20. VERIFICATION OF PARALLAXES

Hipparcos parallaxes will play a major role in the astrophysical applications of the Hipparcos results and in this respect their accuracy is more important than their precision, at least for all the investigations of statistical character. In this Chapter, the systematic errors of the Hipparcos astrometric parameters, including the parallaxes, are evaluated by examining the possible sources of bias arising in the data reduction process. Then, the external errors of the parallaxes are further studied on the basis of individual or statistical comparisons to ground-based distances. The validity of the Hipparcos standard errors are investigated as well.

20.1. Introduction

The distance of the stars was probably the most eagerly awaited fruit of the Hipparcos mission and was indeed the key element that led eventually to the decision to design a dedicated space experiment. The stellar distances are the foundation on which virtually all the stellar and galactic astronomy rest on, and the future development of the astronomical research in these areas will rely to a large extent on the Hipparcos parallaxes. It was then of the utmost importance to validate the results, to certify the standard errors and to assess the magnitude and the kind of systematic errors that may be present in the data.

In practice this validation is not easily achieved. It is commonplace with the Hipparcos data to state that the results have so good an internal accuracy that there is no sample of ground based data which would allow to assess, at least statistically, the pattern of the external errors. This is particularly true for the parallaxes because of the relative paucity of ground–based measurements matching the Hipparcos precision and accuracy. As a consequence the comparison to external data is based on carefully selected sample of stars whose distance is statistically well known, even though it is not for individual objects.

20.2. Errors to be feared and how to check them

The Hipparcos trigonometric parallaxes are essentially absolute, which is not the case of those obtained with ground–based programmes. In principle, given the way the Hipparcos observations were performed and the data reduced, no systematic errors above 0.1–0.2 mas are expected in the Hipparcos parallaxes. However, the possibility of a zero-point shift cannot be ruled out, for example if there has been periodic variations of the basic angle of the instrument beam-combining (Lindegren *et al.* , 1992).

Systematic errors of the order to, or smaller, than 0.1 mas may be evidenced only with samples of several hundred of error–free parallaxes, typically a set of stars known to be farther than few kiloparsecs or cluster members of known distance. The Magellanic Clouds fall short in fulfilling this criterion, because there are less than 50 such stars in the Hipparcos programme which, in addition, are predominantly faint stars. One has then to resort to galactic clusters.

Photometric calibrations ($uvby\beta$), are also used in order to get estimates of the interstellar extinction and to derive visual absolute magnitudes. With these data and a simple galactic model it is possible to compute an unbiased estimate of the global zero-point of the parallaxes of distant stars along with its unit–weight error.

The absence of a significant zero-point error on parallaxes would probably imply the same absence on the other parameters, as the parallax does not play a special role in the astrometric reduction. It is as well possible to have a general view of the systematic errors on all the astrometric parameters, using the residuals from astrometric reduction. For this reason, the Hipparcos data are systematically studied as a function of the astrometric and photometric data of the stars: positions, parallaxes, proper motions, apparent magnitudes and colours.

Regarding the random errors, the standard errors of the Hipparcos parallaxes vary mostly with magnitude, and also with ecliptic latitude as a result of the scanning law of the satellite. Internal tests by Lindegren (1995) and external tests by Arenou *et al.* (1995) on the 30–month solution reached the conclusion that the standard errors on parallaxes were good estimates of true external errors. However, in the H30 catalogue, the astrometric parameters were obtained with a straight average of FAST and NDAC data, and their assigned standard error was the quadratic average of FAST and NDAC standard errors; unlike the final merged solution, these averages did not take into account the correlation between Consortia data. It was thus necessary to study the random errors in the final Catalogue. Given their large range (from 0.5 to 5 mas at the faint end), the standard errors themselves are not evaluated directly but the unit-weight error is studied instead.

20.3. Comparison to ground-based data

In this section, Hipparcos parallaxes are compared to various sources of ground-based parallaxes. Ground-based measurements are generally affected by atmospheric or mechanical effects and suffer from lack of homogeneity. Thus, if the ground–based data cannot be used to assess the external precision of Hipparcos parallaxes, they are very useful to cast light on the systematic errors present in ground-based measurements at the millisecond level.

In all the following comparisons robust estimates have been used to secure results insensitive to outliers. The estimates rely heavily on the median of the distributions instead of the average as location parameter, and on the half–width between $15.85^{\rm th}$ and $84.15^{\rm th}$ percentile as an unbiased estimate of the standard deviation.

USNO parallaxes

The US Naval has been conducting a systematic photographic program for trigonometric parallaxes since 1964 with the 61-inch telescope at Flagstaff. The latest list has brought the program to 1013 stars and over the years the typical parallax precision for a completed series, has evolved from ± 4 mas to ± 2 mas. This program is now discontinued and superseded by the parallaxes determined by the CCD initiated in 1983. Results from that program demonstrated that *relative* parallaxes with formal mean errors in the 0.5 to 1.2 mas range are readily achieved if suitable reference star frames are available (Monet et al., 1992).

