# TOWARDS INPOP07, ADJUSTMENTS TO LLR DATA

H. MANCHE[1], S. BOUQUILLON[2], A. FIENGA[1,3], J. LASKAR[1], G. FRANCOU[2], M. GASTINEAU[1]
[1] IMCCE, Observatoire de Paris
77 avenue Denfert-Rochereau, 75014 Paris
e-mail: manche@imcce.fr
[2] SYRTE, Observatoire de Paris
77 avenue Denfert-Rochereau, 75014 Paris
e-mail: Sebastien.Bouquillon@obspm.fr
[3] Observatoire de Besançon
41 bis av. de l'Observatoire, 25000 Besançon
e-mail: agnes@obs-besancon.fr

ABSTRACT. INPOP06 is the latest numerical planetary ephemeris developed at IMCCE (Paris-Observatory). In this version, the motion of planets has been fitted to observations (Fienga et al. 2008). In INPOP07, currently in development, the motion of the Moon will be moreover fitted to Lunar Laser Ranging observations (about 17000 data over 36 years, from 3 different sites). We present here our fitting process, the physical effects taken into account in the computation of the residuals and our latest results.

## 1. REDUCTION OF OBSERVATIONS

A LLR data is the measurement of the round-trip travel time for laser pulses between a station on the Earth and a lunar reflector. The expression of the outward journey (a similar computation can be made for the downward one) is:

$$\Delta T = \frac{\|\overrightarrow{BL_2} + \overrightarrow{LR_2} - (\overrightarrow{BE_1} + \overrightarrow{ES_1})\|}{c} + \Delta T_{GR} + \Delta T_{atm} \quad (1)$$

where

- $c$ is the speed of the light
- $\overrightarrow{BL_2}$ is the solar system barycentric position of the center of mass of the Moon at time of reflection
- $\overrightarrow{LR_2}$ is the selenocentric position of the reflector at time of reflection
- $\overrightarrow{BE_1}$ is the solar system barycentric position of the center of mass of the Earth at time of emission
- $\overrightarrow{ES_1}$ is the geocentric position of the station at time of emission
- $\Delta T_{GR}$ is the time delay due to the light deviation due to the curvature of space
- $\Delta T_{atm}$ is a time delay due to the atmosphere

All these vectors are expressed in the ICRF.

The coordinates of $\overrightarrow{BL_2}$ and $\overrightarrow{BE_1}$ are directly provided by the INPOP ephemeris. From the fixed positions of the reflectors in the selenocentric reference frame, some small displacements are added, due to the solid tides raised by the Earth and the Sun, and due to the variation of the spin of the Moon. The transformation to the ICRF to obtain $\overrightarrow{LR_2}$ is then obtained using the libration angles that are integrated in INPOP at the same time as the orbits of the planets. Finally, $\overrightarrow{ES_1}$ is computed according to the IERS Conventions 2003 (McCarthy and Petit, 2004). From the position of the station in ITRF2000, some small displacements due to the following physical effects are taken into account:

- tectonic plate motion
- solid tides raised by the Sun and the Moon

- atmospheric loading
- ocean loading
- polar tide

The transformation to ICRF is then computed with the method explained in IERS Conventions 2003 (chapter 5), using the coordinates of the Celestial Intermediate Pole and the Earth Orientation Parameters given by the C04 series (UT1-UTC, polar motion, and corrections to the CIP coordinates). Finally, relativist corrections due to the transformation from a frame whose origin is the center of mass of the Earth to the ICRF whose origin is the solar system barycenter are applied. The same kind of corrections should be taken into account for the Moon, but have been neglected up to now.

The expression of $\Delta T_{GR}$ can be found in (Williams & al. 1996); only the terms due to the Sun and the Earth are taken here into account. To compute $\Delta T_{atm}$, the (Marini & Murray 1973) model is used, it is described in the IERS Conventions 2003 (chapter 9).

Up to now, the transformation between TT and the time used in the ephemeris ($T_{INPOP}$) is taken from the expression of Fairhead & Bretagnon (1990). But this expression, computed from the planetary solution VSOP (fitted on DE200), is not entirely consistent with another ephemeris. In INPOP07, for better consistency, the difference $TT - T_{INPOP}$ will be integrated at the same time as the orbits of the planets, using the formalism of S. Klioner (2007) and in agreement with the IAU 2006 Resolution 3. Nevertheless, it should be noted that this change will have no significant effect on the residuals (Observation minus Computation).

