Workshop sulla Gravitazione Sperimentale: misure laser, fisica fondamentale e applicazioni in INFN-CSN2

12 e 13 Novembre 2020

SaToR-G: collaborazioni e prospettive

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Outline: collaborations and perspectives

- The SaToR-G Team
- Space Flight Dynamics Laboratory (ISTI/CNR)
  - Results of the LARASE experiment: Part III
- International Laser Ranging Service (ILRS)
  - LARASE as an Associated Analysis Center (AAC)
- National Scientific Committee 2 (CSN2)
  - MoonLIGHT-2
  - GINGER

The SaToR-G Team

- IAPS/INAF
  - David Lucchesi
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  - Carmelo Magnafico
  - Roberto Peron
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  - Massimo Bassan
  - Giuseppe Pucacco
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  - Luciano Anselmo
  - Carmen Pardini

Space Flight Dynamics (SFD) Laboratory

Since 1975, the laboratory provided flight dynamics support to national and international space projects, covering new or very specific topics and tasks not suitable for industry involvement

In order to maintain a competitive edge in a rapidly changing environment, the areas of interest and the expertise progressively evolved, adapting to changing needs, innovative technologies and new problems

For these reasons, since the 1980s the laboratory has progressively focused its interests on the uncontrolled satellite re-entry predictions for civil protection applications, on space debris modeling, mitigation and remediation in support of the sustainable utilization of circumterrestrial space, and on the use of accurate satellite tracking and astrodynamics techniques for fundamental physics research

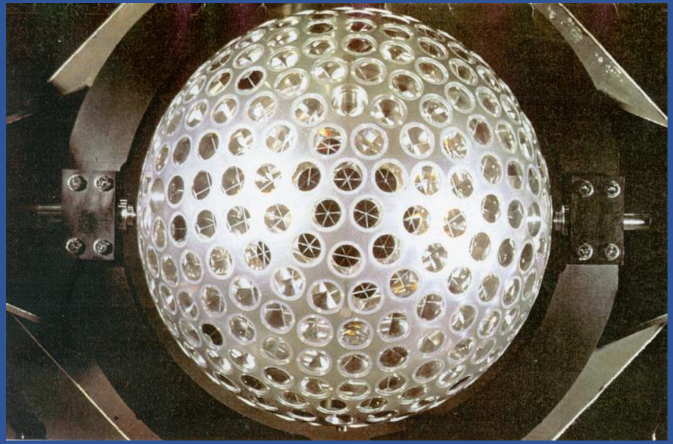
Space Flight Dynamics (SFD) Laboratory

Among the main activities:

- Flight Control Systems
- Mission Analysis and Design
- Mission Planning and Operations
- Orbital Dynamics
- Reentry Predictions of Risk Space Objects
- Space Debris Modeling
- Stratospheric Balloons Flight Dynamics
- Astrodynamics for Fundamental Physics Applications

Space Flight Dynamics (SFD) Laboratory

On October 22, 1992, NASA and ASI launched LAGEOS II. The satellite was launched from the Space Shuttle Columbia cargo bay by the IRIS (Italian Research Interim Stage) propulsion system.
IRIS was able to transfer LAGEOS II to a height of about 5900 km and was built by Alenia and Snia Bpd (ex Fiat group) for the engine part



The researchers of the SFD Laboratory were strongly involved in all these activities for the ASI side:

- investigation of the feasibility of the mission
- mission profile
- strategy for the LAGEOS II orbital maneuvers
- analysis of the statistical distribution of the final orbital parameters as a function of the performance characteristics of the apogee and perigee stages

Space Flight Dynamics (SFD) Laboratory

The SFD Laboratory has been part of the LARASE experiment since its inception, and now is part of the SaToR-G experiment. Up to now the collaboration has mainly (but not only) focused on the analysis of the Non-Gravitational Perturbations (NGP) on the orbits of the satellites considered and, in particular, on that of LARES

The main activity has been the investigation of the impact of the neutral atmosphere on the orbit of LARES

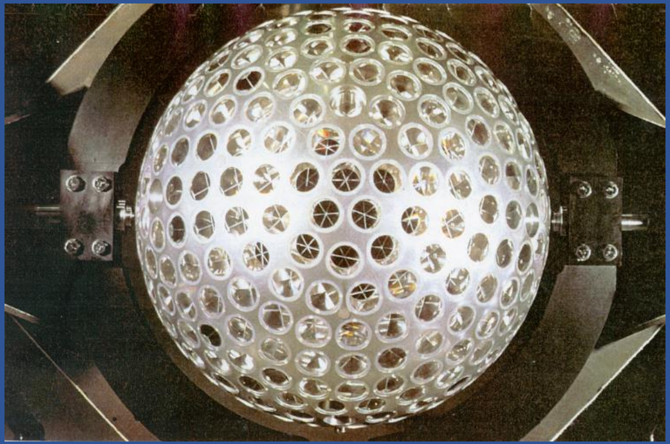
Results of the LARASE experiment: Part III

The effects of the neutral atmosphere on the orbit of LARES

Neutral drag

LAser **RE**lativity **S**atellite

LAGEOS (NASA 1976)
LAGEOS II (NASA/ASI 1992)
LARES (ASI 2012)



LAser **GEO**dynamic **S**atellite
LAGEOS II

Parameter		LARES	LAGEOS	LAGEOS II
a	[km]	7 820	12 270	12 163
e		0.001	0.004	0.014
I	[deg]	69.5	109.8	52.7
R	[cm]	18.2	30	30
M	[kg]	386.8	406.9	405.4
A/M	[m2/kg]	$2.69 \cdot 10^{-4}$	$6.94 \cdot 10^{-4}$	$6.97 \cdot 10^{-4}$

The accurate modeling of both gravitational and non-gravitational perturbations, coupled with a range accuracy approaching 1 cm, makes it possible an orbit determination of comparable accuracy

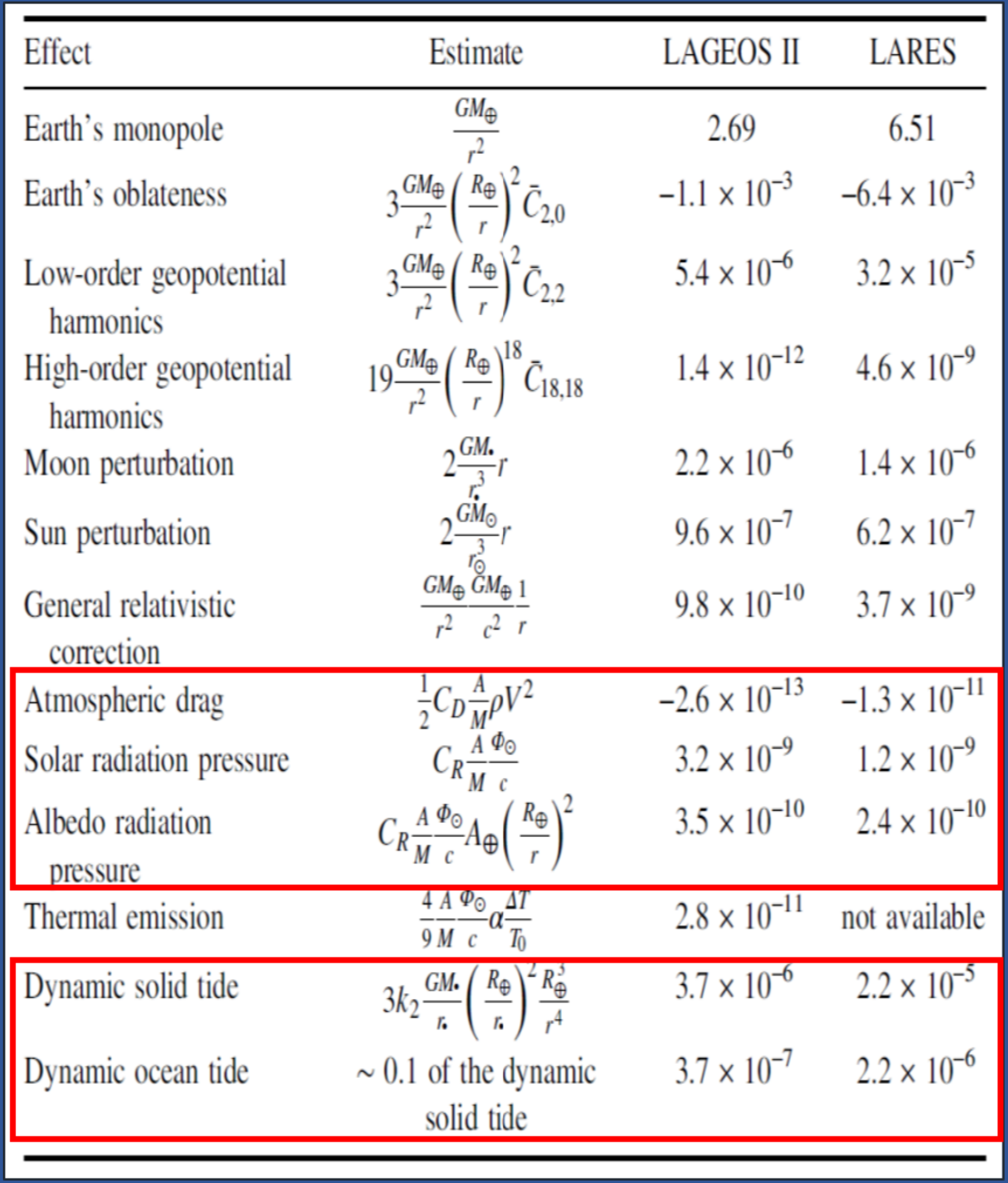
$$\left.\frac{A}{M}\right|_{Lares} \cong \frac{1}{2.6}\left.\frac{A}{M}\right|_{Lageos}$$

	LARES	LAGEOS
material	Tungsten	Al/Brass/Be/Cu
CCR (suprasil 311)	92	422 + 4
bin	30 s	120 s

Neutral drag

LARES

- Despite the smaller A/M ratio, the non-gravitational accelerations are not always smaller in magnitude for LARES with respect to LAGEOS II (or LAGEOS), due to the lower height (1450 vs. 5900 km) and the higher density of neutral atmosphere
- The drag of the neutral atmosphere on LARES is 50 times larger than on the two LAGEOS, therefore its modeling needs special attention, because it might mask the presence of smaller and subtler effects



Effect	Estimate	LAGEOS II	LARES
Earth's monopole	$\frac{GM_\oplus}{r^2}$	2.69	6.51
Earth's oblateness	$3\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^2\bar{C}_{2,0}$	-1.1×10^{-3}	-6.4×10^{-3}
Low-order geopotential harmonics	$3\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^2\bar{C}_{2,2}$	5.4×10^{-6}	3.2×10^{-5}
High-order geopotential harmonics	$19\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^{18}\bar{C}_{18,18}$	1.4×10^{-12}	4.6×10^{-9}
Moon perturbation	$2\frac{GM_{\leftmoon}}{r_{\leftmoon}^3}r$	2.2×10^{-6}	1.4×10^{-6}
Sun perturbation	$2\frac{GM_\odot}{r_\odot^3}r$	9.6×10^{-7}	6.2×10^{-7}
General relativistic correction	$\frac{GM_\oplus}{r^2}\frac{GM_\oplus}{c^2}\frac{1}{r}$	9.8×10^{-10}	3.7×10^{-9}
Atmospheric drag	$\frac{1}{2}C_D\frac{A}{M}\rho V^2$	-2.6×10^{-13}	-1.3×10^{-11}
Solar radiation pressure	$C_R\frac{A}{M}\frac{\Phi_\odot}{c}$	3.2×10^{-9}	1.2×10^{-9}
Albedo radiation pressure	$C_R\frac{A}{M}\frac{\Phi_\odot}{c}A_\oplus\left(\frac{R_\oplus}{r}\right)^2$	3.5×10^{-10}	2.4×10^{-10}
Thermal emission	$\frac{4}{9}\frac{A}{M}\frac{\Phi_\odot}{c}\alpha\frac{\Delta T}{T_0}$	2.8×10^{-11}	not available
Dynamic solid tide	$3k_2\frac{GM_{\leftmoon}}{r_{\leftmoon}}\left(\frac{R_\oplus}{r_{\leftmoon}}\right)^2\frac{R_\oplus^3}{r^4}$	3.7×10^{-6}	2.2×10^{-5}
Dynamic ocean tide	~ 0.1 of the dynamic solid tide	3.7×10^{-7}	2.2×10^{-6}

Neutral drag

In the early 1980’s it was a puzzling problem to explain the unexpected decay of LAGEOS semimajor axis:

- Indeed, the neutral atmosphere was not expected to produce the observed decay of about −1.1 mm/day

Celest. Mech. 26, 361-382 (1982)

