Updates from INPOP ephemerides : Data reduction model and parameter estimation using IR LLR data from OCA.

V.Viswanathan [1,2], A.Fienga[1], H.Manche[2], C.Courde[1], J.M.Torre[1], P.Exertier[1], J.Laskar[2]
[1] Observatoire de la Côte d'Azur, CNRS-Géoazur, OCA
[2] Observatoire de Paris, CNRS-IMCCE, PSL
email: viswanat@geoazur.unice.fr

Introduction

The OCA station is dedicated for Earth-Moon distance measurement, built in 1984 on the plateau of Caussols, situated near the city of Grasse in France. Its precision evolved from 15 cm range at its inception, to the centimeter level in 1987, and to millimeter level since 1995 (Samain et al. 1998, Samain 1995, Veillet et al. 1993, Veillet et al. 1987). Since 2015, OCA operates also in the infrared wavelength (1064nm). A detailed description on the IR instrumentation and detection at OCA is available in Courde et al. 2016.

In this paper, we present our results for the construction of a new INPOP rotational and dynamical lunar ephemeris obtained in combining 1 year (2015-2016) of IR LLR data (907 normal points) from Calern (Grasse) ILRS station along with the historical data from 5 ground stations, totaling 22314 LLR observations spanning a time period of 46 years. INPOP15a planetary ephemeris (Fienga et al. 2015) was used for the planetary ephemeris.

Dataset

The historical LLR data spanning over 1969-2015 from all stations is available publicly in the "MINI" format at (http://polac.obspm.fr/llrdatae.html). Recent LLR observations from OCA is made available at (http://www.geoazur.fr/astrogeo/?href=observations/donnees/lune/brutes).

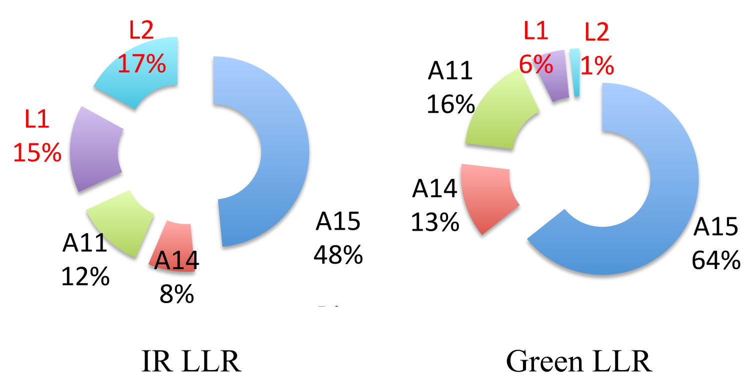

Figure 1: Spatial distribution over the lunar reflectors (L1: Lunakhod1; L2: Lunakhod2; A11: Apollo11; A14: Apollo14 and A15: Apollo 15) of LLR data obtained with IR (2015-16) and Green (2014-15) at Grasse, France

Owing to the spatial distribution of the reflectors on the Moon, Apollo reflectors offer principally longitude libration sensitivity, whereas Lunakhod reflectors offer sensitivity both in the latitude and longitude libration of the Moon (Viswanathan et al. 2015). However, statistics drawn from the historical LLR dataset (1969-2015) show an observer bias to range to the larger Apollo reflector arrays. This trend is also present on statistics taken during time periods after the re-discovery of Lunakhod 1 by (Murphy et al. 2011). This is due to the higher return rate and thermal stability over a lunar day on the Apollo reflectors, thereby contributing to the higher likelihood of success in a typical ranging attempt lasting about 10 minutes for the observer (Courde et al. 2017). This observational trend is moving towards a more uniform reflector-wise distribution due to the ease of detection associated with a high signal to noise ratio achieved through IR detection. Hence, uniformity in the reflector-wise distribution helps to reduce the dependency of regression procedures (used in data fits to lunar ephemeris) to the selection bias from the Apollo retro-reflector arrays.

Data reduction: GINS

LLR observed time of flight (or equivalent distance traveled by light) data includes inherent signatures resulting from orbital dynamics, geophysical and relativistic phenomena present in the Earth-Moon system. Known effects are modeled and a simulated station-reflector distance is computed. The difference of observed and computed light time includes all the un-modeled and unknown dynamics present within the observation, the magnitude of which relates inversely to the accuracy of the model (currently less than 2 cm in one-way light-time). Here after this difference is referred to as the LLR post-fit residual.

