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Lunar Laser Ranging: Recent Activities of the Paris Observatory Lunar Analysis Center

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Abstract. *We report the activities of the Lunar analysis center POLAC during the last two years (2012-2013) with specific focus on the two main works done to support respectively LLR observers and LLR data users. Concerning the support to LLR observers, we present the recent improvements achieved in the "LLR data Prediction and Validation tools" (*http://polac.obspm.fr/PaV/*). Concerning the support to LLR data users, we present a set of LLR observations (from the 20th of August 1969 until the 20th of May 2013) based on a critical analysis of an extended LLR data gathering which includes the two databases of ILRS (hosted by DGFI and GSFC) and the archives maintained by POLAC, by the MéO station and by the APOLLO station (*http://polac.obspm.fr/llrdatae.html*).*

Introduction.

POLAC – Paris Observatory Lunar Analysis Center – is one of the four lunar anlysis centers of the International Laser Ranging Service. Founded by J. Chapront, M. Chapront-Touzé and G. Francou in 1996, it is located at SyRTE laboratory of the "Observatoire de Paris" (France). The current members of this service are S. Bouquillon, G. Francou and C. Le Poncin-Lafitte. This center works in close cooperation with the observers of the MéO Laser station (Calern, France), with the EOP and ICRS product centers of the International Earth Rotation Service and with the group in charge of the development of INPOP planetary ephemeris.

The main specificity of this service is, compared to the other analysis centers of ILRS, to base the LLR data reduction on semi-analytical solutions of the lunar motion. For the orbital motion of the Moon we use the "Ephéméride Lunaire Parisienne" (ELP) developed by Chapront and Chapront-Touzé while the Lunar Libration Theory of M. Moons is used for the rotational motion (1988, 1999, 2002).

There are two main sections in this report. The first one concerns the improvements achieved in the "LLR data Prediction and Validation tools" and the second one concerns the extended gathering of LLR observations performed by the POLAC group. Some planned improvements of these works will be underlined in a short concluding part.

Improvements of "LLR data Prediction and Validation Tools".

Since 2010, we have developed two tools usable on-line on the web to assist LLR observers: the first tool enables to compute predictions of topocentric and geocentric coordinates of lunar targets (as retro-reflectors or craters) and predictions of round-trip times of laser-pulses between terrestrial stations and lunar retro-reflectors. The second tool enables observers to compute differences between their LLR observations and different "LLR models"[1]. These tools are accessible on a single web site: http://polac.obspm.fr/PaV/. These tools have been extensively described in a proceeding of the 17th ILRS workshop (Bouquillon et al., 2011). In this report only the improvements of these tools will be expounded.

A – The prediction tool.

Concerning the first tool, we implemented, for performing the computation of LLR prediction, an up-to-date version of the POLAC LLR model. The main differences between this model named ELPMPP02 (Chapront and Francou, 2003) and the previous one named ELP96 is the use of the new planetary perturbations MPP01 (Bidart, 2001). The numerical ephemeris DE405 is used for the motion of the Earth-Moon barycenter and for the numerical complements to the lunar librations and orbital motion. This solution is fitted to the Lunar Laser Ranging observations made from 20/08/1969 until 20/05/2013. The initial positions of the stations are given in ITRF 2008 and the transformation between the terrestrial reference frame and the celestial reference frame is done with the help of SOFA routines and consistent with IERS Conventions 2003.

Some other slight improvements have been made (as the addition of the Shanghai SLR station (SHA2) in the list of laser stations or some minor changes of the TPF format of prediction files that were requested by LLR observers).

