HIGHLIGHTS OF THE HIPPARCOS MISSION

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1. INTRODUCTION

The ESA Hipparcos satellite was launched from Kourou on 8 August 1989 for a mission dedicated to fundamental astrometry that was expected to last 2.5 years. The central objective was the construction of a large catalogue of nearly 118 200 pre–selected stars well distributed over the sky with an unprecedented accuracy of 2 mas in position and parallax and 2 mas per year in proper motion. This was to constitute an improvement close to two orders of magnitude compared to the best ground–based catalogues of fundamental positions. At the same time the number of optical sources available allows to build a practical realization of the quasi-inertial reference frame much more accurate than before and above all with a number of sources 40 times larger.

After an inauspicious start due to the failure of the apogee boost motor, the scientific mission eventually began in November 1989, in a highly elliptical orbit instead of the nominal geostationary one. The data collection lasted 37 months in total, during which the satellite functioned properly until degradation of the gyroscopes and eventual failure, in June 1993, of the on-board computer. Communications with the spacecraft were finally turned off on 15 August 1993 by the ESA Operations Centre (ESOC) in Darmstadt.

From all the measurements made at many different scanning directions and many different epochs an astrometric catalogue covering the whole celestial sphere has been computed, containing the positions at mid epoch, the proper motions and the parallaxes. In addition, from the amplitude of the signal recorded on the grid it was possible to determine the star apparent brightness, and through a careful time-dependent calibration to produce a consistent photometric solution for all the programme stars and carry out analysis for variability. Finally, comparison of the expected signal of a point source with the actual signal allows construction of sensitive statistical tests to recognise double and multiple stars and, subsequently, to solve for both the relative and absolute astrometry of these systems.

As the data processing is nearing its end, the sample results presented below are representative of the overall quality of the final product to be delivered in a few months, although there is still a margin of improvement in the final adjustments, and finally in the merging of the solutions computed by the two data reduction consortia.

Table 1: Astrometric accuracy of the Hipparcos catalogue

Parameter	Magnitude			
	6	8	10	12
Longitude (mas)	0.8	1.0	1.5	4
Latitude (mas)	0.6	0.8	1.2	3
Parallax (mas)	1.0	1.2	1.8	5
PM Longitude (mas/yr)	0.9	1.2	1.8	5
PM Latitude (mas/yr)	0.8	0.9	1.4	3

2. ASTROMETRY

Because the processing of single stars differs significantly from that applied to multiple systems, it is better to present the statistics of these two subsets independently.

2.1. Astrometry of single stars

The general principles of the data reduction have been described at length in various publications (Kovalevsky et al. 1992, Lindegren et al. 1992 and all the papers in the same issue of Astronomy & Astrophysics) and will not be repeated here. The main results are shown in Table 1, which gives the internal accuracy of the astrometric solution as a function of magnitude, averaged over the whole sky. A typical programme star being of 8.5 mag, one can conclude from this table that the basic objective of 2 mas–astrometry has been reached, at least if the formal errors are representative of the true positional uncertainties.

One must add that this accuracy is also dependent on the ecliptic latitude as a result of the scanning law. This is illustrated in Fig. 1, which gives the formal error of the astrometric parameters, in mas and mas/yr. Again these 'errors' are obtained directly from the least-squares solutions of the data reduction. There is a variation of a factor two in longitude and parallax between the stars of low ecliptic latitude and those in the polar region, the latter being more accurate than the former. The same pattern appears also in the proper motions. This diagram has been drawn for stars of 8–10 mag, and so is perfectly representative of the typical formal errors of the solution. The overall shape of these curves was known from simulation and theoretical assessments before the processing of real data and is a mere consequence of the various con-

