1.2 SPACE MISSIONS

PROPERTIES OF THE HIPPARCOS CATALOGUE: WHAT CONFIDENCE CAN WE HAVE IN THE FINAL DATA?[1]

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Abstract. The foreseen complexity of the the ESA Hipparcos mission led to the establishment of two independent scientific consortia (FAST and NDAC) for the parallel processing of all main mission data. The validation of Hipparcos data through internal and external checks and by interconsortia comparisons is outlined. Examples are given based on preliminary solutions. The various checks indicate that the overall accuracy and reliability of the Hipparcos Catalogue will be extremely high.

1. Status of the Hipparcos Catalogue

The Hipparcos satellite delivered high-quality astrometric and photometric data during 37 of the 40 months from December 1989 to March 1993. This information is now being processed by the three 'data reduction consortia' TDAC (for the Tycho mission of about a million stars) and FAST and NDAC (for the main mission of 118,000 selected stars). According to current planning the Hipparcos Catalogue will be released around 1997.0, but selected data will be available a year earlier for approved investigations.

The FAST and NDAC consortia have both completed their independent solutions (here called F30 and N30[2]) based on the first 30 months of data. In this paper I discuss the properties of the final catalogue (HIP) as can be extrapolated from these solutions and the provisional catalogue called H30,

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[1] Based on observations with the ESA Hipparcos satellite

[2] Not to be confused with the 'normal system' N30 created by H.R. Morgan in 1952. The Hipparcos N30 catalogue, like F30 and H30, will never be published.

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Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, 55–60.

obtained by the averaging and merging of F30 and N30. Table 1 summarizes the main characteristics of H30 and HIP.

TABLE 1. Median formal standard errors in the provisional catalogue H30, and extrapolated to the final catalogue (HIP). The apparent non-improvement from H30 to HIP is due to the assumption that the additional stars all fall above the median accuracy of HIP

Quantity	H30	HIP	Unit
Number of stars (approx)	107,500	118,000	–
Mean epoch, J1900+	91.14	91.24	year
$\sigma_\alpha \cos\delta$	1.17	1.17	mas
σ_δ	0.96	0.95	mas
$\sigma_{\mu\alpha} \cos\delta$	1.65	1.51	mas yr^{-1}
$\sigma_{\mu\delta}$	1.35	1.22	mas yr^{-1}
σ_π	1.45	1.45	mas

The standard errors in Table 1 are *formal* ones obtained from the least-squares solutions of the data reductions. The actual or *external* errors of any experiment are usually larger due to modelling errors, which in general also introduce biases, or *systematic* errors, of the parameters. External and systematic errors are most directly checked by comparison with independent data, but relatively little data of sufficient accuracy is available. Internal checks and interconsortia comparisons can on the other hand be performed on a massive scale, but provide only indirect evidence of data properties. Both kinds of tests are briefly reviewed in Sections 3 to 5.

2. Parallel Reductions

The expected complexity of the Hipparcos science data processing motivated ESA to appoint two independent groups, or consortia, to perform the complete reduction from raw satellite data to the end product. The groups are known by their acronyms FAST (Kovalevsky et al., 1992) and NDAC (Lindegren et al., 1992). Although the general principles of the reductions are the same, each group has developed its own algorithms, software implementation and processing strategy. As for the modelling of the instrument and mission, the goal has been to take into account all known effects that may correspond to a shift of 0.1 mas or more in a single observation.

The main interaction between FAST and NDAC has been to compare intermediate results at various levels of the processing, first using simulated input data and later the real satellite data. As a direct consequence of this activity a number of errors and shortcomings have been identified and corrected on both sides, and some algorithms have been considerably improved.

In retrospect it appears that the strategy of parallel reductions has been very successful, and the most important guarantee that the final Hipparcos Catalogue will fully reflect the high quality of the satellite data.

3. Internal Checks

Within each consortium the consistency between the satellite data and the reduction model can be checked by a number of statistical tests and solution experiments. The simplest tests concern the size and distribution of the residuals and possible correlations with other parameters such as magnitude, colour and position on sky. In general such tests have yielded satisfactory results if allowance is made for a small fraction of outliers. The use of robust estimation techniques is essential at all stages of the reductions.

