GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SPACE RADIO TELESCOPE RADIOASTRON

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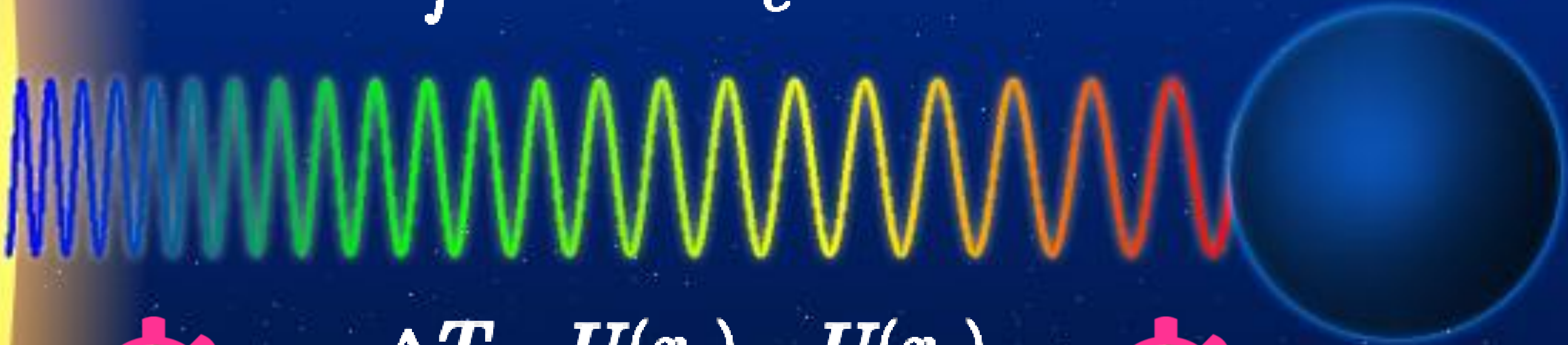
GRAVITATIONAL REDSHIFT

Einstein, 1911:

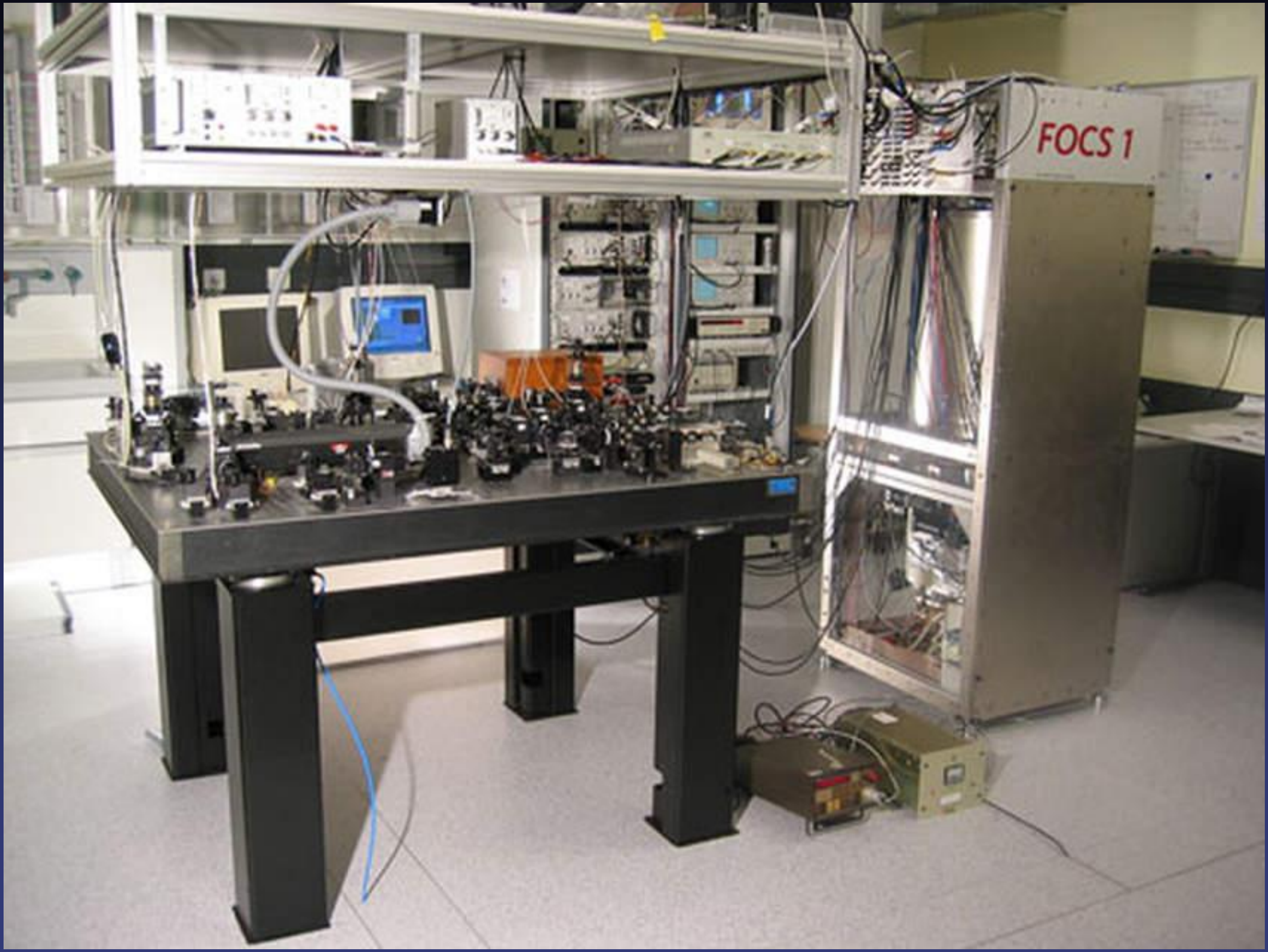
$$\frac{\Delta f}{f} = \frac{U(x_1) - U(x_2)}{c^2}$$



$$\frac{\Delta T}{T} = \frac{U(x_1) - U(x_2)}{c^2}$$

Pound, Rebka, 1960: laboratory test

ATOMIC FREQUENCY STANDARDS



Caesium fountain clock FOCS 1, Switzerland

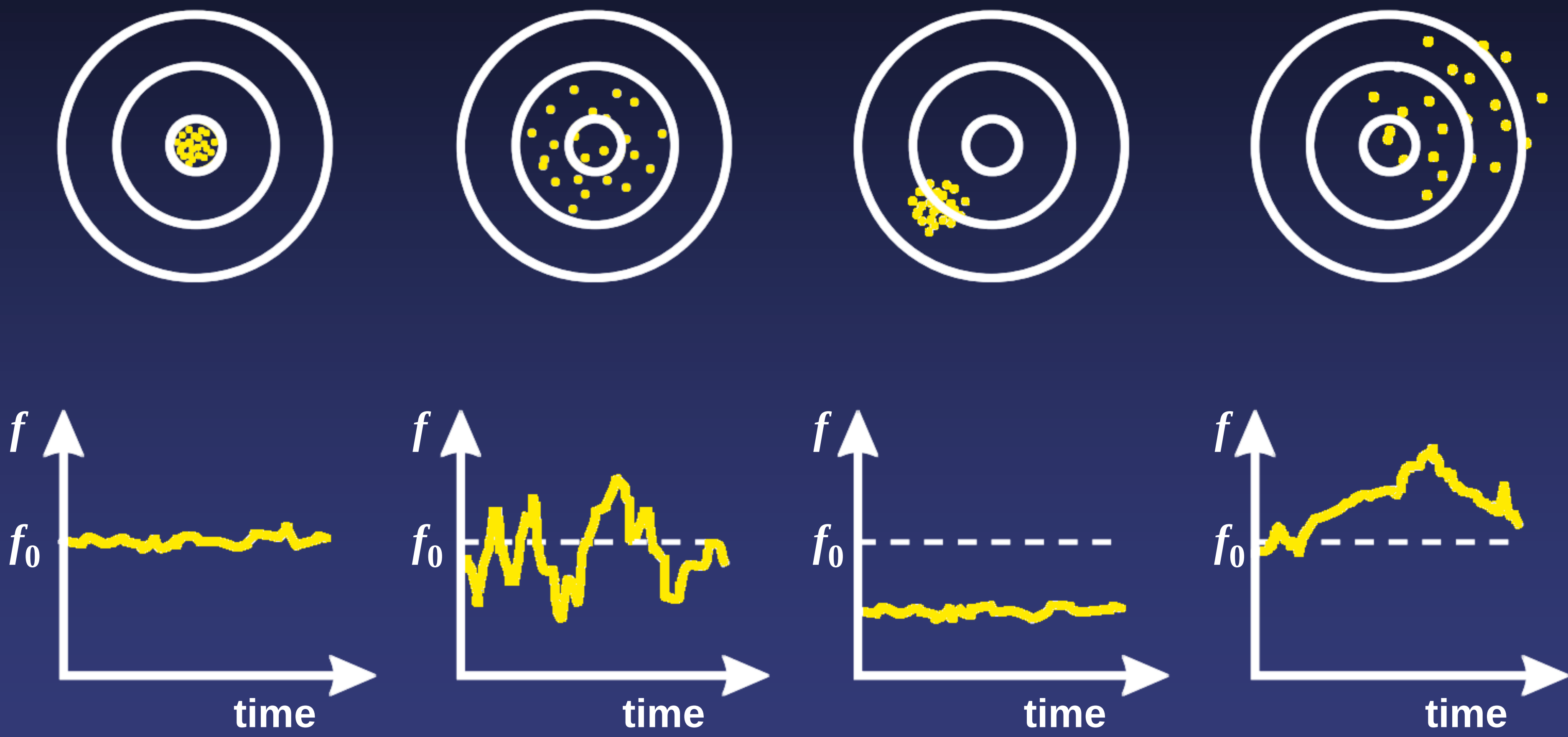
ATOMIC FREQUENCY STANDARDS

Tiny caesium clock

VCH-1010
Hydrogen maser frequency standard
of the space radio telescope "RadioAstron"

