Atomic Clock Ensemble in Space

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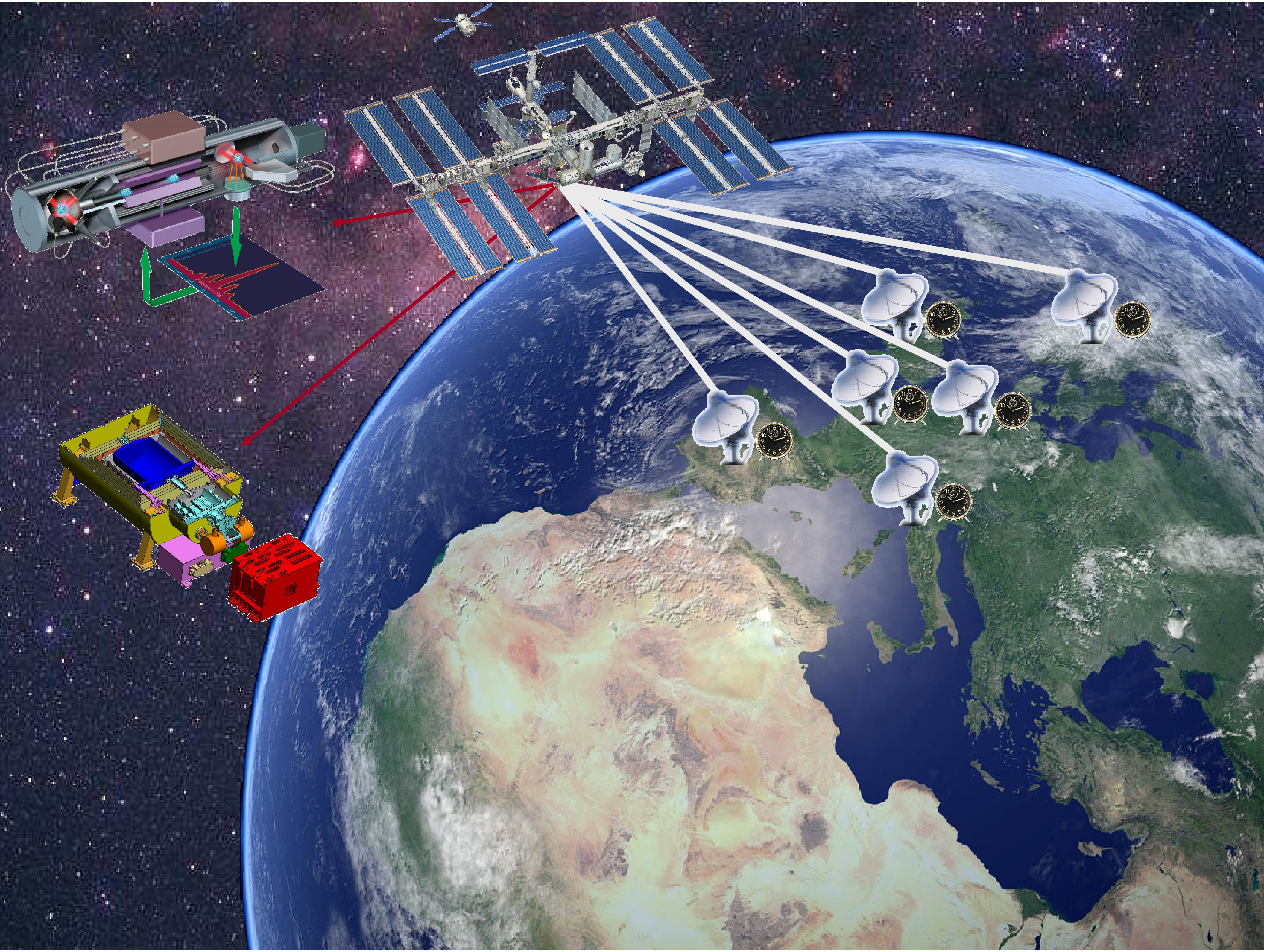
ESA-ESTEC

SCI-SA

International Workshop on

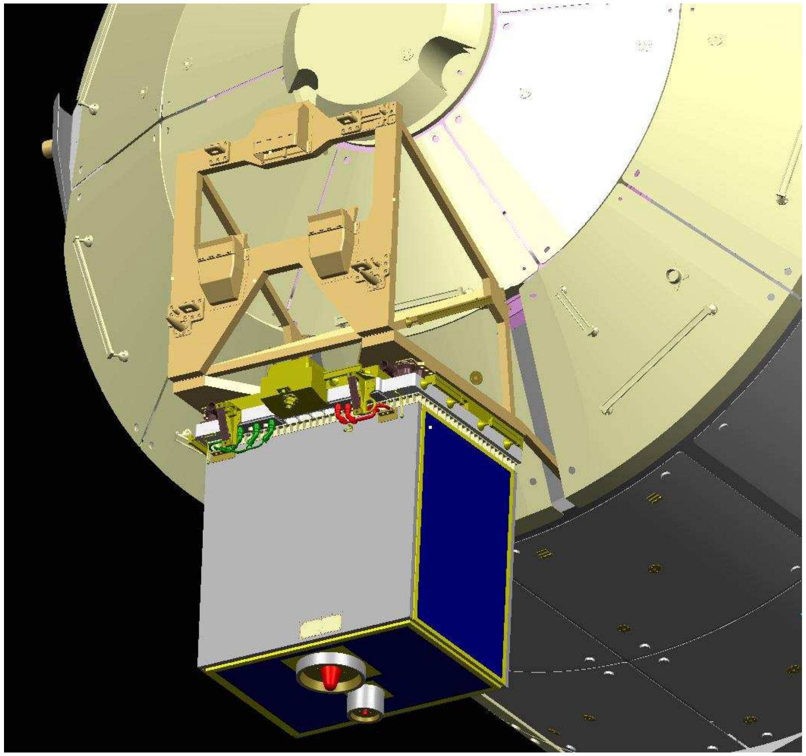
Advances in Precision Tests and Experimental Gravitation in Space

