The LARES and LARES 2 space missions

Claudio Paris, Ignazio Ciufolini

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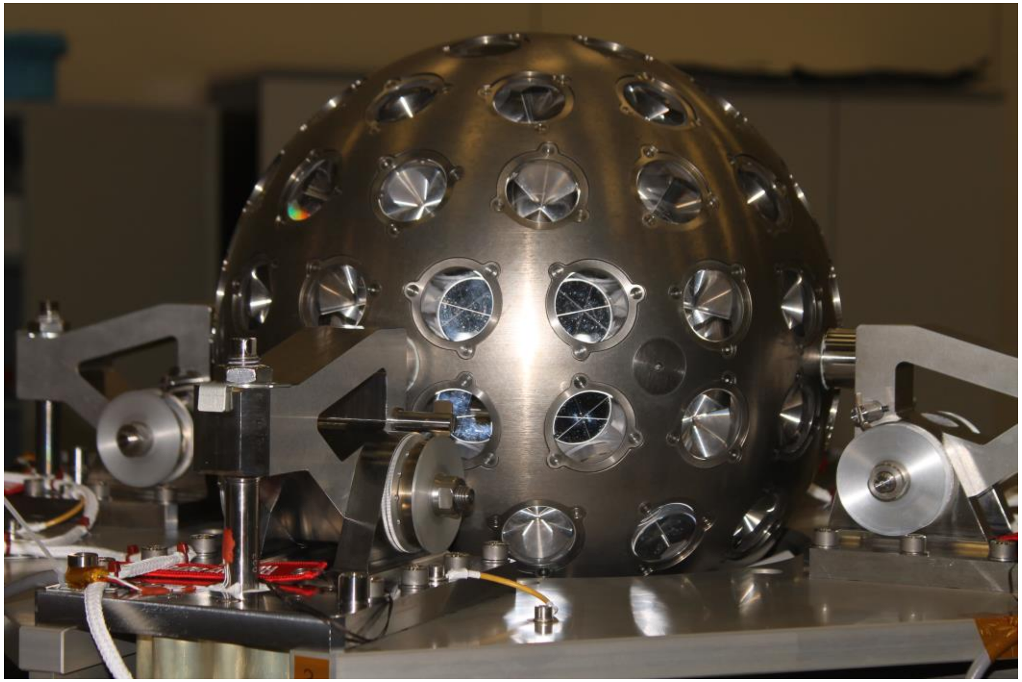

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CONTENT OF THIS TALK

- A brief introduction on frame-dragging and General Relativity and some history of tests of frame-dragging

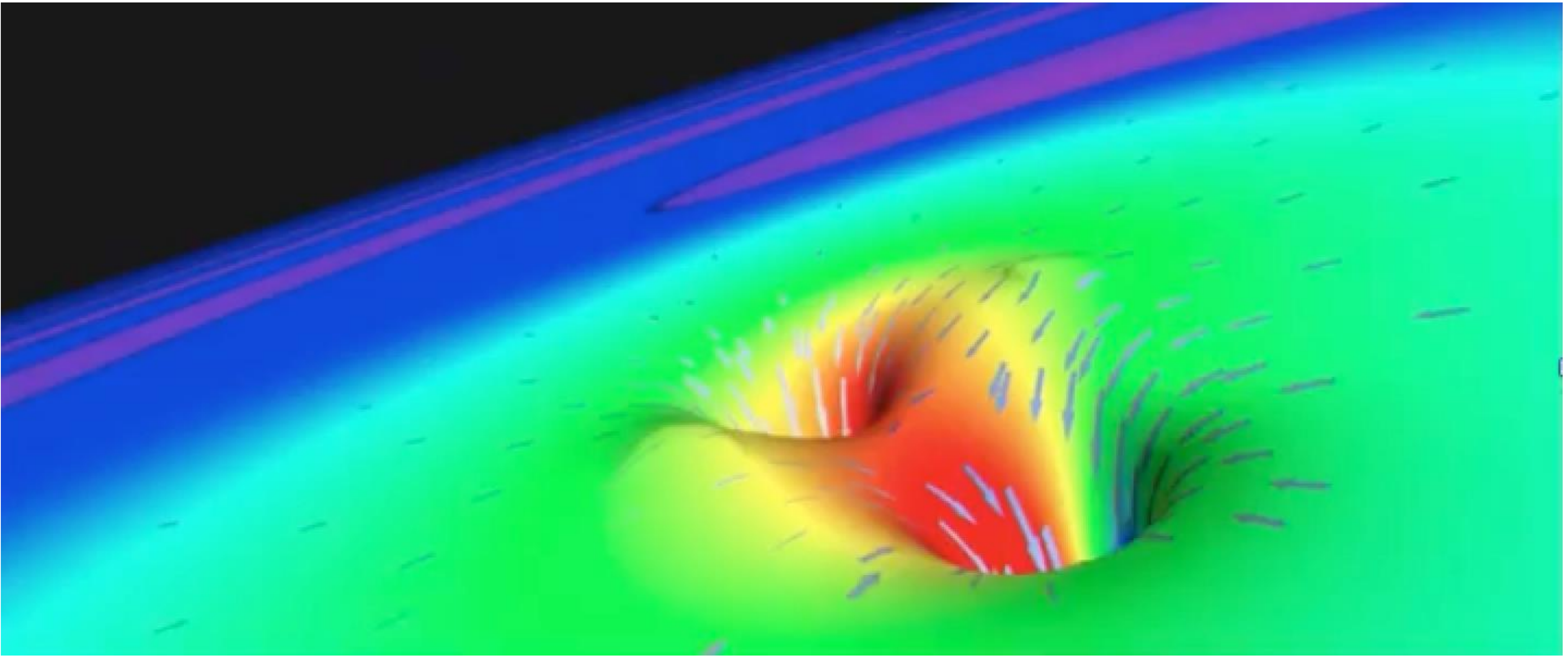
- The LARES satellite and its present and future results.

- The LARES 2 satellite and its objectives.

DRAGGING OF INERTIAL FRAMES
(*FRAME-DRAGGING* as Einstein named it in 1913)

- **Spacetime curvature is generated by mass-energy currents.**
- **It plays a key role in high energy astrophysics (Kerr metric).**
- **Frame-dragging and Kerr metric can play a key role in the computer analysis of the detection of gravitational waves due to the coalescence of two spinning black holes to form a Kerr spinning black hole.**

