PROLOGUE

This chapter provides a general background to the Hipparcos mission leading up to launch. It summarises the requirements for improved astrometric measurements (positions, parallaxes and proper motions) of the stars, a short history of the development of astrometric measurements, and a summary of the development of the Hipparcos project itself.

Introduction and Historical Background

Introduction

The achievable accuracy of stellar positions measured from the ground is limited by numerous observational difficulties, important among them being the effects of an inhomogeneous and fluctuating atmosphere, instrumental flexure, and the inability to observe all parts of the celestial sphere simultaneously or even sequentially from any single observing location. There are, nevertheless, important astronomical and astrophysical reasons why more precise positional measurements have been urgently needed.

The observational situation promised to make a rapid and dramatic change when, at the request of the scientific community, and following an internal feasibility study supported by its member state scientists, the European Space Agency (ESA) undertook the Hipparcos space mission. This mission was dedicated to the precise positional measurement of some 120 000 stars. Launched by Ariane 4 on 8 August 1989, the final outcome of the mission is two major catalogues—the Hipparcos and Tycho Catalogues—of star positions, parallaxes, and proper motions, along with photometric and other data on the stars observed.

Historical Context

Confirmation of the Earth's spherical form, assumed by the Pythagorian School as early as the sixth century B.C., first emerged with the evidence provided by Aristotle in *De Caelo* (around 340 B.C.) and the first scientific measurements of the Earth's size by Eratosthenes in about 240 B.C. And while the principle of the measurement of the Earth–Moon distance had already been described by Aristarchus of Samos around 250 B.C., it was about 120 B.C. when Hipparchus first calculated the distance of the Moon from the Earth, by measuring the Moon's parallax. A comparison of Hipparchus' star catalogue of 1080 stars with the work of his predecessors led to the discovery of the precession of the equinoxes and the eccentricity of the Sun's path. All this was achieved by measurements with the naked eye, the resolution power of which is limited to a few minutes of arc. These early observations were rarely accurate to better than about 30 minutes of arc, due to the primitive instruments used.

Little advance was made in astrometry, as in other branches of science, during the millenium of the 'Middle Ages', in which western civilisation remained with the concept of a universe with the Earth at its centre. However, the awakening of man's scientific curiosity at the time of the Reformation led to revised interest in astrometry. Copernicus propounded the heliocentric concept, and Tycho Brahe, using his brass azimuth quadrant and many other new instruments, carried out a long series of observations during the second half of the sixteenth century. These observations were to provide the basis for Kepler's Laws of planetary motion.

Although observations were still being made with the naked eye, this was soon to change. By 1609 Galileo, using information obtained from Holland (where the instrument was invented and first built in 1604), was making use of the optical telescope, and this landmark was to be of particular significance for astrometry. The angular error in astrometric measurements fell to about 15 seconds of arc by 1700, and to about 8 seconds of arc by 1725. This made it possible to detect stellar aberration (small positional displacements due to the vectorial composition of the velocity of light to the Earth's orbital velocity) and nutation (an 18.6 year wobble in the Earth's spin axis produced by the gravitational influence of the Sun and Moon).

Remeasurement of the rate of precession was made by Edmund Halley, who compared contemporary observations with those that Hipparchus and others had made. While most of the stars displayed a general drift amounting to a precession of about 50 seconds of arc per year, Halley announced in 1718 that three stars, Aldebaran, Sirius and Arcturus, were displaced from their expected positions by large fractions of a degree. Halley deduced that each star had its own 'proper motion'.

Eventual improvements in observational precision during the 18th century (see Figure 1), revealed the motions of many more stars, and in 1783 William Herschel found that he could partly explain these motions by assuming that the Sun itself was moving. This suggested that some stars might be relatively close to the Sun, and so astronomers intensified their efforts to detect 'trigonometric parallax', the apparent oscillation in a star's position arising from the Earth's annual motion around the Sun.