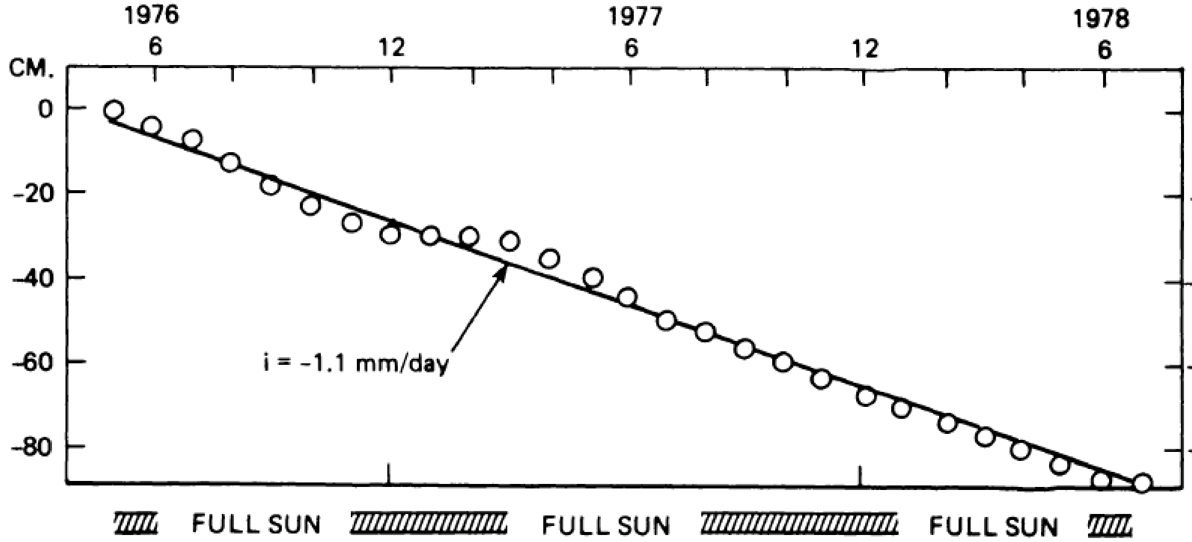
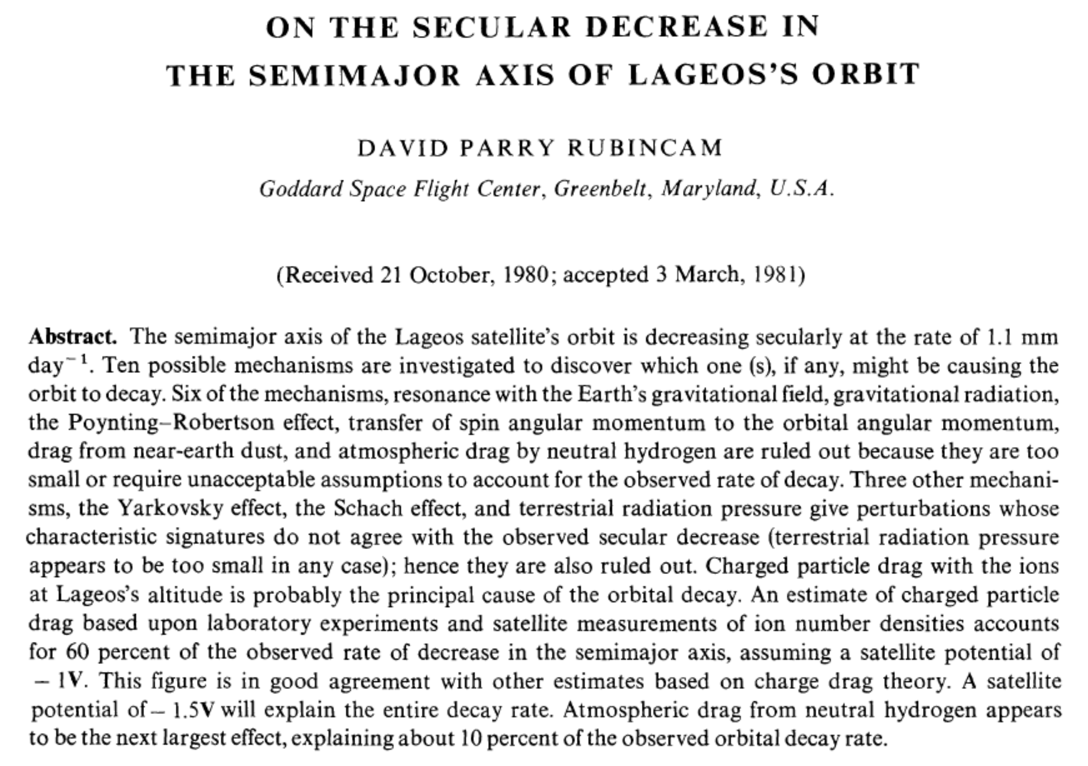


Fig. 1. The secular decrease in the semimajor axis of Lageos’s orbit. The straight line fitted through the data points has a slope of -1.1 mm day^{-1}. When the orbit is in full sunlight and shadow is shown along the horizontal axis.



ON THE SECULAR DECREASE IN THE SEMIMAJOR AXIS OF LAGEOS’S ORBIT

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(Received 21 October, 1980; accepted 3 March, 1981)

Abstract. The semimajor axis of the Lageos satellite’s orbit is decreasing secularly at the rate of 1.1 mm day^{-1}. Ten possible mechanisms are investigated to discover which one (s), if any, might be causing the orbit to decay. Six of the mechanisms, resonance with the Earth’s gravitational field, gravitational radiation, the Poynting–Robertson effect, transfer of spin angular momentum to the orbital angular momentum, drag from near-earth dust, and atmospheric drag by neutral hydrogen are ruled out because they are too small or require unacceptable assumptions to account for the observed rate of decay. Three other mechanisms, the Yarkovsky effect, the Schach effect, and terrestrial radiation pressure give perturbations whose characteristic signatures do not agree with the observed secular decrease (terrestrial radiation pressure appears to be too small in any case); hence they are also ruled out. Charged particle drag with the ions at Lageos’s altitude is probably the principal cause of the orbital decay. An estimate of charged particle drag based upon laboratory experiments and satellite measurements of ion number densities accounts for 60 percent of the observed rate of decrease in the semimajor axis, assuming a satellite potential of -1V. This figure is in good agreement with other estimates based on charge drag theory. A satellite potential of -1.5V will explain the entire decay rate. Atmospheric drag from neutral hydrogen appears to be the next largest effect, explaining about 10 percent of the observed orbital decay rate.

Neutral drag

After some years the observed decay was explained in terms of:

- Thermal thrust effects (mainly Earth-Yarkovsky effect) ≈ 70%
- Charged particle drag ≈ 16%
- Neutral drag ≈ 14%

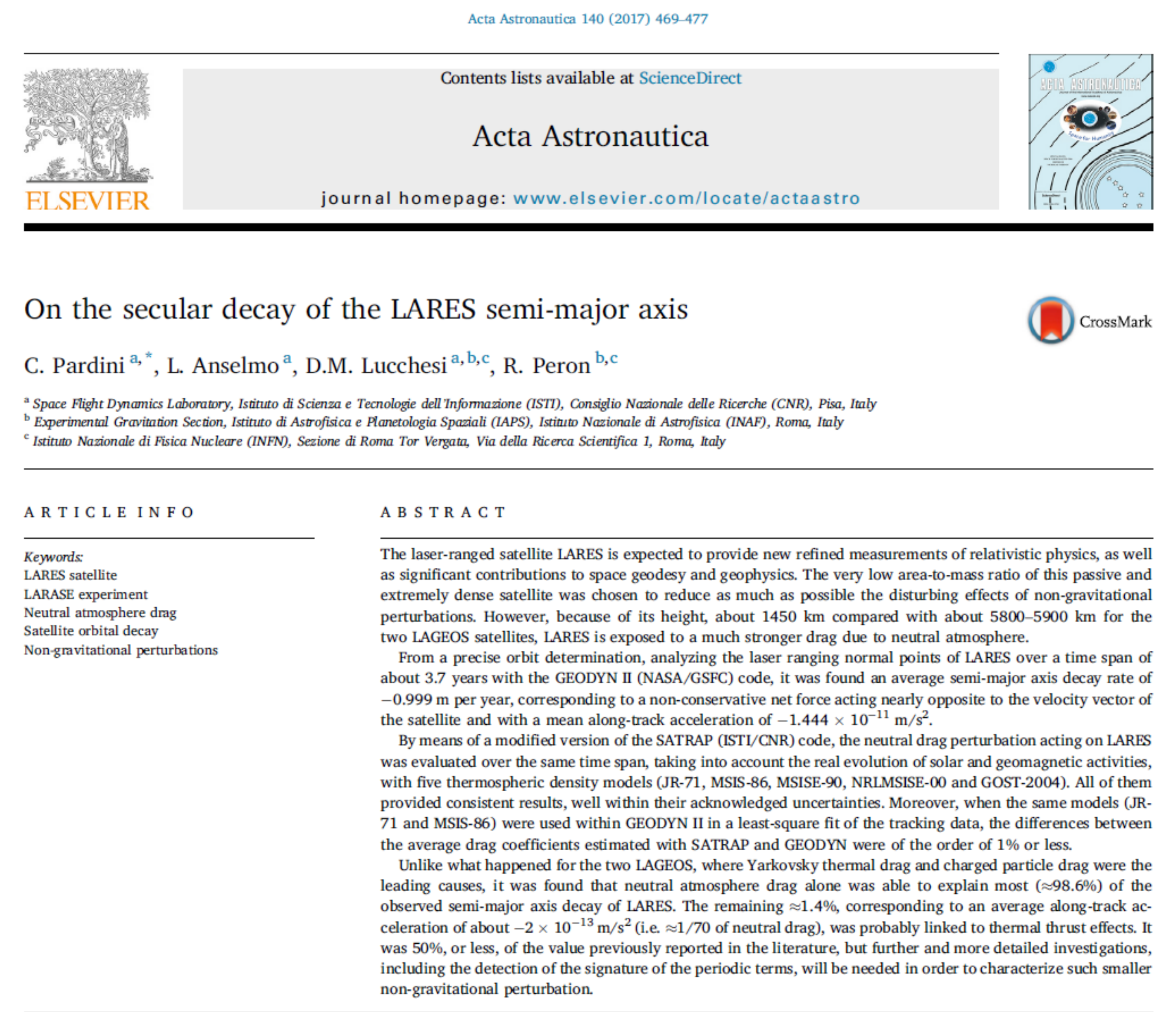
In the case of LARES, because of its lower height (about 1450 km vs. 5900), it was reasonable to expect a main contribution from the neutral drag, with some differences due to:

- Its smaller A/M, that minimize the NGP
- Its different composition (tungsten vs. aluminum)

Neutral drag

Within the activities of LARASE, since we are interested in improving the modeling of the NGP of the two LAGEOS and LARES satellites, we started to study the effects of the neutral atmosphere on the orbit of LARES, starting from its semimajor axis behavior with two different S/W:

- GEODYN II (NASA/GSFC)
- SATRAP (ISTI/CNR)



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On the secular decay of the LARES semi-major axis

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ABSTRACT

The laser-ranged satellite LARES is expected to provide new refined measurements of relativistic physics, as well as significant contributions to space geodesy and geophysics. The very low area-to-mass ratio of this passive and extremely dense satellite was chosen to reduce as much as possible the disturbing effects of non-gravitational perturbations. However, because of its height, about 1450 km compared with about 5800–5900 km for the two LAGEOS satellites, LARES is exposed to a much stronger drag due to neutral atmosphere.

From a precise orbit determination, analyzing the laser ranging normal points of LARES over a time span of about 3.7 years with the GEODYN II (NASA/GSFC) code, it was found an average semi-major axis decay rate of −0.999 m per year, corresponding to a non-conservative net force acting nearly opposite to the velocity vector of the satellite and with a mean along-track acceleration of -1.444×10^{-11} m/s^2.

By means of a modified version of the SATRAP (ISTI/CNR) code, the neutral drag perturbation acting on LARES was evaluated over the same time span, taking into account the real evolution of solar and geomagnetic activities, with five thermospheric density models (JR-71, MSIS-86, MSISE-90, NRLMSISE-00 and GOST-2004). All of them provided consistent results, well within their acknowledged uncertainties. Moreover, when the same models (JR-71 and MSIS-86) were used within GEODYN II in a least-square fit of the tracking data, the differences between the average drag coefficients estimated with SATRAP and GEODYN were of the order of 1% or less.

Unlike what happened for the two LAGEOS, where Yarkovsky thermal drag and charged particle drag were the leading causes, it was found that neutral atmosphere drag alone was able to explain most (≈98.6%) of the observed semi-major axis decay of LARES. The remaining ≈1.4%, corresponding to an average along-track acceleration of about -2×10^{-13} m/s^2 (i.e. ≈1/70 of neutral drag), was probably linked to thermal thrust effects. It was 50%, or less, of the value previously reported in the literature, but further and more detailed investigations, including the detection of the signature of the periodic terms, will be needed in order to characterize such smaller non-gravitational perturbation.

Neutral drag

What were our goals in this study?

1. Define as clearly as possible the impact of the neutral drag on the orbit of LARES and, in particular, its signature on the different orbital elements
2. Verify independently by means of SATRAP the validity of atmospheric models currently implemented in GEODYN
3. Point out the characteristics of the final residuals in the different elements with the aim of highlighting the nature of further perturbations not modeled in GEODYN
4. Develop new perturbative models in order to improve the POD of the satellite and, at the same time, the precision and accuracy of measurements in the field of Fundamental Physics

Neutral drag

First step in this study

- From a POD of LARES over a time span of about 3.7 years, we measured a mean orbital decay in the residuals of its semi-major axis of about –1 m/year, i.e. –2.74 mm/d
- This POD has been obtained analyzing the LARES normal points with the GEODYN II (NASA/GSFC) software
- Neither the neutral and charged atmosphere drag, nor the thermal effects, have been included in the dynamical models
- The corresponding unmodeled mean transversal acceleration of about -1.444×10^{-11} m/s^2 then includes all the effects of the perturbations not taken into account in the POD and eventually giving a secular and/or long-period contribution to the transversal acceleration component

The first line of attack was therefore the accurate modeling of neutral atmosphere drag, in order to evaluate how much of the unaccounted for acceleration can be explained by current thermospheric density models

Neutral drag

Second step in this study

- A modified version of the SATRAP tool, developed at ISTI/CNR, was used to compute the neutral drag acceleration acting on LARES, as a function of time, taking into account the real evolution of solar and geomagnetic activities and the observed secular semi-major axis decay

- Several thermospheric density models were used within SATRAP to compute the components of the neutral drag acceleration in the reference system R (Radial), T (Transverse) and W (Out-of-Plane): JR-71, MSIS-86, MSISE-90, NRLMSISE-00, GOST-2004 and JB2008

