Interest of old data for the determination of the heliocentric distance of Pluto

Laurène Beauvalet

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L. Beauvalet[1]

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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

Abstract

Pluto was discovered in 1930. It is also the multiple system which has been known for the longest time with the discovery of its first satellite Charon in 1978. Because of Pluto's distance to the Sun, the system still has not completed a revolution since its discovery, hence an uncertain heliocentric distance. The difference between the different ephemeris available far exceeds the uncertainty needed for the mission New Horizons, that is 1,000 km. A new astrometric reduction of old photographic plates may be an efficient way to constrain it.

1 Introduction

Pluto was discovered in 1930. Because its period of revolution is about 248 years, it has not completed an entire revolution. As a consequence, its distance to the Sun is not accurately known.

Pluto has a unique trait among the dwarf planets, a very massive satellite. Its main satellite Charon has a mass of one tenth of Pluto's while the mass of the other satellites Nix, Hydra, P4 and P5 are on the contrary nearly negligible. Because of this mass ratio the center of mass of the system is outside of Pluto. Pluto's motion is also the result of the combination of both its motion around the Sun, and its motion around the barycenter of the system. This situation is the same for all planets, except that for planets the center of mass lies inside the most massive object of the system. In the case of Pluto, the motion around the Sun is heavily disturbed by Charon. Thus any modelization of Pluto's motion needs to include these perturbations. Up to now, there were studies separating the satellites [1] and the dwarf planet motions [2], [3].

The first in-situ exploration of the system will be in 2015 by the probe New Horizons. The probe will not orbit around Pluto or another object of the system. It will make a fly-by of the system, crossing it in a few hours, before going on exploring another transneptunian object. Because of this, the probe needs a precision of 1000 km on the heliocentric distance of Pluto. In this proceeding, we present the ephemeris of Pluto's system developed, as well as a comparison between the different ephemeris available. Then, we discuss the use of photographic plates to achieve the needed precision for the ephemeris of Pluto.

2 Dynamical model : ODIN

We specifically developed the numerical model ODIN (Orbite, Dynamique et Intégration Numérique) to study the orbit of multiple systems [4], [5]. With ODIN, we integrated the equations of motion of the bodies of the system in a Solar System barycentric reference frame with inertial axes coinciding with the ICRF. We also included the perturbations due to the Sun and the planets.

Because we found the second order harmonics of the gravity fields of Pluto and Charon to be non-detectable with observations [4], we did not take them into account. As a result, the equations of motion only consisted in the gravitational interactions between the center of mass of the bodies and their interaction with the main bodies of the Solar System:

$$\ddot{\mathbf{r}}_i = \sum_{j=1}^{\mathcal{N}} -\frac{GM_j(\vec{r}_i - \vec{r}_j)}{r_{ij}^3} + \sum_{l=1,\ l\neq i}^{4} \left(-\frac{Gm_l(\vec{r}_i - \vec{r}_l)}{r_{il}^3} \right), \tag{1}$$

where i is an integrated body, j is the Sun or a planet, l is a body of Pluto's system, M_j is the mass of the body j, m_l is the mass of the body l, $\vec{r}_j$ is the position vector of the body j with respect to Solar System barycenter and r_{ij} is the distance between bodies i and j.

Our model was fitted to observations using the least-square method. We may approximate the relationship between the calculated residuals and the model parameter errors by its linear part :

$$\Delta\overrightarrow{r_{li}} = \sum_{k=1}^{6N+N'} \left.\frac{\partial f^i}{\partial c_k}\right|_{t_l, c_k} \Delta c_k \tag{2}$$

To obtain the needed partial derivatives, we used Newton's second law :

$$\frac{d^2\overrightarrow{r_{li}}}{dt^2}(t_l) = \frac{\overrightarrow{F}}{m_i}(t_l, \overrightarrow{r_{l1}}, \dot{\overrightarrow{r_{l1}}}, \ldots, \overrightarrow{r_{lN}}, \dot{\overrightarrow{r_{lN}}}, c_1, \ldots, c_{6N+N'}) \tag{3}$$

