A&A 376, 325–332 (2001)
DOI: 10.1051/0004-6361:20010928

Astronomy & Astrophysics

M2000: An astrometric catalog in the Bordeaux Carte du Ciel zone $+11° \leq \delta \leq +18°$*

M. Rapaport, J.-F. Le Campion, C. Soubiran, G. Daigne, J.-P. Périé, F. Bosq, J. Colin, J.-M. Desbats, C. Ducourant, J.-M. Mazurier, G. Montignac, N. Ralite, Y. Réquième, and B. Viateau

Observatoire de Bordeaux, CNRS UMR 5804, BP 89, 33270 Floirac, France

Received 28 May 2001 / Accepted 26 June 2001

Abstract. During four years, systematic observations have been conducted in drift scan mode with the Bordeaux automated meridian circle in the declination band $+11° \leq \delta \leq +18°$. The resulting astrometric catalog includes about 2.3×10^6 stars down to the magnitude limit $V_M = 16.3$. Nearly all stars (96%) have been observed at least 6 times, the catalog being complete down to $V_M = 15.4$. The median internal standard error 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 also provides one band photometry with a median internal standard error of ∼0.04 mag. Comparisons with the Hipparcos and bright part of Tycho-2 catalogs have enabled us to estimate external errors in position to be lower than 40 mas. In this zone and at epoch 1998, the faint part of Tycho-2 is found to have an accuracy of 116 mas in α instead of 82 mas deduced from the model-based standard errors given in the catalog.

Key words. astrometry – catalogs

1. Introduction

Accurate proper motions for large samples of stars are of considerable interest for both the maintenance and extension of optical reference frames and for the understanding of the structure and evolution of the Galaxy. At present the largest and most precise all-sky catalogs of proper motions are Hipparcos (ESA 1997), very precise but concerning only 120 000 bright stars, and the recent Tycho-2 (Høg et al. 2000) which is complete down to $V = 11$ with 2.5×10^6 stars. In 2003, the USNO CCD Astrograph catalog (UCAC) will be available with an all-sky coverage down to $V = 16$ and a precision similar to Tycho-2 in positions and proper motions (Zacharias et al. 2000). This will provide a valuable database for galactic studies but until then there is a lack of large and complete samples of stars with accurate proper motions at intermediate magnitude 11–16.

The accuracy of proper motions depends on the accuracy of individual positions at different epochs and the time baseline which separate them. An invaluable source of old epoch positions is the Carte du Ciel, an international program conducted at the beginning of the century. It was the first photographic survey of the entire sky. In this ambitious program, fields of $2.5° \times 2.5°$ were observed twice, to limiting blue magnitudes of ∼15 and ∼12.5 respectively. The bright part, the Astrographic Catalog (AC), was entirely measured and produced a positional catalog of 4.6×10^6 stars, the AC 2000 (Urban et al. 1998), which was combined to the recent Tycho catalog into the ACT catalog (Urban et al. 1998) and which was also used to produce the Tycho-2 catalog. While the AC positions have been used to a large extent, it is not the case for the faint survey of the Carte du Ciel, which has only been used in punctual studies.

As one of the participants of the Carte du Ciel, in charge of the declination band $+11° \leq \delta \leq +18°$, the Bordeaux Observatory owns 511 Carte du Ciel plates covering this band. It was decided to digitize them in order to salvage this astronomical treasure before its deterioration and to conduct at the same time a scientific program. The Bordeaux Observatory is also one of the last urban observatories where astrometric observations are still possible thanks to its meridian circle which has been equipped with a CCD camera. Fully automatic and of a great stability, the Bordeaux meridian circle has been proved to be very efficient with an internal precision better than 40 mas in both coordinates, in the magnitude range $9 < V < 14$ (Viateau et al. 1999). The M2000 program aims at producing a catalog of positions and proper motions from the cross-identification between today's meridian observations and the digitized Bordeaux Carte du Ciel plates. The first observations for the M2000 project began in December 1996 and the programme was completed

Send offprint requests to: M. Rapaport,
e-mail: rapaport@observ.u-bordeaux.fr

* The catalog is distributed on CD-ROM and through the CDS (http://cdsweb.u-strasbg.fr/Cats.html).
Further information is given on the website
http://www.observ.u-bordeaux.fr/∼soubiran/m2000.htm

in December 2000 with a median number of 7 observations per star. Unfortunatly, the digitization of the Carte du Ciel was delayed due to the lack of an available scanner. The plate processing started in December 2000 at the APM measuring machine in Cambridge (UK), and should be finished in July 2001. In this first paper, the meridian catalog of positions is presented. The Bordeaux meridian circle, its CCD drift scan camera and image processing are briefly presented in Sect. 2. Section 3 concerns the global reduction technique in astrometry and photometry. Section 4 presents some tests performed in order to evaluate the internal and external errors of the catalog. Section 5 describes the content of the catalog.

2. Observations and data processing

2.1. Instrument and image processing

The Bordeaux CCD meridian circle has been extensively described in Viateau et al. (1999). Here we briefly recall the main characteristics of the instrument and image processing.

