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Study of USNO photographic plates of the Galilean satellites

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Abstract

About 500 photographic plates of the Galilean satellites made with the 26-inch refractor of USNO in Washington DC from 1967 to 1998 were digitized and reduced using the UCAC2 star catalog. Results on the ephemerides of the Galilean satellites and on the determination of the mass of Amalthea will be presented. An evaluation of the accuracy of several ephemerides of Jupiter on the 1967-1998 period will also be provided.

I. Introduction - The USNO photographic plates

The study of United States Naval Observatory photographic plates of the Galilean satellites was part of Vincent Robert's thesis ; the exact title is "Astrometry of natural satellites to improve the planetary system dynamic parameters" and it was directed by Jean-Eudes Arlot and Valéry Lainey.

The main goal was to analyse past observations of the Galilean satellites with old photographic plates obtained from 1967 to 1998 at the USNO (Pascu, 1977, 1979, 1994) with the 26-inch refractor. Some specifications : the use of a long focal refractor provides a precise astrometry, and an adapted filtering balances the planet, its satellite and the star magnitudes. Some questions : which effects must be taken into account to obtain the desired accuracy ? which accuracy could be obtained ? which applications for the position measurements ? and is it possible to detect the gravitational signature of a non-observed body ?

The USNO photographic plates of the Galiean satellites contain from 4 to 7 exposures shifted on the declination axis, and a trail was realised with each last exposure to determine the orientation of the equator of the date in the case of previous manual measurements. All the informations (metadata) we needed for a precise astrometry are available on the plate jackets (UTC date, exposure starts and times, ground temperature, ...). The main problem consited in the few number of available stars because the average is around 7 and was not enough to easily determine plate constants for a common astrometric reduction.

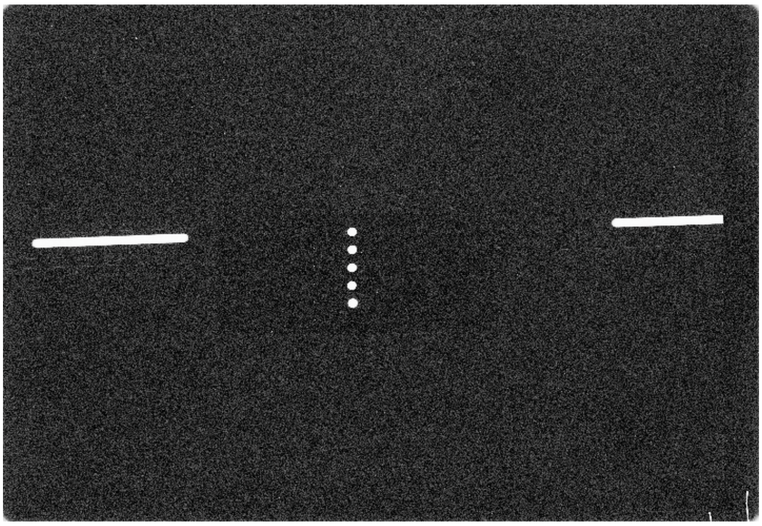

Fig. 1 – Digitization of the USNO plate n2114 (positive).

II. Digitization of the USNO photographic plates - Analysis

500 USNO photographic plates resulting in 2000 individual observations were digitized in 2009 with the DAMIAN (Digital Access to Metric Images Archives Network) scanner.

Fig. 2 – The DAMIAN scanner

The digitization was realized in the cadre of an international partnership with the Royal Observatory of Belgium ROB (J.-P. de Cuyper, G. De Decker), the USNO (D. Pascu) and the IMCCE-Paris Observatory (J.-E. Arlot, V. Lainey, V. Robert).

The most important machine specification for astrometry : the positioning repeatability was calibrated by the manufacturer with a laser interferometer to 0.008 μm and was measured to 0.077 μm after correcting for the camera distortion.

The images were then analyzed by using a specific process to identify the planet, its satellites and the available stars. This process is analog to a pre-reduction and provided the best results. All the available stars (depending on the catalog used) are identified and more, those that are not visible with the eyes. Four star catalogs can be used : Hipparcos (Perryman et al., 1997), Tycho-2 (Hog et al., 2000), UCAC2 (Zacharias et al., 2004) and UCAC3 (Zacharias et al., 2010). The identification method can be applied with all planetary systems ; tests were succesfully performed with Saturn, Mars and Pluto images.

