A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.

doi:10.1017/S1743921308018516

The Hipparcos Catalogue: 10th anniversary and its legacy

C. Turon and F. Arenou

GEPI/UMR-CNRS 8111, Observatoire de Paris, 92190 Meudon, France
catherine.turon@obspm.fr, frederic.arenou@obspm.fr

Abstract. The European Space Agency decision to include the Hipparcos satellite into its Science Programme is placed in the context of the years 1965-1980 and in the historical perspective of the progress of astrometry. The motivation and ideas which lead to the Hipparcos design are reviewed as well as its characteristics and performance. The amount and variety of applications represent an impressive evolution from the original science case and opened the way to much more ambitious further space missions, especially Gaia, based on the same basic principles. A giant step in technology led to a giant step in science. Next steps are presented at this Symposium.

Keywords. astrometry, space vehicles, stars: distances, stars: kinematics, stars: fundamental parameters, Galaxy: fundamental parameters, Galaxy: solar neighbourhood

1. Introduction

It is quite difficult for us, in 2007, to transport ourselves in the context of the years 1965-1970 when Pierre Lacroute, at Strasbourg Observatory, first put forward the idea that the only way out to improve drastically the precision of astrometric observations was by observing stars from space. The best available positions and proper motions at that epoch were included in the fundamental catalogue FK4 (Fricke *et al.* 1963). The internal precision of position was from about $0\rlap{.}''04$ at epoch 1950 for stars in the northern hemisphere to $0\rlap{.}''08$ in the southern hemisphere. Moreover, systematic errors could reach the same order of magnitude in some areas of the sky. The expected improvements were very limited (for example, it was expected to lower the systematic errors to some $0\rlap{.}''03$ by using a network of astrolabes for over 10 years...). The three main difficulties were the deterioration of stellar images caused by the atmosphere, the non-stability of the instruments and the inability of ground-based observatories to observe the whole celestial sphere.

Pierre Lacroute came to the conclusion that, after a long period of instrumental improvements, any new development would ineluctably come up against the main difficulty: the presence of the atmosphere itself, and that only slow and very limited progress could be expected from the ground. He then proposed a very daring solution that he himself qualified as ‘weird’ (farfelue) (Lacroute 1991): to make astrometric observations from a satellite (Lacroute 1966; Lacroute 1982; Kovalevsky 2005). His arguments were very simple: to build a reference system over the whole celestial sphere, you need to measure large angles. Superposing two fields of view at a fixed angular distance with a very stable complex mirror was possible on a satellite, without the atmosphere, thus allowing to measure small angles instead. This was the way to eliminate systematic errors. After a very first proposition to CNES in March 1966 (Lacroute 1966), the idea was presented to the IAU General Assembly in Prague (Lacroute 1967). It was received with much interest.

2. Why and how an astrometric satellite

2.1. *The first steps: 1966-1972*

After the very first steps described above, a new, more detailed version was presented to CNES in November 1967, and a feasibility study performed in 1969-1970 (Husson 1975). In addition to a grid made of regularly spaced opaque and transparent slits, a new crucial modification of the project was the introduction of a complex mirror, in place of the pentagonal prism of the previous version, used to project the two fields of view in the focal plane. This was the key to obtain a stable basic angle. It is noticeable that two of the basic characteristics of the future Hipparcos were already introduced in the project as early as 1967: the complex mirror and the grid. The stars of both fields of view were crossing the grid perpendicularly to the slits, their light was modulated, and measured by two photometers. It was possible to measure the angle between two stars of magnitude $V = 7$ to an accuracy of $0\overset{''}{.}01$.

The CNES feasibility study proposed a satellite of 140 kg to be launched by a Diamant rocket, able to observe at least 700 stars all over the sky with no systematic error and with a precision of about $0\overset{''}{.}01$. In addition, trigonometric parallaxes could be measured with an improvement of the accuracy with respect to ground-based observations by a factor 5 to 10. The scientific perspectives were underlined with enthusiasm by J. Kovalevsky in a note to CNES (Kovalevsky 1969) and by the referee Committee set up by CNES to examine the project of P. Lacroute (Kovalevsky 1970): '*Nearly all fields of astronomy will be concerned*'. In addition to the stellar reference system and its connection to the dynamic reference system, many other topics were quoted: stellar kinematics, Galactic dynamics, fundamental astronomical constants, motions of the Earth crust, stellar and cosmic distance scale, etc. The résumé was '*this experience, if successful, would completely revolutionize astrometry*'. However, there were a number a critical points, more noticeably the realisation of the complex mirror and the stabilisation of the platform, incompatible with a Diamant launcher.

