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Digitization and reduction of old astronomical plates of natural satellites★

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ABSTRACT

Old astrophotographic plates are precious sources of historical data for astronomical studies, especially regarding the improvement of natural satellite orbits. Today, with the advent of new, accurate techniques, these old data can be re-processed so as to give positions that are much more accurate than those initially obtained. Various recent projects, including our Chinese project, have involved measuring and reducing these old plates again. Here we present a method for measurement and reduction that involves the digitization of plates using an advanced commercial scanner, namely the EPSON 10000 XL. We selected a set of 27 plates of the satellites of Jupiter, Saturn and Uranus taken from 1987 to 1990. A total of 125 satellite positions were derived from the new measurement and reduction of these plates using the UCAC4 catalogue. A comparison of the new observed positions with recent ephemerides has shown a general consistency with satellite theory of about 100 mas. The new positions present an accuracy equivalent to the most recent CCD observations, and better than the original positions. Moreover, nearly 30 per cent of the 125 positions obtained in this work are published for the first time here. This paper is a preliminary contribution to the larger project of new measurements and reductions of all the old Chinese plates of natural satellites, which should allow further improvements in the knowledge of the orbits of these satellites.

Key words: techniques: image processing – astrometry – planets and satellites: general.

1 INTRODUCTION

Before CCD detectors were widely employed in observational astronomy, the main method of detection was the use of astrophotographic plates. More than 2 million astrophotographic plates were taken throughout the world over more than a hundred years, including about 30 000 plates in China. Because these plates contain more than a century of valuable original astronomical data, they need to be preserved and the information they contain recorded. Thus, in 2000 the International Astronomical Union (IAU) founded a working group dedicated to the Preservation and Digitization of Photographic Plates (PDPP). This working group asked all observatories around the world to digitize their plates as soon as possible,

before the plates became critically degraded over time. As a result, a project was launched in China in 2011 to digitize the 30 000 plates available in all Chinese observatories. This paper represents part of this Chinese project. A similar project, named the New Astrometric Reduction of Old Observations (NAROO), was launched at the French Institut de Mécanique Céleste et des Ephémérides (IMCCE) by Arlot (2013).

Several attempts to digitize astronomical plates were made using various measuring machines in the last two decades of the 20th century (MacGillivray & Thompson 1992). These machines included the COSMOS and SuperCOSMOS in Edinburgh, Scotland, the Automated Plate Scanner (APS) in Cambridge, England, and the Machine Automatique à Mesurer pour l'Astronomie (MAMA) in Paris, France. These machines generally presented a repeatability of about 1 μm , and 1 hr or more was needed to scan a medium-sized plate. Consequently, only a few plates could be scanned every day. More recently, the DAMIAN measuring machine in Bruxelles, Belgium has provided significantly better specifications, with a repeatability of 0.07 μm and a higher speed: it takes only 9 min to scan a

*The data are available in electronic form by e-mail, as Supplementary Material to the online version of the paper on Blackwell Synergy, at the CDS via Anonymous FTP to cdsarc.u-strasbg.fr, or via <http://cdsweb.u-strasbg.fr/Abstract.html>.

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Table 1. Detailed information on plates, with observed planet, date, number of plates (N), exposure time, and site code of observatory.

Planet	Year Month Day	N	Exposure time [s]	Site code
Saturn	1987.03.10	2	600–1200	334
	1987.05.20-22	8	60–600	286
	1988.05.12	6	240	286
Jupiter	1987.10.12-14	3	120–240	286
Uranus	1990.05.01-04	8	1200–1800	286
Total	1987-1990	27	60–1200	286,334

12 cm \times 17 cm plate (Robert et al. 2011). The main drawback of all these measuring machines is that they have a fixed location in Europe, far from the plate archives of many observatories, particularly those in China. In an effort to avoid the risky transportation of old plates, this work thus represents an attempt to measure old Chinese plates using an advanced mobile commercial scanner. In particular, we propose a method of measurement and reduction of old plates involving the digitization of plates with the advanced commercial scanner EPSON 10 000 XL.

This scanner possesses some clear advantages, namely a satisfactory measuring speed (it takes about 10 min to scan a 16 cm \times 16 cm plate) and mobility. Furthermore, we have evaluated the accuracy of the scanner in order to check that it can be used to derive high-quality astrometric positions of satellites.

In this work, a total of 27 plates of natural satellites of Jupiter, Saturn and Uranus were digitized and reduced using the new UCAC4 astrometric catalogue (Zacharias et al. 2013). In Section 2, we present the observational plate data. The methods of digitization and reduction are described in Sections 3 and 4, respectively. In Section 5, the results of the new observed positions are presented, compared with recent ephemerides, and discussed. Section 6 presents some conclusions.