The reduction model for the LLR data analysis has been implemented within a precise orbit determination and geodetic software: GINS (Viswanathan et al. 2015) maintained by space geodesy teams at GRGS/OCA/CNES and written in Fortran90. The subroutines for the LLR data reduction within GINS is vetted through a step-wise comparison study conducted among the LLR analysis teams in OCA-Nice (this study), IMCCE-Paris and IfE-Hannover, by using simulated LLR data and DE421 as the planetary and lunar ephemeris.

The modeling of geophysical and relativistic effects follows the recommendations of IERS 2010 (Petit et Luzum. 2010) and the light-time computations are as described in Moyer 2003 (Section 8 and Section 11). To avoid any systematics in the reduction model, an upper-limit on the discrepancy between the teams was decided to be 1 mm in one-way light time (corresponding to the accuracy of the best LLR data available till date).

Relativistic corrections, tropospheric corrections, effects of the solid Earth tides, ocean loading, atmospheric pressure loading, rotational deformation due to polar motion, ocean pole tide loading has been taken into account as given in (Petit et Luzum. 2010). A first-order approximation for the solid tides raised on the Moon by the Earth and the Sun is taken into account using equation 7.5 in (IERS2010), adapted for the Moon using lunar degree 2 Love (h2) and Shida (l2) numbers.

As demonstrated in Pavlov et al. 2016, the JPL KEOF series that we had implemented in our procedure, produces better post-fit LLR residuals for observations prior to 1982, due to the inclusion of variation in latitude (VOL) and UT0 determination from LLR observations in the KEOF solution (Ratcliff et al. 2015).

Moon Internal structure and Regression

The lunar part of INPOP ephemeris is generated by fitting numerically integrated orbit and orientation parameters of the Moon to LLR observations. The Moon is seen as a 2-layered body with a mantle and a fluid core in interaction. The INPOP rotational modeling is described in (Manche 2011) and validated in using comparisons to (Pavlov et al. 2016). GRAIL gravity field coefficients (Konopliv et al. 2013) were used in this study. The interaction between the mantle and the fluid core was modeled with a friction term (K CMB) playing a role in the dissipation of the energy of the earth-moon system. The fluid core is characterized in using its flattening, moment of inertia and angular velocity differences with respect to the mantle. The principal axes of the undistorted mantle and the fluid core are aligned with the lunar frame through their definitions.

A weighted least square (WLS) regression procedure is used for the fitting of parameters sensitive to the Earth-Moon system. Table 1 gives the complete list of lunar parameters adjusted. Observations are weighted based on the uncertainties provided in the data. For APOLLO station observations, scaling the uncertainties of the normal points depending on the change of equipment, or a change in the normal point computation algorithm, is advised (see http://physics.ucsd.edu/~tmurphy/apollo/151201_notes.txt). Unrealistic uncertainties present in observations from Grasse, McDonald MLRS2 and Matera between time periods 1998-1999, 1996 and 2010-2012 respectively, are also corrected.

Unaccounted changes in the ground station introduce biases in the residuals. These biases are concurrent either with a known technical development at the station (new electronics, change of optical fiber cables) or systematics (thermal expansion of the telescope mount). Estimated biases are usually correlated with a corresponding change in the ground station, provided the observers have logged the incidents. A list of known and detected biases can be found for example in Pavlov et al. 2016.

The WLS procedure is iterated until the χ^2 reaches a minimum value, after which numerical noise dominates.

Results: Estimates and post-fit residuals

The comparison of the lunar parameter estimates with the DE430 ephemeris (Folkner et al. 2014 and Williams et al. 2014) has been provided in Table 1, where the uncertainties signify formal uncertainties at 2-sigma from the regression procedure. Estimates indicate consistency under their uncertainties except for the fluid core oblateness, due to a strong correlation with C/MR2 of the Moon and the y-component of the angular velocity differences at the core-mantle interface.

