Probing the gravitational redshift effect with VLBI observations of the RadioAstron satellite

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1st International Workshop on VLBI Observations of Near-field Targets
Bonn University, 5-6 October 2016

Basics

Equivalence principle $\rightarrow$ $$\frac{\Delta T_{\mathrm{grav}}}{T} = \frac{\Delta U}{c^2}$$

$$\frac{\Delta T_{\mathrm{spec.rel.}}}{T} = \frac{v_e^2 - v_s^2}{2c^2}$$

Daily time dilation	ISS	RadioAstron
gravitation	**–4 μs**	**–58 μs**
gravitation + kinematics	**25 μs**	**–57 μs**

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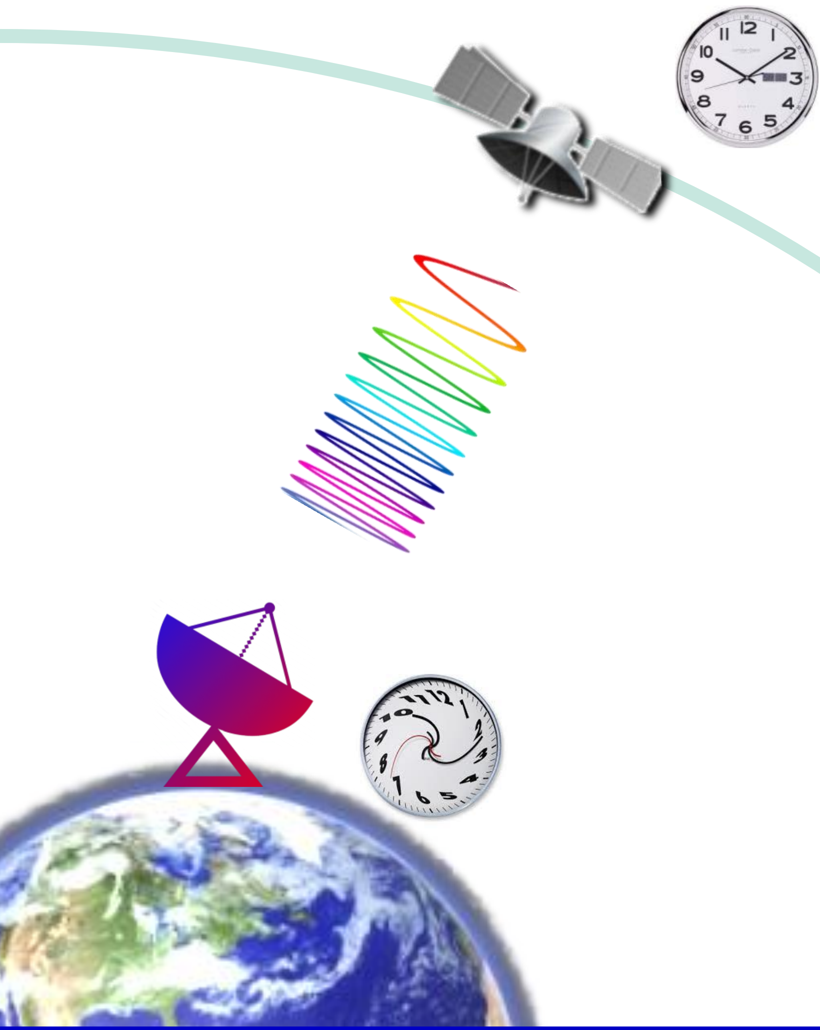

