2. STELLAR DISTANCES

THE HIPPARCOS RESULTS [1]

C. TURON [2]
Dasgal / URA CNRS 335, Observatoire de Paris-Meudon
92 195 MEUDON Cedex, France

Abstract. After a brief presentation of the Hipparcos mission, and an overview of the astrometric and photometric results obtained from the main mission and from Tycho, more details are given on the parallaxes. Absolute parallaxes have been obtained for 117 955 entries of the Hipparcos Catalogue, out of a total of 118 218, with a median precision of 0.97 mas for stars brighter than 9. This precision varies with apparent magnitude and ecliptic latitude. The estimated systematic error is smaller than 0.1 mas. The distances of more than 20 000 stars are determined to better than 10 %. Some more statistics are presented.

A few applications of this fantastic amount of new and accurate data are presented, in the fields of absolute magnitude calibrations, stellar physics, distance scale determination.

1. Introduction

The ESA Hipparcos satellite, included in the European Space Agency scientific programme in 1980, was launched by Ariane in August 1989. High quality scientific data were obtained during 37 months, from November 1989 to March 1993. Operations were terminated on 15 August 1993. Comprehensive description of the Hipparcos mission is given in Perryman et al. (1992). The whole project was supervised by ESA; the satellite and the instrument were constructed under the leadership of Matra Marconi Space and Alenia Spazio; the scientific aspects, supervised by the Hipparcos Science Team, were conducted by four scientific consortia.

[1] Based on observations made with the ESA Hipparcos satellite, and on work performed within the INCA, FAST, NDAC and TDAC Consortia.

[2] For the Hipparcos Science Team

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The INCA Consortium was responsible for the preparation of the observing programme, published as the Hipparcos Input Catalogue (Turon et al. 1992a and 1992b). The two consortia, FAST and NDAC, were responsible for the global treatment of the 1 000 Gbit of the main mission data (Lindegren et al. 1992, Kovalevsky et al. 1992). The TDAC consortium was responsible for the analysis of the star mapper data (Høg et al. 1992).

The final products of the mission are

- the Hipparcos Catalogue, resulting from the merging of the two independent solutions obtained by FAST and NDAC, and including 118 218 preselected entries, brighter than $V = 12.5$, with a median precision at the level of the milliarcsec for each of the five astrometric parameters, and of a few millimagnitudes for the mean photometric parameters,
- annexes to the Hipparcos Catalogue, including details on double and multiple systems, and on variable stars,
- the Hipparcos Epoch Photometry Annex, including calibrated epoch photometry for each programme star, at an average of some 110 different epochs of observation,
- the Tycho Catalogue, including 1 052 031 entries observed in survey mode, brighter than $V = 11.5$, with a median precision at the level of 3 to 50 milli-arcsec (depending on magnitude), for each of the five astrometric parameters, and of 0.003 to 0.12 magnitude for the mean photometric parameters,
- the Tycho Epoch Photometry Annex, including epoch photometry for the brighter stars, at each epoch of observation,

About 115 000 stars are common to the Hipparcos and Tycho Catalogues. 935 000 stars are in the Tycho Catalogue only, not observed by Hipparcos due to limited observing time. 6 300 stars are contained in the Hipparcos Catalogue only, not observed by Tycho due to the crowding of some zones of the sky, due to their faintness (about 2 300 Hipparcos stars were below Tycho detection limits), or to their brightness (very few bright stars were not observed by Tycho). These entries are flagged in the Tycho Catalogue.

2. The Astrometric Parameters

2.1. SUCCESSIVE SPHERE SOLUTIONS

The overall data analysis was decomposed in five major steps: the treatment of the raw photon counts, the attitude determination, the great circle reduction, the sphere solution and the determination of the astrometric parameters. The whole process is described in detail in Volume 3 of 'The Hipparcos and Tycho Catalogues' (ESA 1997). The last four steps were repeated several times, independently by the FAST and NDAC consortia, as successively larger data sets were available from satellite observations. Finally, the results obtained for each star by each consortium, were merged in order to provide a unique set of astrometric parameters together with their associated covariance matrix.

