CROSS - IDENTIFICATION OF HIPPARCOS - 2MASS SECOND INCREMENTAL DATA RELEASE

G. DAMLJANOVIC [1], J. SOUCHAY [2]
[1] Astronomical Observatory
Volgina 7 , 11160 Belgrade, Yugoslavia
e-mail: gdamljanovic@aob.bg.ac.yu
[2] SYRTE/UMR8630 – CNRS, Observatoire de Paris
61 avenue de l'Observatoire, 75014 Paris, France
e-mail: Jean.Souchay@obspm.fr

ABSTRACT. This paper is in line with the current efforts to link large stellar catalogues, both in the visible and infrared, to the ICRF (International Celestial Reference Frame). We did the cross – identification between HIPPARCOS (HIgh Precision PARallax COllecting Satellite) and 2MASS (Two Micron All Sky Survey) and presented here the main results. It was found 37940 common stars, after selecting a rejection criterion, that we set to a 3σ value. Our cross-identification is more than 68.5% successful. There were 117955 HIPPARCOS stars, and 162195232 2MASS Second Incremental Data Release ($\sim$ 47% of the sky) ones in our basic selection. It means, the programme of 3σ criterion is adequate for cross – identification of new catalogues of millions of stars. After that, we calculated the standard error of unit weight of differences $\Delta\alpha$ and $\Delta\delta$, and it was close to $0.''10$, in good agreement with other results (Cutri *et al.* 2001).

1. INTRODUCTION

From 1997, the HIPPARCOS Catalogue (ESA 1997) is considered as the primary optical counterpart of the ICRF. After a decision of the IAU (International Astronomical Union) General Assembly in Kyoto 1997, the ICRF was adopted to materialize the ICRS (International Celestial Reference System) from the beginning of 1998. It is based on a catalogue of 608 compact radio sources (Ma *et al.* 1998) which are determined with an internal precision of 0.3 to 0.5 mas (milliarcsecond). It has been updated recently by the ICRF – Ext.1, which includes 59 new sources (IERS Annual report 1999).

The HIPPARCOS contains roughly 110 000 stars, brighter than magnitude 12, mostly range between $V = 7$ and $V = 9$, which is far too restricting nowadays when searching reference stars for astrometric calibration. The mean density is less than 3 stars/square degree, which is not enough to insure a suitable astrometric reduction in the case of observations carried out in small fields with CCD detectors (more precisely, for the reductions of observations of fainter stars). Therefore it is necessary to produce large stellar catalogues with fainter sources (in the visible and in the infrared) and linked to the ICRF. The HIPPARCOS stars positions and proper motions are bases of the optical frame HCRF (Hipparcos Celestial Reference Frame).

The HIPPARCOS Catalogue, as an optical frame, gives for each object, among a very large number of parameters, the position with an accuracy of the order of 1 mas at 1991.25 (the epoch of the catalogue), and the proper motions in $\mu_\alpha \cos\delta$ and μ_δ with a standard error of about 1 mas/yr.

Let us mention some features of the Tycho-2 Catalogue (Hog *et al.* 2000): it is an astrometric reference catalogue with positions at the precision of 60 mas for all the stars, proper motions with a 2.5 mas/yr accuracy, and two-colour photometric data for roughly 2.5 million brightest stars in the sky. About 4% stars are without proper motion data. The corresponding star density, which depends on the galactic latitude b is about 150 stars/sq.deg. for $b = 0^o$, 50 for $b = \pm 30^o$, and 25 for $b = \pm 90^o$. The limiting magnitude V is near 11.5 mag and the completeness reaches about 90 % .

