A new test of gravitational redshift using eccentric 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.
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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)
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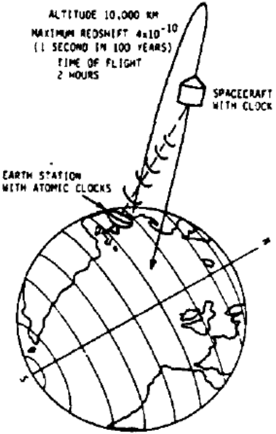
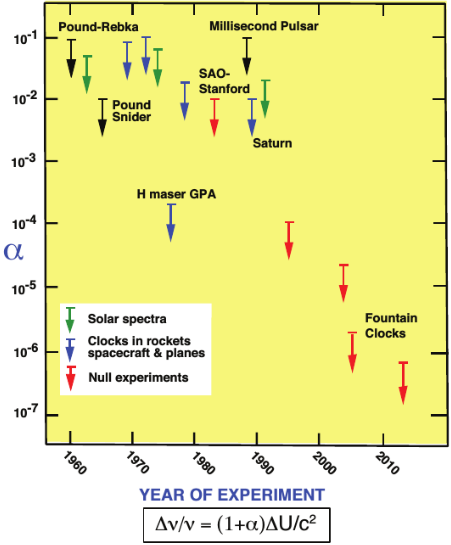
Gravity Probe A (GP-A) (1976)



- 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}

Tests of Local Position Invariance



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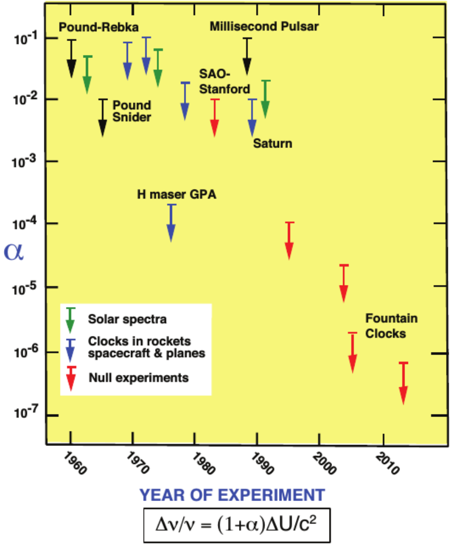

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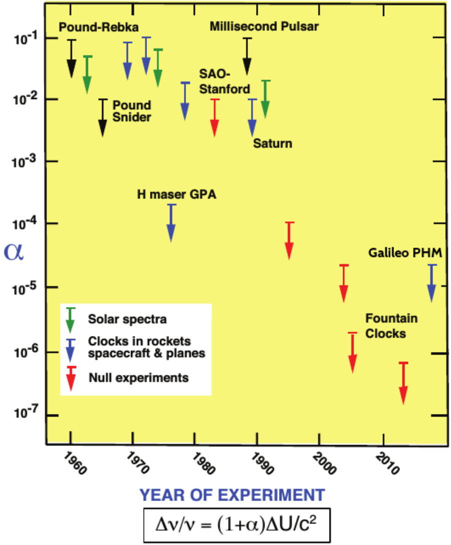

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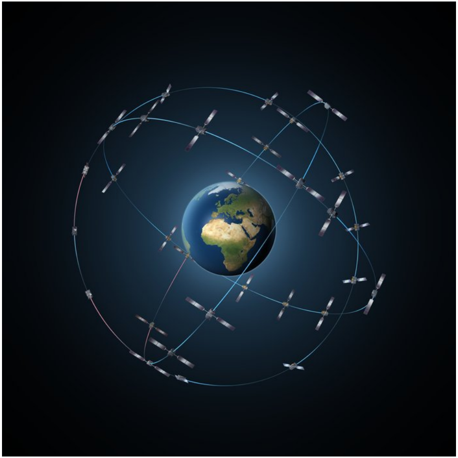
The Galileo system



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- 24 satellites + 6 spares in medium Earth orbit on three orbital planes [actually 26];

