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1994-1996 CCD astrometric observations of Saturn's satellites and comparison with theories

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Abstract. In this paper, we publish 451 measurements of positions of the major satellites of Saturn made in 1994, 1995 and 1996 using a CCD detector attached to the 1.56 m reflector at the Sheshan Station near Shanghai. The observations we have made include the seven major satellites exclusive of the outermost satellite Iapetus. In our implementation the four contemporary theories were used for astrometric calibration of the CCD. Analysis of the data as inter-satellite positions shows that these observations of Tethys, Dione, Rhea and Titan have rms residuals of 0.08 arcsec, which are comparable in quality to the observations made by Harper et al. (1997). For the faint satellites including Mimas, Enceladus and Hyperion we have also obtained the observations in equivalent precision to the photographic observations.

Key words: planets and satellites: satellites of saturn — astrometry

1. Introduction

In 1987 our photographic observing programs aimed at obtaining astrometric data on the eight major satellites of Saturn were commenced on the 1-metre reflector at the Yunnan observatory. After the first successful observing run, a series of exposures on the photographic plate was obtained between 1988 and 1993 at the abovementioned place and at the Sheshan Station near Shanghai (Longitude E121.18417, Latitude N31.09611). A section of the data has been collected into "A catalogue of ground-based observations of the eight major satellites of Saturn, 1874-1989", see Strugnell & Taylor (1990).

With the coming of the CASSINI mission and the need for long-term dynamic predictions of Saturn's satellites to be based on precise astrometric observations, it is becoming more and more important to collect high quality observations and to reduce the many new observations made with CCD cameras. In the 90's Charge Coupled Device technology has been in common use in natural satellite astrometry due to a series of advantages such as high quantum efficiency, good linear response, large dynamical range, low noise and broad spectral response. During the days near to the opposition of 1994 we experimented with the use of CCD as an alternative to photographic plate. The preliminary success in achieving similar results in precision to photo-plate enhances our enthusiasm to continue such observations using the same observational technique in the next two years.

In this paper we publish all of our CCD observations of the positions of the Saturnian major satellites made during observing campaigns in 1994, 1995 and 1996. These observations were compared with positions calculated using the theories given by Taylor & Shen (1988), Harper & Taylor (1993), Duriez & Vienne (1991, 1992) and Dourneau (1987, 1993) respectively. By an iterative least square process to optimize the residuals from the four reductions a set of better calibration parameters was solved. Finally, the anticipated precise observations are generated.

2. The instrumentation and observations

The two different telescopes used for our observation were all sponsored by the United Laboratory for Optical Astronomy of the Chinese Academy. In each of the years 1994, 1995 and 1996 we were allocated 5 days of telescope time to use a CCD camera for observations of Saturnian satellites at the Yunnan and another 8 days at the Sheshan Station. During the 3-year observing campaign, bad weather has prevented us from getting any observations at the Yunnan, so all of the 1994-1996 observations were made with the 1.56 m astrometric telescope.

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Table 1. Specifications of the Sheshan telescope and chip

Focal length	1560 cm
F-ratio	10
Diameter of primary mirror	156 cm
Diameter of second mirror	53 cm
Field of view	$4' \times 4'$
Size of pixel	22 μm
Size of CCD array	1024×1024
Angular extent per pixel	$0\farcs25$

Specifications of the telescope and the chip used are given in Table 1.

CCD suffers from drawbacks. The first problem is the overwhelming brightness of Saturn and its rings. In order to reduce the apparent brightness of the primary, the observations were carried out using an I-type filter with a central wavelength of 900 nm and full width at half maximum (FWHM) of 150 nm. The second is that the much smaller field of view of the CCD does not make it possible to include sufficient reference stars. In order to determine the orientation and scale of the CCD chip, $4 \sim 5$ images were taken of the wide double star 61 Cygni (HD 291091/2) on each night; in the same way bias and flat-field frames were taken during twilight at the beginning and each night of observation.

