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

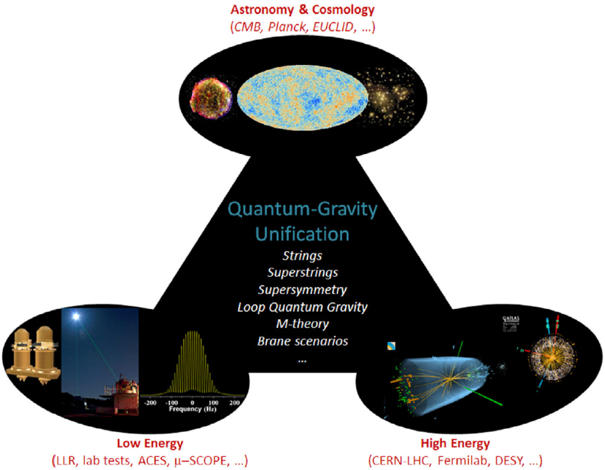

Figure from **Altschul2015**.

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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  - 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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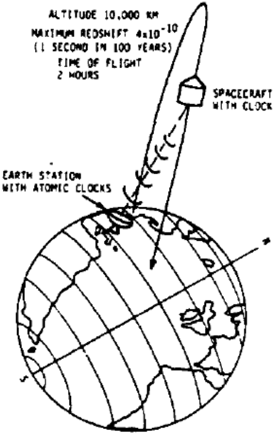
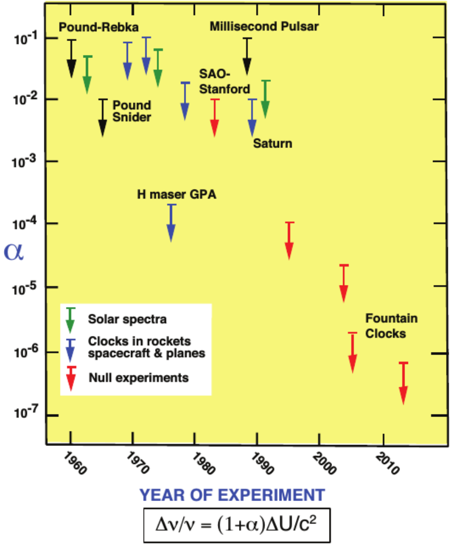
Gravity Probe A (GP-A) (1976)



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

Tests of Local Position Invariance



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

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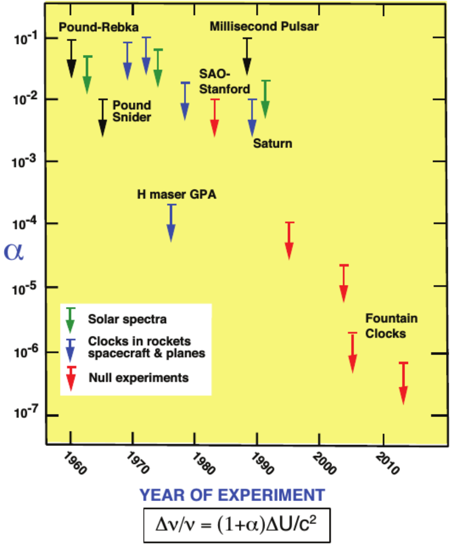

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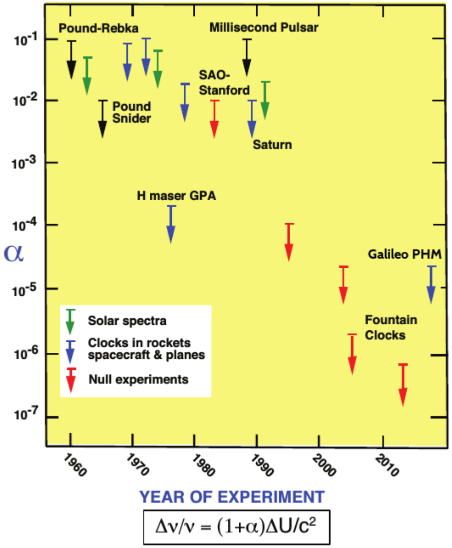

