RadioAstron gravitational redshift experiment: Status update

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A test of a cornerstone of general relativity, the gravitational redshift effect, is currently being conducted with the RadioAstron spacecraft, which is on a highly eccentric orbit around Earth. Using ground radio telescopes to record the spacecraft signal, synchronized to its ultra-stable on-board H-maser, we can probe the varying flow of time on board with unprecedented accuracy. The observations performed so far, currently being analyzed, have already allowed us to measure the effect with a relative accuracy of 4×10^{-4}. We expect to reach 2.5×10^{-5} with additional observations in 2016, an improvement of almost a magnitude over the 40-year old result of the GP-A mission.

Keywords: RadioAstron; gravitational redshift; general relativity; spacecraft Doppler tracking.

1. Introduction

Quantum theory (QT) and general relativity (GR) are the two pillars of modern physics. However, they are incompatible. Theoretical attempts to unify QT and GR lead to violations of GR and, in particular, the equivalence principle (EP). It is hard to estimate the level at which EP may be violated. Therefore equivalence principle tests are considered to "stand out as our deepest possible probe of new physics" [1]. We intend to test the EP with RadioAstron.

According to the Einstein equivalence principle, an electromagnetic wave of frequency f, propagating in a region of space where the gravitational potential is not constant, experiences a gravitational frequency shift:

$$\frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U}{c^2}, \tag{1}$$

where ΔU is the gravitational potential difference between the measurement points and c is the speed of light [2]. Any violation of Eq. (1) in an experiment with two identical atomic frequency standards may be parameterized as

$$\frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U}{c^2}(1 + \varepsilon), \tag{2}$$

where the violation parameter, ε, may depend on element composition of the gravitational field sources and on the specific kind of quantum transition exploited by the frequency standards. It is generally agreed that the best test of Eq. (1) to date was performed with the NASA-SAO Gravity Probe A (GP-A) [3] mission 40 years ago which measured $\varepsilon = (0.05 \pm 1.4) \times 10^{-4}$, giving the accuracy $\delta\varepsilon = 1.4 \times 10^{-4}$. The gravitational potential modulation experienced by RadioAstron is comparable to that of GP-A: $\Delta U/c^2 \sim 3 \times 10^{-10}$. The better stability of the RadioAstron on-board H-maser and the possibility of repeating observations promise a factor of ~ 10 improvement on the GP-A result.

Testing the gravitational redshift effect has recently become an active field of experimental research. The experiment with Galileo 5 & 6 navigational satellites is expected to probe the effect with $(3–4)\times 10^{-5}$ accuracy [4]. The specialized ACES mission [5], to be launched in 2017, is expected to achieve 2×10^{-6}.

2. Outline of the Experiment

In the gravitational redshift experiment with RadioAstron we detect the frequency change of the RadioAstron's on-board H-maser due to gravitation by comparing it, by means of radio links, with an H-maser at a ground station. Either one of the mission's dedicated tracking stations (TS), Pushchino or Green Bank, or a ground radio telescope (GRT) equipped with a 8.4 or 15 GHz receiver and appropriate data acquisition instrument may be used for receiving the spacecraft signal. The frequency variation due to the small gravitational frequency shift ($\Delta f/f \sim 10^{-10}$) needs to be separated from a number of other effects influencing the signal sent from the spacecraft to the ground station[3]:

$$\Delta f_{1\mathrm{w}} = f\left(-\frac{\dot{D}}{c} - \frac{v_{\mathrm{s}}^2 - v_{\mathrm{e}}^2}{2c^2} + \frac{(\mathbf{v}_{\mathrm{s}}\cdot\mathbf{n})^2 - (\mathbf{v}_{\mathrm{e}}\cdot\mathbf{n})\cdot(\mathbf{v}_{\mathrm{s}}\cdot\mathbf{n})}{c^2}\right) + \Delta f_{\mathrm{grav}} + \Delta f_{\mathrm{ion}} + \Delta f_{\mathrm{trop}} + \Delta f_0 + O\left(\frac{v}{c}\right)^3, \tag{3}$$

where "1w" stands for "1-way" (space to ground link), $\mathbf{v}_{\mathrm{s}}$ and $\mathbf{v}_{\mathrm{e}}$ are the velocities of the spacecraft and the ground station (in an Earth-centered inertial reference frame), $\dot{D}$ is the radial velocity of the spacecraft relative to the ground station, Δf_{grav} is the gravitational redshift, $\mathbf{n}$ is a unit vector in the direction opposite to that of signal propagation, Δf_{ion} and Δf_{trop} are the ionospheric and tropospheric shifts, and Δf_0 is the frequency bias between the ground and space H-masers.