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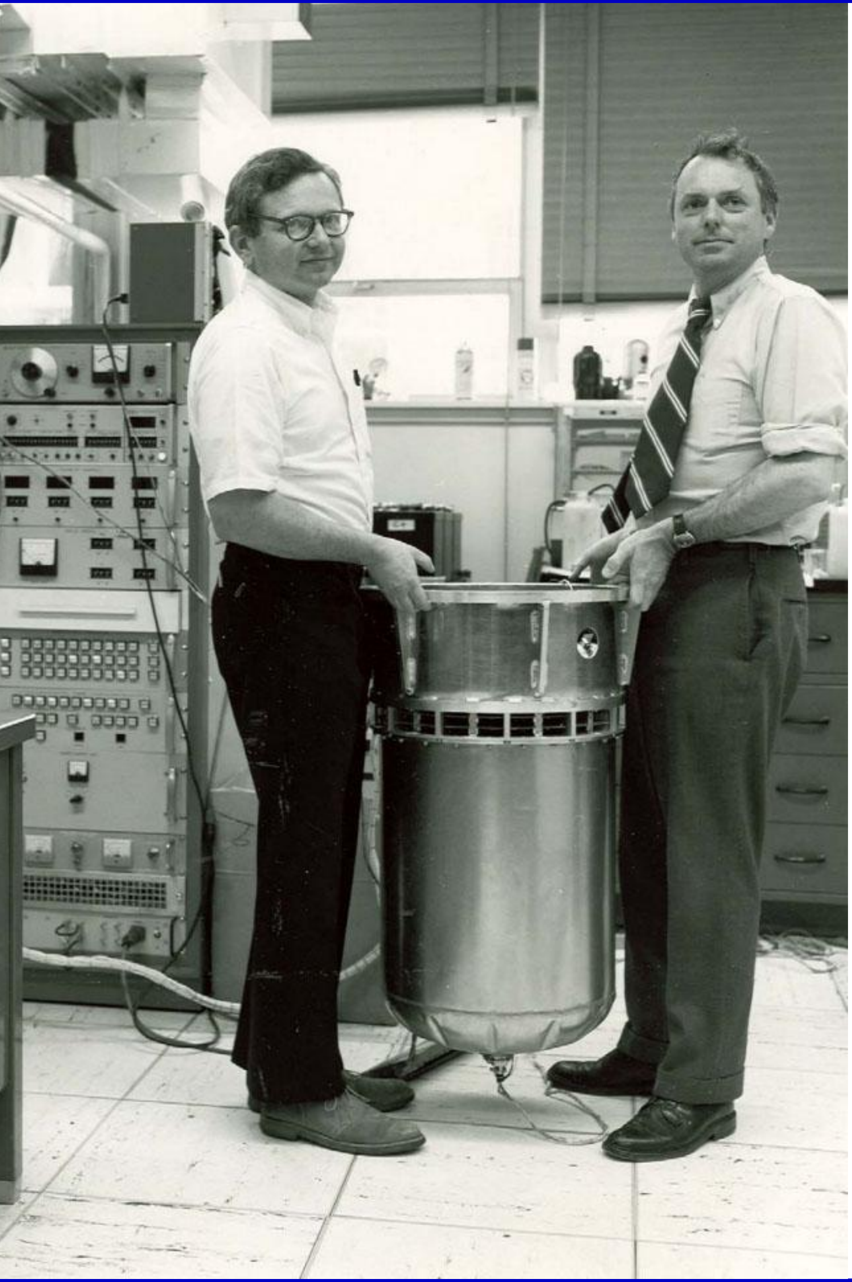
$$\frac{\Delta f_{\text{grav}}}{f} = \frac{\Delta U}{c^2}$$

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

violation parameter

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

Violation magnitude: difficult to predict



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

$$\frac{\Delta f}{f} = \left(1 \pm \underbrace{(0.05 \pm 1.4)\cdot 10^{-4}}_{\delta\varepsilon:\ \text{accuracy}}\right)\frac{\Delta U}{c^2}$$

