Probing general relativity with RadioAstron

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13th EVN Symposium
Saint-Petersburg, 20–23 September 2016

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

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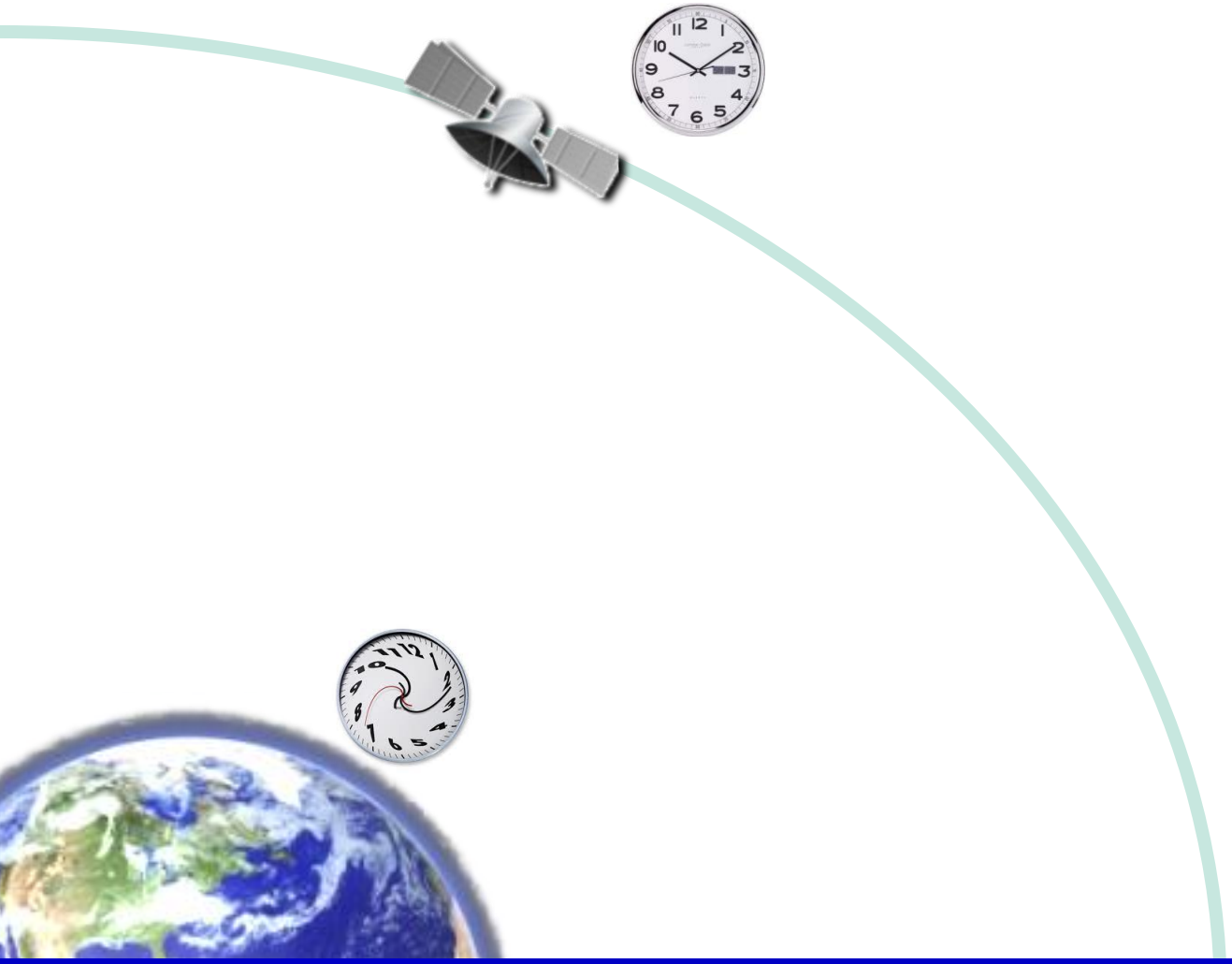

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$$\frac{\Delta T_{\mathrm{spec.rel.}}}{T} = \frac{v_e^2 - v_s^2}{2c^2}$$