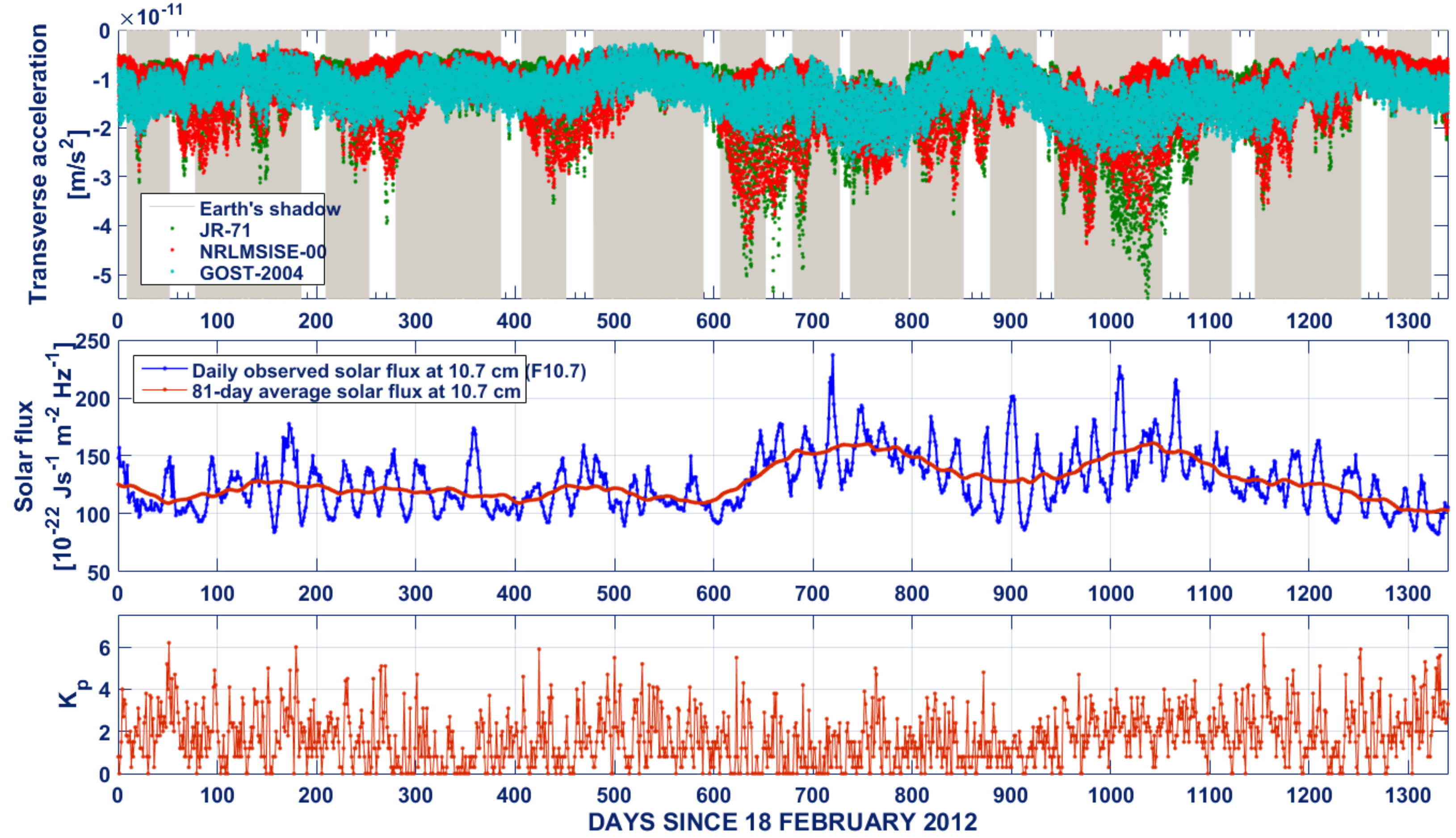
- The analysis covered the first 3.7 years of LARES in orbit and the drag coefficient C_D (a dimensionless quantity which summarizes the interaction of the atmospheric molecules with the surface of the satellite) was adjusted, for each atmospheric density model, in order to reproduce the average decay of the semi-major axis by –2.74 mm/d (–0.9988 m/year), obtained through the analysis of the residuals of the GEODYN II precise orbit determination

$$\vec{\mathcal{A}}_{drag} = -\frac{1}{2}\frac{A}{M}\rho C_D V_r^2 \hat{V}_r$$

$$\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}}\left[T + e(T\cos f + R\sin f)\right]$$

Neutral drag

First analysis on 3.7 years



Neutral drag

For each thermospheric density model used in the analysis, the following mean adjusted drag coefficients were obtained, in order to reproduce the observed semi-major axis decay of LARES over the first 3.7 years of flight:

- JR-71 → $\langle C_D \rangle = 3.95$
- MSIS-86 → $\langle C_D \rangle = 3.71$
- MSISE-90 → $\langle C_D \rangle = 3.73$
- NRLMSISE-00 → $\langle C_D \rangle = 3.78$
- GOST-2004 → $\langle C_D \rangle = 4.21$
- JB2008 → $\langle C_D \rangle = 3.03$

In this analysis the measured decay was accounted for through the unmodeled transversal acceleration previously estimated with GEODYN; here, considering 3 independent atmospheric models we obtained $C_D = 4.0 \pm 0.2$.

The error provided takes into account the variability of the result according to the atmospheric model considered in the analysis

However, considering the same models implemented in GEODYN, i.e. MSIS-86 and JR-71, the differences were of the order of 1%, or less

- The average drag coefficient among the first 5 models was 3.88, with a maximum discrepancy of 8.6%, but MSIS-86, MSISE-90 and NRLMSISE-00 have a common heritage and are very similar
- Taking the average between JR-71, NRLMSISE-00 and GOST-2004, the mean drag coefficient resulted to be 3.98, with a maximum discrepancy of 5.8%
- The differences are well below the intrinsic uncertainties of the models, around 15% (or more)
- The mean densities computed with GOST-2004 were approximately 30% less than those estimated with JB2008

Neutral drag

Third step in this study: Further analysis with GEODYN (black dots) modeling the neutral drag and adjusting the drag coefficient C_D:

- JR-71 → $\langle C_D \rangle \cong 3.96$
- MSIS-86 → $\langle C_D \rangle \cong 3.76$

Three consequences:

1. the results are in good agreement with those obtained with SATRAP (3.95 and 3.71)
2. the model of the neutral atmosphere is able to explain ≈ 98.6% of the observed decay
3. a residual decay is still present:

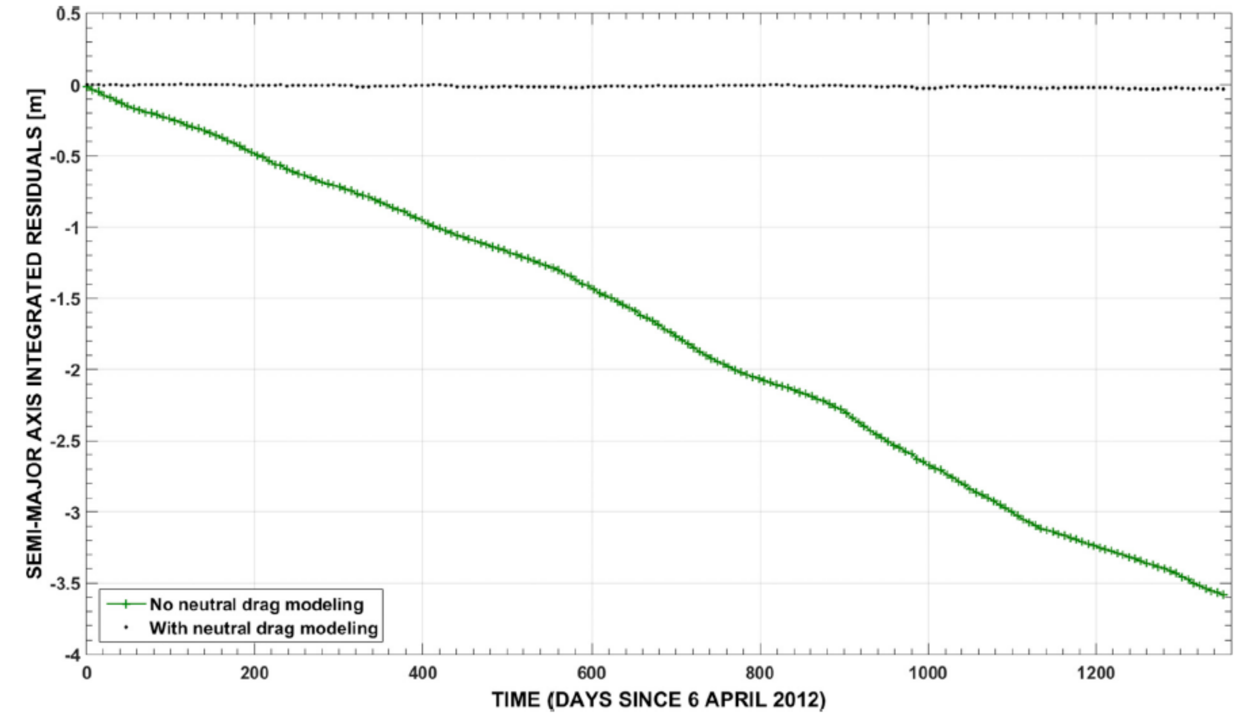


Fig. 8. Semi-major axis cumulative residuals of LARES determined with a precise orbit estimation over 3.7 years using GEODYN II. In one data reduction the neutral atmosphere was not considered, setting to zero the drag coefficient, while in the other data reduction the neutral atmosphere was included and the drag coefficient was a solve for parameter in the differential correction estimation process. The dramatic reduction of the semi-major axis residuals confirmed the overwhelming role played by neutral atmosphere drag in the case of LARES.

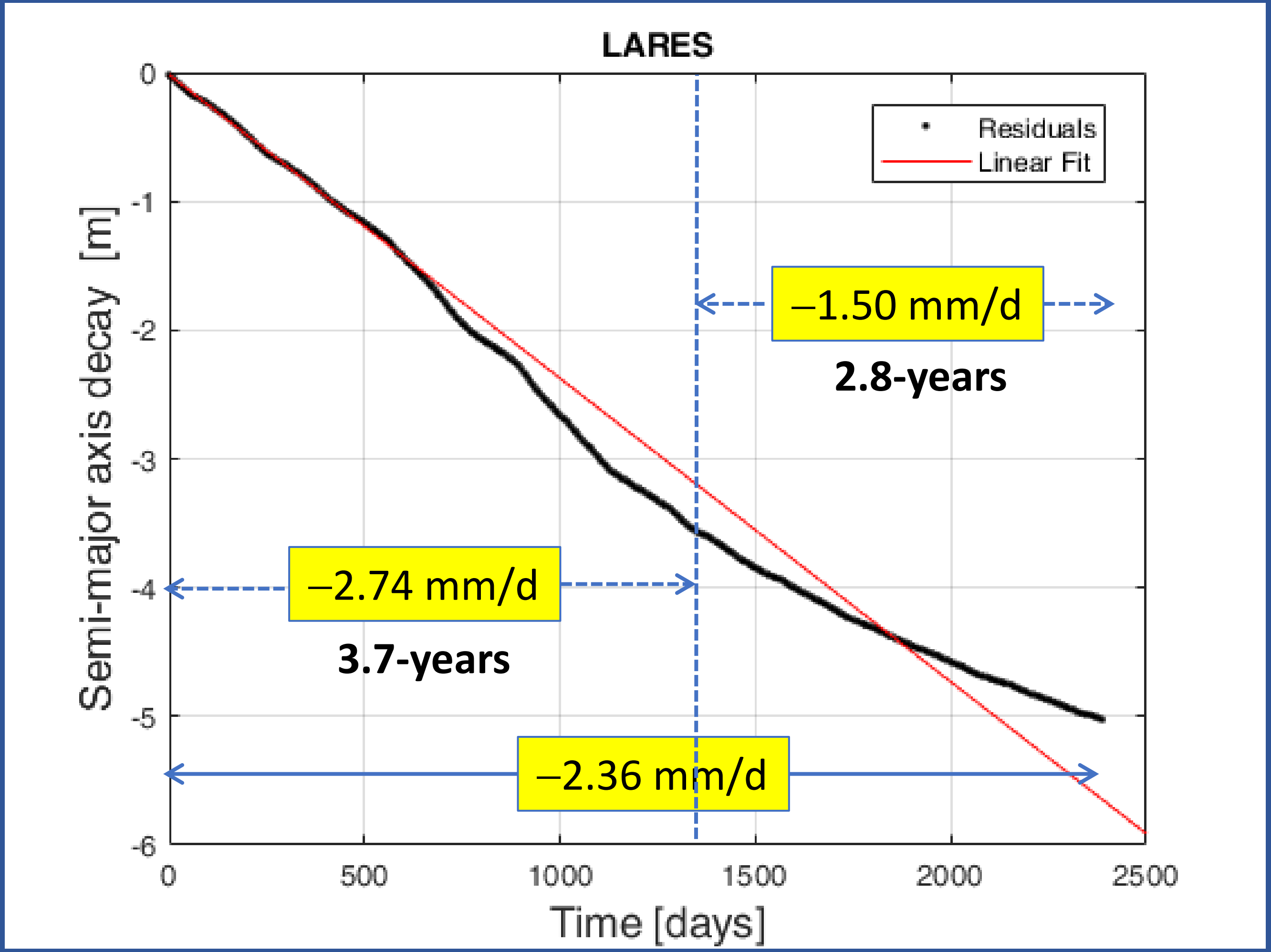
$$\langle T \rangle \cong -2.13 \times 10^{-13} m/s^2$$

about 1.4% of the drag observed for the neutral atmosphere

Neutral drag

Fourth step in this study

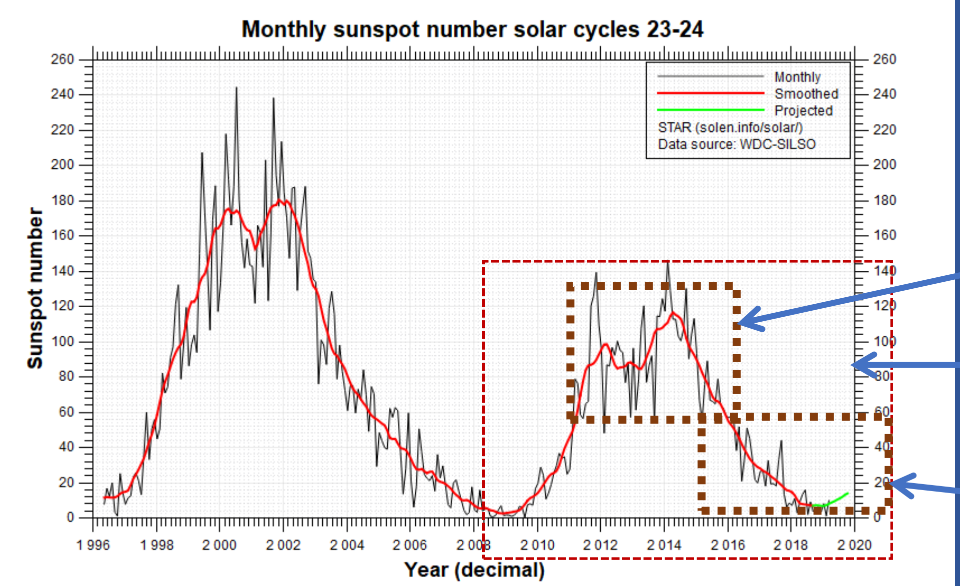
Extended analysis on a time span of about 6.5 years (April 6, 2012 → October 26, 2018)



The smaller decay is due to decrease of the solar activity during the time span of the analysis:

- In the overall 6.5 years, an average variation of the semi-major axis of about –2.36 mm/d was observed, corresponding to an average transverse acceleration of about -1.246×10^{-11} m/s^2
- In the first 3.7 years, an average variation of the semi-major axis of about –2.74 mm/d, corresponding to an average transverse acceleration of about -1.444×10^{-11} m/s^2
- In the last 2.8 years, an average variation of the semi-major axis of about –1.50 mm/d, corresponding to an average transverse acceleration of about -7.9×10^{-12} m/s^2
- Much of this acceleration can be explained by several models of the neutral atmosphere by adjusting the drag coefficient C_D

