
# ACES – Atomic Clock Ensemble in Space

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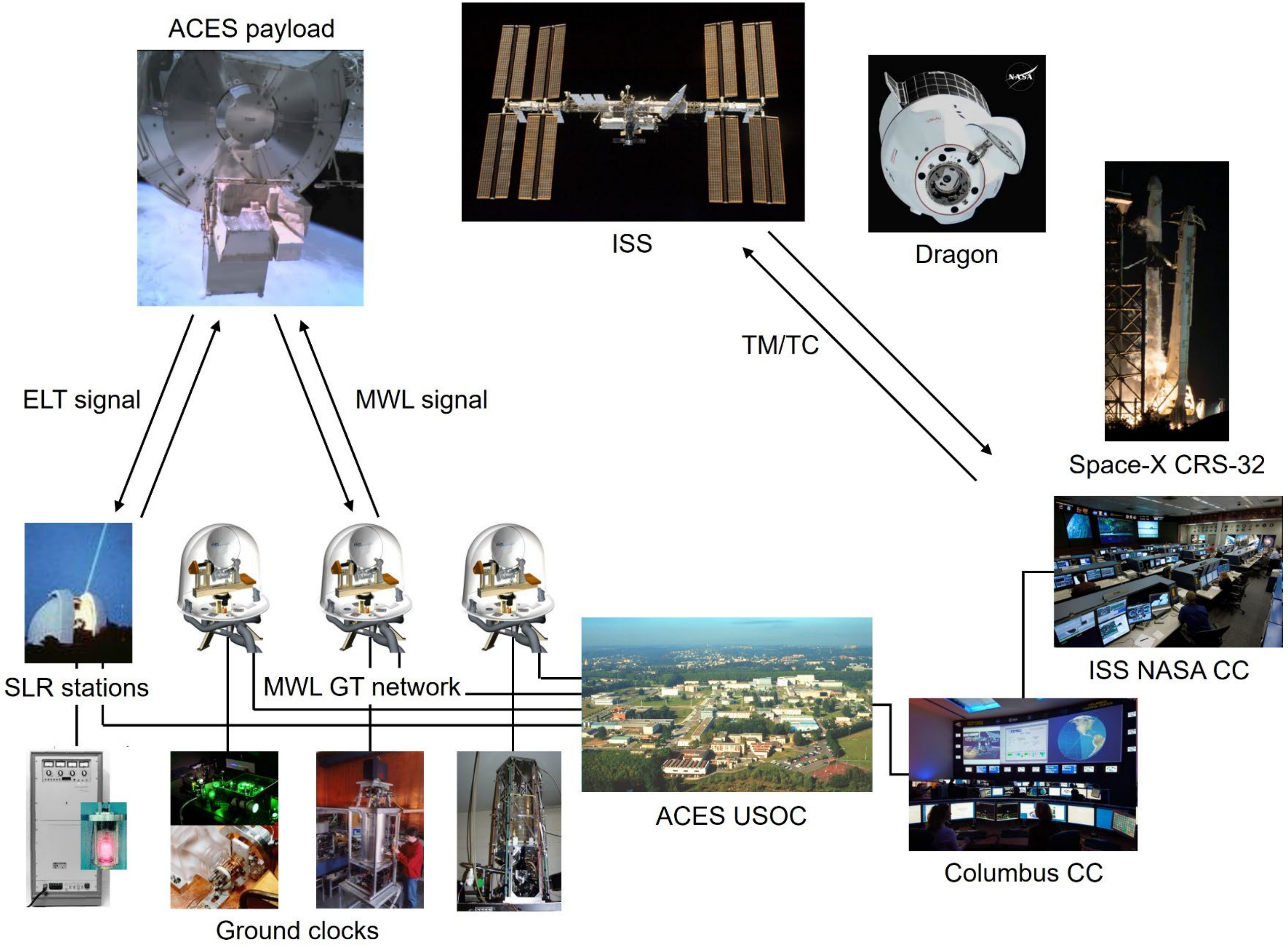
# ACES mission



