A gravitational redshift test using eccentric Galileo satellites

P. Delva[1],* N. Puchades[2,1], E. Schönemann[3], F. Dilssner[3], C. Courde[4], S. Bertone[5], F. Gonzalez[6], A. Hees[1], Ch. Le Poncin-Lafitte[1], F. Meynadier[1], R. Prieto-Cerdeira[6], B. Sohet[1], J. Ventura-Traveset[7], and P. Wolf[1]

[1] *SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire 75014 Paris France*

[2] *Departamento de Astronomia y Astrofisica - Valencia University*

[3] *European Space Operations Center, ESA/ESOC, Darmstadt Germany*

[4] *UMR Geoazur, Université de Nice, Observatoire de la Côte d'Azur, 250 rue A. Einstein, F-06560 Valbonne, France*

[5] *Astronomical Institute, University of Bern, Sidlerstrasse 5 CH-3012 Bern, Switzerland*

[6] *European Space and Technology Centre, ESA/ESTEC, Noordwijk, The Netherlands and*

[7] *European Space and Astronomy Center, ESA/ESAC, Villanueva de la Cañada, Spain*

Journées 2019 – Astrometry, Earth Rotation and Reference Systems

Paris, France, October 07–09, 2019

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.

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.

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)

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)
- Test of LPI searching for variations in the constants of Nature
  - linear temporal drift (Rosenband et al. 2008; Guéna et al. 2012; Leefer et al. 2013; Godun et al. 2014; Huntemann et al. 2014)
  - harmonic temporal variation (Van Tilburg et al. 2015; Hees et al. 2016)
  - spatial variation w.r.t. the Sun gravitational potential (Ashby et al. 2007; Guéna et al. 2012; Leefer et al. 2013; Peil et al. 2013)
  - Transients (Derevianko and Pospelov 2014; Wcisło, Morzyński, et al. 2016; Roberts et al. 2017; Wcisło, Ablewski, et al. 2018)

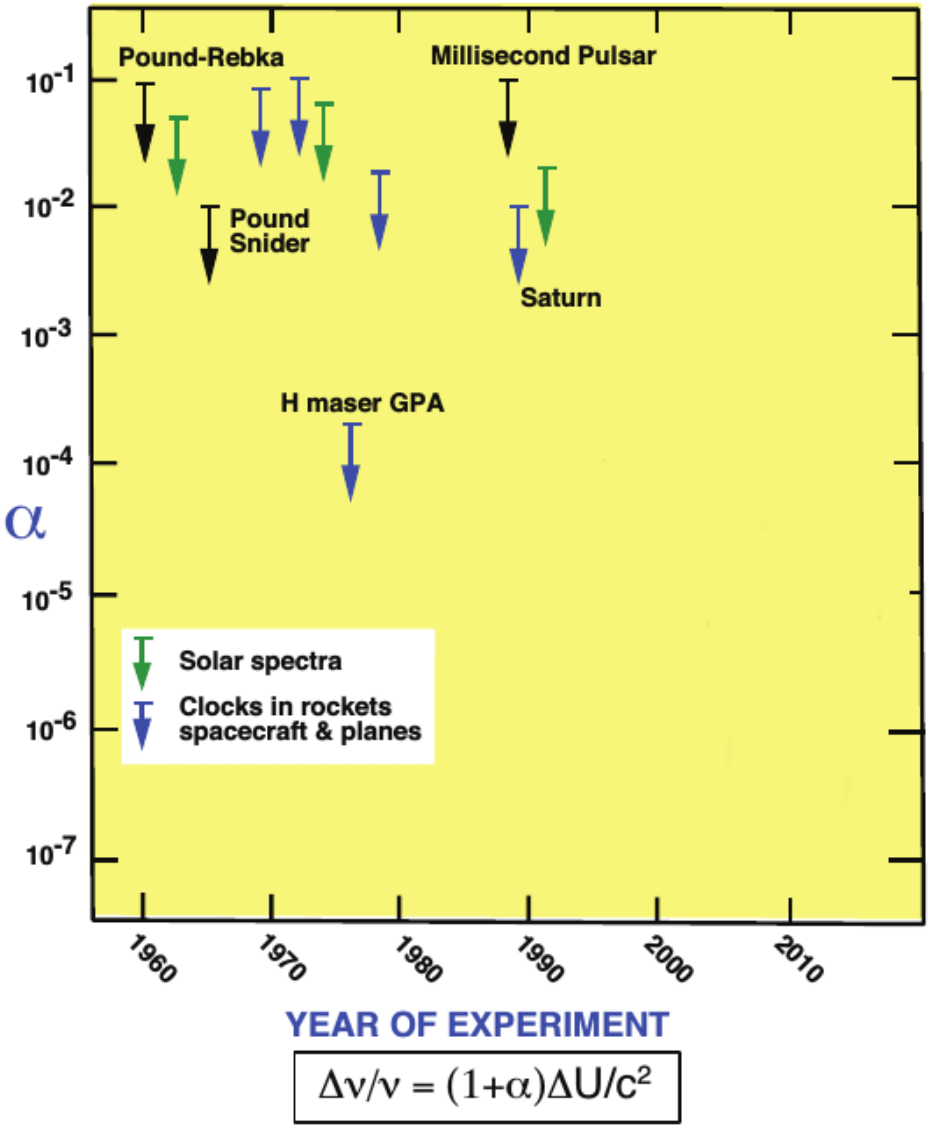
Tests of the EEP with atomic clocks

- 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)
- Test of LPI searching for variations in the constants of Nature
  - linear temporal drift (Rosenband et al. 2008; Guéna et al. 2012; Leefer et al. 2013; Godun et al. 2014; Huntemann et al. 2014)
  - harmonic temporal variation (Van Tilburg et al. 2015; Hees et al. 2016)
  - spatial variation w.r.t. the Sun gravitational potential (Ashby et al. 2007; Guéna et al. 2012; Leefer et al. 2013; Peil et al. 2013)
  - Transients (Derevianko and Pospelov 2014; Wcisło, Morzyński, et al. 2016; Roberts et al. 2017; Wcisło, Ablewski, et al. 2018)
- Test of LPI with a clock redshift experiment (Vessot 1989)