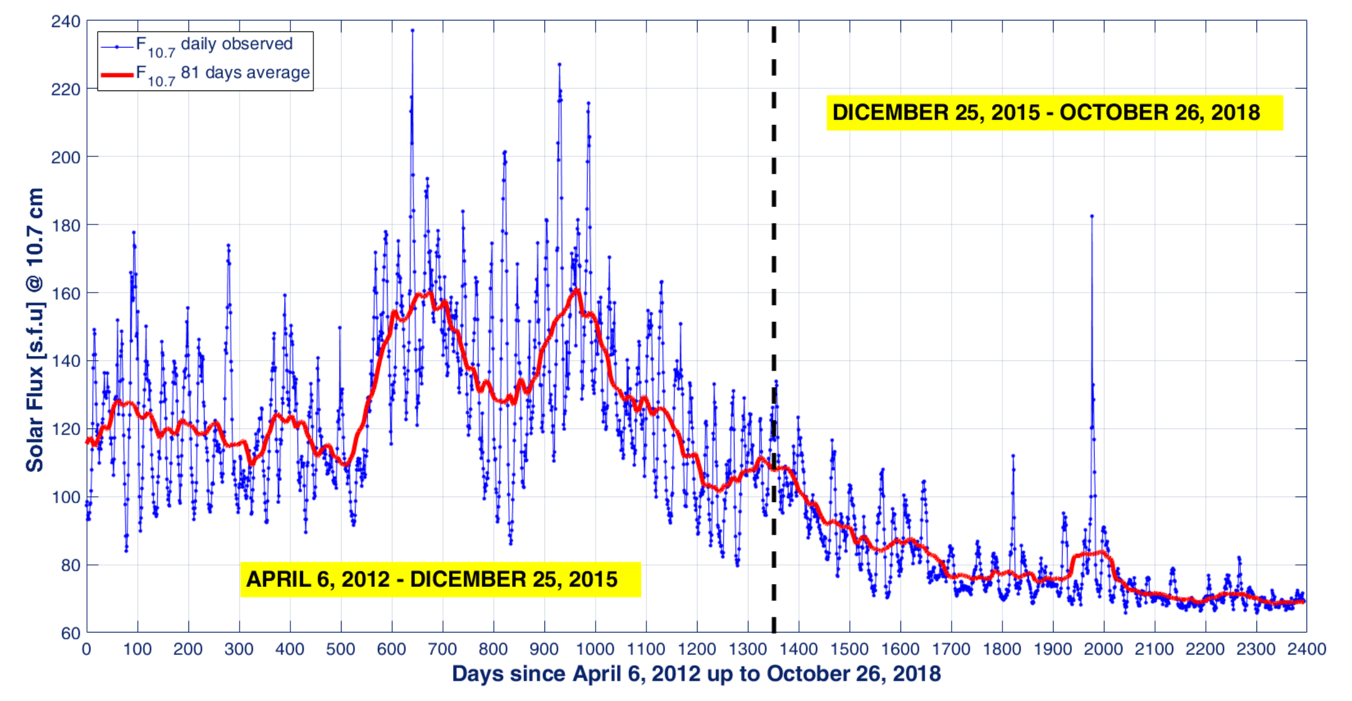
Neutral drag



Relative maximum phase

Solar cycle # 24

decreasing phase



DICEMBER 25, 2015 - OCTOBER 26, 2018

APRIL 6, 2012 - DICEMBER 25, 2015

First period (~3.7 years):
- Decay −2.74 mm/d
- Transverse accel. -1.444×10^{-11} m/s^2

Second period (~2.8 years):
- Decay −1.50 mm/d
- Transverse accel. -7.90×10^{-12} m/s^2

Entire period (~6.5 years):
- Decay −2.36 mm/d
- Transverse accel. -1.246×10^{-11} m/s^2

Neutral drag

Extended analysis on a time span of about 6.5 years (April 6, 2012 → October 26, 2018)

	3.7 years	2.8 years	6.5 years
Atmospheric density model	**Phase of "Maximum" of the solar cycle No. 24 April 6, 2012 – December 25, 2015**	**Decreasing Phase and minimum of the solar cycle No. 24 December 25, 2015 – October 26, 2018**	**Entire period April 6, 2012 – October 26, 2018**
	Transverse acceleration -1.444×10^{-11} m/s^2	**Transverse acceleration -7.90×10^{-12} m/s^2**	**Transverse acceleration -1.246×10^{-11} m/s^2**
	C_D	C_D	C_D
JR-71	**3.96**	**3.95**	**4.24**
MSIS-86	**3.71**	**4.00**	**4.07**
MSISE-90	**3.73**	**4.02**	**4.09**
NRLMSISE-00	**3.78**	**3.92**	**4.10**
GOST2004	**4.21**	**3.40**	**4.22**
JB2008	**3.05**	**2.64**	**3.13***

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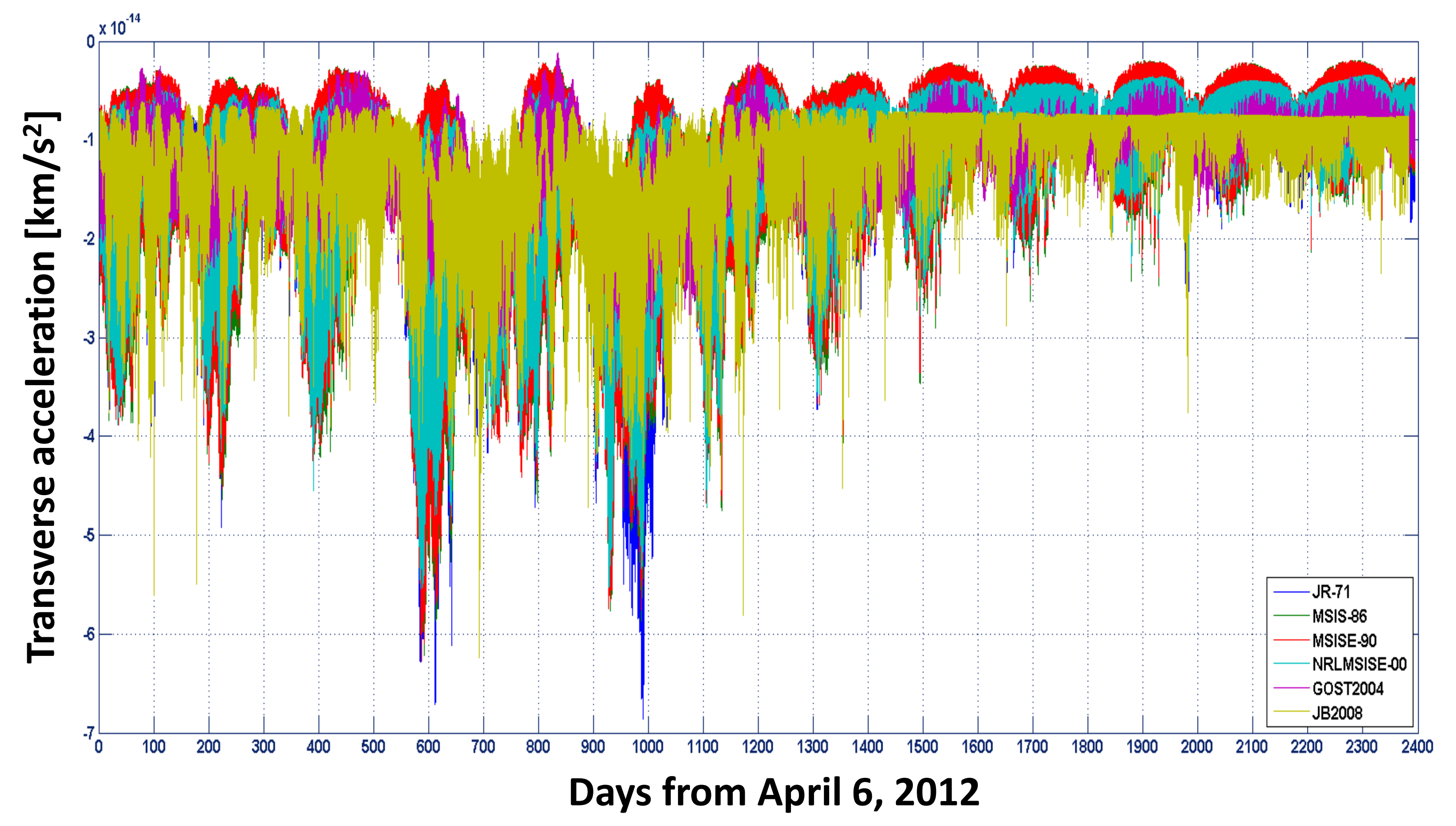
Extension of the analysis

**The final date of propagation is October 14, 2018 (indexes of solar and geomagnetic activity were not available)*

Neutral drag

The transverse acceleration from the different models: **JR-71, MSIS-86, MSISE-90, NRLMSISE-00, GOST2004, JB2008**



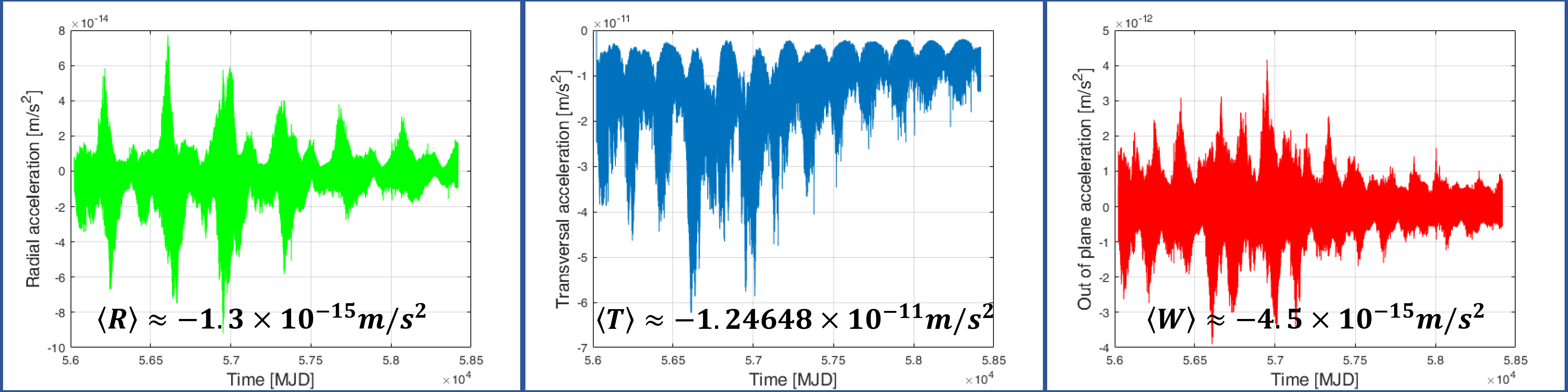
Neutral drag

Fifth step in this study

In the extended analysis of about 6.5 years (April 6, 2012 → October 26, 2018) we also investigated the effects of the neutral drag on all the orbital elements of LARES. In particular:

- from the perturbing accelerations obtained from SATRAP we computed the effects on the orbit via Gauss equations
- we compared these orbital effects with the orbit residuals obtained from GEODYN

Accelerations (in Gauss co-moving frame) due to neutral drag obtained with SATRAP (MSIS-86): $\langle C_D \rangle \cong 4.07$



$\langle R \rangle \approx -1.3 \times 10^{-15} m/s^2$

$\langle T \rangle \approx -1.24648 \times 10^{-11} m/s^2$

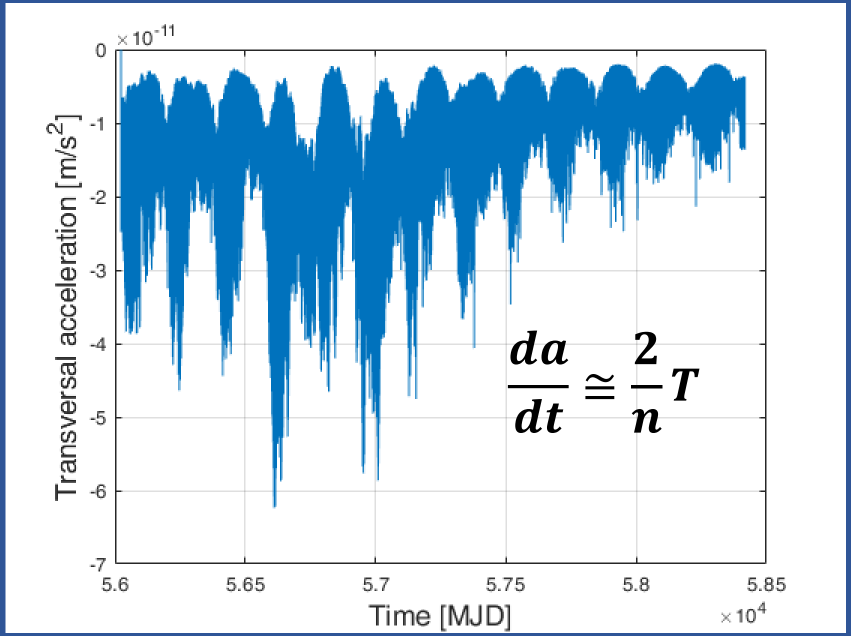
$\langle W \rangle \approx -4.5 \times 10^{-15} m/s^2$

Neutral drag

Neutral drag on the rate of the semimajor axis (m/d):