The Bordeaux meridian circle is a refractor with a Texereau objective (202 mm diameter front lens and 2368 mm focal length). The detector is a front illuminated 1K CCD Thomson 7896M with 19 μm pixels corresponding to a $28'$ field in declination with a scale of $1.65''$ per pixel. Its dark current is lower than the sky background of the city of Bordeaux. Two combined filters (GC495 and BG38) give a visual passband. With the spectral response of the detector cell, the resulting band $V_{\rm M}$ is displaced into the red (520–680 nm). Due to the large bandwith, the effect of chromatic refraction may be significant, as seen by the comparison with the Hipparcos catalog (Sect. 4.2). The instrument works in TDI mode with an integration time of 112 s/cos(δ). This process enables the reconstruction of numerical images of $28'$ in declination and several hours in right ascension. Such images are automatically processed on-line to give a list of detected objects. First, the sky background is estimated using a median filter, and subtracted from the image. Then objects are defined by at least 2 consecutive pixels above a 3σ threshold. The position and flux of each detected object are estimated by fitting a two dimensional gaussian flux distribution on the associated pixels. In case of multiple objects, positions and flux are measured independently if the separation is larger than $5''$. The dynamical range for the CCD detector is larger than 7 mag. In the declination range of the M2000 catalog, the detection limit is about $V_{\rm M} = 16.5$. Objects brighter than $V = 9.5$ are most often saturated, with a systematic effect in declination as a consequence. This effect was easily modeled by fitting polynomials on (Hipparcos minus M2000) residuals, and all saturated stars were systematically corrected in declination.

2.2. Observationnal strategy

In order to observe the whole zone of the Bordeaux Carte du Ciel, $0{\rm h} \leq \alpha < 24{\rm h}, +11^\circ \leq \delta \leq +18^\circ$, 39 strips of $28' \times 24{\rm h}$ were considered, with their centers in declination separated by $13'$. Thanks to this overlap, the 39 strips could be observed 3 times in order to get 6 observations per star plus a thin zone of $2'$ where stars were observed 9 times. The strips had their length in right ascension varying from 1h to 12h depending on the other programs and weather conditions. The observations for the M2000 program started in December 1996 and ended in December 2000, after 3306 hours of observations in a fully automatic mode. The objective to get at least 6 observations per star for more than 95% of the catalog was successfully achieved. The last year of observation was used to fill some gaps in the survey where the faintest stars could not be observed 6 times due to poor weather conditions.

3. Reduction procedure

3.1. Global astrometric reduction

As was explained above, the merdian circle observed strips with the same declination width ($28'$) and variable lengths in right ascension. The strips are parallel in true equatorial coordinates, with overlaps in both directions. For a given observation, the true absissa of a star image is written:

$$x = x_{\rm m} + \epsilon_{\rm m} + S^x_{\rm m}(t) \tag{1}$$

where $x_{\rm m}$ is the measured value of x and $\epsilon_{\rm m}$ its measurement error. The quantity $S^x_{\rm m}(t)$ stands for correlated departures in position measurements of neighbouring stars, mainly attributed to slow variations of the residual angle-of-arrival due to long-period atmospheric fluctuations. Variations faster than one minute or so are averaged in the TDI mode, their residuals being included in $\epsilon_{\rm m}$. As explained by Viateau et al. (1999), the deterministic function S has been taken as a B-spline which attenuates the oscillations caused by these fluctuations. For a given strip, or part of a strip, it is written in terms of a set of fitted parameters: $S^x_{\rm m}(t, \lambda_1, \lambda_2, ..., \lambda_r)$.

A similar equation can be written in y:

$$y = y_{\rm m} + \epsilon'_{\rm m} + S^y_{\rm m}(t). \tag{2}$$

The relation between the true coordinate α of a star and its image abscissa x on a strip is:

$$\alpha = x + a_0 + a_1 x + a_2 y \tag{3}$$

where a_0, a_1 and a_2 are the linear model constants or "instrumental constants" associated with a given strip. a_1 stands for a possible departure from the Earth rotation model, or for any linear drift in the instrument attitude. a_2 stands for misalignement of the CCD columns relative to the meridian plane. a_1 and a_2 are small quantities.

A similar relation can be written between the true coordinate δ and the image ordinate y:

$$\delta = y + b_0 + b_1 x + b_2 y \tag{4}$$

where b_1 has the same meaning as a_1 in the previous relation, and b_2 stands for departure to the nominal focal scale, mainly due to differential refraction in the strip width. The linear model (3)–(4) does not account for possible optical misalignement or tilt of the CCD plane. Any dependence on x (or time) being dealt with by the spline functions, higher order terms would take the form $y^n (n \geq 2)$. We have checked the validity of adding quadratic terms and found it to be insignificant.

The relation between star image coordinates $(x_{\rm m}, y_{\rm m})$ in a strip and the true right ascension is deduced from Eqs. (1) and (3):

$$\alpha - S^x_{\rm m}(t, \lambda_1, ..., \lambda_r) - a_0 - a_1 x_{\rm m} - a_2 y_{\rm m} = x_{\rm m} + \epsilon_{\rm m} \quad (5)$$

with a similar equation in declination. These two relations link the measured image position to the celestial coordinates of a star by means of the model parameters $(a_0, a_1, ..., \lambda_1, ..., \lambda_r)$ for each strip. In practice, strips of several hours in right ascension are cut into bands of one hour with some overlap in order to avoid the propagation of errors in x. In this method, all observed stars are used to determine the model parameters. For 1 million stars observed at least 6 times, one has at least 6 millions relations similar to (5), and as many in declination.