2 PLATES

All 27 plates of the satellites of Jupiter, Saturn and Uranus selected here were taken on five successive missions during the period 1987 to 1990 (Wu & Zhang 1988; Shen (in preparation); Qiao, Shen & Zhang 1995). There are three plates of Jupiter, 16 plates of Saturn, and eight plates of Uranus. No filter was used in these observations. All the astrophotographic plates are Kodak 103ao and of size 16 cm \times 16 cm. Further details on the plates are given in Table 1. The observations were taken with two different telescopes. Most of the plates (25 out of 27) were taken with the 1.0-m astrometric reflector (Telescope A) at Yunnan Astronomical Observatory (E102:788, N25:029, H2000 m, code 286). The focal length of Telescope A is 13.3 m, which corresponds to a scale of about 15 arcsec mm^{-1} . The two remaining plates were taken with the 0.32-m astrometric reflector (Telescope B) at Tsingtao Observatory (E120:317, N36:067, H75 m, code 334). Telescope B has a focal length of 3.58 m, corresponding to a scale of nearly 60 arcsec mm^{-1} . Further instrumental details on both of these telescopes are given in Table 2.

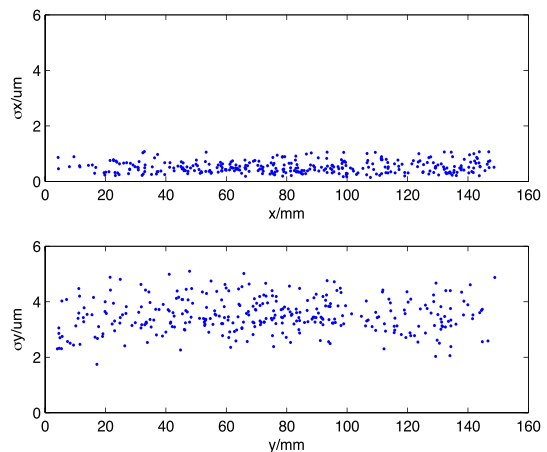
3 DIGITIZATION

3.1 The scanner

Commercial scanners have previously been used for astronomical purposes by authors such as Vicente, Abad & Garzon (2007). There are two main reasons for this astronomical use of scanners. First, they enable a fast measuring speed, a factor that is much

Table 2. Specifications of the two telescopes used to obtain plates at Yunnan Astronomical Observatory (YAO) and Tsingtao Observatory (TTO).

	Telescope A	Telescope B
Site	YAO	TTO
Site code	286	334
Diameter of primary mirror [cm]	100	32
Focal length [mm]	13300	3580
Size of plates [cm \times cm]	16 \times 16	16 \times 16
Field of view [degree \times degree]	0.75 \times 0.75	2.5 \times 2.5
Scale [arcsec mm^{-1}]	15.5	57.6

**Figure 1.** The standard deviations of residuals in X and Y , expressed in μm , for each star on the plate, versus the corresponding star coordinates, expressed in mm. The measured coordinates X and Y correspond to the linear CCD and the scanning direction, respectively.

appreciated in view of the very large number of old plates needing to be re-measured. Second, the mobility of the scanner means that plates in distant observatories can be measured without the need to risk plate transport to the location of a fixed measuring machine.

In our work, we have chosen to use the advanced commercial scanner EPSON 10000 XL. This scanner is equipped with a linear CCD camera giving an optical resolution of up to 2400 dpi. The maximum scanning dimensions are 31.0 cm \times 43.7 cm. The scanner presents a dynamic range of 3.8 D in density and adopts a linear scanning mode. In order to check whether this scanner can provide positions with a high enough accuracy for astronomical purposes, we evaluated its measurement repeatability. With this aim, one of the plates of Uranian satellites was digitized and measured 10 times. A standard deviation of the residuals of measured coordinates X and Y for all stars on the plate was assumed in order to evaluate the measurement repeatability. Fig. 1 displays the standard deviations of residuals in X and Y , expressed in μm , for each star on the plate, versus the corresponding star coordinates, expressed in mm. The X - and Y -axis correspond to the scanning and linear CCD directions, respectively. The values of the mean standard deviations are 0.58 μm in the linear CCD direction (X) and 3.71 μm in the scanning direction (Y). The accuracy of 0.58 μm in the CCD direction is equivalent to that of most photometric data system (PDS) measuring machines. Regarding the scale of the telescopes used, 0.58 μm corresponds to about 8 mas for Telescope A and to about 30 mas for Telescope B, while 3.71 μm corresponds to about 60 mas for Telescope A and to more than 200 mas for Telescope B. The repeatability of the measurements made in the linear CCD direction, which

corresponds to 8 or 30 mas, depending on the telescope used, appears to be fairly consistent with the accuracy of the UCAC4 star catalogue used here. This catalogue accuracy is reported to be between 15 and 100 mas in position and between 1 and 10 mas yr⁻¹ in proper motion, depending on the star magnitude (Zacharias et al. 2013). So, for the old plate material used here and taken more than 10 yr before the mean epoch of UCAC4, the derived accuracy of the catalogued star positions on our plates should be between 30 and about 100 mas. Thus the repeatability of the scanner used in the linear CCD direction (X) is fairly consistent with the UCAC4 accuracy. In contrast, when it is used in the scanning direction (Y), the scanner provides a measurement repeatability that can be critical for Telescope A (60 mas) and quite inconsistent for Telescope B (200 mas).

