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C. Ducourant, J.-F. Le Campion, M. Rapaport, J. I. B. Camargo, C. Soubiran, J. P. Perie, R. Teixeira, G. Daigne, A. Triaud, Y. Requieme, et al.

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The PM2000 Bordeaux proper motion catalogue* ($+11° \leq \delta \leq +18°$)

C. Ducourant[1,2], J. F. Le Campion[1], M. Rapaport[1], J. I. B. Camargo[1], C. Soubiran[1], J. P. Périe[1], R. Teixeira[2,1], G. Daigne[1], A. Triaud[1], Y. Réquième[1], A. Fresneau[3], and J. Colin[4]

[1] Observatoire Aquitain des Sciences de l'Univers, CNRS - UMR 5804, BP 89, 33270 Floirac, France
e-mail: ducourant@obs.u-bordeaux1.fr
[2] Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Rua do Matão 1226, Cidade Universitária, 05508-900 São Paulo, SP, Brazil
[3] Observatoire Astronomique de Strasbourg, 11 rue de l'Université, 67000 Strasbourg, France
[4] Observatoire de la Côte d'Azur, Boulevard de l'Observatoire, BP 4229, 06304 Nice Cedex 4, France

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ABSTRACT

We present a proper motion catalogue of 2 670 974 stars, covering the declination zone $+11° \leq \delta \leq +18°$. Proper motions were derived from the comparison of the positional M2000 catalogue (systematic observations of the Bordeaux *Carte du Ciel* Zone with the meridian circle, completed in 2000) with positions derived from the reduction of 512 Carte du Ciel plates of the Bordeaux zone (scanned at the APM Cambridge), the AC2000.2 catalogue, the USNO−A2.0 catalogue and the unpublished Yellow Sky (YS3) USNO catalogue. The catalogue has a limiting magnitude $V_M = 16.2$ (Bordeaux CCD meridian circle magnitude) and is complete down to $V_M = 15.4$. Depending on magnitude, the positional precision at mean epoch ranges from 50 to 70 mas and the precision of proper motions varies from 1.5 mas/yr to 6 mas/yr. Meridian V_M magnitudes are provided for all objects together with additional photometry from the 2MASS catalogue when available (99.5% of objects). Positions and proper motions are on the ICRS (International Celestial Reference System). Systematic offsets in 2MASS positions and in UCAC2 proper motions were revealed from comparisons with PM2000.

Key words. astrometry – catalogues – Galaxy: kinematics and dynamics – reference systems – surveys

1. Introduction

PM2000 is a project that started in 1998 at Bordeaux Observatory aiming at the production of a catalogue of accurate proper motions for all stars brighter than $V = 15.4$ in the *Bordeaux Carte du Ciel* zone ($+11° \leq \delta \leq +18°$). The principal motivation of this project was that the available astrometric catalogues (Hipparcos and Tycho-2) deal only with bright stars ($V \leq 12.5$) and that actual investigations of the stellar content of our Galaxy and of our solar neighborhood dynamics require accurate proper motions for much fainter objects. The only other all-sky proper motion catalogues available at the present time are the USNO–B.1 (Monet et al. 2003) and the UCAC2 catalogue (Zacharias et al. 2004)

USNO–B.1 is a catalogue that provides proper motions for a huge sample of objects (more than 1042 million stars) down to $V = 21$, but unfortunately these proper motions are not given with an indication of their standard errors and result from data spread over a short time interval. So the major use of these proper motions concerns works dealing with large proper motions.

The only accurate astrometric proper motion catalogue for faint objects is the UCAC2 catalogue. It provides accurate positions and proper motions for most stars brighter than $R = 16$ in a large part of the sky. This catalogue is the combination of the survey conducted on the USNO CCD Astrograph during 1998−2002 and other astrometric material, essentially the AC2000.2 (Urban et al. 1998) and the unpublished YS3.0 catalogue. The AC2000.2 catalogue contains the first epoch material for bright stars ($V \leq 13$) and the precision of the proper motions of these objects in UCAC2 is of a few mas/yr. For fainter stars ($13 \leq V_M \leq 16$) their first epoch material is the YS3.0 catalogue. The resulting proper motions have a precision of about 6 mas/yr.

The PM2000 project is an independent effort to give, in 1/20th of the sky, accurate proper motions for bright and faint stars ($V \leq 16.2$) using the *Carte du Ciel* plates as first epoch. These plates (generally taken around 1900) provide good photographic positions for most stars brighter than $V \leq 14$ and up to $V = 16.2$. The comparison of these positions with present day astrometric catalogues allows one to produce accurate proper motions (few mas/yr). In this work we used our

* The PM2000 catalogue is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/448/1235

proper motion catalogue PM2000 to test the astrometric quality of the catalogues UCAC2 and 2MASS (Cutri et al. 2003) in an extended magnitude domain.

The first phase of the Bordeaux PM2000 project consisted of the systematic observation during four years of the Bordeaux *Carte du Ciel* zone with the CCD meridian circle (operating in drift scan mode). The resulting astrometric catalog M2000 (Rapaport et al. 2001) provides accurate astrometric positions for about 2.3 million stars at the mean epoch 1998.6 down to the limiting magnitude V_M = 16.2 with external positional errors lower than 40 mas for stars with $9 \leq V \leq 15$.

The second phase of this project consisted of the measurement of the 512 Carte du Ciel plates archived at Bordeaux. The plates were sent to the APM (Cambridge) automatic measuring machine in 2000 and digitized there. The reduction of these plates using the Tycho-2 catalogue as the reference catalogue led to the recent publication of the CdC2000 positional catalogue of 372 000 stars with $8.0 \leq V \leq 16.2$ at mean epoch 1900 (Rapaport et al. 2005).

This paper presents the combination of the Bordeaux *Carte du Ciel* plates measurements, the M2000 observations and three other sources of astrometry (AC2000.2, USNO–A2.0 and YS3) to derive accurate proper motions for all stars from the M2000 catalogue ($V_M \leq 16.2$) in the declination zone $+11° \leq \delta \leq +18°$. We obtain a high density, highly accurate, astrometric catalog of 2.5 millions stars. Positions, proper motions and photometry are provided for all stars. V_M magnitudes are derived from the M2000 catalogue, and whenever possible photometry from the 2MASS survey is included.

2. The data

To derive positions and proper motions, we have combined the M2000 positions ($t \sim 1998$) with four different sources of positions: *Carte du Ciel* plate measurements (CdC) ($t \sim 1900$), AC2000.2 positions ($t \sim 1900$), USNO–A2.0 positions ($t \sim 1950$) (Monet et al. 1998) and YS ($t \sim 1978$) positions (Monet 2001).

The participation of each of these catalogues in the production of the PM2000 catalogue is shown in Fig. 1.

The M2000 catalogue (Rapaport et al. 2001) is a positional catalogue resulting from four years of systematic observations with the Bordeaux CCD meridian circle of the declination band $+11° \leq \delta \leq +18°$ (the Bordeaux *Carte du Ciel* zone). The resulting astrometric catalog includes about 2.3×10^6 stars down to the magnitude limit V = 16.2, the catalog being complete down to V_M = 15.4. The median internal standard errors in position is ~35 mas in the magnitude range $11 < V_M < 15$, which degrades to ~50 mas when the faintest stars are considered. M2000 provides also one band photometry with a median internal standard error of ~0.04 mag.