Thirring 1918
Braginsky, Caves and Thorne 1977
Thorne 1986
Ciufolini 1994-2001

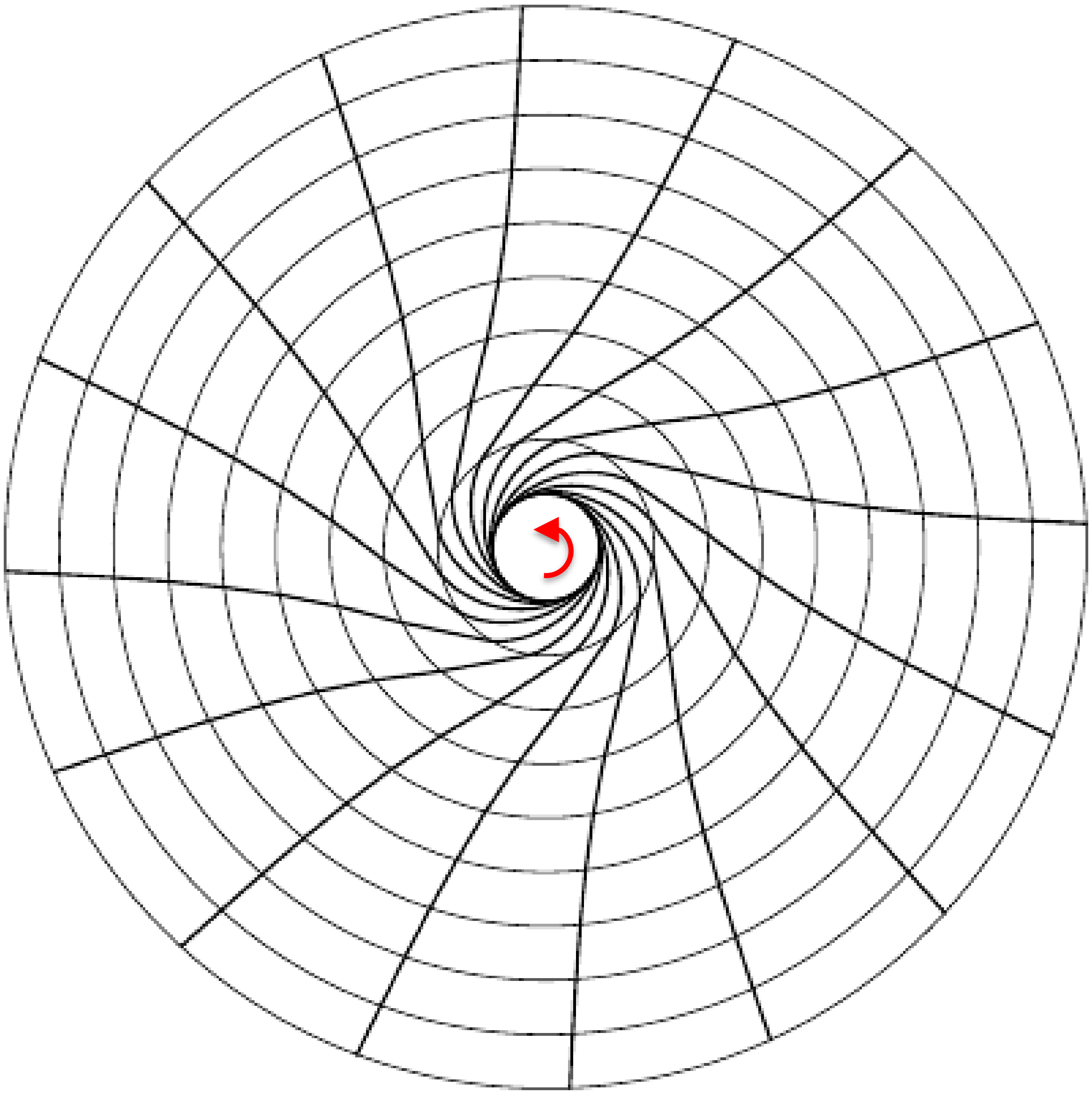


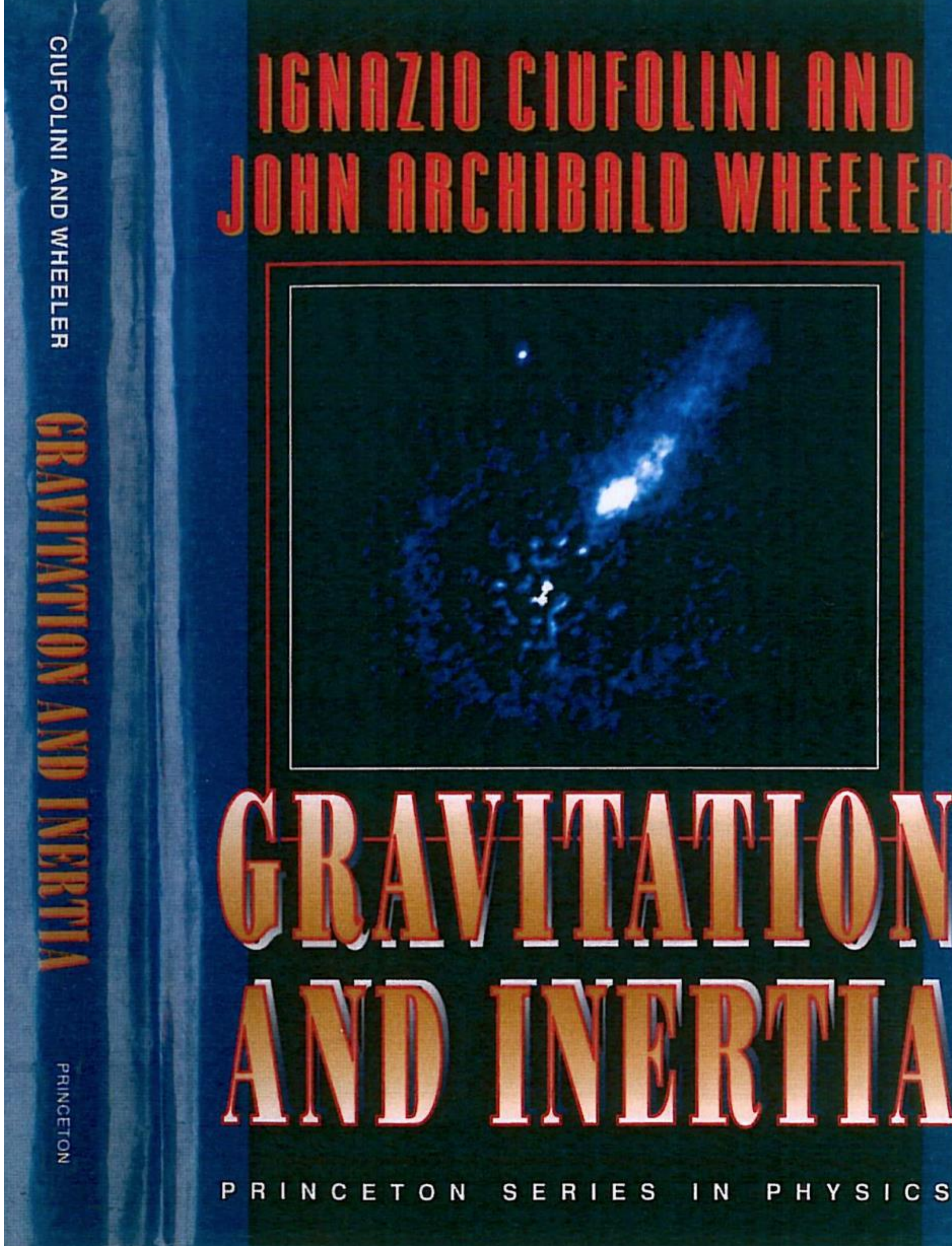
Computer simulation of the collision of two black holes detected by LIGO in 2015 by their emission of gravitational waves.

The silver arrows represent frame-dragging.

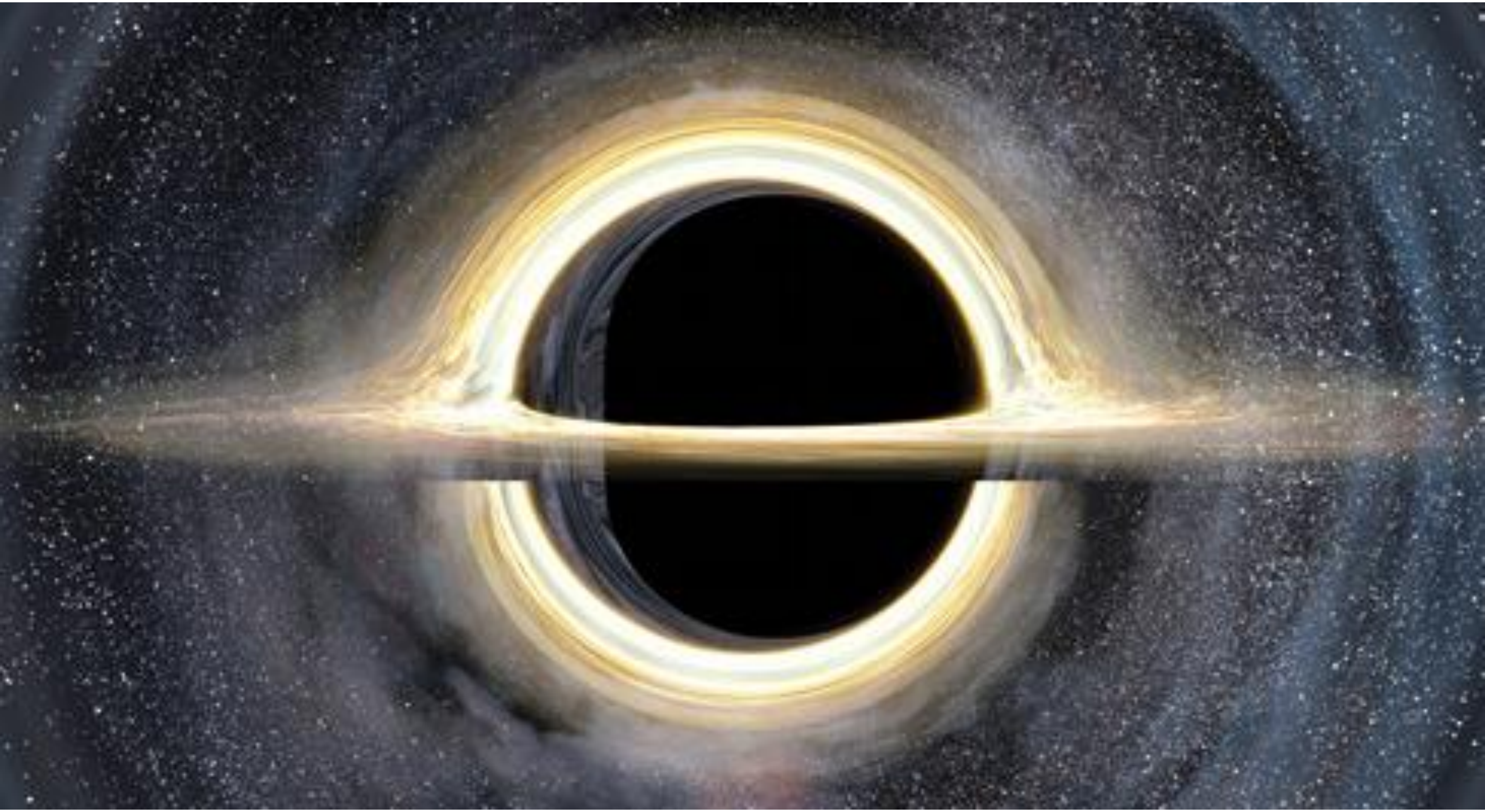
Kip Thorne NSF 2016 presentation

DRAGGING OF INERTIAL FRAMES





CIUFOLINI AND WHEELER
GRAVITATION AND INERTIA
PRINCETON
IGNAZIO CIUFOLINI AND
JOHN ARCHIBALD WHEELER
GRAVITATION
AND INERTIA
PRINCETON SERIES IN PHYSICS



General Relativity and Hollywood.
Frame-dragging plays a key role in the plot of *Interstellar:*
Gargantua is a supermassive rotating black hole

A brief history of the main tests of frame-dragging

GRAVITY PROBE B: since 1960 the GRAVITY PROBE B space mission was under development in USA with the goal of a 0.1% test of frame-dragging. Gravity Probe B was finally launched in 2004 after almost half a century.

LAGEOS (LAser GEOdynamics Satellite) was launched in 1976 by NASA for space geodetic measurements.

LAGEOS 3: In 1984-1989 a new laser-ranged satellite called "LAGEOS 3", identical to the LAGEOS satellite (launched in 1976 by NASA) was proposed with orbital parameters identical to those of LAGEOS but a *supplementary inclination*, that is with *inclination I = 70.16 °* and *semimajor axis = 12270 km*. A number of ASI and NASA studies confirmed its feasibility to measure frame-dragging (I.C. 1984/1986/1989, B.Tapley, I.C et al. NASA/ASI study 1989/1990, J. Ries 1989 …). Support letters for LAGEOS 3 were written to NASA and ASI (Italian Space Agency) by: JOHN ARCHIBALD WHEELER, KIP THORNE, TULLIO REGGE, NICOLA CABIBBO, ..

