THE SCIENTIFIC ORGANISATION OF A FUTURE ASTROMETRY MISSION

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ABSTRACT

Experience gained from the scientific organisation of the Hipparcos project is used to consider possible approaches to the scientific organisation of a future space astrometry mission. It is shown that the preparatory scientific tasks for GAIA will be very significant, albeit of a somewhat different nature to those encountered in the case of Hipparcos—an early start on these tasks is mandatory. Arguments are give for considering a dual, parallel reduction of the GAIA data, as was adopted for Hipparcos. Some consideration is given to the general question of data rights, and to the early distribution of preliminary data.

Key words: space astrometry, GAIA

1. KNOWLEDGE ACQUIRED FROM HIPPARCOS

All of the original scientific goals of Hipparcos have been met, and indeed in all cases, significantly exceeded. More target stars, higher astrometric accuracy, and a massive (originally unforeseen) photometric data base have been realised. The original cost envelope for the mission was exceeded by less than 15 per cent, a cost over-run largely attributable to a one-year launch delay imposed by the Ariane launcher programme. The complex data analysis system—the global treatment of 1000 Gbit of data is considered as the largest single data reduction problem undertaken in astronomy—is on schedule for completion according to the originally foreseen time schedule.

These successes are attributable to a variety of factors, consideration of which can be used to identify the manner in which the implementation of a mission following the GAIA concept could be undertaken. With hindsight, I would identify the following features as having been some of the important organisational aspects contributing to the mission's success:

(a) a clear set of scientific goals was established by the scientific community, and endorsed by the ESA advisory bodies. These were considered as inflexible by the ESA Project Team and, in turn, by industry. Specifications were established at the top level (thus, a mean sky accuracy in the five astrometric parameters at 9 mag of 2 mas), as well as at intermediate level.

(b) many of these intermediate specifications were formulated based upon extensive simulations and studies already carried out during Phase A.

(c) responsibility for *all* scientific aspects was taken by a *single* committee, the Hipparcos Science Team, a non-political group committed to the mission goals and hence its scientific success. All other bodies involved in the scientific aspects—the scientific proposal selection committee, the four scientific consortia, and a variety of working groups, all reported *directly* to this Science Team. The Hipparcos Science Team was in turn, *responsible* for all scientific decisions during the satellite development phase, for overseeing the timely preparation of the observing programme catalogue and the data analysis software, and for controlling all other interfaces with ESA and ESOC having a potential impact on the scientific conduct. The majority of the members of the Science Team were involved with the Hipparcos project, during a period of about 15 years since formal approval of the project by ESA, as their primary research effort.

(d) members of the Hipparcos Science Team were closely involved in project decisions which affected any aspect of the scientific performances, in formal project reviews, and also as direct consultants to industry during the satellite's detailed definition phase, assisting the prime contractor in its interpretation and implementation of the ESA project specifications.

(e) all of the scientific aspects of Hipparcos were entrusted to the scientific community, under their responsibility and financial authority, although with the Science Team coordinating their activities and schedule at the highest level.

(f) in turn, ESA took financial responsibility for the entire satellite (spacecraft and payload), and entrusted its development, manufacture, testing and calibration (on-ground and in-orbit) to the industrial prime contractor. The overall system approach to the satellite as a single entity, adopted by ESA and the prime contractor (MATRA)—including error analysis and allocation, and procurement, integration, verification and calibration of the payload—was a substantial and crucial factor contributing to the eventual success of the mission.

(g) the parallel development of the satellite, the observing programme, and the software and management system for the on-ground data analysis, was crucial. Thus, the deadline for observing proposals terminated in 1982 (at a time when launch was scheduled for 1988) in spite of some suggestions to keep it 'open' for longer. Careful optimisation of the observing programme, and its optimisation with respect to the satellite's operational and observational capabilities, took a team of 30 or so people (some working full time, and some part time) 6 years. But as a result, the Input Catalogue and the associated observations of nearly 120 000 programme stars worked smoothly and flawlessly. Similarly, development of the software for the data analysis tasks started in the two main data reduction teams (FAST and NDAC) in 1981, based on simulation software already available. Consequently, not only was the software finalised and tested pre-launch, but very significant guidance was provided by both consortia, to ESA and to industry directly, in the area of satellite design and operation. The efficiency of the consortia's preparations wee evident from their results: even in spite of the post-launch problems, the first great-circle reductions were completed within a month or so after the start of the routine acquisition of data, and the first 'sphere solution' was reported just one year later.