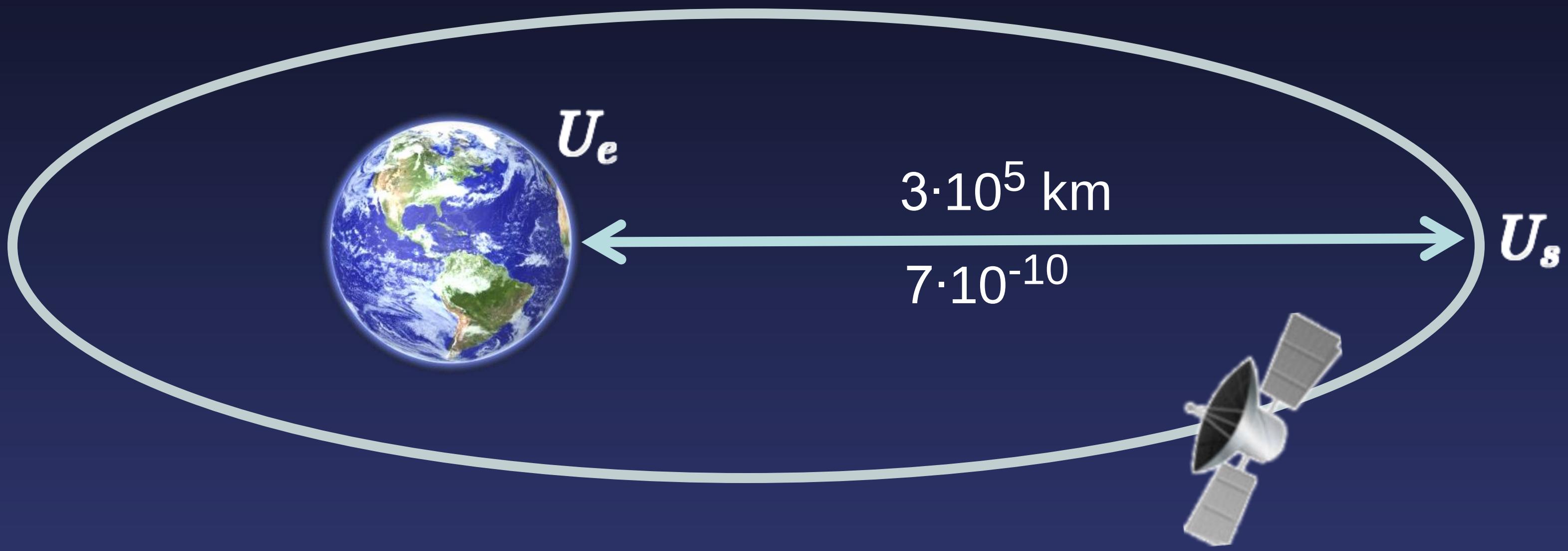
ATOMIC FREQUENCY STANDARDS: ACCURACY AND STABILITY

accurate and stable | **accurate but unstable** | **inaccurate but stable** | **inaccurate and unstable**



ABSOLUTE MEASUREMENT OF THE GRAVITATIONAL FREQUENCY SHIFT

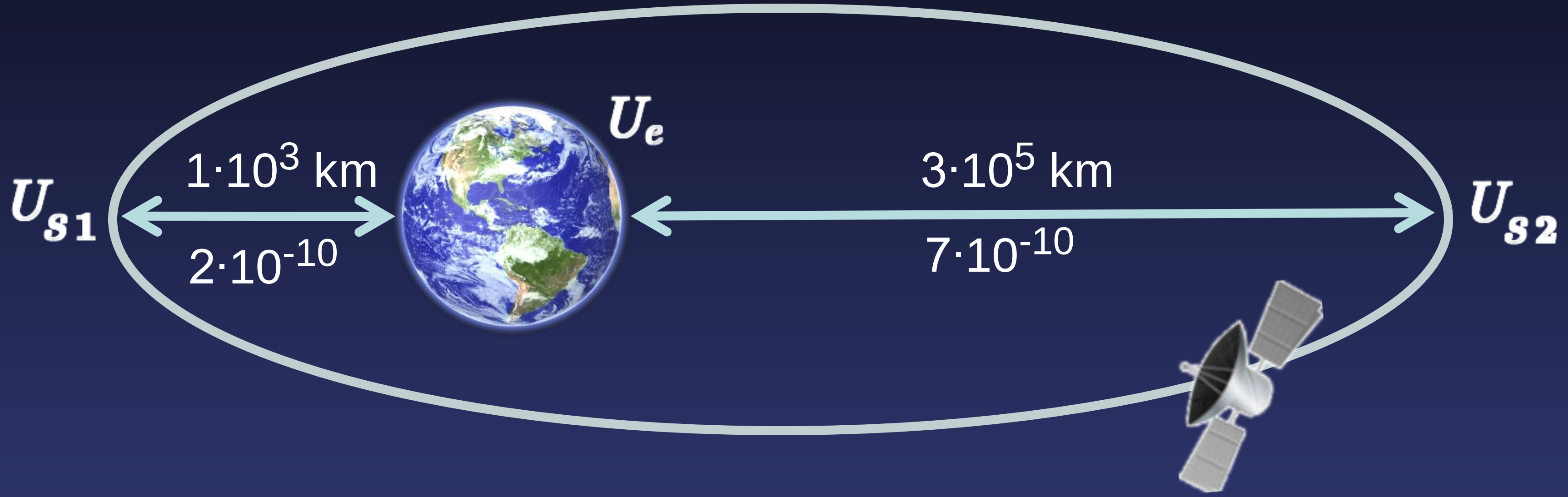
$$\frac{f_s - f_e}{f_e} = (1+\varepsilon)\frac{U_s - U_e}{c^2}$$



	H-maser	Cs-fountain
Frequency accuracy, $\Delta f / f$	$3\cdot10^{-13}$	$\sim1\cdot10^{-16}$
ε-parameter error, $\delta\varepsilon$	$4\cdot10^{-4}$	$1.4\cdot10^{-7}$

MODULATION MEASUREMENT OF THE GRAVITATIONAL FREQUENCY SHIFT

$$\frac{f_{s1} - f_{s2}}{f_e} = (1+\varepsilon)\,\frac{U_{s1} - U_{s2}}{c^2}$$



	H-maser	Cs-fountain
Frequency stability at ~1 day, $\Delta f / f$	$4 \cdot 10^{-15}$	$\sim 1 \cdot 10^{-16}$
ε-parameter error, $\delta\varepsilon$ (after 100 orbits)	$1 \cdot 10^{-6}$	$3 \cdot 10^{-8}$