LAGEOS 2: The LAGEOS 2 satellite was launched in 1992 by ASI and NASA for space geodetic measurements.

LAGEOS and LAGEOS 2, 1997/1998: it was obtained the first ***rough observation*** of frame-dragging using the data of LAGEOS and LAGEOS 2 (*CQG 1997, Science 1998*). In 1996 two nodes were not enough to measure frame-dragging without an accurate enough of Earth's gravity field.

GRACE, 2002: it was launched the DLR (GFZ) and NASA (CSR) space mission to accurately measure the Earth's gravity field.

LAGEOS and LAGEOS 2: 2004-2010: it was published the first **measurement** (with accuracy of approximately 10%) of frame-dragging (*Nature 2004, General Relativity book 2010, etc.*) using GEODYN. *Independently* confirmed by the Univ. of Texas at Austin (2008/2009, with UTOPIA) and GFZ-DLR (2010, with EPOSOC).

LARES (**LA**ser **RE**lativity **S**atellite) launched in 2012.

Gravity Probe B result, 2011-2015: it was published a measurement of frame-dragging with approximately 19% accuracy (*Phys. Rev. Lett. 2011 and CQG 2015*).

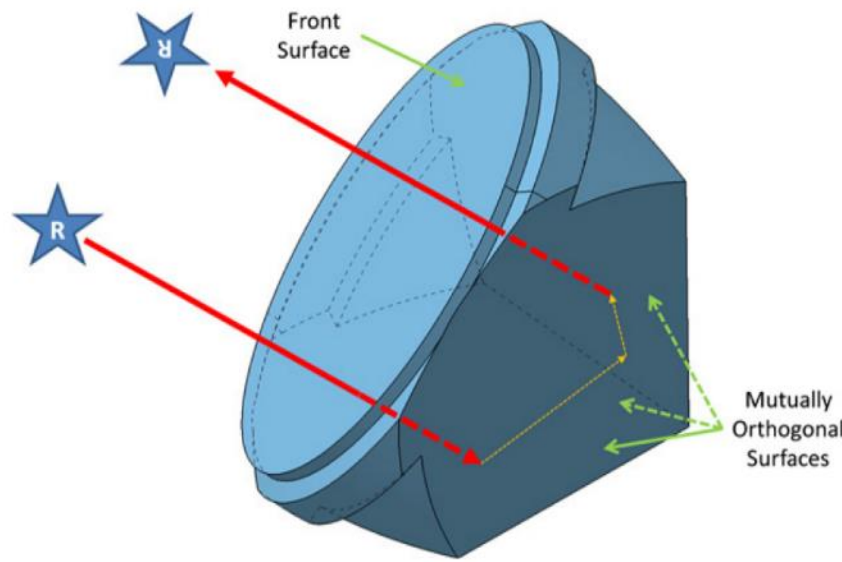
LARES first results, with LAGEOS and LAGEOS 2, 2016: it was published a measurement of frame-dragging with approximately 5% accuracy (*Eur. Phys. J. C, 2016*).

LARES forthcoming results, with LAGEOS and LAGEOS 2: should reach about 2% accuracy.

LARES 2, to be launched in 2019/2020, should reach 0.2% accuracy

Satellite Laser Ranging (and Lunar Laser Ranging)

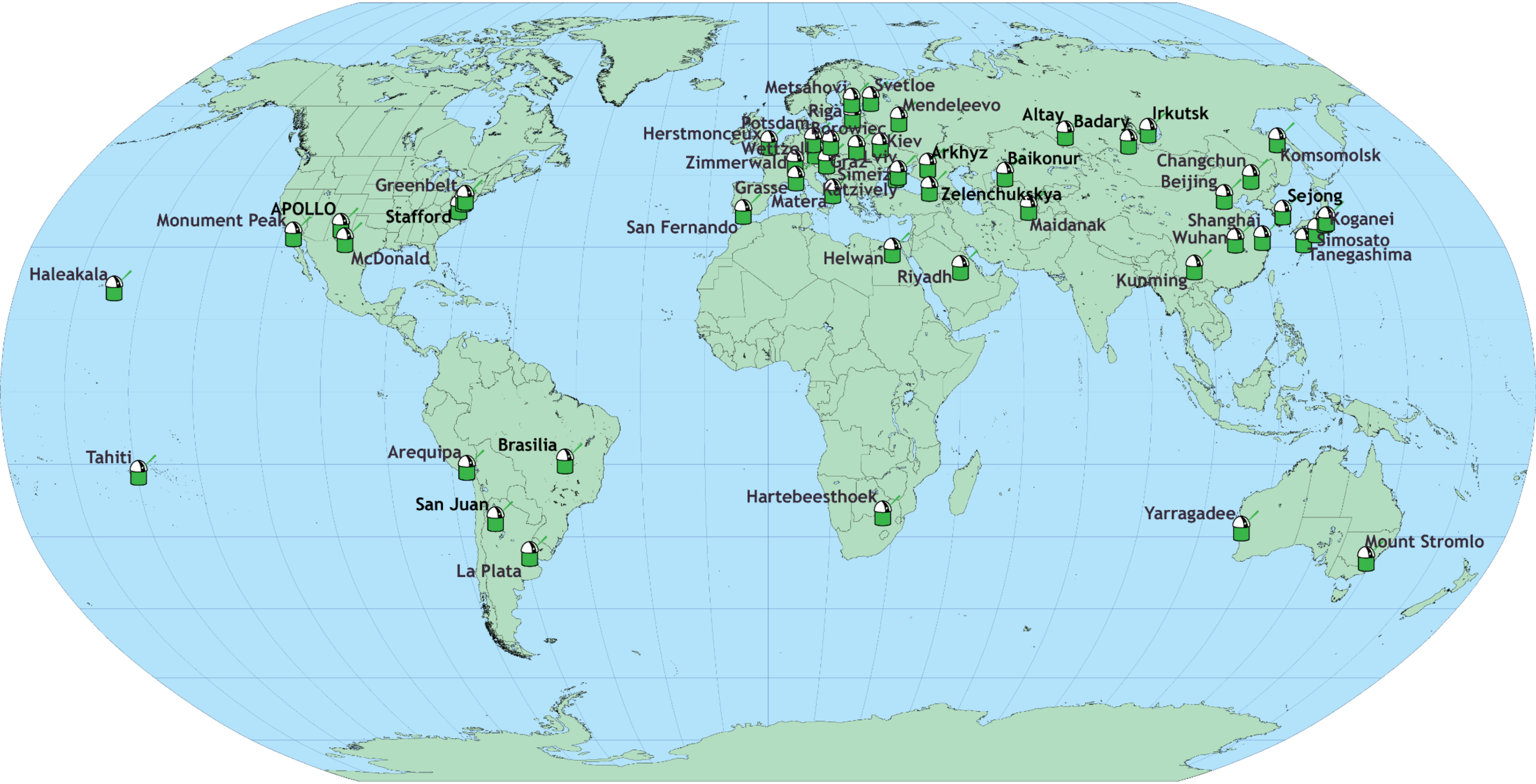
Measurement of the position of the satellite with respect to the ground station by timing the time of flight of short (30 ps – 100 ps) or ultra-short (10 ps) laser pulses reflected by the CCRs mounted on the satellite.



Note:
10^{17} photons in a pulse, few reflected photons detected.

Cube Corner Reflector (CCR)
Reflects the laser impuses toward the ground station, whatever is the inclination of the front surface

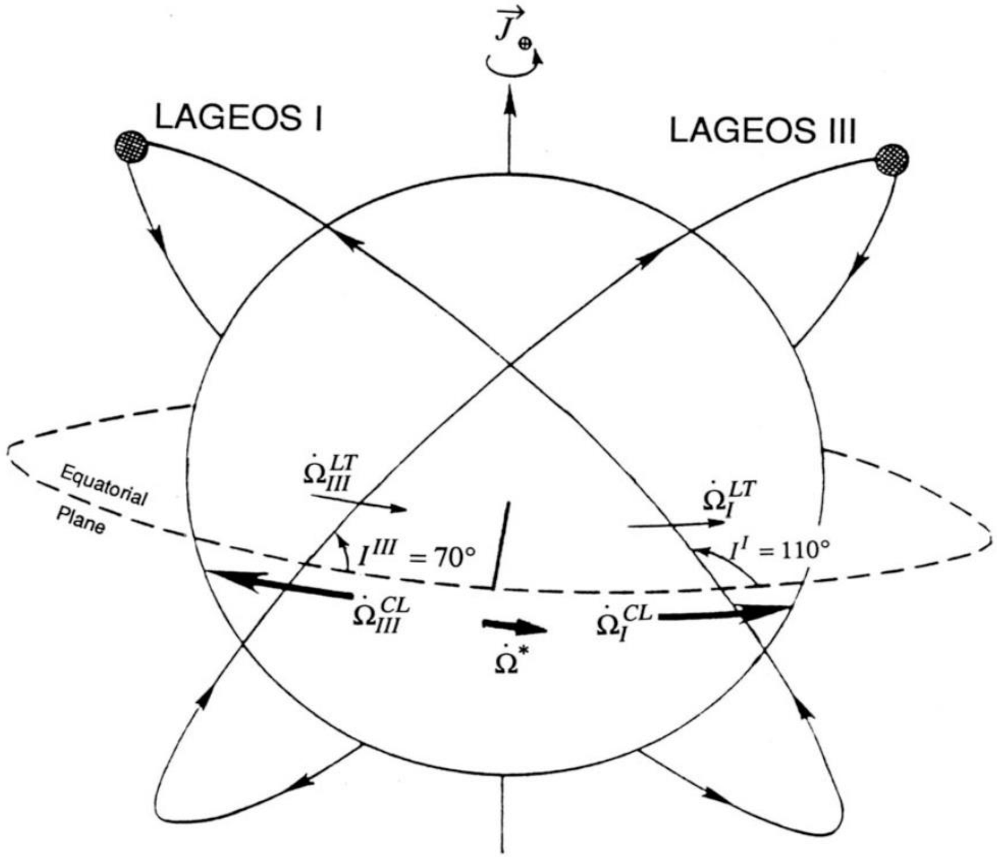
Satellite Laser Ranging (and Lunar Laser Ranging)



The International Laser Ranging Service (ILRS)

The idea of the LARES 2/LAGEOS 3 experiment:

I.C. Phys. Rev. Lett. 1986, I.C. Ph.D. dissertation 1984, I.C. IJMPA 1989, B. Tapley, I.C. et al, NASA and ASI studies 1989, J. Ries 1989).