The attention should be maintained of various recent catalogues which should help to the densification of the ICRF, not only at optical wavelengths, but also at other ones (infrared, radio, X, etc.). Some of them are available in that aim, such as the Tycho-2 Catalogue, the USNO CCD Astrograph Catalogue (UCAC), the 2MASS (infrared), DENIS (Deep Near Infrared Survey of the Southern Sky), etc. One of the most interesting projects is the 2MASS of the near infrared sky which is based on two highly automated 1.3 m telescopes for both hemispheres, equipped with a three channel camera to observe the sky simultaneously at J (1.25 microns), H (1.65 microns) and K_S (2.17 microns).

In this paper we perform the cross – identification of HIPPARCOS – 2MASS PSC stars. Our cross – identification results, based on the programme of 3σ criterion, are hopeful for similar jobs of the cross – identification of new big stellar catalogues. It is in accordance with lot of nowadays efforts to link large stellar catalogues to the ICRF.

2. THE 2MASS CATALOGUE

The 2MASS Second Incremental Data Release includes a Point Source Catalogue (PSC), with positions and photometry for 162213354 sources, an Extended Source Catalogue (XSC) with positions and photometry in the three survey band passes for 585056 objects and an Atlas Images (1897017 FITS images in the three survey bands). The 2MASS catalogue is a joint project between the University of Massachusetts and the Infrared Processing and Analysis Center California Institute of Technology (Cutri *et al.* 2001), with observing facilities at Mt. Hopkins – AZ (N $31^o40'50.''8$, W $110^o52'41.''3$, 2306 m elevation) for the northern and Cerro Tololo – Chile (S $30^o10'3.''7$, W $70^o48'18.''3$, 2171 m elevation) for the southern hemisphere. The 2MASS telescopes map the sky with overlapping strips (tiles), about 6^o in length (in δ direction) and $8.'5$ in width (in α direction) by using a freeze-frame scanning technique. They are operated by the Smithsonian Astrophysical Observatory (SAO) and the National Optical Astronomy Observatories (NOAO); the 2MASS is formed by the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF).

The PSC of the 2MASS Second Incremental Data Release has been divided onto 49 right ascension segments, $0^h \leq \alpha < 24^h$, ordered by increasing declination within each segment. The data are covering 19681 square degrees, which means about 47 % of the sky. The relevant observations were carried out between 1997 June 7^{th} and 1999 February 20^{th} (329 northern and 239 southern nights with at least one photometric period). The northern 2MASS telescope began to observe in June 1997, and the southern one in March 1998. The PSC consists of brightness data in three survey bands and positions, without proper motions. The magnitude limits are: 15.8 mag for J band, 15.1 mag for H one, and 14.3 mag for K_S one. Each telescope is equipped with the three-channel camera, and each channel has got 256x256 array of HgCdTe detectors. The final 2MASS catalogues will contain about 470 million stars and 1.6 million galaxies. The positions are accurate to $< 0.''2$, and α and δ done for J2000 (each star has got

the epoch of observation). The PSC occupies a total of 49 GB (uncompressed data). Because of the very big amount of 2MASS data, it is necessary to use DVD – ROM, big hard disk, fast computer and other modern equipment. The positions of the 2MASS sources are correlated with the ACT or USNO-A optical catalogues. Note that positional associations do not mean necessarily identifications. The positions of 2MASS objects are tied to the ICRS via the ACT Reference Catalogue. Some positional solution may have a random walk as much as $1.''0$ from the ICRS frame. About 77% of the PSC objects have $|b| < 20^o$ (the majority of point sources are concentrated towards the Galactic plane).

3. THE POSITIONAL ERRORS OF STARS OF 2MASS PSC CATALOGUE

Some data from the ACT (Urban *et al.* 1998) or USNO-A catalogues are included in the 2MASS PSC records, but these are not identifications between the infrared and optical sources. These are only associations, and the optical associations for the 2MASS sources are found using a simple closest positional algorithm. The astrometric accuracy of 2MASS PSC is $< 0.''2$. It was reached via the comparison of the positions of stars in the PSC with those in the Tycho-2 and UCAC catalogues (which are not used in 2MASS position reconstruction). The accuracy of 2MASS positions is on line with the number and distribution of ACT astrometric reference stars in each tile. The ACT catalogue has got 988 758 stars to about $V = 11$ mag and with positional error $< 0.''03$. The tiles with few or poorly distributed reference stars have got bad astrometric solution and bigger discrepancy from the reference frame. Concerning the possible sources of 2MASS positions errors, let mention a relative sparsity of ACT reference stars near the Galactic poles, problems of observations/reductions near the Galactic center and near tile ends, etc.

