

The Galileo for Science (G4S_2.0) project: Fundamental Physics experiments with Galileo satellites DORESA and MILENA

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Summary. — G4S_2.0 is a new project of the Italian Space Agency which aims to perform a set of Fundamental Physics measurements with two satellites, DORESA and MILENA, of the Galileo-FOC constellation. The high eccentricity of their orbits and the accuracy of their atomic clocks allow measuring gravitational redshift and relativistic precessions of the orbits. These results will place new constraints on possible alternative theories of gravitation, both metric and non-metric in their structure. Furthermore, constraints on the presence of Dark Matter in our Galaxy can be placed by analyzing data of the satellite atomic clocks.

1. – Introduction

In August 2014, the GSAT0201 and GSAT0202 satellites (Galileo FOC-DORESA, Galileo FOC-MILENA) of the European global navigation system Galileo were launched. Instead of being placed on circular orbits, they were erroneously placed on elliptical orbits ($e \simeq 0.23$). Successively, the orbits were corrected ($e \simeq 0.16$) and it was possible to use these two satellites for navigation. However, their elliptical orbits make them attractive for Fundamental Physics measurements. The elliptic orbit induces a periodic modulation of the on-board atomic clocks frequency with respect to on-ground clocks, the so-called gravitational redshift (GRS). The good clocks stability (about 10^{-14} at the time scale of the orbital period of the satellites, 46584 s) allows testing this periodic modulation to a new level of uncertainty. Different research teams analyzed data of these satellites to study possible deviations from General Relativity (GR). In particular, the scientific team of the GREAT project⁽¹⁾ [1,2] measured the GRS by improving a previous measurement of the Gravity Probe-A experiment [3]. An Italian project funded by the Italian Space Agency (ASI), Galileo For Science 2.0 (G4S_2.0), also aims to perform a set of Fundamental Physics measurements with these two satellites. Three Italian research institutes are involved: the Center for Space Geodesy (CGS-ASI) in Matera, Istituto di Astrofisica e Planetologia Spaziali (IAPS-INAF) in Rome and Politecnico di Torino (POLITO).

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⁽¹⁾ Galileo gravitational Redshift Experiment with eccentric sATellites.

2. – Main activities of G4S_2.0 project at IAPS

Several activities are included in this project, in particular, IAPS is involved in: i) providing a new measurement of the gravitational redshift; ii) measuring the relativistic precessions of DORESA and MILENA orbits; iii) placing constraints on the possible presence of Dark Matter in our Galaxy; iv) developing new models for non-gravitational perturbations (NGPs); v) realizing a new accelerometer concept for a next generation of Galileo satellites. A brief overview of the main IAPS tasks is given below.

2.1. Gravitational redshift measurement. – GR predicts that the relative frequency shift (z) between clocks at different Newtonian potential ΔU in a weak⁽²⁾ gravitational field is $z = \Delta\nu/\nu = \Delta U/c^2$ (with c the speed of light in vacuum). The GRS is not a truly test of GR, since it can be derived by imposing the validity of Special Relativity and the Equivalence Principle. However, the GRS plays a key role, since it represents a Local Position Invariance Test (LPI), according to which the outcome of any local non-gravitational experiment is independent of where and when it is performed in the Universe. To this purpose, an α parameter is introduced and it is non-zero in the case of LPI violation:

$$(1) \quad z = \frac{\Delta\nu}{\nu} = (1 + \alpha) \frac{\Delta U}{c^2}.$$

The α parameter can be deduced by comparing the clock bias (the difference between the time measured by the on-board clocks and the time measured by a clock on Earth) measurements with GR predictions. The theoretical clock bias (τ_{GR}) is calculated from the satellite Precise Orbit Determination (POD), (see sect. 2.2) by integrating the coordinate time to proper time transformation:

$$(2) \quad \tau_{GR} = \int \frac{d\tau}{dt} dt = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_S}{c^2} \right] dt,$$

where τ and t are the proper time and the coordinate time, respectively, and v is the velocity of the clock in the Geocentric Celestial Reference System. The second term in brackets accounts for the relativistic Doppler effect (due to relative motion) whereas U_S is the overall gravitational and tidal potential in the satellite position. To perform a reliable measurement of the GRS, a corrected clock bias (τ_{corr}) has to be calculated from the clock bias solution⁽³⁾ taking into account an apriori relativistic correction⁽⁴⁾ already included. This corrected clock bias will be compared with the prediction of GR to estimate the α parameter. In order to improve the current best measurements of the GRS, we aim to provide an estimation of α with an uncertainty of less than 2×10^{-5} (see table I). To achieve this goal it is essential to improve the POD and its products, as the clocks solution, developing more reliable dynamical models, in particular for the

⁽²⁾ In the weak field approximation, the metric tensor of space-time $g_{\mu\nu}$ can be written as the sum of the Minkowski tensor $\eta_{\mu\nu} = \text{diag}(1, -1, -1, -1)$ of flat space-time and a perturbation $h_{\mu\nu}$ describing the effects of curvature, where $|h_{\mu\nu}| \ll 1$.

⁽³⁾ The clock bias solution is produced by official analysis centers using experimental data. In the case of G4S_2.0, our POD will contribute to the estimation of the satellites clock bias.

⁽⁴⁾ Assuming a perfect Keplerian orbit, the relativistic correction is $\tau_{Kepler} = -2(\mathbf{x} \cdot \mathbf{v})/c^2$, where \mathbf{x} and \mathbf{v} are the position and velocity vectors of the satellite, respectively.