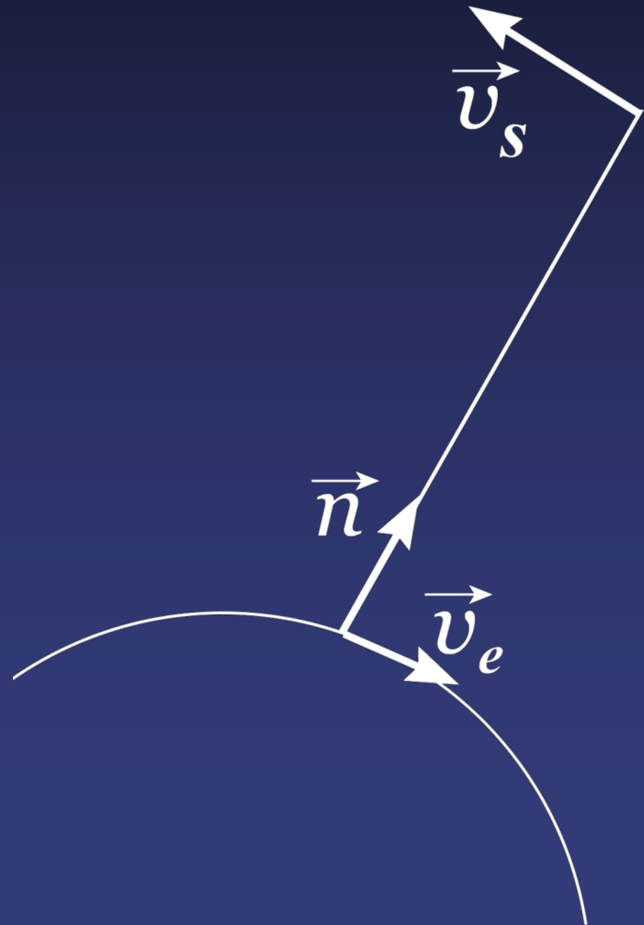
FREQUENCY METHOD: CLOCK MOTION

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

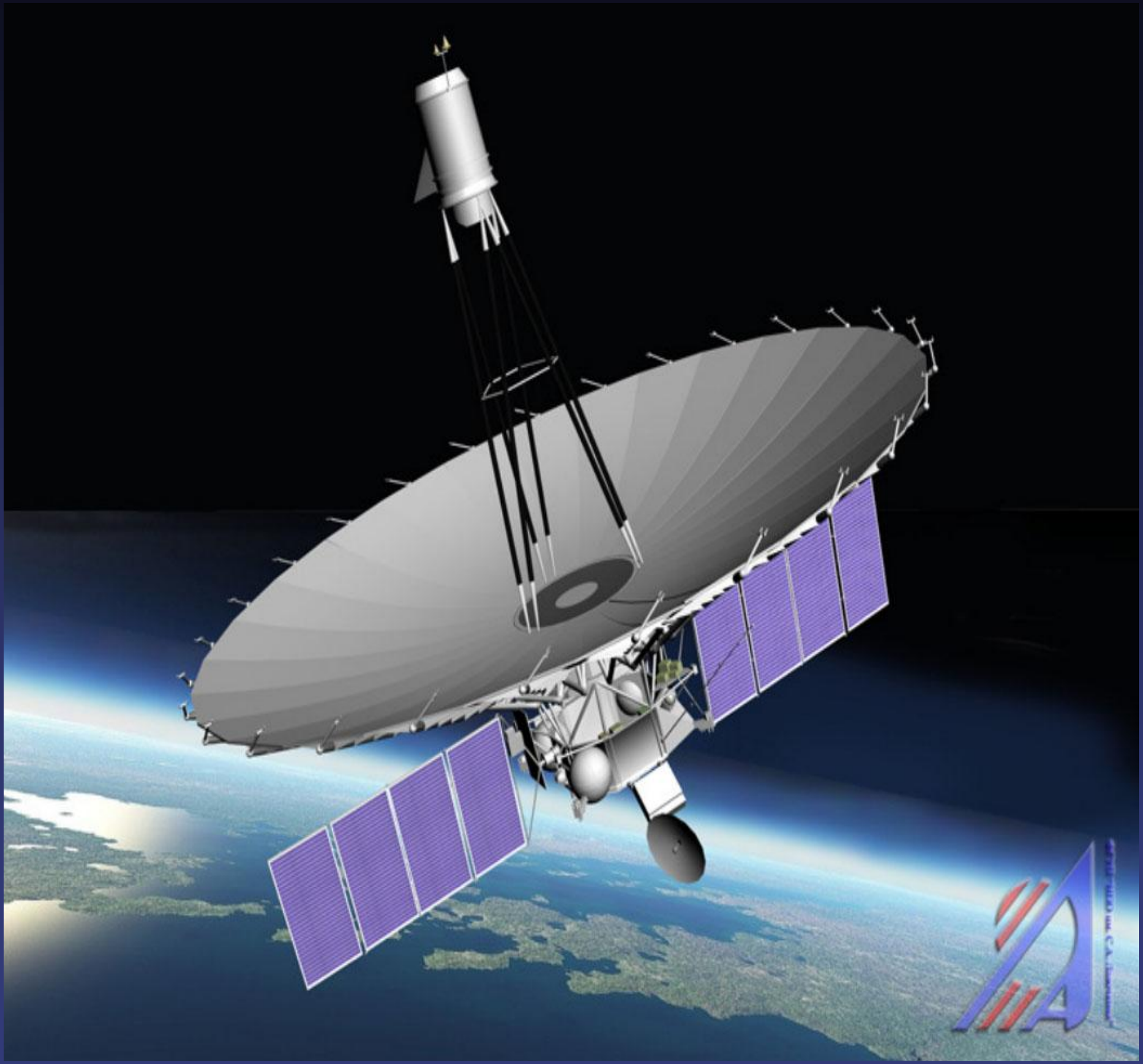
$$\left.\begin{aligned} & v_e,\ v_s \\ & \dot{D} = (v_s)_r - (v_e)_r \\ & \Delta U = U(\vec{r}_s) - U(\vec{r}_e) \end{aligned}\right\} \leftarrow \boxed{\text{orbit}}$$

$$\Delta f_{ion} = \frac{40.5}{cf}\frac{d}{dt}\int_P \rho ds$$

$$\Delta f_{trop} \leftarrow \boxed{\text{meteo data + model}}$$

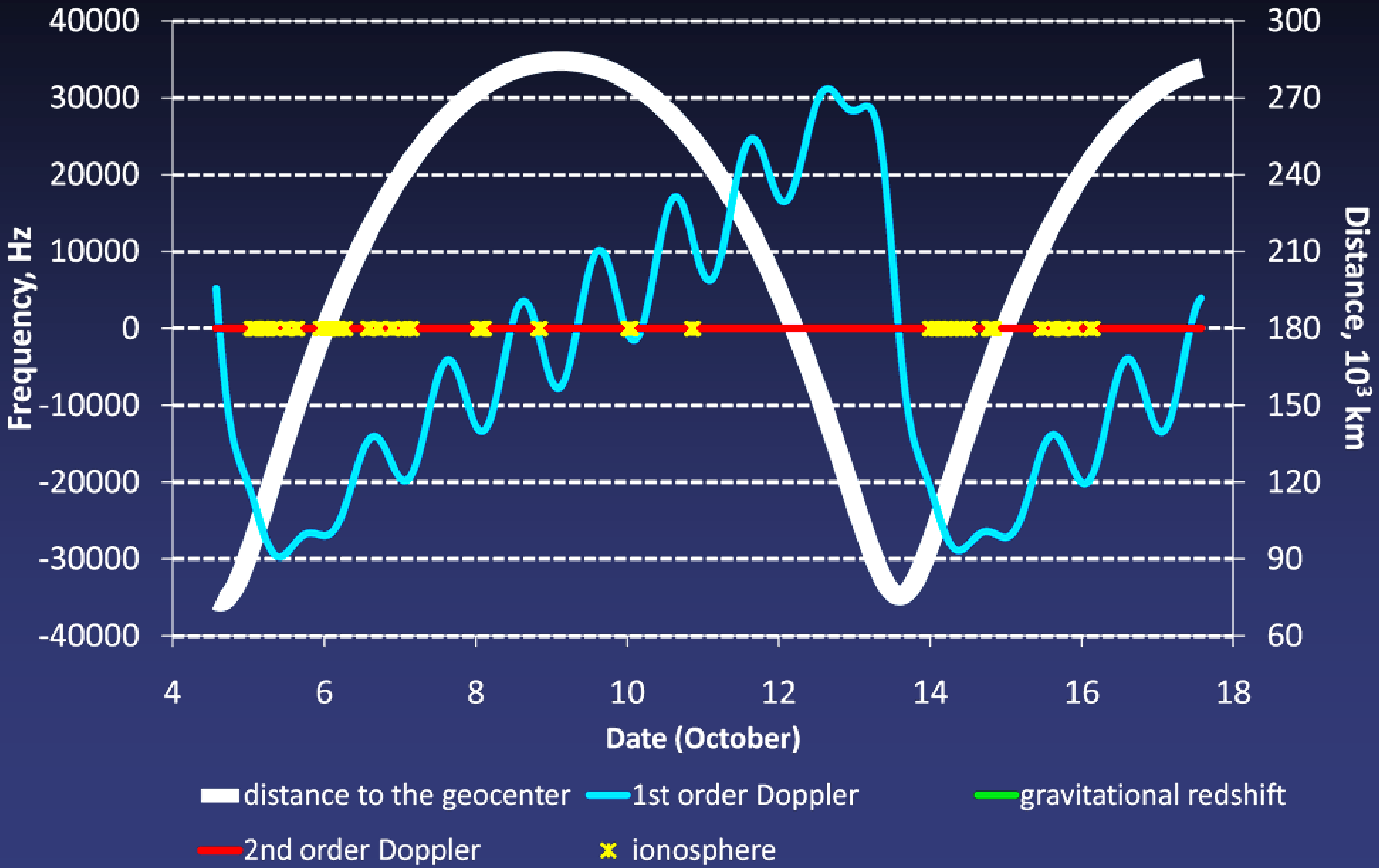


GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SRT "RADIOASTRON"



GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SRT "RADIOASTRON"

Contributions to the total frequency shift of the 8.4 GHz signal.
Puschino TS, Oct 2012



GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SRT "RADIOASTRON"

