ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

JULY **1996**, PAGE 163

Astron. Astrophys. Suppl. Ser. **118**, 163-167 (1996)

New reductions of the Astrographic Catalogue.

Plate adjustments of the Algiers, Oxford I and II, and Vatican Zones

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Received November 23; accepted December 16, 1995

Abstract. — The U. S. Naval Observatory is in the process of making new reductions of the Astrographic Catalogue using a modern reference catalog, the ACRS, and new data analysis and reduction software. Currently ten AC zones have been reduced. This papers discusses the reduction models and results from the Algiers, Oxford I and II, and Vatican zones (those of the Cape zone are discussed elsewhere). The resulting star positions will be combined with those of the U.S. Naval Observatory's Twin Astrograph Catalog to produce a catalog of positions and proper motions in support of the Sloan Digital Sky Survey.

Key words: catalogs — astrometry — reference systems — surveys — methods: data analysis

1. Introduction

The Astrographic Catalogue (AC) is a full-sky catalog containing positional data for stars as faint as the 13th magnitude at epochs as early as 1892. This combination of early epoch, faint magnitude and global coverage provides a rich source of astrometric positions for determining proper motions of faint stars. However, the data in the AC cannot be used as published since plate coordinates, not equatorial coordinates, are given for the images. In order to minimize systematic errors, the data must be reduced using a modern reference catalog and rigorous reduction techniques.

The U.S. Naval Observatory (USNO) has produced such a reference catalog, the Astrographic Catalog Reference Stars (ACRS; Corbin et al. 1991), which has recently been shown to represent the system of the International Reference Stars quite well (Evdokimov et al. 1995; Corbin & Warren 1991). Reduction methodologies designed to investigate and minimize systematic errors likely to be found in the AC data have been developed at the USNO and are detailed in the paper describing the reduction of the Cape AC zone (Urban & Corbin 1996), which will be referred to as Paper I. These techniques have now been used to reduce the data in the Algiers, Oxford I, Oxford II and Vatican zones, and the resulting star positions are available to the astronomical community via the World Wide Web (http://aries.usno.navy.mil/ad/ac.html).

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The results for the four AC zones discussed in this paper will be combined with the positions from the USNO Twin Astrograph Catalog (TAC; Harrington 1978; Zacharias & Douglass 1995) to derive a catalog of positions and proper motions. These data will be used during the test phase of the Sloan Digital Sky Survey (SDSS; Kent 1994). Priority was given to these zones over others to insure they would be completed according to the SDSS schedule. A reference catalog covering the entire SDSS operating area, using the combined AC and TAC data, will be completed in 1996.

2. Measuring techniques and zone specifics

The Algiers, Oxford I and II, and Vatican zones are representative of the inhomogeneity found in the AC data. The four zones contain three types of measuring techniques, four different telescopes, and a 44-year range in the plate epochs. This diversity results in dramatically different accuracies and systematic errors for each zone, meaning that each zone requires individual investigations in the reduction process.

2.1. *Algiers Zone*

The Algiers Observatory was assigned the zone of $-2°$ to $+4°$ (eq. 1900) to photograph. In total, over 330 000 images from 1260 plates were measured and their coordinates were published. All plates were exposed between 1891 and 1911. The Algiers plates were measured by the *micrometer screw* method. All plates in the AC have lines exposed on them (called a réseau), forming a grid segmented into 5 mm squares. To measure a star using the *micrometer screw* method, an area corresponding to one réseau square is magnified and brought into focus under a microscope. The origin of this square, corresponding to the pattern of the réseau, was believed to be known. (This assumption is no longer held to be valid and each réseau is now investigated for its own distortions, as detailed in Paper I). The measurer then manually centers a thin set of wires above the star image by rotating a pair of finely machined screws, one for each coordinate. The distance the screws travel from the square's origin, in addition to where that réseau square's origin is with respect to the plate center, yields the position of the star on the plate. This technique is believed to be the most accurate method used in the measurement of the AC plates; it was also the most time consuming. The measuring technique used by Oxford was faster, but less accurate.

2.2. *Oxford I and Oxford II Zones*

Oxford originally received the zone from +25°to +31°. All plates in this section, known as Oxford I, were exposed between 1892 and 1910. In total, over 470 000 images on 1188 plates were measured and their plate coordinates were printed. In 1928, Oxford also agreed to photograph the sky between +32°and +33°because the Potsdam Observatory was unable to complete its assigned zone (+32°to +39°). This two degree band is known as the Oxford II zone. In the Oxford II zone, there are 320 plates centered on declinations +32°and +33°. All were exposed between 1930 and 1936. These plates yielded more than 160 000 published image coordinates.