Figures 1 and 2 are illustrations of the improvement obtained in the determination of the astrometric parameters by including successively larger sets of data in the solution, and then by merging the two independent solutions obtained by the two data reduction consortia. Distributions of formal standard errors in parallax for the successive NDAC sphere solutions, compared with that of the final Hipparcos Catalogue are shown in Figure 1. The temporal evolution of the fraction of negative parallaxes, for the solutions obtained by each consortium, compared to the successive merged solutions, is illustrated in Figure 2. The parallaxes improve, as expected, roughly as $t^{-1/2}$, if t is the total duration of the observations, the position at the same rate, and the proper motions slightly slower than the expected $t^{-3/2}$. Empirically, the fraction of negative parallaxes improves roughly as $t^{-1.0}$.

Finally, the Hipparcos reference frame was linked to the International Celestial Reference System (ICRS), defined by radio VLBI observations of extragalactic sources, by means of several dedicated programmes (Lindegren and Kovalevsky 1995; Kovalevsky, Lindegren and Perryman 1997): VLBI, Merlin, and VLA observations of radio-emitting stars observed by Hipparcos, Hubble observations of separations of Hipparcos stars next to compact extragalactic objects, wide field photographic plate measurements of Hipparcos stars with respect to compact extragalactic objects, use of Earth orientation parameters. The accuracy of the extragalactic link is estimated to be ± 0.6 mas in the orientation and ± 0.25 mas/yr in the spin.

2.2. THE PARALLAXES

The number of observations per star was conditioned by the scanning motion of the satellite all over the sky. The number of astrometric observations (abscissae on reference great circles) varies from about 10 to about 60, depending principally on the ecliptic latitude. This is directly reflected in the standard errors of the parallaxes. The other parameter of importance is the star magnitude. Median standard errors in parallax, σ_π, as function of the Hp magnitude and of the ecliptic latitude are given in Table 1.

Hipparcos parallaxes have been compared with the best available ground-based parallaxes (Arenou et al. 1997). Twelve optically bright radio-emitting stars were observed by VLBI as part of the Hipparcos link programme (Lestrade et al. 1995). The precision of VLBI parallaxes is 0.2 to 1 mas, and an excellent agreement is found between the two sets of measurements.

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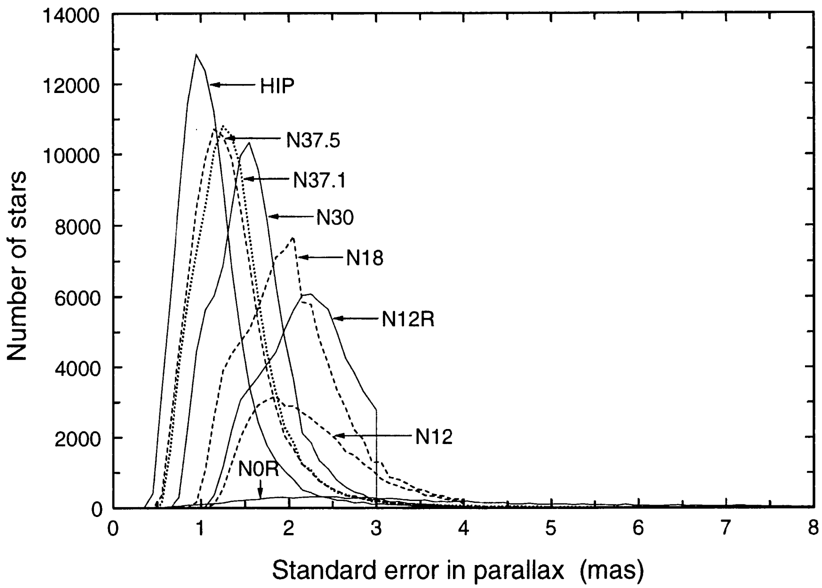

Figure 1. Distribution of formal standard errors in parallax for the successive NDAC sphere solutions (NOR to N37.5) and for the Hipparcos Catalogue (HIP). Courtesy L. Lindegren, Lindegren et al. 1997, Figure 16.13.