Another, very powerful data consistency test is to divide the observations into two similar but distinct data sets, which are reduced independently. The differences of the resulting astrometric parameters, divided by the square root of the sum of the variances from the two solutions, should ideally follow the centred unit normal distribution $N(0,1)$. In reality small deviations are found which are used to adjust the *a priori* weights assigned to the input data. By this procedure the formal standard errors can be made consistent with the data on a global scale.

A quite different kind of test is to expand the reduction model by introducing additional *ad hoc* parameters that are estimated along with the 'normal' parameters. Judiciously chosen such parameters may reveal subtle instrumental effects which would otherwise be masked by a much larger observation noise. In the NDAC sphere solution, for example, the temporary introduction of a sixth unknown for each star (in addition to the five astrometric parameters) has allowed a detailed mapping of the instrument chromaticity as function of colour index. This new information will be incorporated in an improved reduction model for the final solution.

Another example of *ad hoc* parameters are the global harmonic coefficients Γ_2 to Γ_{12} introduced to model possible thermally induced periodic variations of instrument parameters (Lindegren et al., 1992). In the N30 solution these coefficients are estimated with formal standard errors below 0.01 mas, and none is found to exceed 0.025 mas in absolute value. This indicates an extremely good short-term stability of the basic angle, and indirectly supports the assertion that the parallaxes are absolute at the 0.1 mas level.

4. FAST–NDAC Comparisons

There are 95,579 stars in common between the two provisional catalogues F30 and N30. After global re-orientation and rotation of the catalogues to a common system the median differences, taken in the sense N30 – F30, are -0.064 ± 0.004 mas in δ, -0.024 ± 0.005 mas/yr in μ_δ and -0.048 ± 0.005 mas in π. (In α and μ_α the median differences are by definition zero after transformation to the common system.) Dividing the material according to hemisphere, magnitude and colour does not produce any larger differences. A significant colour-dependent rotation difference is however noted in the proper motions, possibly caused by inadequate chromatic modelling. Full clarification of this effect is required, if it is still present in the 37 months data, before the results can be accepted as final.

The rms differences are typically about the same size as the formal standard errors in Table 1. Due to the varying precision it is more useful to consider the normalized differences, $\Delta p^* = (p_{\rm N} - p_{\rm F})/(\sigma^2_{p{\rm N}} + \sigma^2_{p{\rm F}})^{1/2}$, where p stands for each of the five astrometric parameters. Normal probability plots of the five quantities Δp^* are shown in Fig. 1. The distributions are remarkably close to normal, especially for the parallaxes. The rms values of the normalized differences are less than unity because of the positive correlation of the errors in $p_{\rm N}$ and $p_{\rm F}$. The circumstance that they are still relatively large for the preliminary catalogues (~ 0.7) indicates that there is still room for improvement by iteration and by averaging the consortia results.

5. External Comparisons

Positions. Standard catalogues of stellar positions are totally inadequate for checking the positions in H30. Two sources do however provide a small number of very accurate positions useful for a comparison with Hipparcos.

The USNO Mark III optical stellar interferometer (Hummel et al., 1994) has yielded positions for a small number of bright stars in the 10–20 mas accuracy range. A comparison of arc length differences with respect to H30 for nine stars shows very good agreement within the quoted standard errors, thus confirming the accuracy of both the Mark III results and H30 at the 10 mas level.

