The Astronomical Journal, 124:3299–3304, 2002 December

COMPUTING THE PARALLAX OF THE PLEIADES FROM THE *HIPPARCOS* INTERMEDIATE ASTROMETRY DATA: AN ALTERNATIVE APPROACH

Valeri V. Makarov
Universities Space Research Association, 300 D Street, SW, Suite 801, Washington, DC 20024; and US Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392; makarov@usno.navy.mil
Received 2002 June 11; accepted 2002 September 9

ABSTRACT

The inconsistency between the mean parallax of the Pleidaes open cluster from the *Hipparcos* catalog and that obtained from the stellar evolution theory and photometric measurements is probed by recomputing the *Hipparcos* data in a different way that reduces the propagation of the along-scan attitude errors. This is achieved by coupling observations of stars made nearly simultaneously in the two separate fields of view of the telescope. A direct calculation of astrometric quantities of 54 Pleiades members by the new method, based on the Intermediate Astrometry Data, provides a correction of -0.71 ± 0.14 mas to the weighted mean parallax of the cluster. The mean corrected parallax of the Pleiades is 7.75 ± 0.20 mas.

Key words: astrometry — open clusters and associations: individual (Pleiades) — stars: distances

1. INTRODUCTION

The absolute calibration of the main sequence became a controversial subject in 1997, when the *Hipparcos* astrometric catalog was made publicly available (ESA 1997). The location of some main sequences of nearby open clusters on the HR diagram, drawn from the *Hipparcos* parallaxes, does not check well with the currently accepted theory of stellar evolution, backed by numerical modeling and pre-*Hipparcos* observational data. This theory predicts a relatively simple behavior of the main sequence depending mainly on two parameters, age and metallicity. Open clusters are believed to comprise stars of the same age and chemical composition, thus providing a test field for the stellar physics models and the basis for the cosmic distance scale. Pinsonneault et al. (1998) investigated the main-sequence fitting method in detail and found a distance modulus of the Pleiades of 5.60 ± 0.05 mag, corresponding to a parallax of 7.59 mas, consistent with many previous estimations. The *Hipparcos*-based distance modulus of the Pleiades is considerably smaller (between 5.33 and 5.37, with a formal error of 0.06), implying a smaller distance and hence intrinsically fainter stars. Pinsonneault et al. (1998) suggested that the *Hipparcos* parallaxes of the Pleiades are corrupted by a systematic error, correlated on small angular scales (about 2° radius). The hypothesis of a star-to-star correlated error within the small areas occupied by rich clusters was further discussed by Narayanan & Gould (1999). Using a variation of the moving cluster method, they reiterated the pre-*Hipparcos* distance of the Pleiades and suggested a certain distribution of the error across the sky area occupied by the cluster.

Attempts were made to account for the discordant *Hipparcos* Pleiades main sequence by adopting a lower metallicity than previous determinations. Stello & Nissen (2001) conducted a careful reexamination of the main sequence of field F stars with the same metallicity as the Pleiades stars, based on Strömgren photometry. A distance modulus of 5.61 ± 0.03 was obtained again, in stark disagreement with the *Hipparcos* determination (see Table 1 summarizing selected determinations of the Pleiades distance modulus and parallax). Another line of argument that the error is hidden in the *Hipparcos* parallaxes is that, assuming the *Hipparcos* distance, subluminous stars like the Pleiades (0.3 mag below the zero-age main sequence) are not found elsewhere, including the young nearby solar-type stars (Soderblom et al. 1998). Van Leeuwen (1999b), however, argued that five other young open clusters seem to share the Pleiades main sequence, as determined by the *Hipparcos* parallaxes, while three older clusters appear to be brighter. A new physical age-luminosity relation was suggested, calling for a change of the existing stellar evolution theory.

Mermilliod et al. (1997) also noticed a significant difference between the *Hipparcos* and photometric parallaxes for a few clusters beside the Pleiades. They also concluded that the *Hipparcos* results contradicted the commonly accepted interpretation of the metallicity effects equally for the *UBV*, *uvby*, and Geneva photometric systems.

