General Relativity Experiment with eccentric Galileo satellites

(WG-B Session, 4 Dec 2017)

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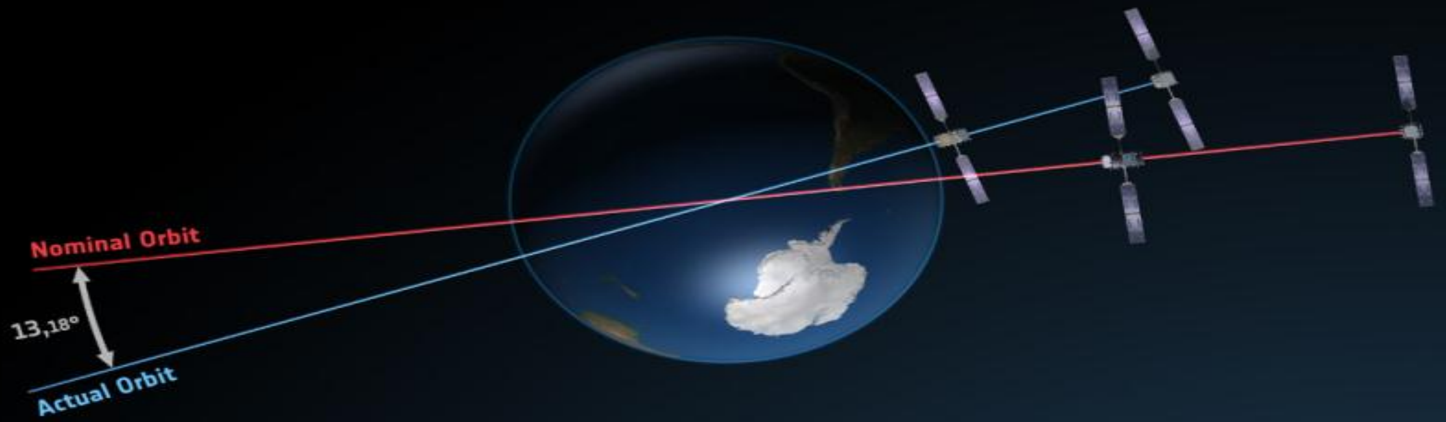
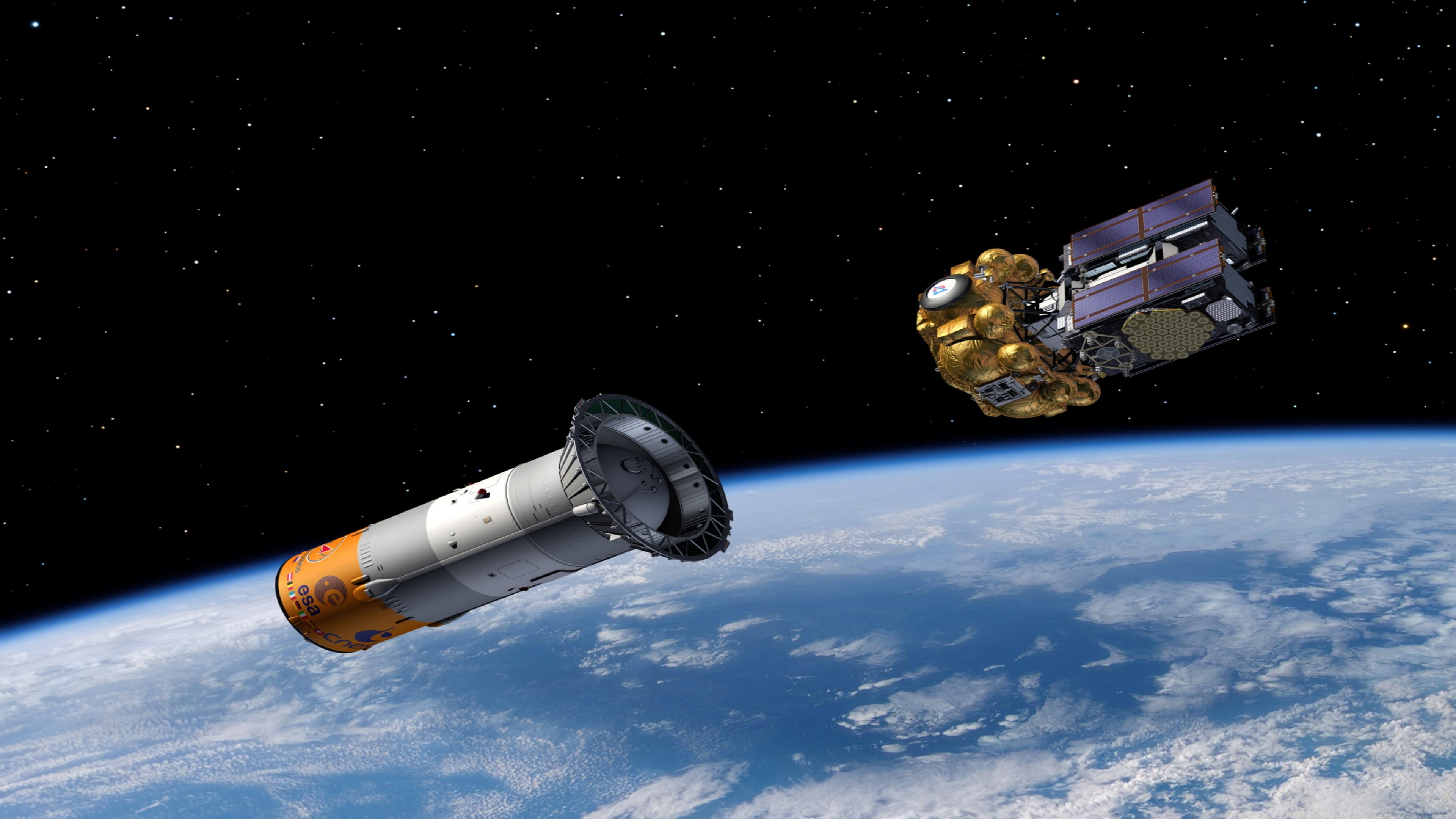
Galileo Sat 5+6

