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Thermal thrust accelerations on LAGEOS satellites

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Summary

- Thermal thrust effects
- The LATOS thermal model
- Preliminary results
- Conclusions

LAser RAnged Satellites Experiment

2013/2019

Satellites Tests of Relativistic - Gravity

Thermal thrust effects

An intricate role, among the complex non-gravitational perturbations, is played by the subtle thermal thrust effects that arise from the radiation emitted from the satellite surface as consequence of the non uniform distribution of its temperature

In the literature of the older LAGEOS satellite this problem was attacked since the early 80s' of the past century to explain the (apparently) anomalous behavior of the along-track acceleration of the satellite, characterized by a complex pattern:

Rubincam, Afonso, Ries, Scharroo, Farinella, Metris, Vokrouhlicky, Slabinsky, Lucchesi, Andres, …

represents a non exhaustive list of the researchers that have successfully worked on this very important issue

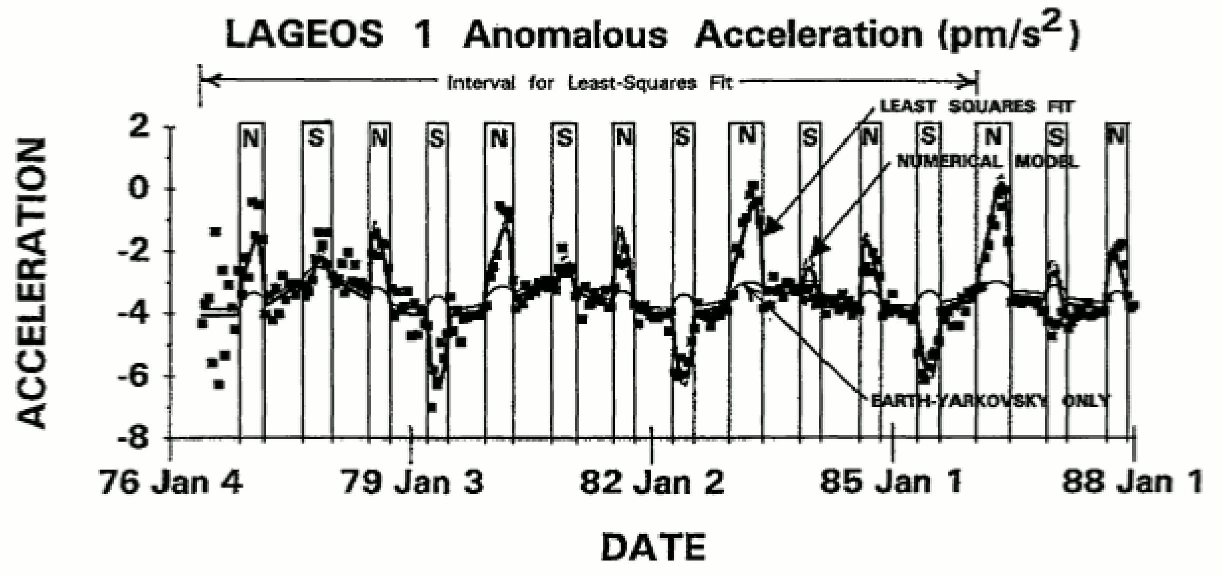
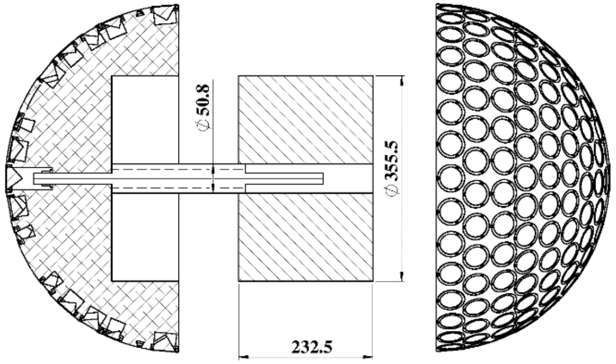


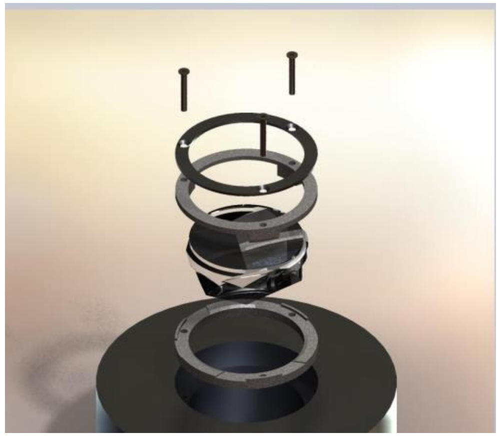
Figure 2. LAGEOS 1 anomalous acceleration: observed data points (squares) are based on 15 day fits to laser data by the Center for Space Research, University of Texas at Austin. The vertical bars mark eclipse seasons. N at top of bar denotes season when satellite travels northward through earth shadow; S denotes season with southward travel.

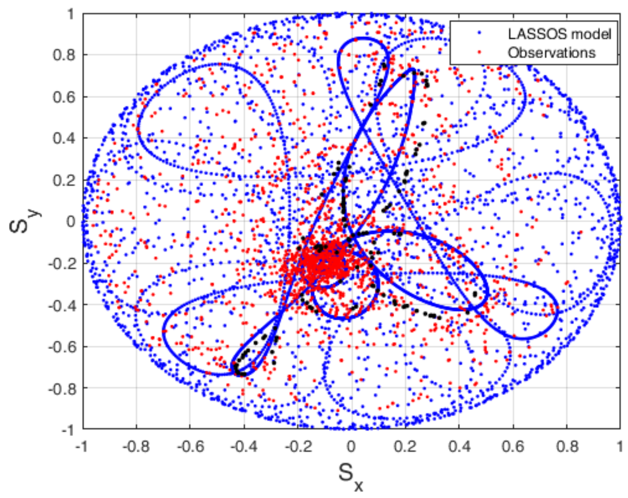
Thermal thrust effects

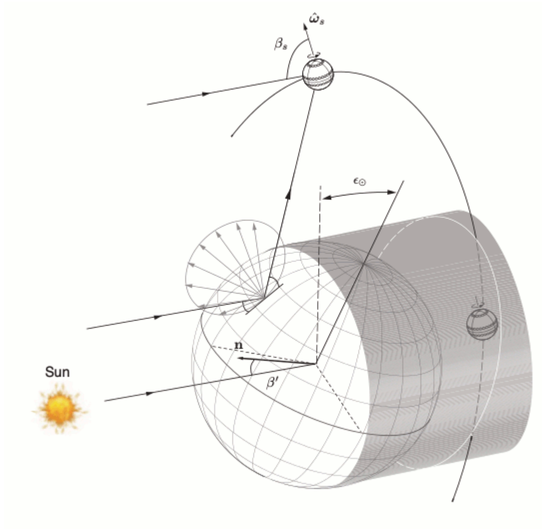
The dynamical problem to solve is quite complex and should account for the following main aspects:

- A deep physical characterization of the satellite
  - **emission and absorption coefficients, thermal conductivity, heat capacity, thermal inertia, …**
- Rotational dynamics of the satellite
  - **Spin orientation and rate**
- Radiation sources
  - **Sun and Earth**









Thermal thrust effects

We have tackled the problem following the two approaches considered in the past in the literature (but with some differences):

- We developed a simplified thermal model of the satellite based on
  - **the energy balance equation on its surface**
  - **a linear approach for the distribution of the temperature with respect to its equilibrium (mean) temperature**

