

Atomic Clock Ensemble in Space

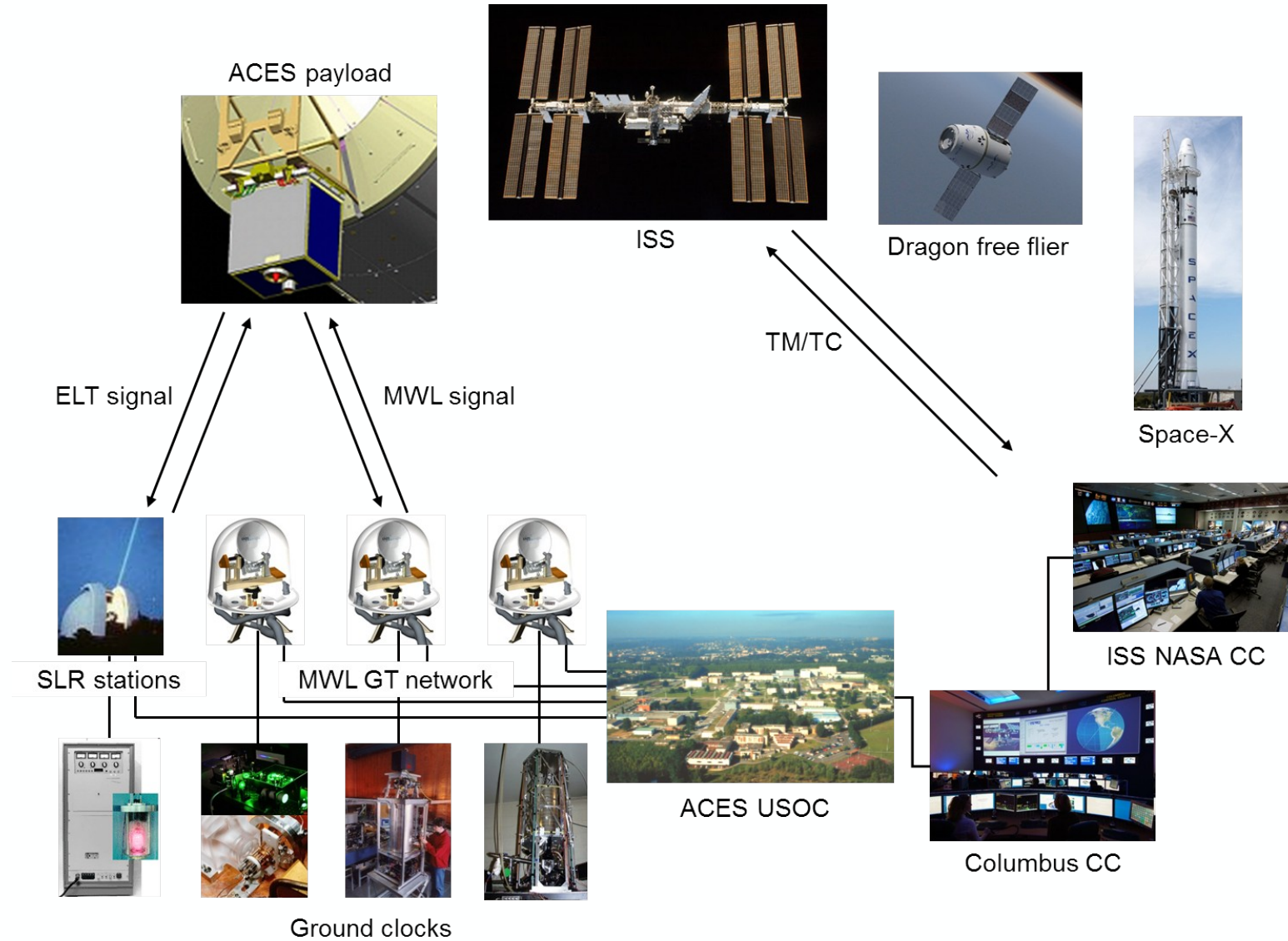
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ACES mission concept

