Dynamical parameter determinations in Pluto's system

Expected constraints from the New Horizons mission to Pluto

L. Beauvalet[1], V. Lainey[1], J.-E. Arlot[1], and R. P. Binzel[2,1]

[1] Institut de Mécanique Céleste et de Calcul des Éphémérides-Observatoire de Paris, UMR 8028 du CNRS, Université Pierre et Marie Curie, Université Lille 1, 77 avenue Denfert Rochereau, 75014 PARIS, France

[2] Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139 USA

ABSTRACT

Pluto is the multiple system that has been observed the longest. Yet, the masses of its smallest satellites, Nix and Hydra, which were discovered in 2005, are still imprecisely known, because of the short time span and number of available observations. We present a numerical model that takes into account the second order gravity fields and Pluto's orbital motion in the solar system. We investigated the dynamical parameters that may be reliably determined today. We also assessed the possible improvements on the parameter uncertainties with the future increase of observations, including the New Horizons mission. Fitting our model to simulated data, we show that the precision of observations prevents the quantification of the polar oblateness J_2 and equatorial bulge c_{22} of Pluto and Charon. Similarly, we show that the masses are on the detection limit. In particular, unless 25 observations are made every year, the mass of Nix may be constrained with confidence only with New Horizons data. Hydra's mass will only be constrained by the probe. The recent discovery of P4 might change this situation, but our knowledge of this object is still too vague to draw any conclusion.

Key words. Celestial mechanics – Planets and satellites: fundamental parameters – planets and satellites: individual: Pluto – Methods: numerical – Kuiper belt: general

1. Special tailored Ephemerides (STE) for Jupiter irregular satellites

1.1. Observations used

The last observations used to develop JPL current ephemeris of the irregular satellites of Jupiter were obtained in 2012 (Jacobson et al. 2012). As a result, the errors on the residuals of recent observations are too important for the ephemeris to accurately predict stellar occultations without anny corrections. In order to have efficient ephemerides for predicting the stellar occultations by irregular satellites, we need predictions based on recent observations. This is why we decided to develop our own ephemeris based on the observations published in Gomes-Júnior et al. (2015).

Here comes your paragraphs from *Correction of the ephemeris* about your observations from Gomes-Junior 2015 and how they present systematic errors. Also, the little blurb I write just before will need to be reread and edited (because editing others is sooooo easier and more efficient than editing oneself)

1.2. Description of the model

Our numerical model describes the dynamical evolution of the irregular satellites of Jupiter in a jovicentric reference frame. The satellites are submitted to the influence of the Sun and the rest of the solar system, as well as those of the Galilean satellites and the first harmonics of Jupiter's gravity field. The axis of the reference frame are those of the equatorial reference frame J2000.

We use the following notations:

- i and l one of the irregular satellites of Jupiter
- J Jupiter
- j another body of the Solar System
- M_j the mass of the j body, not an irregular satellite
- m_i the mass of the irregular satellite i
- $\mathbf{r}_i$ the position of the i body with respect to the barycentre of Jupiter System
- r_{ij} the distance between bodies i and j
- R_J the radius of Jupiter
- J_n the dynamic polar oblateness of the nth order for Jupiter's gravity field
- $U_{\bar{l}\hat{j}}$ potential generated by the oblateness of Jupiter on the satellite l
- Φ_i is the inclination of the i satellite with respect to Jupiter's equator.

For an irregular satellite i, under the gravitational influence of Jupiter, the $\mathcal{N}' - 1$ other irregular satellites, the regular Jovian satellites and the rest of the Solar System ($\mathcal{N}$ bodies), the equation of motion is:

$$
\ddot{\mathbf{r}}_i = -GM_J \frac{\mathbf{r}_J - \mathbf{r}_i}{r_{iJ}^3} - \sum_{l=1, l \neq i}^{\mathcal{N}'} Gm_l \frac{\mathbf{r}_l - \mathbf{r}_i}{r_{il}^3}
$$
$$
- \sum_{j=1}^{\mathcal{N}} GM_j \left(\frac{\mathbf{r}_j - \mathbf{r}_i}{r_{ij}^3} - \underbrace{\frac{\mathbf{r}_j - \mathbf{r}_J}{r_{Jj}^3}}_{\mathrm{undirect\,perturbations}} \right)
$$
$$
+ GM_J \nabla U_{\bar{l}\hat{j}} - \underbrace{\sum_{l=1}^{\mathcal{N}} Gm_l \nabla U_{\bar{l}\hat{j}}}_{\mathrm{undirect\,perturbations}} \quad (1)
$$

where the oblateness potential seen by the body i because of Jupiter is:

$$
U_{\bar{l}\hat{j}} = -\frac{R_J^2 J_2}{r_{iJ}^3} \left(\frac{3}{2} \sin^2 \Phi_i - \frac{1}{2} \right)
$$
$$
-\frac{R_J^4 J_4}{r_{iJ}^5} \left(\frac{35}{8} \sin^4 \Phi_i - \frac{15}{4} \sin^2 \Phi_i + \frac{3}{8} \right) \quad (2)
$$
$$
-\frac{R_J^6 J_6}{r_{iJ}^7} \left(\frac{231}{16} \sin^6 \Phi_i - \frac{315}{16} \sin^4 \Phi_i + \frac{105}{16} \sin^2 \Phi_i - \frac{5}{16} \right)
$$