Concerning the TPF format, it should be noted that, since March 2013, it is the operational prediction file format for lunar laser ranging at MéO station. The Figure 1 shows the LLR residuals "Observations - Prediction" computed at the MéO station during the night 19th of March 2013 when the first echoes from Lunokhod 1 have been obtained by J-M. Torre and D. Féraudy. The improvements provided by using POLAC TPF prediction files – used during the second part of the night – are clearly visible on the plot below: the residuals slope that is visible during the first part of the night disappears during the second part of the night and the Lunokhod 1 is detected only when POLAC prediction has been used.
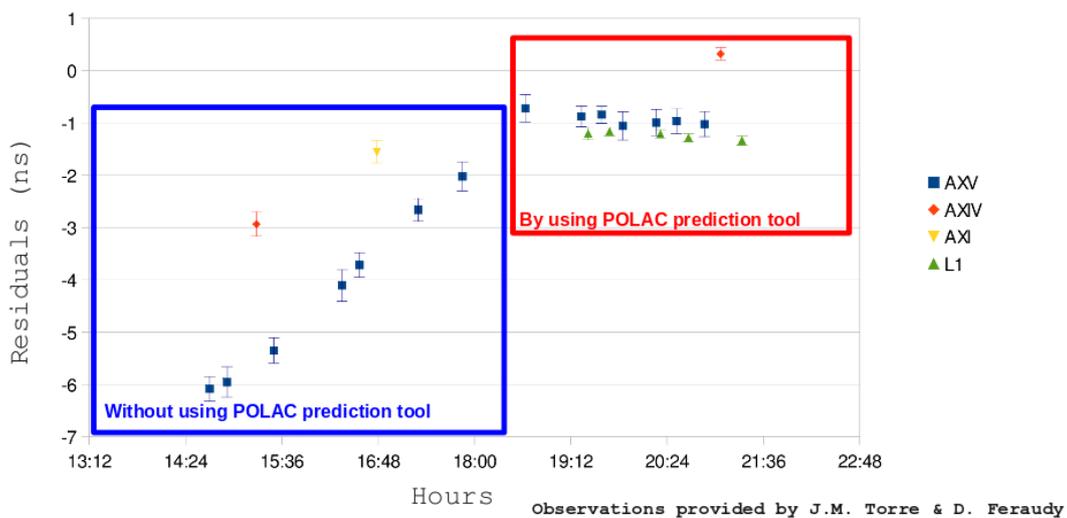

Figure 1. Example using the prediction tool: first detection of Lunokhod 1 with MeO.

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1 - In this report, the term "LLR model" includes a lunar ephemeris (as model of orbital and rotational motion of the Moon) and a LLR data reduction model for the round-trip time of the laser-pulses between the ground based stations and the lunar retro-reflectors.

B – The validation tool.

Since 2010, this second tool has allowed LLR observers to compute differences between their LLR observations and the POLAC LLR model ELP96. We recently added the possibility for the LLR observers to choose between two new LLR models for performing LLR residuals. These new available models are:

- ELPMPP02: the up-dated version of the POLAC LLR model (see the previous section).
- INPOP10e: this LLR model, developed at IMCCE, is based on the latest version of the planetary and lunar numerical ephemeris INPOP fitted on planetary and LLR data (Fienga et al. 2008, 2009, 2011). The associated LLR reduction program to model laser-pulses round-tip times is the one used by the INPOP group for the LLR data fitting. As the one of ELPMPP02, this LLR reduction model is consistent with IERS Conventions 2003.

