A new method of testing the gravitational redshift effect with radio interferometers

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ABSTRACT
We propose a new method to measure gravitational redshift effect using simultaneous interferometric observations of a distant radio source to synchronize clocks. The first order by \( v/c \) contribution to the signal (the classical Doppler effect) is automatically canceled in our setup. When other contributions from the velocities of the clocks, clock imperfection and atmosphere are properly taken into account, the residual gravitational redshift can be measured with the relative precision of \( \sim 10^{-3} \) for RadioAstron space-to-ground interferometer or with precision up to few \( 10^{-5} \) with the next generation of space radio interferometers.

Key words: gravitation – techniques: interferometric – astrometry

1 INTRODUCTION

General relativity forms the basis of the modern physical picture of nature. However, it is not compatible with quantum theory (e.g. Carlip 2008). Attempts to unify general relativity and quantum theory lead to violation of the Einstein Equivalence Principle (EEP). Improving the accuracy of experimental tests of the EEP is thus one of the most important ways of finding hints to new physics (Braginski˘i & Rudenko 1970; Braginski˘i & Panov 1972; Braginski˘i & Manukin 1977; Will 2014).

One way to experimentally test the EEP is by measuring the gravitational redshift:

\[
\frac{\Delta \nu_{\text{grav}}}{\nu} = \frac{\Delta U}{c^2}(1 + \epsilon),
\]

where \( \delta U \) is the gravitational potential difference between the measurement points, \( c \) is the speed of light and \( \epsilon \) is the EEP violation parameter to be determined. The most accurate results may be obtained by maximizing \( \Delta U \), i.e. using measurements performed with the help of spacecrafts in the gravitational fields of the Earth, Moon or Sun. In what follows we assume that one of the measurement points is at the spacecraft (SC), while the other is at a ground tracking station (TS) located on the Earth.

There are several options for setting up an experiment to measure the gravitational redshift. In the simplest “one-way” experiment, a highly stable and/or accurate clock on board a spacecraft is used to synchronize its downlink signal frequency, \( f \), which is then measured at the receiving station. However, such a scheme is difficult to realize due to the fact that in addition to the gravitational redshift, many other significant factors contribute to the frequency shift: the Doppler effect, frequency shift due to the troposphere and ionosphere, etc. Instead, a specific configuration of spacecraft’s communication links pioneered by Gravity Probe A (Vessot & Levine 1979; Vessot et al. 1980) is usually used to cancel the Doppler and propagation effects. In this “compensation scheme” the ground TS transmits a signal of frequency \( \nu \), which is received by the SC with frequency \( \nu' \). The SC then coherently re-transmits this signal back to Earth, and also simultaneously emits a signal of frequency of \( \nu \) synchronized to its onboard clock. By comparing the initial frequency and the frequencies of the two signals received at the TS, it is possible to eliminate the tropospheric frequency shift and also that due to the Doppler effect in the first order in \( v/c \). This scheme was also successfully used on RadioAstron satellite (Briukov et al. 2014; Litvinov et al. 2016).

In this paper, we propose a new method to test the gravitational redshift that is based on clock comparison by observing distant quasars with a space-to-ground very-long baseline interferometer (VLBI), such as RadioAstron (Kardashev et al. 2013). The paper is organized as follows. In Section 2 we give an outline of the experiment under a simplifying assumption that the TS used to measure the SC’s radial velocity and the ground radio telescope (GRT), where the ground clock resides, are co-located. In Section 3 we
present a detailed account of the experiment taking into account that the TS and the GRT may be separated by several hundred or even thousand kilometers. In Section 4 we consider the accuracy of the proposed approach achievable with the RadioAstron space VLBI mission. We conclude by discussing the results and possible applications in Section 5.

2 SIMPLIFIED MODEL

Consider a two-element radio interferometer made up of stations A and B, each equipped with a radio telescope, a reference frequency standard (clock) and a VLBI back-end for signal registration. Suppose each radio telescope is receiving the same radio signal emitted by a distant point-like radio source, e.g. a quasar. At each station, the signal is heterodyned using a reference signal from its local clock, usually a hydrogen maser, and then digitized. After the signal has been recorded at each station, standard VLBI data processing is performed, probably at a different site, which allows one to determine the delay between the stations, τ, by maximizing the so-called visibility function (Thompson et al. 2017). Several factors contribute to this delay: the difference in the optical path lengths from the source to each stations, delays in the equipment, station clock offsets, gravitational time dilation experienced by the station clocks, etc. This delay is slowly changing and in the first order may be approximated by:

\[ \tau = \tau_0 + \tau_0 (t - t_0) + \ldots, \]

where \( t_0 \) is some fixed moment of time. If one of the stations is a spacecraft, the quadratic term is also usually taken into account to compensate for acceleration of the spacecraft. Let station A be the reference one, then:

\[ \dot{\tau} = \frac{\nu_B - \nu_A}{\nu_A}, \]

where \( \nu_A \) and \( \nu_B \) are the frequencies of the signal received by, respectively, station A and B. On the other hand, \( \dot{\tau} \) can be obtained by differentiating the delay:

\[ \dot{\tau} = -\frac{\mathbf{B} \cdot \mathbf{n}}{c} + \dot{\tau}_{\text{grav}} + \dot{\tau}_{\text{clock}} + \ldots, \]

where \( \mathbf{B} = \mathbf{V}_B - \mathbf{V}_A \) is the rate of change of the baseline vector (i.e. the vector pointing from A to B) and \( \mathbf{n} \) is a unit vector in the direction of the source (Fig. 1). The first term in this equation corresponds to the Doppler effect, however, for simplicity, it is shown here only in the first order in \( v/c \).

Equation (4) can be used to measure \( \dot{\tau}_{\text{grav}} \) if the terms on the right-hand side are known or small enough. The ground station position and velocity are usually known with sufficient accuracy, and the main uncertainty is due to additional phase rotation in the ionosphere and troposphere. Another major difficulty is to determine the velocity of the spacecraft, let it be station B, with sufficient accuracy. Therefore, apart from the ground station A, we must consider another tracking station (or several such stations), which measures the spacecraft radial velocity by Doppler tracking. We will assume that this additional tracking station is close enough to station A, so that the projection of the spacecraft velocity onto vector B can be measured accurately enough by Doppler tracking at this additional station. The velocity component in the direction orthogonal to B can be be determined with much lower accuracy. This fact restricts the allowed orientations of the interferometer significantly, making observations possible only in the directions very close to that of vector B. In this case the transverse velocity gives only a small contribution to Eq. (4).

In this case the distant radio source, the spacecraft and the tracking station are approximately aligned, with the spacecraft being in the middle. Therefore, the Doppler effect is, in the first order, of different sign as measured by the receiving station compared to Eq. (12). In other words, in the disposition of Fig. 1 the spacecraft is moving away from the Earth and the tracking station registers a negative Doppler shift, while the spacecraft is approaching the source and registers a positive Doppler shift, which will accordingly be reflected in the delay. This means that one can get rid of the Doppler effect in the first order, just like in the compensation scheme.

3 ACCURACY OF THE EXPERIMENT

3.1 Two stations

Suppose that during the time of measuring the position of the stations vary slightly compared to the distance between them. Then, based on the equation (4), we obtain the following relation for the measurement error \( \dot{\tau}_{\text{grav}} \):

\[ \sigma^2_{\text{grav}} = \frac{1}{c^2} \left( \sigma^2_{\nu_A} \cos^2 \alpha + \sigma^2_{\nu_B} \cos^2 \alpha + |\mathbf{V}_B - \mathbf{V}_A|^2 \sigma^2_{\cos \alpha} \right) + \sigma^2_{\text{fit}} + \sigma^2_{\text{clock}} + \sigma^2_{\text{atm}} + \ldots, \]

where \( \sigma_{\nu_A}, \sigma_{\nu_B} \) — station speed errors, \( \cos \alpha \) — cosine of the angle between the base vector and the direction to the source, \( |\mathbf{V}_B - \mathbf{V}_A| \) — absolute difference of station speeds, \( \sigma_{\cos \alpha} \) — measurement error of the cosine of the angle between the base vector and the direction to the source, \( \sigma_{\text{fit}} \) — error in determining the rate of change of the delay in the process of searching for interference lobes, \( \sigma_{\text{clock}} \) — clock error, \( \sigma_{\text{atm}} \) — phase change error as it passes through the atmosphere.

The velocity measurement errors for a network of terrestrial radio telescopes participating in geodetic measurements...
are $\sim 1 \mu m/s$. Direction error to the source $\sigma_{\cos \alpha} = \sigma_{\alpha} \sin \alpha$, where $\sigma_{\alpha} \sim 10^{-8}$ for sources used for geodetic tasks (Sovers et al. 1998; Thébault et al. 2015; Pavlis et al. 2012). The accuracy of the clock $\sigma_{\text{clock}}$ depends on the accumulation time. For estimates, we take the characteristic value of $\sigma_{\text{clock}} = 3 \times 10^{-12}$ for an accumulation time of 1000 seconds.

