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HIPPARCOS - THE ESA SPACE ASTROMETRY MISSION: OVERVIEW AND STATUS

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ABSTRACT. This paper summarises the key features of the Hipparcos satellite design, and presents an overview of the current project status including results of the evaluation of the first hardware items. A recent assessment of the achievable accuracy for the main mission and for Tycho is also presented.

1. INTRODUCTION

The Hipparcos satellite, due for launch by Ariane in July 1988, will be dedicated to the precise positional measurements of some 100 000 selected stars brighter than B = 13 mag. Typical target accuracies will be 0.002 arcsec for each parallax and for each positional component and 0.002 arcsec per year for each proper motion component. Variation in these accuracies are expected as a function of stellar magnitude and ecliptic coordinates, although the variation in precision as a function of stellar magnitude will be minimised through the appropriate allocation of observing time. As a by-product of the measurements precise 'Hipparcos' magnitudes will be obtained for each programme star and for each of the 100 or so transits of each star throughout the 2.5-year mission, and a large quantity of data on stellar multiplicity will be obtained. Data from the satellite's 'star mapper' attitude measurement system will also provide positions of lower precison as well as two-colour photometric measurements of all stars down to a limiting magnitude of B = 10-11 mag, the resulting data constituting the Tycho Catalogue of some 500 000 or more additional stars.

Extensive presentations of various aspects of the mission and the satellite may be found in the literature, including a general presentation of all aspects of the mission (Perryman 1985), as well as proceedings of workshops dedicated to the scientific aspects of the mission, to the preparation of the Input Catalogue and to the data processing tasks (Høg, Jaschek & Perryman 1982, Turon & Perryman 1985, Kovalevsky 1985). Other general reports (Kovalevsky 1984, Bouffard 1985) as well as specialised presentations of the Hipparcos payload optics (Peraldi 1982) and of the satellite's attitude determination and control (Vilain &

J.-P. Swings (ed.), Highlights of Astronomy, 673–682.

Harris 1984) remain largely valid. Accompanying papers in this volume are also devoted to various aspects of the Input Catalogue preparation and the data analysis tasks.

2. MEASUREMENT PRINCIPLE

Two fields of view, 0.9 degrees square and separated by 58 degrees, are brought together by a novel feature of the payload optics - the beam combiner. Following the beam combiner in the optical train comes an all-reflecting imaging telescope, and the star images from both fields of view, superimposed by the beam combiner, are focussed onto a modulating grid. This grid is a highly accurate and regular system of opaque and transparent slits which, once the telescope is set in motion around an axis perpendicular to the two viewing directions, yields modulated light signals. Ideally, a simultaneous sampling of the modulated signals from all stars contemporaneously present in the combined field of view would yield the component of the angular separation of the stars as viewed from the satellite along the scanning direction. In practice the modulated signals are sampled by an image dissector tube whose sensitive area is piloted to switch rapidly between the star images crossing the focal surface and to track the star images during an integration time determined by the star's magnitude, and by the pressure of competing programme stars also present within the combined field of view. Such quasi-simultaneous measurements result in adequate suppression of possible spacecraft jitter. The resulting angular measurements, determined from the phase differences between the modulated signals, are undetermined to within a multiple of the grid period.

The satellite attitude is continuously monitored by means of bright star transits across the 'star mapper' - a region to one side of the main modulating grid containing a small number of opaque and transparent slits both perpendicular and inclined to the scan direction. The entire region of the star mapper is monitored by two photmultipliers preceeded by a dichroic beam splitter. In this way, all stars transitting the star mapper grid system yield information on the 3-axis attitude of the spacecraft, transit times and hence abscissae coordinates of all stars along the great circle being scanned, and two-colour photometric information on all detected stars at each transit time. In between the transits of bright stars across the star mapper, the satellite attitude information is provided by gyro measurements.

The satellite will make about eleven revolutions about its spin axis (perpendicular to the two viewing directions) every 24 hours, so that any given star lying on an appropriate great circle will cross the telescope's preceeding field of view in a little more than 20 seconds, then again for the same time some 20 minutes later as the following field of view sweeps across the same area of sky. In the data reduction process all star transits measured during a few great circles are taken together, and the star abscissae (measured relative only to each other at this stage) along a projected 'reference great circle' are derived. This projection makes use of the satellites's 3-axis attitude measured by the star mapper. The measurement principle is illustrated in Fig. 1.