The expressions of $\nabla_l U_{\bar{l}\hat{i}}$ and $\nabla_i U_{\bar{l}\hat{i}}$ have been developed in Lainey et al. (2004). The equations of motion are integrated with the numerical integrator RADAU (Everhart 1985). Our model was fitted to the observations through a least-squares procedure. The satellites were integrated one dynamical family at a time, to gain computing time, while losing minimum precision. Indeed, the interactions between satellites not belonging to the same dynamical family are negligible considering the short timespan of our integration.

Table 1. Initial osculating elements for Jupiter irregular satellites at JD 2451545.0. For Themisto's case, the small number of observations meant that the statistical uncertainty was even greater than the obtained elements, though the fitting proved satisfying. We decided to provide its elements with significant number comparable to the other satellite for information, but left it without uncertainty.

Satellite	a (km)	e	incl. (EQJ2000)	Ω
Himalia	11372100 ± 500	0.166 ± 0.002	45.14 ± 0.15	39.77 ±
Elara	11741170 ± 690	0.222 ± 0.002	28.64 ± 0.18	68.42 ±
Pasiphae	23425000 ± 5000	0.379 ± 0.001	152.44 ± 0.10	284.59
Sinope	22968800 ± 5200	0.316 ± 0.002	157.76 ± 0.12	256.62
Lysithea	11739900 ± 1300	0.136 ± 0.004	51.12 ± 0.27	5.53 ±
Carme	24202924 ± 4800	0.242 ± 0.001	147.13 ± 0.10	154.01
Ananke	21683800 ± 7200	0.380 ± 0.002	172.29 ± 0.20	56.9 ±
Leda	11140300 ± 4300	0.173 ± 0.007	16.15 ± 0.75	272.6
Themisto	7393800	0.198	25.77	220

The initial osculating elements at the origin of integration are presented in Table 1, while the residuals are presented in Fig **??** to **??**.

All the orbits determined for the satellites show satisfying residuals. Yet, one of the satellites has a peculiar situation. Its small number of observations in our set means that its orbit is definitely loosely constrained. The residuals are lower than those obtained with JPL ephemeris, but the accuracy of an ephemeris decreases when we get further from the time of observations. The main risk of divergence over time comes from the possible absence of long-term effects when fitting to a short timespan of observations. If that were the case, our ephemeris would diverge too quickly to be of any use. JPL ephemerides are fitted over all the available observations. As a result, they will diverge less quickly than our own. Though they are no longer precise enough for our use, they remain a recious reference to identify whether our own model presents a quick divergence. We compared our ephemeris to the JPL for all the Jupiter satellites we fitted, until 2017. The divergence between 2015 and 2018 is at most *insert value here* for *insert right satellite name here*. A example of this difference for satellites Himalia and *whichever satellite you want, if you want)* is presented in Figure **??**.

The obtained ephemeris is hereafter refered as STE, for special-tailored ephemeris.

References

E. Everhart. An efficient integrator that uses Gauss-Radau spacings. In A. Carusi and G. B. Valsecchi, editors, *Dynamics of Comets: Their Origin and Evolution, Proceedings of IAU Colloq. 83, held in Rome, Italy, June 11-15, 1984. Edited by Andrea Carusi and Giovanni B. Valsecchi. Dordrecht: Reidel, Astrophysics and Space Science Library. Volume 115, 1985, p.185*, page 185, 1985.

A. R. Gomes-Júnior, M. Assafin, R. Vieira-Martins, J.-E. Arlot, J. I. B. Camargo, F. Braga-Ribas, D. N. da Silva Neto, A. H. Andrei, A. Dias-Oliveira, B. E. Morgado, G. Benedetti-Rossi, Y. Duchemin, J. Desmars, V. Lainey, and W. Thuillot. Astrometric positions for 18 irregular satellites of giant planets from 23 years of observations. *A&A*, 580:A76, August 2015. .

R. Jacobson, M. Brozović, B. Gladman, M. Alexandersen, P. D. Nicholson, and C. Veillet. Irregular Satellites of the Outer Planets: Orbital Uncertainties and Astrometric Recoveries in 2009-2011. *AJ*, 144:132, November 2012. .

V. Lainey, L. Duriez, and A. Vienne. New accurate ephemerides for the Galilean satellites of Jupiter. I. Numerical integration of elaborated equations of motion. *A&A*, 420:1171–1183, June 2004. .