



ACES: Preliminary Results from Space

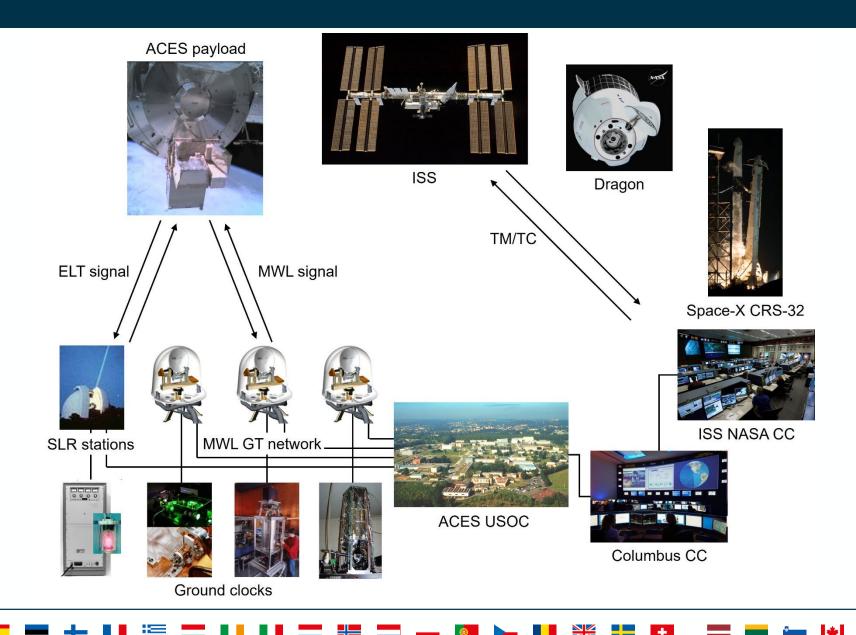
Luigi Cacciapuoti LGWA Workshop University of Camerino, Italy 15-19 September 2025

ESA UNCLASSIFIED – For ESA Official Use Only



ACES mission





ACES launch: 21 April 2025

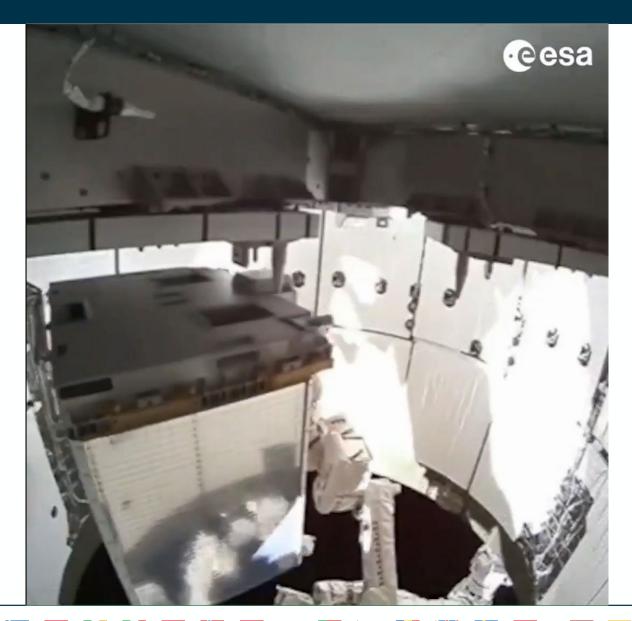




Credits NASA-ESA

ACES robotic operation: 25 April 2025





Credits NASA-ESA

The ACES payload



 PHARAO (CNES): Atomic clock based on laser cooled Cs atoms

SHM: Active hydrogen maser

FCDP: Clocks comparison and distribution

MWL: T&F transfer link

GNSS receiver

ELT: Optical link

Support subsystems

XPLC: External PL computer

PDU: Power distribution unit,

Mechanical, thermal subsystems

CEPA: Columbus External PL Adapter



Volume: 1172x867x1246 mm³

Mass: 240 kg (w/o CEPA)

