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Gravitational Redshift Test Using Eccentric *Galileo* Satellites

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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, 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 modeling and control of other systematic effects we measure the fractional deviation of the gravitational redshift from the prediction by general relativity to be $(0.19 \pm 2.48) \times 10^{-5}$ 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.

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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., Ref. [1]). Also dark matter and energy are so far only observed through their gravitational effects, but might be hints towards a modification of GR [2,3].

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 [4], while LLI was recently constrained, e.g., by using a ground fiber network of optical clocks [5] (see, e.g., Refs. [1,6,7] for reviews). In this paper we focus on testing LPI.

LPI stipulates that the outcome of any local nongravitational 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., Refs. [8,9] 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 introduce a new parameter α defined through (see, e.g., Ref. [1])

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

with α vanishing when the EEP is valid.

So far, the most accurate test of the gravitational redshift has been realized with the Vessot-Levine rocket experiment

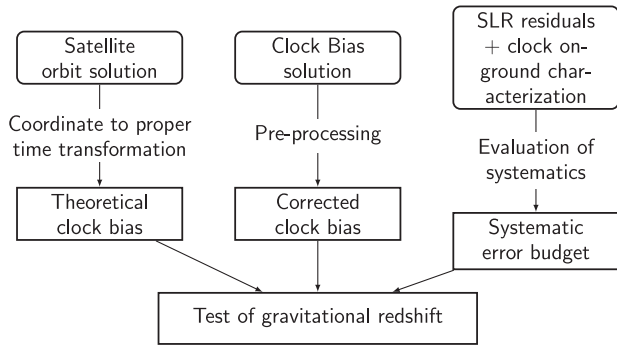


FIG. 1. Data analysis flowchart: as input we use ESOC orbit and clock solution files, SLR residuals, as well as clock on-ground characterization. The evaluation of systematics is completely independent from the clock measurements.

in 1976, also named the Gravity Probe A (GP-A) experiment [12–14]. The frequency differences between a spaceborne 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 h constrained to the parabolic trajectory of the GP-A rocket, and reached an uncertainty of $|\alpha| \leq 1.4 \times 10^{-4}$ [14]. The future Atomic Clock Ensemble in Space (ACES) experiment [15,16], 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 Space-Time Explorer and Quantum Equivalence Principle Space Test propose to test the gravitational redshift at the level of 10^{-7} [17]. Finally, observations with the RadioAstron telescope are hoping to reach an uncertainty of the order of 10^{-5} [18].

In this Letter, following the proposal in Ref. [19], 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, 2014 and because of a technical problem on the launcher’s upper stage, they were placed in a nonnominal 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 h), while the good stability of recent GNSS clocks allows us to test this periodic modulation to a new level of uncertainty. The *Galileo* 5 and 6 satellites, with their large eccentricity ($e = 0.162$) and onboard passive hydrogen-maser (PHM) 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 international laser ranging service (ILRS) campaign took place during the years 2016–2017 [20].

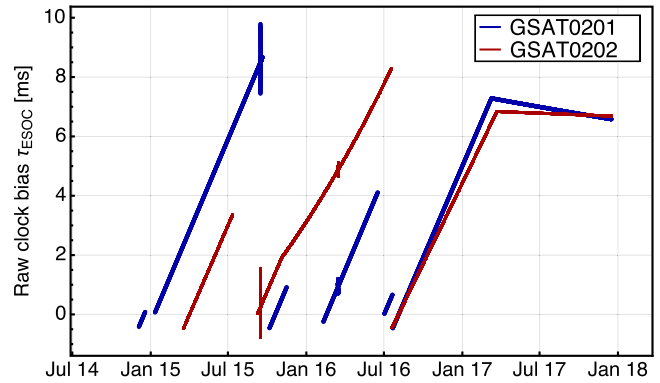


FIG. 2. Raw clock bias τ_{ESOC} , as read in the ESOC clock solution file.

