Revista Mexicana de Astronomía y Astrofísica, **39**, 303–310 (2003)

CCD-BASED ASTROMETRIC MEASUREMENT OF PHOTOGRAPHIC PLATES

I. H. Bustos Fierro[1] and J. H. Calderón[2]

Observatorio Astronómico
Universidad Nacional de Córdoba, Rep. Argentina

Received 2003 June 3; accepted 2003 August 12

RESUMEN

Se ha desarrollado la metodología para la medición astrométrica de placas fotográficas haciendo uso de una cámara CCD. Para la medición de una placa de $2^\circ \times 2^\circ$ se tomó un mosaico de 8×8 imágenes con 50% de superposición en ambas coordenadas. La segmentación y el centrado de las imágenes estelares se llevó a cabo con SExtractor, y por medio de software propio se identificaron las exposiciones triples. Se encontró una notable distorsión radial producida por el sistema óptico que fue corregida. La reducción a coordenadas celestes se efectuó mediante la técnica de ajuste en bloque, usándose el catálogo Tycho-2 como referencia. Las diferencias con Tycho-2 sugieren que el error de las posiciones obtenidas con CCD a partir de la placa CdC está entre $0.''20$ y $0.''25$. También se discute la completitud de los catálogos obtenidos.

ABSTRACT

We have developed a methodology for the astrometric measurement of photographic plates making use of a CCD camera. In order to measure a complete $2^\circ \times 2^\circ$ plate a mosaic of 8×8 frames with 50% overlap in both coordinates was taken. The detection and centering of stellar images was performed with SExtractor, and by means of our own software triple exposures were identified. A noticeable radial distortion produced by the optical system was found and corrected. The reduction to celestial coordinates was performed by means of the block-adjustment technique, using Tycho-2 as reference catalog. Differences with Tycho-2 suggest that the errors of CCD-based positions obtained from the CdC plate are between $0.''20$ and $0.''25$. Completeness of the catalogs obtained is also discussed.

Key Words: **ASTROMETRY — CARTE DU CIEL — METHOD: BLOCK-ADJUSTMENT — OPEN CLUSTERS: INDIVIDUAL (NGC 2587) — PHOTOGRAPHIC ASTROMETRY**

1. INTRODUCTION

Unique records of the sky taken in the last century are contained in the photographic plates of old observatories. That material can provide useful data for current research if measured with accurate techniques and devices available today such as microdensitometers. The Observatory of Córdoba has an important archive of photographic plates, many of them almost one century old, but it has not been able to afford the acquisition of a PDS. Therefore, the use of the available scientific-grade CCD camera to produce high quality digital images of photographic plates was proposed, so as to allow accurate measurements.

Since the main interest of measuring old plates is to obtain first-epoch positions for the determination of proper motions, we have developed a methodology for the astrometric measurement of photographic plates based on the use of a CCD camera for the acquisition of digital images and the block adjustment technique for the reduction. The photometric usefulness of these data has not been explored yet.

[1]Agencia Córdoba Ciencia S. E., Córdoba, República Argentina.

[2]Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina.

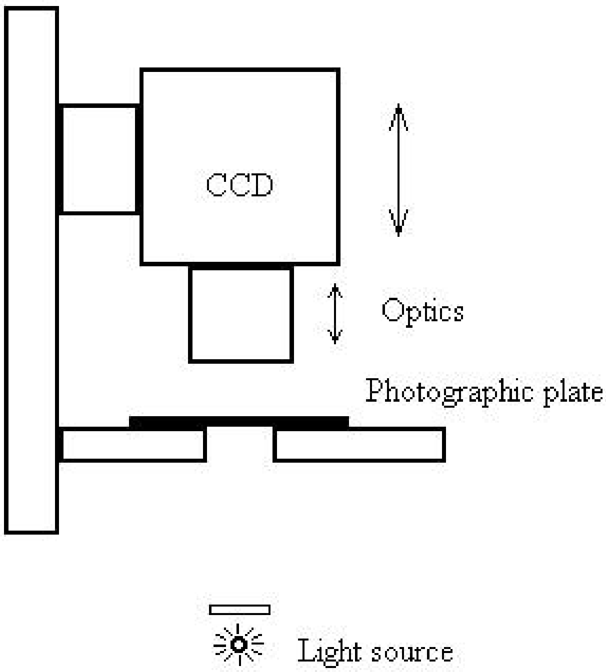

Fig. 1. Schematic representation of the mounting of the CCD camera for the digitization of photographic plates.