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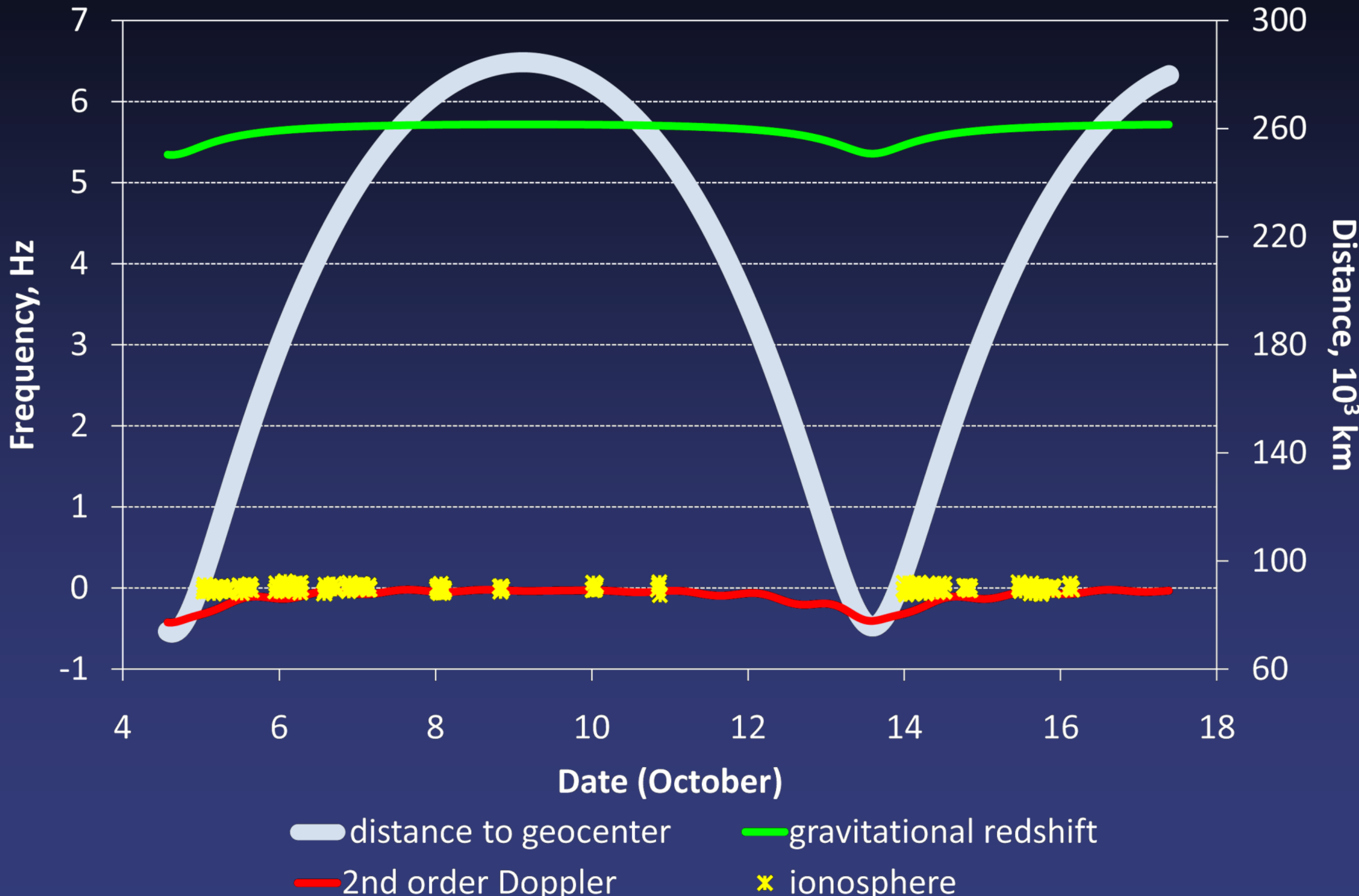
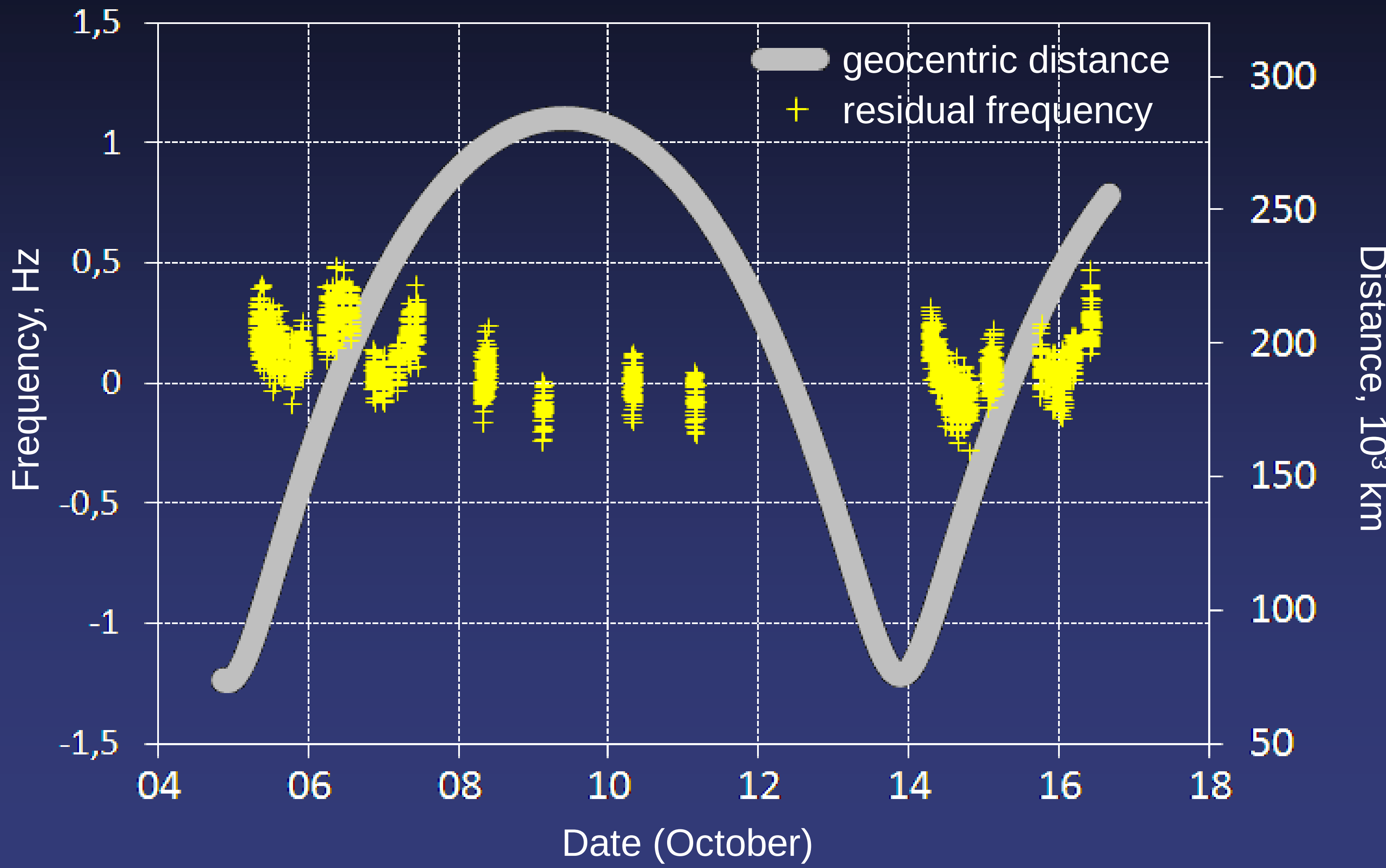


GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SRT "RADIOASTRON"

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

Residual frequency of the 8.4 GHz signal. Puschino TS, Oct 2012



AGREEMENT BETWEEN THEORY AND EXPERIMENT: 3%

TIMING METHOD

T_e

T_s

Daily time dilation, due to	GPS	RadioAstron
gravitation	45 μs	58 μs
gravitaiton and kinematics	38 μs	57 μs

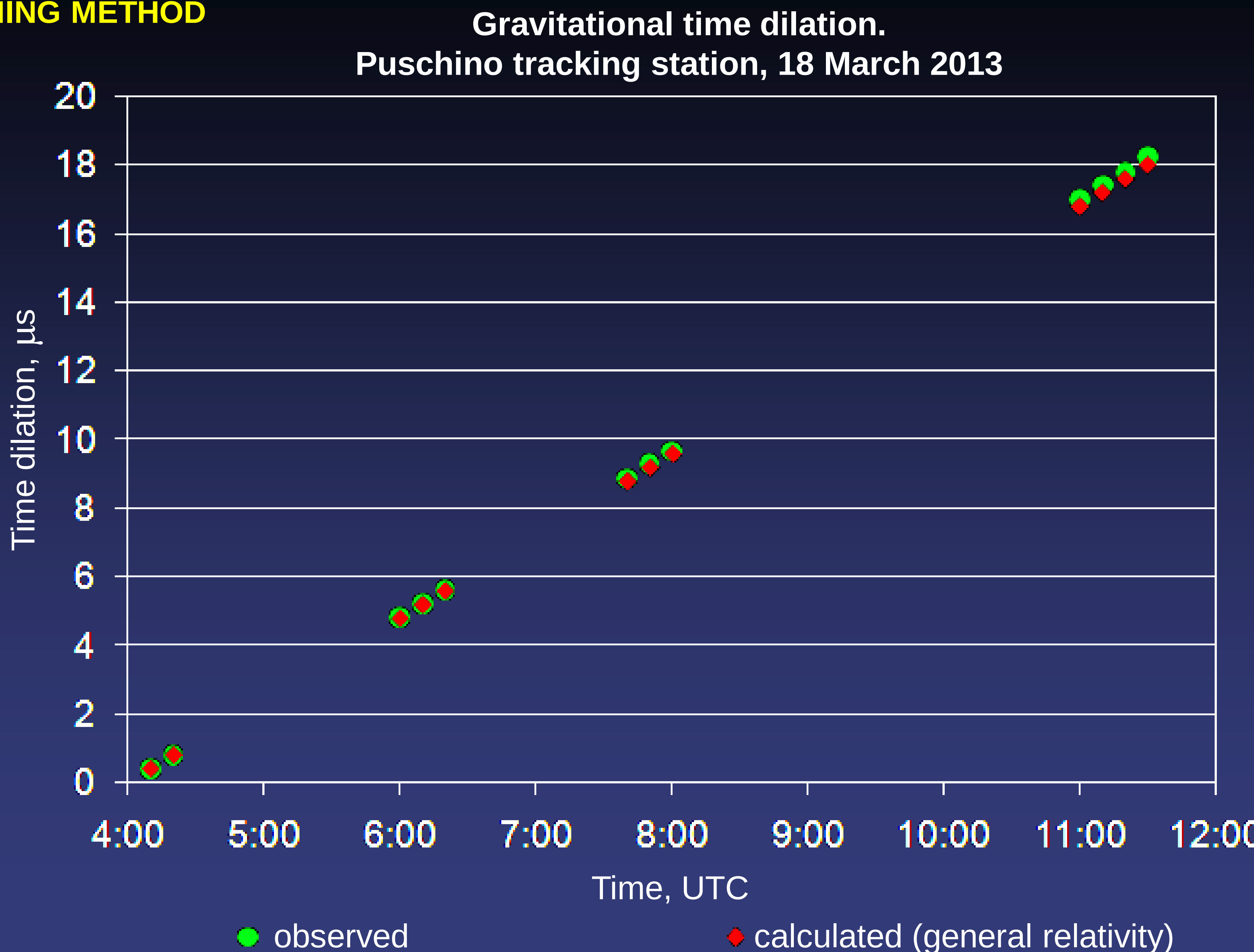
$$T_e = T_s - \tau_1 + \tau_2 + \Delta T_{grav} + \Delta T_{sr}$$