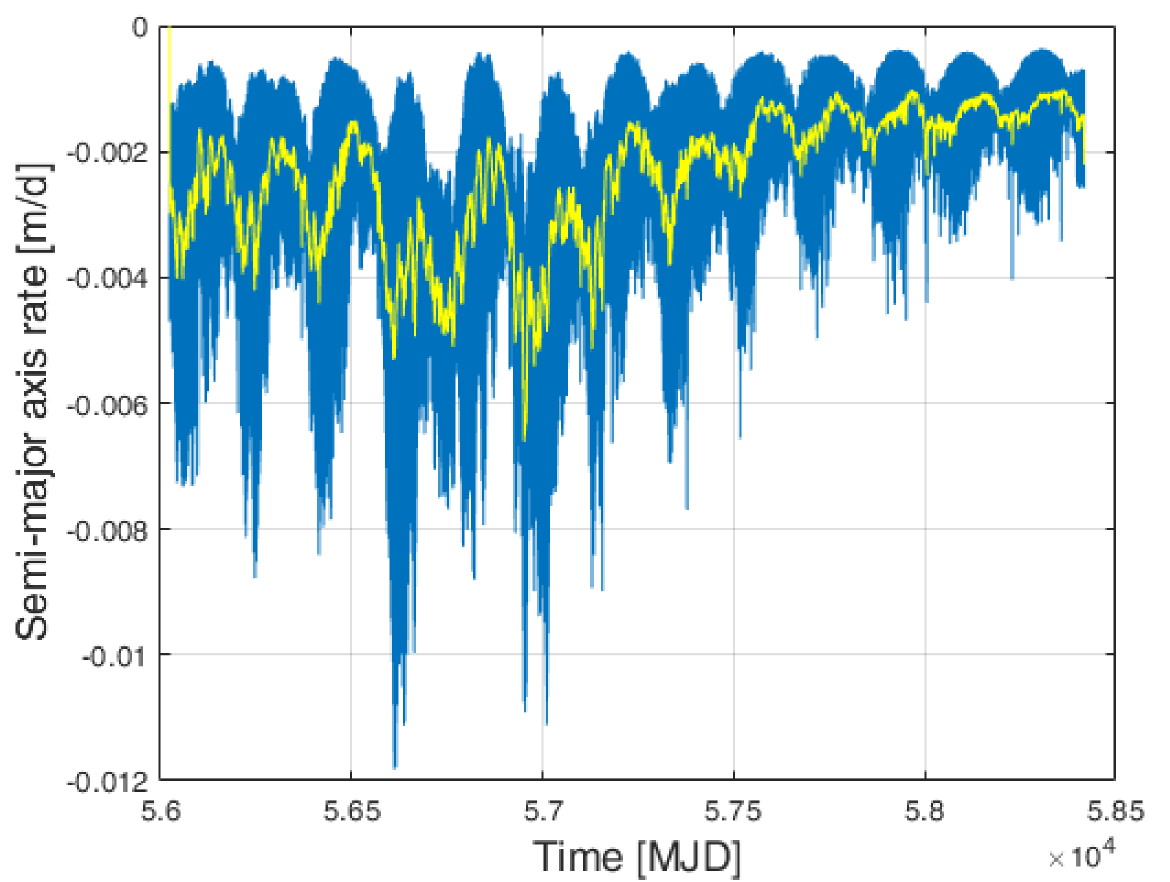
$$\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}}[T + e(T\cos f + R\sin f)]$$

The behavior mainly depends on the transverse acceleration T:



$$\frac{da}{dt} \cong \frac{2}{n}T$$

The neutral drag produces a secular effect in the semimajor axis

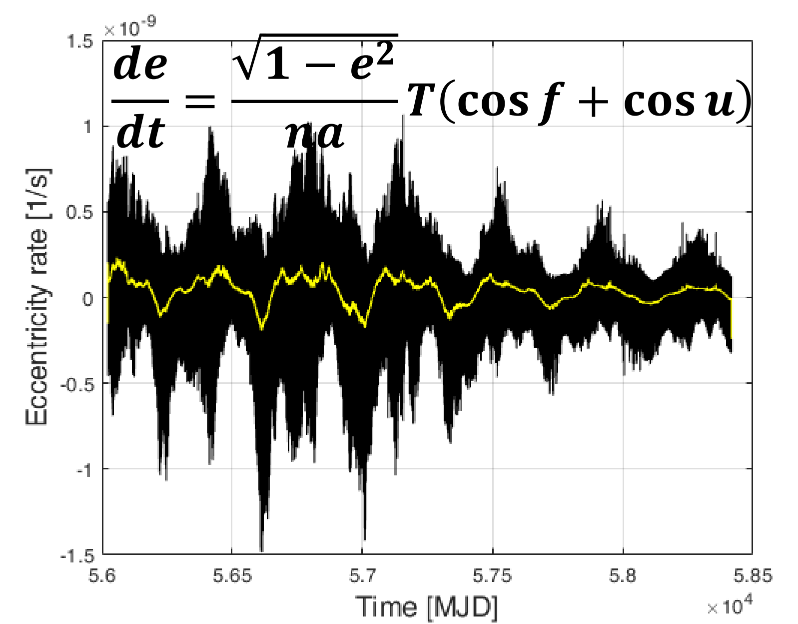


Neutral drag

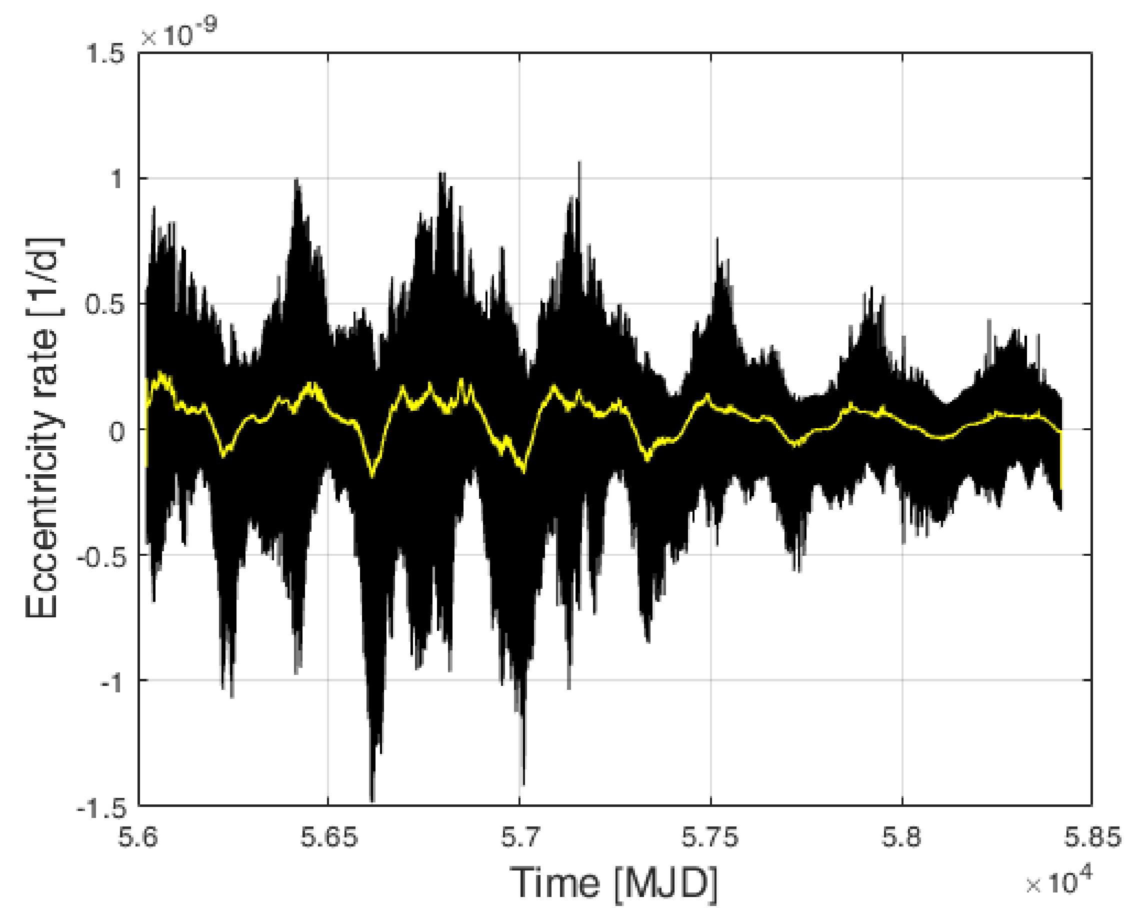
Neutral drag on the rate of the eccentricity (1/d):

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}\left[R \sin f + T(\cos f + \cos u)\right]$$

The behavior mainly depends on the transverse acceleration T:


$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na} T(\cos f + \cos u)$$

The neutral drag does not produces a secular effect on the eccentricity



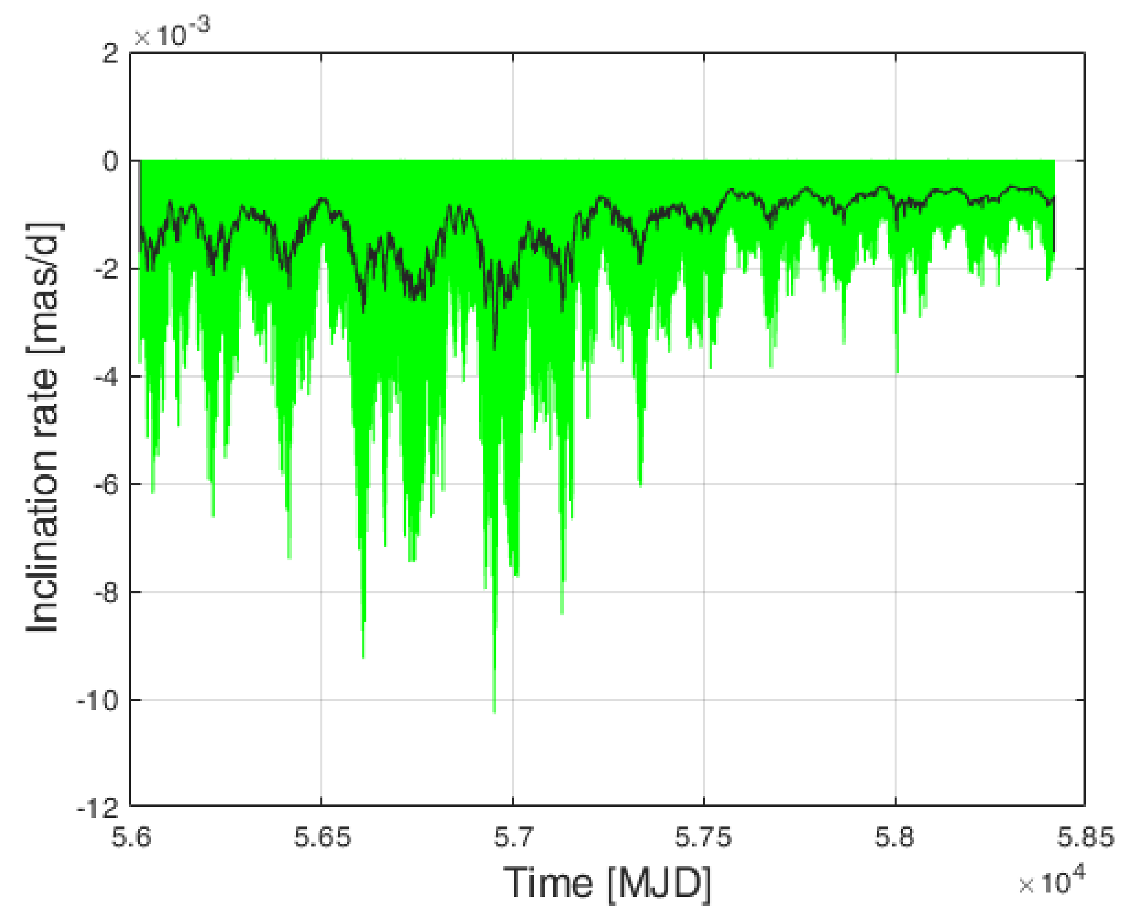
Neutral drag

Neutral drag on the rate of the inclination (mas/d):

$$\frac{di}{dt} = \frac{W}{H} r \cos(\omega + f)$$

The behavior depends only from the out-of-plane acceleration W

The neutral drag produces a secular effect on the inclination



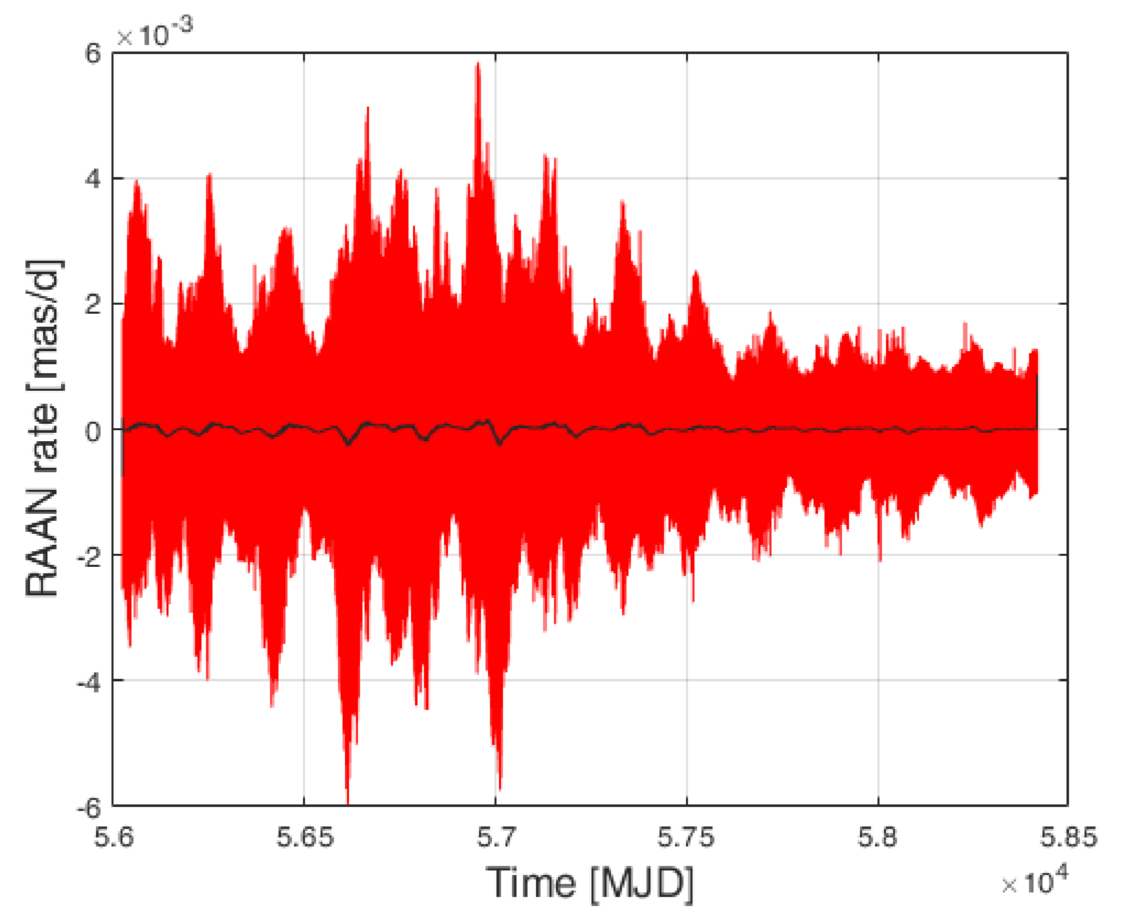
Neutral drag

Neutral drag on the rate of the node (mas/d):

$$\frac{d\boldsymbol{\Omega}}{d\boldsymbol{t}} = \frac{\boldsymbol{W}}{\boldsymbol{H}\sin\boldsymbol{i}}\boldsymbol{r}\sin(\omega + f)$$

