Galileo gravitational Redshift Experiment with eccentric sATellites (GREAT)

Executive Report

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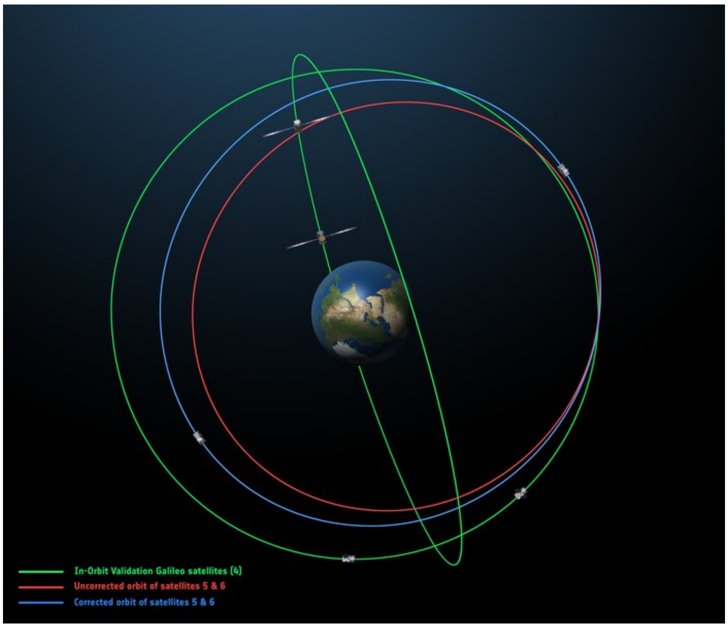

We report on a new test of the gravitational redshift and thus of local position invariance, an integral part of the Einstein equivalence principle, which is the foundation of general relativity and all metric theories of gravitation. We use data spanning 1008 days from two satellites of Galileo, Europe's global satellite navigation system (GNSS), which were launched in 2014, but accidentally delivered on elliptic rather than circular orbits. The resulting modulation of the gravitational redshift of the onboard atomic clocks allows the redshift determination with high accuracy. Additionally specific laser ranging campaigns to the two satellites have enabled a good estimation of systematic effects related to orbit uncertainties. Together with a careful conservative modelling and control of other systematic effects we measure the fractional deviation of the gravitational redshift from the prediction by general relativity to be $(-0.14 \pm 2.48) \times 10^{-5}$ at 1 sigma, improving the best previous test by a factor 5.6. To our knowledge, this represents the first reported improvement on one of the longest standing results in experimental gravitation, the Gravity Probe A hydrogen maser rocket experiment back in 1976.

The classical theory of general relativity (GR) provides a geometrical description of the gravitational interaction. It is based on two fundamental principles: (i) the Einstein equivalence principle (EEP) and (ii) the Einstein field equations that can be derived from the Einstein-Hilbert action. Although very successful so far, there are reasons to think that sufficiently sensitive measurements could uncover a failure of GR. For example, the unification of gravitation with the other fundamental interactions, and quantum theories of gravitation, generally lead to small deviations from GR (see e.g. [18]). Also dark matter and energy are so far only observed through their gravitational effects, but might be hints towards a modification of GR.

From a phenomenological point of view, three aspects of the EEP can be tested: (i) the universality of free fall (UFF); (ii) local Lorentz invariance (LLI); and (iii) local position invariance (LPI). Constraints on UFF have been recently improved by the Microscope space mission [13], while LLI was recently constrained, for example, by using a ground fibre network of optical clocks [4] (see e.g. [18, 8, 12] for reviews). In this paper we focus on testing LPI.

LPI stipulates that the outcome of any local non-gravitational experiment is independent of the space-time position of the freely-falling reference frame in which it is performed. This principle is mainly tested by two types of experiments: (i) search for variations in the constants of Nature (see e.g. [6], and [14] for a review) and (ii) gravitational redshift tests. The gravitational redshift was observed in a ground experiment for the first time by Pound, Rebka and Snider [10, 11].

In a typical clock redshift experiment, the fractional frequency difference $z = \Delta\nu/\nu$ between two clocks located at different positions in a static gravitational field is measured, by exchange of electromagnetic signals. The EEP predicts $z = \Delta U/c^2$ for stationary clocks, where ΔU is the gravitational potential difference between the locations of both clocks, and c is the velocity of light in vacuum. A simple and convenient formalism to test the gravitational redshift is to