Power: 600 W







Atomic Clock Ensemble in Space

Science

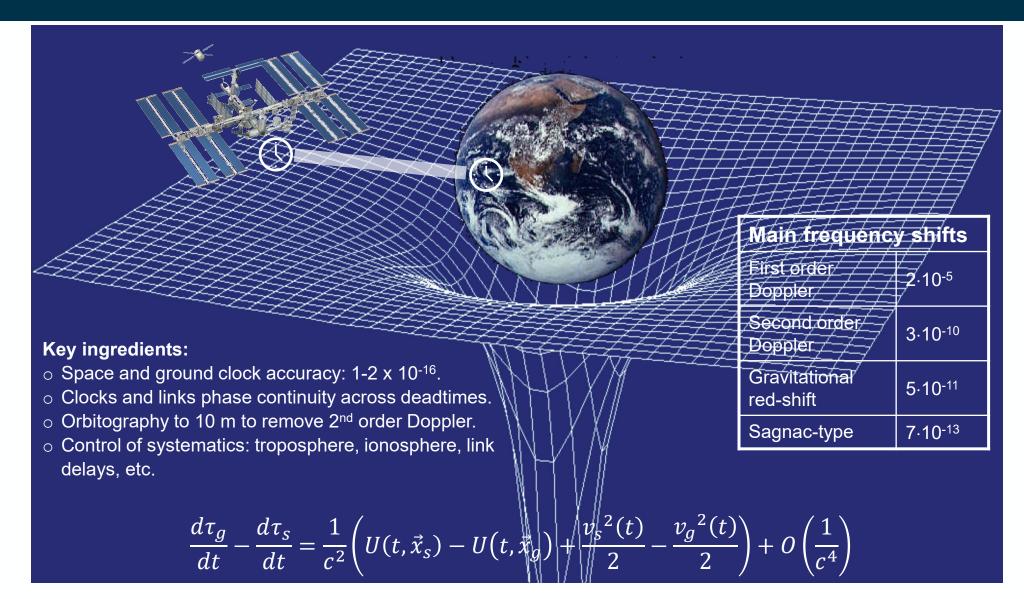
ACES – Fundamental Physics tests



ACES Mission Objectives	ACES performances	Scientific background and recent results	
Gravitational red-shift	Absolute measurement of the gravitational redshift to < 2·10 ⁻⁶ after 10 days of integration time, after having validated PHARAO accuracy.	Factor 70 improvement over the GPA experiment and factor 10 over tests involving Galileo 5 and 6 satellites.	
Time drifts of fundamental constants	Time variations of α constrained to $\alpha^{-1} \cdot d\alpha/dt < 3 \cdot 10^{-18}$ yr $^{-1}$ after 3 years of mission.	Comparisons of clocks based on different atoms and atomic transitions on a worldwide scale to constrain α , m_e/Λ_{QCD} and m_q/Λ_{QCD} .	
Dark matter search with atomic clocks	Establish bounds on topological dark matter models based on the comparisons of clocks in the ACES network.	Comparisons via the ACES network imposing limits on the three coupling constants Λ_{α} , Λ_{e} , and Λ_{q} in the model Lagrangian. Measurements over an interval T between encounters of 20 d. Simultaneous observation with several clocks along different baselines providing ways to confirm any observation above the sensitivity threshold and control the measurement systematics. Screening effect on the dark matter field due to the Earth mass reduced to about 0.06 on the space clock PHARAO with respect to ground clocks (~ 10^{-7}).	

Gravitational redshift test





ACES – Scientific applications



Relativistic geodesy

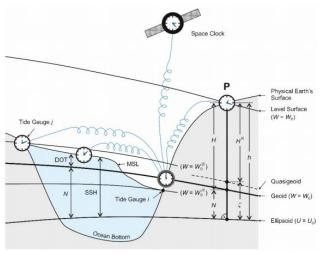
- Relativistic geodesy: measurement of geopotential differences based on the redshift measured between two clocks at two different locations.
- ACES intercontinental comparisons of optical clocks at the 10⁻¹⁷ level after 4 days, corresponding to a resolution on the local height above the geoid at the 10 cm level.
- The global coverage offered by ACES will complement the results of the CHAMP, GRACE, and GOCE missions.

Clocks synchronization

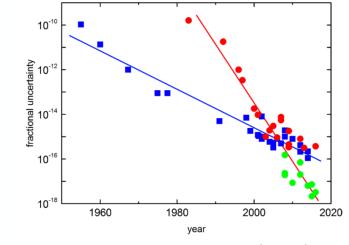
MWL and ELT clocks synchronization at the 100 ps and 50 ps level, respectively.

Atomic time scales (TAI)

- The PHARAO clock is accurate to 1-2⋅10⁻¹⁶.
- MWL will provide means to compare atomic clocks on a worldwide scale:
 - PHARAO and primary standards on ground contributing to TAI.
 - Optical clock comparisons to 1·10⁻¹⁷ will help SI second redefinition.