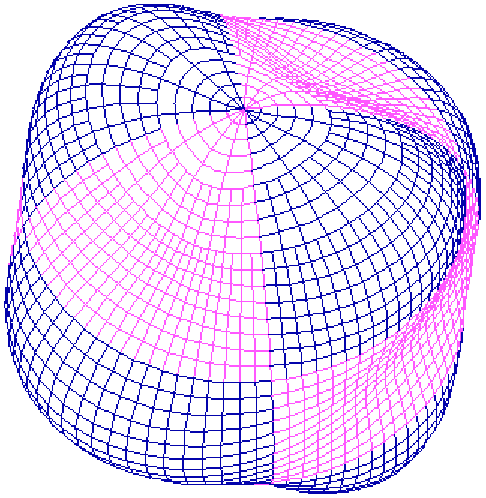


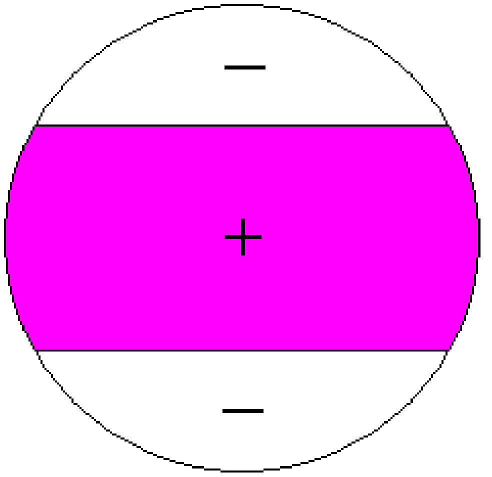
Object of measurement:

$$\dot{\Omega}^* = ½ (\dot{\Omega}^I + \dot{\Omega}^{III})$$

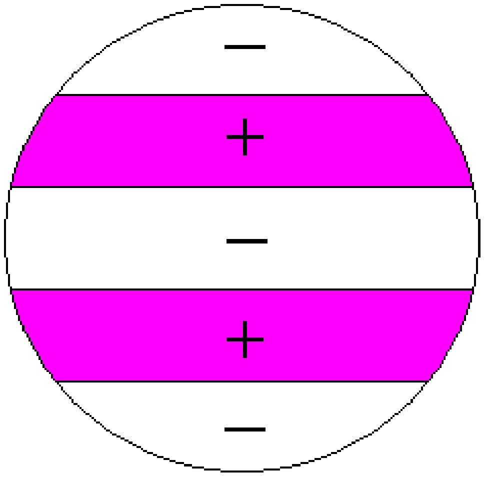
EVEN ZONAL HARMONICS

l=3, m=1





J_2



J_4

Using two satellites with supplementary inclinations, we can eliminate the uncertainty due to all the even zonal harmonics J_{2n}

Periodical effects due to tesseral harmonics are eliminated by averaging over several years of data.

Two approaches for measuring Frame-Dragging with Satellite Laser Ranging:

(1) Use two LAGEOS-type satellites with supplementary inclinations to eliminate the effect of **all** the J_{2n}
(**LAGEOS 3/LARES 2**).

or

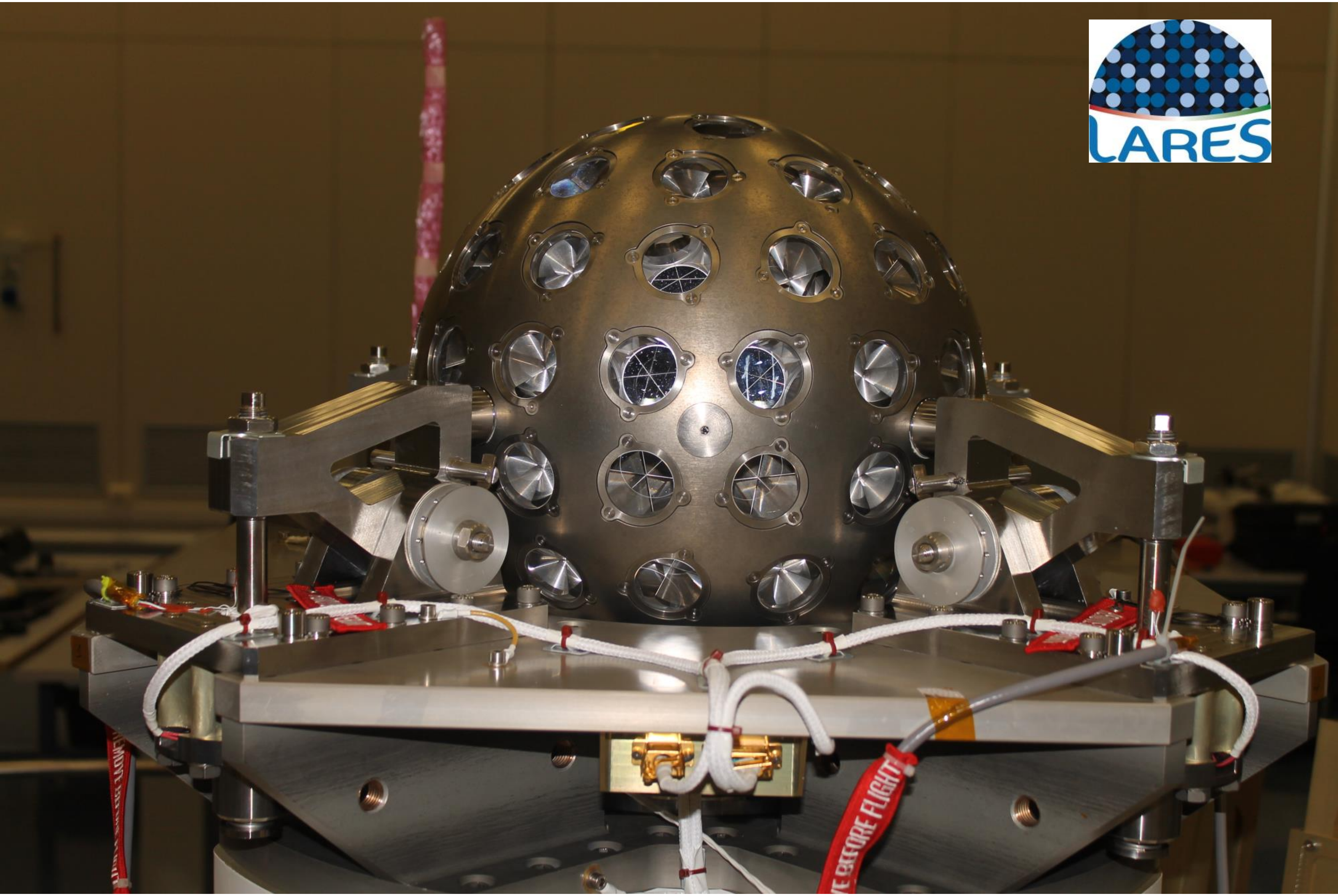
(2) Use *n* satellites of LAGEOS-type to measure the first *n-1* even zonal harmonics: J_2, J_4, … and the frame-dragging effect (**LARES**).

I.C. IJMPA 1989: Analysis of the orbital perturbations affecting the nodes of LAGEOS-type satellites

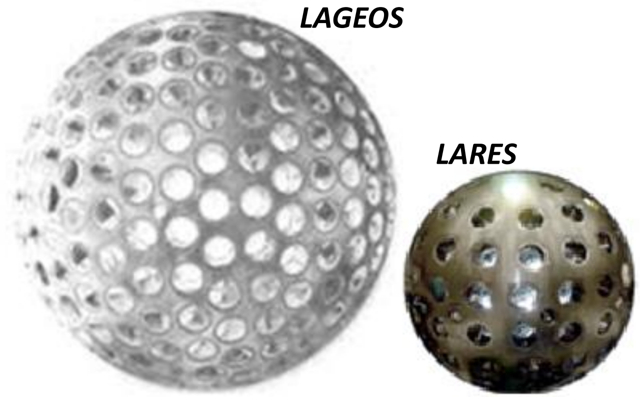
LARES (LAser RElativity Satellite)

LARES was successfully launched and accurately injected in the nominal orbit on February 13th 2012 with the ESA launcher VEGA from Kourou, French Guyana

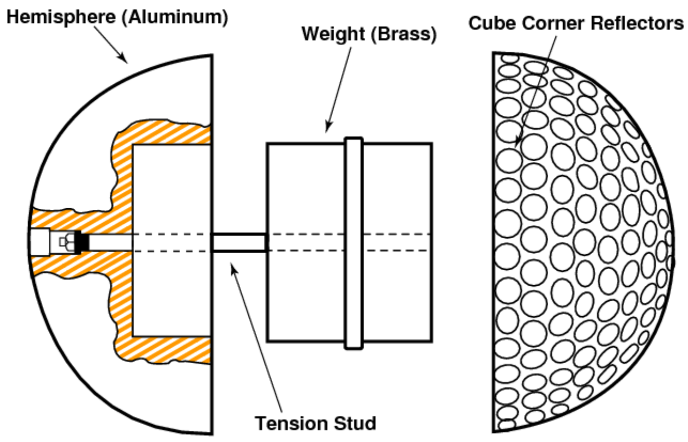
Combined with the LAGEOS and LAGEOS 2 orbital data and using the GRACE Earth gravity field determinations, LARES provides a confirmation of Einstein General Relativity, the measurement of frame-dragging, with accuracy of about a few percent (so far 5%.)


