Stanisław OSZCZAK, Professor, Ph.D. Eng.

Polish Air Force Academy
Faculty of Aeronautics

THE ESA’S SCIENTIFIC PROJECTS FOR GALILEO SATELLITES 5 AND 6 WITH ECCENTRIC ORBITS

Abstract

The experts of the ESA Galileo Scientific Advisory Committee (GSAC) have been involved in the analysis and technical discussions on the possibility of using Galileo Satellites 5 and 6 with eccentric orbits to support some Fundamental Physics experimentation, especially to perform a test of the gravitational redshift, a part of Einstein Equivalence Principle (EEP) General Relativity (specifically testing the LPI, Local Position Invariance).

The gravitational redshift was performed with Gravity Probe-A (GP-A) in 1980 with the accuracy of 1.4 x 10^-4. The analysis made by independent experts showed that using Galileo Satellite 5 data for one year (and if possible also Sat 6), in their final corrected orbits with an eccentricity of about 0.15, the accuracy could be improved by a factor of 5 and is optionally estimated to be even higher.

Moreover, as noted by the involved experts, these tests are of high scientific relevance, as many alternative theories of gravitation predict violations of the Einstein Equivalence Principle at some level of the accuracy.

The final recommendation of the GSAC provides the ESA with the possibility of establishing a scientific project activity, named as GREAT with two research groups (ZARM/SYRTE). The main objectives of this scientific project and expected results of gravitational redshift improvement are discussed.

Keywords: Galileo satellites, eccentric satellite orbits, general relativity, Einstein equivalence principle, gravitational redshift.

Introduction

As a part of the Galileo constellation, the Europe’s Galileo satellite 5 (GSAT0201) and satellite 6 (GSAT0202) were launched on August 22, 2014 by a Soyuz rocket from Europe’s Spaceport in French Guiana¹.

Shortly after the launch, the Galileo’s Launch and Early Orbit Phase (LEOP) team at the ESA’s ESOC operations centre in Darmstadt (Germany), jointly manned from the ESA and a French space agency CNES personnel, raised the alarm. Due to a malfunction of the Soyuz Fregat launch vehicle, they have observed very low power and instability in the radio signals they were receiving from the pair of satellites showed. They were not where they should have been in orbit positions. The team

¹ http://galileognss.eu/galileo-5-and-6-recovery/.
of experts from the Independent Enquiry Commission of Arianespace, the European Commission and the ESA which was created to work closely with Russia’s Roscosmos space agency, discovered the Fregat upper stage anomaly which was due to eventually pinned down to a single bracket of aluminium, used to hold the propellant and helium lines in place. The cold liquid helium froze the nearby propellant line and blocked the use of Fregat’s attitude control thrusters. Now, revised installation procedures prevent from reoccurrence of the problem.

![Image 1. Galileo launch – Soyuz VS09](http://galileognss.eu/galileo-5-and-6-recovery/)

The satellites were located in an elliptical orbit with apogee as high as 25 900 km above the Earth and perigee of 13 713 km, and the orbit plane was wrongly inclined with respect to the equator. The team determined the actual orbit, then generated new commands to repoint the ground antennas and established robust radio links to ensure the satellites were safe and stable. The LEOP team also developed procedures to release the trapped solar wings, boosting the available power to a safe margin as they pointed towards the Sun. As a result, both satellites were pointed to the Sun, however they could not be used for navigation purpose nor be tested. In such a situation, the ESA supported by experts from industry and national space agencies prepared different scenarios and proposed to the European Commission which decided to recover both satellites.

The control of both satellites is transferred to the Galileo Control Centre in Oberpfaffenhofen, Germany, overseen by the SpaceOpal company. However, their incorrect orbits do not allow their navigation payloads to be switched on for testing because the Earth’s sensors used to point their navigation antennas stopped working around perigee (their lowest point) in which the Earth’s disc filled their field of view. The lower orbits were also exposing them to heightened levels of harmful radiation.

The satellites cannot reach their originally assigned standard destination due to the limited fuel capacity. However, to make them suitable for navigation purposes, their orbits could still be modified. A wide group of experts from the ESA’s Galileo team, ESOC flight dynamics specialists, along with the personnel from SpaceOpal, OHB with the support of the French (CNES), Italian (ASI), German (DLR) and British (UKSA) space agencies prepared a recovery plan. The procedures involved a multiple series of manoeuvres correcting the lowest point of the satellites’ orbits more than 3 500 km and making them more circular.
At the end of November 2014, the Galileo Sat-5 entered its corrected orbit, while the Sat-6 followed it during March 2015. They overflew the same location on the ground every 20 days specifying their positions now mirroring each other. The standard Galileo constellation repeats a pattern of 10 days, therefore this period enables to synchronize eccentric satellites ground tracks with the rest of the constellation and to perform testing of both their navigation, as well as search and rescue payloads.