The exposure time of most of our CCD frames is $1 \sim 4$ seconds depending on the weather and elevation above the horizon. Provided the usable number of satellites is ensured, an appropriate increase in exposure time can contribute to an improvement in quality of the satellite images. As the CCD produces digitized images of natural satellites, we can partially reduce the effect due to difference between satellite magnitudes by adjusting contrast.

A total of 165 CCD frames of the satellites of Saturn were obtained. A summary of the number of frames of the target satellites in each year is presented in the last column of Table 2. Because we were unable to observe the outermost satellite Iapetus in such a small field of view, it is not given in this table.

3. Reduction of the observations

3.1. Centering of the images

The accurate measurement of astrometric position of the natural satellites on the CCD target is closely related to the center determination of the satellite images. The methods we used for center-finding was similar to that used by Beurle et al. (1993); it was accomplished by the aid of a software "centroid" algorithm with a Poisson noise model extracted from IRAF that isolates a square range (box) around the image for the purpose of suppressing or removing the effects of gradient in the background close to the heavily overexposed image of the planet and rings. In using the software the user is required to choose the parameters for himself, of which only three parameters will effect the position determination. We give 5 to FWHM, 8-12 to Cbox (centering box width) and 50-80 to Threshold.

3.2. Solution for calibration parameters

Our reduction shows the observations of 61 Cygni can provide calibration data with better internal consistency. The 1.56 m telescope we used at the Sheshan Station is an astrometric reflector with better stable focal length. The variations in scale for this telescope on different nights during the same observing campaign are quite small, see Table 2, consequently the scale can be much better determined. However, the orientation of the CCD device changes from one night to another because the device was remounted on different nights. Thus we had to have run calibration determination for each night. We made the similar reductions to those described by Colas & Arlot (1991) to obtain the orientation of the CCD device. In our implementation of this method only four well-known satellites Titan, Rhea, Tethys and Dione, which are expected to have the most accurate predictions with the lowest dispersions ($\sim 0\farcs10$), were used to give the small corrections to the scale and orientation of the CCD target by an iterative least squares process for optimizing the (O − C) residuals when compared to an orbital model. This technique was efficiently adopted in the work of Veillet & Ratier (1980), Veillet & Dourneau (1992) and Harper & Taylor (1997). However as Pascu (1987) and Colas (1991) point out, this technique presents a problem that the errors in the computed ephemerides of the brighter moons enter directly into the derived positions for the satellites. To minimize the systematic error induced by the use of one theory, we used the four orbital models, which are developed by Taylor & Shen (1988), Harper & Taylor (1993), Duriez & Vienne (1997) and Dourneau (1987, 1993) respectively. For each date of observation of the above-mentioned four satellites the differences between the observation data and computed values produced from their respective theories were incorporated into the sum of the squares of the (O − C) residuals to form normal equations, then the improvement of the corrections were completed in an iterative solving process. Table 2 gives the calibration parameters for each night of observation.

3.3. Format of the data

The data in our measurements are adopted in the form of polar coordinates which are position angle P and separation S. Relevant calculated values are denoted as P_c and S_c. Let $(\triangle x, \triangle y)$ denote the measured relative coordinates of satellites B with respect to satellite A as a

Table 2. Calibration parameters for each night of observation

Dates	ρ(arcsec/pixel)	δP(degree)	Nb. frames
94.08.11	0.249900	−5.4898	16
94.08.13	0.249400	−5.5750	39
94.10.22	0.249713	2.1549	23
94.10.23	0.249857	2.2064	14
94.10.24	0.249850	1.4520	5
94.10.25	0.249850	2.2044	6
95.08.15	0.249800	2.2485	20
95.08.16	0.249850	2.2585	7
95.09.22	0.249950	2.2450	9
96.10.18	0.251170	7.5142	12
96.10.19	0.251275	7.4782	14
weight standard error	±0.000025	±0.0070	

Table 3. Statistics of RMS of the (O − C) residuals of the inter-satellite measurements including the Saturnian major satellites exclusive of Iapetus for each reduction made from the four contemporary orbital theories. Satellite numbers conform to the conventional IAU numbering system, so S1-S7 denote the satellites in increasing order of the distance from the primary. SA is referred to the reference satellite (Titan). T1-T4 denote the theory of Taylor & Shen, Harper & Taylor, TASS1.7 and Dourneau respectively

