Testing the principle of equivalence at a very large distance from the Earth according to the data of the Radioastron space experiment

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Abstract

We report on the recent results of testing one of the aspects of Einstein's principle of equivalence - the effect of gravitational redshift, by means of its precision measurement using the Spectr-R as part of the VLBI mission Radioastron. The spacecraft, which orbits Earth in a ~9 d eccentric orbit, along with ground stations at Pushchino, Russia and Green Bank, USA, were each equipped with high stability hydrogen maser frequency standards. To compensate for non-relativistic effects, we used a combination of one way and two way operating modes. We report success in updating the clock offset value by re-processing the accumulated data from 5% to 15%. This makes it possible to bring the error of correspondence of the measured gravitational shift to the calculation formula of general relativity to the level of 10^{-3}. It should be noted that never before has the gravitational redshift been measured with such accuracy at such large distances from the Earth of 350,000 km.

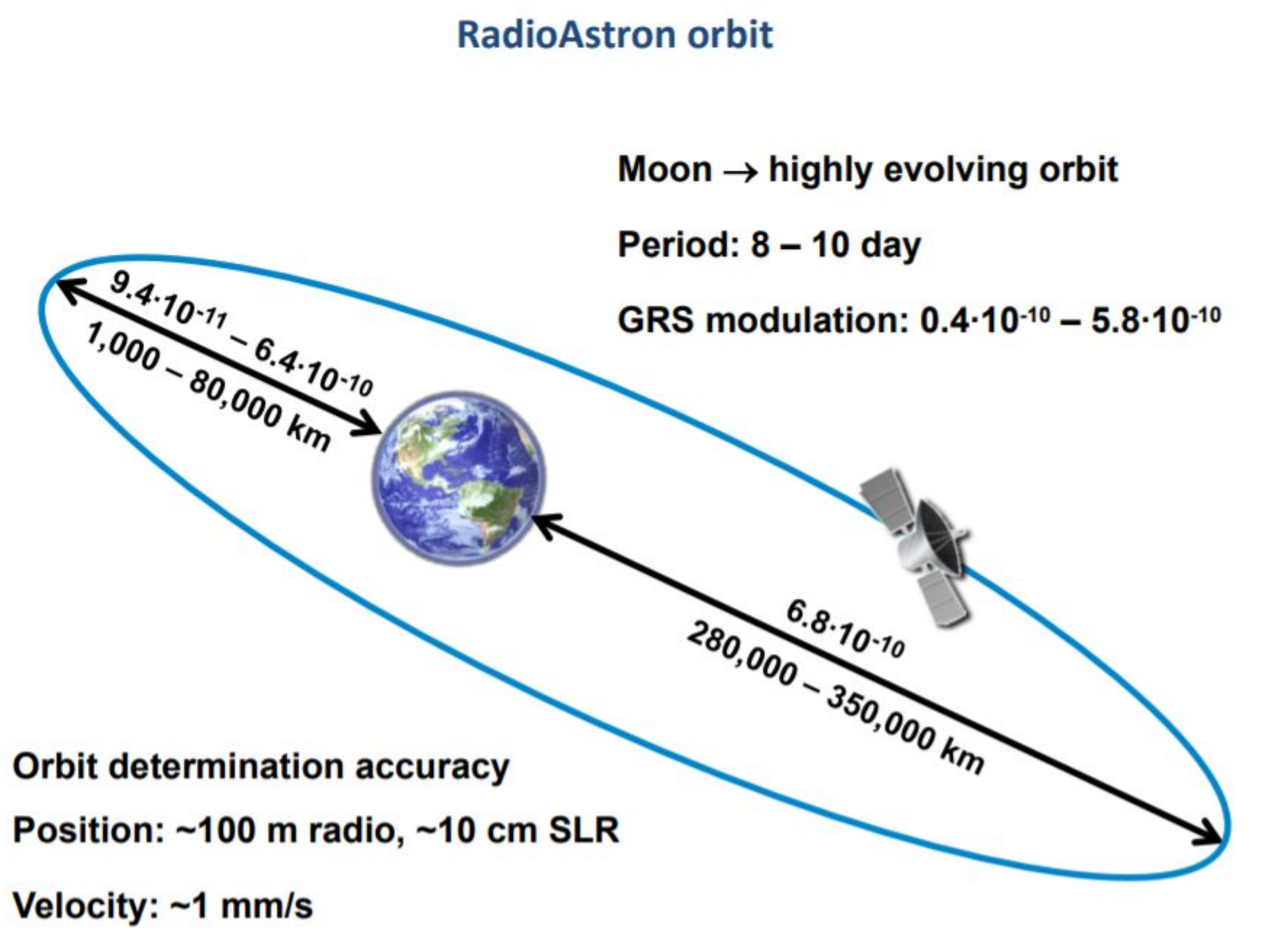
Introduction

The gravitational redshift is a direct consequence of the Einstein Equivalence Principle (EEP) which is at the foundation of General Relativity. Therefore, accurate measurements of the gravitational redshift that can be compared with prediction are of prime importance. In 1907, Einstein predicted the gravitational time dilation or gravitational redshift of the frequency of electromagnetic waves from the equivalence principle. According to this effect, the frequency of the electromagnetic wave during the transit of the gravitational potential difference ΔU changes by an amount:

$$\frac{\Delta f_{grav}}{f} = \frac{\Delta U}{c^2}$$

Project Overview

The spacecraft was launched in 2011, had on board highly stable hydrogen frequency standards, a radio transmitter with a large network of ground tracking stations, as well as an orbital eccentricity of $e = 0.9059$. Due to the highly elliptical orbit, and hence the large modulation of the gravitational shift ($0.4 * 10^{-10} – 5.8 * 10^{-10}$), we can measure the modulation of the gravitational shift with unprecedented accuracy better than 10^{-15}.