On the other hand, van Leeuwen (1999a) bolstered the *Hipparcos* astrometry giving more arguments of the astrometric kind. He investigated the correlations in *Hipparcos* star abscissae coming from the geometry of the *Hipparcos* scanning method and showed them to be present only on the scale length below $1\overset{\circ}{.}2$ and of negligible amplitude (0.1 mas). It is noted that the correlations in question were assumed to be generated only by errors of the great circle zero points thus leaving out possible nonrigidity of the great circles. Possible disturbances in the instrument's basic angle at the Pleiades were also considered and ruled out. V. Makarov (1998, unpublished) studied possible large-scale distortions in the *Hipparcos* parallax system all over the sky by simulating periodic intrarevolution errors in the basic angle estimates or in star abscissae, using the spherical harmonic technique (Makarov 1998). Such periodic variations could result from thermal changes in the instrument or from the general instability of the one-dimensional abscissae solution (Makarov 1992; Makarov, Høg, & Lindegren 1995). It was shown that, in order to reproduce a 1 mas error at the Pleiades, the amplitude of the intrarevolution variations must be at least 4 mas, which seems quite unlikely. Besides, any large-scale distortion in the parallaxes would add to the overall scatter of *Hipparcos* parallaxes, which is not the case (Lindegren 1995; Arenou et al. 1995).

TABLE 1

Determinations of the Pleiades Parallax and Distance Modulus

Source (1)	$(m-M)_0$ (2)	π (3)	Method (4)
Pinsonneault et al. 1998.......	5.60 ± 0.05	7.59 ± 0.18	P
Stello and Nissen 2001.........	5.61 ± 0.03	7.55 ± 0.11	P
Robichon et al. 1999...........	5.36 ± 0.06	8.46 ± 0.22	H
This paper..........................	5.57 ± 0.06	7.75 ± 0.20	H

Notes.—The source of data is given in col. (1). The distance modulus and its formal standard error in mag are in col. (2). The parallax and its formal standard error in milliarcseconds are presented in col. (3). The method of determination is in col. (4) ("P" for photometric, and "H" for *Hipparcos* trigonometric parallaxes).

Irrespective of astrophysical methods and models, there are observational clues pointing at *Hipparcos* as the origin of the disparity. Recent determination of trigonometric parallaxes of the Pleiades yields a parallax of 7.64 ± 0.43 mas (Gatewood, de Jonge, & Han 2000), in general agreement with values based on main-sequence fitting but 1 mas smaller than the *Hipparcos* value (Robichon et al. 1999). Li & Junliang (1999) applied the same method as Narayanan & Gould (1999) and arrived at a close to traditional parallax of 7.37 ± 0.05 mas. In the extreme case of the open cluster NGC 6231, the *Hipparcos* parallaxes for all six member stars (HIP 82543, 82669, 82671, 82691, 82706, and 82783) are negative with a mean of -0.62 ± 0.48 mas (Arenou & Luri 1999), while the expected parallax is 0.8 mas.[1] The gathered evidence of a position-correlated astrometric error is compelling to look for clues in the techniques and algorithms of *Hipparcos* data reductions.

2. DIRECT AND ITERATIVE METHODS OF ASTROMETRIC SOLUTION

Contrary to the traditional techniques of *absolute* ground-based astrometry, where celestial positions of stars are measured with respect to definite directions on the surface of Earth, a space-borne astrometric satellite measures only small differences between the instantaneous directions of its optical axes and the lines of sight of observed stars. The presence of a beam combiner device in a *Hipparcos*-like instrument is essential, because it combines the images of stars separated by a wide basic angle in the single focal plane of the telescope, allowing angular distances to be determined between widely separated stars, thus avoiding the shortcoming of narrow-field differential astrometry. Still, any measured direction can be expressed only in relation to the instantaneous orientation of the instrument, which is called the attitude.

