CARLSBERG OPTICAL ASTROMETRY OF THE OUTER SOLAR SYSTEM

L.V. MORRISON AND M.E. BUONTEMPO
Royal Greenwich Observatory
Madingley Road
Cambridge CB3 0EZ, UK

Abstract. The Carlsberg astrometric telescope has made about 17 000 observations of outer Solar System objects since it began operation in 1984. The observed positions of the major planets are compared with JPL DE200 and DE403. The agreement with DE403 is good in general, but unresolved discrepancies of the order $0\rlap{.}''1$ are found in Jupiter and Saturn. The run-off between the observations and DE200 which was fitted to observations before 1980 emphasize the need to continue optical observations of the outer planets.

1. Carlsberg astrometric telescope

The Carlsberg astrometric telescope (formerly known as the Carlsberg Automatic Meridian Circle) has been operating almost continuously since 1984 on the island of La Palma at the international observatory *Roque de los Muchachos* of the Instituto Astrofisica de Canarias. It is situated at a latitude of 28.7° north and an altitude of 2400 m and is operated jointly by Copenhagen University Observatory, the Royal Greenwich Observatory and the Real Instituto y Observatorio de la Armada, San Fernando. The operating procedure is described in Helmer & Morrison (1985) and a description of the scanning-slit micrometer and photoelectric detector system can be found in Helmer *et al.* (1991). The positions of the Solar System objects are measured once nightly as they cross the prime meridian. Only one satellite in each planetary system is observed each night. About 2% of the observing time is spent on Solar System objects.

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2. Observations

The observations discussed in this paper are published in an annual series of catalogues, Carlsberg Meridian Catalogues Numbers 1-8 (1985-1994). The number of observations of Solar System objects in each catalogue is listed in Table 1. The accuracy of the positions is a function of zenith distance

TABLE 1. Carlsberg observations of outer Solar System objects

Catalogue	Year	Ganymede	Callisto	Rhea	Titan	Hyperion	Iapetus
CMC1	1984	–	–	–	–	–	–
CMC2	1985	–	–	–	–	–	–
CMC3	1986	–	67	–	–	–	–
CMC4	1987	–	26	–	70	–	–
CMC5	1988-89	–	44	–	89	–	–
CMC6	1990	–	24	–	40	–	30
CMC7	1991-92	24	76	7	63	4	59
CMC8	1992-93	35	28	5	39	17	36

Catalogue	Year	Uranus	Oberon	Neptune	Pluto	Minor planets(~60)
CMC1	1984	54	–	78	–	667
CMC2	1985	64	–	47	–	1632
CMC3	1986	101	–	103	–	2501
CMC4	1987	65	–	64	–	2030
CMC5	1988-89	105	–	110	32	2467
CMC6	1990	76	–	105	11	1106
CMC7	1991-92	148	8	184	107	2108
CMC8	1992-93	57	21	72	26	1793

and magnitude (see Table 2). The best accuracy of $\pm 0\rlap{.}''12$ is obtained in the zenith (Dec $\sim +30^\circ$). The diminution in the errors with time is a consequence of improvements in instrumentation and processing of the raw data. The positions are referred to a smoothed FK5 system, as described by Morrison *et al.* (1990).

3. Comparison with JPL DE200 and DE403

The comparison of the observations for the years 1984-1995 with JPL DE200 and DE403 are shown in a series of plots. They show the residuals in RA and Dec in units of arcseconds for individual observations which are centred on the date of opposition each year and extend over about five

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TABLE 2. Accuracy of Carlsberg observations

Catalogue	Year	RA		Dec	
		δ=+30	δ=−30	δ=+30	δ=−30
CC1	1984	0.″19	0.″28	0.″18	0.″34
CC2	1985	”	”	”	”
CC3	1986	”	”	”	”
CC4	1987	”	”	”	”
CC5	1988-89	0.″15	0.″22	0.″15	0.″27
CC6	1990	”	”	”	”
CC7	1991-92	0.″12	0.″19	0.″12	0.″26
CC8	1992-93	”	”	”	”

months. Where observations of satellites were made, an ephemeris based on the theory of their orbital motion was used to reduce the observed positions to the barycentre of the system. So the plots of the residuals for Ganymede and Callisto, for example, effectively show the comparison of Jupiter with DE200 and DE403. The DE200 comparison is the zero line in each plot, and the DE403 comparison is the continuous wavy line.

The following points are noted from these plots.