The behavior depends only from the out-of-plane acceleration W

The neutral drag does not produces a direct secular effect on the node



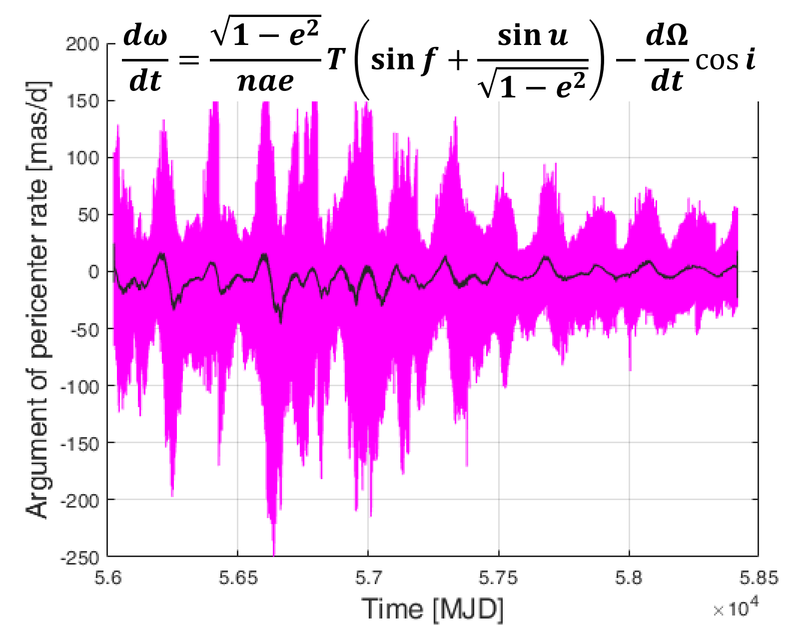
Neutral drag

Neutral drag on the rate of the argument of pericenter (mas/d):

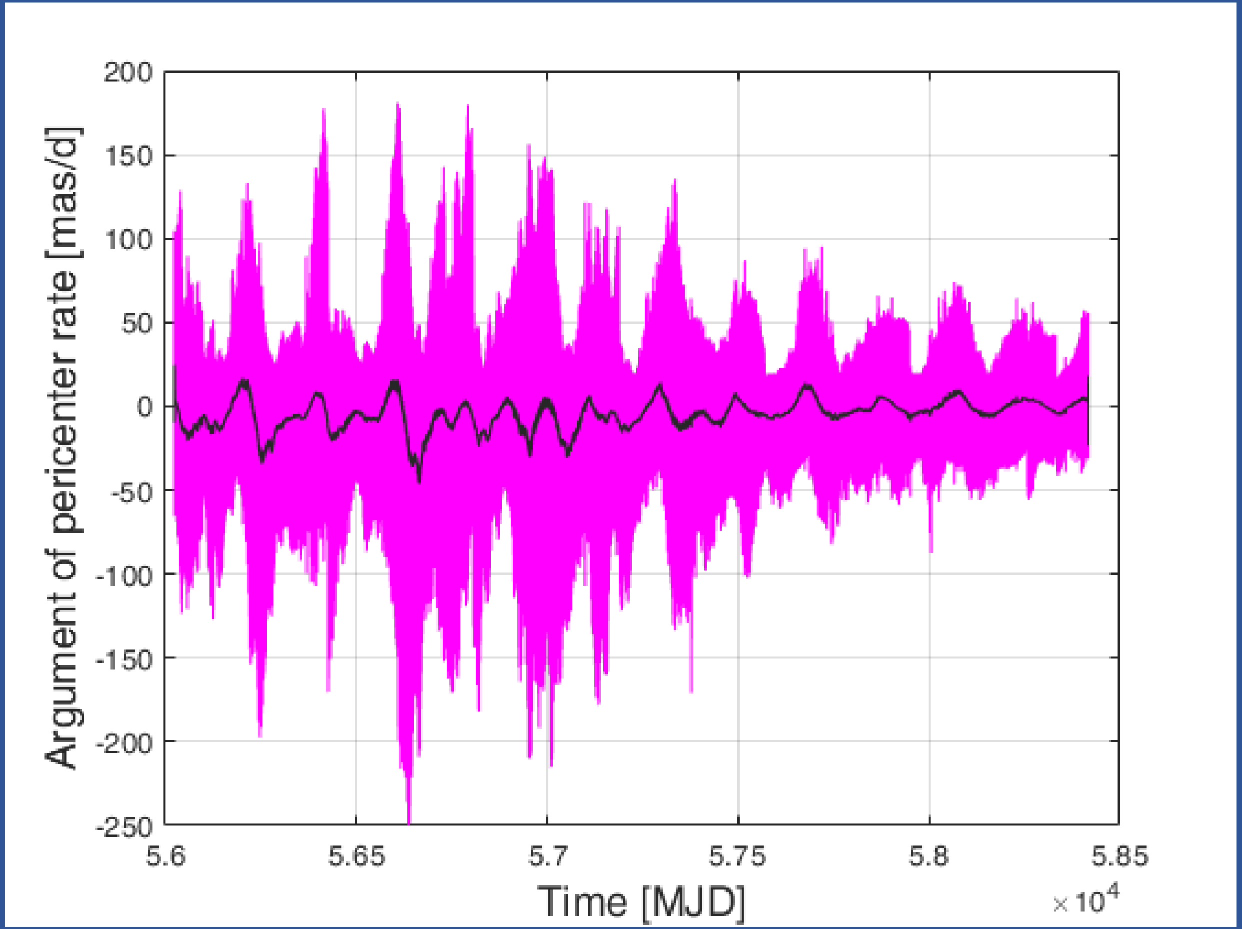
$$\frac{d\omega}{dt} = \frac{\sqrt{1-e^2}}{nae}\left[-R\cos f + T\left(\sin f + \frac{\sin u}{\sqrt{1-e^2}}\right)\right] - \frac{d\Omega}{dt}\cos i$$

The neutral drag does not produces a direct secular effect on the pericenter

The behavior depends from the out-of-plane, W, and the transverse, T, accelerations



$$\frac{d\omega}{dt} = \frac{\sqrt{1-e^2}}{nae}T\left(\sin f + \frac{\sin u}{\sqrt{1-e^2}}\right) - \frac{d\Omega}{dt}\cos i$$



Neutral drag

Sixth step in this study

Neutral drag model from SATRAP and its comparison with the orbital residuals of GEODYN:

- We run GEODYN II over a time span of about 6.5 years (2359 days) from MJD 56023, i.e. April 6th 2012, and we computed the effects on the orbit elements of LARES:

- Background gravity model: EIGENGRACE02S
- Arc length of 7 days
- No empirical accelerations
- Thermal thrust effects not modelled
- General relativity modelled with the exception of the Lense-Thirring effect

Dynamical Model

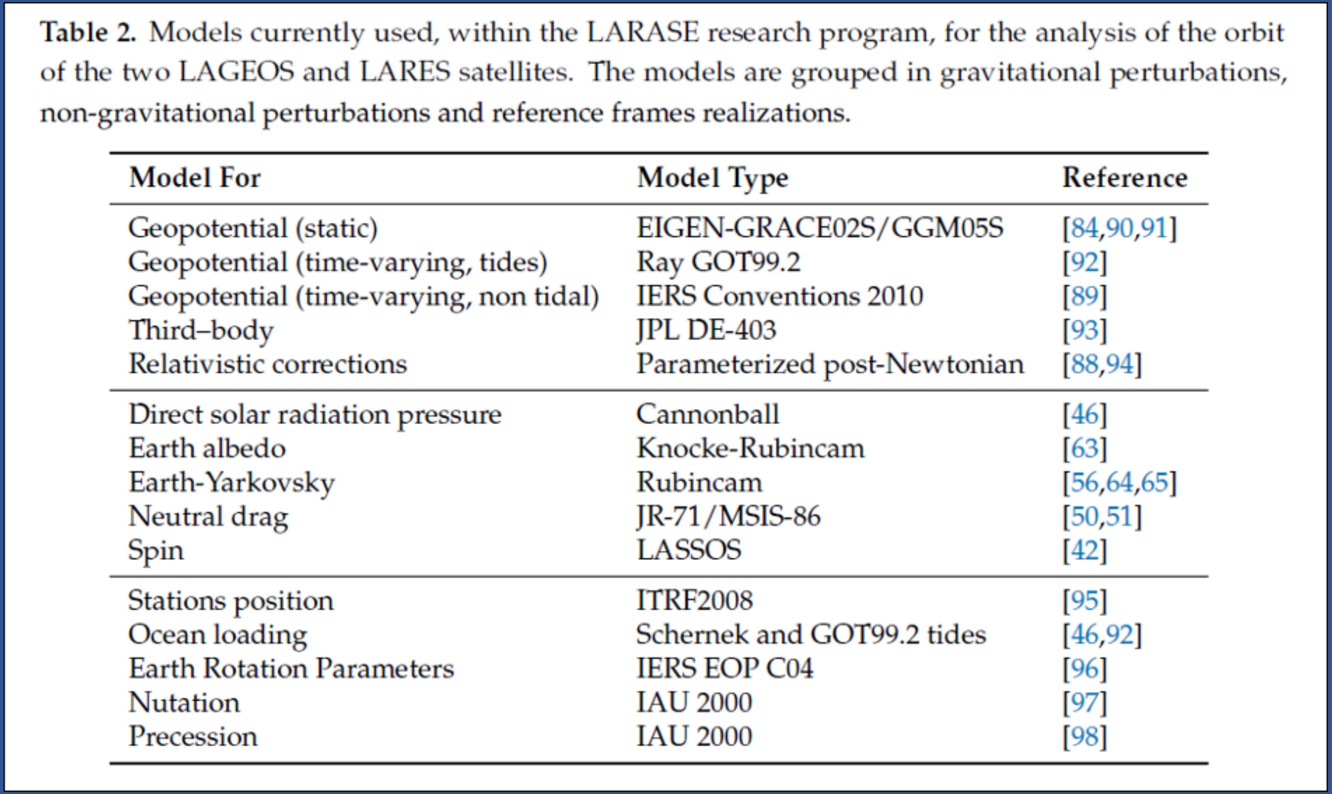
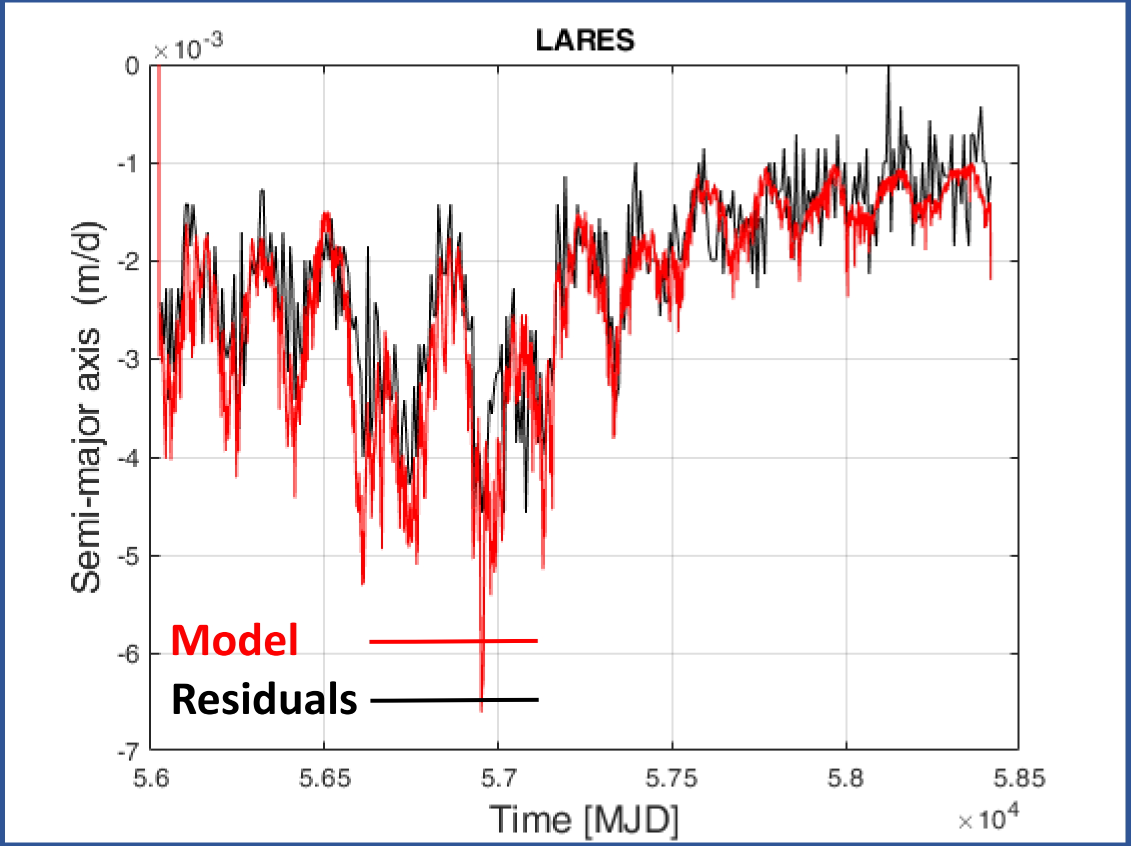