Generally, the relation between the measured focal plane position $\boldsymbol{g}_{\mathrm{ik}} = (u_i, v_i)$ at time t_k of star i and its astrometric parameters $\boldsymbol{s}_i$ can be realized as a succession of coordinate transformations $H(\boldsymbol{s}_i, \boldsymbol{a}_k, \boldsymbol{c}_j | t_k)$:

$$\boldsymbol{g}_{\mathrm{ik}} = H(\boldsymbol{s}_i, \boldsymbol{a}_k, \boldsymbol{c}_j | t_k) \ , \tag{1}$$

where $\boldsymbol{a}_k$ is the vector of attitude parameters at time t_k, and $\boldsymbol{c}_j$ is the vector of instrument parameters, which are assumed to vary slowly with time. The time t_k to the right of the vertical bar is given (i.e., known); there are other given parameters involved in the transformations that are omitted in the formula for simplicity.

Although the transformation is nonlinear, one may seek small corrections to a predetermined model of parameters ($\boldsymbol{s}_i$, $\boldsymbol{a}_k$, $\boldsymbol{c}_j$), which by direct, nonlinear computation produces a predicted (calculated) position $\boldsymbol{g}_{\mathrm{ik}}$. The inverse problem, dealing with unknown small corrections only, can be linearized in a first-order approximation.

Thus linearized, the formalism results in a huge design matrix, to be solved by a weighted least-squares method. For *Hipparcos*, the size of the matrix is 2370K (number of unknowns) by approximately 44,400K (number of individual observations) for reference stars. Solving this least-squares problem by a direct method (i.e., constructing the normal matrix of 2370K by 2370K and the inverse of it) is the most straightforward and *correct* way to handle the problem. Although the normal matrix will be sparse, a significant number of nonzero off-diagonal elements will create a certain pattern of covariances between various free parameters. Through these covariances, the astrometric parameters of any star will be correlated with a large number of other astrometric parameters and nuisance (nonastronomical) parameters. The propagation of positionally correlated errors is governed by the covariances of the astrometric and nuisance parameters, while the number of the latter is greater by a factor of 8. Exact knowledge of star-to-star correlations may be achieved only if the whole covariance matrix is computed.

Handling such a large matrix was deemed impossible at the time of the *Hipparcos* data reduction (ESA 1997, Vol. 3, p. 488); it may still be a challenge for the present-day computers. As an alternative to the global direct solution, a three-step iterative procedure was implemented. Essentially, this is an approximation to the direct solution, which neglects the off-diagonal blocks of the normal matrix between the astrometric and nuisance parameters of different kinds. Solving the truncated normal matrix is a converging process, as was demonstrated by numerical simulations and by the *Hipparcos* data reductions. However, there is no guarantee that it converges to the same solution vector that would have been obtained with the full-size normal matrix. In particular, the astrometric parameters may be affected in the three-step iterative procedure by the neglect of their inherent covariances with the attitude parameters.

3. ELIMINATING ATTITUDE ERRORS IN *HIPPARCOS* EQUATIONS

The *Hipparcos* Intermediate Astrometry Data, HIAD (ESA 1997, CD-ROM No. 5), is one of the annexes complementing the main catalog. It contains one-dimensional coordinates (abscissae) of 118,204 objects on reference great circles obtained by FAST and NDAC over the whole period of the satellite's operation. The abscissae are given in the form of residuals "observed minus calculated," $\Delta\nu$, strictly related to the reference astrometric parameters given in the header record for each star. Besides the abscissae, their standard errors and partial derivatives, $\partial\nu/\partial u_i$, with respect to the five astrometric parameters $u_i = \alpha^*(=\alpha \cos \delta)$, δ, π, $\mu_{\alpha *}$, μ_δ, are given in the file. This set of data is meant to be "ready

[1] See http://obswww.unige.ch/webda/navigation.html.

to use " linearized equations:

$$\sum_{i=1}^{5} \frac{\partial \nu}{\partial u_i} \Delta u_i = \Delta \nu \ , \tag{2}$$

where $\Delta u_{\rm i}$ are the unknown corrections to the astrometric parameters. The system of equations for each star separately can be solved by the weighted least-squares method, taking into account the correlations between the FAST and NDAC abscissae determinations.