- A general thermal model based on
  - **a satellite (metallic structure) in thermal equilibrium**
  - **the CCRs rings are at the same temperature of the satellite**
  - **for each CCR the thermal exchange with the satellite is computed**

Thermal thrust effects

The main perturbations to be taken into account are:

- **The solar Yarkovsky-Schach effect**
  - **an anisotropic emission of thermal radiation that arises from the temperature gradients across the surface produced by the solar heating and the thermal inertia of the various parts (mainly from the CCRs)**
  - **it produces long-term effects when the thermal radiation is modulated by the eclipses**
- **The Earth Yarkovsky thermal (or Rubincam) effect**
  - **the temperature gradients responsible of the anisotropic emission of thermal radiation are produced by the Earth's infrared radiation**
  - **the bulk of the effect is due to the CCRs and their thermal inertia**
- **The asymmetric reflectivity effect**
  - **A different reflectivity of the hemispheres**

The LATOS thermal model

We have developed **LATOS** a new thermal model for LAGEOS satellites

LArase Thermal mOdel Solutions (LATOS)

Motivation:

Necessity of improved models for the NGP

- **Thermal drag/thrust effects (Yarkovsky effect, Yarkovsky-Schach effect)**
- **Asymmetric reflectivity (LAGEOS, LAGEOS II)**

Previous models:

Rubincam, D.P., 1987. *LAGEOS orbit decay due to infrared radiation from Earth*. J. Geophys. Res. 92, 1287–1294.

Rubincam, D.P., 1988. *Yarkovsky thermal drag on LAGEOS*. J. Geophys. Res. 93, 13805–13810.

Rubincam, D.P., 1990. *Drag on the LAGEOS satellite*. J. Geophys. Res. 95, 4881–4886.

Farinella, P., **Nobili**, A.M., **Barlier**, F., **Mignard**, F., 1990. *Effects of thermal thrust on the node and inclination of LAGEOS*. Astron. Astrophys. 234, 546–554.

Farinella, P., **Vokrouhlicky**, D., 1996. *Thermal force effects on slowly rotating, spherical artificial satellites-I. Solar Heating*. Plan. Space Sci. 44, 1551–1561.

Vokrouhlicky, D., **Farinella**, P., 1996. *Thermal force effects on slowly rotating, spherical artificial satellites-II. Earth infrared heating*. Plan. Space Sci. 45, 419–425.

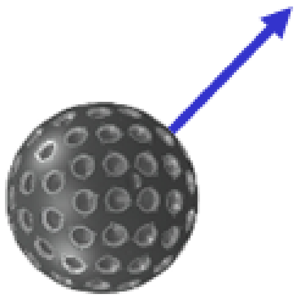
Slabinski, V.J., 1996. *A numerical solution for LAGEOS thermal thrust: the rapid-spin case*. Celestial Mech. Dyn. Astron. 66, 131–179.

Andrés de la Fuente, J.I., 2007. *Enhanced Modelling of LAGEOS Non-Gravitational Perturbations* (Ph.D. thesis). Delft University Press. Sieca Repro, Turbineweg 20, 2627 BP Delft, The Netherlands.

The LATOS thermal model

The thermal thrust force:

$$\mathbf{dF_T} = -\frac{2}{3}\frac{\epsilon\sigma T^4 dA}{c}\mathbf{n}$$



The force, normal to each surface element *dA* depends from the temperature *T* and emissivity *ε* of the part considered.

It is necessary to know the temperature distribution inside the satellite and the satellite position with respect to the external heat sources (Sun and Earth).

The LATOS thermal model

The thermal equations:

$$\frac{dT_i}{dt} C_i = \left(\Sigma_k P_{abs\ k} - P_{em\ i}\right) + \Sigma_j R_{i,j}\left(T_i^4 - T_j^4\right) + \Sigma_j C_{i,j}\left(T_i - T_j\right)$$

Thermal capacity

Difference between the total Power absorbed and emitted

Heat exchanged between the different elements of the satellite due to radiation and conduction

The input to the system of differential equations are:

- **Attitude of the satellite (from LASSOS model)**
- **Thermal and optical parameters of the satellite (from technical documentation and tests) that contribute to the different constants in the system**

The LATOS thermal model

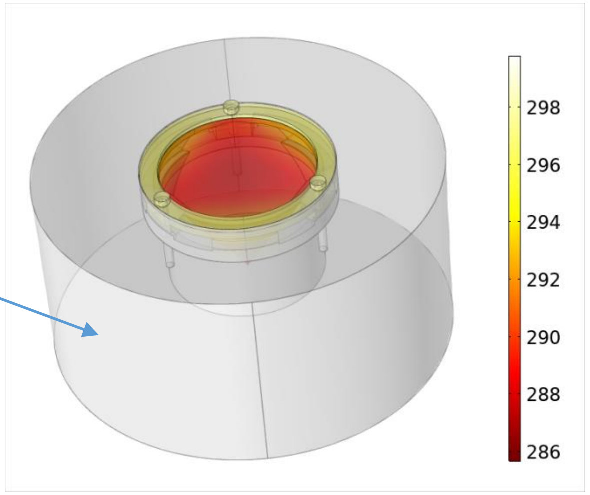
- The satellite is divided into several parts which are assumed to have no thermal gradient within them. For the two **LAGEOS**: the CCRs, the two **hemispheres** and the core. The **rings** that block the **CCRs** are considered isothermal to the hemispheres.

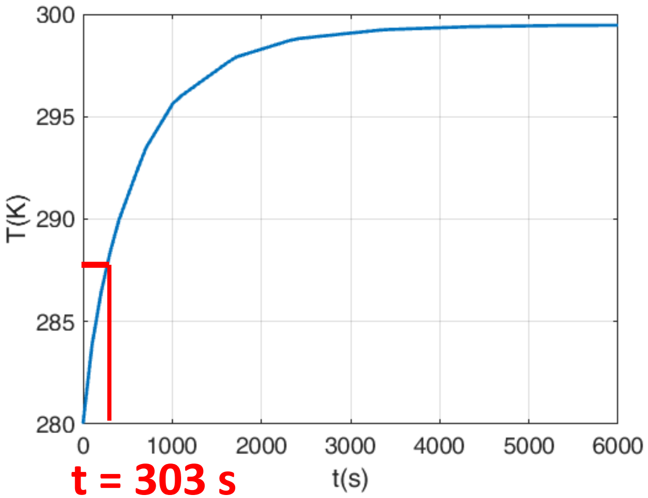
- The conduction constant between the **CCRs** and the hemisphere in which they are inserted was numerically calculated using a **FEM** model.