For the present comparison to the Hipparcos parallaxes, a set of $n_\pi = 88$ stars (Harrington, 1980, 1993) has been used. The median quoted formal precision for these stars is ≈ 2.5 mas. Differences between Hipparcos and USNO results are plotted in Figure 20.1 and shows that a very good agreement is found, with no obvious outlier. The median of the differences between these ground–based parallaxes and their Hipparcos counterparts is 0.2 ± 0.35 mas, typically of the order of $\sigma/\sqrt{n_\pi}$, suggesting the absence of bias and of systematic differences between the two technics. The distribution of normalized differences computed as

$$\frac{\pi_{\rm USNO} - \pi_{\rm H}}{(\sigma^2_{\rm USNO} + \sigma^2_{\rm H})^{1/2}}$$

has a standard deviation of 0.96, a good indication that the formal errors are probably realistic.

VLBI parallaxes

The systems of positions and proper motions resulting from the analysis of the Hipparcos data has a remarkable internal consistency, meaning that the angular separation between two stars is known with a millisecond accuracy, but without any connection to any predefined reference system. In order to link the Hipparcos reference system to the ICRS, several link programmes were undertaken (Lindegren and Kovalevsky, 1995) and used to rotate the provisional Hipparcos solution to the ICRS. Although this link has no influence on the parallaxes, it happens that the extragalactic link programme based on the VLBI observations of radio stars carried out by Lestrade *et al.* (1995), yielded positions, proper motions and parallaxes of 12 optically bright radio-emitting stars to the outstanding precision of 0.2–1 mas, the only instance where individual ground-based parallaxes are of better quality than Hipparcos.

The 12 VLBI stars are listed in Table 20.1 with the parallaxes measured by Hipparcos and by radio–interferometry (Lestrade *et al.* , 1997). The comparison illustrated by the plot of Figure 20.2 shows that a very good agreement is found between the two sets of measurements. Given the accuracy of the VLBI data, and the fact that as far as

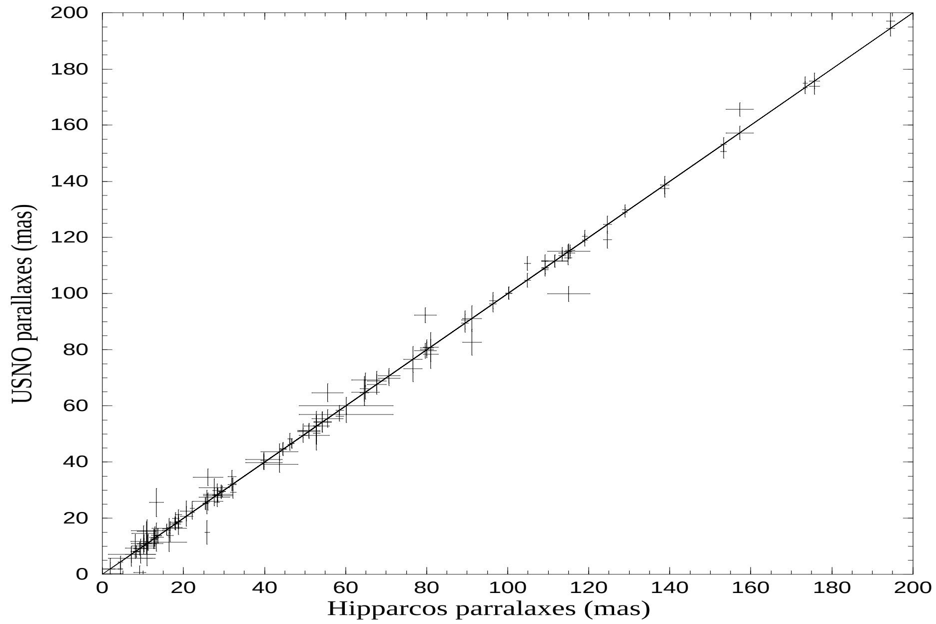

Figure 20.1. *Comparison between Hipparcos and USNO parallaxes.*

Table 20.1. List of radio stars observed in the VLBI programme.