The flowchart of the data analysis is given in Fig. 1. We use an orbit and clock solution generated by ESA’s Navigation Support Office, located at the European Space Operations Centre (ESOC). The details of the ESOC processing strategy are given in the Supplemental Material [21]. The satellite orbit solution contains positions and velocities of multiple GNSS satellites in the terrestrial reference frame ITRF2014 with respect to GPS time epochs. Orbit solutions are independent of a possible violation of the gravitational redshift (at the required accuracy), as no assumptions or models of the clock evolution, are made. Instead the clock solutions are obtained as a free parameter for each epoch.

The satellite orbits and time epochs are calculated in the Geocentric Celestial Reference System (GCRS) thanks to the Standards of Fundamental Astronomy (SOFA) routines [35]. Then, we calculate the theoretical proper time of the onboard clock τ_{GR} —predicted by GR—by integrating the coordinate time to proper time transformation:

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

where τ and t are the proper time and the coordinate time (geocentric coordinate time TCG) of the clock, respectively, c is the velocity of light in vacuum, and v is the velocity of the clock in the GCRS. Also, U_E is the Newtonian gravitational potential of the Earth at the location of the satellite

$$U_E = \frac{GM}{r} + \frac{GMR_0^2 J_2}{2r^3} (1 - 3 \cos^2 \theta), \quad (3)$$

where G is the gravitational constant, M , R_0 , and J_2 are the mass, the equatorial radius, and the zonal coefficient of order 2 of Earth, respectively, and r and θ are the distance from the center of Earth and the colatitude of the satellite, respectively. U_T is the tidal potential due to external bodies [36],

TABLE I. Master clock on board each eccentric satellite with dates and corresponding standard deviation of the clock bias prefit residuals. In bold are the chosen clocks for the gravitational redshift test.

Satellite	Clock	Start	Stop	Clock residuals stand. dev. (ns)
GSAT0201	PHM-B ^a	11/29/14	06/25/16	0.16
	PHM-A	06/26/16	12/16/2017	0.69
GSAT0202	PHM-B	03/17/15	11/03/15	0.20
	RAFS	11/04/15	07/01/16	2.21
	PHM-A ^b	07/02/16	12/16/2017	0.11

^aGSAT0201 PHM-B was interrupted for 4 days as a master clock in favor of RAFS-B on 12/04/14. These data were removed.

^bGSAT0202 PHM-A was interrupted for 13 days as a master clock in favor of RAFS-B on 10/30/16. These data were removed.

$$U_T = \sum_A GM_A \left[\frac{1}{|\mathbf{r} - \mathbf{r}_A|} - \frac{1}{|\mathbf{r}_A|} - \frac{\mathbf{r} \cdot \mathbf{r}_A}{|\mathbf{r}_A|^3} \right], \quad (4)$$

where M_A is the mass of external body A , and \mathbf{r} and \mathbf{r}_A are, respectively, the position vectors of the satellite and external body A in the geocentric frame. We take into account the Moon and Sun, while other bodies can be neglected.

The main gravitational effect is the sum of a linear and a periodic term, which amounts to 400 ns peak to peak (see Fig. 4). Earth's flatness leads to a 40 ps peak-to-peak periodic effect at twice the orbital frequency. Tidal effects from the Moon and the Sun lead to a periodic signal of around 12 ps peak to peak, higher than the uncertainty goal of the experiment.

The deviation of the proper time from the GR prediction, τ_{LPI} , is quantified by the LPI violation parameter α as given in Eq. (1) and proportional to the gravitational part of the coordinate to proper time transformation:

$$\tau_{\text{LPI}} = -\alpha \int \frac{U_E + U_T}{c^2} dt. \quad (5)$$

The raw clock bias τ_{ESOC} from the ESOC clock solution is shown in Fig. 2 for satellites GSAT0201 and GSAT0202, with respect to a daily reference clock on the ground. A large drift of the order of $34 \mu\text{s d}^{-1}$ is present most of the time. The linear part of the relativistic redshift between the Galileo clocks and a ground clock is $\approx 40 \mu\text{s d}^{-1}$ assuming a nominal 10.23 MHz frequency. However, each PHM clock is also affected by an intentional frequency offset ($\approx -6 \mu\text{s d}^{-1}$) to this nominal frequency which explains the observed drift. Additionally, after each activation the clock retraces to the nominal frequency with an accuracy not better than $\pm 0.18 \mu\text{s d}^{-1}$. We remove this unknown frequency offset (together with the known $34 \mu\text{s d}^{-1}$) by removing from the clock bias a daily linear fit (DLF), which can be written in the form

