A gravitational redshift test using Galileo satellites

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Einstein Equivalence Principle (EEP)

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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Motivation: a quantum theory of gravitation

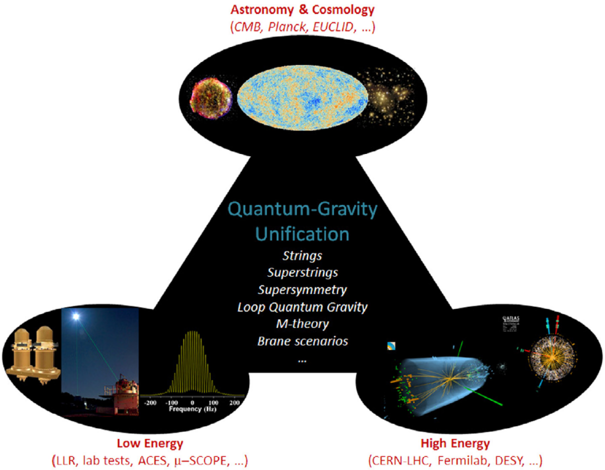

Figure from Altschul et al. 2015.

Tests of the EEP with 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)
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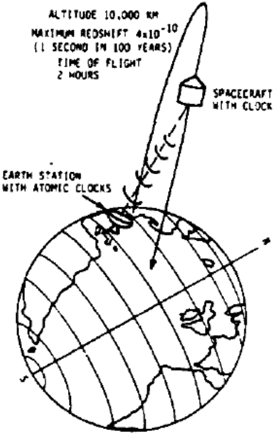
Gravity Probe A (GP-A) (1976)



- 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 7×10^{-5}
- Gravitational redshift verified to 1.4×10^{-4}

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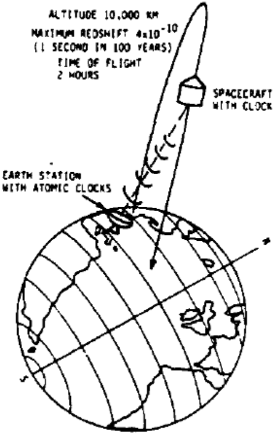

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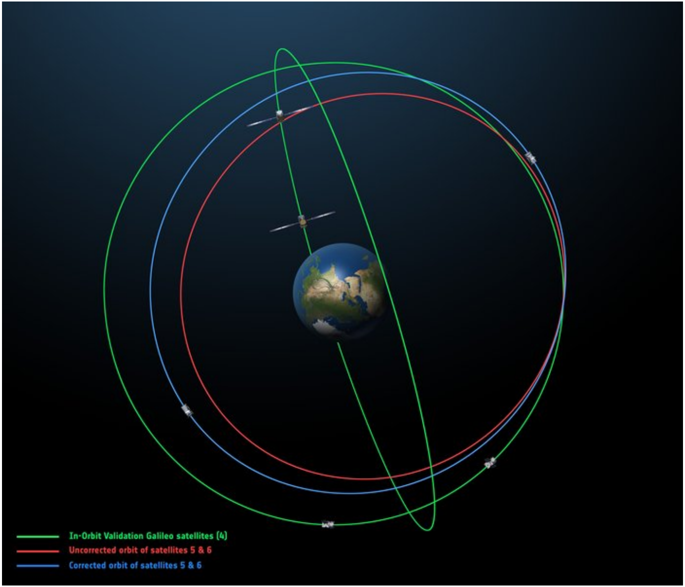
Galileo satellites 201&202 orbit



Galileo sats 201&202 launched in 08/22/2014 on the wrong orbit due to a technical problem $\Rightarrow$ GRedshift test (GREAT Study)