$$\frac{\Delta T_{grav}}{T} = \frac{U(\vec{r}_1) - U(\vec{r}_2)}{c^2}$$

$$\Delta T_{sr} = \int_{T_e} dt \left(1 - \sqrt{1 - \frac{v_e^2}{c^2}}\right) - \int_{T_s} dt \left(1 - \sqrt{1 - \frac{v_s^2}{c^2}}\right)$$

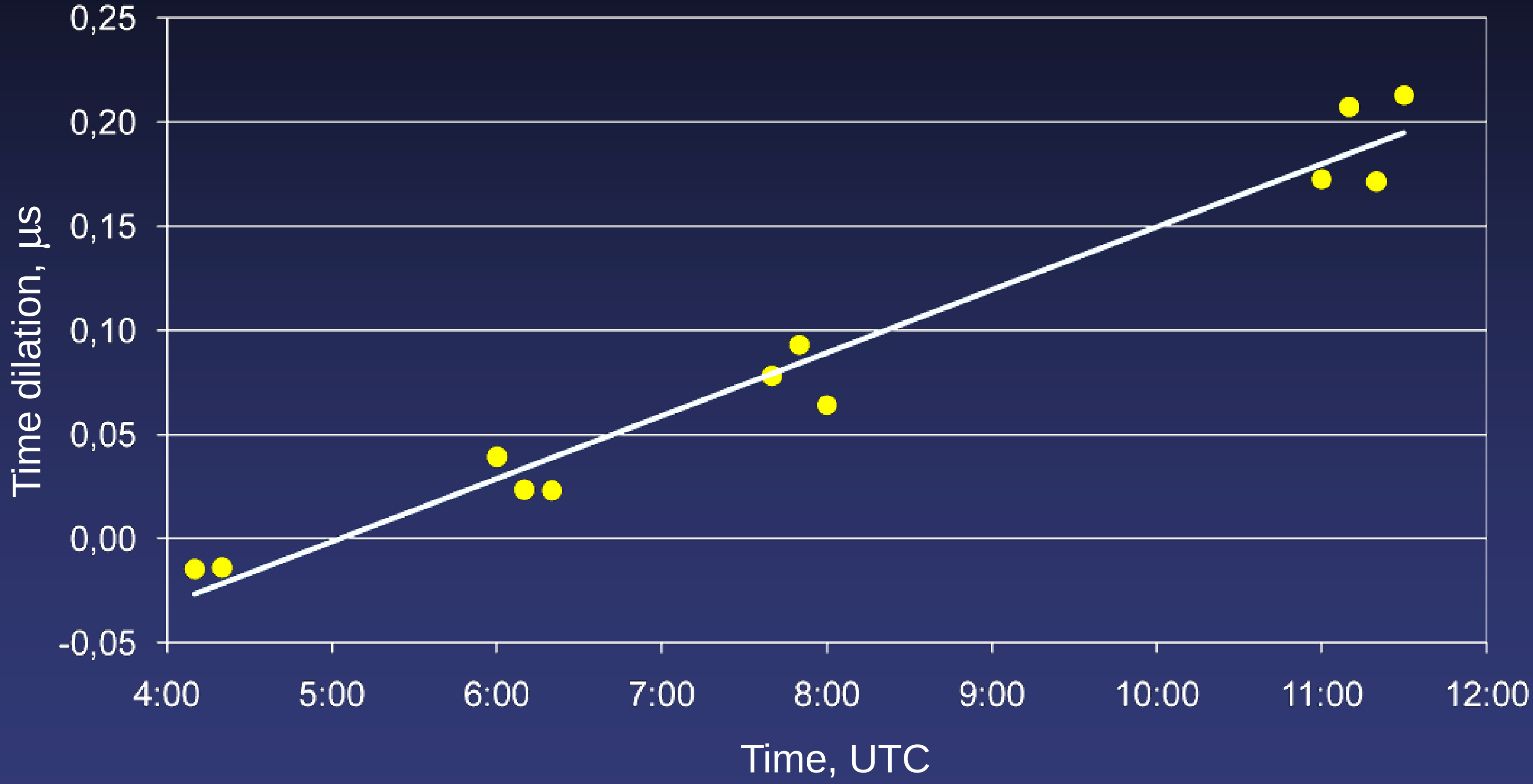
$$\tau_1 - \tau_2 = \left(1 + \frac{\dot{D}_1}{c}\right)\frac{D_1}{c} - \left(1 + \frac{\dot{D}_2}{c}\right)\frac{D_2}{c} + \Delta\tau_{ion} + \Delta\tau_{trop}$$

GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SRT "RADIOASTRON": TIMING METHOD



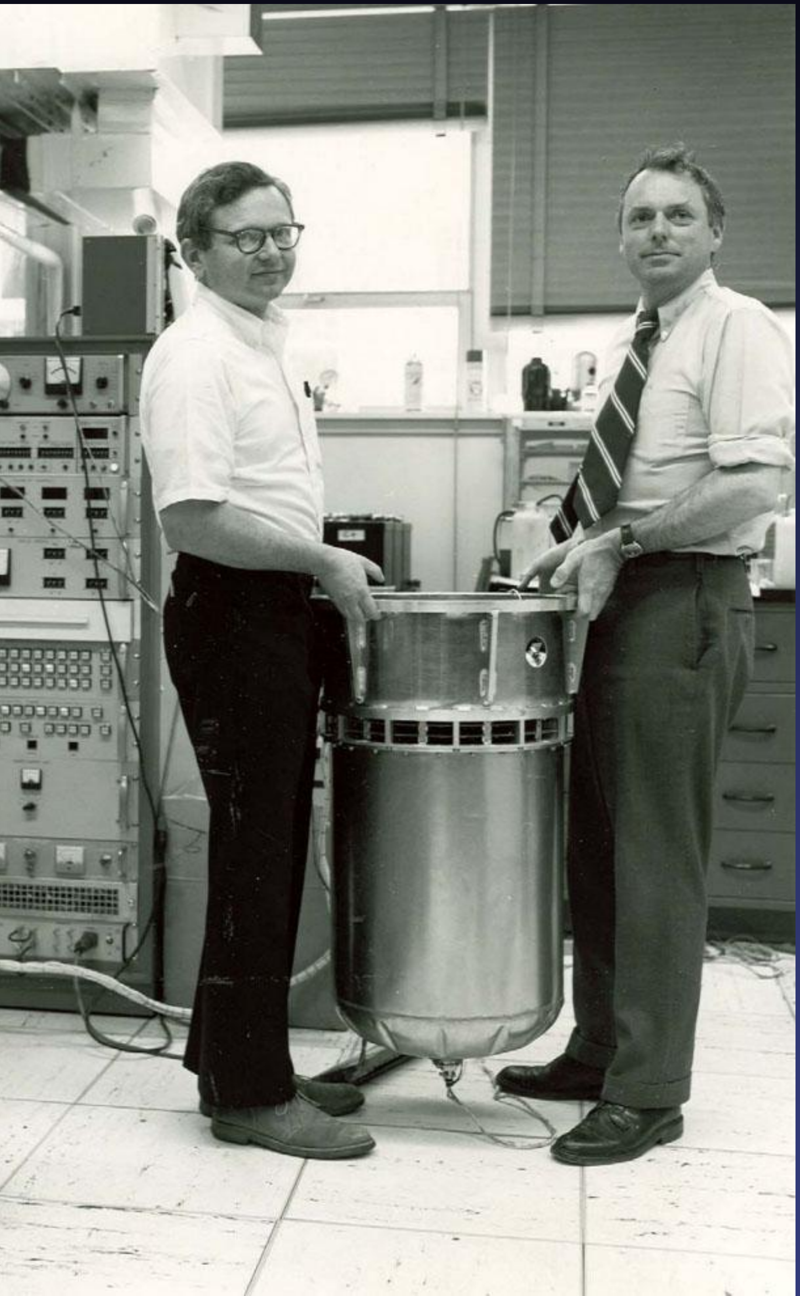
GRAVITATIONAL REDSHIFT EXPERIMENT WITH THE SRT "RADIOASTRON": TIMING METHOD

Gravitational time dilation: observed – calculated (general relativity).
Puschino tracking station, 18 March 2013