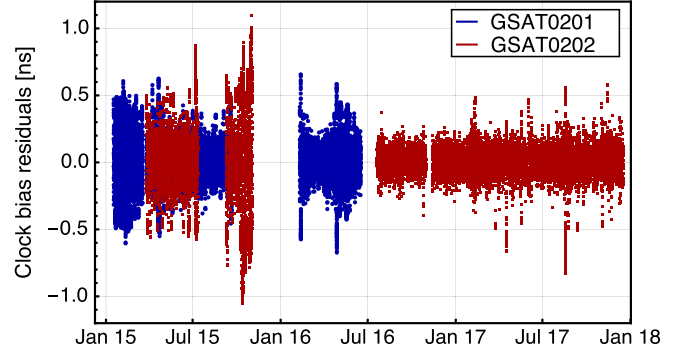


FIG. 3. Clock bias pre-fit residuals are obtained by removing from the raw clock bias τ_{ESOC} a daily linear fit. Here only the times taken into account in the analysis are shown.

$$\tau_{\text{DLF}} = \sum_{i=1}^N f_i(t)(a_i + b_i t), \quad (6)$$

where N is the number of days in the data, a_i and b_i are the clock offset and linear drift for day i , respectively, and $f_i(t)$ is equal to 1 for day i , and 0 otherwise. The clock bias residuals for the times chosen in the analysis are shown in Fig. 3.

The master clock on board the *Galileo* satellites may change over time due to maintenance routine. There are two PHM clocks as well as two rubidium clocks (RAFS) on board each of the satellites. In Table I we show the dates of each master clock as well as the standard deviation of the corresponding clock residuals. We exclude from the analysis data from PHM-A of GSAT0201 and from RAFS of GSAT0202, because of the higher standard deviation of their residuals. Obvious outliers at typically more than 10σ are removed, which represents around 7.7% and 4.3% of the total data for GSAT0201 and GSAT0202, respectively. Finally, our data analysis contains 359 days of data from GSAT0201 and 649 days of data from GSAT0202, spanning from January 2015 to December 2017. The raw clock bias τ_{ESOC} is corrected to account for the full GR prediction given in Eq. (2), giving the corrected clock bias τ_{corr} . This is explained in detail in the Supplemental Material [21].

The data analysis 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 defined from Eqs. (5) and (6) 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 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 mismodeling of the orbital motion of the satellites.

The stochastic noise of the clock bias is modeled as a sum of white frequency and flicker phase noise [in the time domain that corresponds to power spectral density (PSD) with f^{-2} and f^{-1} slopes, respectively], with the amplitudes

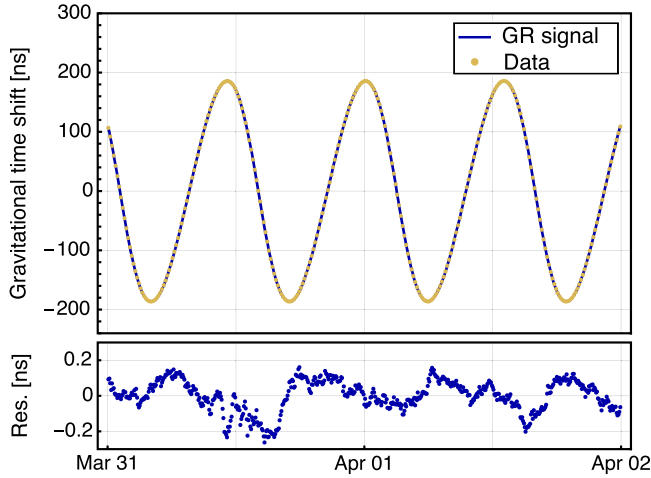


FIG. 4. GR prediction, clock data (after removal of a daily linear fit) and residuals are shown for 2 days from March 31, 2016. The peak-to-peak effect is around $0.4 \mu\text{s}$, therefore the model and systematic effects at orbital period should be controlled down to 4 ps in order to have a 1×10^{-5} uncertainty on the LPI violation parameter α .