2. PHOTOGRAPHIC MATERIAL

The Astrographic Congress held in Paris in 1887 decided the construction of a photographic catalog of the whole sky complete to photographic magnitude 11, the Astrographic Catalog (AC), and of a celestial chart complete to photographic magnitude 14, the Carte du Ciel (CdC). To this end, the sky was photographed on plates of $2° \times 2°$ with a scale of $1'$/mm. The zone with plates centered between declination $-24°$ and $-31°$ was assigned to the Astronomical Observatory of Córdoba in 1900.

The plates for the AC of the Córdoba zone were taken between 1903 and 1913; they were measured and the catalog was finally published between 1925 and 1934. The plates for the CdC were taken between 1913 and 1926; some of them were printed on paper but they were never measured, since the plan was to construct a sky chart and not a catalog. However they go deeper than the AC plates and they constitute an excellent first-epoch material for the determination of proper motions. The plate selected for the present measurement was plate number 6448 that corresponds to a field close to the galactic center, containing the open cluster NGC 2587.

3. CCD-BASED DIGITIZATION

In order to measure photographic plates, CCD images are taken with the camera of Bosque Alegre Astrophysical Station. This is a Photometrics CH260 camera, which has a scientific-grade chip Thompson TH7896 with 1024×1024 square pixels of 19μm and 16 bits of digital resolution (Díaz et al. 1997).

A special mounting for the CCD camera was designed for the digitization of photographic material (Figure 1). This mounting allows a vertical displacement of the camera, thus changing the scale factor from frame to plate. The plate is back-illuminated with diffuse light, and the optical system consists of a 80 mm focal distance multi-coating macro-lens f/1.2, used with an aperture stop at f/5.6 (Bustos Fierro & Calderón 2001).

In this work, every frame covers an area of approximately 30 mm by 30 mm, equivalent to $30' \times 30'$ on the sky. This sampling was chosen to ensure that triple exposures are well resolved and that there are enough link stars in the overlapping area of neighbouring frames. In order to measure a complete $2° \times 2°$ plate a mosaic of 8×8 frames is taken with a 50% overlap in both coordinates. Since this is a dense region, there are many stars in common between overlapping frames, typically 40 stars on frames with 50% overlap (center-side) and 20 stars on frames with 25% overlap (center-corner). In the experimental device employed for the present measurement there is no tilt control, but since its effect on positions is a linear transformation it will be absorbed in the fitting.

4. OBJECT DETECTION AND CENTERING

After standard CCD corrections, the first step toward the measurement of stellar positions is the detection of pixels corresponding to every stellar image on the plate, a process called segmentation in the image-processing vocabulary. Once those pixels are identified for a given star, a centroid of them has to be defined in order to obtain the rectangular coordinates of that star in that frame.

A characteristic feature of CdC plates from Córdoba is that they contain triple exposures of equal exposure times, resulting in every star having a triple image forming an equilateral triangle of approximately $7''$ side (Figure 2). In addition, a superimposed grid with 5 mm separation between lines, some scratches and the granularity of the emulsion make the detection more difficult than on direct CCD images from the sky.

4.1. *Object Detection with IRAF*

The first attempt at detection of stellar images was made using the task DAOFIND of IRAF. Only approximately 10% of the stellar images were detected and many spurious detections were obtained.

