CHECK ON JPL DEXXX USING HIPPARCOS AND TYCHO OBSERVATIONS

L.V. Morrison[1], D. Hestroffer[2], D.B. Taylor[1], F. van Leeuwen[1]

[1]Royal Greenwich Observatory, Madingley Road, Cambridge, UK
[2]Astrophys Division, ESTEC, NL-2200 AG Noordwijk, The Netherlands

ABSTRACT

Obervations of the positions of Europa (J2) and Titan (S6) by Hipparcos, and Ganymede (J3) and Callisto (J4) by Tycho are analysed to give checks on the latest JPL ephemerides of the planets Jupiter and Saturn. The observed positions of the satellites are compared with DExxx using the G5 theory of the Galilean satellites and D.B. Taylor's theory of Titan to calculate their offsets from the barycentres of the two systems.

The Hipparcos observations of J2, and Tycho of J3 and J4 put tight constraints on the orbit of Jupiter, and agree closely with the series of ground-based observations made by the Carlsberg Meridian Telescope.

Key words: space astrometry; ephemerides; Jupiter; Saturn.

1. INTRODUCTION

Ephemerides of the Solar System are generated at JPL by numerical integration of the equations of motion of the planetary system, with initial conditions determined from observations. The initial conditions are continuously being refined with the addition of more recent observations, and the resultant ephemerides are issued in the series JPL DExxx, where xxx is a sequence number.

The most widely used ephemeris of the planetary system is DE200, in which the initial conditions were determined using observations prior to 1980. These comprised mainly optical positions and radar ranging to spacecraft. Recent observations of the planetary system reveal the limitations in the accuracy of DE200 from Jupiter outwards. Amongst these observations is a series of optical observations made by the Carlsberg Meridian Telescope at the international observatory of *El Roque de los Muchachos*, La Palma, Islas Canarias, starting in 1984 (Carlsberg Meridian Catalogues 1-9, 1985-1997). Optical positions of Jupiter and Saturn are not measured directly because of the difficulty of deriving the centre of light and hence the centre of mass. Rather, observations are made of some of their bright, starlike satellites, and theories of their orbits are used to reduce the observations to the barycentre of the system.

During the mission from 1989 to 1993, 64 and 38 observations of Europa and Titan, respectively, were made by Hipparcos, and 13 and 16 of Callisto and Ganymede, respectively, by Tycho. In this paper we analyse these Hipparcos and Tycho observations and derive positions of Jupiter and Saturn which we compare with DE200 and the latest development ephemeris DExxx (as yet not numbered).

2. HIPPARCOS AND TYCHO OBSERVATIONS OF EUROPA, TITAN, CALLISTO AND GANYMEDE

Whereas the satellites Callisto and Ganymede were scanned by Tycho using slits inclined at different angles, Europa and Titan were scanned unidirectionally by Hipparcos. The multi-directional scans by Tycho give directly two-dimensional coordinates (right ascension and declination) of Callisto and Ganymede for each observation. The unidirectional observations by Hipparcos, on the other hand, have to be combined in groups having preferably orthogonal directions of scan in order to solve for positions in right ascension and declination. The treatment of the Hipparcos data is given in some detail in the next section.

2.1. Hipparcos Observations of Europa and Titan

The quantity observed by Hipparcos is the abscissa $\lambda_{\rm GC}$ of the projected position on a reference great circle with pole P (see Figure 2.7.1 in Volume 1 of the *Hipparcos and Tycho Catalogues*, ESA, 1997). The observed position is somewhere on an arc of a great circle perpendicular to this reference great circle. The published quantities defining this arc are reckoned in the tangent plane of a reference point $(\alpha_o,\ \delta_o)$. Besides this reference point, the position angle θ of the scan direction $\mathbf{w}$ and the time of the observation are given.

The difference in the scan direction $\mathbf{w}$ between the reference point and the ephemeris position $(\alpha_c,\ \delta_c)$, calculated as the sum of the position in DE200 and the offset of the satellite, is expressed by the following equation of condition:

$$\Delta\alpha \cos\delta \sin\theta + \Delta\delta \cos\theta = (\alpha_o - \alpha_c)\cos\delta\sin\theta + (\delta_o - \delta_c)\cos\theta - \frac{2k+1}{2k+2}\cos(S-\theta)\, s \sin(\frac{i}{2}),$$

where the unknowns $\Delta\alpha$ and $\Delta\delta$ are corrections to the ephemeris right ascension and declination. The last term on the RHS is the correction of the observation for phase, where k is the Minnaert exponent, S the position angle of the sub-solar point, s the semi-diameter and i the phase angle. For Europa a value of 0.6 was adopted for k, and 1.0 for Titan.

This observational equation was solved by least-squares by grouping the observations in time, such that the scan angle varied sufficiently to reduce the correlation between the unknowns to less than 0.3. A group solution is referred to here as a normal point. There are three normal points for Europa and four for Titan in our solution. The differences O–C in the scan direction **w** and the post-fit residuals are plotted in Figures 1 and 2.

