FISP - Fundamental Physics in Space
and
the LARES and LARES 2 Satellites

Claudio Paris

with Ignazio Ciufolini, Antonio Paolozzi and Giampiero Sindoni

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LARES

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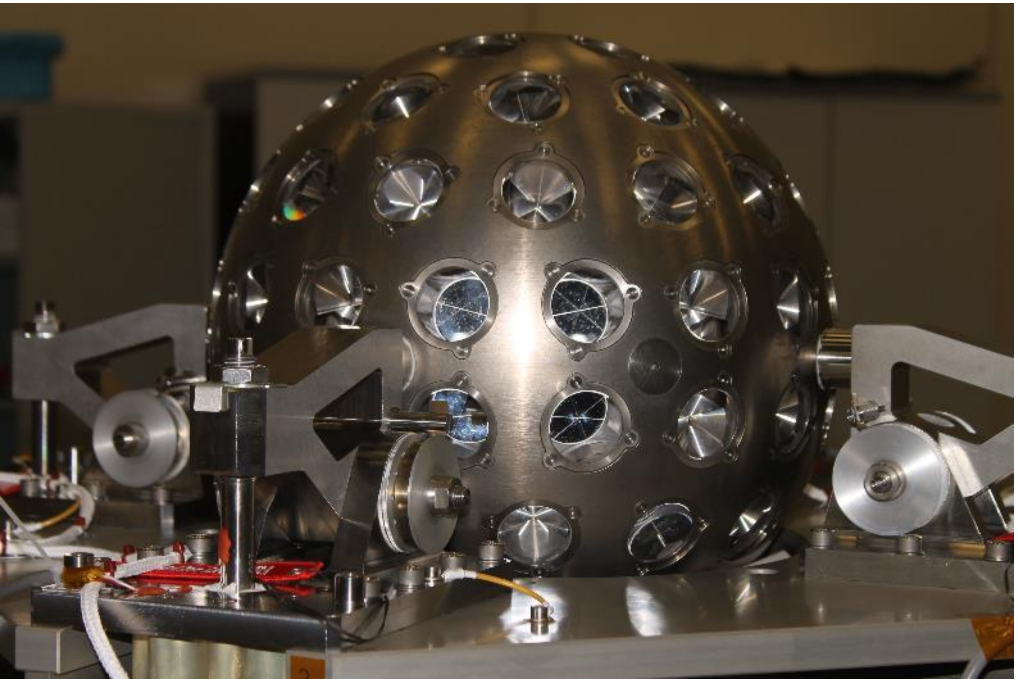

I. Ciufolini*
A. Paolozzi*,
C. Paris*
G. Sindoni*
E. Pavlis*,
R. Koenig*,
J. Ries*,
R. Matzner*,
V. Gurzadyan*,
R. Penrose*,

*Un. Salento, Lecce/Centro Fermi
*Sapienza Un. Rome
*Centro Fermi
*Maryland Un.,
*Helmholtz Cent.-GFZ, Potsdam
* CSR Un. Texas Austin
*Un. Texas Austin
*Alikhanian Nat. Lab., Yerevan
*Oxford Un.

TESTS ALREADY ACHIEVED WITH LARES

- A test of gravitomagnetism and frame-dragging with less than 2% accuracy:

  Eur. Phys. J. C 2019

- A test of the weak equivalence principle with accuracy of about one part in a billion using previously untested materials, Tungsten and Brass, at a previously untested range of about 10000 km: Nature-Scientific Reports 2019

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Regular Article - Theoretical Physics

An improved test of the general relativistic effect of frame-dragging using the LARES and LAGEOS satellites

Ignazio Ciufolini[1,2], **Antonio Paolozzi**[3], **Erricos C. Pavlis**[4], **Giampiero Sindoni**[3,a], **John Ries**[5], **Richard Matzner**[6], **Rolf Koenig**[7], **Claudio Paris**[2,3], **Vahe Gurzadyan**[8], **Roger Penrose**[9]

[1] Dip. Ingegneria dell'Innovazione, Università del Salento, Lecce, Italy
[2] Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Rome, Italy
[3] Scuola di Ingegneria Aerospaziale, Sapienza Università di Roma, Rome, Italy
[4] Joint Center for Earth Systems Technology, (JCET), University of Maryland, Baltimore, USA
[5] Center for Space Research, University of Texas at Austin, Austin, USA
[6] Theory Center, University of Texas at Austin, Austin, USA
[7] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany
[8] Center for Cosmology and Astrophysics, Alikhanian National Laboratory and Yerevan State University, Yerevan, Armenia
[9] Mathematical Institute, University of Oxford, Oxford, UK

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Abstract We report the improved test of frame-dragging, an intriguing phenomenon predicted by Einstein's General Relativity, obtained using 7 years of Satellite Laser Ranging (SLR) data of the satellite LARES (ASI, 2012) and 26 years of SLR data of LAGEOS (NASA, 1976) and LAGEOS 2 (ASI and NASA, 1992). We used the static part and temporal variations of the Earth gravity field obtained by the space geodesy mission GRACE (NASA and DLR) and in particular the static Earth's gravity field model GGM05S augmented by a model for the 7-day temporal variations of the lowest degree Earth spherical harmonics. We used the orbital estimator GEODYN (NASA). We measured frame-dragging to be equal to 0.9910±0.02, where 1 is the theoretical prediction of General Relativity normalized to its frame-dragging value and ±0.02 is the estimated systematic error due to modelling errors in the orbital perturbations, mainly due to the errors in the Earth's gravity field determination. Therefore, our measurement confirms the prediction of General Relativity for frame-dragging with a few percent uncertainty.

1 General relativity, dragging of inertial frames and the objectives of the LARES space mission

Einstein's gravitational theory of General Relativity is fundamental to understand our universe [1–4]. It has a number of outstanding experimental verifications [4–6], among which are the recent impressive LIGO laser interferometers direct detections of gravitational waves and observation of black holes, and of their collision, through the emission of gravitational waves [7,8].

LARES (LAser RElativity Satellite) [9] is a laser-ranged satellite of ASI, the Italian Space Agency, dedicated to test General Relativity and fundamental physics, and to measurements of space geodesy and geodynamics. Among the tests of General Relativity, the main objective of LARES is a measurement of dragging of inertial frames, or frame-dragging, with an accuracy of a few percent. In addition to the test of frame-dragging, LARES, together with the LAGEOS (LAser GEOdynamcs Satellite of NASA) [11] and LAGEOS 2 (of ASI and NASA), has recently provided a test of the weak equivalence principle [10], at the foundations of General Relativity and other viable gravitational theories, with an accuracy of about 10^{-9}, at a previously untested range between about 7820 and 12270 km, and using previously untested materials of a tungsten alloy (the material of LARES) and aluminum–brass (the material of LAGEOS and LAGEOS 2). The orbital parameters and characteristics of the LARES and LAGEOS satellites are provided in the next section.