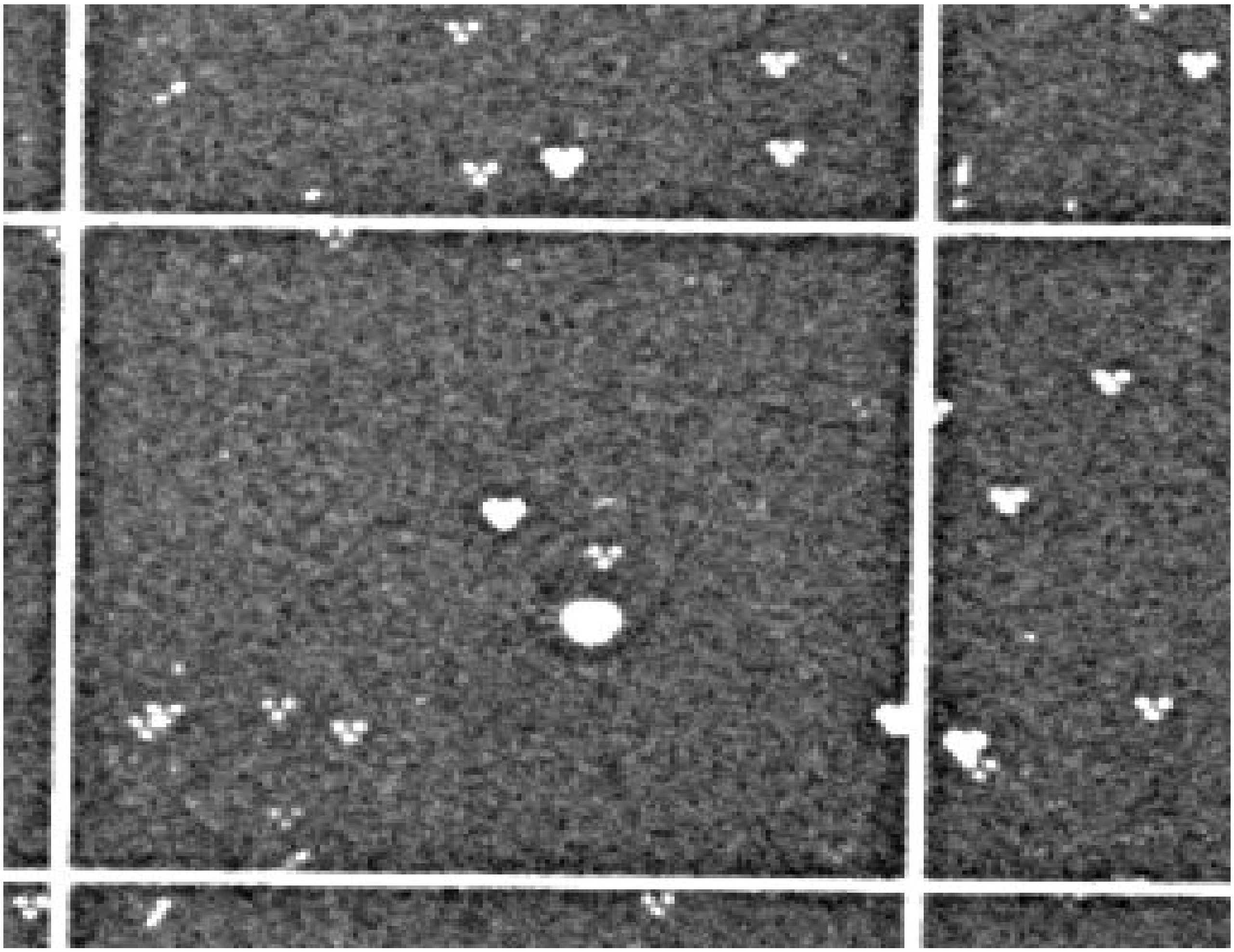

Fig. 2. Partial view of a CCD frame taken near the center of the plate. Triple exposures and the superimposed grid lines can be seen.

After convolution with a triangular kernel similar to the triple exposures, the stellar images were enhanced, resulting in a larger number of detected stars—around 50%—but still too low and with many spurious detections. Therefore this approach was abandoned.