Firenze, 28-30 September 2006

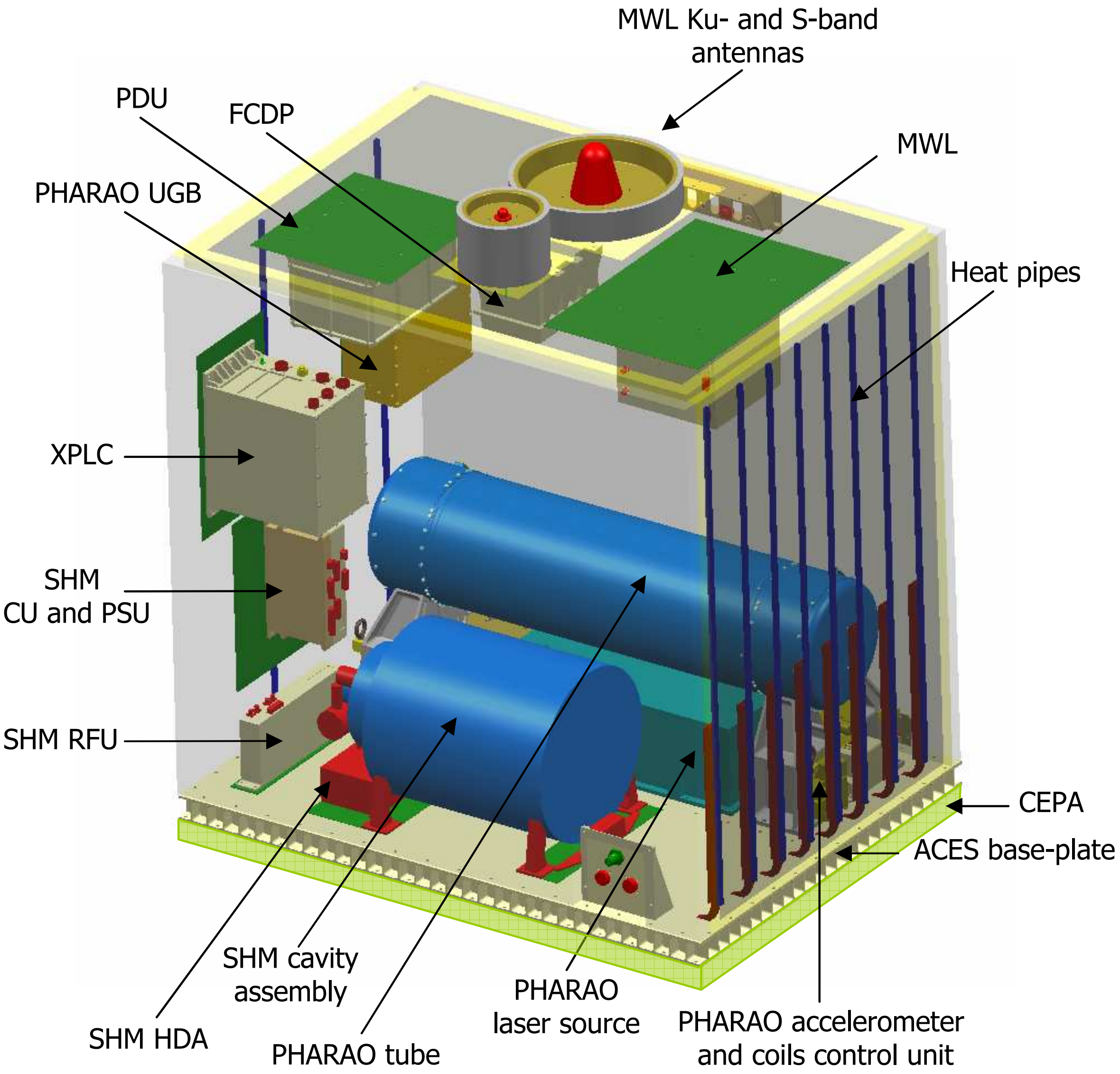


The ACES Payload

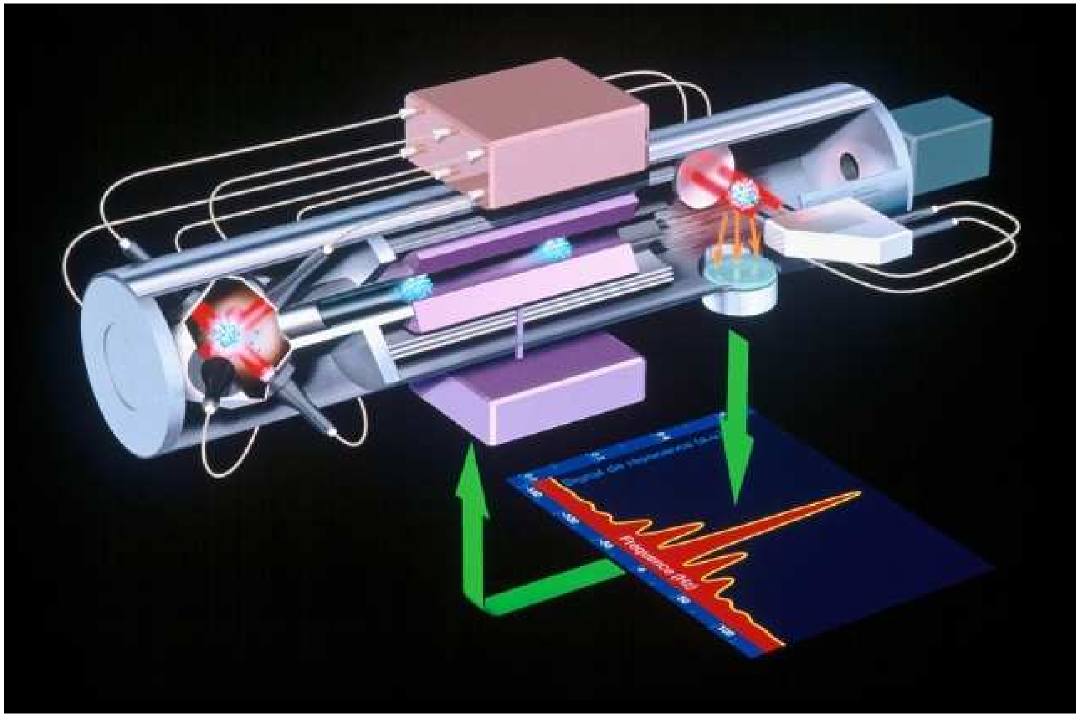
ASTRIUM

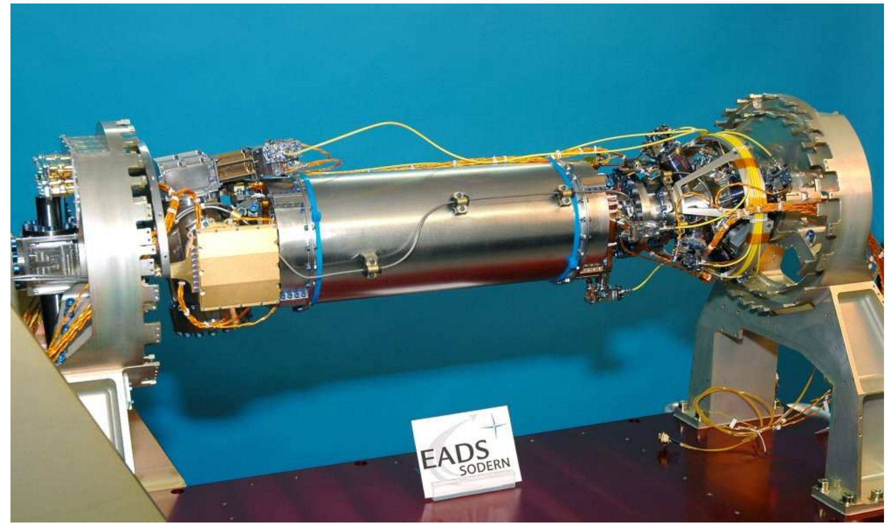


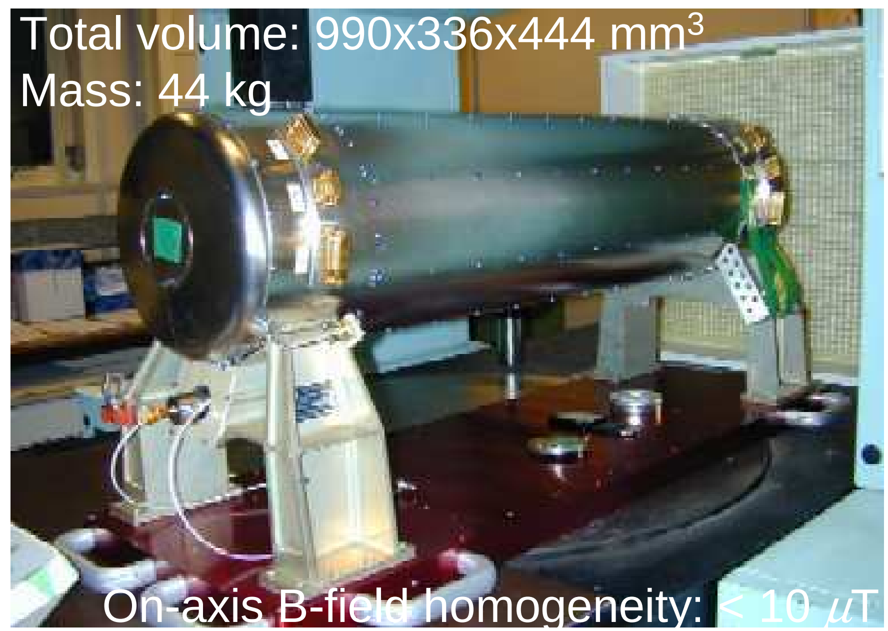
Volume: 1172x867x1246 mm³
Total mass: 227 kg
Power: 450 W



PHARAO: A Cold-Atom Clock in μ-gravity







l'Observatoire de Paris | BNM-SYRTE

Bureau National de Métrologie - Systèmes de Référence Temps-Espace

ENS LETTRES SCIENCES ECOLE NORMALE SUPERIEURE

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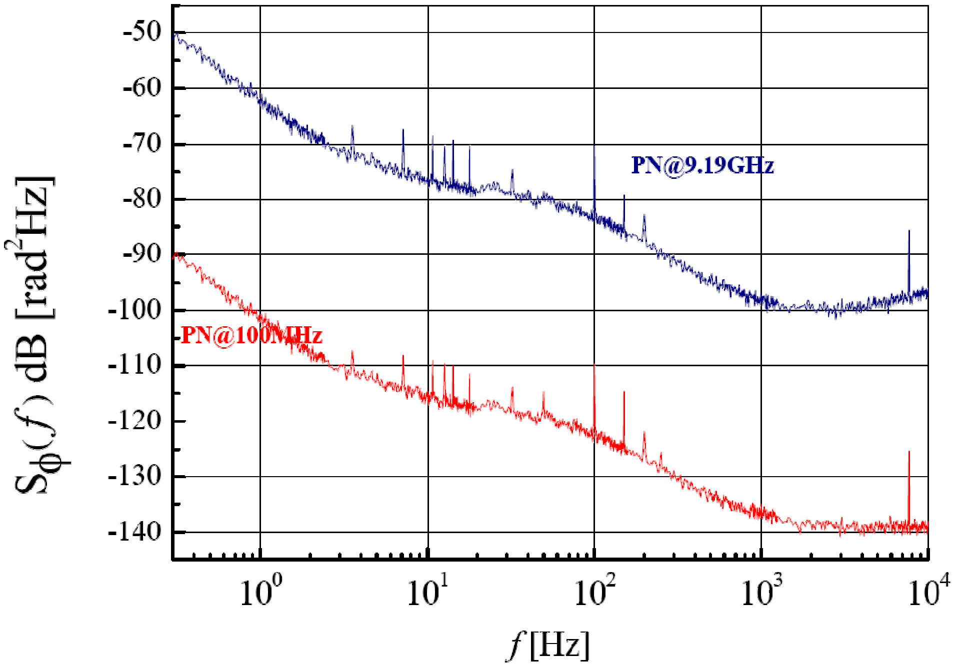
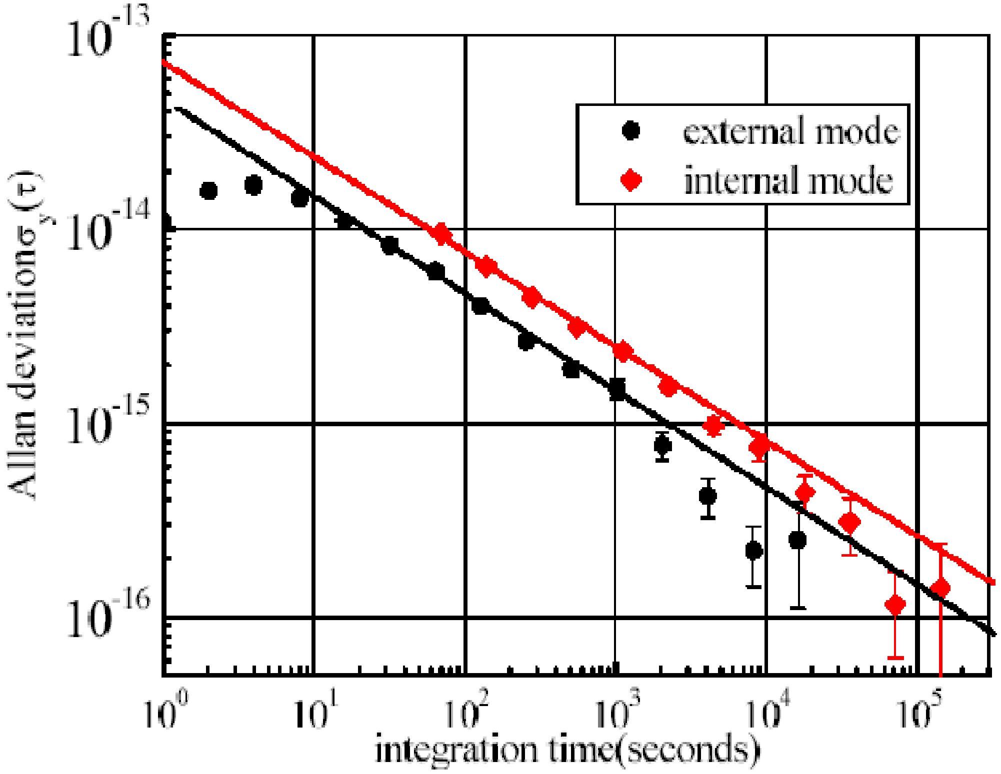
PHARAO

THALES

PHARAO Oscillator and Synthesis Chain



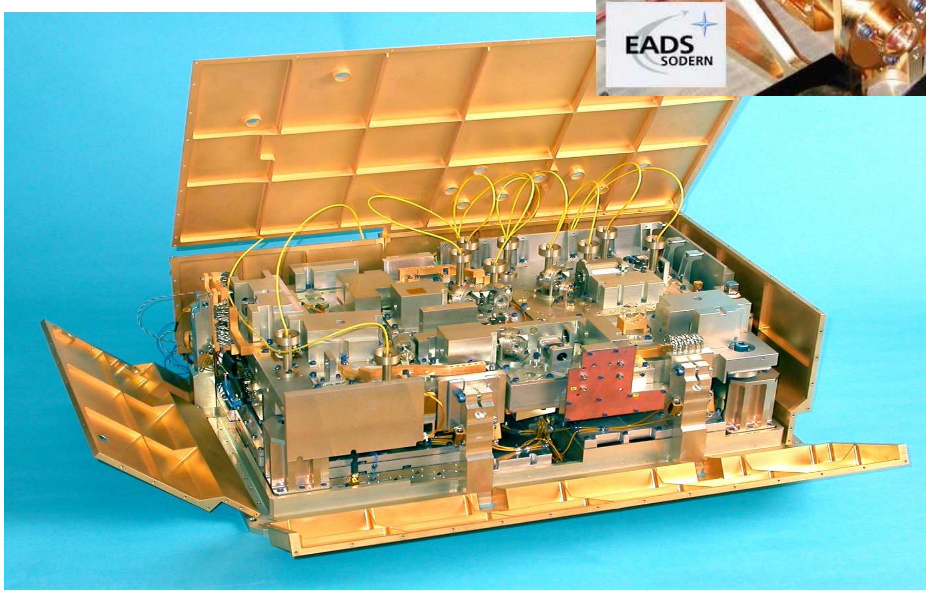


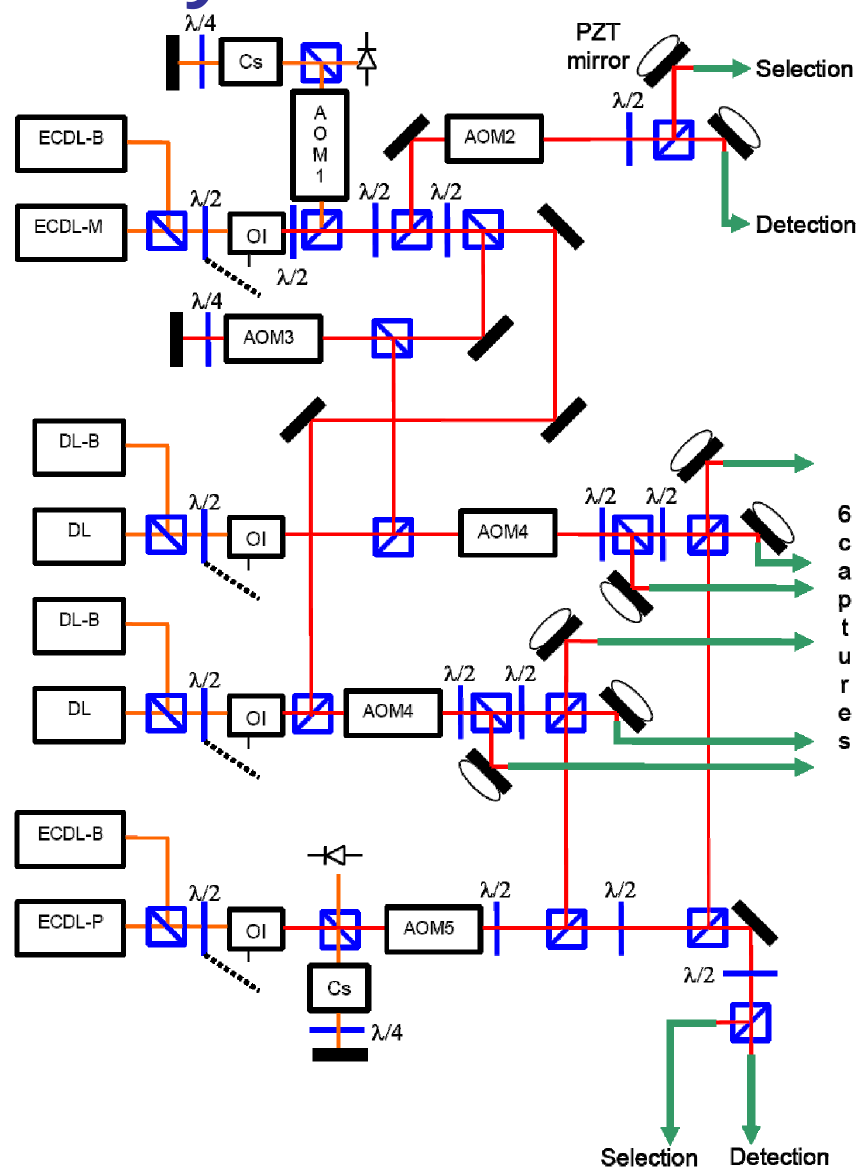
Tested at LNE-SYRTE on the F02 fountain clock