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

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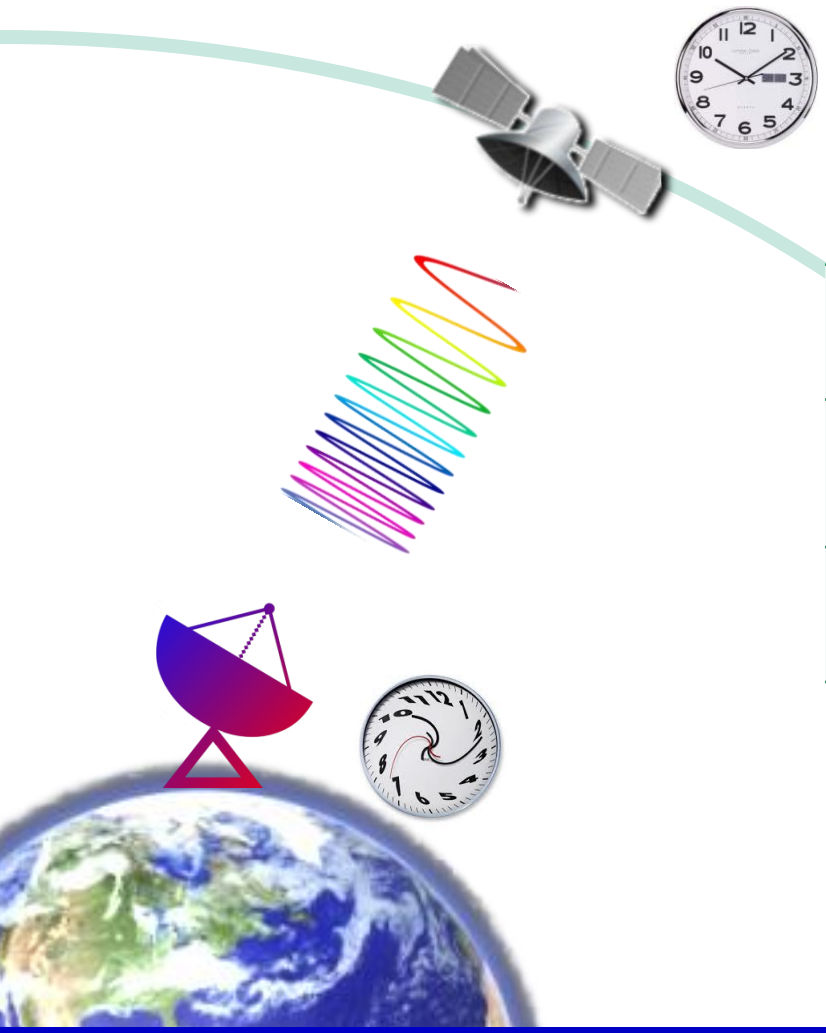

Daily time dilation	ISS	RadioAstron
gravitation	–4 μs	–58 μs
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$$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}$$

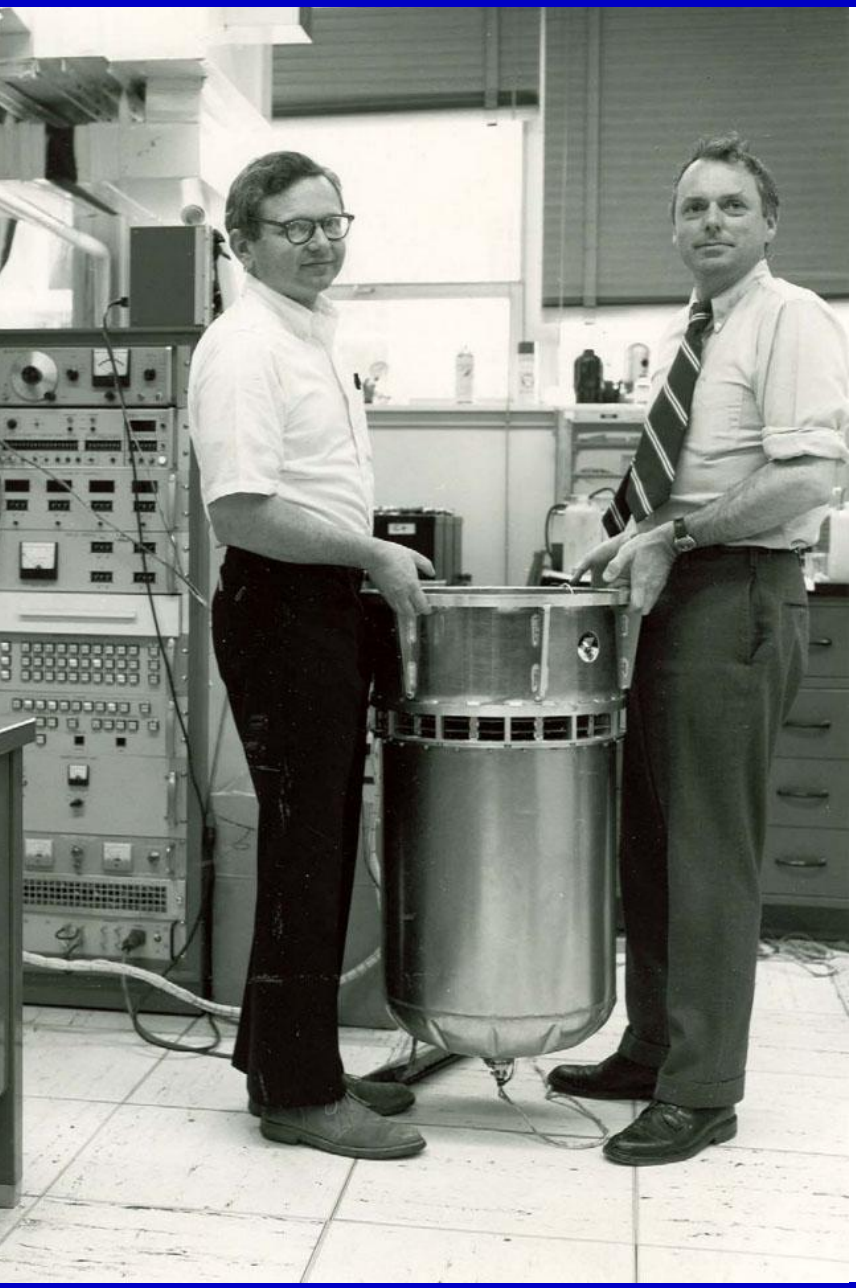
Grand Unification: $$\frac{\Delta f_{\mathrm{grav}}}{f} = \frac{\Delta U}{c^2}(1+\varepsilon)$$

violation parameter

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

Violation magnitude: difficult to predict

Gravity Probe A (1976)