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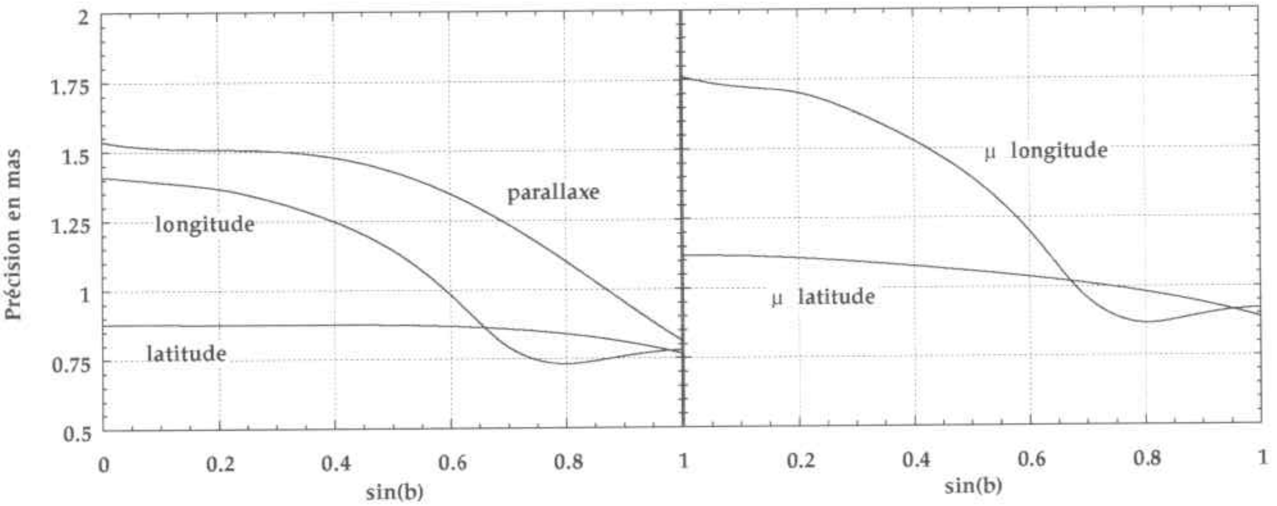

Figure 1: Astrometric accuracy as a function of ecliptic latitude

straints that have led to the final choice of the scanning law.

These results are quite remarkable for a mission which was on the brink of total failure. However one cannot escape the important question: are the formal errors representative of the true accuracy of the Hipparcos results? A full answer to this question is by nature impossible, and one must rely on partial indications.

A first tool, that has been extensively used, was based on the fact that two groups have performed the reductions in parallel using largely independent methods and strictly independent algorithms, thus enabling full cross checks of both intermediate and final results. The groups are known by their acronyms as FAST and NDAC, and description of their respective organisation is given in Kovalevsky et al. 1992 and Lindegren et al. 1992.

The two solutions are first referred to a common reference system by the application of a global time dependent rotation, since any Hipparcos sphere is rigid but has an undefined origin in position and proper motion. A comparison of the positions and parallaxes for more than 100 000 single stars is shown in Fig. 2. The vertical axis is logarithmic, so that the tails remain visible. The horizontal axis gives the difference between the two solutions in units of 0.001 arcsec. The core of the distributions show that the scatter between the two solutions, measured by the root mean square of the differences, is below 1 mas in latitude and slightly above 1 mas in longitude. More important is the lack of systematic offset between the parallaxes of FAST and NDAC.

The scatter between the two solutions as a function of ecliptic latitude is shown in Fig. 3 for the same parameters. Not surprisingly, the observed differences follow the same pattern as the formal errors. However the amplitudes are smaller than $\sqrt{2}$ times the σs and even tend to be smaller than the formal error of the solution, as a result of the correlation between the two solutions. As the two solutions have in common the random photon noise and differ only in the instrument calibration and the observation modelling they become more correlated for faint stars than at the brighter end. Based on the parallaxes, the correlation coefficient is negligible for stars brighter than 4 mag, is of the order of 0.5 for an average Hipparcos star, and reaches 0.7 for faint stars.

A better validation would be a direct comparison of the results with reference data of comparable accuracy. However there are practically no external reference positions and parallaxes with an accuracy matching those of Hipparcos, except for a few VLBI stars observed at about the same epoch (Lestrade et al. 1994). For these 11 stars, several of which are double, the parallax comparison is very satisfactory, with the deviation from the VLBI value falling into the common error bar. One can infer that the consistency in position and proper motion is likely to be just as good. This is fortunate, because the final Hipparcos Catalogue will be obtained by a rotational transformation to the extragalactic system via this small set of radio-stars.