3.1. JUPITER (GANYMEDE AND CALLISTO)

The ephemeris in the *Connaissance des Temps* (CdT), which is based on the G-5 theory (Arlot, 1982), was used to reduce the satellite positions to the barycentre of the Jovian system. The residuals in Dec show systematic deviations with respect to DE403. The mean offsets in 1992 and 1993 for both Ganymede and Callisto are nearly −0.″1, yet in 1994 the offset appears to be about +0.″05. The scatter is greater in 1994 because the observations for that year are still provisional. Further treatment of the observations will reduce the scatter but will not alter them systematically.

The explanation of these offsets in Dec lies in the construction of DE403 which attempts to reconcile the inconsistencies between the long series of optical data, which are referred to the FK5 frame, and the fairly recent high-precision radio data which are referred to the extagalactic VLBI frame. The latter frame is now to replace the FK5 as the International Celestial Reference Frame and DE403 is referred to this new frame. This problem is addressed by Standish (1995) elsewhere in the proceedings of this Symposium. The problem seems to be common to the optical data from other telescopes.

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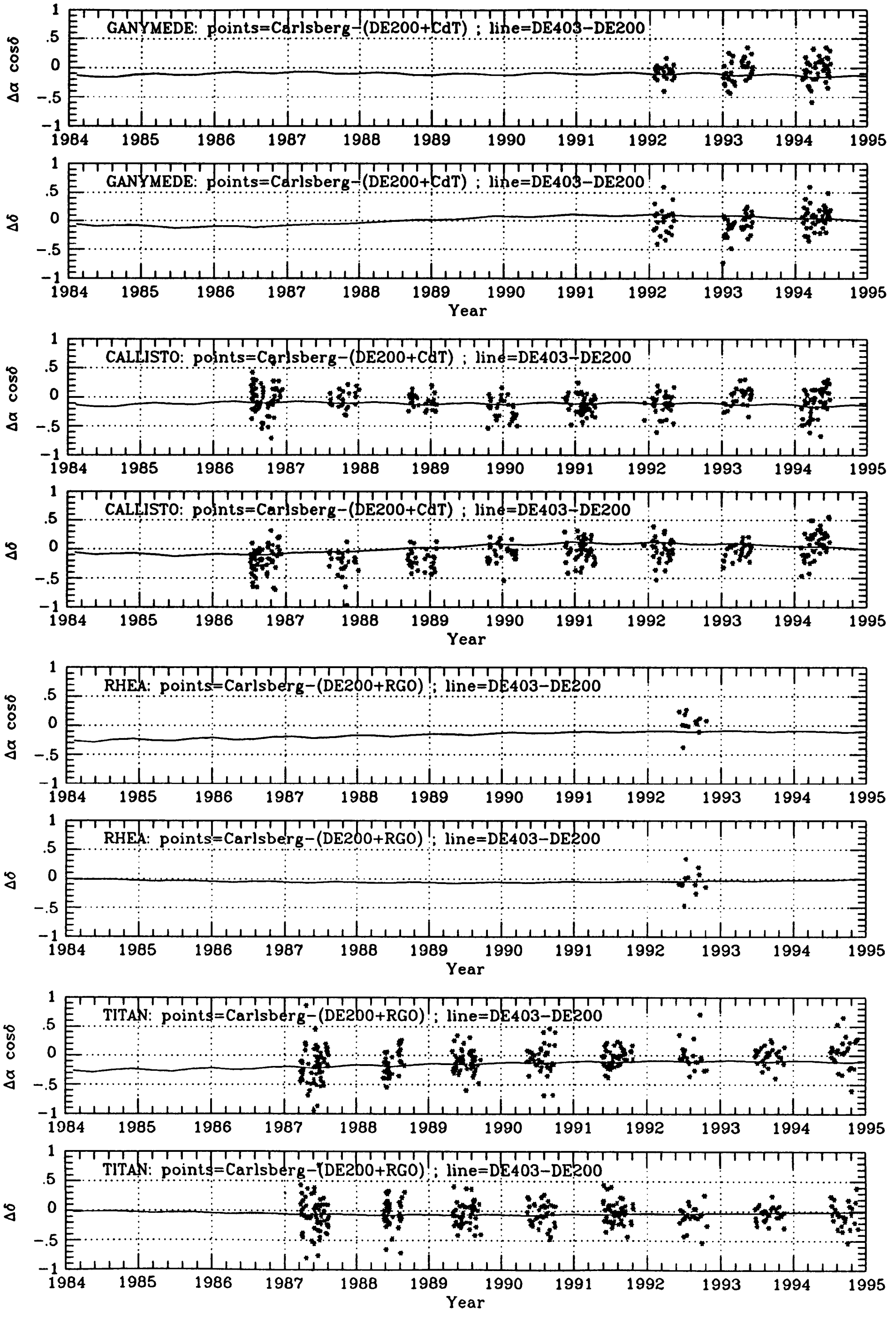