Frame-dragging [12] is an intriguing phenomenon of General Relativity: in Einstein's gravitational theory the inertial frames, which can only be defined locally (according to the equivalence principle [1,2,4]), have no fixed direction with respect to the distant stars but are instead dragged by the currents of mass-energy such as the rotation of a body, e.g., the rotation of the Earth (the axes of the local inertial frames are determined in General Relativity by local test-gyroscopes.) For a detailed description of such intriguing phenomenon and

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[a] e-mail: giampiero.sindoni@uniroma1.it

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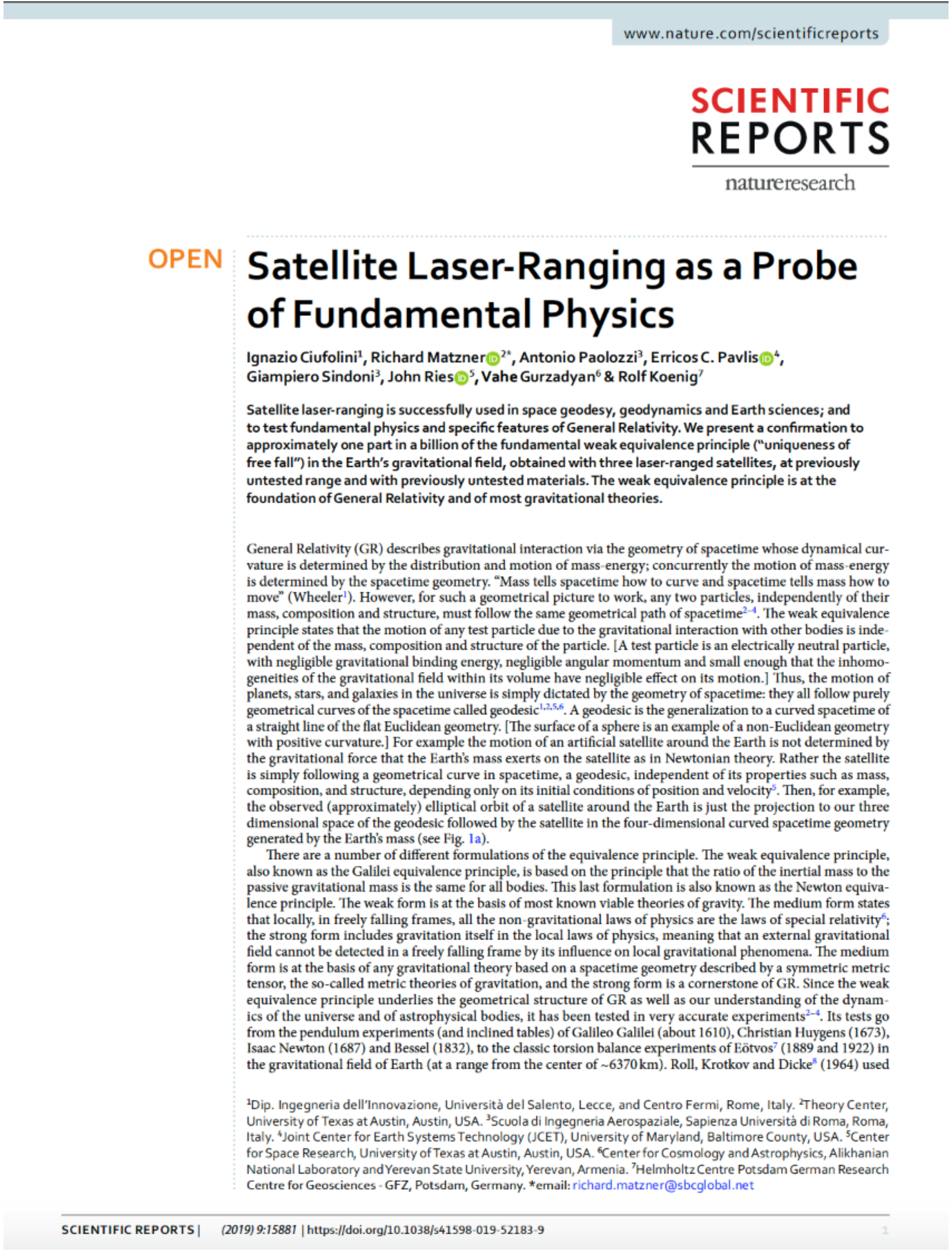

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Satellite Laser-Ranging as a Probe of Fundamental Physics

Ignazio Ciufolini[1], Richard Matzner[2*], Antonio Paolozzi[3], Erricos C. Pavlis[4], Giampiero Sindoni[3], John Ries[5], Vahe Gurzadyan[6] & Rolf Koenig[7]

Satellite laser-ranging is successfully used in space geodesy, geodynamics and Earth sciences; and to test fundamental physics and specific features of General Relativity. We present a confirmation to approximately one part in a billion of the fundamental weak equivalence principle ("uniqueness of free fall") in the Earth's gravitational field, obtained with three laser-ranged satellites, at previously untested range and with previously untested materials. The weak equivalence principle is at the foundation of General Relativity and of most gravitational theories.

General Relativity (GR) describes gravitational interaction via the geometry of spacetime whose dynamical curvature is determined by the distribution and motion of mass-energy; concurrently the motion of mass-energy is determined by the spacetime geometry. "Mass tells spacetime how to curve and spacetime tells mass how to move" (Wheeler[1]). However, for such a geometrical picture to work, any two particles, independently of their mass, composition and structure, must follow the same geometrical path of spacetime[2–4]. The weak equivalence principle states that the motion of any test particle due to the gravitational interaction with other bodies is independent of the mass, composition and structure of the particle. [A test particle is an electrically neutral particle, with negligible gravitational binding energy, negligible angular momentum and small enough that the inhomogeneities of the gravitational field within its volume have negligible effect on its motion.] Thus, the motion of planets, stars, and galaxies in the universe is simply dictated by the geometry of spacetime: they all follow purely geometrical curves of the spacetime called geodesic[1,2,5,6]. A geodesic is the generalization to a curved spacetime of a straight line of the flat Euclidean geometry. [The surface of a sphere is an example of a non-Euclidean geometry with positive curvature.] For example the motion of an artificial satellite around the Earth is not determined by the gravitational force that the Earth's mass exerts on the satellite as in Newtonian theory. Rather the satellite is simply following a geometrical curve in spacetime, a geodesic, independent of its properties such as mass, composition, and structure, depending only on its initial conditions of position and velocity[5]. Then, for example, the observed (approximately) elliptical orbit of a satellite around the Earth is just the projection to our three dimensional space of the geodesic followed by the satellite in the four-dimensional curved spacetime geometry generated by the Earth's mass (see Fig. 1a).