To expedite the measuring of the plates, Oxford utilized the *eyepiece scale* method. In this method, the glass plate was mounted on a frame movable in the y-direction. A glass diaphragm with two perpendicular scales, each divided into 0.01 réseau interval (about 3 arcsecs), was used for the measurement. This diaphragm was movable in the x-direction. The plate and the diaphragm were positioned so that a star was centered at the intersection of the two scales. The position of the star was read to an accuracy of 0.001 réseau units (about 300 mas) at the four points where the réseau crossed the scales. A diagram of the micrometer's field of view can be seen in Plate II of the Greenwich Vol. I introduction (Christie 1904). This method proved to be much faster, though less accurate, than using a micrometer screw. Vatican employed a third, even less accurate measuring method.

2.3. *Vatican zone*

The Vatican Observatory covered the sky between declinations +55°and +65°. All 1046 plates were exposed between 1891 and 1926 yielding about 480 000 published measures. The Vatican Observatory suffered from a lack of personnel assigned to the Astrographic Catalogue work, so a quick method for measuring plates was needed if the project were to be completed in a reasonable amount of time. Instead of using a micrometer screw or eyepiece slide, they used an eyepiece grid, called a *diaframma*, that resembled a see-through piece of graph paper. To measure the plate, a section corresponding to four réseau intervals (two-by-two) along with the *diaframma* were brought into the focus of the microscope. The positions of the stars were then deduced from their coordinates on the *diaframma*. Although this method was fast relative to using the *micrometer screw* method (used by Algiers), the accuracy was two times lower, as shown in Table 3.

Characteristics of each zone are summarized in Table 1.

Table 1. Characteristics of AC zones

Zone	Dec. Range	Epochs	Measuring Technique
Algiers	-2°to +4°	1891-1911	micr. screw
Oxford I	+25°to +31°	1892-1910	eyepiece scale
Oxford II	+32°to +33°	1930-1936	eyepiece scale
Vatican	+55°to +65°	1891-1926	eyepiece grid

3. Plate models

An eight constant plate model, shown in Eqs. (1) and (2) is used in the reductions of the Algiers, Oxford I and II, and Vatican plates.

$$\xi = ax' + by' + c + ex' + fy' + x'^2 p + x'y'q \qquad (1)$$

$$\eta = ay' - bx' + d - ey' + fx' + x'y'p + y'^2 q \qquad (2)$$

This model, as described in Paper I, contains six linear and two *tilt* variables, all of which are solved on a plate-by-plate basis using the Astrographic Catalog Reference Stars as the reference catalog. The values x' and y' are the printed x and y values corrected for radial distortions, magnitude effects and field distortions, as shown in Eqs. (3) and (4). The values of x, x', y, and y' are hereby defined in units of arcseconds.

$$\begin{aligned} x' &= x + \mathrm{DST}(x^2+y^2) + S_x mx + \mathrm{ME}_x(m) + \\ &\quad \mathrm{MC}_x(x,m) + \mathrm{FDP}_x(x,y) \end{aligned} \qquad (3)$$

$$\begin{aligned} y' &= y + \mathrm{DST}(x^2+y^2) + S_y my + \mathrm{ME}_y(m) + \\ &\quad \mathrm{MC}_y(y,m) + \mathrm{FDP}_y(x,y). \end{aligned} \qquad (4)$$

In Eqs. (3) and (4), DST is the correction applied to compensate for radial distortion, S_x and S_y are the coefficients of the coma correction, ME_x and ME_y are the coefficients of the magnitude equation independent of image position on the plate, MC_x and MC_y are the x, y-dependent magnitude terms, and FDP is the correction for the remaining field distortion pattern. The variable m is the value for magnitude of a star derived from its image diameter as estimated by the plate measurer. The parameters shown in Eqs. (3) and (4) remain constant for an individual AC zone unless otherwise noted. These values are generally telescope-dependent and so must be handled individually for each zone.

3.1. *Algiers*

The Algiers data contain a third-order distortion term that accounts for a systematic error of about 100 mas near the plate edges. This distortion is not present for stars brighter than magnitude 9.0. Using stars in common to the ACRS catalog, a positionally independent magnitude equation has been found in both the x and y direction. For x, the value of the correction is 50 mas/mag and is present only for stars fainter than magnitude 8.0. For y, the correction is 100 mas/mag for all stars. For the Algiers data, no coma, field distortion or positionally dependent magnitude equation was found.

3.2. *Oxford I*

The Oxford I data do not contain a significant third-order distortion or coma, so DST, S_x and $S_y = 0$. However, the data do contain a magnitude equation, ME_x, equaling 150 mas/mag. There is also a positionally dependent magnitude equation, $MC_x(x, m)$, which is of the form

$$MC_x = a_1 x^2 + a_2 x + a_3 \quad (5)$$

where a_1, a_2 and a_3 are functions of magnitude. The values for a_1, a_2 and a_3, in units of mas/arcsec^2, mas/arcsec and arcsec respectively, have been solved via linear least-squares and are

$$a_1 = -7.5\ 10^{-6} m + 5.5\ 10^{-5} \quad (6)$$

$$a_2 = -8.7\ 10^{-4} m + 8.6\ 10^{-3} \quad (7)$$

$$a_3 = -44m + 350. \quad (8)$$

There is no magnitude equation in y. After correcting for magnitude-dependent terms, a remaining field distortion is present, as seen in Fig. 1. This field distortion pattern is independent of réseaux, epoch and measuring machine.

