GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SPACE RADIO TELESCOPE RADIOASTRON

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ABSTRACT. A unique test of general relativity is possible with the space radio telescope RadioAstron. The ultra-stable on-board hydrogen maser frequency standard and the highly eccentric orbit make RadioAstron an ideal instrument for probing the gravitational redshift effect. Large gravitational potential variation, occurring on the time scale of ∼24 hr, causes large variation of the on-board H-maser clock rate, which can be detected via comparison with frequency standards installed at various ground radio astronomical observatories. The experiment requires specific on-board hardware operating modes and support from ground radio telescopes capable of tracking the spacecraft continuously and equipped with 8.4 or 15 GHz receivers. Our preliminary estimates show that ∼30 hr of the space radio telescope's observational time are required to reach $\sim 2 \times 10^{-5}$ accuracy in the test, which would constitute a factor of 10 improvement over the currently achieved best result.

1. INTRODUCTION

According to Einstein's principle of equivalence an electromagnetic wave propagating in a region of space where the gravitational potential is not constant experiences a gravitational frequency shift, $\Delta f_{\rm grav}$, proportional to the gravitational potential difference between the measurement points, ΔU, and the frequency, f, of the wave:

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

where c is the speed of light (Misner et al. 1973). Any violation of Eq. (1) in an experiment with two identical atomic frequency standards can be parameterized in the following way:

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

where the violation parameter, ε, may depend on element composition of the gravitational field sources and on the kind of frequency standards. It is generally agreed that the best test of Eq. (1) to date was performed in the suborbital Gravity Probe A (GP-A) experiment, which measured $\varepsilon = (0.05 \pm 1.4) \times 10^{-4}$ for two hydrogen masers (Vessot et al. 1980). A similar experiment with RadioAstron, benefitting from a more stable hydrogen maser (H-maser) and longer data acquisition, could tentatively measure ε with an accuracy of $\delta\varepsilon \sim 2 \times 10^{-5}$. Below we outline two approaches to the anticipated experiment and give an account of the technical tests made for it.

2. OUTLINE OF THE EXPERIMENT

In the gravitational redshift experiment with RadioAstron we use microwave radio links to monitor the redshifted frequency of the satellite's on-board H-maser as it moves in the regions with different gravitational potential. The satellite radio payload includes two transmitters at 8.4 and 15 GHz and a

7.2 GHz receiver. The transmitters can be fed with a signal phase-locked either to the on-board H-maser, the 7.2 GHz uplink or a specific mixture of the two (see below). Measuring the frequency of a one-way satellite downlink signal at a ground station we see it shifted by (Vessot & Levine 1979):

$$\Delta f = f\left(-\frac{\dot{D}}{c} - \frac{v_s^2 - v_e^2}{2c^2} + \frac{(\mathbf{v}_s\cdot\mathbf{n})^2 - (\mathbf{v}_e\cdot\mathbf{n})\cdot(\mathbf{v}_s\cdot\mathbf{n})}{c^2}\right) + \Delta f_{grav} + \Delta f_{ion} + \Delta f_{trop} + \Delta f_0 + O\left(\frac{v}{c}\right)^3, \quad (3)$$

where $\dot{D}$ is the radial velocity of the spacecraft relative to the ground station, $\mathbf{v}_s$ and $\mathbf{v}_e$ are the velocities of the spacecraft and the ground station, $\mathbf{n}$ is a unit vector in the direction opposite to that of signal propagation, Δf_{grav} is the gravitational redshift, Δf_{ion} and Δf_{trop} are the ionospheric and tropospheric shifts, Δf_0 is an unknown frequency offset between the ground-based and space-borne H-masers and each quantity is referred to the geocentric inertial reference frame. Terms of $O\left(\frac{v}{c}\right)^3$ need to be taken into account only if aiming for an experiment accuracy of $\delta\varepsilon \lesssim 10^{-6}$ (Salomon et al. 2001).

The value of Δf_0 could be relatively large for H-masers due to their low intrinsic accuracy. For RadioAstron's H-maser $\Delta f_0/f \sim 10^{-11}$, which makes it impossible to experimentally determine the total value of the gravitational redshift effect $\Delta U/c^2 \sim 7\times10^{-10}$ with an accuracy higher than $\sim10^{-2}$. However, since the rate of change, or drift, of Δf_0 is typically small ($\sim1\times10^{-15}$ per day for RadioAstron), the relatively large value of Δf_0 does not prohibit us from conducting a high-accuracy experiment as long as only the variation, but not the total value, of the gravitational redshift effect is to be determined. Then the fundamental limit to the accuracy, $\delta\varepsilon$, is set by the available gravitational potential variation along the orbit, the frequency standard's instability and its drift. For RadioAstron this theoretical limit is 2×10^{-6} if the experiments are performed in the periods of the lowest perigee height $\sim$1,000 km.

