Probing general relativity with RadioAstron

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Basics

Equivalence principle \[ \rightarrow \quad \frac{\Delta T_{\text{grav}}}{T} = \frac{\Delta U}{c^2} \]
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\[ \frac{\Delta T_{\text{spec.rel.}}}{T} = \frac{v_e^2 - v_s^2}{2c^2} \]

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\[ \frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U}{c^2} \]
Motivation

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

Possible mechanisms: Local Position Invariance broken (dark matter halo, etc.)

Violation magnitude: difficult to predict
Gravity Probe A (1976)

Experiment duration 1 hr 58 min
Apogee 10,000 km
Grav. redshift variation $\Delta U/c^2$ $4 \times 10^{-10}$
H-maser stability $\sigma_y$ $1 \times 10^{-14}$ at 100 s

$$\frac{\Delta f}{f} = (1 \pm (0.05 \pm 1.4) \cdot 10^{-4}) \frac{\Delta U}{c^2}$$

$\delta \varepsilon$: accuracy

R. F. C. Vessot (right) and M. Levine (left) with the VLG-10 H-maser
Grav. redshift modulation:

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

RA: Better H-maser stability:
\[ \sigma_y = 2 \times 10^{-15} \text{ at 1 hr} \]

Target accuracy of the test:
\[ \delta \varepsilon = 2.5 \times 10^{-5} \]
Problem: nonrelativistic Doppler

For a spacecraft:

\[
\frac{\Delta f}{f} = -\frac{\dot{D}}{c} - \frac{v_s^2 - v_e^2}{2c^2} + \frac{(\vec{v}_s \cdot \vec{n})^2 - (\vec{v}_e \cdot \vec{n}) \cdot (\vec{v}_s \cdot \vec{n})}{c^2} \\
+ \frac{\Delta U}{c^2} + \frac{\Delta f_{\text{trop}}}{f} + \frac{\Delta f_{\text{ion}}}{f} + \frac{\Delta f_{\text{instr}}}{f} + O\left(\frac{v}{c}\right)^3
\]

In principle: 1-way down-link synchronized to on-board H-maser and 2-way phase-locked loop synchronized to ground H-maser

1\textsuperscript{st} order Doppler shift in 2-way link is twice that in 1-way link
Two approaches:
1) Compensation: switching between 1-way and 2-way modes
2) Calculation: laser tracking (experimental)

Frequency measurement

RadioAstron is the “celestial” source

Phase-stopped signal spectrum
(Ef, raks10ae, 2015/02/15)

Phase residual (Ef, raks10ae)

Allan deviation

Intermediate frequency, Hz

Power (normalized)

10^0 10^-2 10^-4 10^-6 10^-8

1498 1499 1500 1501 1502

Time, UTC (2015/02/15)

Phase, rad

0 0.5 1 1.5 2

17:40 17:45 17:50 17:55

Allan deviation $\sigma_0(\tau)$

Averaging time $\tau$, s

10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15}

0.01 0.1 1 10 100 1000 10000 100000

Ground telescope (Effelsberg)
Tracking station (Green Bank)
RadioAstron on-board H-maser
Interleaved measurements mode

2015/10/31 EL053C Effelsberg
250,000 km

Distance: 250,000 km

Session time, s
Interleaved measurements mode

2015/11/02 EL053D Effelsberg
55,000 km

Residual frequency, Hz

Session time, s

Redshift modulation: 0.42 Hz
Low-distance tracking

Stopped-phase signal spectrum

Svetloe

Wettzell 20m

Wettzell 12m (Wn)

Yarragadee

Residual phase

Svetloe

Wettzell 20m

Wettzell 12m (Wn)

Yarragadee

New antennas struggle from saturation
Interleaved measurements mode

2016/05/29 EL053G Onsala
54,000–42,000 km

Discrepancy: 3 mHz
Additional effects

Minor kinematic effects:
(+) $2^{nd}$-order Doppler, etc.

Media:
(+) troposphere, ionosphere (GNSS, WVR, models)

Instrumental:
(+) H-maser frequency drift
(−) temperature (to do)
(−) external magnetic field (to do)
   etc.
Systematics: drift

On-board H-maser frequency drift rel. to the Green Bank H-maser

Drift: \(1.5 \times 10^{-14} \text{ /day} \rightarrow 3.6 \times 10^{-14} \text{ /day}\)
Summary of results

Accuracy goal: $2 \times 10^{-5}$

Accuracy achieved: $4 \times 10^{-4}$

To do: data processing lag, systematic effects

Competition:

- Galileo 5 & 6: $(3-4) \times 10^{-5}$, 2017
- ACES: $2 \times 10^{-6}$, 2018
- STE-QUEST, E-GRIP?
Thank you!