In order to try to characterize the possible systematic errors of the measuring system, we scanned four plates (two plates of Saturnian satellites and two plates of Uranian satellites taken with the 1-m telescope) at 0° and then again at 180° orientation, and we compared the derived positions of objects. The differences of measured coordinates thus obtained (ΔX , ΔY) are presented in Fig. 2. The figure clearly shows that the differences ΔX are small, generally less than 3 μm , and do not present any characteristic values from plate to plate. However, the ΔY appear to be much higher than ΔX , with generally negative and periodic values, and are very different from plate to plate. Hence, Fig. 2 shows that the differences (ΔX , ΔY) cannot characterize any possible scanner systematic errors. The small differences ΔX seem to correspond to random errors, and the higher values of ΔY could arise from a consistent non-linear motion in the scanning direction of the scanner.

The distribution of measured coordinate differences (ΔX , ΔY) for the four plates is also presented in Fig. 3. The plots confirm the higher values of ΔY compared with those of ΔX , as well as their significant different values from plate to plate. Thus Figs 2 and 3 show that the differences (ΔX , ΔY) do not characterize the systematic errors of the measuring system. These differences therefore cannot be used to remove the systematic errors of the system. Consequently, in order to avoid the significant errors arising from the non-linear movement of the scanner in the scanning direction Y , we decided to avoid any measurement in the scanning direction and to measure both of each coordinates in the linear CCD direction in order to derive the final measured coordinates of the objects on the plates. Thus X is scanned at 0° and Y at 90° orientation for each plate. Further details of the measurement process are given in Section 4.1.

3.2 Digitization process

Some of the old plates that had originally been processed by manual methods included marks for object identification. These marks could have interfered with the new data processing, so the plates had to be cleaned prior to scanning. However, because these marks are an important part of plate archive information, we preserved them by first scanning the plates at a low resolution. Then, after the plates had been carefully cleaned of their marks, they were scanned again at high resolution. The EPSON 1000XL scanner only provides images in TIFF format. We therefore converted the scanned images to FITS format, which is more widely used in the astronomical community. We manually completed the FITS header of each image with observational plate information such as exposure time, date, etc.

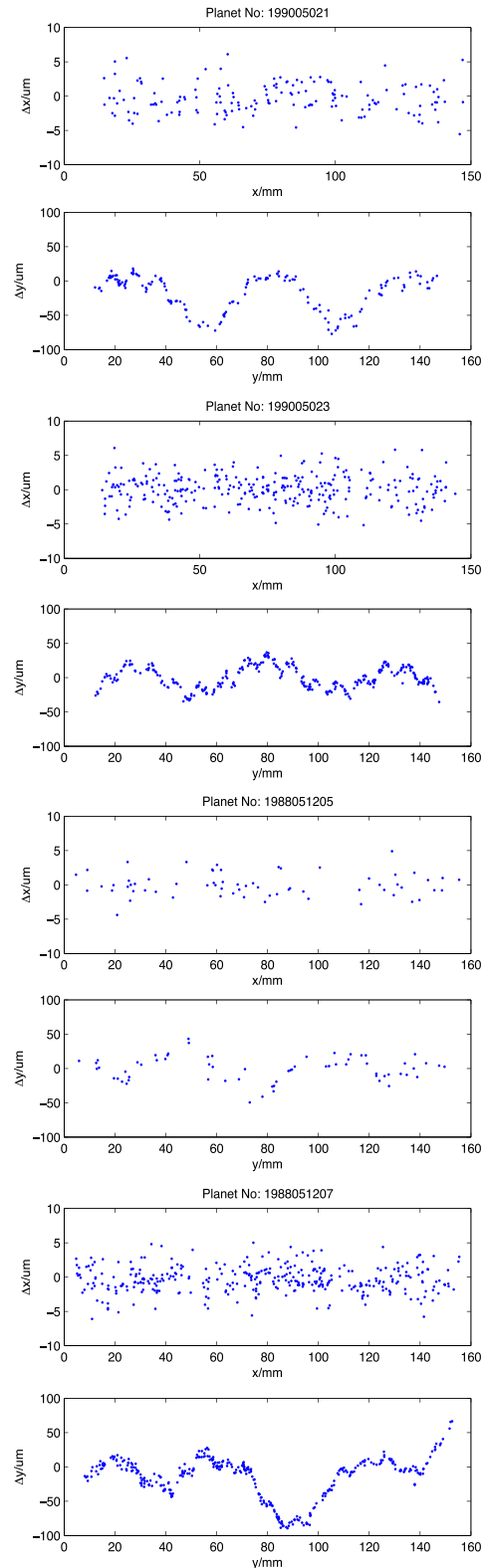


Figure 2. Measured coordinate differences (ΔX , ΔY), expressed in μm , versus star measured coordinates, expressed in millimetres, for four different plates. Differences are derived from the comparison of measured coordinates obtained at 0° and at 180° orientation of plates.