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)
- Test of LPI searching for variations in the constants of Nature
  - linear temporal drift (Rosenband et al. 2008; Guéna et al. 2012; Leefer et al. 2013; Godun et al. 2014; Huntemann et al. 2014)
  - harmonic temporal variation (Van Tilburg et al. 2015; Hees et al. 2016)
  - spatial variation w.r.t. the Sun gravitational potential (Ashby et al. 2007; Guéna et al. 2012; Leefer et al. 2013; Peil et al. 2013)
  - Transients (Derevianko and Pospelov 2014; Wcisło, Morzyński, et al. 2016; Roberts et al. 2017; Wcisło, Ablewski, et al. 2018)
- Test of LPI with a clock redshift experiment (Vessot 1989)

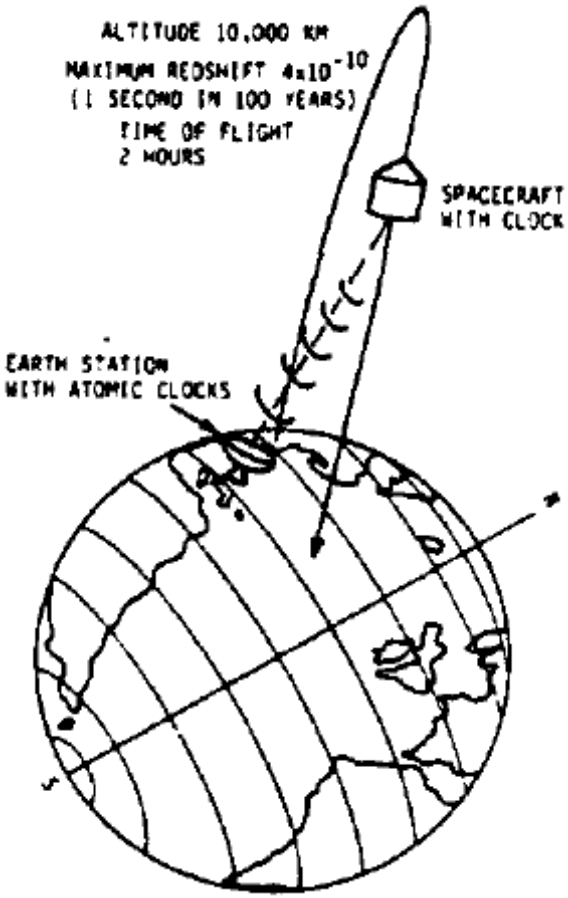
Tests of Local Position Invariance: GP-A



(Will 2014)

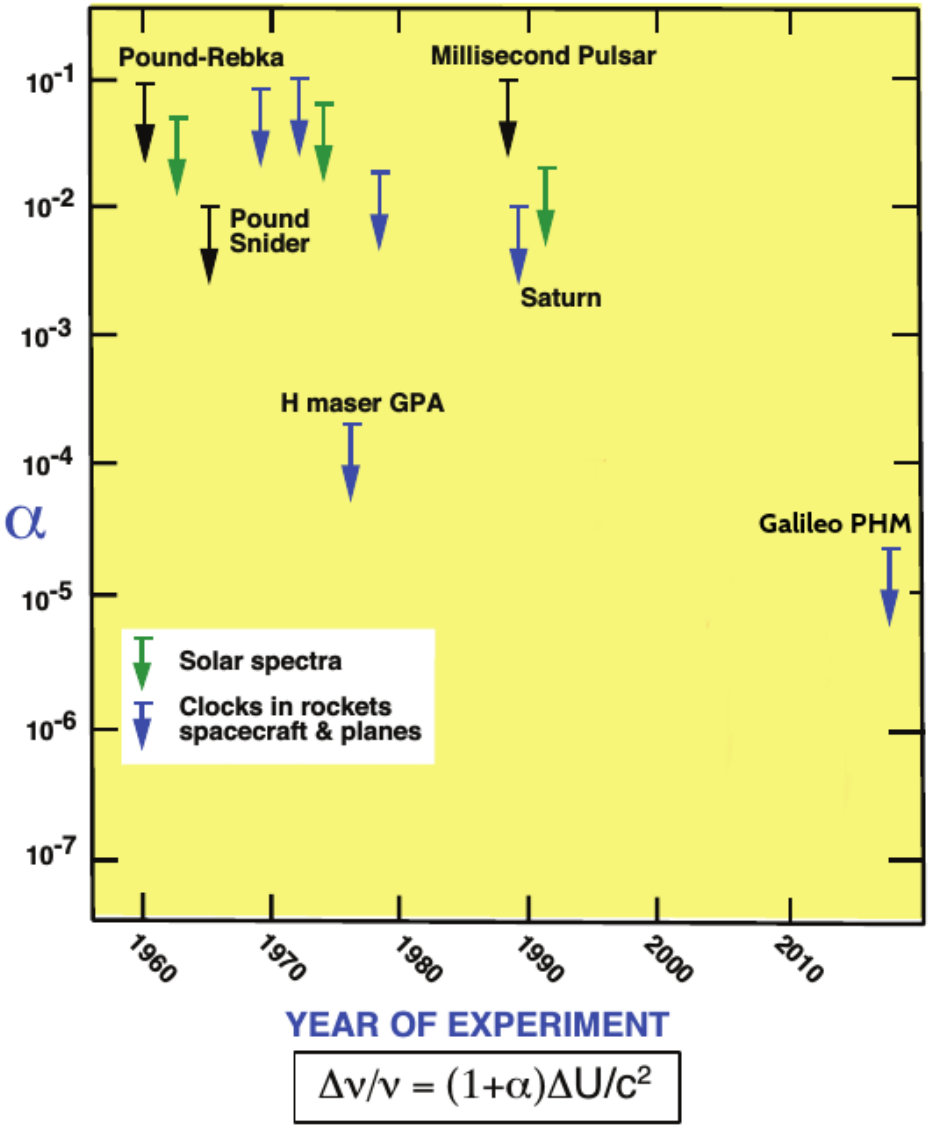
- H-Maser Gravity Probe A (1976)