AGREEMENT BETWEEN THEORY AND EXPERIMENT: 1.5%

GRAVITY PROBE A EXPERIMENT (1976)



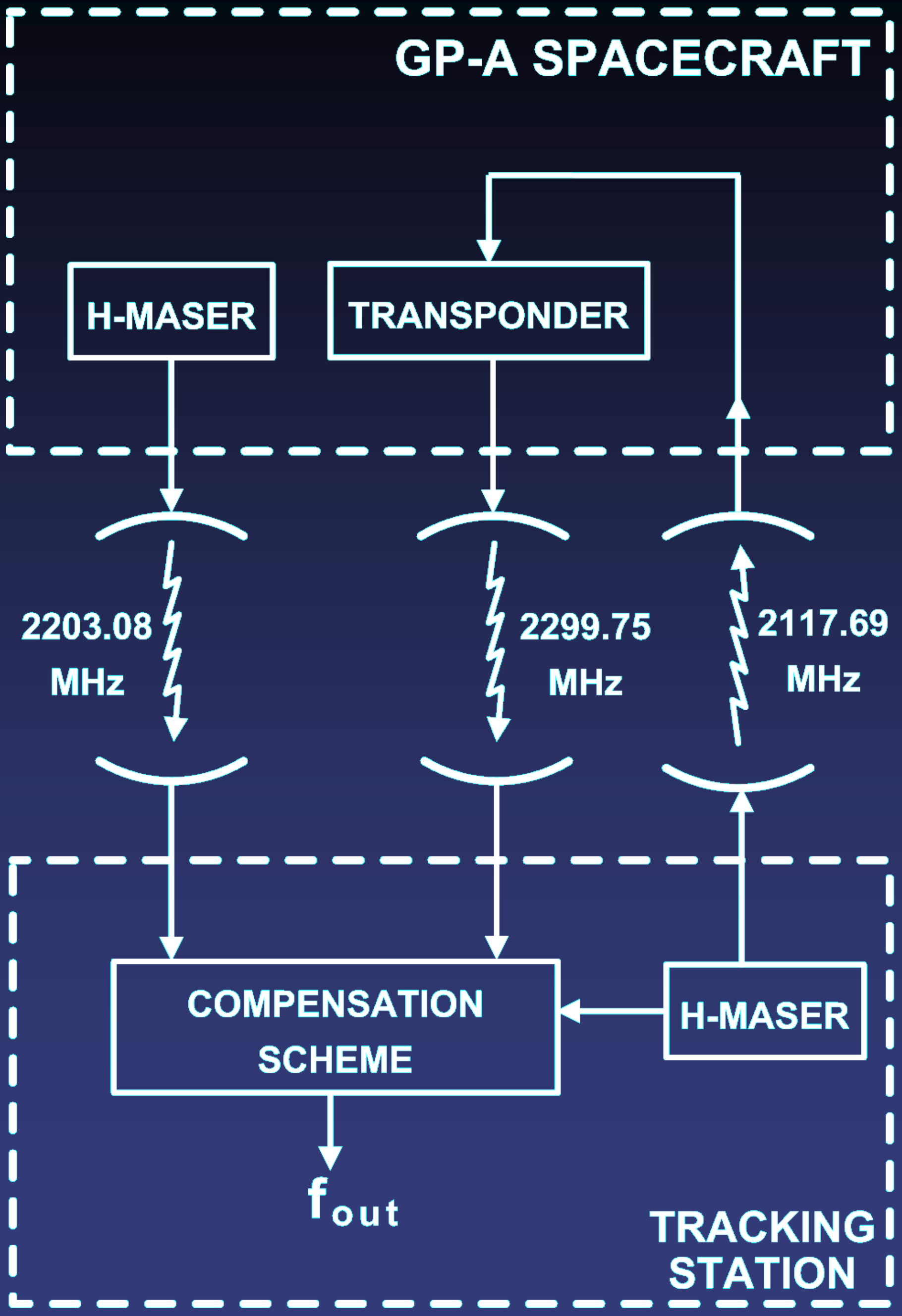
Flight duration	**1 h 58 min**
Apogee	**10,000 km**
Gravitational potential difference $\Delta U/c^2$	**$4 \cdot 10^{-10}$**
H-maser stability σ_y	**$1 \cdot 10^{-14}$ at 100 s**

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

Gravity Probe A project leaders
R. F. C. Vessot (right) and M. Levine (left)
beside the mission's H-maser

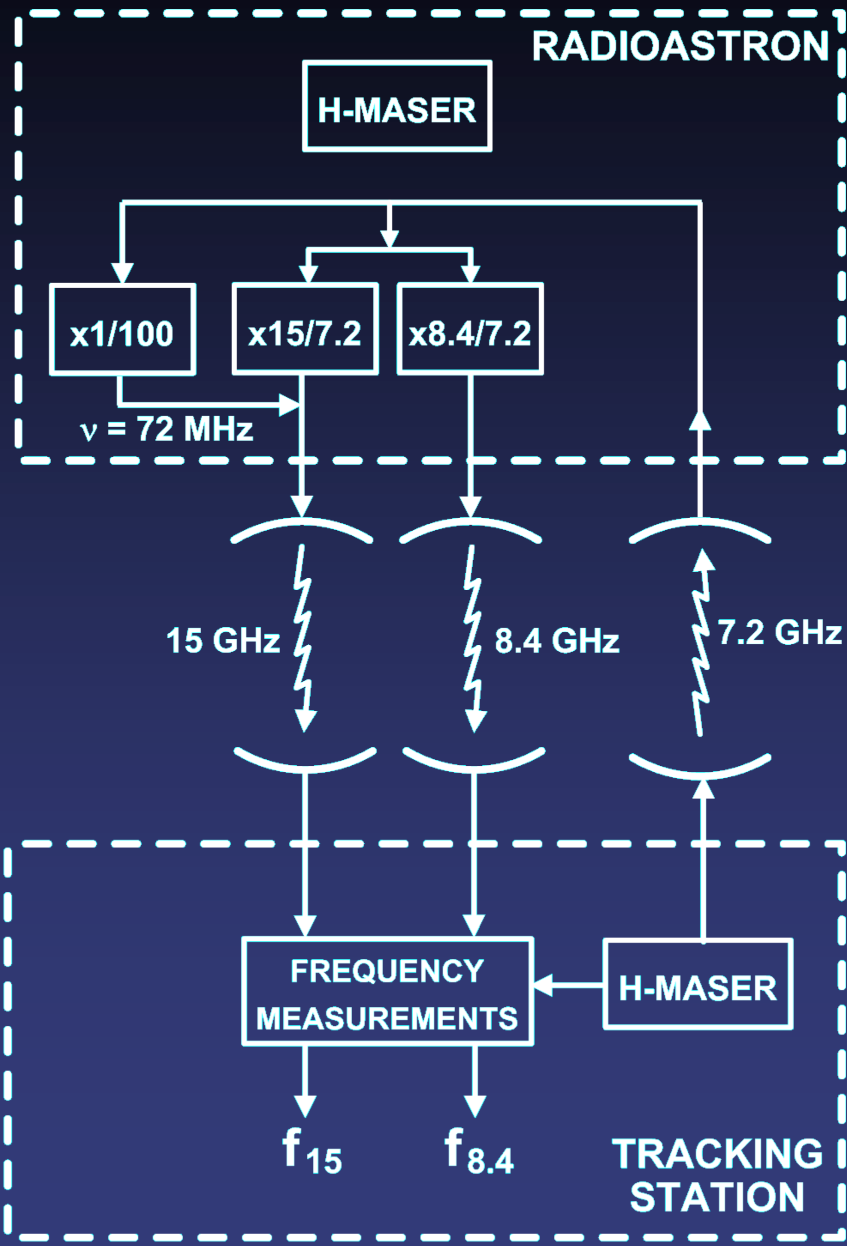
GRAVITY PROBE A EXPERIMENT (1976)

$$\frac{f_{out}}{f} = \frac{1}{2}\frac{|\vec{v}_s - \vec{v}_e|^2}{c^2} + \frac{\Delta U}{c^2} + \dots$$