The measurement of the gravitational shift with only 1way data (~3000 astronomical sessions) made it possible to measure the gravitational shift with an accuracy of 10^{-12}.

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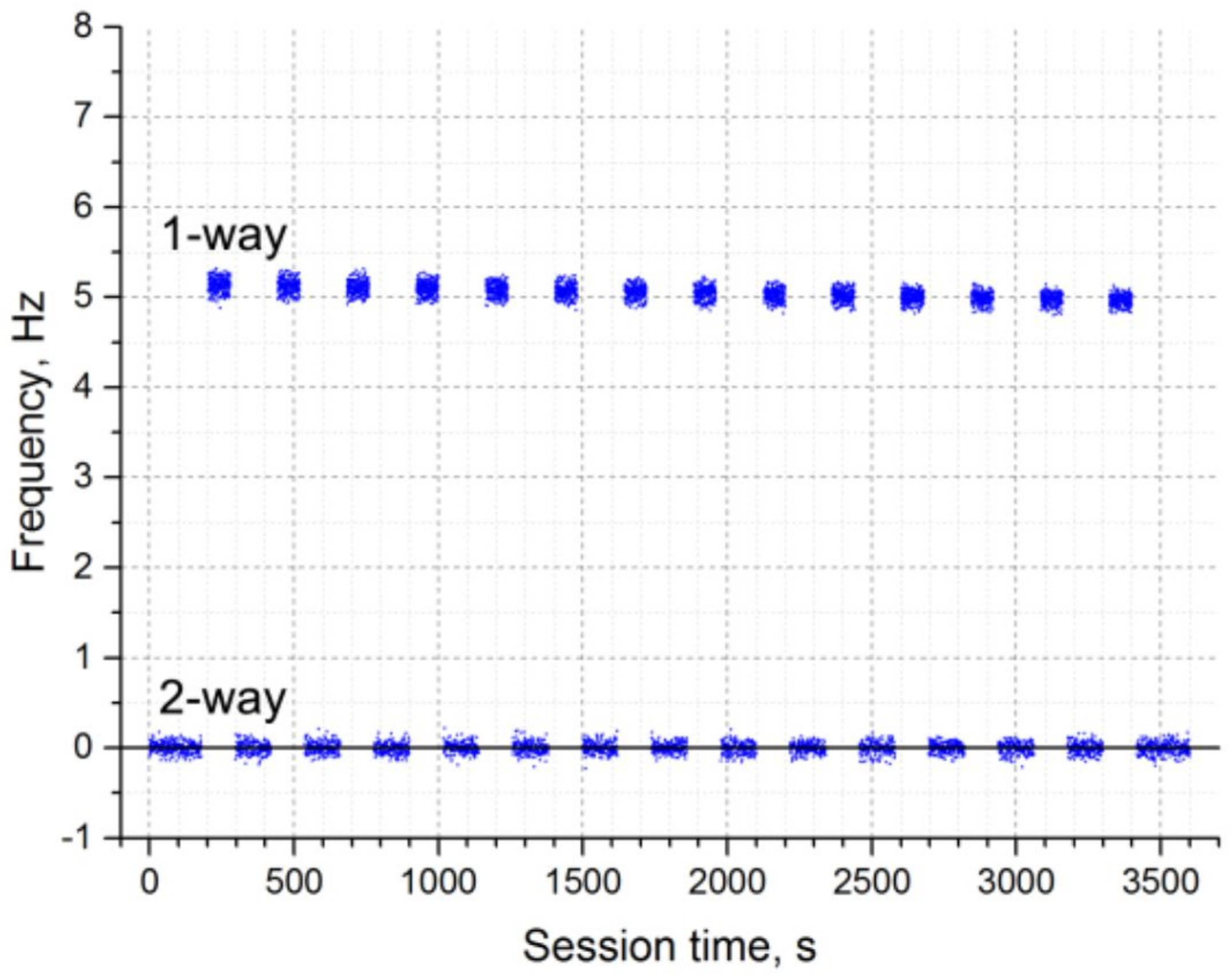
Gravitational Redshift

We extracted a small gravitational shift from a number of other effects that affect the signal sent from the spacecraft to the NRT: Doppler 1, order 2, ionosphere, troposphere, instrumental effects, standard drift.

A typical post-processing session is represented by frequent switching between 1-way / 2-way modes, for example, as in the graph below:



Using such a session scheme, we can remove kinematic effects and troposphere without resorting to trajectory data.

Latest Result

Since we are checking the effect of the gravitational shift, we introduce the epsilon violation parameter, which, if the theory is confirmed, will be zero.

So far, the best result is an **ε** estimate with an accuracy of:

$$\boldsymbol{\varepsilon = (0.2 \pm 2.0) \times 10^{-3}}$$

VLBI data recordings from the dedicated interleaved observations are also available and are expected to provide a 10 to 100-fold reduction in uncertainty of ε. When using the method of maximum likelihood and Cramer-Rao inequality, we obtained a decrease in the error by an order of magnitude for one session; however, further analysis requires consideration of higher-order effects.