Assuming that the derivations with respect to time and to a dynamical parameter are independent, we determined the differential equations [6]:

$$\frac{\partial}{\partial c_l}\left(\frac{\mathrm{d}^2\vec{r}_i}{\mathrm{d}t^2}\right) = \frac{1}{m_i}\left[\sum_j \left(\frac{\partial \vec{F}_i}{\partial \vec{r}_j}\frac{\partial \vec{r}_j}{\partial c_l} + \frac{\partial \vec{F}_i}{\partial \dot{\vec{r}}_j}\frac{\partial \dot{\vec{r}}_j}{\partial c_l}\right) + \frac{\partial \vec{F}_i}{\partial c_l}\right], \tag{4}$$

where c_l is a parameter we need to adjust. We numerically integrated these equations alongside the equations of motion. Note that our model can be fitted to both resolved and unresolved observations of Pluto's system in (RA, Dec) spherical coordinates and to observations of the satellites relative to Pluto.

3 Observations used

We used sets of observations taken from 1914 to 2011 and because of this large time span, the number of observations and their accuracy changed significantly between the different sets. Over this period, there is a gap in both the precision and the number of observations because of the introduction of CCD targets. Most of these observations are unresolved, the first images separating Pluto and Charon being those taken by the Hubble Space Telescope [7]. The characteristics of the unresolved observations and stellar occultations used are given in the Table 1.

4 Fitting to the observations

Because of the small perturbations due to the rest of the Solar System on the satellites, we first fitted the motion of the satellites and then we used this first solution to fit the heliocentric motion of the system.

Table 1: Properties of the observations to which ODIN was fitted

Origin	Number	Reference frame	Observations	Reference	Years
Lowell, Yerkes and McDonald Observatory	552	B1950	Photographic	[8]	1914-1965
Asiago Observatory	175	B1950	Photographic	[9], [10], [11], [12]	1971-1997
A.J. Dyer Observatory	15	B1950	Photographic	[13]	1965-1981
La Silla	45	B1950	Photographic	[14], [15]	1980 & 1985
Torino Observatory	39	B1950	Photographic	[16], [17]	1973-1982
Brorfelde Observatory	15	B1950	Photographic	[18]	1975-1978
Lick Observatory	11	B1950	Photographic	[19], [20], [21]	1980-1985
Flagstaff Observatory	5	B1950	Photographic	[22]	1980 & 1983
La Silla	29	J2000	Photographic	[23]	1989-1990
Pulkovo astrograph	207	J2000	Photographic	[24]	1930-1993
FASTT	914	J2000	CCD	IAU Comm. 4 [a] FASTT website[b]	from 1995
Table Mountain	259	J2000	CCD	IAU Comm. 4 [a]	1997-2010
Bordeaux-Floirac Observatory	87	J2000	CCD	[25]	1995-2005
Observatoire de Haute-Provence	242	J2000	CCD		1997-2010
Observatoire du Pic du Midi	73	J2000	CCD		2011
Stellar occultations	14	J2000	Occultations	[26], Bruno Sicardy (private communication)	2005-2008

[a] http://iau-comm4.jpl.nasa.gov/plan-eph-data/

[b] http://www.nofs.navy.mil/data/plansat.html

Table 2: Mean value and standard deviation for the residuals of photographic observations with ODIN, DE421 and INPOP08 ephemerides.

	ODIN		DE421 INPOP08	
	$\Delta\alpha$ (")	$\Delta\delta$ (")	$\Delta\alpha$ (")	$\Delta\delta$ (")
old observations	-0.026 ± 1.162	0.023 ± 1.558	-0.104 ± 1.163	0.088 ± 1.553
			0.754 ± 1.342	0.142 ± 1.560
Pulkovo	0.034 ± 0.398	0.163 ± 0.418	-0.081 ± 0.388	0.027 ± 0.414
			0.352 ± 0.657	0.035 ± 0.414
A.J. Dyer-Lick-Mink	-0.467 ± 0.960	-0.034 ± 0.480	-0.617 ± 0.932	-0.146 ± 0.500
			-0.564 ± 0.990	-0.147 ± 0.523
Tokyo-Bordeaux-Flagstaff	-0.029 ± 0.100	-0.004 ± 0.097	-0.053 ± 0.0962	-0.028 ± 0.105
			-0.068 ± 0.095	-0.021 ± 0.105
Gemmo-USNO	-0.075 ± 0.197	-0.024 ± 248	-0.110 ± 0.199	-0.014 ± 0.252
			-0.129 ± 0.200	-0.004 ± 0.251
Bordeaux	-0.069 ± 0.098	-0.077 ± 158	-0.078 ± 0.091	-0.075 ± 0.146
			-0.129 ± 0.200	-0.004 ± 0.251

4.1 Heliocentric motion of the system

The semi-major axis differs by 0.2% from that given by DE423 [27] for the same date. A more complete comparison between the JPL ephemeris of Pluto and our own fitted model is given in Table 2 with the standard deviation and mean value of the residuals obtained with the two theories for the photographic observations. The residuals of both theories are quite close considering their statistics.