Coupling of a CCR with the structure

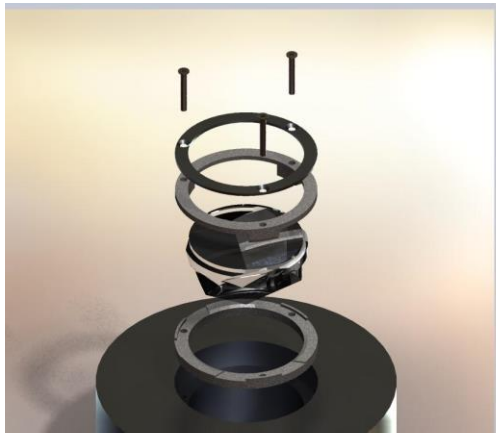
T = 300 K

t = 303 s





t = 303 s

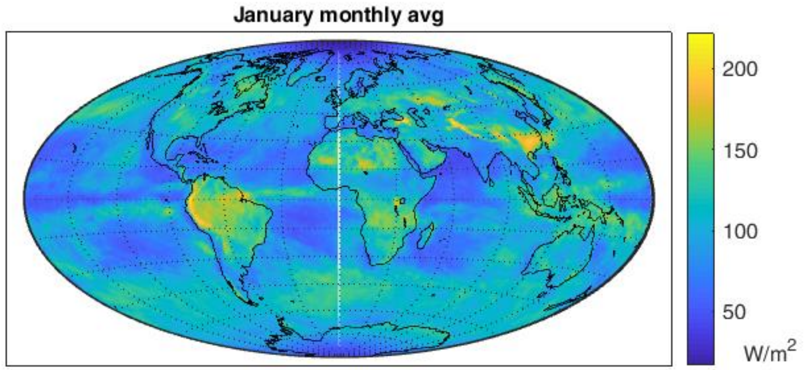


The LATOS thermal model

We considered three external heat sources:

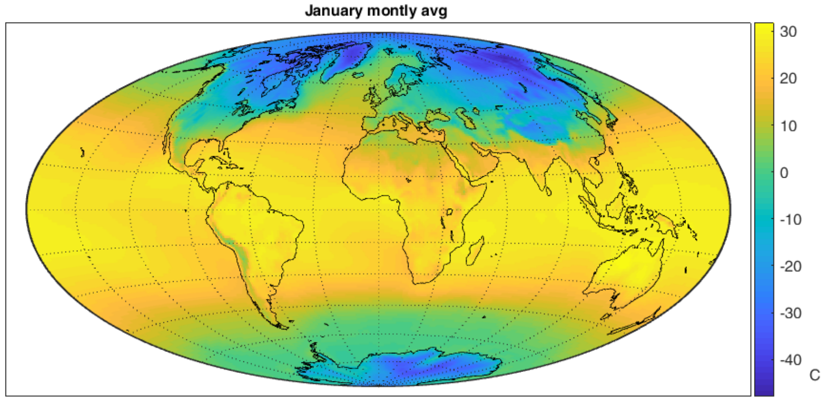
- The direct Sun radiation – using the standard value of $\phi_{\odot} = 1360.8 \, \frac{W}{m^2}$ at 1 A.U.
- The Sun radiation reflected from Earth (Albedo)

  We use CERES monthly averaged SW radiation data at the top of the atmosphere taking into account night-day alternance, satellite attitude and orbital position. The grid is 1°x1° Latitude-Longitude.



- The infrared radiation from the Earth

  We take into account the temperature of the different parts of the Earth using the monthly averaged data from Land + Ocean 1°x1° Latitude-Longitude grid from Berkeley Earth Organization. Attitude and orbit of the satellite are considered.



Preliminary results

- We developed two versions of the model (**LATOS**), an averaged one, usable for fast-spin conditions, and a general one, not averaged, to be used when the spin is slow with respect to the orbital period.

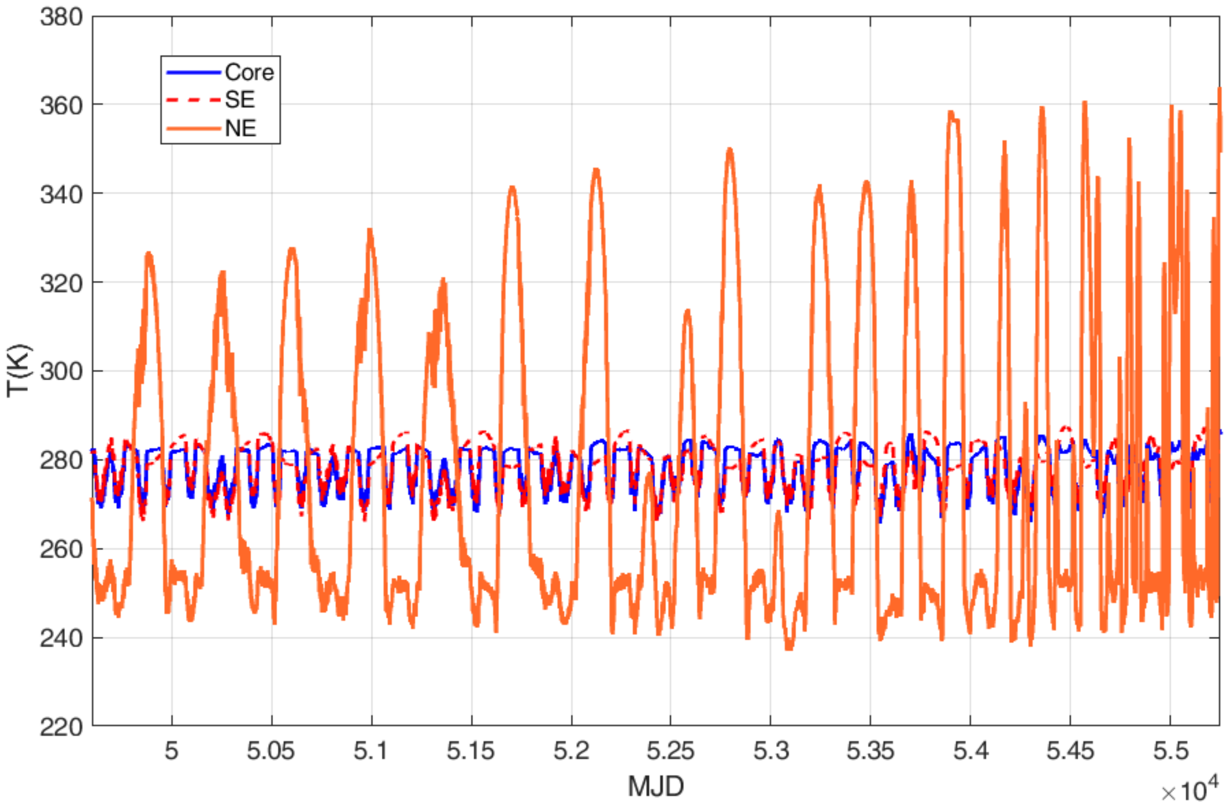
- By integrating the thermal equations we get the temperature distribution in the satellite and from this distribution we calculate the thermal thrust accelerations.

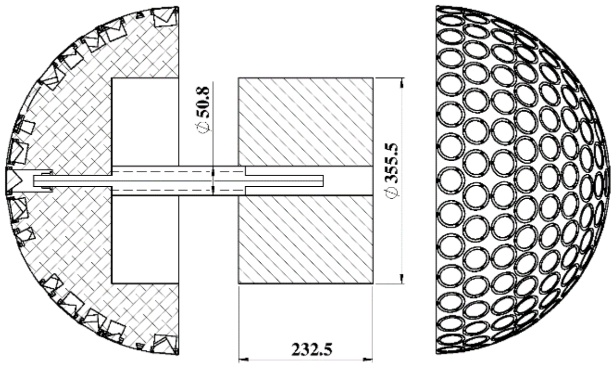
- We then calculated the effects of the thermal accelerations (via **Gauss** equations) on the rate of the Keplerian elements. The results can be compared with the corresponding rate residuals from a **precise orbit determination** (**POD**).

