A new test of gravitational redshift using eccentric Galileo satellites

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General Relativity is based on 2 fundamental principles:

- the Einstein Equivalence Principle (EEP)
- the Einstein field equations

Following Will (1993), EEP can be divided into three *sub-principles*

- **WEP/UFF**: If any uncharged test body is placed at an initial event in space-time and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition.
- **LPI**: The outcome of any local non-gravitational test experiment is independent of *where and when* in the universe it is performed.
- **LLI**: The outcome of any local non-gravitational test experiment is independent of the velocity of the (freely falling) apparatus.
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Tests of the EEP with atomic clocks

- Tests of **Lorentz Invariance** using comparisons of
  - atomic clocks onboard **GPS satellites w.r.t. ground clocks** (Wolf and Petit 1997)
  - **optical clocks** linked with optical fibres (Delva, Lodewyck, et al. 2017)
- Test of **Lorentz Invariance in the Matter Sector** (Wolf, Chapelet, et al. 2006; Hohensee et al. 2011; Pihan-Le Bars et al. 2017; Sanner et al. 2019)
- Transients (Derevianko and Pospelov 2014; Wcislo et al. 2016; Roberts et al. 2017; Wcislo et al. 2018)

Test of **Lorentz Invariance with a clock redshift experiment** (Vessot 1989)
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Gravity Probe A (GP-A) (1976)

- Test of LPI with a clock redshift test (Vessot and Levine 1979; Vessot, Levine, et al. 1980; Vessot 1989)
- Continuous two-way microwave link between a spaceborne hydrogen maser clock and ground hydrogen masers
- One parabola of the rocket $\lesssim 2$ hours of data
- Frequency shift verified to $7 \times 10^{-5}$
- Gravitational redshift verified to $1.4 \times 10^{-4}$
Tests of Local Position Invariance

(Will 2014)

- Null tests: 2 different co-located clocks in the Sun potential
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H-Maser Gravity Probe A (1976)
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The Galileo system

- European Global Navigation Satellite System (GNSS) $(22.2 \times 10^9$ euros in 20 years)
- 24 satellites + 6 spares in medium Earth orbit on three orbital planes [actually 26];
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- ESA: **GNSS Science Support Centre (GSSC: gssc.esa.int)** and **GNSS Science Advisory Committee (GSAC)**
- More than 100 GNSS satellites, with global coverage and continuous measurements: major contributions in **Earth Science**, **Fundamental Physics**, **Metrology** and many other fields
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Galileo satellites 201&202 orbit

Galileo sats 201&202 launched in 08/22/2014 on the wrong orbit due to a technical problem ⇒ GRedshift test (GREAT Study)
Why Galileo 201 & 202 are perfect candidates?

- An elliptic orbit induces a periodic modulation of the clock proper time at orbital frequency

\[ \tau(t) = \left(1 - \frac{3Gm}{2ac^2}\right) t - \frac{2\sqrt{Gma}}{c^2} e \sin E(t) + \text{Cste} \]

- Very good stability of the on-board atomic clocks → test of the variation of the redshift
- Satellite life-time → accumulate the relativistic effect on the long term
- Visibility → the satellite are permanently monitored by several ground receivers
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Orbit and clock solutions: ESA/ESOC
Transformation of orbits into GCRS with SOFA routines
Theoretical relativistic shift and LPI violation

\[ x_{\text{redshift}} = \int \left[ 1 - \frac{v^2}{2c^2} - \frac{U_E + U_T}{c^2} \right] dt ; \quad x_{\text{LPI}} = -\alpha \int \frac{U_E + U_T}{c^2} dt \]

Peak-to-peak effect
\[ \sim 400 \, \text{ns: model and systematic effects at orbital period should be controlled down to 4 ps in order to have} \]
\[ \delta \alpha \sim 1 \times 10^{-5} \]
Choice of clock

- GAL-201: only PHM-B (PHM-A is removed) → 359 days of data
- GAL-202: only PHM (RAFS is removed) → 649 days of data
Fit of the LPI violation model with Linear Least Square in a Monte Carlo routine: 1 GR violation parameter ($\alpha$) + 2 parameters per day fitted (daily clock offset $a_i$ and drift $b_i$)

$$x = \sum_i f_i(t)(a_i + b_i t) - \alpha \int \frac{U_E + U_T}{c^2} dt$$
## Results of MC-LLS

<table>
<thead>
<tr>
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<th>LPI violation parameter [×10^{-5}]</th>
<th>Statistical uncertainty (Monte-Carlo) [×10^{-5}]</th>
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The bias is significant for GAL-202
Systematic errors (Delva, Hees, et al. 2015)

1. Effects acting on the frequency of the reference ground clock → can be safely neglected
2. Effects on the links (mismodeling of atmospheric delays, variations of receiver/antenna delays, multipath effects, etc...) → very likely to be uncorrelated with the looked for signal, averages with the number of ground stations
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Local systematics: Temperature

Poor access to environmental data, but environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)

Temperature systematics

- Temperature sensitivity is assumed $< 2 \times 10^{-14} \text{ / K (rel.freq.)}$
- Temperature systematics is supposed to be maximum when the Sun is in the $\pm z$ direction, and minimum when the Sun is in the $+x_{\text{IGS}}$ direction

from Montenbruck et al. 2015

ESA document
Local systematics: Magnetic Field

Magnetic Field systematics

- Magnetic Field along sat. trajectory calculated with International Geomagnetic Reference Field (IGRF) model
- Projection of Magnetic Field into the sat. local frame
- Magnetic Field sensitivity is assumed $< 3 \times 10^{-13} / G$ (rel.freq.) along each local frame axis

from Montenbruck et al. 2015
Orbit systematics

Fit the LPI violation model on Satellite Laser Ranging (SLR) residuals

- Orbital errors are dominated by Solar Radiation Pressure mismodelling
- 1 year SLR Campaign thanks to International Laser Ranging Service

SLR residuals give the range error $\Rightarrow$ clock error in a 1-way time transfer
Local Position Invariance is confirmed down to $2.5 \times 10^{-5}$ uncertainty, more than 5 times improvements with respect to Gravity Probe A measurement.

The test is now limited by the clock magnetic field sensitivity (along the z axis), which effect is highly correlated to the LPI violation.
## Galileo final result

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