From Fig. 1, the CdC contribution is limited at V = 15.5. while USNO-A2 and YS3.0 contributions concern objects as faint as V = 16.5. At V = 14 for example, not all objects benefit from a CdC measurement. There are several reasons for this, the main being the absence of many plates in the Bordeaux *Carte du Ciel* archive near the Galactic plane. Another reason

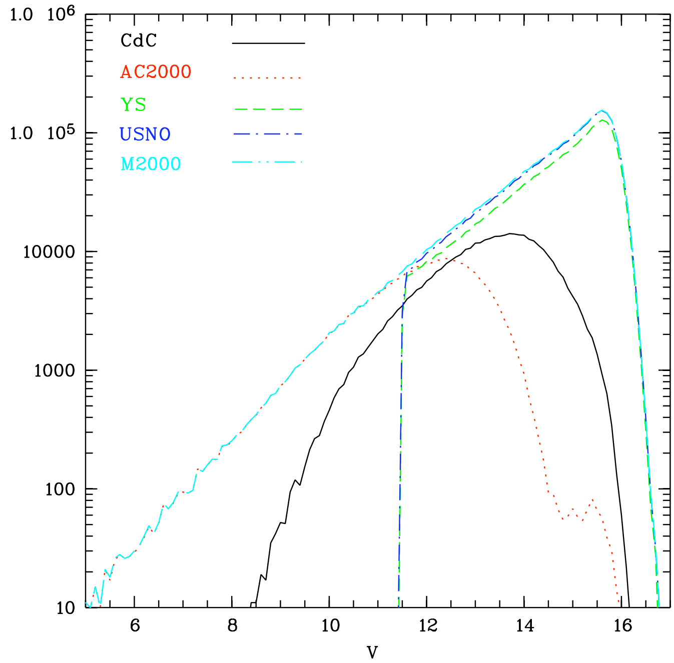

Fig. 1. Histogram of astrometric sources of position used in this work to derive mean positions and proper motions. USNO and YS participations concern objects fainter than V_M = 11.5.

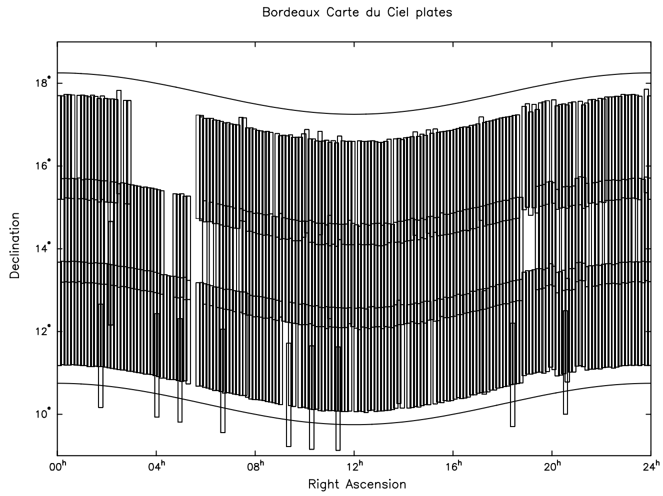

Fig. 2. Sky coverage with the Bordeaux *Carte du Ciel* plate material in equatorial coordinates. Each vertical strip corresponds to one plate.

is that the CdC plates do not cover completely, as far as the borders are concerned, the totality of the M2000 band (see Fig. 2). Moreover photographic gelatin degradation over time, as well as sky conditions during the observations is responsible for a difference of up to 2 mag between the plate limiting magnitudes.

The AC2000.2 is a revised version of its first 1997 release, comprising about 4.6 million all-sky distributed stars. This material provides good positions at the average epoch of 1907, so that 1−3 mas/yr level accuracies are generally achieved by the proper motions derived from the combination of good current epoch positions with the AC2000.2 data.

The USNO−A2.0 is a catalogue of about 0.5 billion objects throughout the sky, and represents the scans made by the USNO Flagstaff Station's (NOFS) Precision Measuring Machine (PMM) of red and blue POSS–O and POSS–E, SERC–J and ESO–R photographic surveys (see Lasker et al. 1990, for details). A study of the astrometric quality of USNO−A2.0 catalogue (Assafin 2001) pointed out systematic deviations of positions depending of the zone of the sky. For that reason we had to perform verifications and large scale corrections of the USNO−A2.0 positions before its use in the PM2000 project as described in Sect. 5.

The YS3 consists in unpublished NOFS scans of the NPM (Northern Proper Motion) and the SPM (Southern Proper Motion) plates kindly made available by Dr. Monet (NOFS). Details about the NPM and SPM projects can be found in Klemola & Hanson (1987) and Platais et al. (1998), respectively. As in the case of USNO–A2.0, further investigations in these data were also performed before its use in the PM2000 project (see Sect. 6).

3. The meridian M2000 catalogue

The source of current epoch positions used here is the M2000 meridian observations described in detail in Rapaport et al. (2001). This positional catalogue provides precise positions, nevertheless it suffers from linear deviations in declinaison as a function of the color index. At the epoch of the constitution of the M2000 catalogue it was not possible to correct this effect since photometry in a band other than V_M was not available to the magnitude of M2000 objects. Subsequently, the 2MASS all-sky survey release was published so we could correct our meridian observations for this effect for the PM2000 project.

3.1. Correction of chromatic effects

The equation was determined from the analysis of $\Delta\delta$ as a function of the color-index ($V_M - K_s$).

Tycho-2 (Høg et al. 2000) or UCAC2 catalogues were used to provide the $\Delta\delta$ quantities in the sense Catalogue minus M2000 at the epoch of this latter, about 1998. Only Tycho-2 stars already present in the first version of the Tycho Catalogue (ESA 1997) were used, because of their better precision compared to the new ones. V_M magnitudes were obtained directly from the M2000, and the K_s ones from the 2MASS All-Sky Survey.

In Tycho-2, very red objects ($V - K_s > 4.53$) are underrepresented. For these objects, differences obtained from the comparison with the UCAC2 were used to test and correct our chromatic effect (UCAC2 has proved not to be affected by chromatic bias).

Equations (1) and (2) present the final employed correction models.

$$\Delta\delta = a(V - K_s) + b_1 \quad : (V - K_s) \leq 4.53 \text{ (Tycho2)} \qquad (1)$$

$$\Delta\delta = b_2 \quad : (V - K_s) > 4.53 \text{ (ucac2)} \qquad (2)$$

where $\Delta\delta$ is the correction in declination and a, b_1 and b_2 are the coefficients to be determined.

Solutions to Eqs. (1) and (2) were given by a weighted least-squares fit. In order to eliminate the most discrepant data, an iterative 3σ elimination process was used. Declinations and magnitudes were selected according to their nominal precisions and/or quality flags. The coefficients so obtained are:

$$a = -23.9 \pm 0.3 \text{ mas/mag}$$
$$b1 = 48.1 \pm 0.5 \text{ mas}, \quad \rho^{a}_{b1} = -0.8887$$
$$b2 = -60.2 \pm 0.4 \text{ mas}.$$

Hereafter, any use of the M2000 data implies that they are corrected for the color-index effects.

4. Carte du ciel plates of the Bordeaux zone

4.1. Photographic plate data

The Bordeaux *Carte du Ciel* plate archive contains 512 photographic plates (2.4° × 2.4°) taken with the Bordeaux *Carte du Ciel* astrograph between 1893 and 1937. These plates were measured with the APM automatic measuring machine in Cambridge and reduced from (x, y) to (α, δ) using the TYCHO-2 catalogue. The reduced positions of this archive at the epoch of the plates constitute the CdC2000 catalogue (Rapaport et al. 2005). The final PM2000 catalogue will not directly use the CdC2000 equatorial positions but will use the (x, y) *Carte du Ciel* measurements (hereafter CdC) in an iterative reduction process.

We give in Fig. 2 the sky coverage of the CdC plates. Fifty one plates of our archive (including Hyades area) were lost over time and correspond to the uncovered zones of this figure.

4.2. Quality control

One important point in this work is the introduction of the *Carte du Ciel* plates measurements which will allows to derive accurate proper motions for a large number of objects. It is therefore important to be sure that these measurements do not suffer from any significant systematic effects.

For this purpose we calculated preliminary proper motions by comparing the M2000 positions (1998) and the CdC2000 positions (1900) (hereafter M2000/CdC). The M2000 catalogue has been extensively tested (Rapaport et al. 2001) and does not show a bias (except the chromatic bias already discussed). Therefore these preliminary proper motions are a good test to investigate the eventual bias introduced by the Carte du Ciel measurements.