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}

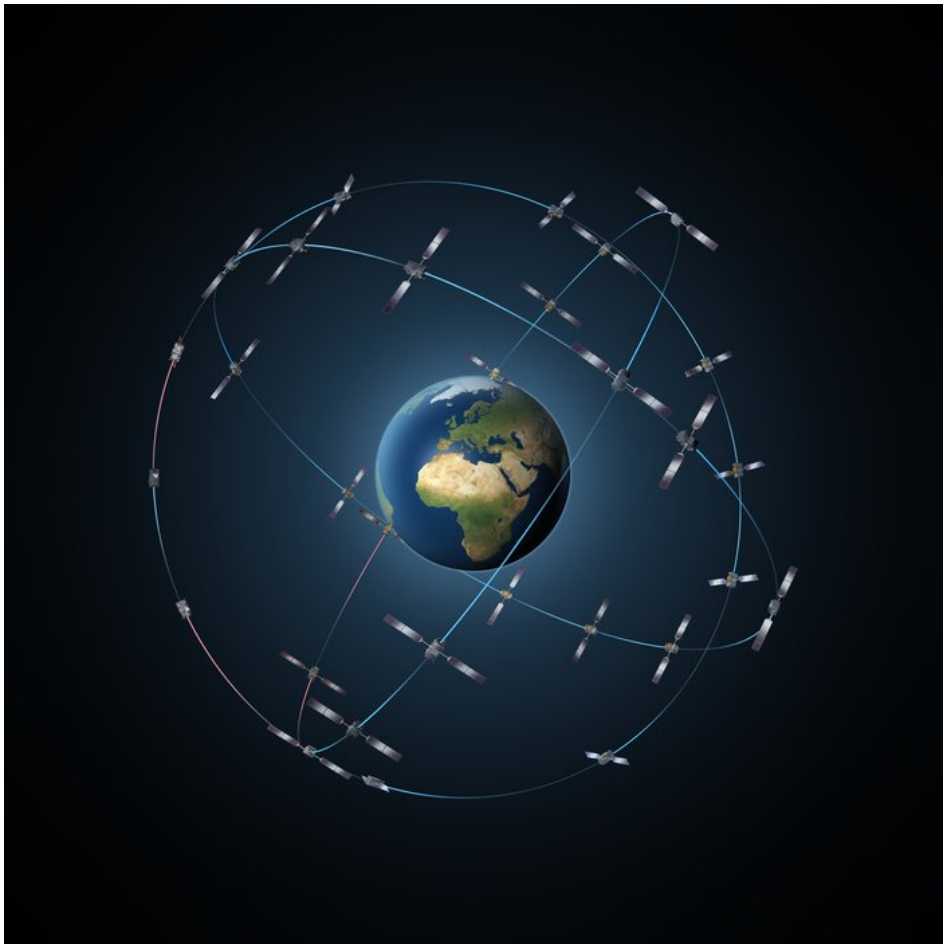
Tests of Local Position Invariance: Galileo



(Will 2014)

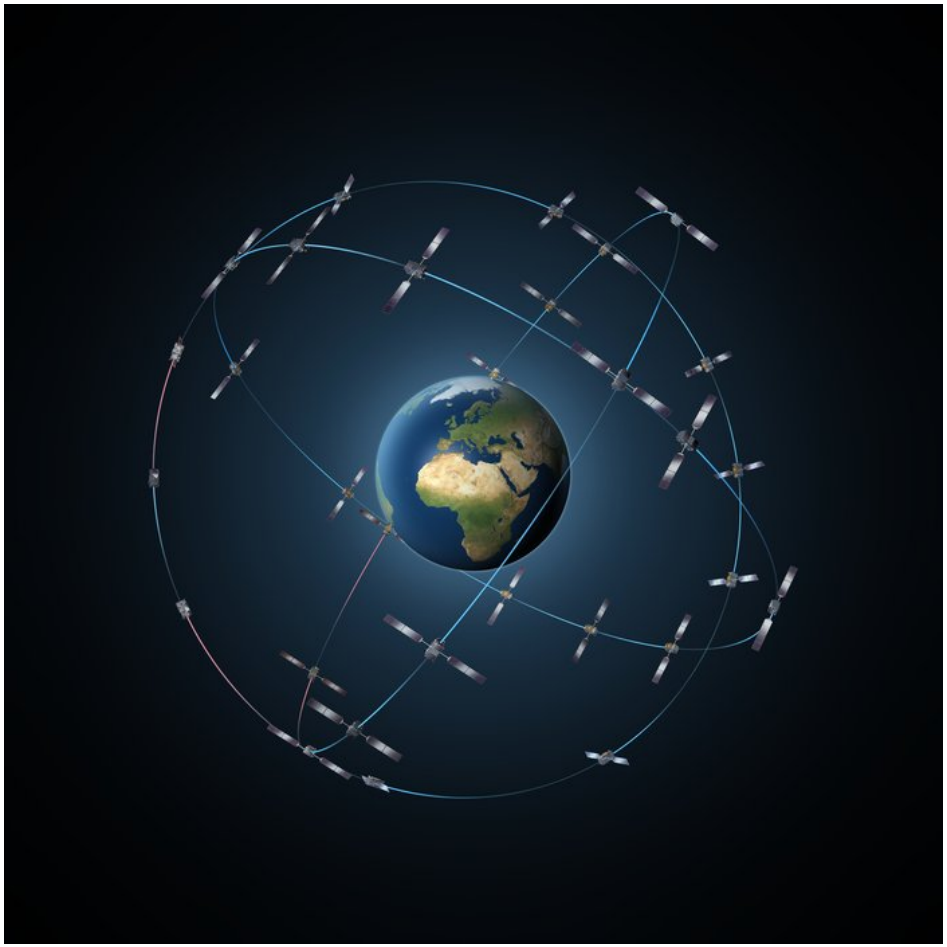
- H-Maser Gravity Probe A (1976)
- New test: Galileo eccentric satellites (Delva, Puchades, et al. 2018; Herrmann et al. 2018)