- Fractional frequency instability: $7 \cdot 10^{-14} \cdot \tau^{-1/2}$

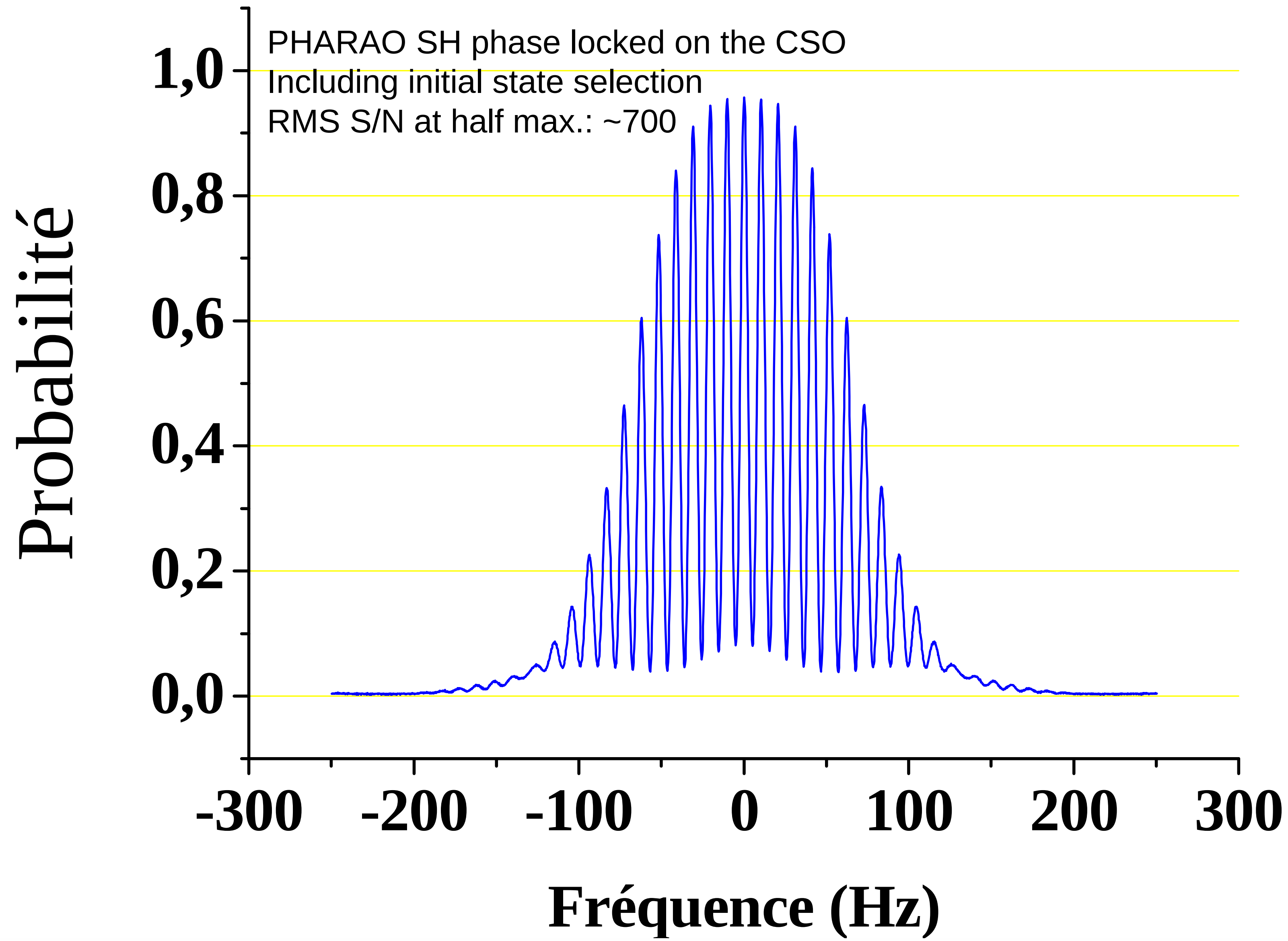
PHARAO Optical System

- Dimensions: 530x350x150 mm^3
- Mass: 20.054 kg
- Cooling beams: 6 x 17 mW
- Repumper used for cooling, selection, and detection
- Detection system
  - Standing wave (F=4)
  - Pushing beam (F=4)
  - Pumping beam (F=3)
  - Standing wave (F=4)

