Fundamental Physics with Galileo:

GNSS General Relativity Experiment (GREAT)

Executive Summary

The GREAT Science Case

The GREAT project provides an improved test of Einstein's theory of General Relativity by analyzing the relativistic gravitational redshift as observed in the clock data from GSAT-0201 and GSAT-0202. These satellites have been injected into highly eccentric orbits following a launch mishap, providing us with the unique chance to perform an important test of fundamental physics.

The gravitational redshift describes the slowing down of the ticking rate that a clock experiences in a gravitational potential. This effect is a fundamental aspect of Einstein's theory of General Relativity. Its universal validity is a direct manifestation of Einstein's Equivalence Principle, which the theory is built upon. It is thus of fundamental importance to test the gravitational redshift as one of the cornerstones of General Relativity and thus of our current understanding of gravity and space-time itself.

The most accurate test of the gravitational redshift dates back to 1976, when R. Vessot and M. Levine launched the Gravity Probe A mission. This mission sent a hydrogen maser onboard a Scout rocket on a trajectory reaching 10000 km in altitude. During the flight they could perform an accurate frequency comparison to a ground based maser and verify the total relativistic frequency shift to within 7×10^{-5} total uncertainty. The effect they measured included both the gravitational redshift and the relativistic Doppler effect.

Today the relativistic effect of gravitational redshift is routinely taken into account in GNSS by including a so called eccentricity correction, which for nominal satellites on a circular orbit adds a small correction only. With the Galileo satellites GSAT-0201 and GSAT-0202 however, the eccentricity of the orbit is at 0.16 and the relativistic eccentricity correction is largely increased. In fact, as this study shows, to derive valid clock and orbit products for those satellites the relativistic correction needs to be applied with a precision already beyond the limit, that Einstein's theory has ever been tested before.

GREAT Results

In this report, we first give an assessment of the data, the magnitude of the relativistic effect and show how the standard treatment of relativistic effects in IGS products needs to be refined in order to account for the relativistic effects at the required precision. We find that two refinements are necessary: the first one is to include the effect of earth's mass quadrupole J_2 and the second one is to apply numerical integration along the actual non-Keplerian orbit.

To quantify a potential violation of relativity we perform least squares fits of our relativistic model to the clock data and use a test parameter α, to describe a possible deviation from the GR prediction. Fits are done on daily data sets, corresponding to the usual data binning of IGS products. This procedure results in a distribution of daily results for α, which is statistically analyzed to obtain an estimate for the test parameter from the full data spanning almost 3 years.

The data from the two satellites shows very different quality depending on which clock (PHM or RAFS) was set as the active transmitting clock onboard the satellites. For further analysis we concentrate on 3 of the available clocks and exclude one PHM on GSAT-0201 which has been declared non-nominal and one RAFS on GSAT-0202 due to its inferior frequency stability.

We then derive an error budget for systematic corrections and uncertainties on our estimates. For this we consider direct effects on the clock, such as temperature and magnetic fields, as well as potential modeling errors from the applied orbit model or atmospheric models. We find that the dominant systematic contribution is due errors in the orbit model. To assess and correct for these errors we make use of independently taken satellite laser ranging measurements.

With this correction applied and after combining statistical and all systematic uncertainties the best of the three clocks analyzed yields a value

$$\boldsymbol{\alpha = (2.2 +/- 1.6) \times 10^{-5},}$$

which is consistent with the GR prediction within 2σ and improves on the GPA result of $\alpha = (0.1 +/- 7.0) \times 10^{-5}$ by a factor of four.

Thus we can state that more than 40 years after the GPA mission the Galileo satellites have enabled a precise confirmation of the relativistic redshift at an unprecedented precision.

As an additional effort of this activity we have developed an improved SRP model based on a geometrical satellite model of the Galileo FOC satellites. Evaluation of this model by ESOC shows that it is now on par with improved SRP model applied by ESOC in derivation of the orbit products. With orbit modelling errors arising from SRP identified as the main source of systematic bias and uncertainty, our model now offers several possibilities for further improvements such as additional modelling of thermal radiation pressure which could be pivotal to further improve the quality of the orbit products.