The Galileo system



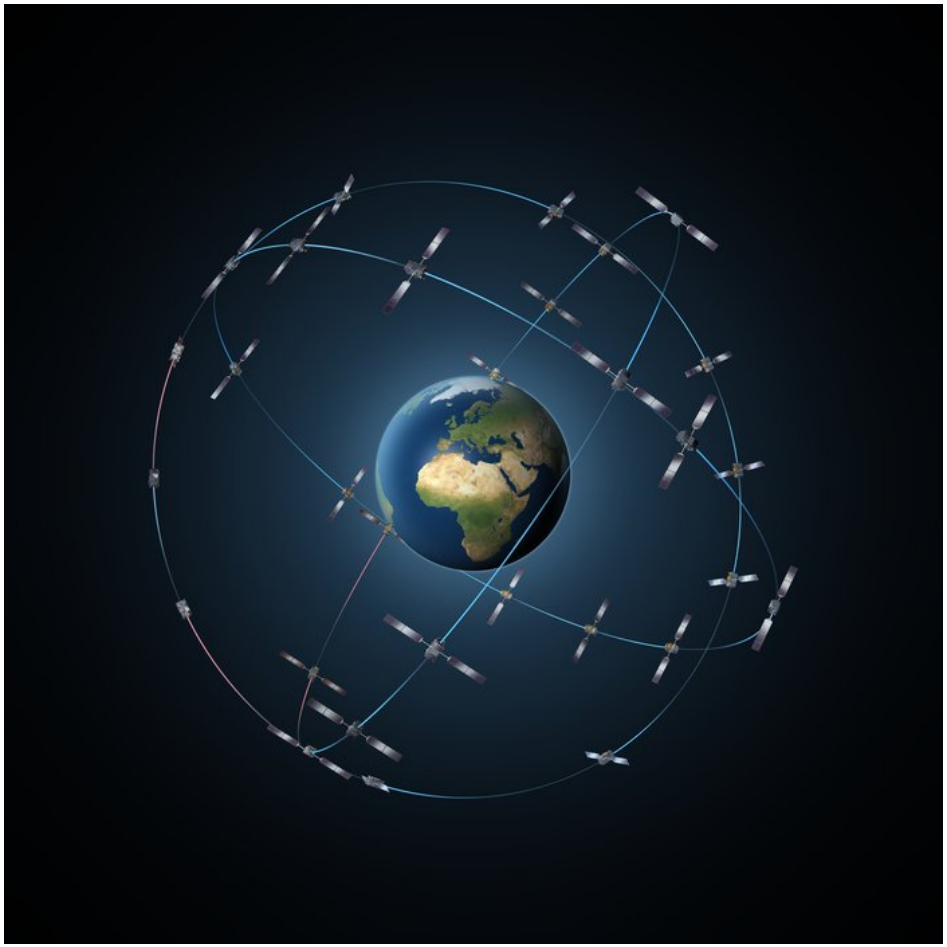
- European Global Navigation Satellite System (GNSS) (22.2×10^9 euros in 20 years)
- 24 satellites + 6 spares in medium Earth orbit on three orbital planes;

The Galileo system



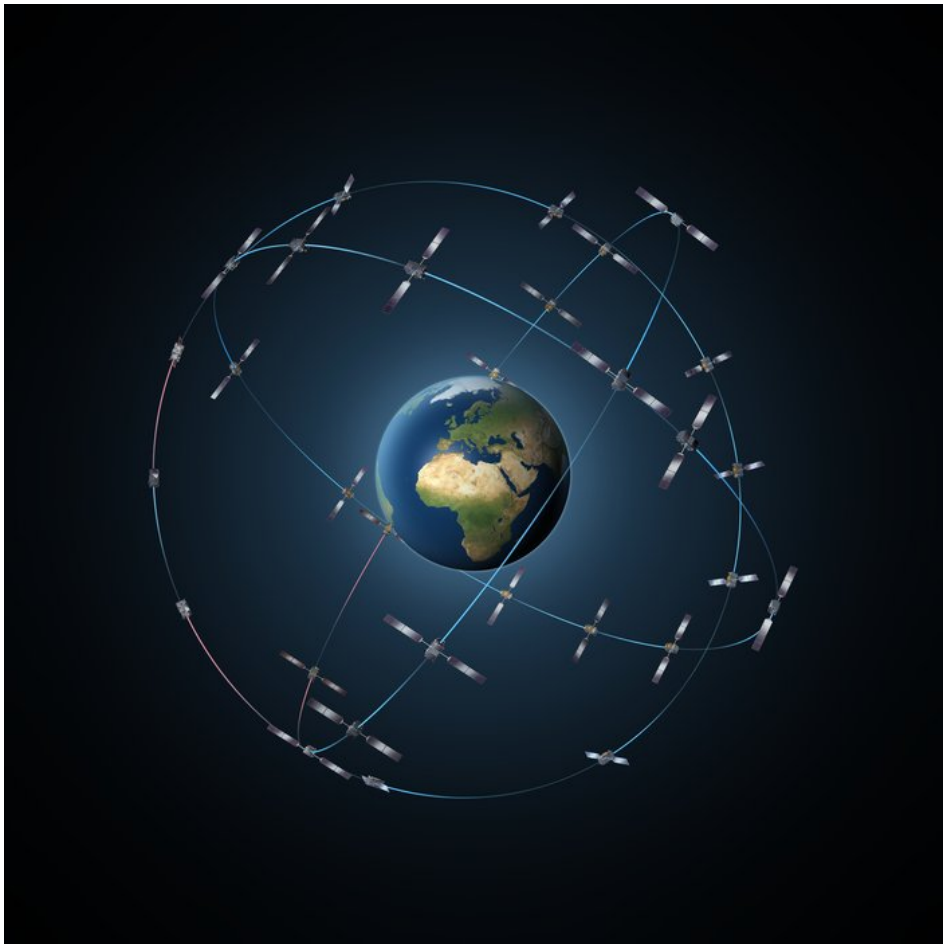
- European Global Navigation Satellite System (GNSS) (22.2×10^9 euros in 20 years)
- 24 satellites + 6 spares in medium Earth orbit on three orbital planes;
- A global network of sensor stations receiving information from the Galileo satellites;

The Galileo system



- European Global Navigation Satellite System (GNSS) (22.2×10^9 euros in 20 years)
- 24 satellites + 6 spares in medium Earth orbit on three orbital planes;
- A global network of sensor stations receiving information from the Galileo satellites;
- The control centres computing information and synchronising the time signal of the satellites;