Rep. Prog. Phys. 81, 064401 (2018)



Metrologia 55, 188 (2018)

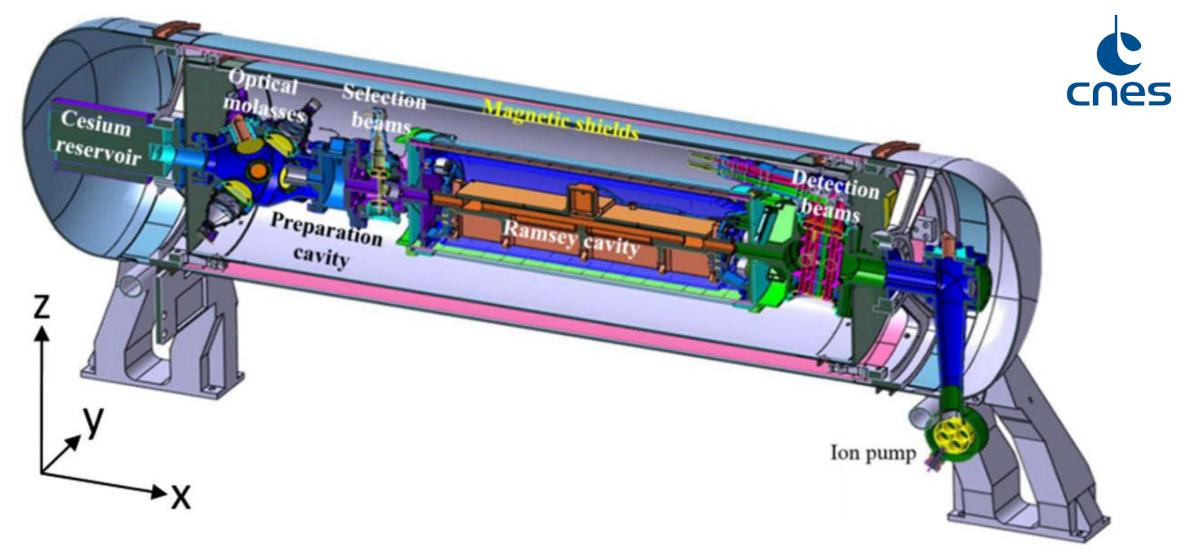


Atomic Clock Ensemble in Space

In-orbit status

The PHARAO clock

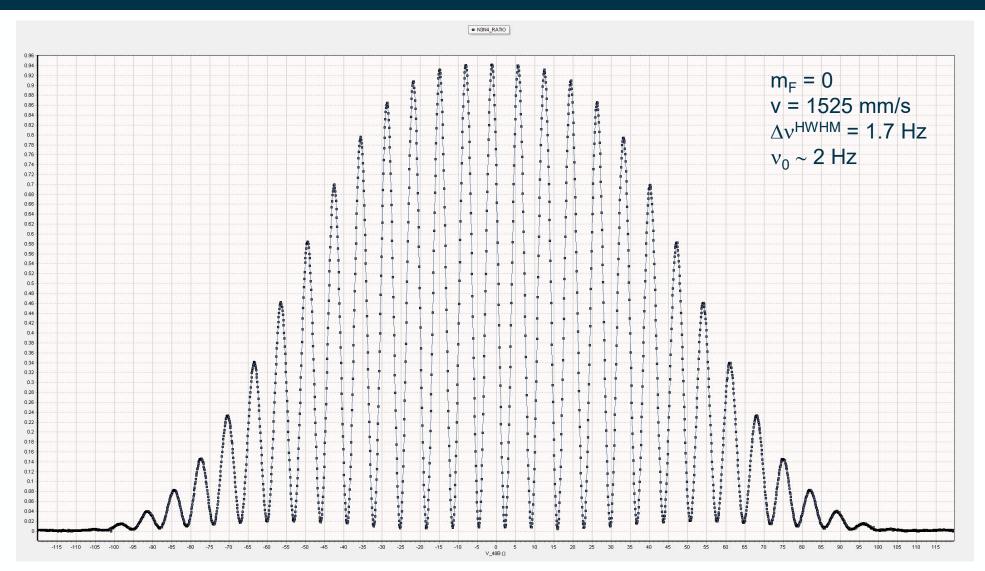




Metrologia **57** (2020) 055005

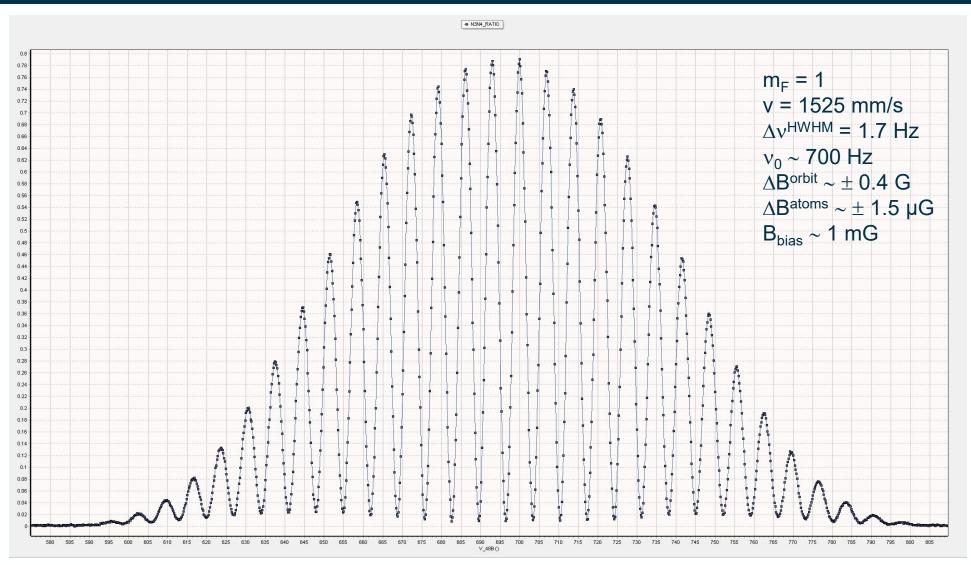
PHARAO Ramsey fringes I





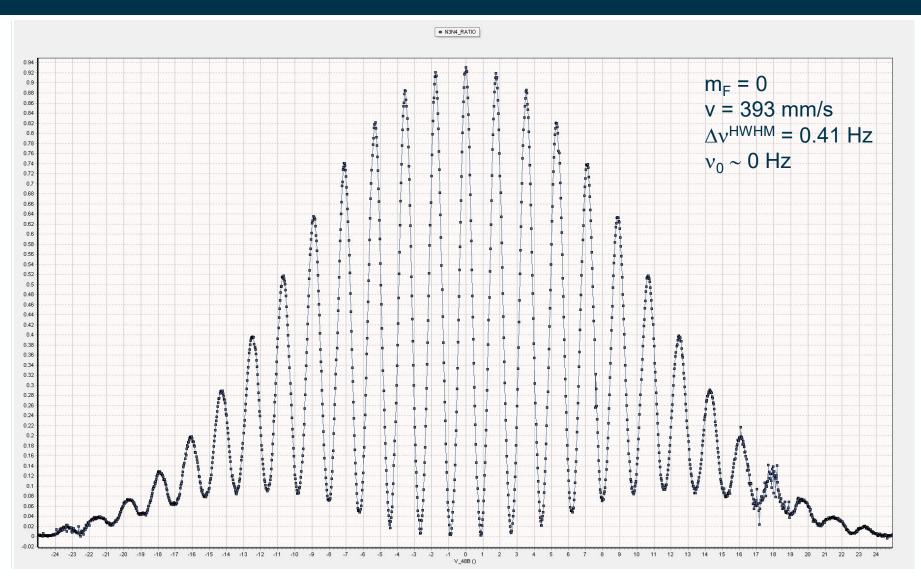
PHARAO Ramsey fringes II





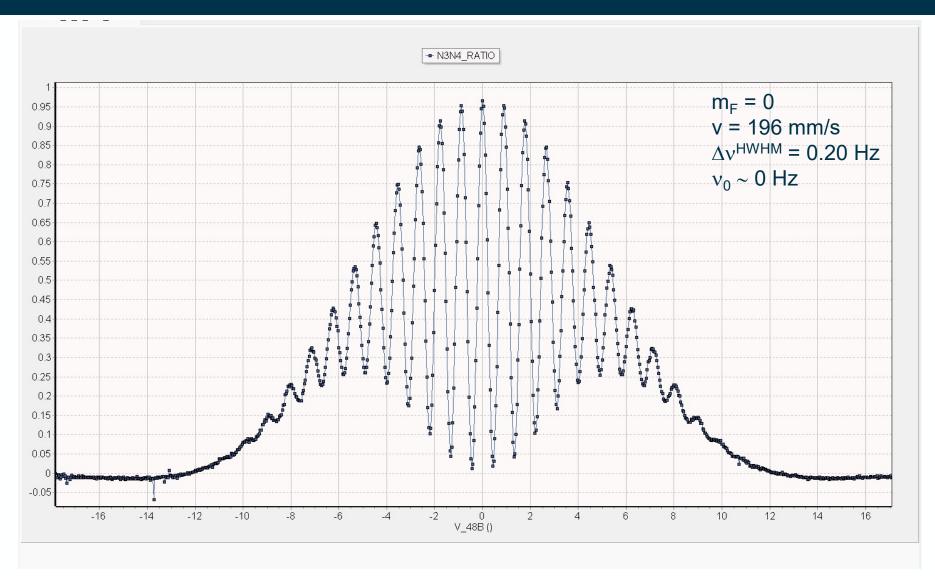
PHARAO Ramsey fringes III



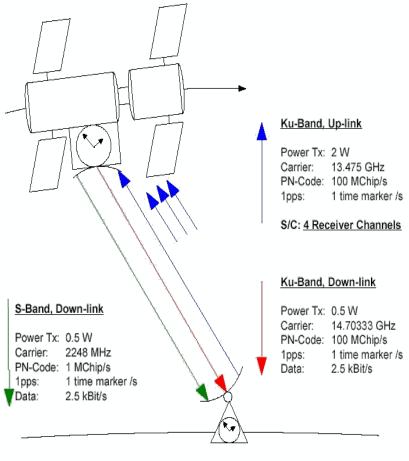


PHARAO Ramsey fringes IV









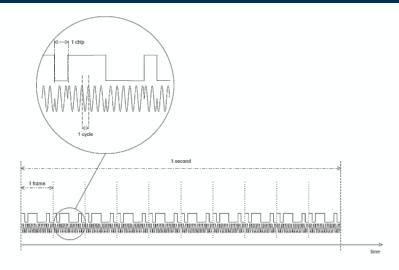




- Two-way link:
 - Removal of the troposphere time delay (8.3-103 ns).
 - Removal of 1st order Doppler effect.
 - Removal of instrumental delays and common mode effects.