In terms of the stars' astrometric parameters such an abscissae set provides essentially an instantenous one-dimensional set of star positions. The satellite's spin axis is then allowed to take up a large number of positions distributed densely and uniformally over the celestial sphere, at a variety of epochs. In this way, the great circle abscissae measurements may be combined to yield the two positional components of each star relative to the others and as a function of time - ultimately yielding the position, proper motion and parallax of each star. The attitude control adopted for this purpose is described in a later section.

Futher details of the data reduction process are given by Lindegren & Kovalevsky (1985) for the Hipparcos Catalogue resulting from the image dissector tube measurements across the main modulating grid, and by Grewing & Høg (1985) for the Tycho Catalogue resulting from the photomultiplier measurements of transits across the star mapper modulating grid.

Since the angular measurements are made relative to one another, the resulting astrometric catalogue should be rigid, but with 6 degrees of freedom. These will be determined in a variety of ways - for example by comparison with FK5, by the observations of minor planets yielding a dynamical system reference, and by observations of radio stars or stars near to radio quiet or radio loud quasars which may be observed by the Space Telescope and thus providing zero points for the positional and proper motion reference frame and ties with the radio reference frame. Further details on the latter aspects are given by Argue (1985).

From the principal of operation described above, it is evident that

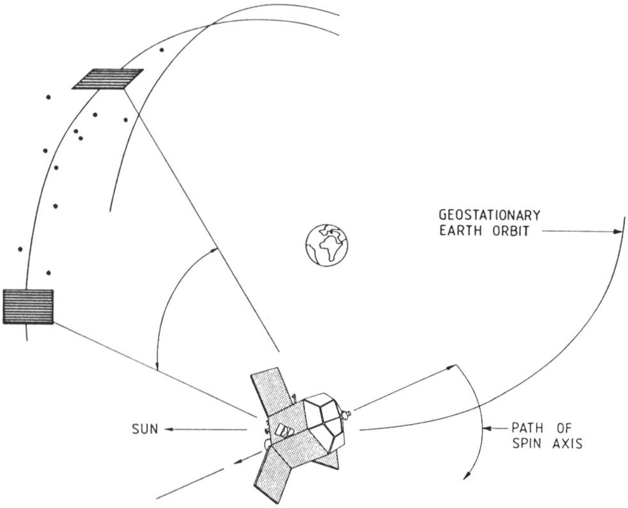

Figure 1. Measurement principle - as the satellite sweeps out a great circle across the sky, stars continually enter and leave the telescope's two fields of view. All stars simultaneously present in the combined field of view have their relative angular separations along the scan direction measured with very high precision.

the stars contained in the final catalogue should be uniformally distributed over the sphere, with an adequate density of bright stars with accurately known positions for the attitude determination.

The latter requirement, the need to have the star images always well-centred in the image dissector tube's instantaneous field of view, and the desire to avoid grid-step ambiguities in the great-circle abscissae solutions leads to a requirement on a priori knowledge of all star positions to some 1-1.5 arcsec rms at epoch. The desire to optimise the distribution of available observing time between the stars present in the combined field of view furthermore leads to the requirement concerning the knowlegde of a priori 'Hipparcos magnitudes' of each star, including variable stars, to some 0.5 mag.

The immense work needed to unify the stars proposed by the scientific community, to implement the recommendations of the specially appointed Scientific Selection Committee, and to provide the above information on each star necessary for the proper operation of the satellite observations, has been undertaken by the so-called 'Input Catalogue Consortium' of scientists and scientific institutes, whose work is most recently described by Turon & Crifo (1985), Requième (1985) & Grenon (1985). The work of the Input Catalogue Consortium is on schedule to deliver the final Input Catalogue to ESA one year before satellite launch.

In the following section more description, and the present status, of the key spacecraft and payload elements are provided. This status overview covers the beam combiner and the remaining telescope optics, the modulating grids, the detection systems, the scanning law and the corresponding attitude and orbit control system, and the on-board computational aspects responsible for the dynamical allocation of observing time - the 'star observing strategy'.

3. HARDWARE ELEMENTS

3.1. The Optical System

The imaging telescope is a 290 mm diameter, 1400 mm focal length all-reflective Schmidt telescope in a folded configuration (Fig. 2). The beam combiner, at the entrance pupil of the telescope, has its two halves figured aspherically so that it functions also as the Schmidt corrector. Since the star abscissae measured in grid coordinates are measured by the phase of the modulated signal, it is crucial that the optical performance introduces minimal phase shift at any spatial frequency with respect to an arbitrary phase reference. While the split pupil is largely symmetrical with respect to an axis orthogonal to the scanning direction, the tilted non-rotationally symmetric Schmidt profile results in a phase shift for almost any type of optical aberration.