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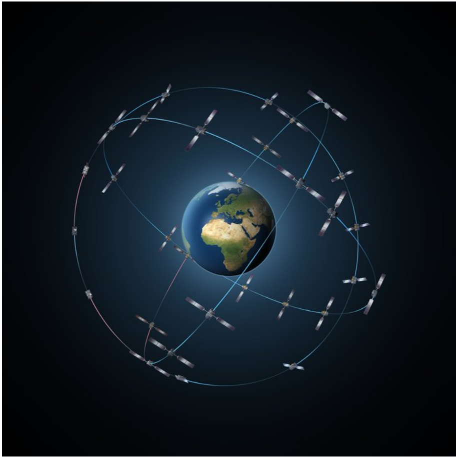

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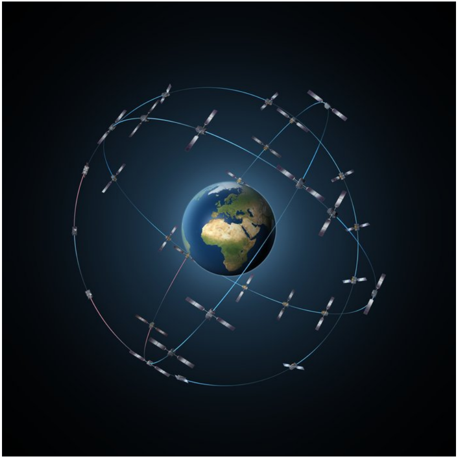

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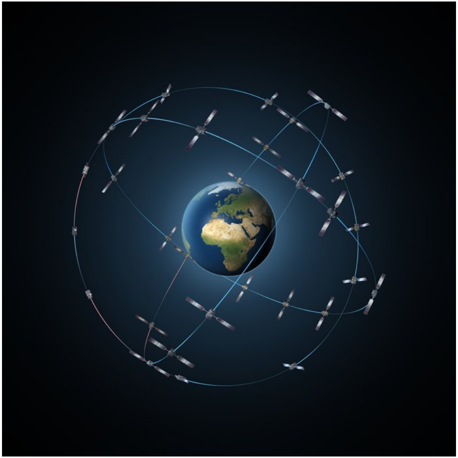

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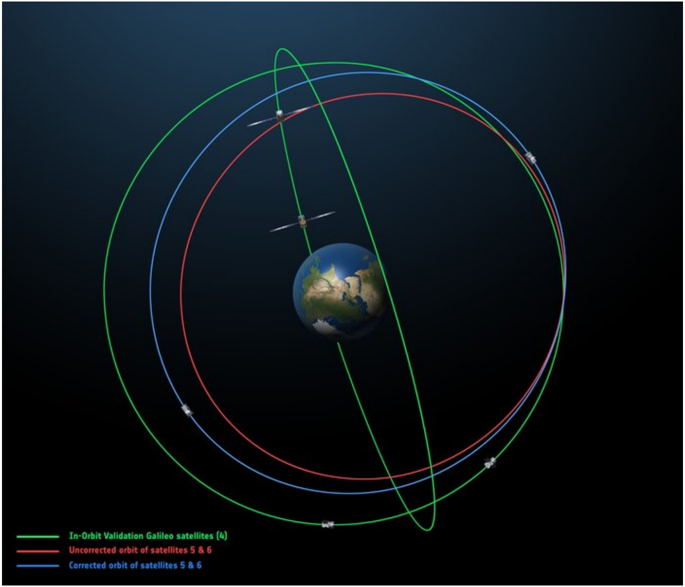
Galileo satellites 201&202 orbit

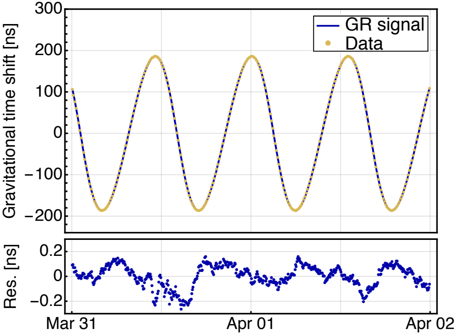


Galileo sats 201&202 launched in 08/22/2014 on the wrong orbit due to a technical problem $\Rightarrow$ GRedshift test (GREAT Study)

Why Galileo 201 & 202 are perfect candidates?

