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Constraining multiple systems with GAIA

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ABSTRACT

GAIA will provide observations of some multiple asteroid and dwarf systems. These observations are a way to determine and improve the quantification of dynamical parameters, such as the masses and the gravity fields, in these multiple systems. Here we investigate this problem in the cases of Pluto's and Eugenia's system. We simulate observations reproducing an approximate planning of the GAIA observations for both systems, as well as the New Horizons observations of Pluto. We have developed a numerical model reproducing the specific behavior of multiple asteroid system around the Sun and fit it to the simulated observations using least-square method, giving the uncertainties on the fitted parameters. We found that GAIA will improve significantly the precision of Pluto's and Charon's mass, as well as Petit Prince's orbital elements and Eugenia's polar oblateness.

1. Introduction

Astrometric monitoring of multiple systems is a powerful way in the Solar System to have access to the physical properties of small bodies. Indeed, the satellite motions provide the mass of the primary, as well as the harmonics of its gravity field. The bodies involved can be very different in size and masses, from dwarf planets to small asteroids. These systems can be very compact and, as a result, are difficult to observe from Earth without adaptive optics. We can expect GAIA to observe the components of such systems, both the primary and its satellites, if these later are far enough from the primary (Bancelin et al., this issue). GAIA will make precise and regular observations of them, and as a result, will probably improve our knowledge of their dynamical parameters.

The purpose of this paper is to estimate the precision on the dynamical parameters we can expect for multiple systems thanks to GAIA. This kind of systems have been discovered among nearly every family of small bodies. We have investigated the contribution of GAIA's observations for one system in the Kuiper Belt: Pluto, and one in the Main Belt: 45 Eugenia. After a presentation of the dynamical model used especially to describe multiple systems in Section 1, we will develop the case of each system in a different section.

2. Dynamical model

We use here the same numerical model which has been developed in Beauvalet et al. (submitted for publication). We consider the motion of every bodies of a multiple system in the inertial reference frame ICRF centered on the barycenter of the Solar System. We compute the motion of the bodies disturbed by the Sun and the planets, whose positions are obtained through the numerical ephemeris DE405 (Standish, 1998). The initial positions, velocities and masses in Pluto's system come from (Tholen et al., 2008). When needed, we include the second order harmonics of the polar oblateness of the primary, J_2. We use the following notations:

- i an integrated body from the considered system,
- j the Sun or a planet,
- m_i the mass of the body i,
- $\mathbf{r}_j$ the position vector of the body j with respect to the Solar System barycenter,
- r_{ij} the distance between bodies i and j,
- R_l the equatorial radius of body l, $J_2^{(l)}$ the polar oblateness of body l,
- $U_{\tilde{i}\tilde{l}}$ the potential of the l body's oblateness on the i body's center of mass.

We then obtain the following equation of motion:

$$\ddot{\mathbf{r}}_i = \sum_{j=1}^{10} -\frac{Gm_j(\mathbf{r}_i-\mathbf{r}_j)}{r_{ij}^3} + \sum_{l=1,\, l\neq i}^{3} \left(-\frac{Gm_l(\mathbf{r}_i-\mathbf{r}_l)}{r_{il}^3} + Gm_l \nabla_l U_{\tilde{l}\tilde{i}} - Gm_l \nabla_i U_{\tilde{i}\tilde{l}} \right) \quad (1)$$

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where $U_{\tilde{i}l}$ is a function of the oblateness of l, and ϕ_i the latitude of i with respect to l equator:

$$U_{\tilde{i}\,\hat{i}} = -\frac{R_l^2}{r_{il}^3} J_2^{(l)} \left(\frac{3}{2} \sin^2(\phi_i) - \frac{1}{2} \right) \tag{2}$$

Numerical integration of the equations of motion has been made using the 15th order Gauss–Radau integrator developed by Everhart (1985). Then we can adjust our model to the observations through a least-square procedure without constraints.

3. Pluto's system

3.1. Description

In 2013, Pluto will be about 33 AU from the Sun. We consider a four bodies system: Pluto, its most massive satellite Charon (Christy and Harrington, 1978), Nix and Hydra (Weaver et al., 2005). Physical details on these objects are given in Table 1. A last satellite has been discovered in July 2011 (Showalter et al., 2011) and has not been included in the model.

The particularity of Pluto among other systems in the Kuiper Belt is that it will be observed *in situ* by the probe New Horizons in 2015. This means that the system will then be observed simultaneously by this probe and by GAIA. Nonetheless, New Horizons will observe the four bodies of the system during a very short amount of time, whereas GAIA will only be able to detect Pluto and Charon, but its observations will be regularly made during five years. The contribution of New Horizons' observations to our knowledge of the dynamical parameters of the system has been investigated in Beauvalet et al. (submitted for publication). In this previous study, we have found that the only parameters which can be estimated are the masses of the bodies, while the oblate gravity fields will not be obtained, even at the time of New Horizons arrival. We use here the same method for GAIA.