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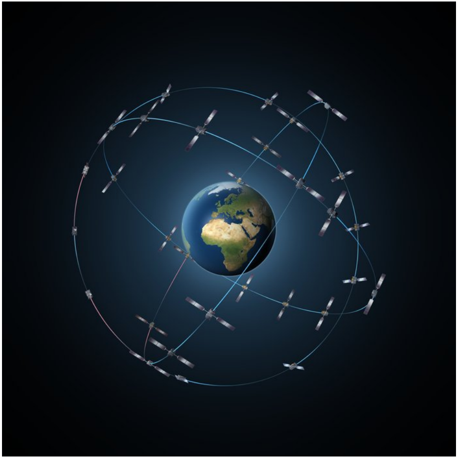
The Galileo system



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

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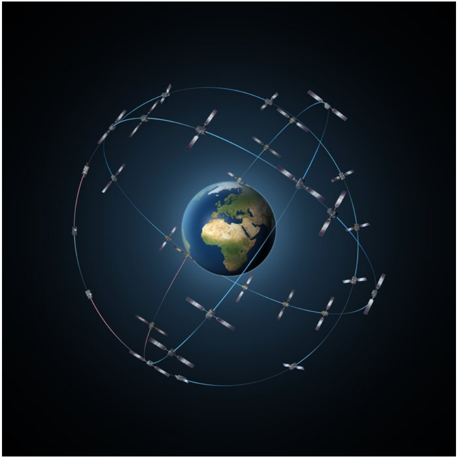

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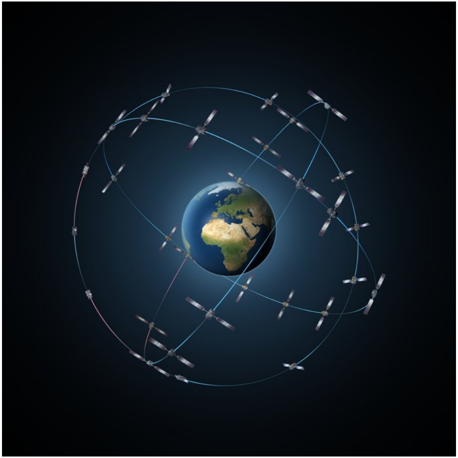

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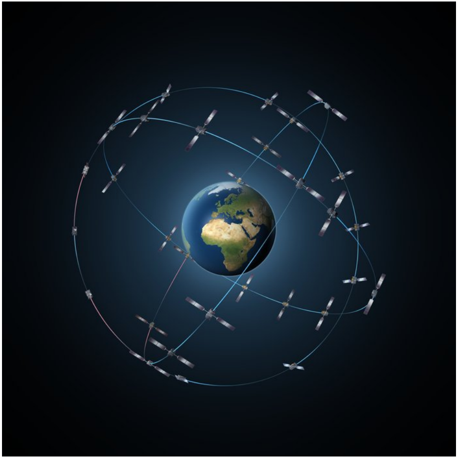

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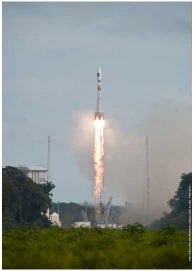
The story of Galileo satellites 201 & 202

- Galileo satellites 201 & 202 were launched with a Soyuz rocket on 22 august 2014 on the wrong orbit due to a technical problem
- 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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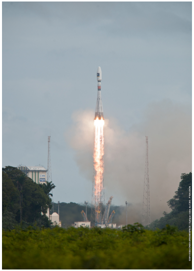
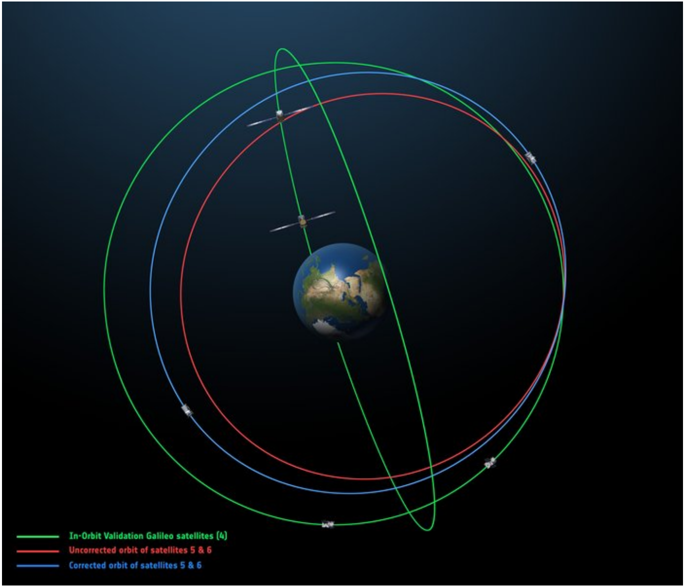