TABLE 1. Median standard errors in parallax, σ_π, as function of the Hp magnitude and of the ecliptic latitude

	Ecliptic latitude ($\|\beta\|$, deg)								Nb of
Hp	0-20	20-30	30-40	40-50	50-60	60-70	70-90	all	stars
< 6	0.86	0.81	0.75	0.67	0.56	0.52	0.49	0.75	4559
6-7	0.91	0.86	0.81	0.73	0.61	0.55	0.52	0.80	9381
7-8	1.02	0.97	0.92	0.86	0.72	0.63	0.59	0.91	23679
8-9	1.20	1.16	1.12	1.07	0.89	0.77	0.71	1.09	40729
9-10	1.48	1.43	1.37	1.35	1.11	0.94	0.86	1.36	27913
10-11	1.99	1.93	1.82	1.84	1.54	1.24	1.13	1.85	8563
11-12	2.97	2.81	2.74	2.73	2.26	1.88	1.73	2.72	2501
≥ 12	4.26	4.11	4.10	4.00	3.67	3.49	2.51	4.11	630
all	1.23	1.20	1.15	1.11	0.89	0.77	0.71	1.10	
Nb	34775	18286	17354	16878	13954	9728	6980		117955

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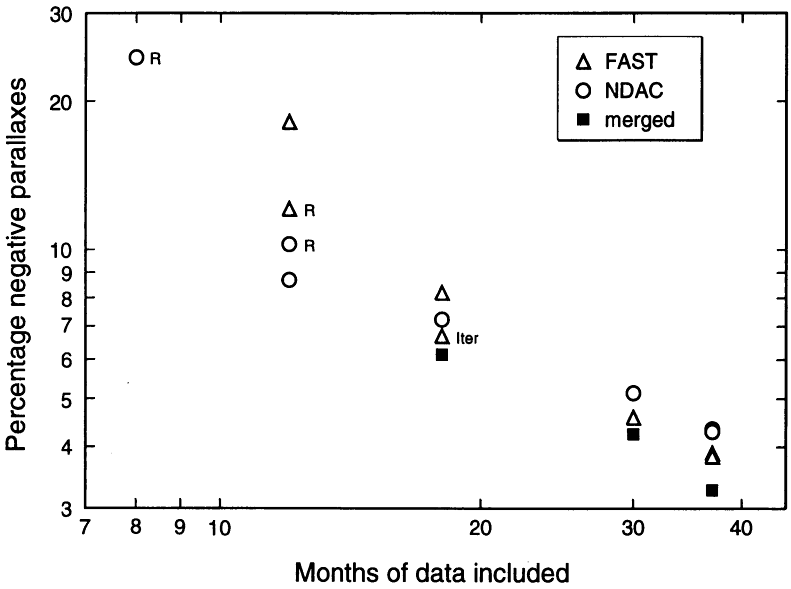

Figure 2. Fraction of negative parallaxes in the various solutions as function of the length of the data set, compared with the merged solutions. Note that the points for the merged catalogues H18, H30 and HIP (filled squares) are significantly below the corresponding points for the FAST and NDAC solutions. Courtesy L. Lindegren, Lindegren et al. 1997, Figure 16.22.

Comparison with the US Naval Observatory photographic trigonometric parallax programme with formal mean errors in the range 1 to 4 mas (Harrington et al. 1993) shows a median difference of 0.2 ±0.35 mas for 88 common stars. Comparison with the last edition of the General Catalogue of Trigonometric parallaxes (GCTP, van Altena et al. 1995), shows a median difference of 1.8 ±0.2 mas for 4292 common stars (2.6 ±0.3 for stars farther than 50 parsecs, 0.5 ±0.4 for stars nearer than 20 parsecs; 1.2 ±0.3 mas for northern stars farther than 50 parsecs). Systematic differences up to 7 mas are found at δ = - 30 deg. Apart from these systematic differences, the standard width of the differences divided by the combined standard errors is 1.04 ±0.01.

Finally the zero-point and unit-weight error of the Hipparcos parallaxes have been investigated using Hipparcos stars for which the distance can be estimated by other methods: stars in the Magellanic Clouds and in open clusters, stars with $uvby\beta$ photometry (Arenou et al. 1997). These external comparisons shows that the zero-point can be safely assumed to be smaller than 0.1 mas and that the standard errors of the parallaxes are not underestimated by more than 10 per cent.

3. Photometry

In addition to astrometric parameters, the Hipparcos data reduction produced high precision, fully calibrated, photometry in the Hp broad-band filter (spectral range: 375-750 nm). The Hp band has more or less the same effective wavelength as the V-magnitude from the Johnson system, so that the amplitude of $Hp - V$ is smaller than 0.2 mag for stars with B-V < 1.5. However, its sensitivity is extended towards the extreme red. A total of 13 000 000 epoch photometric measurements were obtained, an average of 110 per star, ranging approximately from 30 to 380, depending principally on the object ecliptic latitude.