VLBI observations of some radio stars relative to quasars already yield astrometric parameters at the sub-mas accuracy level. Preliminary VLBI data for seven radio stars in H30, observed as part of the programme to link Hipparcos to the extragalactic VLBI system (Lestrade et al., in preparation), shows rms residuals of about 2.1 mas. The expected rms residual, from the formal standard errors, is about 1.2 mas. This agreement is quite satisfactory in view of the problematic nature of these stars (binaries, pos-

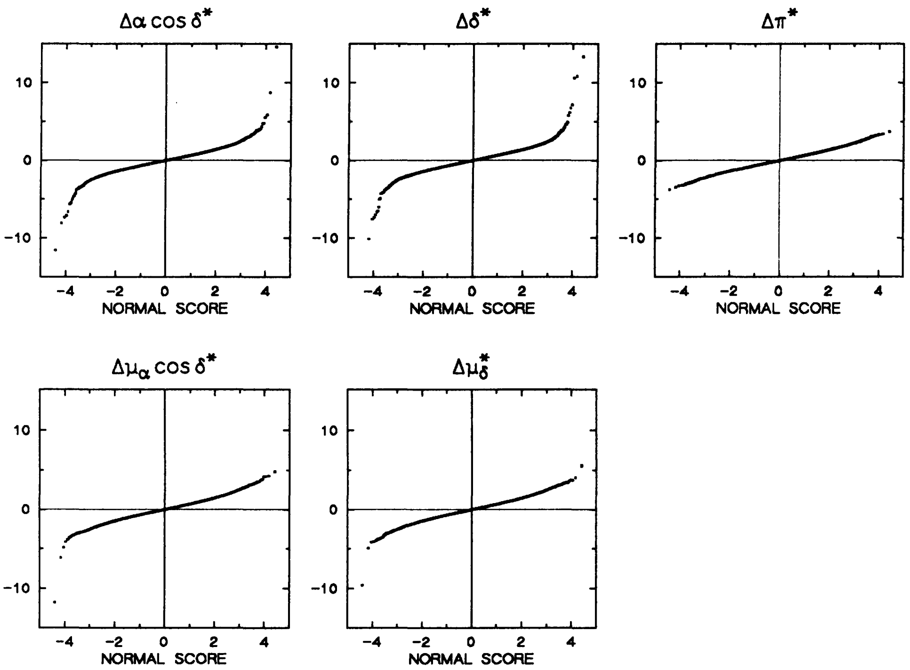

Figure 1. Normal probability plots of the normalized differences Δp^* between N30 and F30 (see text for explanation).

sible offset of visual photocentre from radio centre) and the preliminary state of the data.

Proper Motions. The FK5 proper motions, with estimated standard errors of about 1 mas/yr, should provide a valuable test of Hipparcos proper motions. The distribution of differences is strongly non-gaussian, but there appears to be a 'core' of standard width ~ 2.5 mas/yr, to be compared with the expected rms difference of 1.7 mas/yr. It is likely that systematic (mostly zonal) errors of the FK5 proper motions, and perhaps underestimated individual errors, account for a major part of the discrepancy.

The previously mentioned preliminary VLBI proper motion data for radio stars give a very good agreement, about 1.1 mas/yr, fully consistent with the formal errors.

Parallaxes. The parallaxes offer by far the most substantial confirmation of the quality of the preliminary Hipparcos data. The main reason for this is that photometric and spectroscopic parallaxes become very precise for sufficiently distant stars, and there is a sizable number of distant stars in the Hipparcos programme. An extensive comparison with cluster distances and spectroscopic, photometric and dynamical parallaxes (Arenou et al., in preparation) gives strong evidence that the zero point of the preliminary Hipparcos parallaxes is correct to within 0.1 mas, and that the formal standard errors in H30 are correct to within a few percent.

These conclusions are supported by comparisons with some of the most accurate ground-based parallaxes obtained both by classical optical methods (Harrington et al., 1993) and from the VLBI observations of radio stars (Lestrade et al., in preparation). The external errors of the H30 parallaxes have also been studied from the distribution of negative values (Lindegren, in preparation) resulting in an estimated external/internal error ratio very close to unity.

6. Conclusions

Although the whole set of Hipparcos data is not yet analysed, several kinds of internal and external checks have been applied to the preliminary catalogues. All tests indicate a very high degree of internal consistency and agreement with the best available external data. In particular it appears that the Hipparcos parallaxes are absolute at least to the level of 0.1 mas, and that the standard errors in Table 1 essentially represent the true accuracies of the data.

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