- Galileo Sat 5 + 6 launch: August 22nd, 2014

Satellite IDs: GSAT-0201 = E18 = Sat 5
GSAT-0202 = E14 = Sat 6

Galileo L3 launch (VS09) had an Orbit injection anomaly which left Galileo Sat 5 /Sat 6 (GSAT0201/GSAT0202) satellites in a highly eccentric orbit.

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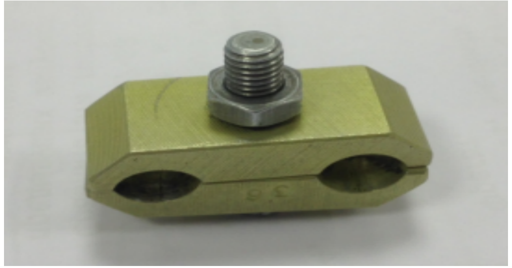
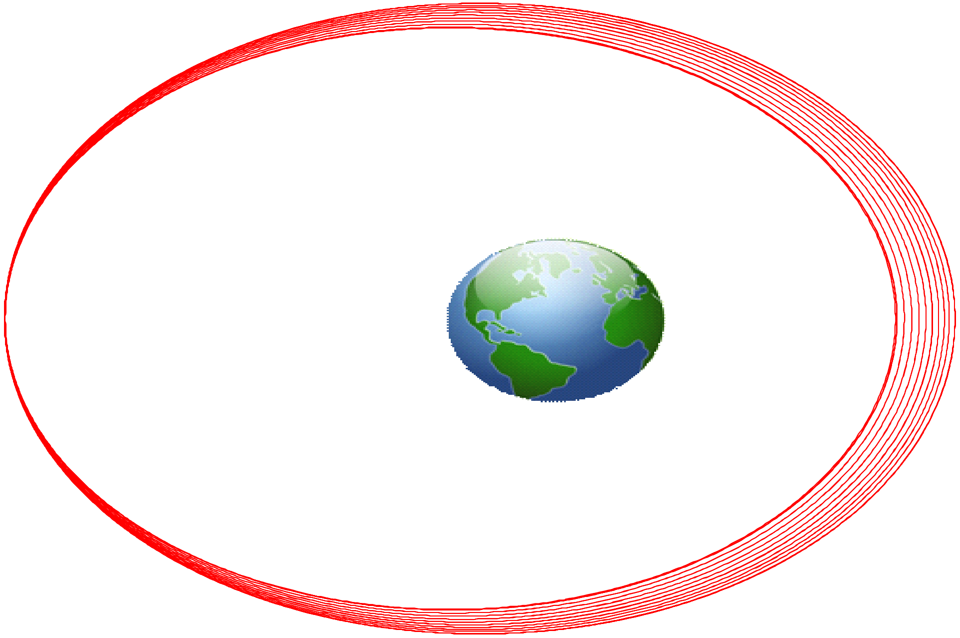
Anomalous injection FOC-M1 (L3 Launch)

- Anomalous orbit injection:
  - Basic root cause:
    - Hydrazine line assembled together with a cold helium line
    - Hydrazine feed line temporary freezing -> lost of control of yaw attitude -> 40deg misalignment at second Fregat burn