## 2. ADJUSTMENTS AND FIRST RESULTS

The first version INPOP05 was built to retrieve the JPL's solution DE405, with the same dynamical model, initial conditions and parameters. In INPOP06, after some improvements of the dynamical model, the initial conditions and parameters were fitted to planetary observations (Fienga et al. 2008). But LLR data were not used in the fit of INPOP06, and in order to constrain the orbit of the Moon, its initial conditions (and time delays used in the computations of tide effects) were fitted on the Earth-Moon distance of DE405. As a result, over 30 years around J2000, the difference on the Earth-Moon distance between DE405 and INPOP06 is less than 8 mm.

In a first step, we use the model described in the previous section for the reduction of the LLR observations with INPOP06. The observations are the ones of Grasse (Observatoire de la Côte d'Azur, France), between 1987 and 2005. We only fit the coordinates of the 4 lunar reflectors in the selenocentric frame. The difference between observation and computation of the light times (O-C), divided by the speed of light and by 2 to get a one way distance are shown in figure 1; the standard deviation ( $\sigma = 30$ cm ) is important compared to the precision of the observations (a few cm).

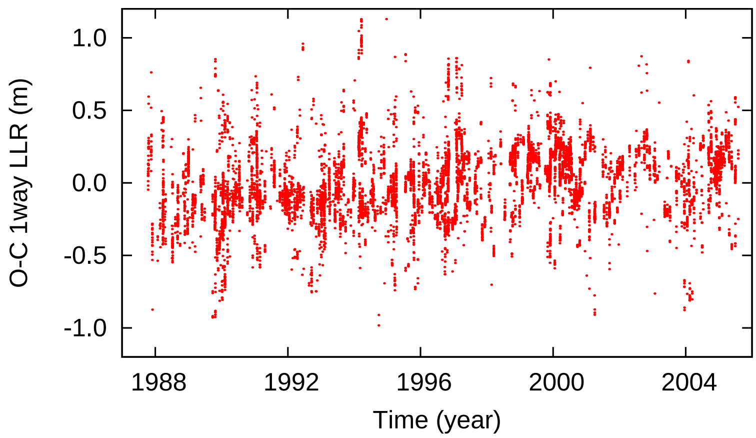


Figure 1: LLR residuals (m) for INPOP06 on Grasse's data from 1987 to 2005.

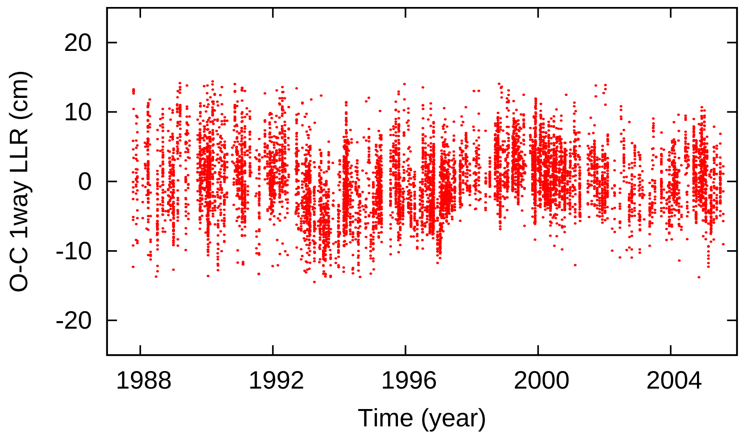


Figure 2: LLR residuals (cm) for INPOP07 on Grasse's data from 1987 to 2005.

With INPOP07 (work in progress), initial conditions and parameters are directly fitted to same LLR data (Grasse between 1987 and 2005). In this second step, the different fitted constants (used in the dynamical model and/or in the reduction process) are:

- inital conditions (at J2000) of the Earth-Moon vector
- initial conditions of the libration angles
- selenocentric positions of the reflectors
- geocentric position of the station (Grasse)
- time delays used in the computation of the tide effects
- Love numbers of the Moon
- lunar coefficients of the potential
- $C/MR^2$ of the Moon (third moment of inertia divided by the mass and the square of the mean equatorial radius)
- the value of an offset observed in the residuals between February 1997 and June 1998 (around 0.7ns)

That is a total of 53 parameters.

The residuals are shown in figure 2. The standard deviation is $\sigma = 4.64$ cm much better than the one obtained with the solution INPOP06. Note that 179 observations over 8441 have been rejected according to the $3\sigma$ criterion during the fitting process.

We use the parameter fitted to Grasse's LLR data to compute the residuals with Mac Donald's observations between 1969 and 2006.