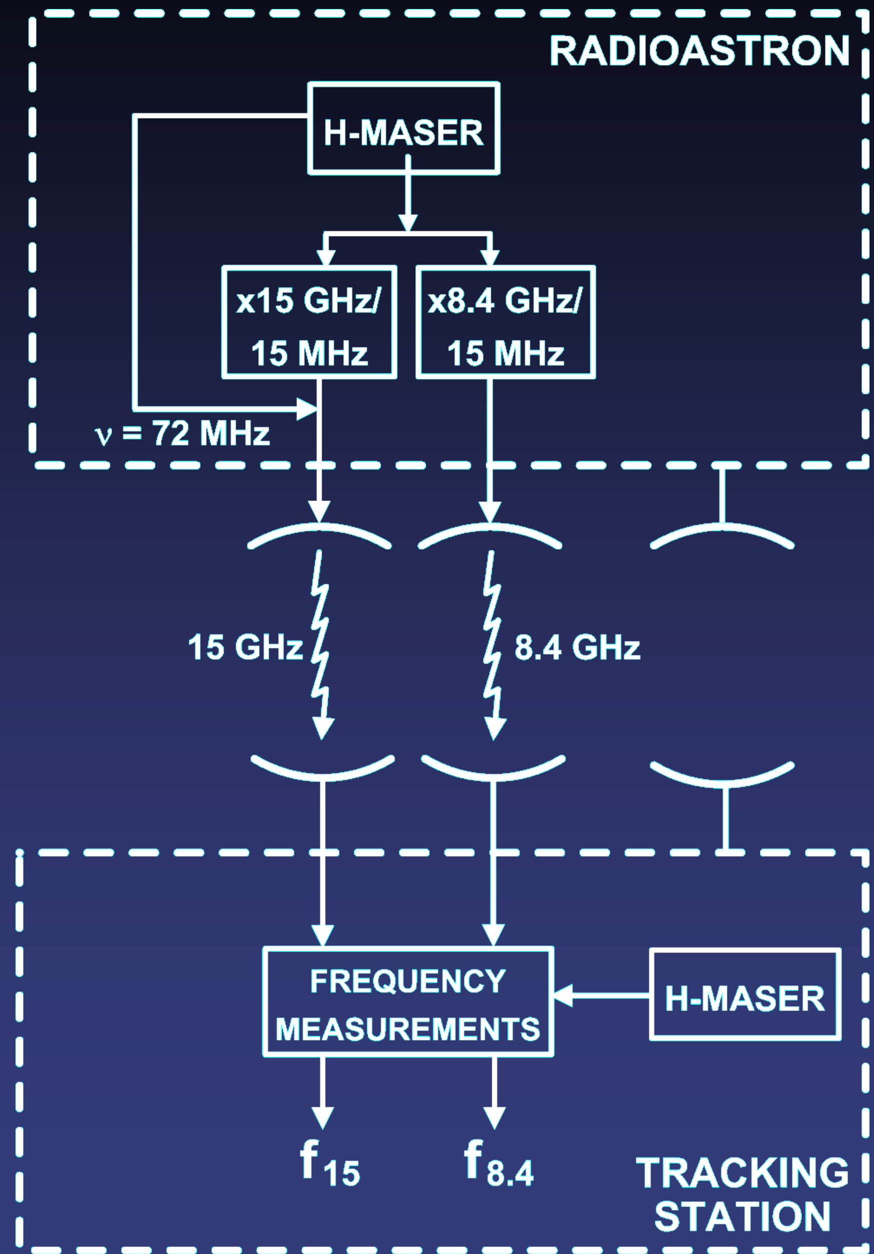


SRT RadioAstron on-board hardware synchronization

"COHERENT" MODE

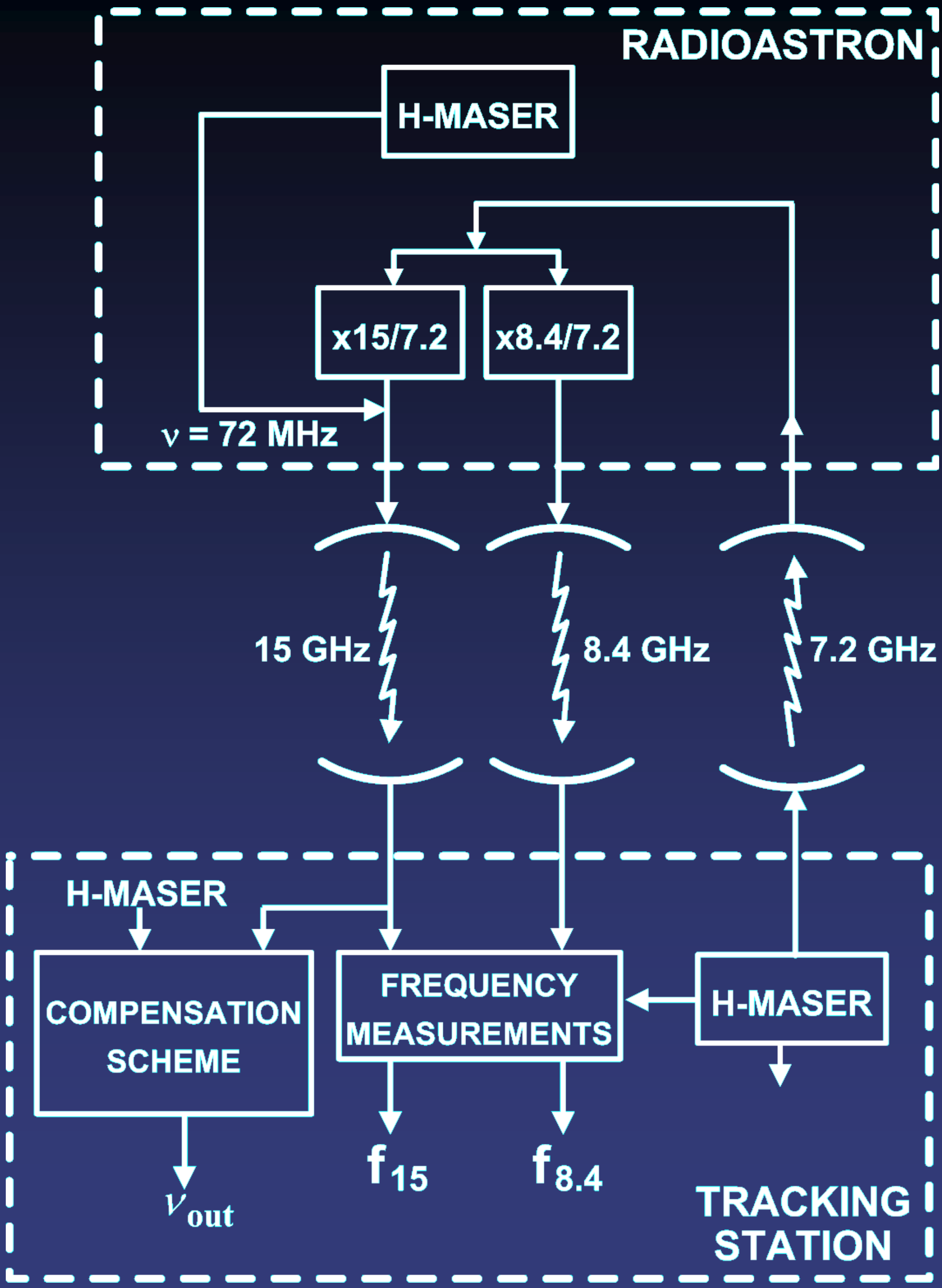


"H-MASER" MODE



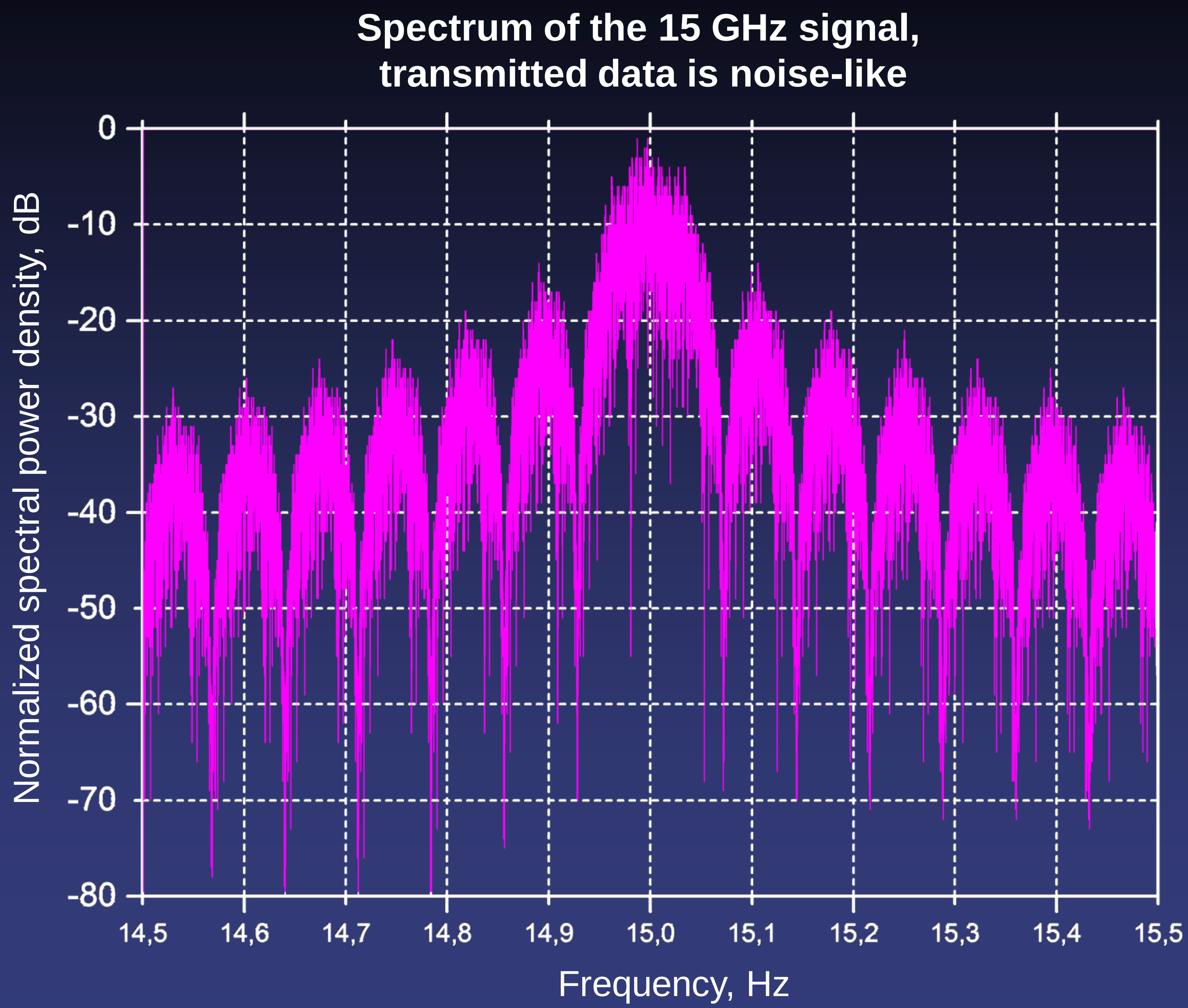
SRT RadioAstron on-board hardware synchronization: "Semi-coherent" mode

$$\frac{\nu_{out}}{\nu} = \frac{1}{2}\frac{|\vec{v}_s - \vec{v}_e|^2}{c^2} + \\ + \frac{\Delta U}{c^2} + \ldots$$