4.2. *Object Detection with SExtractor*

In SExtractor (Bertin & Arnouts 1996) the segmentation process is accomplished in several stages: determination and subtraction of background, filtering (optional), detection of pixels over a certain threshold, de-blending of close images by a multi-threshold algorithm, and calculation of the barycenter and shape parameters of detected objects. With this software, although many spurious detections were obtained, the three components of stellar images were correctly and separately detected in most cases. The barycenter of each exposure is employed as centroid, and its coordinates are recorded in the catalog of objects constructed by the software.

4.3. *Detection and Centering of Triple Images*

Ad-hoc software (Bustos Fierro & Calderón 2001) was developed for the identification of triple images and for the rejection of spurious detections. The program scans the SExtractor catalog and for every object it searches another two, each one within a searching area defined around the expected positions for the southern exposures if the first object was the northern exposure of a star (Figure 3). If both southern exposures are found, then it is assumed that those three objects in the catalog correspond to the three separate components of a triple image, the position of which is calculated as the average of the three centroids given by SExtractor. In this way, a catalog of triple images is obtained from the original SExtractor catalog. An average of 170 triple images

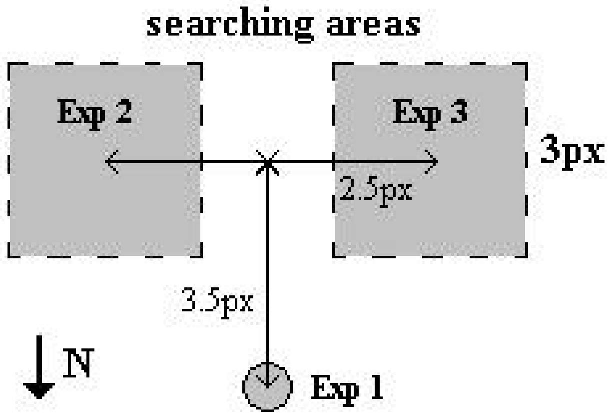

Fig. 3. Shape and size of searching areas for the identification of triple exposures.

were identified on each CCD frame, totalizing more than 10,000 in all of them.

The internal errors of the centroids provided by SExtractor are shown in Table 1 for different brightness intervals; for a more realistic estimation of the centering error ten shots were made on the center of the plate. By comparing the positions of the triple images in the resulting ten CCD frames it is possible to calculate a dispersion for every star. The medians of those dispersions for different brightness intervals, shown in Table 2, are noticeably smaller than the errors of SExtractor detections, as can be expected provided that each stellar position is the average position of three single detections.

When the separation of triple exposures is plotted against the brightness of the stars (Figure 4) no evidence of a Kostinsky effect is found. In fact, the dispersion and the mean separation seem to decrease with the brightness of the stars, as found by Geffert et al. (1996) on CdC plates from Paris. The Kostinsky effect (de Vaucouleurs, Dragesco, & Selme 1956) consists of an apparent increase of the separation of close images with high photographic density, i.e., bright stars, as found by Ortiz-Gil, Hiesgen, & Brosche (1998) on a similar plate from Bordeaux, and by Dick et al. (1993) on a plate from Paris. Nevertheless, despite the observed trend the average position of the three exposures should not be affected, due to their arrangement on an equilateral triangle.

5. COMPARISON WITH MAMA BASED CATALOG

A few CdC plates from Córdoba were digitized with MAMA of the Observatory of Paris (Bustos Fierro & Calderón 2000). The catalog of SExtractor detections was provided by the Centre d'Analyse d'Images of the Observatory of Paris, while triple