The solution of these equations are obtained with a global method (Eichhorn 1960; Benevides-Soares & Teixeira 1992) in which the set of equations is considered as a single system to be solved by a least-square procedure. The equations in α can be written in form of a matrix:

$$A\boldsymbol{\alpha} + B\boldsymbol{\lambda} + C\boldsymbol{a} = \boldsymbol{l}. \quad (6)$$

The unknown vectors $\boldsymbol{\alpha}, \boldsymbol{\lambda}, \boldsymbol{a}$ are respectively the right ascensions of all the observed stars, the coefficients of the model for atmospheric fluctuations and the linear model constants of the different strips. $\boldsymbol{l}$ is the set of coordinates measured on the strips.

This system of equations is singular as can be seen in Eq. (5): the unknowns α and a_0 appear through their difference which means that the origin of right ascensions cannot be determined. Consequently, the system (6) has an infinity of solutions and some constraints must be imposed to get a unique solution. We shall see that these constraints correspond to the choice of the reference system.

The system (6) is solved by the iterative method of Gauss-Seidel (see Rapaport & Le Campion 1990; Le Campion et al. 1992 for more details). Two reasons have motivated this choice: (1) this method is well adapted to the structure of the matrix of equations where only "small systems" have to be solved, (2) mathematical results have proved the convergence of the iterations toward a solution of the equations.

The successive steps of the process can be described as follows. From any reference catalog (Tycho-2 in the present case) a linear fit will give a first estimate of the "instrumental constants", and then a first estimate of coordinates $\boldsymbol{\alpha}_0, \boldsymbol{\delta}_0$ for all the stars.

Starting with $\boldsymbol{\alpha} = \boldsymbol{\alpha}_0$, the system is solved in $\boldsymbol{a}$ and $\boldsymbol{\lambda}$ by least square fit:

$$C\boldsymbol{a} + B\boldsymbol{\lambda} = (\boldsymbol{l} - A\boldsymbol{\alpha}_0). \quad (7)$$

The solution is then introduced to solve the system in $\Delta\alpha = \alpha - \alpha_0$:

$$A\Delta\boldsymbol{\alpha} + B\boldsymbol{\lambda} + C\boldsymbol{a} = \boldsymbol{l} - A\boldsymbol{\alpha_0} \quad (8)$$

and then the process is iterated. These steps and their interpretation are described in Le Campion et al. (1992) and Viateau et al. (1999). The process typically converges toward a least square solution in 5 iterations.

A single solution is obtained by imposing a constraint:

$$\Sigma_i(\alpha_{i,\rm M2000} - \alpha_{i,\rm Tycho-2}) = 0 \quad (9)$$

$$\Sigma_i(\delta_{i,\rm M2000} - \delta_{i,\rm Tycho-2}) = 0. \quad (10)$$

This constraint is equivalent to adding a constant to each coordinate, which puts the M2000 catalog in the reference system of Tycho-2, i.e. the ICRS. From its construction, the final positions of the M2000 catalog are independent of the starting catalog, except on the zero point. This has enabled a direct comparison with the Tycho-2 catalog as described in Sect. 4.3.

In what was just described, it must be noted that each star was observed several times at different epochs over four years. Strictly, the proper motions should be introduced in the equations. Except for very high proper motion stars, the 4 years of observations do not enable a correct determination of proper motions. Consequently, we have chosen to temporarily neglect the proper motion displacement over the observing period. The proper motion determination will be possible when data from the scanning of the Carte du Ciel plates will be introduced in the global reduction.

3.2. Photometric reduction

The photometric reduction was performed simultaneously with the astrometric reduction, stellar magnitudes being entered as a third unknown parameter after α and δ. The flux Φ of each object is initially converted into a magnitude using the standard formula:

$$V_{\rm M} = V_0 - 2.5 \log \Phi \quad (11)$$

where V_0 is a constant determined by least squares using Tycho-2 $V_{\rm T}$ magnitudes. As our $V_{\rm M}$ magnitude system is slightly different from the $V_{\rm T}$ system, a color term should be introduced in Eq. (11). But colors are not available for most stars yet and a more accurate calibration of magnitudes is not possible. The color effect reaches 0.3 mag for the bluest stars. In a second step the variations of the atmospheric transparency are modeled iteratively by fitting a B-spline on the residuals of each night:

$$V_{\rm M} = V_0 - 2.5 \log \Phi + S_\Phi(t, \lambda_1, \lambda_2, ..., \lambda_r). \quad (12)$$

4. Quality control

4.1. Internal precision

It was decided to keep in the M2000 catalog all the objects which were observed at least 3 times. The observing

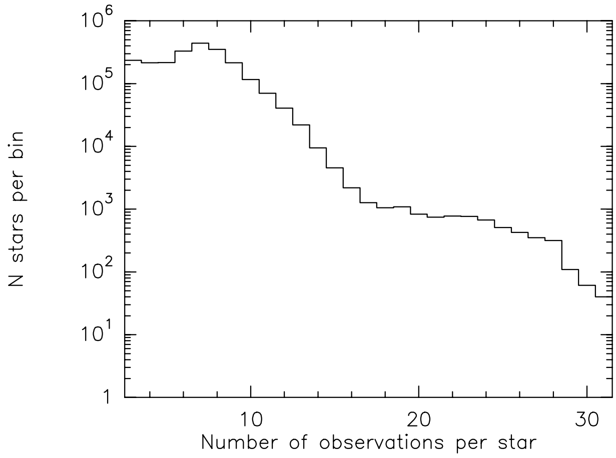

Fig. 1. Histogram of the number of observations per star.

