ASTROMETRIC PROPERTIES OF THE HIPPARCOS CATALOGUE*

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ABSTRACT

The main statistical astrometric properties of the Hipparcos Catalogue are reviewed. This includes the overall figures useful to characterize the content of the Hipparcos Catalogue, meaningful for an average star of 9 mag. The formal errors of the five astrometric parameters are discussed in different coordinate systems as a function of the position on the sky and of the magnitude of the stars. While there is almost no sizeable effect with the ecliptic longitude, the formal errors of the ecliptic longitude and parallax display large variations with the ecliptic latitude. For the other coordinate systems the precision of all the astrometric parameters is a function of both positional coordinates. A more detailed investigation of the distribution of the parallaxes and their expected errors as a function of the magnitude and of the location of the star on the sky is also carried out with a particular emphasis on the relative error σ_π/π.

Keywords: Astrometry, Hipparcos, Parallaxes.

1. INTRODUCTION

The ESA astrometric mission Hipparcos was the first space experiment fully dedicated to astrometry. The observation program came to an end in August 1993 after 37 months of effective observation. This was followed by three more years of data processing ending up with the merging of the two solutions produced, to a large extent, independently by the NDAC and FAST Consortia. One more year was necessary to arrange all the results into a consistent product and write an extensive documentation, including a user guide of the Catalogue and detailed chapters on the construction of the Hipparcos and Tycho solutions.

The primary result is an astrometric catalogue of 118 218 entries nearly evenly distributed over the sky with an astrometric precision in position, proper motion and parallax of 1 mas or mas/yr, or better for the brightest stars. The positions and proper motions of the Catalogue define an optical reference frame with a likely global accuracy of about 0.1 mas and 0.1 mas/yr and no regional distortion. This set of stars formed a pre–defined observing programme selected after a wide consultation of the astronomical community about their scientific interest and the possibility to allocate sufficient observational time to each selected star. The median magnitude of the Catalogue is $Hp = 8.7$ and half of the Catalogue lies in the interval $8 < Hp < 9.5$. The exact distribution is shown in Figure 1, drawn with a logarithmic scale to show the small populations at the bright and faint ends.

The Catalogue completeness depends on the Galactic latitude and spectral type and varies from $Hp = 7.3$ near the galactic plane to $Hp = 9$ in the polar regions. The stellar density is $\simeq 3$ stars per square degree on the average, with local densities as large as 5.5 stars per square degree in the galactic plane and close to 2 stars per square degree in many isolated spots. Because of the selection of stars in the Input Catalogue, a zone a few degrees wide, and in the direction of the galactic anti-centre ($l = 180$ deg) is above the average sky density.

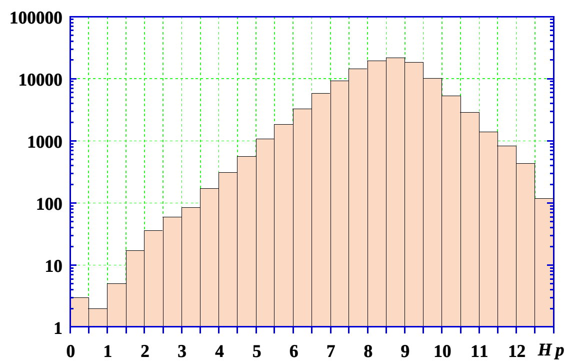

Figure 1. Magnitude distribution of the 118 218 entries of the Hipparcos Catalogue. The vertical scale is logarithmic and the labels indicate the beginning of a class 0.5 mag wide. The linear envelope of the distribution on the bright side indicates that the Catalogue is comprehensive up to Hp= 7.5.

The observational procedure and the principles of the data reduction have been presented in the scientific literature in many instances. The most detailed and updated presentation is in any case available in Volumes 1–4 of the published catalogue (ESA 1997).

*Based on observations made with the ESA Hipparcos satellite.