Friedrich Bessel was the first to publish a parallax value, in 1838, following his studies of the motion of 61 Cygni. Bessel's careful analysis of the measurement errors and his use of both coordinates on the sky gave credibility to his results, after many previous claims from astronomers to have measured a stellar parallax. Thomas Henderson is credited with the first measurement of stellar parallax, that of the bright star Alpha Centauri, from observations made at the Cape of Good Hope, in 1832–33, although he did not analyse the measurements for some years; the two components of this star, together with a faint companion called Proxima Centauri, form the nearest known group of stars to the Sun, at a distance of a little more than 4 light years. Wilhelm Struve measured the parallax of Vega in 1837–38.

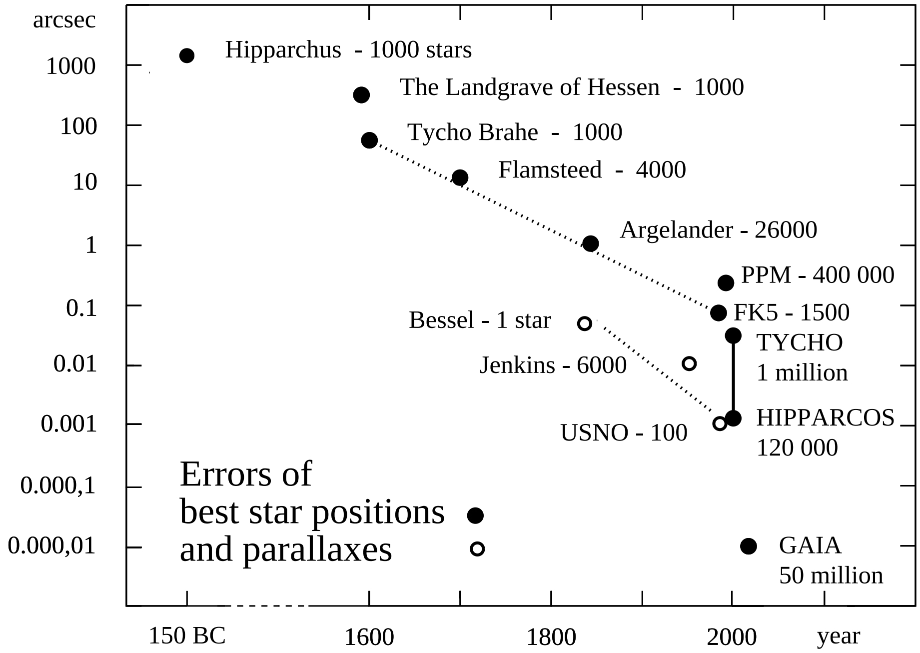

Figure 1. *Improvement in the angular precision of astrometric measurements as a function of time. All points refer to ground-based observations or catalogues, with the exception of the Hipparcos and Tycho Catalogues derived from the Hipparcos mission, and the proposed GAIA space astrometry mission (courtesy E. Høg).*

Observations improved substantially with the invention of photography, which gave astrometry yet another tool it could use. In 1887 a world-wide cooperative programme was started to make a full photographic survey of the sky. Eighteen countries were involved in this project, called the 'Carte du Ciel'. All observatories involved used the same design of astrograph, plates, and observing protocols. In the mean, a precision of around 1 arcsec was obtained by this programme for 13 million stars.

Determinations of photographic trigonometric parallaxes have been made at more than a dozen observatories since the early part of this century. The technique is to measure the shift of the selected star relative to a few stars surrounding it on some 20 or more plates taken over a number of years. Several thousand trigonometric parallaxes have now been measured from the ground; however, only a few hundred are considered to be known with an accuracy of better than about 20 per cent, while the systematic effects remain both conspicuous but uncertain.

Effort over the past one hundred years or so has resulted in observational uncertainties in astrometric measurements being reduced by an order of magnitude due to instrumental refinements. However, further rapid progress on the ground was considered unlikely, since the most significant uncertainties remaining are caused by the Earth's atmosphere. Averaging out the dominant effects of atmospheric turbulence proved to be relatively efficient, yet the comparisons between results from different observatories still showed systematic differences due to slowly varying refraction effects. The study of these effects has as yet eluded their precise description; in consequence they cannot therefore be reduced with confidence.