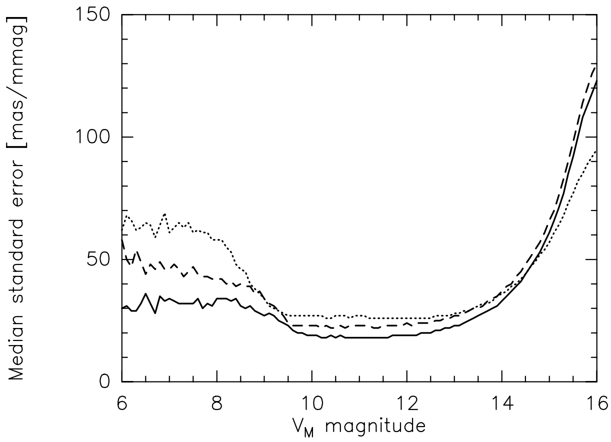

Fig. 2. Standard errors in α (full line), in δ (dashed line) and $V_{\rm M}$ (dotted line) versus magnitude. The median standard errors have been computed in bins of 0.1 magnitude.

program was stopped when more than 95% of the stars detected in the zone had been observed at least 6 times. Figure 1 shows the histogram of the number of observations per star. In several fields corresponding to other observing programmes, stars have been observed up to 31 times. The median number of observations per star is 7.

After the global reduction, the 3 parameters $(\alpha, \delta, V_{\rm M})$ could be recovered for each star at the different epochs of observations, and their standard errors computed. The median standard error is a good estimate of the internal precision of the catalog. As shown in Fig. 2, standard errors are larger for stars brigther than $V = 9.5$ due to saturation, and for the faintest stars of the catalog. The best results are obtained in right ascension where standard errors are below 25 mas in the magnitude range $9.5 \leq V_{\rm M} \leq 13.5$. In the same magnitude interval, the standard errors in declination and magnitude are lower than 30 mas and 0.03 magnitude respectively. In Fig. 3, the histograms of standard errors in α, δ and $V_{\rm M}$ are presented for the whole catalog and for stars brighter than 15. The modes and medians of these 6 histograms are summarized in Table 1.

It is worth noticing that the standard errors in right ascension and declination are slightly increased by the fact that no attempt was made to calculate the proper motions in the astrometric reduction. As a matter of fact, during 4 years of observations the contribution of the neglected proper motion to the standard error can reach several mas. The contribution of proper motions in the dispersion of the M2000 measurements is not easy to estimate as the observations are not uniformly distributed along the time baseline from one strip to another. The typical time baseline between the first and last observation of a star is 3 years. The spacing between 2 consecutive observations has 2 typical values: several days and about 1 year. If σ_μ is the standard deviation of the proper motion distribution of all M2000 stars, then the maximal contribution of the neglected proper motions is $2\sigma_\mu$ in the unfavourable and unprobable case of observations only at the beginning and end of the 4 years baseline. Unfortunately σ_μ is not known

Table 1. Modes and medians of the distribution of standard errors in α, δ and $V_{\rm M}$ for the M2000 catalog, with a cut in magnitude and for the whole catalog. The units are mas for α and δ and milli-magnitudes for $V_{\rm M}$.

	$V_{\rm M} < 15$ $N \sim 1.2 \times 10^6$		full catalog $N \sim 2.3 \times 10^6$	
	mode	median	mode	median
α	20	31	20	48
δ	25	34	25	52
$V_{\rm M}$	28	34	31	47

yet. From bright nearby Hipparcos stars, σ_μ was estimated to be 24 mas yr^{-1} for μ_α and 16 mas yr^{-1} for μ_δ. To get an idea of the value at fainter magnitudes, the typical stellar content of the M2000 catalog has been simulated with the Besançon model of stellar population synthesis of the Galaxy (Bienaymé et al. 1987; Robin et al. 1996) in 2 representative fields at high and low galactic latitudes. This simulation showed that the standard deviation of the proper motion distribution reaches 18 mas yr^{-1} at high galactic latitude. We conclude that the contribution of the neglected proper motions to the standard errors in position is significant, especially for the bright part of the catalogue ($V < 15$) where random errors on individual positions have a similar magnitude than the dispersion due to proper motions. We expect the median standard errors in equatorial coordinates to improve significantly for bright stars ($\sigma_\alpha \simeq 30$ mas for $V < 15$) when the proper motions will be determined from old Carte du Ciel plates.

4.2. External accuracy

4.2.1. Comparison with Hipparcos

The Hipparcos catalog has a positional accuracy better than M2000 by one order of magnitude. As a consequence, the dispersion of the differences between the two catalogs mainly reflect the external errors of M2000. The mean epoch of the 2 catalogs are different: 1991.25 for Hipparcos, ∼1998 for M2000. To enable a direct