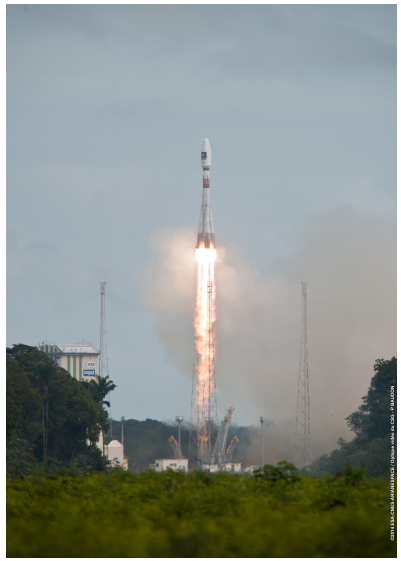
The Galileo system



- European Global Navigation Satellite System (GNSS) (22.2×10^9 euros in 20 years)
- 24 satellites + 6 spares in medium Earth orbit on three orbital planes;
- A global network of sensor stations receiving information from the Galileo satellites;
- The control centres computing information and synchronising the time signal of the satellites;

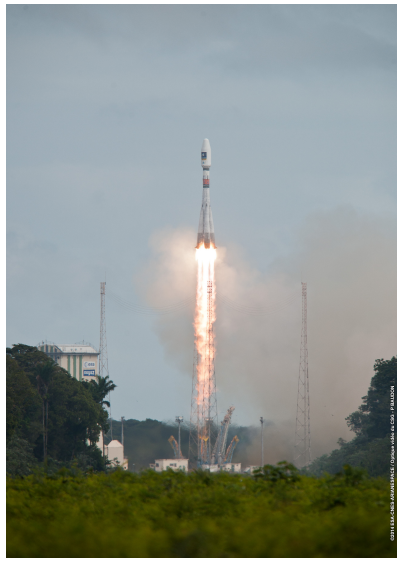
The story of Galileo satellites 201 & 202

- Galileo satellites 201 & 202 were launched with a Soyuz rocket on 22 august 2014 on the wrong orbit
- Launch failure was due to a temporary interruption of the propellant supply to the thrusters, resulting on a wrong orientation of the satellites during the last stage of orbit injection

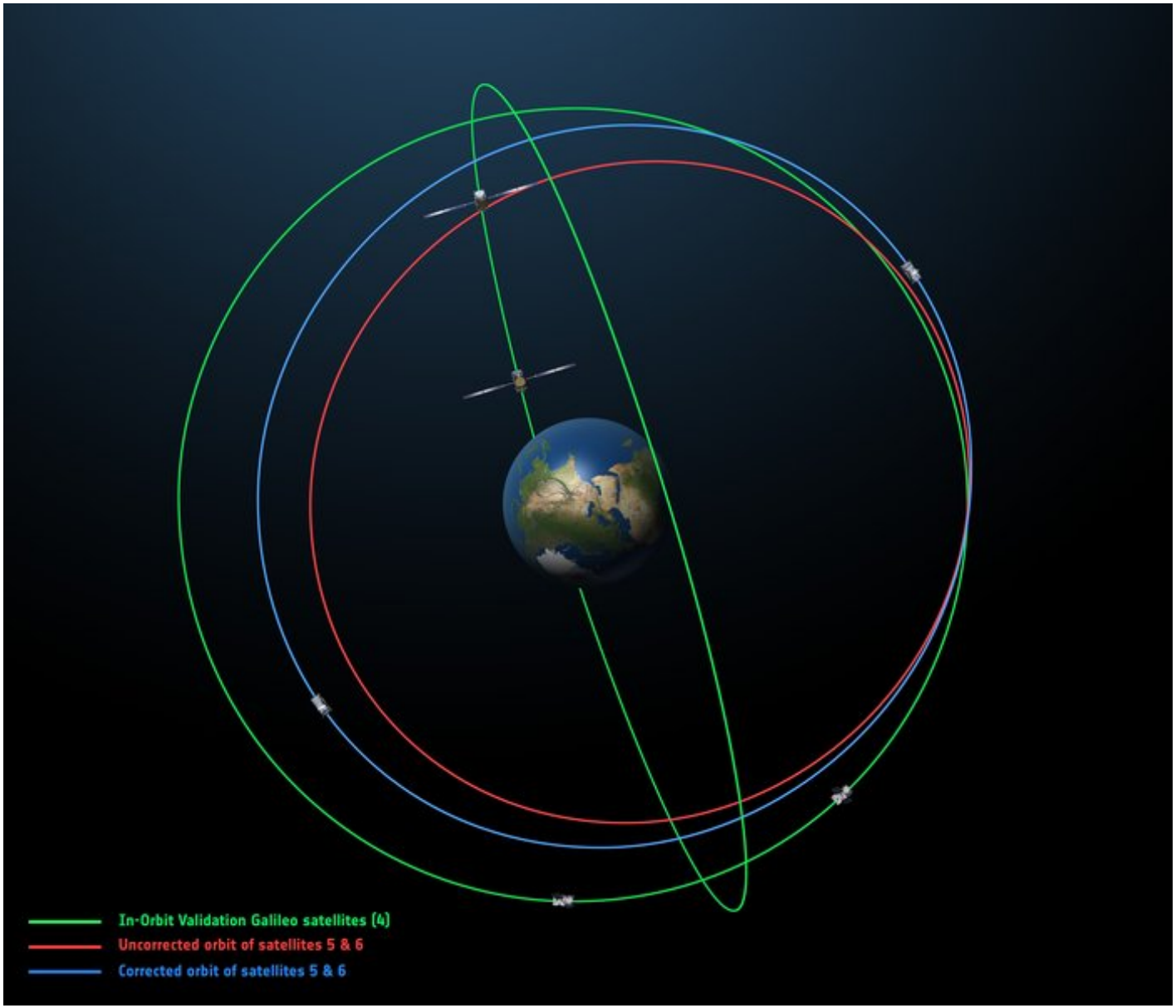


The story of Galileo satellites 201 & 202

- Galileo satellites 201 & 202 were launched with a Soyuz rocket on 22 august 2014 on the wrong orbit
- Launch failure was due to a temporary interruption of the propellant supply to the thrusters, resulting on a wrong orientation of the satellites during the last stage of orbit injection