Figure 3 shows the residuals for Mac Donald between 1969 and 1985. The standard deviation ($\sigma = 42$ cm ) is consistent with the precision of the observations at that epoch.

Between 1988 and 2006, some problems appear for recent observations of Mac Donald's observatory (see figure 4). Before 1999, the standard deviation ($\sigma = 4.7$ cm) is quite the same as for Grasse's data on the same period. But suddenly, after 1999, one can notice a severe degradation in the residuals ($\sigma > 1$ m). According to Randall L. Ricklefs (Mac Donald's observatory), it seems that this problem could come from the detector, that is 30 years old and not as efficient as in the past. Nevertheless, we can take into account these recent observations by eliminating at each step some of them according to the $3\sigma$ criterion. On that period, with 30% of data rejected, a first estimation of the standard deviation is $\sigma = 7$ cm.

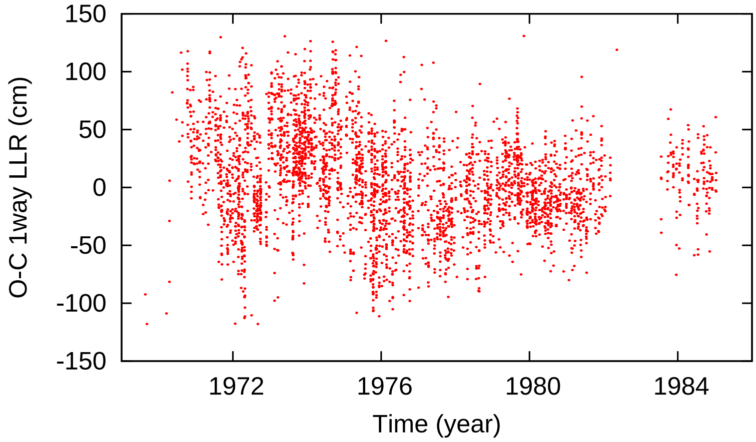


Figure 3: LLR residuals (cm) for INPOP07 on Mac Donald's data from 1969 to 1985.

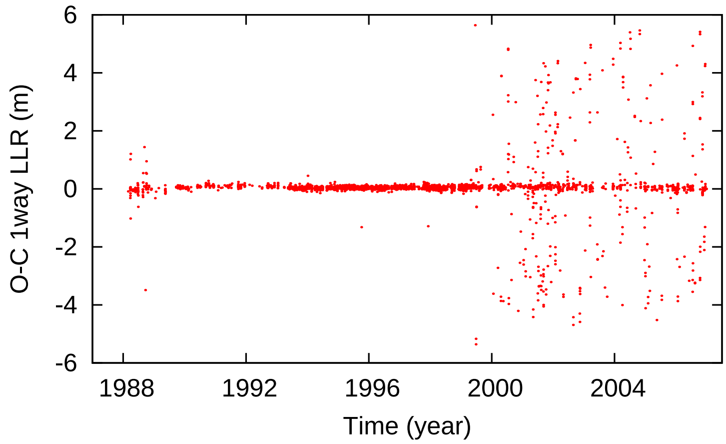


Figure 4: LLR residuals (m) for INPOP07 on Mac Donald's data from 1988 to 2006.

Finally, it should be stressed that the INPOP07 solution described here is still a preliminary version; the final solution will be fitted on all available LLR data, from the 3 sites, Mac Donald, Grasse and Haleakala, from 1969 to 2006.

## 3. REFERENCES


Fairhead L., Bretagnon P., 1990, "An analytical formula for the time transformation TDB-TT", A&A 229, pp. 240-247

Fienga, A., Manche, H., Laskar, J., Gastineau, M., 2008, "INPOP06. A new planetary ephemeris", A&A 477, 315-327

IAU 2006 Resolution 3, "Re-definition of Barycentric Dynamical Time, TDB", XXVIth International Astronomical Union General Assembly, 2006, Prague

Klioner, S., 2007, *personnal communication*

Marini, J. W., Murray, C. W., 1973, "Correction of laser range tracking data for atmospheric refraction at elevations above 10 degrees", NASA-TM-X-70555, Goddard Space Flight Center, Greenbelt, MD

McCarthy, D. D., Petit, G., 2004, "IERS Conventions (2003)", IERS technical Note n 32

Williams, J. G., Newhall, X. X., Dickey, J. O., 1996, "Relativity parameters determined from lunar laser ranging", Physical Review D, Volume 53, Issue 12, pp. 6730-6739