LARES

Design: LARES vs LAGEOS

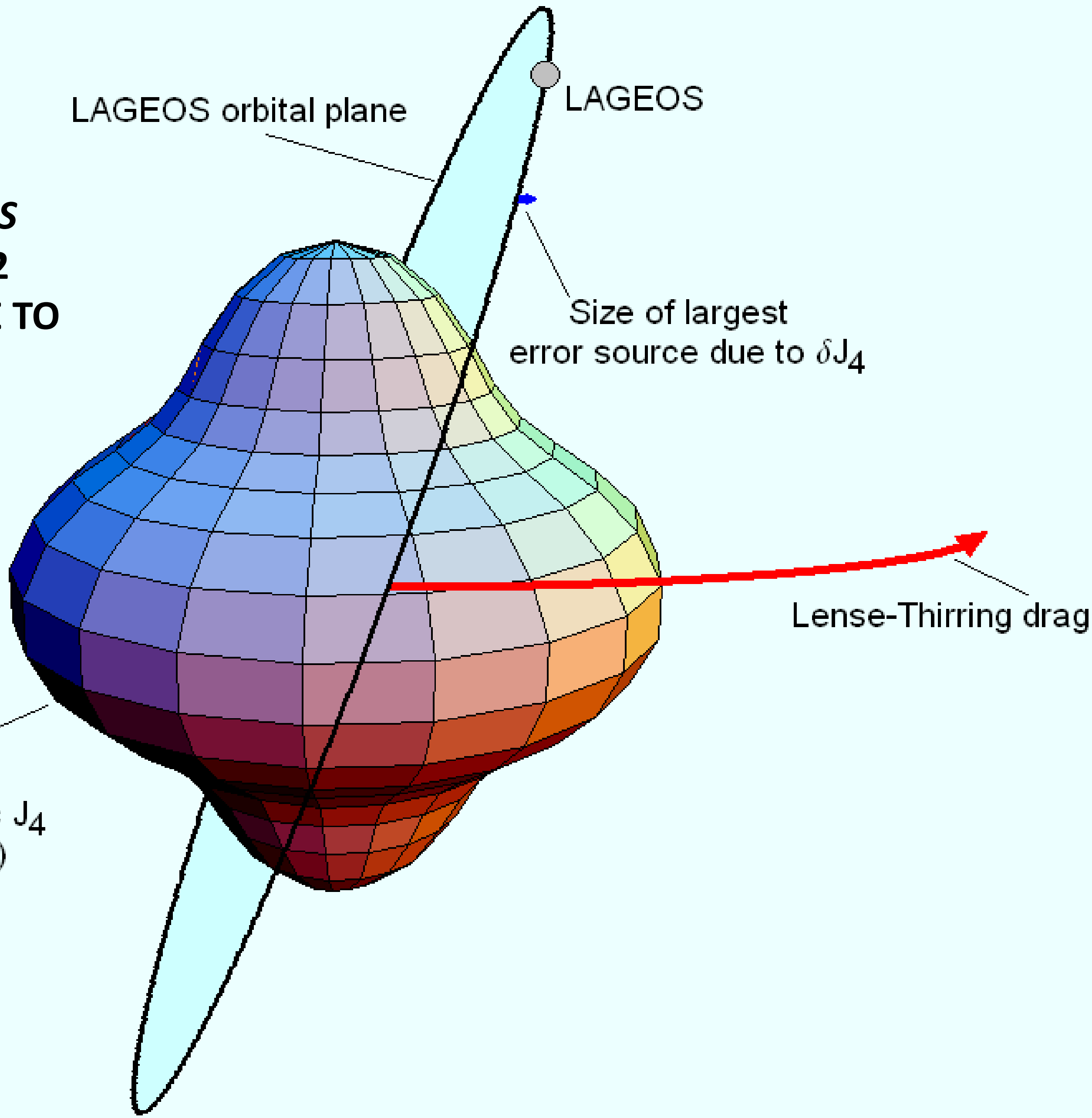


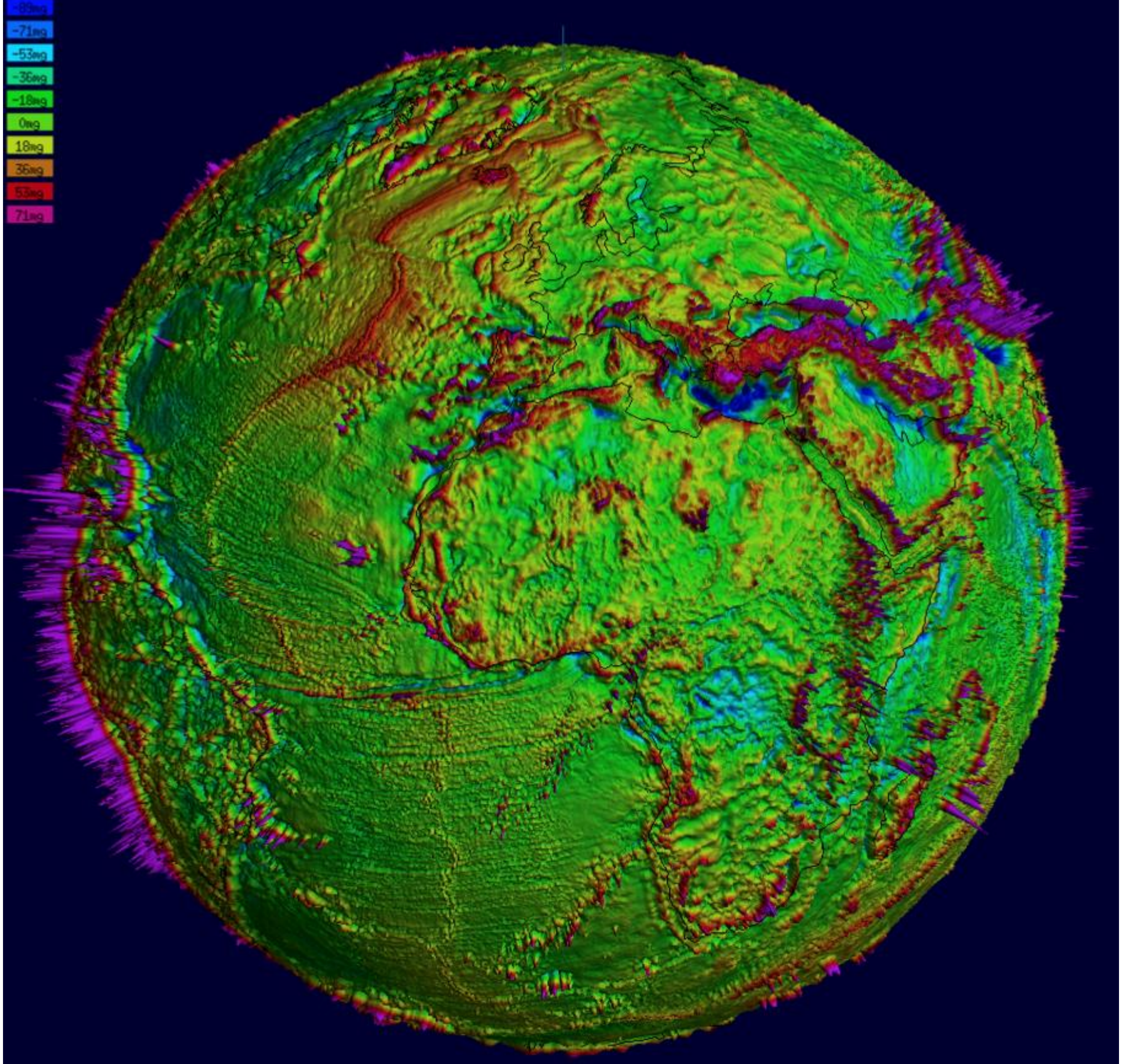
LAGEOS Assembly



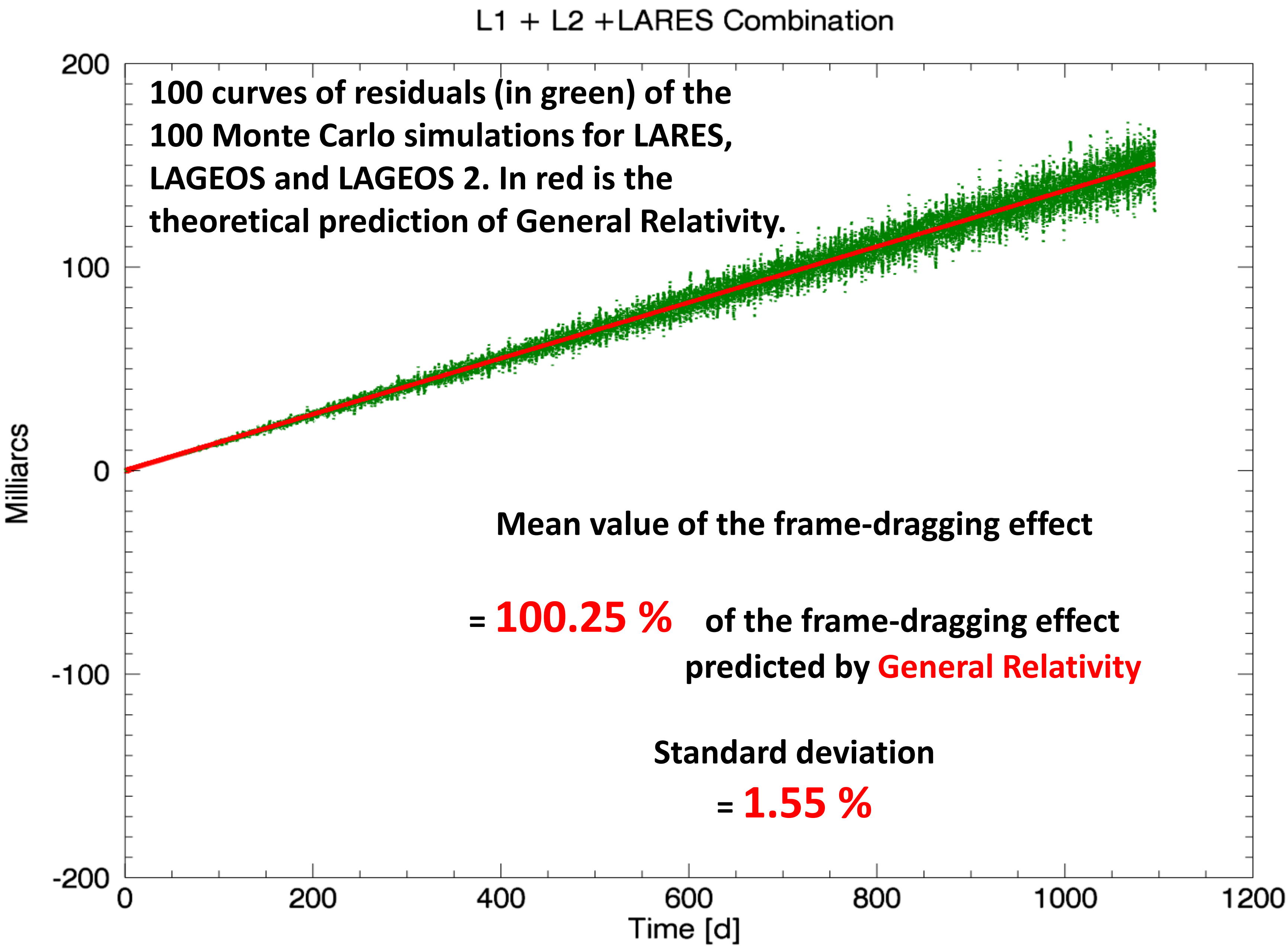
	LAGEOS	LARES
Launch:	• 1976 (1) • 1992 (2)	2012
Mass:	• 406.9 kg (1) • 405.3 kg (2)	386.8 kg
Diameter:	60 cm	36.4 cm
Body:	Assembly.	Single piece.
Material:	Al alloy hemisphere; Denser alloy core.	Tungsten alloy (ρ = 18000 kg/m^3)
N. CCR:	426	92
Eccentricity:	• 0.0045 (1) • 0.0135 (2)	0.0005
Altitude:	• 5860 km (1) • 5620 km (2)	1430 km

USING THE 3 OBSERVABLES PROVIDED BY THE 3 NODES OF *LAGEOS*, *LAGEOS 2* AND *LARES* WE ELIMINATE THE 2 UNCERTAINTIES DUE TO *J2* AND *J4* AND MEASURE FRAME-DRAGGING

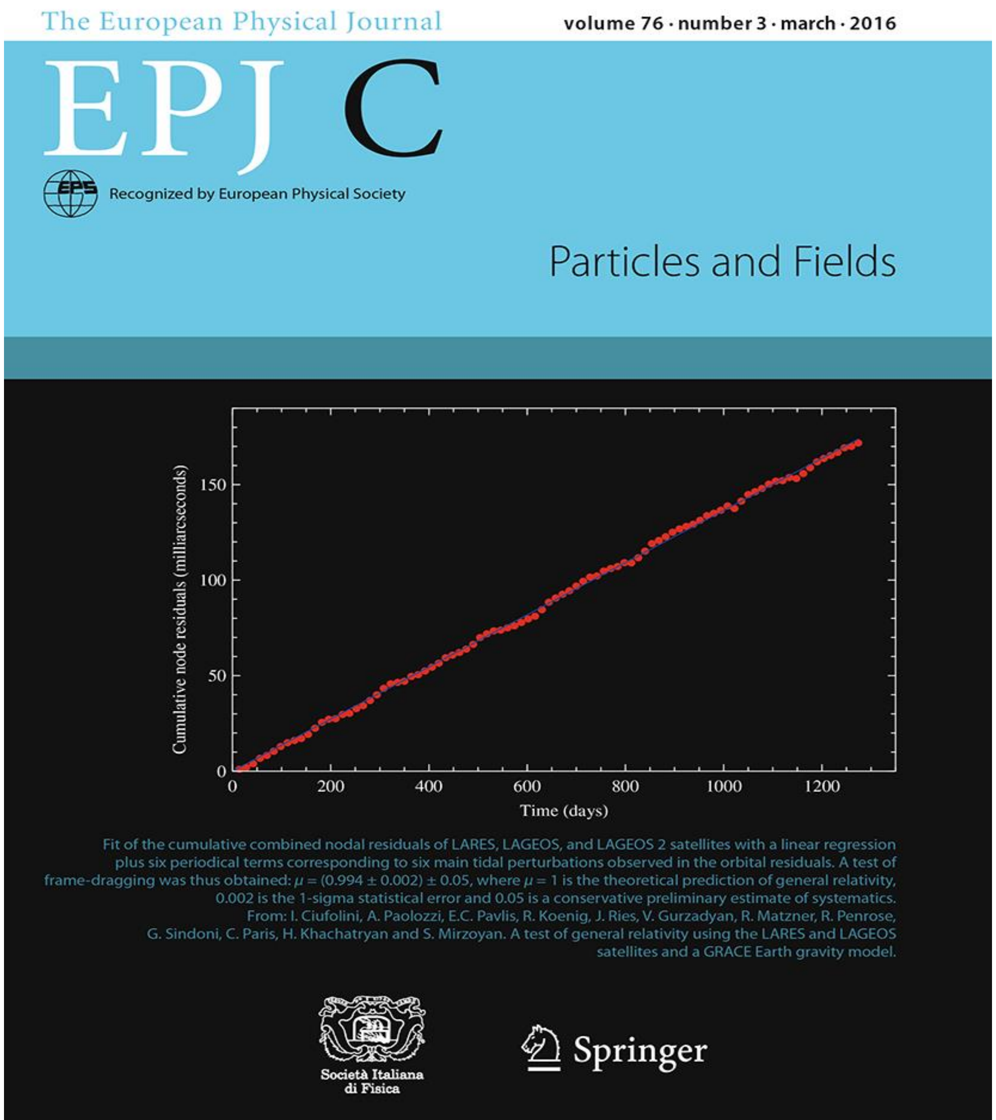




One of the latest GRACE models


L1 + L2 +LARES Combination
100 curves of residuals (in green) of the 100 Monte Carlo simulations for LARES, LAGEOS and LAGEOS 2. In red is the theoretical prediction of General Relativity.
Mean value of the frame-dragging effect
= 100.25 % of the frame-dragging effect predicted by General Relativity
Standard deviation
= 1.55 %
Milliarcs
200
100
0
-100
-200
0
200
400
600
800
1000
1200
Time [d]

I. Ciufolini et al., A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model. Measurement of Earth's dragging of inertial frames. *Eur. Phys. J. C* (2016) 76:120



RESULT:

(0.994 +/- 0.002) +/- 0.05

1 is the Earth's dragging of inertial frames normalized to its general relativity value,

0.002 is the 1-sigma statistical error

0.05 is our preliminary estimate of systematic error mainly due to the uncertainties in the Earth gravity model GGM05S