# ACES launch: 21 April 2025

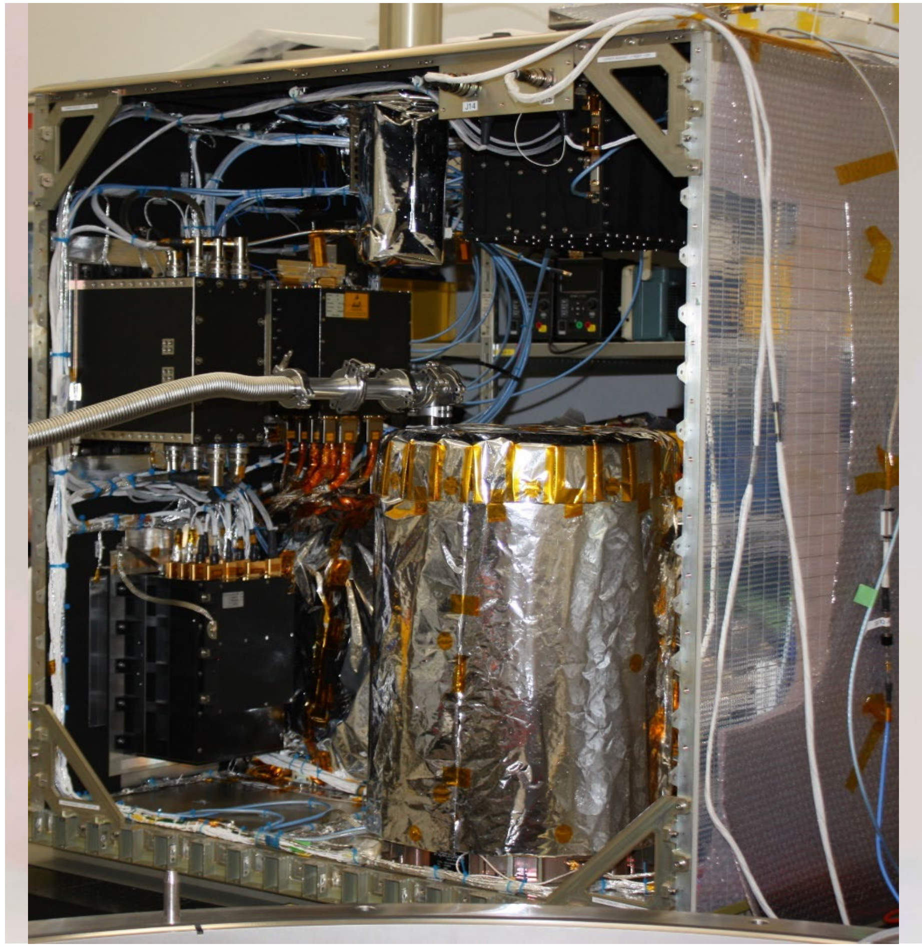

Credits NASA-ESA

# 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 $mm^3$
Mass: 240 kg (w/o CEPA)
Power: 600 W

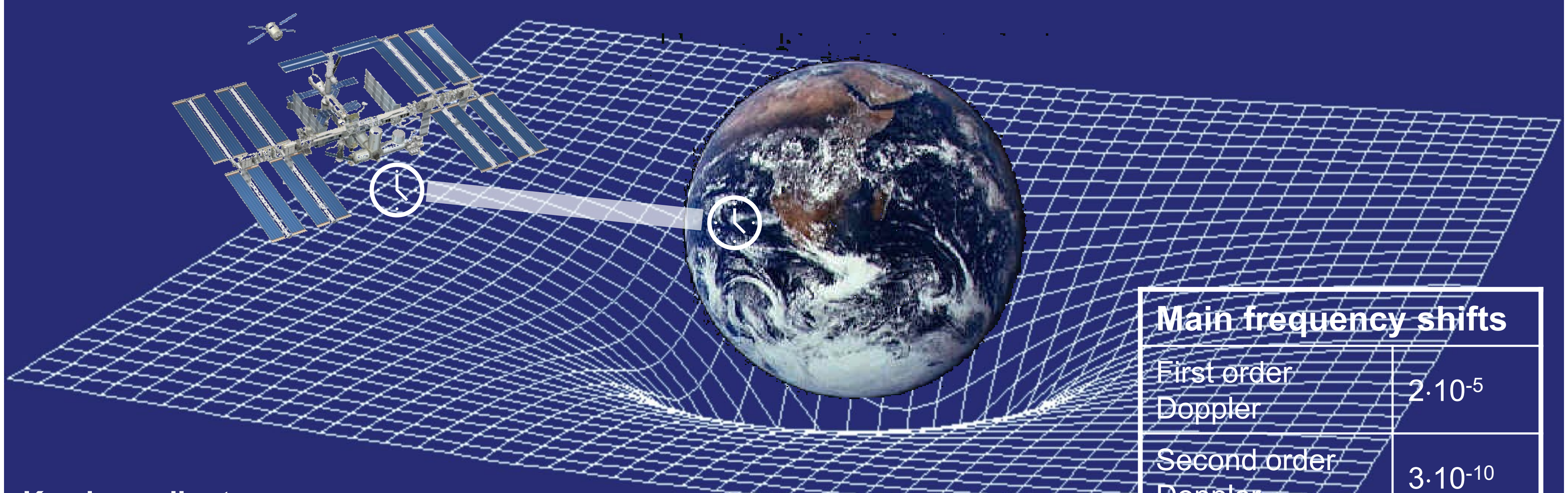
Atomic Clock Ensemble in Space

# Science

# ACES – Fundamental Physics tests

| ACES Mission Objectives | ACES performances | Scientific background and recent results |
|---|---|---|
| ***Gravitational red-shift*** | Absolute measurement of the gravitational red-shift to $< 2 \cdot 10^{-6}$ 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 $\alpha$ 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 $\alpha$, $m_e/\Lambda_{QCD}$ and $m_q/\Lambda_{QCD}$. |
| ***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 $\Lambda_\alpha$, $\Lambda_e$, and $\Lambda_q$ in the model Lagrangian. Measurements over an interval $\mathrm{T}$ 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



| Main frequency shifts | |
|---|---|
| First order Doppler | $2{\cdot}10^{-5}$ |
| Second order Doppler | $3{\cdot}10^{-10}$ |
| Gravitational red-shift | $5{\cdot}10^{-11}$ |
| Sagnac-type | $7{\cdot}10^{-13}$ |

**Key ingredients:**

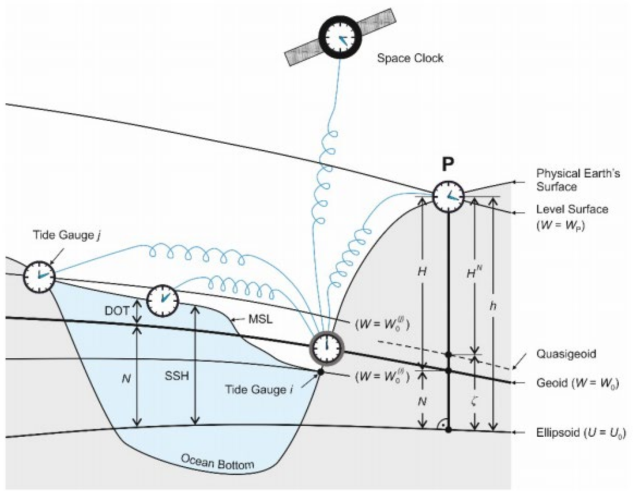
- Space and ground clock accuracy: 1-2 x $10^{-16}$.
- Clocks and links phase continuity across deadtimes.
- Orbitography to 10 m to remove 2nd order Doppler.
- Control of systematics: troposphere, ionosphere, link delays, etc.

$$\frac{d\tau_g}{dt} - \frac{d\tau_s}{dt} = \frac{1}{c^2}\left(U(t,\vec{x}_s) - U(t,\vec{x}_g) + \frac{{v_s}^2(t)}{2} - \frac{{v_g}^2(t)}{2}\right) + O\left(\frac{1}{c^4}\right)$$

# ACES – Scientific applications

## Relativistic geodesy

- Relativistic geodesy: measurement of geopotential differences based on the red-shift 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.



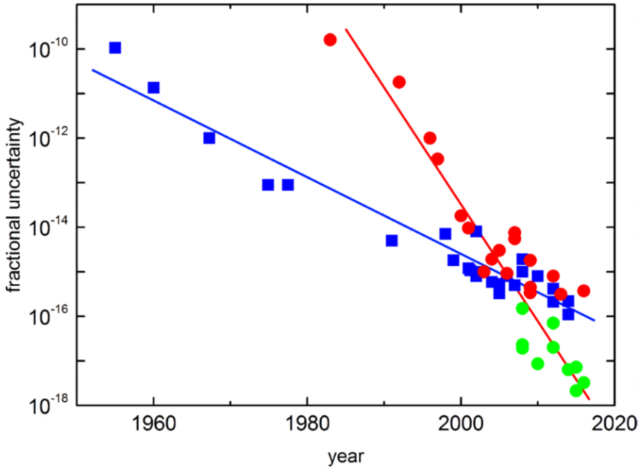

Rep. Prog. Phys. 81, 064401 (2018)

## 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 $1\text{-}2{\cdot}10^{-16}$.
- 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 $1{\cdot}10^{-17}$ will help SI second redefinition.