We selected in this preliminary M2000/CdC catalogue 53452 stars present in the TYCHO-2 reference catalogue. We present in Fig. 3 the comparison of our positions and proper motions with those of TYCHO-2.

We notice a very good agreement between our preliminary catalogue and TYCHO-2 in position and in proper motion. A slight offset in our positions $\Delta\delta \sim 7$ mas for $10 \leq V \leq 12$ is visible, probably resulting from a bias in the the CdC measurements. Our proper motions are very well aligned on TYCHO-2's ones indicating that the impact of the possible bias of CdC measurements in declination on the proper motion

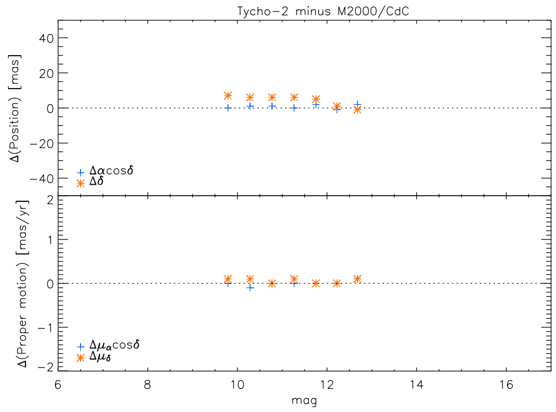

Fig. 3. Average differences in mean positions and proper motions, in the sense TYCHO-2 minus M2000/CdC, at the epoch of the M2000/CdC positions. Error bars are negligible. Each point is the mean of at least one thousand values.

determination can be neglected in the following. No effect is detected either as a function of position or color index.

The work on the reduction of *Carte du Ciel* plates using TYCHO-2 catalogue as a reference (CdC2000, Rapaport et al. 2005) showed that CdC measurements do not suffer from a magnitude effect. We therefore extend to the magnitude domain $8 \leq V_M \leq 16.2$ our conclusion that the use of Carte du Ciel measurements do not introduce significant systematic deviations in the proper motion calculations and we assume that the CdC provides a valuable set of good quality ancient epoch positions. Unfortunately there is no external data to compare with in this magnitude domain to confirm this assumption; nevertheless there is no indication that Carte du Ciel measurement suffers from systematic effects. We also conclude from these comparisons that the M2000/CdC intermediate catalogue is suitable material to investigate the eventual systematic deviations of USNO–A2.0 and YS3 positions.

5. USNO–A2.0 data

As seen in Fig. 1, USNO–A2.0 data will participate in each proper motion determination, either as intermediate epoch data (~300 000 objects), or first epoch data (~2 010 000 objects). In this case, it is more critical that these data do not introduce systematic deviations whose repercussion would be direct on proper motions. The poor intersection between TYCHO-2 and USNO–A2.0 well measured (not saturated) objects does not allow a direct test of the astrometric quality of USNO–A2.0 positions in the studied zone. For this reason we used the intermediate M2000/CdC catalogue to perform this comparison.

Figure 4 gives the comparison M2000/CdC minus USNO–A2.0 at the epoch of USNO−A2.0 as a function of the V_M magnitude (about 2 300 000 common stars). This comparison concerns objects brighter than $V = 11.5$ (well measured in USNO−A2.0).

Assuming that the M2000/CdC catalogue is free from bias (as demonstrated in Sect. 4.2), the differences visible in Fig. 4 were attributed to the USNO−A2.0 data and corrected with B-spline fits before using these data in the proper motion determination.

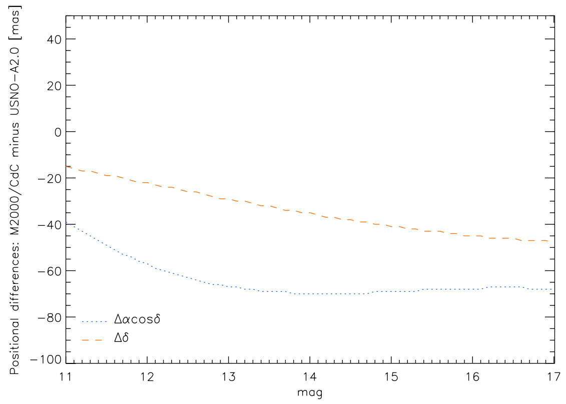

Fig. 4. Positional differences in the sense M2000/CdC minus USNOA–2.0 as a function of the magnitude.

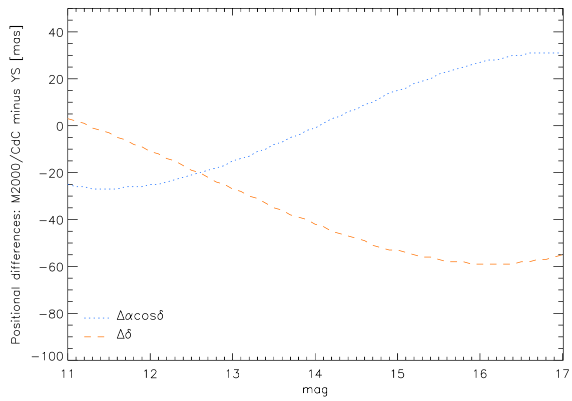

Fig. 5. Mean differences in the sense M2000/CdC minus YS as a function of the magnitude.

6. YS data

YS data will also be used in the majority of proper motion determinations, but never as first epoch material. As for USNO–A2.0, we had to perform the comparison M2000/CdC minus YS at the epoch of YS as a function of the V_M magnitude to investigate eventual systematic effects in the YS positions. We present this comparison in Fig. 5.

Assuming that the M2000/CdC catalogue is free from bias (as demonstrated in Sect. 4.2), the differences visible in Fig. 5 were attributed to the YS data and corrected before using these data in the proper motion determination.

7. Global astrometric reduction

Once all sources of positions were tested and eventually corrected for biases, we performed a global iterative reduction (Eichhorn 1960; Benevides-Soares & Teixeira 1992) of the whole set of data (CdC (x, y), AC2000.2 (α, δ), USNO–A2 (α, δ), YS (α, δ) and M2000 (x, y) measurements).

7.1. The equations

The equations associated with the observations of a star on a Carte du Ciel plate use the measured coordinates (x_m, y_m) of the star and its standard coordinates $(X(\alpha(t), \delta(t)), Y(\alpha(t), \delta(t)))$

by means of a model introducing the plate constants of each plate. These equations take the general form:

$$X(t) - (aX(t) + bY(t) + c + dX(t)^2 + eX(t)Y(t) + fY(t)^2) = x_m + \epsilon_x \quad (3)$$

where: $X(t) = X(t_0) + \mu_\alpha \cos(\delta)(t - t_0)$; (a, b, c, d, e, f) are the unknown plate constants corresponding in this work to a second degree model, $(X(t), Y(t))$ are the unknown standard coordinates of the stars at the epoch t of the plate; $(X(t_0), Y(t_0))$ are the unknown standard coordinates of the stars at an arbitrary epoch t_0; (μ_α, μ_δ) are the unknown proper motions of the stars. (x_m, y_m) are the measurements of the stellar images with errors (ϵ_x, ϵ_y). A similar equation holds for the y_m measurements.