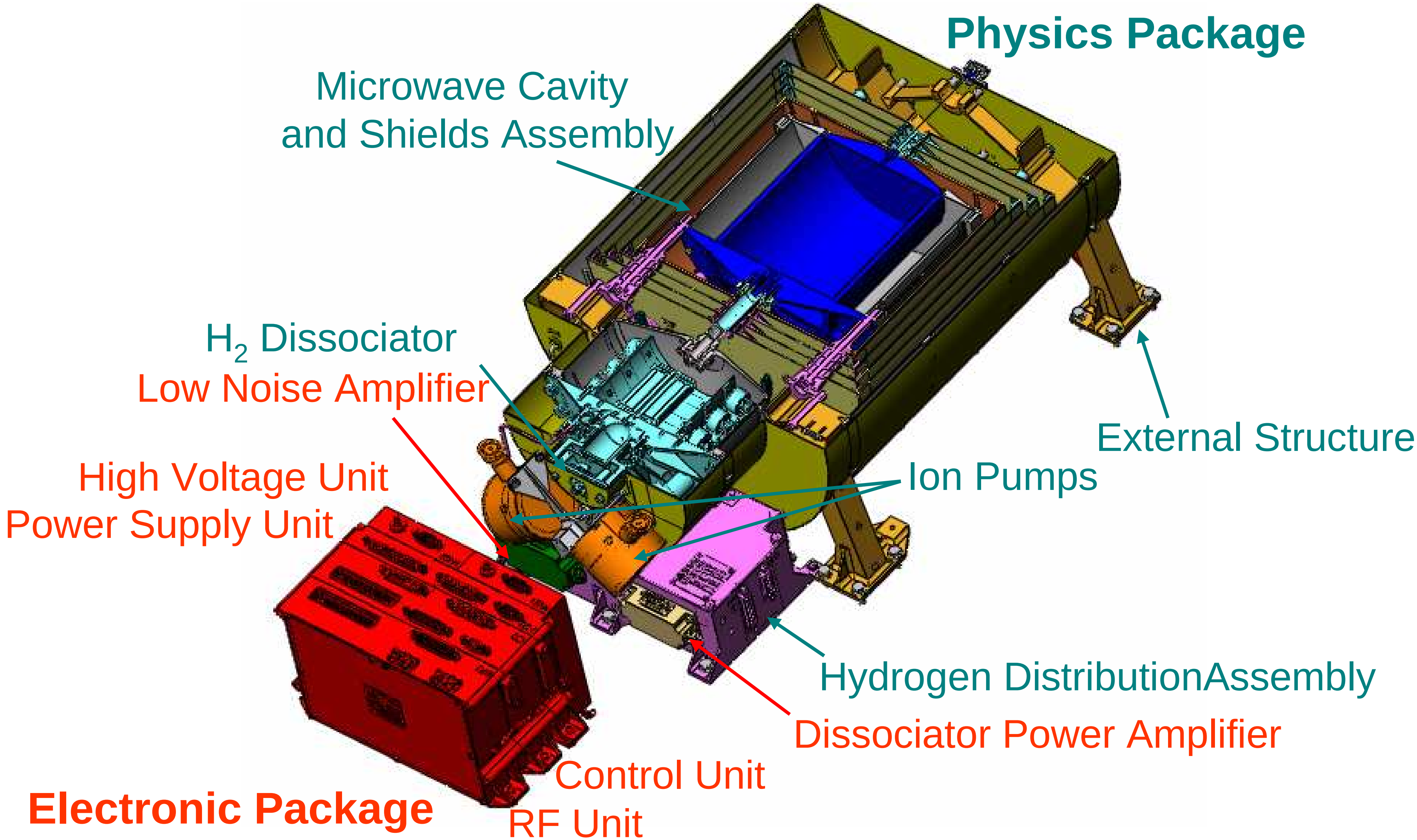




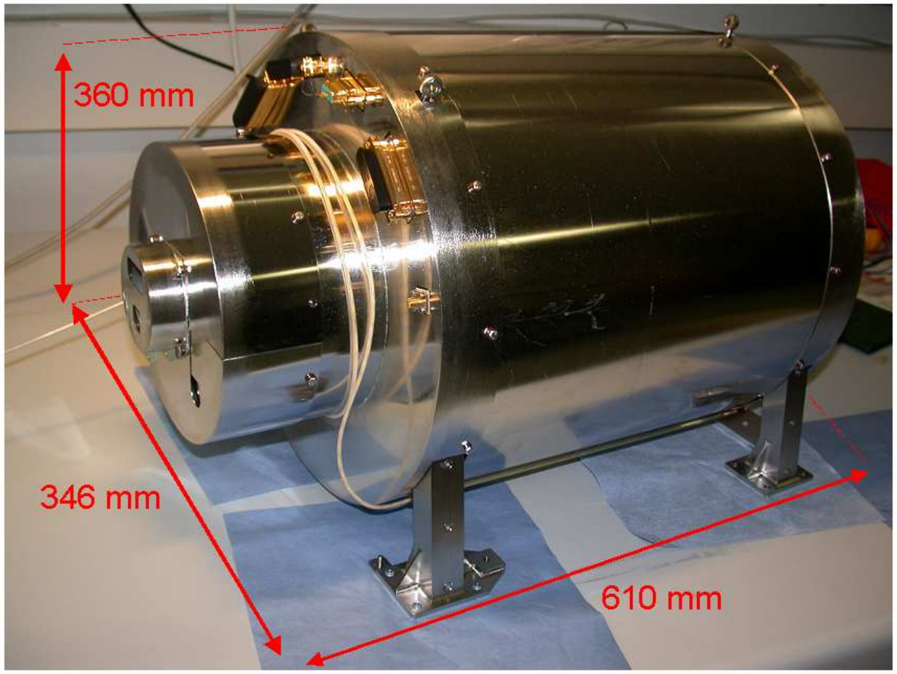
PHARAO Ramsey Fringes



SHM: An Active Maser for Space

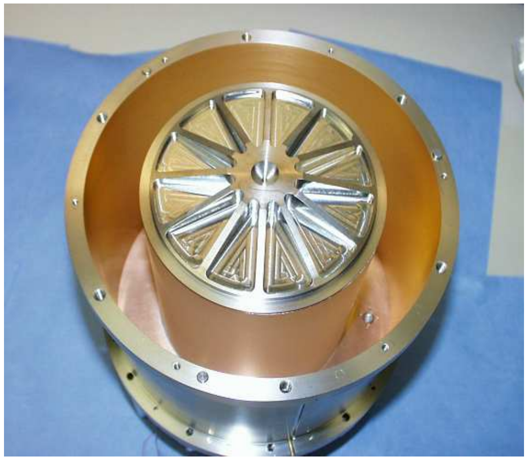


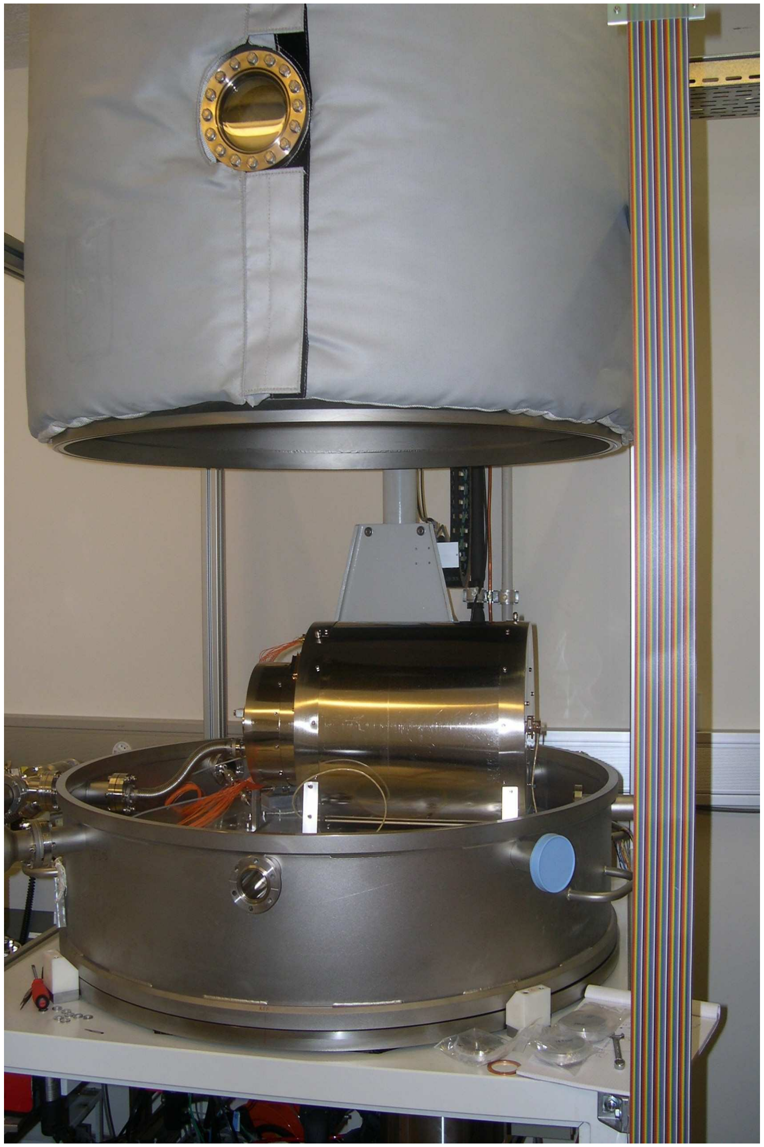
SHM Physics Package



Observatoire de Neuchâtel

Contraves Space

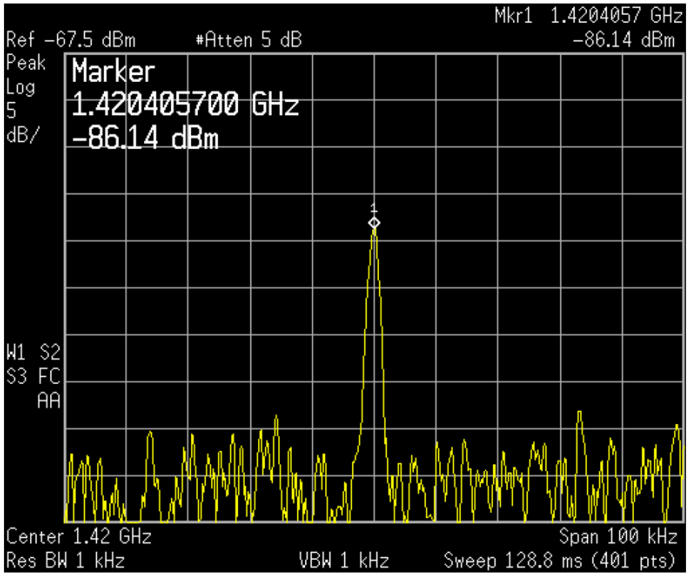


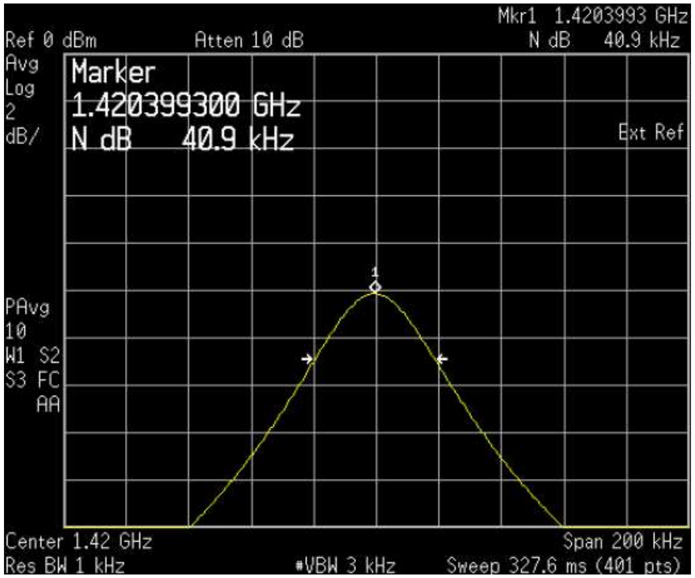


SHM Parameters

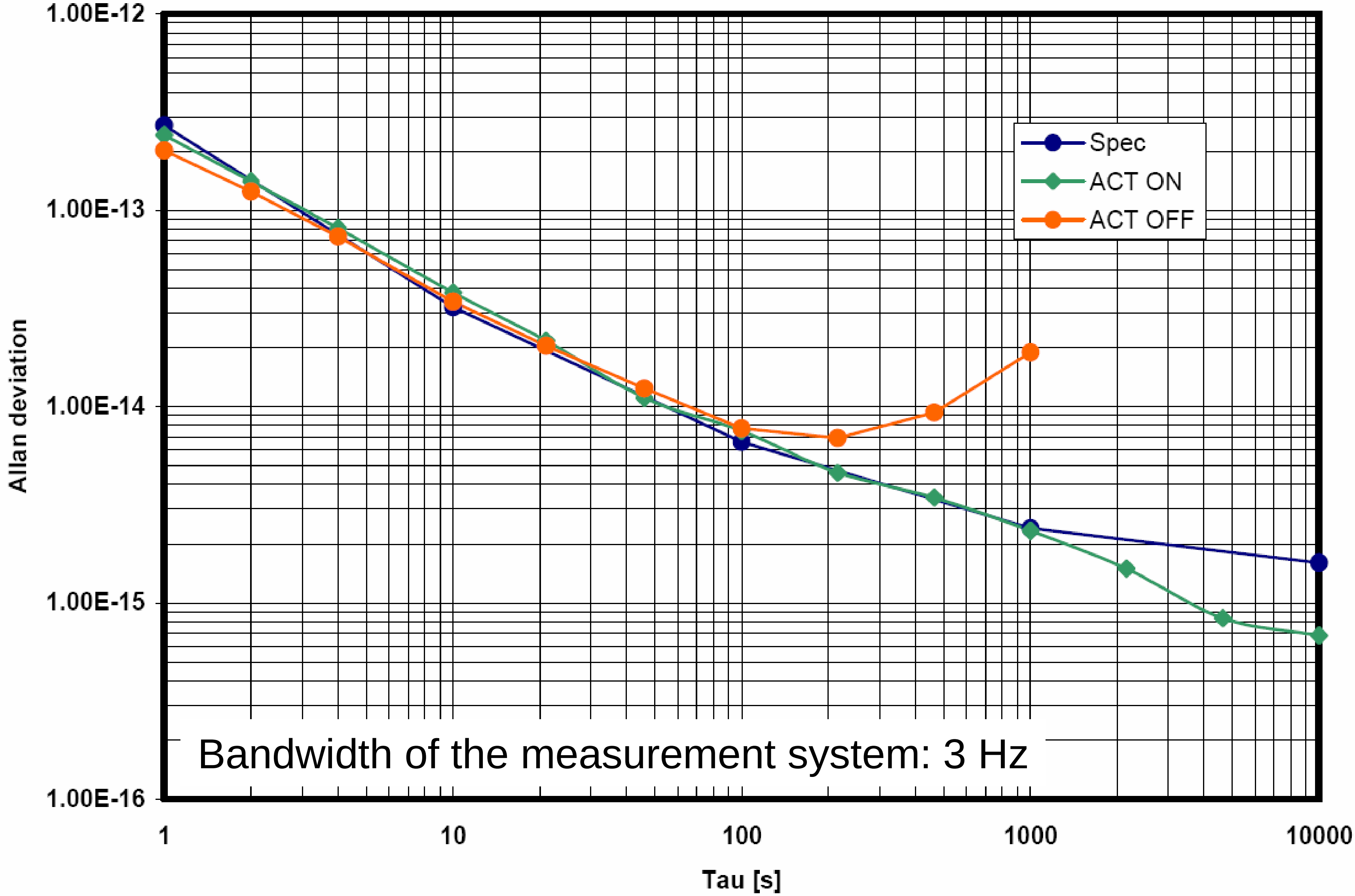
Measured Parameters

- Temperature stabilization of the microwave cavity: <1mK
- Active oscillation: power level of -104 dBm (specified: -105 dBm)
- Measurement of the atomic quality factor via the cavity pulling effect: $1.5 \cdot 10^9$ (specified: $1.5 \cdot 10^9$)
- Cavity quality factor: (35487 ±164) Hz
- Measurement of the spin-exchange tuning point: 8741 Hz
- Characterization of the maser signal vs B-field
- Magnetic shielding factor: $2 \cdot 10^5$





Allan Deviation: Preliminary Results



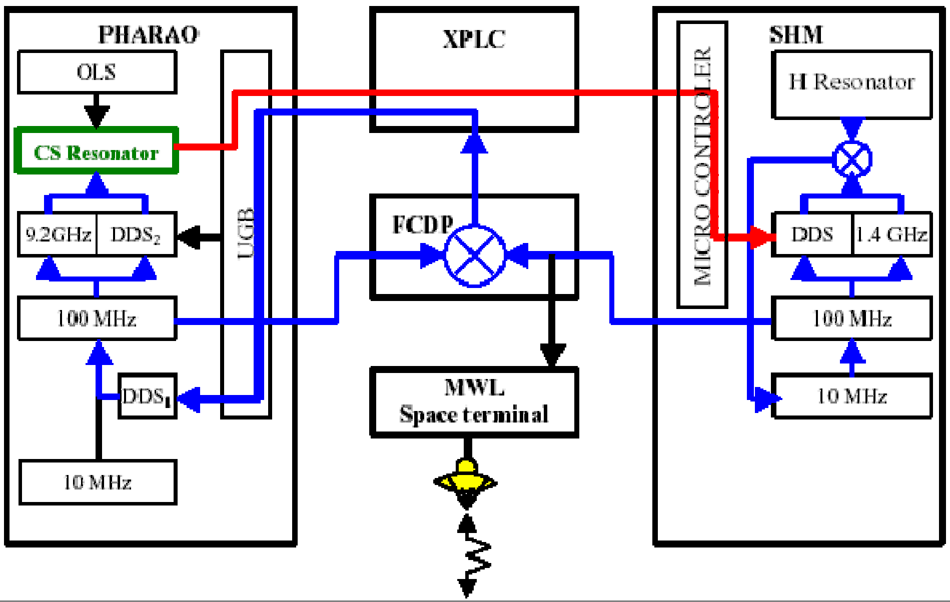
The ACES Clock Signal

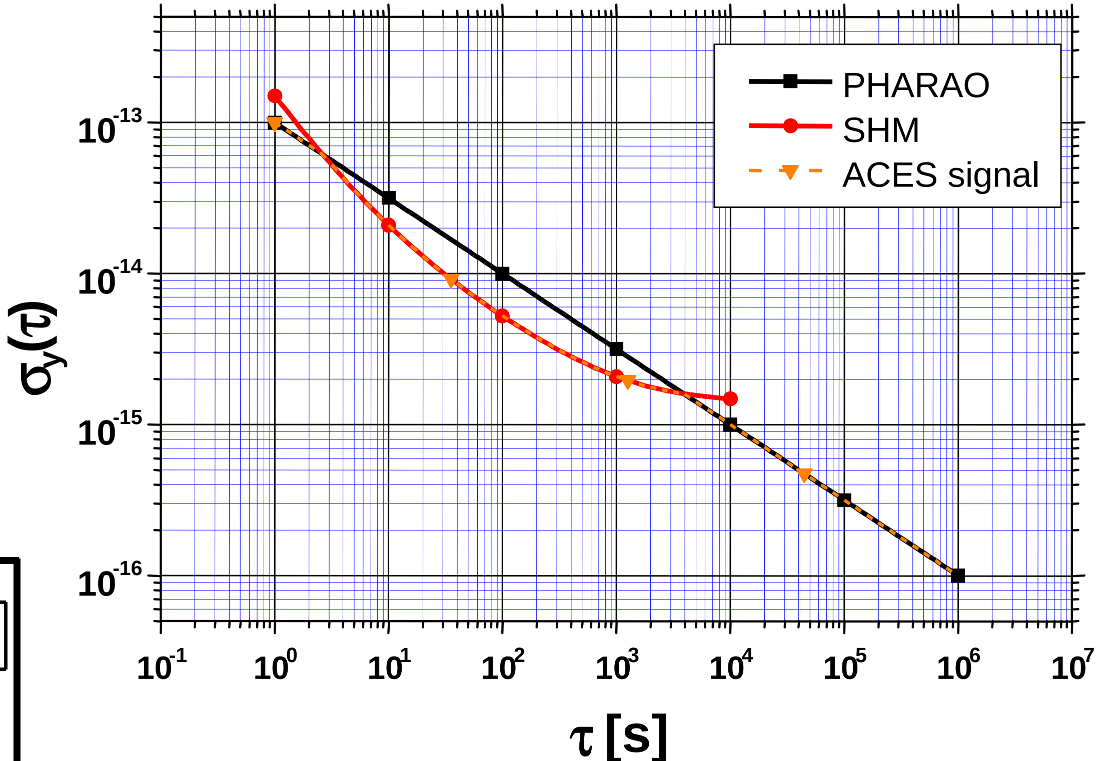
Short term servo loop

Locks PHARAO local oscillator to SHM ensuring a better short and mid-term stability