In August 1970, during the IAU General Assembly in Brighton, P. Lacroute made presentations to Commissions 8 and 24 about the advantage of space observations for astrometry, drawing the attention of the astronomical community to the possibility of measuring absolute trigonometric parallaxes to better than $0\overset{''}{.}005$. Commission 8 unanimously adopted a resolution underlining the big interest of space for rapidly obtaining a major improvement of the astrometric accuracy, improvement which was very difficult, if not impossible, to obtain from the ground (Lacroute 1970).

2.2. *Two different options: SpaceLab and TD, 1973-1974*

In November 1973, P. Lacroute proposed to ESRO two possible options of a space astrometry satellite, further presented to the ESRO advisory structure by Jean Kovalevsky (Bacchus & Lacroute 1974). These two options were different in their scientific objectives and, as a consequence, in their principles. The TD option proposed to use a TD1 type satellite, systematically scanning the sky and observing all 150 000 stars brighter than a given magnitude. The SpaceLab option would on the contrary observe a pre-defined programme of up to 40 000 selected stars prepared in advance. This option permitted '*to include objects of special interest*' but required long and complex pointing. No less than 8 missions of 11 days over two years were planned to obtain the astrometric parameters of the programme stars (!).

In this context, ESRO was advised by the Launching Programme Advisory Committee to organize a symposium with a twofold motivation: the scientific significance and objectives of a space astrometry mission, and the support by the community. This Symposium was held in Frascati in October 1974 and was a big success. It marked the opening of a new era where space astrometry was considered not only for its astrometric applications, but also, and mainly, for its astrophysics science case. The conclusions of the Symposium recommended the SpaceLab option for its capability of pre-selection of programme stars.

2.3. *ESA studies: 1975-1979*

Following the success of the Frascati Symposium, demonstrating '*the fundamental importance of improving astrometric data for a large scientific community, and highlight*(ing) *the potential of* (astrometry) *space projects*', a 'Mission Definition Group' composed of five scientists and four ESA engineers was set up by ESA. Two configurations, intentionally very different, were studied in order to fully explore the range of capabilities of space astrometry (Mission definition study 1977): option A, with preselection of stars (under E. Høg's leadership), option B with the simplest observation procedure and systematic observation of all stars brighter than 10.5^{m} (under P. Lacroute's leadership). A major improvement in overall efficiency was obtained thanks to the introduction of an Image Dissector Tube (Høg 1975). This device allowed both a systematic scanning of the sky **and** the selection of the programme stars. It is noticeable that E. Høg also proposed simultaneous photometric observations (low dispersion spectra).

The Mission definition study was followed, in 1976-1979, by a feasibility study of a project to be launched by Ariane on a geostationary orbit (Phase A study 1978, 1979). The Hipparcos mission was aiming at the accurate measurement of trigonometric parallaxes and annual proper motions of about 100 000 selected stars with an expected average mean error of about $0\overset{\prime\prime}{.}002$.

2.4. *The inclusion of Hipparcos in the ESA Science Programme: 1979-1980*

Even though, in the 1970s, a '*new impetus* (was) *given to astrometry by the use of large reflecting telescopes, automatic measuring machines, radio astrometry and photoelectric astrometry, ... astrometry to many* (was looking) *dull and old-fashioned'* in comparison with the spectacular evolution of astrophysics (Høg 1979). Moreover, it is worth remembering that, at that epoch, unlike observations in X or infrared wavelengths or exploration of solar system objects, astrometry was not considered as a space science. However, the progress on many problems of Galactic and stellar astronomy was blocked because of the lack of reliable trigonometric parallaxes and proper motions. Hence, more and more astronomers (astrophysicists as well as astrometrists) were becoming very supportive of the necessity of finding ways to obtain these quantities with a much higher accuracy and for many more stars. For example, let us quote Hodge (1981): '*The determination of the extragalactic distance scale, like so many problems that occupy astronomers attention, is essentially an impossible task. The methods, the data, and the understanding are all too fragmentary at this time to allow a reliable result to be obtained. It would probably be a wise thing to stop trying for the time being and to concentrate on better establishing such things as the distance scale in our Galaxy*'.

The main reference for trigonometric parallaxes was the General Catalogue of Trigonometric Stellar Parallaxes (Jenkins 1963), including about 7000 stars, but mostly of quite poor quality. Only for about 5% of them, the closest to the Sun (mostly less than 10 pc), were the distances known with probable errors less than 10 %. For less than 300 stars were the trigonometric parallaxes accurate enough to use the derived absolute magnitude for calibration purposes of the spectral type-luminosity or colour-luminosity relations of main sequence stars. Moreover, the differences between individual measurements obtained at different observatories were not understood and the sample was strongly biased towards bright stars ($5 < V < 10$), towards common spectral types in the solar neighbourhood (main sequence G and K stars) and towards high proper motion stars (Gliese 1975, Turon 1975). For proper motions, the situation was better, but the same biases were present in the samples of stars with accurate proper motions. As a result, many studies in our Galaxy were using indirect methods, more or less reliable, to determine distances.