There are two major problems in using Eq. (3) to determine Δf_{grav} directly, at least for RadioAstron. The first is caused by the unknown frequency bias, Δf_0, which cannot be determined after launch without making use of Eq. (1). We solve this problem by measuring only the variation of the gravitational effect and taking into account the bias drift. The second problem is that the nonrelativistic Doppler shift, $-\dot{D}/c$, cannot be calculated accurately enough from the available spacecraft state vector data. We solve this problem with the help of the frequency measurements of the 2-way link, which let us cancel the nonrelativistic Doppler term:

$$\Delta f_{1\mathrm{w}} - \frac{1}{2}\Delta f_{2\mathrm{w}} = \Delta f_{\mathrm{grav}} + f\left(-\frac{|\mathbf{v}_{\mathrm{s}}^2 - \mathbf{v}_{\mathrm{e}}^2|}{2c^2} + \frac{\mathbf{a}_{\mathrm{e}}\cdot\mathbf{n}}{c}\Delta t\right) + O(v/c)^3, \tag{4}$$

where $\mathbf{a}_e$ is the ground station acceleration and Δt is the signal light time. (Eq. (4) is relevant for a TS, similar but more complex equation holds for the case of the 2-way link signal received by a nearby GRT.) The idea of the compensation scheme based on Eq. (4) was first implemented in the GP-A experiment. For RadioAstron, however, it is not directly applicable due to impossibility of the 1- and 2-way links to be using different reference signals simultaneously (Fig. 1). Nevertheless, two options for realizing the compensation scheme (4) with RadioAstron are available.

The first option requires interleaving the 1-way (Fig. 1a) and 2-way (Fig. 1b) modes[6]. The data recorded by GRTs (and the TS) contain only one kind of signal at any given time. However, if the switching cycle is short enough (~ 4 min at 8.4 GHz) we are able to interpolate into the gaps with an error of $\Delta f/f \sim 5 \times 10^{-15}$. Thus we obtain quasi-simultaneous frequency measurements of both kinds and can apply the compensation scheme (4) to them directly.

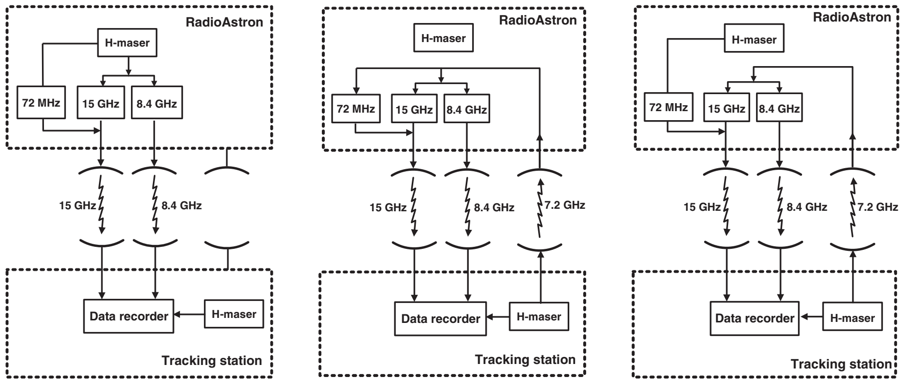


Fig. 1. On-board hardware synchronization modes. (a) "H-Maser". (b) "Coherent". (c) "Semi-Coherent". Note that, due to a fixed architecture of the RadioAstron on-board radio system, the 8.4 GHz tone and the carrier of the 15 GHz data link must use one and the same reference signal at any given time: either from the on-board H-maser or from the tracking station uplink.

The second option involves recording the 15 GHz data link signal in the "Semi-Coherent" mode of the on-board scientific and radio equipment (Fig. 1c). In this mode the 7.2 GHz uplink tone, the 8.4 GHz downlink tone and the 15 GHz data downlink carrier are phase-locked to the ground H-maser signal, while the modulation frequency of the data downlink is phase-locked to the on-board H-maser[7]. We do not give a detailed account of this approach here because it will not likely be used in the observations due to technical reasons. The basic data processing algorithms in each approach are those developed originally for PRIDE (Planetary Radio Interferometry and Doppler Experiment)[8].