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

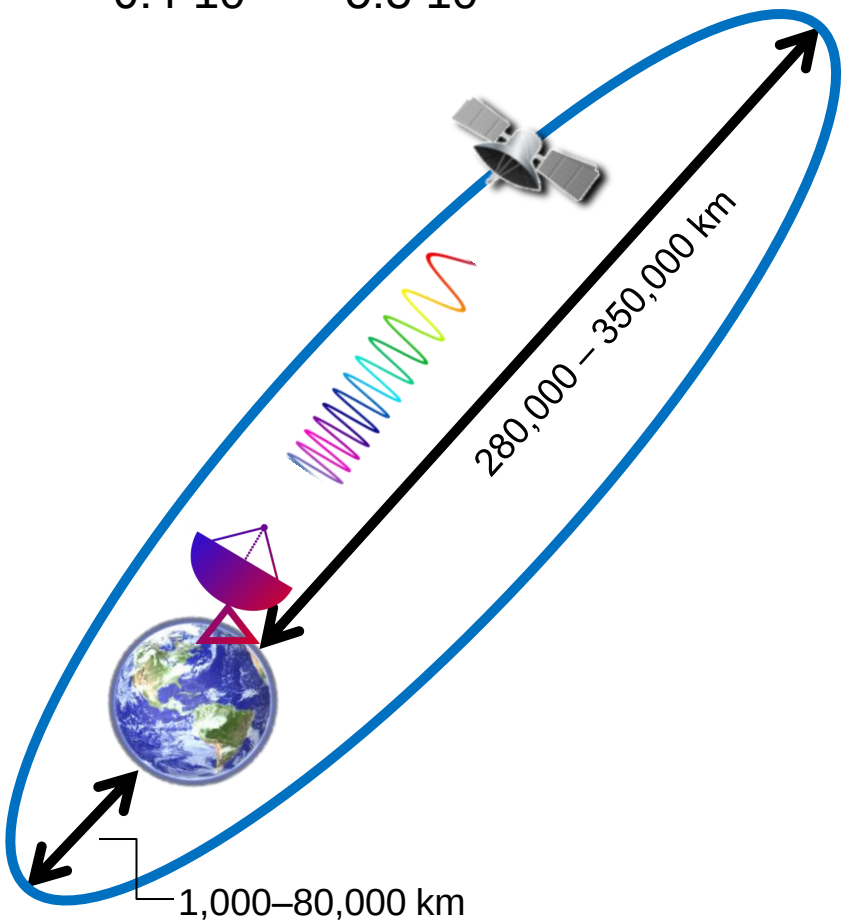
$$\frac{\Delta f}{f} = \left(1 \pm \underbrace{(0.05 \pm 1.4)\cdot 10^{-4}}_{\delta\varepsilon\text{: accuracy}}\right)\frac{\Delta U}{c^2}$$

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

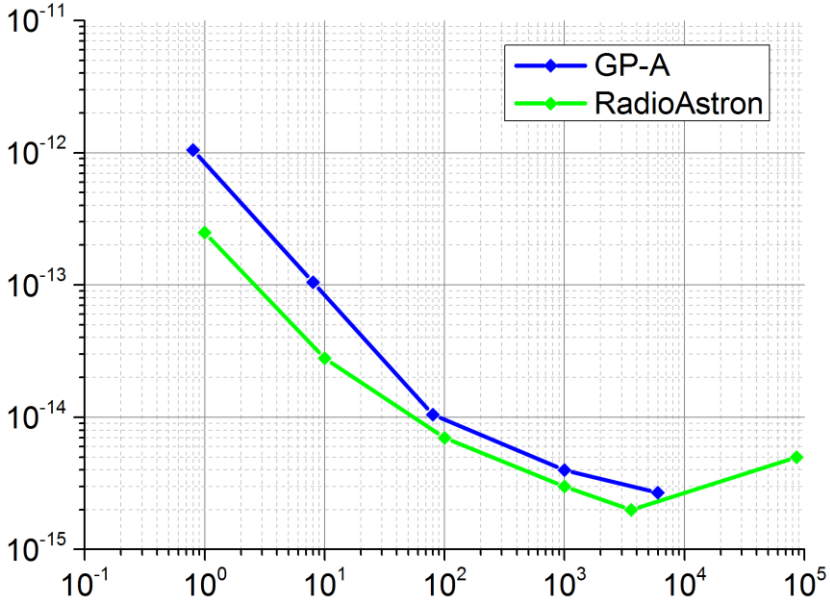
RadioAstron gravitational redshift experiment prerequisites

Grav. redshift modulation:

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



Allan deviation



RA: Better H-maser stability:

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

Target accuracy of the test:

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

Problem: nonrelativistic Doppler

For a spacecraft:

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

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

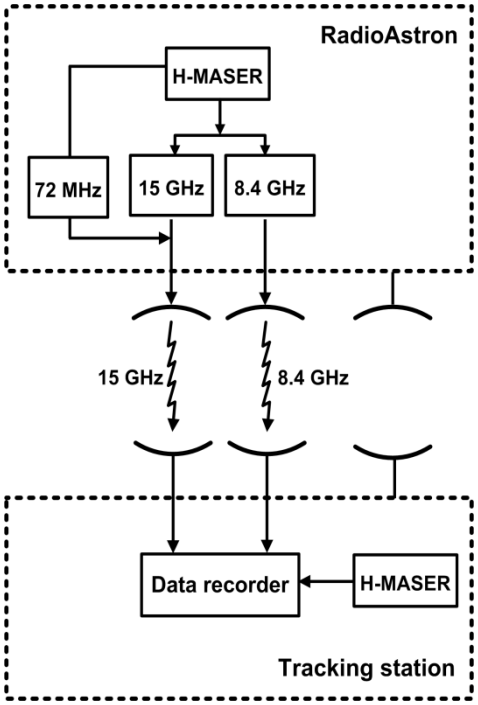
1st order Doppler shift in 2-way link is twice that in 1-way link

Problem: nonrelativistic Doppler

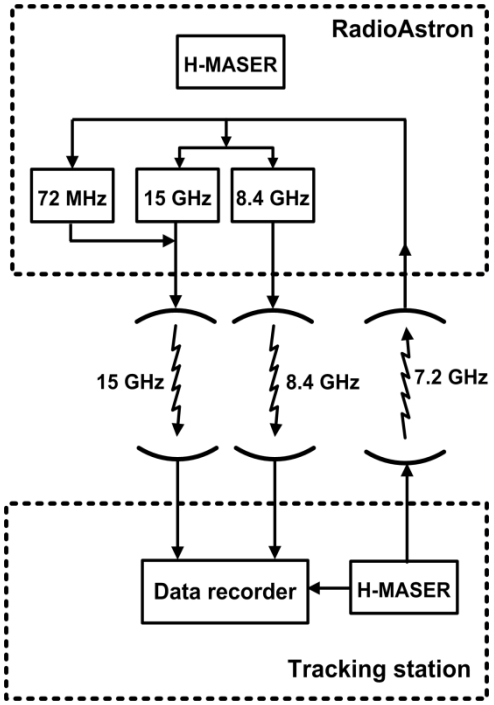
Two approaches:

1) Compensation: switching between 1-way and 2-way modes
2) Calculation: laser tracking (experimental)

1-way "H-maser"



2-way "Coherent"

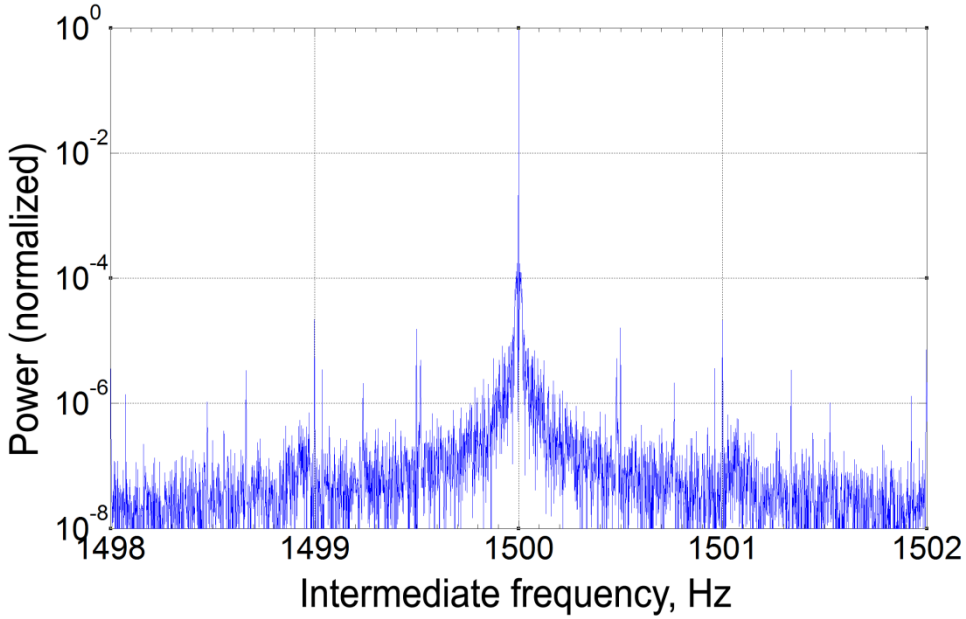


Biriukov et al., Astron. Rep. 2014

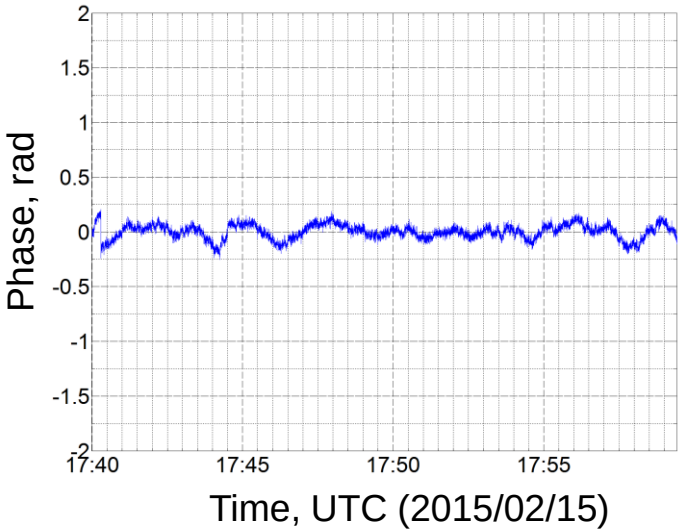
Frequency measurement

RadioAstron is the "celestial" source → PRIDE

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



Phase residual (Ef, raks10ae)