Between June 1978 and February 1980 a large promotional campaign was conducted throughout Europe in favour of Hipparcos. An early and informal call for proposals of observation, in an attempt to judge the scientific interest in the project, was released independently by E. Høg and C. Turon. They were able to collect about 170 research proposals submitted by 125 astronomers from 12 countries. The Hipparcos satellite was decided in this context, in March 1980. Later on, in March 1981, E. Høg proposed the addition of the two-colour star mapper channels. This led to the Tycho experiment.

3. Science case versus publications

It is enlightening to illustrate the evolution of the Hipparcos science case from the early proposal to the research proposals from which the Input Catalogue was built (Turon *et al.* 1992a) and, finally, to the actual use of Hipparcos.

The scientific programme as defined by Lacroute in March 1966 was planned in several steps, depending on the possible impact on telemetry link or power consumption of the satellite. By priority order he first defined a) as a minimum, the study of the FK4 errors, b) a precise reference sphere (up to 8200 stars with $V<7$), and he discussed at length the way to resolve the equation system, c) proper motions, repeating four times the operation over 15 yr, d) solar system for the Jupiter satellites and a few minor planets. Then Lacroute mentioned '*Other possible applications ?*' The first item was '*Trigonometric parallaxes ?*', with the comment '*Yes*', as if these were just a by-product. Instead, a factor 10 improvement could be obtained when compared to photographic observations with the same number of measurements. Finally, research for obscure companions (planets) to nearby stars was presented with a single sentence: '*the system appears well adapted to the study of small deviations of the proper motion on nearby bright stars*'. In the proposal of Nov. 1967, the very same programme was described, except that the question mark to '*parallaxes*' had disappeared.

The first conference devoted to the applications of Space Astrometry was organized by ESRO and held in Frascati on 22-23 October 1974 (ESRO 1975). As already mentioned above, the astronomical community at large was invited to present the consequences of high accuracy astrometric data on their respective fields of activity. Still, many of the communications at this Symposium were related to fundamental astronomy: improvement of the Earth-Moon system (Meyer & Froeschlé 1975), motion of Earth's pole (Proverbio & Uras 1975) extension of the stellar reference system by Walter (1975), or the definition of an absolute reference frame foreseen by Kovalevsky (1975). Besides, Gliese (1975) considered the trigonometric parallaxes as improving the absolute luminosities and thus the luminosity calibrations and luminosity function, the space velocities, and the Hyades distance as one first step in the cosmic distance scale ladder. This latter point was also the one developed by Turon (1975), with the knowledge of the galactic evolution and structure in mind, and by Murray (1975), though with the use of proper motions. Van de Kamp (1975) also mentioned the hunt of unseen companions. The first conclusion of the Frascati symposium, which could also be the one of the present symposium, 33 years later, was the following: '*Improvements in astrometric data have a fundamental scientific significance and would provide decisive progress in astronomy, astrophysics and geodynamics*'. This text, prepared by Jean Kovalevsky, insisted on the multiple improvements expected for astrophysics, depending on the duration of the mission and whether proper motions were obtained or not.

In 1976, the ESA Mission Definition study report (ESA 1977) discussed the current status of astrometry, noting first how the fundamental system of reference was affected by the then poor astrometric precision and spatial density. The report then recalled that '*the motions are the main data for deriving distances, and all theories of evolution of our Universe depend, therefore, on these motions*', with little improvement in parallax precision or number of stars to expect on ground in the future. Besides, due to the systematic errors (e.g. a north-south systematic difference amounting to 5 mas), little improvement could be obtained using groups of stars. Pointing out the role of the Hyades in the distance scale, the report insisted that if a '*space astrometry mission could determine the parallax of 30 or so*' Hyades stars, '*these observations alone would already warrant this mission*'! Obtaining a 1% precision on the Hyades distance would improve a) the age of open clusters, b) the distance scale, c) the Cepheid period-luminosity relation, d) stellar luminosities (stellar physics), e) the space velocities of subdwarfs. Apart from the Hyades, parallaxes combined to other observations would also improve the knowledge of the velocity dispersion, space distribution of stars, and reddening within 100 pc. Finally, and probably for the first time, the need for a ground-based parallel effort was also indicated, concerning radial velocities, colours and luminosity determination for astrophysics, and a higher density of relative position measurements for the reference system. Depending which satellite option was chosen (with or without input catalogue), the expected improvement of the HR diagram was discussed.