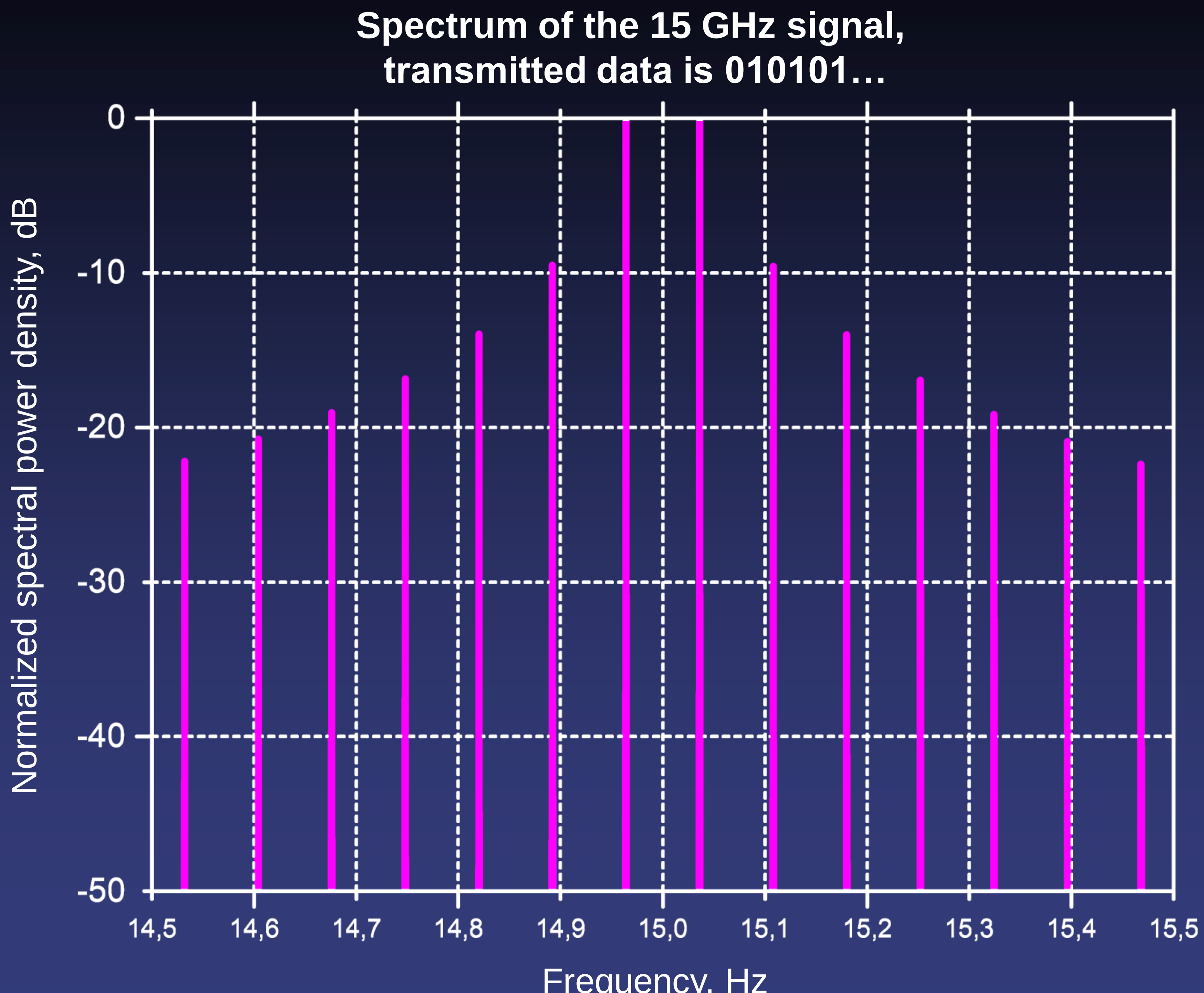


Biriukov et al. 2014, Astron. Rep. 58, p.783 (in print)

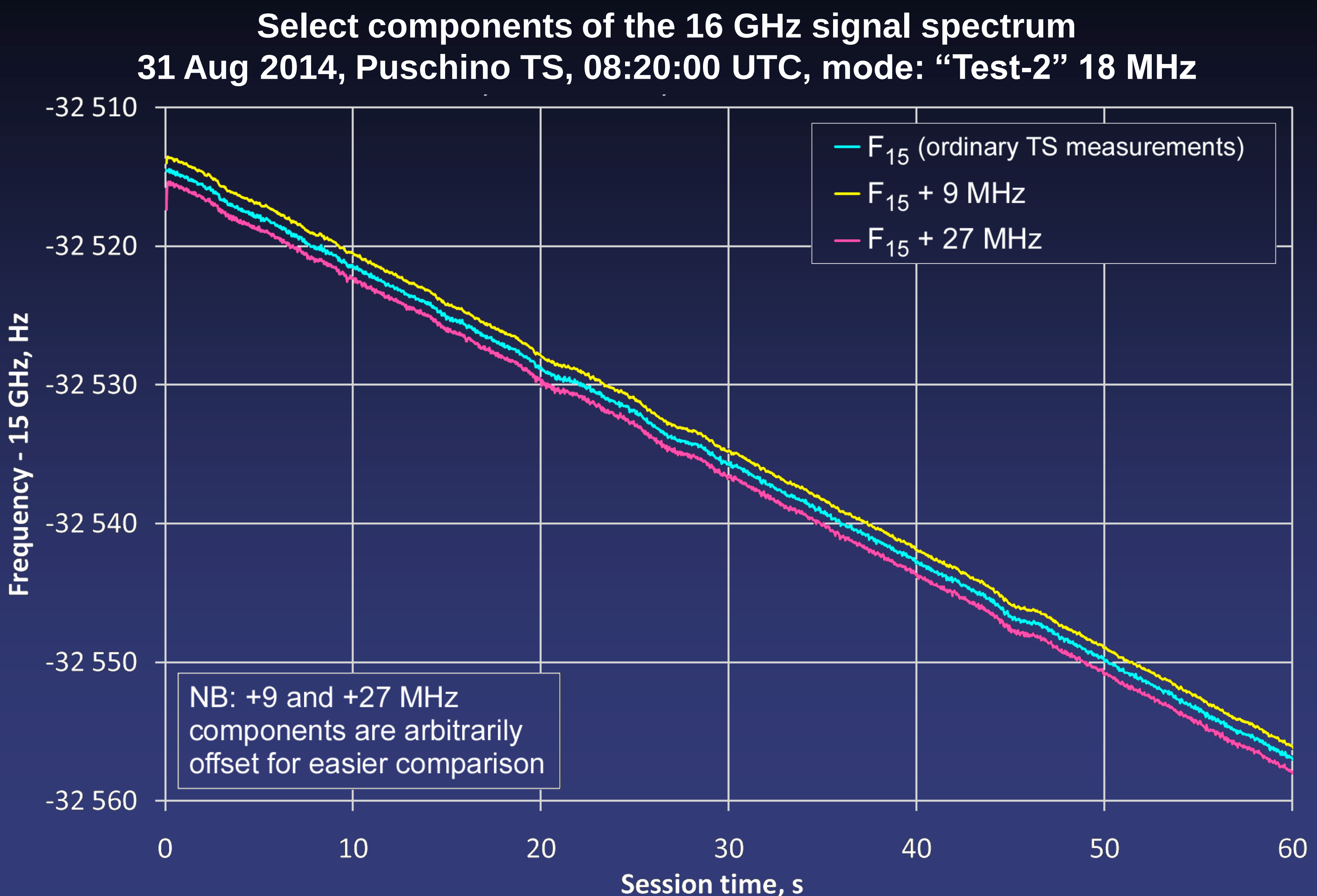
SRT RadioAstron on-board hardware synchronization: "Semi-coherent" mode



SRT RadioAstron on-board hardware synchronization: "Semi-coherent" mode



SRT RadioAstron on-board hardware synchronization: "Semi-coherent" mode



GRAVITATIONAL REDSHIFT TESTS

Mission	Launch/ status	Frequency standard	Achieved/ planned accuracy
Gravity Probe A	1976 completed	H-maser	$1.4 \cdot 10^{-4}$
RadioAstron	2011 active	H-maser	$1 \cdot 10^{-5}$
ACES	2016	Cs-fountain + H-maser	$2 \cdot 10^{-6}$
STE-Quest	≥ 2026	?	$2 \cdot 10^{-8}$