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

RadioAstron: a radio astronomy space-VLBI mission

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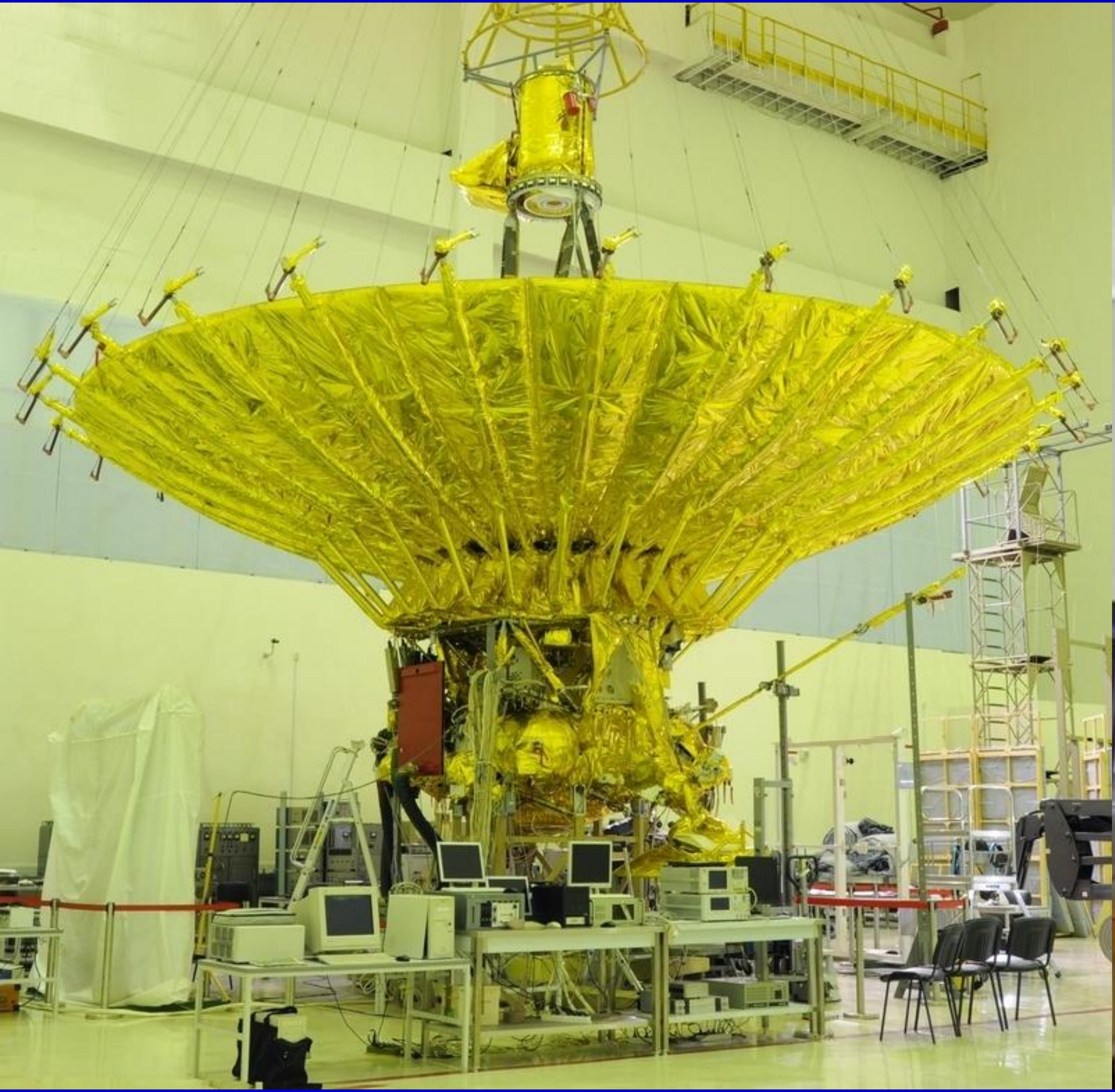
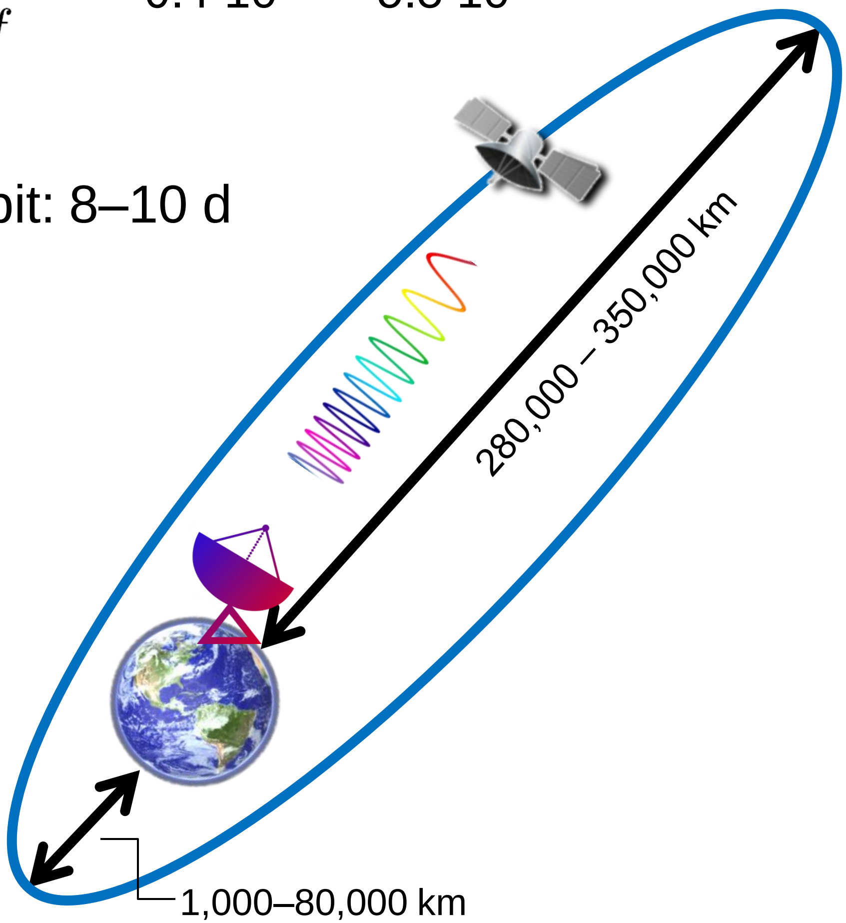


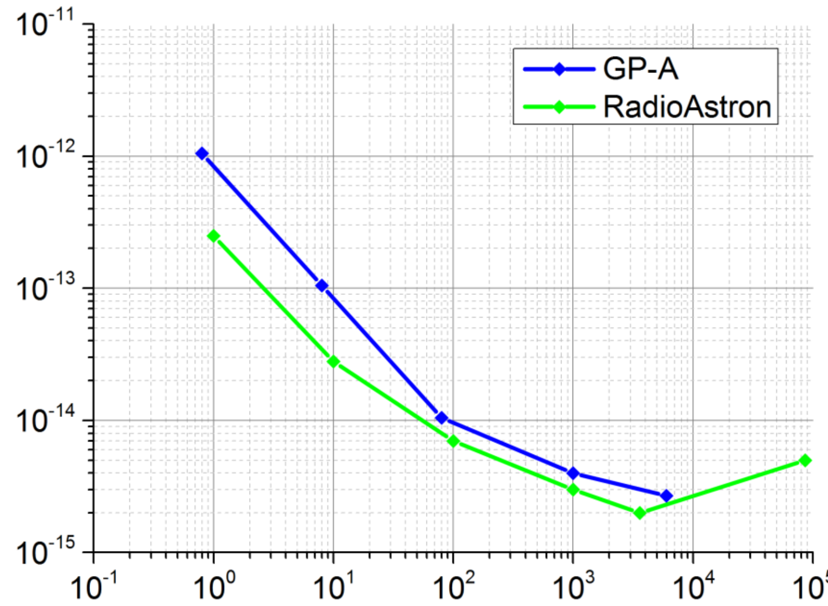
Grav. redshift modulation:

$$\frac{\Delta f_{\rm grav}}{f} = 0.4\cdot10^{-10} - 5.8\cdot10^{-10}$$

Orbit: 8–10 d



Allan deviation



RA: Better H-maser stability:

$\sigma_y = 2\times10^{-15}$ at 1 hr

Target accuracy of the test:

$\delta\varepsilon = 2.5\times10^{-5}$

RadioAstron: communications links and ground terminals


Green Bank tracking station (USA)


Pushchino tracking station (Russia)

Links:

8.4 GHz down (tone)
15 GHz down (data)
7.2 GHz up (tone)
S-band T&C

+SLR

Idea:

Compare the on-board H-maser frequency with that of H-masers at various radio astronomy observatories

Gb, Ef, Hh, On, Sv, VLBA, Wn, Wz, Yg, Zc + tracking stations

Problem: nonrelativistic Doppler

For a spacecraft:

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

measured

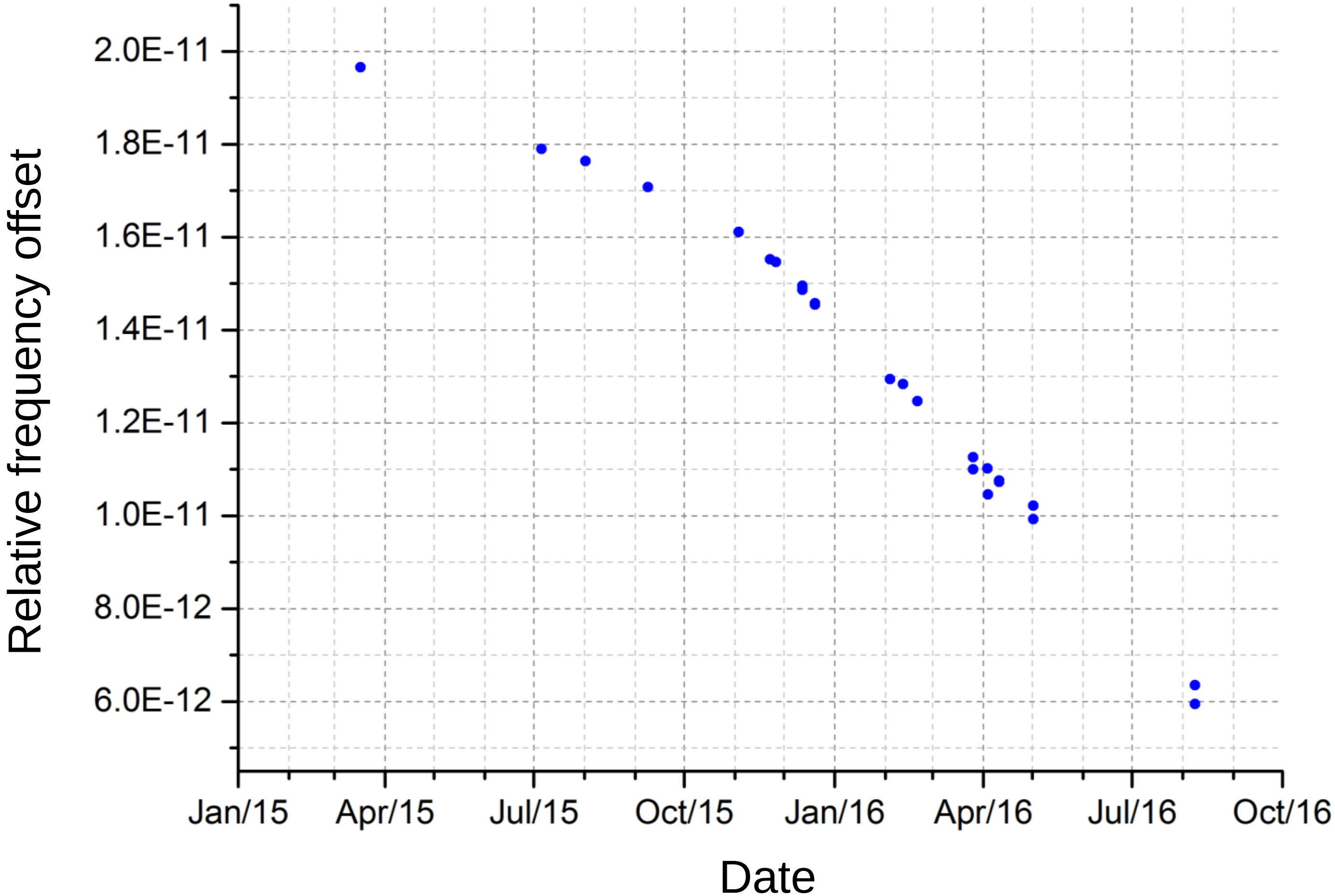
Nonrelativistic Doppler:

1) Compensation: switching between 1-way and 2-way modes
2) Calculation: co-located SLR tracking – Yg, Hh (experimental)

