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The Galileo for Science (G4S 2.0) project: Measurement of the Gravitational Redshift with the Galileo satellites DORESA and MILENA

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Summary. — The G4S 2.0 project represents an important opportunity to perform fundamental physics measurements with the two Galileo-FOC satellites DORESA and MILENA in elliptic orbits. In this paper, we discuss the possibility to improve the current constraints on local position invariance via a new measurement of the gravitational redshift, taking into account both a new model of the satellites and more in-depth considerations on non-gravitational perturbations.

1. – Introduction

The classical theory of General Relativity (GR) is widely considered the best description of the gravitational interaction. The theory itself is a geometric theory, *i.e.*, the gravitational field is identified with the spacetime curvature and it is essentially based on two assumptions. The first is the Einstein Equivalence Principle (EEP) which is built on the three fundamental pillars: the universality of free fall (UFF), the local position invariance (LPI) and the local Lorentz invariance (LLI). The second is the Einstein-Hilbert action, whose variation allows us to derive the Einstein field equations, that represent the essential tool to describe how spacetime behaves. GR has made a number of predictions, largely confirmed by astrophysical and cosmological experiments with a high level of precision. However, GR seems to manifest shortcomings at infrared (IR) and ultraviolet (UV) scales(1) and, typically, it is expected to be the low energy effective field theory of a more fundamental gravitational or unified framework. This means that if we probed suited physical scales with sufficiently sensitive measurements we would reveal physics beyond GR. Such a possibility is extremely challenging and pushes us to design new experiments in order to constrain generic deviations from GR as well as alternatives or extensions both (purely) metric (affine) and non-metric [1, 2]. The literature

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(1) In a sense, GR should be valid only for a given range of length scales.

describes some ways to test GR or some of its fundamental assumptions. The latter do not represent truly or complete tests of GR but are equally important in order to capture possible physics beyond the standard model of particle physics and gravity. One of the most interesting examples is LPI. The LPI can be tested by (1) searching for variation of fundamental constants like the fine-structure constant or the electron-proton mass ratio or (2) constraining gravitational redshift (GRS). In particular, GRS was firstly observed in a ground experiment by Pound, Rebka, and Snider [3, 4] while the first test exploiting stable atomic clocks (AC) is due to Vessot *et al.* via the Gravity Probe A (GP-A) rocket experiment in 1976 [5, 6]. The possibility of improving the GP-A constraints appeared some years ago in the context of the Global Navigation Satellite Systems (GNSS). Indeed, in August 2014, the two Galileo FOC satellites DORESA and MILENA were launched, and instead of being placed on the designed nominal, circular orbits ($e \simeq 0$), they were erroneously placed on elliptical orbits ($e \simeq 0.23$). Then, the orbits were partially corrected ($e \simeq 0.16$) and it was possible to recover the two satellites for navigation goals. However, it was soon realized that the new orbital configuration made these two satellites suitable for testing fundamental physics, and in particular the GRS. In fact, the structure of the orbit induces a periodic modulation of the gravitational potential that turns into a periodic modulation of the satellite AC frequency with respect to the terrestrial reference AC frequency. The AC good clock stability ($\sim 10^{-14}$ at the time scale of the orbital period $T = 46584\,\mathrm{s}$) allows testing this periodic modulation to a new level of uncertainty. In 2018, the European GREAT(²) project, using the data of these satellites, provided new constraints on the GRS taking into account a number of systematic effects and improving the GP-A results [7, 8]. The new Galileo For Science 2.0 project (G4S 2.0) aims to perform a new measurement of the GRS taking in consideration a refined set-up for the geometric and optical satellite properties and non-gravitational perturbations [9-11]. This project is funded by the Italian Space Agency (ASI) and involves three centres of excellence: Istituto di Astrofisica e Planetologia Spaziali (IAPS-INAF) in Rome, the Center for Space Geodesy (CGS-ASI) in Matera and Politecnico di Torino (POLITO). Below, we have provided a very general introduction to the issues of the GRS measurement and our related activities at IAPS.

2. – G4S and improved constraints on Gravitational Redshift

The theory of GR allows computing the relative frequency shift, z, between two clocks placed in two different positions in a gravity field. In the weak field limit, this quantity reads as

$$z \sim \frac{\Delta\nu}{\nu} \sim \frac{\Delta U}{c^2}, \tag{1}$$

where ΔU is the Newtonian potential difference and c the speed of light in vacuum. In order to search for deviations from this standard prediction, namely, deviation from the LPI, one can add a simple linear correction to the above expression of the form [12]

$$z \sim \frac{\Delta\nu}{\nu} \sim (1+\alpha)\frac{\Delta U}{c^2}, \tag{2}$$

(²) Galileo gravitational Redshift Experiment with eccentric sATellites.

