Precise Orbit Determination of the two LAGEOS and LARES satellites and the LARASE activities

David Lucchesi[1,2,3], Roberto Peron[1,3], Luciano Anselmo[3], Massimo Bassan[4,2], Carmelo Magnafico[1,3], Anna Maria Nobili[5,6], Carmen Pardini[3], Giuseppe Pucacco[4,2], Ruggero Stanga[7,8], Massimo Visco[1,2]

[1]Istituto di Astrofisica e Planetologia Spaziali (IAPS/INAF), Via Fosso del Cavaliere 100, 00133 Roma, Italy
[2]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Tor Vergata, Via della Ricerca Scientifica 1, 00133 Roma, Italy
[3]Istituto di Scienza e Tecnologie dell'Informazione (ISTI/CNR), Via Moruzzi 1, 56124 Pisa, Italy
[4]Dipartimento di Fisica, Università di Tor Vergata, Via della Ricerca Scientifica 1, 00133 Roma, Italy
[5]Dipartimento di Fisica, Università di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[6]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[7]Dipartimento di Fisica, Università di Firenze, xxx, sss Firenze, Italy
[8]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Firenze, xxx, sss Firenze, Italy

Poster X2.307 EGU2016-15626

European Geosciences Union General Assembly 2016
Vienna | Austria | 17–22 April 2016

INTRODUCTION

The LAser RAnged Satellites Experiment (LARASE) research program (Lucchesi et al., 2015) aims to provide an original contribution in testing and verifying Einstein's theory of General Relativity (GR) in its Weak-Field and Slow-Motion (WFSM) limit by means of the powerful Satellite Laser Ranging (SLR) technique (**Lucchesi and Peron, 2010; 2014**). Therefore, in this perspective, a Precise Orbit Determination (POD) of a dedicated set of passive laser-ranged satellites is required. In particular, the joint analysis of the orbit of the two LAGEOS (LAser GEOdynamic Satellite) satellites with that of the more recently launched LARES (LAser RElativity Satellite) satellite will be exploited in order to obtain precise measurements of the gravitational interaction in the field of the Earth. A major point to be reached within the activities of LARASE is to provide the relativistic measurements with an error budget of the various systematic effects (both gravitational and non-gravitational) that be robust and reliable. This requires a careful analysis of the various disturbing effects on the orbit of the considered satellites, especially for the new LARES (Ciufolini et al., 2009). This activity has been planned both for the gravitational and the non-gravitational perturbations (NGP). Therefore, we started to re-visit, update and improve previous dynamical models, especially for the NGP, and we also developed new models in such a way to improve the current dynamical models used in space geodesy to account for the main perturbations acting on the orbit of LAGEOS and LARES. We focused especially on the spin dynamics, the drag effects (especially for LARES, because of its much lower height with respect to the two LAGEOS) and, at a preliminary level, the thermal ones that, as it is well known from the literature, are very important for the LAGEOS satellites. These studies are of fundamental importance not only for the objective of a reliable error budget, but also in order to improve the POD. In this context, because of the importance of the LAGEOS satellites in the fields of space geodesy and geophysics (and the foreseeable importance of LARES in the near future) we expect that all the geodetic products within those provided the International Laser Ranging Service (ILRS), will benefit of such improvements in order to contribute to the goal of a sub-mm precision in the Root Mean Square (RMS) of the SLR residuals with respect to the current cm precision (Pearlman et al., 2002). In this POSTER we are going to focus upon the POD results we obtained for the considered satellites within the LARASE activities. The analysis strategy and models setup will be discussed, along with the POD quality in terms of fit statistics and residuals. The current level of accuracy will be briefly assessed, along with current work for its improvement. The use of empirical accelerations will be described, as well as their removal (or minor role) in the case of the implementation in the POD software of new dynamical models.