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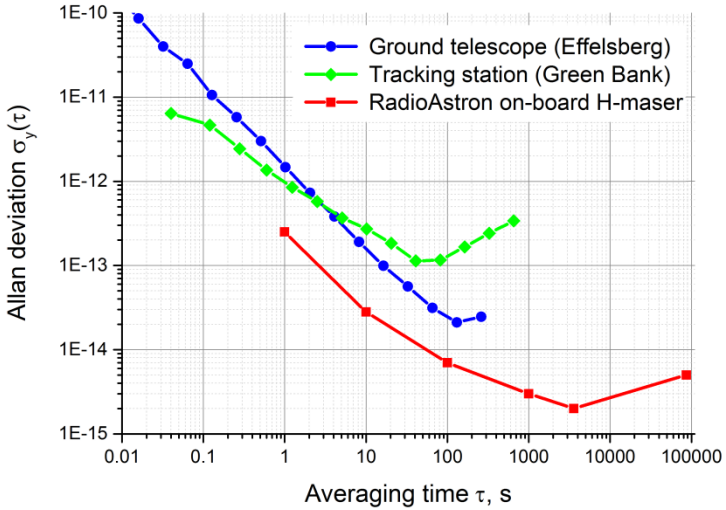
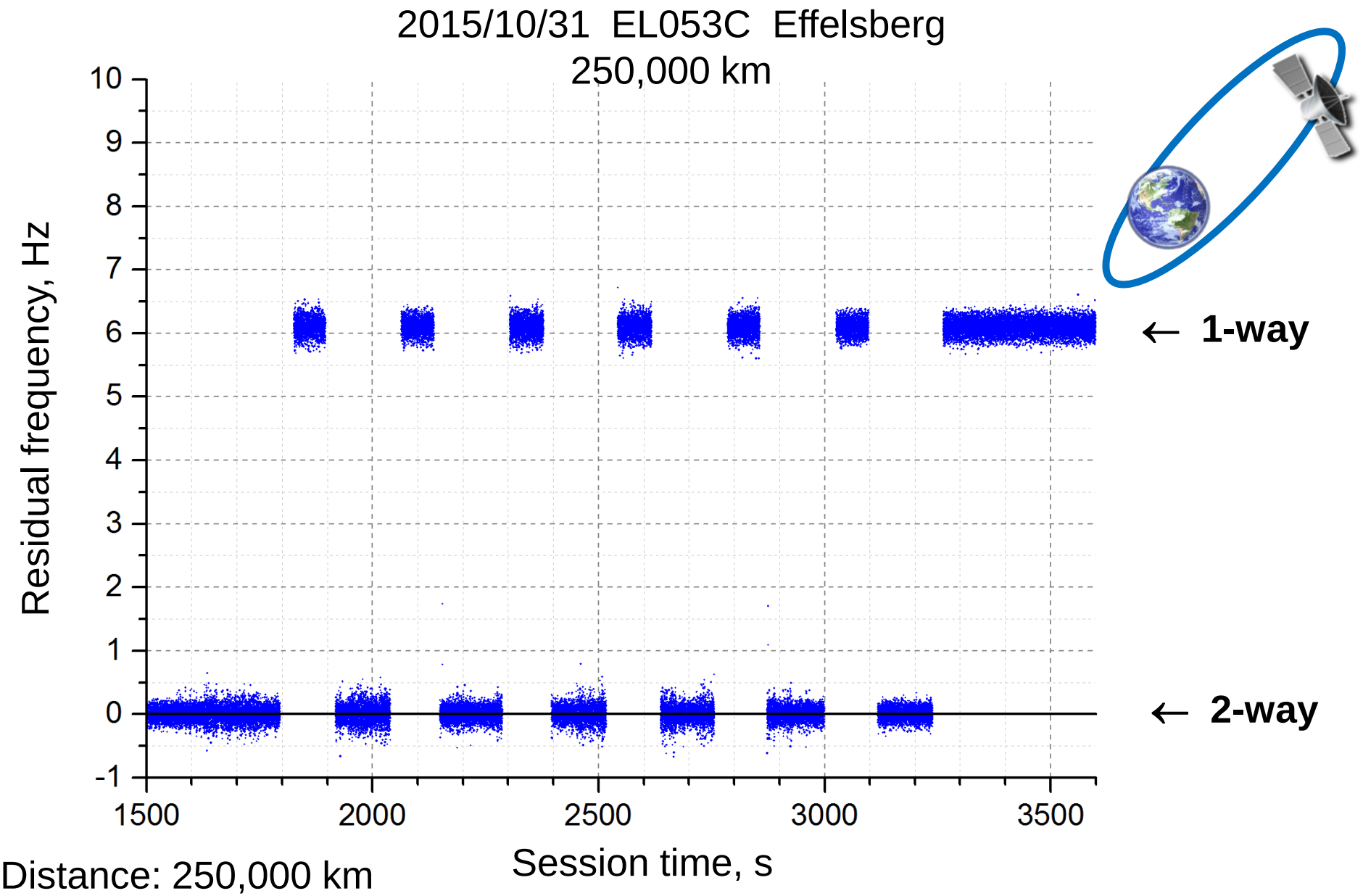