The procedures of testing of the Sat-5 began in December 2014, and Sat-6 in spring 2015. Such test procedures fully confirmed the quality of the new-generation satellites. The satellite 5 has been even combined with its Galileo constellation to determine the position fixes with an excellent level of performance as it is expected in the normal orbit.

The main problem for positioning and navigation is their orbits fall outside of the ‘almanacs’ broadcast within navigation messages to locate satellites. However, the satellite’s signal can still be received in an open sky search. The entire integration of both satellites in the operational constellation is still under an analysis, especially the generation of the navigation message by the operational ground segment. The final decision on the operational use of these satellites depends on the results of a cost-benefit analysis.

The final Sat-5 orbital parameters\(^2\) are confirmed as follows:
- Semimajor Axis: 27 978 km
- Eccentricity: 0.15601
- Inclination: 49.775 degrees
- RAAN: 82.691 degrees
- Arg. Perigee: 28.968 degrees
- True Anomaly: 0.0 deg

\(^2\) [http://www.esa.int/Our_Activities/Navigation/The_future_Galileo/Launching_Galileo](http://www.esa.int/Our_Activities/Navigation/The_future_Galileo/Launching_Galileo).
Apogee High: 25 818 Km
Perigee High: 17 382 Km
Orbit 37 rev/20 days

The target final Sat-6 orbital parameters are as follows:
Epoch: 2015/03/05-10:36:16
    Semimajor Axis: 27 978 km
    Eccentricity: 0.15617
    Inclination: 49.874 degrees
    RAAN: 77.518 degrees
    Arg. Perigee: 34.309 degrees
    True Anomaly: 0.0 deg
Apogee High: 25 818 Km
Perigee High: 17 382 Km
Orbit 37 rev/20 days

The provided manoeuver strategy information shows the on-going move of Sat-6 which will be placed in the same orbit with 180 degrees phase opposition to Sat-5.

It is noted an interest of the ESA on the possibility of using Galileo satellites 5 and 6 for Navigation, however the decision has some technical/cost implications and the final decision will be made by the European Commission, as the Galileo Programme Manager.

However, currently (Feb 2015) Sat-5 is transmitting with a dummy navigation signal and nowadays an associated navigation message needs to be transmitted through other means to obtain the positioning using this satellite.

As it will be presented in the paper, the final resulting eccentricity (0.156), although lowered than the injected orbit (0.23), will still be sufficiently high to benefit for an adequate gravitational redshift measurement, providing that all other necessary related assumptions are also adequate (for example, clock stability per orbit; orbit accuracy; data access; etc.).

Using Galileo satellites 5 and 6 to support some fundamental physics experimentation

S. Herrmann, Ph.D. from the Zentrum für Angewandte Raumfahrttechnik und Mikrogravitation (ZARM)\(^3\) – the University of Bremen presents their proposal on the use of Galileo satellites 5 and 6 for some fundamental Physics measurements.

It is explained by ZARM that according to some assumptions, the following effects could be potentially measured with corresponding orders of magnitude improvements (with respect to the current state):
- gravitational redshift - up to 2 orders of magnitude improvement;
- perihelion shift, with one order of magnitude improvement;
- gravito-magnetic clock effect, claimed detectable for first time;
- test of alternative gravity – up to 5 orders of magnitude improvement.

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It is noted that for the gravitational redshift and perihelion shift tests, Galileo Sat-5/Sat-6 eccentricity is necessary which justifies an interest for the use of these two Galileo eccentric satellites.

For their eccentric orbits, assuming Galileo clock accuracy (per day) of the order of $7 \times 10^{-15}$ and assuming the integration over 1000 orbits, the accuracy of the order of $4.6 \times 10^{-6}$ is claimed to be obtainable. This value is about 30 times better than today’s state of the art measurement values (performed with Gravity Probe-A (GP-A) in 1980, where it was verified with the accuracy of $1.4 \times 10^{-4}$), which, if confirmed, could be of a great scientific interest.

Dr Pacôme Delva from SYRTE/Observatoire de Paris also presents their proposal on the use of Galileo eccentric satellites 5 and 6 for the test of the Gravitational Redshift.

