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An SLR campaign on Galileo satellites 5 and 6 for a test of the gravitational redshift – the GREAT experiment

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Abstract. *We describe the scientific objectives of the GREAT project (Galileo gravitational Redshift Experiment with eccentric sATellites) which is funded by the European Space Agency (ESA). A specific campaign of SLR on Galileo 5&6 is ongoing with Geoazur/OCA, and a concerted ILRS campaign is proposed.*

1. Scientific objectives

The classical theory of General Relativity (GR) is the current paradigm to describe the gravitational interaction. Since its creation in 1915, GR has been confirmed by experimental observations. Although very successful so far, it is nowadays commonly admitted that GR is not the ultimate theory of gravitation. Attempts to develop a quantum theory of gravitation or to unify gravitation with the others fundamental interactions lead to deviations from GR.

GR is built upon the Einstein Equivalence Principle (EEP) which gives to gravitation a geometric nature. From a phenomenological point of view, three aspects of the EEP can be tested (Will 1993): (i) the Universality of Free Fall (UFF), (ii) the Local Lorentz Invariance (LLI) and (iii) the Local Position Invariance (LPI). The LPI can be tested by constraining space-time variations of the constants of Nature (see e.g. Rosenband et al. 2008; Guéna et al. 2012) or by redshift tests.

The most precise test of the gravitational redshift to date has been realized with the Vessot-Levine rocket experiment in 1976, also named the Gravity Probe A (GP-A) experiment (Vessot and Levine 1979; Vessot, Levine, et al. 1980; Vessot 1989). The frequency differences between a space-borne hydrogen maser clock and ground hydrogen masers were measured thanks to a continuous two-way microwave link. The gravitational redshift was verified to 1.4×10^{-4} accuracy (Vessot 1989). The

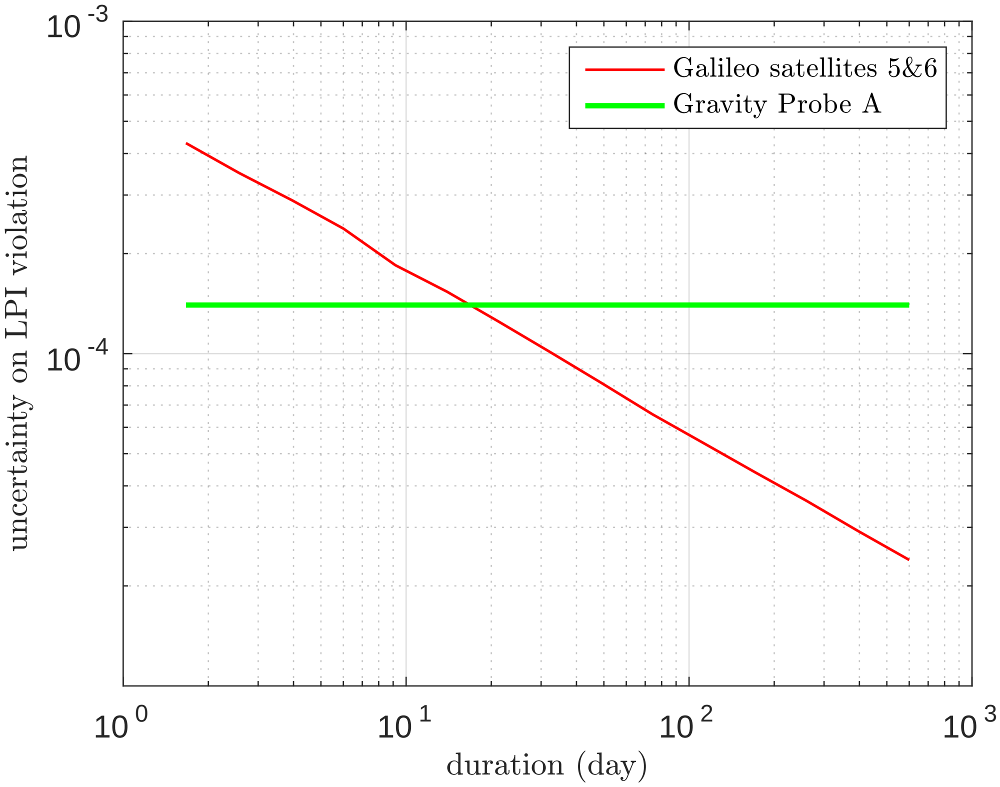

Figure 1. Expected statistical sensitivity of the gravitational redshift test with respect to the duration of the experiment when all systematics effects can be modeled or decorrelated. In green is the accuracy of the Gravity Probe A experiment for reference.

future Atomic Clock Ensemble in Space (ACES) experiment, an ESA/CNES mission, planned to fly on the ISS in 2017, will test the gravitational redshift to around $2-3\times10^{-6}$ accuracy (Cacciapuoti et al. 2009). Furthermore, other projects like STE-QUEST (Altschul et al. 2015) propose to test the gravitational redshift at the level of 10^{-7}, and observations with the RadioAstron telescope may reach an accuracy of the order of 10^{-5} (Litvinov et al. 2015). Finally, it has been previously suggested in (Svehla 2010) to use Galileo satellites for such a test.