In addition, any lateral misalignment results in a form of coma constant across the field-of-view resulting in a corresponding field-of-view dependent phase shift. Both effects are of potential importance for Hipparcos which works over an extended spectral range of 380-700 nm, both because of the consequent colour-dependent phase shift (referred to as the chromaticity error) and the potential degradation of the instrumental MTF. The Hipparcos optical system was designed to have low asymmetrical aberrations, and to preserve the alignment of the optical elements throughout the launch and in-orbit environmental changes. Structural tolerances are generally very tight, typically in the micron range, demanding the utilisation of a thermally stable structure combined with a precise active thermal control. The optical elements themselves contribute to the chromaticity effects through the asymmetrical components of the wavefront error, due to both figuring errors and manufacture and mount-induced stresses. Asymmetrical terms in the wave-front error each result in approximately 1 milli-arcsec chromaticity for a $\lambda/40$ peak deformation.

Specification of the quality of the optical components for Hipparcos called for wave-front errors of $\lambda/60$ rms for the spherical and flat-folding mirrors, and an allowable chromaticity error (defined as the difference in grid coordinates for stars of colour B-V = -0.25 or 1.25 and those of B-V = 0.5) of 1 milli-arcsec. The optical support programme undertaken before manufacturing of the flight model has demonstrated polishing to some $\lambda/90$ rms for the spherical and flat-folding mirrors. Polishing, cutting, coating and bonding of the aspherical and asymmetric beam combiner, identified as a critical element of the payload during the early project studies, has been even more of a challenge. Present indications are that a chromaticity error of some 3 milli-arcsec may be achievable.

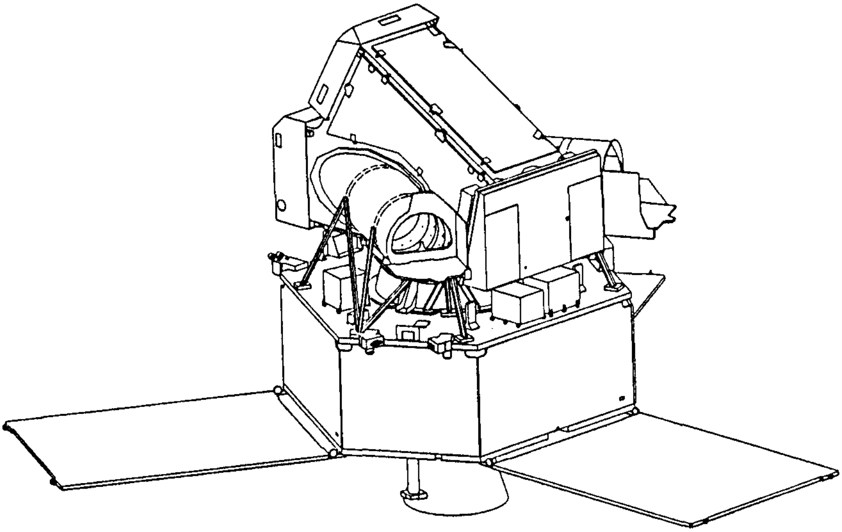

Figure 2. The Hipparcos on-station configuration, without shade structure and thermal hardware. The solar panels (bottom) are deployed, and the two baffles, corresponding to the two viewing directions, lie on either side of the payload.

3.2. The Modulating Grid

Together with the beam combiner, the modulating grid has probably received the most development attention. With a grid period of 1.208 arcsec, difficulties in the grid manufacture have been heightened by the relatively short telescope focal length and the field curvature. Grids meeting the exacting manufacturing requirements have now been produced by electron-beam lithography. The writing procedure compensates the limited deflection of the electron beam, and the variation of focus resulting from the field curvature, by a stepwise mechanical motion of the grid substrate. 168 x 46 scanfields of 131.2 x 480 microns (the grid period is 8.2 microns, and the width of each slit is 3.2 microns) are written, with demanding tolerances being placed on all parameters in order to preserve the grid accuracy despite the multiplicity of scan fields. Results of grid calibrations show encouraging performances, consistent with the final accuracy requirements.

3.3. The Detection Systems

Flight model image dissector tubes and photomultiplier tubes have now been selected, all meeting the necessary specifications set by the industrial prime contractor on the basis of the accuracy models. Measurement results confirm that it will be possible to calibrate the Hipparcos magnitude of stars, given their magnitudes and colour indices in classical stellar photometric systems (Johnson, Geneva), with a precision necessary for efficient operation of the star observation strategy.

Recent laboratory test results have demonstrated the ability of the sensitive area of the image dissector tube to track images moving across the field of view, and to switch between images with marginal loss of integration time.