Galileo satellites 201&202 orbit

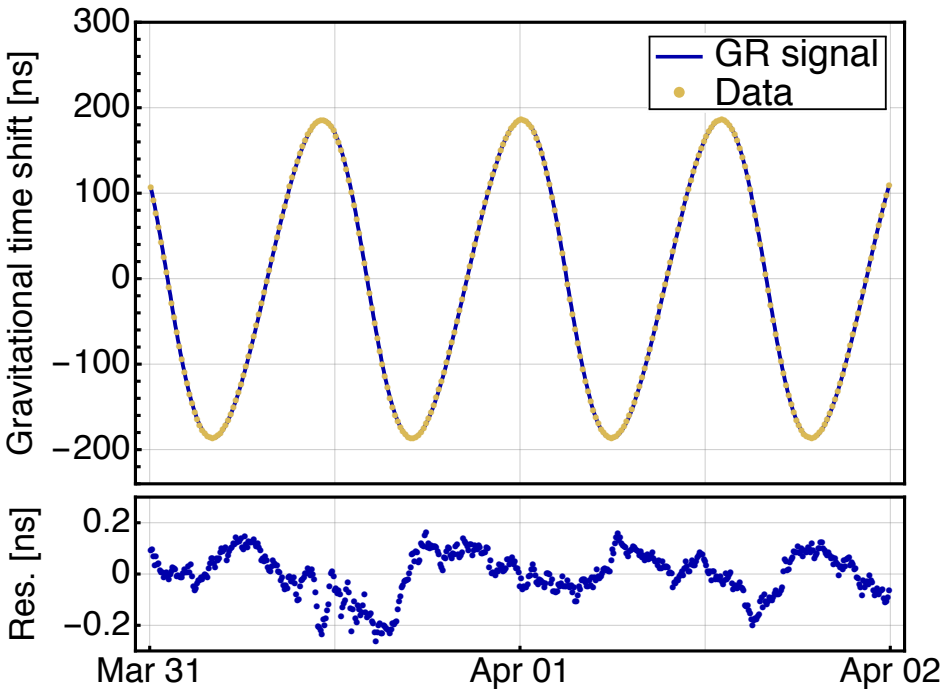


Galileo sats 201&202 launched in 08/22/2014 on the wrong orbit due to a technical problem $\Rightarrow$ GRedshift test (GREAT Study)

Why Galileo 201 & 202 are perfect candidates?

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

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

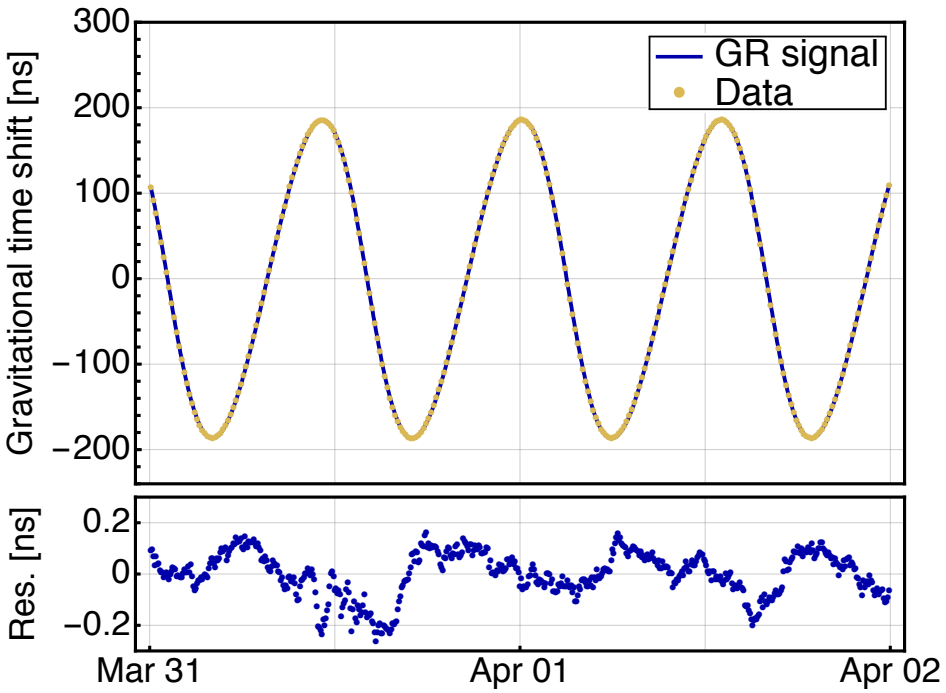


- Very good stability of the on-board atomic clocks → test of the variation of the redshift
- Satellite life-time → accumulate the relativistic effect on the long term
- Visibility → the satellite are permanently monitored by several ground receivers

Why Galileo 201 & 202 are perfect candidates?

