Study of USNO photographic plates of the Galilean satellites

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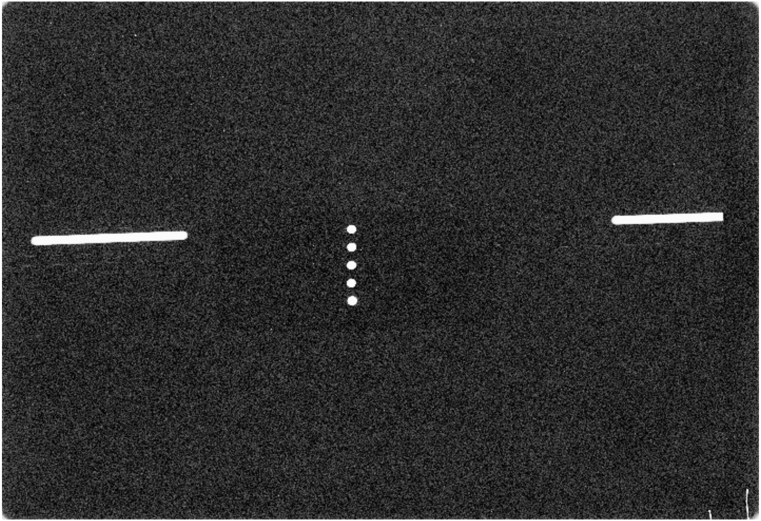
Workshop NAROO-GAIA
June 20, 2012

Introduction

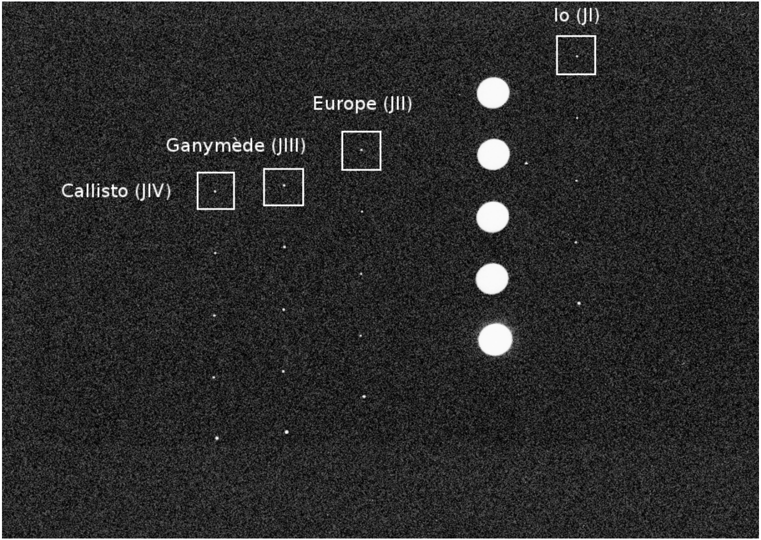
- Part of Vincent Robert's thesis : astrometry of natural satellites to improve the planetary system dynamic parameters, with Jean-Eudes Arlot and Valéry Lainey.
- Analysis of past observations with old photographic plates obtained from 1967 to 1998 at the USNO (Pascu, 1977, 1979, 1994).

- Specifications :
  - the use of a long focal refractor provides a precise astrometry ;
  - an adapted filtering balances the planet, its satellite and the star magnitudes.

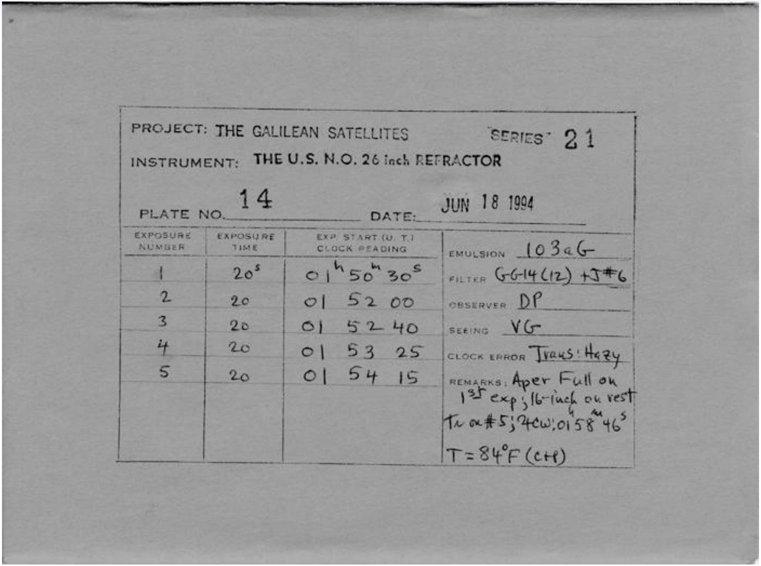
- Problematic :
  - which effects must be taken into account to obtain the desired accuracy ?
  - which accuracy could be obtained ?
  - which applications for the position measurements ?
  - is it possible to detect the gravitational signature of a non-observed body ?