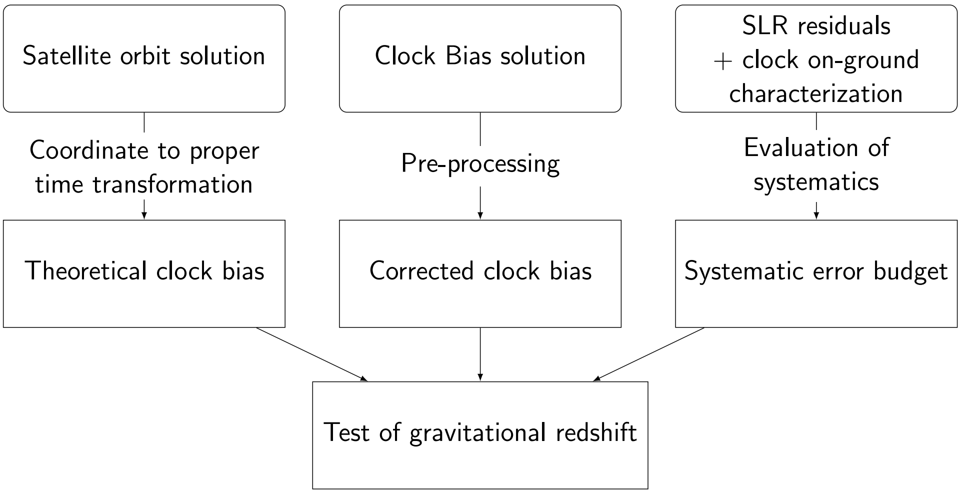

Figure 1: Data analysis flowchart

introduce a new parameter α defined through (see e.g. [18]):

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

with α vanishing when the EEP is valid.

The so far most accurate test of the gravitational redshift has been realized with the Vessot-Levine rocket experiment in 1976, also named the Gravity Probe A (GP-A) experiment [16, 15, 17]. The frequency differences between a space-borne hydrogen maser clock and ground hydrogen masers were measured thanks to a continuous two-way microwave link. The total duration of the experiment was limited to 2 hours constrained to the parabolic trajectory of the GP-A rocket, and reached an uncertainty of $|\alpha| \leq 1.4 \times 10^{-4}$ [17]. The future Atomic Clock Ensemble in Space (ACES) experiment [2, 9], an ESA/CNES mission, planned to fly on the ISS in 2020, will test the gravitational redshift to around $|\alpha| \leq 3 \times 10^{-6}$. Furthermore, other projects like STE-QUEST propose to test the gravitational redshift at the level of 10^{-7} [1]. Finally, observations with the RadioAstron telescope are hoping to reach an uncertainty of the order of 10^{-5} [7].

In the GREAT (Galileo gravitational Redshift Experiment with eccentric sATellites) experiment, following the proposal in [5], we use the onboard atomic clocks of the Galileo satellites 5 and 6 (named Doresa and Milena, or GSAT0201 and GSAT0202) to search for violations of the EEP/LPI. These two satellites were launched together on a Soyuz Rocket on August, 22^{nd} 2014 and because of a technical problem on the launcher's upper stage, they were placed in a non-nominal elliptic orbit. Although the satellites' orbits were adjusted after the launch, they remain elliptical, with each satellite climbing and falling some 8500 km twice per day. The elliptic orbit induces a periodic modulation of the gravitational redshift at orbital period (around 13 hours), while the good stability of recent GNSS clocks allows us to test this periodic modulation to a very good level of accuracy. The Galileo 5 and 6 satellites, with their large eccentricity ($e = 0.162$) and onboard passive H-maser clocks, are hence perfect candidates to perform this test. Contrary to the GP-A experiment, it is possible to integrate the signal over a long duration, therefore improving the statistics. Moreover, Satellite Laser Ranging (SLR) data are used for a characterization of systematic effects. A specific ILRS (International Laser Ranging Service) campaign took place during the years 2016–2017 [3].

The flowchart of the data analysis is given in Figure 1. It is done in three steps. First, we fit a model for the stochastic noise to the corrected clock bias residuals. In a second step, we fit the model of the LPI violation to the corrected clock bias by using a Monte Carlo approach, using the stochastic noise model estimated in the first step. This gives us the fitted value for the LPI violation parameter α as well as an estimation of its statistical uncertainty. In a third step, we estimate the systematic uncertainty by considering the main sources of systematics: effects of magnetic field, of temperature and mismodelling of the orbital motion of the satellites.

Finally, by analysing 1008 days of data from the two eccentric Galileo satellites, GSAT0201 and GSAT0202, and through a careful analysis of systematic effects, we were able to improve the gravitional redshift test done by GP-A in 1976 by a factor 5.6, down to $\alpha = (-0.14 \pm 2.48) \times 10^{-5}$. Our result is at the lower edge of the predicted sensitivity in [5]. This is due to the very favourable configuration of GSAT0201 with respect to the orbit systematics on the clock bias, which is almost 90° out-of-phase with the LPI violation signal. At this point, the main residual limiting factor is the uncertainty due to the magnetic field variations, which cannot be overcome without more information about the clock sensitivity (e.g. directional dependence) and the actual local magnetic field after e.g. shielding from the satellite itself. A refinement of the magnetic field characterisation of the PHM per axis could be performed to improve the magnetic field contribution uncertainty and reduce further the LPI overall total uncertainty. In any case, we can see that the three main uncertainties, i.e., statistical, orbit and magnetic field, are of the same order. Therefore, envisaging a potential future mission of the same type, it would be of interest to improve these three aspects of the experiment: a more stable clock to have better statistics, a careful shielding, modelling or measurement of the magnetic field, and a careful modelling or measurement of non-gravitational accelerations. Also increasing the signal (higher ellipticity, lower perigee) would improve the test significantly (see e.g. the STE-QUEST proposal [1]). Finally, a two-way link would strongly reduce the effect of orbit determination uncertainties (see e.g. the ACES proposal [2, 9]).

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