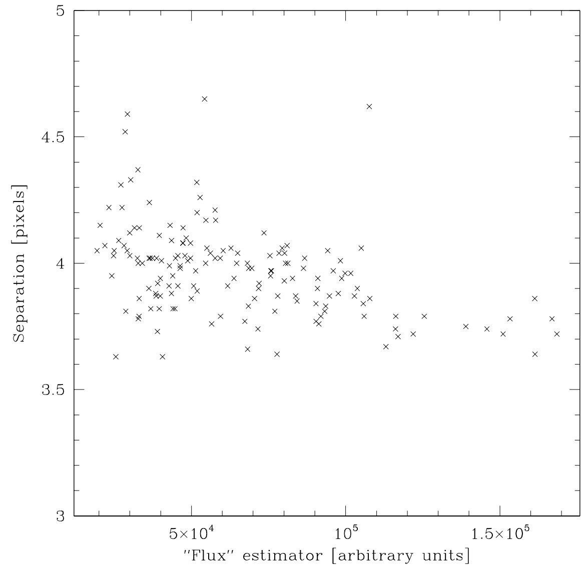

Fig. 4. Mean distance between the three exposures of every star in a frame close to the center of the plate. The instrumental flux provided by SExtractor is employed as an indicator of brightness.

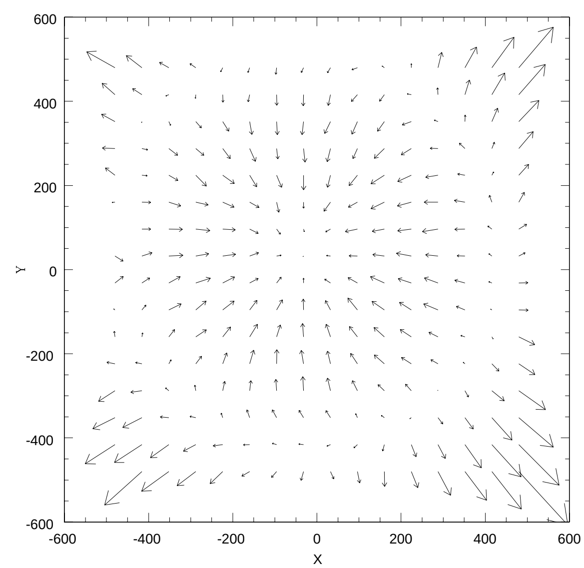

Fig. 5. Differences between CCD-based and MAMA-based positions averaged within a grid of square cells of 64 pixels. X, Y are coordinates of grid cells on the CCD frame, in pixels. Vectors have been enlarged 200 times, so the biggest ones in the corners represent approximately 0.8 $pixel (\approx 1.''4)$.

TABLE 1

SEXTRACTOR INTERNAL ERROR

Flux Estimator (Arbitrary Units)	Median Error in X (Pixels)	Median Error in Y (Pixels)
less than 40,000	0.058	0.062
40,000–60,000	0.047	0.047
60,000–80,000	0.035	0.035
80,000–100,000	0.031	0.030
more than 100,000	0.026	0.025
Total	0.041	0.042

TABLE 2

DISPERSION IN TEN SHOTS

Flux Estimator (Arbitrary Units)	Median Dispersion in X (Pixels)	Median Dispersion in Y (Pixels)
less than 40,000	0.037	0.037
40,000–60,000	0.028	0.028
60,000–80,000	0.026	0.022
80,000–100,000	0.022	0.021
more than 100,000	0.026	0.022
Total	0.030	0.026

images were identified with the software mentioned above, after modification of the position and size of the searching areas according to the scale of digitization with MAMA ($1px_{MAMA} = 10.0\ \mu m$). An external estimate of the error in our CCD-based catalog of triple images was obtained by comparing it with the MAMA-based catalog of the same plate.

At this stage transformations between CCD and MAMA-based catalogs were not adjusted for the comparison of coordinates but for cross-identification only, since they could hide or add some systematic effect. Therefore, the distances between pairs of stars were studied instead of their individual coordinates.

In the absence of errors of any type, the distance between any pair of stars in one catalog should be equal to the distance between the same pair of stars in the other catalog multiplied by a constant factor related to their digitization scales. Therefore, it should be possible to fit the the following relation to all pairs of stars:

$$\rho^{ij}_{CCD} = a\rho^{ij}_{MAMA} + b\,,$$

where ρ^{ij} is the distance between the i-th and j-th star. In the error-free case this fitting would result in a null dispersion, a being constant and b=0, both with no error. For real measurements the dispersion in the fitting is not null and it provides an estimate of the errors in the catalogs under comparison. From the fitting a mean scale factor $a = 0.357px_{CCD}/px_{MAMA}$ was found, indicating $1px_{CCD} = 28.0\ \mu m$, and a dispersion of $0.32px_{CCD} = 0.89px_{MAMA}$, that is equivalent to $0.''54$ on the sky. Since this dispersion is larger than the expected errors for MAMA-based measurements, it is presumably mostly due to errors in the CCD measurement.