Post-fit residuals (Figure 2) obtained with our analysis indicate consistency with other LLR analysis groups, within 1.8 cm (rms). The mean and standard deviations indicated on the respective figures have been computed after a 5-sigma rejection filter.

Parameter	INPOP15b	DE430[4]
Radius Moon [km]	**1.738E+03**	**1.738E+03**
EMRAT	**81.3005718**	**81.3005691±0.0000024**
GM EMB [au^3/day^2]	8.99701141E-10	8.99701139E-10
k2 Moon	**2.4059E-02**[6]	**2.4059E-02**[6]
h2 Moon	4.315E-02 ± 1E-04	4.76E-02 ± 6.4E-03
l2 Moon	**1.070E-02**	**1.070E-02**
C/MR2 Moon	3.9313E-01 ± 1E-06	3.93142E-01
Lunar gravity field coefficients	GRAIL 660b[6] (upto degree,order : 6)	GRAIL 660b[6] (upto degree,order : 6)
C(2,0) Core	-4.74E-08 ± 3E-10	-6.78E-08 (derived)
C/MR2 Core	**2.75E-04**	**2.75E-04 (derived)**
K CMB [day^{-1}]	6.20E-09 ± 1E-11	6.43E-09
Angular velocities differences (mantle-core) [rad/day]	6.241E-03 ± 3E-06	6.664E–03 (derived)
	-5.14E-04 ± 1E-06	1.071E-03 (derived)
	-1.89E-04 ± 5E-06	–2.96E-04 (derived)
Cf/C ratio	**7.0E-04**	**7.0E-04**
Tau Moon [days]	9.82E-02 ± 1E-03	9.58E-02 ± 1.09E-02

Table 1: Comparison of estimates from INPOP15b and DE430. Parameters in **bold** have been fixed to model values during the regression procedure.