There are a number of different formulations of the equivalence principle. The weak equivalence principle, also known as the Galilei equivalence principle, is based on the principle that the ratio of the inertial mass to the passive gravitational mass is the same for all bodies. This last formulation is also known as the Newton equivalence principle. The weak form is at the basis of most known viable theories of gravity. The medium form states that locally, in freely falling frames, all the non-gravitational laws of physics are the laws of special relativity[6]; the strong form includes gravitation itself in the local laws of physics, meaning that an external gravitational field cannot be detected in a freely falling frame by its influence on local gravitational phenomena. The medium form is at the basis of any gravitational theory based on a spacetime geometry described by a symmetric metric tensor, the so-called metric theories of gravitation, and the strong form is a cornerstone of GR. Since the weak equivalence principle underlies the geometrical structure of GR as well as our understanding of the dynamics of the universe and of astrophysical bodies, it has been tested in very accurate experiments[2–4]. Its tests go from the pendulum experiments (and inclined tables) of Galileo Galilei (about 1610), Christian Huygens (1673), Isaac Newton (1687) and Bessel (1832), to the classic torsion balance experiments of Eötvos[7] (1889 and 1922) in the gravitational field of Earth (at a range from the center of ~6370 km). Roll, Krotkov and Dicke[8] (1964) used

[1]Dip. Ingegneria dell'Innovazione, Università del Salento, Lecce, and Centro Fermi, Rome, Italy. [2]Theory Center, University of Texas at Austin, Austin, USA. [3]Scuola di Ingegneria Aerospaziale, Sapienza Università di Roma, Roma, Italy. [4]Joint Center for Earth Systems Technology (JCET), University of Maryland, Baltimore County, USA. [5]Center for Space Research, University of Texas at Austin, Austin, USA. [6]Center for Cosmology and Astrophysics, Alikhanian National Laboratory and Yerevan State University, Yerevan, Armenia. [7]Helmholtz Centre Potsdam German Research Centre for Geosciences - GFZ, Potsdam, Germany. *email: richard.matzner@sbcglobal.net