6. SYSTEMATIC ERRORS

In previous numerical simulations (Bustos Fierro 1998) it was found that optical distortions may be the limiting factor for the accuracy achievable with this technique. In order to find a possible systematic pattern in the CCD-MAMA differences, linear transformations between rectangular coordinates in the 64 CCD frames and the MAMA-based ones were fitted. Using these transformations, coordinates could be

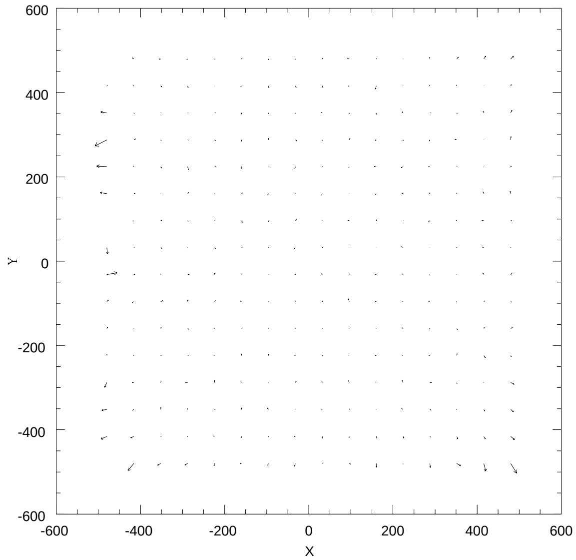

Fig. 6. Idem Fig. 5 built after correction of measured rectangular coordinates.

compared and their differences were stored as function of the position on the CCD. These differences show a dispersion of $0.15\,pixels = 0.''25$ in X and $0.16\,pixels = 0.''26$ in Y and a clear radial pattern when averaged over a grid (Figure 5).

7. CORRECTION OF SYSTEMATIC ERRORS

No mathematical model was assumed for the observed differences CCD-MAMA; instead, the correction to every rectangular coordinate on the CCD-based catalog was computed as a local weighted average of differences with MAMA, following the interpolation scheme in Stock & Abad (1988) which makes use of a bidimensional polynomial and a weighting function dependent on the distance to the interpolating point $w(r) = \{[1-(r/r_0)^2]^{1/2}\}^n$. The polynomial was chosen constant for every star, the interpolation radius was $r_0 = 50\,pixels$, and the exponent $n = 1$, assuring the continuity of the interpolanting function and its derivative. After this correction, the systematic pattern was succesfully eliminated (Figure 6) and the dispersions in differences with the MAMA-based catalog were reduced to $0.08\,pixels = 0.''14$ in X and $0.10\,pixels = 0.''16$ in Y.

8. ASTROMETRIC REDUCTION

Given N overlapping plates, the block adjustment technique, developed for photographic astrometry, reduces all plates simultaneously, imposing on the solution for each plate not only the condition of best fit with the reference catalog, but also a best fit with neighboring plates. A full description and the formulae involved can be found in the work of Stock (1981).

TABLE 3

RMS DIFFERENCES WITH TYCHO-2

B_T mag	$\sigma_{\alpha^\star}['']$	$\sigma_\delta['']$
less than 10	0.21	0.21
10–11	0.23	0.23
11–12	0.31	0.29
12–13	0.28	0.27
more than 13	0.32	0.26
Total	0.28	0.27