given by a fit to the PSD of the clock bias residuals. The PSD is calculated thanks to the Lomb-Scargle algorithm [37,38], which takes into account data gaps. Typical PSD noise levels are $3 \times 10^{-25} \text{ s}^2 \text{ Hz}^{-1} \times (f/f_0)^{-2}$ and $1 \times 10^{-21} \text{ s}^2 \text{ Hz}^{-1} \times (f/f_0)^{-1}$, where $f_0 = 1 \text{ Hz}$. As discussed in Ref. [19] the clocks are also subject to flicker frequency noise at low frequencies (typically $\leq 1 \text{ d}^{-1}$), which (anyway) plays no role in our analysis because it is absorbed by the daily linear fit τ_{DLF} given in Eq. (6).

As the noise from the clock bias is mostly composed by random walk noise, it is not possible to use a simple linear least-square approach which assumes white noise, and would lead to a strong underestimation of the parameter uncertainties by 1 or more orders of magnitude. Therefore a Monte Carlo linear least-square (MC LLS) approach is used. The LLS minimizes the quantity $S(p) = [y - f(p)]^T [y - f(p)]$, where p is the set of parameters, y is the observation vector, and $f(p)$ is the model estimated at p (see, e.g., Chap. 15.6 of Ref. [39]). In our case, $y = \tau_{\text{corr}}$, $f(p) = \tau_{\text{LPI}} + \tau_{\text{DLF}}$, and $p \equiv \{\alpha, a_i, b_i\}$, which are the same parameters as defined in Eqs. (5) and (6). Moreover, the two clocks from GSAT0202 are weighted following their respective clock residuals standard deviations given in Table I. This provides our estimates of the parameters p . Then we determine the statistical uncertainties of the parameters with the MC routine: we generate 1000 independent noise series mimicking our data, and fit the same model $f(p)$ to each of them, as to the data. This provides 1000 sets of the parameters p , coming only from the modeled stochastic noise. The standard deviation of the obtained parameter values give their statistical uncertainty at 1σ .

We report the results of the MC LLS, i.e., the value of the LPI violation parameter α and its statistical uncertainty, in Table II. We obtain $\alpha = (-0.77 \pm 1.48) \times 10^{-5}$ and $\alpha = (6.75 \pm 1.41) \times 10^{-5}$ for satellites GSAT0201 and GSAT0202, respectively. The value of α for GSAT0202 is 5 times its uncertainty at 1σ , and therefore significant. A careful analysis of systematic effects is discussed in the Supplemental Material to explain this value [21]. We compared the MC LLS approach to a general least-square (GLS) approach for GSAT0201, where we take into account the full noise covariance matrix on a day by day basis. The value of α found with GLS is still consistent with a null value within the 1σ uncertainty, and the uncertainty found with GLS is 20% smaller. However, the GLS approach neglects long term (across day boundaries) correlations and we consider the MC LLS uncertainty value to be more conservative.

The main likely systematic effects were identified in Ref. [19]. Effects acting on the frequency of the reference ground clock, as well as effects acting on the radio link can be safely neglected, as explained in Ref. [19]. We will assess effects acting directly on the frequency of the onboard clock, namely, temperature and magnetic field variations, as well as systematic effects coming from orbit modeling errors, which are strongly correlated to the clock solution in the case of a one-way time transfer (see, e.g., Refs. [22,23]). During this experiment, no additional environmental data (onboard magnetic field or temperature) were available. Therefore, we will only evaluate an upper limit of the systematic effects rather than trying to correct them. In doing so we do not use the clock data itself, so our limits are independent of a putative violation of the gravitational redshift.