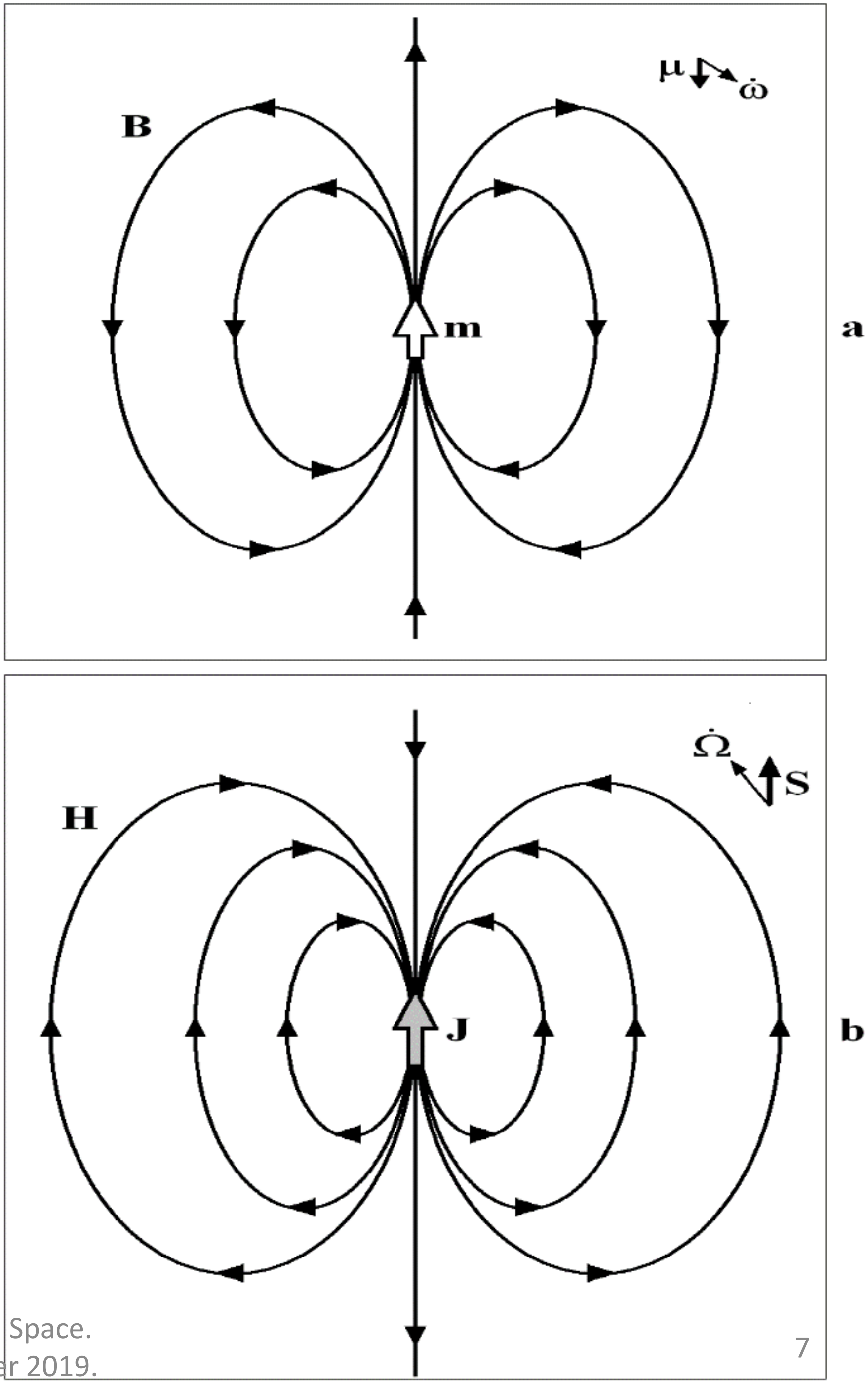
LARES, MISSIONE COMPIUTA! E LA PROSSIMA È QUASI IN RAMPA DI LANCIO

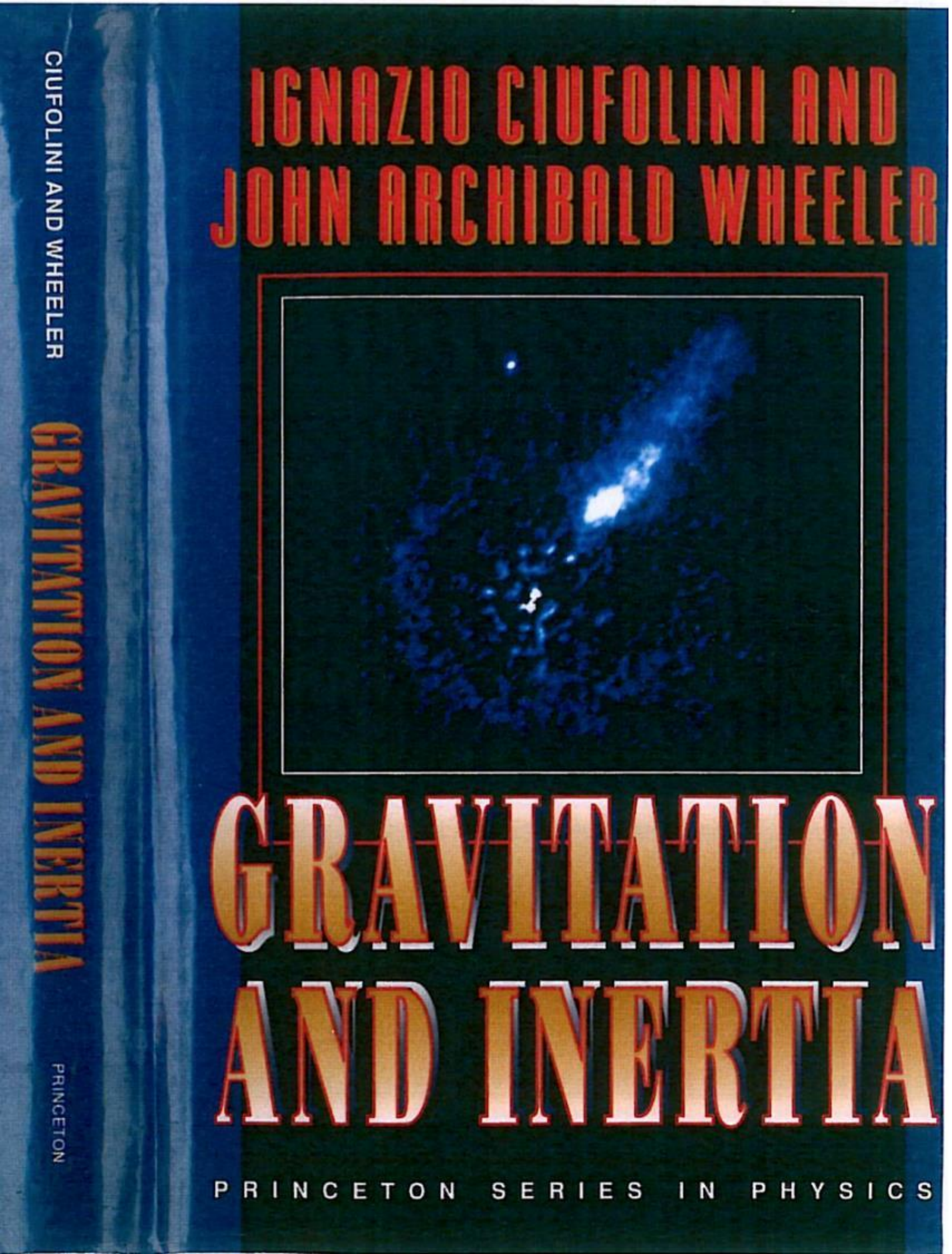
Dopo sette anni di lavoro, il satellite ASI ha prodotto dati rilevanti per verificare la teoria della relatività di Einstein

GRAVITOMAGNETISM

There is a interesting analogy of weak-field and slow-motion General Relativity with electromagnetism

Magnetic field **B**, gravitomagnetic field **H** and the precession of a magnetic dipole μ and of a gyroscope **S**





CIUFOLINI AND WHEELER

GRAVITATION AND INERTIA

PRINCETON

IGNAZIO CIUFOLINI AND
JOHN ARCHIBALD WHEELER

GRAVITATION
AND INERTIA

PRINCETON SERIES IN PHYSICS

More on frame-dragging, gravitomagnetism and General Relativity can be found in this monography

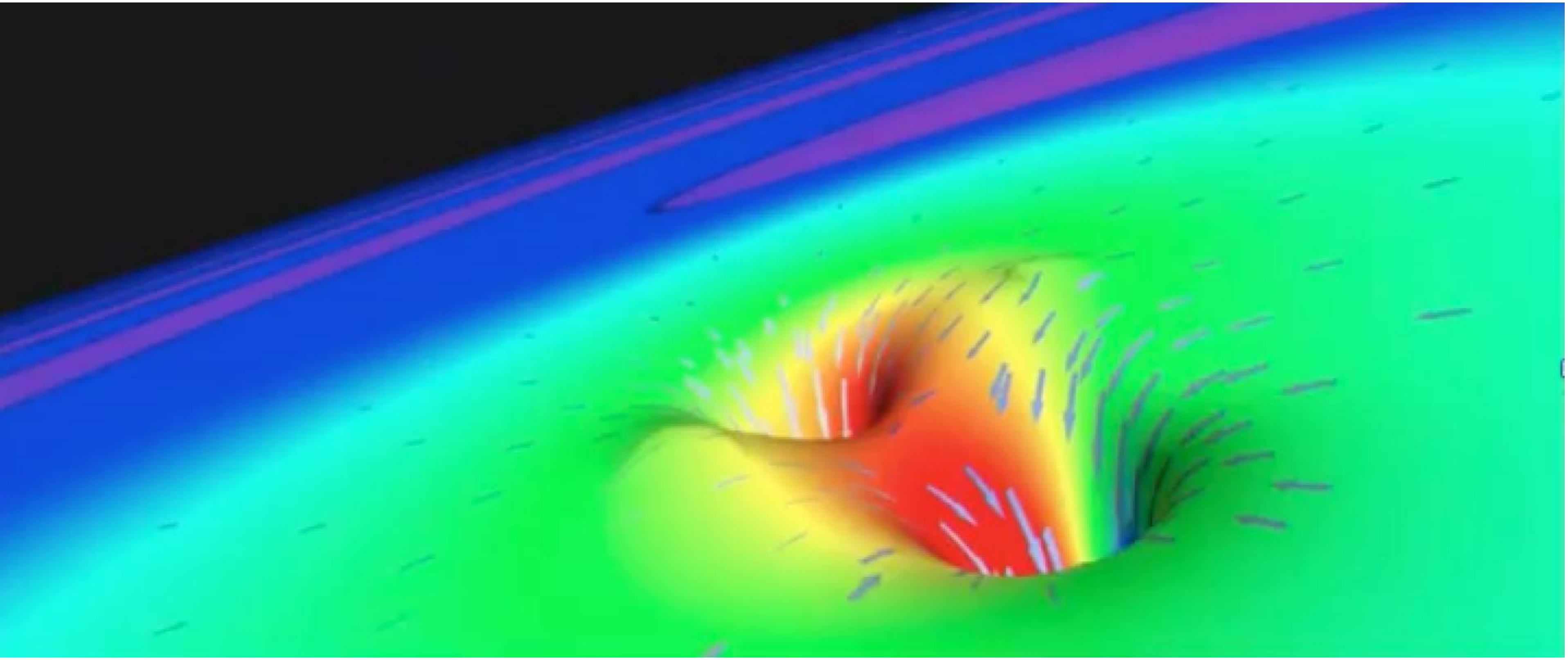
LARES

(LAser RElativity Satellite)

LARES was successfully launched and very accurately injected in the nominal orbit on the 13th of February 2012 with the VEGA launching vehicle.