Table 1. Summary of the astrometric solution

Catalogue epoch	1991.25	
Measurement period	1989.85–1993.21	
Reference system	ICRS	
Mean sky density	$\simeq 3$ stars/deg^2	
	$\alpha \cos\delta$	δ
Median precision of positions ($Hp < 9$) (mas)	0.77	0.64
Median precision of proper motions ($Hp < 9$)(mas/yr)	0.88	0.74
Median precision of parallaxes ($Hp < 9$)(mas)	0.97	
Number of stars with $\sigma(\pi)/\pi < 0.1$	17 900	single stars
	3 000	double or multiple stars
Number of stars with $\sigma(\pi)/\pi < 0.2$	49 500	

2. THE HIPPARCOS ASTROMETRIC CATALOGUE

2.1. Main Features

The main characteristics of the astrometric solution are summarised in Table 1. The Catalogue epoch, $T_0 =$ J1991.25, is close to the mean epoch of all the observations. The true mean observation epoch of a particular star may differ from the Catalogue epoch by up to six months in the worst cases, although it usually ranges within two months of the Catalogue epoch. This was a deliberate choice permitted by the publication of the full covariance matrix of the astrometric parameters of every star. The Hipparcos Catalogue is aligned with the extragalactic reference frame and constitutes a materialisation of the International Celestial Reference System in the visible.

The absolute astrometry with a typical accuracy of 1 mas, provides an improvement by nearly two orders of magnitude with respect to the best fundamental catalogue available before Hipparcos and more than two orders of magnitude when compared to compilation catalogues of similar size, like the SAO and the PPM. As for the proper motions, the improvement is not so large as a result of the very limited timebase on which the Hipparcos measurements were performed, compared to the several tens of years used for the ground-based proper motions. This implies in particular, that the quality of the Hipparcos reference frame will degrade rather quickly, if no effort is done to maintain it in the years to come.

2.2. Standard Errors of the Astrometric Parameters

For the vast majority of the single stars the astrometric model adopted assumes a uniform space motion relative to the barycentre of the solar system. The complete description of the apparent star position is then given by the five astrometric parameters, namely two coordinate positions at the Catalogue reference epoch for the barycentric direction of a star, the parallax π and the two components of the tangential motion expressed in angular measures as $\mu_{\alpha*}$, μ_δ. In the case of compound sources with two or more components, the treatment was somewhat more complex but at the end led to a similar description for each of the components. The Catalogue entries which needed a more elaborate modeling, such as the acceleration solution, are usually not included in the subsequent statistical analysis.

The distributions of the formal standard errors of the astrometric parameters are shown in Figure 2 for the three main coordinate systems: ecliptic, equatorial and galactic. The plots are based on the 100 038 'single stars', or to be more precise, all the catalogue entries which do not belong to the Double and Multiple Systems Annex (hereafter DMSA). One must bear in mind that the transformation of the errors from one system to another is not simply the distribution of a mean error on the sky expressed in two different systems, but a full transformation of the components of the covariance matrix from one system to another. Only the standard errors of the parallaxes are invariant in a change of coordinate system.

The ecliptic system is the most appropriate to show the Hipparcos standard errors and correlations. In this system there is virtually no dependence of the standard errors with the longitude, as a consequence of the ecliptic-driven scanning law, and a plot as a function of latitude produces meaningful results with no averaging along a small circle of latitude. In contrast, in the equatorial system, and above all, in the galactic system, the standard errors are function of the two positional coordinates ($\sigma_x = \sigma_x(l, b)$) and a plot as a function of b involves an averaging over the longitudes. In these two cases, only sky charts can convey visually and without distortion the full properties of the astrometric precision.

Basically, the error in ecliptic latitude is fairly constant on the sky, while the errors in longitude and parallax exhibit marked variations with the ecliptic latitude. These features are a mere (and foreseen) consequence of the scanning law which yields less observations in the ecliptic plane that in the higher latitude, and a better geometrical configuration to determine the latitude near the ecliptic plane than at $b = 50$ degrees, and just the opposite for the longitude. The two effects cancel each other for the latitude while they add for the longitude.

