers and closure arguments, oscillations over shorter time scales need to be monitored directly, probably by using laser metrology. Casertano et al. (1995) estimate that an equivalent baseline error of 250 pm would dominate the measurement error for stars with $V < 12$ mag; even a baseline error as small as 50 pm would be significant at $V = 9$ mag. Therefore, accurate monitoring of the baseline will be necessary if accurate measurements are desired for bright stars. On the other hand, the astrometric accuracy that can be achieved for faint objects is essentially photon limited, and requires only nanometer-level metrology.

2.3. Time Sampling

If all stars were single, measuring their position two or three times a year would be sufficient to determine position, parallax and proper motion. However, many stars are in multiple systems, and therefore can benefit from more frequent position measurements. This is true even for long-period binaries: Wielen (1995) advocates at least 20 observations per year, and indicates that statistically significant errors can be introduced by infrequent sampling. Similarly, planet detection, especially for short-period planets, is made much easier by more frequent time sampling (Casertano et al. 1995). The identification and study of variable stars, an extremely interesting byproduct (Mennessier 1995), would also benefit from more frequent time sampling. Planetary detection, binaries and variable stars would of course also benefit from a longer mission.

Since the observations must cover the whole sky, increasing the frequency of individual observations requires changing the scanning law, which in turn would probably require individual spins to be completed more quickly; in other words, the satellite must spin faster. This is to be expected: if the whole sky is to be observed more frequently, individual observations must be shorter, and therefore the spin rate must be higher. It is possible to improve slightly on these constraints by increasing the field of view, but the current size is already very large, and appears difficult to increase substantially.

A faster spin rate would have a slight negative impact on the limiting magnitude, but probably not in a significant amount. It will also, however, make detector technology more difficult (Gai et al. 1995) and increase the data rate; both challenges may be difficult to meet.

2.4. Spectral Energy Distribution of Feasible Targets

Besides improving the overall sensitivity, as discussed in Section 2.1, it is possible to look for different classes of objects at similar flux levels by changing the wavelength range for coherent mode imaging. The main trade-off that can be envisaged in this area is a shift towards the infrared. Observations in the K band would greatly improve the accessibility of heavily reddened objects near the galactic plane, and therefore impact the study of the dynamics of the Milky Way in a very positive way. The counterpart is a significant loss of accuracy for stars of normal colors, as discussed in Section 2.2. Direct fringe detection may be easier in the infrared, but the detector technology is probably less mature than in the visible, and the difficulties will be more significant. Readout noise would likely be a factor, barring substantial improvements in the detectors.

A less drastic shift towards the red, perhaps to I band (within the capabilities of normal CCD), may be an acceptable compromise. Absorption would be substantially reduced with respect to V, although still much larger than in K, and the impact on astrometric accuracy would be insignificant. At the same time, detector technology would be made slightly easier, and direct fringe detection would probably become more feasible.

Many important projects in the area of Galactic dynamics can be carried out with the accuracy obtained in incoherent mode imaging (Gilmore & Høg 1995). Therefore, much of the galactic dynamics in heavily reddened areas that could be lost in the visible or near infrared may well be recovered by including K-band detectors among those covering the outer region of the focal plane.

2.5. Confusion Limit

With of order 50 million targets, the GAIA concept aims at observing an average of just over a thousand stars per square degree. However, some of the most interesting areas of the sky have a much higher star density, with mean separations well below 10 arcsec. With field lenses and a modulating grid, the baseline concept uses individual subfields of about 400 square arcsec, and such subfields will contain numerous stars at low galactic latitude (especially towards the galactic center) and in other interesting areas, such as parts of the Magellanic Clouds and towards globular and open clusters. The confusion problem may be even more serious, if much fainter stars within the subfield can act as 'spoilers' and alter the measured position of the photocenter of the target star.

The confusion problem can be alleviated enormously if interference fringes are detected directly in the focal plane. In that case stars that are resolved by the individual subapertures will have separate fringe systems, and therefore stars separated by more than about 0.02 arcsec (this value depends on wavelength, of course) can be treated separately. Simple systems with separation smaller than this limit can also be treated easily.

3. DISCUSSION

It is now worthwhile to examine each of the mission aspects that were presented at the beginning, and to evaluate the alternatives on the basis of the above discussion.

(a) Spin rate and scanning law: a longer spin period has the advantage of slightly improving the limiting magnitude and of a lower data rate. Faster spin allows a scanning law with better (more frequent) sampling per star, which benefits plantary search, binaries, and variables; it also helps limit the statistical effect of long period binaries. Since the limiting magnitude can be improved substantially by other means, it appears that a faster spin rate and a better time sampling are desirable, as long as the necessary data transfer rate can be achieved.

(b) Wavelength range: the two reasons for a longer wavelength (IR) are: better coverage of regions at low galactic latitude and larger pixel for critical sampling in the focal plane. The drawbacks are: much lower astrometric accuracy for objects with 'normal' colors and less mature detector technology. A reasonable compromise could be to use I band (700–900 nm), where CCD can still be used, absorption is less than at 500 nm, and the accuracy would not be affected significantly for most objects. Most Galactic dynamics in heavily obscured areas could be recovered by using incoherent mode imaging for K band. If direct fringe detection proves impossible at I, a longer wavelength should be considered again.

(c) Detection strategy: the issue here is whether direct fringe detection is technically feasible. If it is, the advantages are so clear-cut (confusion, limiting magnitude, accuracy) that the choice is obvious. If direct fringe detection is only possible within a certain wavelength range, that wavelength would be preferred.

(d) Baseline tolerance: again, the issue is what level of accuracy can be reached in the short-term measurement of variations in the position of all optical elements. An accuracy of about 1 nm (equivalent baseline error) is necessary to achieve the minimum mission goals. Better baseline tolerance is required to reach the accuracy allowed by photon statistics for bright stars (250 pm at $V = 12$ mag, 50 pm at $V = 9$ mag). The higher accuracy will be beneficial for a range of specialized problems, such as binaries, planetary search, gravitational wave detection, and extragalactic work. Improving baseline tolerance beyond 1 nm is important, but perhaps a lower priority than direct fringe detection.

(e) Mission length: a longer mission will increase overall accuracy, improve identification of long-period variables (and planets), and reduce the statistical error due to unidentified binaries. Therefore a longer mission is beneficial, but perhaps a somewhat lower priority than points (d) and (e).

It should be stressed again that these choices will have to be considered again in much greater detail, on the basis of community response and interest, budgetary considerations, and technology advances. The emphasis here is on illustrating the process by which rational choices can be made, rather than on the choices themselves.

In conclusion, the enormous scientific returns that can be achieved by the baseline GAIA project can be further increased by a judicious choice of mission parameters. While it is too early to predict the specific decisions that will be most advantageous, some possible trade-offs can already be discussed. Science can be an important driver in the future development of a high accuracy astrometric mission, by indicating the areas that are most worthy of effort, and thus help optimize the scientific productivity of the mission.

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