Paris Observatory Lunar Analysis Center: from LLR Predictions to Tests of Fundamental Physics

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Abstract

POLAC (Paris Observatory Lunar Analysis Center) is an ILRS analysis center dedicated to the data processing of Lunar Laser Ranging observations (LLR). In this presentation, we introduce POLAC activities that go from LLR predictions to tests of fundamental physics. POLAC is thus simultaneously a support to LLR staff observers who aim at pointing their telescope to a specific target (a retro-reflector on the surface of the Moon or a lunar orbiter) and also a support to theoretical physicists who aim at using the Earth-Moon system to search for new Physics beyond General Relativity.

1. Introduction

POLAC (Paris Observatory Lunar Analysis Center) is an ILRS analysis center founded in 1996 by J. Chapront, M. Chapront-Touzé, and G. Francou. The activities of the service being related to all aspects linked to the data processing of Lunar Laser Ranging observations (LLR), the POLAC's members initially developed a semi-analytical lunar ephemeris called ELP (Ephémérides Lunaires Parisiennes) to describe the orbital and rotational motion of the Moon. The original purpose of POLAC was the fitting of ELP solutions to the LLR observations in order to improve the determination of fundamental astronomical parameters, such as the free modes of the lunar physical librations, the tidal secular acceleration of the lunar longitude, or the transformation between celestial reference systems. Since its beginning, POLAC worked in close collaboration with the laser ranging station at Grasse (MéO) by providing *a posteriori* validation of their LLR normal points in order to avoid calibration and format issues.

Since 2010, POLAC has evolved. First, it additionally provides *a priori* predictions for the laser ranging observations – mainly for the Moon tracking but also, in an experimental mode, for two-way LRO (Lunar Reconnaissance Orbiter) tracking. Secondly, with the elaboration of a new fully numerical Lunar ephemeris called ELPN (Ephémérides Lunaires Parisiennes Numériques), POLAC also takes part to the long legacy of testing fundamental Physics with LLR observations. Indeed, even if ELPN was built originally in the framework of General Relativity (GR), it can also be used to test alternative theories of gravity. One of particular interest is the Standard-Model Extension (SME) framework which parametrizes, at the low energy scale, Lorentz Symmetry (LS) violations that are predicted from high energy theories beyond the Standard-Model of particle physics and GR. By fitting ELPN to 50 years of collected data considering signatures from the SME framework within the pure gravity sector (including operators of mass dimension 4 and 5) and within the gravity-matter sector, we have been able to provide accurate and realistic estimates on possible LS violations arising at the level of the weak and the strong equivalence principles.

2. POLAC to support LLR observers

Receiving echos after the reflection of photons at the level of a retro-reflector located on the surface of the Moon from an initial laser pulse emitted by a station on Earth, represents a tremendous achievement. The link budget is unbelievably low; according to Samain *et al.*, (1998), among the 10^{18} emitted photon/pulse (in the green wavelength), only 0.01 are eventually detected back on Earth, which represents an overall signal loss at the level of 10^{20}. At a transmiting rate of 10 pulse/sec, only 0.1 to 1 photon are detected per second, and hence, several tens of minutes are needed to construct a normal point with an acceptable signal-to-noise ratio. In addition to the low link budget, the longitudinal pointing of the telescope is also an issue that LLR observers must deal with. The laser light transmitted from the collimated telescope spreads out to an area of approximatively 7 km in diameter on the surface of the Moon. For the reflection back to Earth to happen, the spread beam must in fact encompasses the surface of a retro-reflector array and this necessitates a longitudinal precision at the level of few arcsecond in the pointing of the telescope. At this level of precision, the relativistic aberration effect must be corrected when solving for the pointing of the telescope in the geocentric frame from barycentric positions and velocities of the Earth and Moon.

Since 2010, in order to support LLR observers, POLAC has developed a prediction and a validation tools available on-line: http://polac.obspm.fr/PaV/. The first one allows to compute the topocentric and geocentric coordinates of lunar targets (retro-reflectors and craters) and also the predicted round-light light-time of laser pulses between terrestrial stations and lunar retro-reflectors on the surface of the Moon. The predictions are supplied in two different formats, the TPF (Topocentric Prediction Format) and CPF (Consolidated Prediction Format) files; the latter being, since 2019, the official ILRS predictions for ranging to the Moon. Recently, using POLAC's predictions, LLR Grasse observers in collaboration with scientists at NASA/GSFC, achieved the first two-way ranging to LRO from ground (Mazarico *et al.*, 2020).

The validation tool allows observers to compute the difference between their LLR observations and the predictions of the round-trip light-time from a lunar ephemeris; among the lunar ephemeris that can be used on POLAC's web site, ELPN is the most recent one. It consists of a numerical integration of the equations for the orbital and the rotational motion of the Moon. It takes into account all the known physical effects with a theoretical signature above the centimeter level over the time span of the LLR data. In figure 1, we show the annual post-fit residuals obtained from ELPN computed in pure GR. The difference between ELPN predictions and LLR observations remains at the level of the centimeter for the most recent observations.