The GREAT study

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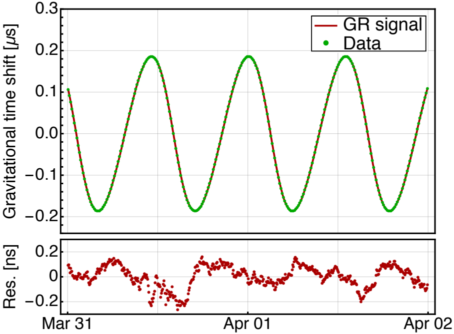
to S. Loyer (CNES/CLS) and Krzysztof Sośnica (Wrocław University of Environmental and Life Sciences), C. E. Noll (ILRS Central Bureau) and all ILRS stations who participated the GREAT SLR campaign

A parallel study is done by ZARM

Why Galileo 201 & 202 are perfect candidates?

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

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



- 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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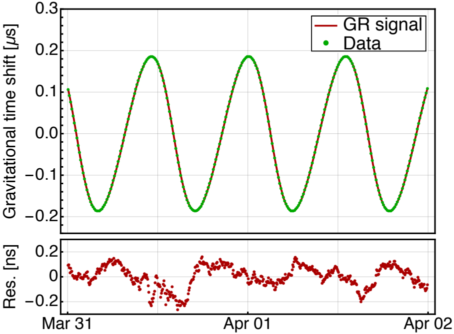

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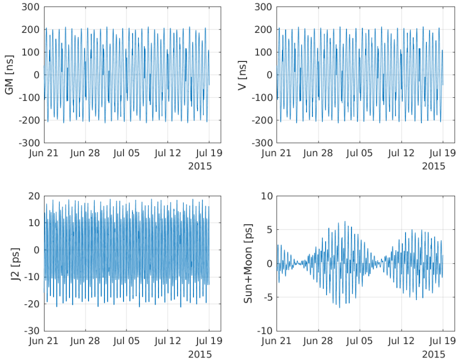
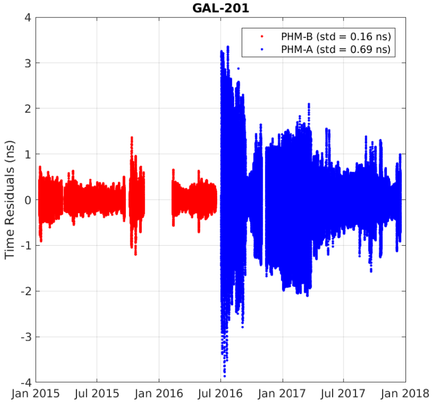
- Orbit and clock solutions: ESA/ESOC
- Transformation of orbits into GCRS with SOFA routines
- Theoretical relativistic shift and LPI violation

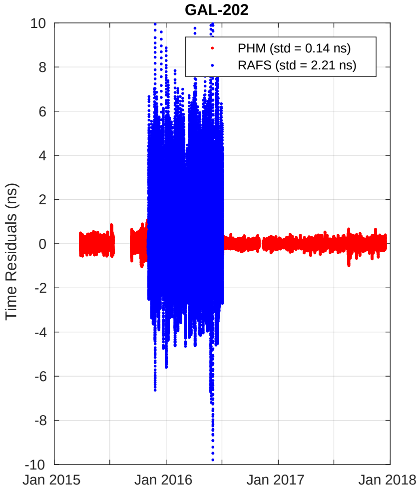
$$x_{\mathrm{redshift}} = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_E + U_T}{c^2} \right] dt \; ; \; x_{\mathrm{LPI}} = -\alpha \int \frac{U_E + U_T}{c^2} dt$$