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

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



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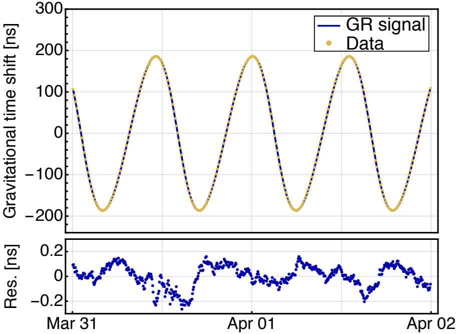

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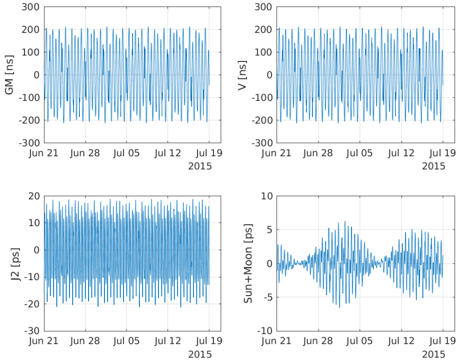
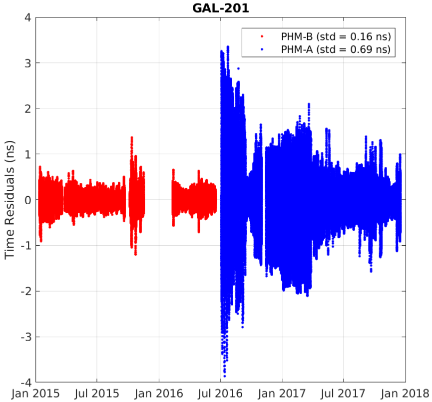
- Orbit and clock solutions: ESA/ESOC
- Transformation of orbits into GCRS with SOFA routines
- Theoretical relativistic shift and LPI violation

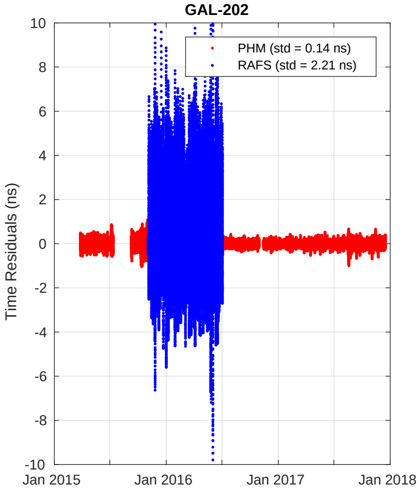
$$x_{\mathrm{redshift}} = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_E + U_T}{c^2} \right] dt \; ; \; x_{\mathrm{LPI}} = -\alpha \int \frac{U_E + U_T}{c^2} dt$$



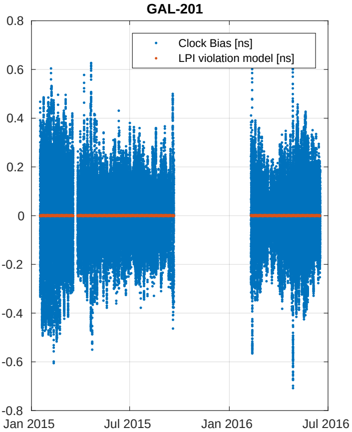
Peak-to-peak effect $\sim 400\,\mathrm{ns}$: model and systematic effects at orbital period should be controlled down to 4 ps in order to have $\delta\alpha \sim 1 \times 10^{-5}$

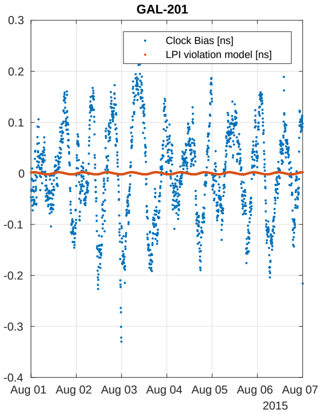
Choice of clock





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





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)

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

Results of MC-LLS

	LPI violation parameter [$\times 10^{-5}$]	Statistical uncertainty (Monte-Carlo) [$\times 10^{-5}$]
GAL-201	-1.12	1.48
GAL-202	$+6.56$	1.41

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 $\rightarrow$ can be safely neglected
2. Effects on the links (mismodeling of atmospheric delays, variations of receiver/antenna delays, multipath effects, etc...) $\rightarrow$ very likely to be uncorrelated with the looked for signal, averages with the number of ground stations

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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
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