In addition, the Mission Definition Group '*strongly recommend*(ed)*, as the most significant scientific improvements, that a Space Astrometry programme should be established, calling for the launching of a second spacecraft, identical or similar to the first one, after a time of some ten years*' which paved the way for Gaia more than two decades later. The main motivations were the improvement of proper motion for stellar kinematics and the detection of invisible companions, a small part indeed of the huge Gaia scientific case!

In 1976, the IAU Commission 8 urged '*that space astrometry should be developed and carried out as soon as possible*', but was also prudent: '*This however should not affect the planning of ground based programmes before the accuracy, reliability and long term continuity of space astrometry have been assured*'.

Three years later, the Hipparcos science case described in the report on the Phase A study (ESA 1979) was yet more mature, most of the future use being anticipated. Not less than 21 pages were devoted to the scientific objectives. The astrometric data were described as '*the very base of most astrophysical theories and of our conception of the Universe*'. Clearly, beside the improved reference system, space astrometry was now described as a tool for astrophysics: six open clusters would benefit from the parallax measurements, the fine structure of the H-R diagram would be determined, and a catalogue of astrometric parameters would be useful for '*an enormous variety of kinematical, dynamical and astrophysical investigations*', and for the detection and measurement of binaries. '*Indirect benefits on the distance scale, the chemical and dynamical evolution of the Galaxy, the testing of cosmological theories*' were also mentioned. An illustrative comparison between several ground-based parallax programs and that of Hipparcos showed that the annual rate of parallax information with Hipparcos would be 3000 times (in terms of statistical weight) that of the best ground based programs (USNO). It was foreseen that Hipparcos could allow to get at last an unbiased sample of the closest (< 20 pc) neighbourhood for stars intrinsically brighter than $M_V = 7.5$. While showing the performances of Hipparcos for the five nearby open clusters, it should be underlined that the Hipparcos potential weakness was already noticed in this phase A report, '*taking* *into account the reduction of statistical weight because of correlation between parallaxes of adjacent stars*'.

Capitalizing on this broad scientific interest, the observing program for Hipparcos was built from the 214 world-wide scientific proposals received in 1982. This work, performed by the 'Input Catalogue Consortium', established in 1981, had to take into account the scientific priorities allocated by the Hipparcos Scientific Selection Committee, but also the satellite observing capabilities (Turon *et al.* 1992b).

Now, ten years after the publication of the results, the scientific outcomes of the mission are considerable, and are described in this volume by M.A.C. Perryman. Up to 1996, the average number of scientific papers mentioning Hipparcos in their abstract (indicating an intensive use of Hipparcos results) was 50 papers per year on the average. Between 1997, year of the publication, and 2000, this increased to more than 400, dropping to 200 in 2004, but remaining constant since. In total, nearly 6000 publications quote either Hipparcos or Tycho in their abstract. In parallel, the number of publications citing the bibliographical reference of the Hipparcos Catalogue is constant at about 250-300 per year from 1998 onward. This number is probably, and will be more and more, underestimated, as one may quote the distance of a star as given by SIMBAD instead of quoting the source catalogue: the main compliment that can be paid to Hipparcos is that its results are now in the public domain.

The legacy of Hipparcos is not simply how the data has been used but also how it **will** be used, especially in a micro-arcsecond era. In this respect, one may note that the technological progresses are 'too fast': the initial suggestion done by the Hipparcos instigators of having another satellite launched to improve the proper motions is no more valid, as the recent gain in precision is now larger than the linear gain than can be obtained with time, so that the proper motion precision with Gaia (a few μas) is preferable to the 1 mas over 20 years = 50 μas. In spite of this, the outcome of the Hipparcos mission may still be significant 20 years later: Olling (2007) shows that Solar System Analogs having periods of several decades may be detected using SIM and Hipparcos as first epoch. The Hipparcos and Tycho data base will also be used for what concerns photometry: already the HD 209458 and HD 189733 stars have had their planetary transits unveiled in the Hipparcos data, and their transiting period found with exquisite precision.

4. Conclusion

Hipparcos has been the result of many convergent efforts: the vision and tenacity of its first proposer, P. Lacroute, his understanding that going to space would be a great advantage for astrometric measurements, the commitment of an increasing number of colleagues in the mission, and the decision of the European Space Agency to investigate further this original perspective, while staying open to new innovations. Once included in the ESA Science Programme, the close collaboration and constant exchanges between the Agency, the Scientific Consortia and Industry were crucial in leading to a satellite design which fully reflected the scientific requirements carefully established for the mission (Perryman *et al.* 1997). Finally, we should also be grateful to ESOC saving and operating a satellite on a wrong orbit.