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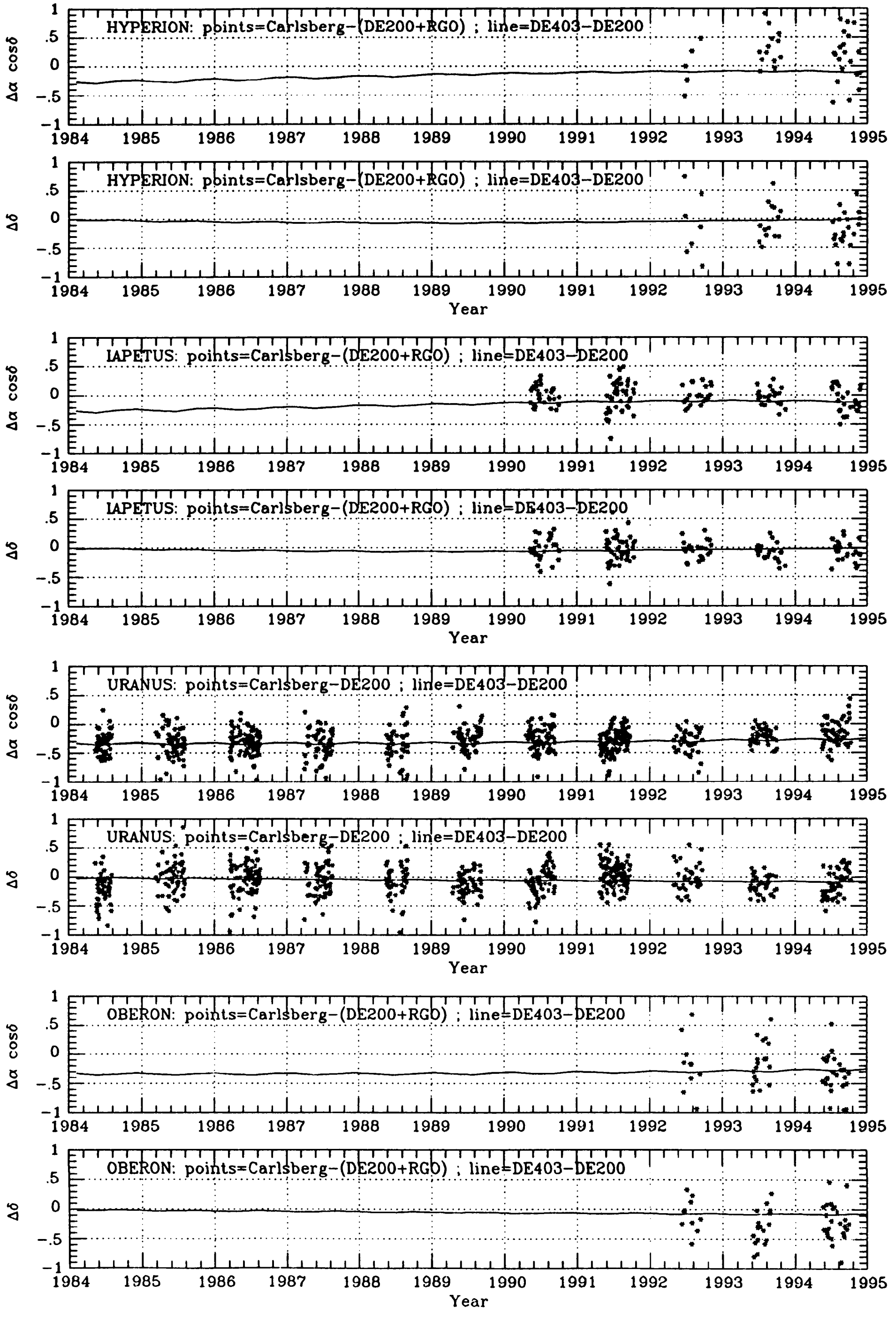

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The reconciliation of the two data types requires a rotation of $0''.2$ about the x-axis (in the plane of the equator and directed to zero RA) between the FK5 and extragalactic frames. However, the results from other work of comparing the optical and radio positions of galaxies (as yet unpublished), produces a rotation between the reference frames of less than half this amount. A rotation of $0''.2$ about the x-axis produces a wave of $0''.2\sin(\mathrm{RA})$ in declination. This wave appears with the $\sim$12-yr orbital period of Jupiter in the comparison of the optical observations with the ephemeris. Such a wave was found to be incompatible with the optical observations. So, in the production of DE403 the rotations about the x (and y-axis) were reduced to less than $0''.1$. This reduced the discrepancy between the optical observations and DE403, but did not entirely remove it, as can be seen from the plot.