Galileo satellites 201&202 orbit



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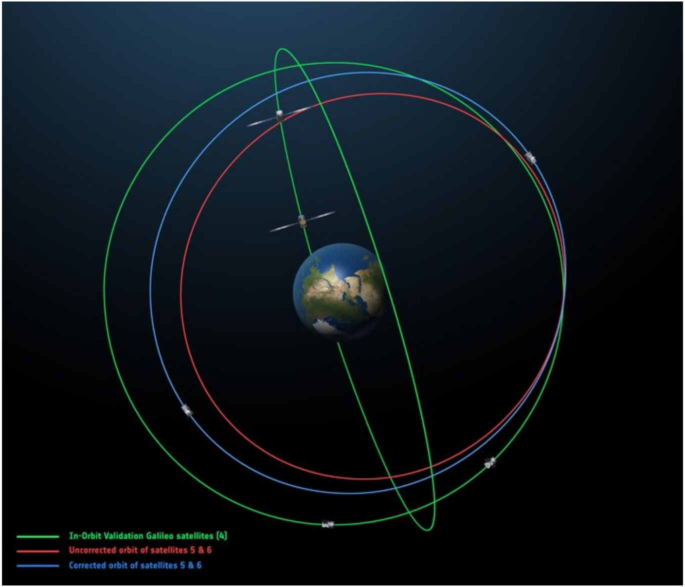
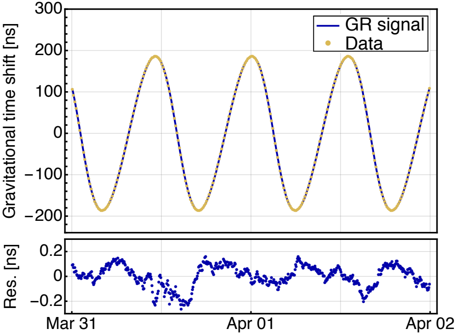


Galileo sats 201&202 launched in 08/22/2014 on the wrong orbit due to a technical problem ⇒ GRedshift test (GREAT Study)

Why Galileo 201 & 202 are perfect candidates?

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

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



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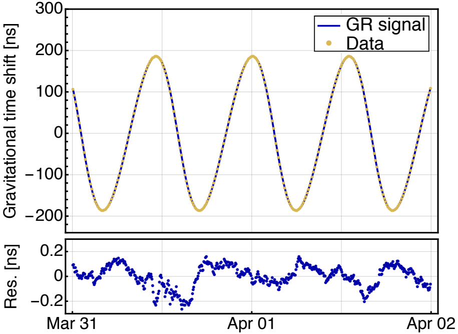

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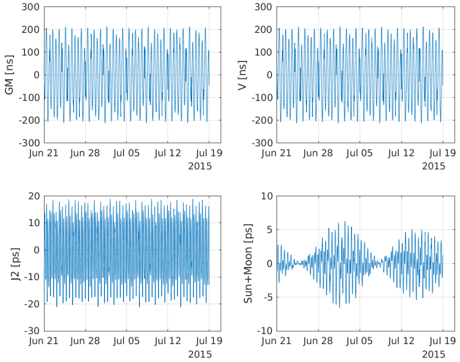
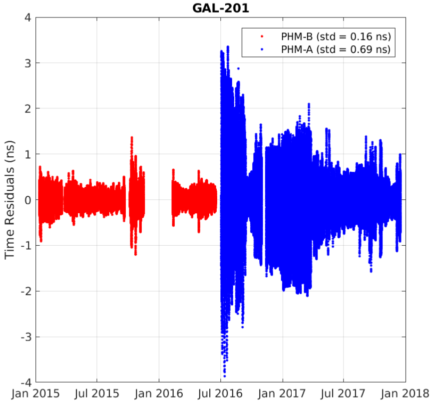
- Orbit and clock solutions: ESA/ESOC
- Transformation of orbits into GCRS with SOFA routines
- Theoretical relativistic shift and LPI violation