Because of the few number of available stars, the astrometric reduction was here quite different with a common one : the star $(\alpha, \delta)_c$ equatorial coordinates were corrected for all-known spherical effects, the star $(x, y)_m$ measured coordinates were corrected for the evaluated instrumental effects, and the astrometric reduction was realised through the atmosphere so that (α, δ) equatorial coordinates were deduced from apparent (X, Y) tangential coordinates. Only 4 parameters are fitted for a minimum of 2 reference stars with our adapted $(x, y)_m \mapsto (X, Y)_{m,a}$ model :

$$X_{m,a} = \rho \cos\theta \times x_m - (\rho + \epsilon_1 \sin(\epsilon_2 t_m + \epsilon_3)) \sin\theta \times y_m + \Delta_x + C_x \times x_m \times (m - m_0)$$
$$Y_{m,a} = \rho \sin\theta \times x_m + (\rho + \epsilon_1 \sin(\epsilon_2 t_m + \epsilon_3)) \cos\theta \times y_m + \Delta_y + C_y \times y_m \times (m - m_0)$$

III. Positioning results

	$\overline{(O-C)}_{\alpha\cos\delta}$	$\sigma_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	σ_δ
JI	-3.1	33.4	8.5	32.9
JII	3.3	34.3	-3.6	33.2
JIII	0.3	34.6	4.9	37.5
JIV	-0.6	41.3	-9.5	40.3
Mean	0.0	36.2	0.0	36.9

Tab. 1 – Means and rms residuals for intersatellite positions, in mas.

The intersatellite accuracy is less than 37 mas ($\simeq$ 111 km) ; this result is better than those obtained from most recent observational programs such as the Flagstaff Astrometric Scanning Transit Telescop FASTT with an intersatellite accuracy about of 50 mas ($\simeq$ 150 km) (Stone et al., 2003).

The (RA,Dec) accuracy is less than 77 mas ($\simeq$ 230 km) ; this result is better than those obtained from most recent observational programs such as FASTT with a (RA,Dec) accuracy about of 100 mas ($\simeq$ 300 km) (Stone et al., 2003).

	$\overline{(O-C)}_{\alpha\cos\delta}$	$\sigma_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	σ_{δ}
JI	1.0	68.2	43.2	75.1
JII	6.2	69.0	32.1	73.4
JIII	3.5	72.3	39.0	79.4
JIV	1.8	69.2	25.0	76.0
Mean	3.1	69.7	34.7	76.4

Tab. 2 – Means and rms residuals for (RA,Dec) positions, in mas.

We also found that the planetary ephemerides introduce a systematic error about of 35 mas in declination : first because the other possible sources were rejected, and because the bias is only visible with (RA,Dec) statistics for which the planet effects are dominating. Pascu et al. (1990) detected a declination bias with Saturn observations due to DE125 ephemeris (Standish et al., 1985) and more recently, Stone et al. (2003) detected a systematic positive error in declination about of a few tens of mas regardless of the "recent" planetary ephemeris used. The part in adjustments of old transits is an explanation for Hog (1972), Standish et al. (1976), Seidelmann et al. (1985), Pascu et al. (1990) and Stone et al. (2003). These observations introduce an offset for the modern period that we clearly show with our positioning results. But the question remains because the general effect, over our 30 years interval, would be analog to a shift of Jupiter above the ecliptic.

We compared the most recent Galilean ephemerides with our observations. The differences could be moderated because an accuracy less than 4 mas over a 30 years interval was never reached with old observations. The L2 (Lainey et al., 2009) and jup230 (Jacobson) ephemerides are comparable in terms of accuracy and precision.

	$\overline{(O-C)}_{\alpha\cos\delta}$	$\sigma_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	σ_{δ}
JI / L2	-3.1	33.4	8.5	32.9
JII / L2	3.3	34.3	-3.6	33.2
JIII / L2	0.3	34.6	4.9	37.5
JIV / L2	-0.6	41.3	-9.5	40.3
Mean / L2	0.0	36.2	0.0	36.9
JI / jup230	-2.7	33.8	7.4	33.0
JII / jup230	0.7	34.5	-4.8	34.0
JIII / jup230	0.9	36.2	6.0	37.5
JIV / jup230	1.0	42.7	-8.4	40.5
Mean / jup230	0.0	37.1	0.0	37.1

Tab. 3 – Means and rms residuals for intersatellite positions, in mas.