It is known (Lindegren *et al.*, 1995) that in the zodiacal belt of the FK5 there is a large-scale systematic warp in declination. This warp is in the sense that the optical declinations which are referred to the FK5 should be increased by $0''.06$. This is in the right direction to reduce the offset in the plots between Carlsberg and DE403, but is not the complete answer, particularly in 1994. When *Galileo* reaches Jupiter at the end of 1995 we may have the answer to this conundrum.

3.2. SATURN (RHEA, TITAN, IAPETUS, HYPERION)

DE403 is in good overall agreement with the observations in Dec, but there appears to be an offset of about $0''.1$ in RA in both Titan and Iapetus from 1990 onwards. There are no observations of Saturn made with respect to the extragalactic VLBI frame, so DE403 is basically dependent on the optical data, and therefore the conflict between the reference frames which arose with Jupiter does not arise here. The cause of the $0''.1$ bias is unknown. The residuals for Hyperion show a greater scatter on account of its faintness and the weakness of the theory of its orbit used in reducing the observations.

3.3. URANUS AND OBERON

The observations show the run-off in RA from DE200 which reaches $0''.35$. DE200 was fitted to observations before 1980; whereas DE403 was fitted to observations up till 1994.

3.4. NEPTUNE

The continuing run-off in RA of observations from DE200 can be seen clearly in the plot.

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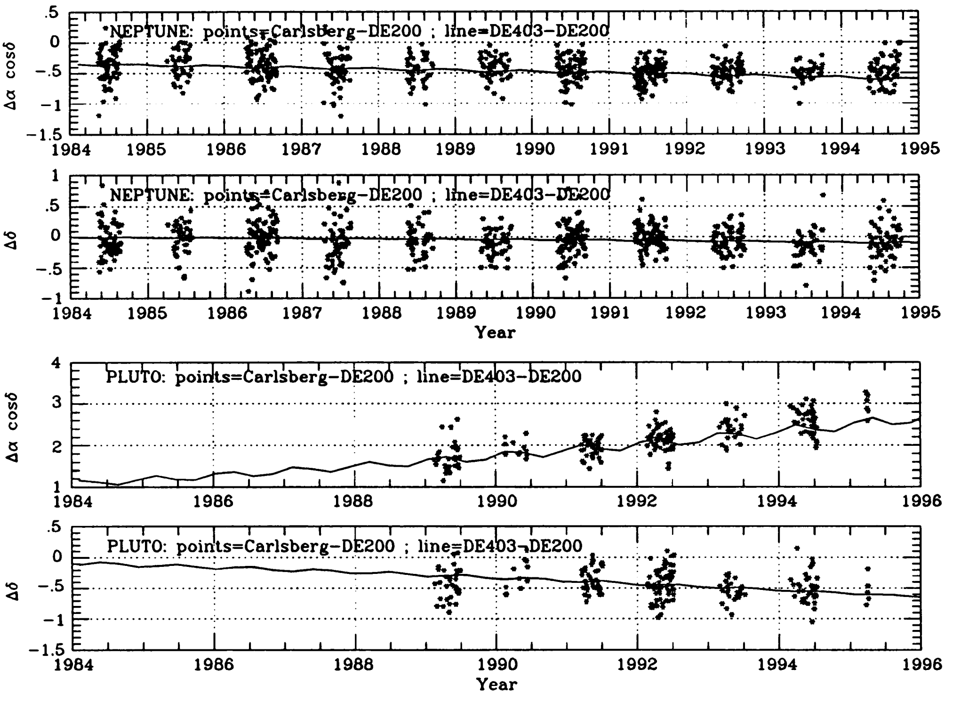

3.5. PLUTO

Pluto has run-off by 3.″0 in RA from DE200. Even DE403 does not quite keep up with the observations in 1994. A few preliminary observations in 1995 appear to confirm this.

4. Future developments

Improvements in the accuracy of the optical observations will follow soon from the availability of the HIPPARCOS catalogue, the axes of which will be accurately aligned with the extragalactic frame. The use of CCD detectors on the Carlsberg Telescope in some form or another (as reported by Stone at this Symposium) will enable planetary positions to be measured relative to the HIPPARCOS frame. This will reduce both the systematic and accidental errors of optical positions to well below 0.″1, provided that the satellites rather than the planetary discs are observed. This proviso does not apply to Pluto. The magnitude limit will be extended to V=16 which will enable more satellites and asteroids to be included in the observational programme.

5. Conclusion

The considerable run-offs from DE200 in the past 15 years and the absence of high-precision VLBI data beyond Jupiter, emphasize the need to continue monitoring the positions of the planets in the outer Solar System.

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