Instrumental effects such as the inhomogeneities of the sensitive surface and of the residual defects of the optics, the ageing of the optics and of the detector as function of time, the slight differences between the preceding and the following fields of view, were carefully calibrated. The average error per field transit (epoch photometry) is ranging from 0.003 mag for stars brighter than 4, to 0.015 for stars of magnitude Hp=9, to 0.049 for stars of magnitude 12. From this epoch photometry, high accuracy median magnitudes were obtained for constant stars, and nearly 12 000 variable stars (8200 new) were investigated. Average error on median Hp magnitudes as function of Hp magnitude are given in Table 2.

TABLE 2. Average errors, in milli-magnitudes, on the median Hp magnitude as function of Hp, for stars found to be constant.

Hp	2	3	4	5	6	7	8	9	10	11	12
error	0.4	0.4	0.5	0.6	0.7	0.9	1.3	1.9	2.8	4.4	7.2

Among the variable stars, 2 712 were found to be periodic (970 new), 5 542 non-periodic or unsolved (4 145 new). Among the periodic variables, there are 273 Cepheids (2 new), 186 RR Lyrae (9 new), 108 Delta Scuti and SX Phoenicis (35 new), 917 eclipsing binaries (347 new), and many other types such as Mirae, SR, RV Tau, etc. (1 238, 576 new).

In addition to the photometry obtained from the main detector, photometry in two pass-bands was recorded by the star mapper detectors. These photon counts were processed in the Tycho reduction chain, and B_T and V_T magnitudes obtained for stars brighter than $V_T \sim 11.5$ mag, with median standard errors ranging from 0.003 mag for stars brighter than $V_T = 6.0$ mag to 0.014 mag for stars in the range 8-9 mag, to 0.12 mag for stars fainter than $V_T = 11.0$ mag.

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4. Some statistics on the results

4.1. THE OBSERVING PROGRAMME

The Hipparcos observing programme has been defined, in successive steps, over the period 1982–1991, on the basis of scientific proposals submitted to the European Space Agency, while taking into account the observing possibilities of the satellite. Much attention has been paid to the selection of stars in order to enhance the scientific return expected from the mission (Turon et al. 1992c, Turon et al. 1995). In parallel, extensive ground-based programmes were organised to obtain, before launch, good positional and photometric data about programme stars in order to optimise the observation with the satellite (Jahreiß et al. 1992, Grenon et al. 1992).

As a result, 118 000 stars, one quasar (3C273), 48 minor planets, and three satellites of major planets were selected. The stellar part of the catalogue is essentially complete for stars brighter than $V = 7.9 + 1.1\ |sin\ b|$ for spectral types earlier than G5 (included), and for stars brighter than $V = 7.3 + 1.1\ |sin\ b|$ for spectral types later than G5. The 60 000 fainter stars have been selected from the proposals on grounds of scientific merit. As a results, most stars are in the range 7-10 in Hp, with a selection of fainter stars down to $Hp = 12.7$. Due to the pre-selection, most programme stars are closer than 500 parsecs.

4.2. SOME STATISTICS ON PARALLAXES

The Hipparcos data are providing a dramatic increase, qualitatively and quantitatively, of the basic distance information available for any application. The numbers of stars for which a relative accuracy better than 1, 5, 10 and 20 % is available from Hipparcos data and from ground-based data are given in Table 3.

TABLE 3. Number of stars per range of relative accuracy of trigonometric parallaxes

	Hipparcos	ground-based
$\sigma_\pi / \pi < 1\%$	442	a few tens
$\sigma_\pi / \pi < 5\%$	7 388	100 ?
$\sigma_\pi / \pi < 10\%$	22 396	1 000 ?
$\sigma_\pi / \pi < 20\%$	50 643	

Moreover, the range of spectral types and luminosity classes for which precise parallaxes are available is considerably enlarged, especially towards

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the upper part of the main sequence and towards the giant branch, where the 'clump' is already clearly marked when considering stars with relative accuracy better than 5 %. The bottom of the main sequence is populated down to absolute Hp magnitude 14. The ranges of absolute Hp magnitude and $B-V$ covered by Hipparcos observations per range of relative accuracy on trigonometric parallaxes are shown in Table 4.