Model for	Model type
Geopotential (static))	EIGEN-GRACE02S
Geopotential (time-varying, tides)	Ray GOT99.2
Geopotential (time-varying, non tidal)	IERS Conventions (2010)
Third-body	JPL DE-403
Relativistic corrections	Parameterized post-Newtonian (PPN)
Direct solar radiation pressure	Cannonball
Earth Albedo	Knocke-Rubincam
Earth-Yarkovsky	Rubincam (1987-1990)
Neutral drag	NRLMSISE-2000
Spin evolution	LARASE (2015)
Stations position	ITRF2008
Ocean loading	Schernek and GOT99.2 tides
Earth Rotation Parameters	IERS EOP C04
Precession	IAU 2000
Nutation	IAU 2000

TABLE 1. Current modeling setup included in GEODYN II within the LARASE analysis of laser-ranged satellites NPs.

CONCLUSIONS

The activities of LARASE are ongoing. Although our final objective is to provide refined measurements of the gravitational interaction in the field of the Earth, in such a way to tightly constrain Einstein's theory of General Relativity with respect to other alternative theories of Einstein's gravitation, a major effort of our work is to refine and improve the current dynamical models used for the satellites POD, as well as to develop new dynamical models, particularly for LARES. Such attention is devoted both to gravitational and non-gravitational disturbing effects. In particular, within this Poster we presented some of the activities and results we developed and obtained to improve the POD of the two LAGEOS and of LARES. Especially for LARES some work is still necessary in order to reach a POD at the level of the two older geodetic satellites. Such work is also important under the perspectives of space geodesy and of geophysics in order to include properly the LARES satellite as the 5th satellite among those used (the two LAGEOS and the two ETALONS) in the operational product developments of the ILRS.

Finally, Einstein's General Relativity is today considered as the standard theory for the description of the gravitational interaction, both at low and high energies scales. However, several modern theories of physics — not only new gravitational theories, but also those that aim to include General Relativity into the realm of quantum theories — suggest the existence of additional fields in mediating the gravitational interaction to complement the spacetime tensor of General Relativity. These fields may have a scalar or vector character, as well as a tensorial one. Therefore, under the very significant implications that follow from the above considerations, such as the possibility of a violation of the inverse square law and/or of the Einstein Equivalence Principle, new and more refined tests and measurements of gravitation are needed. The new experiment denominated LARASE aims to contribute to these new measurements of relativistic gravity in the WFSM limit of General Relativity with a set of new measurements that should be reliable in terms of precision and accuracy of the results to be obtained.

PRECISE ORBIT DETERMINATION (POD)

In order to improve the POD of the two LAGEOS satellites and of the newly LARES satellite we try to follow as close as possible well established Modeling Conventions, such as those from the International Earth Rotation Service (IERS) and from the International Astronomical Union (IAU), as well as the recommendations of the International Laser Ranging Service (ILRS).
A list regarding some of the aspects on which we have worked on in order to improve the POD is the following:

1. change of terrestrial frame (ITRF)	5. increase of the number of considered satellites
2. extension of the analysis period	6. Station biases estimate
3. change of the reference geopotential model	7. reconsideration of a priori observation uncertainties.
4. updated precession/nutation models	

Indeed, these points are related with three main categories in which we can divide the models used in the POD:

- those related with the Satellite dynamics
- those related with Measurement procedures
- those related with Reference Frame transformations.