Metrologia 55, 188 (2018)

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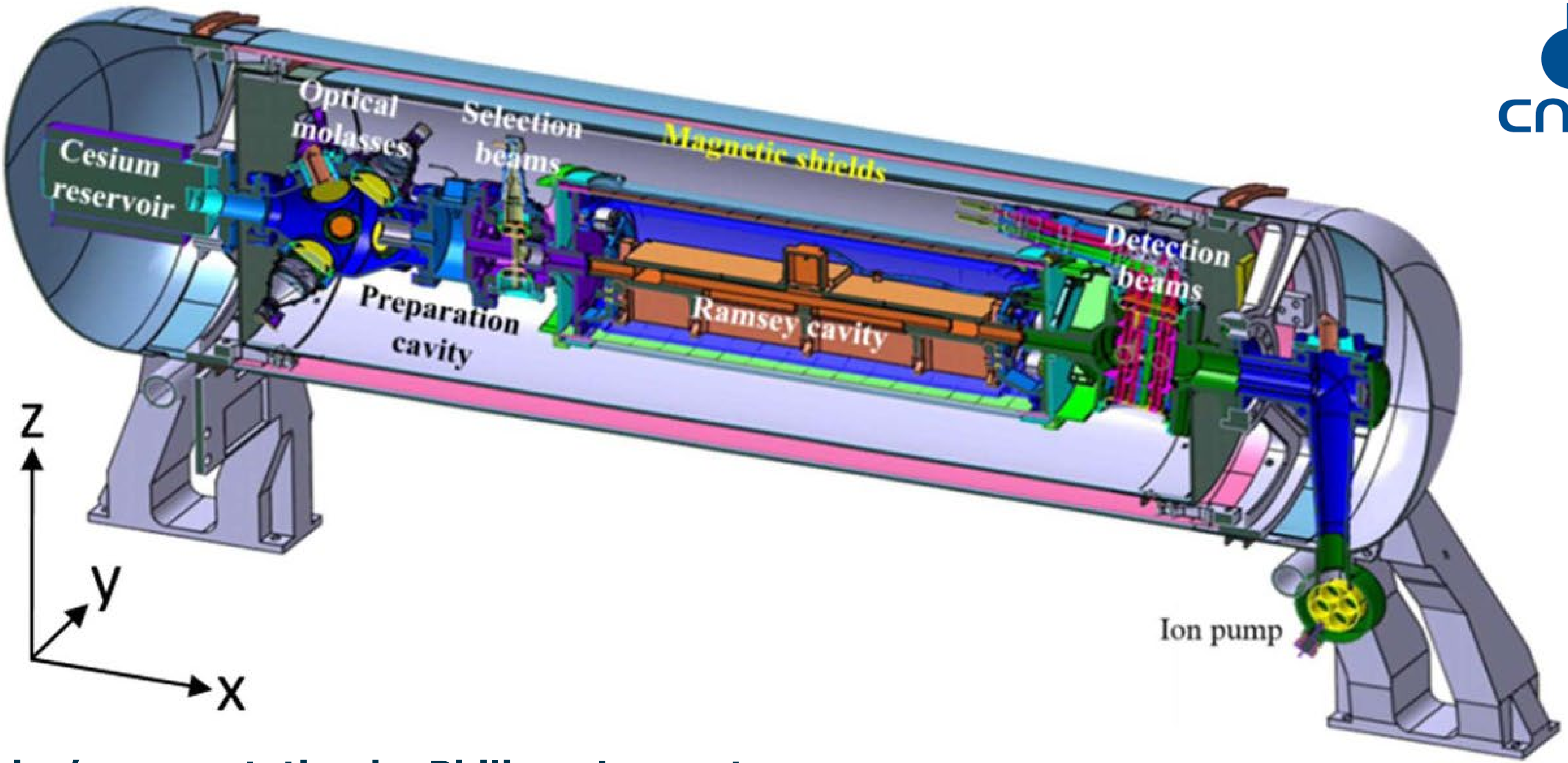
# In-orbit status