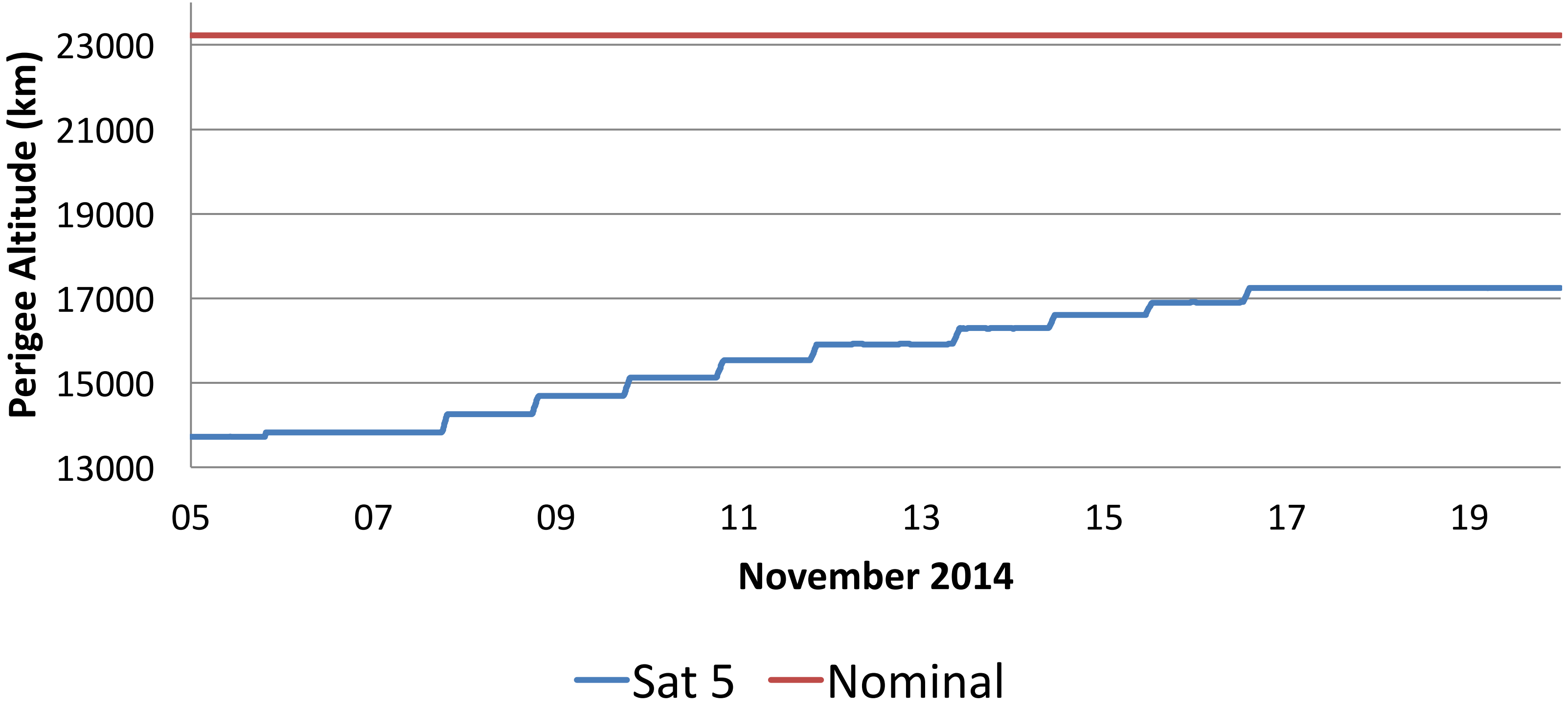


Assembly modified and three successful Soyuz/Fregat launches since August 2014

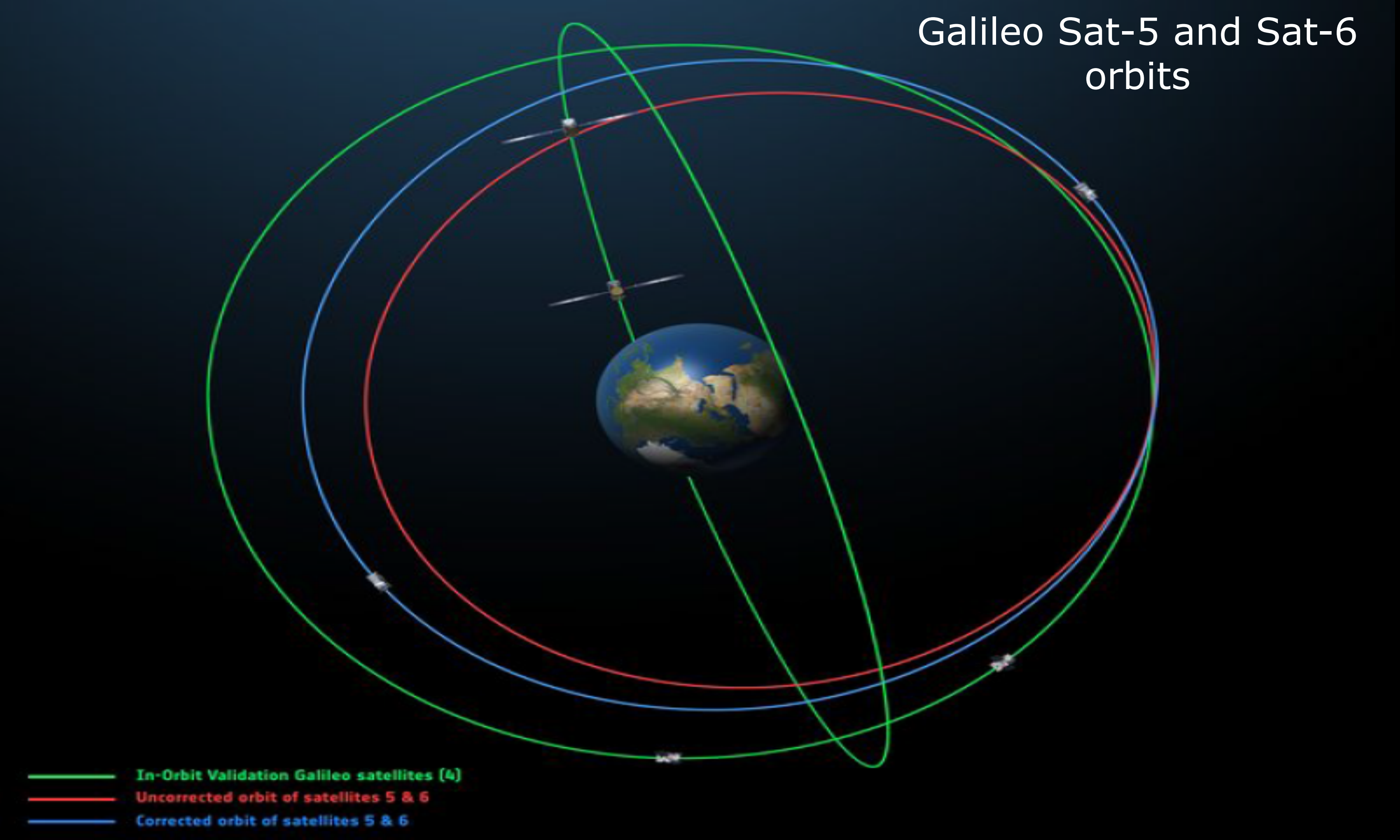
Sat 5 Orbit Evolution



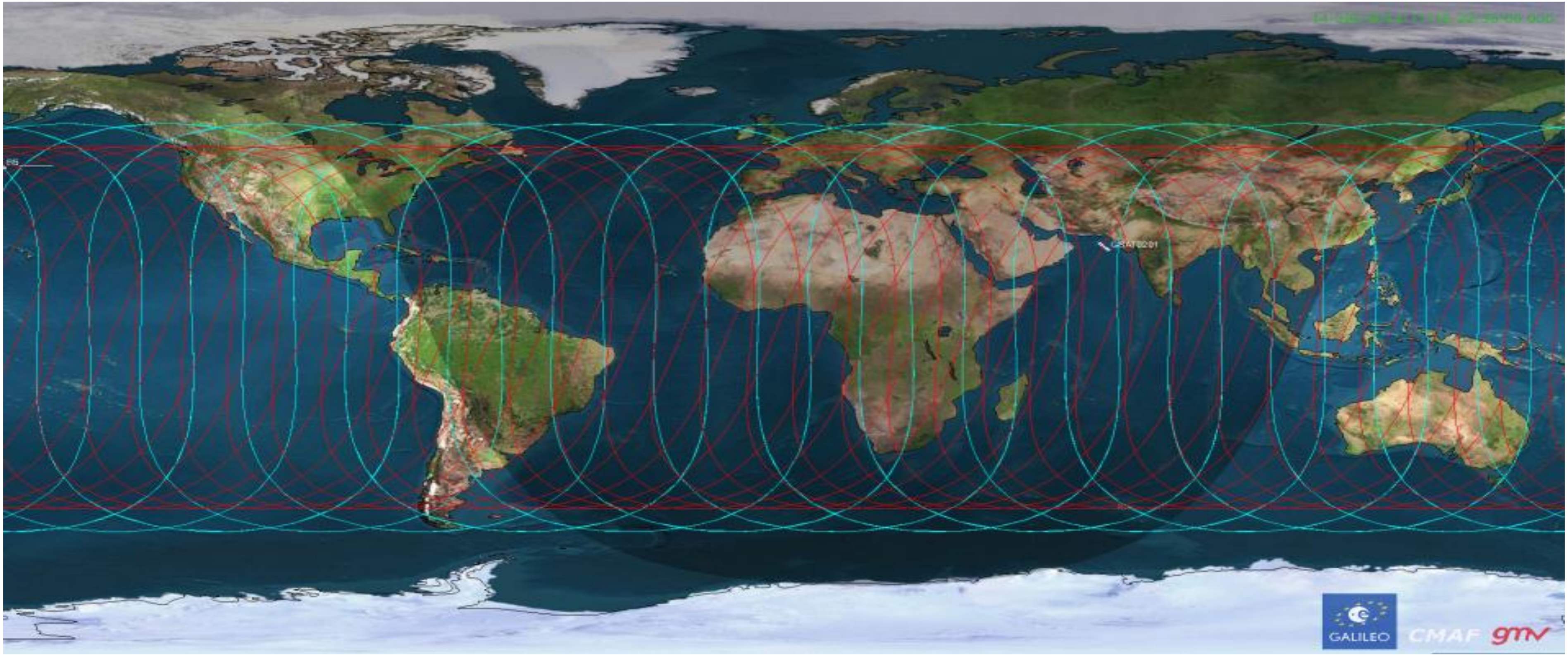