Actually, the main interest for adding different LLR models is not for the validation of LLR observations but rather for the comparison and the improvement of these LLR models. For instance, the Figure 2, plotted with the help of this tool, allows to compare the residuals obtained with respectively the INPOP10e and the ELPMPP02 LLR models for the same set of observations.
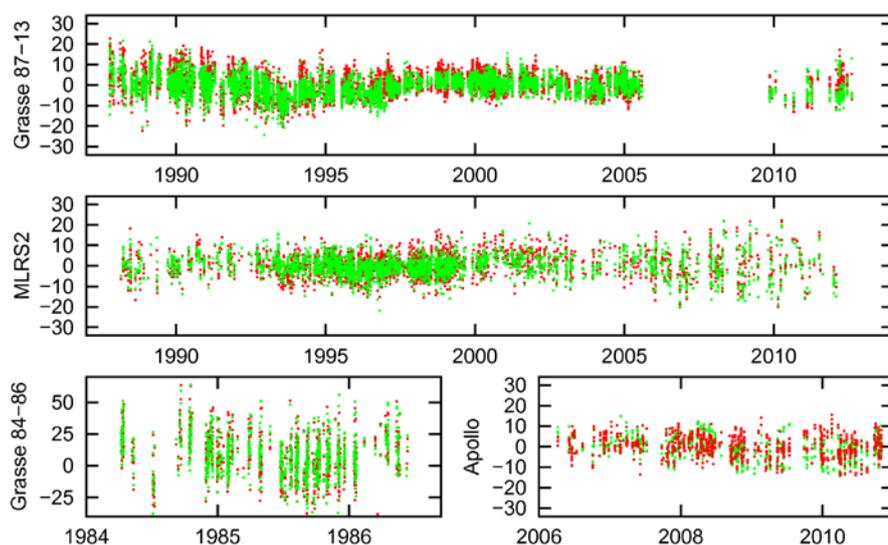

Figure 2. Reduction of all LLR observations since 1984 carried out with this interface:
O-C for two different LLR models in centimeters: INPOP10e in red and ELPMPP02 in green.

Table 1. For further information, the table below gives the root mean square in centimeters of LLR residuals for the main stations (per station and per period) carried out with this tool by using the ELPMPP02 LLR model (the same statistics performed with INPOP10e LLR model are very similar: the RMS differences are less than 8 mm). The current RMS values close to 5 cm and larger than the precision of the LLR observations, allow to point out some persistent problems in both LLR models (ELPMPP02 and INPOP10e) probably due to the way for modeling the lunar librations.

Stations (*periods*)	ELPMPP02
GRASSE (1984-1986)	15.41
GRASSE (1987-1995)	5.48
GRASSE (1995-2012)	3.82
MLRS2 (1985-1996)	4.29
MLRS2 (1996-2012)	5.08
APOLLO (2006-2012)	5.34

Extended gathering of LLR observations.

A – Original sources and formats of gathered LLR data.

We finalized this year an extended gathering of LLR observations begun in 2012. We collected a total of 49497 LLR normal points from the five following distinct LLR archives:

- **POLAC archive**:   LLR normal points given to POLAC directly by the CERGA in 1997 or via e-mails from Grasse and McDonald after 1997 (or from colleagues of the ILRS).
- **OCA archive**: LLR normal points available on the server of the "Observatoire de la Côte d'Azur" (OCA): http://www.obs-azur.fr/gemini/donnees/las_lune/.
- **APOLLO archive**: LLR normal points produced by the APOLLO team (Apache Point Observatory, USA) and available on the server: http://physics.ucsd.edu/~tmurphy/apollo/.
- **The ILRS data center CDDIS** (NASA GSFC, Greenbelt, USA): LLR normal points available on the server: ftp://cddis.gsfc.nasa.gov/slr/data/npt/moon/.
- **The ILRS data center DGFI** (Munich, Germany): LLR normal points available on the server: ftp://ftp.dgfi.badw-muenchen.de/pub/slr/data/npt/.

These LLR data were originally stored with one of the four following distinct formats:

- **ZN Original Format:** Format created by COSPAR Working Group 1 (Mulholland, 1971) (used since 1969 until 1986).
- **MINI Format**: Format created by NASA Management/Operations Working Group on LLR, (COSPAR Information Bulletin No. 108, April, 1987) (used since 1987). This format is the mostly used format in LLR community.
- **CSTG Format:** "Coordination of Space Techniques for Geodesy and Geodynamics". ILRS Normal Point Format (used since 1997).
- **CRD Format:** "Consolidated Laser Ranging Data Format", ILRS Normal Point Format (R.L. Ricklefs, C.J. Moore, October 2009) (used since 2009).