A detailed description of the systematic effect analysis is given in the Supplemental Material [21]. Here we summarize the main results. The magnetic field vector is calculated along the trajectory of each satellite, and projected onto each axis of the PHM clock. The sensitivity of the clock to the magnetic field, as determined in ground tests, then translates the modeled magnetic field variations along each axis of the clock into a variation of the fractional frequency of the clock. The model $f(p) = \tau_{\text{LPI}} + \tau_{\text{DLF}}$ is then fitted to this variation to obtain the highest possible value of α due to this effect. Our approach is conservative as we do not assume any shielding from the satellite or the clock. The result is reported in Table II in the magnetic field uncertainty column. A similar approach is used to estimate the highest possible value of α due to temperature variations, acting both directly on the clock and on the rest of the payload. We assume that temperature variations of the clock are due to the change of the orientation of the satellite with respect to the Sun, and take their amplitude as the highest peak-to-peak variation allowed by the thermal control system, which is a very conservative assumption as explained in the Supplemental Material [21]. The result

TABLE II. Final result of the EEP-LPI test. Each row is a separate output from fits of, respectively, GSAT0201 data and models, GSAT0202 data and models, and a joint fit of both sets of data and models. The uncertainties due to systematic effects are evaluated independently from the clock data, and are the result of individual fits of models of systematics (for temperature and magnetic field), and a fit of SLR residuals for the orbit uncertainty, thus giving an upper limit of each effect. A single value is computed for the magnetic field uncertainty by summing in quadrature the X, Y, Z values. The total uncertainty column, for each row, is derived from the quadratic sum of the individual uncertainties to the right.

	LPI violation [$\times 10^{-5}$]	Total uncertainty [$\times 10^{-5}$]	Stat. unc. [$\times 10^{-5}$]	Orbit unc. [$\times 10^{-5}$]	Temperature unc. [$\times 10^{-5}$]	Magnetic field tot. unc. (X, Y, Z) [$\times 10^{-5}$]
GSAT0201	-0.77	2.73	1.48	1.09	0.59	1.93 (0.52, -0.36, 1.82)
GSAT0202	6.75	5.62	1.41	5.09	0.13	1.92 (-0.07, 0.58, 1.83)
Combined	0.19	2.48	1.32	0.70	0.55	1.91 (0.48, -0.29, 1.82)

is reported in Table II in the temperature uncertainty column. Finally, we estimate uncertainties due to orbit modeling errors thanks to SLR data. Indeed, SLR residuals have been shown to be highly correlated to the clock bias, as it is expected in a one-way time transfer [22,23]. We fit the same model $f(p) = \tau_{\text{LPI}} + \tau_{\text{DLF}}$ to the (scaled) SLR residuals in order to get the highest value of α due to orbit modeling errors. The result is reported in Table II in the orbit uncertainty column.

When we quadratically add the statistical and systematic uncertainties due to each considered error source, we obtain for the LPI violation parameter $\alpha = (-0.77 \pm 2.73) \times 10^{-5}$ for GSAT0201 and $\alpha = (6.75 \pm 5.62) \times 10^{-5}$ for GSAT0202 (see Table II).

Finally, we combine the data from both satellites using a global MC LLS analysis, where the only parameter common to both satellites is the LPI violation parameter α . The relative weight of both satellites in the MC LLS is chosen following their orbit uncertainty in Table II. The uncertainties coming from systematics are evaluated in the same way as for each satellite alone, except that we combine the modeled clock variations due to systematics from both satellites in the fit, with the same weight as for the clock biases. The results are reported in Table II.

To conclude, 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 gravitational redshift test done by GP-A in 1976 by a factor 5.6, down to $\alpha = (0.19 \pm 2.48) \times 10^{-5}$. Our result is at the lower edge of the predicted sensitivity in Ref. [19]. This is due to the very favorable 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 characterization 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, modeling, or measurement of the magnetic field, and a careful modeling or measurement of nongravitational accelerations. Also increasing the signal (higher ellipticity, lower perigee) would improve the test significantly (see, e.g., the STE-QUEST proposal [17]). Finally, a two-way link would strongly reduce the effect of orbit determination uncertainties (see, e.g., the ACES proposal [15,16]).

Part of the data used in this Letter will be published by ESA on the ESA GNSS Science Server [40].

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