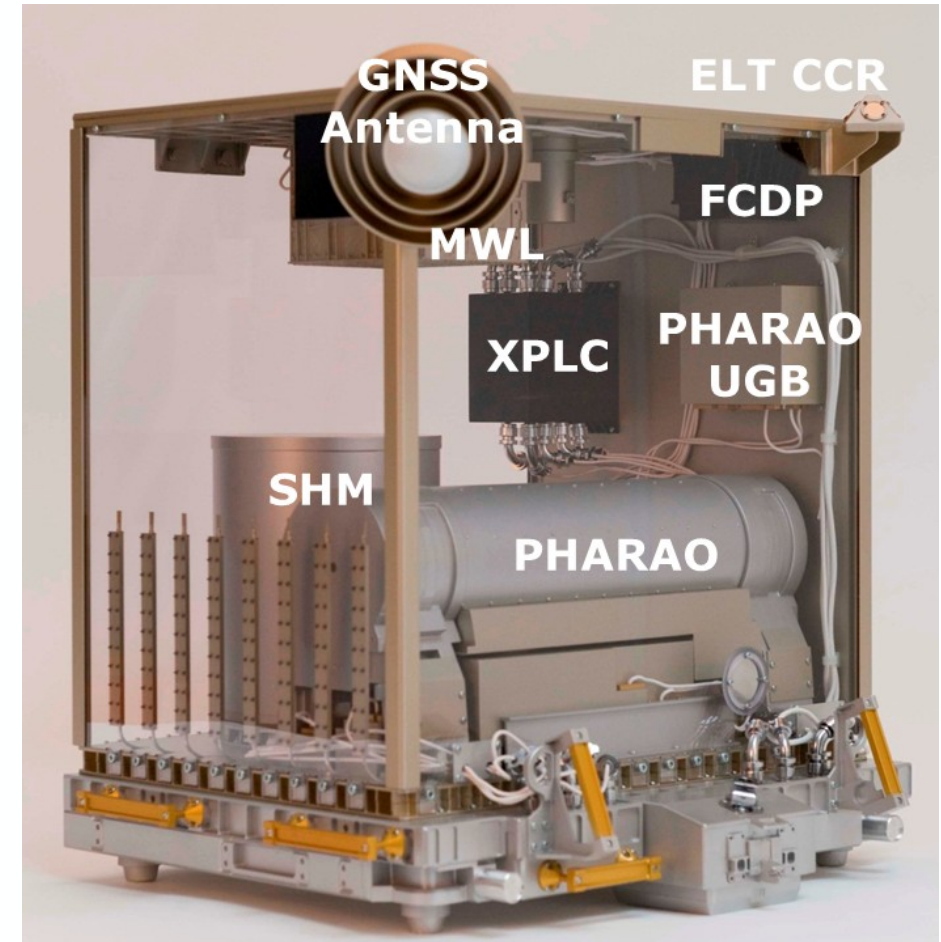


The Columbus module



The ACES payload

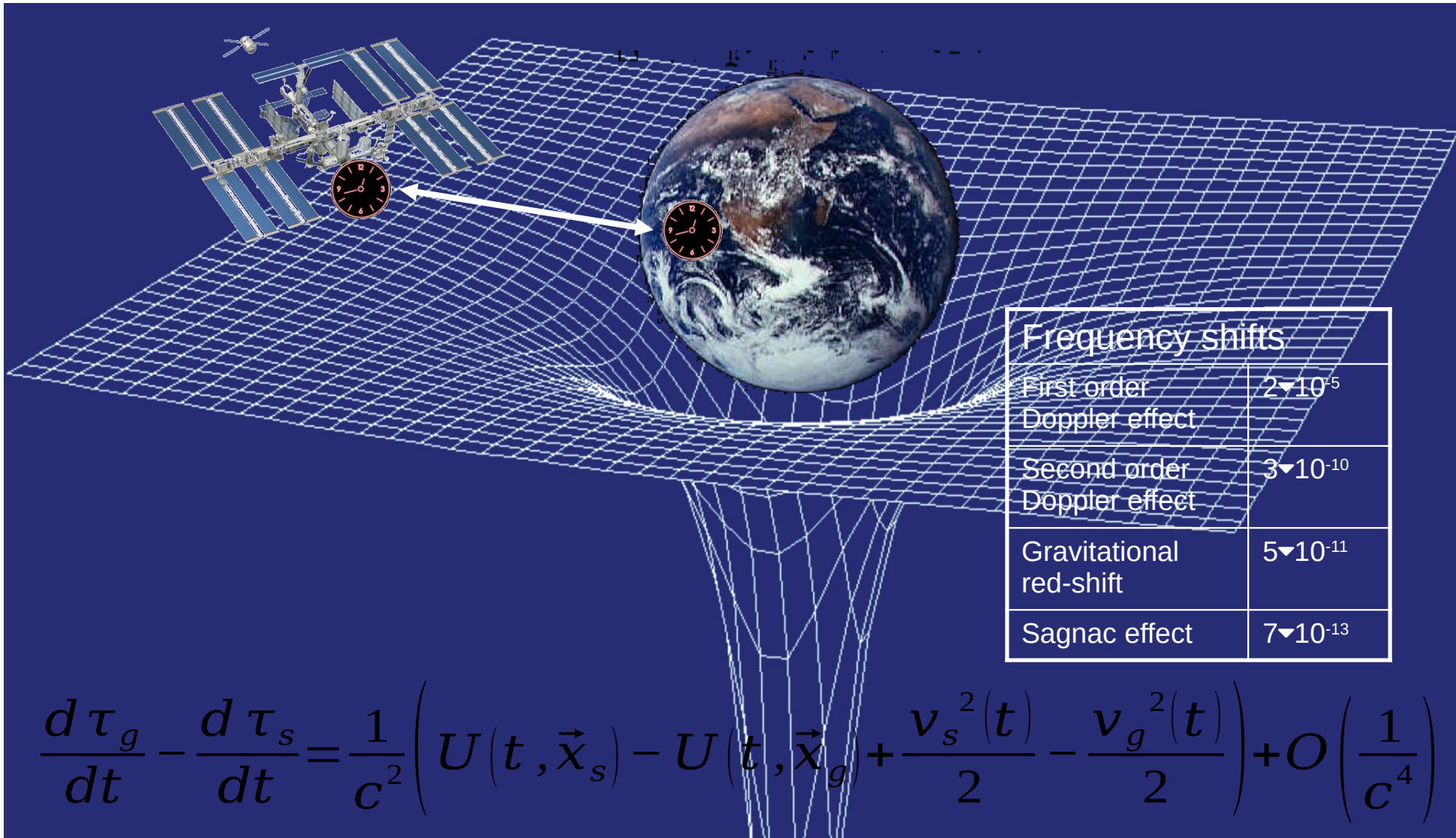
- **PHARAO** (CNES): Atomic clock based on laser cooled Cs atoms
- **SHM**: Active hydrogen maser
- **FCDP**: Clocks comparison and distribution
- **MWL** : T&F transfer link
- **GNSS** receiver
- **ELT**: Optical link
- **Support subsystems**
 - **XPLC**: External PL computer
 - **PDU**: Power distribution unit,
 - Mechanical, thermal subsystems
 - **CEPA**: Columbus External PL Adapter