Where does the along-scan attitude angle come in this equation? Implicitly, it is included in the abscissa residual in the right-hand part of the equation. Indeed, what the instrument measures at a given time t_k is only a small angle $\eta(t_k)$ between the instantaneous coordinate $a(t_k)$ of the optical axis and the actual position of the star ν, projected on the reference circle,

$$\eta(t_k) = \nu - a(t_k) \ . \tag{3}$$

The abscissa residual is

$$\Delta\nu = \nu_{\rm obs} - \nu_{\rm calc} = \eta_{\rm obs} - \nu_{\rm calc} + a(t_k) \ . \tag{4}$$

Errors propagate into the right-hand parts of the equations both through the directly observable quantity $\eta_{\rm obs}$ and $a(t_k)$, since the latter is determined at a separate stage of the data reduction (attitude reconstruction) from the same observations. It is important, in the context of this paper, that for bright stars, such as many of the Pleiades are, the attitude error dominates the photon noise error (cf. ESA 1997, Vol. 3, Table 9.9).

The attitude angle $a(t_k)$ was modeled with a continuous smooth function of time (ESA 1997, Vol. 3, § 9). Using smooth functions to fit $a(t)$ was proven to significantly improve the precision of astrometry. In fact, the along-scan angle was estimated for each consecutive frame of $0\overset{\circ}{.}1$ and smoothed as a function of time with cubic B-splines. A transit of an open cluster corresponds to an interval of a spline function including typically 10–20 individual attitude (also called spin phase) points. A normal partition of the spin phase function also includes 15–20 frames, although sometimes smaller partitions were used after a visual analysis in order to fit in more rapid variations (C. Skovmand Petersen 2000, private communication). Since a cubic spline is a polynomial of third degree, the fit as a whole can be considered in the Fourier domain as a smoothing filter with a cutoff wavelength somewhat shorter than $\sim 1\overset{\circ}{.}5$. Thus, the typical scale of an open cluster matches the reproducible wavelength of the spline fit. The smoothness of the fitting function implies that any error in $a(t)$, whatever origin it may have, will propagate almost by the same amount into abscissae ν of stars observed within a short interval of time. Such stars may be close (members of the Pleiades, for example) but may also be separated by an angle close to the basic angle. Indeed, consider star m observed simultaneously (or nearly so) with star n in the other viewport. Subtracting the corresponding equations (eq. [2]) obtains

$$\sum_{i=1}^{5} \left(\frac{\partial \nu_m}{\partial u_i} \Delta u_{i(m)} - \frac{\partial \nu_n}{\partial u_i} \Delta u_{i(n)} \right) = \eta_{{\rm obs}(m)} - \eta_{{\rm obs}(n)} - \left(\nu_{{\rm calc}(m)} - \nu_{{\rm calc}(n)}\right) \ . \tag{5}$$

The attitude unknown is eliminated, but the equation includes now two observable values and 10 astrometric parameters for two stars. This transformation of the equations does not reduce the rank of the problem nearly by half, as it may first appear, due to the annihilation of numerous attitude unknowns. A full-rank design matrix can be constructed by coupling all simultaneous observations made in different fields of view.[2] The possibility of putting the equations in this differential form, and of ensuing attitude parameter elimination was mentioned in (ESA 1997, Vol. 3, p. 486), but deemed inferior, since it assumes an attitude model of a large number of unrelated discrete instantaneous orientations, precluding a dynamical smoothing. However, the compelling advantage of the design matrix in this incarnation is that the attitude errors, which we suspect of being the major source of correlated astrometric errors, do not propagate into the solution. Setting up equations in the form of equation (5) and solving them consistently should ultimately prove or rule out this hypothesis.

4. PARALLAXES OF THE PLEIADES REVISITED

A full-scale computation of *Hipparcos* astrometry, as outlined in the previous section, is impossible with the available data. Individual observations with timing data were never published for all the *Hipparcos* stars. The published HIAD contains observational equations in a much reduced and preprocessed form. Each equation represents a combination of a few observations made at various instances within one orbit. Thus, coupling individual observations in the way described earlier is not feasible. To bypass the difficulty, the problem can be restated in the following way. For each star m that belongs to the Pleiades, N stars may be found at angular distance about 58° that could be observed quasi-simultaneously on the same great circle. These stars will be called reference stars henceforth. The observational equation corresponding to a given great circle is restated as

$$\sum_{i=1}^{5} \frac{\partial \nu_m}{\partial u_i} \Delta u_{i(m)} = \eta_{{\rm obs}(m)} - \nu_{{\rm calc}(m)} - \frac{R}{N} \sum_{n=1}^{N} \left(\eta_{{\rm obs}(n)} - \nu_{{\rm calc}(n)}\right) \ . \tag{6}$$