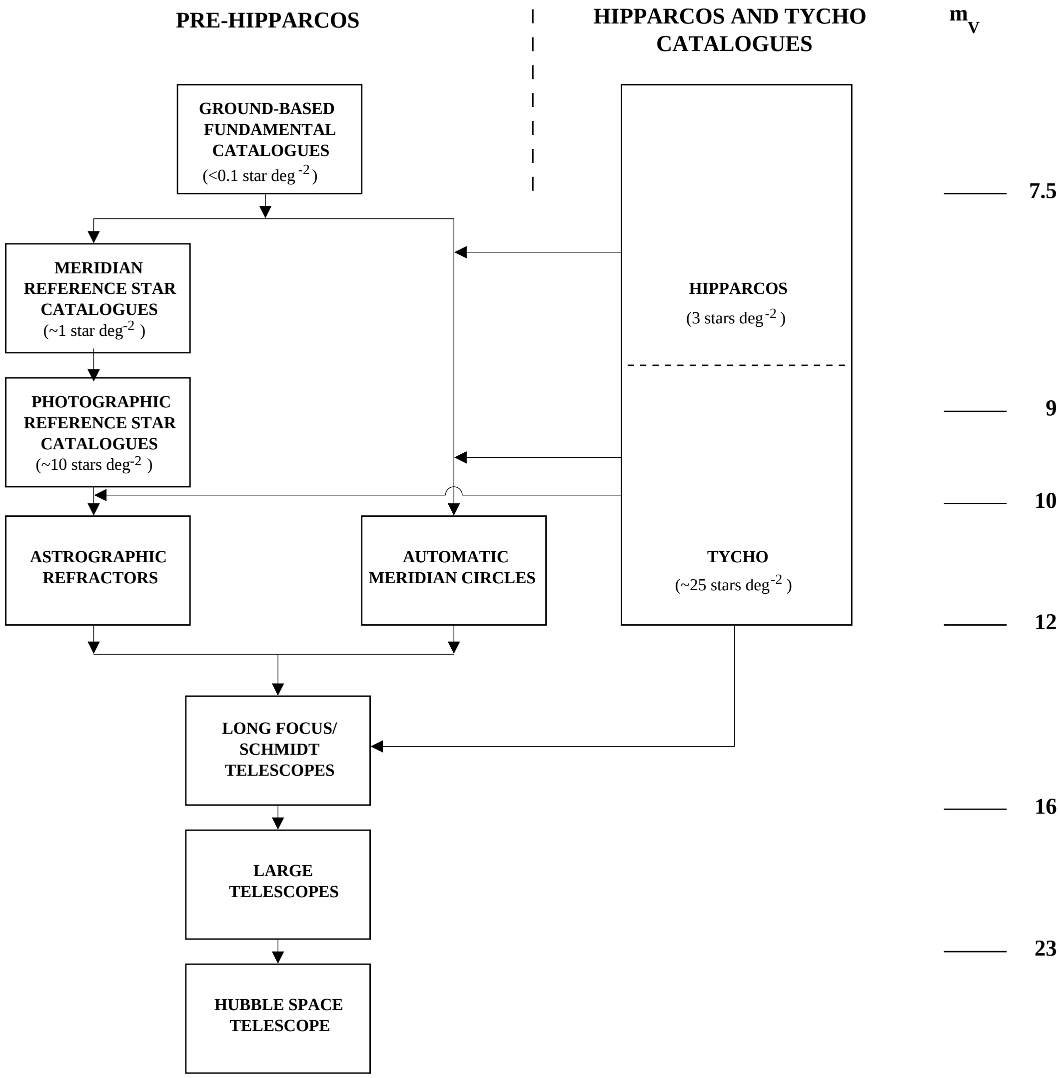

Figure 2. *The expected role of the Hipparcos and Tycho positional measurements in the determination of the position of faint objects (right), compared with the situation existing before launch (left).*

New approaches to astrometry were necessary, and in the 1960's, some astronomers considered that the best prospect for major advances in this field was to go into space. The Hipparcos mission was undertaken to revolutionise this long, difficult, and very important task. The expected role of the Hipparcos and Tycho positional measurements in the determination of the position of faint objects, compared with the previous situation, is shown in Figure 2. A summary of the key features of the intended and actual mission results is given in Table 1.