Interleaved measurements mode



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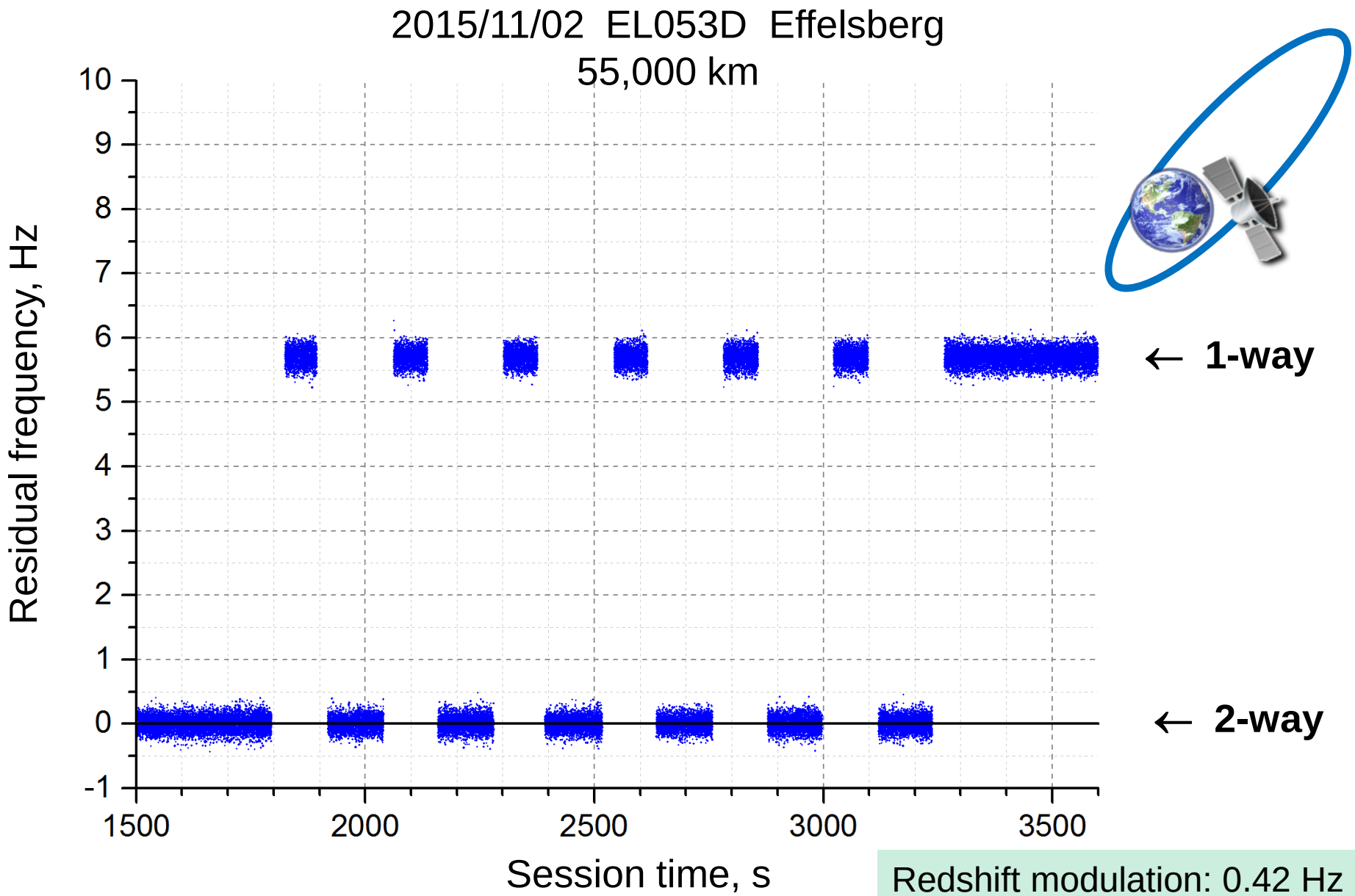
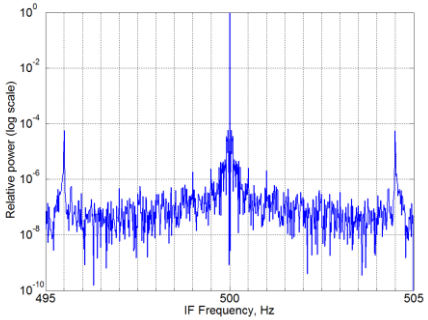


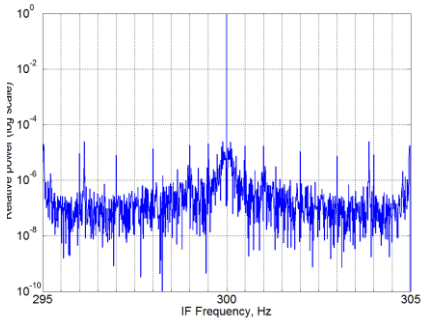
Redshift modulation: 0.42 Hz

Stopped-phase signal spectrum

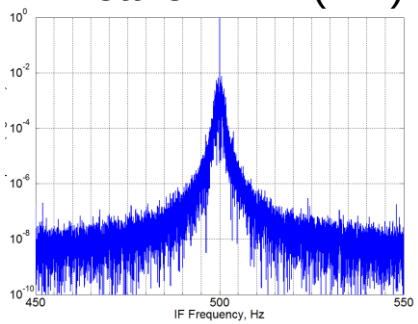
Svetloe



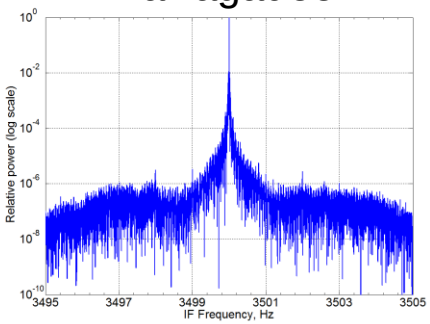
Wettzell 20m



Wettzell 12m (Wn)

