A new test of gravitational redshift using eccentric Galileo 5 & 6 satellites

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Time Machine Factory 2019
La Turin, Italy, September 22–25 2019
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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.
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Motivation: a quantum theory of gravitation

Figure from Altschul2015.
Tests of the EEP with atomic clocks

- Tests of **Lorentz Invariance** using comparisons of
  - atomic clocks onboard **GPS satellites** w.r.t. ground clocks *(Wolf1997)*
  - **optical clocks** linked with optical fibres *(Delva2017e)*

- Test of **Lorentz Invariance in the Matter Sector** *(Wolf2006; Hohensee2011; Pihan2017; Sanner2019)*
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- **Test of LPI** searching for variations in the constants of Nature
  - linear temporal drift *(Guena2012; Rosenband2008; Leefer2013; Godun2014; Huntemann2014)*
  - harmonic temporal variation *(VanTilburg2015; Hees2016)*
  - spatial variation w.r.t. the Sun gravitational potential *(Guena2012; Peil2013; Leefer2013; Ashby2007)*
  - **Transients** *(Derevianko2014; Wcislo2016; Roberts2017; Wcislo2018)*
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Gravity Probe A (GP-A) (1976)

- Test of LPI with a clock redshift test (Vessot1979; Vessot1980; Vessot1989)
- 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

(Will2014)

- Null tests: 2 different co-located clocks in the Sun potential

\[ \frac{\Delta v}{v} = (1 + \alpha) \frac{\Delta U}{c^2} \]
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- New test: Galileo eccentric satellites (Delva2018c; Herrmann2018)
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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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The story of Galileo satellites 201 & 202

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- Launch failure was due to a temporary interruption of the joint hydrazine propellant supply to the thrusters, caused by freezing of the hydrazine, which resulted from the proximity of hydrazine and cold helium feed lines.
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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 \text{ 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

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<th>LPI violation parameter [$\times 10^{-5}$]</th>
<th>Statistical uncertainty (Monte-Carlo) [$\times 10^{-5}$]</th>
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The bias is significant for GAL-202.
Systematic errors *(Delva2015q)*

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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We model systematic effects and fit for each the corresponding LPI violation parameters $\rightarrow$ conservative approach
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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. *rocha:2012rz*)

**Temperature systematics**

- Temperature sensitivity is assumed $< 2 \times 10^{-14} / \text{K} \text{ (rel.freq.)}$
- 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

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![Galileo FOC](image1.png)

from *Montenbruck2015*

![ESA document](image2.png)
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 Montenbruck2015
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
Galileo final result

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- 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.

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