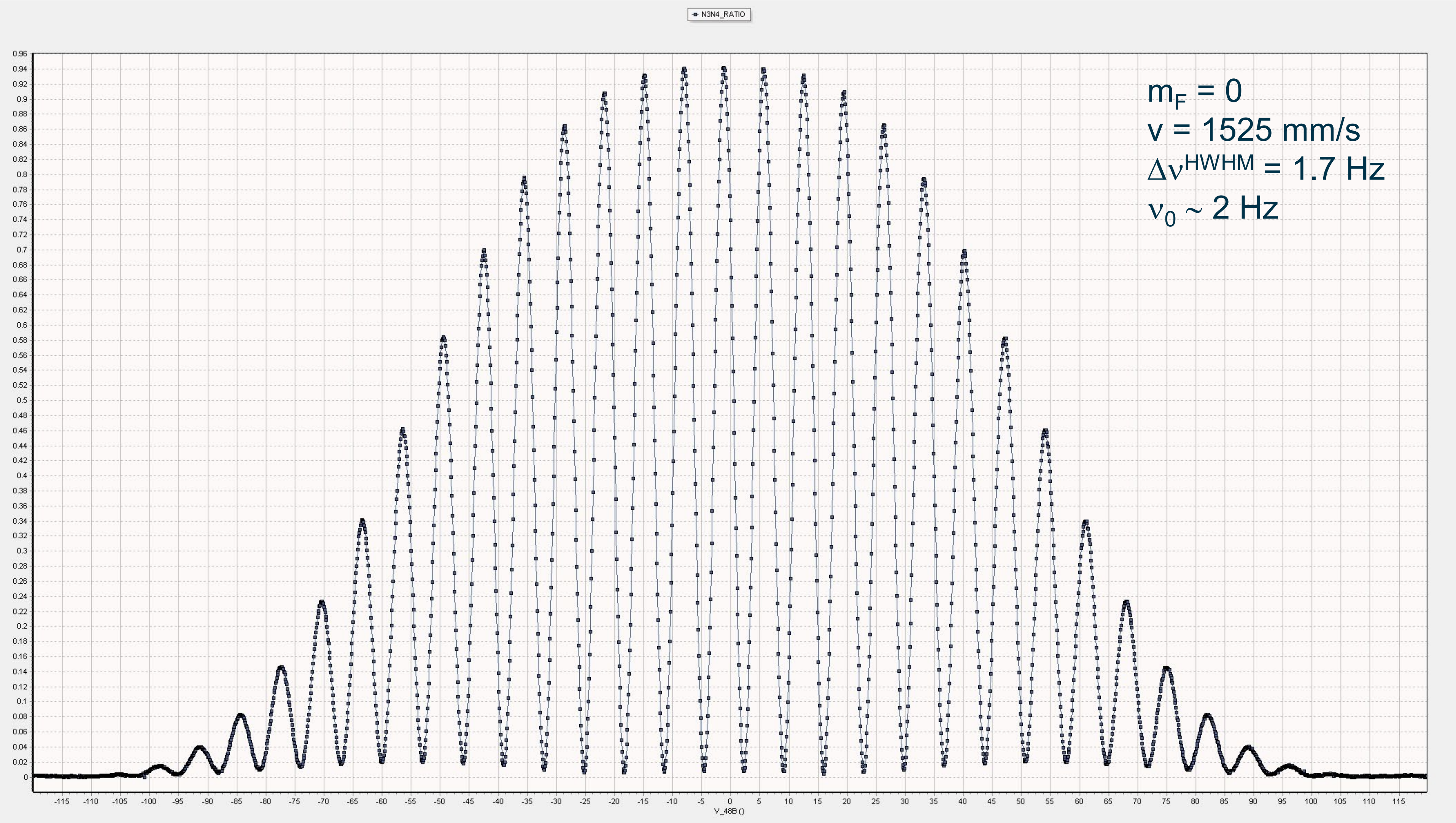
# The PHARAO clock




**Yesterday's presentation by Philippe Laurent**

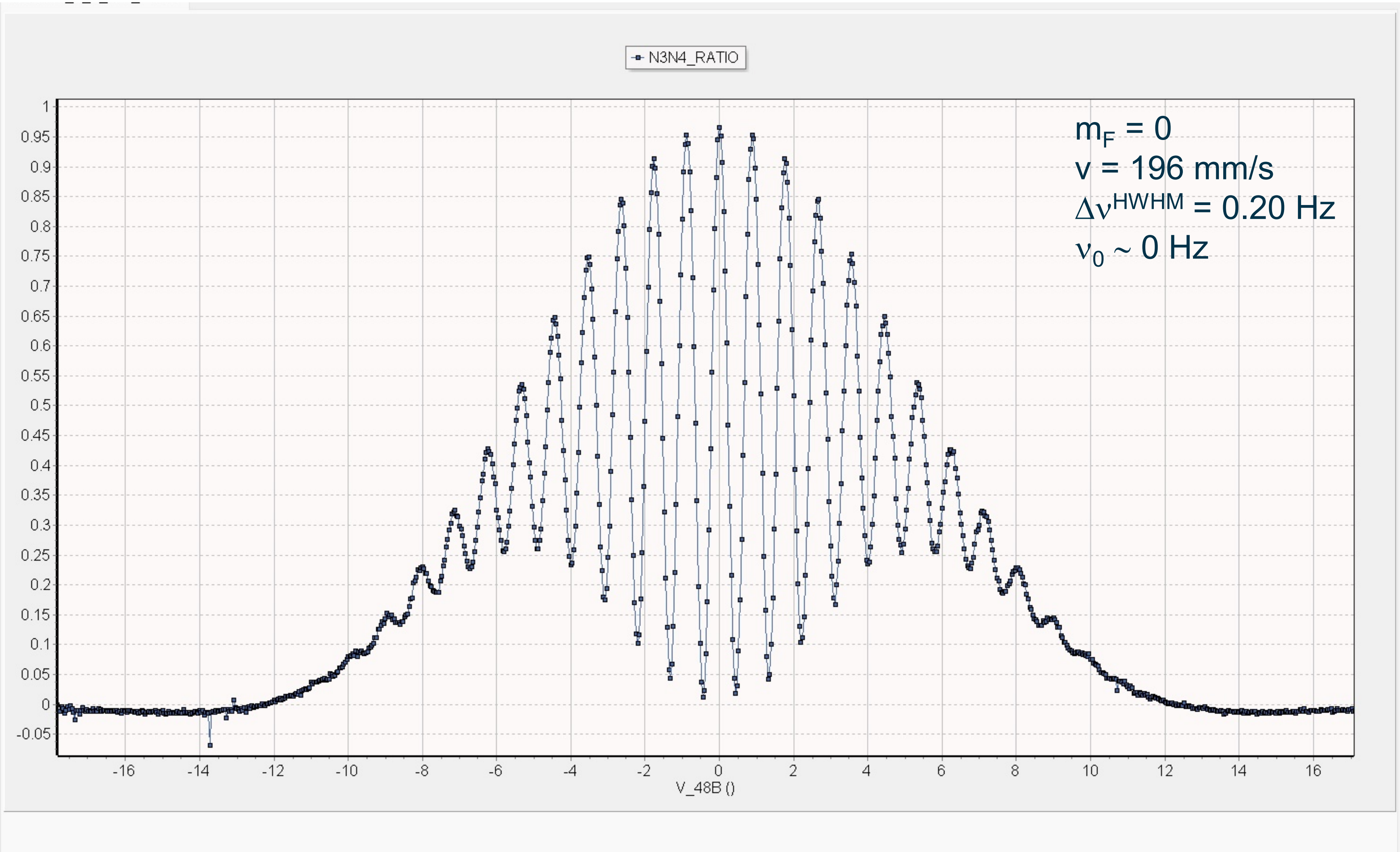
Metrologia **57** (2020) 055005

# PHARAO Ramsey fringes I

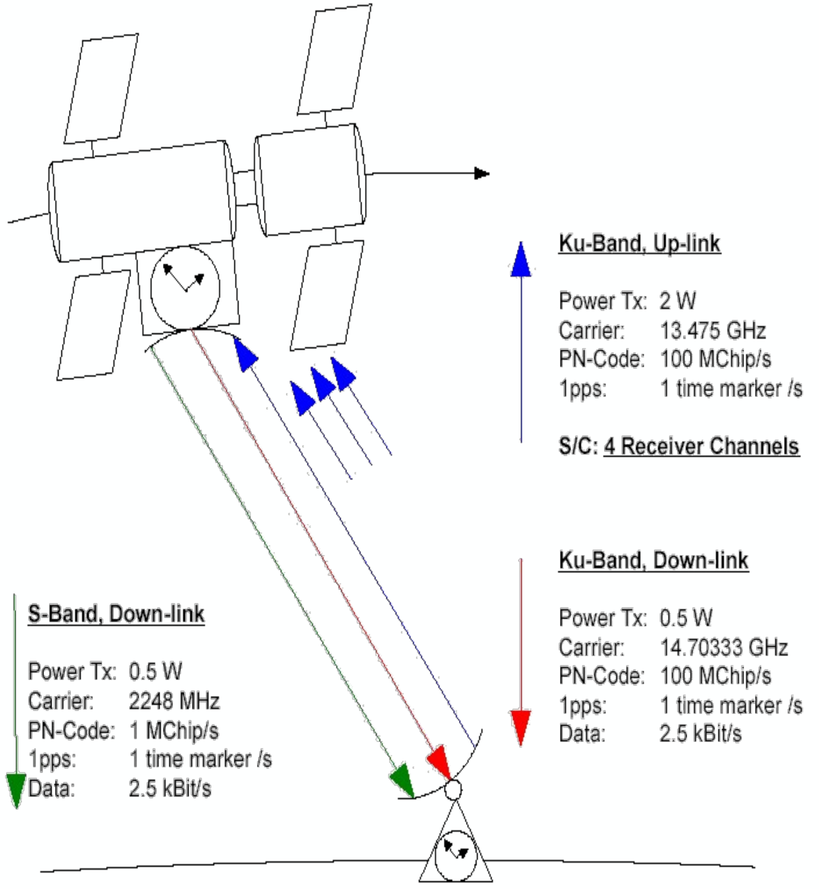



PhL, LTE/CNES, ESA, OP, LNE, PSL, SU

# PHARAO Ramsey fringes IV



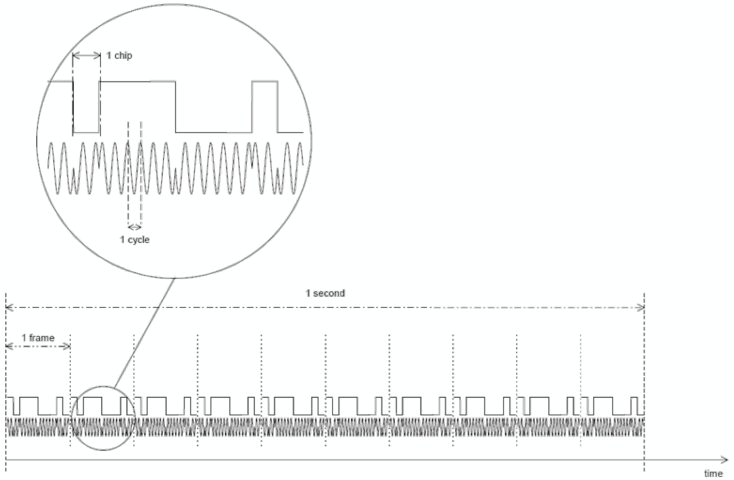
# MWL

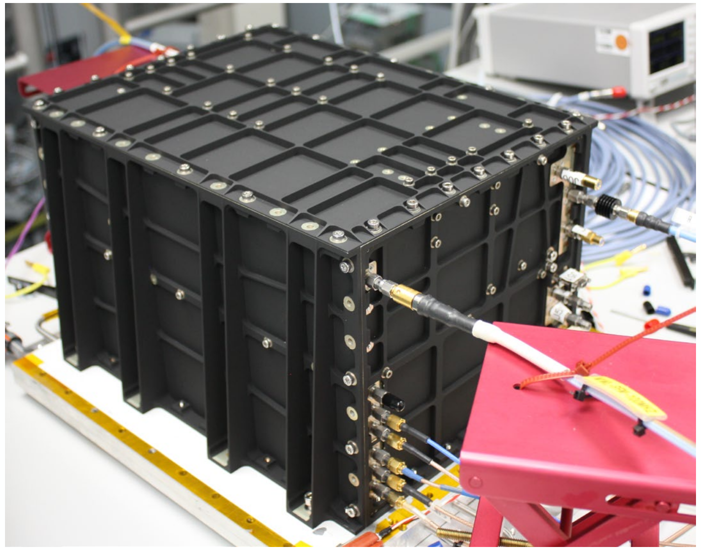



AIRBUS DEFENCE & SPACE TIMETECH TZR EREMS

- 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 $2\pi$ 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

$$\Delta\tau^s\left(\tau^s(t_2^o)\right) = Des(t_2^o) - \left[[\Delta^g_{T1}]^t + T_{12} + [\Delta^s_{R1}]^t\right]^g \quad \Delta\tau^g\left(\tau^g(t_4^o)\right) = -Des(t_4^o) - \left[[\Delta^s_{T2}]^t + T_{34} + [\Delta^g_{R2}]^t\right]^s$$

and S-band down-link

$$\Delta\tau^g\left(\tau^g(t_6^o)\right) = -Des(t_6^o) - \left[[\Delta^s_{T3}]^t + T_{56} + [\Delta^g_{R3}]^t\right]^s$$

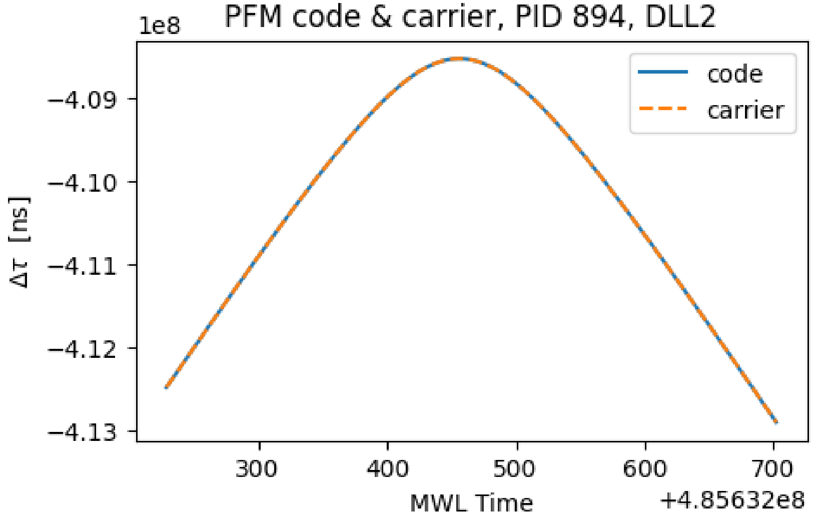
where

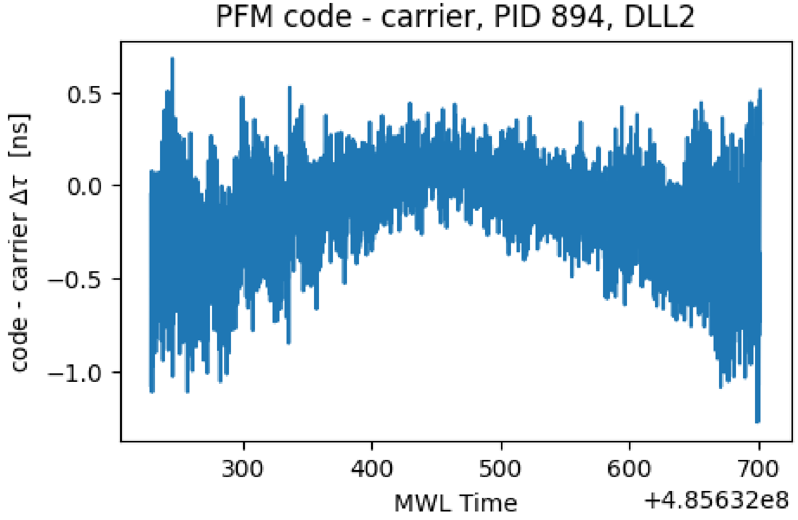