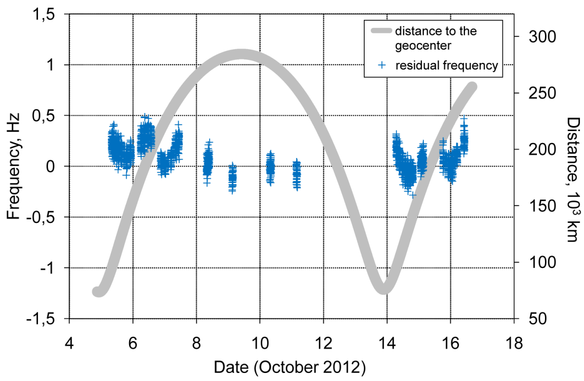
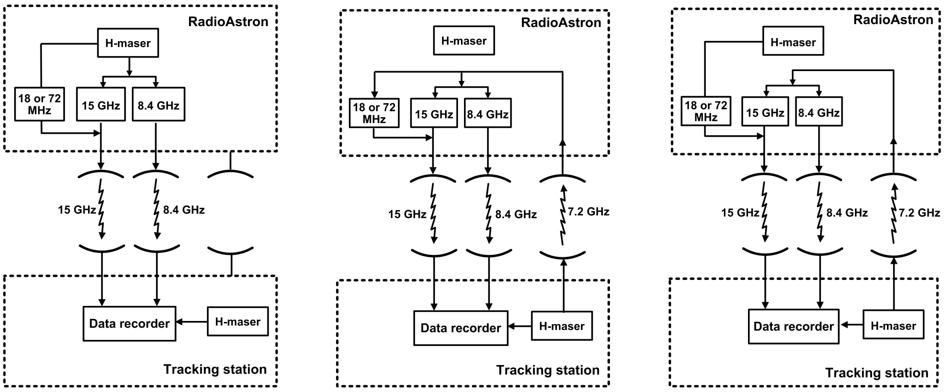


Figure 1: Frequency residuals (observed–predicted) as a function of epoch for the 8.4 GHz link. RMS of residuals: 0.18 Hz; gravitational redshift Δf_{grav}: 5 to 6 Hz (not plotted).

The principal source of error, when using Eq. (3) directly, is not the on-board H-maser performance but the spacecraft radial velocity uncertainty $\delta\dot{D} \sim 1$ mm/s, which sets the limit to the experiment accuracy $\delta\varepsilon \sim 3\%$ (Fig. 1). Obviously, since the Doppler term cannot be determined sufficiently accurately, the best would be to eliminate it completely from the analysed signal. This is indeed possible if two kinds of radio links are available, a one-way downlink, synchronized to the on-board H-maser, and a two-way phase-locked loop (PLL), synchronized to the ground H-maser. The 1st-order Doppler shift of the two-way link is twice that of the one-way downlink, but the gravitational frequency shift is zero. The signals of these two links can be combined by a radio engineering scheme, first used in GP-A, so that its output fully retains the gravitational contribution but eliminates the 1st-order Doppler term.

For RadioAstron the GP-A compensation scheme is not directly applicable, because 1- and 2-way carrier frequency measurements (Fig. 2) cannot be performed simultaneously. Nevertheless, two modified versions of the Doppler compensation scheme are possible, both of which rely on spacecraft tracking by ground radio telescopes equipped with 8.4 or 15 GHz receivers (Duev et al. 2012). The first option requires switching back and forth between the 1-way ("H-maser") and 2-way ("Coherent") modes of operation (Fig. 2a, b). Interleaving the two synchronization modes results in two sets of gapped 1-way and 2-way frequency measurements, which, after interpolation, allow for direct application of the original GP-A 1st-order Doppler compensation scheme. The approach with interleaved measurements does not



a) b) c)

Figure 2: On-board hardware synchronization modes: a) "H-Maser"; b) "Coherent"; c) "Semi-Coherent". Note that the 8.4 GHz tone and the carrier of the 15 GHz data link cannot be synchronized independently.

rely on any features of the signal spectrum, and thus can be realized with telescopes equipped with any type of receiver (8.4 or 15 GHz).