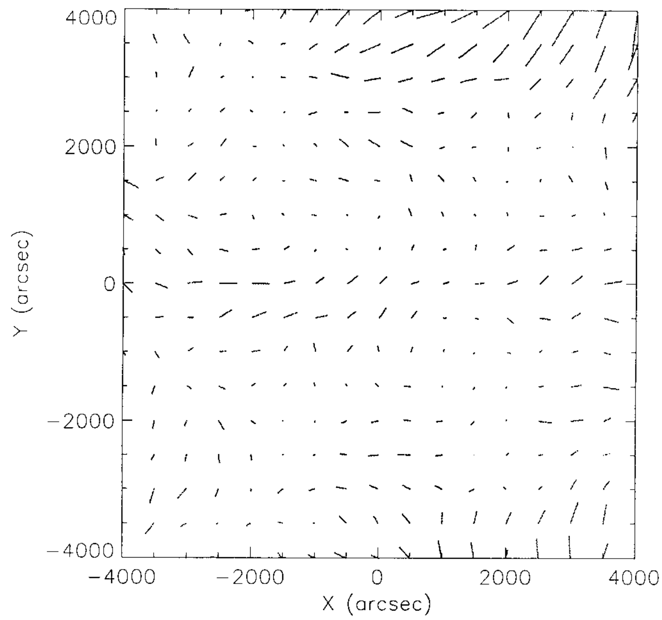


Fig. 1. Differences in the Oxford I zone between mean position and individual image positions as a function of plate coordinate of the individual image. Vectors are multiplied by 2000 to show detail

3.3. *Oxford II*

The plates comprising the Oxford II data were really taken on two telescopes: one at Oxford, which was the same used for the Oxford I plates, and one at Greenwich, which photographed the last 32 plates to finish this zone. The coefficients for Eqs. (3) and (4) have been investigated for the two instruments separately. For the Oxford telescope, neither radial distortion nor coma errors were found. Both positionally independent and dependent magnitude equations were found in both coordinates. The value for ME_x is 180 mas/mag and ME_y is 50 mas/mag. The positionally dependent terms follow the general form of Eq. (5). For MC_x, the coefficients are

$$a_1 = -1.3\ 10^{-5} m + 1.3\ 10^{-4} \quad (9)$$

$$a_2 = 9.6\ 10^{-3} m - 1.0\ 10^{-1} \quad (10)$$

$$a_3 = 40m - 150 \quad (11)$$

and for MC_y they are

$$a_1 = -1.1\ 10^{-5} m + 9.7\ 10^{-5} \quad (12)$$

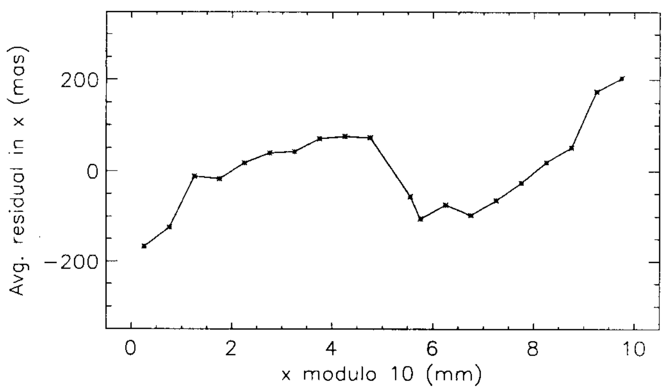
$$a_2 = -6.5\ 10^{-4} m + 2.8\ 10^{-3} \quad (13)$$

$$a_3 = 43m - 410. \quad (14)$$

A remaining field distortion pattern that is independent of réseau, epoch or measuring micrometer is present in the Oxford II data. The plates taken with the Greenwich telescope have a significant radial distortion term accounting for 250 mas systematic error at the plate edge. No evidence of magnitude equation was detected. There are too few data to investigate coma or field distortion pattern, so no corrections have been applied.