In the Analysis part of the 2MASS Second Incremental Data Release Explanatory Supplement, three astrometric tests were done. They consist on a comparison of 2MASS positions with those given by the ACT catalogue (used in the reconstruction), with the Tycho-2 catalogue and with the UCAC catalogue, these two last ones having been released respectively just before and after the 2MASS Second Incremental Data Release. After the comparison to ACT Reference Catalogue positions and the analysis of $\Delta\alpha$ and $\Delta\delta$ of 2MASS the standard deviation was roughly $\sigma \approx 0.''11$, (slightly higher in δ and lower in α) and the mean differences could be rounded to $\approx 0.''0$. For some tiles, the number and distribution of ACT stars were insufficient (as reference stars during 2MASS data processing). In these specific cases, for which the reconstruction errors are typically larger, the USNOA catalogue was used. Note that because of the procedure, the 2MASS positional errors are small in the vicinity of ACT reference stars, but errors would grow in the intervals between them.

The Tycho-2 catalogue includes the same set of stars as those contained in the ACT. For the comparison only the set of new Tycho-2 stars which are supposed to be single, and whose proper motions data are available, have been retained (~ 1.5 million stars). From the 2MASS catalogues only stars detected in all three bands, with $J < 15.8$ mag, $H < 15.1$ mag and $K_S < 14.3$ mag were used. The position r.m.s. was $\sigma \approx 0.''18$.

The 2MASS positions comparison to the UCAC positions show residuals for a huge set of ~ 10 million stars in common with a brightness up to $V = 12.5$ mag. The agreement between 2MASS and UCAC is noticeably better than the equivalent one between 2MASS and Tycho-2, with a value of $\sigma \approx 0.''12$. The UCAC is the first release of the U.S. Naval Observatory CCD Astrograph Catalogue which contains most of the southern hemisphere stars with brightness up to $V = 16$ mag and a δ range between -90^o and -5^o. Therefore UCAC positions seem to be more accurate and with higher density than the Tycho-2 ones. The above results might point

out an inconsistency of UCAC with Tycho-2.

4. THE CROSS - IDENTIFICATION OF HIPPARCOS - 2MASS

The first step consists of carrying out HIPPARCOS - 2MASS cross - identification, after selecting a rejection criterion, that we set to a 3σ value. In the present paper we make the 2MASS PSC positions comparison with respect to the positions given by the HIPPARCOS Catalogue. The mean density of Hipparcos Catalogue is about 3 stars per sq.deg., while 2MASS density is about 8 242 stars per square degree (2 stars per square arc minute). Thanks to easy comparison, we did separately the cross - identification in each of 49 segments adopted for 2MASS, and our cross - identification programme made it only into 3^m long α respective segments (not across the all celestial Hipparcos sphere for each 2MASS star). Of course, we made a matrix with the information about the 3^m segments locations for the Hipparcos Catalogue. In that way, for a suitable limited Hipparcos zone of the sky, each 2MASS star was compared with some numbers of Hipparcos ones. The identification was considered as effective when the Hipparcos star could be coupled to only one 2MASS star within a 3σ vicinity in both coordinates (α and δ).

At the beginning of our cross - identification procedure, we tested our method inside a very small part of the sky including a few Hipparcos stars, just to check the quality of our results, and we ran our detection algorithm within the 49 above mentioned 2MASS segments. Some stars were without enough data and we removed these stars before beginning the cross-identification procedure. Therefore 18 122 stars, which represent about 0.01% of the 2MASS PSC were removed from this catalogue. In a similar way, 263 stars were removed from the Hipparcos Catalogue (about 0.22%), because of the absence of proper motion data. Finally, we had 117 955 Hipparcos stars.

