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CCD astrometry of Saturn's satellites in 1995 and 1997*

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Abstract. In this paper, we publish measurements of 1514 positions of the major satellites of Saturn made in 1995 and 1997 using CCD detectors attached to the 1-metre Jacobus Kapteyn Telescope on the island of La Palma. Analysis of the data as inter-satellite positions shows that the observations of Tethys, Dione, Rhea and Titan have root-mean-square residuals of $0\rlap{.}''08$ in 1995 and $0\rlap{.}''10$ in 1997.

Key words: satellites of Saturn — astrometry

1. Introduction

In a previous paper (Harper et al. 1997) we published astrometric observations of the major satellites of Saturn made between 1990 and 1994 using the 1-metre Jacobus Kapteyn Telescope on the island of La Palma and we described the techniques employed in making and analysing the observations.

In this paper, we publish a further series of observations made in 1995 and 1997. The methods of observing and calibration remain essentially the same, and the reader is referred to Harper et al. (1997) for full details.

2. Observing conditions

In 1995, observations were obtained on the nights of 24 August to 6 September. Full Moon was on 9 September. The observers were A Fitzsimmons and I M Cartwright for the nights of 24–30 August and D. Harper and K. Beurle for the nights of 31 August to 6 September.

In 1997, observations were obtained on the nights of 21–23 October. Full Moon was on 16 October. The observers were D. Harper and K. Beurle.

In both years, we used a TEK chip with 24 μm pixels, giving an approximate scale of $0\rlap{.}''33$ in the focal plane. The chip has a useful imaging area of 1024×1024 pixels giving a field of view of approximately $335'' \times 335''$.

Table 1. Number of images of each satellite

Satellite	1995	1997	Total
Mimas	14	1	15
Enceladus	56	63	119
Tethys	78	193	271
Dione	67	145	212
Rhea	84	171	255
Titan	67	194	261
Hyperion	57	135	192
Iapetus	-	189	189
TOTAL	423	1091	1514

Table 2. Number of satellites per CCD frame

Number of satellites in frame	1995	1997
2	14	1
3	19	3
4	34	11
5	26	80
6	7	57
7	-	42
8	-	-

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* Tables 6 to 9 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

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*** The Royal Greenwich Observatory was closed on 31 October 1998; see Appendix A.

Table 3. Data sets obtained in 1997 October

Data set	Night	Number of CCD frames
1997a	October 21–22	94
1997b	22–23	74
1997c	23–24	39

Table 4. Calibration parameters for the observations

Dataset	δP (degrees)	ρ (arcsec/pixel)
1995	$+0.1529 \pm 0.0019$	0.330352 ± 0.000011
1997a	$+0.5684 \pm 0.0036$	0.330407 ± 0.000021
1997b	$+0.6126 \pm 0.0013$	0.330389 ± 0.000008
1997c	$+0.6449 \pm 0.0030$	0.330349 ± 0.000017

A summary of the number of images of each target satellite is given in Table 1 and Table 2 which are extensions of Tables 2a and 2b respectively in Harper et al. (1997).

3. Measurement and calibration

In previous years, the positions of the satellites in each CCD frame were measured manually using the IRAF (Image Reduction and Analysis Facility) software. This is a laborious and time-consuming task, and it was decided to develop software which would automate the process. This software is described elsewhere (Harper, in preparation); it was tested on the 1993 and 1994 data and found to produce pixel coordinates identical to those obtained manually and published in Harper et al. (1997).

The 1995 and 1997 observations are published in the form of raw pixel coordinates in order that future investigators can make direct use of the CCD images if they wish.

The orientation of the CCD in both years is such that the column coordinate (ξ) increases *eastwards* and the row coordinate (η) increases *southwards*. However, the axes of the device are not aligned exactly in the north-south and east-west directions and a small rotation is therefore required to convert row and column coordinates into differential coordinates referred to the true equator and equinox of date.

Let $\Delta\xi$ and $\Delta\eta$ represent the column and row coordinates, measured in pixels, of one satellite relative to another. These may be converted to differential coordinates $\Delta\alpha \cos\delta$ and $\Delta\delta$ referred to the true equator and equinox of date by the following transformation:

$$\begin{pmatrix} \Delta\alpha \cos\delta \\ \Delta\delta \end{pmatrix} = \rho \cdot \begin{pmatrix} \cos\delta P & \sin\delta P \\ -\sin\delta P & \cos\delta P \end{pmatrix} \begin{pmatrix} \Delta\xi \\ -\Delta\eta \end{pmatrix}.$$

The scale (ρ) and orientation (δP) of the CCD were determined empirically for each observing campaign by comparing the positions of the satellites Tethys, Dione, Rhea and Titan with those calculated from the theories of Harper & Taylor (1993) as described in Sect. 3 of Harper et al. (1997). In Table 4 we give the values of ρ and δP together with their standard errors from the least-squares fitting process. This method was first used for CCD observations by Colas & Arlot (1991) in their reduction of observations of the satellites of Mars.