HIP	Hp	α	δ	π_{H}	σ_{H}	π_{VLBI}	σ_{VLBI}
		deg	deg	mas	mas	mas	mas
12469	10.8	40.1	61.2	5.65	2.28	-0.66	0.62
14576	2.1	47.0	41.0	35.14	0.90	32.51	0.59
16042	6.6	51.7	28.7	19.91	1.25	19.89	0.39
16846	6.0	54.2	0.6	34.52	0.87	33.88	0.47
19762	10.9	63.6	28.2	9.88	2.71	6.93	0.25
23106	8.2	74.6	-75.3	3.43	0.61	4.02	0.80
66257	5.0	203.7	37.2	22.46	0.62	22.21	0.45
79607	5.4	243.7	33.9	46.11	0.98	43.93	0.10
98298	9.0	299.6	35.2	0.58	1.01	0.73	0.30
103144	7.4	313.5	44.4	10.68	0.73	8.59	0.33
109303	6.3	332.2	45.7	23.79	0.59	23.97	0.37
112997	6.0	343.3	16.8	10.33	0.76	11.29	0.68

Hipparcos is concerned, these stars are not peculiar, the comparison looks very favorable

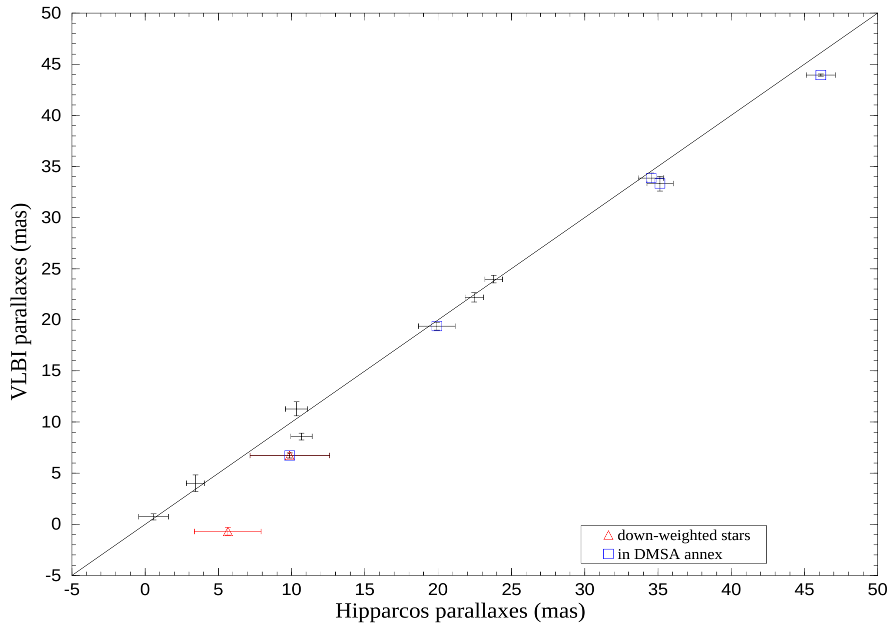

Figure 20.2. *VLBI versus Hipparcos parallaxes (mas). Two stars were down-weighted for the extragalactic link, due respectively to their jet structure or duplicity, and five stars are in the Hipparcos Double and Multiple Star Annex.*

for the Hipparcos determination, although the small number of objects precludes from drawing too general a conclusion.

Yale parallaxes

The Yale University Observatory has published in 1995 a completely revised and enlarged edition of the *General Catalogue of Trigonometric Stellar Parallaxes* containing 15 994 parallaxes for 8 112 stars published before the end of 1995 and obtained at various places. (GCTP, van Altena *et al.*, 1995). The mode of the parallax accuracy for the $\approx 1\,700$ newly added stars of 4 mas is considerably better than in the previous editions (about 16 mas). The relative parallaxes which constitute the basic data, are corrected to absolute parallaxes using corrections that are based on an improved model of the Galaxy. Altogether the median formal errors of the GCTP parallaxes is about 10.5 mas. An attempt is made by the authors to determine the accidental and systematic errors of the parallaxes.

Compared to the small samples studied in the previous sections, the *General Catalogue of Trigonometric Stellar Parallaxes* provides a sample of 4 292 stars suitable for the comparisons with the Hipparcos single stars. A more in-depth cross-identification process could have probably yielded more stars, however the sample has been considered large enough for our comparison purpose, in regard of the extra effort needed to get a comprehensive intersection of the two catalogues.

A straight comparison between GCTP and Hipparcos parallaxes gives a median difference $\pi_{\mathrm{GCTP}} - \pi_H = 1.8 \pm 0.2$ mas, which differs significantly from zero. This bias comes partly from distant stars: the difference amounts to 2.6 ± 0.3 mas for stars farther away than 50 parsecs whereas it is only 0.5 ± 0.4 mas for stars nearer than 20 parsecs, that is to say hardly significant. It could originate from the transformations applied to correct to the absolute parallaxes using a model of the Galaxy, although this statement needs to be substantiated.