We have now as many observational equations as there are great circles crossing the Pleiades star m. The above equation is derived from equation (5) assuming

$$\sum_{n=1}^{N} \sum_{i=1}^{5} \frac{\partial \nu_n}{\partial u_i} \Delta u_{i(n)} = 0 \ . \tag{7}$$

This assumption is justified by the fact that the bulk of reference stars, located in a narrow ring of 58° radius around the Pleiades star, are supposed to be free of significant systematic errors in the *Hipparcos* realization; the mean corrections to the astrometric parameters over a large sample is expected to be negligibly small. Each of the reference stars n is observed on many different great circles; only a small fraction of observations link it to the Pleiades. Propagation of the supposed systematic error in the Pleiades parameters

[2] In fact, *Hipparcos* observations are never strictly simultaneous, because only one star could be observed at a time. Practically, this difficulty can be resolved by associating the nearest in time observation to any given one, without much loss of precision.

can therefore affect only this small fraction of simultaneously conducted observations.

The observational equations in the new setup (eq. [6]) differ from the canonical ones only by the correction $-(R/N)\sum_{n=1}^{N}(\eta_{\mathrm{obs}(n)}-\nu_{\mathrm{calc}(n)})$ to the right-hand part. The logic of the modification is clear enough. We believe that the observations of the Pleiades stars are affected by an error in the attitude parameter $a(t)$ that evokes, for example, a correlated error of the parallaxes. The error is also present in the measured residuals of the reference stars and therefore can be annihilated by subtracting the weighted mean of the reference star residuals. This correction would not, statistically, change the solution if the attitude error in question does not exist, nor if it is uncorrelated. The multiplier R is a correcting factor that takes into account which observations are used in computing the residual correction term. Ideally, one should use only those observations that were made simultaneously with the passage of the corresponding Pleiades member, in which case $R = 1$. This is impossible to achieve, because the residuals in HIAD are already an average of a few observations made on a given orbit. A reference star is typically observed twice during one full revolution of the satellite, once in the preceding and once in the following field of view. Therefore, only half of the measurements involved in the computation of each orbit-average residual refer to the Pleiades, while the other half are made with the telescope pointing away from the cluster. These latter do not bear the same attitude error; thus, they reduce the attitude-related correction by roughly a factor of 2. To compensate for this reduction of weight, we have to use $R = 2$. Unfortunately, the compressed character of the HIAD does not provide for a more quantitative analysis than that. On a given orbit, some reference stars may have more observations in one of the fields of view than in the other; besides, their weights could be different in the reductions. This introduces some additional uncertainty in R and the subsequent solution, and the standard errors quoted in this paper should be taken as a lower bound.

The actual algorithm of computation adopted in this paper consists of four steps:

1. For each of the 54 Pleiades members with *Hipparcos* solutions, listed in Table 2 (from Robichon et al. 1999), all other single *Hipparcos* stars are found with goodness of fit (field H30) F2 $= 0.21 \pm 2.0$, separated by $58^\circ \pm 0\overset{\circ}{.}5$.
2. For each of the 54 Pleiades members, the orbit numbers are recorded from the HIAD files.
3. For each of these orbits, all observation of the reference stars made on this orbit are selected, and the weighted mean corrections are computed from the final astrometric parameter solutions.
4. The corrections are subtracted from the right-hand parts of the observational equations for each of the Pleiades stars, and a new solution is computed by weighted least squares.