For the data reduction of the satellites we used the NASA/GSFC GEODYN II code (Pavlis et al., 1998), while for the background gravitational field in the various POD we performed we used as reference the EIGEN-GRACE02S model (Reigber et al., 2005). However, several different gravity models from the GRACE and GOCE missions have been tested.
Given the current precision of SLR data — about 1 mm in the RMS of the Normal points (NPs) of the best tracked laser-ranged satellites — it would be of fundamental importance to reach a cm accuracy in the satellite orbit reconstruction, in terms of the RMS of the range residuals (observed – computed), without the use of empirical accelerations, as currently is done by the best software developed for the orbit determination and the differential correction procedure. This objective can be reached by means of the improvement of the dynamical model used for the POD of the satellites and, in particular, by the improvement of the models for the Non-Gravitational Perturbations (NGPs) and their full inclusion in the software used.
In the context of the LARASE (Lucchesi et al., 2015) research program, we begun our activities from the very beginning, i.e. by reconstructing the internal and external structure of the satellites from the original drawings (Visco and Lucchesi, 2016), by developing a new and refined model for their spin-axis evolution (paper in preparation), and by attacking the issue of an overall reliable thermal model of the considered satellites (paper in preparation). Indeed, before the measurements of the general relativity effects on the orbit of the satellites, our goal is to achieve a precise and accurate POD of the two LAGEOS satellites and of LARES (paper in preparation).
In Figure 1, we compare the range residuals and their corresponding RMS for the two LAGEOS satellites and for LARES, while in Table 1 are shown the models implemented in the GEODYN II software.
The orbit determinations shown in Figure 1 correspond to our current best results with regard the POD of these three geodetic satellites. However, such POD is not yet optimized neither for the measurements in the field of geophysics nor for the relativistic ones. In Figure 2 we compare our current best POD for the three satellites with respect to their best POD as obtained in 2015. In all these POD, the empirical accelerations have been included in the models of GEODYN II. Conversely, in Figure 3 are shown two POD of LAGEOS and LAGEOS II where the empirical accelerations have not been used but where the spin axis evolution of the two satellites has been modeled with the LARASE Spin Model in the rapid-spin approximation (Visco et al., 2016 Poster X2-308) in order to account of the Earth-Yarkovsky thermal-thrust effect. These POD are compared with those obtained when the spin was not considered within the GEODYN II models. Finally, in Figure 4 we show the decay we observed in the semi-major axis residuals of LARES. The observed decay can be almost all explained in terms of the neutral drag perturbation (Pardini et al., 2016 Oral presentation); however, a residual acceleration is still present, probably related to thermal effects.