		RMS							
Sat.	Nb of	$S_c\Delta P$(arcseconds)				ΔS(arcseconds)			
-SA	obs.	T1	T2	T3	T4	T1	T2	T3	T4
S1-SA	15	.2106	.0926	.0892	.1197	.2006	.2128	.1921	.2097
S2-SA	47	.0827	.0795	.0831	.0915	.1102	.1583	.1510	.2013
S3-SA	82	.0794	.0962	.0918	.1050	.1304	.0920	.0933	.1278
S4-SA	147	.0742	.0783	.0822	.0837	.1022	.0953	.0817	.1179
S5-SA	152	.0688	.0711	.0705	.0926	.1148	.0859	.0863	.1107
S7-SA	10	.1315	.1214	.0454	.3068	.1219	.1011	.2372	.2761

reference object. We use δP, ρ to denote the corresponding calibration parameters. The relations between ($\triangle x$, $\triangle y$) and (P, S, δP, ρ) are given as follows:

$$P = \mathrm{arctg}\,(\triangle x/\triangle y) + \delta P$$

$$S = \rho(\triangle x + \triangle y)^{1/2}.$$

For separation the residual is $\triangle S$, but for position angle the residual is the product $S_c\triangle P$ where $\triangle P$ is the (O − C) in radians.

The use of such a format for the data has the advantage that the corrections to the scale and orientation may be solved individually.

3.4. Sources of systematic error

In addition to the systematic errors coming from the above-described theories used to define the reference system for calibration, such inter-satellite measurements are affected by differential parallax, aberration and refraction. The first two effects have been incorporated into the positions derived from the orbital models. For differential refraction a correction has been incorporated in our published data. For the effects of refraction our reduction indicates that the changes introduced by it can not exceed $0''.02$ when satellites are observed at zenith distance less than 45°. Hence we can conclude that in such a small field atmosphere is not a major contributor to the systematic errors that affect the measurements. This is consistent with the conclusion given by Colas (1991) from his CCD observation study. He claimed that the correction of refraction can not be outdated a few hundredths of an arcsecond, so it should not be responsible for large residuals.

No position of catalogue star as the reference star is required in our method. The only errors come from the double star catalogue used for as calibration, which have been minimized in the iterative calibrating process. The errors induced by the flexure of the telescope are difficult to model. For this error we assume that it is sufficiently small to be considered as an accidental error.

3.5. Measurements of the faint satellites

Mimas and Enceladus are the two faint satellites close to the bright primary. In most case it was difficult to discern them from the bright background in the proximity of the planet and ring. Similarly, it was also not easy to obtain the discernible image of Hyperion due to its smallness and faintness. Fortunately, valuable observations of these faint objects have been reliably obtained in our observation, although their images do not seem to us good enough to be measured precisely. From Table 3 we can see that the precision attainable for the faint objects can be considered to be satisfactory. It seems to give an indication that the software "centroid" from IRAF is very effective in removing the effects of the steep background slope around the planet.

4. Datasets of the observations

In Table 4, we give an extract from our observations made in 1996, which were differenced to form the positions of each satellite relative to Titan and are given in the form of polar coordinates, as described in the previous section. These are apparent topocentric data after differential refraction reduction, no correction has been made for the effects of stellar aberration and parallax. The times of the middle of the exposures are given in Universal Time. Table 5 gives the raw data of the measured satellites positions with the corresponding dates of observations as presented in Table 4. The full observations, which can be supplied by E-mail, are available on request (pub2@ms.sxso.ac.cn).