Sat 5 Perigee altitude evolution



Galileo Sat-5 and Sat-6 orbits



Resonant 37 rev / 20 days



Galileo Sat 5+6

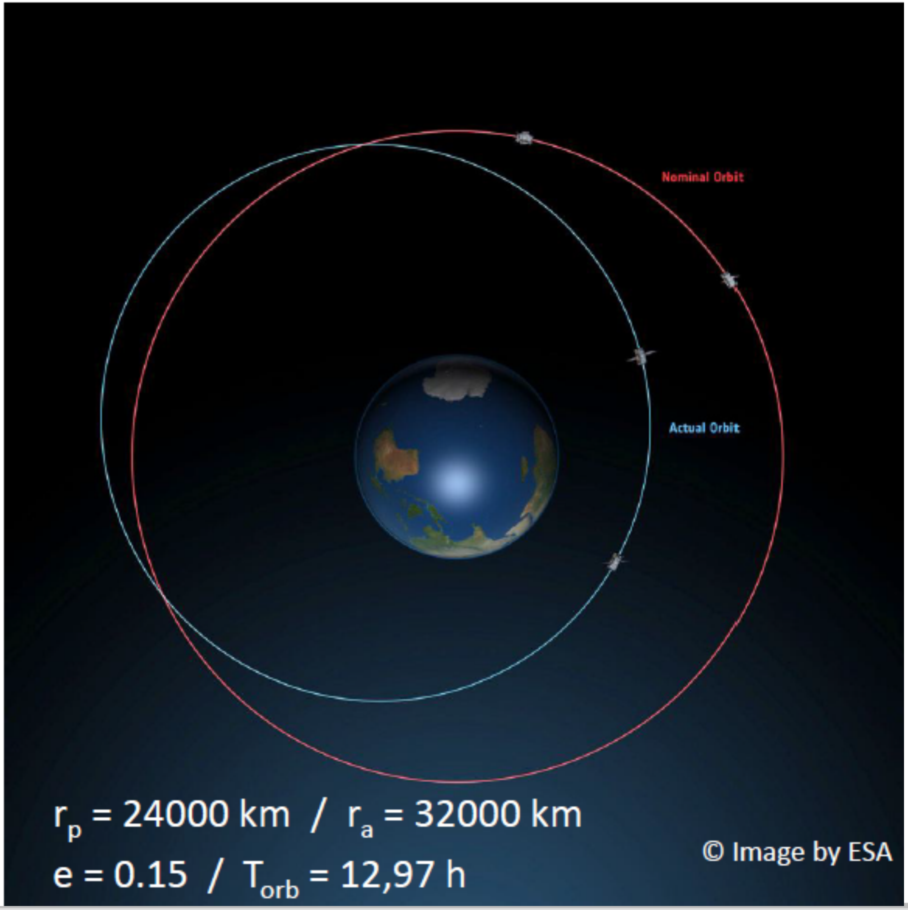
- Final orbit parameters after correction maneuvers:

	GSAT-5	GSAT-6
Semimajor axis a	27978 km	27978 km
Eccentricity ε	0.15601	0.15167
Inclination i	49.775°	49.874°
Height in apogaeum	25818 km	25818 km
Height in perigaeum	17382 km	17382 km
Orbital period	12,97 h	12,97 h

Galileo Sat 5+6

- 8000 km change in height, approx. twice per day
- Highly stable atomic clocks onboard
- Expected frequency shift:

$$\frac{\Delta\nu}{\nu} = 5\times10^{-11}$$



Galileo Sat-5 and Sat-6: A unique opportunity for General relativity scientific experimentation

Galileo Satellites 5 and Sat 6 are perfect candidates to test Gravitational Redshift:

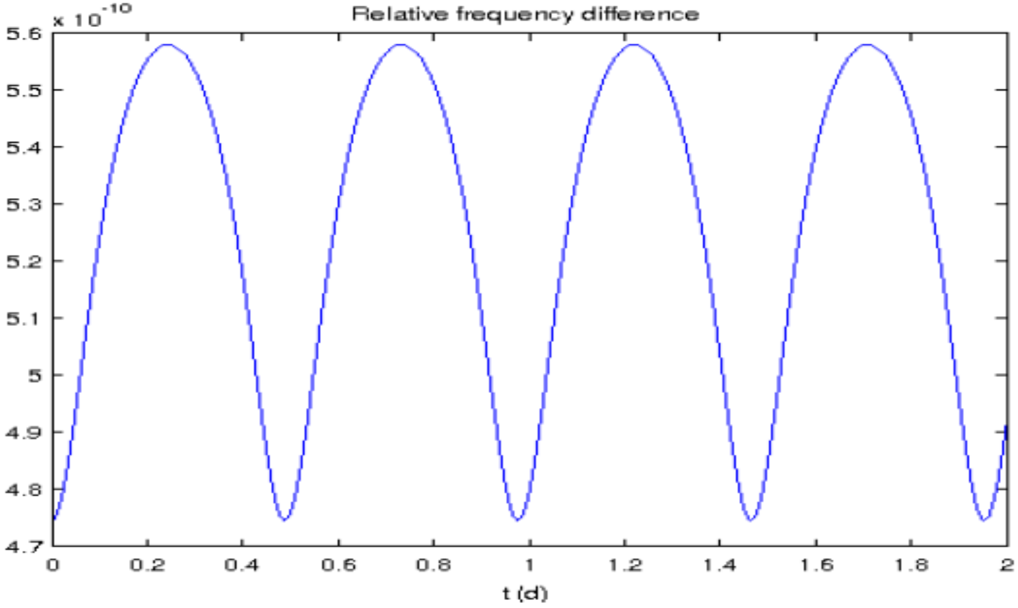
1. The elliptic orbits produce a regular modulation of the **gravitational redshift** (a way of testing Local Position Invariance (LPI), one of the 3 aspects of Einstein Equivalence Principle EEP).
2. On-board PHM clocks offer unique clock stability
3. Long satellite life-time with possibility to integrate measurements during a long time
4. Satellites are permanently monitored and include Laser tracking (SLR), which could allow to perform uncorrelated radial orbit estimations
5. No interference on potential nominal use of Satellites 5 and 6 for Navigation
6. Our estimation show that if systematics are duly modelled, the achievable accuracy of the gravitational redshift measurements could become “state of the art” (until this year, the best measurements was based on GP-A experiment performed in 1976)

Periodic variation of the gravitational redshift Galileo Sat-5 and Sat-6

$$y = \frac{GM}{c^2}\left(\frac{1}{r_g} - \frac{1}{r_s}\right)$$

$$\tilde{y}(\alpha) = -(1+\alpha)\frac{GM}{c^2 r_s}$$

$$\frac{\Delta\nu}{\nu} = \alpha\frac{\Delta U}{c^2}$$



ESA GNSS Relativity Test Activities launched

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Two parallel contracts were launched (Oct 2015) by ESA with SYRTE/Observatoire de Paris and ZARM/University of Bremen to perform these tests in detail. **GREAT: Galileo gravitational Redshift test with Eccentric sATellites.**

Results, after 2 years of work were presented at the 6th International Colloquium on Scientific and Fundamental aspects of GNSS/Galileo

The success of these tests opens a major area of Fundamental Physics research using Galileo satellites and GNSS technology