The error $\sigma_{\alpha}$ depends on the delay model used when searching for interference lobes, on the algorithm for maximizing the visibility function, and on the signal-to-noise ratio for a particular experiment. We start from the delay model used in the PIMA Petrov et al. (2011) program. Namely, the interference lobe search procedure consists in finding the maximum of the function

$$C(\tau_p, \tau_g, \tau_\phi, \tau_\gamma) = \sum_k \sum_j c_{kj} w_{kj} \times e^{i(\omega_0 \tau_p + \omega_\beta \tau_\phi + (\omega_\gamma - \omega_0) \tau_\gamma + (\omega_\delta - \omega_0) \tau_\delta(t_k - t_0))},$$

where $\tau_p$, $\tau_g$ — phase and group delay, $\tau_\phi$, $\tau_\gamma$ — phase and group delay variation rates, $c_{kj}$ — discretized cross-correlation function, index $k$ runs on time, index $j$ — on frequency, $w_{kj}$ — weight measurements, $\omega_0$ and $t_0$ — reference circular frequency and time.

The frequency change due to the gravitational redshift leads to a change in both the phase and group rate of change of the delay in accordance with the equation (3). Transforming equation (14) from Whitney et al. (1976), we obtained the accuracy of determining these velocities:

$$\sigma_{\tau_p} = \frac{6 \eta}{\pi S \nu_0 \Delta \nu},$$

$$\sigma_{\tau_g} = \frac{6 \eta}{\pi S \Delta \nu / \Delta \tau},$$

where $\eta$ is the quantization efficiency coefficient, $S$ is the signal-to-noise ratio, defined as the ratio of the antenna temperature to the system noise temperature in the case of identical antennas, $\nu_0 = \omega_0 / 2\pi$ — reference frequency, $\Delta \nu$ — the width of the observation bandwidth, $\Delta \tau$ — the accumulation duration. Since radioastronomical observations at frequencies above gigahertz are usually $\nu_0 \gg \Delta \nu$, as can be seen from the equations (7) and (8), the accuracy of measuring the phase rate of change of the delay higher than the group, so it is proposed to use $\tau_p$ to measure the gravitational redshift.

The estimates of the terms of the equation (5) are given in Table 1. The greatest contribution to the total error is given by the station speed errors.

### 3.2 Earth-space interferometer

If one telescope is in space, direct measurement of the radial velocity component using the Doppler effect between the spacecraft and the ground tracking station is possible. In general, the tracking station does not have to coincide with the ground-based telescope, therefore, we introduce into the scheme shown in Fig. 1 another station $C$, located on the surface of the Earth. The expression for the measurement error of the gravitational redshift is given in Appendix A:

$$\sigma_{\nu_0}^2 = \sigma_{\Delta \nu / \nu}^2 \cos^2 \beta + \left(\frac{\nu_B - \nu_C}{\nu_{\beta}} \right) \sin^2 \beta \sigma_{\beta}^2 + \sigma_{\Delta \nu / \nu}^2 \sin^2 \beta \sigma_{\Delta \nu / \nu}^2 + \sigma_{\text{clock}}^2 + \sigma_{\text{atm}}^2 + \ldots,$$

where $\sigma_{\Delta \nu / \nu}$ is the measurement error of the frequency shift of the signal transmitted from the spacecraft to the receiving station $C$, $\beta$ is the angle between the direction to the source and the CB line connecting the spacecraft and the receiving station, $\gamma$ — the angle between the direction to the source and the line CA connecting the ground-based telescope and the receiving station, $\sigma_\beta$, $\sigma_\gamma$, are the errors in determining the corresponding angles, $\sigma_{\Delta \nu / \nu}$ is the error in measuring the projection of the velocity of spacecraft relative to station $C$ perpendicular to the direction to this station. The remaining quantities were entered in the equation (5).

As an example, we consider the space-space interferometer Radioastron. For it, the frequency shift can be measured with an accuracy of about $\sigma_{\Delta \nu / \nu} \sim 3 \times 10^{-13}$, while the lateral velocity is measured by restoring the orbit from many measurements and has an error about 2 mm / s (Zaslavskiy et al. 2016), which corresponds to the error $\sigma_{\beta} \sim 7 \times 10^{-12}$. Therefore, to increase the accuracy of gravitational redshift measurements, it is necessary to make $\sin \beta$ as small as possible. The Table 2 provides estimates of accuracy for the angle $\beta = 3^\circ$. Even with such a small value of this angle, the measurement error $\sigma_{\nu_0}^2$ for the ground-space interferometer is determined mainly by the error in measuring the speed of the spacecraft perpendicular to the direction to the receiving station.