Based on the error budget of the experiment using the interleaved measurements approach (Table 1), we expect the accuracy of the redshift test to reach

$$\delta\varepsilon \sim 2.5 \times 10^{-5}, \tag{5}$$

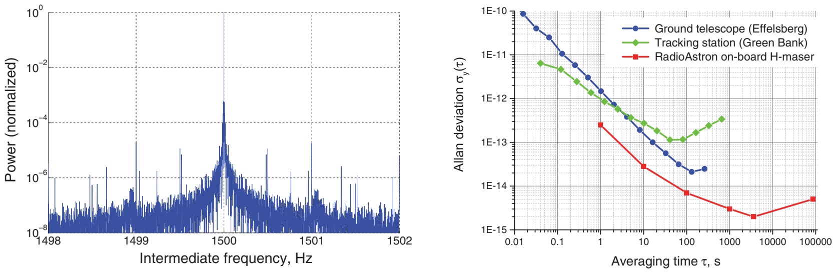
which is almost an order of magnitude better than the result of the GP-A mission. This value takes into account a number of factors not covered in the discussion above, such as ionospheric and tropospheric correction of GRT data using on-site GPS measurements, uncertainty of orbit reconstruction, etc.

Table 1. Error budget of the RadioAstron gravitational redshift experiment.

Random errors in $\frac{\Delta f}{f}$:	
Frequency instability $\sigma_y(\tau = 1000\ \mathrm{s})$:	
1-way signal	$2 \cdot 10^{-14}$
2-way signal	$3 \cdot 10^{-14}$
Interpolation error	$5 \cdot 10^{-15}$
Uncancelled tropospheric noise	$2 \cdot 10^{-15}$
Uncancelled ionospheric noise	$1 \cdot 10^{-15}$
Net random error $\delta_r \frac{\Delta f}{f}$:	
single experiment	$4 \cdot 10^{-14}$
30 experiments	$8 \cdot 10^{-15}$
Systematic errors in $\frac{\Delta f}{f}$:	
Residual space and ground clock drift over single experiment	$1 \cdot 10^{-15}$
Redshift and 2nd-order Doppler prediction errors due to orbit inaccuracy	$1 \cdot 10^{-15}$
Tropospheric and ionospheric bias	$2 \cdot 10^{-15}$
Net systematic error $\delta_s \frac{\Delta f}{f}$	$2 \cdot 10^{-15}$
Total error (random + systematic) $\delta \frac{\Delta f}{f}$:	
single experiment	$4 \cdot 10^{-14}$
30 experiments	$8 \cdot 10^{-15}$
Average variation of $\Delta U/c^2$	$3.0 \cdot 10^{-10}$
Predicted experiment accuracy $\frac{\delta(\Delta f/f)}{\Delta U/c^2}$:	
single experiment	$1.0 \cdot 10^{-4}$
30 experiments	$2.5 \cdot 10^{-5}$

3. Current Status

A total of 6 experiments have been performed in the period from October to December 2015, all using the interleaved measurements approach. Half of them were performed with the National Radio Astronomy Observatory radio telescopes: the R. C. Byrd Green Bank Telescope and several Very Long Baseline Array antennas (supported by the RadioAstron mission's Green Bank tracking station, West Vir-



(a) (b)

Fig. 2. Frequency stability of the 8.4 GHz RadioAstron downlink signal. (a) Phase-stopped signal spectrum (data recorded by the Effelsberg telescope, 2015/11/19). (b) Comparison of the frequency stability in terms of the Allan deviation of the signal recorded by a radio telescope (blue, circles) and a tracking station (green, diamonds). Allan deviation of the on-board H-maser obtained during laboratory tests (red, squares).

ginia, US). The other 3 experiments were performed with the telescopes of the European VLBI network (EVN): Effelsberg, Onsala, Wettzell, and the Russian QUASAR network[9] stations Svetloe and Zelenchukskaya (supported by the Pushchino tracking station, Moscow region, Russia). Each experiment was made up of a pair of ~ 1 hr long sessions separated by ~ 20–30 hr, which provided a gravitational redshift modulation between the two sessions of $\sim (0.5-0.8)\times 10^{-10}$. The observations went fairly smoothly; the frequency stability of the recorded signal meets our expectations (Fig. 2).

The data from the RadioAstron mission's tracking stations (Pushchino and Green Bank) have been processed and yielded an accuracy of $\delta\varepsilon \sim 4\cdot 10^{-4}$. The data from the radio telescopes, of higher quality than tracking station data (Fig. 2b), are currently being processed. We expect to reach an accuracy of $\sim 8\cdot 10^{-5}$ after processing these data in full. The most sensitive experiments, i.e. with the gravitational redshift effect modulation as large as 3×10^{-10}, are planned for the summer of 2016. The quality of the data already collected gives a reason to believe that the accuracy of the gravitational redshift test of $\sim 2.5\times 10^{-5}$ can be achieved.

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