$$\begin{cases} T_{12} = \dfrac{R_{12}}{c} + \dfrac{2GM_E}{c^3}\ln\left(\dfrac{x_g(t_1)+x_s(t_2)+R_{12}}{x_g(t_1)+x_s(t_2)-R_{12}}\right) + \Delta_{12}^{tropo} + \Delta_{12}^{iono} + O(\dfrac{1}{c^4}) \\ T_{34} = \dfrac{R_{34}}{c} + \dfrac{2GM_E}{c^3}\ln\left(\dfrac{x_g(t_4)+x_s(t_3)+R_{34}}{x_g(t_4)+x_s(t_3)-R_{34}}\right) + \Delta_{34}^{tropo} + \Delta_{34}^{iono} + O(\dfrac{1}{c^4}) \\ T_{56} = \dfrac{R_{56}}{c} + \dfrac{2GM_E}{c^3}\ln\left(\dfrac{x_g(t_6)+x_s(t_5)+R_{56}}{x_g(t_6)+x_s(t_5)-R_{56}}\right) + \Delta_{56}^{tropo} + \Delta_{56}^{iono} + O(\dfrac{1}{c^4}) \end{cases}$$

| **Scientific Products** | | **…from** |
|---|---|---|
| Space-to-ground Desynchronization | $\tau^g(t_a) - \tau^s(t_a)$ | $\Delta\tau^s\left(\tau^s(t_2^o)\right) - \Delta\tau^g\left(\tau^g(t_4^o)\right)$ |
| Ionosphere Total Electron Content | $(\frac{1}{f_3^2} - \frac{1}{f_2^2})\frac{40.308}{c}C_e$ | $\Delta\tau^g\left(\tau^g(t_4^o)\right) - \Delta\tau^g\left(\tau^g(t_6^o)\right)$ |
| Range + Tropospheric Delay | $D(t_4)$ & $\Delta_{34}^{tropo}$ | $\Delta\tau^s\left(\tau^s(t_2^o)\right) + \Delta\tau^g\left(\tau^g(t_4^o)\right)$ |