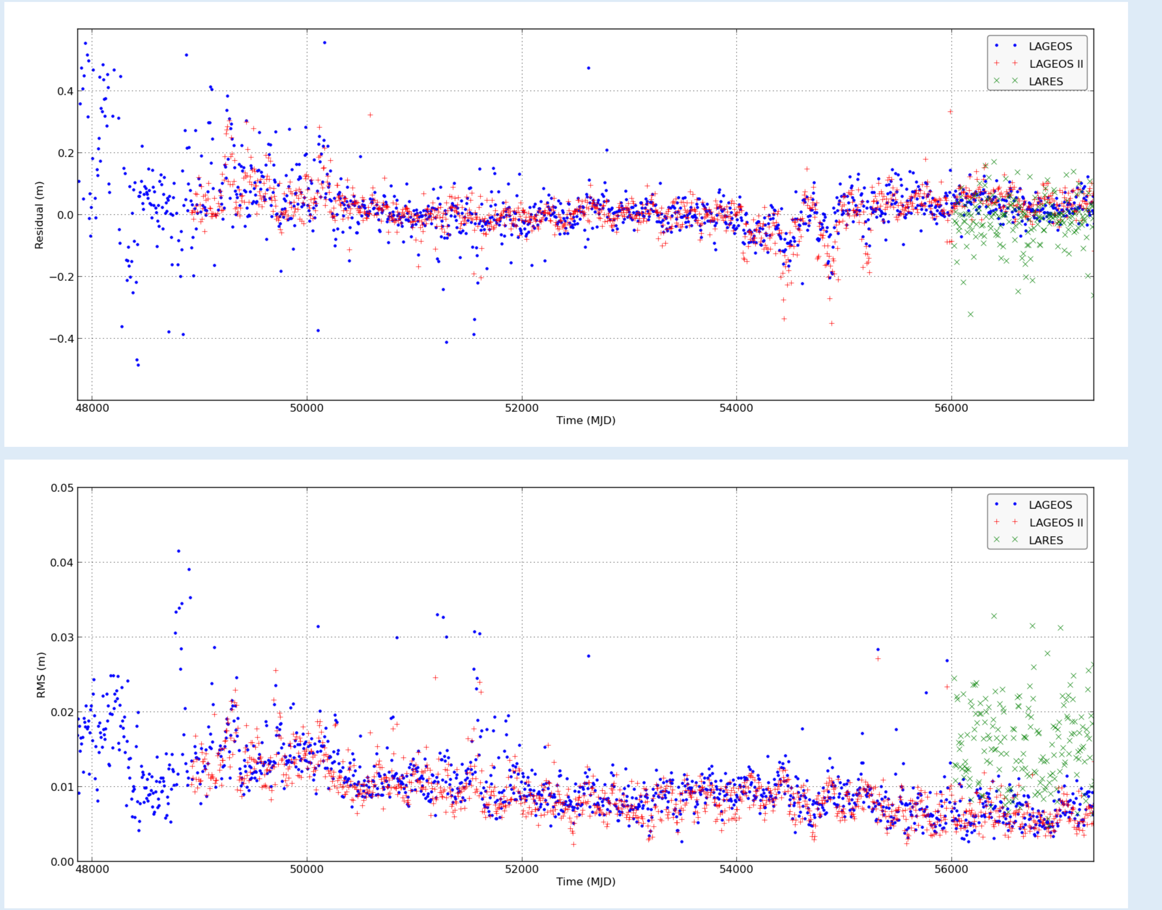

FIGURE 1. Mean of the range residuals (TOP) and their corresponding RMS (BOTTOM) for the three considered satellites: LAGEOS (blue), LAGEOS II (red) and LARES (green). The starting epoch is MJD 47868 (December 8, 1989) for LAGEOS, MJD 48932 (November 13, 1992) for LAGEOS II and MJD 56023 (April 6, 2012) for LARES. The final epoch is December 25, 2015, for all three satellites. In the case of LAGEOS we obtained a mean of about 2.2 cm for the residuals and a RMS of about 1 cm. In the case of LAGEOS II the residuals have a mean of about 1 cm with a RMS of 0.9 cm. Finally, for LARES residuals we obtained a mean value close to -2 cm with a RMS of about 1.7 cm. Empirical accelerations have been estimated over an arc length of 7 days.

FIGURE 2. RMS of LAGEOS (TOP), LAGEOS II (MIDDLE) and LARES (BOTTOM). The colored RMS are the same of Figure 1. Top: current (2016) best POD of LAGEOS (blue) compared with the best POD obtained in 2015 (black); the current mean RMS is about 1 cm vs 2.1 cm of previous analysis. Middle: current (2016) best POD of LAGEOS II (red) compared with the best POD obtained in 2015 (black); the current mean RMS is about 0.9 cm vs 1.8 cm of previous analysis. Bottom: current (2016) best POD of LARES (green) compared with the best POD obtained in 2015 (black); the current mean RMS is about 1.7 cm vs 3.7 cm of previous analysis. Empirical accelerations have been always estimated. The improvements for the three satellite with the new analysis reflects the activities performed within LARASE in order to refine continuously the satellites data reduction and their orbit best fit.