(h) Similarly, the data distribution system established by ESOC was prepared in parallel with the data reception software being developed by the consortia. This ensured that, when data first started flowing from the satellite—at 24 kbit/s—it could be received and treated almost immediately by the consortia.

(i) an 'Agreement', or Memorandum of Understanding, was drawn up at an early stage between ESA and the four scientific consortia involved in the project, setting out deliverables and schedules for all groups, and their respective 'rights' in terms of pre-release data. This included the agreement not to circulate, release, or publish preliminary data, or scientific results based on such preliminary data; this has had the very beneficial effects of not propagating incorrect or misleading data into the literature, and not distracting the work of the catalogue finalisation by motivations to publish investigations into such *preliminary* data.

All of this can be summarised by stating that a systems approach was adopted for Hipparcos, with all of the many complex tasks encountered in a satellite project viewed as part of the same system. A unique goal—the final catalogue, of the highest possible astrometric accuracy, precision and rigour—was also established early on as the final mission product; this ensured that the ultimate objectives of the mission were apparent to all, both inside and outside the project. The simple advisory and decision-making structure was efficient and successful, with a clear identification of responsibilities.

A similar approach would seem equally evident in the case of a future astrometry mission: the preparation of the observing programme, its execution, and the resulting data analysis and final catalogue preparation should be seen as complementary aspects of a much larger single collective task. It calls for substantial commitments, both in terms of manpower, infrastructure, and eventually costs from the scientific community. These resources must not be underestimated by way of attempts at false economies.

Similarly, the achievement of a precise set of scientific goals implies that a system approach be adopted for the satellite. The accuracy analysis and error allocation budget for Hipparcos during the development phase was a highly complex activity, comprising diverse but inter-related aspects such as spacecraft attitude control and jitter, optical performance and stability, detector characteristics, spacecraft and payload thermal control, data rates, spacecraft and payload shielding (electromagnetic and particle/Cerenkov), straylight, satellite spin rate, scanning law, mission duration, and so on. Global missions like Hipparcos and GAIA demand that target accuracies are met and, in turn, that a minimum operational lifetime is also achieved. Hipparcos was unusual amongst ESA missions in that the development of the spacecraft and payload was entrusted to a single prime contractor (rather than separate PI groups providing the payload instruments). In the case of GAIA, this would also seem to provide the most satisfactory and risk-free route to be followed.

2. PREPARATION OF THE OBSERVING PROGRAMME

A very challenging problem for Hipparcos was to identify the desired subset of programme stars (about 120 000 could be accommodated) from amongst all those potentially observable (a few million down to about 12 mag). This required (a) an announcement of opportunity for observing proposals (600 000 objects were eventually proposed for study); (b) scientific assessment and priority allocation by an *ad hoc* (independent) selection committee; (c) extensive mission simulations covering scientific and operational considerations; (d) a careful compromise between scientific desires and aspirations and technical capabilities (e.g., general requirements on the uniformity of the overall sky distribution of programme stars, and the inability to observe many faint stars in a small region of the sky); (e) an extensive, laborious, and complex programme for the compilation of the requisite *a priori* astrometric and photometric data.

GAIA will survey the entire sky to a certain limiting magnitude (around $V = 15$ mag, and perhaps fainter, in particular in its incoherent mode). All objects brighter than this limit will, according to present expectation, be observed, their data analysed, and their astrometric and photometric parameters eventually published. Thus, *a priori* target selection will not be needed, at least in principle, neither will an observing programme defined on the basis of scientific proposals. This would vastly facilitate preparations for the mission.

On the other hand, there will be requirements on positional reference stars for the real-time satellite attitude control—which might, for example, be provided by the Hipparcos and Tycho Catalogues. Telemetry rate limitations might also lead to demands for on-board preprocessing, perhaps thus demanding the use of an input catalogue.

Even though perhaps not mandatory for the data analysis, it would without doubt simplify the reduction tasks if *a priori* a homogeneous body of high-accuracy astrometric and photometric data would nevertheless be available. In this respect, present plans for the production of GSC-II at the STScI (Lasker et al. 1995) is a very timely initiative: this ambitious plate measurement programme is expected to provide absolute positional accuracies, for 2×10^9 objects over the entire sky down to $V = 18$ mag, of 0.5 arcsec (worst case) at epoch J2000, and 0.59 arcsec at epoch J2025. Two-colour photometry with an accuracy of better than 0.2 mag is also planned. GSC-II will probably not be able to supply all information desirable in crowded regions, e.g., in certain regions of the galactic plane. For the Magellanic Clouds the catalogue described by Tucholke (1995) would be useful.