Evolution of the Hipparcos Project

Developments before Acceptance by ESA

A preliminary proposal for a space astrometry mission was submitted by P. Lacroute to the Centre National de la Recherche Scientifique (CNRS) in France in March 1966. The proposal was made to build up a reference system using about 700 stars brighter than 7 mag, with relative positions known to better than about 0.01 arcsec. Already, in his first proposal, two key features of Hipparcos were used: a beam combiner (more complex than that eventually adopted, with three surfaces resulting in a symmetric image), and the observation of the light modulated by scanning slits.

In August 1967, a new version of the project was presented in Prague at the meeting of the International Astronomical Union (IAU). A revision of this proposal was then presented to the Centre National d'Etudes Spatiales (CNES) in France, in November 1967. Not only was this version technically more elaborate than before, but also, and perhaps more importantly, the scientific significance of the prospective results was better emphasised. Amongst the ideas that were submitted to CNES in order to demonstrate the feasibility of the project, was the idea—quickly rejected—that it could be flown on a balloon. Some funds were subsequently made available by CNES for optical calculations, and for the trial manufacture of a 'beam-combining mirror' in 1969. It proved to be impossible, however, to construct such a mirror that would be able to resist the vibrations encountered during launch.

In August 1970, a paper was presented at the IAU meeting in Brighton on the subject of astrometric measurements from space. There were no major changes to the technical proposal, and it served to draw the attention of the astronomical community to the possibility of measuring absolute trigonometric parallaxes to better than 0.005 arcsec. In 1970, CNES stopped their studies of the project, not only because of technical difficulties which, at that time, seemed to be beyond the state of the art in space technology, but also as a result of the political decision taken to stop the French national space programme, and to use the funds to support European cooperation within the European Space Research Organisation (ESRO).

New ideas were introduced at the Astrometry Symposium in Perth in 1973. A description of the mission was made at a meeting of the ESRO Astronomy Working Group in Frascati in 1973 by J. Kovalevsky. The Working Group selected thirteen projects that merited further consideration. In November 1973, a report was submitted to the European Space Research Organisation pointing out—in addition to a design based on that of the earlier satellite TD1—the technical potential of a similar system that could be flown on Spacelab. Such a system could use more powerful optics and could reach fainter stars, but would not have yielded as many measurements as a scanning satellite. By that time, the prohibitive cost of the eight shuttle launches required for an astrometric Spacelab mission was not fully recognised.

This report was followed by a symposium on 'Space Astrometry' organised by ESRO, soon to become the European Space Agency, in October 1974 in Frascati. This symposium was organised in order to assess the support of these ideas amongst astronomers, and many astronomers interested in the possibilities of space astrometry attended this meeting.

Table 1. Summary of the results from the Hipparcos mission intended before launch, and the actual results contained in the Hipparcos and Tycho Catalogues.

	Intended	Actual
Hipparcos Catalogue:		
Number of stars	100 000 (in 1980)	118 218
Limiting magnitude	V = 12.4 mag	V = 12.4 mag
Completeness	7.3–9.0 mag*	7.3–9.0 mag*
Positional accuracy (B = 9 mag)	0.002 arcsec	~ 0.001 arcsec
Parallax accuracy (B = 9 mag)	0.002 arcsec	~ 0.001 arcsec
Annual proper motion accuracy (B = 9 mag)	0.002 arcsec	~ 0.001 arcsec
Systematic errors	<0.001 arcsec	~ 0.0001 arcsec
Tycho Catalogue:		
Number of stars	> 400 000 (in 1982)	1 058 332
Limiting magnitude	B = 10 – 11 mag	B ~ 12.2 mag
Positional accuracy (B = 10 mag)	0.03 arcsec	~ 0.01 arcsec
Photometric precision (B = 10 mag)	0.05 mag	~ 0.02 mag
Observations per star	~ 100	130