Another indication of the absence of bias larger than 0.1–0.2 mas is provided by the parallaxes of the 47 stars of the Hipparcos programme that lie in the Magellanic Clouds, at so large a distance that their parallax is negligible. Those stars are all fainter than 10 mag and the error bar is larger than the average; nonetheless significance tests show that the distribution of the parallaxes does not deviate significantly from zero.

As for the Tycho catalogue results, about one million stars down to 11 mag have been successfully detected and solved for their astrometric parameters. Typically, for stars of comparable magnitude, the accuracy is ten times smaller than in the main mission.

3. Astrometry of Double Stars

About 21 000 stars of the programme have been recognised as non-single, including some 12 000 already known as double and multiple before the mission, and about 9000 discovered by Hipparcos. Also, a subset of 16 000 stars among the 21 000 have been successfully solved for their

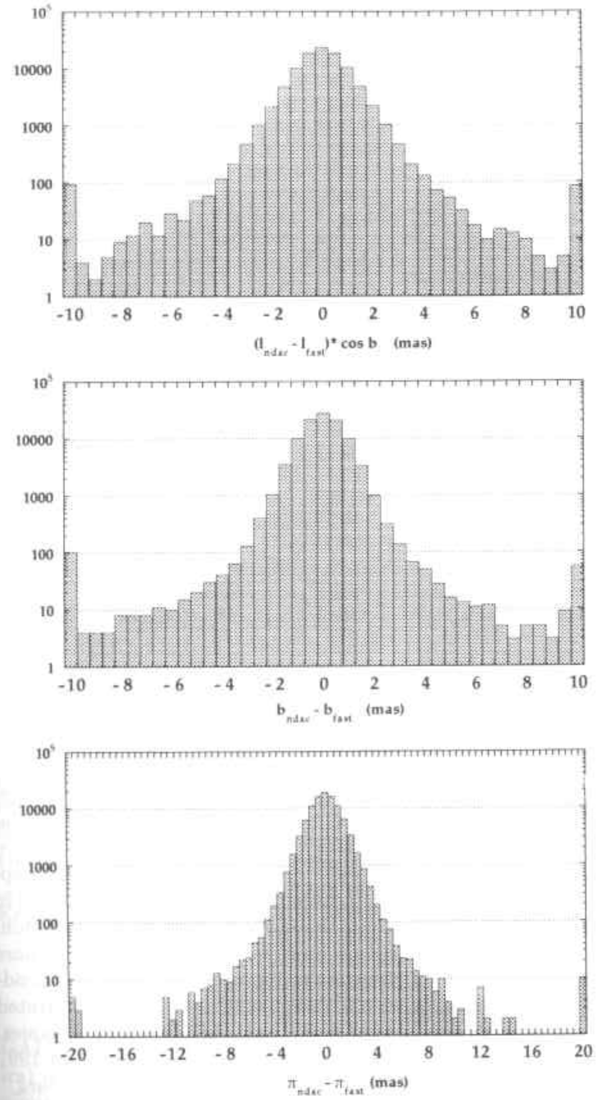

Figure 2: Distribution of the differences in the astrometric parameters between FAST and NDAC. The differences are in mas, and the vertical axis is on a logarithmic scale.

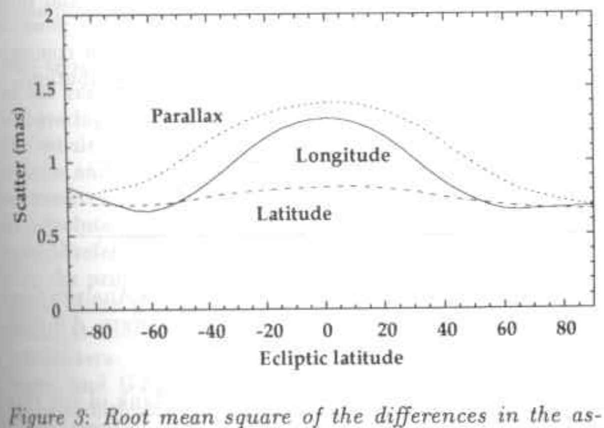

Figure 3: Root mean square of the differences in the astrometric parameter solutions between FAST and NDAC as a function of the ecliptic latitude.