3.4. Scanning of the Celestial Sphere - Attitude and Orbit Control

The scanning motion of the satellite, adopted to provide the necessary sky coverage, is the composition of a spinning around an axis perpendicular to the two viewing directions at 11.25 revolutions per day, combined with a movement of the spin axis around the sun. The angle between the spin axis and the sun is maintained at 43 degrees, and the spin axis makes 6.4 revolutions about the sun per year. The satellite thus keeps a constant attitude with respect to the sun, facilitating thermal control and straylight protection, whilst providing a systematic and reasonably uniform coverage of the celestial sphere by the two viewing directions. Control of the satellite's attitude will be performed by means of cold gas jet firings at suitable intervals in such a way that prohibitive jitter of the payload optical axes will not be generated. Computer simulations have shown that the time intervals between cold gas jet actuations necessary to maintain the required satellite orientation are at least 200 seconds. Deviations from the nominal 3-axis attitude of up to 10 arcmin are permitted. Between the thruster actuations, which will be synchronised about all three axes, the dynamical motion of the satellite is expected to be very smooth.

3.5. The Star Observing Strategy

For any configuration of star images in the combined field of view, an observing sequence will be accomplished by appropriately driving the deflection coils of the image dissector tube's instantaneous field of view. Rapid switching between star images allows for quasi-simultaneous measurement of the modulated photon counts, thereby minimising the effects of the line-of-sight jitter on the final accuracy. The adopted star observing strategy is built around a rigid time hierarchy, and uses the real-time attitude determination and the parameters of the Input Catalogue, uplinked to the satellite, in order to pilot the detectors instantaneous field of view. The Star Observing Strategy is described in detail by Vaghi (1985).

The values of the star-dependent parameters may vary with time, in order to take into account the past and projected observational history of the star during the mission. The star observing strategy forms the essential link between the Input Catalogue and the satellite operations. Simulations of successive iterations of the Input Catalogue made by the Input Catalogue Consortium are demonstrating that the Catalogue is converging towards a star list satisfying both the complex scientific requirements of Hipparcos and the demanding constraints imposed by the satellite operations.

4. MISSION ACCURACY AND SCHEDULE STATUS

A system analysis activity is running continuously with the industrial prime contractor with software packages performing the detailed simulations. A detailed error model has been operational since the start of the project's definition phase, and this has become progressively more sophisticated as the project has developed. The target astrometric accuracies are part of the top-level industrial specifications, so that intensive effort has been channelled into understanding origins and effects of potential contributions to the final accuracies. The accuracy model has been used continuously as a reference for lower-level specifications and sub-system design, and is updated as tests and evaluation of hardware results become available.

After launch, the contracter responsibility ends with the production of valid spacecraft and payload data, and the two independent data analysis consortia, known by the acronyms FAST and NDAC for the main mission reduction and TDAC for the Tycho data reduction, assume responsibility for the data treatment and final catalogue production. The work of these consortia began at the start of the project's detailed definition phase, and their close and detailed involvement with ESA since that time has provided invaluable advice on the satellite design, as well as guidance on the accuracy models developed by the industrial contractor and on the partitioning of the final error budget between the hardware and the complex on-ground data processing tasks.

Table 1 presents the main mission accuracy results based on the industrial prime contractor's Accuracy Report published in June 1984, and Table 2 presents the corresponding results for Tycho. The situation has not changed significantly since this report was issued, although it should be noted that the number of stars tabulated as a function of B magnitude is a model dating from the the time of ESA's acceptance of the project in 1980. The work of the Input Catalogue Consortium of defining the contents of the Input Catalogue is still going on, but it is now evident that the model will not be respected in detail, the number of stars presently expected between B = 8-9 mag and between B = 9-10 mag being respectively smaller and larger than the model shown. Recent studies have nevertheless demonstrated that the final achievable accuracy is only marginally degraded when 20 000 or more 9 mag stars are added to the reference star model so that depending on the forthcoming

Table 1. Accuracy status for the main mission. Mean errors are sky averages, and are star colour dependent.

B	Number of stars	Completeness (per cent)	Mean error (milli-arcsec) λ, β	μ_λ, μ_β	ω
<6	3000	100	1.2	1.7	1.6
6-7	5400	100	1.2	1.7	1.7
7-8	14800	100	1.2	1.8	1.7
8-9	40800	100	1.3	1.8	1.8
9-10	16000	15	1.4	2.0	2.0
10-11	12000	4	1.7	2.3	2.3
11-12	6000	0.8	2.4	3.4	3.3
12-13	2000	0.1	3.4	4.9	4.8

Table 2. Accuracy status for Tycho astrometry and photometry. Errors are for a single crossing of the star mapper grid - the astrometric error σ_α refers to the abscissa error on the relevant great circle.