3.4. *Vatican*

The Vatican data contain a magnitude-dependent, radial distortion term. None is seen for stars brighter than magnitude 8.0. It increases until magnitude 11.0, then remains constant. This distortion at 11th magnitude results in a systematic error of 170 mas at the plate edges. No coma or magnitude equation is seen. A remaining field distortion is present and is a function of measuring microscope. Additionally, systematic errors in both x and y were found that repeat every other réseau interval, as shown in Fig. 2. This represents a measuring error similar to periodic screw errors, and is most likely caused by a combination of the *eyepiece grid* itself and personal differences, since this pattern changes with measurer. However, for each measurer and grid, this pattern repeats every other réseau interval which corresponds to the size of the *eyepiece grid* itself. Even after removing all known systematic effects, the accuracies of the Vatican AC positions are the worst of those reduced at this time. The average standard deviation of a single image is 410 mas in right ascension and 430 in declination.



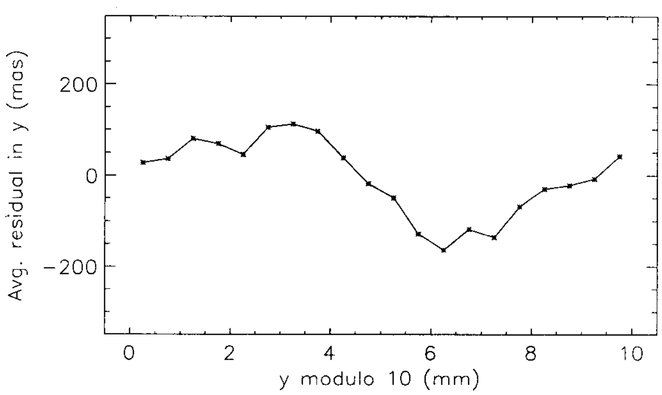


Fig. 2. Residuals in the Vatican AC data resembling periodic screw errors. Measures are original values modulo 10, so values between 0 and 5 mm are from even réseau divisions, values greater than 5 mm are from the odd divisions. Each point represents the average residual of all reference stars contained on that segment of the réseau square. The data plotted are for measurer=E, grid=2

Further investigations of the three main measurers, each identified by a letter, reveal that stars solely measured by measurer "E" have mean errors about 25% larger than those measured by the other two. Measurer "E"'s errors increase for fainter magnitudes, whereas those of the other two measurers do not. Unfortunately, "E" measured 621 of the 1046 plates. With these facts, it was decided to weight the plates of the Vatican zone based on measurer, as opposed to the procedures given in Paper I.

Table 2 summarizes the systematic errors investigated in the data. An error type is considered significant if it accounts for a systematic change in the data of 50 mas or more at its maximum.

Table 2. Systematic errors investigated in the Algiers, Oxford I and II, and Vatican AC zones. YES indicates the error is significant, no indicates non-significance and NA means too few data to investigate adequately

	Alg	Ox I	Ox II(Ox)	Ox II(Gr)	Vat
Rad. Dist.	YES	no	no	YES	YES
Coma	no	no	no	NA	no
ME_x	YES	YES	YES	no	no
ME_y	YES	no	YES	no	no
MC_x	no	YES	YES	no	no
MC_y	no	no	YES	no	no
Field Dist.	no	YES	YES	NA	YES

4. Accuracies

The final catalog positions and error estimates are based on weighted means, the calculations of which are described in Paper I. The results are shown in Table 3. It is believed that the range in errors seen in Table 3 is due largely to the different measuring processes used by each observatory. This is because all four telescopes were of the same basic design, the reduction software used to reduce each data set was identical and all zones were reduced using the same reference star catalog. Unfortunately, the poor measurement of the Vatican plates will have a negative impact

Table 3. Results of AC reductions. Average standard deviation of a single image

Zone	$\overline{\sigma}_\alpha$ (mas)	$\overline{\sigma}_\delta$ (mas)
Algiers	190	190
Oxford I	320	310
Oxford II	320	310
Vatican	410	430

on astrometry for the next several decades, since there are plans to derive proper motions for the Tycho stars using AC data. The Vatican plates should be re-measured to bring the accuracies in line with other AC zones.

5. Summary

The Algiers, Oxford I and II, and Vatican zones of the Astrographic Catalogue have now been reduced on a plate-by-plate basis by the United States Naval Observatory. The data have been reduced using the ACRS and the data are on equinox J2000.0 and the epoch of observation. The accuracies achieved in the Algiers data demonstrate that re-measurement of some of the other AC plates, in particular the Vatican plates, is well worth considering. The data are currently available on the World Wide Web at the site http://aries.usno.navy.mil/ad/ac.html. The remaining AC zones are currently being reduced in the same manner.

Acknowledgements. We thank Gary L. Wycoff for matching the Tycho Input Catalogue to each of the zones discussed in this paper. A thanks is extended to Atlantic Associates, Inc. and Jurgen Stock of CIDA for providing much of the manpower needed to get the x, y data in machine-readable form. Acknowledgment is also given to Chris Sande, formerly of USNO, who ensured the keypunched data were complete and of high quality. We also thank C. de Vegt of the Hamburg Observatory for providing much of the analytical software.

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