The equations associated with the observation of a star on a meridian strip have a very similar form. $(\alpha(t), \delta(t))$ are used instead of the standard coordinates $(X(t), Y(t))$. The atmospheric fluctuations are taken into account (Rapaport et al. 2001) by the introduction of B spline functions (S^x_m, S^y_m) depending on the epoch t of the observation, and on coefficients $(\lambda_1, \lambda_2, ..., \lambda_r)$ which must be determined together with the instrumental constants. The associated equations have then the following form:

$$\alpha(t_0) + \mu_\alpha(t - t_0) - (a_0 + a_1 x_m + a_2 y_m) - S^x_m(t, \lambda_1, \lambda_2, ..., \lambda_r) = x_m + \epsilon_x. \quad (4)$$

We also use in this work star positions coming from the USNO–A2.0, YS and AC2000.2 catalogues. The corresponding equations have the form:

$$\alpha(t_0) + \mu_\alpha(t - t_0) \ = \ \alpha_{\rm cat}(t) + \epsilon_{\rm cat} \quad (5)$$

where t is the epoch for the position given by the considered catalogue and $(\alpha_{\rm cat}(t), \delta_{\rm cat}(t))$ the catalogue positions and $\epsilon_{\rm cat}$ the associated catalogue errors.

The unknowns of the resulting system of equations of condition are the stellar parameters (positions and proper motions of all stars) and the instrumental parameters (plates constants). This system is singular and admits an infinity of solutions due to the existence of a kernel of dimention four in which the component of the solution is arbitrary. We therefore have to apply constraints to this component of the solution to produce a unique solution. We used the following constraints and applied them to all TYCHO-2 stars: $\sum \Delta\alpha_i \cos\delta_i = \sum \Delta\delta_i = \sum \Delta\mu_{\alpha_i} \cos\delta_i = \sum \Delta\mu_{\delta_i} = 0$, where $\Delta\alpha_i, \Delta\delta_i, \Delta\mu_{\alpha_i}, \Delta\mu_{\delta_i}$ are the corrections to the TYCHO-2 parameters as given by our solution. These constraints mean that the referential defined by our catalogue is aligned with the system defined by HIPPARCOS via TYCHO-2.

7.2. The normal equations

One characteristic of the global reduction of a system of equations as Eqs. (3)–(5) is that it allows the simultaneous determination of all plates constants, all meridian strips instrumental constants, the determination of the position and proper motion of all stars together with the determination of the coefficients λ_i associated with the atmospheric fluctuations. The global system of equations of condition associated with all stars on all plates, meridian strips and intermediate catalogues is then written as:

$$\boldsymbol{M u} \ = \ \boldsymbol{k} \quad (6)$$

where $\boldsymbol{k}$ is the vector of second hand terms. The vector $\boldsymbol{u}$ of the unknowns can be partitioned as follows:

$$\boldsymbol{u} \ = \ (\boldsymbol{a}^t, \alpha^t, \mu^t, \lambda^t). \quad (7)$$

Where $\boldsymbol{a}$ represents the vector of all plates or strip constants; α represents the vector of all star positions at a given epoch t_0; μ the vector of all star proper motions and λ represents the vector of coefficients appearing in the B splines functions.

By natural correspondence, M is split as:

$$M = (A, B, C, D).$$

Equation (6) then becomes:

$$A\boldsymbol{a} + B\alpha + C\mu + D\lambda = \boldsymbol{k}. \quad (8)$$

The structure of these submatrices is very simple. For example, A is a block diagonal matrix, each block corresponding to the usual matrix associated with the classical astrometric reduction of a plate. The noticeable advantage of this formulation is that a Gauss-Seidel iterative method can be applied to solve the normal equations associated with Eq. (8). Indeed, starting from arbitrary values $(\alpha_0, \mu_0, \lambda_0)$ (not necessarily near the solution), the method consists of solving in the least squares sense:

$$\begin{aligned} Aa &= \boldsymbol{k} - B\alpha_{\bf 0} - C\mu_{\bf 0} - D\lambda_{\bf 0} && \text{and obtain } a_{\bf 1} \quad (9)\\ B\alpha &= \boldsymbol{k} - A\boldsymbol{a}_1 - C\mu_{\bf 0} - D\lambda_{\bf 0} && \text{and obtain } \alpha_{\bf 1}\\ C\mu &= \boldsymbol{k} - A\boldsymbol{a}_1 - B\alpha_{\bf 1} - D\lambda_{\bf 0} && \text{and obtain } \mu_{\bf 1}\\ D\lambda &= \boldsymbol{k} - A\boldsymbol{a}_1 - B\alpha_{\bf 1} - C\mu_{\bf 1} && \text{and obtain } \lambda_{\bf 1}. \end{aligned}$$

The process is then iterated until convergence. In our problem, five iterations are sufficient to obtain the solution. The matrix of the normal equations being positive semi definite, the iterative process converges towards the solution of Eq. (8), whatever the departure point may be.

The seed $(\alpha_0, \mu_0, \lambda_0)$ used to start the iterations is taken as follows: α_0, μ_0 were obtained by the comparison of the astrometric reduction of the plates and of the meridian strip using the TYCHO-2 stars present on the plates and strips as reference stars (the M2000/CdC intermediate catalogue); the coefficients λ_i are taken as null.

The positional data used here have very different origins and precisions. For this reason we had to weight our equations. For the intermediate positions coming from the quoted catalogs, we adopt the values proposed by the authors, i.e. σ = 200 mas for AC2000.2 positions, σ = 110 mas for Yellow Sky positions and σ = 250 mas for USNO–A2.0 positions.

For the data coming from the CdC plates we took the residual of classical reduction of the plates using TYCHO-2 as reference catalogue leading to σ = 130–210 mas depending on the quality of the plate; for the meridian observations we took the residual of the classical reduction of each meridian strip using TYCHO-2 as the reference catalogue, which gives σ = 70–200 mas depending on the quality of the nights.

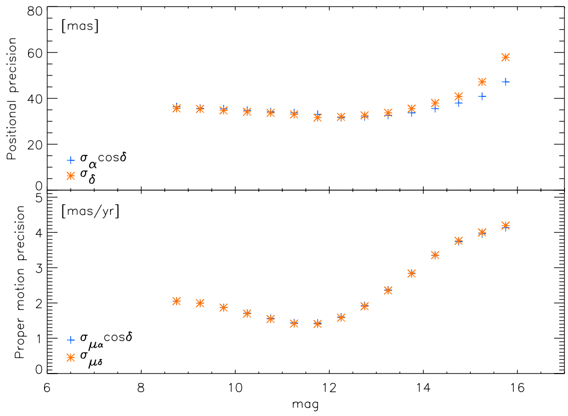

Fig. 6. Distribution of model-based standard errors on positions and proper motions of PM2000 as a function of V_M magnitude.

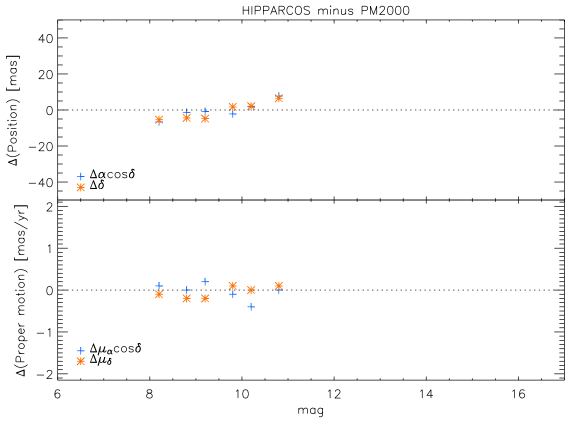

Fig. 7. Average differences in mean positions and proper motions, in the sense HIPPARCOS minus PM2000, at the epoch of the PM2000 positions as function of V_M after a 3σ elimination. Error bars are negligible. Each point is the mean of at least three hundred differences. The dispersions of these differences in position and proper motions around their mean values are $\sigma_{\Delta_{\alpha*}} = 55$ mas, $\sigma_{\Delta_\delta} = 53$ mas, $\sigma_{\Delta_{\mu\alpha*}} = 2.27$ mas/yr and $\sigma_{\Delta_{\mu\delta}} = 2.74$ mas/yr. Where * stands for $\cos\delta$.

8. Error budget

We applied this global reduction to our data and calculated for more than 2.5 millions stars a mean position at a mean epoch and proper motion together with the associated standard errors.