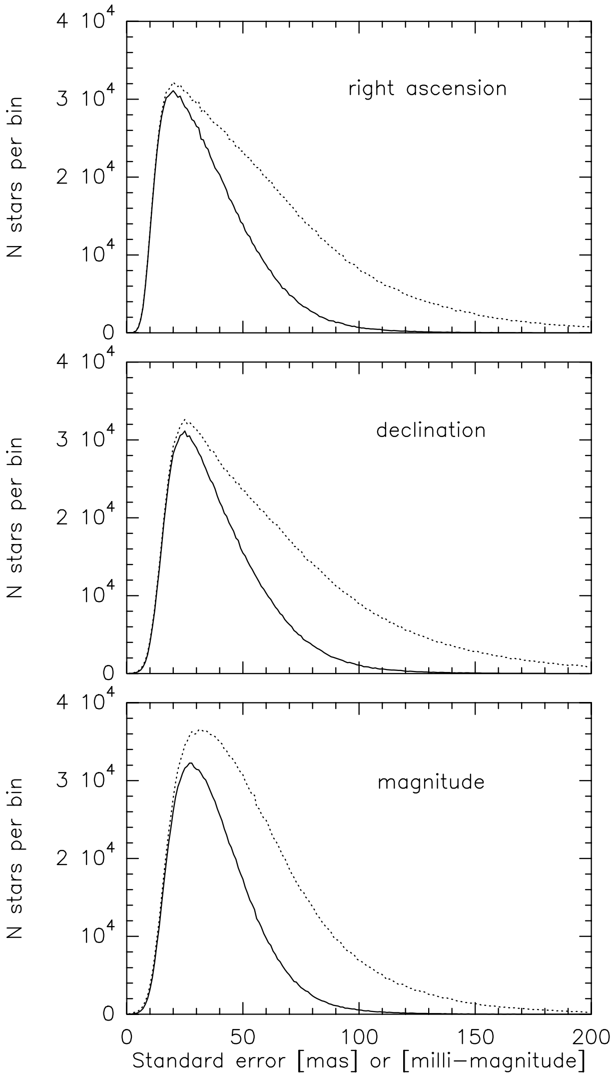

Fig. 3. Histogram of standard errors in right ascension, declination and magnitude for the whole catalog (dotted lines), and for stars with $V_{\mathrm{M}} \leq 15$ (full lines). The bin size is 1 mas, or 1 milli-magnitude.

comparison, Hipparcos coordinates of each star have been translated to its mean epoch of observation in M2000. Then the differences in α, δ were computed for the 6613 stars in common. The mean and dispersion around the mean have been computed with an iterative 3σ rejection for the whole set of stars and for a subset of stars with $V_{\mathrm{M}} > 9$, where the M2000 measurements are less affected by saturation. In the 3σ rejection some 1% to 3% of the stars were rejected and mainly correspond to double images which were measured as a single object or double object depending on the atmospheric conditions. Some double stars also have poor measurements in the Hipparcos catalog. Most of the time, they are easily recognized with their high standard error in one or both catalogs.

The first look at the results of the comparison showed that declination measurements were probably affected with a significant systematic error. The dispersion of the δ differences was 59 mas for the whole sample and 46 mas for $V_{\mathrm{M}} > 9$, significantly larger than the dispersion in α. The most obvious cause is chromatic refraction. As a matter of fact, a correlation was clearly observed between declination departure and colour index of the stars as seen in Fig. 4. A linear fit to the data, eliminating outliers, is:

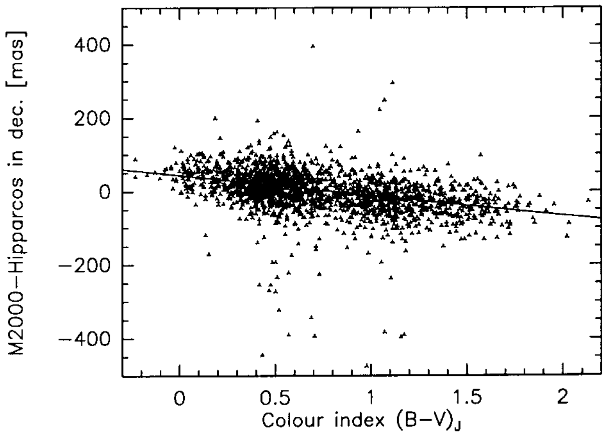

Fig. 4. Declination departure for Hipparcos stars versus $B\!-\!V$ colour.

$$\Delta_\delta = -55(B - V)_{\mathrm{J}} + 44 \text{ [mas]}. \tag{13}$$

The uncertainty on each coefficient is about 1 mas. Due to the refraction dependence on zenithal distance, we have searched for slope variations within the declination band, without significant results. The measured chromatic dependence is in fact larger than the modeled one, obtained with the instrument transmission, CCD quantum efficiency and blackbody emission spectra for the observed stars. In the range $0.0 \leq B - V \leq 1.2$, the model slope is found to be -36 mas at mean zenithal distance of M2000, with variations from -41 to -31 in the declination range $+11°$ to $+18°$. The significant difference with the observed slope in (13) may indicate additional effects from the instrument optics. Unfortunatly the colour index $B - V$ is now only available for a tiny part of the M2000 catalog ($\sim$127 000 Tycho-2 stars) where the correction (13) should be applied. For future developments of M2000 which include the proper motion determination, we plan also to cross-identify the M2000 catalog with the 2MASS catalog (Skrutskie et al. 1997) in order to estimate the colour index $V_{\mathrm{M}}\!-\!K$ for each star and apply the adequate correction in declination with this index. The results of the comparison of M2000 with Hipparcos are presented in Table 2. The effect of saturation is seen with the higher dispersion in δ when all Hipparcos stars are considered.