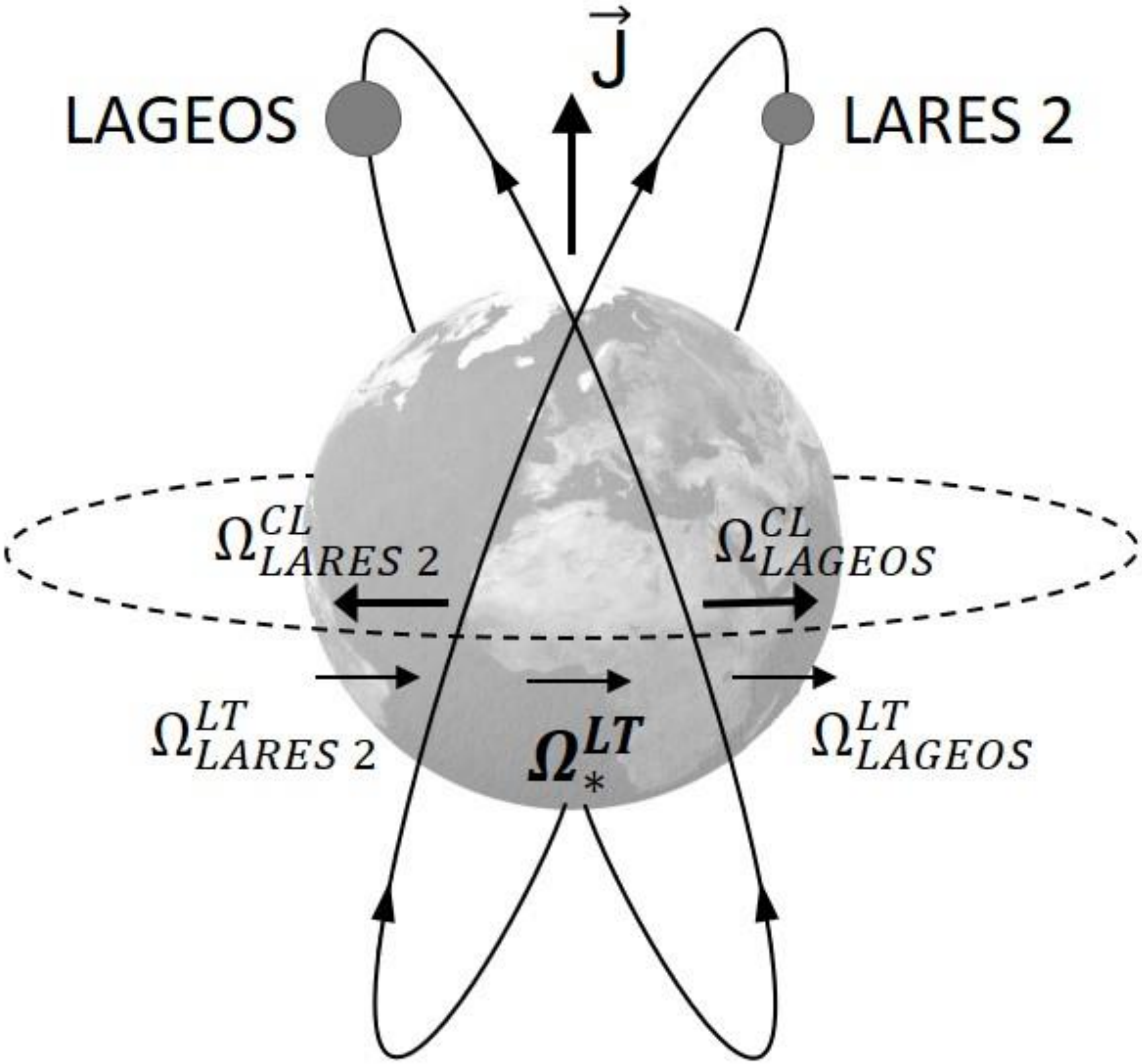
LARES already shows an outstanding behaviour for testing General Relativity and gravitational physics.

LARES-type satellites could well test other fundamental physics effects and much improve the existing limits on C-S mass.

After a couple of years of laser-ranging data of the LARES satellite, together with LAGEOS and LAGEOS 2 and with the future improved Earth's gravity models, we would be able to measure the frame-dragging effect with accuracy of about 2%

The measurement will have other implications for fundamental physics such as improving the limits on C-S mass and placing further limits on String Theories equivalent to Chern-Simon gravity.

LARES 2
(to be launched end 2019 / beginning of 2020)

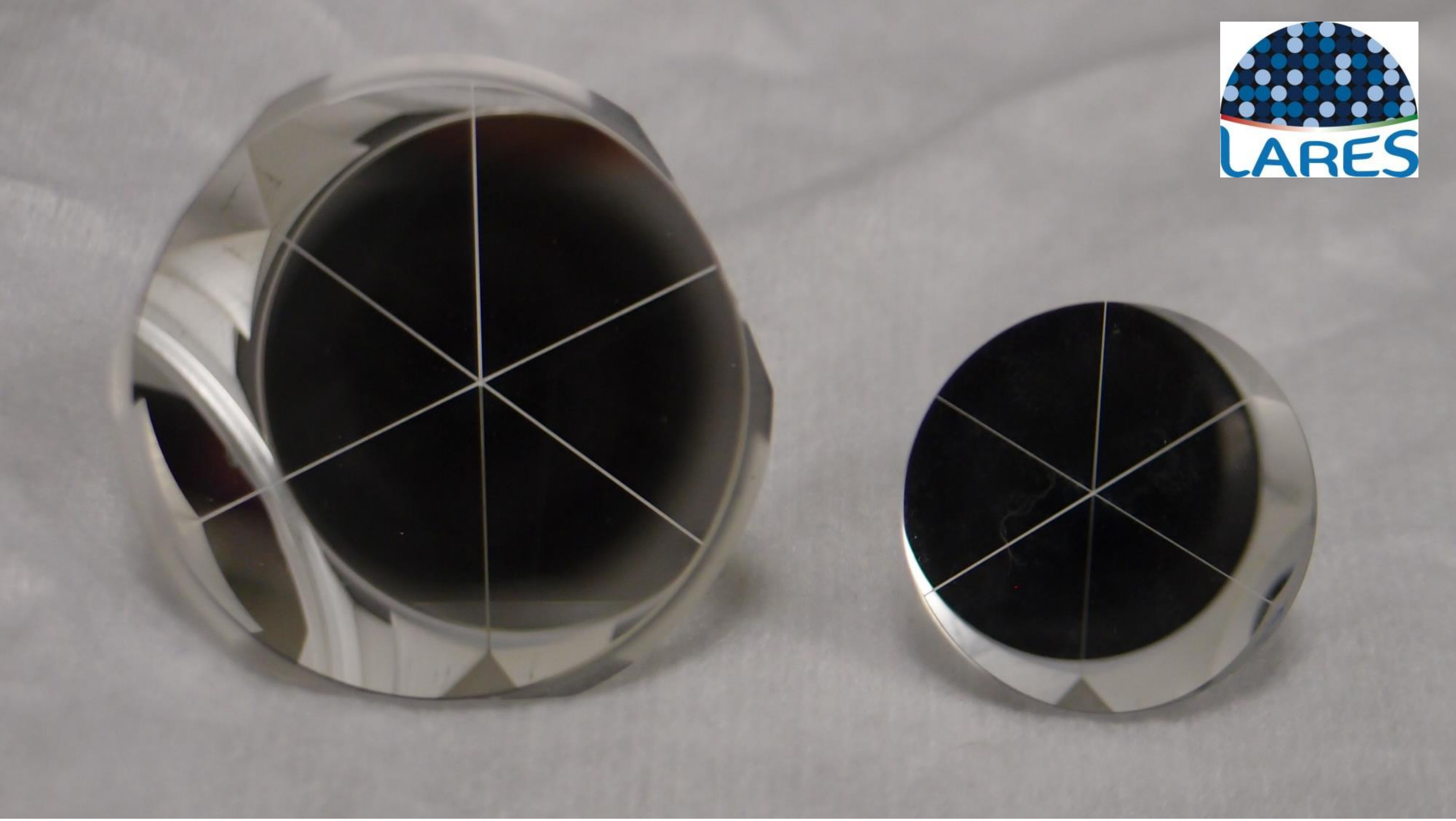


LARES 2: what is new with respect to LAGEOS 3?

1) The Earth gravity field and the even zonal harmonics are today extremely improved thanks to the **GRACE** space mission (and the **GRACE Follow On** space mission has been launched).
The Earth quadrupole moment, J_2, is improved by a factor of more than 100 with respect to the Earth gravity field determinations in 1984!
The satellite can be injected into the orbit supplementary to LAGEOS with better accuracy than in 1984.

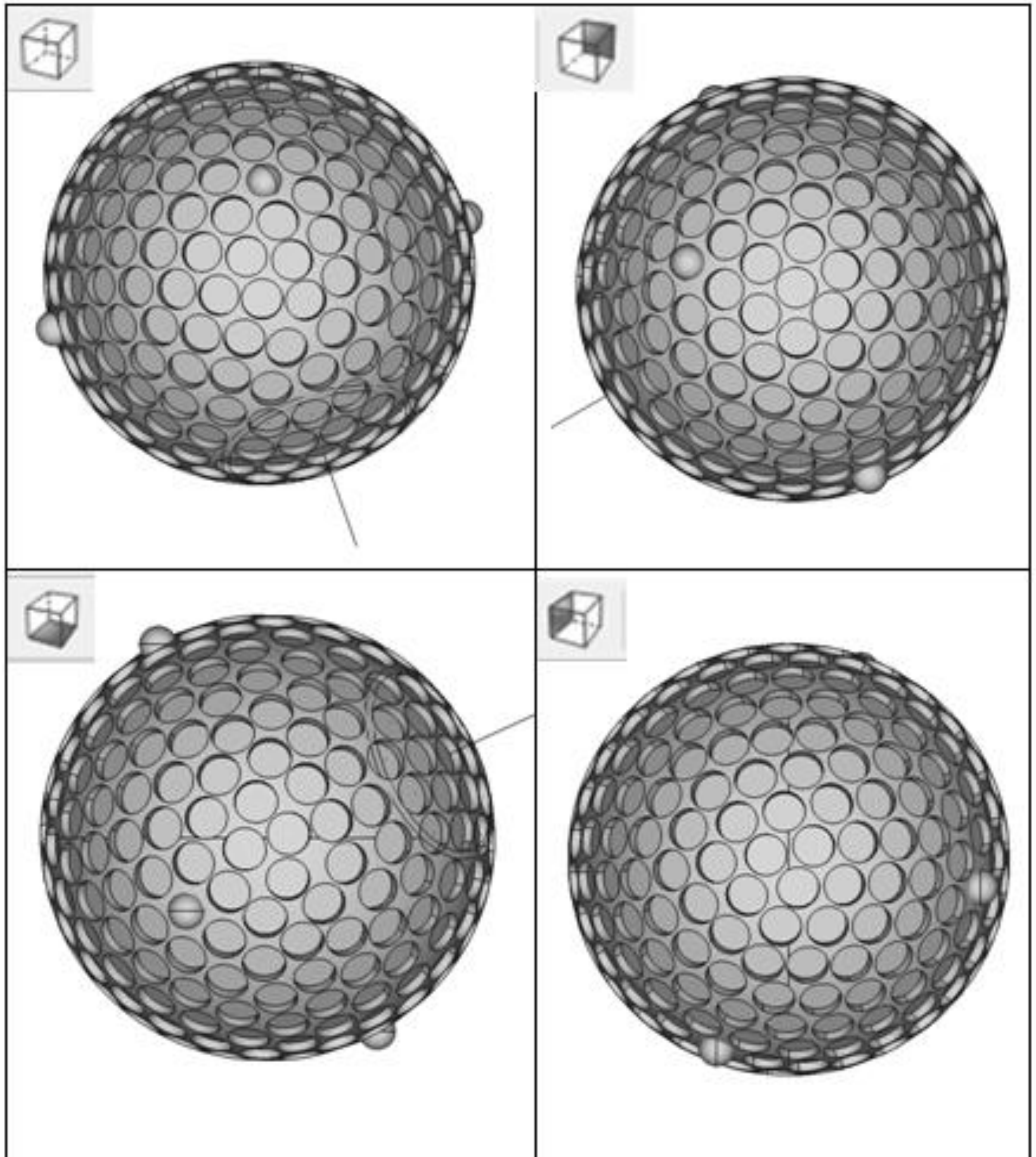
2) The knowledge of other orbital perturbations, such as the Earth's tidal perturbations, is quite improved with respect to 1984.