2[nd] order kinematic terms $\leftarrow$ orbit

media, instrumental effects $\leftarrow$ meteo, GPS, WVR, telemetry, models, calibration

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

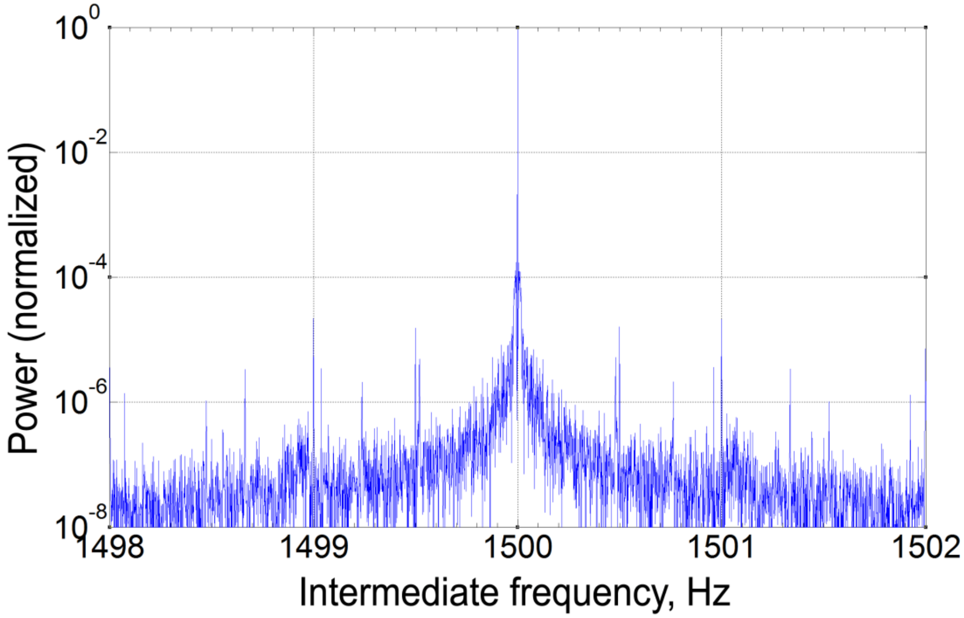


$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}$$

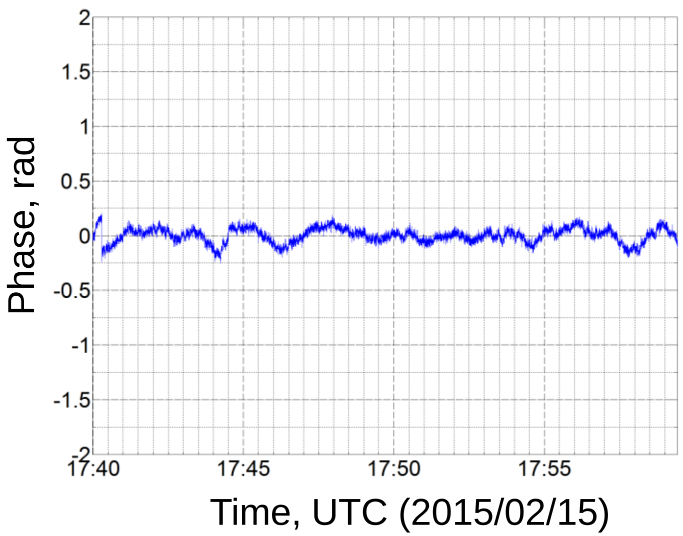
Drift: $1.5 \times 10^{-14}/\mathrm{day} \rightarrow 3.6 \times 10^{-14}/\mathrm{day}$

RadioAstron is the "celestial" source → **PRIDE (subset)**

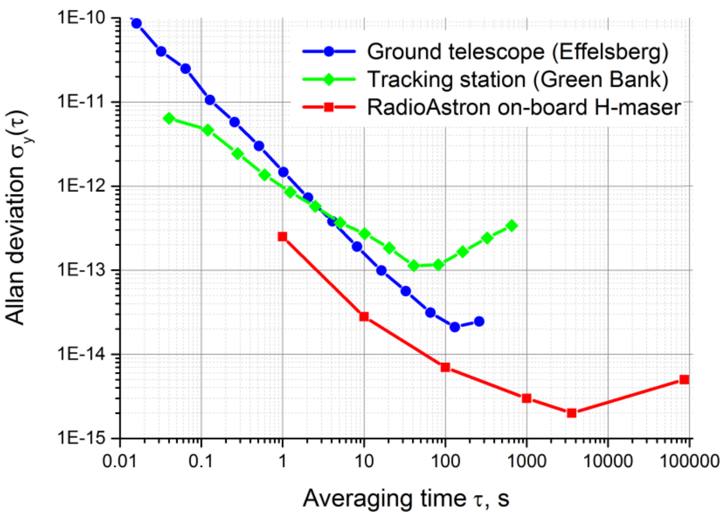
Phase-stopped signal spectrum
(Ef, raks10ae, 2015/02/15)



Phase residual (Ef, raks10ae)