In order to estimate exactly the external errors of M2000, the contribution of the errors of Hipparcos and their propagation from 1991.25 to 1998 were computed. We found the errors of the 6613 Hipparcos stars in the M2000 field to be on average 9 mas and 7 mas (medians) respectively in α and δ at epoch 1998 (12 mas and 10 mas for $V_{\mathrm{M}} > 9$). As the M2000 measurements of bright stars are clearly affected by saturation, from Hipparcos stars with $V_{\mathrm{M}} > 9$, the external errors of M2000 are estimated to be 35 mas and 37 mas in α and δ respectively.

Table 2. Results of the comparison of M2000 with Hipparcos, after the correction (13) in δ. N is the number of stars in common after the iterative 3σ rejection, Δ is the mean difference Hipparcos – M2000 in coordinates (mas), σ is the standard deviation around the mean.

	N	Δ	σ
α	6372	−5	38
δ	6378	2	46
$\alpha, V_{\rm M} > 9$	2106	−1	37
$\delta, V_{\rm M} > 9$	2108	3	38

4.2.2. Comparison with Tycho-2

Tycho-2 was used as the starting point of the iterative global reduction method. As explained in Sect. 3.1 the final M2000 catalog is independent, except on the zero point, of the reference catalog which was used to initialize the reduction. It is then possible to compare directly M2000 with Tycho-2. M2000 has also been compared with a subsample of Tycho-2 made of Tycho-1 stars (ESA 1997) because of its higher quality. In order to check the quality of the faint part of Tycho-2, we have also compared M2000 with a subsample made of Tycho-2 stars not included in Tycho-1. The limiting magnitude of Tycho-1 is about 11.5, whereas it reaches 12.5 for Tycho-2. As for Hipparcos, an iterative 3σ rejection was necessary to eliminate from the comparison spurious measurements mainly due to multiple stars. As $B-V$ colours were available for all these stars, we tried to estimate the chromatic refraction from Tycho-2 measurements. Due to large random errors, this could not be done in a satisfactory way, but restrincting the dataset to Tycho-1 stars, the correction was found to be similar, within the error bars, to Eq. (13) obtained with Hipparcos and it was applied to the declinations. The results are presented in Table 3, where are also given the Tycho-2 median standard errors ($\sigma_{\rm T}$, model-based) for the comparison stars. The standard deviations (σ) presented in Table 3 result from the convolution of the external errors of Tycho-2 ($\sigma_{\rm T}$) and M2000 ($\sigma_{\rm M2000}$), so we can write:

$$\sigma^2 = \sigma^2_{\rm M2000} + \sigma^2_{\rm T}. \quad (14)$$

In Table 3, $\sigma'_{\rm T}$ is an estimate of $\sigma_{\rm T}$ deduced from Eq. (14), assuming M2000 external errors of 35 mas in α and 37 mas in δ.

There is no systematic difference between the right ascensions of M2000 and Tycho-2, while there is an offset of 2 mas in δ resulting from the correction of refraction. In Table 3, $\sigma_{\rm T}$ has to be compared with $\sigma'_{\rm T}$. They are in a very good agreement in both coordinates for the sample made of Tycho-1 stars. The agreement is also satisfactory in δ for the 2 other samples. But a large difference is observed in α between the model-based external errors of Tycho-2 and their estimates with M2000. External errors of M2000 were estimated in the magnitude range [9–10.5] and in Sect. 4.1 we have shown that M2000 measurements have internal errors lower than 30 mas in the magnitude range [9.5–13.5]. We thus exclude M2000 to be responsible for the resulting high dispersion when compared with Tycho-2. We conclude that the model-based external errors of Tycho-2 were underestimated in α for the faintest part of the catalog.

Table 3. Results of the comparison of M2000 with Tycho-2, with a subsample of Tycho-2 made of Tycho-1 stars and with the complementary sample made of the Tycho-2 stars which were not included in Tycho-1 and which represents the faint part of Tycho-2. The columns Δ and σ are the same as in Table 2. $\sigma_{\rm T}$ is the Tycho-2 median standard error of the comparison stars. $\sigma'_{\rm T}$ is an estimate of $\sigma_{\rm T}$ assuming M2000 external errors of 35 mas in α and 37 mas in δ. Chromatic effects in δ have been corrected.

	N	Δ	σ	$\sigma_{\rm T}$	$\sigma'_{\rm T}$
α, Tycho-1	49476	−1	48	30	33
δ, Tycho-1	49657	4	48	34	31
α, Tycho-2	120645	0	87	56	80
δ, Tycho-2	122210	2	79	67	70
α, Tycho-2 faint	73673	1	121	82	116
δ, Tycho-2 faint	74486	0	105	101	98

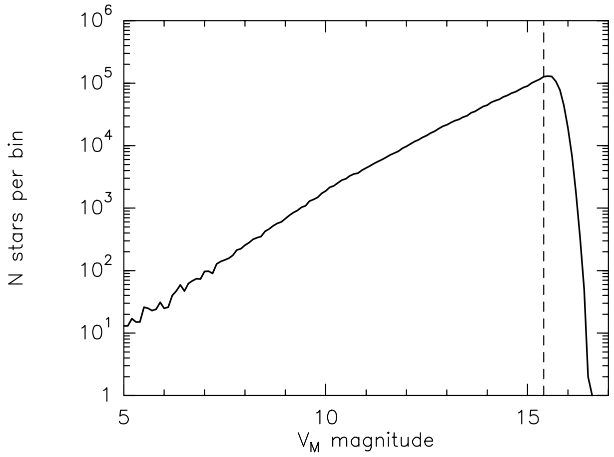

Fig. 5. Histogram of the $V_{\rm M}$ magnitudes. The bins are of 0.1 magnitude. The vertical line at $V_{\rm M} = 15.4$ shows the limit of completness of the M2000 catalog.