Within the GREAT project (Galileo gravitational Redshift Experiment with eccentric sATellites), ESA is funding two parallel studies led by SYRTE/Paris Observatory and ZARM. The goal is to use the on-board atomic clocks of the Galileo satellites 5 and 6 (named Doresa and Milena, or Galileo 201 and 202) to look for violations of the EEP/LPI. These two satellites were launched on August, 30th 2014 and, because of a technical problem, the launcher brought them on a wrong, elliptic orbit. An elliptic orbit induces a periodic modulation of the gravitational redshift while the good stability of recent GNSS clocks allows to test this periodic modulation to a very good level of accuracy. The Galileo 5 and 6 satellites, with their large eccentricity and on-board H-maser clocks, are hence perfect candidates to perform this test. Contrary to the GP-A experiment, it is possible to integrate the signal on a long duration, therefore improving the statistics.

The proposed approach to reach an improved test of the EEP/LPI requires an accurate knowledge of the frequency of the satellite clock as it orbits the Earth. These data are made available by several Analysis Centers (ACs) of the International GNSS Service (IGS) in the framework of the Multi-GNSS-EXperiment (MGEX); moreover, ESOC is generating specific dedicated products for this experiment. The orbit solution of Galileo 5 and 6 satellites will be used to calculate the behaviour of the onboard clocks and the gravitational redshift as predicted by GR. The latter will then be compared to the clock solution from the IGS processing to recover any violation of the EEP/LPI.

In order to have a solid and robust scientific result, the most important and difficult task will be to understand and characterize all systematic effects. In order to achieve this control of systematics, we propose to perform a campaign of satellite laser ranging (SLR) on Galileo satellite 5. The SLR data will be very valuable in order to reduce the effects of systematics, in particular to decorrelate the orbit perturbations from the clock errors in the IGS solutions. It will enhance the success of the experiment, and the robustness of the scientific result. Finally, sophisticated statistical analysis will be used to calculate robust limits and uncertainties on the parameters of the EEP/LPI violation.

A realistic simulation has been done to predict what we can expect from the GREAT experiment (Delva et al. 2015) . We have shown that the Galileo 5 and 6 GNSS satellites can improve on the GP-A (1976) limit on the gravitational redshift test, down to an accuracy of a few 10^{-5}. If all systematic effects can be decorrelated thanks to SLR data, then one month is sufficient to reach the GP-A limit (see Figure 1).

2. Satellite Laser Ranging Campaign

The French OCA Grasse Satellite/Lunar Laser Ranging (SLR/LLR) is involved in laser ranging activities to artificial satellites and the Moon for many years. Laser ranging data are essential in order to determine the altitude variations of Galileo satellites very accurately and independently from the ESA-GNSS observing system itself. The challenge is thus to provide an orbit coverage by laser as large as possible during about one year.

The ILRS network is tracking the Galileo satellites regularly as it is the case for numerous targets as Earth observing and geodetic satellites. Around 35-40 SLR stations form currently the basic ILRS network (Pearlman et al. 2002). In case of Galileo and GPS, the laser technique is *a priori* not used in support to the precise orbit determination from an operational point of view. But it revealed an essential tool to provide GNSS services with independent and very accurate data to study and even monitor the overall stability of the computed orbits (Sośnica et al. 2015).

The GREAT experiment is ultimately limited by systematic errors. It has been shown that the radial systematic errors on the satellite orbit IGS solution is correlated with the onboard clock solution (Montenbruck et al. 2014). Moreover, this systematic error amplitude shows a correlation with the β-angle, i.e. the angle between the orbital plane of the satellite and the direction of the Sun. This is due to a large extent to mismodelling errors in the Solar Radiation Pressure (SRP) model. The radial error of the IGS orbit determination of Galileo 5&6 can be monitored thanks to SLR observations, which will help to disentangle systematic errors coming from the orbit determination in the IGS clock solution.