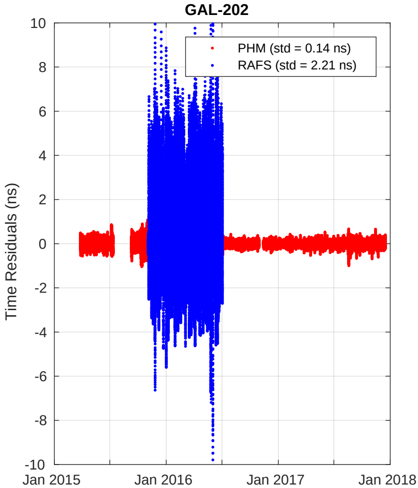
$$x_{\rm redshift} = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_E + U_T}{c^2}\right] dt \; ; \; x_{\rm LPI} = -\alpha \int \frac{U_E + U_T}{c^2} dt$$



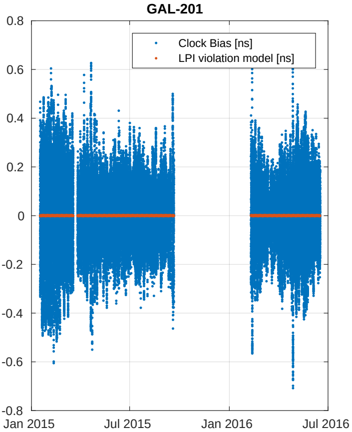
Peak-to-peak effect ~ 400 ns: model and systematic effects at orbital period should be controlled down to 4 ps in order to have $\delta\alpha \sim 1 \times 10^{-5}$

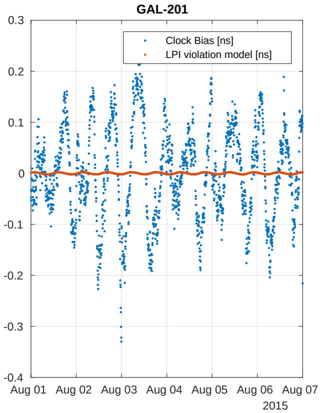
Choice of clock





- 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 (**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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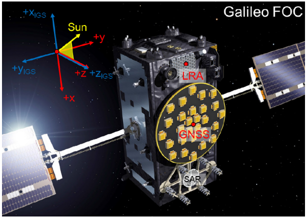
Local systematics: Temperature

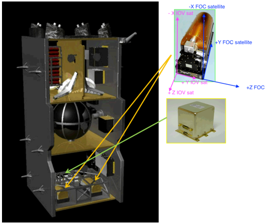
Poor access to environmental data, but environmental sensitivity of the PHMs has been characterized on the ground (see e.g. **rocha:2012rz**)

Temperature systematics

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



from **Montenbruck2015**

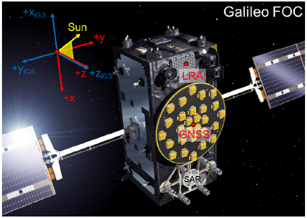


ESA document

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



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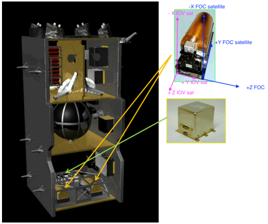

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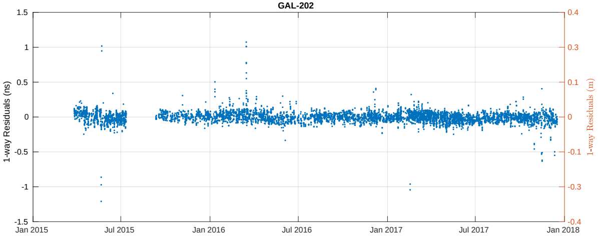
Orbit systematics

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 ⇒ clock error in a 1-way time transfer



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

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