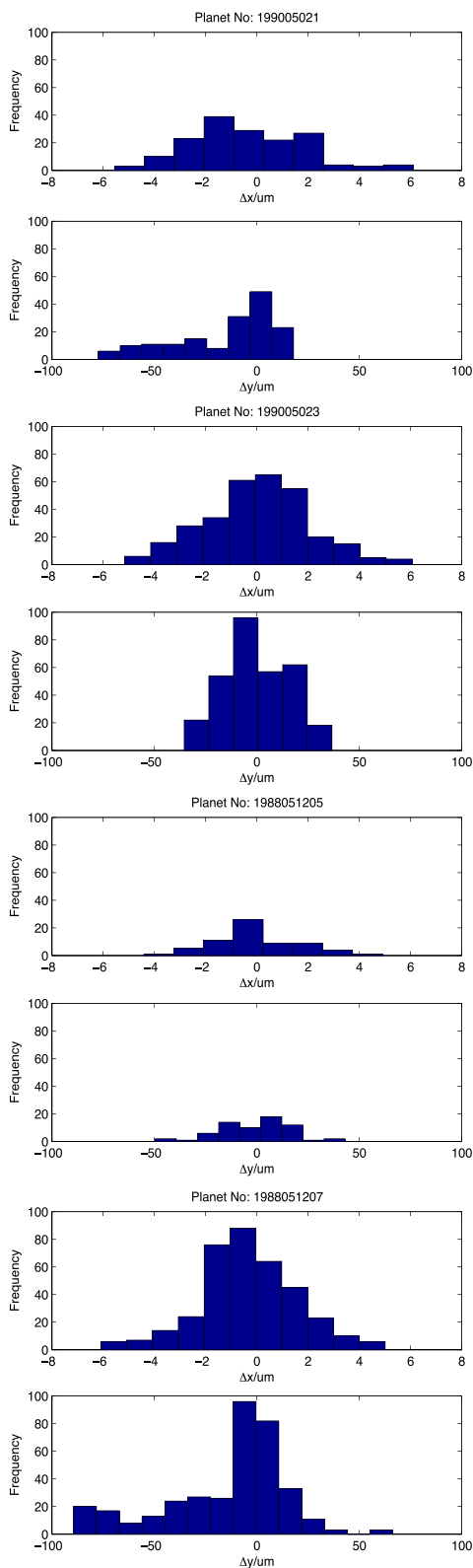


Figure 3. The distribution of measured coordinate differences (ΔX , ΔY) for four plates. Measured coordinate differences, expressed in μm , are reported on the abscissa, and the corresponding number of stars is reported on the ordinate.

Table 3. Standard deviations of residuals for the reference stars derived from measured coordinates obtained in the initial plate position A (XA_i , YA_i) and in the 90° rotated position B (XB_i , YB_i). The final measured coordinates, both obtained in the linear CCD direction X, are $Xm_i = XA_i$ and $Ym_i = XB_i$.

Planet	Plate no.	(XA_i, YA_i)		(XB_i, YB_i)		(Xm_i, Ym_i)	
		σ_α (")	σ_δ (")	σ_α (")	σ_δ (")	σ_α (")	σ_δ (")
Saturn	1988051206	0.097	0.235	0.207	0.125	0.078	0.099
	1988051207	0.099	0.230	0.212	0.111	0.089	0.096
Uranus	199005041	0.150	0.265	0.229	0.179	0.149	0.165
	199005042	0.129	0.261	0.214	0.207	0.114	0.195

4 DATA REDUCTION

4.1 Measurement process

We used the measurement software recently used by Qiao et al. (2014), which includes some automatic processes. For example, it eliminates images with only one pixel and images with a signal-to-noise ratio (SNR) that is too low. The centring of images is determined by the method of two-dimensional modified moment (Stone 1989; Ji & Wang 1996). As previously noted, we use the measurements made in the linear CCD direction, along the X-axis, in preference to measurements made in the scanning direction, along the Y-axis, to determine the final measured coordinates. Thus each plate is scanned and measured in two orientations: first in an initial position A, and then, after being rotated by 90° , in position B. For each object i on the plates, (XA_i, YA_i) and (XB_i, YB_i) are the raw measured coordinates obtained in positions A and B, respectively. Then, the final measured coordinates (Xm_i, Ym_i) need to be derived from the raw measurements. As only measurements made in the CCD direction can be used, the measured coordinate Xm_i must be derived from scanning position A, and the measured coordinate Ym_i must be derived from scanning position B. So we have

$$\begin{aligned} Xm_i &= XA_i, \\ Ym_i &= XB_i. \end{aligned} \quad (1)$$

Table 3 provides the standard deviations of the residuals (σ_α , σ_δ) of reference stars obtained for the three different pairs of measured coordinates (XA_i, YA_i) , (XB_i, YB_i) and (Xm_i, Ym_i) . It can be seen that the accuracy derived from (Xm_i, Ym_i) is higher than that obtained by the two other pairs of measured coordinates, as a consequence of the better accuracy of the measurement repeatability of the scanner in the CCD direction that we noted above.

