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 above-mentioned 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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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, 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 $(\Delta x, \Delta y)$ denote the measured relative coordinates of satellites B with respect to satellite A as a
For separation the residual is $\Delta \rho$, reference object. We use $\delta P$, $\rho$ to denote the corresponding calibration parameters. The relations between $(\Delta x, \Delta y)$ and $(P, S, \delta P, \rho)$ are given as follows:

$$P = \arctg \left( \frac{\Delta x}{\Delta y} \right) + \delta P$$

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

For separation the residual is $\Delta S$, but for position angle the residual is the product $S_c \Delta P$ where $\Delta P$ 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\(^{\circ}\)02 when satellites are observed at zenith distance less than 45\(^{\circ}\). 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).

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**Table 2.** Calibration parameters for each night of observation

<table>
<thead>
<tr>
<th>Dates</th>
<th>$\rho$ (arcsec/pixel)</th>
<th>$\delta P$ (degree)</th>
<th>Nb. frames</th>
</tr>
</thead>
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<tr>
<td>94.08.11</td>
<td>0.249900</td>
<td>-5.4898</td>
<td>16</td>
</tr>
<tr>
<td>94.08.13</td>
<td>0.249400</td>
<td>-5.5750</td>
<td>39</td>
</tr>
<tr>
<td>94.10.22</td>
<td>0.249713</td>
<td>2.1549</td>
<td>23</td>
</tr>
<tr>
<td>94.10.23</td>
<td>0.249857</td>
<td>2.2064</td>
<td>14</td>
</tr>
<tr>
<td>94.10.24</td>
<td>0.249850</td>
<td>1.4520</td>
<td>5</td>
</tr>
<tr>
<td>94.10.25</td>
<td>0.249850</td>
<td>2.2044</td>
<td>6</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>95.09.22</td>
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<td>9</td>
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<tr>
<td>96.10.18</td>
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<td>7.5142</td>
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<tr>
<td>96.10.19</td>
<td>0.251275</td>
<td>7.4782</td>
<td>14</td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>Sat. Nb. of</th>
<th>$S_c \Delta P$ (arcseconds)</th>
<th>$\Delta S$ (arcseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-SA</td>
<td>15</td>
<td>2.1069 ± 0.0926 0.0892 1197 2006 2128 1921 2007</td>
</tr>
<tr>
<td>S2-SA</td>
<td>47</td>
<td>0.0677 ± 0.0301 0.0151 1102 1583 1510 2013</td>
</tr>
<tr>
<td>S3-SA</td>
<td>82</td>
<td>0.0794 ± 0.0068 0.0198 1050 1304 0.0920 0.0933 1278</td>
</tr>
<tr>
<td>S4-SA</td>
<td>147</td>
<td>0.0742 ± 0.0028 0.0082 0.0387 1022 0.0953 0.0817 1179</td>
</tr>
<tr>
<td>S5-SA</td>
<td>152</td>
<td>0.0688 ± 0.0710 0.0705 0.0926 1148 0.0859 0.0863 1107</td>
</tr>
<tr>
<td>S7-SA</td>
<td>10</td>
<td>0.1315 ± 0.1214 0.0454 0.3608 0.1219 1011 2372 2761</td>
</tr>
</tbody>
</table>
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
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 $\Delta S$. We will continue to develop such research for observation of the Saturnian satellite system.

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