ZARM

l'Observatoire de Paris SYRTE

Systèmes de Référence Temps-Espace

The mission Gravity Probe A

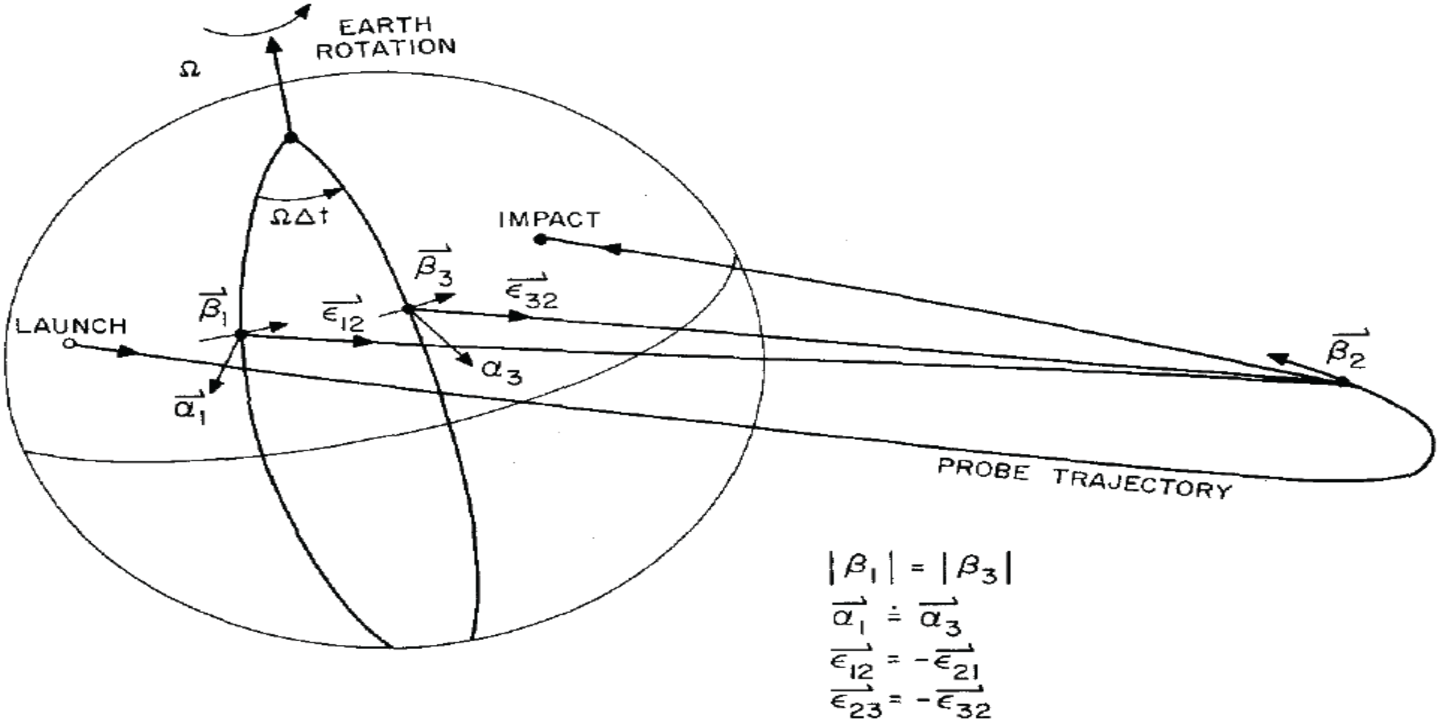
- precise measurement of gravitational redshift: $|\alpha - 1| \leq 10^{-4}$