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

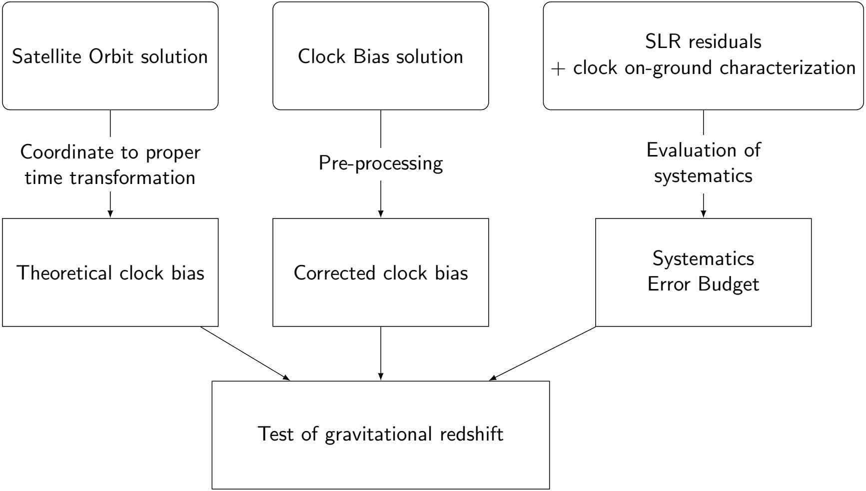
Choice of clock

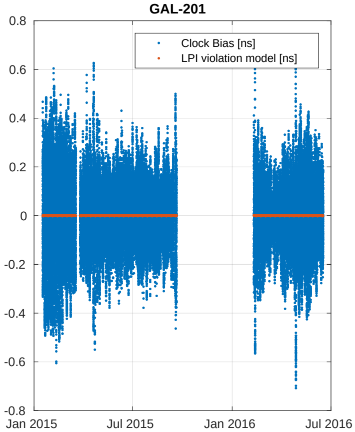


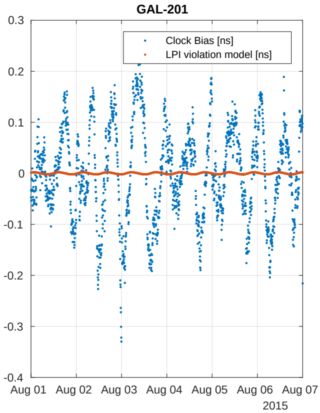


- GAL-201: only PHM-B (PHM-A is removed) → 359 days of data
- GAL-202: only PHM (RAFS is removed) → 649 days of data

Data analysis flowchart







Fit of the LPI violation model with Linear Least Square in a Monte Carlo routine: 1 GR violation parameter (α) + 2 parameters per day fitted (daily clock offset a_i and drift b_i)

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

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
3. Effects acting directly on the frequency of the space clock (temperature and magnetic field variations on board the Galileo satellites) → simple models
4. Orbit modelling errors (e.g. mismodeling of Solar Radiation Pressure) are strongly correlated to the clock solution → SLR residuals (ILRS campaign)

We fit for each (3 and 4) the corresponding LPI violation parameters → conservative approach

Galileo final result

	LPI violat [$\times 10^{-5}$]	Tot unc [$\times 10^{-5}$]	Stat unc [$\times 10^{-5}$]	Orbit unc [$\times 10^{-5}$]	Temp unc [$\times 10^{-5}$]	MF unc [$\times 10^{-5}$]
GAL-201	-0.77	2.73	1.48	1.09	0.59	1.93
GAL-202	6.75	5.62	1.41	5.09	0.13	1.92
Combined	0.19	2.48	1.32	0.70	0.55	1.91

- Local Position Invariance is confirmed down to 2.5×10^{-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

Conclusion

- Atomic clocks are a great tool to constrain alternative theories in fundamental physics
- Best constraint on Grav. Redshift deviation with PHM on-board Galileo satellites, more than $5\times$ improvement w.r.t. 1976 GPA experiment
- Soon to be improved by one order of magnitude with the ACES experiment
- Other fundamental tests using atomic clocks
  - Best constraint of special relativity dilation parameter with ground networks of optical clocks (Delva, Lodewyck, et al. 2017)
  - Best constraint for some dark matter models and some parameters of Standard Model Extension (Hees et al. 2016; Pihan-Le Bars et al. 2017; Roberts et al. 2017)

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