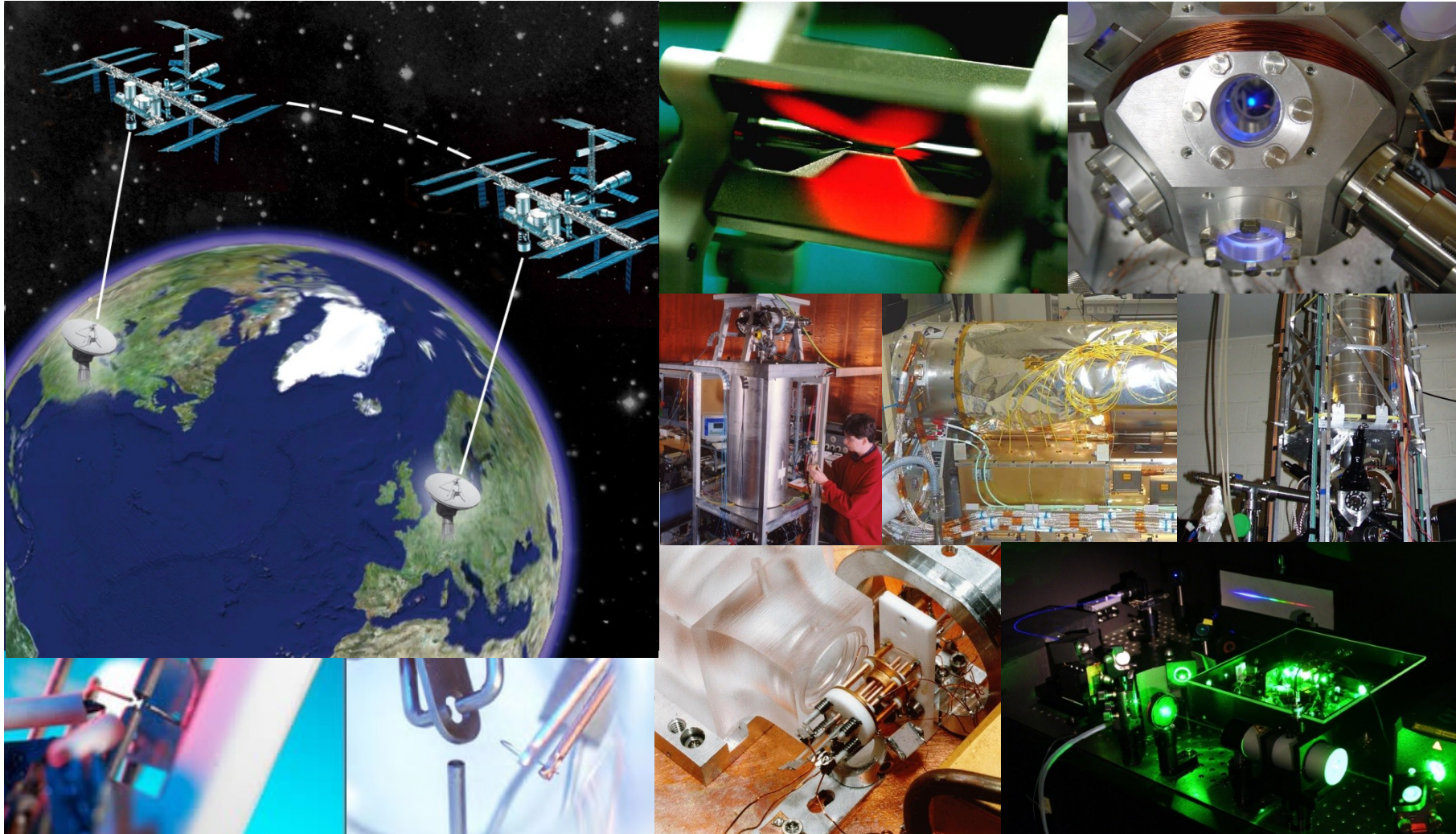
Volume: 1172x867x1246 mm³
Mass: 240 kg (w/o CEPA)
Power: 600 W

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.	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 $\alpha^{-1} \nabla d\alpha / dt < 3 \cdot 10^{-18} \text{ yr}^{-1}$ 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 testing different terms in the scalar field model Lagrangian and imposing limits on the three coupling constants β , γ , and δ . Measurements over a interval between encounters of 20 d. Simultaneous observation with several clocks compared along different baselines providing ways to confirm any observation above the sensitivity threshold and control the measurement systematics.