We plot in Figure 3, the distribution of all these LLR data according to their dates of observation (along x-axis), their original archives and formats (along y-axis) and their ground based laser stations (color code). It should be noted that overlapping and data duplications are abundant: it is the main difficulty to create a clean, complete and homogeneous set of LLR observations.
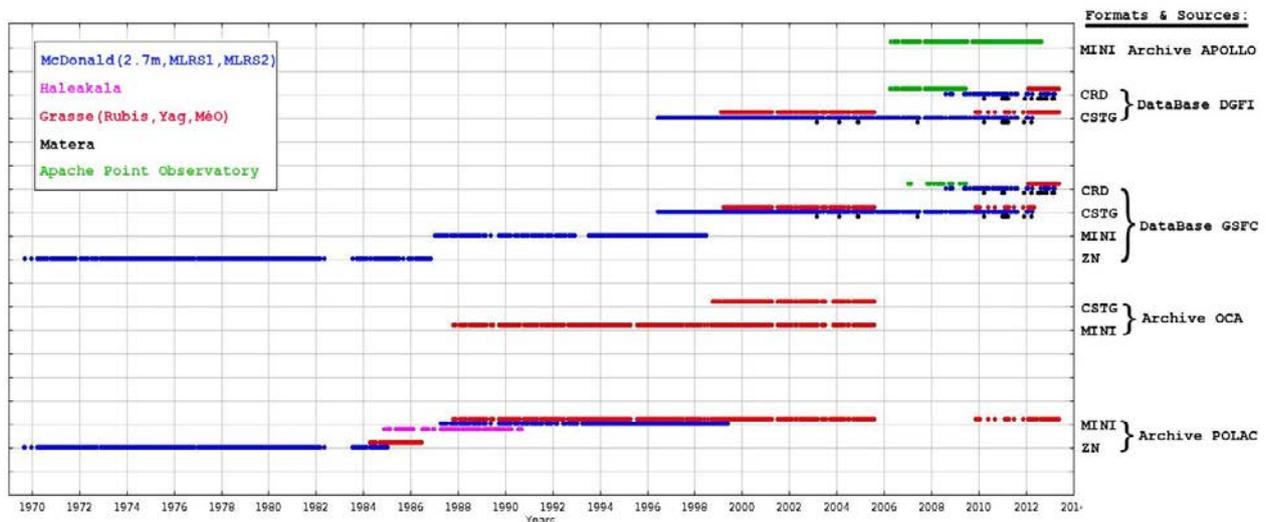

Figure 3. Distribution of all LLR observations per archive center & format.

B – Main steps of this LLR data gathering.

Our method to create a clean, complete and homogeneous set of LLR observations can be split into three steps:

First Step: data normalization.

This first step consists to apply the following process to each LLR archives:

- Split LLR data by LLR station and by format.
- Check the consistency of each data (values, format nomenclature, etc.).
- Remove redundant data (only strictly identical normal points).
- Change the data format in the LLR standard format "MINI".
- Check this new file consistency.
- Sort the data chronologically.
- Keep a trace of original archive and format.

We obtained 49497 normal points

Second Step: rejection of data with residuals larger than 100 meters.

This step is performed with the help of ELPMPP02 LLR models. The threshold of 100 meters has been chosen arbitrarily. This step rejects 411 LLR normal points (103 NPs of Grasse station, 305 NPs of McDonald station and 3 NPs of Matera Station). It remains 49086 normal points.

Third Step: identification and selection of data duplications.