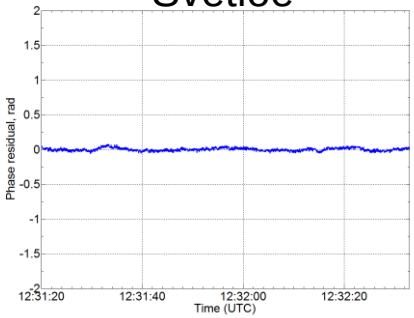


Yarragadee



Residual phase

Svetloe



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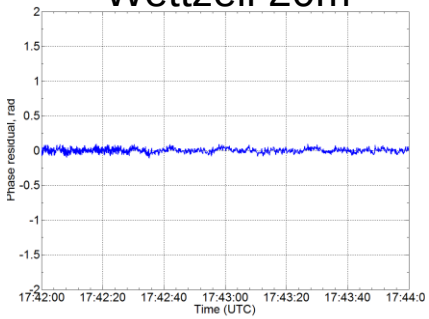

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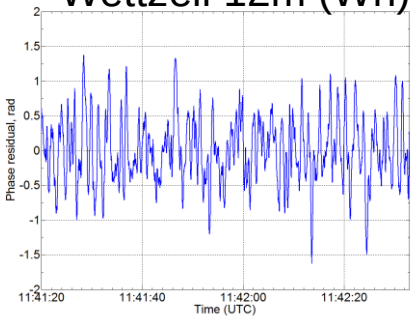

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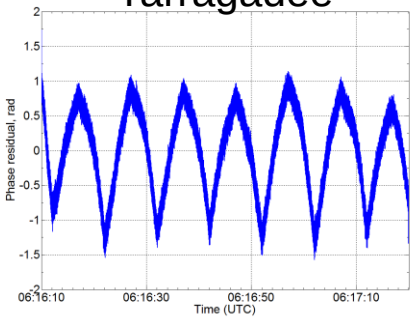
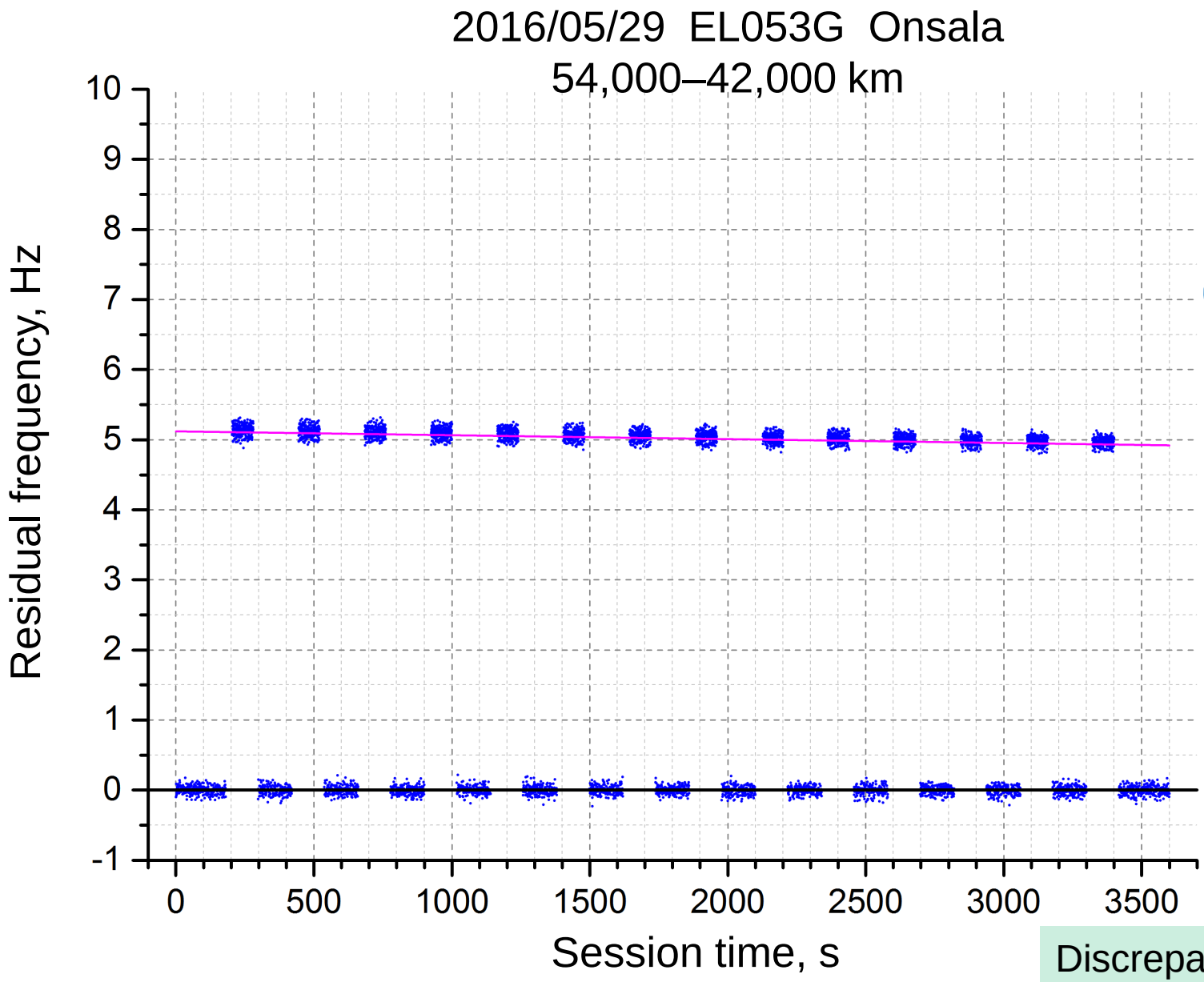