In the equatorial system, the situation is quite similar, just slightly smoothed out, because the obliquity is not very large. In the case of the galactic coordinates, the averaging over the galactic longitudes on a small circle of constant galactic latitude, flattens all

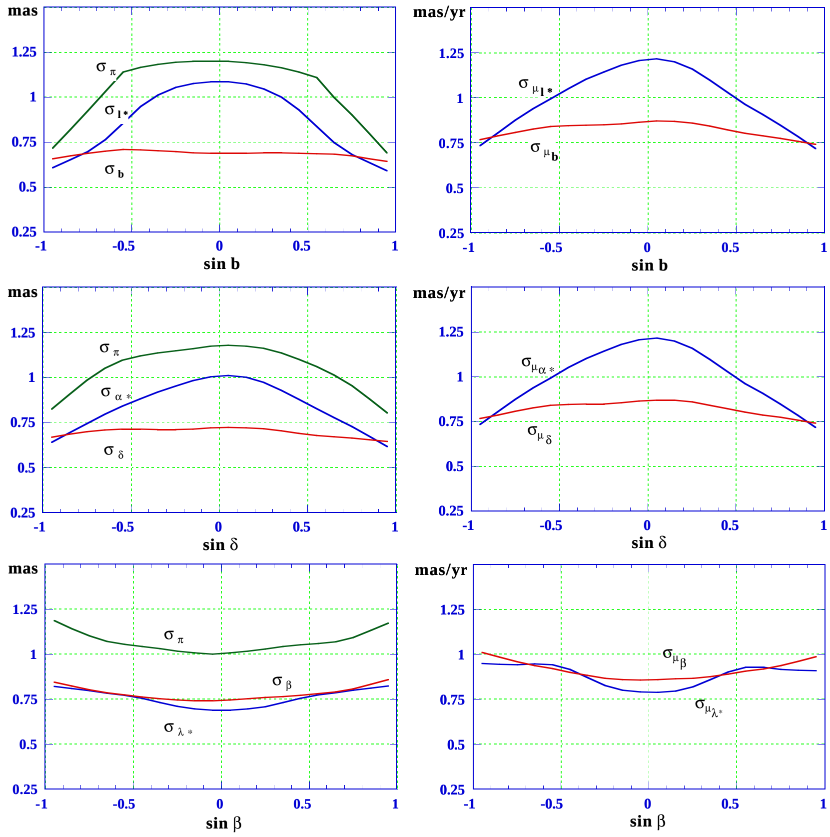

Figure 2. Medians of the standard errors at J1991.25 of the five astrometric parameters as a function of the ecliptic latitude (top), declination (middle) and galactic latitude (bottom). The standard errors are expressed in mas for the position and parallax and in mas/yr for the components of the proper motion. Only the approximately 100 000 single stars are considered in these plots.

the curves showing eventually the median precision of the Hipparcos astrometry.

The median accuracies in Table 1 and in Figures 2 are typical of the bulk of the catalogue, that is to say apply directly to a star of 8.7 mag. The variation of the median accuracy of the five astrometric parameters with the star magnitude is shown in Figure 3. At the faint end the photon noise was the limiting factor and the diagrams match the expected increase in the standard error with the magnitude. For stars brighter than 7 mag, the precision is more or less independent of the brightness as the limiting factor is chiefly instrumental and weakly sensitive to the magnitude.

Since many astrophysical applications of the Hipparcos data will rest on samples of bright stars, it is important to notice that the precision in this range of magnitude is much better than 1 mas or 1 mas/yr on all the astrometric parameters. A useful rule of thumb of the astrometric accuracy applicable to the bright stars ($Hp < 7$) is:

$$\sigma_{\alpha*} \simeq 0.55, \quad \sigma_\delta \simeq 0.45, \quad \sigma_\pi \simeq 0.75 \quad \text{in mas} \qquad (1)$$

and:

$$\sigma_{\mu_{\alpha*}} \simeq 0.65, \quad \sigma_{\mu_\delta} \simeq 0.55 \quad \text{in mas/yr} \qquad (2)$$