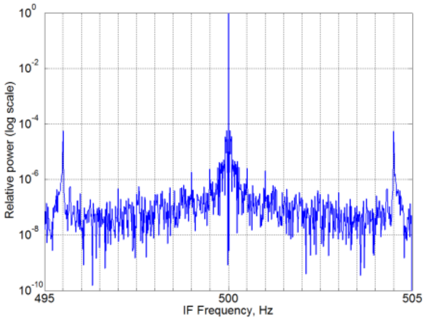


Allan deviation

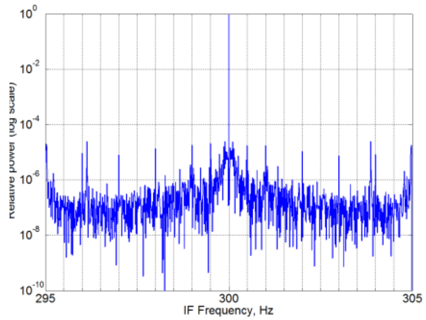


Stopped-phase signal spectrum

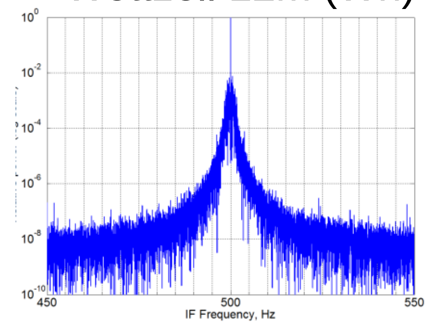
Svetloe



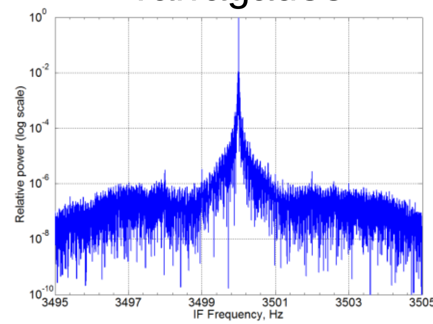
Wettzell 20m



Wettzell 12m (Wn)

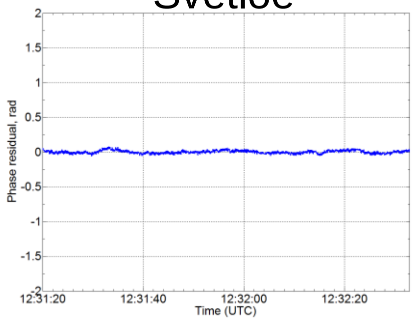


Yarragadee



Residual phase

Svetloe



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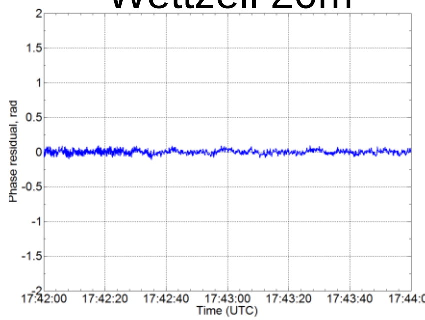

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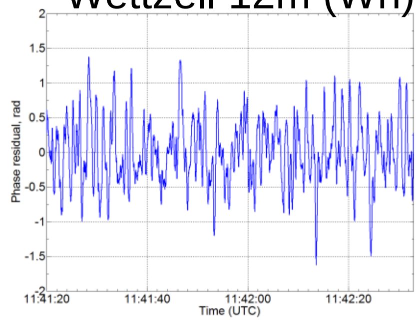
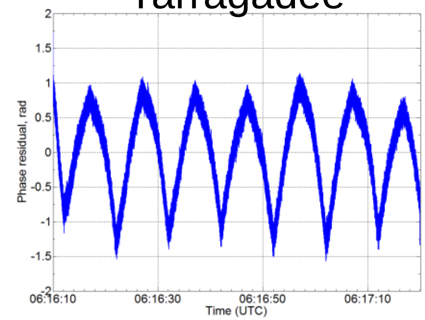