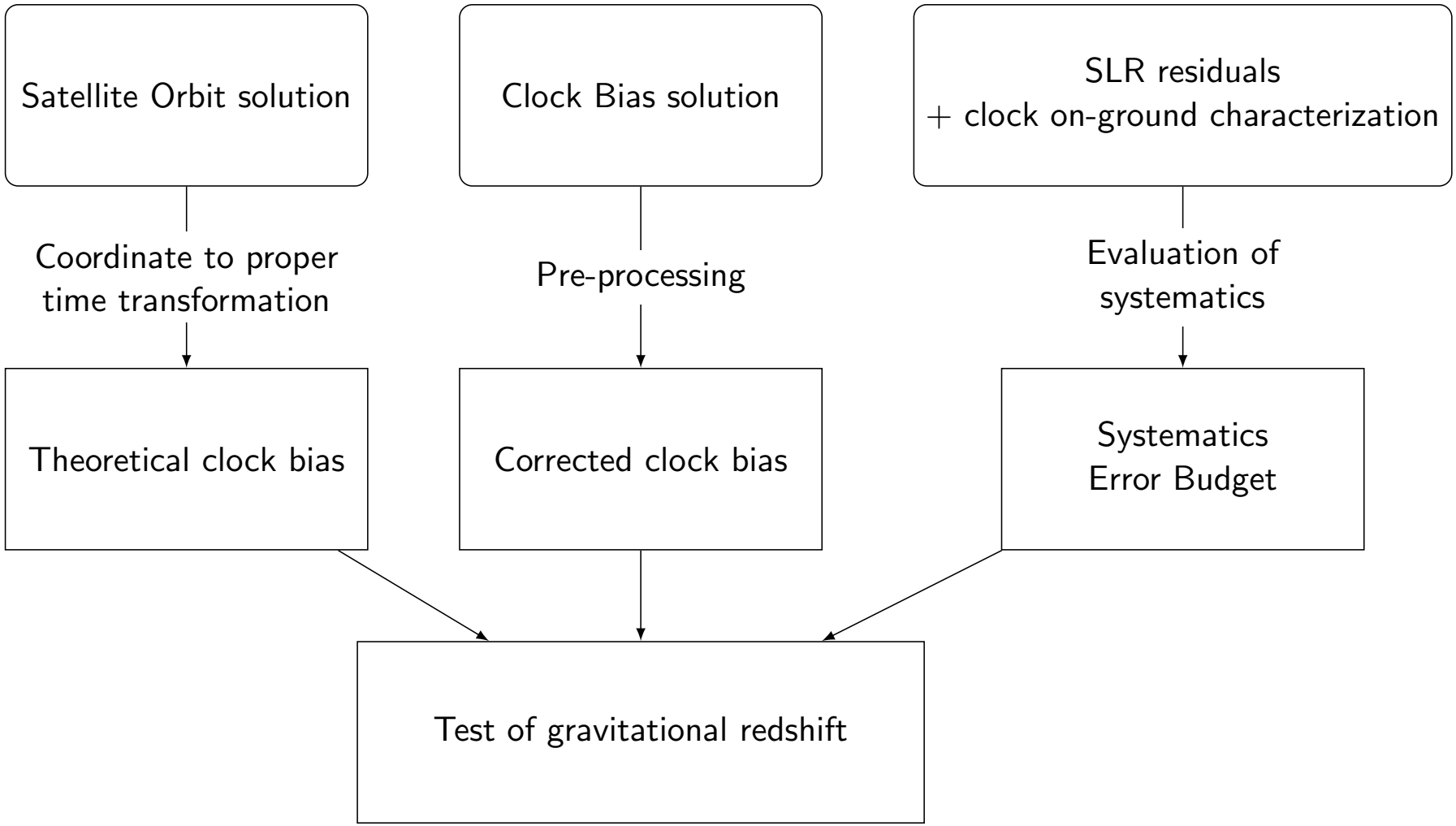
- An elliptic orbit induces a periodic modulation of the clock proper time at orbital frequency

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



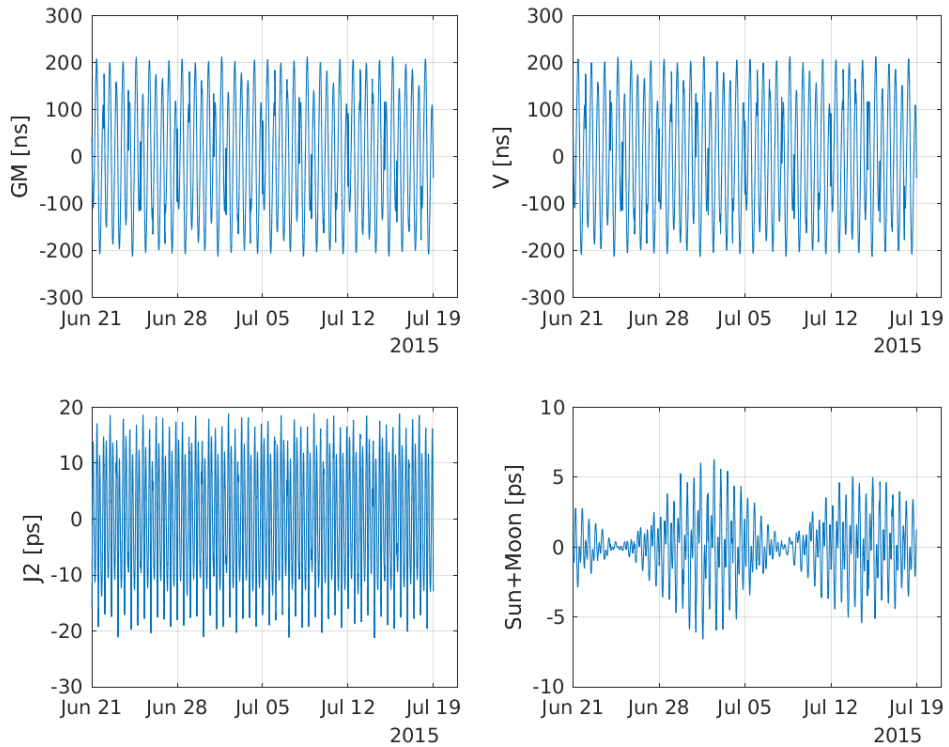
- Very good stability of the on-board atomic clocks → test of the variation of the redshift
- Satellite life-time → accumulate the relativistic effect on the long term
- Visibility → the satellite are permanently monitored by several ground receivers

Data analysis flowchart



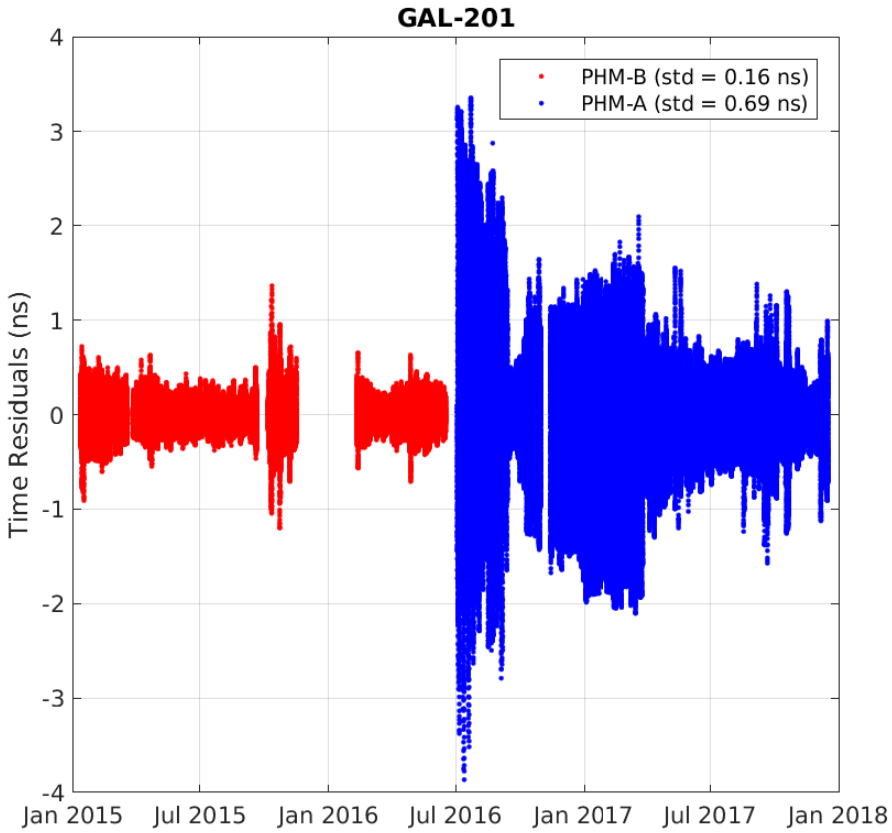
- Orbit and clock solutions: ESA/ESOC
- Transformation of orbits into GCRS with SOFA routines
- Theoretical relativistic shift and LPI violation