LArase Thermal mOdel Solutions (LATOS)

Preliminary results

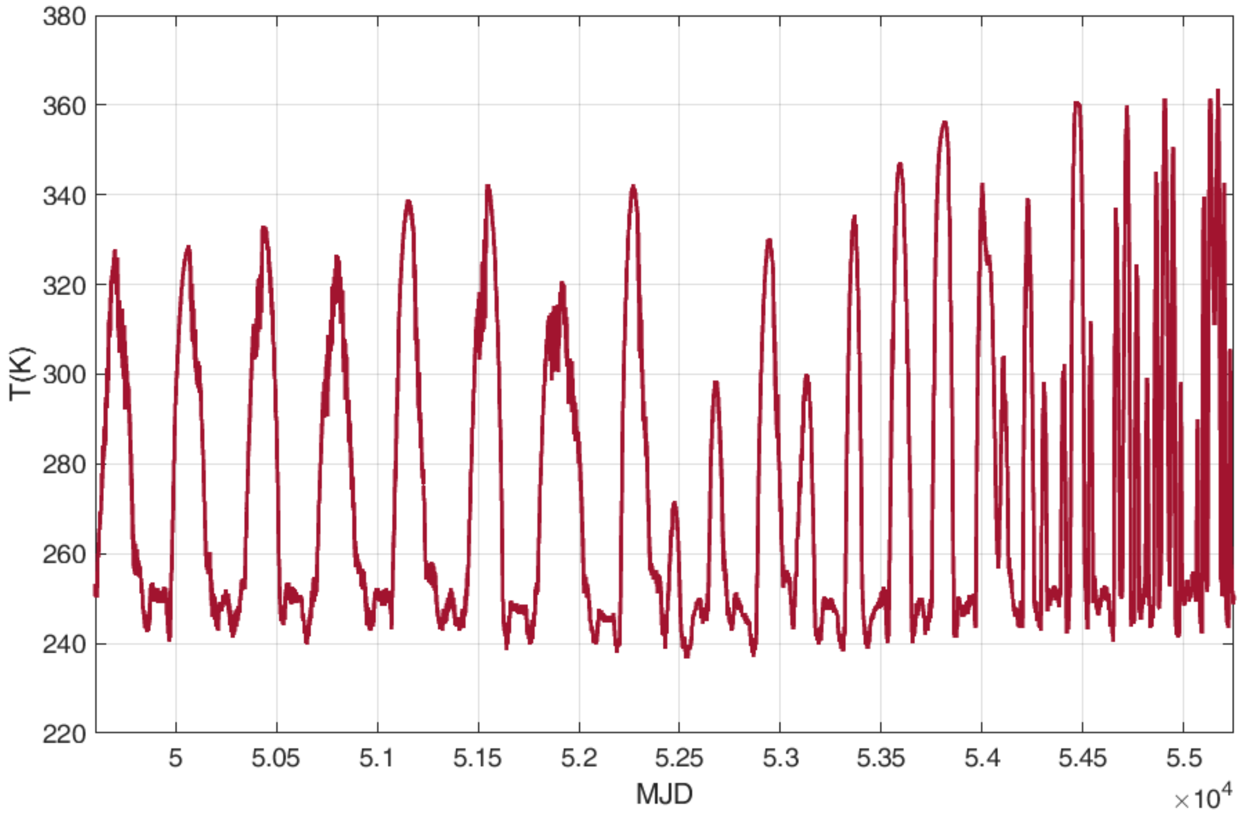
LAGEOS II: Temperatures of core and of the hemispheres