However, the main source of bias comes from zonal errors, as may be seen in Figure 20.3. Systematic errors, up to 7 mas at declination $\delta = -30$ deg, and to a smaller extent in right ascension, are found. If the comparison is restricted to the north hemisphere, the median difference between GCTP and Hipparcos parallaxes is reduced to 1.2 ± 0.3 mas for stars farther than 50 parsecs. The difference between the two hemispheres is striking, and comes as no surprise given the number of observatories and variety of instruments involved in the compilation made by van Altena *et al.*. Moreover, variations with magnitude cannot be ruled out: a bias is also possibly present at the bright and faint ends.

Apart from the systematic errors reported above, no indisputable outlier was found (the largest deviation is of 4.7 σ). The width of the normalised differences (see Equation 20.1) is 1.04 ± 0.01, indicating that their is no global scale defect in the formal errors of the *General Catalogue of Trigonometric Stellar Parallaxes*.

20.4. Systematic errors on Hipparcos astrometric parameters

The search of a zero-point error, or of more complex systematic effects, on the five astrometric parameters is not straightforward since their observed value cannot be compared to their unknown true value. It is however possible to test for neglected terms in the position, by reprocessing the data with an improved model including either a constant term or by extending the five-parameter model of star motion which was adopted for the majority of the Hipparcos stars, including systematically acceleration components in right ascension and declination. These terms being physically spurious, they should average to zero. If the observed averages happen not to be significantly different from zero, one could conclude that the astrometric parameters are also free of significant systematic errors of global nature.

During the data processing, every star has been tested for the significance of the acceleration terms. When the test was negative, the usual five parameter model was taken as the baseline. Now, if we exclude all the double stars and the suspected astrometric binaries, and process all the other stars with the extended model, the average value of the components of the acceleration should be zero. Any departure from this would be an indication that small systematic effect could pervade the astrometric solution. One must add that there are only a handful of nearby stars with perspective acceleration larger than 0.1 mas and they do not affect the overall statistics.

Therefore a dedicated run of the astrometric processing was set, with either a six-parameter model (a constant term c was also computed) or a seven-parameter (including the acceleration components $g_{\alpha*}$ and g_δ). Only stars never flagged as double, were

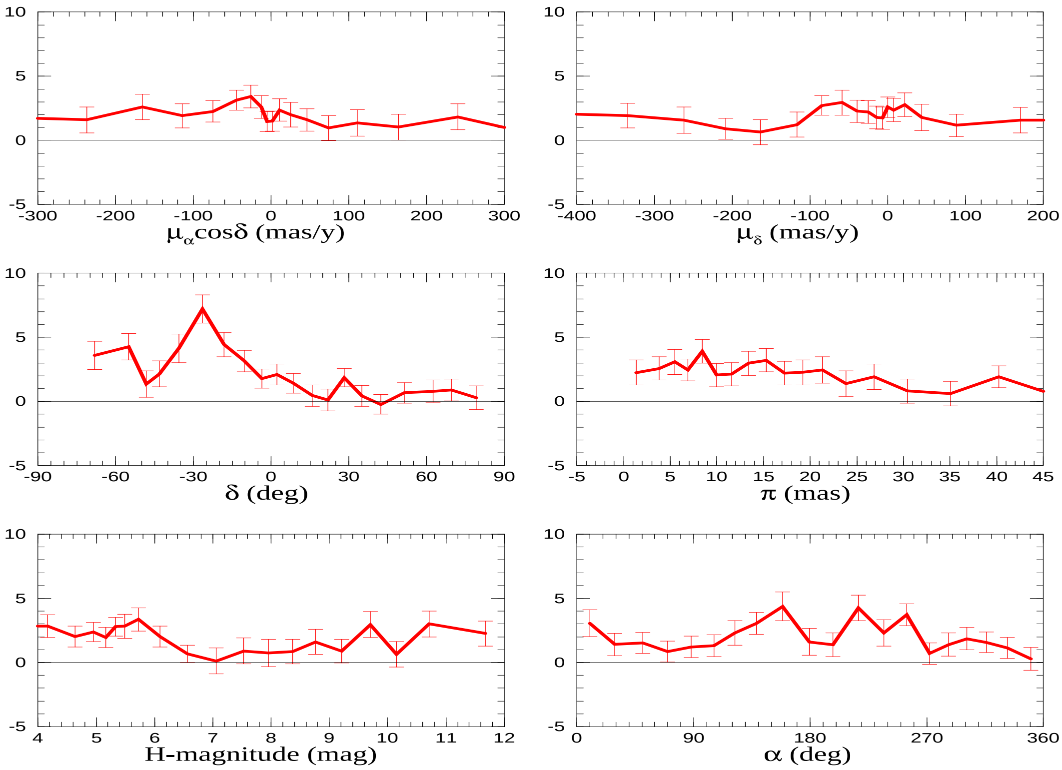

Figure 20.3. *Distribution of the parallax differences between the General Catalogue of Trigonometric Stellar Parallaxes and Hipparcos.*

considered. This amounts to $\approx 92\,000$ stars for the six-parameter solution, with an *a priori* exclusion of outliers, and $\approx 95\,000$ stars for the seven-parameter solution. On the average, the formal errors on the offset c, and the acceleration components $g_{\alpha}*$ and g_{δ} were respectively about 0.6 mas, and 3.1 and 2.4 mas/yr^2. In both models, the unit-weight error of these terms were found to be 1.07, suggesting that the standard errors of the Hipparcos astrometric parameters might be slightly underestimated.