TABLE 4. Ranges of absolute Hp magnitude and $B-V$ per range of relative accuracy of trigonometric parallaxes

	Hp	$B-V$
$\sigma_\pi / \pi < 1\%$	0.5-13.5	0.0-1.8
$\sigma_\pi / \pi < 5\%$	-3.0-14.0	-0.2-1.8
$\sigma_\pi / \pi < 10\%$	-5.5-14.5	-0.3-1.8

The comparison with the last edition of the Catalogue of Nearby Stars (CNS3, Gliese & Jahreiß 1991) shows the outstanding improvement expected from the Hipparcos data: in CNS3, which is the best available compilation of nearby stars, there are 851 stars with a relative accuracy of trigonometric parallaxes better than 10% and a measured $B-V$. The main sequence is well populated for absolute V magnitudes between 10 and 15, very sparsely between 5 and 10, with a few stars at brighter magnitudes (including a few subgiants). The white dwarf sequence is well represented. In contrast, a similar HR diagram drawn from Hipparcos observations includes 21 739 stars, a very dense main sequence between absolute Hp magnitudes 0 and 8, very dense subgiant and giant sequences, and a few white dwarfs (Perryman et al. 1995).

The new CCD ground-based parallax programmes (Dahn 1997), reaching precisions of the milliarcsecond level, are very much complementary of the Hipparcos data as they include stars in the faintest parts of the HR diagram.

4.3. SOME APPLICATIONS

4.3.1. *Open clusters*

Stars in galactic open clusters have been carefully selected for Hipparcos observations (Mermilliod & Turon 1989), and some of the closest clusters are nicely sampled: 210 stars observed in the Hyades, 120 in Coma Ber, 80 in the Pleiades, 130 in α Per, etc. In addition to detailed studies of these very nearby clusters, Hipparcos observations allow to determine the mean distances with relative precision better than 10% for about 10 clusters of various ages and metallicities, and for 10 other clusters with relative precision between 10 and 20%.

4.3.2. *Pulsating variable stars*

The Hipparcos observation of variable stars raised specific problems: the observing time for each type of variable stars had to be chosen according to their light curve, and ephemerides had to be predicted for large amplitude variable stars (Mennessier & Figueras 1989, Mennessier at al. 1992). Both the astrometric and the photometric results obtained from the satellite will greatly improve our knowledge of the physics of these stars and the use which can be made of some of these in distance scale determinations (Turon & van Leeuwen 1995).

Parallax results obtained by Hipparcos for five types of pulsating variables are given in Table 5. About twenty Cepheids can be used to rediscuss the zero-point of the period-luminosity relation, with periods in the range 2 to 36 days. In addition cluster membership will be greatly improved, and it will be possible to reassess the effect of coulour and metallicity on the period-luminosity relation.

TABLE 5. Pulsating variables in the Hipparcos Catalogue. Relative precisions on parallax

Type	Observed stars	Stars in clusters	(σ_π / π)			
			< 0.05	$0.05 - 0.10$	$0.10 - 0.20$	$0.20 - 0.30$
δ Ceph	273	6	0	1	2	7
RR Lyr	186	0	1	0	8	3
δ Scu	87	14	12	31	22	11
SX Phe	21	0	1	2	1	4
Mirae	233	0	0	0	5	8

Accurate parallaxes are obtained for a dozen of RR Lyrae, half of these being newly detected as variables by Hipparcos. In addition, many objects of various metallicity have been measured very accurately by Hipparcos, especially stars with low metallicity such as subdwarf stars (Pont et al. 1997). These observations are leading to the revision of the calibration of the position of the main sequence in the HR diagram as function of the metallicity, and to a re-discussion of the dependence of RR Lyrae absolute magnitudes with metallicity.

5. Conclusion

Hipparcos is providing a dramatic improvement in distance determination which will lead to a reassessment of many topics of astrophysics such as stellar physics and evolution; galactic structure, kinematics, dynamics and evolution; distance scale zero points through the study of open clusters, pulsating variables, sub-dwarf stars. Accurate direct distance determinations are now available within a sphere of 100 to 150 parsecs centred on the sun. The next step forward, leading to direct distance determination throughout our Galaxy, would be obtained from a space mission such as Gaia (Lindegren & Perryman 1996), estimated to lead to parallaxes for some 50 million objects, with an accuracy better than 10 microarcsec. This has been recommended as a future ESA cornerstone mission, and detailed studies of this mission are now beginning.

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