The comparison of M2000 with Tycho-1 stars from Tycho-2, has also provided a rough estimate of the external error in photometry, 0.13 mag, which is not very significant because the bandpass wave lenght of the 2 instruments are not exactly the same. The dispersion of the residuals in magnitude reaches 0.20 mag when all Tycho-2 stars are considered, and 0.26 if the faint part of Tycho-2 is considered.

5. Content of the catalog

5.1. Stellar content

The catalog is made up of 2 275 933 objects measured at least 3 times. Figure 5 shows the histogram of these objects in $V_{\rm M}$. The limiting magnitude is $V_{\rm M} = 16.3$. From the shape of the histogram, the limit of completness is estimated to be $V_{\rm M} = 15.4$. The field of M2000 covers

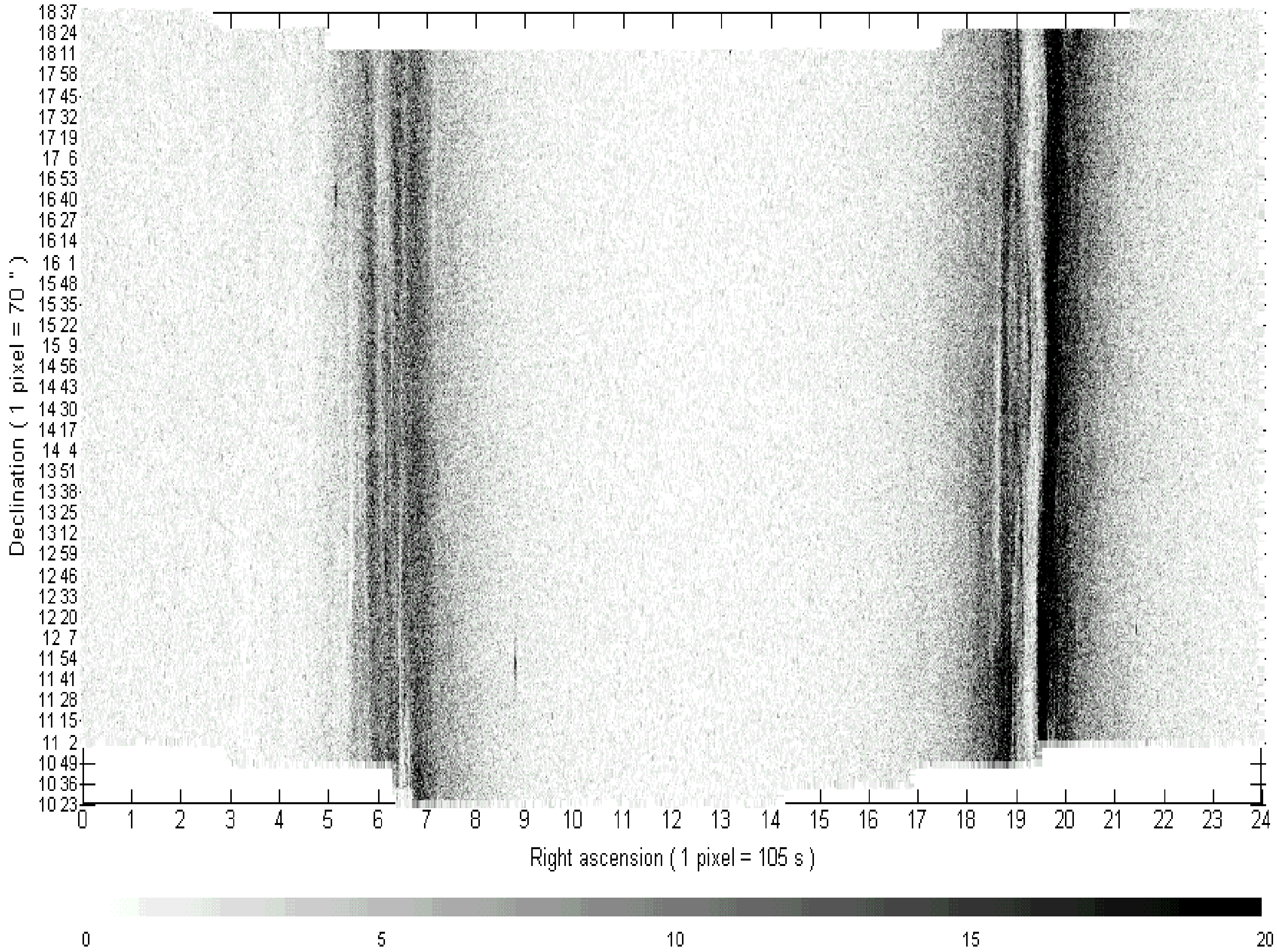

Fig. 6. The map of density of objects with $V \leq 15.4$. The grey scale indicates the number of objects in pixels of 105 s $\times$ 70″.