Digitization of the USNO plate n°2114 (positive).



Centre of the digization of the USNO plate n°2114 (positive).



PROJECT: THE GALILEAN SATELLITES SERIES 21

INSTRUMENT: THE U.S. N.O. 26 inch REFRACTOR

PLATE NO. 14 DATE: JUN 18 1994

EXPOSURE NUMBER	EXPOSURE TIME	EXP. START (U. T.) CLOCK READING
1	20^s	$01^h 50^m 30^s$
2	20	01 52 00
3	20	01 52 40
4	20	01 53 25
5	20	01 54 15

EMULSION 103aG

FILTER GG-14 (12) +J#6

OBSERVER DP

SEEING VG

CLOCK ERROR Trans: Hazy

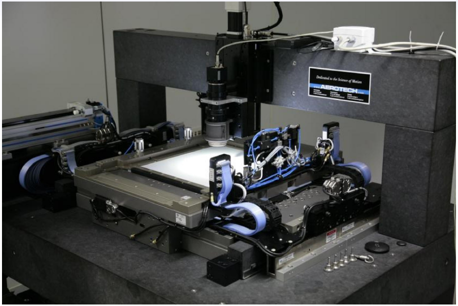
REMARKS: Aper Full on 1st exp; 16-inch on rest

Tr on #5; 4cw: $01^h 58^m 46^s$

T = 84°F (ctP)

Observational data from the USNO plate jacket n°2114.

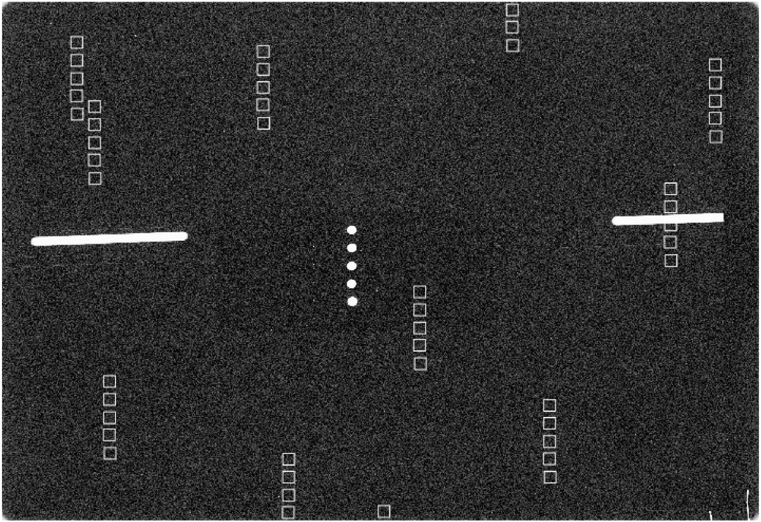
Digitization of the USNO photographic plates



The DAMIAN scanner

- Three partners : ROB (J.P. De Cuyper, G. De Decker), USNO et IMCCE.
- Calibration of the DAMIAN scanner from 2007 to 2009.
- Aerotech positioning stability : ± 10 nm in X-axis and ± 15 nm in Y-axis.
- Positioning repeatability : 0.008 μm Aerotech and 0.077 μm after correcting for the camera distortion (Moving Dot, Winter, 2005, 2008).

500 USNO photographic plates resulting in 2000 individual observations were digitized in 2009 with the DAMIAN scanner.



Object identification method.

- Our identification method is analog to a pre-reduction ; it 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.

- Five star catalogs can be used :
  - Hipparcos (Perryman et al., 1997) ;
  - Tycho-2 (Hog et al., 2000) ;
  - UCAC2 (Zacharias et al., 2004) ;
  - NOMAD (Zacharias et al., 2005) ;
  - 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.