3) **The satellite structure** is quite improved with respect to all the other laser-ranged satellites because of a special distribution of the retroreflectors, a specifically designed mounting system, 1 inch retroreflectors. LARES 2 will be the first satellite with both a very high mass-to-surface ratio (second only to LARES) and a signature effect below 1 mm.

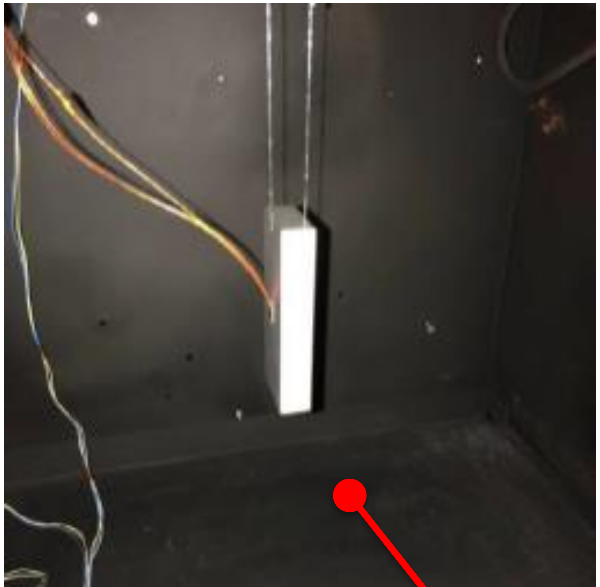


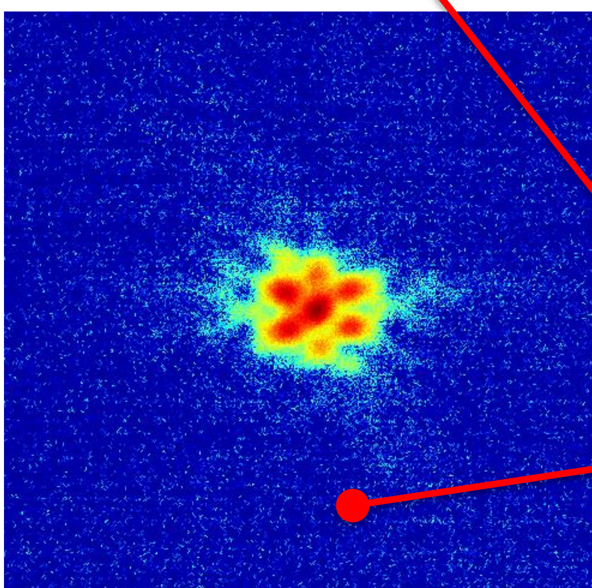
1.5 inches CCR (LAGEOS, LAGEOS 2, LARES) and 1 inch CCR (LARES 2)

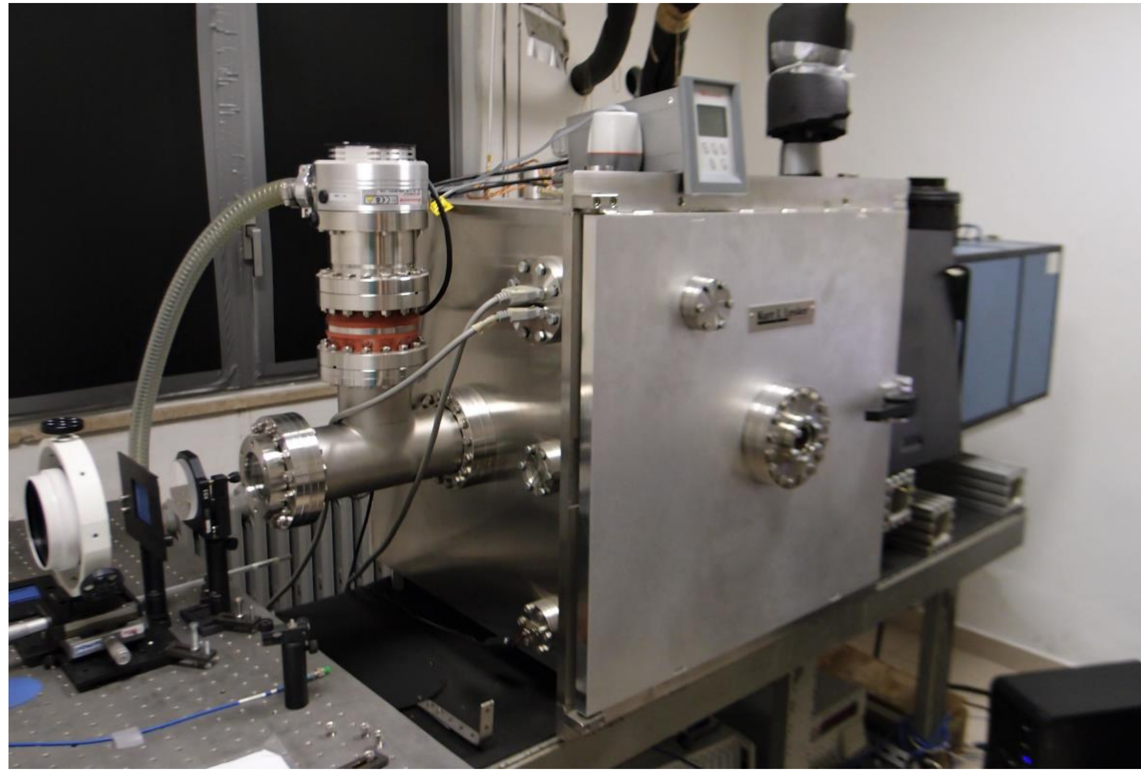
Improved and original distribution of CCR to maximize ranging accuracy



Testing activities in the LARES-Lab







Thermo-vacuum chamber and optical testing facility.

- Assessing the thermo optical properties of materials for LARES 2.
- Optical testing of CCRs and mounting system.

Source of Error	Estimated error
Injection Error and Even Zonal Harmonics	≅ 0.1\% of frame-dragging
Non-zonal harmonics and tides	≅ 0.1\% of frame-dragging
Albedo	≅ 0.1\% of frame-dragging
Thermal Drag and Satellites Eclipses	≅ 0.1\% of frame-dragging
Measurement Error of the LAGEOS and LARES 2 Orbital Parameters	≅ 0.1\% of frame-dragging
Total RSS Error	≅ 0.2\% of frame-dragging

Error Budget of frame-dragging test with LARES 2 and LAGEOS

Papers on Journals and Conferences Proceedings – Year 2018.

I. Ciufolini, R. A. Matzner, J. C. Feng, A. Paolozzi, D. P. Rubincam, E. C. Pavlis, J. C. Ries, G. Sindoni, C. Paris, A new laser-ranged satellite for General Relativity and space geodesy: IV. Thermal drag and the LARES 2 space experiment. The European Physical Journal Plus, 2018, 133:333.

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I. Ciufolini, C. Paris, The LARES and LARES 2 space missions, XXIII SIGRAV Conference, 9–15 September 2018, Santa Margherita di Pula (Cagliari), Italy, http://sigrav2018.ca.infn.it

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Dissemination and outreach events 2017-2018.

- "Maggio museale alla Sapienza – Sabato al museo", Scuola di Ingegneria Aerospaziale, 20 Maggio 2017. Presentation of LARES mission and public opening of the LARES-Lab thermo-vacuum and optical testing facility (C. Paris, A. Paolozzi).
- ICARA 2017 – XIII Congress of Amateur Radioastronomy, Gorga Astronomical Observatory, 21-22 Ottobre 2017, Space debris and the LARES mission (C. Paris)
- European Researchers' Night 2018, Gorga Astronomical Observatory, September 29 (A. Paolozzi).
- ITIS Cannizzaro Colleferro (RM), Settimana di diffusione della Cultura Scientifica e Tecnologica (April 16-21, 2018), Discussion about General Relativity after the screening of the film " *The Theory of Everything" (2014),* Colleferro 20 aprile 2018 (C. Paris).
- "Maggio museale alla Sapienza – EUREKA (Comune di Roma)". Scuola di Ingegneria Aerospaziale, sabato 19 maggio 2018. Presentation about "Space and Music" (A. Paolozzi) and public opening of the LARES-Lab thermo-vacuum and optical testing facility (C. Paris).

Conclusions

- Frame-dragging was measured in 2016 with about **5%** accuracy using **LARES** + LAGEOS + LAGEOS 2.

- Frame-dragging will be measured with about **2%** accuracy using **LARES** + LAGEOS + LAGEOS 2.

- **LARES 2** will be launched in a couple of years, and after about 3 years of data we may reach an accuracy of about **0.2%** in testing frame-dragging, plus other tests of fundamental physics (under study).