8.1. Internal errors

There are two techniques to determine standard errors associated with mean positions and proper motions: the *model method* and the *scatter method* (Høg et al. 2000). The *model method* uses the predetermined estimate of individual catalogue/observation position errors to compute a standard error (also called *formal error*). The *scatter method* computes the standard errors using the residual of the fit to the data. This latter method may underestimate the errors. We give in our catalogue the *model*-based standard errors together with the *goodness of fit* which is the ratio of the *scatter*-based and the *model*-based errors. This *goodness of fit* is only defined when the number of epoch of observations is greater than 2. Large *goodness of fit* point out objects for which the residual of the fit is much larger than expected and probably indicates doubtful proper motions. We give in Fig. 6 the distribution of these *model*-based standard errors as a function of V_M.

The distribution of model-based standard errors on positions of PM2000 are 35 mas for $8.5 \leq V_M \leq 14$ and reach 60 mas at $V_M = 16$. The standard errors of proper motions are about 1.5 mas/yr for $8.5 \leq V_M \leq 13$ and reach 4.5 mas/yr for $V_M = 16$. The inhomogeneity of the precisions of the proper motions is derived directly from the material used for the first epoch in its calculation. If a Carte du Ciel measurement or an AC2000.2 position is available, the precision of proper motions is close to 1.5 mas/yr.

8.2. External errors

The evaluation of the external errors of PM2000 can be obtained from the comparison with catalogues with which we do not have common data. This is the case of HIPPARCOS (ESA 1997) (which unfortunately only concerns very bright stars); this is also the case of the 2MASS positional catalogue which is not properly speaking an astrometric catalogue but whose astrometric quality has been proved by comparisons with other sources and which covers an extended domain of magnitude (almost each object of PM2000 is present in 2MASS).

8.2.1. Comparison to HIPPARCOS

We present in Fig. 7 the comparison of PM2000 positions and proper motions with the ones given by HIPPARCOS at the mean epoch of PM2000 for the 4384 common stars ($V_M > 8$) as function of V_M magnitude.

This comparison concerns the bright part of our catalogue for which a CdC measurement and/or an AC2000.2 position was available. Unfortunately, as shown in the CdC2000 work, the CdC measurements are generally of lower quality in the magnitude domain $V \leq 12$ (problems of saturation) which is the domain of comparison with Hipparcos. Therefore the results obtained here will probably indicate upper values of our errors.

One notices in Fig. 7 a general excellent agreement in position and proper motion.

The dispersions of these differences around their mean values are $\sigma_{\Delta\alpha*} = 55$ mas, $\sigma_{\Delta\delta} = 53$ mas, $\sigma_{\Delta\mu\alpha*} = 2.27$ mas/yr and $\sigma_{\Delta\mu\delta} = 2.74$ mas/yr.

These dispersions are the result of PM2000 and HIPPARCOS errors: $\sigma^2_\Delta = \sigma^2_{\rm ext} + \sigma^2_{\rm hip}$ where $\sigma_{\rm ext}$ are the external errors of PM2000 and $\sigma_{\rm hip}$ are the errors of Hipparcos in position at the epoch of PM2000 and in proper motion. Knowing the errors of HIPPARCOS at the epoch of comparison, we deduced estimates of the external precision of PM2000 for the bright objects ($V < 11$). We thus obtained $\sigma_{{\rm ext}(\alpha\delta)} = 50$ mas and $\sigma_{{\rm ext}(\mu)} = 1.5$–2 mas/yr.

No systematic deviation of right ascensions or declinations were found as function of position.

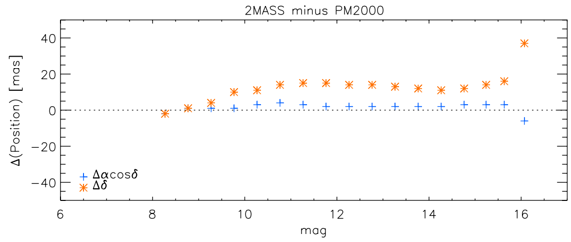

Fig. 8. Average differences in mean positions 2MASS minus PM2000, at the epoch of 2MASS positions as function of V_M. The dispersions of these differences in position around their mean values are $\sigma_{\Delta\alpha*}$ = 106 mas and $\sigma_{\Delta\delta}$ = 114 mas. Each point is the mean of at least one thousand differences.

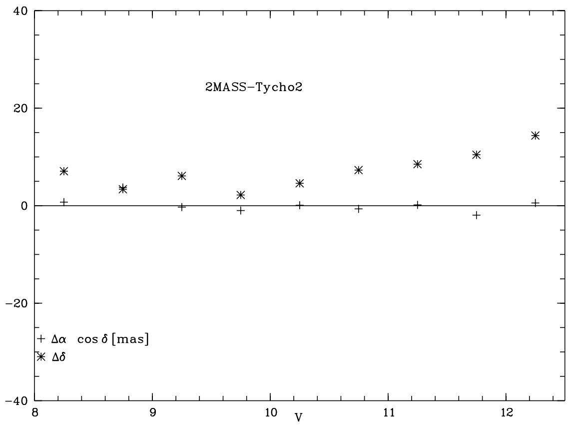

Fig. 9. Average differences in position TYCHO-2 minus 2MASS in the Bordeaux zone at the epoch of 2MASS. The magnitude bins size is 0.5 mag and contain more than 1000 stars for comparison.

We conclude from this analysis that realistic evaluation of errors of PM2000 are $\sigma_{\rm pos}$ = 50 mas and σ_μ = 1.5–2 mas/yr in the magnitude domain $8 \le V \le 11$. These values are probably upper limits of our errors since it concerns a part of PM2000 for which saturation on plates may degrade the precision.

8.2.2. Comparison to MASS

The PM2000 has also been compared to the 2MASS all-sky infrared catalog, which was released in april 2003. This catalogue announces a positional precision of 80–110 mas and appears as an interesting astrometric source for comparison. Differences between PM2000 and 2MASS positions are given in Fig. 8. The PM2000 proper motions have been used to bring the 2 656 992 PM2000 positions to the 2MASS observational epoch. The mean epoch of 2MASS observations is 1999.5 in the PM2000 zone.

The mean epoch of PM2000 is 1991.8. One observes in Fig. 8 systematic deviations of differences of declinations as large as 10–18 mas. These differences result from a systematic effect either in PM2000 proper motions or in the 2MASS positions. Based on the conclusions of the comparison of PM2000 with HIPPARCOS, these differences have to be attributed to 2MASS positions. To investigate this bias, we have compared 2MASS positions with TYCHO-2 ones (projected at the 2MASS epoch). We present this comparison in Fig. 9.

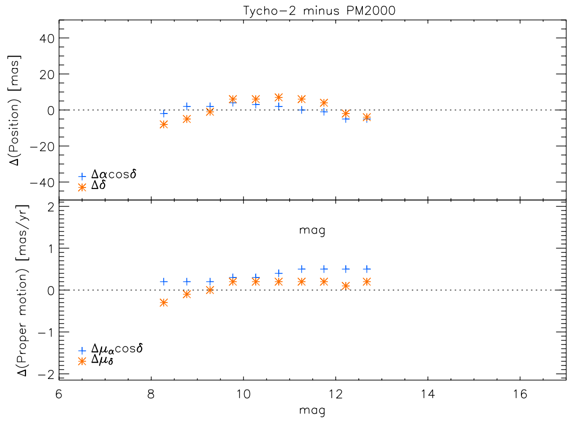

Fig. 10. Average differences in mean positions and proper motions, in the sense TYCHO-2 minus PM2000, at the epoch of the PM2000 positions as function of V_M after a three sigma elimination. Error bars are negligible. Each point is the mean of at least one thousand differences.