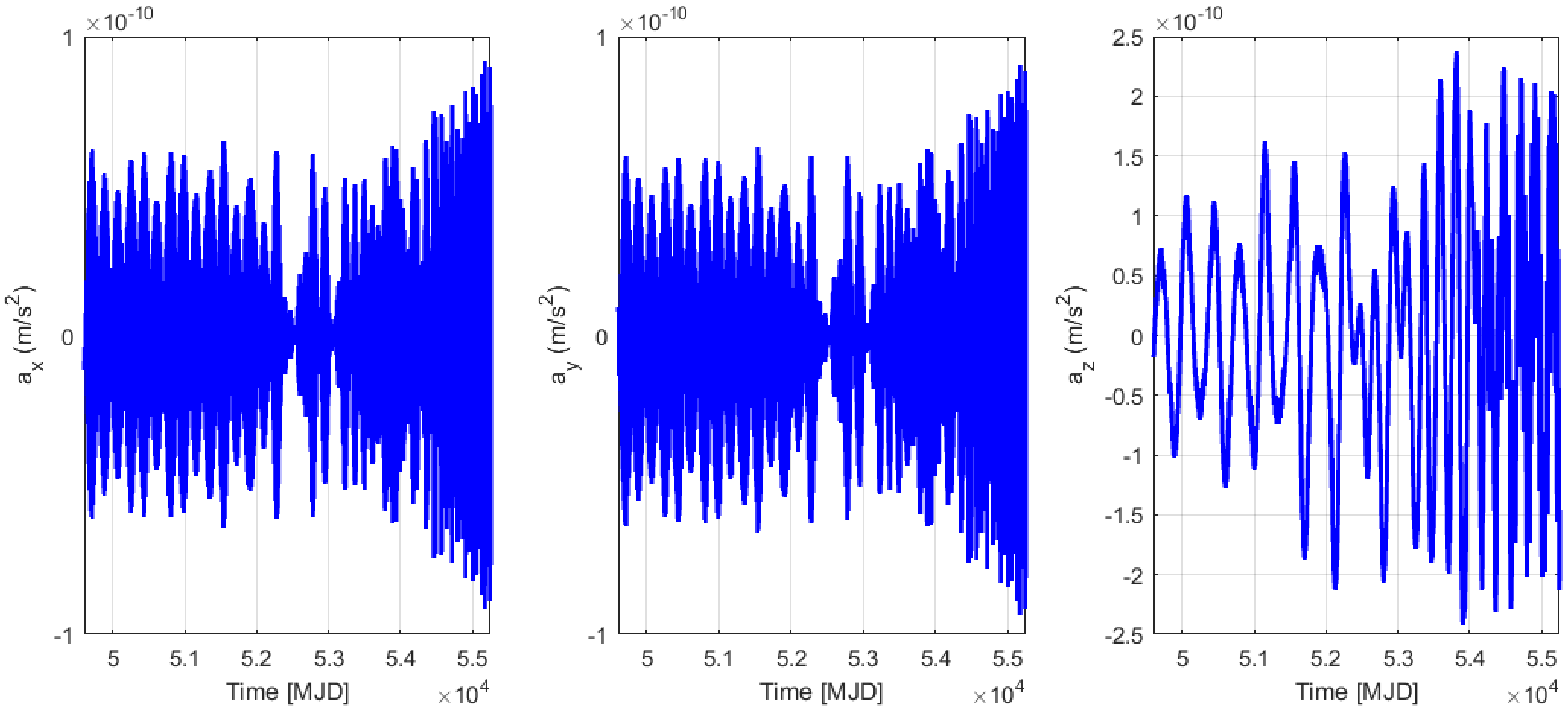
Preliminary results

LAGEOS II: Temperature of CCR #1



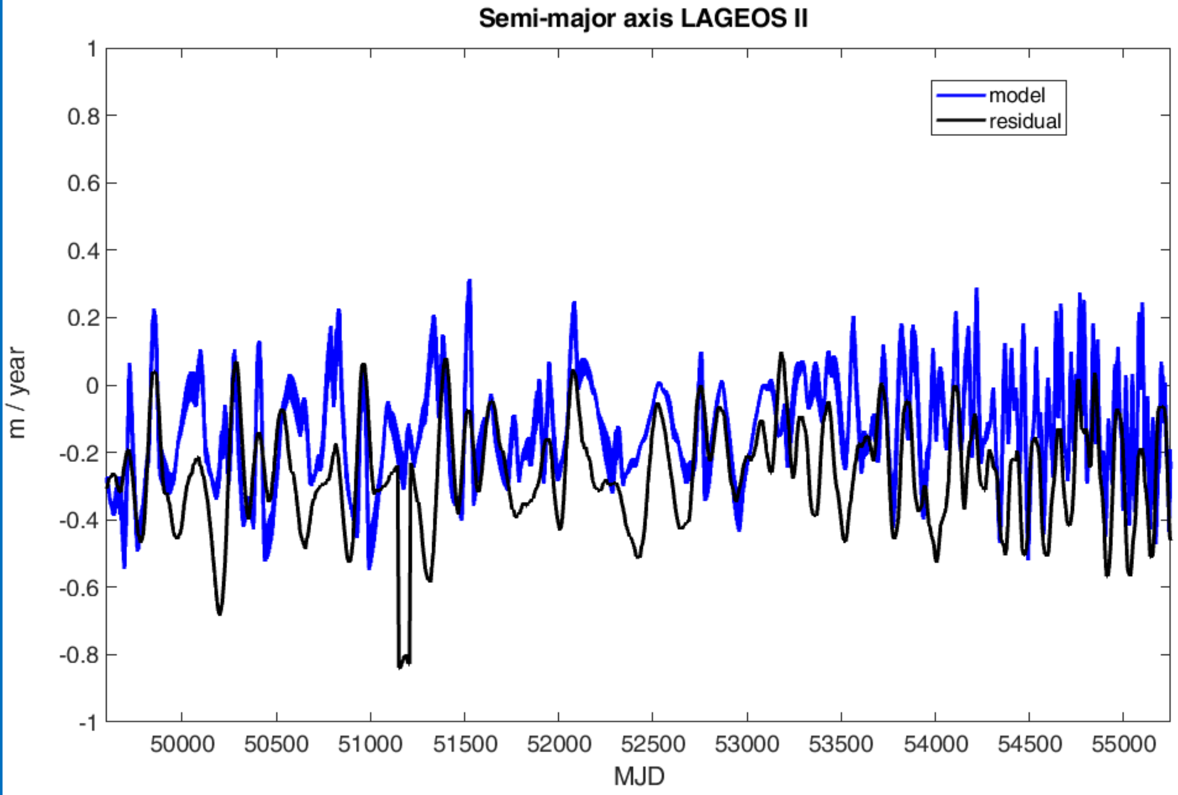
Preliminary results

LAGEOS II: accelerations in Gauss reference frame

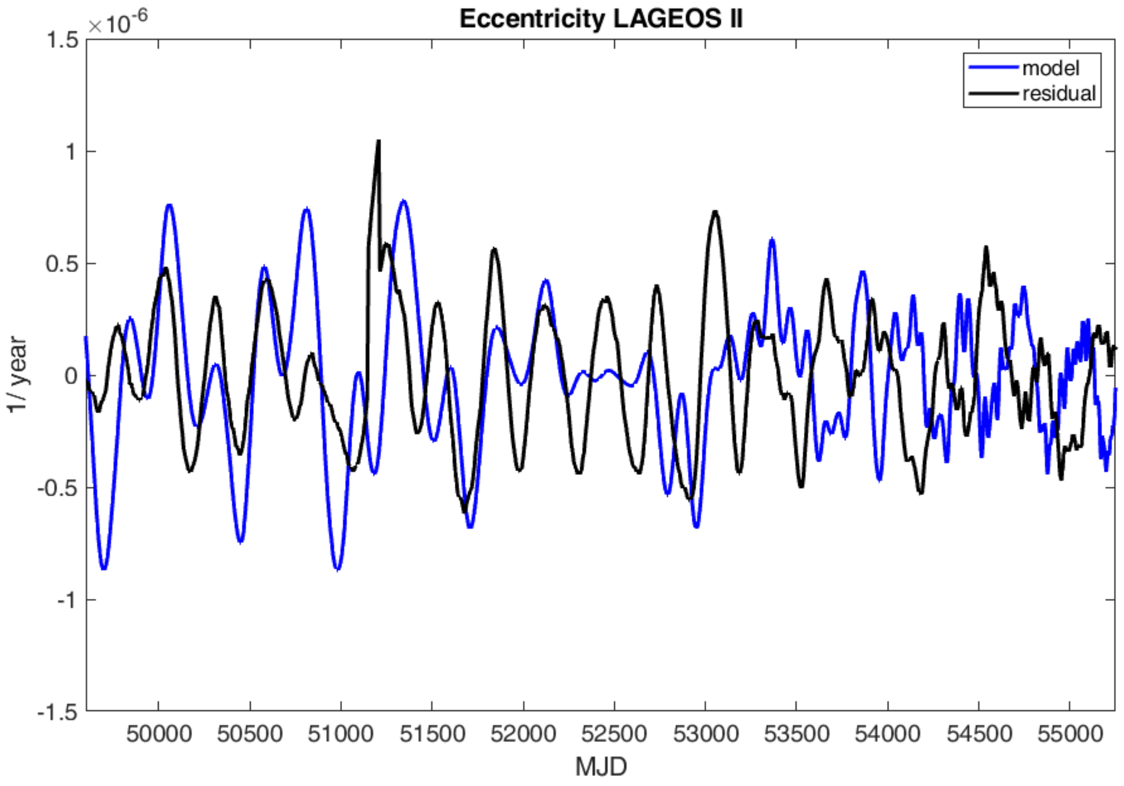


Radial Transverse Out-of-plane

Preliminary results



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

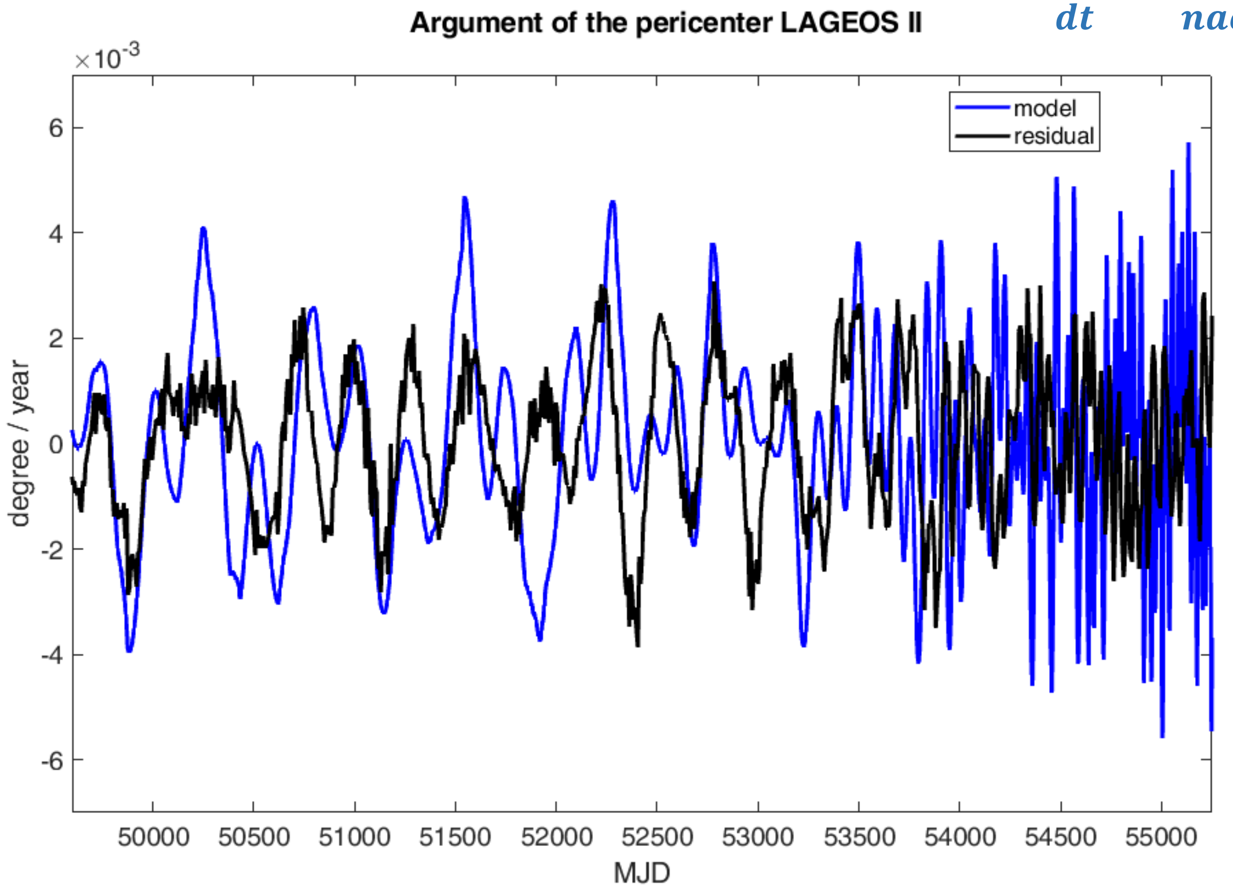


$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}[R\sin f + T(\cos f + \cos u)]$$

About 27 years POD of LAGEOS II with GEODYN II

Preliminary results

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



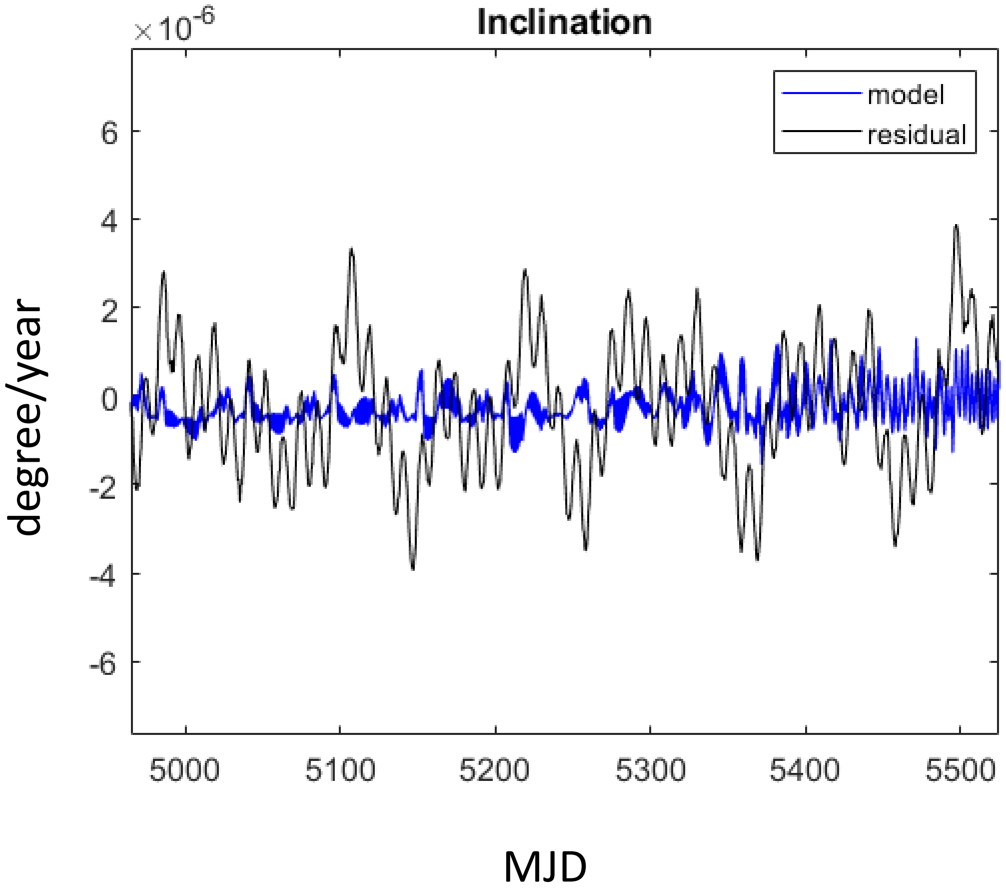
- Being able to clean up this parameter has a particular importance for us: it contains a secular effect from **General Relativity**, due to the **Gravitoelectric** field (M) and to the **Gravitomagnetic** field (J)

About 27 years POD of LAGEOS II with GEODYN II

Preliminary results

LAGEOS II: residuals vs thermal effects in the rate of the inclination

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



About 27 years POD of LAGEOS II with GEODYN II

Conclusions

- We have developed a new general model **LATOS** to manage the thermal thrust acceleration acting on the satellites **LAGEOS** and **LAGEOS II**
- We presented the preliminary results for the thermal thrust accelerations on **LAGEOS II** based on the new model
- These results are in good agreement with the orbital residuals
- Thermal accelerations determined from a reliable model may reduce the use of empirical accelerations in the satellites' **POD**, with possible improvements in
  - **Geophysical products**
  - **Fundamental physics measurements**

Many thanks for your kind attention

Backup slides