4.2 Astrometric reduction

We used the UCAC4 catalogue, which is the latest star catalogue developed at the US Naval Observatory by Zacharias et al. (2013). UCAC4 is a compilation of more than 113 million stars, from the brightest ones to those with magnitude 16, and includes 105 million proper motions. Positional accuracy is between 15 and 100 mas, and formal errors in proper motions are between 1 and 10 mas yr^{-1} , depending on the magnitude. The number of reference stars available on our astronomical plates could reach 100 and was always higher than 20.

In order to obtain the optimal model, we tested various polynomial models, from first to fourth order, for the astrometric reduction of four plates. To do this we used four plates, with an average number of reference stars. We then derived the observed coordinates of reference stars with these four different models, and analysed the

Table 4. Standard deviations of the residuals of the reference stars with various models from first to fourth polynomial order. σ_α (") and σ_δ (") are standard deviations in right ascension and declination expressed in arcseconds.

Plate no.	Planet	Model order	σ_α (")	σ_δ (")
1988051206	Saturn	1	0.214	0.198
		2	0.081	0.108
		3	0.077	0.098
		4	0.077	0.100
1988051207	Saturn	1	0.174	0.196
		2	0.097	0.108
		3	0.089	0.095
		4	0.095	0.102
199005041	Uranus	1	0.249	0.283
		2	0.180	0.191
		3	0.151	0.165
		4	0.149	0.169
199005042	Uranus	1	0.239	0.275
		2	0.146	0.213
		3	0.114	0.195
		4	0.112	0.198

corresponding standard deviation of residuals. The smallest-order model leading to the minimum standard deviation was assumed to be the optimal model. The standard deviations of residuals derived from the various models are given in Table 4. The standard deviations of residuals obtained with the third-order model appear basically equivalent to those obtained with the higher fourth-order model. We therefore adopted the third-order polynomial model with 20 parameters for the astrometric reduction of our plates. Moreover, the third-order model has the advantage of efficiently compensating for various instrumental and physical effects on the plates.

The expressions for the third-order polynomial model are as follows:

$$\begin{aligned}\xi &= ax + by + c + dx^2 + exy + fy^2 \\ &\quad + gx^3 + hx^2y + ixy^2 + jy^3, \\ \eta &= a'x + b'y + c' + d'x^2 + e'xy + f'y^2 \\ &\quad + g'x^3 + h'x^2y + i'xy^2 + j'y^3,\end{aligned}\quad (2)$$

where x and y are the measured coordinates, and ξ and η are the tangential coordinates. The 20 parameters (a to j and a' to j') in these expressions were determined for each plate using the least-squares method.

5 RESULTS

5.1 New observed satellite astrometric positions

We present here 125 new satellite astrometric positions obtained from 27 selected plates taken from 1987 to 1990. The numbers of positions for each satellite are given in Table 5. In Table 6 we present an extract from the list of the new observed positions. The first column gives the name of the satellite, and the next three columns provide the year, month and decimal day in UTC of the middle time of each observation. The next two columns list the right ascension, expressed in hours, and the declination, expressed in degrees. The final column provides the observatory code. These data are topocentric and refer to the J2000.0 ICRF reference frame.

Table 5. Visual magnitude V and number of observations (N) for each observed satellite of Jupiter, Saturn and Uranus. Visual magnitudes are derived from the MULTISAT server of the IMCCE.

Satellite		V	N
Io	J1	4.8	2
Europa	J2	5.1	1
Ganymede	J3	4.8	3
Callisto	J4	5.5	3
Mimas	S1	13.3	1
Enceladus	S2	12.1	9
Tethys	S3	10.6	14
Dione	S4	10.8	16
Rhea	S5	10.2	16
Titan	S6	8.7	16
Hyperion	S7	14.6	8
Iapetus	S8	11.5	12
Ariel	U1	14.3	4
Umbriel	U2	14.9	4
Titania	U3	13.8	8
Oberon	U4	14.1	8

Table 6. An extract from the list of the observed equatorial coordinates of satellites obtained here. They are topocentric and referred to the J2000 ICRF reference frame. Satellite positions published for the first time are marked with an asterisk (*).