Table 4. An extract from reduced dataset made in 1996

JD(UTC)	Sat. B	Sat. A	P(degree)	S(arcsec.)
2450376.059074	Rhea	Titan	278.021395	167.550158
2450376.059074	Dione	Titan	278.490638	143.413744
2450376.071574	Rhea	Titan	277.945693	168.560260
2450376.071574	Dione	Titan	278.393711	144.514888
2450376.071574	Tethys	Titan	279.579380	122.145650
2450376.120891	Dione	Titan	278.125688	148.475273
2450376.120891	Tethys	Titan	279.183552	129.834870
2450376.125752	Rhea	Titan	277.627482	172.797195
2450376.125752	Dione	Titan	277.988560	148.618989
2450376.125752	Tethys	Titan	279.087220	130.453981
2450376.130613	Rhea	Titan	277.662510	173.166755
2450376.130613	Dione	Titan	278.025018	148.020689
2450376.130613	Tethys	Titan	279.073102	131.241320
2450376.130613	Enceladus	Titan	278.523919	126.205858
2450376.134780	Rhea	Titan	277.621577	173.625224
2450376.134780	Dione	Titan	278.002996	149.406345
2450376.134780	Tethys	Titan	279.065239	131.875556
2450376.141725	Rhea	Titan	277.600855	174.061104
2450376.141725	Dione	Titan	277.942748	149.852966
2450376.141725	Tethys	Titan	278.968130	132.765666
2450376.141725	Enceladus	Titan	278.514187	126.672830
2450376.145891	Rhea	Titan	277.582619	174.295992
2450376.145891	Dione	Titan	277.936147	150.038480
2450376.145891	Tethys	Titan	278.942799	133.267035
2450376.145891	Enceladus	Titan	278.511734	126.545810
2450376.152951	Rhea	Titan	277.536260	174.773220
2450376.152951	Dione	Titan	277.879969	150.469654
2450376.152951	Tethys	Titan	278.868050	134.190047
2450376.152951	Enceladus	Titan	278.438365	126.894047
2450376.162674	Rhea	Titan	277.506223	175.484812
2450376.162674	Dione	Titan	277.832660	151.094708
2450376.162674	Tethys	Titan	278.790510	135.422150
2450376.162674	Enceladus	Titan	278.356886	127.106535
2450376.171007	Rhea	Titan	277.462386	175.997675
2450376.171007	Dione	Titan	277.783085	151.535623
2450376.171007	Tethys	Titan	278.733299	136.445189
2450376.171007	Enceladus	Titan	278.331110	127.299254
2450376.173785	Rhea	Titan	277.450322	176.185431
2450376.173785	Dione	Titan	277.769926	151.682398
2450376.173785	Tethys	Titan	278.714626	136.751488
2450376.173785	Enceladus	Titan	278.310598	127.294193

5. Comparison with the theories

The observed relative positions of the satellites were compared with the calculated positions deduced from the above-mentioned four contemporary theories; for TASS we used a revised new version TASS1.7 (1997). Validity of TASS has been preliminarily examined by Shen & Qiao (1995). These theories fitted well to all the known observations in the past. The orbital elements of the satellites corresponding to these theories were taken from their respective paper. Table 3 gives the rms of the residuals for each of the satellite pairs obtained from the four reductions made. It appears that we have obtained the anticipated results, most of the observations have an rms

Table 5. The raw measured pixel coordinates for each data listed in Table 4. Sat. 1, 2, 3, 4, 5, 6 and 7 denote the satellites Titan, Rhea, Dione, ..., Tethys and Enceldus respectively