IOP Publishing Classical and Quantum Gravity
Class. Quantum Grav. 32 (2015) 155012 (50pp) doi:10.1088/0264-9381/32/15/155012

Testing the gravitational interaction in the field of the Earth via satellite laser ranging and the Laser Ranged Satellites Experiment (LARASE)

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Mass and moments of inertia…

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Advances in Space Research 57 (2016) 1928–1938

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Review and critical analysis of mass and moments of inertia of the LAGEOS and LAGEOS II satellites for the LARASE program

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Available online 15 February 2016

Mass and moments of inertia…

- We reconstruct information about the structure, the material used and the moments of inertia of the two LAGEOS
- We built a 3D-CAD model of the satellites structure useful for finite element-based analysis
- We also solve for contradictions and overcome several misunderstanding present in the historical literature of the older LAGEOS (carefully re-analyzing the earlier technical documents)

LAGEOS

LARES

Mass and moments of inertia…

Table 3
Mass and moments of inertia of LAGEOS and LAGEOS II to be used in the future. The masses are the one measured. The moments of inertia are those computed in the present work with normalized densities.

Satellite	Mass (kg)	Moments of inertia (kg m^2)		
	M	I_{xx}	I_{yy}	I_{zz}
LAGEOS flight arrangement	406.97	11.42 ± 0.03	10.96 ± 0.03	10.96 ± 0.03
LAGEOS II flight arrangement	405.38	11.45 ± 0.03	11.00 ± 0.03	11.00 ± 0.03

This work was also extended to **LARES**:

Table 1. Principal moments of inertia of LAGEOS, LAGEOS II and LARES in their flight arrangement.