In summary, it seems likely that the GAIA observing programme, despite its size, could be established relatively rapidly from existing or planned material, *without the great complexities and overheads created by a call for* *observing proposals.* Such a call for observing proposals could nevertheless be considered for the question of 'data rights' allocation; this aspect is briefly addressed in Section 5.

3. DATA ANALYSIS: A DEDICATED INSTITUTE?

The data analysis problem for GAIA will be similar in nature to that for Hipparcos: global and complex. It might follow, very crudely, the precepts established by Hipparcos, but probably employing an even more rigorous approach to the global reduction problem than was possible with the Hipparcos data because of computing constraints. It will also have to handle very much larger quantities of data, at a much higher level of precision, and with a far greater degree of complexity in terms of the effects that will have to be taken into account (Fabricius & Høg 1995).

The Hipparcos reduction problem was broken down into a serious of three 'steps': (1) solving for one-dimensional positions on a 'reference great circle'; (2) reconstructing the origins of these reference great circles; and (3) back-substitution of the one-dimensional coordinates within the reference great circle system in order to estimate the astrometric parameters. This method introduces approximations in the projections onto the reference great circles, and to an extent decouples the solution of the astrometric parameters from the problem of the satellite attitude determination. Truly global reduction algorithms for the Hipparcos data have been studied; they could possibly lead to small improvements in the overall astrometric accuracies and the suppression of certain potential systematic errors (which would be more crucial in the case of GAIA), but were not adopted due to time, schedule and computer resource constraints.

The reductions for the GAIA data might therefore follow the established principles adopted for the Hipparcos reductions, but with certain improvements included. On the other hand, treatment of error sources such as chromatic terms, timing errors, relativistic (metric) effects, orbit corrections and Earth ephemeris, secular acceleration, effects of double and multiple stars (including astrometric binaries), computational rounding errors, and so on, will be considerably more complex. This, in turn, offers great intellectual and organisational challenges to the scientific teams that would be called upon to take charge of the data reductions.

The Hipparcos reductions were characterised by the unusual (and by some 'outsiders' poorly-understood) feature of two independent data analysis groups treating the entire data set in parallel. In brief, this proved to be a remarkably powerful method of cross-verification, identification of software coding errors or incorrect comprehension of interface specifications, etc, as well as providing important information on the final data quality, and the possible contribution of modelling terms to the final accuracy estimations. Many errors or imperfections were rapidly identified in this way. It is difficult to overemphasize how important and successful this has been for Hipparcos, and it is difficult to avoid recommending a similar approach for the global treatment of the GAIA data.

Why should two independent reductions have been necessary with Hipparcos? Aside from the fact that complex problems generally benefit from an independent approach to their solution, the nature of the Hipparcos data means that any future re-analysis of the raw satellite data seems highly unlikely. Confidence by the scientific community in the results of the processing is very important. Unlike many other types of astronomical observations, astrometric data have a crucial historical relevance: a new experiment with a more modern instrument cannot simply be expected to reproduce or confirm measurements that were made previously. One specific example may suffice: as of the time of writing, FK5 and Hipparcos proper motions have not been fully reconciled: one very likely explanation seems to be that the existence of (astrometric) binaries and the corresponding photocentric motion due to orbital effects means that proper motions measured at one epoch will not necessarily agree with, or will not necessarily be superficially consistent with, proper motions at another. Thus, even given the very much higher instantaneous accuracy of the GAIA astrometric measurements, effects due to orbital motions occurring on a time-scale long compared with the mission duration, will result in an inconsistency with measurements made at a previous epoch. The lesson is clear: all efforts to eliminate artificially induced random or systematic errors within the GAIA data will have to be made, and independent reductions of the satellite data, along with appropriate cross-verifications, would seem to offer the best possibilities of controlling such errors.

Although it could be argued that the principles of such a global astrometric reduction have now been established, so that the need for two separate reduction groups might superficially seem less compelling, one could perhaps even more forceably argue that the degree of complexity of the GAIA data and the criticality of achieving the expected astrometric and photometric accuracies would be so extreme as to demand this parallel reduction approach.