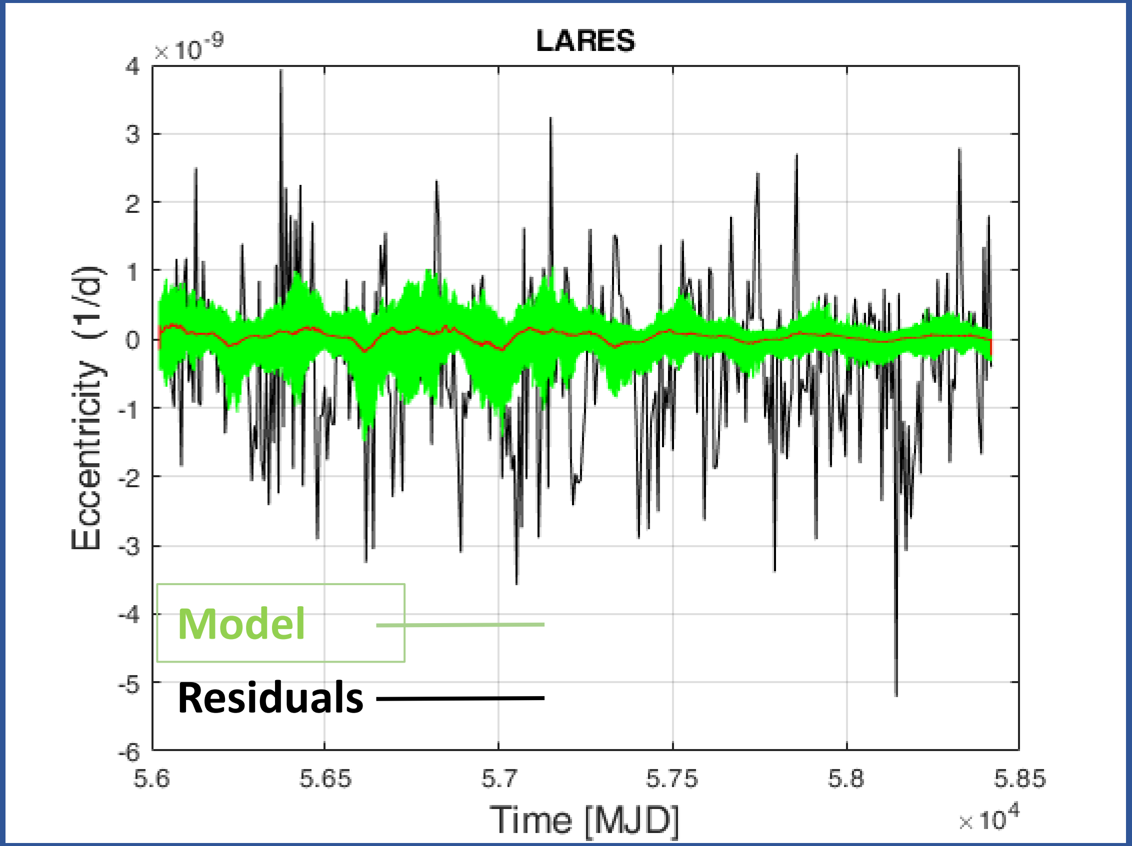
Table 2. Models currently used, within the LARASE research program, for the analysis of the orbit of the two LAGEOS and LARES satellites. The models are grouped in gravitational perturbations, non-gravitational perturbations and reference frames realizations.

Model For	Model Type	Reference
Geopotential (static)	EIGEN-GRACE02S/GGM05S	[84,90,91]
Geopotential (time-varying, tides)	Ray GOT99.2	[92]
Geopotential (time-varying, non tidal)	IERS Conventions 2010	[89]
Third–body	JPL DE-403	[93]
Relativistic corrections	Parameterized post-Newtonian	[88,94]
Direct solar radiation pressure	Cannonball	[46]
Earth albedo	Knocke-Rubincam	[63]
Earth-Yarkovsky	Rubincam	[56,64,65]
Neutral drag	JR-71/MSIS-86	[50,51]
Spin	LASSOS	[42]
Stations position	ITRF2008	[95]
Ocean loading	Schernek and GOT99.2 tides	[46,92]
Earth Rotation Parameters	IERS EOP C04	[96]
Nutation	IAU 2000	[97]
Precession	IAU 2000	[98]

Neutral drag

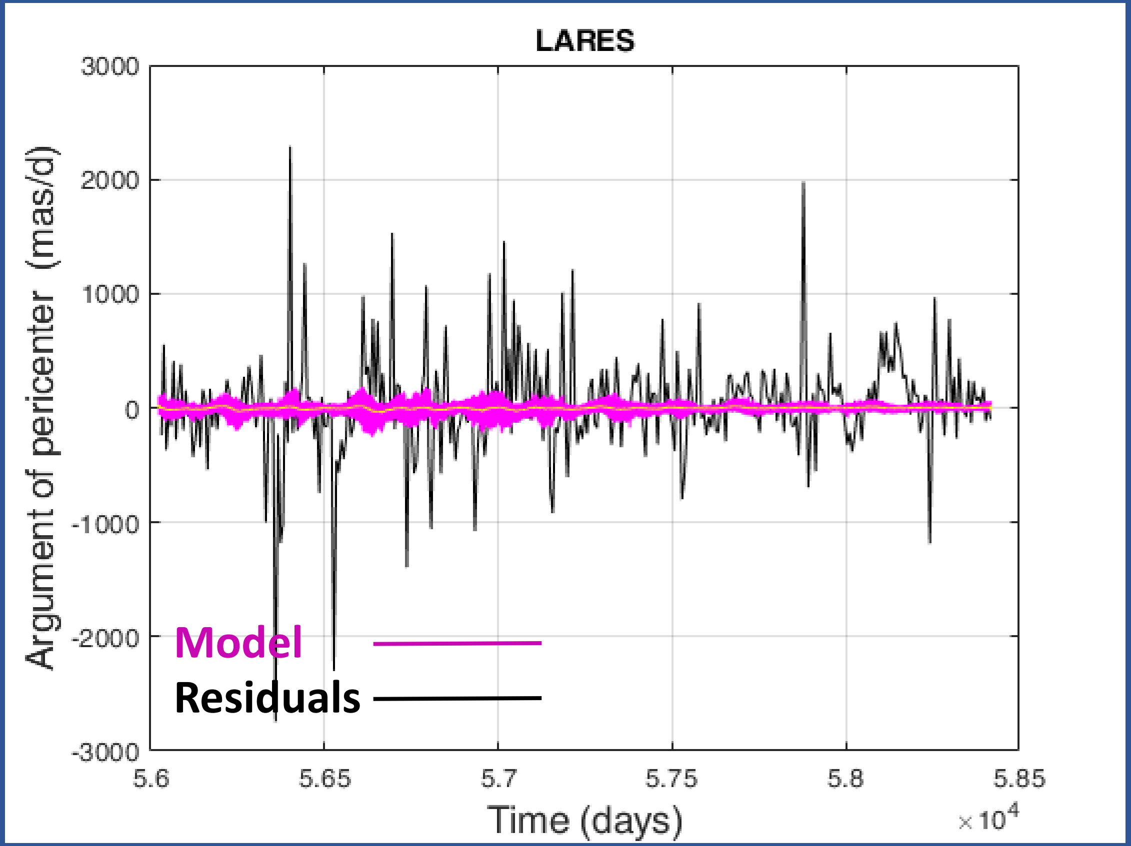
Semimajor axis and Eccentricity





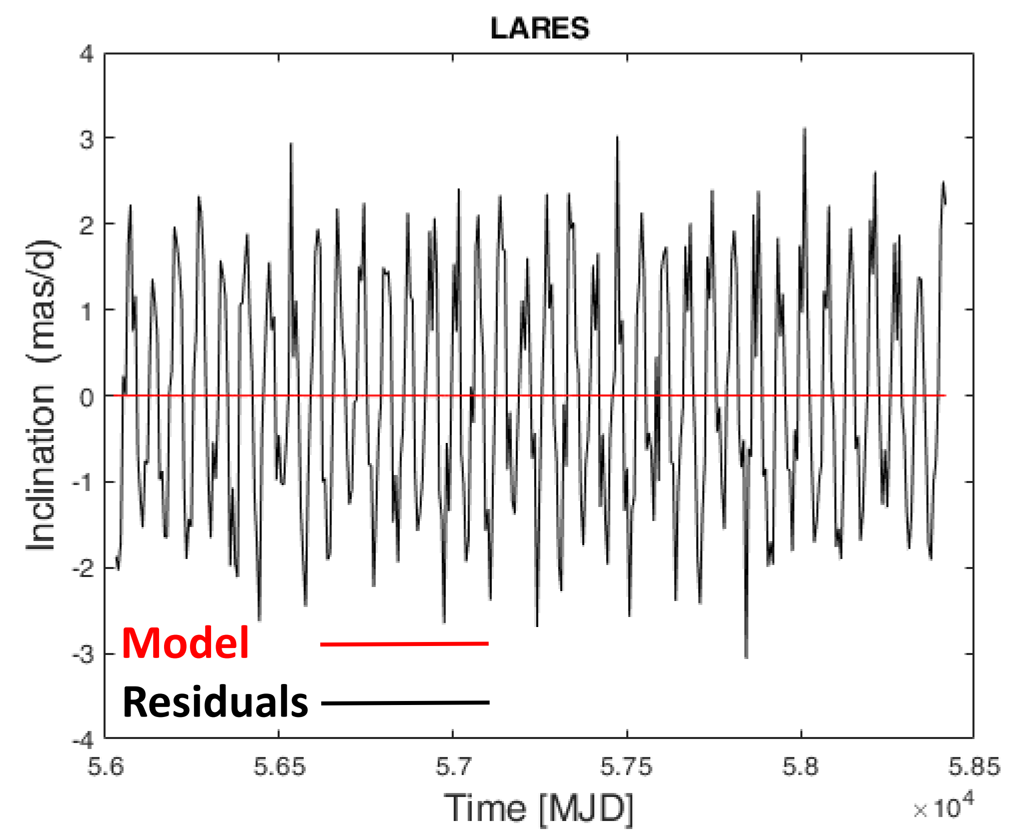
Neutral drag

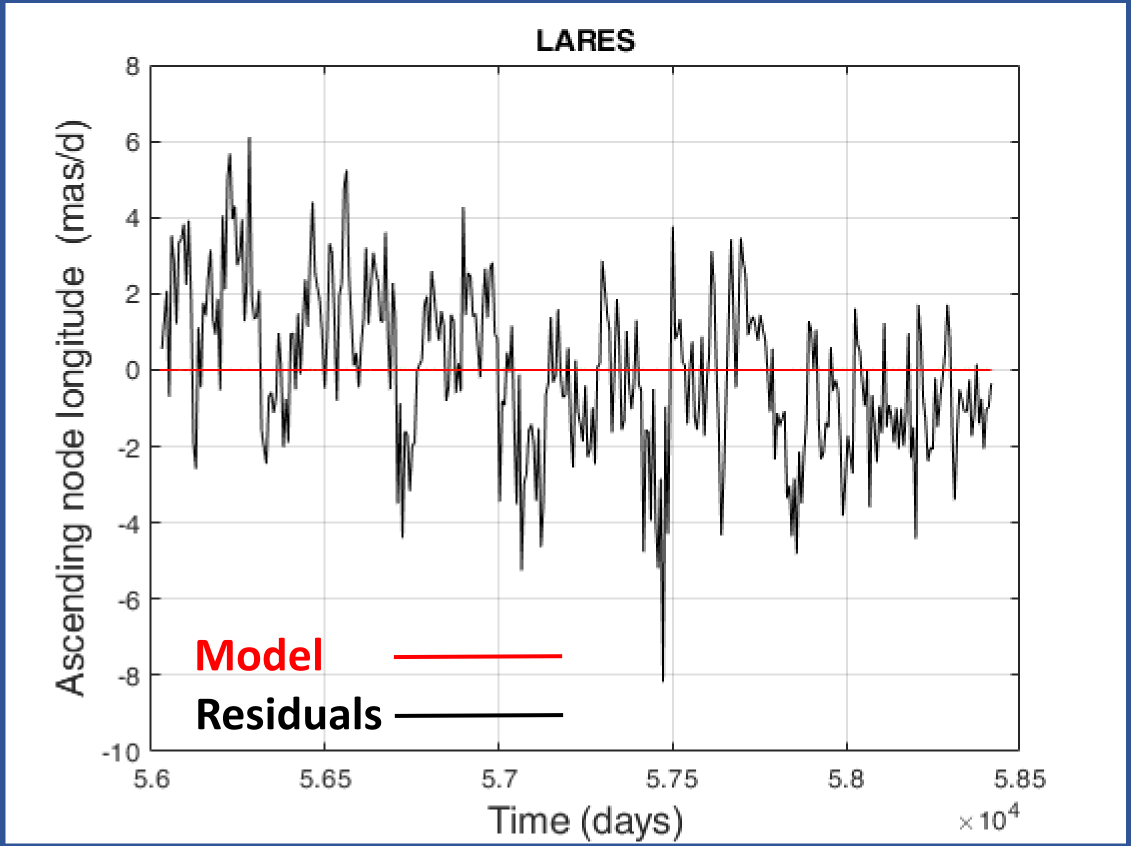
Argument of Pericenter



Neutral drag

Inclination and RAAN





Neutral drag

Discussion. The orbital residuals of LARES obtained by a data reduction of the SLR normal points with GEODYN II on a time span of about 6.5 years clearly show that:

- the neutral drag has (of course as expected) a strong impact on the satellite orbit and on the long-term evolution and decay of its semimajor axis
- the signature of the neutral drag is also clear on the eccentricity and pericenter
- the effects on the inclination and on the ascending node longitude are negligible

The comparison between SATRAP and GEODYN also shows that:

- other unmodelled NGP are acting on the orbit of LARES
  - see the residual along track deceleration explicitly estimated on the first period analyzed after the modeling of the neutral drag, about -2.13×10^{-13} m/s^2
  - see the residual in the orbital elements…
- possibly due to thermal thrust effects and charged particle drag

Conclusions and future work

- The work carried out on neutral atmosphere drag was just one of several aspects addressed in the framework of LARASE to deeply understand and evaluate all error sources affecting the primary and secondary goals of the experiment
- This analysis made it possible to independently check and validate the conditions of applicability of the atmospheric density models implemented in GEODYN II
- The results outlined strongly support the conclusion that most of the observed secular semi-major axis decay of LARES is due to neutral atmosphere drag
- This conclusion is fully consistent with the predictions, uncertainties and range of applicability of some of the best thermospheric density models available and used by the orbital dynamics community
- Neutral atmosphere drag is, for LARES, a major player among non-gravitational perturbations. This is in contrast with the case of the two LAGEOS, where it accounts for ≈ 10% of the observed semi-major axis decay. The signature of this drag, be it secular, long-term and short-term, deserves detailed investigation and modeling, in order to reliably detect and characterize other (smaller) perturbing accelerations

Publications

- Pardini, C., Anselmo, L., Lucchesi, D.M. and Peron, R., On the secular decay of the LARES semi-major axis. *Acta Astronautica* 140, 469–477, DOI: 10.1016/j.actaastro.2017.09.012, 2017
- Pardini, C., Anselmo, L., Lucchesi, D.M., Peron, R., Neutral Atmosphere Drag at the altitude of LARES and AJISAI. IAC-18-C1.1.12, 2018
- Pardini, C., Anselmo, L., Lucchesi, D.M., Peron, R., Bassan, M., Magnafico, Pucacco, G., Visco, M., Sounding the Atmospheric Density at the Altitude of LARES and Ajisai During Solar Cycle 24. Transactions of the Japan Society for Aeronautical and Space Sciences, 2020