2.3. Correlations

The covariance matrix of the five astrometric parameters includes the ten correlation coefficients, which are necessary to express the standard errors and the correlations in other coordinates systems, or to propagate the covariance matrix at an epoch different from T_0. The least correlation between the two positional coordinates appears in ecliptic coordinates, with $\rho(l,\, b) \in [-0.2,\, 0.2]$ while in equatorial coordinates $\rho(\alpha,\, \delta) \in [-0.4,\, 0.4]$. Again this is attributable to the natural symmetry of the scanning law with respect to the ecliptic. Similar values are found for the correlation between the two components of the proper motion. Regarding $\rho(\alpha,\, \mu_\alpha)$ and $\rho(\delta,\, \mu_\delta)$ they may be quite large ($|\rho| > 0.5$) in some regions of the sky. But this is not very significant, because they can be made negligible simply by referring each star to its mean observation time rather than the mean catalogue epoch. Indeed the distribution of the correlations is similar to that expected from the deviation of the individual mean observation time from T_0.

Only one correlation involving the parallax is noticeable: $\rho(\alpha, \pi)$. A sky chart would show a conspicuous dipolar distribution with $\rho \simeq -0.4$ around $\alpha = 18$ h and $\rho \simeq +0.4$ around $\alpha = 6$ h from the equator to latitude ± 60 degrees (see ESA 1997, Vol. 1). This is the largest single systematic effect seen in the Hipparcos

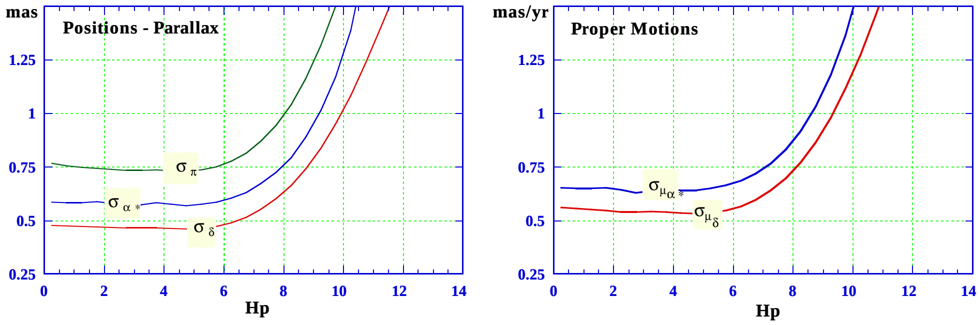

Figure 3. Medians of the standard errors at J1991.25 of the five astrometric parameters as a function of the Hipparcos magnitude. The standard errors are expressed in mas for the position and parallax and in mas/yr for the components of the proper motion. Only the approximately 100 000 single stars are considered in this plot.

Catalogue and it is well accounted for by the time distribution of the observations. While the effective observing period lasted 37 months, it does not cover an integral number of years (Table 1): the first observations were made in November 1989 and the last ones in March 1993, with an interruption of nearly three months in fall 1992. Thus there is an imbalance in the observations distribution in $l - l_{\odot}$, which is ultimately responsible for the correlation between the longitude (or right ascension) and the parallax. The centre of the missing observations is very nearly the autumn equinox when the longitude of the Sun is 180 degrees. Therefore the parts of the sky not observed are in the vicinity of $l = 90$ deg or $l = 270$ deg, because the scanning law implies that the observations are centred at ± 90 deg from the Sun. The observed correlations match quite precisely the theoretical values expected from this asymmetry with respect to the Sun.

3. PROPERTIES OF THE HIPPARCOS PARALLAXES

3.1. Construction of the Parallaxes

There is little doubt that the Hipparcos parallaxes will play a major role for many years to come in the applications of the Hipparcos results to stellar physics and galactic astronomy. Recent and much heralded investigations have shown already the impact of the Hipparcos parallaxes in the revision of the cosmic distance scale and in the re-evaluation of the ages of the oldest stars, although the discussion is not closed yet. The construction of a high resolution Hertzsprung-Russell diagram, is already a vivid and appealing illustration of the impact of accurate stellar distances in the mere description of where the stars lie in a magnitude-colour diagram (Perryman et al. 1995, Perryman et al. 1997).