2440 square degrees, i.e. 6% of the whole celestial sphere. With its sky coverage, limiting magnitude and astrometric accuracy, M2000 is already a valuable sample to test models of the stellar content of our Galaxy from star counts. In the near future, proper motions and colours will become available. A project has already started to take the census of high proper motion stars in this area. Figure 6 is a map of density which shows the whole Bordeaux zone, with stars brighter than $V = 15.4$. The disc of the Galaxy is observed at mean galactic longitudes $\ell \simeq 45°$ and $\ell \simeq 200°$. Irregular bands of dust are clearly identified by the deep interstellar absorption through the disc. The open cluster, M 67 ($08^{\rm h}50.4^{\rm min} + 11°49'$) is clearly seen as a peak of density, as well as two close open clusters, NGC 1817 ($05^{\rm h}12.1^{\rm min}+16°42'$) and NGC 1807 ($05^{\rm h}10.7^{\rm min}+16°32'$).

5.2. Format of the catalog

The catalog is distributed in the form of 24 ASCII files corresponding to one hour intervals in right ascension. A system of identification has been elaborated which relies on the strips of observations. Tycho-2 stars are identified by their catalog number. An attempt to identify high proper motion stars from the catalogs NLTT (Luyten 1979) and Lowell (Giclas et al. 1971), and galaxies from the catalog RC3 (de Vaucouleurs et al. 1991) has been made but it is incomplete due to frequent inaccurate coordinates in these catalogs. For each M2000 object, the J2000 coordinates at the mean epoch of observations, the $V_{\rm M}$ magnitude, the standard errors of $(\alpha, \delta, V_{\rm M})$, the number of observations used in each variable, the mean epochs of observation in α and δ (they can differ due to the 3σ elimination which separately treats the coordinates) are given. The M2000 catalog is available at the CDS but due to its large size a CD-ROM can be ordered through the website `http://www.observ.u-bordeaux.fr/~soubiran/m2000.htm`

6. Conclusion

We have presented M2000, an astrometric catalog in the zone $+11° \leq \delta \leq +18°$. M2000 provides J2000 coordinates and $V_{\rm M}$ magnitudes for $\sim 2.3 \times 10^6$ objects which have been observed at least 3 times, 7 times on average and up to 31 times. Coordinates α and δ have an internal precision (median standard error) of 31 and 34 mas for $V < 15$ ($\sim 1.2 \times 10^6$ objects), and 48 and 52 mas for the whole catalog. The precision of the $V_{\rm M}$ magnitudes is $\sim$40 millimag.

From comparison with Hipparcos and the bright part of Tycho-2, we have estimated the external errors to be 35 in α and 37 mas in δ. We are aware of a significant chromatic effect in δ, partly due to the atmospheric refraction. External errors reach 50 mas in δ if a correction is not applied. This correction will be possible very soon for all stars when the cross-identification with the near-infrared survey 2MASS will be achieved and colours available for the whole catalog.

We have shown that the model based standard errors of the faint part of the Tycho-2-catalog have probably been underestimated.

The measurement of proper motions is now under progress with old Carte du Ciel plates. We expect to obtain a precison of 2 mas yr^{-1}. With colours and accurate proper motions on 2440 square degrees, with a limit of completness of $V_{\rm M} = 15.4$, M2000 will be a major dataset for galactic structure studies.

Acknowledgements. We are very thankful to R. Teixeira and P. Benevides-Soares who are closely associated to the evolution of the Bordeaux meridian circle. We aknowledge with gratitude financial support from the CNRS "Programme National de Physique Stellaire" to maintain the instrument.

References

Benevides-Soares, P., & Teixeira, R. 1992, A&A, 253, 307

Bienaymé, O., Robin, A., & Crézé, M. 1987, A&A, 180, 94

Colin, J., Daigne, G., Ducourant, C., et al. 1998, in The Message of the Angles – Astrometry from 1798 to 1998, ed. P. Brosche, W. R. Dick, O. Schwarz, & R. Wielen, Acta Historica Astronomiae, vol. 3 (Harri Deutsch, Frankfurt), 133

Eichhorn, H. 1960, AN 285, 233

ESA, 1997, The Hipparcos and Tycho catalogs, ESA SP-1200, CDS I/239

Giclas, H. L., Burnham, Jr. R., & Thomas, N. G. 1971, Lowell Obs., Flagstaff, AZ, CDS I/79

Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 355, 27, CDS I/259

Le Campion, J.-F., Geffert, M., Dulou, M.-R., & Colin, J. 1992, A&AS, 95, 233

Luyten, W. J. 1979, Minneapolis, University of Minnesota, CDS I/98A

Rapaport, M., & Le Campion, J.-F. 1990, in Proceedings of the Journées 1990 Systèmes de référence spatio-temporels, Paris, 75

Robin, A., Haywood, M., Crézé, M., Ojha, D., & Bienaymé, O. 1996, A&A, 305, 125

Skrutskie, M. F., Schneider, S. E., Stiening, R., et al. 1997, in The Impact of Large Scale Near-IR Sky Surveys, ed. F. Garzon et al. (Kluwer – The Netherlands), 25

Urban, S. E., Corbin, T. E., & Wycoff, G. L. 1998, AJ, 115, 2161

Urban, S. E., Corbin, T. E., Wycoff, G. L., et al. 1998, AJ, 115, 1212

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., et al. 1991 (Springer-Verlag: New York), CDS VII/155

Viateau, B., Réquième, Y., Le Campion, J.-F., et al. 1999, A&AS, 134, 173

Zacharias, N., Urban, S. E., Zacharias, M. I., et al. 2000, AJ, 120, 2131