Yarragadee



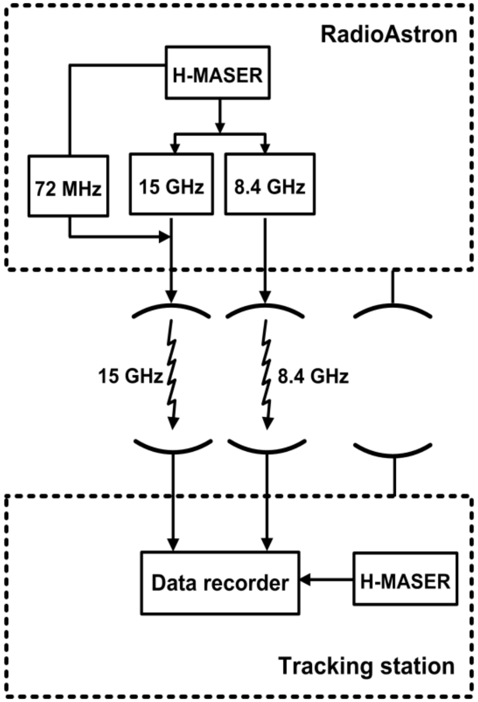
New antennas struggle from saturation

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

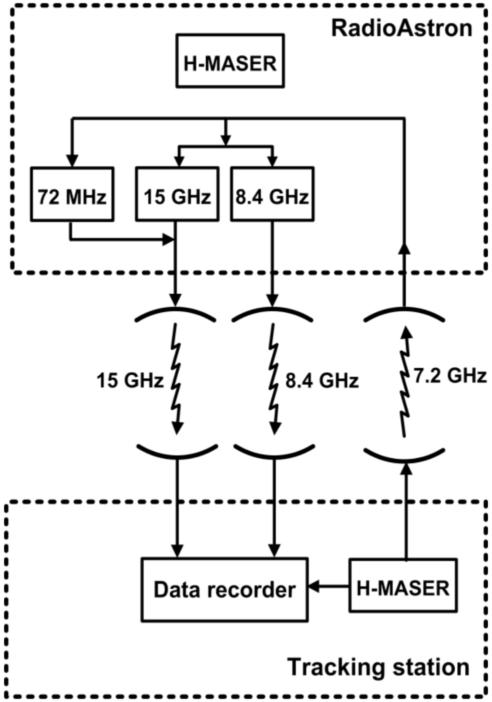
1st order Doppler shift in 2-way link is twice that in 1-way link

1-way "H-maser"