The Hipparcos parallaxes are trigonometric and by construction are virtually absolute, in that sense they do not use reference background stars. Truly absolute parallaxes would have needed to refer the tiny parallactic motion to a fixed direction, while in fact Hipparcos tied pairs of stars at wide angle. However, the number of objects associated to a particular star is large enough and in sufficiently many directions to eliminate the risk of systematic effects. Numerous analyses of the Hipparcos parallaxes with the preliminary and final solutions confirm this view and indicate that the global zero-point offset, common to all stars, is smaller than 0.1 mas (Arenou et al. 1995, ESA 1997). A recent search of a global zero–point in the parallaxes in the 5.4×10^6 residuals of the astrometric data by Frœschlé et al. 1997 supports also this claim with a non-significant offset of -0.010 ± 0.010 mas.

3.2. Distribution of the Parallaxes

The distribution of the parallaxes measured by Hipparcos is plotted in Figure 4 for all the entries of the Catalogue, including double and multiple stars. Half of the stars are closer than 230 pc. This average depends however on the region of the celestial sphere: the median parallax for Hipparcos stars lying close to the galactic plane is of the order of 2.5 mas, while it reaches 6 mas at mid-galactic latitude, being locally as large as 9 mas. This reflects essentially the initial selection of stars from their astrophysical interest, rather than a true physical distribution. In any case, this is a basic property of the Catalogue that one must be aware of in future investigations.

Only 4100 stars in 118 000 or 3.3 per cent, are found with negative parallaxes, primarily between 0 and 2 mas. Most of this negative tail is of statistical origin, as the parallaxes were not constrained to be positive. The statistical distribution of the measured parallaxes of the distant stars, those with true parallaxes < 1 mas, has a tail of typical width equal to two to three times the standard deviation, $\simeq 3$ mas, extending into the negative region. The ~ 200 parallaxes more negative than $\simeq 3$ mas are more likely to belong to unreliable solutions, multiple stars or stochastic solutions, and should not be considered a part of the statistics.

The right plot in Figure 4 refers to the same data as the left one but with a scale in $\log \pi$ and bins of width 0.1 dex. The distribution is remarkably symmetric from $\pi = 0.1$ mas to the largest parallaxes. The dashed line superimposed is a Gaussian distribution of mean $\mu = 0.68$ and standard deviation $\sigma = 0.38$ and indicates that the distribution of the measured parallaxes is very close to log–normal

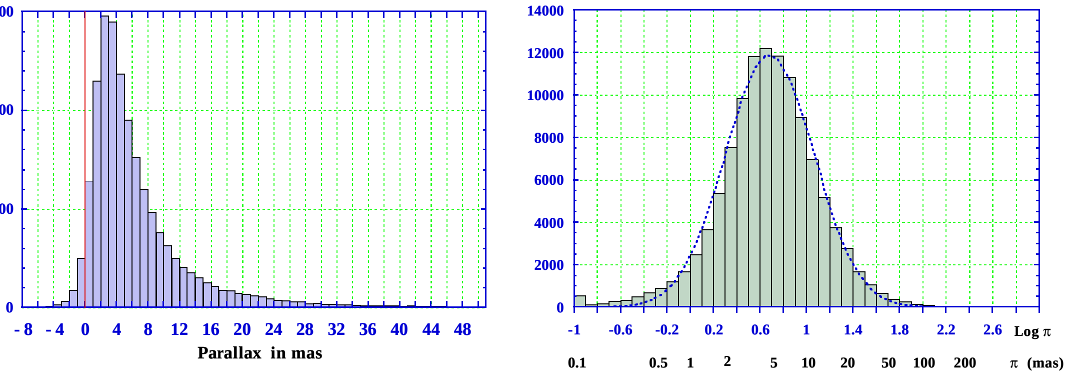

Figure 4. Distribution of the parallaxes measured by Hipparcos. The plots are based on the full content of the Hipparcos Catalogue: single stars, doubles and multiples, acceleration and stochastic solutions. A logarithmic scale in the right plot shows that the parallaxes follow nearly a log-normal distribution. The best normal distribution is superimposed as a dashed line.