(B+V)/2 (mag)	B-V (mag)	σ_α (arcsec)	σ_{B_T} (mag)	σ_{V_T} (mag)
8.65	0.0	0.031	0.07	0.10
	0.7	0.037	0.09	0.09
	1.5	0.038	0.12	0.08
9.65	0.0	0.064	0.12	0.18
	0.7	0.079	0.16	0.17
	1.5	0.083	0.23	0.14
10.65	0.0	0.147	0.24	0.37
	0.7	0.187	0.34	0.34
	1.5	0.195	0.50	0.28

studies of the Input Catalogue Consortium even the total number of stars adopted in the model (presently 100 000) may be enlarged.

Even with the above provisos, the sky-averaged mean errors shown in the figure are likely to be a good indication of the final achievable accuracies. Individual proposers will be informed which of their proposed objects will be contained within the Input Catalogue towards the end of 1986.

In preparation for the data analysis tasks, simulated data are now being communicated to and between the data reduction consortia, and results of increasingly detailed analyses of the data are being compared. The goal of both consortia is to treat long stretches of simulated data, in the same way as for the operational data, before launch. Plans for the comparison of results of the two consortia throughout the satellite operational phase and beyond are being drawn up with the goal of converging towards an agreed final Hipparcos Catalogue some three years after the end of satellite operations. The overall project planning, showing the satellite schedule until launch in mid-1988 and a 2.5-year operational phase, and the parallel work of the Input Catalogue and Data Analysis Consortia, is shown in Fig. 3.

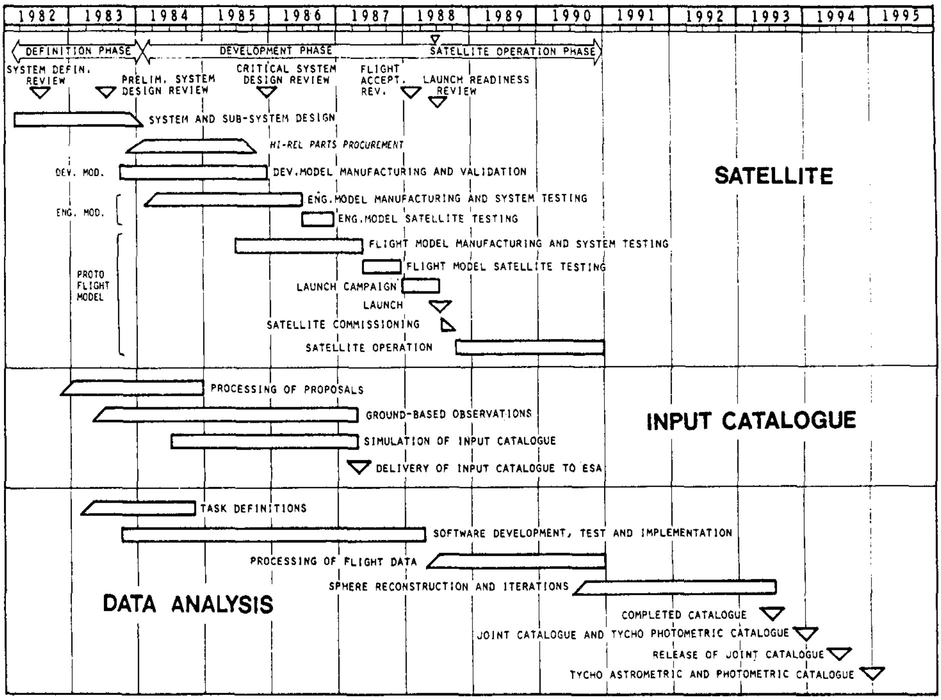

Figure 3. Hipparcos project schedule

ACKNOWLEDGEMENTS

The Hipparcos project involves a team of 30 ESA management and engineering staff, some 1500 personnel working in European industry within the MESH industrial consortium led by MATRA, and nearly 200 scientists within the four scientific consortia. The efforts of all these individuals has resulted in the very strong position of the project today. With responsibility for the scientific coordination of the project within ESA, I would like to acknowledge the dedication of the above teams, and in particular the guidance and work of the Agency's Hipparcos Science Team, the continued advice of the Scientific Selection Committee responsible for setting scientific priorities chaired by Professor Adriaan Blaauw, and the collaboration and support of the scientific consortia and in particular their leaders Drs E. Høg, J. Kovalevsky and C. Turon.

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