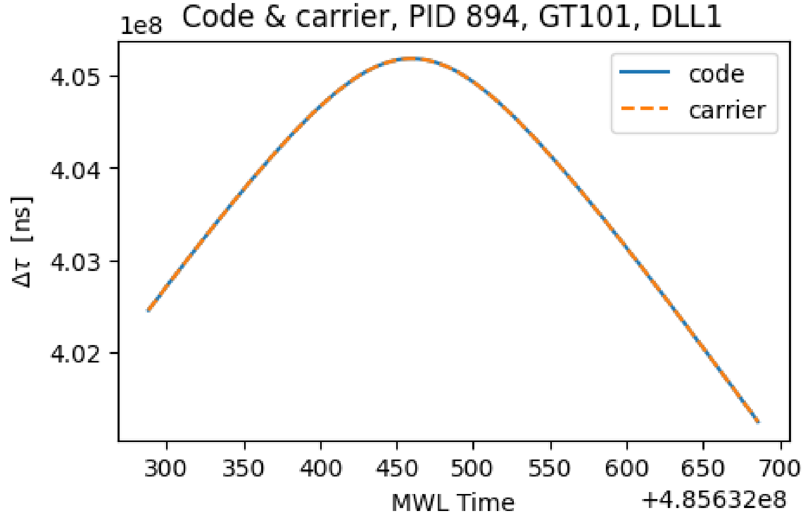
# MWL – First space-to-ground link above LTE (Paris)