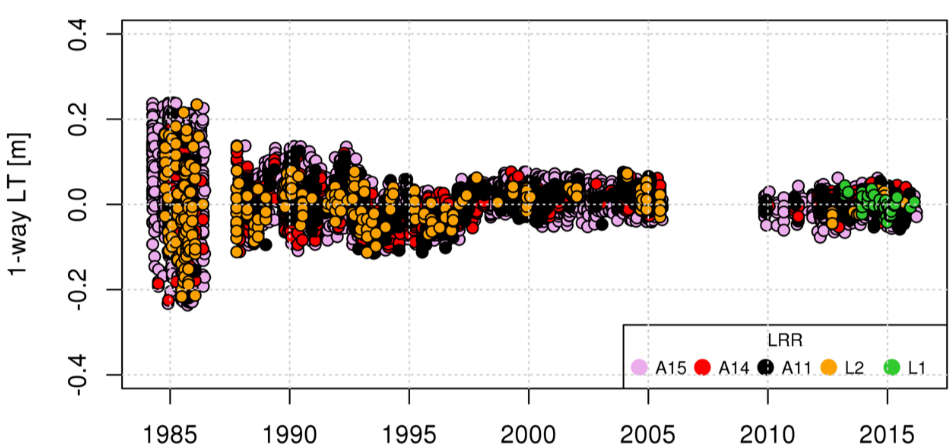

Figure 2a: Calern (Green) residuals (0.000 +/- 0.045 m : #11038 NPTs) vs years

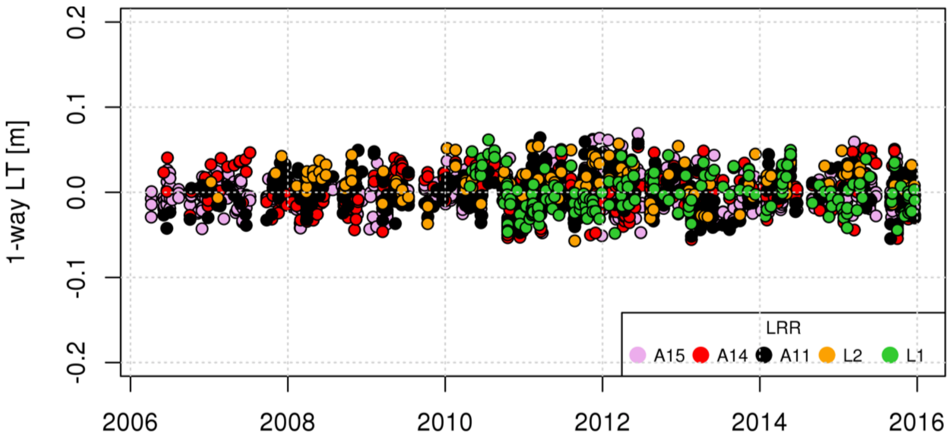

Figure 2b: APOLLO residuals (0.001 +/-0.019 m : #2352 NPTs) vs years

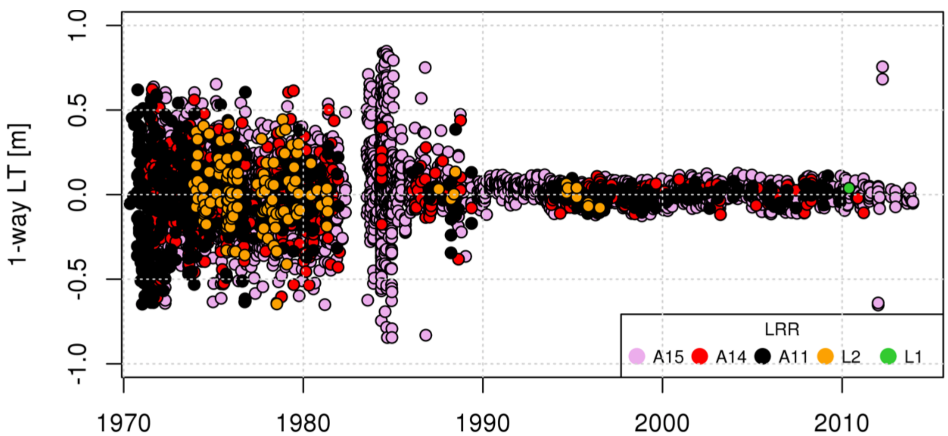

Figure 2c: McDonald residuals (0.007 +/- 0.166 m : #7098 NPTs) vs years

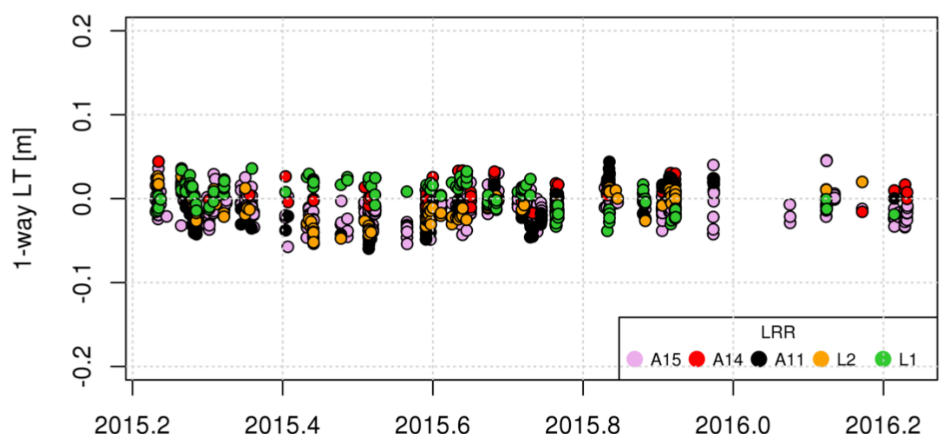

Figure 2d: Calern (IR) residuals (-0.006 +/- 0.018 m : #907 NPTs) vs years

Summary and future work

The axisymmetric lunar fluid core within INPOP has been activated and its rotation closely follows the mantle with small perturbations due to the viscous torques at the CMB. Unlike Pavlov et al. 2016 and Williams et al. 2014, we chose not to include fitted periodic correction terms to the longitude libration of the Moon for this study. Instead, a detailed paper (Viswanathan et al. in prep) will address correlation between fitted parameters as well as possible tracks for reducing the anomalous extra eccentricity rate in the lunar orbit, found in the analyses by Pavlov and Williams. A parallel study (Viswanathan et al. in prep) is also in progress regarding the impact of well-sampled IR LLR data on the sensitivity tests of the equivalence principle.

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