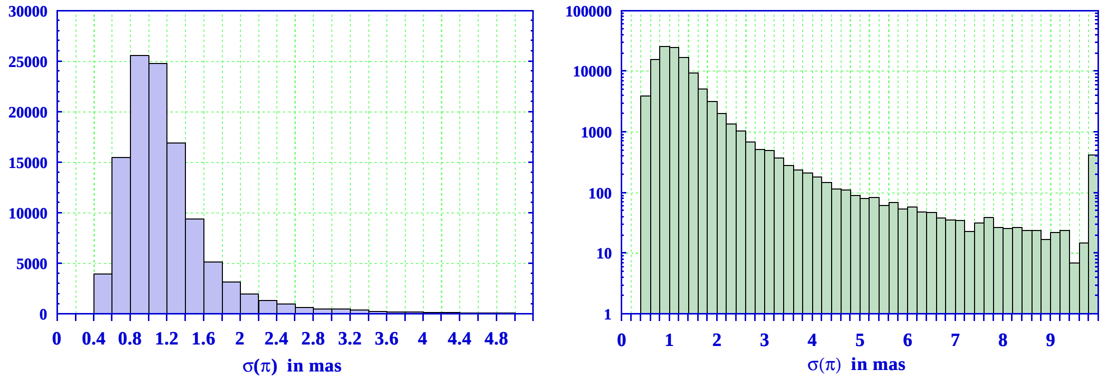

Figure 5. Histogram of the standard errors of the Hipparcos parallaxes for the 118 000 entries of the Catalogue. The same distribution is shown in the left and right plots, with a logarithmic vertical axis in the latter to reveal the small population at the extremes of the distribution.

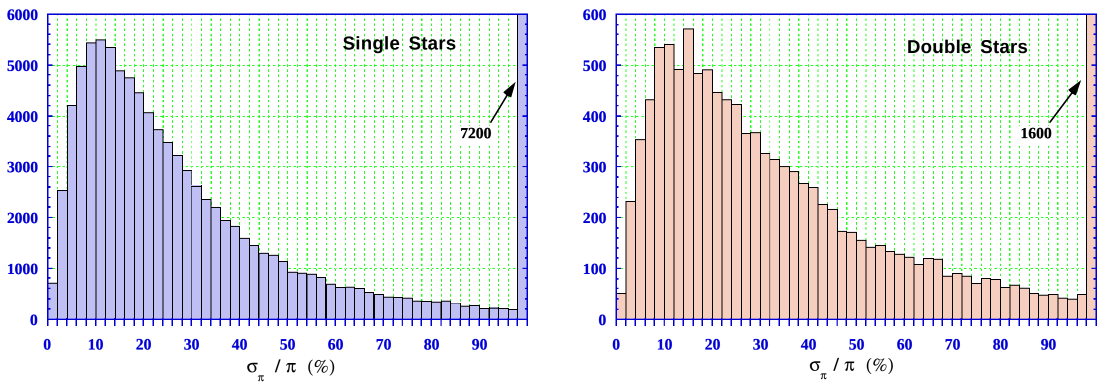

Figure 6. Relative standard errors of the Hipparcos parallaxes for the entries of the Catalogue with a positive parallax. The left plot refers to the 96 700 single stars and the right one to the 12 600 double and multiple systems of Annex C.

Table 2. Number and fraction of the population of single and multiple stars with a relative error of the parallax less than the limit set in the first column. About 8500 entries with negative parallaxes or which are in the DMSA G, O, V or X are not included in the statistics.