In this late comparison, we observe a systematic difference in declination between Tycho-2 and 2MASS of 10–17 mas for $10.5 \le V \le 12.5$. This effect is large enough to explain partially to totally the differences between PM2000 and 2MASS in declination. We there fore conclude that the observed differences between PM2000 and 2MASS in Fig. 8 are caused by a systematic offset of 2MASS positions.

As in the comparison with HIPPARCOS, we can deduce here from the dispersions of the differences "2MASS minus PM2000" the external errors of PM2000 at the 2MASS epoch: $\sigma^2_\Delta = \sigma^2_{\rm ext} + \sigma^2_{\rm 2mass}$; where the external errors of PM2000 are: $\sigma^2_{\rm ext} = \sigma^2_{\alpha\delta} + \sigma^2_{\rm mu}(t_{\rm 2mass} - t_{\rm pm200})^2$.

We thus obtained $\sigma_{\rm ext}$ = 50 mas for $V \le 14$ and $\sigma_{\rm ext}$ = 75 mas for $V \sim 16$ using the errors of 2MASS as given in "the explanatory Supplement to the 2mass All Sky Data Release". The difference of epoch between PM2000 and 2MASS is about 8 years. These results are compatible with the external precisions of the PM2000 of $\sigma_{\rm pos}$ = 50 mas and σ_μ = 1.5 mas/yr for $V \le 14$, these precisions degrading to $\sigma_{\rm pos}$ = 70 mas and σ_μ = 6 mas/yr at V = 16. No systematic deviation of right ascensions or declinations were found as function of position.

8.3. Comparison with other catalogues

To probe the coherence of the PM2000 catalogue, we have compared our positions and proper motions with the ones given by TYCHO-2 and UCAC2 at the mean epoch of PM2000. Nevertheless, we have common material with TYCHO-2 (AC2000.2) and with UCAC2 (AC2000.2, YS). Our positions and proper motions are therefore correlated and the comparison to those catalogues will only test the coherence of our results and detect the presence of systematic effects.

8.3.1. Comparison to Tycho-2

We present in Fig. 10 the comparison of PM2000 positions and proper motions with the ones given by TYCHO-2 at the mean

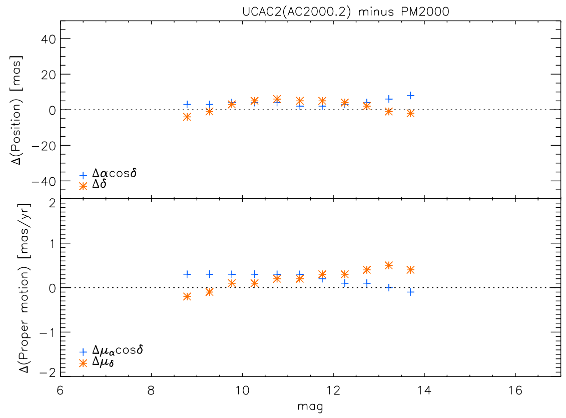

Fig. 11. Average differences in mean positions and proper motions, in the sense UCAC2 minus PM2000, at the epoch of the PM2000 positions as function of V_M. This comparison concerns 93 613 UCAC2 objects whose proper motion is based on an AC2000.2 position and PM2000 objects whose proper motion is based on a CdC position. Each point is the mean of at least one thousand differences. $\sigma_{\Delta_{\mu\delta}}$ = 2.1 mas/yr.

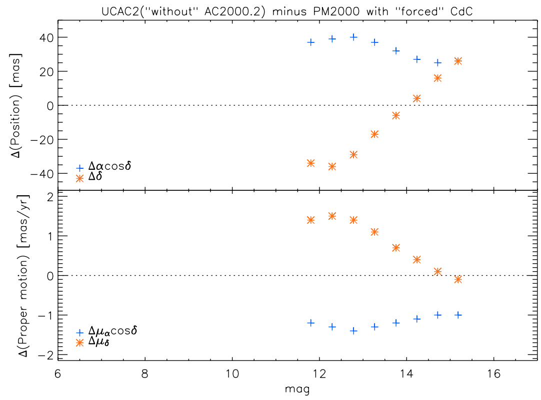

Fig. 12. Average differences in mean positions and proper motions, in the sense UCAC2 minus PM2000, at the epoch of the PM2000 positions as function of V_M. This comparison concerns the 213 530 UCAC2 objects whose proper motion is *not* based on an AC2000.2 position while PM2000 objects have been selected so that their proper motions are based on a CdC measurement. Each point is the mean of at least one thousand differences.

epoch of PM2000 for the 125 172 common stars as function of V_M magnitude.

This comparison concerns the bright part of our catalogue for which a CdC measurement and/or an AC2000.2 position was available. This is a general excellent agreement in position and proper motion with a possible systematic offset of PM2000 positions (depending on the magnitude) $\Delta\delta \sim 5{-}7$ mas for $9.5 \leq V \leq 12$ and a light offset of our proper motions in right ascension $\Delta\mu_\alpha \cos(\delta) \sim 0.5$ mas/yr for objects with $11 \leq V_M \leq 13$. The bias in declination is the same as observed in Fig. 3 and probably results from a systematic effect in the CdC measurements. We already noticed that this offset has no impact on the proper motions and can be neglected.

8.3.2. Comparison to UCAC2

UCAC2 is the only astrometric catalogue available for stars with $13 \leq V_M \leq 16$. Nevertheless Zacharias (2004) indicates possible biases of UCAC2 proper motions. To segregate UCAC2 biases from ours we carried out this comparison as follows:

- *Comparison 1*: we compared PM2000 objects based on a CdC measurement with UCAC2 objects based on an AC2000.2 first epoch material. This comparison allows us to evaluate the systematic effects of UCAC2 for bright objects since in this configuration our systematic effects are known from Sect. 8.3.1. We give this comparison in Fig. 11.
- *Comparison 2*: we compared PM2000 objects based on a CdC measurements with UCAC2 objects not based on an AC2000.2 first epoch material (and therefore of degraded precision in proper motions). In this comparison we can evaluate the systematic effects of UCAC2 for fainter objects. We give this comparison in Fig. 12.
- *Comparison 3*: we compared the whole PM2000 with UCAC2. We give this comparison in Fig. 13.

Comparison 1: we present in Fig. 11 average differences (93 613 objects) in mean positions and proper motions, between UCAC2 and PM2000, at the epoch of the PM2000 positions as a function of V_M. This comparison concerns UCAC2 objects whose proper motions are based on an AC2000.2 positions and PM2000 objects whose proper motions are based on a CdC position.

From this comparison we conclude that for the sub-sample of UCAC2 objects for which an AC2000.2 position was used ($8.5 \leq V \leq 14$), there is an excellent agreement between PM2000 and UCAC2. We notice a slight bias in the differences $\Delta_{\mu\delta} \sim 0.5$ mas/yr and that could be attributed to UCAC2 proper motions since no similar effect was detected in the PM2000 comparison to TYCHO-2 and to HIPPARCOS.

Comparison 2: we present in Fig. 12 average differences in mean positions and proper motions, in the sense UCAC2 minus PM2000, at the epoch of the PM2000 positions as a function of V_M. This comparison concerns the 213 530 UCAC2 objects whose proper motions are *not* based on an AC2000.2 position while PM2000 objects have been selected so that their proper motions are based on a CdC measurement.

In Fig. 12 the lower panel presents differences of proper motion between both catalogues ($11.5 \leq V \leq 15$). Systematic discordances appear reaching $\Delta_{\mu_\alpha \cos\delta} = -1$ mas/yr and $\Delta_{\mu_\delta} = +1.4$ mas/yr. Clearly this bias is due to the UCAC2 proper motions since no similar effect was detected in the PM2000 comparison to TYCHO-2 and HIPPARCOS. We notice the impact of UCAC2 systematic errors in proper motions propagated over time, in the upper panel of Fig. 12 and leading to differences as large as 40 mas. The systematic effects found here in the UCAC2 proper motions are compatible with the Zacharias (2004) conclusions announcing systematic errors in the proper motions of UCAC2 of about 0.5−1 mas/yr.