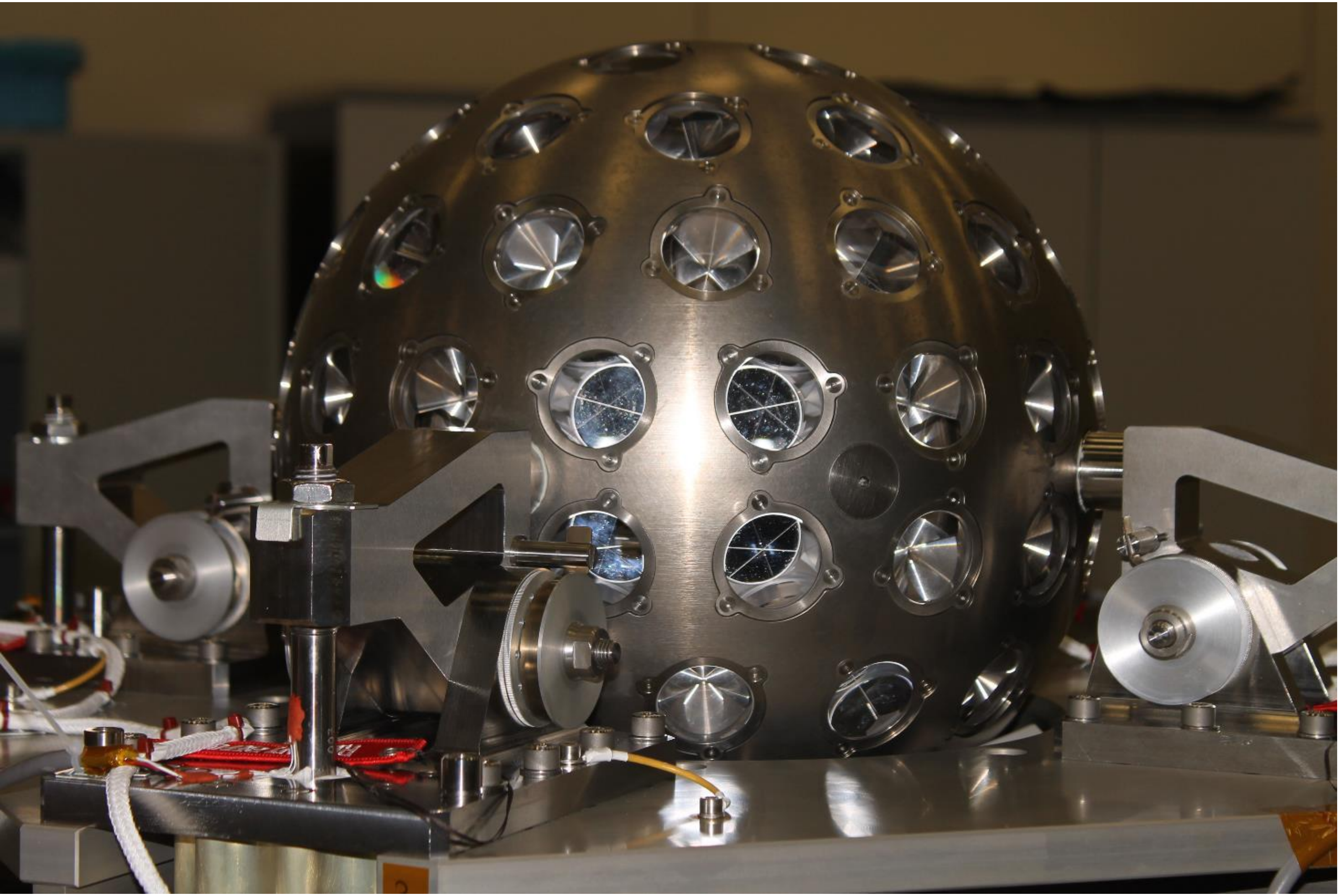
Frame-dragging and Kerr metric can play a key role in the computer analysis of the detection of gravitational waves by LIGO due to the coalescence of two spinning black holes to form a Kerr spinning black hole

The LARES tests of frame-dragging have been used by cosmologists and theoretical physicists to put limits on theories of gravity alternative to General Relativity, such as the Chern-Simons theory of gravity equivalent to a type of String Theory that may explain the riddle of dark energy and of the accelerating universe



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.