We compared the most recent planetary ephemerides with our observations. Accuracy and precision orders are analog with the DE421 (Folkner et al., 2008), DE423 (JPL, 2010), INPOP06 (Fienga et al., 2008), INPOP10 (Fienga et al., 2010) and EPM08 (Pitjeva, 2009, 2010). Each model introduces a systematic error less than 5 mas in right ascension and up to 35 mas in declination. This is not the case with the INPOP08 ephemeris but our results are in agreement with those in Fienga et al., 2009.

	$\overline{(O-C)}_{\alpha\cos\delta}$	$\sigma_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	σ_{δ}
DE421	-1.3	70.1	39.0	79.0
DE423	-1.6	69.8	36.6	77.0
INPOP06	-5.6	70.0	36.2	77.3
INPOP08	42.7	74.3	47.9	94.9
INPOP10	3.1	69.7	34.7	76.4
EPM08	-2.1	70.1	36.2	76.9

Tab. 4 – Means and rms residuals of (RA,Dec) positions, in mas.

We re-fitted the L2 Galilean model with the USNO observations in order to get post-fit residuals and thus to evaluate the real accuracy of our methods. The astrometric reductions are different : the relative L2 positioning data are now replaced with data derived from (RA,Dec) positions. Thus we created the L3 Galilean ephemeris.

	L2 USNO observations	L3 USNO observations
JI	766	1104
JII	775	1140
JIII	788	1213
JIV	832	1193
Total	3161	4650

Tab. 5 – Number of satellite observations in L2 and L3 fits.

By comparison of the residuals, the new accuracy is 0.6 mas better. This result could be moderated because differential observations provide positioning data better than (RA,Dec) positioning data by a factor 2 ; the process does not introduce any divergency in the solution.

Because we can find the quality of an ephemeris in its extrapolation accuracy, we compared the L2 and L3 ephemerides with the astrometric reduction of 74 mutual events that were not used in the fit (Emelyanov et al., 2009). The mean benefit is 1.5 mas for these phenomena ; the quality of the L3 extrapolation was refined.

We finally identified and extracted Almathea's disturbing signal from the residual analysis of Io's USNO positions. In fact Amalthea is the biggest and most massive internal satellite of the Jovian system :

Model	Term	Argument	Magnitude (km)	Period (day)
L2	λ_{Io}	$\lambda_{Amalth\acute{e}e} - \lambda_{Io}$	20 ± 2	0.5016 ± 0.0022
L3	λ_{Io}	$\lambda_{Amalth\acute{e}e} - \lambda_{Io}$	20 ± 2	0.5016 ± 0.0022
jup230	λ_{Io}	$\lambda_{Amalth\acute{e}e} - \lambda_{Io}$	21 ± 2	0.5016 ± 0.0020

Tab. 6 – Measured signals due to Amalthea's gravitational potential on Io.

If we assume that the motion is plan and the orbits are circular, we can deduce the following approximate variation :

$$\Delta L = \frac{4\mu a}{n_I a_I^4 (n - n_I)} \sin(M - M_I)$$

Model	USNO magnitude (km)	Amalthea's mass ($\times 10^{18}$ kg)
Galileo	-	2.08 ± 0.15
L2	20 ± 2	2.00 ± 0.20
L3	20 ± 2	2.00 ± 0.20
jup230	21 ± 2	2.05 ± 0.20

Tab. 7 – L2, L3 and jup230 Amalthea's mass estimations.

A first estimation of Amalthea's mass is obtained from the USNO position analysis ; thus a high-precise astrometric reduction can contribute to a basic physic.

Through all these applications, we demonstrate the interest in reducing old photographic plates to fit gravitational and orbital parameters over long and past periods.

IV. Conclusion

By comparison with the previous USNO analysis and for the first time, (RA,Dec) equatorial coordinates are determined. All the available sources are identified and used. The intersatellite accuracy is improved by a factor 3 !

By comparison between the 1967-1998 USNO data and the 1998-2003 FASTT data, the intersatellite accuracy is 30% better *i.e.* 40 km ! The (RA,Dec) accuracy is 25% better *i.e.* 70 km !

With the analysis of its gravitational signature, we confirm that Amalthea's density is close to that of water !

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