4.2 Heliocentric distance of the system

Concerning the issue of Pluto's heliocentric distance, the least-square method provides a statistical uncertainty of the fitted semi-major axis. Yet this uncertainty is based on the hypothesis that the errors of the observations follow a Gaussian law, which is not the case because of systematic errors. As a consequence, this uncertainty is only linked to the residuals and to the correlations between the parameters in the model. What we need to know is the error we do because of the differences between the real motion we try to determine and our model.

To determine this error, we need to compare the heliocentric distance given by different theories which can be considered as having the same quality concerning the residuals. For this purpose, we compared the heliocentric distance of Pluto to the Sun between ODIN, DE421 [2], DE423 [27], INPOP08 [28], and INPOP10 [3]. These ephemerides are based on three models and are fitted to similar sets of observations. The differences on the heliocentric distance will be a lower estimation of the external precision of Pluto's motion.

The result is shown in figure 1. As we can see, there is a large discrepancy between the models and the New Horizons spacecraft needs a 1,000 km precision of the heliocentric distance of Pluto to make observations. In 2015, the most recent theories can have up to 5,000 km differences. Even when comparing the two models with the smallest difference in distance, that is ODIN and DE421/423, we still have about 4,000 km difference.

The best way to try to reduce this uncertainty would be either to increase the number of observations, or to improve the accuracy of those already existing. We know that observations of

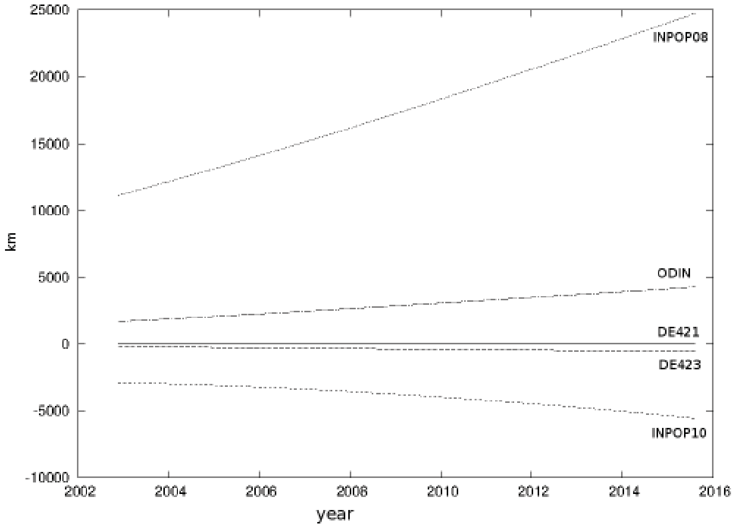

Figure 1: Evolution of the difference in the heliocentric distance of Pluto between DE421 and other models.

Pluto are taken every year and used in the models. But the fly-by of New Horizons is due in 2015. It is doubtful a few years of observations will constrain the models enough. The second source of improvement would be to make a new reduction of the observations taken with photographic plates. The uncertainties with these observations are widely larger than those with the more recent observations and these observations span on many decades. Reducing the uncertainties attached to the old observations would naturally reduce the differences between the models.

5 Conclusion

We developed a numerical model specifically dedicated to the study of multiple systems: ODIN. After fitting our model to observations of Pluto's system, we obtained a dynamical solution for Pluto's heliocentric motion and for the satellite plutocentric motions. This dynamical solution provided similar results to those obtained with different dynamical models.Yet, we found that the heliocentric distance of Pluto is known with less precision than what we expected. The New Horizons probe needs a 1,000 km accuracy on the heliocentric distance of Pluto. Even though the expected precision of the different available ephemerides are less than this threshold, the differences between the models are far greater. The different models have similar results for the most recent observations. The oldest observations of the system have far greater residuals. A new reduction of these old observations would certainly reduce these residuals and then enough constrain the heliocentric distance of Pluto.

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