2.2. Satellite Orbits

The ephemeris in the *Connaissance des Temps* (CdT), which is based on the G-5 theory (Arlot, 1982), was used to reduce the observations of the satellites of Jupiter to the barycentre. For Titan, the theory of Taylor & Shen (1988) was used. The tolerance limit of the ephemeris for Europa is 60 mas, and for Titan it is 50 mas. These should be adequate for the present investigation of systematic errors in the DExxx ephemerides.

2.3. Comparison with DE200 and DExxx

The normal points from the Hipparcos observations and the individual results from the Tycho observations are plotted with respect to DE200 in Figures 3, 4, and 5. In some cases, the internal errors of the Hipparcos normal points are smaller than the filled squares. These figures also show the offset of the latest development integration DExxx from DE200.

Table 1 lists the normal positions and the formal errors of Jupiter and Saturn derived from the Hipparcos observations. These errors may be underestimated, in the light of the discussion which follows.

3. Discussion

A cursory glance at Figures 1 and 2 shows that by far the greatest signature in the difference (O–C) between the Hipparcos positions of Europa and Titan and their ephemerides is in the correction to the planetary position in DE200. The standard deviations of the post-fit residuals are 21 mas for Europa and 35 mas for Titan; whilst the estimates of the internal Hipparcos errors are ~3 mas and ~10 mas, respectively. So, the post-fit residuals are dominated by the limitations of the satellite ephemerides. The standard deviations of 21 mas and 35 mas for the post-fit residuals are well within the tolerance limits of the satellite ephemerides.

Further utilisation of the Hipparcos observations will require an analysis for corrections to the orbital elements of the satellite orbits, as well the adjustment of the planetary ephemerides.

Figures 3, 4, and 5 include the opposition means for the series of Carlsberg observations. Each opposition mean and its standard deviation is derived from about 50 observations which are referred to the same reference frame as the Hipparcos Catalogue (the ICRF).

3.1. Jupiter

The Hipparcos and Tycho observations confirm the superiority of DExxx over DE200 for the ephemeris of Jupiter. However, in declination, DExxx appears to run off from the Carlsberg observations in 1995. Ground-based optical data from the US Naval Observatory support the Carlsberg results.

The explanation of this run-off in declination (and to a lesser extent in right ascension) lies in the construction of DExxx which attempts to reconcile inconsistencies between the long series of optical data and the high-precision radio data which comprise observations from the Pioneer, Voyagers, Ulysses and Galileo missions and VLA observations of thermal emission from Jupiter. The Voyager I data of 1979 and the VLA of 1983 are particularly discordant with one another and the optical data. Investigations into this matter are still proceeding.

3.2. Saturn

Again, the Hipparcos observations confirm the superiority of DExxx over DE200. In this case, the agreement between observation and DExxx in declination is excellent. In right ascension, however, there is a systematic offset of ~60 mas between DExxx and the Carlsberg observations. This also occurs in observations of Iapetus not shown here. The Hipparcos observations in right ascension are also internally discordant: any reasonable adjustment of DExxx will simply move the curve vertically in Figure 5 and will not change the slope around 1991, as required by the observations. This suggests that the errors of the Hipparcos normal points in right ascension may have been underestimated. This could occur if corrections to the orbital elements of Titan (not considered here) were correlated with corrections to the planetary ephemerides. This may be the case because the Hipparcos observations tend to be clumped in time, as can be seen from Figure 2. However, this is not the whole explanation, because grouping the observations of Titan into two normal points instead of four, still leads to disparate results in right ascension. This problem is unresolved at the time of going to press.

Table 1. Normal positions of Jupiter and Saturn derived from Hipparcos observations.

Date	JD(TT)	Apparent, Geocentric of date RA (deg)	DEC (deg)	$\sigma_{\rm RA}$ (mas)	$\sigma_{\rm dec}$ (mas)
Jupiter					
1990 03 29	2447979.5	92.6737557	+23.4907060	13	10
1991 08 12	2448480.5	145.8072238	+14.4969250	7	4
1992 11 08	2448934.5	185.7099122	−1.2399092	12	7
Saturn					
1990 03 29	2447979.5	296.1031512	−21.0679424	21	16
1991 01 08	2448264.5	298.5330264	−21.0075858	15	12
1991 10 28	2448557.5	302.9629572	−20.5536945	26	19
1992 05 24	2448766.5	321.1767043	−16.0946368	36	17

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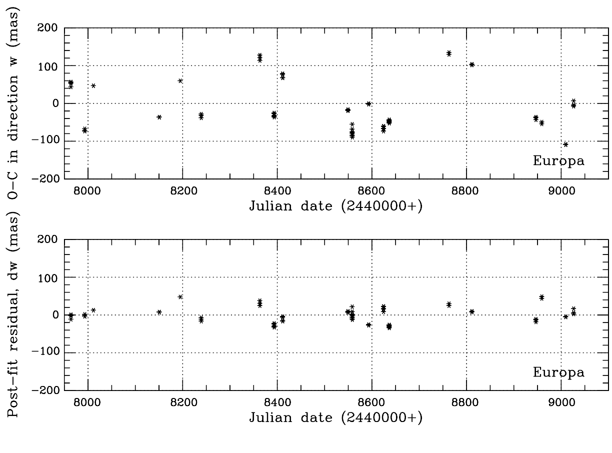