The medians of the three terms are plotted in Figure 20.4 as a function of magnitude and colour, and as a function of the five Hipparcos astrometric parameters. Our concern is about all significant variations larger than 0.1 mas. Although this limit may appear very small, it is about one quarter of the best standard errors of the parallaxes (0.42 mas) in the Hipparcos Catalogue. Possible departures from zero of the plotted data should however be appreciated with their formal errors in mind, at a 2σ level for instance. The quoted error bars depend both on standard errors (which increase with magnitude) and on the number of stars in each bin.

1. For the brightest stars a significant offset is found: the median value of c for the $\approx 1\,000$ stars brighter than $Hp = 5$ mag is 0.11 ± 0.01 mas.

2. The chromaticity effect played an important role in the Hipparcos data reduction; a clear trend may be seen, especially concerning redder stars. For the ≈ 900 stars

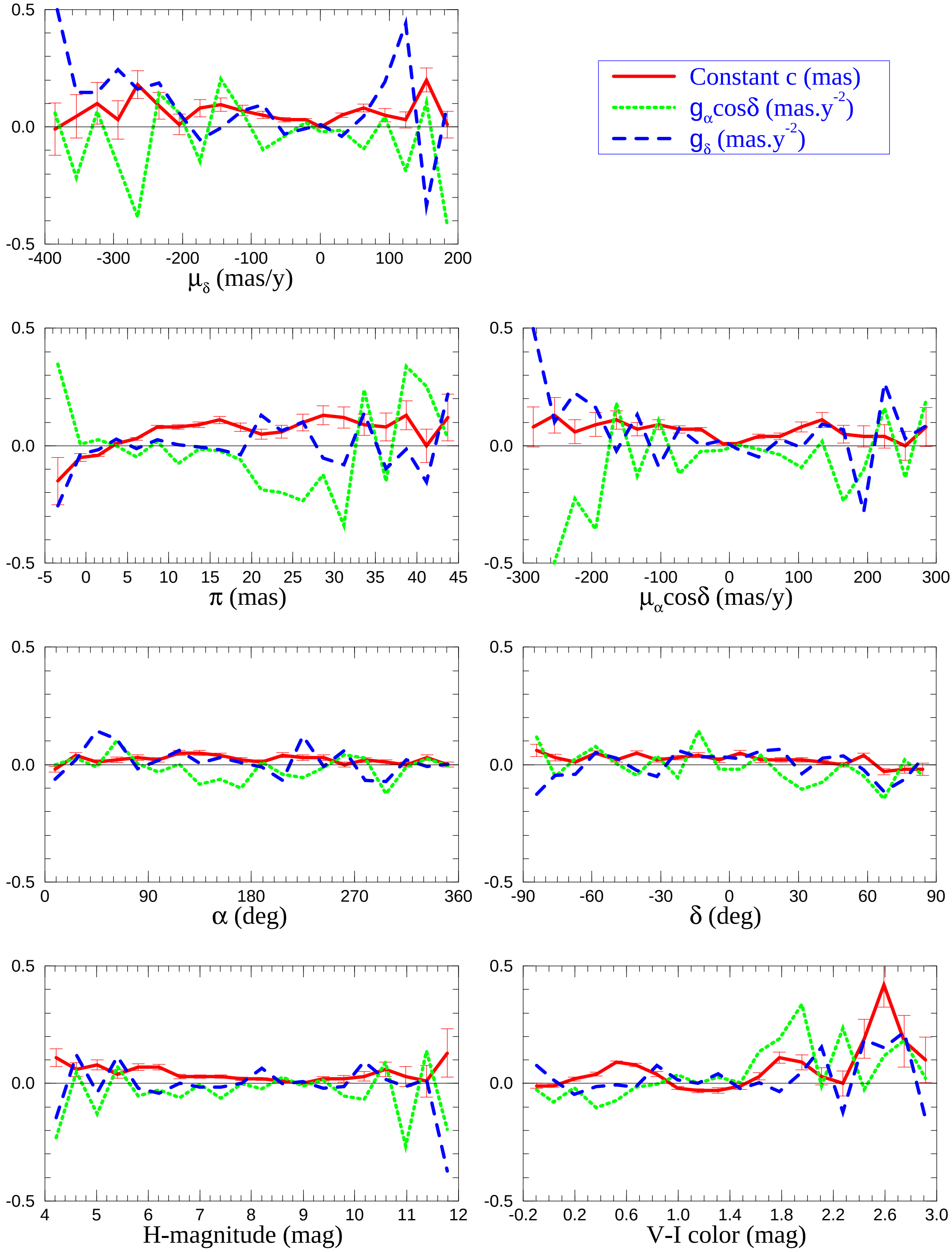

Figure 20.4. *Variation of a constant term and of the acceleration components, obtained respectively with a six and seven-parameter astrometric model, as a function of photometric and Hipparcos astrometric data. For clarity purpose, only c error bars are indicated; the errors on $g_{\alpha*}$ and g_δ are about 5 and 4 times larger. Within their error bars, these terms are expected to be around 0 if the astrometric parameters are free from systematic errors.*

with $V-I > 2.5$, one finds a median value of c of 0.24 ± 0.04 mas, significantly larger than 0.1 mas. The acceleration components exhibits the same trend. Significant peaks around $V-I = 0.6$ and $V-I = 1.8$ are also found.

3. No significant effect is found as a function of position.

4. Concerning parallaxes, no conclusion may be drawn from the small parallaxes or from the negative tail, since in this case the parallax value represents merely the observation error, which is obviously correlated with the observation errors on c, $g_{\alpha*}$ and g_δ; however, for larger parallaxes, the c term remains constant and significantly positive.

5. Variations of accelerations with high proper motions, noticeable for $\mu_{\alpha*} < -200$ mas/yr are possibly due to the expected correlation between g and μ.

Although the occurrence of systematic errors greater than 0.2 mas is possible for the reddest stars, it must be stressed that this analysis was done by adding one or two unknowns in the astrometric reduction. In the case of the baseline model with five astrometric parameters, these errors are probably distributed among the five unknowns. Apparently, parallax and proper motions are more sensitive to this effect than coordinates.

Finally, one must remark that the number of stars affected by a possible systematic error above 0.1 mas remains in any case very small. As may be seen in Figure 20.4, the bulk of the Hipparcos stars ($Hp \approx 9$, $\pi_\mathrm{H} \approx 3$ mas, low proper motion) corresponds to values of c, $g_\alpha*$ and g_δ completely negligible on the average.