Comparison 3: we present in Fig. 13 average differences in mean positions and proper motions, in the sense UCAC2 minus PM2000, at the epoch of the PM2000 positions as a function

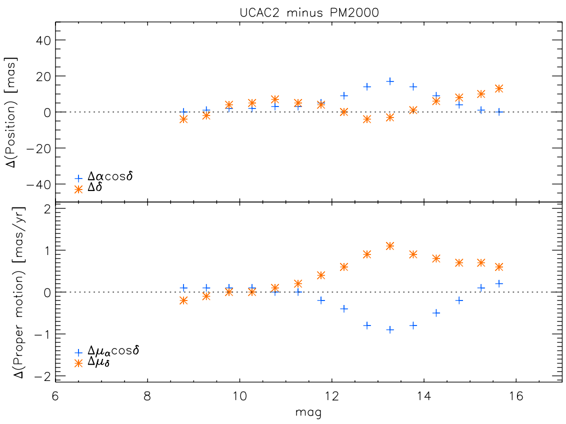

Fig. 13. Average differences in mean positions and proper motions, in the sense UCAC2 minus PM2000, at the epoch of the PM2000 positions as function of V_M. This comparison concerns the 1 977 179 common stars between both catalogues. Each point is the mean of at least one thousand differences.

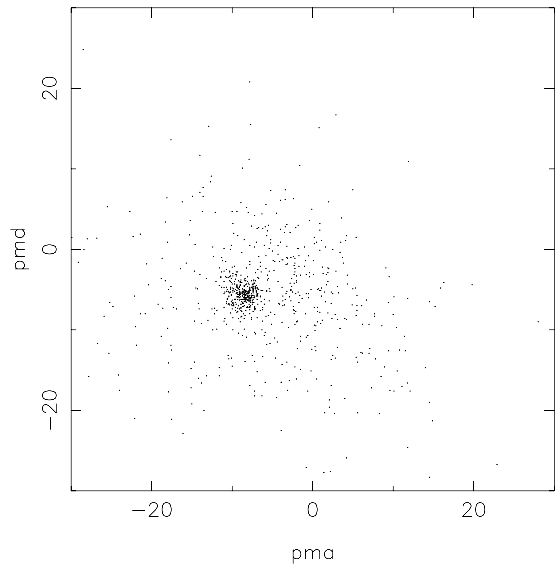

Fig. 14. Proper motion distribution in a circular field of 1° radius around M 67, restricted to stars brighter than V = 14.

of V_M. This comparison concerns the 2 054 989 stars common to both catalogues.

In Fig. 13, systematic differences in both proper motions and in declination are evident and are as large as $\Delta\mu_\alpha \cos\delta = -1$ mas/yr and $\Delta\mu_\delta = +1.1$ mas/yr. These effects are very similar to those observed in Figs. 11 and 12 and nearly of the same amplitude suggesting that UCAC2 proper motions are the origin of the systematic discrepancies. The smaller amplitude of the differences in position result from the fact that considering the intersection of both catalogues, their mean epochs are closer to each other and the impact of systematic effects in proper motion is less.

8.4. Internal velocity dispersion in open clusters as test for PM2000 proper motion accuracy

The direct comparison of the PM2000 proper motions to those from HIPPARCOS gives an external estimate of our precision up to $V \simeq 11$, however nothing can be said for fainter magnitudes because no other fainter catalogue with an equivalent precision at the epoch of PM2000 is available in this area of the celestial sphere. Open clusters offer an opportunity to assess the consistency of our determinations of proper motions and their errors. Open clusters have coherent motions in space which are related to coherent proper motions. The standard deviation of the proper motion distribution of an open cluster is the result of the convolution of internal motions and measurement errors. We have used this property to verify using M 67 that the errors given in the catalogue are realistic.

M 67 is a thoroughly studied old open cluster, at a distance of 908 pc. The internal velocity dispersion of the cluster was established to be 0.5 km s^{-1} by Mathieu (1985) from a radial velocity study and translates into a negligible (in this context) proper motion dispersion of 0.11 mas/yr at the distance of the cluster. The observed dispersion of proper motions is thus representative of the internal precision of the PM2000 catalogue.

Instead of relying on previous membership studies to identify the cluster's stars, we have used a statistical approach. Despite the mean proper motion of M 67 being very close to the mean proper motion of field stars, it is such a dense cluster that its highly peaked distribution is easily seen in Fig. 14. In order to deconvolve the overlapping proper motion distributions of the cluster and the field we have used the SEM algorithm (Celeux & Diebolt 1986), a non-informative method that iteratively solves the maximum likelihood equation, with a stochastic step, in the case of a multivariate mixture of Gaussian distributions. With the only assumption that the proper motions in a circular field of 1° radius around the cluster center are distributed in two Gaussian populations, the cluster and the field, SEM provides the proportions, mean and standard deviation of each population. We give in Table 1 the results of the SEM de-convolution per bin of magnitude, together with the median PM2000 formal proper motion error. The dispersions are slightly higher than the formal errors, but stay at a very good level, lower than 1 mas/yr in the bright part, up to 1.3 mas/yr at fainter magnitudes. The consistency of the mean proper motions in the 4 bins of magnitude is quite remarkable. It proves that no drift as a function of magnitude is present in our data. For comparison, we also present in Table 1 the Tycho2 mean proper motion and dispersion of 36 members of the cluster. They have been selected from a list of 52 Tycho2 members identified in the WEBDA database (Mermilliod 1992), reduced to 36 stars after a 3σ rejection. The very good agreement of the mean values obtained with Tycho2 and PM2000 shows that the 2 catalogues are perfectly aligned in terms of proper motions.

8.5. Conclusion on the PM2000 error budget

We performed various comparisons in order to estimate the PM2000 Gaussian errors together with eventual systematic errors of positions and proper motions. These tests led us to the following estimations: In the magnitude domain $8 \le V \le 14{-}15$, $\sigma_{\rm pos} = 50$ mas and $\sigma_\mu = 1.5$ mas/yr (objects that benefit from a CdC or an AC2000.2 measurement). These precisions

Table 1. Mean proper motion and standard deviation of M 67 in several bins of magnitude in a circular field of 1° radius resulting from the SEM deconvolution of field and cluster distributions. N is the number of stars per bin of magnitude, $\mathrm{err}_{\mu_\alpha}$ and $\mathrm{err}_{\mu_\delta}$ the median standard PM2000 errors, and P the proportion of cluster stars. The last line gives the statistics for Tycho2 proper motions for 36 members of the cluster.

V	N	$\mathrm{err}_{\mu_\alpha}$	$\mathrm{err}_{\mu_\delta}$	$P(\%)$	μ_α	μ_δ	σ_{μ_α}	σ_{μ_δ}
<12	113	0.6	0.8	28.8	–8.8	–5.6	0.9	0.9
12–13	202	0.4	0.4	52.1	–8.6	–5.5	1.1	1.1
13–14	358	0.5	0.5	48.9	–8.5	–5.7	1.2	1.3
14–15	484	0.9	0.8	22.8	–8.2	–6.0	1.3	1.0
Tycho2	36	1.9	1.9	–	–8.7	–5.9	1.8	1.7

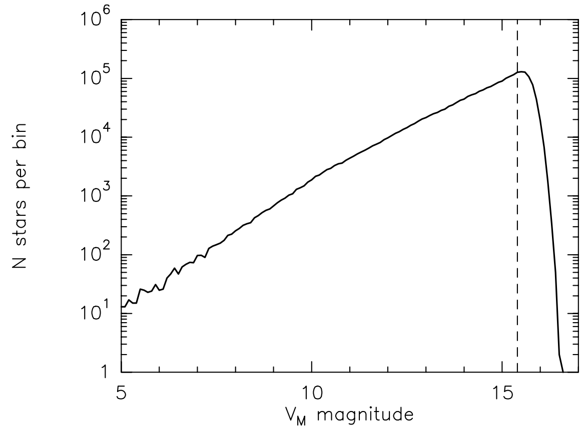

Fig. 15. Histogram of the V_M magnitudes of the PM2000 catalogue. The vertical line at $V_M = 15.4$ shows the limit of completeness of the PM2000 catalogue.

degrade to $\sigma_{\mathrm{pos}} = 70$ mas and $\sigma_\mu = 6$ mas/yr for $14–15 \le V \le 16.4$. Offsets $\Delta\delta \sim 5–7$ mas and $\Delta\mu_{\alpha\cos(\delta)} \sim 0.5$ mas/yr can be expected. We estimate that these offsets are introduced by biases contained in USNOA2.0 data and that we could not completely remove.