A giant step in technology allowed to go from ground-based astrometry to space astrometry and reach milli-arcsecond accuracy for more than 100 000 target stars. A new giant step is now promising to lead to micro-arcsecond accuracy with second generation space astrometry missions: ESA's Gaia, direct heritage of Hipparcos, but with on-board systematic detection of targets objects, on-board observations of the third component of the space velocity, and on-board observations of astrophysical parameters; JAXA's

Jasmine, taking benefit of its observation in infrared to obtain direct distances in the galactic center; NASA's SIM the most accurate of the planned experiments. All these, and a few smaller projects, are described in this Symposium.

Acknowledgements

We gratefully thank Erik Høg, Jean Kovalevsky and Michael Perryman for their comments and the documentation they could recover. This text has also benefited from-NASA's Astrophysics Data System.

References

Bacchus, P. & Lacroute, P. 1974, in: W. Gliese, C. A. Murray, and R. H. Tucker (eds), *New Problems in Astrometry*, IAU Symp. 61, Reidel, p. 277

ESA 1977, *Space Astrometry*, Report on the Mission definition study, ESA DP/PS(76)11, Rev. 1, 25 January 1977

ESA 1978, *Space Astrometry, Hipparcos*, Report on Phase A study, ESA DP/PS(78)13, 26 April 1978

ESA 1979, *Hipparcos, Space Astrometry*, Report on the Phase A study, ESA SCI(79)10, December 1979

ESRO 1975, *Space Astrometry*, ESRO SP-108, T. D. Nguyen & B. T. Battrick (eds)

Fricke, W., Kopff, A., Gliese, W. & al. 1963, *Veröff. des Astronomischen Rechen-Instituts Heidelberg*, Nr. 10

Gliese, W. 1975, in: ESRO 1975, p. 109

Hodge, P. W. 1981, *ARAA* 19, 357

Høg, E. 14 November 1975, Projects in optical astrometry

Høg, E. 1979, in: C. Barbieri & P. L. Bernacca (eds), *European Satellite Astrometry*, Université de Padoue, p. 7

Husson, J. C. 1975, in: ESRO 1975, p. 43

Jenkins, L. F. 1963, *General catalogue of trigonometric stellar parallaxes*, New Haven: Yale University Observatory

Kovalevsky, J. 28 July 1969, *Remarques sur le projet de Satellite Astrométrique de M. P. Lacroute*, Note to CNES

Kovalevsky, J. 13 May 1970, *Rapport sur l'intérêt scientifique du projet de Satellite Astrométrique de M. Lacroute*, Report to CNES on the proposal of M. Lacroute

Kovalevsky, J. 1975, in: ESRO 1975, p. 67

Kovalevsky, J. 2005, in: A. Heck (ed.), *The Multinational History of Strasbourg Astronomical Observatory*, ASSL, Springer, p. 215

Lacroute, P. 1966, *Projet d'observation spatiale en Astronomie Fondamentale*, March 1966, proposal to CNES

Lacroute, P. 1967, *Proceedings of the Thirteenth General Assembly, IAU Trans.*, XIIIB, 63

Lacroute, P. 1970, *Proceedings of the Fourteenth General Assembly, IAU Trans.*, XIVB, 95

Lacroute, P. 1982, in: M.A.C. Perryman & T. D. Guyenne (eds), *The Scientific Aspects of the Hipparcos Mission*, ESA SP-177, p. 3

Lacroute, P. 1991, Mémoires de l'Académie des sciences, arts et belles-lettres de Dijon, 132, 95

Meyer, C. & Froeschlé, M. 1975, in: ESRO 1975, p. 95

Murray, A. 1975, in: ESRO 1975, p. 129

Olling, R. P. 2007, ArXiv e-prints, 704, arXiv:0704.3059

Perryman, M. A. C., Lindegren, L., Kovalevsky, J., Høg, E., *et al.* 1997, A & A 323, L49

Proverbio, E. & Uras, S. 1975, in: ESRO 1975, p. 83

Turon, C. 1975, in: ESRO 1975, p. 115

Turon, C., Gòmez, A., Crifo, C., *et al.* 1992a, A & A 258, 74

Turon, C., Crézé, M., Egret, D., Gòmez, A. *et al.* 1992b, ESA SP-1136

Van de Kamp, P. 1975, in: ESRO 1975, p. 121

Walter, H. G. 1975, in: ESRO 1975, p. 73