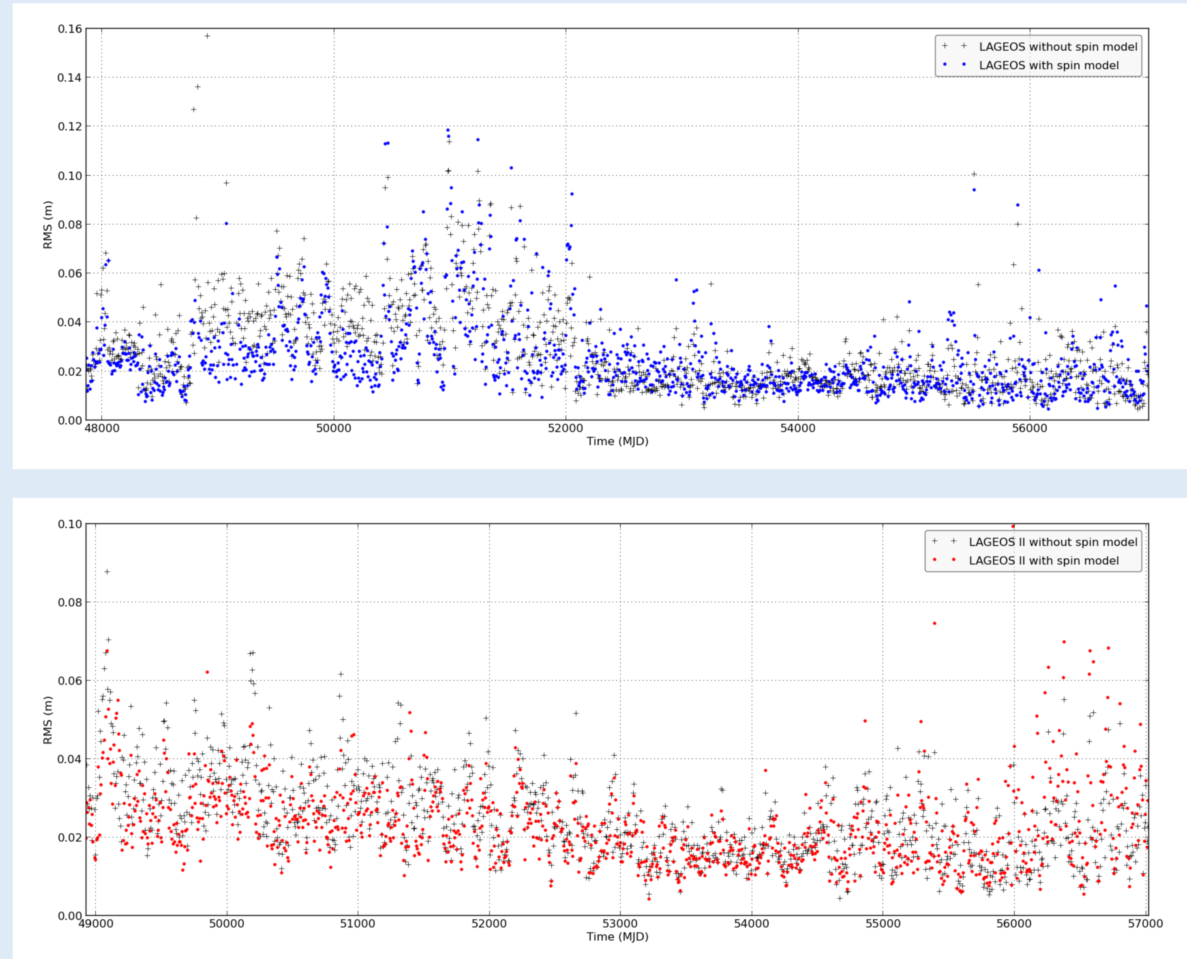

FIGURE 3. TOP: RMS (blue) of LAGEOS range residuals obtained modeling the Earth-Yarkovsky thermal-thrust effect by means of the LARASE Spin Model compared with the RMS (black) obtained when neglecting the thermal-thrust perturbation produced by Earth's infrared radiation. BOTTOM: the same RMS comparison in the case of LAGEOS II. The mean value of the RMS is close to 2.5 cm in the case of LAGEOS when modeling the Earth-Yarkovsky effect with the LARASE Spin Model, compared to 2.8 cm when the thermal effect is not included in the GEODYN II setup. Conversely, in the case of LAGEOS II, the mean RMS is about 2.2 cm when the effect is modeled vs 2.5 cm when the effect is not modeled. In these analyses the empirical accelerations have been not included in the GEODYN II models.