9. The PM2000 catalogue

The resulting PM2000 catalogue consists of 2 670 974 stars with positions for a given mean epoch and proper motion. Positions and proper motions are in the ICRS. We also provide the V_M magnitude. Photometry from the 2MASS catalogue is given whenever possible. Figure 15 presents the V_M distribution of these objects. The limiting magnitude is $V_M = 16.2$ and the limit of completeness is estimated to be $V_M = 15.4$. The sky coverage of the PM2000 catalogue is the same as M2000. Figure 16 gives the $V - K$ color-index distribution. The mean color index is $V - K = 2.41$ mag, with a dispersion of 0.95. For the reddest objects $V - K$ can reach 14 mag.

Tycho-2 stars are identified by their catalog number. We give for each PM2000 object the coordinates α, δ at their respective mean epochs t_α, t_δ, the proper motions $\mu_\alpha \cos\delta, \mu_\delta$, the associated *model-based* standard errors $\sigma_\alpha \cos\delta, \sigma_\delta, \sigma_{\mu_\alpha \cos\delta}, \sigma_{\mu_\delta}$, together with the goodness of fit in α and δ. We give the V_M magnitude with its standard error σ_{V_M},

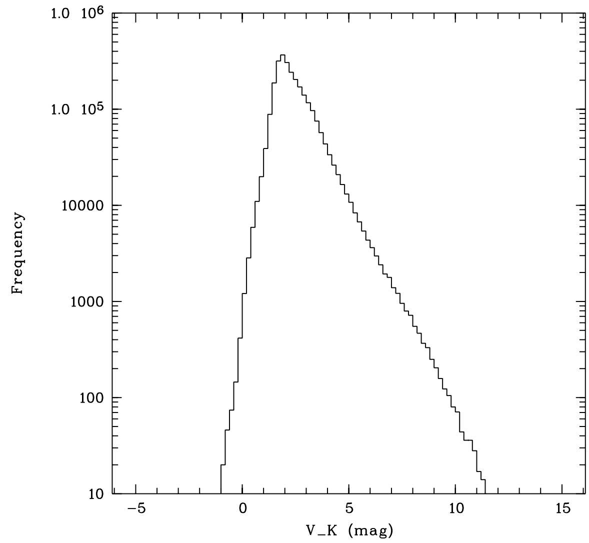

Fig. 16. Histogram of the $V - K$ color index of the PM2000 catalogue.

and for the objects for which a counter part was encountered in 2MASS we also give the 2MASS identifier and J, H, K_s magnitudes. We also give the number of observations associated with each object. The PM2000 catalog is available at the CDS. A separate file is also provided that contains the subsample of the 370543 stars of PM2000 for which a Carte du Ciel measurement was used to derive the proper motion.

10. Conclusion

We have presented PM2000, a compiled astrometric catalog in the zone $+11° \le \delta \le +18°$ which provides accurate positions and proper motions for all stars in the 8th to 16.2th magnitude range with a sky coverage of 1/20 of the whole sky. Meridian V_M photometry together with 2MASS photometry are also provided.

We have investigated the various sources of errors to give a realistic evaluation of our random external errors. We also evaluate the systematic bias of our catalogue.

To evaluate our external errors we performed comparisons with HIPPARCOS and with 2MASS catalogues. The comparison with HIPPARCOS is in a very restricted magnitude domain and the comparison with 2MASS is restricted to the comparison of positions. From the comparison with HIPPARCOS we derived the external precision of PM2000 to be $\sigma_{\mathrm{pos}} = 50$ mas and and $\sigma_\mu = 1.5–2$ mas/yr for stars with $V \le 12$. 2MASS is not, properly speaking, an astrometric catalogue. The comparison with it allowed us to roughly evaluate our external errors for faint objects but also to measure the 2MASS biases. The dispersions of the differences of 2MASS minus PM2000 are compatible with an external precisions of the PM2000 to be $\sigma_{\mathrm{pos}} = 50$ mas and $\sigma_\mu = 1.5$ mas/yr for $V \le 14$. These precisions would degrade to $\sigma_{\mathrm{pos}} = 70$ mas and $\sigma_\mu = 6$ mas/yr at $V = 16$. Moreover a systematic effect in declination of ~15 mas has been detected in the 2MASS catalogue.

The comparison of PM2000 with two others catalogues (TYCHO-2 and UCAC2) allowed us to test the coherence of our results and to detect systematic offsets in PM2000 or in these catalogues. The comparison with TYCHO-2 revealed that offsets $\Delta\delta \sim 5-7$ mas and $\Delta\mu_\alpha \cos(\delta) \sim 0.5$ mas/yr could be expected in PM2000. From the comparison with UCAC2 we evaluated UCAC2 proper motion biases in the Bordeaux zone when the AC2000.2 first epoch is absent to be $\sim 1-1.4$ mas/yr.

From the velocity dispersion of PM2000 proper motions in the M 67 open cluster we find that the external errors of the PM2000 proper motions are less than 1 mas/yr in the bright part and degrades to 1.3 mas/yr at fainter magnitudes. It also confirms that the faint part of the PM2000 proper motions are aligned with those of TYCHO-2.

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References

Assafin, M., Andrei, A., Martins, R., et al. 2001, ApJ, 552, 380
Benevides-Soares P., & Teixeira, R. 1992, A&A, 253, 307
Celeux, G., & Diebolt, J. 1986, Rev. Statistique Appliquée, 35, 36
Cutri, R. M., Skrustskie, M. F., Van Dyk, S., et al. 2003
Eichhorn, H. 1960, AN, 285, 233
ESA 1997, The Hipparcos and Tycho catalogs, ESA SP-1200, CDS I/239
Eichhorn 1960, Astron. Narchr., 283, 233
Høg, E., Fabricius, C., Makarov, V., et al. 2000, A&A, 355, L27
Klemola, A. R., & Jones, B., & Hanson, R. 1987, AJ, 94, 501
Lasker, B., Sturch, C., McLean, B., et al. 1990, AJ, 99, 2019
Mathieu, R. D. 1985, IAUS, 113, 427
Mermilliod, J.-C. 1992, Bull. Inform. CDS, 40, 115
Monet, D., Bird, A., Canzian, B., et al. 1998, in USNOA–V2.0. A Catalog of Astrometric Standards
Monet, D. 2001, private communication
Monet, D. G., Levine, S. E., Casian, B., et al. 2003, AJ, 125, 984
Platais, I., Girard, T., Kozhurina-Platais, V., et al. 1998, AJ, 116, 2556
Rapaport, M., & Le Campion, J. F. 1990, in Proc. of the Journées 1990 Systèmes de référence spatio-temporels, Paris, 75
Rapaport, M., Le Campion, J. F., Soubiran, C., et al. 2001, A&A, 376, 325
Rapaport, M., et al. 2005, submitted
Urban, S. E., Corbin, T., & Wycoff, J. L. 1998, The AC2000 Catalogue, Cat. 1247
Zacharias, N., Urban, S., Zacharias, M., et al. 2000, AJ, 120, 2131
Zacharias, N., Urban, S., Zacharias, M., et al. 2004, AJ, 127, 3043