Long term servo loop

Corrects for SHM drifts providing the ACES clock signal with the long-term stability and accuracy PHARAO



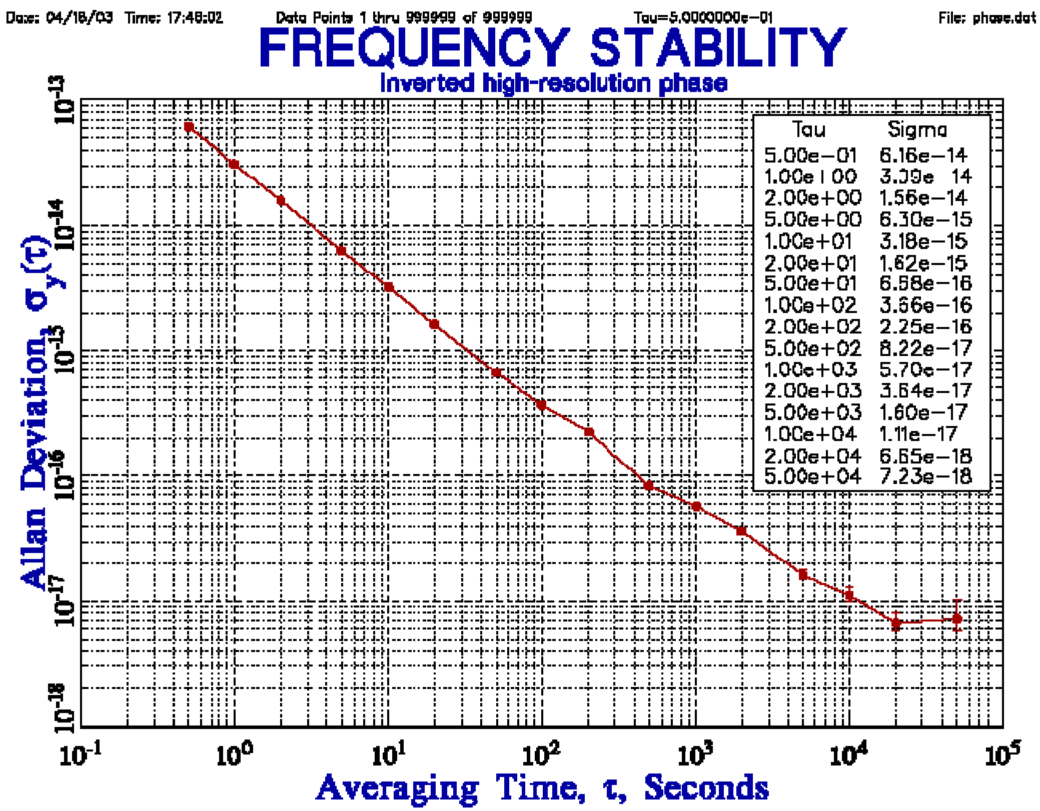


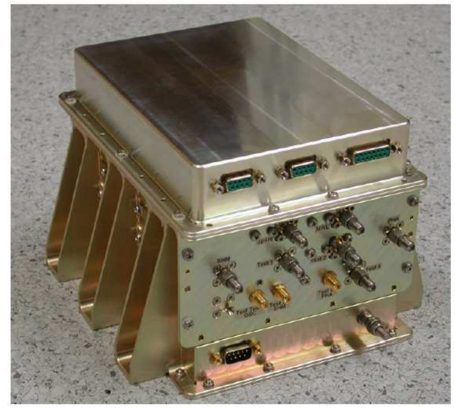
Stability of the ACES clock signal:

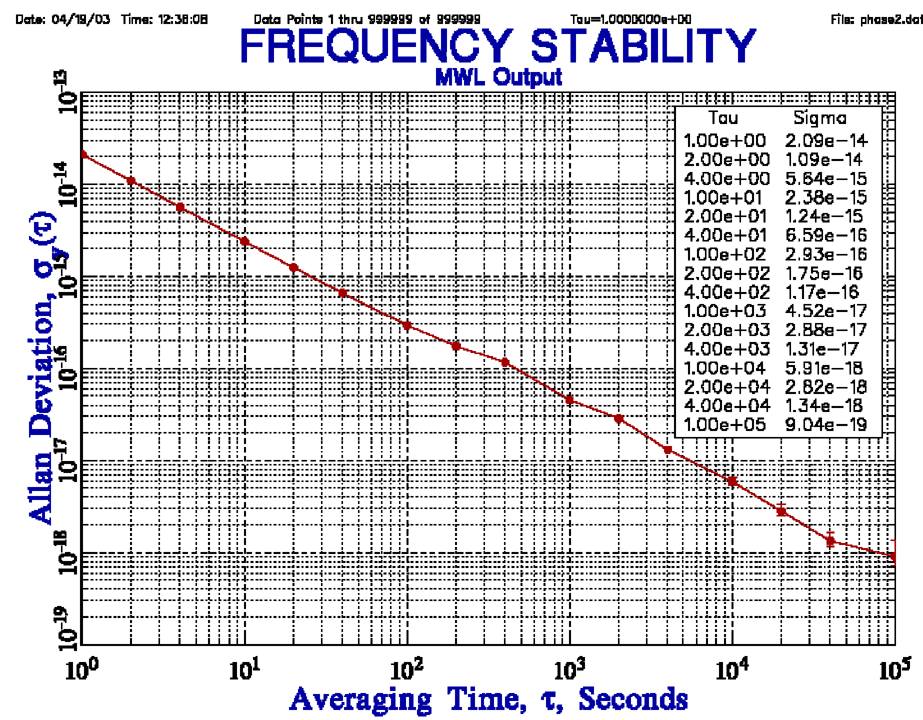
- $3 \cdot 10^{-15}$ at 300 s (ISS pass)
- $3 \cdot 10^{-16}$ at 1 day
- $1 \cdot 10^{-16}$ at 10 days