- Additional down-link in the S-band:
 - Determination of the ionosphere TEC.
 - Correction of the ionosphere time delay (0.3-40 ns in S-band, 6-810 ps in Ku-band).
- Phase PN code modulation: Removal of 2π phase ambiguity.
- High chip rate (100 MChip/s) on the code:
 - Higher resolution.
 - Multipath suppression.
- Carrier and code phase measurements (80 ms sampling time).
- 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

MWL measurements and scientific products





Code and carrier phase measurements on Ku-band up/down-link

$$\Delta \tau^{s}\left(\tau^{s}(t_{2}^{o})\right) = Des(t_{2}^{o}) - \left[\left[\Delta_{T1}^{g}\right]^{t} + T_{12} + \left[\Delta_{R1}^{s}\right]^{t}\right]^{g} \Delta \tau^{g}\left(\tau^{g}(t_{4}^{o})\right) = -Des(t_{4}^{o}) - \left[\left[\Delta_{T2}^{s}\right]^{t} + T_{34} + \left[\Delta_{R2}^{g}\right]^{t}\right]^{s}$$

and S-band down-link

$$\Delta \tau^{g}(\tau^{g}(t_{6}^{o})) = -Des(t_{6}^{o}) - \left[[\Delta_{T3}^{s}]^{t} + T_{56} + [\Delta_{R3}^{g}]^{t} \right]^{s}$$

where

$$T_{12} = \frac{R_{12}}{c} + \frac{2GM_E}{c^3} \ln \left(\frac{x_g(t_1) + x_s(t_2) + R_{12}}{x_g(t_1) + x_s(t_2) - R_{12}} \right) + \Delta_{12}^{tropo} + \Delta_{12}^{iono} + O(\frac{1}{c^4})$$

$$T_{34} = \frac{R_{34}}{c} + \frac{2GM_E}{c^3} \ln \left(\frac{x_g(t_4) + x_s(t_3) + R_{34}}{x_g(t_4) + x_s(t_3) - R_{34}} \right) + \Delta_{34}^{tropo} + \Delta_{34}^{iono} + O(\frac{1}{c^4})$$