### 4 MEASURING THE GRAVITATIONAL REDSHIFT USING RADIOASTRON

In this section we evaluate the accuracy of the experiment achievable with the space radio telescope RadioAstron based on equation (4). We add several noise terms on its right-hand side. We assume the noise of the on-board clock (Zaslavskiy, Zachvatkin, Stepanyants, Tuchin & Shishov) is characterized by the following power spectral density (PSD):

$$F_{\text{clock}} = 1.5 \times 10^{-26} + 7.5 \times 10^{-31} f^{-1}.$$  \hfill (10)

In our simulations we also include the noise of the troposphere, which, following (Keihm et al. 2004; Boehm et al. 2006; Hernández-Pajares et al. 2009) we characterize by the following PSD:

$$F_{\text{atm}} = 2.8 \times 10^{-28} f^{-0.4}.$$  \hfill (11)

Other parameters of the experimental setup are summarized in Table 3. To account for orbit determination errors, we also introduce an uncorrelated gaussian process with zero mean and a standard deviation corresponding to the magnitude of the velocity error. We assume the duration of a single observation is 2400 s, the experiment lasts for 200 days and consists of 400 observations equally spaced over this time period.

We note that the RadioAstron spacecraft has several observational limitations (i.e. the spacecraft has attitude limitations with regard to the Earth, the Sun and the Moon).
Table 1. Estimation of gravitational redshift measurement errors for two radio telescopes in the equation (5).

| Component | Value | Comment |
|-----------|-------|---------|
| $\sigma_{V_A}/c$, $\sigma_{V_B}/c$ | $3 \times 10^{-14}$ | Accuracy 0.01 mm/s |
| $|V_B - V_A|/c$ | $3 \times 10^{-15}$ | $\alpha \sim 90^\circ$, $\sigma_{\cos \alpha} = 10^{-8}$, $|V_B - V_A| = 100 / c$ |
| $\sigma_{\text{fit}}$ | $3 \times 10^{-15}$ | $S = 100$, $v_0 = 5$ GHz, $\eta = 0.7$, $\Delta t = 1000$ s |
| $\sigma_{\text{clock}}$ | $3 \times 10^{-15}$ | $\Delta t = 1000$ s |
| $\sigma_{\text{grav}}$ | $5 \times 10^{-14}$ | |

Table 2. Estimation of gravitational redshift measurement errors for the ground-space interferometer in the equation (??).

| Component | Value | Comment |
|-----------|-------|---------|
| $\sigma_{\Delta v/\nu}$ | $3 \times 10^{-13}$ | |
| $\sigma_{\nu_B - \nu_C} \sin \beta$ | $2 \times 10^{-15}$ | $\nu_B - \nu_C = 3 \times 10^{-6}$, $\sigma_{\beta} = 10^{-8}$, $\beta = 3^\circ$ |
| $\sigma_{\nu_C} \sin \beta$ | $3.5 \times 10^{-13}$ | $\sigma_{\Delta v_3} = 20$ mm/s, $\beta = 3^\circ$ |
| $\nu_C - \nu_A \cos \gamma$ | $3 \times 10^{-14}$ | |
| $\sigma_{\text{fit}}$ | $1 \times 10^{-14}$ | $S = 20$, $v_0 = 5$ GHz, $\eta = 0.7$, $\Delta t = 1000$ s |
| $\sigma_{\text{clock}}$ | $3 \times 10^{-15}$ | $\Delta t = 1000$ s |
| $\sigma_{\text{grav}}$ | $5 \times 10^{-13}$ | |

Therefore it is possible to make observations only during certain periods of time. We examined the observational capabilities for the experiment during the period of July 2018 - June 2019 (RadioAstron AO-6 period). The results are presented in Fig. 2.

Using the maximum likelihood estimation we obtain the dependence of the accuracy of measuring the LPI violation parameter on the duration of the experiment depicted in Fig. 3. The accuracy is mostly limited by the uncertainty of orbit determination, and, specifically, the radial velocity of the spacecraft relative to the ground tracking station.