20.5. The zero-point and unit-weight error of the parallaxes

It was shown in the previous section that the astrometric parameters may have small, but significant, systematic errors. The purpose of this section is to assess the magnitude of the zero-point z of the Hipparcos parallaxes. Simultaneously, the standard errors of the parallaxes are also studied by means of the determination of the unit–weight error $k =< \sigma_\mathrm{ext}/\sigma_\mathrm{H} >$, that is to say the ratio of the external to the internal errors. If both parallaxes and standard errors are unbiased, the expected values are $z \approx 0$ and $k \approx 1$.

Magellanic Cloud stars

Magellanic clouds stars were included in the Hipparcos programme in order to determine the proper motion of the SMC and LMC. The two *Clouds* are distant enough, with parallaxes of ≈ 0.02 and 0.015 mas, so that they can be used to search for a systematic bias in the Hipparcos parallaxes. Out of the 46 Hipparcos stars lying in the Magellanic Clouds which were regularly observed during the mission, 8 have been solved with a poor parallax accuracy. They have been detected as non single stars and placed in the Double and Multiple Star Annex. Three of these stars belong to the category of the stochastic solutions, due to the impossibility to reconcile the final residuals with the *a priori* abscissa errors.

Using the 38 remaining single stars, the average weighted parallax is $z_{\mathrm{M}} = -0.1 \pm 0.23$ mas. However, due to the correlation between great circle abscissae, the precision on the mean parallax of a group of n adjacent stars is about $\frac{\sigma_\pi}{n^{0.35}}$ instead of the expected $\frac{\sigma_\pi}{\sqrt{n}}$ (Lindegren, 1989). This has not been taken into account in the quoted error bar of the average parallax. The unit–weight error is $k_{\mathrm{M}} = 1.04 \pm 0.12$. This analysis on a very limited and peculiar sample (the stars in the Magellanic Clouds are predominantly faint) leads to the conclusion that the zero-point in the parallax determination is not larger than 0.4 mas, too high an upper bound to qualify the Hipparcos distances.

Open cluster stars

The open star clusters are the most recognisable stellar systems and are easily observable even with a small telescope. Astronomers have long recognised their interest for understanding the stellar evolution as well as their link with the physics and dynamics of the Galaxy. To date, they are just over 1 200 known open clusters, nearly all within 2 000 parsecs.

Because the members of a star cluster form a more or less bound system, they are essentially all at the same distance. This property associated with the assumption of a common origin has made possible to measure the distance of an open cluster with some confidence. The distances of galactic open clusters are believed to be known with a relative error of the order of ten percent. Using far enough clusters (> 200 parsecs) and assigning to each member of a particular cluster, the distance of that cluster, allows to get an absolute error on their parallax better than 0.5 mas.