Satellite	Moments of Inertia (kg m^2)		
	I_{zz}	I_{xx}	I_{yy}
LAGEOS	11.42 ± 0.03	10.96 ± 0.03	10.96 ± 0.03
LAGEOS II	11.45 ± 0.03	11.00 ± 0.03	11.00 ± 0.03
LARES	4.77 ± 0.03	4.77 ± 0.03	4.77 ± 0.03

- The two **LAGEOS** have almost the same oblateness of about 0.04
- **LARES** is practically spherical in shape, even if an oblateness as small as 0.002 is however possible

The LASSOS model…

PHYSICAL REVIEW D **98,** 044034 (2018)

Comprehensive model for the spin evolution of the *LAGEOS* and *LARES* satellites

Massimo Visco[1,2] and David M. Lucchesi[1,2,3]

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The LASSOS model…

The model for the magnetic torque. Since we are working with conductive satellites moving and rotating in the Earth's magnetic field $\boldsymbol{B}$, a magnetic moment $\boldsymbol{m}$ will be induced in their body and, consequently, a torque $\boldsymbol{M}_{mag}$ will be applied:

$$\boldsymbol{M}_{mag} = \boldsymbol{m} \times \boldsymbol{B}$$

In previous works, **LAGEOS** was modeled as a conducting sphere rotating in a **static magnetic** field

- **The value of the constant magnetic field was computed averaging the magnetic field over the entire orbit of the satellite**

The LASSOS model…

This solution, which is completely valid in a **quasi-stationary** field, can be suitably used as long as the rotation period of the satellite is much shorter than its orbital period as well as of the Earth's rotation period, but it could produce wrong results when is used in slow-spin conditions.

$$\boldsymbol{T_{rot} \ll T_{orb} \qquad T_{rot} \ll T_{\oplus}}$$

In order to obtain a more general expression of the magnetic torque we faced the problem to find an easily integrable expression for the torque acting on a conducting sphere rotating in an **alternating magnetic** field.

The LASSOS model…

LASSOS Spin Model: results for LAGEOS II

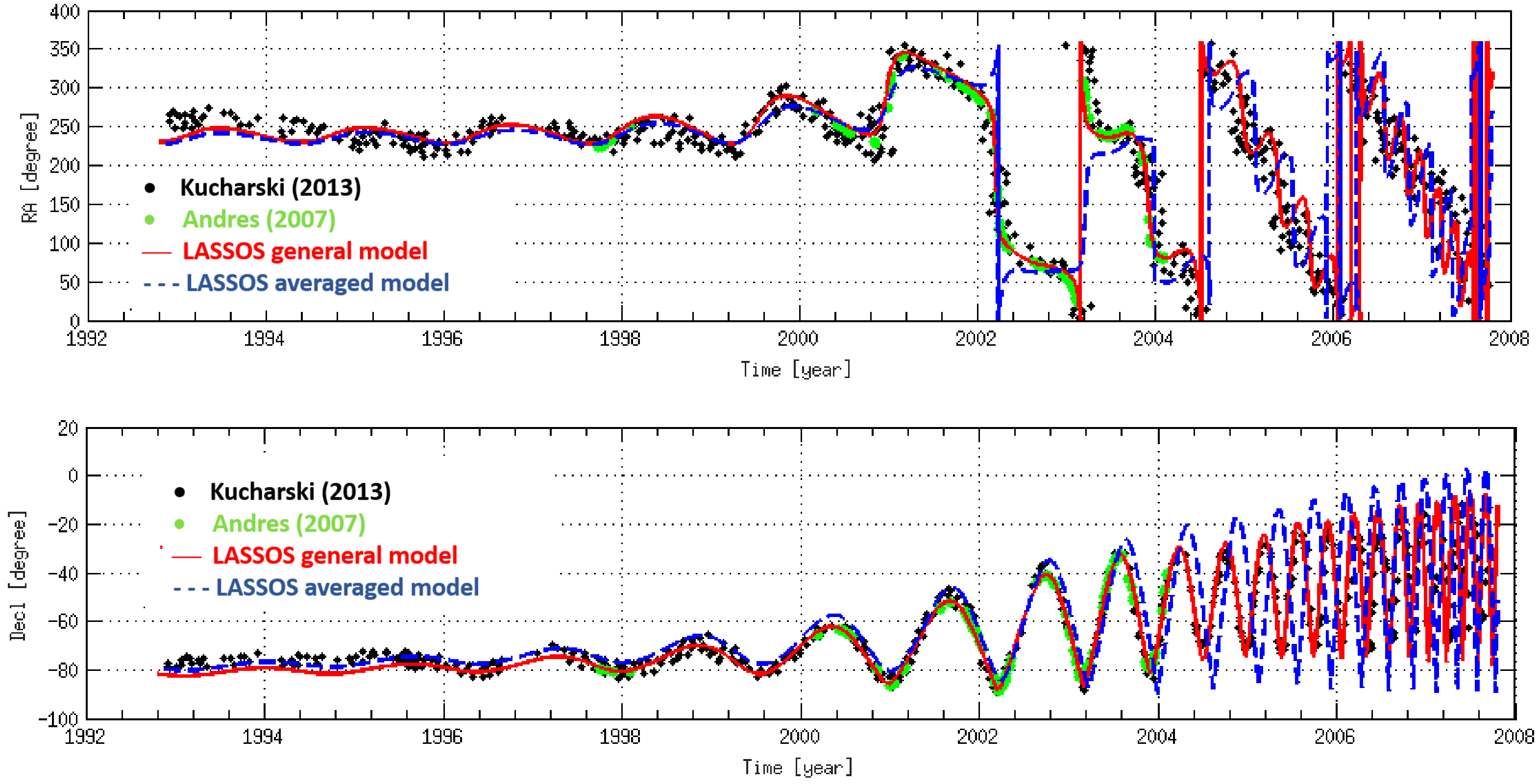
LArase **S**atellites **S**pin m**O**del **S**olutions (**LASSOS**)

Blue = LASSOS model for the rapid-spin
Red = LASSOS general model

Spin Orientation: α, δ

Andrés de la Fuente, J.I., 2007. *Enhanced Modelling of LAGEOS Non-Gravitational Perturbations* (Ph.D. thesis). Delft University Press. Sieca Repro, Turbineweg 20, 2627 BP Delft, The Netherlands.

Kucharski, D., **Lim**, H.C., **Kirchner**, G., **Hwang**, J.Y., 2013. *Spin parameters of LAGEOS-1 and LAGEOS-2 spectrally determined from Satellite Laser Ranging data*. Adv. Space Res. 52, 1332–1338.