$$\frac{\Delta f_{1\mathrm{w}}}{f} = -\frac{\dot{D}}{c} + \ldots$$

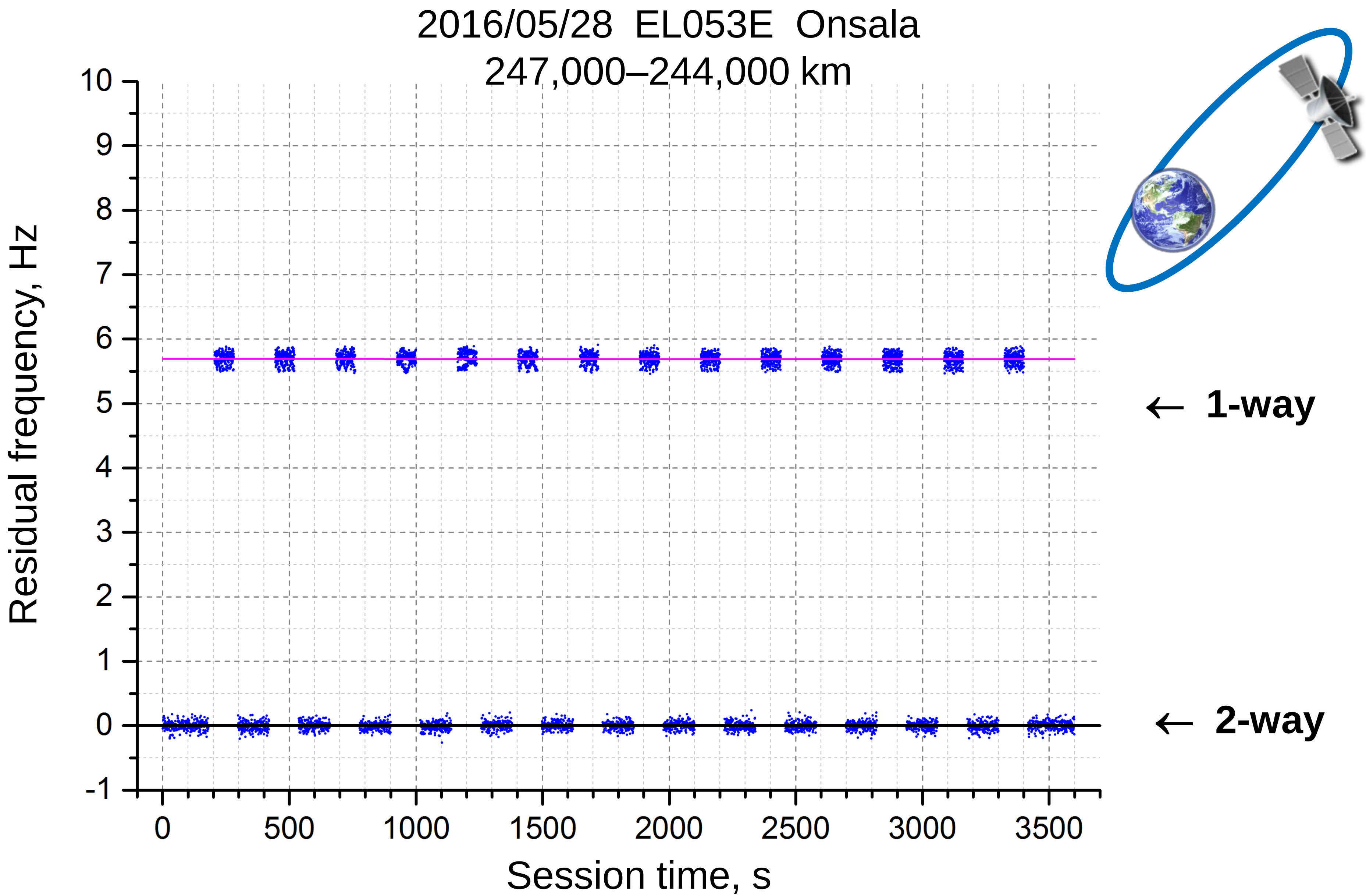


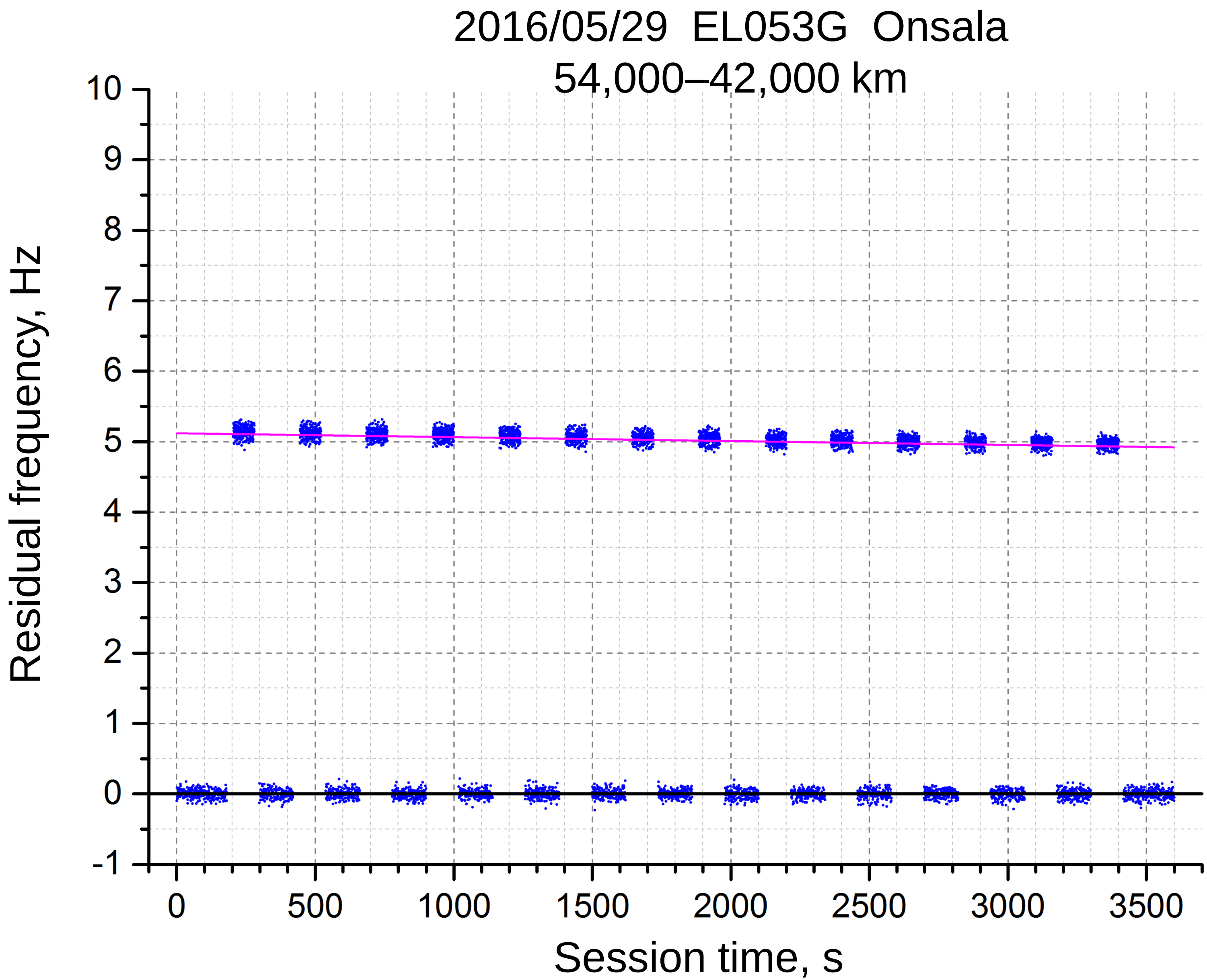
2-way "Coherent"



$$\frac{\Delta f_{2\mathrm{w}}}{f} = -\frac{2\dot{D}}{c} + \ldots$$

Biriukov et al., Astron. Rep. 2014


2016/05/28 EL053E Onsala
247,000–244,000 km
Residual frequency, Hz
10
9
8
7
6
5
4
3
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500
Session time, s
← 1-way
← 2-way


2016/05/29 EL053G Onsala
54,000–42,000 km
Residual frequency, Hz
10
9
8
7
6
5
4
3
2
1
0
-1
0
500
1000
1500
2000
2500
3000
3500
Session time, s
← 1-way
← 2-way

RadioAstron gravitational redshift experiment:

An experiment to test general relativity with 2.5×10^{-5} accuracy

Accuracy achieved: 4×10^{-4} (GP-A: 1.4×10^{-4})

Better account of systematic effects (troposphere, temperature, magnetic field sensitivity, etc.)

Co-located SLR+VLBI mode

Competition:

Galileo 5 & 6:	$(3–4) \times 10^{-5}$, 2017
ACES:	2×10^{-6}, 2018

STE-QUEST, E-GRIP, E-GRASP

Thank you!