Somewhat independently of the question of whether there would be one or two independent data reductions teams is the question of whether the data analysis tasks could or should be located in a single, dedicated institute (which, if it existed, would, presumably, be attached to some existing institute). Arguments for and against such an idea can easily be formulated.

Advantages of a centralised institute would include (i) centralisation of expertise and improved possibilities for the exchange of ideas; (ii) ease of communications (even in the age of fast computer networks meetings are necessary, and the problem of defining and controlling interfaces of different tasks is complicated by geographical separation); (iii) centralisation of documentation and the consequent improvement in the exchange of information (the problem of keeping large numbers of individuals in many different institutes up to date with a large, rapidly moving project was formidable one, and is absolutely crucial at all stages of the project); (iv) exchange of data (in the multi-step, sequential processing of the Hipparcos and Tycho data, large quantities of data had to be moved from institute to institute). In this approach the need for two independent reduction groups could be relaxed, with critical steps perhaps being undertaken by two or more separate individuals or groups within the central institute.

Disadvantages of a centralised institute would include: (i) the difficulties of attracting and retaining the necessary individuals to work away from their home institutes for prolonged periods of time; (ii) making this approach attractive to participating countries or institutes, both financially and intellectually. Despite the evident advantages of a central data reduction institute, it is difficult to imagine that it could be established, precisely because of these difficulties. A similar conclusion was reached independently by Mignard (1995).

Whatever solution is adopted to the question of data reduction, the tasks would need to be entrusted to the scientific community, at the very start of the mission studies, and these groups would need to be in place during the satellite Phase B development. The technical and scientific trade-offs encountered will only be possible if the software tools necessary to reduce the data, and estimate the associated accuracies, are available during the development phase.

4. ASTROPHYSICAL EXPLOITATION

In Section 2, it was explained that the observing programme, and with it the observations and satellite operations, would not require the same type of preparatory work undertaken for the Hipparcos programme. However, for the data analysis, and especially for the astrophysical exploitation, the situation is less clear. While this may be considered as outside of the responsibilities of the ESA scientific programme, some words of explanation are in order.

With the Hipparcos programme of 120 000 stars, many of the target objects were known, in advance, as objects of astrophysical or astrometric 'interest'. In many cases their spectral types and/or multi-colour photometry, and details of their multiplicity or (coarse) photometric variability, were known. Metallicities, luminosity types, and many radial velocities were known or are in the process of being acquired as part of dedicated support programmes. Nevertheless, it must be pointed out that much of this 'auxiliary' material is of very inhomogeneous quality: when the final Hipparcos Catalogue is published, two-dimensional MK spectral types will be available for some 60 000 of the 120 000 programme stars; while radial velocities will only be available for some 20 000 of the programme stars (although many others have meanwhile been acquired by associated principal investigators).

The absence of radial velocities for the majority of the Hipparcos objects (let alone for the one million Tycho objects) is quite unfortunate—radial velocities provide the third space velocity component of the star, and high velocity accuracy can be achieved—very important supplementary information for any kinematical or dynamical interpretation of the proper motion data. At the same time, repeated radial velocity measurements provide a powerful method of inferring and characterising double or multiple systems (and consequently, for mass determinations). And finally, radial velocities will be of significance in the assessment of secular (perspective) acceleration, the contribution to the apparent photocentric motion due to the (apparent) time-dependent proper motion, an effect which will attain increasing significance with improved astrometric measurements.

These considerations imply that very careful thought will have to be given to the large-scale acquisition of complementary astrophysical data necessary for a complete astrophysical exploitation of the resulting astrometric data.

The questions to be asked are the following: whether, and to what accuracy (depending on scientific aim), parameters such as radial velocity, spectral type, and metallicity are demanded, and on what time-scale? Can the acquisition of such data wait until the astrometric measurements have been acquired? Is a specific dedicated ground-based observational programme required in advance of launch? What parameters can be estimated through appropriate payload design? Can a spectroscopic facility on-board simply provide radial velocities to some useful accuracy? Would the use of an energy-sensitive detector on board, or appropriate photometric filter selection, provide spectral classification material to an adequate accuracy?

For further consideration of the issues raised in this section, see Favata & Perryman (1995), Bastian (1995), and Gilmore (1995).