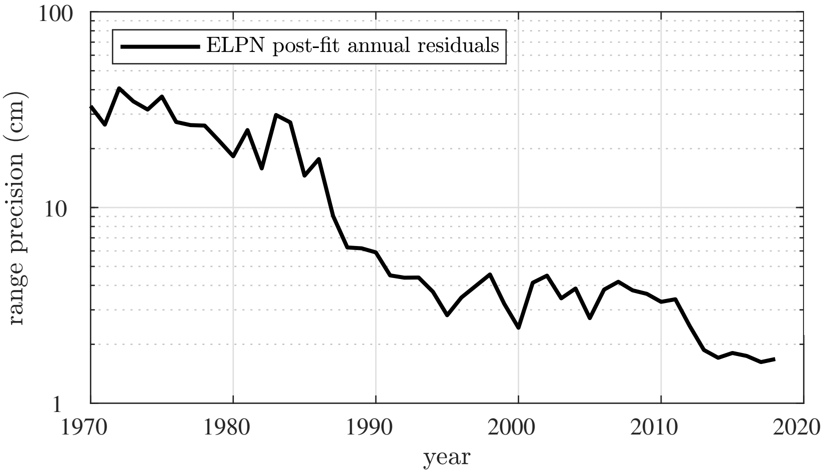

Figure 1 : Evolution of LLR annual post-fit residuals from 1970 to 2019. The theoretical prediction is computed with POLAC's lunar ephemeris ELPN computed in pure GR.

3. POLAC to test fundamental Physics

In the early 60's, under the impulse of R. H. Dicke, the LLR was motivated to conduct precise tests of Einstein's theory of gravity. At that time, the main prediction of the new Bans & Dicke scalar theory – which incorporate Mach's principle unlike GR – was the variation of the gravitational constant. It was soon recognized that the precise timing of ranges to the Moon could help to measure any variations of this constant and thus provide a test of GR. Later on, K. Nordtvedt realized that such an experiment could provide a way to test the strong equivalence principle of GR through the well-known Nordtvedt's effect. Since then, the LLR data were used at multiple occasions to put on test different aspects of Einstein's theory (Merkowitz, 2010).

Since 2016, with the elaboration of ELPN, a numerical lunar ephemeris computed either in GR or in an alternative theory of gravity, POLAC is involved in the long legacy of testing GR by analyzing LLR data. The main focus has been the search for LS breakings which is motivated by unification theories (e.g., string theory, loop quantum gravity, etc.) which all require violations of the Lorentz invariance as a basic ingredient. The LS being a fundamental symmetry of spacetime, it is thus present in GR (under a local form) and in the Standard-Model of particles physics too (under a global form). To systematically test the possibility for LS breakings, Colladay & Kostelecky, (1997; 1998) have developed a wide theoretical framework called the SME, a phenomenological framework that can be used to process data of experiments in all sector of Physics. The SME framework parametrizes all possible LS violations by means of coefficients (called the SME coefficients) whose amplitude must be determined by confrontation with experiments.

In this context, the activities of POLAC rely on the computation of ELPN in the SME framework for conducting the full LLR data processing in Colladay & Kostelecky's alternative phenomenology. Since 2016, POLAC has been able to set constraints on SME coefficients at different levels of the SME formalism. For instance, in Bourgoin *et al.*, (2016), we determined the SME coefficients $\bar{s}^{\mu\nu}$ representing LS violations in the pure gravity sector for mass dimension four operators. We showed that these are compatible with zero with an absolute precision ranging from 10^{-8} to 10^{-12}. In this way, we reported no LS violations at the level of the strong equivalence principle from the monitoring of the lunar orbit. In Bourgoin *et al.*, (2017), we determined additionally the SME coefficients $(\bar{a}_{\text{eff}})^{\mu}$ representing LS violations at the level of gravity-matter couplings. We showed that these are compatible with zero with an absolute precision at the order of 10^{-8} GeV/c^2. In this way, we reported no LS breaking at the level of the weak equivalence principle. At their time, these tests improved the determination of some SME coefficients up to three orders of magnitude with respect to previous determinations from binary pulsars, atom interferometry, etc. (see e.g., Kostelecky & Russel, 2023). More recently, in Bourgoin *et al*., (2020), we investigated the higher order operators in the pure gravity sector of the SME framework, namely the mass dimension five operators. Usually, the higher the order the shorter the scale of the deviation from GR. Therefore, higher orders terms are usually better constrained by laboratory experiments. However, when applied to the two-body problem, these new terms exhibit a perturbative acceleration that is proportional to the relative velocity between the bodies and that is inversely proportional to the cubic power of their relative separation. Such perturbations are new and do not arise neither in GR nor in the widely used Parameterized Post-Newtonian framework. All in all, it turns out that the best techniques to constrain the mass dimension five parameters are the timing of binary pulsars and LLR. By conducting the LLR data processing in the SME framework, we were able to constrain several linear combinations of the mass dimension five coefficients $q^{\mu\rho\alpha\nu\beta\sigma\gamma}$. We showed that these terms are compatible with zero with an absolute precision at the level of 10^2 m, an improvement of one to three orders of magnitude compared to the timing of binary pulsars. These works have shown that the lunar orbit is fully compatible with the predictions by GR at the current data precision.

4. Conclusion

Thanks to a close collaboration between POLAC and the LLR staff observers at Grasse station MéO in France, both experimental and theoretical aspects linked to the experiment have been improved. In a near future, we shall continue this collaborative effort in order to prepare the acquisition and the data processing of the future generation of LLR observations (new retro-reflectors, differential LLR, etc.). In this way, we expect to gain an order of magnitude gain on the data precision and hence to explore a new parameter space to search for new physics beyond GR.

Acknowledgements

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