These estimates provide a reliable basis for a comparison with the Hipparcos parallaxes, providing that all the test stars are true members of the corresponding clusters. As is well known, to decide unambiguously on the membership of a star to a particular cluster is a prerequisite for all cluster studies and is not a trivial task. Indeed, Hipparcos results will be widely used for this purpose. The basic assumption is that individual members of a star cluster move essentially in the same direction, an indication that they have a common origin. In this work, to assess the cluster membership, the average proper motion of the cluster was computed with all the candidates stars. Then all the stars with a proper motion component relative to the average, five times greater than its standard error were rejected.

Using the BDA cluster data base (Mermilliod, 1992), and the distance moduli quoted by Lyngå (1987), parallaxes were available for 391 stars, after exclusion of non-members. The median difference between the Hipparcos and cluster parallaxes was found to be $z_{\mathrm{C}} = 0.04 \pm 0.06$ mas, thus not significantly different from zero, and the unit–weight error is $k_{\mathrm{C}} = 1.06 \pm 0.07$. This is a much more significant result than with the Magellanic clouds, although the contribution of the uncertainty of the distance of the clusters to the error of the median would require a more refined appraisal.

Estimation using photometric data

After trigonometric and moving cluster parallaxes, calibrated intrinsic luminosities provide the most widely used and reliable distance estimators for individual stars. Numerous $uvby\beta$ calibrations were used in order to obtain an estimate of the photometric distance modulus for all available stars. The major part of the HR diagram was covered: dwarfs B to M2, supergiants B to G5, population II F stars; red giants are of course missing. A program was built to choose automatically the calibration which must be applied, and from these calibrations, estimates of intrinsic (corrected for the reddening) photometric indices, $B-V$ colour excess, interstellar extinction A_V, absolute magnitude, effective temperature, gravity and metalicity were obtained. Photometric errors were propagated through the different steps so that formal errors on the stellar parameters were also estimated. Eventually the absolute magnitude, the extinction, and the apparent magnitude were used to determine the distance modulus $t = V - M_V - A_V$.

The $uvby\beta$ input data comes from the Hauck & Mermilliod (1990, 1996) Catalogue in an updated version. In order to minimize the error on the distance modulus based on photometric data, only the most distant stars must be kept since a relative error in parallax translates directly into an absolute error in the distance modulus. For this reason, the sample was restricted to stars with a distance modulus $8.5 < t < 14.5$. In addition, stars known to have a variability > 0.2 mag, having a joint photometry associated to binaries or those with $\sigma_t > 0.35$ were not included in the sample. After all this filters were applied the final sample numbered 467 stars.

The truncation in distance moduli combined with the random measurement errors causes the sample average parallax to be biased. In order to take this bias into account and limit its adverse effect, a specific statistical method was applied by Arenou *et al.* (1995) and is now briefly summarised.

The conditional probability density function (pdf) that the Hipparcos parallax of a star is $\pi_{\rm H}$, given its observed distance modulus t, its galactic latitude b, the Hipparcos zero–point error (z) and the unit–weight error (k), reads :

$$f(\pi_{\rm H}|t,b,z,k) = \frac{\int_0^{+\infty} p_1(\pi_{\rm H}|\pi,k,z)p_2(t|\pi)p_3(b|\pi)p_4(\pi)d\pi}{\int_{-\infty}^{+\infty}\int_0^{+\infty} p_1(\pi_{\rm H}|\pi,k,z)p_2(t|\pi)p_3(b|\pi)p_4(\pi)d\pi d\pi_{\rm H}} \qquad [20.1]$$

where the conditional probability distributions p_1 to p_4 are determined in Arenou *et al.* (1995). In this equation the unknown parameters are the zero–point and the unit–weight errors; they can be estimated from the observed parallaxes and distance moduli. The estimator of (k,z) is found numerically from the maximum of log-likelihood function $\mathcal{L} = \sum \ln f(\pi_{{\rm H}_i}|t_i,b_i,z,k)$ of our n-sample. The method also checks the quality of the fit to the model, filters out the outliers and gives the standard errors of the unknowns.

The distribution of the errors on Hipparcos parallax was shown to be approximately Gaussian by Arenou *et al.* (1995). Thus p_1 is a Gaussian of expectation $\pi + z$ and standard deviation $k\sigma_{\rm H}$. A possible censorship on $\pi_{\rm H}$ was taken into account, although no truncation was actually applied to Hipparcos parallaxes. The moduli t were assumed Gaussian around the true value $-5\log\pi - 5$ and the truncation on t was also explicitly taken into account. Concerning the joint distribution of the galactic latitude and parallax, $p(b,\pi) = p_3(b|\pi)p_4(\pi)$, the distribution perpendicular to the galactic plane was assumed exponential with a mean scale height of 100 pc. However this assumption is not critical for the sample investigated here.