For each star, we calculated the standard deviation σ both in the α direction and in the δ one, respectively σ_α and σ_δ, by using Hipparcos and 2MASS data. There were enough data to do it. The calculated value of σ_α (and σ_δ) depends of few parts, $\sigma_\alpha^2 = \sigma_{\alpha 1}^2 + \sigma_{\alpha 2}^2 + \sigma_{\alpha 3}^2 + ...$ (and $\sigma_\delta^2 = \sigma_{\delta 1}^2 + \sigma_{\delta 2}^2 + \sigma_{\delta 3}^2 + ...$). The values $\sigma_{\alpha 1}$ and $\sigma_{\delta 1}$ are on line with the standard errors of the Hipparcos positions, and calculated by using the Hipparcos data. The values $\sigma_{\alpha 2}$ and $\sigma_{\delta 2}$ are on line with the observational epochs difference between Hipparcos and 2MASS (both catalogues data) and the errors of proper motions $\mu_\alpha \cos\delta$ and μ_δ (from Hipparcos data). The values $\sigma_{\alpha 3}$ and $\sigma_{\delta 3}$ are on line with the position error ellipse, and calculated by using the 2MASS data. The position error ellipse 2MASS data have: major axis ($2a$), minor axis ($2b$), and position angle (β). The position angle is in degrees, with the zero point in the northern direction N and via the eastern E one (of the error ellipse major axis). It was necessary that $\sigma_{\alpha 1}$ and $\sigma_{\alpha 3}$ ($\sigma_{\delta 1}$ and $\sigma_{\delta 3}$) are consistent between each other, and because of it we calculated the values of the standard error ellipse in the α direction

$$\sigma_{\alpha 3} = \left[x'^2 + y'^2\right]^{1/2} = \frac{ab}{\left[(a\cos\beta)^2 + (b\sin\beta)^2\right]^{1/2}} \qquad (1)$$

and in the δ one

$$\sigma_{\delta 3} = \left[x^2 + y^2\right]^{1/2} = \frac{ab}{\left[(a\sin\beta)^2 + (b\cos\beta)^2\right]^{1/2}} \qquad (2).$$

We did it by using the next formulas (determined from the ellipse formula which is done in rectangular plane coordinates):

$$x' = \frac{ab\sin\beta}{\left[(a\cos\beta)^2 + (b\sin\beta)^2\right]^{1/2}} \tag{3}$$

$$y' = \frac{-ab\cos\beta}{\left[(a\cos\beta)^2 + (b\sin\beta)^2\right]^{1/2}} \tag{4}$$

$$x = \frac{ab\cos\beta}{\left[(a\sin\beta)^2 + (b\cos\beta)^2\right]^{1/2}} \tag{5}$$

$$y = \frac{ab\sin\beta}{\left[(a\sin\beta)^2 + (b\cos\beta)^2\right]^{1/2}} \tag{6},$$

where $(x/a)^2 + (y/b)^2 = 1$ with $x = r\cos\beta$, $y = r\sin\beta$, $x' = r'\sin\beta$ and $y' = -r'\cos\beta$. The star is the coordinate origin of mentioned rectangular plane which is the tangent plane of the sphere. The value r is the distance between the star and the cross - point of the star's error ellipse with major axis; the cross - point has got the coordinates x and y. The value r' is the same, but with minor axis; the coordinates of that cross - point are x' and y'. The directions r and r' have got 90^o between each other. We get the Eq. (1), Eq. (2), Eq. (3), Eq. (4), Eq. (5) and Eq. (6) after a few trigonometric transformations.