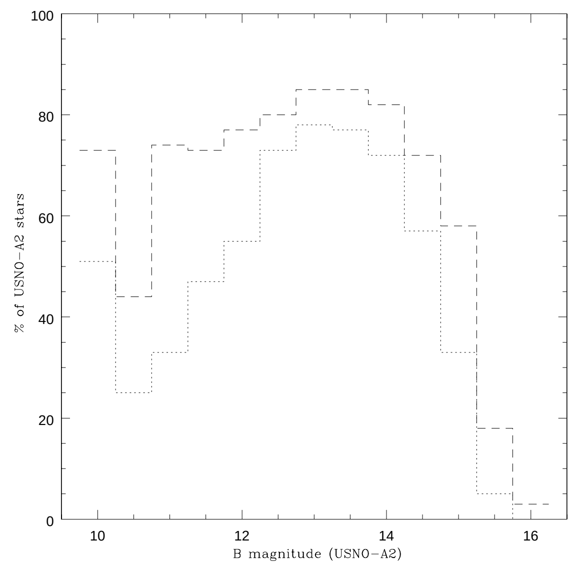

Fig. 7. Fraction of USNO-A2 stars detected in the CdC plate within a circle of 1° around its center. Dotted line: CCD-based catalog; dashed line: MAMA-based catalog.

The astrometric reduction of our plate was performed making use of the block-adjustment procedure of Stock (1981), replacing the set of N overlapping plates by a set of N overlapping CCD frames taken from a single plate. Therefore, it was necessary not only to recognize the reference stars from Tycho-2 (Høg et al. 2000) but also to determine the cases when two or more images in the overlapping zone between frames correspond to the same star in the photographic plate.

With a starting set of less than ten reference stars and approximate displacements between frames for the identification of some link stars between neighboring frames, a first block-adjustment was performed which allowed to obtain preliminary celestial coordinates for all the triple images detected. These preliminary coordinates were employed to recognize other overlapping stars, and by comparing them with Tycho-2 further reference stars were added. This process was repeated until no new reference star was found, which usually happened near the fifth iteration for different starting sets of reference stars. Finally, 268 Tycho-2 stars were identified and employed as reference stars in the reduction of the plate, and almost 3700 different stars were recognized.

9. EVALUATION OF ERRORS

The block-adjustment was accomplished with three least-squares fits using the routine LFIT in Press et al. (1989). Each of these three fittings corresponds to one axis in a three-dimensional Cartesian coordinate system, where every stellar position is considered as a point on a sphere with unit radius. Dispersions found in the fits were $6-9\times10^{-7}$, which correspond to $0.''12 - 0.''20$. When a test reduction was made without correction for the radial distortion these dispersions were about three times larger.

Due to the lack of accurate positions for the epoch of CdC plates, an estimation of the error was obtained from the comparison with Tycho-2, even though it was the reference catalog. Since the block-adjustment technique also makes use of the overlapping stars which are much more numerous than the reference stars, its weight is, however, relatively low. The rms differences with Tycho-2 as function of Tycho B apparent magnitude are shown in Table 3. Their values for the whole sample are $0.''28$ in $\alpha \cos\delta$ and $0.''27$ in δ. Considering that the error of Tycho-2 positions is about $0.''20$ for the epoch of this plate, these dispersions suggest that the errors of CCD-based positions obtained from the CdC plate are between $0.''20$ and $0.''25$ for the magnitude range covered by Tycho-2, but may be worse for the faintest stars.

10. COMPLETENESS AND LIMITING MAGNITUDE

In order to estimate the completeness and limiting magnitude of the sample of stars detected on the CdC plate, both the CCD-based and the MAMA-based catalogs were compared with the much denser USNO-A2.0 catalog (Monet et al. 1998, USNO-A2 hereafter). This comparison was performed assuming that an entry in USNO-A2 corresponds to a given star in a CdC catalog if the positions in both catalogs differ by less than certain coincidence radius. Due to the very large difference in the epochs of the catalogs and the lack of known proper motions, the coincidence radius was chosen relatively large, equal to $2.''5$. In order to avoid contamination by the faint stars of USNO-A2 a cutoff at B magnitude 16.0 was set.