For the purpose of comparison we also estimate the accuracy achievable for the hypothetical case of the uncertainty of the radial velocity at the level of 1 $\mu$m/s. We expect this accuracy to be realistic for future space VLBI missions. In this case the accuracy of the redshift test quickly exceeds that of the dedicated Gravity Probe A experiment Vesovt et al. (1980) and after 200 days reaches $\sim 3 \times 10^{-5}$ (see Fig. 4).

5 CONCLUSIONS

Using ground-to-space radio interferometers to measure the gravitational redshift effect appears to be a viable option to testing the Einstein Equivalence Principle. We discussed the experiment setup and particularly noted the necessity to accurately determine the velocity of the spacecraft and discussed a possible way to decrease the influence of insufficient accuracy of determination of the transverse component of the velocity by observing sources near the line of sight of the distant quasar. We showed that the accuracy achievable with the current space VLBI mission RadioAstron is two orders of magnitude below the current best test of the redshift obtained by Gravity Probe A. If future space VLBI missions are equipped with better means for orbit determination (e.g. permanently reachable laser retroreflectors, GNSS receivers and so on) testing the gravitational redshift may become an important science case for future space VLBI missions.

Table 3. Parameters of the simulation to estimate the accuracy of the experiment with RadioAstron

| Parameter | Value |
|-----------|-------|
| radial velocity accuracy | 2 mm/s |
| observation frequency | 4.8 GHz |
| bandwidth | 32 MHz |
| amplitude quantization | 2 bit |
| signal-to-noise ratio | 20 |
A new method of testing the gravitational redshift effect with radio interferometers

Figure 2. The accuracy of the experiment to measure the gravitational redshift using the RadioAstron space-to-ground radio interferometer. Spacecraft velocity determination: 2 mm/s.

Figure 3. The accuracy of the experiment to measure the gravitational redshift using the RadioAstron space-to-ground radio interferometer. Spacecraft velocity determination: 2 mm/s.

Figure 4. The accuracy of the experiment to measure the gravitational redshift using the RadioAstron space-to-ground radio interferometer. Spacecraft velocity determination: 1 µm/s.

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APPENDIX A

The measured values are the rate of change of the delay between ground station A and space B, \( \dot{\tau} \), as well as the radial and tangential (with respect to station C) components of the difference in speed of receiving station C and KA. Let us rewrite the equation for rate of change delays (4) so that it includes these measured values:

\[
\dot{\tau} = -\frac{(v_B - v_C) + (v_C - v_A)n}{c} + \dot{\tau}_{\text{grav}} + \dot{\tau}_{\text{clock}} + \ldots \quad (12)
\]

The difference \((v_B - v_C)\) is represented as the sum of two components of \(\Delta v_r\) and \(\Delta v_t\), directed along and across the CB line, respectively. Denote the angle between the direction to the source and the line CB as \(\beta\), and between the line CA and the direction to the source as \(\gamma\). Then the equation (12) is rewritten as:

\[
\dot{\tau} = -\frac{\Delta v_r \cos \beta + \Delta v_t \sin \beta + |v_C - v_A| \cos \gamma}{c} + \dot{\tau}_{\text{grav}} + \dot{\tau}_{\text{clock}} + \ldots \quad (13)
\]

To determine \(\Delta v_r\), measurements of the frequency shift of the signal transmitted from the spacecraft to the receiving station C will be used:

\[
\frac{\nu_B - \nu_C}{\nu_C} = \frac{\Delta \nu_r}{c} + \left(\frac{\Delta \nu_{BC}}{\nu}\right)_{\nu} + \left(\frac{\Delta \nu_{BC}}{\nu}\right)_{\text{grav}}, \quad (14)
\]

where \(\left(\frac{\Delta \nu_{BC}}{\nu}\right)_{\nu}\) is the part of the frequency shift that contains terms of the second and higher orders in \(v/c\) for the effect Doppler, \(\left(\frac{\Delta \nu_{BC}}{\nu}\right)_{\text{grav}}\) is the contribution of the gravitational red shift between the spacecraft and station C to
the measured frequency difference. If the reference signal is emitted from the Earth to measure speed, and then the SC is coherently re-emitted to Earth (analogous to the “Coherent” mode in Radio Astron), \( \left( \frac{\Delta \nu_{BC}}{\nu} \right)_{\text{grav}} = 0 \) with accuracy up to the second order in \( v/c \).