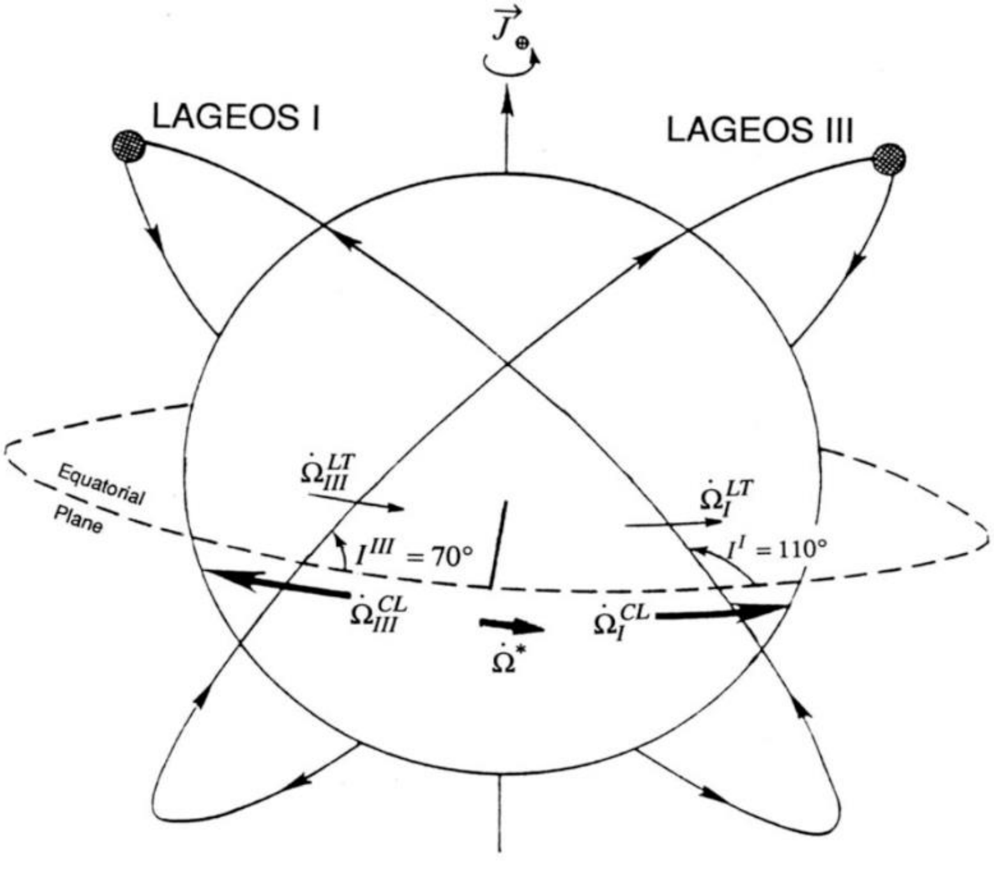
Kip Thorne NSF 2016 presentation



LARES 2/LAGEOS 3

The LARES 2 (LAGEOS 3) satellite for test of frame-dragging with accuracy at the 0.2% level and other tests of General Relativity and Fundamental Physics (and space geodesy and geodynamics).

LARES 2/LAGEOS 3



Object of measurement:

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

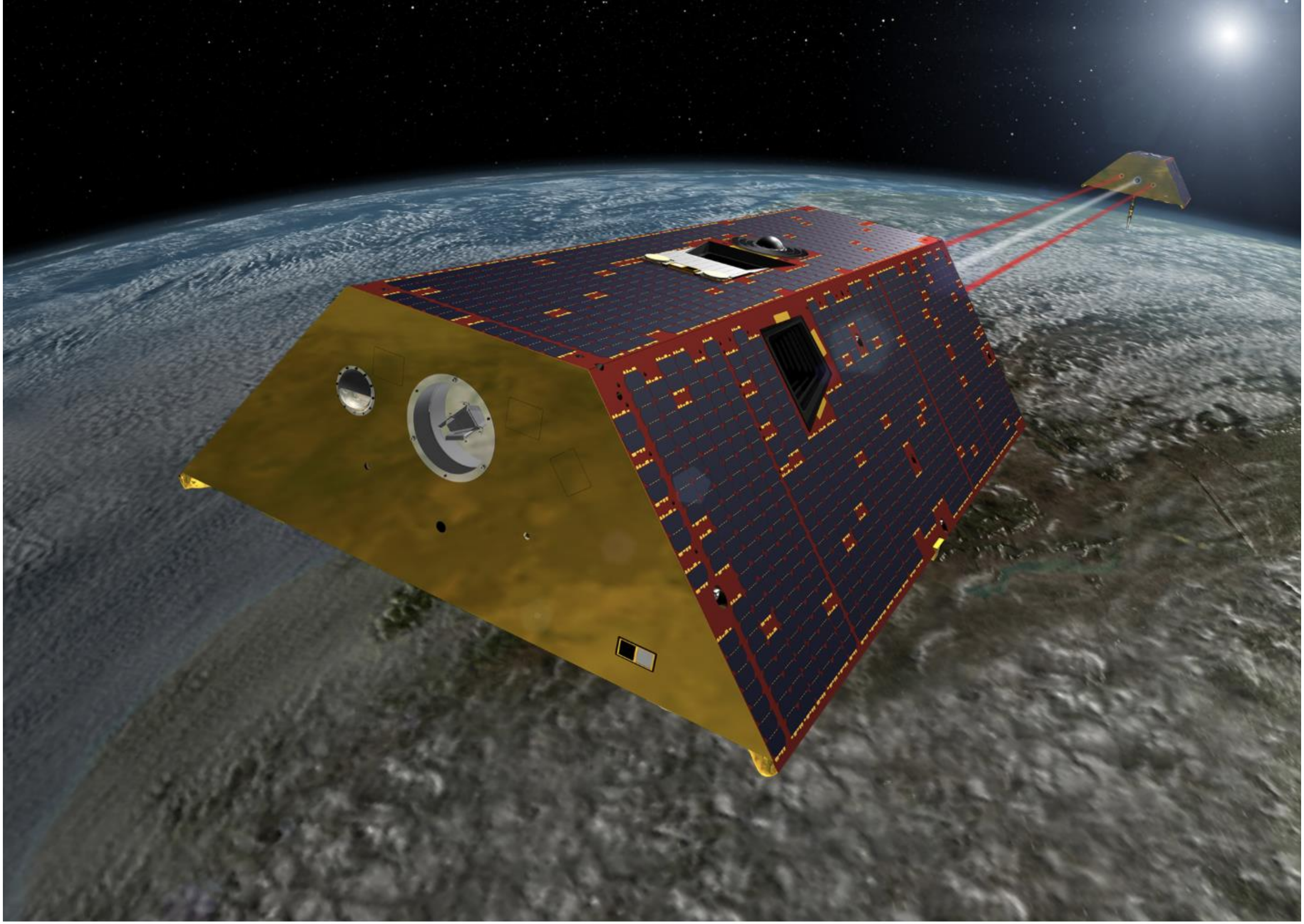
The idea of the LARES 2/LAGEOS 3 experiment: **I.C. Phys. Rev. Lett. 1986,** I.C. Ph.D. dissertation 1984, I.C. IJMPA 1989, B. Tapley, I.C. et al, NASA and ASI studies 1989, J. Ries 1989).