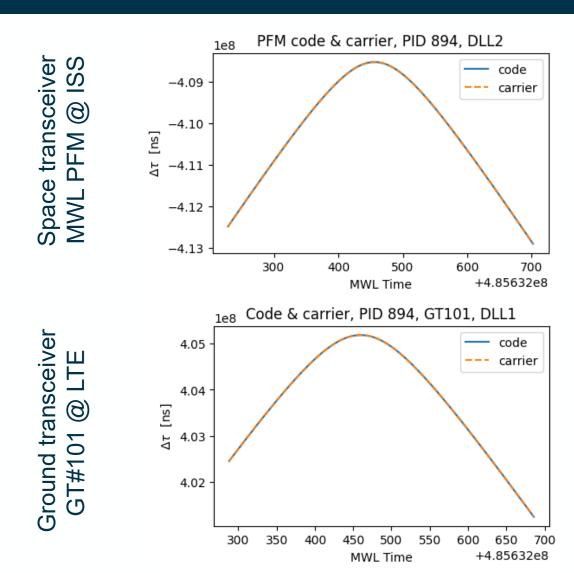
$$T_{56} = \frac{R_{56}}{c} + \frac{2GM_E}{c^3} \ln \left(\frac{x_g(t_6) + x_s(t_5) + R_{56}}{x_g(t_6) + x_s(t_5) - R_{56}} \right) + \Delta_{56}^{tropo} + \Delta_{56}^{iono} + O(\frac{1}{c^4})$$

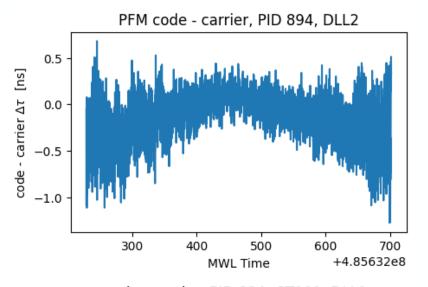


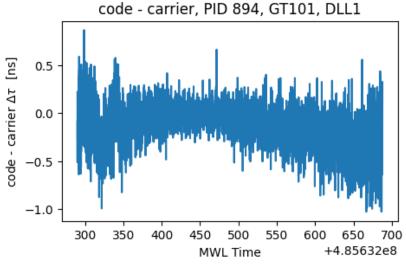
Scientific Products	from	
Space-to-ground Desynchronization	$ au^g(t_a) - au^s(t_a)$	$\Delta \tau^{s}\left(\tau^{s}(t_{2}^{o})\right) - \Delta \tau^{g}\left(\tau^{g}(t_{4}^{o})\right)$
Ionosphere Total Electron Content	$(\frac{1}{f_3^2} - \frac{1}{f_2^2}) \frac{40.308}{c} C_e$	$\Delta \tau^g(\tau^g(t_4^o)) - \Delta \tau^g(\tau^g(t_6^o))$
Range + Tropospheric Delay	$D(t_4)$ & Δ_{34}^{tropo}	$\Delta \tau^{s} \left(\tau^{s}(t_{2}^{o}) \right) + \Delta \tau^{g} \left(\tau^{g}(t_{4}^{o}) \right)$

MWL – First space-to-ground link above LTE (Paris)





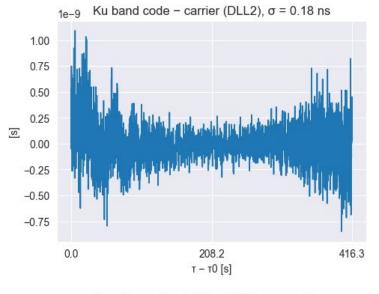


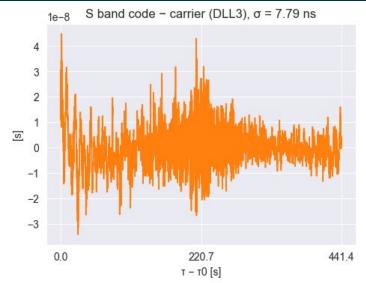


LTE Data Analysis Centre 18

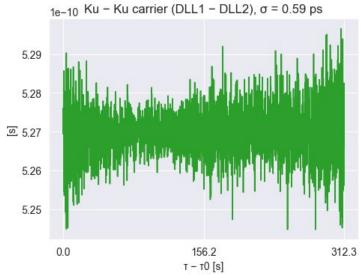
MWL GT code phase performance on a dynamic pass