TABLE I. – *Past and recent measurements of the α parameter.*

Source	α
Vessot <i>et al.</i> (1980)	$\alpha = (1 \pm 2) \times 10^{-4}$
Delva <i>et al.</i> (2018)	$\alpha = (0.19 \pm 2.48) \times 10^{-5}$
Herrmann <i>et al.</i> (2018)	$\alpha = (4.5 \pm 3.1) \times 10^{-5}$

Non-Gravitational Perturbations (NGPs) and also exploiting the Laser tracking of the satellites.

2.2. New models for non-gravitational perturbations. – In our analysis, a fundamental point is obtaining a satellite orbit-solution which is as precise as possible by fitting the tracking data with a suitable set of dynamical models for the different effects (including the NGPs) in an accurate POD. The NGPs are the most difficult to model because of the complex shape of the Galileo satellites and their attitude law. In particular, the main challenge is to enhance the dynamical model, developed until now, of the solar radiation pressure (SRP), which is the major perturbation. To derive the perturbing accelerations, our ultimate goal is to develop a Finite Element Model (FEM) of the satellite. As a starting point, a box-wing (BW) model and a 3D-CAD of the satellite have been developed. The BW model simplifies the satellite to the central bus (‘box’) and two rectangular solar panels (‘wing’). The surfaces have been characterized, until now, with the geometry and the optical properties according to ESA’s Galileo-Metadata⁽⁵⁾. Finally, a fundamental point in the NGPs models is modelling umbra, penumbra and multiple reflections effects on the satellite itself, exploiting the so-called Ray-Tracing technique.

2.3. Relativistic precessions. – Another goal of the project is measuring relativistic precessions of DORESA and MILENA orbits. Given a non-rotating central mass, GR predicts a precession effect on the orbit of a satellite connected to the central mass. This precession is the so-called Schwarzschild precession or Einstein precession [4]. If the central mass is rotating, the Lense-Thirring precession occurs [5]. Another effect must be taken into account, which is the de Sitter precession (or geodetic precession) due to the motion of the Earth-Moon system in the Sun gravitational field [6]. Measurements of these precessions have already been performed with the LAGEOS (LAser GEOdynamic Satellite) satellites [7, 8]. Now, exploiting the Galileo satellites for this purpose is the new challenge [9]. It is worth stressing that these measurements are much harder in the case of Galileo satellites, with respect to the LAGEOS ones, because of the smaller relativistic effects and of the larger NGPs. As relativistic precessions come from Einstein field-equations, their measurements will allow us to study possible deviations from GR and to compare its prediction with those of other theories of gravitation.

2.4. Search for domain wall Dark Matter. – Dark Matter (DM) could arise from very light quantum fields that form macroscopic objects or clumps. Examples of clumpy

⁽⁵⁾ <https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata>.

DM candidates are topological defects⁽⁶⁾, such as domain walls. The GNSS (Global Navigation Satellite System) can be useful to search for such objects: as the Earth moves through the galactic dark matter halo, interactions with domain walls could cause a sequence of atomic clock perturbations that propagate through the satellite constellation in terms of a correlated sequence of glitches in their clocks. Analyzing 16 years of GPS-data, Roberts *et al.* (2017) [10] have found no evidence for the existence of domain walls. Assuming a quadratic scalar interaction between DM and clock atoms, the relative frequency shift can be expressed in terms of relative variations in the effective values of fundamental constants (the electromagnetic fine-structure constant (α), the electron and proton mass (m_e, m_p), the ratio of the light quark mass to the quantum chromodynamics (QCD) energy scale (m_q/Λ_{QCD}).) The current constellation of the Galileo FOC satellites can allow an improvement of this constraint by taking advantage of the higher sensitivity of the on-board atomic clocks with respect to the GPS ones.

3. – Conclusions and future perspectives

We presented the main objectives and activities developed within the G4S_2.0 project at IAPS. This project is relevant for the variety of its goals (from gravitation to cosmology) by exploiting, mainly, two satellites that were erroneously placed on elliptical orbits. To pursue these objectives, improving the models of the NGPs acting on the satellite is essential. A preliminary BW model allowed us to assess the characteristics of the resulting accelerations. By acquiring a more detailed knowledge of the physical and geometric properties of the satellites, we will be able to build an improved BW model and finally a FEM. On this model we will apply Ray-Tracing techniques, further improving the NGPs effects estimation.

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REFERENCES

- [1] DELVA P. *et al.*, *Phys. Rev. Lett.*, **121** (2018) 231101.
- [2] HERRMANN S. *et al.*, *Phys. Rev. Lett.*, **121** (2018) 231102.
- [3] VESSOT R. F. C. *et al.*, *Phys. Rev. Lett.*, **45** (1980) 2081.
- [4] EINSTEIN A., *Ann. Phys.*, **354** (1916) 769.
- [5] LENSE J. and THIRRING H., *Z. Phys.*, **19** (1918) 156.
- [6] DE SITTER W., *Mon. Not. R. Astron. Soc.*, **76** (1916) 699.
- [7] CIUFOLINI I., *Eur. Phys. J. C*, **79** (2019) 872.
- [8] LUCCHESI D. M. *et al.*, *Universe*, **6** (2020) 139.
- [9] LUCCHESI D. M. *et al.*, in *Proceedings of the VI International Colloquium on Scientific and Fundamental Aspects of GNSS/Galileo, Valencia (Spain), 25-27 October 2017*, <https://gssc.esa.int/education/galileo-science-colloquium/>.
- [10] ROBERTS B. M. *et al.*, *Nat. Commun.*, **8** (2017) 1195.

⁽⁶⁾ Topological defects may be formed during cooling of the early Universe through a spontaneous symmetry breaking phase transition.