Figure 1. The distance (in mas) along the scan direction **w** *before (upper) and after (lower) adjustment of the DE200 positions of Jupiter.*

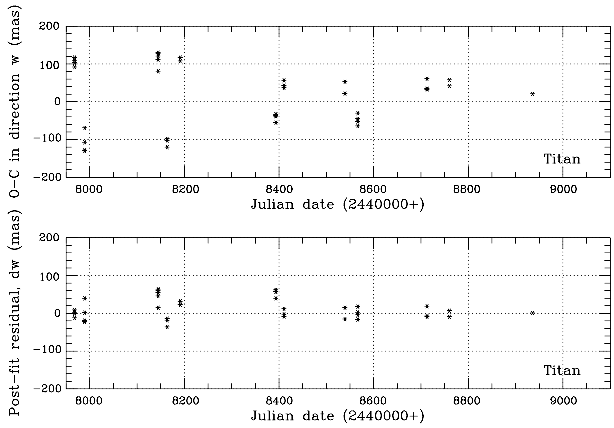

Figure 2. The distance (in mas) along the scan direction **w** *before (upper) and after (lower) adjustment of the DE200 positions of Saturn.*

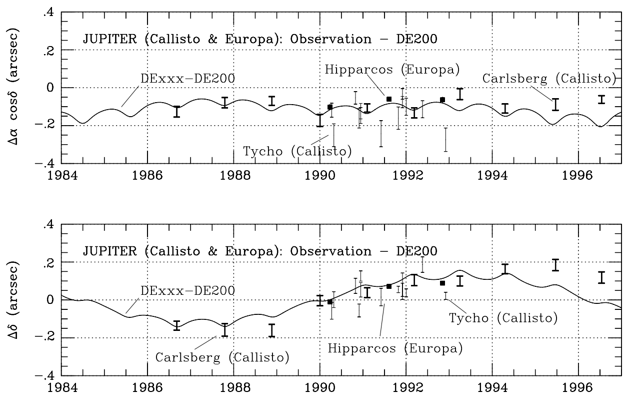

Figure 3. Comparison of the observation positions of Jupiter with DE200 and DExxx ephemerides (upper, right ascension; lower, declination). The Hipparcos normal points derived from observations of Europa are shown as filled squares. Individual Tycho positions derived from observations of Callisto are plotted as light error bars. The opposition means derived from Carlsberg Meridian Telescope observations of Callisto are plotted as heavy error bars.

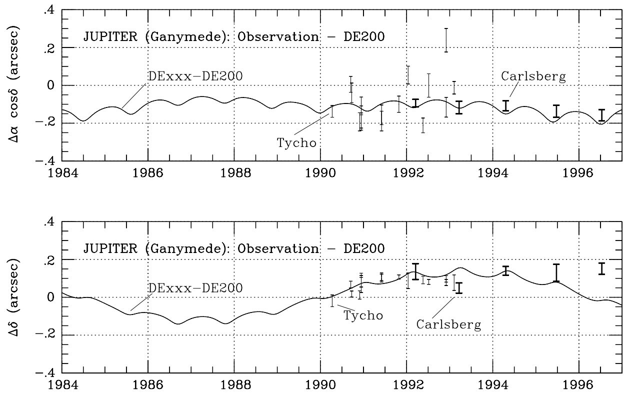

Figure 4. Comparison of the observation positions of Jupiter with DE200 and DExxx ephemerides (upper, right ascension; lower, declination). Individual Tycho positions derived from observations of Ganymede are plotted as light error bars. The opposition means derived from Carlsberg Meridian Telescope observations of Ganymede are plotted as heavy error bars.

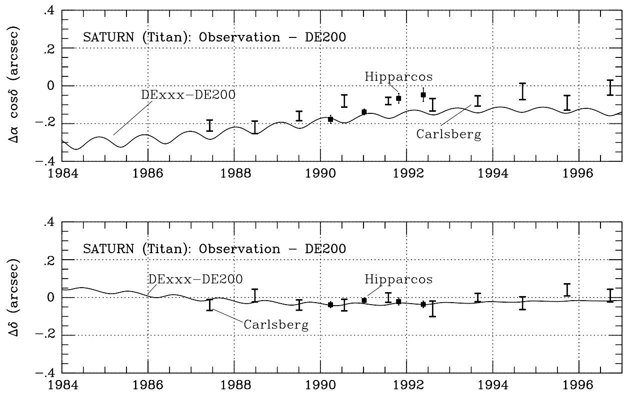

Figure 5. Comparison of the observation positions of Saturn with DE200 and DExxx ephemerides (upper, right ascension; lower, declination). The Hipparcos normal points derived from observations of Titan are shown as filled squares. The opposition means derived from Carlsberg Meridian Telescope observations of Titan are plotted as error bars.