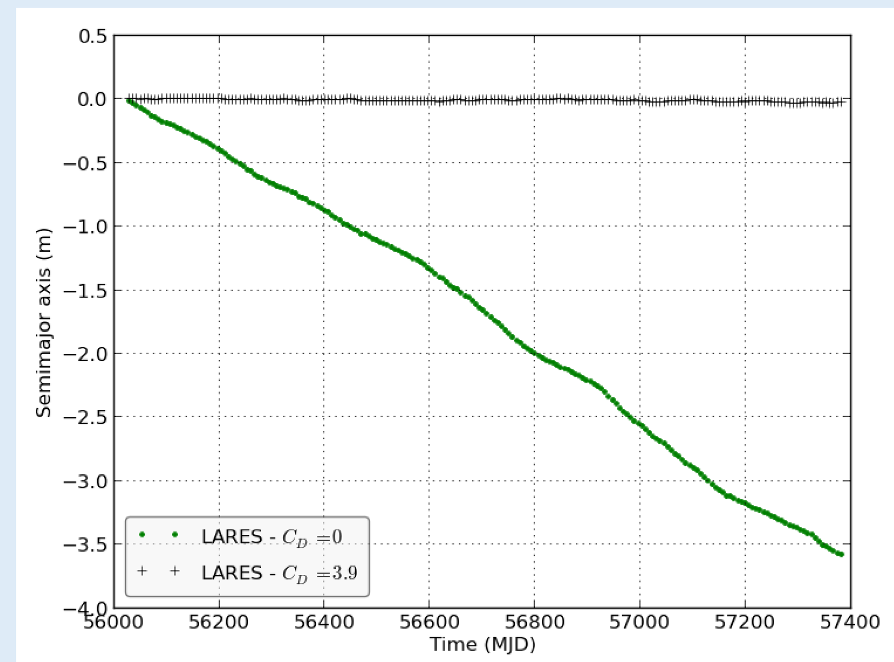

FIGURE 4. The observed decay of LARES semi-major axis residuals (green) compared to the decay obtained (black) by modeling the neutral drag perturbation in GEODYN II and adjusting at the same time the satellite drag coefficient CD from an a priori value. The time span of the analysis is about 3.7 yr. In the first data reduction the drag coefficient was set to zero, while in the second data reduction the estimated value for the drag coefficient is about 3.9. The observed decay of LARES semi-major axis residuals is about 0.9988 m/yr (i.e., about 2.7 mm/day!). Such decay corresponds to an average along-track deceleration of about $1.444 \cdot 10^{-11}$ m/s^2. Very interesting, after modeling the neutral drag perturbation in GEODYN II, we still observe a residual decay that corresponds to an average deceleration of about $2 \cdot 10^{-13}$ m/s^2. Probably, the thermal-thrust effects come to play a role at this level.

REFERENCES

- Ciufolini I., Paolozzi A., Pavlis E.C., Ries J.C., Koenig R., Matzner R.A., Sindoni G. and Neumayer H.: Towards a One Percent Measurement of Frame Dragging by Spin with Satellite Laser Ranging to LAGEOS, LAGEOS 2 and LARES and GRACE Gravity Models. Space Sci. Rev. 148 71-104 (2009)
- Lucchesi, D.M., Peron, R.: Accurate Measurement in the Field of the Earth of the General-Relativistic Precession of the LAGEOS II Pericenter and New Constraints on Non-Newtonian Gravity. Phys. Rev. Lett. 105(23), 231,103 (2010). DOI 10.1103/PhysRevLett.105.231103
- Lucchesi, D.M., Peron, R.: LAGEOS II pericenter general relativistic precession (1993-2005): Error budget and constraints in gravitational physics. Phys. Rev. D 89(8), 082002 (2014). DOI 10.1103/PhysRevD.89.082002
- Lucchesi, D.M., Anselmo, L., Bassan, M., Pardini, C., Peron, R., Pucacco, G., Visco, M.: Testing the gravitational interaction in the field of the Earth via satellite laser ranging and the Laser Ranged Satellites Experiment (LARASE). Class. Quantum Grav. 32(15), 155012 (2015). DOI 10.1088/0264-9381
- Pardini, C., Anselmo, L., Lucchesi, D.M., Bassan, M., Magnafico, C., Nobili, A.M., Peron, R., Pucacco, G., Stanga, R., Visco, M.: The orbital decay of the semi-major axis of LARES and the LARASE. contribution to SLR measurements for applications in the fields of space geodesy and geophysics. Vol. 18, EGU2016-14231, 2016. Oral presentation G6.1
- Pavlis, D.E., et al.: GEODYN II Operations Manual. NASA GSFC (1998)
- Pearlman, M.R., Degnan, J.J., Bosworth, J.M.: The International Laser Ranging Service. Adv. Space Res. 30, 135–143 (2002)
- Reigber, C., Schmidt, R., Flechtner, F., K¨onig, R., Meyer, U., Neumayer, K.H., Schwintzer, P., Zhu, S.Y.: An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S. J. Geodyn. 39, 1–10 (2005). DOI 10.1016/j.jog.2004.07.001
- Visco, M., Lucchesi, D.: Review and critical analysis of mass and moments of inertia of the LAGEOS and LAGEOS II satellites for the LARASE program. Adv. Space Res. (2016). DOI 10.1016/j.asr.2016.02.006
- Visco, M., Lucchesi, D.M., Anselmo, L., Bassan, M., Magnafico, C., Nobili, A.M., Pardini, C., Peron, R., Pucacco, G., Stanga, R.:The LARASE Spin Model of the two LAGEOS and LARES satellites. Vol. 18, EGU2016-8304, 2016. Poster X2-308, Session G6.1