The LASSOS model…

LASSOS Spin Model: results for LAGEOS II

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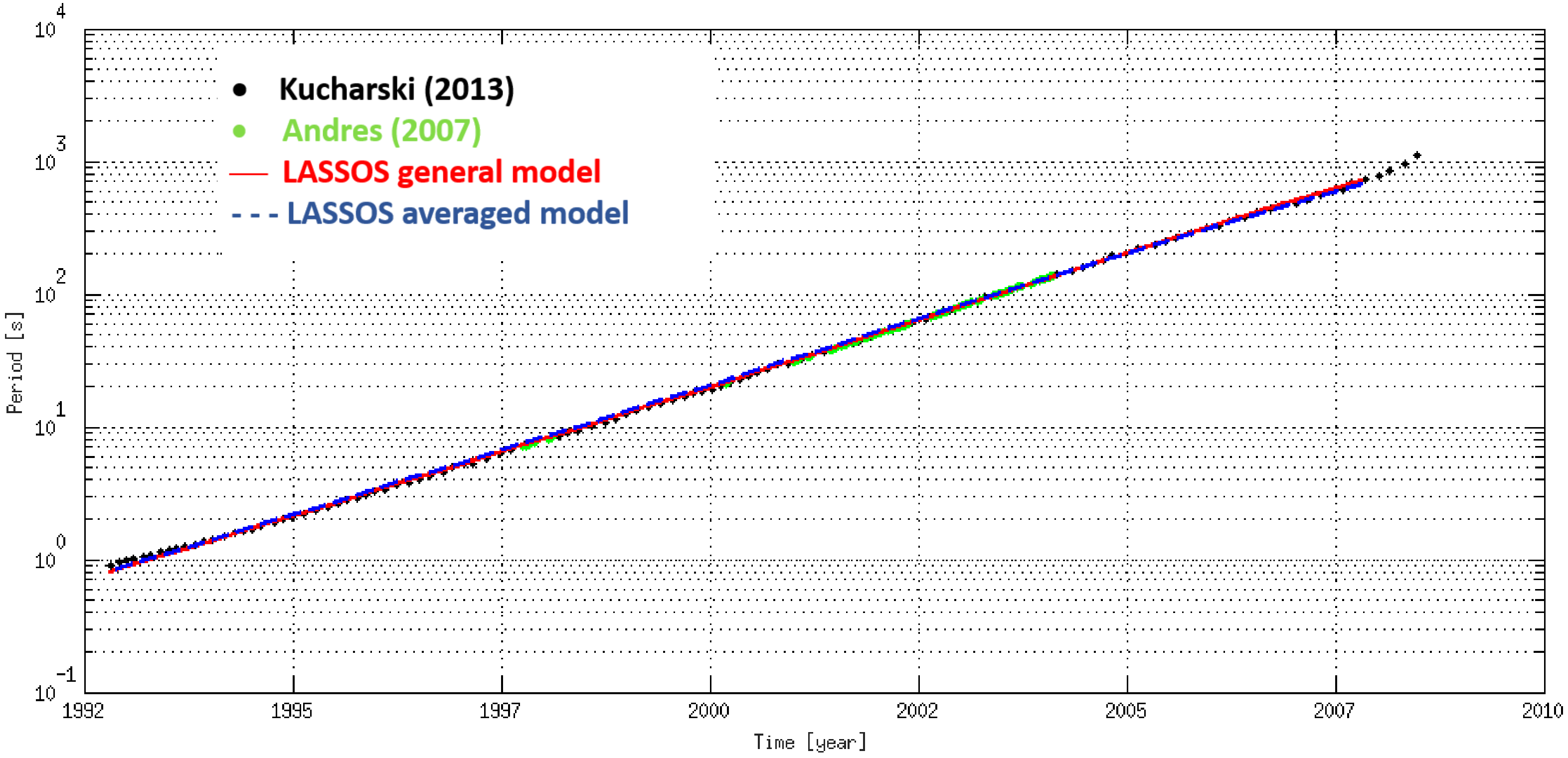
Rotational Period: P



The LASSOS model…

TABLE I. Mechanical parameters used in the equations: moments of inertia **I**, ray R and offset **h** of the satellites.

	LAGEOS	*LAGEOS* II	*LARES*
I_x[kg m^2]	10.96 ± 0.03	11.00 ± 0.03	4.76 ± 0.03
I_y[kg m^2]	10.96 ± 0.03	11.00 ± 0.03	4.76 ± 0.03
I_z[kg m^2]	11.42 ± 0.03	11.45 ± 0.03	4.77 ± 0.03
R[cm]	30.0	30.0	18.2
h_x[cm]	0.000	0.000	0.000
h_y[cm]	0.000	0.000	0.000
h_z[cm]	0.040	0.055	0.000

TABLE II. Electromechanical parameters used in the equations: dimensionless magnetic factors β' and β'', electrical conductivity σ and the relative magnetic permeability μ_r.

	LAGEOS	*LAGEOS* II	*LARES*
β'	$< 10^{-2}$	$< 10^{-2}$	1
β''	0.22	0.23	1
$\sigma[s]$	2.37×10^{17}	2.38×10^{17}	5.1×10^{16}
$\mu_r - 1$	2.2×10^{-5}	2.2×10^{-5}	3.3×10^{-7}

TABLE III. Optical parameters used in the equations: radiation coefficient C_R and reflectivity difference between the hemispheres $\Delta\rho$ of the satellites.

	LAGEOS	*LAGEOS* II	*LARES*
C_R	1.13	1.12	1.07
$\Delta\rho$	0.013	0.012	0

TABLE IV. Spin initial conditions: reference epoch in Modified Julian Date (MJD), rotational period P_s, right ascension RA and declination dec.

	LAGEOS	*LAGEOS* II	*LARES*
Epoch [MJD]	42913.5	48918	55970
P_s [s]	0.48	0.81	11.8
RA [degree]	150	230	186.5
dec [degree]	−68	−81.8	−73

universe

MDPI

Article

General Relativity Measurements in the Field of Earth with Laser-Ranged Satellites: State of the Art and Perspectives

David M. Lucchesi [1,2,3,*], Luciano Anselmo [2], Massimo Bassan [3,4], Carmelo Magnafico [1,3], Carmen Pardini [2], Roberto Peron [1,3], Giuseppe Pucacco [3,4] and Massimo Visco [1,3]

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Abstract: Recent results of the LARASE research program in terms of model improvements and relativistic measurements are presented. In particular, the results regarding the development of new models for the non-gravitational perturbations that affect the orbit of the LAGEOS and LARES satellites are described and discussed. These are subtle and complex effects that need a deep knowledge of the structure and the physical characteristics of the satellites in order to be correctly accounted for. In the field of gravitational measurements, we present a new measurement of the relativistic Lense-Thirring precession with a 0.5% precision. In this measurement, together with the relativistic effect we also estimated two even zonal harmonics coefficients. The uncertainties of the even zonal harmonics of the gravitational field of the Earth have been responsible, until now, of the larger systematic uncertainty in the error budget of this kind of measurements. For this reason, the role of the errors related to the model used for the gravitational field of the Earth in these measurements is discussed. In particular, emphasis is given to GRACE temporal models, that strongly help to reduce this kind of systematic errors.

Keywords: satellite laser ranging; LAGEOS satellites; perturbations; models; general relativity; Lense-Thirring effect

An improved measurement of the Lense-Thirring precession on the orbits of laser-ranged satellites with an accuracy approaching the 1% level

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We present a new measurement of the Lense-Thirring effect on the orbits of the geodetic satellites LAGEOS, LAGEOS II and LARES. This secular precession is a general relativity effect produced by the gravitomagnetic field of the Earth generated by its rotation. The effect is a manifestation of spacetime curvature generated by mass-currents, a peculiarity of Einstein's theory of gravitation. This measurement stands out, compared to previous measurements in the same context, for its precision ($\simeq 7.4 \times 10^{-3}$) and accuracy ($\simeq 16 \times 10^{-3}$), i.e. for a reliable and robust evaluation of the systematic sources of error due to both gravitational and non-gravitational perturbations. For this new measurement, we have largely exploited the results of GRACE mission to significantly improve the description of the gravitational field of the Earth, by also modeling its time dependence. In this way, we strongly reduced the systematic errors due to the uncertainty in the knowledge of the Earth even zonal harmonics and, at the same time, avoided a possible bias of the final result and, consequently, of the precision of the measurement, linked to a non-reliable handling of the unmodeled and mismodeled periodic effects.

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