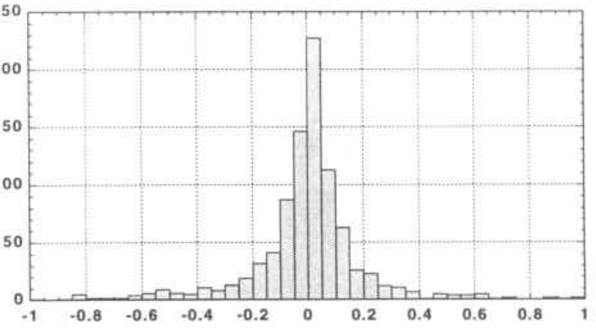

Figure 4: Comparison of the Hipparcos double star photometry with 1000 stars recently measured with CCDs. The horizontal axis is in magnitude.

relative coordinates (position angle and separation) with an accuracy in the range of 3–30 mas, including 6000 new double stars. The separations range from 0.1 arcsec for the closest binaries to 25 arcsec for the most separated, both limitations having an instrumental origin. The absolute astrometry has been derived for nearly all these stars, and yields parallaxes degraded by a factor 30% for the close binaries (separation < 0.35 arcsec) and 60% for the wide pairs, compared to the solution of the single stars. At the mission completion a reliable distance will be derived for most of the known orbital binaries with good orbital elements, allowing then to fulfill one of the best expectations of Hipparcos, namely the determination of stellar masses.

It happens however that, for the faint double stars (faint either because the separation is too small to be accurately measured with Hipparcos or due to the magnitude difference larger than 3 mag) two or more solutions fit the observations and there is no way to decide which, if any, is the best. Likewise, when a single solution is provided for those difficult stars it is often very uncertain. Thus it will be wise to start additional ground-based programmes to observe specifically this set of stars, likely to be multiple with a high probability.

At the same time a photometric solution is provided for the magnitude difference of the components, with an accuracy highly variable according to the separation and the magnitude difference itself, but which typically lies in the range 0.05–0.2 mag, a remarkable improvement with respect to the current situation for a sample of this size. A comparison with recent CCD observations carried out in the V and R band (Argue et al. 1992) in La Palma is shown in Fig. 4. The scatter is typically 0.14 mag, giving an idea of the accuracy of the Hipparcos photometry, if one takes for granted that the ground-based data is virtually error free compared to Hipparcos and neglects the residual difference in the effective wavelength. The scatter between the Hipparcos solutions is of the order of 0.09 mag.

4. THE PHOTOMETRIC SOLUTION

Although the Hipparcos mission was primarily planned and optimised to produce good astrometric measurements, it was soon realized that the signal conveyed much