Accuracy: $\sim 1 \cdot 10^{-16}$

FCDP Engineering Model

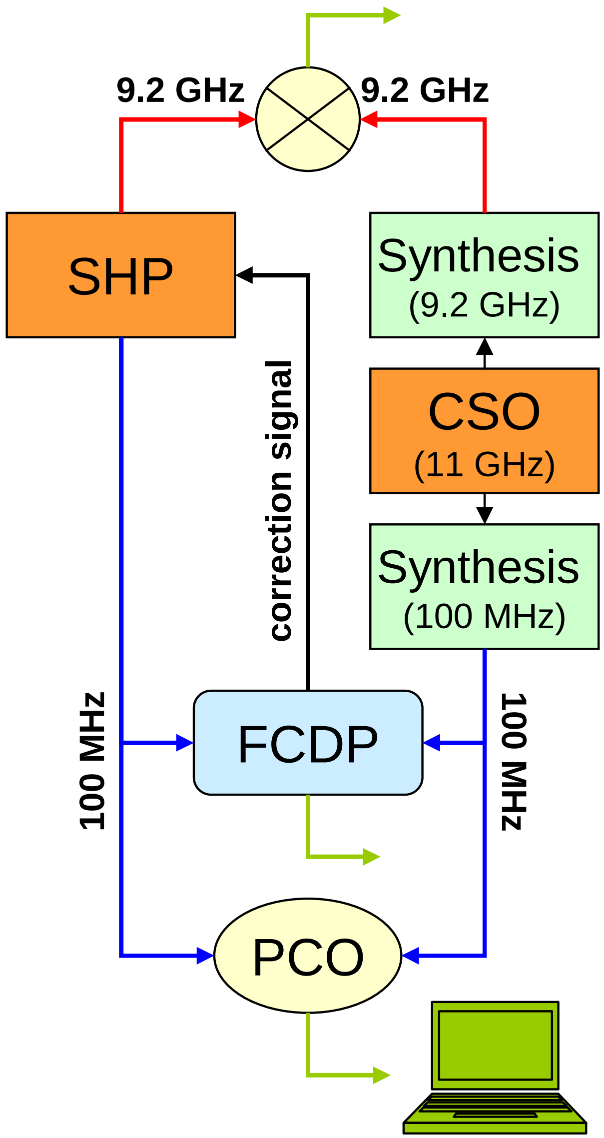


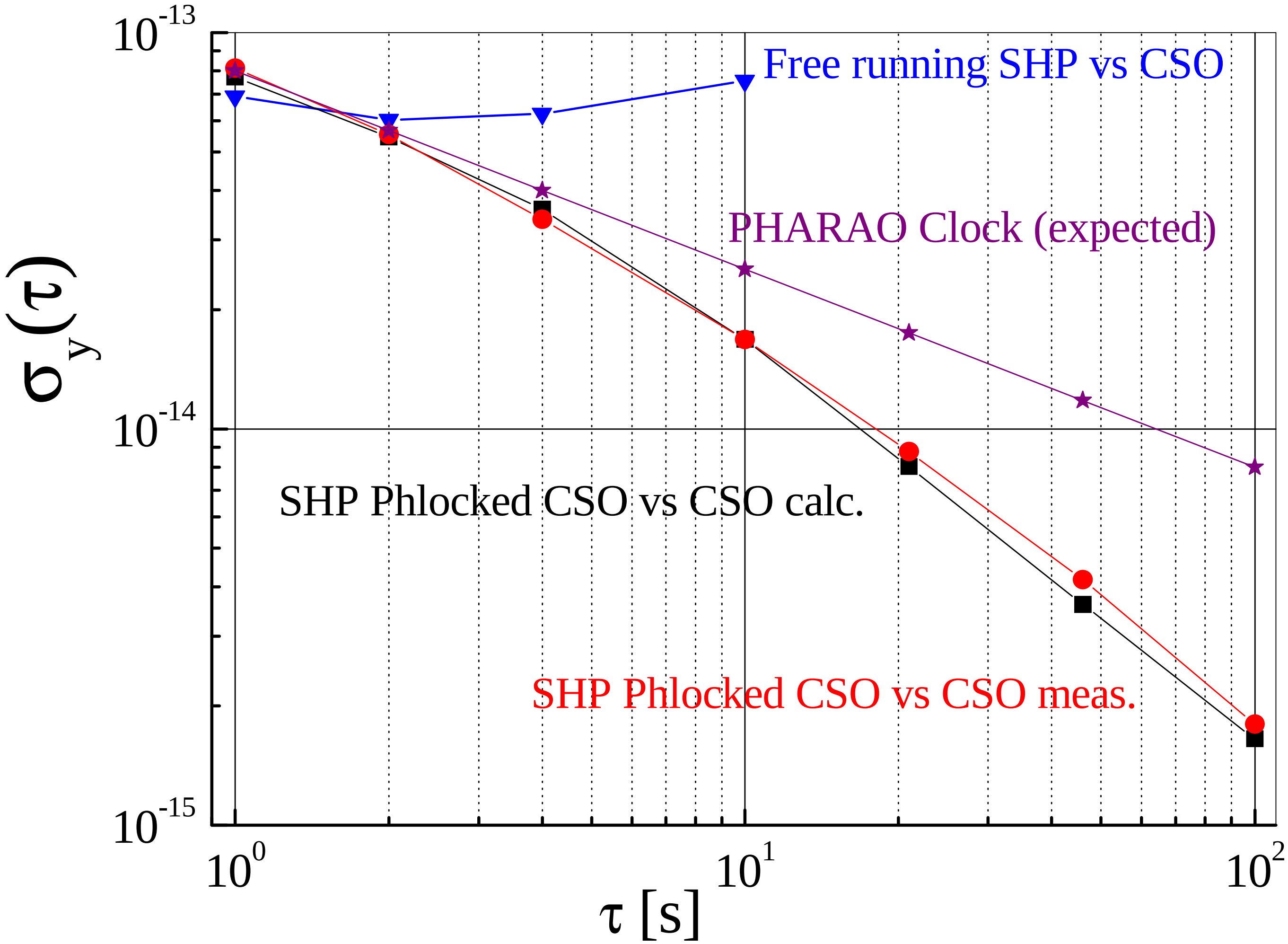




ASTRIUM TIMETECH KAYSER-THREDE

Short-term Servo Loop Test

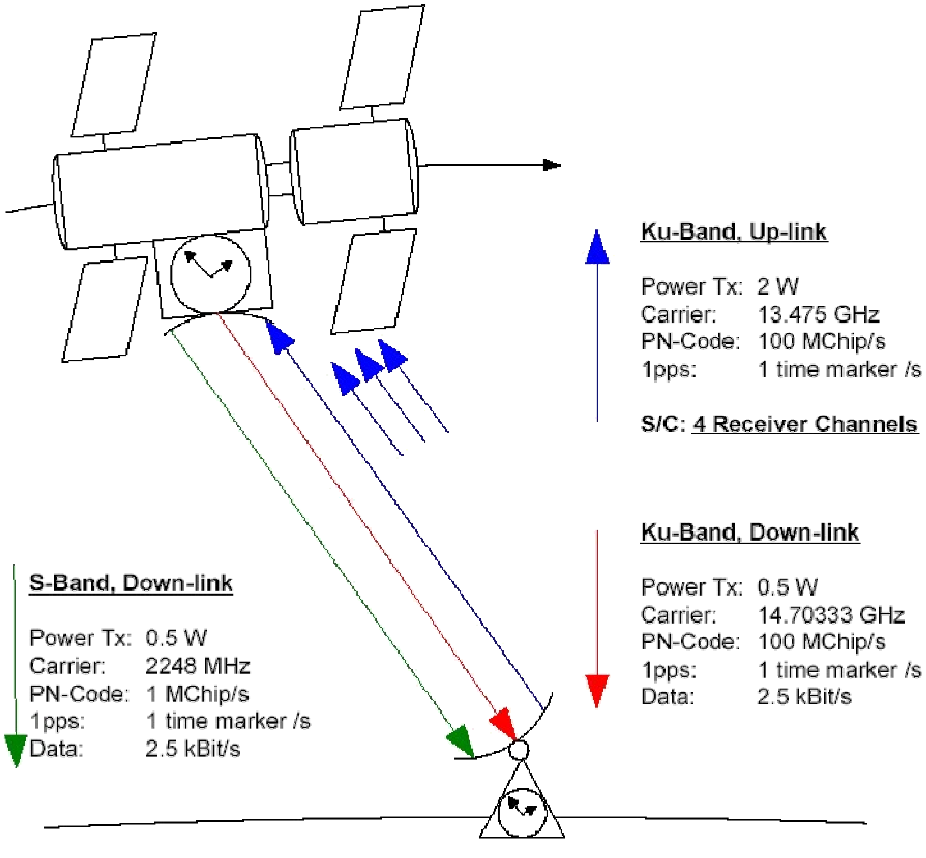




FCDP-SHP integrated tests performed at CNES

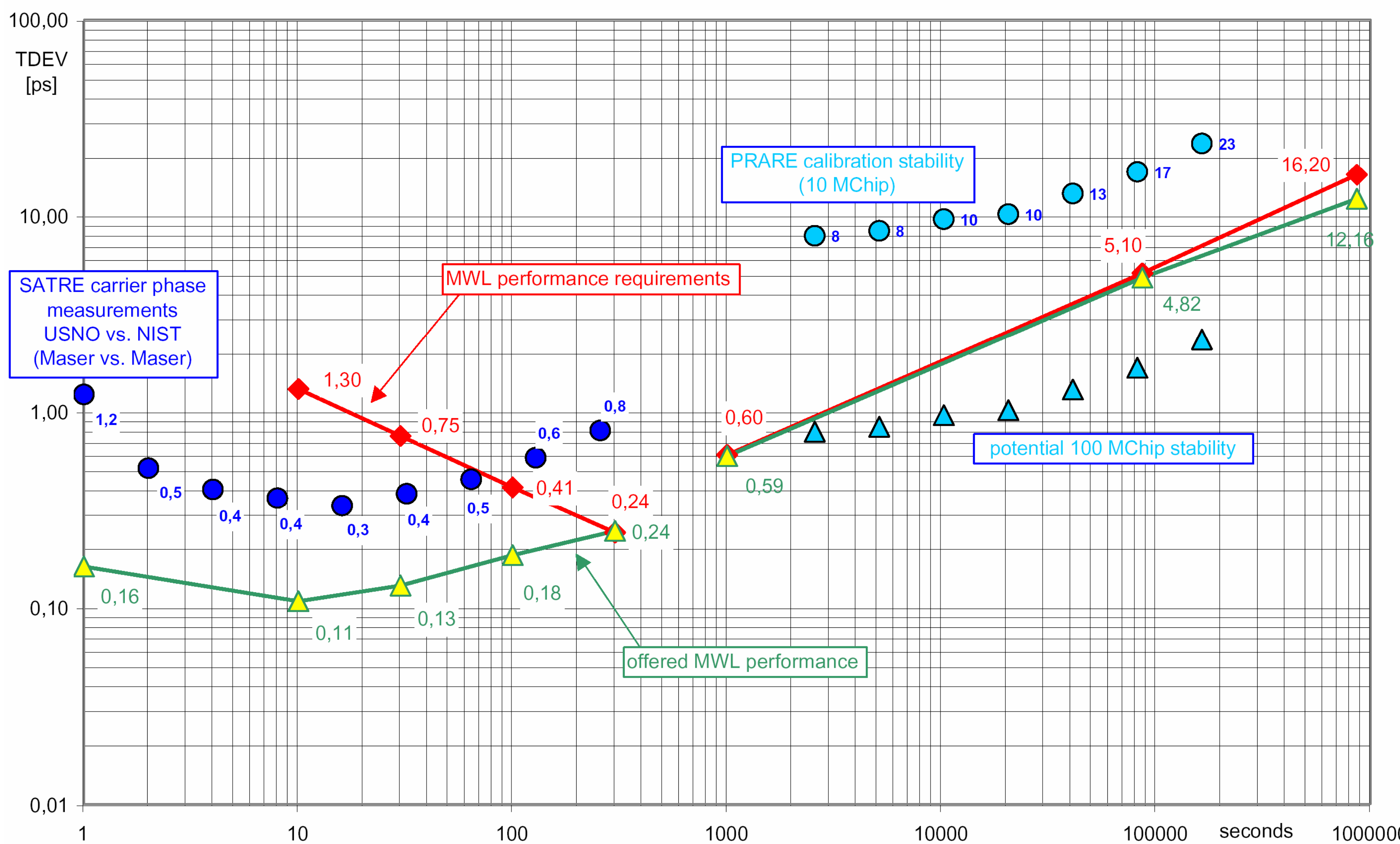

cnes
cnes

ACES Microwave Link



- Two-way link:
  - Removal of the troposphere time delay (8.3-103 ns)
  - Removal of 1st order Doppler effect
  - Removal of instrumental delays and common mode effects
- Additional down-link in the S-band:
  - Determination of the ionosphere TEC
  - Correction of the ionosphere time delay (0.3-40 ns in S-band, 6-810 ps in Ku-band)
- Phase PN code modulation: Removal of 2π phase ambiguit
- High chip rate (100 MChip/s) on the code:
  - Higher resolution
  - Multipath suppression
- Carrier and code phase measurements (1 per second)
- Data link: 2 kBits/s on the S-band down-link to obtain clock comparison results in real time
- Up to 4 simultaneous space-to-ground clock comparisons

ACES MWL Performances



- Time stability: 0.3 ps at 300 s, 6 ps at 1 day, 23 ps at 10 days of integration time
- Accuracy: absolute calibration at the 100 ps level
- Clock comparisons: 10^{-17} regime after 1 day of integration time

MWL Code/Carrier Phase Measurement

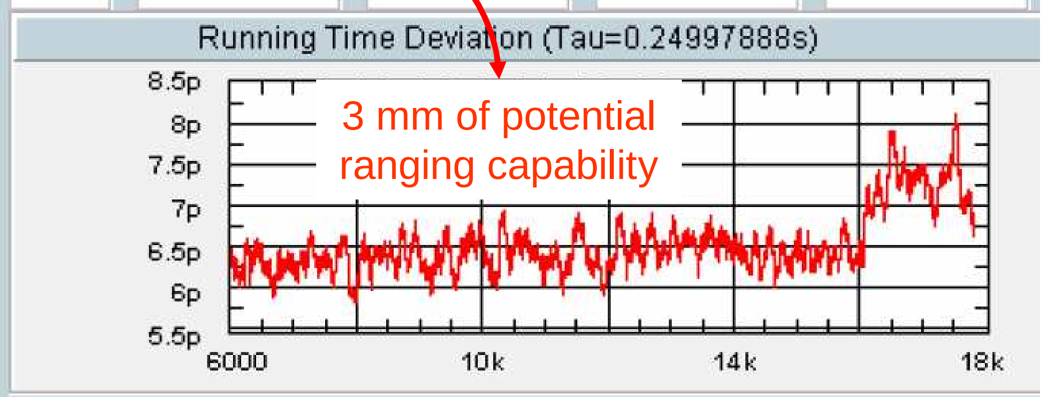
Code phase measurements

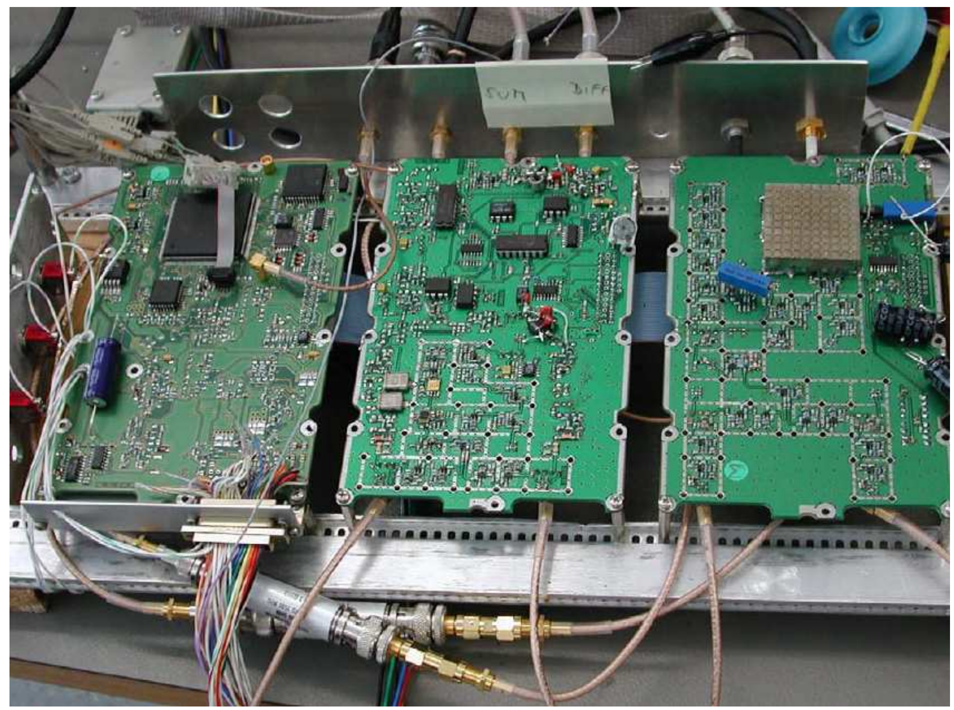
- Long-term stability ensured by the built-in test translator, removing thermally induced drifts
- Short-term stability (~300 s) depending on noise performances and reproducibility of each DLL receiver channel after proper calibration
- Four to five times improvement wrt 20 MChip/s commercial products demonstrated

Carrier phase measurements

- Ultimate phase stability for short integration time obtained with carrier phase measurement.
- TDEV evaluated from Ku-band Tx and IF local oscillator of Ku Band Rx: $2.3 \cdot 10^{-13}$ s up to 300 s
- …still margin for improvement

Tau[s]	Time Deviation	Max.	Min.	Sample
0	6.837E-012	8.438E-012	5.266E-012	17806
1	3.610E-012	3.860E-012	2.735E-012	17806
3	1.937E-012	2.387E-012	1.399E-012	17804
10	9.209E-013	1.455E-012	6.044E-013	17795