New antennas struggle from saturation

Interleaved measurements mode



← **1-way**

← **2-way**

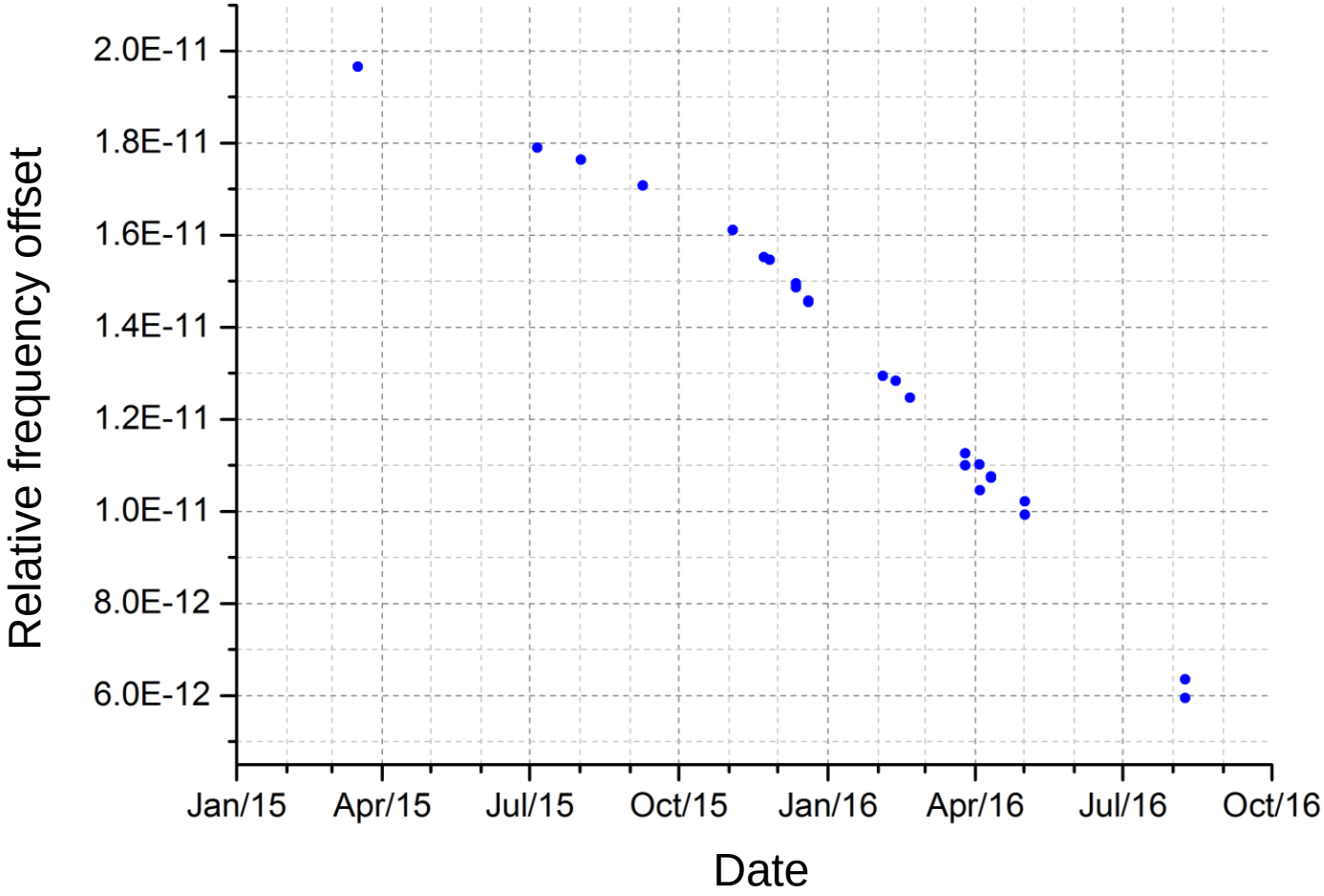
Discrepancy: 3 mHz

Minor kinematic effects:
(+) 2nd-order Doppler, etc.

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

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

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



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

Summary of results

Accuracy goal: 2×10^{-5}

Accuracy achieved: 4×10^{-4}

To do: data processing lag, systematic effects

Competition:

Galileo 5 & 6:	$(3–4)\times10^{-5}$, 2017
ACES:	2×10^{-6}, 2018

STE-QUEST, E-GRIP ?

Thank you!