5. DATA 'RIGHTS' AND RELATED ISSUES

The question of data rights, publication policies, and early release of data, are complex issues which face the conduct of any space mission and, of course, all scientific experiments conducted as large collaborations. Much energy is devoted to these issues, for which there is rarely a clear-cut right or wrong answer. In Section 1, for example, it was explained that a policy of non-distribution of preliminary data was adopted by the Hipparcos Science Team. I believe that this was, globally, the 'correct' decision, and one which has proved to the considerable benefit of the project as a whole (and, perhaps even to astronomy in general). It should also be stressed that the entire catalogue production and finalisation will only have taken two years since the availability of the final satellite data from ESOC—small compared with the duration of the project.

On the other hand, most of us can understand the views occasionally expressed by 'outsiders': could you not just provide us with this or that piece of information in advance—we promise not to read too much into the preliminary data!

Perhaps, more than other astronomical disciplines, astrometry has a rather altruistic tradition: catalogue construction is perceived as a service provided to users. To a large extent, such an approach offers great advantages: the scientists skilled and motivated by the problems of instrumental design and data reduction (I refer now to any large ground- or space-based astronomical project) may work unencumbered by problems of data rights; certainly, those who have devoted many years to the production of such final products may not necessarily be those best placed to exploit the resulting data scientifically.

Consideration might therefore be given, during any assessment phase of the GAIA concept, to partitioning responsibilities even more clearly: with no scientific proposals needed to drive the observing programme, no associated data rights would be needed or allocated. Only those motivated by the desire to create a final product of the highest possible accuracy and fidelity, a task at times inconsistent with data exploitation, would become involved. Consortia members would be free to publish material illustrating the statistical progress of the data analysis tasks. Once the final catalogue is compiled, it would be available to all, without delay.

But the disadvantages of such an approach are equally evident: scientific recognition is bestowed almost exclusively on those who publish; and little acknowledgement is available to those who have laboured for many years on such a project in the absence of such publications. Some of the heaviest and most complex tasks in the Hipparcos data reductions did not necessarily lend themselves to refereed publications. Unless scientific productivity or value is somewhat decoupled from publication rate, or unless their fundamental contributions to the success of such missions are recognised in some other way, instrument builders, principal investigators and co-investigators will have to continue to negotiate for 'data rights', and we will have to accept the complications that go with them. Of course, ESA missions do not exist solely for principle investigators and their teams, and it is a further difficulty to determine the correct balance in allocating data to community scientists who have had no direct role in the project, but who nevertheless have 'rights' as member state scientists.

Could GAIA be organised in a manner which provides greater flexibility for the 'external' user? This may be an important question in the case of a mission duration significantly longer than that of Hipparcos. How would teams working on the catalogue production maintain their attention on this task, whilst not becoming 'side-tracked' into questions of data exploitation? Perhaps by invoking an operational team for the routine reduction of the data stream after the first two to three years of satellite operation.

How could scientific users gain access to preliminary (but presumably already very high-quality) data, whilst not compromising the fidelity of the final published catalogue? One way might be to have a subset of the data analysis teams whose responsibility would be to generate a preliminary catalogue as rapidly as possible, one which would not be confused with the ultimate catalogue product, one in which some deficiencies were accepted, and whose release might be restricted to successful proposers in a previous 'Announcement of Opportunity' or, more simply, made generally available at the earliest opportunity. In this sense, GAIA could provide an 'observatory-type facility', without the labour and complications of proposal submission (and evaluation!).

These preliminary ideas are not considered as intending to establish the rules under which scientific participation in a future astrometric mission would be governed; rather they are presented to illustrate questions of deontology that must be faced early on in such a complex and unusual programme.

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The ideas expressed in this contribution are personal, and do not necessarily reflect the opinions of other members of the Hipparcos project or scientific teams. The outcome of GAIA will ultimately depend, as it did with Hipparcos, on having highly competent and committed individuals, excellent project teams at ESA and ESOC, and outstanding technical and managerial competence within the industrial prime and sub-contractors. The Hipparcos Science Team having determined the successful elements of the Hipparcos project as outlined above, it is a pleasure to acknowledge the roles in the scientific organisation of Hipparcos played by the four scientific consortium leaders—E. Høg, J. Kovalevsky, L. Lindegren & C. Turon—and the other members of the Hipparcos Science Team—U. Bastian, P.L. Bernacca, M. Crézé, F. Donati, M. Grenon, M. Grewing, F. van Leeuwen, H. van der Marel, F. Mignard, C.A. Murray, R.S Le Poole, and H. Schrijver—who represent, of course, the work of many other consortia members.

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