Gravitational redshift test



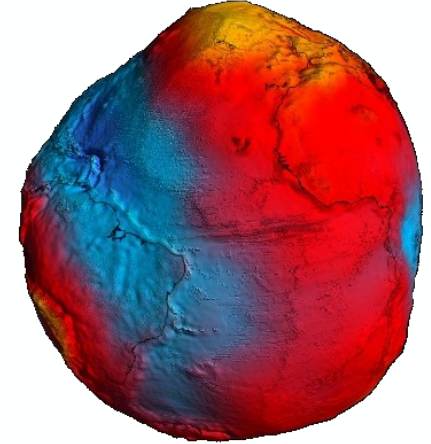
A network of atomic clocks to test fundamental physics



- Atomic clock networks can be used to search for dark matter and place boundaries on certain models, e.g. topological dark matter (TDM).
- TDM is represented by a scalar field that couples to fundamental constants thus inducing fluctuations of atomic transition frequencies.
- The ACES network can ensure comparisons of atomic clocks based on different atomic transitions down to 1×10^{-17} , in the optical domain, in the microwave domain, and optical vs microwave.
- Limits on variations for each of the three fundamental constants can be established thus testing different terms in the model Lagrangian and imposing limits on the three energy scales , , and .
- The simultaneous observation with several clocks compared along different baselines will provide ways to confirm any observation above the sensitivity threshold and control the measurement systematics.
- Clock comparisons can be performed continuously on 20 d intervals thanks to the ACES MWL, extending the time between encounters.
- Screening effect of the dark matter field due to the Earth mass reduced to about 0.06 on the space clock PHARAO with respect to ground clocks ($\sim 10^{-7}$).

Relativistic geodesy

- Relativistic geodesy: mapping of the Earth gravitational potential 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.