$$\frac{\Delta\nu}{\nu} = \alpha \frac{\Delta U}{c^2}$$

- precise test of Doppler effect

GP A H-maser

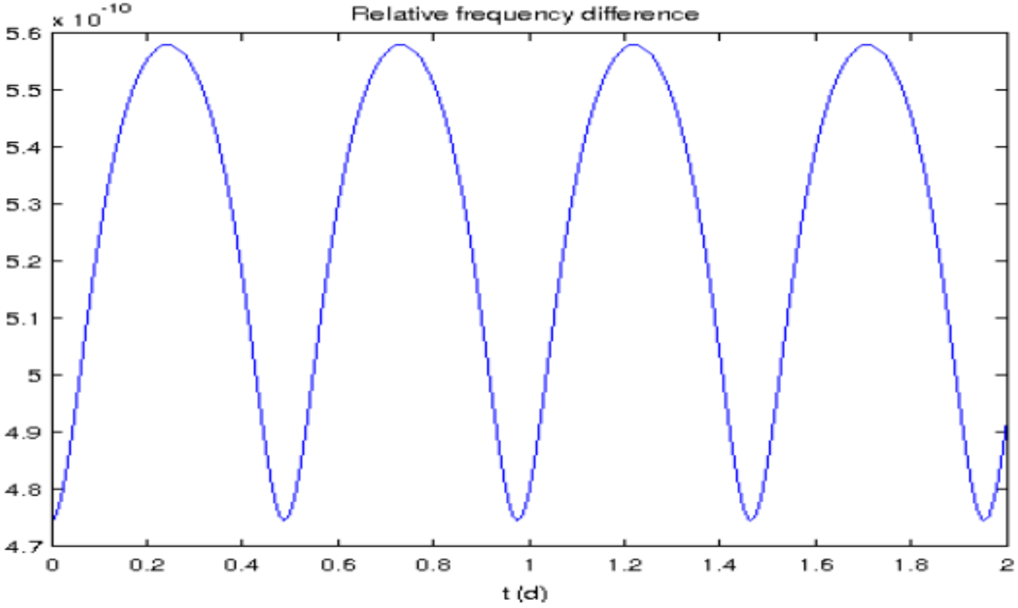
The mission Gravity Probe A



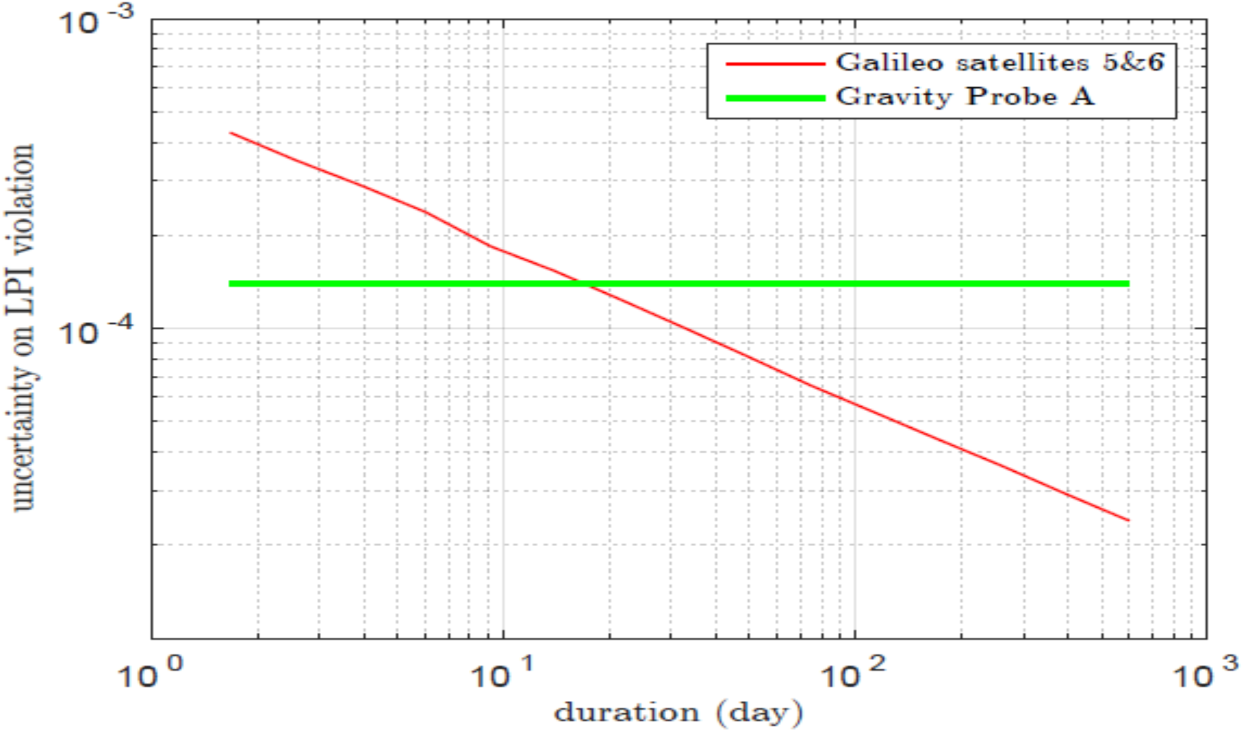
Gravity Probe-A limit of the gravitational redshift was established in a value of **1.4×10^{-4}**

Periodic variation of the gravitational redshift Galileo Sat-5 and Sat-6

$$y = \frac{GM}{c^2}\left(\frac{1}{r_g} - \frac{1}{r_s}\right)$$

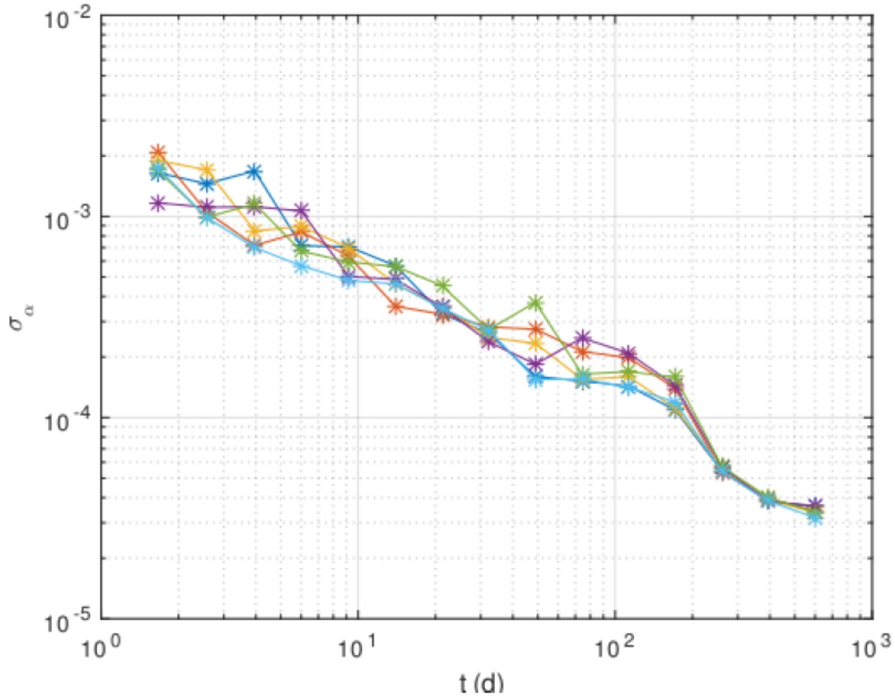


Statistical sensitivity of the gravitational redshift test with respect to the duration of the experiment



Note: assuming here all systematics effects can be duly modeled or decorrelated.