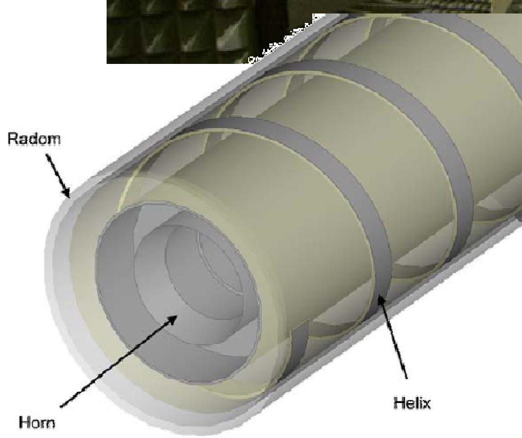




MWL Antennas

Ku-band antenna

S-band antenna

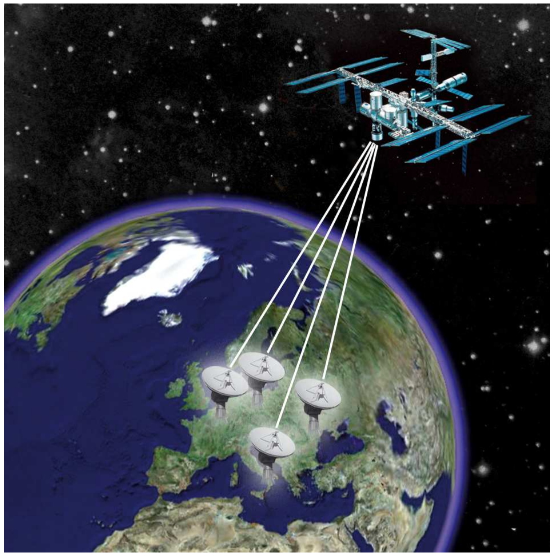


Dual feed system with 60 cm offset reflector

- Horn antenna for the Ku-band
- Helix antenna for the S-band

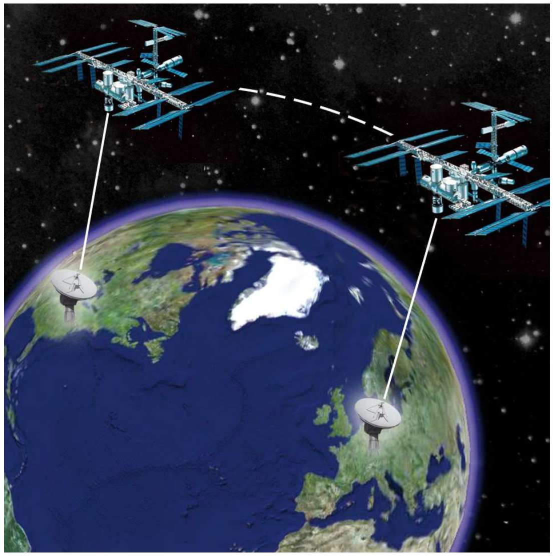
ACES Operational Scenario

- Mission duration: 1.5 years up to 3 years
- ISS orbit parameters:
  - Altitude: ~ 400 km
  - Inclination: ~ 51.6°
  - Period: 90 min
- Link according to orbit characteristics:
  - Link duration: up to 400 seconds
  - Useful ISS passes: at least one per day
- MWL ground terminals
  - Located at ground clock sites
  - Distributed worldwide



Common view comparisons

- Up to 4 simultaneous comparisons of ground clocks
- Uncertainty below 1 ps per ISS pass (~ 300 s)



Non-common view comparisons

- ACES clocks as *fly wheel*
- Uncertainty below 2 ps over 1000 s and 20 ps over 1 day

ACES Mission Objectives I

ACES Mission Objectives	ACES performances	Scientific background and recent results
	Test of a new generation of space clocks	
Cold atoms in micro-gravity	Study of cold atom physics in microgravity	Essential for the development of atomic quantum sensors for space applications (optical clocks, atom interferometers, atom lasers)
Test of the space cold atom clock PHARAO	Frequency instability: $< 3 \cdot 10^{-16}$ at 1 day Inaccuracy: $\sim 10^{-16}$ Short term frequency instability evaluated by direct comparison to SHM. Long term instability and systematic frequency shifts measured by comparison to ultra-stable ground clocks.	PHARAO will be one of the most accurate frequency standards ever built. Recent progress of clocks in the optical domain is making available frequency standards with performances comparable to or better than PHARAO, increasing the scientific return of the ACES mission.
Test of the space hydrogen maser SHM	Frequency instability: $< 2.1 \cdot 10^{-15}$ at 1000 s $< 1.5 \cdot 10^{-15}$ at 10000 s Medium term frequency instability evaluated by direct comparison to ultra-stable ground clocks. Long term instability determined by on-board comparison to PHARAO in FCDP.	Performances of state-of-the-art masers

Maser	σ_y (1000 s)	σ_y (10000 s)
GALILEO	$3.2 \cdot 10^{-14}$	$1.0 \cdot 10^{-14}$
EFOS C	$2.0 \cdot 10^{-15}$	$2.0 \cdot 10^{-15}$

ACES Mission Objectives II

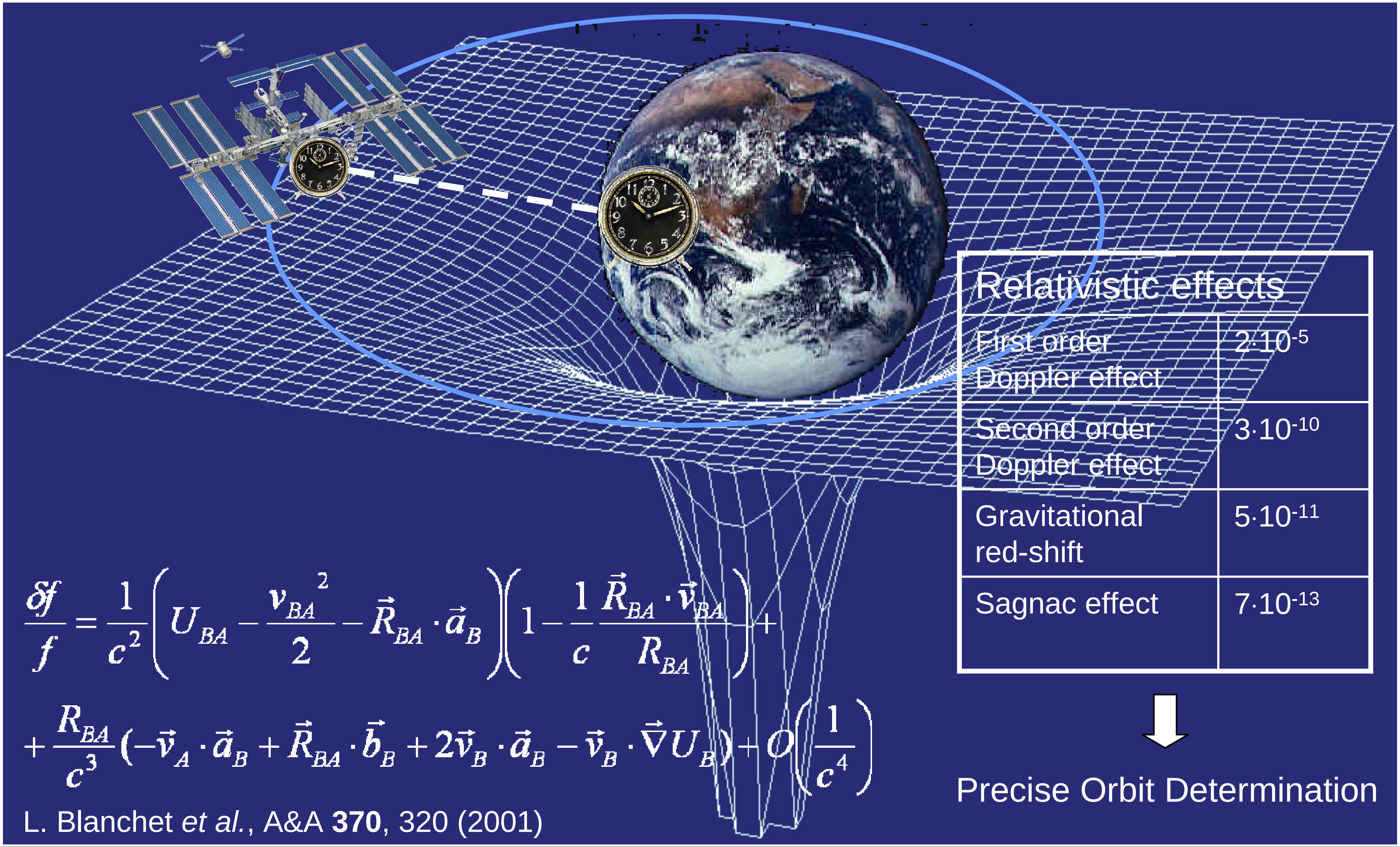
ACES Mission Objectives	ACES performances	Scientific background and recent results
	Stable time and frequency transfer	
Test of the time and frequency link MWL	Time transfer stability: < 0.3 ps at 300 s < 7 ps at 1day < 23 ps at 10 days	At present, no time and frequency transfer link has performances comparable to MWL.
Time and frequency comparisons between ground clocks	Common view comparisons with an uncertainty level below 1 ps per ISS pass. Non common view comparisons at an uncertainty level of - 2 ps for τ=1000 s - 5 ps for τ=10000 s - 20 ps for τ=1 day	(see table below)
Absolute synchronization of ground clocks	Absolute synchronization of ground clock time scales with an uncertainty of 100 ps.	These performances will allow time and frequency transfer at an unprecedented level of stability and accuracy. The development of such links is mandatory for space experiments based on high stability frequency standards.
Contribution to atomic time scales	Comparison of primary frequency standards with accuracy at the 10^{-16} level.	

Existing T&F links	Time stability (1day)	Time accuracy (1day)	Frequency accuracy (1day)
GPS-DB	2 ns	3-10 ns	$4\cdot10^{-14}$
GPS-CV	1 ns	1-5 ns	$2\cdot10^{-14}$
GPS-CP	0.1 ns	1-3 ns	$2\cdot10^{-15}$
TWSTFT	0.1-0.2 ns	1 ns	$2\text{-}4\cdot10^{-15}$

ACES Mission Objectives III

ACES Mission Objectives	ACES performances	Scientific background and recent results
	Fundamental physics tests	
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level $< 50 \cdot 10^{-6}$ after 300 s and $< 2 \cdot 10^{-6}$ after 10 days.	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 30 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-16}$ year $^{-1}$	Crossed comparisons of clocks based on different atomic elements to impose strong constraints on the time drifts of α, m_e / Λ_{QCD} , *and* m_q / Λ_{QCD} .
Search for violations of special relativity	Search for anisotropies of the speed of light at the level $\delta c / c \sim 10^{-10}$. Measurements relying on the time stability of SHM, PHARAO, MWL, and ground clocks over one ISS pass.	ACES results will improve previous tests based on GPS satellites by at least one order of magnitude.

Relativistic Frequency Transfer



$$\frac{\delta f}{f} = \frac{1}{c^2}\left(U_{BA} - \frac{v_{BA}^{\ 2}}{2} - \vec{R}_{BA}\cdot\vec{a}_B\right)\left(1 - \frac{1}{c}\frac{\vec{R}_{BA}\cdot\vec{v}_{BA}}{R_{BA}}\right) +$$

$$+\frac{R_{BA}}{c^3}\left(-\vec{v}_A\cdot\vec{a}_B + \vec{R}_{BA}\cdot\vec{b}_B + 2\vec{v}_B\cdot\vec{a}_B - \vec{v}_B\cdot\vec{\nabla}U_B\right) + O\left(\frac{1}{c^4}\right)$$

L. Blanchet *et al.*, A&A **370**, 320 (2001)

Relativistic effects	
First order Doppler effect	$2{\cdot}10^{-5}$
Second order Doppler effect	$3{\cdot}10^{-10}$
Gravitational red-shift	$5{\cdot}10^{-11}$
Sagnac effect	$7{\cdot}10^{-13}$

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Precise Orbit Determination

ACES Mission Objectives III

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Time Variations of Fundamental Constants I

Frequency of hyperfine transitions: $\nu_{\mathrm{hfs}}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\mathrm{hfs}}^{(i)} \times g^{(i)} \left(\frac{m_e}{m_p}\right) \alpha^2 F_{\mathrm{hfs}}^{(i)}(\alpha)$

Frequency of electronic transitions: $\nu_{\mathrm{elec}}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\mathrm{elec}}^{(i)} \times F_{\mathrm{elec}}^{(i)}(\alpha)$

Ratios between atomic frequencies:

$$\frac{\nu_{\mathrm{elec}}^{(ii)}}{\nu_{\mathrm{elec}}^{(i)}} \propto \frac{F_{\mathrm{elec}}^{(ii)}(\alpha)}{F_{\mathrm{elec}}^{(i)}(\alpha)} \qquad \frac{\nu_{\mathrm{hfs}}^{(ii)}}{\nu_{\mathrm{elec}}^{(i)}} \propto g^{(ii)} \frac{m_e}{m_p} \alpha^2 \frac{F_{\mathrm{hfs}}^{(ii)}(\alpha)}{F_{\mathrm{elec}}^{(i)}(\alpha)} \qquad \frac{\nu_{\mathrm{hfs}}^{(ii)}}{\nu_{\mathrm{hfs}}^{(i)}} \propto \frac{g^{(ii)}}{g^{(i)}} \frac{F_{\mathrm{hfs}}^{(ii)}(\alpha)}{F_{\mathrm{hfs}}^{(i)}(\alpha)}$$