The number of reference stars in the ring of $58^\circ \pm 0\overset{\circ}{.}5$ radius turns out to be between 700 and 900 per Pleiades star. The number of orbits in HIAD for each Pleiades member is about 40, but a considerable number of orbits are shared by the Pleiades stars. In computing the right-hand part corrections, the correlations between the FAST and NDAC residuals must be taken into account (van Leeuwen & Evans 1998), lest the formal standard errors be unrealistically small. I simply down-weighted the pairs of FAST/NDAC observations assuming a constant correlation of 0.56. The procedure was verified by computing the astrometric parameters with the original right-hand parts, which produced a statistically consistent result, both in the parameters and formal errors, with the official *Hipparcos* data for most of the 54 stars.

The results for the parallaxes are summarized in Table 2. The majority of the Pleiades stars obtained a smaller parallax than the *Hipparcos* value. The average parallax, computed as a simple weighted mean of the 54 new parallaxes, is 7.75 ± 0.20 mas in the new solution, which is smaller by 0.71 mas than the mean catalog parallax. This correction goes a good way toward the photometric parallax (see Table 1).

5. DISCUSSION

The technique of correcting the measured residuals by the average residual of the reference stars (situated in the reference ring) brings the *Hipparcos* parallax of the Pleiades close to the photometric values. The origin of the suspected attitude error still remains a matter of speculation. When up to a hundred nearby clusters are considered, the dispersion of the differences between the *Hipparcos* mean parallaxes and photometric determinations appears to be larger by only 15% than the expected combined unit weight (Arenou & Luri 1998). This implies, that the parallax error is, on the average, much smaller than the estimated $\approx$1 mas for the Pleiades. Therefore, the error at the Pleiades may be an accidental fluctuation of noise, or the error propagation could be confined only to the densest and brightest clusters. A possible, qualitative explanation to the latter option is a possible imbalance of the statistical weight of stars in the two fields of view that enhances the attitude error propagation. When one of the *Hipparcos* fields of view is centered on a rich cluster, up to a few tens of member stars are observed quasi-simultaneously in that field and typically two to three stars in the other pointing direction, 58° apart. The along-scan attitude angle is computed from the average observed abscissae residuals of all the stars transiting at this moment, but the numerous cluster members may by far outweigh the stars in the other field of view. All the member stars have essentially the same parallax and proper motion. Regarding the attitude determination, this is equivalent to having only one star with a great weight in calculations. The magnitude of the correlated (i.e., common to all cluster members) error cannot be larger than the typical astrometric error for an average bright star, since the latter includes the attitude error and other sources of noise. A standard deviation of 1 mas could be expected. For a given cluster, the error is a realization of a random process; hence, for some clusters, it may be close to zero, as is apparently the case with the Hyades.

Currently, it is impossible to provide a direct and impeccable *proof* that the *Hipparcos* parallaxes are in error. The ground-based observing techniques still lag too much in accuracy, and the planned astrometric missions of the second generation like GAIA (Perryman et al. 2001) and FAME (Johnston et al. 2001) will not deliver any data sooner than a decade from now. We need to exploit other methods for secondary, indirect evidence. The classical convergent point method, for example, can yield quite precise (but not necessarily accurate) kinematic parallaxes, taking advantage of the relatively more precise proper motions and