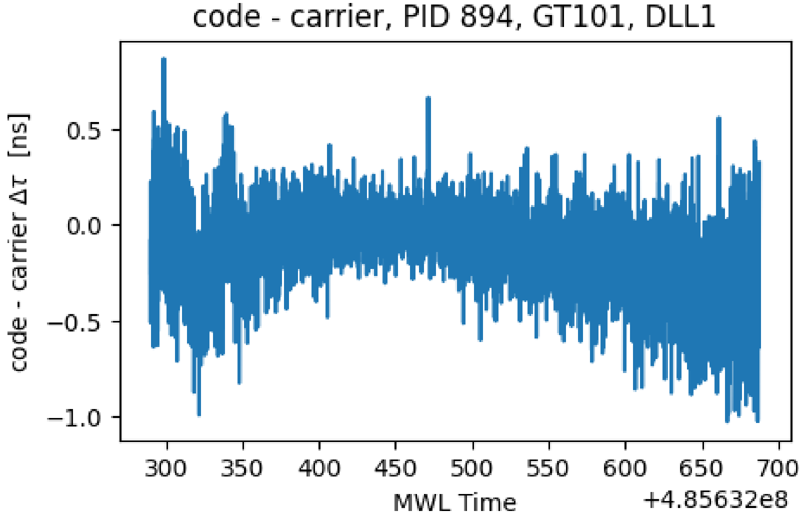
Space transceiver
MWL PFM @ ISS



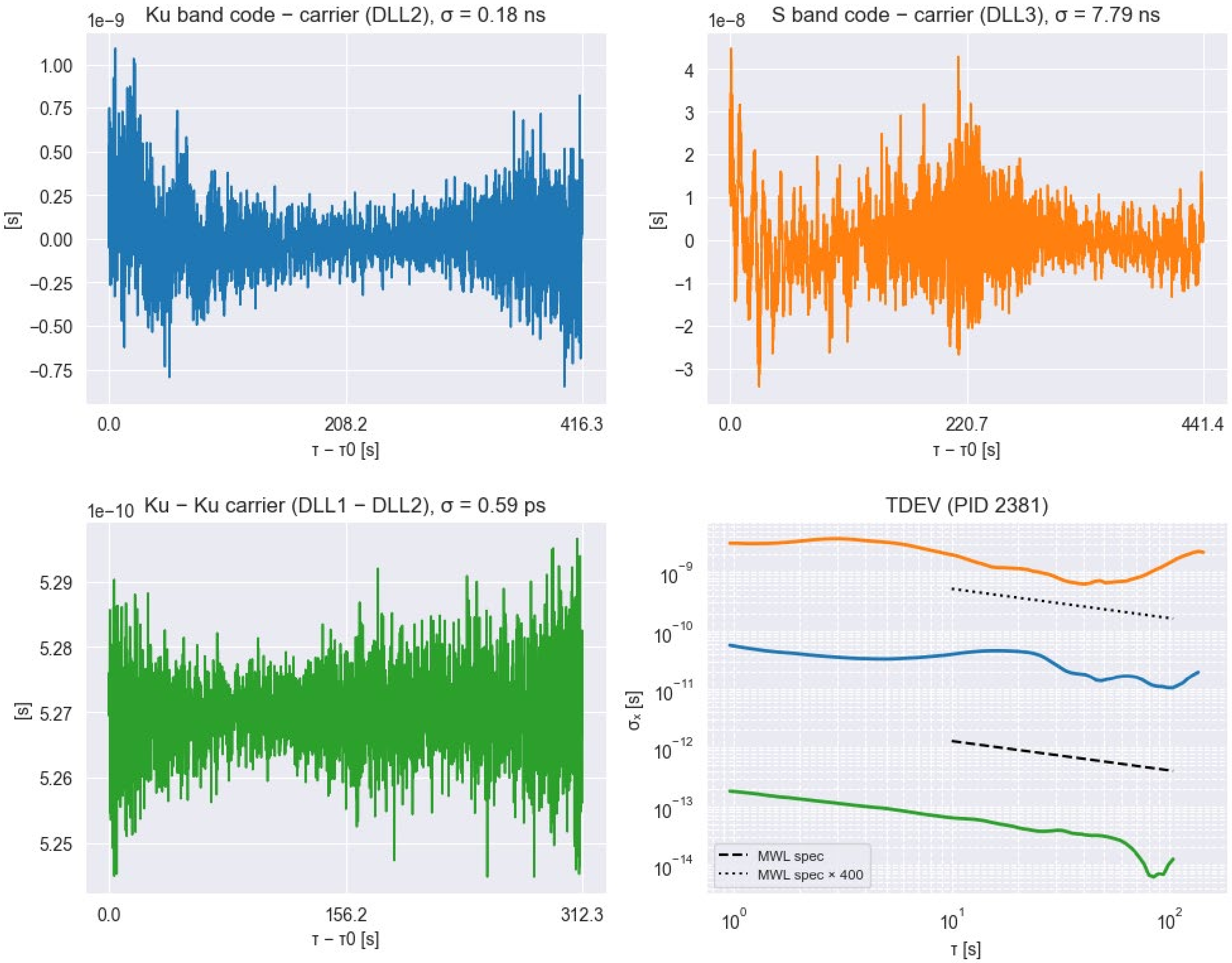




Ground transceiver
GT#101 @ LTE



# MWL GT code phase performance on a dynamic pass



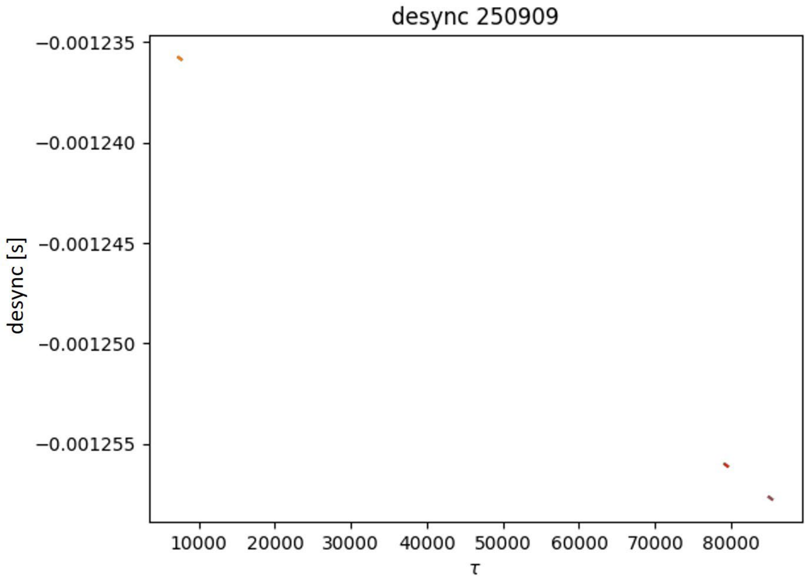

No calibrations and no signal travel time corrections applied

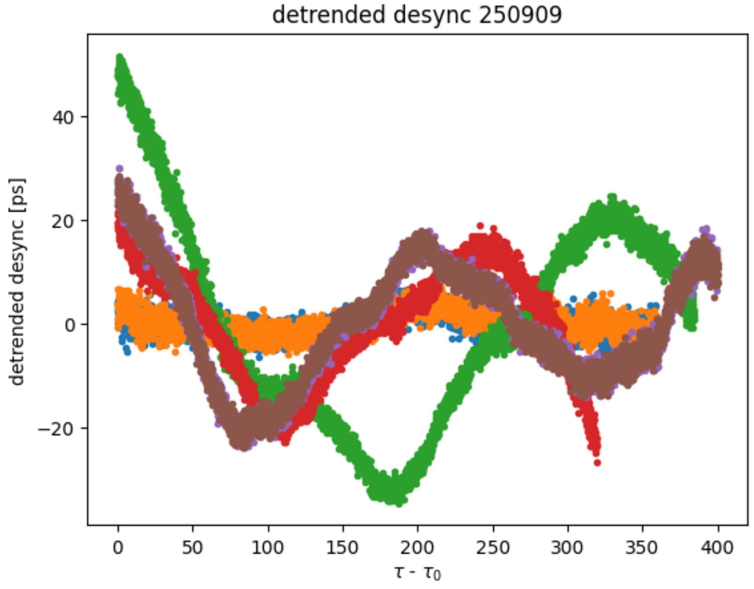
→ Time stability of S-band code phase measurements (no iono correction).

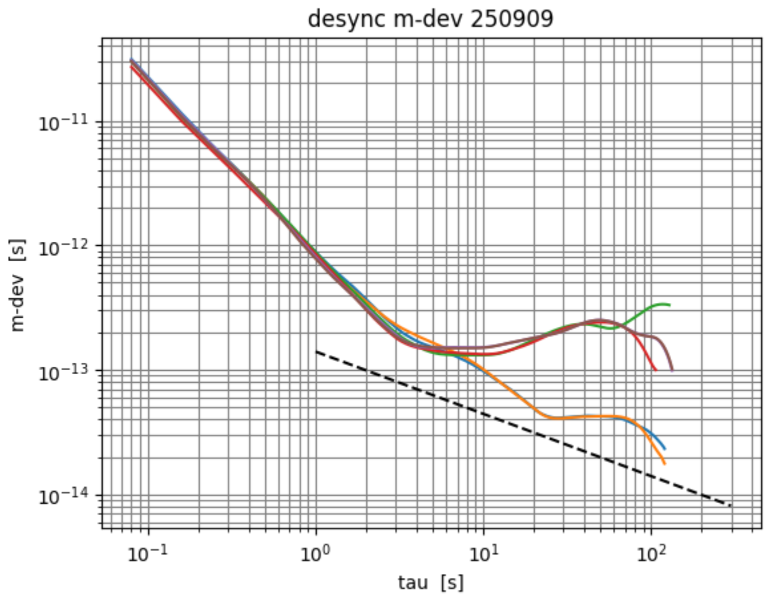
→ Time stability of Ku-band code phase measurements (no iono correction).

→ Lower limit of Ku-band carrier phase measurements time stability.