The 1997 data are treated as three separate sets, corresponding to the three nights on which observations were obtained. During the observing run, engineering work was in progress on the telescope following a major refurbishment of the primary mirror, and it could not be determined whether the CCD camera had been dismounted from the telescope during the daytime. It was therefore decided to calibrate and analyse each night's data separately. The 1997 data sets are summarised in Table 3.

4. The observations

In Table 6, Table 7, Table 8 and Table 9 we give the observed positions of the satellites in the form of pixel coordinates. These are apparent topocentric data; no correction has been made for the effects of refraction, stellar aberration or parallax. The date and time of the middle of the exposure are given in Universal Time. The exposure time is also given. The satellites are listed in the conventional order of increasing semi-major axis.

5. Analysis of the observations

We have calculated the root-mean-square residuals of the observations in the form of inter-satellite $\Delta\alpha \cos\delta$ and $\Delta\delta$ measures. In Table 5 we present the statistics for Tethys, Dione, Rhea and Titan. The rejection level was $0\rlap{.}''5$. For comparison, we give the same statistics for the observations published in Harper et al. (1997). The orbital models are those of Harper & Taylor (1993).

6. Conclusions

The observations made in 1995 and 1997 continue the series of astrometric observations of the major satellites of Saturn made using CCD detectors on the Jacobus Kapteyn Telescope. Despite adverse weather and technical problems in 1997, both the quantity and standard of the observations have been maintained.

These data have been used to improve the orbital theories of the satellites in preparation for the NASA/ESA *Cassini/Huygens* mission which will reach Saturn in 2004.

The relative ease with which such high-precision observations can be obtained and reduced with minimal manual intervention demonstrates the value of CCD astrometry applied to the satellites of the major planets.

Table 5. Statistics of observed-minus-computed residuals for observations of Tethys, Dione, Rhea and Titan. $N_{\rm U}$ is the number of observations included in the solution. $N_{\rm T}$ is the total number of observations in the dataset. μ is the mean residual and σ is the standard deviation about the mean

	$\Delta\alpha\cos\delta$				$\Delta\delta$			
Dataset	$N_{\rm U}$	$N_{\rm T}$	μ arcsec	σ	$N_{\rm U}$	$N_{\rm T}$	μ arcsec	σ
1997a	378	379	-0.023 ± 0.005	0.09	373	379	$+0.002 \pm 0.004$	0.08
1997b	387	387	$+0.002 \pm 0.003$	0.05	387	387	$+0.004 \pm 0.003$	0.06
1997c	183	183	-0.025 ± 0.007	0.10	183	183	$+0.049 \pm 0.009$	0.12
1995	296	296	-0.012 ± 0.004	0.07	296	296	$+0.005 \pm 0.004$	0.06
1994	106	106	0.000 ± 0.008	0.08	106	106	-0.007 ± 0.008	0.09
1993	177	177	-0.028 ± 0.006	0.08	177	177	0.014 ± 0.006	0.08
1991	184	184	-0.003 ± 0.006	0.08	184	184	0.000 ± 0.008	0.11
1990c	37	37	0.010 ± 0.009	0.06	37	37	-0.009 ± 0.008	0.05
1990b	54	54	-0.009 ± 0.008	0.06	54	54	0.006 ± 0.012	0.09
1990a	333	333	-0.001 ± 0.003	0.06	333	333	-0.003 ± 0.005	0.09

Table 6. Observations made in 1995. This table is only available in electronic form at the CDS via anonymous ftp.

Table 7. Observations made during the night 1997 October 21–22. This table is only available in electronic form at the CDS via anonymous ftp.

Table 8. Observations made during the night 1997 October 22–23. This table is only available in electronic form at the CDS via anonymous ftp.

Table 9. Observations made during the night 1997 October 23–24. This table is only available in electronic form at the CDS via anonymous ftp.

Appendix A: The Royal Greenwich Observatory, 1675–1998

The Royal Greenwich Observatory was founded in 1675 by decree of King Charles II. The first Astronomer Royal, John Flamsteed, was charged "*to apply himself with the most exact care and diligence to the rectifying of the tables of the motions of the heavens, and the places of the fixed stars, so as to find out the so much desired longitude of places for the perfecting of the art of navigation*".

In its 323-year history, the Royal Greenwich Observatory maintained a tradition of high-precision astrometry of planets and satellites and was always at the forefront of technology and observational techniques. This paper is a continuation of that proud tradition.

The Royal Greenwich Observatory was closed on 31 October 1998 by the UK Particle Physics and Astronomy Research Council.

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