3.2. Data simulation

Our goal is to determine the precision on the masses we can expect thanks to GAIA's observations. To do so, we simulate data at the moment of already existing and expected future observations of the system. We then fit our model to the simulations and extract the 1-σ uncertainty from the least-square method. We did not include noise to our simulation. This comes from the fact that we only want the statistical uncertainty, a quantity which depends only on the uncertainty of the observations, the influence of the parameter on the system and the correlations between the parameters. We used the Rendez-vous software to obtain a possible schedule of observations of Pluto's system by GAIA between 2013 and 2017. This software code has been developed by Ordenovic, Mignard and Tanga (OCA) for GAIA DPAC. The uncertainty attached to these simulated GAIA observations is considered to be 1 mas. As a first approximation, we neglect the fact that this precision is available only in the direction of the scan.

The dates used for GAIA simulations are given in Table 2. The simulated ground-based observations consist of ten observations per year, with the same uncertainties as current ground-based observations. The New Horizons simulations are obtained using a preliminary schedule of the mission, as well as its estimated uncertainties. More details on these two sets of simulations are given in Beauvalet et al. (submitted for publication).

As a result, we have two different sets of simulated data:

- 1992–2014+NH: reproducing the existing observations, the future possible observations and New Horizons temporary observation schedule.
- GAIA: reproducing observations of the system by GAIA.

Simulations with GIBIS suggest that the two bodies, Pluto and Charon, should always be detected as separated objects. Nix and Hydra have respective magnitude of about 23.7 and 23 (Stern et al., 2006), so these two bodies will not be detected by GAIA.

3.3. Results

3.3.1. Contribution of GAIA's whole mission

The uncertainties on the masses for every object of the system is given in Table 3. We can see that GAIA's observations will lower

Table 1
Characteristics of Pluto and its satellites.

Parameters	Pluto	Charon
Semi-major axis	39.26 AU	19 570.45 km
Diameter	2340 km	1206 km
Angular diameter	100 mas	55 mas
Magnitude	15.1	16.8
GM (km^3 s^{-2})	870.3	101.4
	Nix	Hydra
Semi-major axis	49 242. km	65 082. km
Diameter	88 km	72 km
Angular diameter	4 mas	3 mas
Magnitude	23.7	23.3
GM (km^3 s^{-2})	0.039	0.021

Table 2
Dates used for the simulation of GAIA observations for Pluto's system.

Dates	
29/04/2013 17:16:31	05/04/2014 20:14:44
29/04/2013 19:03:05	23/08/2014 07:18:58
13/05/2013 13:08:54	23/08/2014 13:19:11
13/05/2013 17:22:33	23/08/2014 09:05:32
13/05/2013 19:09:06	07/09/2014 07:24:37
16/08/2013 14:40:26	07/09/2014 09:11:11
16/08/2013 18:54:05	11/10/2014 18:49:60
16/08/2013 20:40:39	11/10/2014 20:36:33
17/08/2013 00:54:18	25/02/2015 13:29:17
17/08/2013 02:40:52	25/02/2015 15:15:51
17/08/2013 06:54:31	15/03/2015 15:19:11
17/08/2013 08:41:04	17/04/2015 01:03:56
20/08/2013 18:57:21	01/09/2015 15:35:38
20/08/2013 20:43:54	22/09/2015 07:48:31
21/08/2013 00:57:33	22/09/2015 09:35:05
21/08/2013 02:44:07	22/10/2015 15:11:01
21/08/2013 06:57:46	06/03/2016 14:02:18
21/08/2013 08:44:20	29/03/2016 15:43:50
30/09/2013 18:15:16	27/04/2016 01:39:15
30/09/2013 20:01:50	10/09/2016 20:21:33
07/11/2013 19:22:56	10/09/2016 22:08:07
07/11/2013 23:36:35	05/10/2016 21:58:12
08/11/2013 01:23:09	01/11/2016 07:58:37
16/11/2013 11:42:28	01/11/2016 09:45:11
16/11/2013 13:29:02	17/03/2017 04:23:16
16/11/2013 17:42:41	13/04/2017 10:08:01
16/11/2013 19:29:15	07/05/2017 16:00:14
17/02/2014 02:45:53	21/09/2017 08:55:12
17/02/2014 06:59:32	21/09/2017 10:41:46
17/02/2014 08:46:06	20/10/2017 10:21:17
27/02/2014 13:06:04	11/11/2017 14:31:42
27/02/2014 14:52:38	11/11/2017 16:18:16
05/04/2014 18:28:10	