Differences with a common astrometric reduction :

1. the star $(\alpha, \delta)_c$ equatorial coordinates are corrected for the main spherical effects ;
2. the star $(x, y)_m$ measured coordinates are corrected for the evaluated instrumental effects ;
3. the astrometric reduction is realised through the atmosphere so that (α, δ) equatorial coordinates are deduced from apparent (X, Y) tangential corrdinates.

Adapted $(x, y)_m \mapsto (X, Y)_{m,a}$ model

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

Only 4 parameters are fitted for a minimum of 2 reference stars !

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

Means and rms residuals for intersatellite positions, in mas.

Intersatellite accuracy

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 FASTT with an intersatellite accuracy about of 50 mas ($\simeq$ 150 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

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

(RA,Dec) accuracy

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).

The planetary ephemerides introduce a systematic error about of 35 mas in declination :

1. the other possible sources were rejected ;
2. the bias is only visible with (RA,Dec) statistics for which the planet effects are dominating ;
3. Pascu et al. (1990) detected a declination bias with Saturn observations due to DE125 ephemeris (Standish et al., 1985) ; 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.

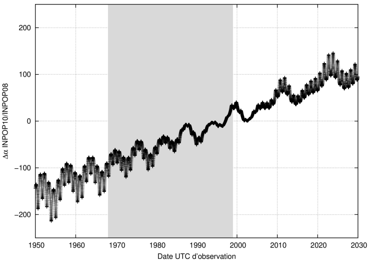
- The part in adjustments of old transits is an explanation for Hog (1972), Standish et al. (1976), Seidelmann et al. (1985), Pascu et al. (1990) and Stone et al. (2003).
- These observations introduce an offset for the modern period that we clearly show with our positioning results.

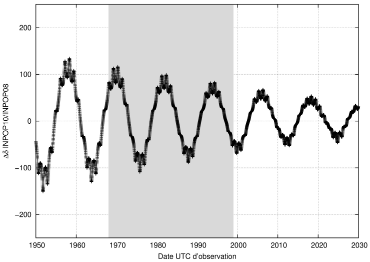
The question remains because the general effect, over our 30 years interval, would be analog to a shift of Jupiter above the ecliptic.

	$\overline{(O-C)}_{\alpha \cos \delta}$	$\sigma_{\alpha \cos \delta}$	$\overline{(O-C)}_{\delta}$	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

Means and rms residuals for intersatellite positions, in mas.

- 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 and jup230 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}
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

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

- Each model introduces a systematic error less than 5 mas in right ascension and up to 35 mas in declination.

- 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 by data derived from (RA,Dec) positions.

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

- 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.

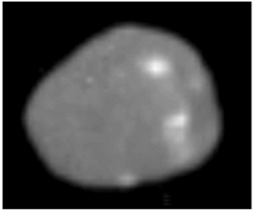
- We can find the quality of an ephemeris in its extrapolation accuracy.
- Test : L2/L3 comparison with the astrometric reduction of 74 mutual events that are not used in the fit (Emelyanov et al., 2009).

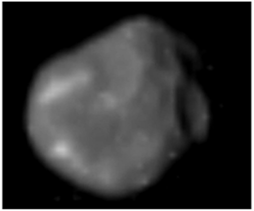
	L2 ephemeris		L3 ephemeris	
	σ_X	σ_Y	σ_X	σ_Y
1o2	47.0	52.2	46.8	51.2
2o3	73.4	101.5	73.5	100.9
3o1	50.8	64.8	50.9	63.8
3o2	38.9	28.8	39.0	28.2
1e2	34.1	93.0	34.5	91.6
1e3	60.6	108.8	60.4	105.2
4e2	20.8	25.1	18.1	24.4
4e3	24.8	45.1	24.8	45.1
74 phenomena	51.9	76.2	50.1	74.9

rms residuals of tangential positions, in mas.

- The mean benefit is 1.5 mas for these phenomena ; the quality of the L3 extrapolation was refined.

- Amalthea is the biggest and most massive internal satellite.





- We identified and extracted its disturbing signal from the residual analysis of Io's USNO positions :

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

- We assume that the motion is plan and the orbits are circular :

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

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

- 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.
- We demonstrate the interest in reducing old photographic plates to fit gravitational and orbital parameters over long and past periods.

Conclusion

Comparison with the previous USNO analysis

- (RA,Dec) equatorial coordinates are determined for the first time ;
- all the available sources are identified and used ;
- the intersatellite accuracy is improved by a factor 3 !

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 !

Gravitational signature

We confirm that Amalthea's density is close to that of water !

Questions