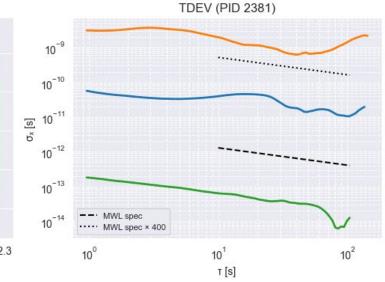






No calibrations and no signal travel time corrections applied

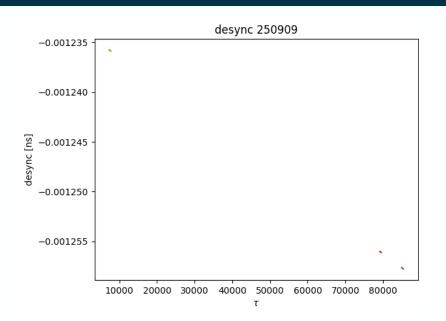


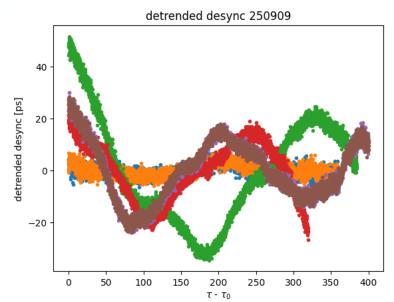


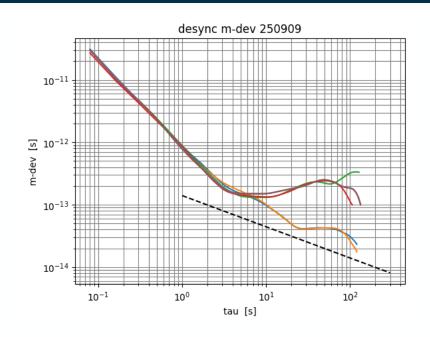
- → Time stability of S-band code phase measurements (no iono correction).
- → Time stability of Ku-band code phase measurements (no iono correction).
- → Lower limit of Ku-band carrier phase measurements time stability.

PHARAO vs LTE H-maser comparison via MWL









Preliminary results: No calibrations applied

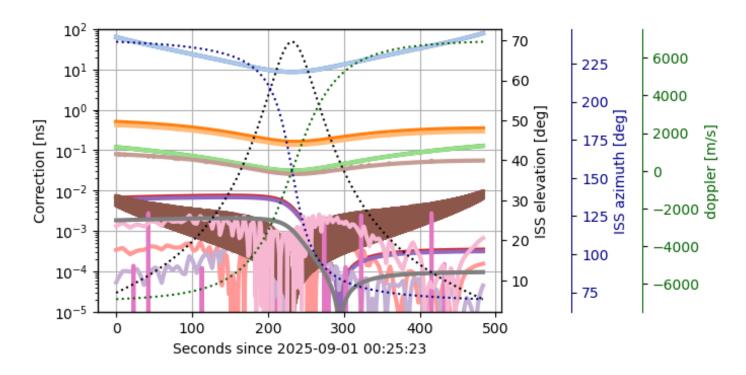
- 2-way combination of MWL PFM and GT101 measurements across three consecutive passes.
- Overall slope is -2.83×10⁻¹⁰, consistent with expectation from GR (mainly 2nd order Doppler effect).
- o First pass is PHARAO in autonomous mode (orange and blue). Others are free running PHARAO USO.
- O Dashed line corresponds to an Allan deviation of $2 \times 10^{-13}/\sqrt{\tau}$, as expected from PHARAO for this test configuration.

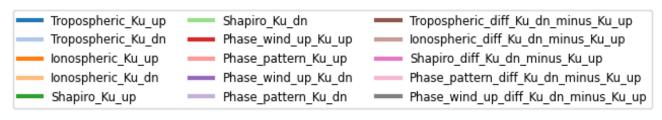
MWL signal travel time corrections



- Troposphere: Numerical raytracing using the Saastamoinen model + VMF3.
- lonosphere: TEC measurement based on S-band and Ku-band downlink.
- Shapiro time delay: Curvature effect from Earth mass monopole (negligible).
- Antenna phase wind-up: Geometric antenna rotation effect on carrier phase.
- PFM antenna phase pattern:
 Calibrated in anechoic chamber.