TABLE 2

Parallaxes of the Pleiades Members

HIP (1)	$\pi_{\rm HIP}(\sigma_\pi)$ (mas) (2)	$\pi_{\rm ref}(\sigma_\pi)$ (mas) (3)	$\pi_{\rm kin}$ (mas) (4)	HIP (1)	$\pi_{\rm HIP}(\sigma_\pi)$ (mas) (2)	$\pi_{\rm ref}(\sigma_\pi)$ (mas) (3)	$\pi_{\rm kin}$ (mas) (4)
16217	8.20 (1.31)	8.08 (1.42)	8.66	16407	7.62 (1.15)	7.16 (1.24)	8.06
16423	8.44 (1.45)	9.33 (1.52)	8.77	16635	9.62 (2.18)	7.60 (2.14)	7.52
16639	8.11 (1.47)	6.66 (1.52)	7.73	16753	9.98 (1.58)	9.71 (1.60)	7.92
16979	5.86 (1.77)	5.50 (1.78)	7.77	17000	7.88 (1.00)	8.69 (1.14)	8.00
17020	3.20 (2.21)	3.65 (2.28)	7.61	17034	6.87 (1.08)	7.91 (1.21)	8.22
17043	7.78 (0.98)	6.81 (1.06)	7.63	17044	8.85 (2.11)	10.26 (2.18)	7.77
17091	9.97 (1.82)	10.66 (1.9 0)	7.90	17125	7.69 (1.51)	7.69 (1.51)	7.90
17225	9.21 (1.45)	8.10 (1.52)	8.01	17245	5.91 (1.67)	5.53 (1.71)	7.92
17289	7.29 (1.50)	6.26 (1.55)	7.80	17316	6.28 (1.66)	6.13 (1.65)	8.71
17317	6.66 (1.98)	5.70 (2.03)	8.25	17325	8.53 (1.20)	6.63 (1.29)	8.26
17401	9.48 (1.11)	6.98 (1.21)	7.79	17481	10.10 (1.27)	7.40 (1.32)	7.77
17489	9.75 (1.05)	7.53 (1.23)	7.84	17497	9.76 (1.29)	7.66 (1.37)	7.56
17499	8.80 (0.89)	5.72 (1.05)	...	17511	10.00 (1.64)	9.00 (1.71)	7.54
17527	8.87 (0.89)	9.06 (1.00)	7.96	17531	8.75 (1.08)	7.38 (1.24)	7.89
17547	8.27 (1.14)	7.89 (1.27)	8.82	17552	11.21 (1.09)	10.14 (1.16)	8.41
17573	9.06 (1.03)	8.68 (1.20)	7.86	17579	8.43 (0.89)	8.28 (1.00)	7.98
17583	8.50 (1.17)	8.71 (1.28)	8.03	17588	9.21 (0.92)	9.25 (1.02)	7.61
17608	9.08 (1.04)	6.84 (1.27)	8.11	17625	4.73 (1.48)	3.38 (1.52)	8.09
17664	6.66 (0.99)	6.99 (1.08)	8.18	17692	8.35 (1.00)	7.05 (1.11)	7.92
17702	8.87 (0.99)	7.87 (1.17)	...	17704	9.05 (0.97)	8.85 (1.07)	7.92
17729	7.61 (1.17)	9.59 (1.24)	8.11	17776	9.64 (0.91)	6.67 (1.07)	8.19
17791	6.90 (0.99)	6.85 (1.07)	7.64	17851	8.42 (0.86)	8.13 (1.00)	8.34
17862	8.02 (0.91)	7.78 (0.98)	7.78	17892	10.12 (1.04)	8.41 (1.14)	7.83
17900	8.58 (0.93)	7.81 (1.04)	7.64	17999	9.83 (1.00)	8.98 (1.08)	8.01
18050	7.56 (1.47)	8.13 (1.49)	8.06	18091	7.71 (1.89)	6.63 (1.87)	7.92
18154	8.57 (1.57)	9.06 (1.54)	7.68	18431	8.66 (1.53)	5.53 (1.51)	8.13
18544	9.68 (1.50)	8.75 (1.50)	8.61	18955	6.13 (1.42)	6.87 (1.42)	7.90

Notes.—The *Hipparcos* identification number is given in col. (1). The parallax and its formal standard error as given in the *Hipparcos* catalog are presented in col. (2). The recomputed parallax and its formal standard error are in col. (3). Kinematic parallax from the convergent point method is given in col. (4).

low internal velocity dispersions in open clusters. Table 2 lists, in column (4), kinematic parallaxes for 52 stars with Tycho-2 proper motions, derived with the convergent point and other parameters defined in Makarov & Robichon (2001). Unfortunately, the mean kinematic parallax is determined with a huge error due to the uncertainty of the convergent point position on the line connecting it with the cluster; it is therefore meaningless to compare the mean kinematic and *Hipparcos* parallaxes. The width of $\pi_{\rm ref} - \pi_{\rm kin}$ and $\pi_{\rm HIP} - \pi_{\rm kin}$ distributions, however, is directly related to the precision of the two solutions. The distribution of the corrected parallaxes seems to be somewhat narrower than the original one, but the difference is hardly significant.