We now describe the characteristics and the planification of the SLR campaign on Galileo 5&6 satellite at the Grasse SLR station, and discuss the possibility of an ILRS concerted campaign. We present here only the main conclusions of a longer study.

Satellite priority. Galileo 5 is operating with Passive Hydrogen Maser clock (PHM), whereas Galileo 6 is currently operating with Rubidium (RAFS). On this basis, Galileo 5 is the preferred target, with Galileo 6 as secondary preferred target. ESA would communicate in events where there are changes on the current satellite clock / payload operations. Both satellite orbits have a 20 days repeat cycle, containing 37 revolutions, with a good global coverage. They are separated by 180 degrees in mean anomaly, such that the ground track for the first 10 days of sat 5 is the same as sat 6 for the next 10 days.

Observations strategy. Observations should be well distributed over the orbit in order to contain both the perigee and apogee. For this reason, it is necessary to have a good spatial distribution of the ground stations, as well as an homogeneous distribution of observations in time.

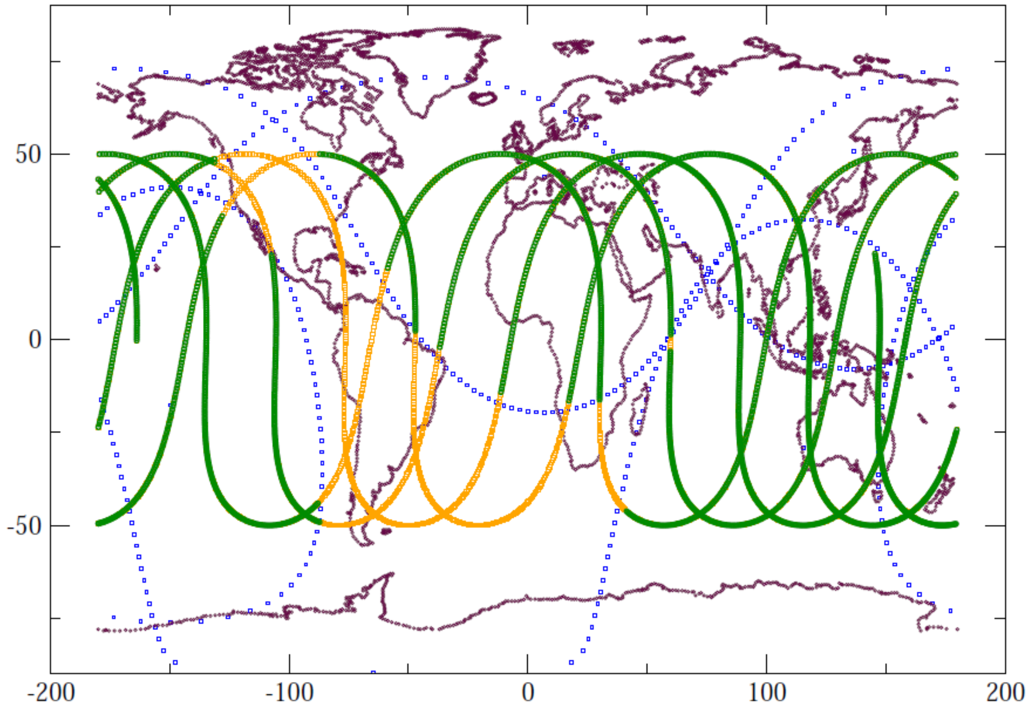

Figure 2. Illustration of ILRS network potential coverage for Galileo satellites; with 4 stations in green (Yaragadee, Grasse, Papeete, Komsomolsk) and 6 stations in orange (plus Hartebeesthoek and Arequipa).

We simulated an optimal scenario with six stations: Komsomolks, Yaragadee, Papeete, Grasse, Hartebeesthoek and Arequipa (see Figure 2). Each pass should be observed from the beginning to the end (around four hours), with one or two normal points every ~ 50 mn. These observations could be performed each month of year 2016 for a period of four days up to one week. Observations should span one year to be able to see the variation of the SLR residuals with the β-angle.

Measurement performance. Conservative values for the measurement performance can be chosen as ~ 1 cm noise on normal points, and a ranging stability of ~ 0.5 cm over 10 days, with possibly the same stability over one year. We emphasize that we are looking for a variation of the signal. Therefore a global shift of the SLR residuals is not important, as long as it stays compatible with the stability requirement.

ILRS campaign. A concerted ILRS SLR campaign on Galileo 5&6 has been suggested at the Matera workshop. ILRS has suggested to ask for a limited campaign in time where several stations could join, of the order of one month. Figure 1 suggests than one month of data would permit to constrain the LPI violation parameter down to 1×10^{-4}.