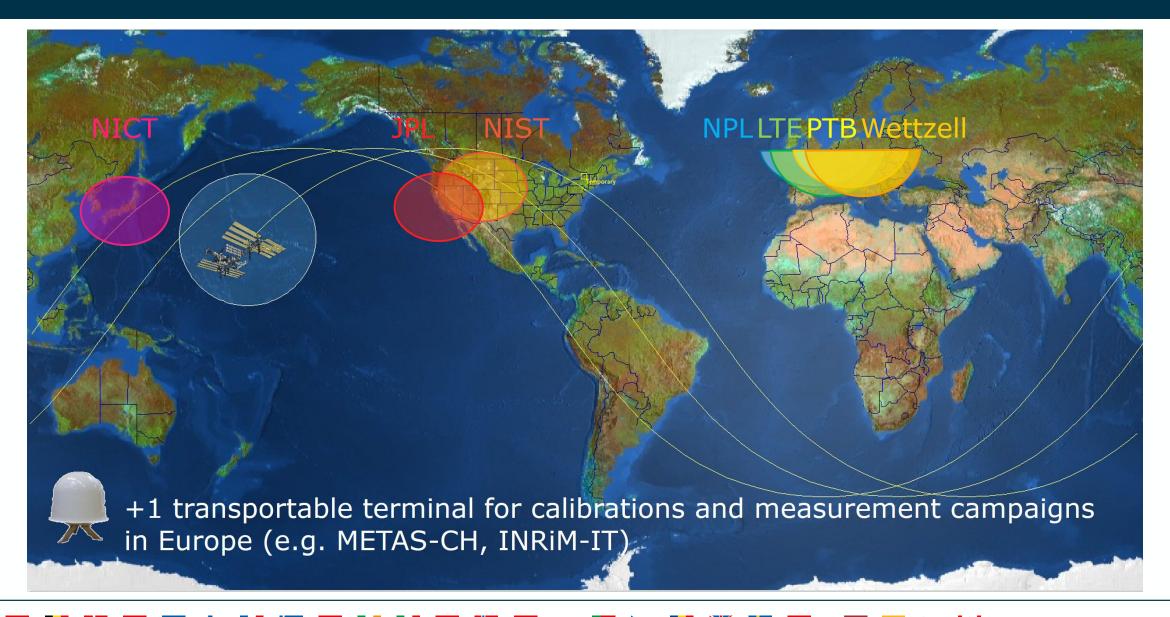
ACES - GT101 pass ID 2254 corrections





MWL GT network







Atomic Clock Ensemble in Space

Summary and outlook

Next steps



- PHARAO clock is operating correctly, following the expected behaviour:
 - Sub-Hz linewidths recorded at 393 mm/s and 196 mm/s launch velocity.
 - Further optimization ongoing.
- SHM clock is showing an anomalous behaviour. No atomic signal could be detected so far.
- MWL space-to-ground link established:
 - Ku-band performance in line with expectation.
 - S-band performance to be improved for iono correction.
 - More work is needed to ensure reliable operation of the MWL GTs.
- Commissioning activities are progressing. They include:
 - Characterization of the clocks' stability and accuracy:
 - Evaluation of MWL and ELT in space:
 - Common clock comparisons with two co-located MWL GTs.
 - Common view comparisons with two MWL GTs and OGSs.
 - Common clock comparisons with co-located MWL GT and OGS.
- Commission activities will continue until end October 2025 to release ACES for the routine science phase.



L. Cacciapuoti¹, S. Pataraia¹, T. Peignier¹, M. Plumaris¹, S. Weinberg¹, U. Bishoff², P. Crescence², A. Helm², J. Kehrer², R. Lachaud², D. Mitschke², T. Niedermaier², F.X. Esnault³, B. Léger³, E. Thulliez³, D. Massonnet³, D. Goujon⁴, J. Pittet⁴, A. Perri⁴, Q. Wang⁴, P. Rochat⁴, S. Liu⁵, W. Schaefer⁵, T. Schwall⁵, I. Prochazka⁶, A. Schlicht⁷, U. Schreiber⁷, P. Laurent⁸, M. Lilley⁸, J. Rozé⁸, P. Wolf⁸, K. Gibble⁹, C. Salomon¹⁰

> ¹European Space Agency, ESTEC, Noordwijk, The Netherlands ²Airbus Defence and Space, Friedrichshafen, Germany ³CNES, Toulouse, France ⁴Orolia Switzerland (Spectratime), Neuchâtel, Switzerland ⁵Timetech, Stuttgart, Germany ⁶Czech Technical University in Prague, Prague, Czech Republic ⁷Technical University of Munich, Munich, Germany ⁸SYRTE, Observatoire de Paris-PSL, CNRS, Sorbonne Université, LNE, Paris, France ⁹The Pennsylvania State University, University Park, USA ¹⁰Laboratoire Kastler Brossel, ENS, Paris, France

