Sensitivity to time variations of fundamental constants:

$$\delta \ln \left(\frac{\nu_{\mathrm{hfs}}^{(i)}}{R_\infty c}\right) \simeq \frac{\delta g^{(i)}}{g^{(i)}} + \frac{\delta(m_e/m_p)}{(m_e/m_p)} + \left(2 + \alpha \frac{\partial}{\partial \alpha} \ln F_{\mathrm{hfs}}^{(i)}(\alpha)\right) \times \frac{\delta \alpha}{\alpha}$$

$$\delta \ln \left(\frac{\nu_{\mathrm{elec}}^{(i)}}{R_\infty c}\right) \simeq \left(\alpha \frac{\partial}{\partial \alpha} \ln F_{\mathrm{elec}}^{(i)}(\alpha)\right) \times \frac{\delta \alpha}{\alpha}$$

Time Variations of Fundamental Constants II

$g^{(i)}$ and m_p are not "fundamental" constants; they depend on

- QCD mass scale Λ_{QCD}
- Quark mass $m_q = (m_u + m_d)/2$

therefore comparisons of atomic frequency will test the time stability of the three fundamental constants $\alpha, \quad \frac{m_q}{\Lambda_{\mathrm{QCD}}}, \quad \frac{m_e}{\Lambda_{\mathrm{QCD}}}$

In general $$\delta \ln\left(\frac{\nu^{(i)}}{R_\infty c}\right) \simeq K_\alpha^{(i)} \times \frac{\delta\alpha}{\alpha} + K_q^{(i)} \times \frac{\delta(m_q/\Lambda_{\mathrm{QCD}})}{(m_q/\Lambda_{\mathrm{QCD}})} + K_e^{(i)} \times \frac{\delta(m_e/\Lambda_{\mathrm{QCD}})}{(m_e/\Lambda_{\mathrm{QCD}})}$$

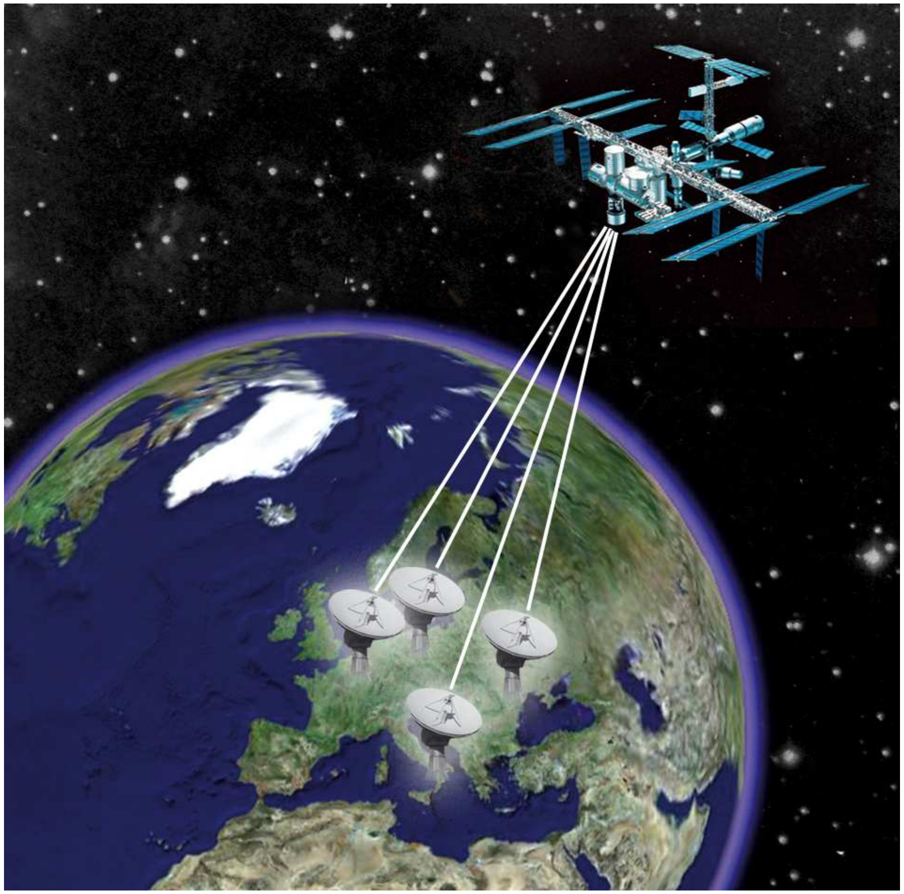
$K_\alpha^{(i)} \neq 0, K_q^{(i)} \neq 0, K_e^{(i)} \simeq 1$ hyperfine transitions

$K_\alpha^{(i)} \neq 0, K_q^{(i)} \simeq 0, K_e^{(i)} \simeq 0$ electronic transition

$K_\alpha^{(i)} \simeq 0, K_q^{(i)} \simeq 0, K_e^{(i)} \simeq 1/2$ vibrational transitions in molecules

V.V. Flambaum, arxiv:physics/0302015
V.V. Flambaum *et al.*, Phys. Rev. D **69**, 115006 (2004)

Time Variations of Fundamental Constants III



- Worldwide access to the ACES frequency standard
- Common view comparisons up to 4 different clocks based on different atomic transitions to constrain time variations of $\alpha, m_q/\Lambda_{\mathrm{QCD}}, m_e/\Lambda_{\mathrm{QCD}}$
- Non common view comparisons of distant clocks
- Redundancy possible with more than 4 atomic clocks
- Frequency comparisons at the 10^{-16} level possible

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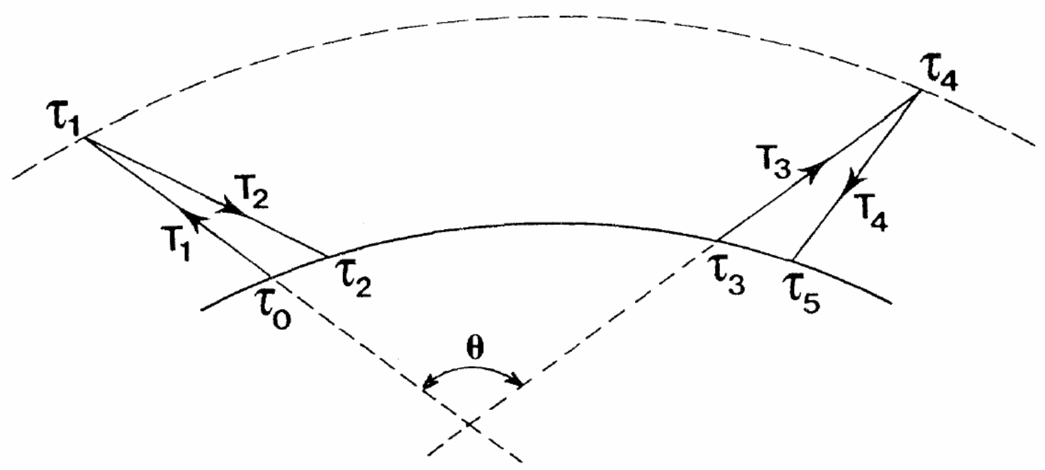
Clock Tests of Special Relativity

- Kinematic test theories (RMS framework): Preferred reference frame (CMB) in which light is assumed to propagate isotropically
- Dynamic test theories (SME framework): Lorentz transformations violating terms in the Hamiltonian of the system



$$T_1 - T_2 = \Delta_s + \Delta_l + 2\frac{\delta c}{c} T \cos\theta$$

$$(T_1 - T_2) - (T_3 - T_4) + \Delta_a = 2\frac{\delta c}{c} T (1 - \cos\theta)$$

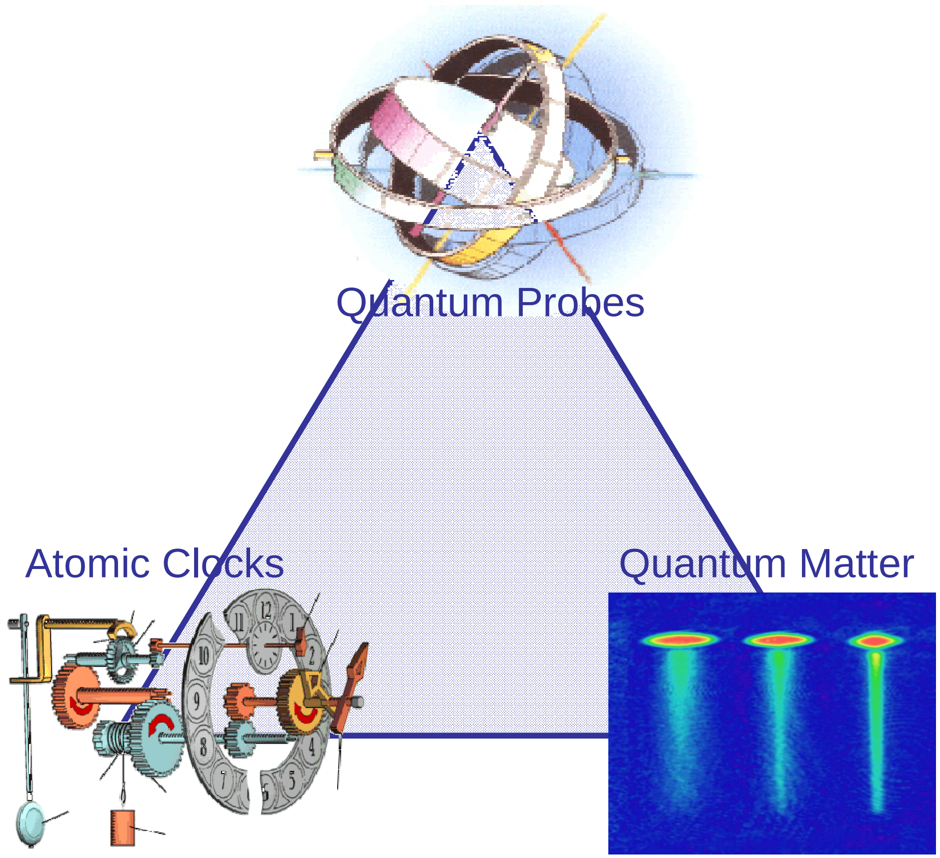
P. Wolf, PRA **51**, 5016 (1995)

Measurement principle:

- Exchange of microwave signals between ACES clocks and ground clocks along the ISS orbit
- Difference of measured reception and emission times provides the one-way travel time of the signal plus some unknown constant offset (desynchronization, path asymmetries, propagation delays,…)
- Difference of the up and down travel times sensitive to a non zero value of $\delta c/c$

Pioneering Aspects of ACES

- Technology demonstrator for cold atom based missions
- First μg experiments with cold atoms
- Validation in space of complex laser systems, UHV equipment, ultra-stable RF electronics…
- Validation of a new generation of atomic clocks
- Demonstration of stable and accurate time and frequency transfer
- Long-distance clock-to-clock comparisons
- Precursor of optical clocks: towards the 10^{-18} stability and accuracy regime



from E. Rasel *et al.*

These results will arrive in time to prepare the next generation of atomic quantum sensors for space

Atomic Quantum Sensors in Space

Atomic Clocks

Fundamental Physics

- Standard Model Extension tests
- Universality of the gravitational red-shift
- Time variations of fundamental constants
- Gravitational red-shift
- Shapiro time delay and $1/c^3$ effects
- Gravitational waves detection

Applications

- Atomic time scales (TAI)
- Time & Frequency metrology
- Deep space navigation
- Doppler tracking
- Synchronization of DSNA
- VLBI
- Time & Frequency transfer
- Gravity mapping
- Planetary exploration

Atom Interferometers

Fundamental Physics

- Weak Equivalence Principle tests
- Measurement of fundamental constants
- Time variations of fundamental constants
- Measurement of the gravito-magnetic effect
- Tests of the Newton's law at short distances
- Gravitational waves detection

Applications

- Inertial navigation
- Earth observation and monitoring
- Geology and vulcanology
- Gravity and gravity-gradient mapping
- Planetary exploration

Degenerate Quantum Gases

Fundamental Physics

- Thermodynamics of the phase transition at ultra-low temperatures
- Collective excitations in the weak trapping regime
- BEC coherence properties in microgravity
- Role of interactions in BEC: dipolar forces and short range interactions
- Dynamics of Bose mixtures in microgravity

Applications

- Atomic sources for atom interferometry
- High-resolution interferometric measurements with dilute coherent matter waves

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