Dense observations for a period of one month would permit to disentangle completely the orbit solution from the clock solution, and characterize the systematic errors acting directly on the clock (temperature, magnetic field, ...). This one month of data needs not to be consecutive.

The data should span one year to have a good characterization of the variation of the radial error enveloppe which shows an amplitude modulation of one year (Steigenberger et al. 2015). Therefore, two strategies can be proposed:

- to observe each month for a period of four days up to one week, during one year;
- to observe when the β-angle is minimum and maximum, during 4 different campaigns of 9 days each separated by around 3 months when the β-angle is null and extremal. On figure 3

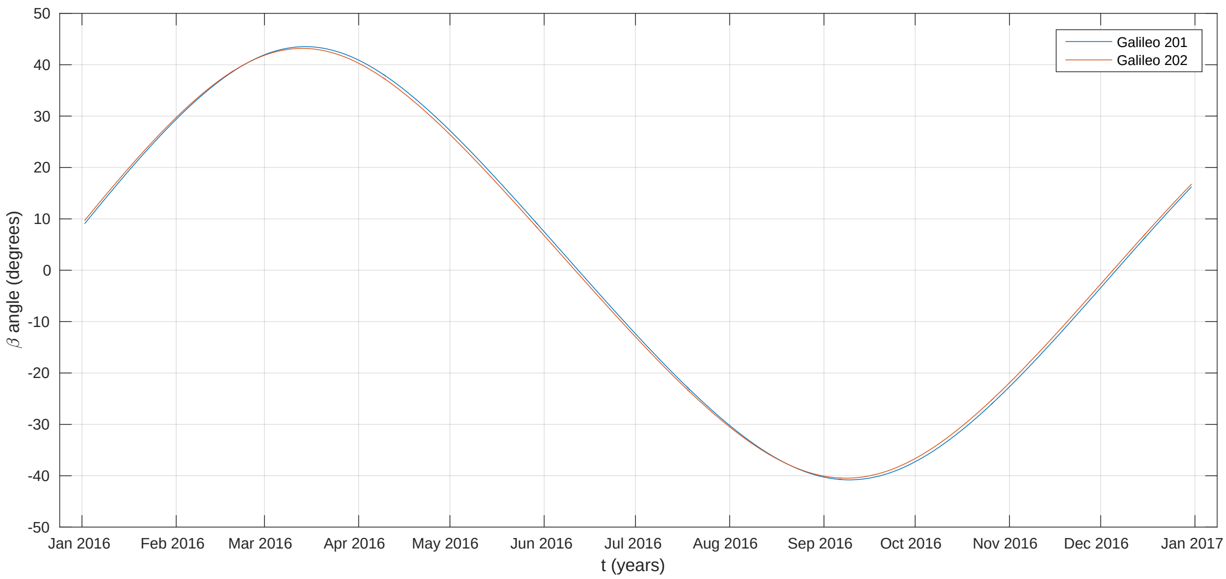

Figure 3. β-angle prediction for Galileo satellites 5&6 for the year 2016. $\beta = 0$ in June 11th and December 05th; and β is extremal in March 14th and September 08th.

the β-angle prediction for 2016 is shown for Galileo 5&6. The prediction is accurate to better than one degree if no manoeuvers occurs – which should be the case as the orbits of these two satellites are not controlled. The evolution of the β-angle is periodic with a period equal to the draconitic year, which is around 356 days.

These two strategies are compatible and can be both adopted to have a robust result. The distribution of the ground stations has been already discussed. In addition to the six proposed stations, there could be more stations joining to account for the possible bad weather at one station.

3. Conclusions and recommendations

The looked-for LPI/EEP violation signal is periodic at the orbital frequency. However, systematic effects are polluting this signal with perturbations which are periodic at the orbital frequency, modulated by an annual frequency. Therefore, we propose our best strategy for 2016 to reach a robust analysis of the systematic effects:

- focus the SLR observations on Galileo 5 (201) which is in PHM mode. If Galileo 5 emission is interrupted, switch to Galileo 6 (202);
- the distribution of ground stations should be well chosen, a possible optimal configuration uses six stations: Komsomolks, Yaragadee, Papeete, Grasse, Hartebeesthoek and Arequipa, with possibly more stations joining to account for the possible bad weather at one station;
- observations should span one year, with two possible strategies: observe each month for four days up to one week, or observe when the β-angle is null and extremal (four periods of 9 days; see Figure 3); these two strategies can be both adopted;
- during the period of observations of the satellite each pass should be observed from the beginning to the end, with one or two normal points every ~ 50 mn.

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