The epoch of Hipparcos observations is 1991.25, and each star of 2MASS PSC has its own epoch of observation. Because of it, it is necessary to take into account the standard error rate for the proper motions influence by using the values of $\mu_\alpha\cos\delta = \mu_{\alpha*}$, μ_δ and the epoch differences t (in years). Therefore, the positions in both catalogues are on line with J2000.0 epoch. It means, before carrying out the cross - identification procedure by using $3\sigma_\alpha$ rejection threshold in the α direction and $3\sigma_\delta$ one in the δ one, we took into account the changes of the Hipparcos coordinates α_H and δ_H due to the epoch differences t (in years) by using the Hipparcos proper motions $\mu_{\alpha*}$ and μ_δ, $\alpha_{Hipp} = \alpha_H + \mu_{\alpha*}t/\cos\delta$ and $\delta_{Hipp} = \delta_H + \mu_\delta t$, where α_{Hipp} and δ_{Hipp} are at the epoch of 2MASS observations. Finally, we did the cross - identification of Hipparcos - 2MASS, and our cross - identification procedure identifies the common star if its position satisfies
$\alpha_{Hipp} - \alpha_{2MASS} = \Delta\alpha < 3\sigma_\alpha$ and
$\delta_{Hipp} - \delta_{2MASS} = \Delta\delta < 3\sigma_\delta$.

Following this principle we found 37 940 common stars, which represents about 32.2% of the 117 955 Hipparcos stars in our basic selection. Because of the fact that the 2MASS Second Incremental Data Release covers about 47% of the sky, this means that our cross - identification procedure is more than 68.5% successful. At present, one of the reasons for $100\% - 68.5\% = 31.5\%$ cases is the systematic part of σ_α (and σ_δ) which we did not know at the beginning of our cross - identification procedure. If we suppose that the the systematic error between HIPPARCOS and 2MASS coordinates is less than $0.''1$ (in line with our preliminary investigations about the systematic discrepancies of HIPPARCOS-2MASS coordinates), and put it into our 3σ programme, we can reach near 80 % of common stars. Another reason is that the 2MASS PSC Second Incremental Data Release covers 47% of the sky. Some of the stars are not presented in both catalogues, but only in one of them. We removed 18122 stars from the 2MASS PSC and 263 stars from the HIPPARCOS because these stars were without enough data for our programme, etc.

Our set is divided into 19 572 common stars with $\delta \geq 0^o$ (northern hemisphere) and 18 368 ones with $\delta < 0^o$ (southern one). As a total, only two unsuccessful cross – identifications (of

37 940 common stars) have been found. Each of the Hipparcos stars H16658 and H85045 can be associated with two 2MASS objects. In the Hipparcos Catalogue, the star H16658 is noted as a single star, but the star H85045 is noted as a double star (WDS17229+1628, J1248 AB). From our results, both H16658 and H85045 are close double stars, or maybe the star H16658 is not double, but there is another one with close coordinates. During the next step of our investigations we need to include more data (the magnitude, for example) to solve these cases even there are only two cases for now.

5. CONCLUSIONS

In this paper, only two unsuccessful cross - identifications of 37940 detected common stars have been found. We conclude that these two cases are close double stars or just near each other on the sphere: H85045 is already marked as a double star (WDS17229+1628), H16658 is marked as the single star in the Hipparcos Catalogue. In the future, for these kinds of cases we are going to include the cross – identification part with photometric data into 3σ criterion. If we compare any two catalogues with hundreds millions stars each of them and if there are many unsuccessful (astrometrical) cross - identification cases, it is good to create the cross - identification part with photometric data to solve them.

The cross – identification of HIPPARCOS – 2MASS stars are presented by using our programme based on the 3σ criterion and the information of the positions of stars, the proper motions, etc. It is on line with the similar actions about the cross – identifications of new catalogues of millions stars. It is the part of nowadays efforts to link big stellar catalogues (the visible and infrared ones) to the ICRF.

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