where α represents the parameter to constrain. In general, the α parameter can be constrained from the AC data, basically the time series of *clock bias*, *i.e.*, the difference in the *time reading* between the satellite and the terrestrial reference clock in a given sample time t_i: $S_i = \tau_{i,sat} - \tau_{i,ref}$. The required time series of clock bias should be constructed by implementing a couple of corrections to the bias τ_{esoc} estimated by the Precise Orbit Determination (POD) performed by ESOC(3) so as to suppress GR contributions and highlight a possible *new physics* signal. First of all, the clock bias τ_{esoc} contains a *keplerian correction* needed for navigation purposes in order to take into account the eccentricity of the orbit(s). This correction is characterized by an intrinsic negative sign and takes the form

$$\tau_{Kepler} = \left|\frac{2\vec{x}\cdot\vec{v}}{c^2}\right|, \tag{3}$$

where $\vec{x}$ and $\vec{v}$ are the position and velocity vectors of the satellite, respectively. Therefore, we need to counteract this contribution and get a basic clock bias solution. Second, we have to apply a full general relativistic correction associated to the theoretical proper time τ_{GR} of the satellite clock. This correction must be computed by a refined POD, by integrating the coordinate time-to proper time transformation along a given time interval

$$\tau_{GR} = \int_{\Delta t} \mathrm{d}t \frac{\mathrm{d}\tau}{\mathrm{d}t} = \int_{\Delta t} \mathrm{d}t \left(1 - \frac{v^2}{2c^2} - \frac{U_S}{c^2}\right), \tag{4}$$

where τ is the proper time, t is the coordinate time, v the clock velocity and U_S is the sum of the Earth gravitational potential and lunisolar tidal potential in the satellite position. Hence, the second contribution is the Doppler effect whereas the third one is the overall gravitational effect. Typically, coordinate time and velocity are referred to the Geocentric Celestial Reference System (GCRS) as defined by the latest IAU resolution. In conclusion, we can build the so-called *corrected clock bias*

$$\tau_{corr} = \tau_{esoc} - \tau_{Kepler} - \tau_{GR}. \tag{5}$$

In 1976, Vessot *et al.* found $\alpha = (1 \pm 2) \times 10^{-4}$. In 2018, Delva *et al.* provided $\alpha = (0.19 \pm 2.48) \times 10^{-5}$ while Herrmann *et al.* found $\alpha = (4.5 \pm 3.1) \times 10^{-5}$. In G4S 2.0, we aim to improve such estimates by providing an estimation of α with an uncertainty of less than 2×10^{-5} due to the main systematic error sources, such as those related to the POD, on-board temperature distribution and the varying geomagnetic field. In the case of POD, we plan to achieve this level of uncertainty via the GEODYN (NASA/GSFC) and Bernese (Berna Univ.) s/w [13, 14]. The Bernese s/w, thanks to its high quality, will be used primarily for the estimation of the clock bias solution needed for the GRS measurement and consequent constraints in α. In particular, we aim to exploit two aspects that are inherently related to each other. First, the development of a Finite Element Model (FEM) to catch the complex geometry of the spacecraft, based on the optical and thermal (time-dependent) properties of the surfaces and the complex attitude-law. In this regard, we want to apply a Ray-Tracing technique to take into consideration umbra, penumbra and multiple reflections on the satellite itself. Currently, we have

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(3) European Space Operation Center.

developed a preliminary Box-Wing model looking forward to obtaining the necessary information to fully characterize the satellite for the construction of the FEM. Second, we are developing new refined models for non-gravitational perturbations (NGP), acting on the spacecraft. In general, there are many sources of NGP. However, the direct solar radiation pressure (SRP) represents the dominant contribution and the main challenge is to develop a more refined and reliable model for it. In particular, the direct SRP acceleration is $\sim 1 \times 10^{-7}\,\mathrm{m/s^2}$ and is two orders of magnitude larger than the Earth's albedo $\sim 7 \times 10^{-10}\,\mathrm{m/s^2}$ or Earth's infrared radiation $\sim 1 \times 10^{-9}\,\mathrm{m/s^2}$. The inclusion of these aspects and a proper treatment of the other error budgets will provide a more precise POD and clock bias τ_{corr}, useful to determine improved constraints on α.

3. – Conclusions and future perspectives

We have provided an overview on the main activities developed at IAPS for testing the validity of LPI through a new measurement of the GRS. The challenge lies in an accurate estimation of the systematic errors to obtain a robust and reliable result. G4S 2.0 is also designed to measure the relativistic precessions (Schwarzschild, Lense-Thirring and de Sitter) of the DORESA and MILENA orbits and to improve the current bounds on Dark Matter in the Milky Way. These points are of crucial importance, since they could reveal or strongly constrain physics beyond current standard models.

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