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

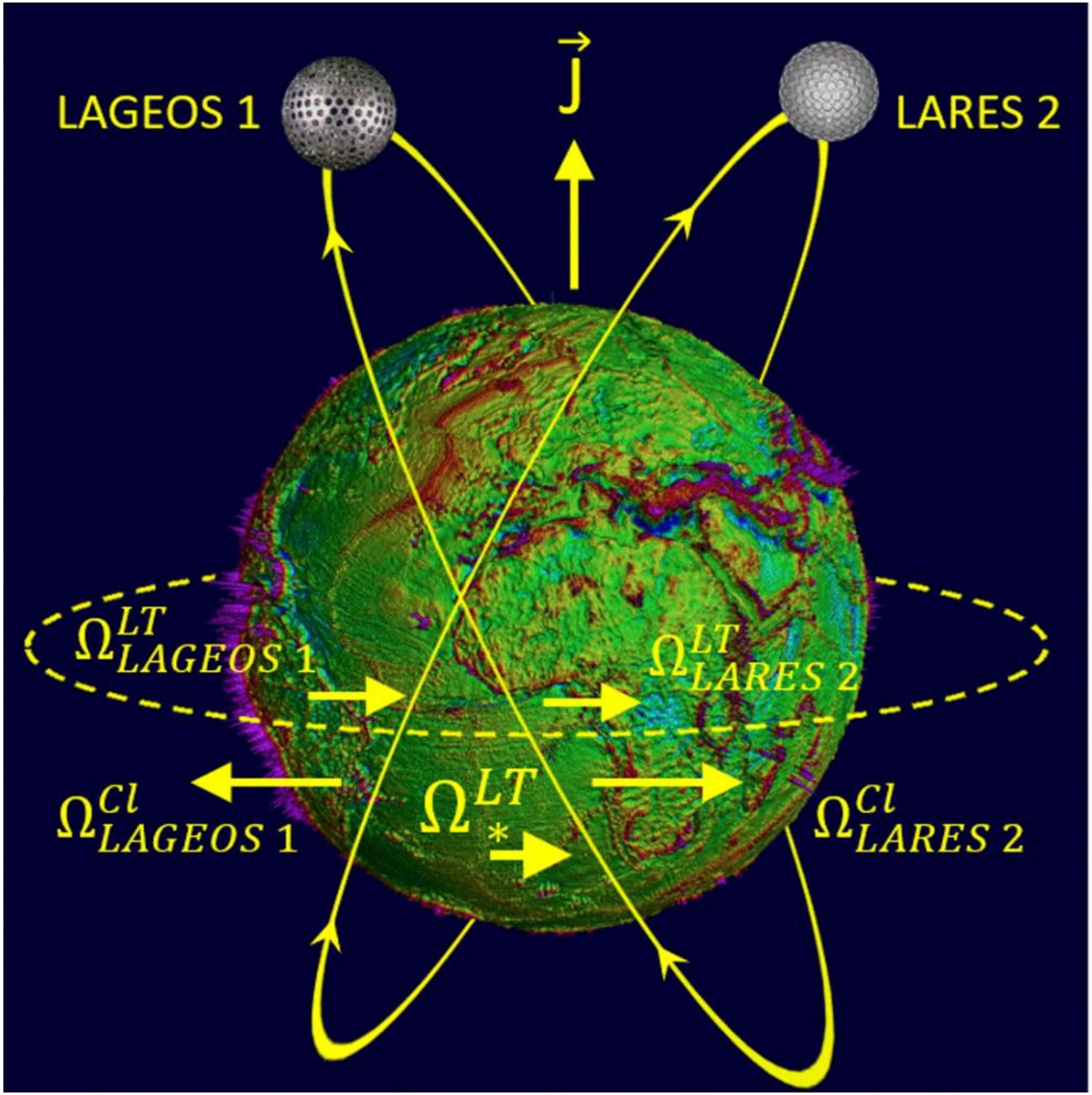
1) The Earth gravity field and the even zonal harmonics are today extremely improved thanks to the **GRACE** space mission (and the **GRACE Follow On** space mission.)
The Earth quadrupole moment, J2, is improved by a factor of more than 100 with respect to the Earth gravity field determinations in 1984!
The satellite can be injected into the orbit supplementary to LAGEOS with better accuracy than in 1984.

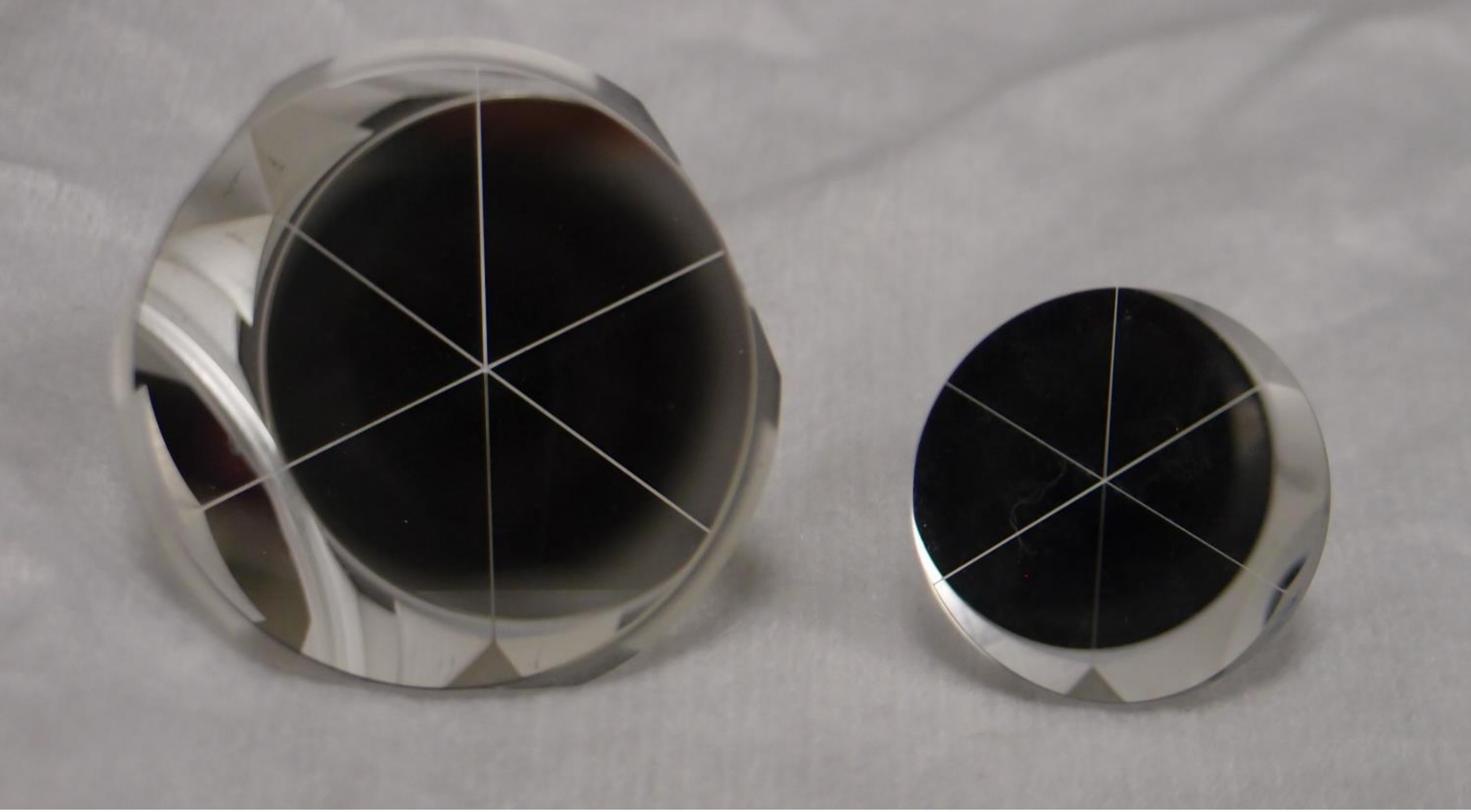
2) The knowledge of other orbital perturbations, such as the Earth's tidal perturbations, is quite improved with respect to 1984.