It can be seen in Figure 7 that within a circle of 1° around the plate center the completeness reaches its maximum for stars with B magnitude—provided by USNO-A2—of about 13.5, being 77% in the CCD-based catalog and 85% in the MAMA-based one. The missing stars may be due to the blending of the three exposures in the bright end, to the low signal-to noise-ratio in the faint end, and to grid lines, scratches and "contamination" by spurious detections in the whole magnitude range. The higher completeness of the MAMA-based catalog may be due to the higher sampling frecuency which allows a better de-blending of close images. Beyond the magnitude of maximum completeness the fraction of USNO-A2 stars detected in the plate decreases, reaching zero for stars with B magnitude greater than 15.5.

11. CONCLUSIONS

Due to the noisy nature of the photographic images and the triple exposures of CdC plates from Córdoba, the most efficient detection of stellar images was achieved with SExtractor and our own software, which recognizes triple exposures and rejects spurious detections.

The mean scale of this digitization was found to be $1 px_{CCD} = 28.029\ \mu m = 1.''7$, but it could be changed by moving the mounting of the camera should it be necessary for a particular application. No evidence of a Kostinsky effect was detected, but we found a noticeable radial distortion produced by the optical system, which could be modeled and corrected.

The comparison of the distances between pairs of stars in a single frame with the ones obtained from a MAMA-based measurement of the same plate suggests that every rectangular coordinate obtained with the CCD has an error around $0.''3$.

The combination of Tycho-2 Catalogue and block-adjustment results in a suitable technique for the reduction of these measurements. The residuals in the fittings were from $0.''12$ to $0.''20$, while the comparison with Tycho-2 positions suggests an error of CCD-based celestial coordinates from $0.''20$ to $0.''25$.

By comparison with USNO-A2 it was found that nearly 80% of stars with B magnitude less than 14 can be detected with a simple identification algorithm.

Further work is being done on the evaluation and correction of distortions of the plate scale, and finally on the combination with positions at other epochs in order to obtain good quality proper motions up to photographic magnitude 15. Also under development is the automatization of the scanning and the cross-identification of stars in overlapping frames so as to allow a faster production of such data.

The authors acknowledge Jean Gibert and the Centre d'Analyse d'Images of the Observatory of Paris their kind cooperation in the digitization with MAMA and the segmentation with SExtractor.

REFERENCES

Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393

Bustos Fierro, I. H. 1998, Universidad Nacional de Córdoba, Fa.M.A.F., trabajo especial de Licenciatura en Astronomía

Bustos Fierro I. H., & Calderón J. H. 2000, BAAA, 44, 62

________. 2001, Medición de Placas Carte du Ciel con CCD. I: Evaluación de errores, in 1^{st} ADeLA, San Juan (Argentina)

De Vaucouleurs, G., Dragesco, J., & Selme, P. 1956, Manuel de photographie scientifique (Paris: De la Revue d'Optique), 148

Díaz, R., Paolantonio, S., Goldes, G., & Carranza, G. 1997, Universidad Nacional de Córdoba, Fa.M.A.F., Serie "A" Trabajos de Astronomía, 1/97, 38

Dick, W. R., Tucholke, H.-J., Brosche, P., Galas, R., Geffert, M., & Guibert, J. 1993, A&A, 279, 267

Geffert, M., Bonnefond, P., Maintz, G., & Guibert, J. 1996, A&AS, 118, 277

Høg, E., Fabricius, C., Makarov, V. V., Urban, S., Corbin, T., Wycoff, G., Bastian, U., Schwekendiek, P., & Wicenec, A. 2000, A&A, 355, L27

Monet, D., et al. 1998, USNO-A V2.0: A Catalog of Astrometric Standards (Washington, D.C.: U.S. Naval Observatory), on CD-ROM

Ortiz-Gil, A., Hiesgen, M., & Brosche, P. 1998, A&AS 128, 621

Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1989, Numerical Recipes in Pascal: The Art of Scientific Computing (Cambridge: CUP)

Stock, J. 1981, RevMexAA, 6, 115

Stock, J., & Abad, C. 1988, RevMexAA, 16, 63

Iván Bustos Fierro and Jesús H. Calderón: Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, Bo. Observatorio, X5000BGR, Córdoba, República Argentina (ivanbf,calderon@oac.uncor.edu).