Analysis of proper motions, theoretically, may provide a test for the *Hipparcos* data. Our corrected solution, apart from the decrease of the mean parallax by 0.71 ± 0.14 mas, changes the mean proper motion by $+0.45 \pm 0.14$ and -0.66 ± 0.11 mas yr^{-1} in $\mu_{\alpha*}$ and μ_δ, respectively. The best ground-based catalogs of proper motions are, in principle, good enough to detect such differences. The Tycho-2 proper motions, for example, compare favorably with *Hipparcos*, but, based on a number of catalogs brought to the *Hipparcos* reference system, they are not independent (Urban, Wycoff, & Makarov 2000). Positions of reference stars in the past epochs are derived from the *Hipparcos* astrometry; thus, possible position-correlated errors are effectively transferred from *Hipparcos* to the new system. Since the *Hipparcos* catalog is unique at its level of astrometric accuracy, there is no way out of this vicious circle.

The technique presented in this paper can be extended for other *Hipparcos* samples of interest and, eventually, for the entire catalog. Since each star with a revised solution serves as a reference star to a number of other stars, it will possibly take a few iterations to obtain a converging, self-consistent, all-sky solution.

The author is grateful to C. Fabricius for very useful discussions of the subject, comments, and corrections to the previous and present versions of the paper. N. Kaltcheva inspired this work by disputing the *Hipparcos*-based distances of some OB associations. C. Skovmand Petersen is thanked for sharing his insight in the *Hipparcos* data reduction algorithms.

REFERENCES

Arenou, F., Lindegren, L., Frœschlé, M., Gómez, A. E., Turon, C., Perryman, M. A. C., & Wielen, R. 1995, A&A, 304, 52

Arenou, F., & Luri, X. 1999, in ASP Conf. Ser. 167, Harmonizing Cosmic Distance Scales in a Post-Hipparcos Era, ed. D. Egret & A. Heck (San Francisco: ASP), 13

ESA. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200) (Noordwijk: ESA)

Gatewood, G., de Jonge, J. K., & Han, I. 2000, ApJ, 533, 938

Johnston, K., et al. 2001, BAAS, 199, 45.04

Li, C., & Junliang, Z. 1999, in ASP Conf. Ser. 167, Harmonizing Cosmic Distance Scales in a Post-Hipparcos Era, ed. D. Egret & A. Heck (San Francisco: ASP), 259

Lindegren, L. 1995, A&A, 304, 61

Makarov, V. V. 1992, Soviet Astron. Lett., 18, 252

———. 1998, A&A, 340, 309

Makarov, V. V., Høg, E., & Lindegren, L. 1995, Exp. Astron., 6, 211

Makarov, V. V., & Robichon, N. 2001, A&A, 368, 873

Mermilliod, J.-C., Turon, C., Robichon, N., Arenou, F., & Lebreton, Y. 1997, in Hipparcos-Venice '97 ed. M. A. C. Perryman & P. L. Bernacca (ESA SP-402) (Noordwijk: ESA), 643

Narayanan, V. K., & Gould, A. 1999, ApJ, 523, 328

Perryman, M. A. C., et al. 2001, A&A, 369, 339

Pinsonneault, M. H., Stauffer, J., Soderblom, D., King, J. R., & Hanson, R. B. 1998, ApJ, 504, 170

Robichon, N., Arenou, F., Mermilliod, J.-C., & Turon, C. 1999, A&A, 345, 471

Soderblom, D. R., King, J. R., Hanson, R. B., Jones, B. F., Fischer, D., Stauffer, J. R., & Pinsonneault, M. H. 1998, ApJ, 504, 192

Stello, D., & Nissen, P. E. 2001, A&A, 374, 105

Urban, S. E., Wycoff, G. R., & Makarov, V. V. 2000, AJ, 120, 501

van Leeuwen, F. 1999a, in ASP Conf. Ser. 167, Harmonizing Cosmic Distance Scales in a Post-Hipparcos Era, ed. D. Egret & A. Heck (San Francisco: ASP), 52

———. 1999b, A&A, 341, L71

van Leeuwen, F., & Evans, D. W. 1998, A&AS, 130, 157