3) The satellite structure is quite improved with respect to all the other laser-ranged satellites: using the new 1 inch retroreflectors we can today reach less than 1 mm precision in ranging!

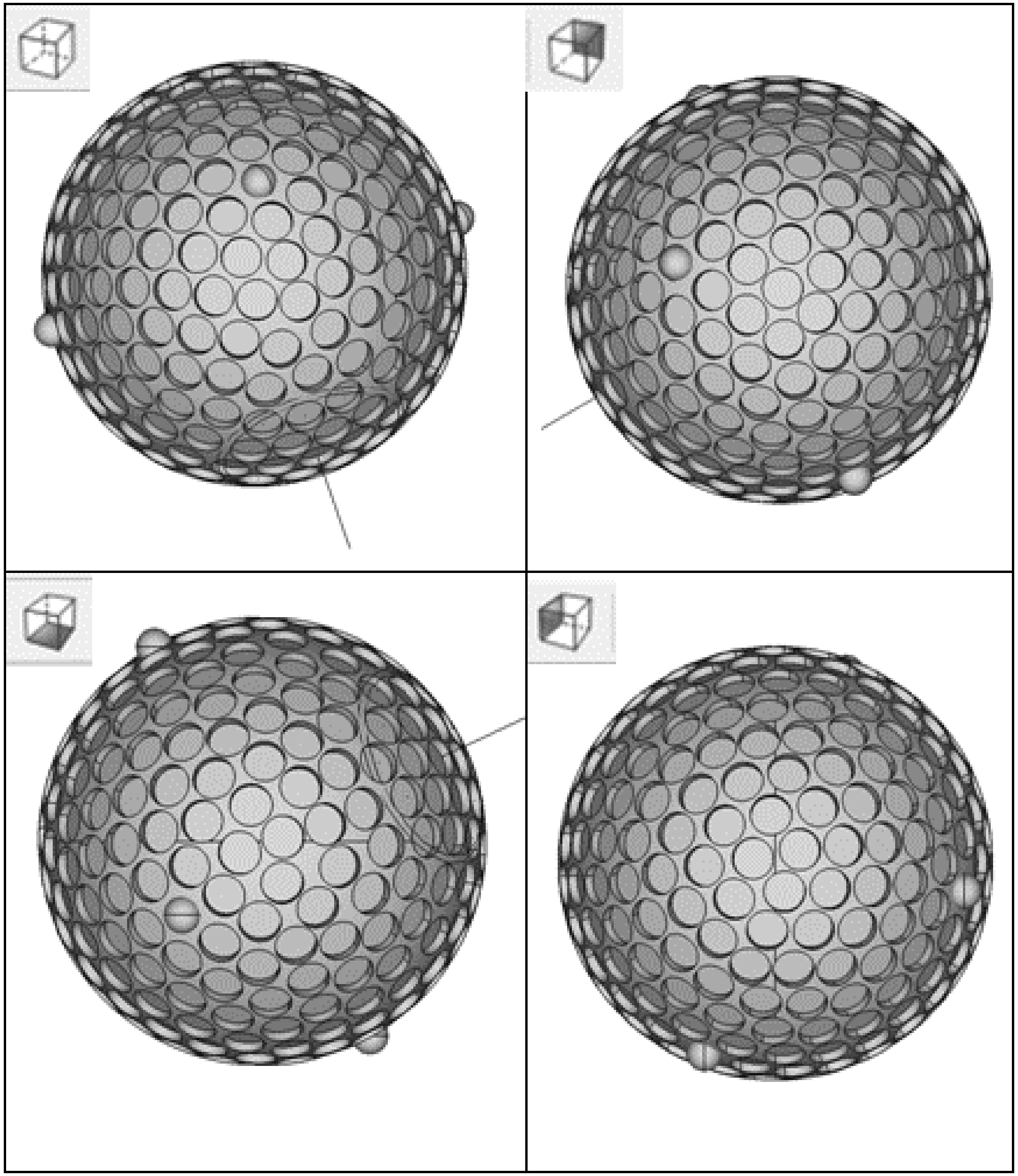


Like GRACE, the twin GRACE-FO satellites will follow each other in orbit around the Earth, separated by about 137 miles (220 km). Seen in an artist's rendering. Credit: NASA


LAGEOS 1
$\vec{J}$
LARES 2
$\Omega^{LT}_{LAGEOS\ 1}$
$\Omega^{LT}_{LARES\ 2}$
$\Omega^{Cl}_{LAGEOS\ 1}$
Ω^{LT}_{*}
$\Omega^{Cl}_{LARES\ 2}$



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



A New Test of the Weak Equivalence Principle with LAGEOS, LAGEOS 2 AND LARES

We obtained a new confirmation to approximately one part in a billion of the weak equivalence principle ("uniqueness of free fall") in the Earth's gravitational field, obtained with the three laser-ranged satellites LAGEOS, LAGEOS 2 and LARES, at previously untested range and with previously untested materials:

$$\delta(m_g/m_i) = 2.0 \times 10^{-10} \pm 1.1 \times 10^{-9}$$

Range: from about 7820 km to 12220 km

Materials: Aluminum and brass (LAGEOS and LAGEOS 2) versus sintered tungsten (LARES)

Conclusions

Frame-dragging was measured in 2019, using about 7 years of data, with less than 2% accuracy using **LARES** + LAGEOS + LAGEOS 2.

Using LAGEOS, LAGEOS 2 and LARES we obtained a test of the equivalence principle with an uncertainty (systematic errors) of about 10^{-9}

LARES 2 will be launched in 2020 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).

Last year publications

- I. CIUFOLINI, A. Paolozzi, E.C. Pavlis, G. Sindoni, J. Ries, R. Matzner, R. Koenig, C. Paris and R. Penrose, An improved test of the general relativistic effect of frame-dragging using the LARES and LAGEOS satellites. **THE EUROPEAN PHYSICAL JOURNAL C, *79***, 872 (2019).
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