* Depending on galactic latitude and spectral type

A mission definition study was subsequently carried out, by a group of European astronomers with the support of ESA personnel. This study was able to define a mission with more emphasis on the astrophysical aspects of an astrometry satellite, because new technical ideas made it possible to observe a larger number of stars, and also faint ones, with a higher precision than previously, and even with a smaller telescope aperture. The following technical innovations were introduced in December 1975 by E. Høg of Copenhagen University Observatory, and were incorporated in the final Hipparcos satellite.

A grid with only one slit direction was introduced for scanning the stars in only one coordinate, namely along the great circle connecting the two fields of view. The relative advantages of chevron and parallel slits had been the subject of lengthy discussions, with the simpler one-dimensional modulating grid having been adopted following simulations which showed that, even with one-dimensional measurements, good rigidity of the sphere solution would result. The one-dimensional scanning utilises the fact that the two-beam telescope is primarily a one-dimensional device. An image dissector tube was proposed instead of the previous photomultipliers, allowing the selection of target stars, and consequently longer and cleaner integration per passage, providing an improvement in overall efficiency of about 100 times with respect to the use of photomultipliers alone. This also allowed for a pre-selection of programme stars, corresponding to the adopted ‘input catalogue’ concept. The passive attitude stabilisation of the TD1 satellite was replaced by an active attitude control, which in turn opened the way for a ‘revolving scanning’ attitude motion, giving a more efficient coverage of the sky. The preferred mission was a dedicated astrometric satellite with a measurement lifetime of three years, during which the positions, parallaxes, and annual proper motions of about 100 000 selected stars would be obtained to some ±0.002 arcsec accuracy.

The study results were presented at an international Colloquium on Space Astrometry held at Copenhagen University in June 1976. Shortly afterwards, ESA approved a feasibility study of the project.

The problem of deriving the astrometric data from one-dimensional measurements of the sky by a scanning satellite was studied at Copenhagen, where L. Lindegren was introduced to the problem in September 1976. He subsequently presented the mathematical formulation of the three-step method, and estimates of the precision and correlation coefficients of the five astrometric parameters. The three-step method was later developed by both data reduction consortia. Their implementations are based on contributions by the geodetic institutes in Copenhagen and Delft starting in 1977, thus exploiting their expertise in solving large systems of similar geodetic networks with least-squares methods.

When the Phase A study started in 1977, ESA had just decided that the Ariane launcher should be used for future missions. This opened the way for a heavier payload and a geostationary orbit. The new possibility was adopted by the science team, and the previous concept of a near-Earth spacecraft in polar sun-synchronous orbit was abandoned.

The proposed active attitude control was based on the use of reaction wheels in the spacecraft, although the small disturbances (or 'attitude jitter') from the mechanical bearings might have jeopardised the astrometric mission, aimed at angular measurements in the range of 2 milliarcsec. In fact, the studies were never able to supply reliable estimates of the attitude jitter before attitude control by cold-gas jets was introduced by the satellite prime contractor in 1982. This control provides the same very smooth attitude motion between each jet firing as the passive stabilisation would have given. The smooth motion can be used to improve the precision for bright stars by 'dynamical smoothing', an idea advocated by P. Lacroute since the TD1-concept was proposed.

The dialogue with the international scientific community was continued at special meetings: at the General Assemblies of the International Astronomical Union in Grenoble in 1976 and in Montreal in 1979, and at the Colloquium on 'European Satellite Astrometry' in Padua in 1978. Coordination with ground-based astrophysical observations of the stars to be selected for Hipparcos was emphasised at these meetings, and so was the coordination with the planned space astrometry from the Hubble Space Telescope. Technical studies by ESA and outside contractors were continued, and members of the ESA science team investigated the data reduction aspects.

