Einstein Equivalence Principle test
with RadioAstron: preliminary results

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Introduction
RadioAstron:  
- Launched in 2011  
- Proposal-driven space-VLBI observatory  
- 10 m dish in space  
- 1.35; 6; 18; 92 cm wavelengths  
- tracking stations: Russia & US
Litvinov: EEP test with RadioAstron

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T&C link not working from Jan 2019. Small but non-zero hope for revival. Science equipment ok
EEP holds:

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EEP broken (LPI violation):
\[ \frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U}{c^2} (1 + \varepsilon) \]
Grav. redshift modulation:

\[ \frac{\Delta f_{\text{grav}}}{f} = 0.4 \cdot 10^{-10} - 5.8 \cdot 10^{-10} \]

RadioAstron compared to GP-A and Galileo:
- more stable H-maser
- greater redshift modulation
- multiple measurements (vs. GP-A)

Estimated accuracy: \( \delta \varepsilon = (1-2) \times 10^{-5} \)
One-way approach to measuring redshift

Fractional frequency shift of the spacecraft downlink:

\[ \frac{\Delta f}{f} = -\frac{\dot{D}}{c} - \frac{v_s^2 - v_e^2}{2c^2} + \frac{\left(\vec{v}_s \cdot \vec{n}\right)^2 - \left(\vec{v}_e \cdot \vec{n}\right) \cdot \left(\vec{v}_s \cdot \vec{n}\right)}{c^2} \]

\[ + \frac{\Delta U}{c^2} + \frac{\Delta f_{trop}}{f} + \frac{\Delta f_{ion}}{f} + \frac{\Delta f_{instr}}{f} + O\left(\frac{v}{c}\right)^3 \]

Pro: 6 years of radio science data

Con: orbit reconstruction accuracy

Accuracy of \( \dot{D} \sim 0.5 \text{ mm/s} \) → \( \delta \varepsilon \sim 2 \times 10^{-3} \)
One-way data analysis results

\[ \varepsilon = (-3.0 \pm 0.2) \times 10^{-2} \]

Systematics partially understood
Data processing

**Dedicated experiments:** as in GP-A, compensate for 1\textsuperscript{st}-order Doppler and troposphere using a 2-way link

\[
\Delta f_{1w} - \frac{1}{2} \Delta f_{2w} = \Delta f_{\text{grav}} + \Delta f_0 + f_0 \left( \frac{|v_s^2 - v_e^2|}{2c^2} + \frac{a_e \cdot n}{c} \Delta t \right) + \Delta f_{\text{ion}}^{(\text{res})} + \Delta f_{\text{fine}} + O(v/c)^4
\]

- measured
- to be determined
- computed from orbit, models, aux. data
- determined

**Fine effects:** \(O(v/c)^3\), environmental sensitivities etc.

**Final step – regression analysis:**

\[
\frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U}{c^2} (1 + \varepsilon)
\]

**Data:** Gb, Ef, Hh, On, Sv, VLBA, Wn, Wz, Yg, Ys, Zc + tracking stations
\[ \frac{\delta f}{f} = \frac{\Delta f_{\text{grav}}}{f} - \frac{\Delta U}{c^2} = \varepsilon \frac{\Delta U}{c^2} \]

\[ \varepsilon = (0.3 \pm 1.7) \times 10^{-4} \]
Experiment: raks17aw/ay/az/ba (29-30 September 2016)

Effect magnitude, $\Delta f/f$

- gravitation
- $(v/c)^2$
- $(v/c)^3$
- magn. field
- troposphere
- ionosphere
- geocent. dist.

Observation

NB: abs. values plotted
Velocity accuracy problem:
orbit determined from all data: 3-5 mm/s
orbit determined from all data excluding one-way doppler: 15-50 mm/s

gives error up to $5 \times 10^{-15}$ in $O(v/c)^2$ terms

Is it a problem that orbit determined using one-way doppler assumes $\epsilon = 0$? Perform covariance analysis.
Systematic errors: covariance analysis

Covariance matrix based on analysis of March 2017 data

Over 800 parameters solved for, including the EEP violation parameter

(Others: spacecraft state vector, SRP coefficients, reaction wheel unloading, etc.)
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Let’s zoom into this area
Systematic errors: covariance analysis

- Momentum perturbations due to desaturation of reaction wheels
- Ground station position & velocity
- Solar radiation pressure coefficients
- Space H-maser frequency biases (piecewise)
- EEP violation parameter \( \varepsilon \)
- Unmodelled accelerations

**Good:** \( \varepsilon \) is not correlated with the spacecraft state vector

**Bad:** it is strongly correlated with the H-maser frequency biases (used in the analysis)
Lessons from the covariance analysis:

1. EEP violation parameter $\varepsilon$ is correlated only with H-maser frequency biases (piece-wise and independent).
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3. Uncertainties in other parameters are harmless, e.g. tracking station position error up to 1 m is ok.
Generalize the redshift violation model:

1. Redshift violation parameter $\varepsilon$ may depend on clock type and element composition of the gravitational field source (null tests)

2. EEP violation due to other bodies is 1st order in respective $\Delta U$’s (Wolf & Blanchet, 2016)
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\[
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\]

\[
\frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U_E}{c^2} + \frac{\varepsilon_E \Delta U_E + \varepsilon_S \Delta U_S + \varepsilon_M \Delta U_M + \ldots}{c^2}
\]

E – Earth
S – Sun
M – Moon
Accuracy of measuring $\varepsilon_E$ with RadioAstron – simulations

Generalizing the redshift violation model

![Graph showing the accuracy of measuring $\varepsilon_E$ over time with RadioAstron simulations. The graph plots the 1σ-error of $\varepsilon_E$ against time (in days from 1 Jan 2012). Four cases are shown: Ignore Sun, $\varepsilon_S = \varepsilon_E$, $\varepsilon_S \neq \varepsilon_E$, and $\varepsilon_S \neq \varepsilon_E \neq \varepsilon_M$. The graph demonstrates a significant decrease in error over time, with the 1 orbit marker indicating a point of interest.]
Generalizing the redshift violation model

Accuracy of measuring $\varepsilon_E$ with RadioAstron – simulations

Little change for accuracy of $\varepsilon_E$ when adding Sun and Moon violations
Summary

1. Data collection finished, analysis in progress

2. One-way data analysis: accuracy of $\sim 10^{-3}$ as expected, systematics

3. Accuracy of $\sim 10^{-4}$ achieved in a single experiment
   (GP-A: $1.4 \times 10^{-4}$, Galileo: $2.48 \times 10^{-5}$, $3.1 \times 10^{-5}$)

4. Work in progress: H-maser clock model

5. Now taking into account the possibility of Sun and Moon redshift violation
Thank you!