σ_π/π	Number		Fraction (per cent)	
per cent	Singles	Multiples	Singles	Multiples
< 1	140	16	0.1	0.1
< 2	710	50	0.7	0.4
< 5	5200	450	5.4	3.6
< 10	17900	1600	18.5	12.8
< 20	42800	4200	44.2	33.3
< 50	78000	8800	80.6	70.0

over a wide range of distances. This is a further hint that the Hipparcos parallaxes are free of systematic effect down to 0.1 mas and are statistically meaningful even for stars much farther than 1 kpc. The slight bump in the first class includes also all the positive parallaxes less than 0.1 mas.

3.3. Distribution of the Standard Errors

The distribution of the standard errors of the parallaxes is shown in Figure 5 with a linear ordinate in the left plot and a logarithmic scale on the right useful to visualise the content of the less populated classes. The main distribution is as regular as possible, with an average at $\sigma_\pi \simeq 0.9$ mas. There are just above 1600 stars with standard errors of the parallax larger than 5 mas, as seen in the right plot. This number is in any case rather small and concerns about 100 very faint single stars ($Hp > 11.5$) with normal solution, about 1000 double or multiple stars of the DMSA-C, quite often the faint component of a two-pointing double, and 500 with stochastic solutions. All these entries are noted in the Catalogue for the poor quality of the astrometric solution as a whole.

More relevant for many astrophysical applications is the relative precision of the distances measured by σ_π/π. The distributions are plotted in Figure 6 separately for the single and non-single stars. All the entries (96 731) not included in the Double and Multiple Systems Annex and with a non-negative parallax make the set of *single stars*, whereas the set *multiple stars* comprises the entries (12 569) of the DMSA-C with non negative parallax. The 8500 missing entries are equally distributed between the solutions with negative parallaxes and the entries in the parts G, O, V or X of the DMSA.

The two distributions in Figure 6 are very alike with a maximum at $\sigma_\pi/\pi \simeq 12$ per cent, although less marked for the double stars than for the singles. However the fraction of entries with $\sigma_\pi/\pi >$ 100 per cent, is much larger for the multiples than for the singles (respectively 12 per cent and 7 per cent).

The vertical scales in Figure 6 differ by a factor 10, which is slightly larger than the ratio of the two populations. This proves that the distribution of the relative error of the parallaxes tends to be of better quality for the single stars than for the multiples, a fact not very surprising. The cumulative distributions given in Table 2 show that the degradation is not very large, with for example 18 per cent of the single stars with $\sigma_\pi/\pi < 0.1$ versus 13 per cent for the multiples. More striking is the fact that the level of 18 per cent of the multiples is reached at $\sigma_\pi/\pi < 0.125$ instead of 0.10 for the singles. This is the result of a fortunate circumstance to the extent that among the astrometric parameters, the positions and proper motions are sensitive to the modelling of the double star, whereas the parallax is not. Thus, one can say, that despite a small difference of quality, the Hipparcos parallaxes are statistically homogeneous irrespective of whether the star was processed as single or not.

4. CONCLUSION

The Hipparcos mission was initially planned to perform global astrometry with a precision of 2 mas for a representative Hipparcos star. The astrometric results after 37 months of effective observation and several years of data analysis surpass significantly this already ambitious goal, thanks to the intrinsic quality of the instrument and the resources deployed in the processing. One must keep in mind that having measured the parallaxes to within 1 mas instead of 2 mas, makes the accessible universe eight times as large as expected from the nominal mission. The examination of the 17 volumes of the printed version of the Catalogue and all the ASCII files shows that Hipparcos has been much more than an astrometric mission, but a genuine advance in stellar astronomy, adding to the astrometric parameters a photometric survey of unprecedented quality and coverage and a renewal in the astronomy of the visual double stars. The Hipparcos legacy will be visible for many years through its far reaching astrophysical applications.

ACKNOWLEDGMENTS

Thanks are due to all the people in the industry or in scientific institutions who have allowed the realisation of this remarkable landmark in science. This overview reflects behind the name of a single author their full dedication to the project over many years. Full names are given in the Hipparcos documentation.

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