Satellite	Date(UTC)	α (hour)	δ (°)	Site code
J1*	1987 10 12.6524	1.6210670	8.4211902	286
J3*	1987 10 12.6524	1.6192411	8.4050179	286
J4*	1987 10 12.6524	1.6136393	8.3697619	286
J1*	1987 10 12.6667	1.6209710	8.4209216	286
J3*	1987 10 12.6667	1.6190649	8.4040104	286
S4*	1987 03 10.8574	17.3554323	-21.5912262	334
S5*	1987 03 10.8574	17.3534350	-21.5813007	334
S6*	1987 03 10.8574	17.3573388	-21.5826703	334
S7*	1987 03 10.8574	17.3545894	-21.6164870	334
S8*	1987 03 10.8574	17.3482055	-21.5444788	334
S3	1988 05 11.7473	18.1412027	-22.2593249	286
S4	1988 05 11.7473	18.1411854	-22.2690415	286
S5	1988 05 11.7473	18.1411809	-22.2722384	286
S6	1988 05 11.7473	18.1412198	-22.2418412	286
U3	1990 05 1.7785	18.6963371	-23.3993310	286
U4	1990 05 1.7785	18.6973951	-23.4114706	286
U2	1990 05 1.8236	18.6971497	-23.4014725	286
U3	1990 05 1.8236	18.6962945	-23.3991543	286
U4	1990 05 1.8236	18.6973358	-23.4116925	286

Note that a large number of satellite positions are published for the first time in this work. They are noted in Table 6 with an asterisk following the corresponding satellite name. In fact, seven plates had never been measured and reduced, namely those made in 1987 during the missions of March (2 plates, 10 positions), May (2 plates, 12 positions) and October (3 plates, 9 positions). Furthermore, some satellite images obtained in 1988 May, 1987 May and 1990 May, namely those of Enceladus (1 image), Hyperion (1 image), Iapetus (5 images) and Umbriel (1 image), could not have been detected or correctly measured with the old visual methods of measurement. It has, however, been possible to detect and measure them properly in this work, owing to plate digitization with the EPSON 1000XL

Table 7. Mean residuals μ (") and standard deviations σ (") of the residuals of the satellites, expressed in arcseconds, computed for each satellite and for each of the five missions. N is the number of observed satellite positions.

Mission	Site code	Satellite	N	μ_α (")	μ_δ (")	σ_α (")	σ_δ (")
1987 Mar	334	S4	2	0.393	-0.009	-	-
		S5	2	0.107	0.026	-	-
		S6	2	-0.370	0.224	-	-
		S7	2	0.430	-0.182	-	-
		S8	2	-0.199	0.112	-	-
		Total 1	10	0.072	0.034	-	-
1987 May	286	S2	4	0.128	0.132	0.235	0.091
		S3	8	-0.027	0.088	0.138	0.080
		S4	8	-0.031	0.010	0.118	0.140
		S5	8	-0.098	0.105	0.149	0.091
		S6	8	-0.060	0.125	0.125	0.114
		S7	5	0.080	-0.091	0.144	0.214
		S8	8	-0.109	0.135	0.122	0.126
				Total 2	49	-0.035	0.077
1988 May	286	S1	1	0.475	0.066	-	-
		S2	5	-0.069	-0.092	0.196	0.193
		S3	6	0.033	-0.001	0.076	0.109
		S4	6	0.055	-0.104	0.044	0.101
		S5	6	0.073	-0.037	0.053	0.125
		S6	6	0.039	-0.085	0.033	0.101
		S7	1	0.047	-0.152	-	-
		S8	2	0.024	0.128	-	-
		Total 3	33	0.043	-0.050	0.113	0.121
1987 Oct	286	J1	2	-0.060	-0.175	-	-
		J2	1	0.158	0.092	-	-
		J3	3	0.084	0.100	0.330	0.199
		J4	3	-0.133	-0.026	0.182	0.195
				Total 4	9	-0.012	-0.013
1990 May	286	U1	4	0.058	-0.094	0.244	0.180
		U2	4	-0.048	0.020	0.330	0.516
		U3	8	-0.081	-0.008	0.226	0.155
		U4	8	0.019	-0.016	0.280	0.237
				Total 5	24	-0.019	-0.020

scanner. Thus, a total of 39 satellite positions are published here for the first time, corresponding to nearly 30 per cent of all the 125 positions presented in this work.

5.2 Comparison with theory

In order to show the reliability of the method of measurement and reduction applied here, we compared all the new satellite positions with their theoretical positions. We used planetary and satellite ephemerides available on the MULTISAT server of the IMCCE. For the planets, we chose the DE431 ephemeris, which is the latest one developed at JPL by Folkner et al. (2014). For the satellites, we chose the most recent ephemerides: Lainey v2.0 (Lainey, Vienne & Duriez 2004) for the Galilean satellites of Jupiter, Lainey et al. (in preparation) for the Saturnian satellites, and Emelyanov & Nikonchuk (2013) for the Uranian satellites. For each mission and each satellite, we computed the mean residuals and the standard deviations of residuals. The values thus obtained, expressed in arcseconds, are presented in Table 7. The first four columns of Table 7 give, respectively, the date of the mission, the observatory code, the observed satellite, and the number of observed satellite positions. The following four columns provide the mean residuals and the standard deviations of residuals for both coordinates,

derived from the comparison of the satellite positions with the new ephemerides mentioned above. Standard deviations are not given when the number of observations is less than or equal to 2.