From June 1978 until February 1980, a large promotional campaign was conducted throughout Europe in favour of Hipparcos. An early and informal call for stars to be included in the observing programme, 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. P.L. Bernacca generated interest in 24 scientific institutes, from 8 countries, for hardware and software aspects of the mission, and demonstrated the potential availability of about 330 man years of effort necessary for the preparation of the data analysis facilities, one of the critical requirements for mission approval. As a result, the project obtained increasing attention from the national delegates in the ESA Science Programme Committee, which approved the project in March 1980.

Many of the astronomers and other scientists involved in the early assessment studies have continued their involvement with the mission, both through the ESA advisory teams, and through the setting up, in 1982, of the consortia who took responsibility for the scientific aspects of this project. The detailed design study was completed in December 1983, and the hardware development phase began early in 1984.

Technical and Scientific Involvement in Hipparcos after 1980

With the inclusion of the Hipparcos project within its mandatory science programme in 1980, the European Space Agency assumed overall responsibility for the satellite design and hardware manufacture, including the payload. This was contracted out to a European industrial consortium, with Matra Espace (France, now Matra Marconi Space) as industrial prime contractor, and with Aeritalia (Italy, now Alenia Spazio) responsible for procurement of the spacecraft, as well as for the integration and testing of the complete satellite.

Industrial responsibility at system level covered management, engineering and assembly, as well as integration and testing of the complete satellite. This responsibility was shared by eleven European firms, with some thirty five sub-contracted European firms, and a total of about 1800 individuals, participating at all levels (see Volume 1).

Working closely with the European Space Agency since the project's approval in 1980, European scientific teams undertook the scientific tasks necessary for the successful completion of the project as a whole. This included the Hipparcos Science Team, set up to advise the Agency on the detailed scientific considerations related to the payload design and development, and operational and calibration aspects, both on ground in advance of the satellite launch, and subsequently in orbit. While the scientific advisory role has been essential for the successful design of the mission concept, and is one shared by all ESA scientific missions, the scientific participation in the Hipparcos project has been especially fundamental.

One aspect of this scientific involvement was the preparation of the Hipparcos Input Catalogue by a consortium of institutes known as the Input Catalogue Consortium (INCA). This consortium was selected by ESA on the basis of responses to an Announcement of Opportunity issued in 1981. The consortium was subsequently entrusted with the task of defining the unique list of stars that were to be observed by the satellite, on the basis of scientific merit and satellite operational requirements.

An Invitation for Proposals was issued by ESA in 1982 to the worldwide (and not only European) scientific community. This resulted in more than 200 observation proposals being submitted, together comprising more then 600 000 objects. Advice on the scientific aspects of the selection of stars from the proposals was given by the Scientific Proposals Selection Committee and the Hipparcos Science Team.

The complete reduction of data from the satellite, from some 10^{12} bits of photon counts and ancillary data, to a catalogue of astrometric parameters and magnitudes for the 120 000 programme stars, was independently undertaken by two scientific consortia, NDAC (the Northern Data Analysis Consortium) and FAST (the Fundamental Astronomy by Space Techniques) Consortium. Both consortia were also selected on the basis of responses to a parallel Announcement of Opportunity issued by ESA in 1981. The selection of two parallel data reduction teams was motivated by the size and complexity of the reductions. The two independent approaches also facilitated the overall validation of the final results. The end product was a single, agreed-upon catalogue.

A later enhancement to the project, which emerged during the detailed design study, was the addition of the two-colour star mapper channels that led to the Tycho experiment, proposed by E. Høg in March 1981, and the subsequent formation of the Tycho Data Analysis Consortium (TDAC) in 1982. The Tycho Consortium was set up to analyse the data from the star mapper data stream, eventually resulting in the Tycho Catalogue of more than a million stars.

The close collaboration between the Agency and the scientific teams led to a satellite design which fully reflected the scientific requirements. The activities of all of the participating scientific institutes were funded by national agencies, universities, and private foundations. Altogether, some 200 scientists were involved in the work of the four scientific consortia. These activities, and the organisation of the scientific consortia, are described in detail in Volumes 3 and 4.