UTC of		Measured		Residuals in	
Mid-Exposure	Sat.	X	Y	X	Y
1996 10 19 13:25:04	1	581.75	875.96	0.04	0.03
1996 10 19 13:25:04	2	403.56	233.41	0.07	0.05
1996 10 19 13:25:04	3	424.73	327.24	0.10	0.08
1996 10 19 13:43:04	1	615.59	854.24	0.03	0.03
1996 10 19 13:43:04	2	437.18	207.58	0.05	0.06
1996 10 19 13:43:04	3	458.30	301.04	0.08	0.10
1996 10 19 13:43:04	6	473.00	389.52	0.06	0.08
1996 10 19 14:54:05	1	647.30	790.49	0.05	0.04
1996 10 19 14:54:05	3	488.36	221.38	0.15	0.13
1996 10 19 14:54:05	6	499.15	295.48	0.11	0.11
1996 10 19 15:01:05	1	647.38	785.89	0.05	0.06
1996 10 19 15:01:05	2	468.17	121.97	0.11	0.11
1996 10 19 15:01:05	3	489.65	215.85	0.19	0.16
1996 10 19 15:01:05	6	499.36	288.27	0.13	0.14
1996 10 19 15:08:05	1	642.54	782.95	0.05	0.05
1996 10 19 15:08:05	2	462.54	117.72	0.10	0.09
1996 10 19 15:08:05	3	484.02	211.47	0.14	0.15
1996 10 19 15:08:05	6	493.75	282.29	0.12	0.12
1996 10 19 15:08:05	7	504.08	300.15	0.22	0.27
1996 10 19 15:14:05	1	638.84	779.90	0.09	0.09
1996 10 19 15:14:05	2	458.84	112.78	0.19	0.20
1996 10 19 15:14:05	3	480.13	206.88	0.30	0.31
1996 10 19 15:14:05	6	489.40	276.80	0.28	0.22
1996 10 19 15:24:05	1	638.37	782.15	0.02	0.03
1996 10 19 15:24:05	2	458.16	113.29	0.05	0.05
1996 10 19 15:24:05	3	479.79	207.25	0.07	0.08
1996 10 19 15:24:05	6	488.78	275.40	0.06	0.07
1996 10 19 15:24:05	7	499.48	297.54	0.11	0.14
1996 10 19 15:30:05	1	636.04	781.51	0.03	0.03
1996 10 19 15:30:05	2	455.80	111.69	0.05	0.06
1996 10 19 15:30:05	3	477.33	205.88	0.07	0.09
1996 10 19 15:30:05	6	486.11	272.78	0.06	0.08
1996 10 19 15:30:05	7	497.31	297.38	0.12	0.13
1996 10 19 15:40:15	1	629.16	776.68	0.01	0.01
1996 10 19 15:40:15	2	448.97	104.88	0.02	0.03
1996 10 19 15:40:15	3	470.56	199.24	0.03	0.04
1996 10 19 15:40:15	6	478.86	264.23	0.03	0.03
1996 10 19 15:40:15	7	490.67	291.04	0.05	0.07
1996 10 19 15:54:15	1	618.89	773.86	0.01	0.01
1996 10 19 15:54:15	2	438.32	99.23	0.03	0.03
1996 10 19 15:54:15	3	460.11	193.89	0.04	0.04
1996 10 19 15:54:15	6	467.91	256.50	0.03	0.04
1996 10 19 15:54:15	7	480.86	287.21	0.06	0.07
1996 10 19 16:06:15	1	610.72	773.73	0.01	0.01
1996 10 19 16:06:15	2	430.14	96.99	0.02	0.03
1996 10 19 16:06:15	3	451.98	191.93	0.03	0.04
1996 10 19 16:06:15	6	459.12	252.31	0.03	0.03
1996 10 19 16:06:15	7	472.70	286.28	0.05	0.06
1996 10 19 16:10:15	1	605.70	772.60	0.01	0.01
1996 10 19 16:10:15	2	425.07	95.10	0.02	0.03
1996 10 19 16:10:15	3	446.94	190.20	0.04	0.04
1996 10 19 16:10:15	6	453.93	249.96	0.03	0.03
1996 10 19 16:10:15	7	467.86	285.12	0.06	0.07

of about 0.08 arcsec except a few faint satellites, which are slightly poorer. For each of the satellites there is better agreement in rms of the residuals obtained from each of the four reductions made, while for those faint satellites where the accuracy is not so good, they seem to be reasonable.

6. Conclusion

The CCD observing campaigns we made at the Sheshan Station during 1994-1996 years are successful. The excellent 1.56m astrometric reflector provided by the observatory together with the good seeing permitted us to obtain the better quality results than photographic observation of Saturn's satellites. Especially, we have now obtained some valuable measurements for the faint satellites, which are usable for improving their theories. Our reduction also shows that the method we used to define the reference system for solving the calibration parameters was adequate for our purpose. From this we have now found in our published data (1996) an inaccurate scale which leads to the overlarge residuals, in particular for $\triangle S$. We will continue to develop such research for observation of the Saturnian satellite system.

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