The lowest standard deviations given in Table 7, about 120 mas, were obtained for the observations of the Saturnian satellites made in 1987 May and 1988 May. This may be a result of the high number of plates taken during both of these missions, as the weather conditions were very satisfactory. In contrast, slightly higher standard deviations of about 200 mas were obtained for the two missions made in 1987 October for Jovian satellites and in 1990 May for Uranian satellites, certainly as a consequence of the poor weather conditions.

The mean residuals presented in Table 7 appear to be generally lower than 100 mas, whatever the satellite, except for some rare exceptions, such as Mimas and Hyperion. This is not surprising because both of these Saturnian satellites have less accurate ephemerides than most of the main natural satellites.

Some higher values of mean residuals, up to 400 mas, were obtained for the only mission of 1987 March. This can be explained because this mission is the only one to have been made at Tsingtao Observatory with Telescope B, which has a smaller diameter and focal length (32 cm, 3.58 m) than Telescope A at Yunnan Astronomical Observatory (1 m, 13.3 m), which was used in all other missions.

Fig. 4 shows the residuals versus time for each of the five missions from 1987 to 1990. It expresses visually and confirms the different levels of accuracy of each mission that we evaluated and discussed above regarding the values given in Table 7.

5.3 Discussion of results

In Table 7, the fact that the values of the mean residuals are generally lower than 100 mas shows that the new observed positions are in good agreement with the recent ephemerides. Furthermore, the new observed satellite positions present an accuracy as good as that of recent CCD observations of natural satellites. For example, the mean residuals that we obtain here for the four major Uranian satellites (from -91 to +20 mas) are very close to those of ~ 100 mas recently obtained by Qiao et al. (2013) for the same satellites with CCD techniques. The mean residuals of Qiao et al. (2013) can be compared with ours as they were derived from positions obtained using the UCAC2 star catalogue, which is very similar to the UCAC4 catalogue used here, and from comparison with the recent satellite ephemeris LA06 (Lainey 2008), also very close to the ephemeris used here (Emelyanov & Nikonchuk 2013). This shows that the new measurements and reductions of the old astronomical plates processed in this work have provided new observed positions with an accuracy just about equivalent to that of recent observations made with modern techniques.

Furthermore, we compared the original satellite positions of Wu & Zhang (1988) with the same ephemerides that we used in Section 5.2. The standard deviations of these residuals were generally about 400 mas, sometimes more. However, we showed in Section 5.2 that the standard deviations of residuals derived from the positions obtained here from new measurement and reduction are between only 120 and 200 mas. This shows that a very significant improvement of residuals, owing to astrometric reduction, has been derived from the original to the new observed satellite positions. This is mainly as a result of the improvement of the used star catalogue, because we used the same satellite ephemerides to compare original and new observed positions. Recent star catalogues such as UCAC4 are not only much more accurate than old