Statistical sensitivity of the gravitational redshift test with respect to the duration of the experiment (with realistic estimation of Systematics)

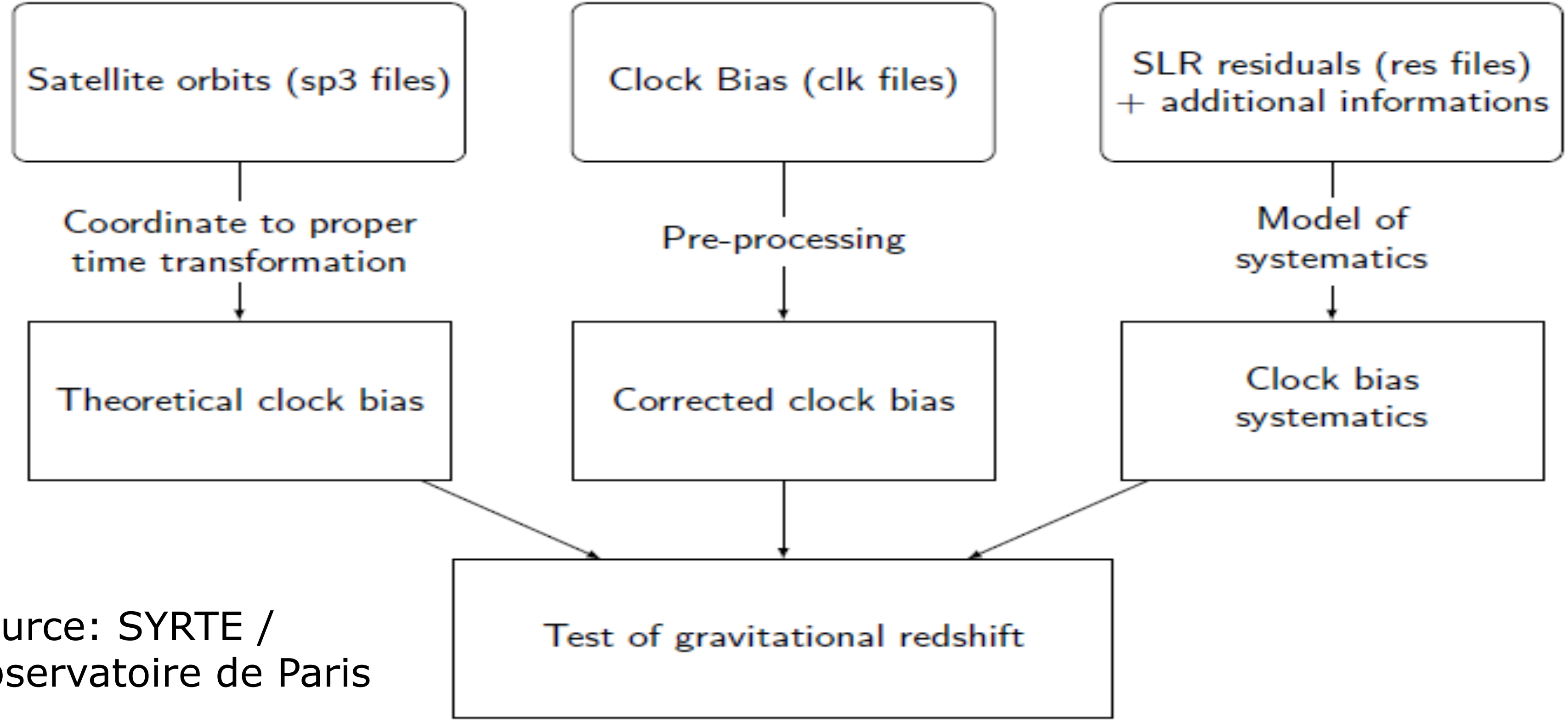


Systematic errors [Delva et al., 2015]

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

Source: P.Delva, SYRTE / Observatoire de Paris

DATA ANALYSIS FLOW CHART



Source: SYRTE / Observatoire de Paris

1 year laser campaign measurement with ILRS

A good control of systematic effects is essential in order to calculate robust limits on the parameters of the GR violation.

In this context, **a dedicated Satellite Laser Ranging measurements was performed for 1 year (June 2016 to May 2017).**

This has been essential to disentangle in a good extent systematic errors coming from the orbit and impacting the clock determination from other systematics.

We would like to express our very high appreciation to the ILRS from ESA


Scientific and Fundamental Aspects of GNSS / Galileo
6th International Colloquium
25 - 27 October 2017, Valencia
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Galileo and General Relativity: new results announced at ESA's GNSS/ Galileo Scientific Colloquium

General Relativity Gravitational redshift have been verified down to a value of 4.4 x 10-5 using eccentric Galileo satellites.

This means an improvement by a factor of 3 with respect to Gravity Probe A measurement and this has therefore become the most accurate measurement so far of the Einstein predicted General Relativity Gravitational Frequency shift so far.

Further improvements may be achieved by further refining the orbit systematics (e.g. exploiting FOC available Metadata)

Source: P.Delva, SYRTE / Observatoire de Paris

Outlook on further GR + GNSS physics

- Further GR effects with Galileo 5+6 to test or look for ?
  - Null-test of LPI (RFAS against PHM)
  - Relativistic perihelion advance (nrad, 10 cm per orbit)
  - Test of alternative gravity theories
  - Shapiro delay (ps level)
  - Gravitomagnetic clock effect (10^{-7} s per orbit)

Source: S. Hermann, ZARM / University of Bremen

Thank you for your attention !