The second approach to Doppler compensation involves recording the 15 GHz data link signal in the "Semi-Coherent" mode of the on-board scientific and radio equipment (Fig. 2c). 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 signal. This approach also depends on the broadband ($\sim$1 GHz) nature of the QPSK-modulated 15 GHz signal and the possibility of turning its spectrum into a comb-like form by transmitting a predefined periodic data sequence (Fig. 3). It was shown by Biriukov et al. (2014) that different subtones of the resulting spectrum act like separate links of the GP-A scheme and can be organized in software postprocessing into a combination, which is free from the 1st-order Doppler and tropospheric noise terms (the ionospheric term persists).

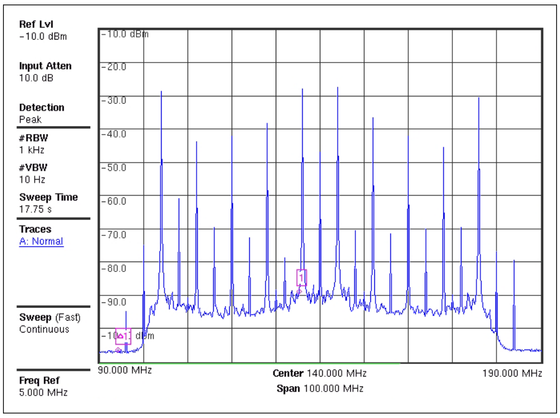


Figure 3: 15 GHz datalink signal spectrum in the "Test-2" 72 MHz mode of the on-board formatter.

Since in Europe only the Effelsberg telescope is equipped with a 15 GHz receiver, most experiments supported by the RadioAstron mission's Pushchino tracking station would use the first approach to Doppler compensation. By contrast, experiments supported by the Green Bank tracking station could use any of the two approaches since the GBT and all VLBA antennas are equipped with 8.4 and 15 GHz receivers and are capable of continuous spacecraft tracking (however, only Hn, NL and, of course, the GBT are located sufficiently close to the Green Bank tracking station to be able to observe RadioAstron during low perigee sessions). A single experiment would be made in two 1-hr sessions, one close to perigee and another close to apogee. The currently predicted RadioAstron orbit allows for 10 to 15 experiments in 2015 to 2016 with a modulation of the gravitational potential along the orbit of $\Delta U/c^2 \sim 3 \times 10^{-10}$ and 1 to 3 radio telescopes tracking the satellite. With preliminary values for the Allan deviation of $\sim 3 \times 10^{-14}$ at 1,000 s for the 1- and 2-way modes, the accuracy of the experiment could be as high as

$$\delta\varepsilon \sim 2 \times 10^{-5}. \tag{4}$$

3. PRESENT STATUS OF THE EXPERIMENT

Currently the experiment is in its testing phase. Up to now we have checked the operability of the required on-board hardware modes and performed a series of recordings of the satellite downlink signals using regular VLBI equipment at the RadioAstron mission's tracking station in Pushchino. The recovered signal frequencies show good agreement with ordinary frequency measurements performed at the tracking station as part of the mission support (Fig. 4). Their stability (Allan deviation of 6×10^{-14} at 1,000 s) is lower than required to achieve $\delta\varepsilon \lesssim 2 \times 10^{-5}$ but in accord with previous satellite tracking experiments at Pushchino. The recordings obtained from the first RadioAstron tracking test in the 2-way mode by a number of EVN and Asian telescopes exhibit at least 2 times better signal stability and give reason to believe that the above accuracy of the gravitational redshift test can be achieved.

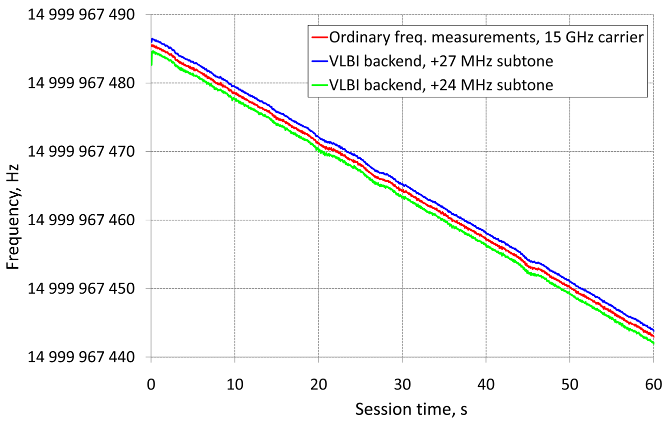


Figure 4: Frequency measurements of the 15 GHz signal subtones in the "Test-2" 18 MHz mode made at the Pushchino tracking station, 2014/08/31 08:20:00 UTC. The carrier frequencies were measured using standard tracking station equipment, the subtone frequencies were recovered from a 2-bit quantization 32 MHz bandwidth recording made by a VLBI backend. Subtone frequencies are offset by ~24 and ~27 MHz for easier comparison with the carrier frequency measurements.

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