International Laser Ranging Service (ILRS): LARASE as an Associated Analysis Center (AAC)

We are an AAC of the ILRS since 2014, and during these years we have participated to several International Workshops organized by ILRS:

ILRS International Workshops:

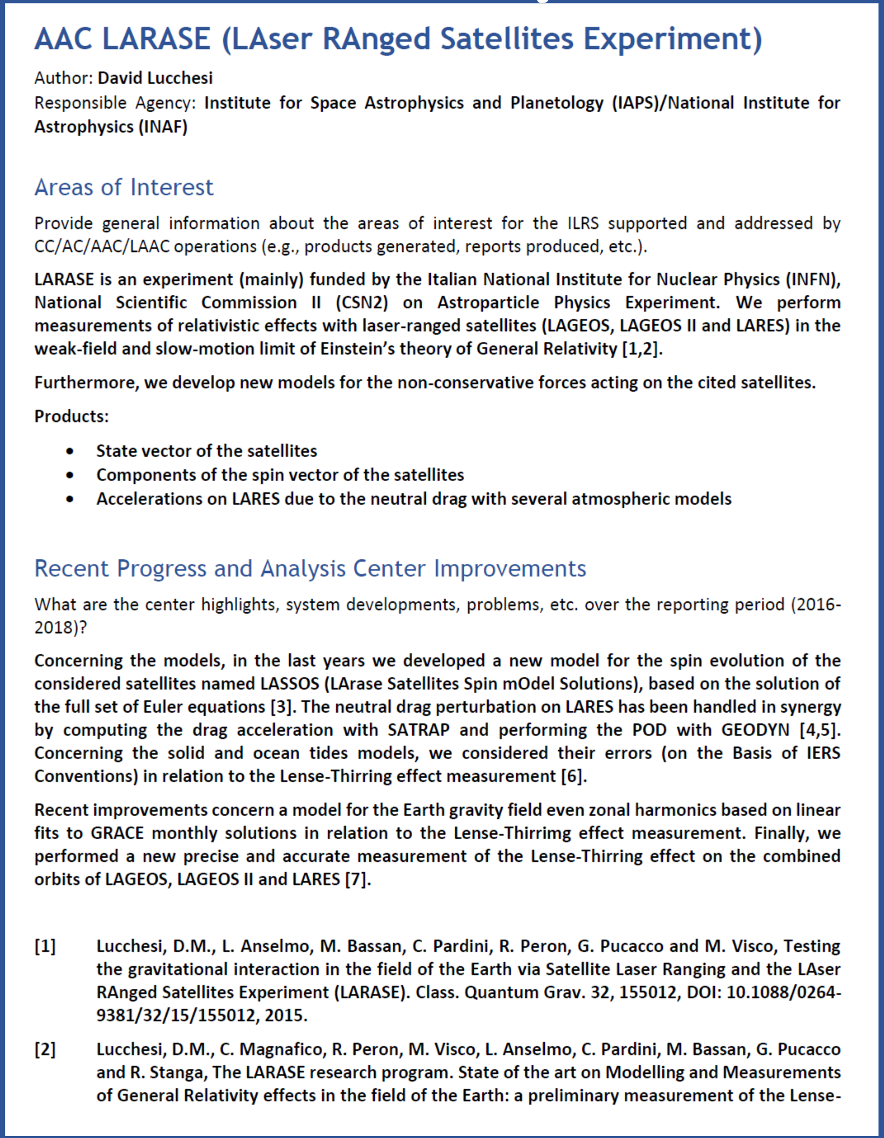
- 2014: 19th International Workshop on Laser Ranging. Celebrating 50 Years of SLR: Remembering the Past and Planning for the Future. Annapolis, MD, USA
- 2016: 20th International Workshop on Laser Ranging. Potsdam, Germany
- 2020: 22nd International Workshop on Laser Ranging. Online virtual tour to SLR stations

ILRS Specialized Technical Workshops:

- 2015: Network Performance and Future Expectations for ILRS Support of GNSS, Time Transfer, and Space Debris Tracking. Matera, Italy
- 2017: Improving ILRS Performance to Meet Future GGOS Requirements. Riga, Latvia
- 2019: Laser ranging: To improve economy, performance, and adoption for new applications. Stuttgart, Germany

International Laser Ranging Service (ILRS): LARASE as an Associated Analysis Center (AAC)

2019 LARASE
report to ILRS



AAC LARASE (LAser RAnged Satellites Experiment)

Author: **David Lucchesi**
Responsible Agency: **Institute for Space Astrophysics and Planetology (IAPS)/National Institute for Astrophysics (INAF)**

Areas of Interest

Provide general information about the areas of interest for the ILRS supported and addressed by CC/AC/AAC/LAAC operations (e.g., products generated, reports produced, etc.).

LARASE is an experiment (mainly) funded by the Italian National Institute for Nuclear Physics (INFN), National Scientific Commission II (CSN2) on Astroparticle Physics Experiment. We perform measurements of relativistic effects with laser-ranged satellites (LAGEOS, LAGEOS II and LARES) in the weak-field and slow-motion limit of Einstein's theory of General Relativity [1,2].

Furthermore, we develop new models for the non-conservative forces acting on the cited satellites.

Products:

- **State vector of the satellites**
- **Components of the spin vector of the satellites**
- **Accelerations on LARES due to the neutral drag with several atmospheric models**

Recent Progress and Analysis Center Improvements

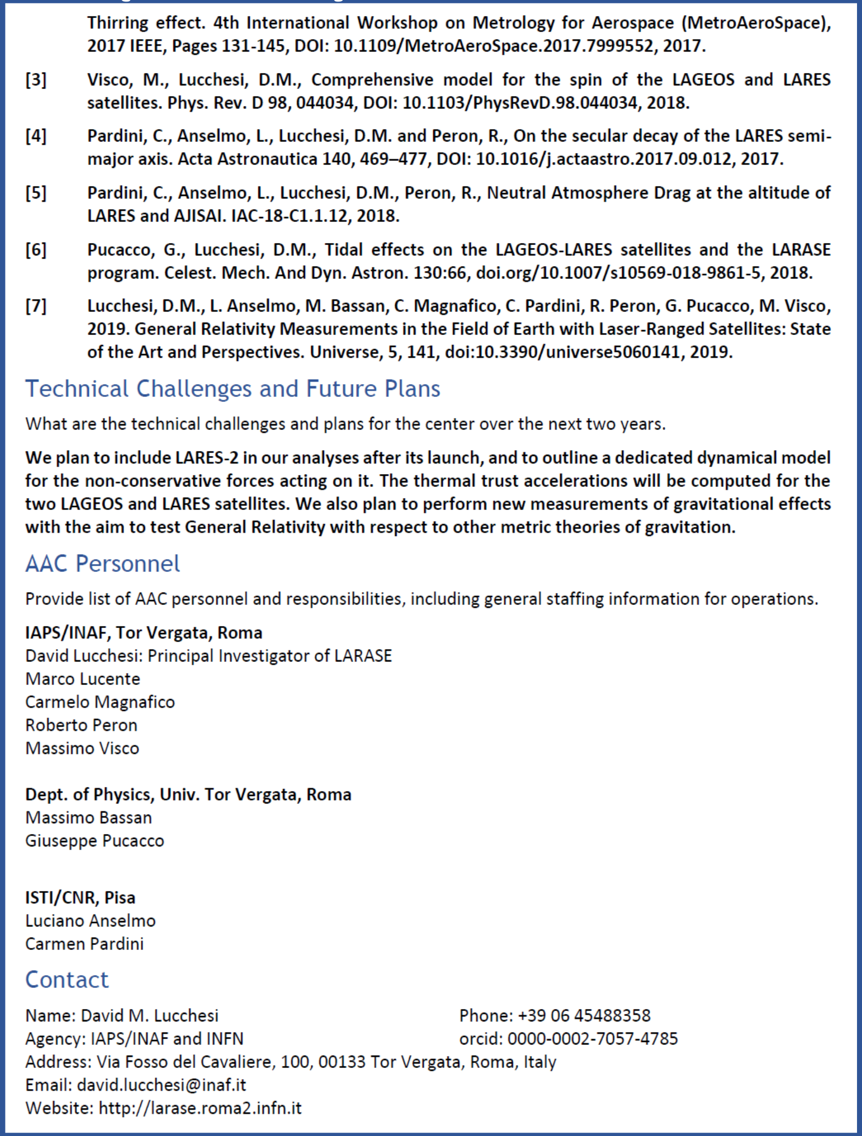
What are the center highlights, system developments, problems, etc. over the reporting period (2016-2018)?

Concerning the models, in the last years we developed a new model for the spin evolution of the considered satellites named LASSOS (LArase Satellites Spin mOdel Solutions), based on the solution of the full set of Euler equations [3]. The neutral drag perturbation on LARES has been handled in synergy by computing the drag acceleration with SATRAP and performing the POD with GEODYN [4,5]. Concerning the solid and ocean tides models, we considered their errors (on the Basis of IERS Conventions) in relation to the Lense-Thirring effect measurement [6].

Recent improvements concern a model for the Earth gravity field even zonal harmonics based on linear fits to GRACE monthly solutions in relation to the Lense-Thirrimg effect measurement. Finally, we performed a new precise and accurate measurement of the Lense-Thirring effect on the combined orbits of LAGEOS, LAGEOS II and LARES [7].

[1] **Lucchesi, D.M., L. Anselmo, M. Bassan, C. Pardini, R. Peron, G. Pucacco and M. Visco, 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, 155012, DOI: 10.1088/0264-9381/32/15/155012, 2015.**

[2] **Lucchesi, D.M., C. Magnafico, R. Peron, M. Visco, L. Anselmo, C. Pardini, M. Bassan, G. Pucacco and R. Stanga, The LARASE research program. State of the art on Modelling and Measurements of General Relativity effects in the field of the Earth: a preliminary measurement of the Lense-**



Thirring effect. 4th International Workshop on Metrology for Aerospace (MetroAeroSpace), 2017 IEEE, Pages 131-145, DOI: 10.1109/MetroAeroSpace.2017.7999552, 2017.

[3] **Visco, M., Lucchesi, D.M., Comprehensive model for the spin of the LAGEOS and LARES satellites. Phys. Rev. D 98, 044034, DOI: 10.1103/PhysRevD.98.044034, 2018.**

[4] **Pardini, C., Anselmo, L., Lucchesi, D.M. and Peron, R., On the secular decay of the LARES semi-major axis. Acta Astronautica 140, 469–477, DOI: 10.1016/j.actaastro.2017.09.012, 2017.**

[5] **Pardini, C., Anselmo, L., Lucchesi, D.M., Peron, R., Neutral Atmosphere Drag at the altitude of LARES and AJISAI. IAC-18-C1.1.12, 2018.**

[6] **Pucacco, G., Lucchesi, D.M., Tidal effects on the LAGEOS-LARES satellites and the LARASE program. Celest. Mech. And Dyn. Astron. 130:66, doi.org/10.1007/s10569-018-9861-5, 2018.**

[7] **Lucchesi, D.M., L. Anselmo, M. Bassan, C. Magnafico, C. Pardini, R. Peron, G. Pucacco, M. Visco, 2019. General Relativity Measurements in the Field of Earth with Laser-Ranged Satellites: State of the Art and Perspectives. Universe, 5, 141, doi:10.3390/universe5060141, 2019.**

Technical Challenges and Future Plans

What are the technical challenges and plans for the center over the next two years.

We plan to include LARES-2 in our analyses after its launch, and to outline a dedicated dynamical model for the non-conservative forces acting on it. The thermal trust accelerations will be computed for the two LAGEOS and LARES satellites. We also plan to perform new measurements of gravitational effects with the aim to test General Relativity with respect to other metric theories of gravitation.

AAC Personnel

Provide list of AAC personnel and responsibilities, including general staffing information for operations.

IAPS/INAF, Tor Vergata, Roma
David Lucchesi: Principal Investigator of LARASE
Marco Lucente
Carmelo Magnafico
Roberto Peron
Massimo Visco

Dept. of Physics, Univ. Tor Vergata, Roma
Massimo Bassan
Giuseppe Pucacco

ISTI/CNR, Pisa
Luciano Anselmo
Carmen Pardini

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International Laser Ranging Service (ILRS): LARASE as an Associated Analysis Center (AAC)

LARASE (and SaToR-G) products (in addition to measurements with the goal to verify and test gravitation)

Current products:

- Satellites state-vector:
  - ☐ LAGEOS; LAGEOS II; LARES
- Spin vector components and rate:
  - ☐ LAGEOS; LAGEOS II; LARES
- Neutral drag accelerations:
  - ☐ LARES
- Thermal thrust accelerations
  - ☐ LAGEOS; LAGEOS II
- Gravity field coefficients
  - ☐ Even zonal harmonics of low degree

New foreseen products:

- Thermal thrust accelerations:
  - ☐ LARES
- Station biases
- Station positions
- EOP parameters

To be seriously considered in the near future…

International Laser Ranging Service (ILRS): LARASE as an Associated Analysis Center (AAC)

Current potential collaborations:

- Technische Universität München (TUM)
- Center for Space Research (CSR), Uni. Texas, Austin, USA
- Herstmonceux (UK)/Yebes (Madrid), Spain
- ASI-CGS, Matera, Italy
- NASA/GSFC, Greenbelt MD, USA

These collaborations mainly concern:

1. LASSOS - Spin model
2. LATOS - Thermal thrust accelerations
3. Satellite attitude and CoM correction

- The first two points concern possible improvements of the POD (with a strong reduction in the use of empirical accelerations) and better final products in the fields of geophysics and space geodesy in general
- Point 3: POD improvements and to meet GGOS (Global Geodetic Observing System) goals of < 1 mm epoch position accuracy and < 0.1 mm/y secular change over a long time

National Scientific Committee 2 (CSN2)

MoonLIGHT-2

Lab measurements

Lab measurements performed on LAGEOS/LARES-1&2 satellites can be very useful in helping us to constrain some of the physical parameters that go into our NGP models for the satellites

LLR/SLR measurements

LLR and SLR techniques comparison: same technique with different models and systematics error sources

National Scientific Committee 2 (CSN2)

GINGER

Lab measurements with Sagnac effect

- Earth’s angular velocity
    - EOP (Earth Orientation Parameters)
    - Lense-Thirring effect
    - Geodetic effect

Many thanks for your kind attention