The case of Gravity Probe - an experiment was explained as the best estimate of the gravitational redshift with the accuracy of $1.4 \times 10^{-4}$ (as referred previously). Based on the Passive Hydrogen Maser (PHM) on-board excellent clocks accuracy, precise orbit determination and the orbits eccentricity, the merits of satellite 5 and 6 for a gravitational redshift experimentation are expected.

The independent analysis was then presented on the basis of two different methodologies:
- Matched Filtering in the frequency domain;
- Linear Least-Square + Monte-Carlo in the time domain.

Taking into account the previous PHM Galileo on-board measured data, a simulated clock noise is assumed for Satellite 5 corrected orbit as follows: a flicker noise of the order of $8 \times 10^{-15}$ and a white noise of the order of $5 \times 10^{-14}$ at integration time of 1000 seconds. The performed analyses, under such assumptions, indicate that the current best estimate of the gravitational redshift could be achieved in only 2 weeks of integration of Sat-5 data using only Galileo Satellite 5. After one year of integration, the achievable accuracy estimated is $\sim 3 \times 10^{-5}$, a factor of 5 better than GP-A.

The results of two methodologies assessed give the same estimation which provides then some further confidence in the analysis.

Mismodelling of the Solar Radiation Pressure is assumed to be, to a large extent (~75%), due to the systematic radial errors in the estimated orbit. Other systematic effects that depend on the Sun direction (solar radiation pressure, onboard thermal effect) can be largely decorrelated from the gravitational redshift signal with (at least) one year of data.

As it was mentioned earlier, the gravitational redshift were performed with Gravity Probe-A (GP-A) with the accuracy of $1.4 \times 10^{-4}$. The independent analysis performed by SYRTE and ZARM showed that using Galileo Sat-5 data for one year (and if possible also Sat 6) in their final corrected orbit (for instance, after correction manoeuvres, with eccentricity of about 0.15), could be greatly improved (SYRTE estimates improvement by a factor of 5).

As noted by the independent experts and researchers, these tests are of high scientific relevance as many alternative theories of gravitation predict violations of the Einstein Equivalence Principle at some level of accuracy.

It is considered by the experts of the GSAC that the emphasized assumptions used by these research groups for such estimates are realistic, and that, therefore, the test’s results are potentially at reach, providing that an adequate test set-up is

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implemented. Such a conclusion comes from the assessed measured Sat-5 PHM clock accuracy/stability results, assessed the PHM clock thermal and environmental stability, as well as having taken note of the measured clock flicker noise, and the current orbital configuration for Sat-5.

It is also noted that the nature of these tests is compatible and transparent with an eventual operational use of the satellites.

For GNSS relativity tests activities, the ESA informed that two parallel contracts (activity named as GREAT) have been started with SYRTE/ Observatoire de Paris and ZARM for a 16 month activity, including one full year of testing data. The details on the planned activity and the most important challenges were noted by P. Delva who is directly coordinating the SYRTE activity. He indicated different perturbations affecting these high-precision clock measurements, emphasizing that the most challenging part is the removal of systematic errors, such as non-gravitational forces from the solar radiation pressure (SRP).

It is noted that a good control of systematic effects will be essential for this experiment. Hence, the ESA and P. Delva demonstrated the plans to launch a dedicated laser measurement campaign (via ILRS network) to mitigate in a good extent systematic errors coming from the orbit and impacting the clock determination on other systematic errors. It will require the best laser observation coverage of Sat-5 (Galileo 201) orbit in space and time. Therefore, a formal application has been submitted in March 2016 to the International Laser Ranging Service (ILRS).

**Scientific objectives of the ESA GREAT project**

The gravitational interaction describes a classical theory of the General Relativity (GR) which has been confirmed by the experimental observations but nowadays is commonly admitted that the GR is not the ultimate theory of gravitation. The development of the quantum theory of gravitation or attempts to unify gravitation with other fundamental interactions lead to deviations from the GR. The Einstein Equivalence Principle (EEP) provides gravitation of a geometric nature. From the methodological point of view, three aspects of the EEP can be tested\(^5\) by different methods, as follows: (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\(^6\) or by redshift tests\(^7\).

The most precise test of the gravitational redshift to date has been realized with the Vessot-Levine rocket experiment in 1976, also known as the Gravity Probe A (GP-A) experiment\(^8\). In this experiment, using a continuous two-way microwave link, the frequency differences between a space-borne hydrogen maser clock and ground hydrogen masers were measured. The gravitational redshift was verified to \(1.4 \times 10^{-4}\) accuracy.