Substituting \( \Delta \nu \) from (14) into (13), we get the following expression:

\[
\dot{\tau} = -\frac{c \nu A - c \nu C}{c^2} \cos \beta - \frac{\Delta \nu}{c} \sin \beta - \frac{\nu}{c^2} (\nu_A - \nu_C) \cos \gamma + \\
+ \left[ \left( \frac{\Delta \nu_{BC}}{\nu} \right)^2 \right] \cos \beta + \dot{\tau}_{\text{grav}} + \dot{\tau}_{\text{clock}} + \ldots.
\]  

(15)

We also introduce the notation

\[
\dot{\tau}'_{\text{grav}} = \dot{\tau}_{\text{grav}} + \left[ \left( \frac{\Delta \nu_{BC}}{\nu} \right)^2 \right] \cos \beta.
\]  

(16)

This value depends on the gravitational potentials at points A, B, C, and also contains terms of the second and higher orders in \( v/c \) for the Doppler effect. Measuring the value of \( \dot{\tau}'_{\text{grav}} \) allows you to check the Einstein equivalence principle, but the type of its dependence on the potentials of the solar system bodies and speeds of the spacecraft and two ground stations is determined by the model deviation from the Einstein equivalence principle. For example, in the simplest case, the gravitational redshift between two points is described by the equation

\[
\Delta \nu_{\text{grav}} = \frac{\Delta U}{c^2} (1 + \epsilon),
\]  

(17)

where \( \epsilon \) — a parameter that characterizes the violation, and it is the same for all navigational bodies. Then

\[
\dot{\tau}'_{\text{grav}} = \frac{U_B (1 + \cos \beta) - U_A - U_C \cos \beta}{c^2} (1 + \epsilon) + O((v/c)^2),
\]  

(18)

where \( U_A, U_B, U_C \) is the sum of the gravitational potentials of all bodies at points A, B and C, respectively, \( O((v/c)^2) \) are members of the second and higher orders for the Doppler effect between the spacecraft and the receiving station C.

As a result, by imposing small deviations on all quantities in (15), we obtain the formula for the measurement error of \( \dot{\tau}'_{\text{grav}} \) for the ground-space interferometer (9).

REFERENCES

Biriukov A. V., Kauta V. L., Kulagin V. V., Litvinov D. A., Rudenko V. N., 2014, Astronomy Reports, 58, 783

Boehm J., Werl B., Schuh H., 2006, Journal of Geophysical Research: Solid Earth, 111, n/a

Braginskii V. B., Manukin A. B., 1977, Measurement of weak forces in physics experiments

Braginskii V. B., Rudenko V. N., 1970, Soviet Physics Uspekhi, 13, 165

Braginskii V. B., Panov V. I., 1972, Soviet Journal of Experimental and Theoretical Physics, 34, 463

Carlip S., 2008, Classical and Quantum Gravity, 25, 154010

Hernández-Pajares M., et al., 2009, Journal of Geodesy, 83, 263

Kardashev N. S., et al., 2013, Astronomy Reports, 57, 153

Keihm S. J., Tanner A., Rosenberger H., 2004, Interplanetary Network Progress Report, 158, 1

Litvinov D. A., et al., 2016, preprint, (arXiv:1605.05832)

Pavlis N. K., Holmes S. A., Kenyon S. C., Factor J. K., 2012, Journal of Geophysical Research: Solid Earth, 117, n/a

Petrov L., Kovaichev Y. V., Fomalont E. B., Gordon D., 2011, AJ, 142, 435

Sovers O. J., Fanselow J. L., Jacobs C. S., 1998, Rev. Mod. Phys., 70, 1393

Thébault, E., et al., 2015, Earth, Planets and Space, 67, 79

Thompson A. R., Moran J. M., Swenson Jr. G. W., 2017, Interferometry and Synthesis in Radio Astronomy, 3rd Edition, doi:10.1007/978-3-319-44431-4.

Vessot R. F. C., Levine M. W., 1979, General Relativity and Gravitation, 10, 181

Vessot R. F. C., et al., 1980, Physical Review Letters, 45, 2081

Whitney A. R., et al., 1976, Radio Science, 11, 421

Will C. M., 2014, Living Reviews in Relativity, 17, 4

Wolf P., Blanchet L., 2016, Classical and Quantum Gravity, 33, 035012

Zaslavskiy G. S., Zakhvatkin M. V., Stepanyants V. A., Tuchin A. G., Shishov V. A., 2016, Vestnik NPO im. S.A. Lavochkina, 3, 25

Active on-board hydrogen maser for Radioastron space mission VCH-1010, https://www.vremya-ch.com/english/product/index6e49.html?Razdel=8&Id=39

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