Applying this method to the available sample of $n = 467$ stars, the zero-point found was $z_P = -0.05 \pm 0.05$ mas, thus not statistically different from 0, the unit–weight error being $k_P = 1.04 \pm 0.04$. The uncertainty of the median is in good agreement with $1/\sqrt{n}$ mas. No outlier was found in the sample.

20.6. Conclusion

Results obtained with the external comparisons are summarized Figure 20.5. The global zero-point error of Hipparcos parallaxes can be safely assumed to be smaller than 0.1 mas. Another important conclusion is that the standard errors of the parallaxes have probably not been underestimated by more than 10%.

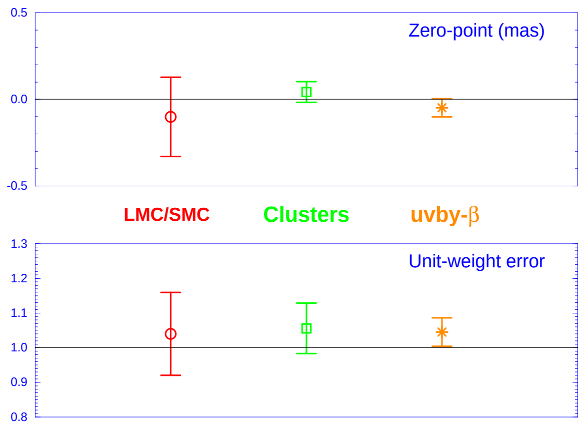

Figure 20.5. *Zero-point and unit-weight of Hipparcos parallaxes, from external comparisons using distant stars.*

These results have been derived from distant stars only, so that one may ask if they are representative of the whole Hipparcos Catalogue. This is probably indeed the case: Firstly, the absolute value of the distance played absolutely no specific role in the Hipparcos data processing, and it is not easy to imagine a systematic effect on the parallax which would be function of the parallax itself. On the other hand no bias was found in the comparisons to the USNO or VLBI parallaxes despite the fact they cover a large range of parallaxes.

Finally, the chromaticity effect exhibited in previous section may also be studied with the distant stars. Although no red star was available for this comparison, Figure 20.6 shows that variations of the with colour of about some tenth of mas cannot be excluded even for blue stars. It is however difficult to assess whether these variations are really in the Hipparcos data or due to ground-based data used for the comparison purpose.

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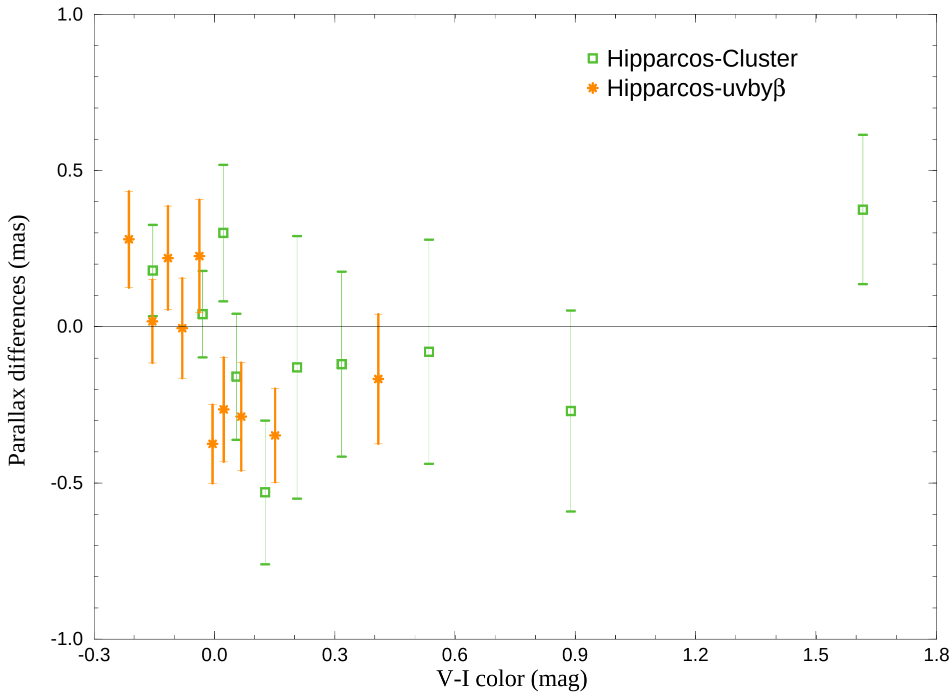

Figure 20.6. *Variation of parallax zero-point versus $V - I$ colour, using cluster and photometric data of distant stars.*

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