# PHARAO vs LTE H-maser comparison via MWL



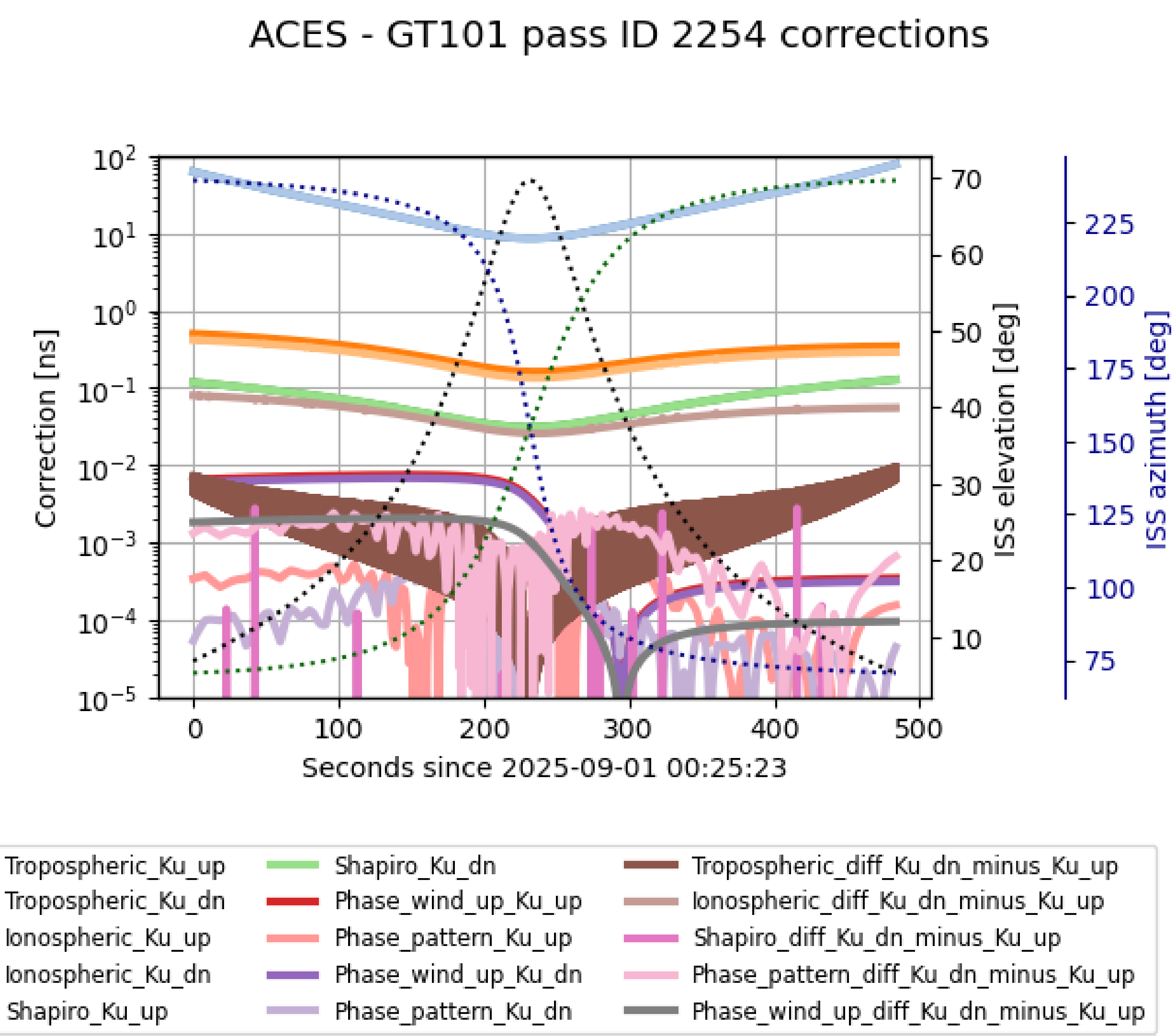




Preliminary results: No calibrations applied

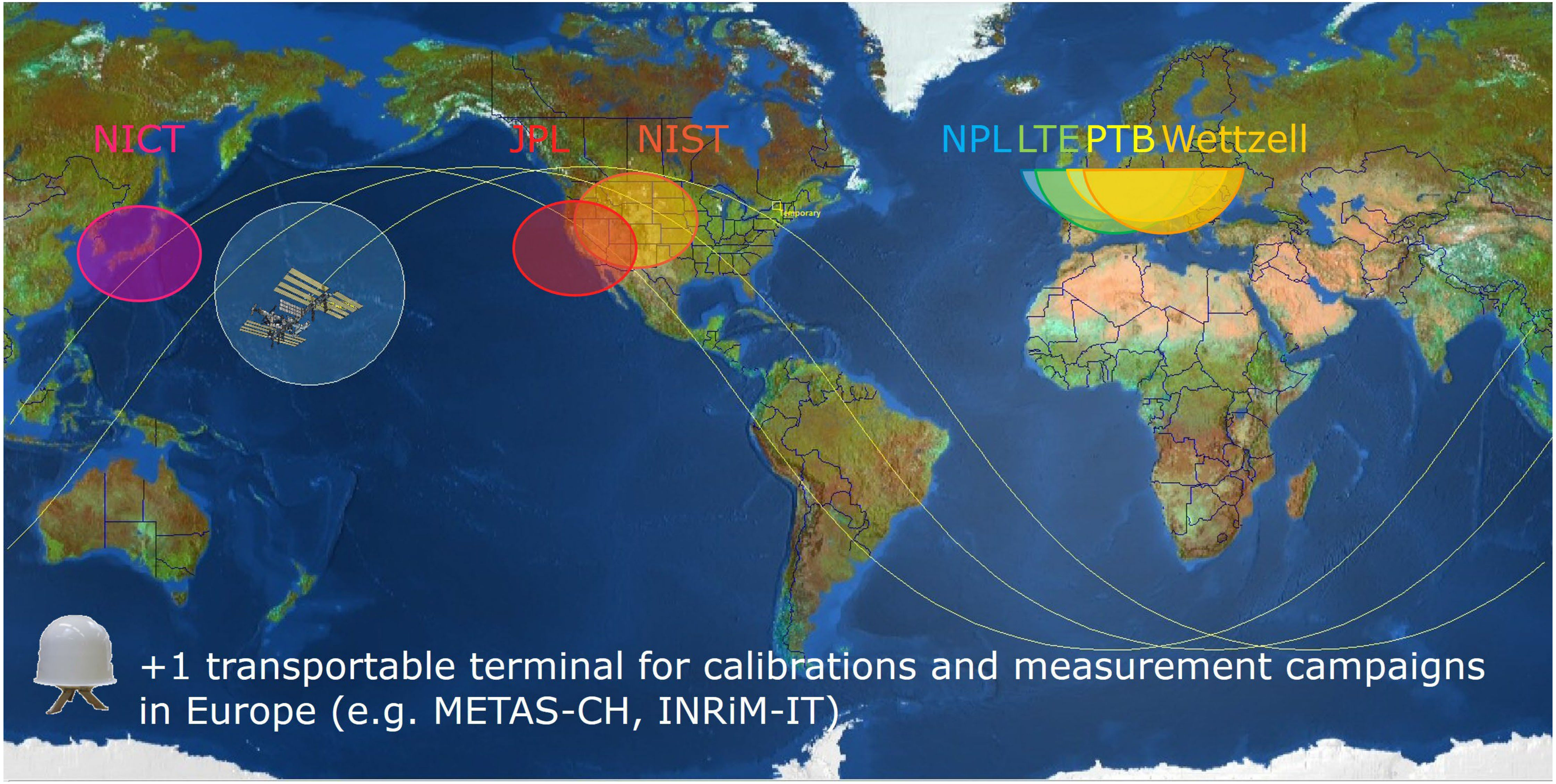
- 2-way combination of MWL PFM and GT101 measurements across three consecutive passes.
- Overall slope is $-2.83\times10^{-10}$, consistent with expectation from GR (mainly 2nd order Doppler effect).
- First pass is PHARAO in autonomous mode (orange and blue). Others are free running PHARAO USO.
- Dashed line corresponds to an Allan deviation of $2\times10^{-13}/\sqrt{\tau}$, as expected from PHARAO for this test configuration.

# MWL signal travel time corrections

- **Troposphere**: Numerical raytracing using the Saastamoinen model + VMF3.
- **Ionosphere**: 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.



# MWL GT network



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# 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. Cacciapuoti[1], S. Pataraia[1], T. Peignier[1], M. Plumaris[1], S. Weinberg[1], U. Bishoff[2], P. Crescence[2], A. Helm[2], J. Kehrer[2],, R. Lachaud[2], D. Mitschke[2], T. Niedermaier[2], F.X. Esnault[3], B. Léger[3], E. Thulliez[3], D. Massonnet[3], D. Goujon[4], J. Pittet[4], A. Perri[4], Q. Wang[4], P. Rochat[4], S. Liu[5], W. Schaefer[5], T. Schwall[5], I. Prochazka[6], A. Schlicht[7], U. Schreiber[7], M. Abgrall[8], P. Laurent[8], M. Lilley[8], J. Rozé[8], P. Wolf[8], K. Gibble[9], C. Salomon[10]

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