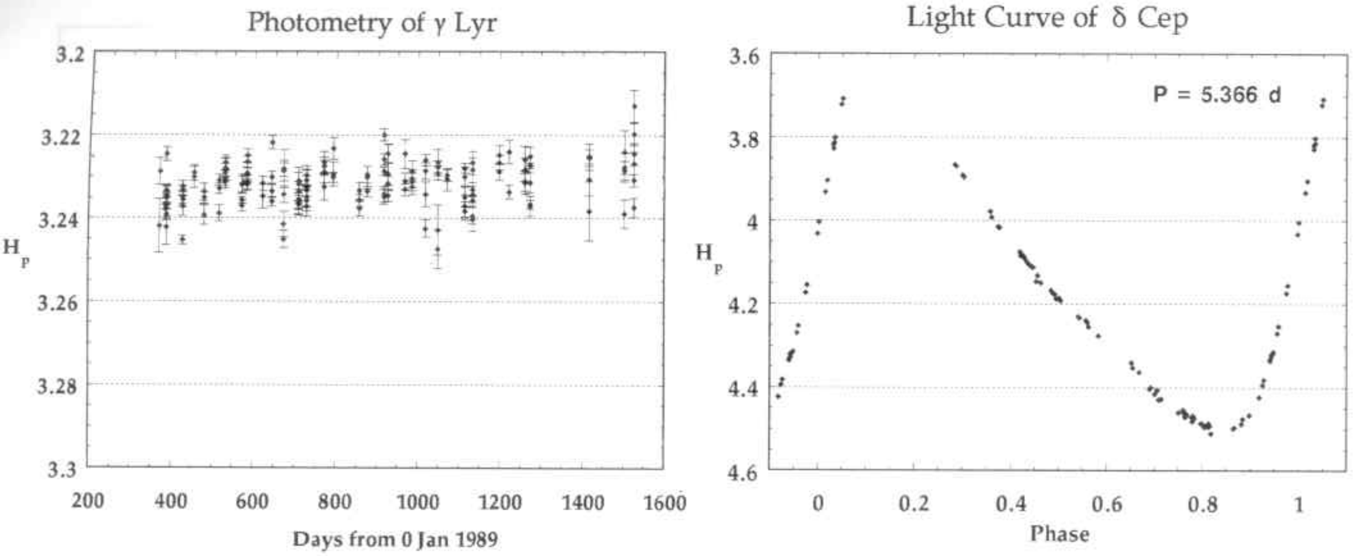

Figure 5: Hipparcos photometry of two bright stars. The error in each data point for δ Cep is less than the size of the diamonds.

information on the star brightness, provided a good monitoring of the instrument sensitivity was undertaken.

At each grid crossing a magnitude is determined for all programme stars in a well-defined photometric system and kept constant during the mission. Altogether the missions ends up with 14×10^6 such measurements spread over 118 200 stars, that is to say an average of 120 magnitude determinations for each star, with an accuracy of 0.01–0.02 mag for a typical Hipparcos star of 8.5 mag. This constitutes the most comprehensive photometric survey so far, combining both precision and homogeneity of the photometric system all over the sky.

About 20 000 stars have been detected as variable and for several thousands it was possible to fit a period and produce folded light-curves. As the detection sensitivity for variability is less than 0.01 mag for the bright end of the programme, it allows detection of micro-variability and to investigate this feature as a function of the spectral type and luminosity class. In any case, most of this work will be done after the mission completion using auxiliary astrophysical data.

In parallel with the main mission, two-colour photometry, close to the Johnson B and V bands, down to 11 mag is provided by the Tycho experiment. The number of high quality solutions is not known yet but should be of the order of 200 000 and will include a variability analysis.

The capability to maintain the photometric system constant over the 37 months despite the instrument ageing has been a major concern in the data reduction. The plot in Fig. 5 for a known constant star (γ Lyr) shows that we did in fact succeed. The observed variations are not different from a random scatter with a standard deviation of 0.005 mag. We have also plotted the folded light curve of δ Cep, the prototype of the Cepheids. The error bar on each data point is less than the size of the plotting symbol. This curve is based on observations scattered over the 37 months, that is to say over more than 200 periods.

5. CONCLUSION

The reduction of the complete set of data should be finished by the end of 1995, after the merging of the solutions produced by each consortium is completed. Then in 1996, early access to the results will be granted for approved investigations to groups that have been involved in the preparation of the mission and in the data reduction. At the same time a full year will be needed to prepare the publication of the catalogue and the CD-ROM products associated with it, along with an extensive printed version and documentation that will total 14 volumes. Finally the results will be made widely available in 1997 with access for example, through the CDS, Strasbourg.

6. ACKNOWLEDGMENTS

This overview reflects the labour of many people who have worked during the last fifteen years, first to design, implement and validate the reduction algorithms and then to process the data in order to produce the best possible solution. They are collectively thanked for their commitment to the project and their invaluable contribution.

REFERENCES

Argue A.N. et al., 1992, MNRAS, 259, 563

Kovalevsky, J. et al., 1992, The FAST Data Analysis Consortium: Overview of the Reduction Software, AA, 258, 326

Lestrade, J.F. et al., 1995, Preliminary Link of the Hipparcos and VLBI Reference Frames, AA, in press

Lindegren, L. et al., 1992, The NDAC Data Analysis Consortium: Overview of the Reduction Methods, AA, 258, 18