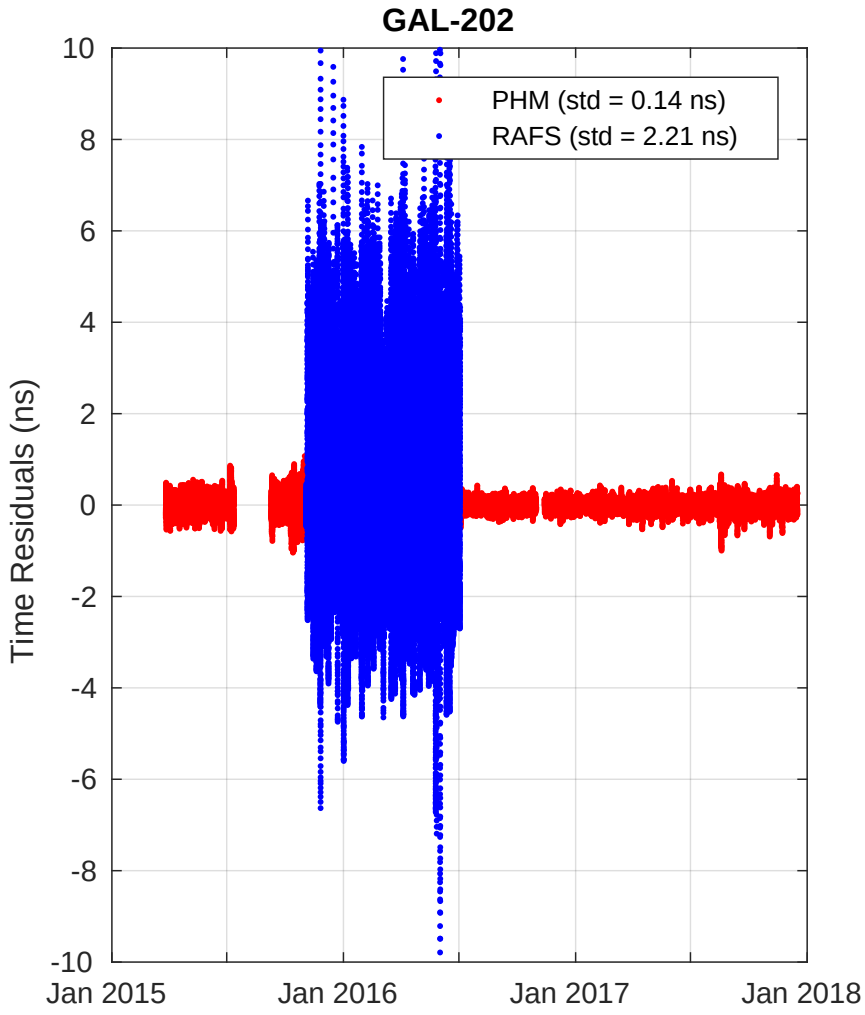
$$x_{\mathrm{redshift}} = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_E + U_T}{c^2}\right] dt \; ; \; x_{\mathrm{LPI}} = -\alpha \int \frac{U_E + U_T}{c^2} dt$$



Peak-to-peak effect ~ 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) $\rightarrow$ 359 days of data
- GAL-202: only PHM (RAFS is removed) $\rightarrow$ 649 days of data

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)
   - We assume nominal sensitivity (upper limit)

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)
   - We assume nominal sensitivity (upper limit)
3. Orbit modelling errors (e.g. mismodeling of Solar Radiation Pressure) are strongly correlated to the clock solution

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)
   - We assume nominal sensitivity (upper limit)
3. Orbit modelling errors (e.g. mismodeling of Solar Radiation Pressure) are strongly correlated to the clock solution
   - 1 year SLR Campaign thanks to International Laser Ranging Service

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)
   - We assume nominal sensitivity (upper limit)
3. Orbit modelling errors (e.g. mismodeling of Solar Radiation Pressure) are strongly correlated to the clock solution
   - 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

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)
   - We assume nominal sensitivity (upper limit)
3. Orbit modelling errors (e.g. mismodeling of Solar Radiation Pressure) are strongly correlated to the clock solution
   - 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

We model systematic effects and fit for each the corresponding LPI violation parameters $\rightarrow$ conservative approach

Random and systematic errors

1. Uncertainties of the fitted parameters are estimated with Monte-Carlo method (noise is dominated by random walk)
2. Systematic effects acting directly on the frequency of the space clock: temperature and magnetic field variations on board the Galileo satellites
   - Environmental sensitivity of the PHMs has been characterized on the ground (see e.g. Rochat et al. 2012)
   - We assume nominal sensitivity (upper limit)
3. Orbit modelling errors (e.g. mismodeling of Solar Radiation Pressure) are strongly correlated to the clock solution
   - 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

We model systematic effects and fit for each the corresponding LPI violation parameters $\rightarrow$ 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

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
- PRL cover: Delva et al. PRL 121.23 (2018) and Herrmann et al., PRL 121.23 (2018)

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
- PRL cover: Delva et al. PRL 121.23 (2018) and Herrmann et al., PRL 121.23 (2018)
- Nice outreach video by Derek Muller on Veritasium (youtube channel)

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
- PRL cover: Delva et al. PRL 121.23 (2018) and Herrmann et al., PRL 121.23 (2018)
- Nice outreach video by Derek Muller on Veritasium (youtube channel)