Future experiments such as Atomic Clock Ensemble in Space (ACES) experiment, the ESA/CNES mission, planned to fly on the International Space Station

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(ISS) in 2017, will test gravitational redshift to around $2-3 \times 10^{-6}$ accuracy\(^9\). Other projects like STE-QUEST\(^10\) propose to test the gravitational redshift at the level of $10^{-7}$, and observations with the RadioAstron telescope\(^11\) may reach the accuracy of the order of $10^{-5}$. Finally, it has been previously suggested\(^12\) to use Galileo satellites for such a test.

Within the GREAT project (Galileo gravitational Redshift Experiment with eccentric sATellites), the 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 search for violations of the EEP/LPI. These two satellites were launched to an elliptic orbit. The elliptic orbit induces a periodic modulation of the gravitational redshift. 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 onboard H-maser clocks, are hence ideal to perform this test. It is possible to integrate the signal on long duration, contrary to the GP-A experiment, therefore improving statistics. The proposed test of the EEP/LPI requires accurate knowledge on the frequency of the satellite clock as it orbits the Earth. These data is made available by several Analysis Centers (ACs) of the International GNSS Service (IGS) in the framework of the MultiGNSS-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 data obtained by the onboard clocks and compute the gravitational redshift as predicted by the GR. The results will then be compared to the clock solution from the IGS processing to recover any violation of the EEP/LPI. In this experiment, the most important and difficult task will be to understand and characterize all systematic effects. In order to determine and control of systematics, it is proposed to perform a campaign of satellite laser ranging (SLR) on Galileo satellite 5 (as a priority). To decorrelate the orbit perturbations from the clock errors in the IGS solutions, the SLR observation data will be very valuable in order to mitigate the effects of systematization. It will enhance the success of the robustness of the scientific result. Finally, a sophisticated statistical analysis will be used to calculate robust limits and uncertainties on the parameters of the EEP/LPI violation. The realistic simulation has been performed to predict what it can be expected from the GREAT experiment. As it has been shown, the Galileo 5 and 6 GNSS satellites can improve on the GP-A (1976) limit on the gravitational redshift test, down to the accuracy of a few 10-5.

The main problem in the GREAT experiment is the success of the project and it depends on elimination or mitigation of all systematic errors. It has been shown that the radial systematic errors on the satellite orbit IGS solution are correlated with the β-angle, for instance, the angle between the orbital plane of the satellite and the


direction of the Sun\textsuperscript{14}. This is due to a large extent to mismodelling errors in the Solar Radiation Pressure (SRP) model. The radial error of the IGS (International GNSS Service) orbit determination of Galileo 5 and 6 can be monitored due to SLR observations which will help to mitigate systematic errors coming from the orbit determination in the IGS clock solution.

Conclusion

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

It is possible with Galileo satellites 5 and 6, and at least one year of observation data, to improve on the GP-A (1976) limit on the gravitational redshift test, down to the accuracy around $3 \times 10^{-5}$. This level of accuracy can be achieved if all sources of systematic errors such as: mismodelling of Solar Radiation Pressure (SLR), onboard thermal effect, etc.) could be eliminated or to a great extent mitigated. For this, the radial error of the IGS orbit determination of Galileo 5 and 6 can be monitored due to SLR observations which will enable to mitigate systematic errors coming from the orbit determination in the IGS clock solution. This will require the best laser observation coverage of Sat - 5 (Galileo 201) orbit in space and in time. Hence, a formal application to ILRS has been submitted in March 2016.

The current (2016) members of the ESA’s GSAC nominated by the ESA Director General for a period between 2012 and 2016 include: Chair: Prof. Gunnar Elgered, Sweden, Members: Andreas Bauch, PhD, Germany; Prof. Bernd Dachwald, Germany, Pascale Defraigne, Ph. D, Belgium; Pacome Delva, Ph.D., France; Prof. Manuel Hernandez-Pajares, Spain; Heidi Kuusniemi, PhD., Finland; Prof. Gérard Lachapelle, Canada; Prof. Terry Moore, United Kingdom; Prof. Stanislaw Oszczak, Poland; Prof. Markus Rothacher, Switzerland; Prof. Frantisek Vejrazka, Czech Republic; Francesco Vespe, Ph.D. Italy; and the ESA representatives: Guenter Hein, Ph.D., Javier Ventura-Traveset, Ph.D; Roberto Prieto and Clovis de Matos, Ph.D.

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On-line resources:
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