In this report, we name "data duplications" neither the strictly identical data nor the data with slight differences due to format since the identification of this kind of redundant data can be performed without great difficulty. By contrast, the identification of two close LLR normal points which share some echoes is more challenging and it is what we name "data duplication" (the presence of these type of duplications in a data set is particularly problematic for the fitting process of a LLR model on LLR data and leads to over-weighted the data which are duplicated). The criterion we chose to identify this type of data duplication is the following one : *"2 normal points are considered as data duplications if there is a temporal overlap larger than 20% of the sum of their half-duration"* (see Figure 4 for graphical visualization of this type of duplication). When the duration of one of two consecutive normal points is not explicitly given, we fix it to 3 minutes (this value is also an arbitrary value).
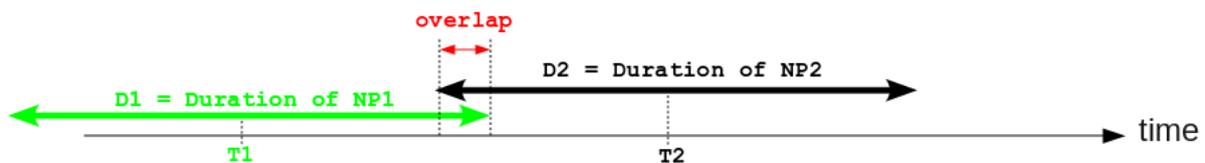

Figure 4. Criterion for the identification of data duplication.

When one data duplication is identified, we have to select and conserve one of the two data. To perform this selection, we compare several parameters to attempt to define the respective qualities of the two normal points. The different parameters and their weights are as follows:

- The residual [O-C] (weight = 2)
- The echoes number (weight = 1)
- The uncertainty (weight = 1)
- The signal to noise ratio (weight = 1)
- The duration (weight = 1).

This step rejects 28615 LLR duplicated normal points. It remains 20471 normal points

C – Resulting LLR data sets.

By the method described in the previous section, we constituted several resulting files which gather all LLR observations made between the 20th of August 1969 and the 20th of May 2013. All these files are available on: ftp://polac.obspm.fr/pub/1_llr_analysis/2_llr_residuals/observations/.

In all these files, the LLR normal points are stored in the LLR standard format MINI. The list below described the contents of the different resulting files.

- **TOTALOBS6913:**   20471 Nps: all valid LLR observations (20/08/1969 – 20/05/2013).
- **OMCD6985:**   3604 NPs made by McDonald station (20/08/1969 – 30/06/1985).
- **OMCD8388:**   631 NPs made by McDonald station (02/08/1983 – 27/01/1988).
- **OMCD8813:**   3653 NPs made by McDonald station   (29/02/1988 – 20/03/2013).
- **OGRA8486:**   1188 NPs made by Grasse station (07/04/1984 – 12/06/1986).
- **OGRA8705:**   8324 NPs made by Grasse station (22/01/1987 – 30/07/2005).
- **OGRA0913:**   654 NPs made by Grasse station (11/11/2009 – 20/05/2013).
- **OHAL8490:**   770 NPs made by Haleakala station (13/11/1984 – 30/08/1990).
- **OMAT0313:**   83 NPs made by Matera station (22/02/2003 – 05/03/2013).
- **OAPO0612:**   1564 NPs made by APOLLO station (07/04/2006 – 28/08/2012)..

On the same repository, a "VO table" version of the file containing all valid LLR observations is available (TOTALOBS6913.xml). The last two files conserved the following information:

- the rejected LLR observations due to residuals larger than 100 meters (TOTALSUP6913).
- the rejected LLR data duplications (TOTALDBL6913).

Conclusion : recent and planned improvements

After some discussions with different LLR observers, we plan to add in the "LLR prediction tool" some useful parameters concerning the observational conditions of the lunar retro-reflectors (as their libration angles, their sun illuminations, etc.).

Concerning the "LLR validation tool", we would like to add some other alternatives to the two available LLR models (ELPMPP02 and INPOP10e). The idea is to collaborate with the other ILRS lunar analysis centers to implement in this web-interface some remote access to their respective LLR models/codes that should allow to the LLR community to easily compare and improve their different LLR models.

Concerning, the gathering of LLR observations, the resulting files have to be regularly updated and the compilation method needs further discussions. At the instigation of J. Mueller, just after the 18th ILRS workshop, collaboration on this subject has begun with F. Hofmann who performed some similar LLR data gathering in the past.

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