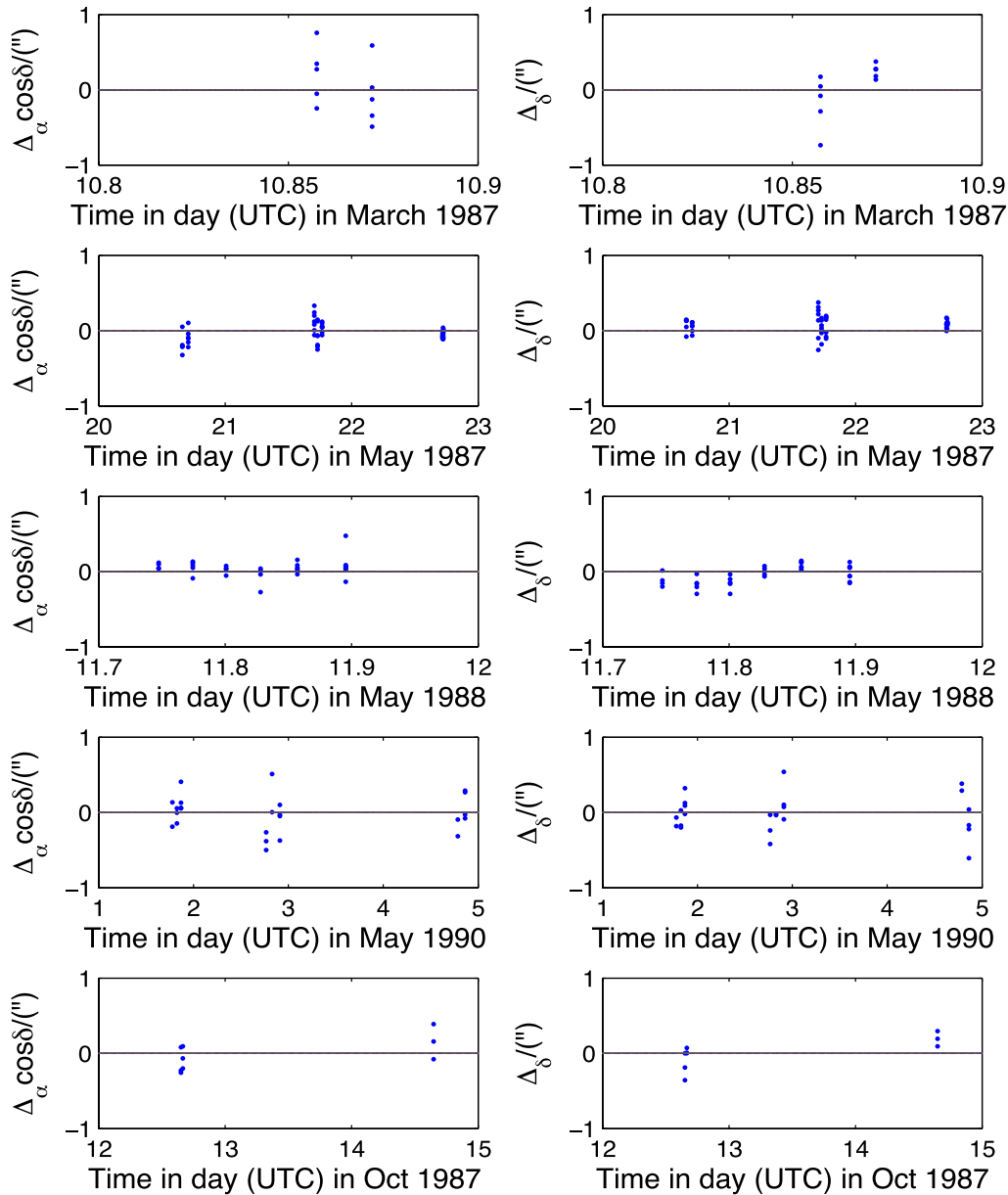


Figure 4. Plots of residuals in right ascension and declination for the five successive missions from 1987 to 1990.

star catalogues such as SAO, which was used to derive the original observed positions of Wu & Zhang (1988), but they also present a much higher star density. Thus the new astrometric reduction of old plates can provide more accurate satellite positions because much more accurate star catalogue positions are available. Moreover, the high star density of catalogues allows a better and more homogeneous astrometric reduction on the whole field of each plate. For example, some plates had only four or five SAO-catalogued stars in their fields, whereas we now have more than 20 UCAC4 stars in the same plate fields. This explains why it is so important to reduce old plates of natural satellites again, either from original measurements when available, which is very rare, or from new measurements, as those presented here.

In this work, then, we have proposed a reliable method for the measurement and reduction of astrophotographic plates that should contribute to the ambitious project of the new measurement and reduction of all old Chinese plates.

6 CONCLUSION

We have presented in this paper a method to measure and reduce the plates of natural satellites by digitizing the plates with an advanced commercial scanner, the EPSON 10000XL. The positioning repeatability of this scanner has been evaluated to $0.58 \mu\text{m}$ in the CCD direction, approximately equivalent to that of most PDS measuring machines. We applied our method of measurement and reduction to a selection of 27 photographic plates of natural satellites taken from 1987 to 1990 [Wu & Zhang 1988; Shen (in preparation); Qiao et al. 1995]. We have obtained 125 new positions of the satellites of Jupiter, Saturn and Uranus. The astrometric reduction was made using the recently produced UCAC4 star catalogue. We compared these new positions with recent ephemerides: DE431 for planets; Lainey et al. (2004) for Jovian satellites; Lainey et al. (in preparation) for Saturnian satellites; and Emelyanov & Nikonchuk (2013) for Uranian satellites. This comparison has shown that the new satellite positions, although derived from old plate data, are consistent

with satellite theory to within ~ 100 mas, roughly equivalent to the consistency obtained from most recent CCD observations. Not only are the new positions much more accurate than the original ones, but some of them are published here for the first time. This is because some images of satellites that had not been originally detected have been properly detected and measured with the measuring method presented here. Furthermore, some plates had not been originally measured and reduced. Hence a total of 39 satellite positions are published for the first time here, representing nearly 30 per cent of the 125 new positions presented in this work.

The method of measurement and reduction of plates presented here appears to be quite reliable for astronomical purpose. Hence this work should contribute to the ambitious project of the new measurement and reduction of all old Chinese astronomical plates, which should in turn allow theoretical work that will result in significant improvements in the orbits of natural satellites.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 6. An extract from the list of the observed equatorial coordinates of satellites obtained here.

(<http://www.mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stw120/-/DC1>).

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