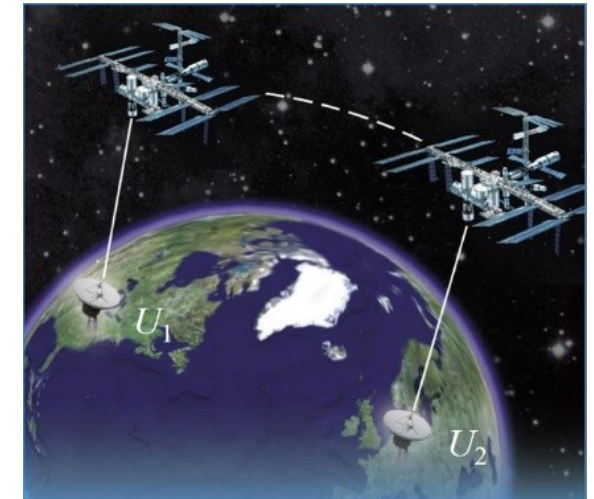


Clocks synchronization

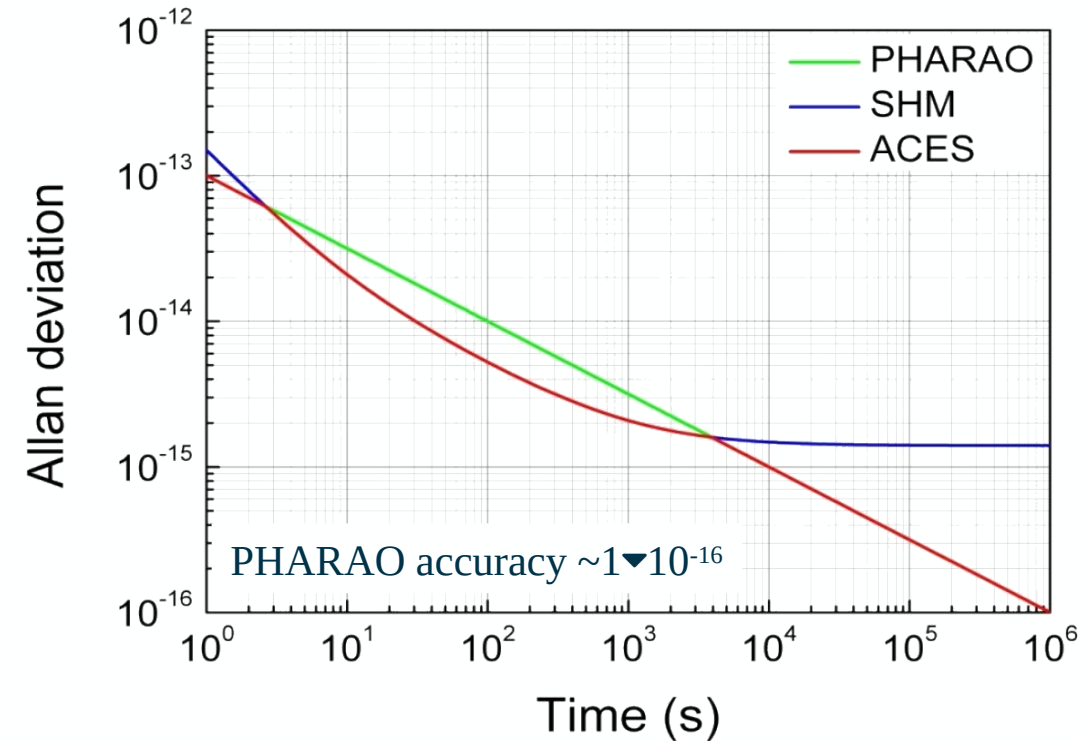
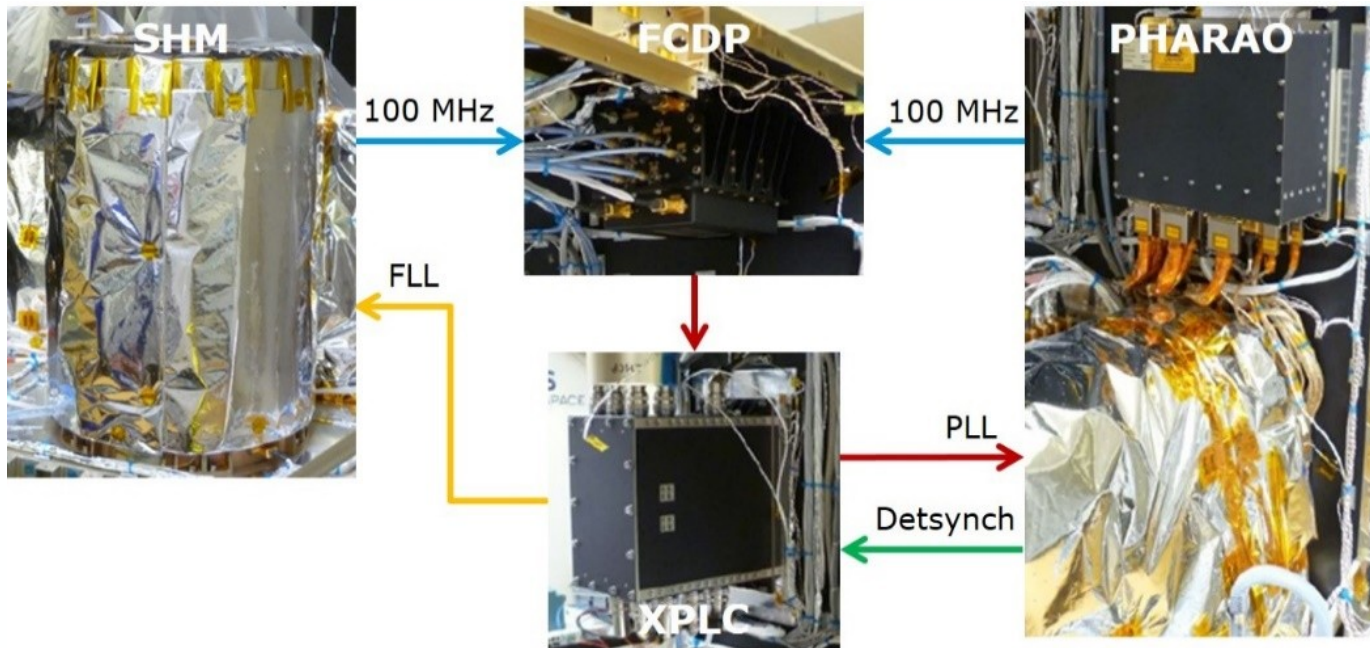
- MWL and ELT clocks synchronization at the 100 ps and 50 ps level, respectively.

Atomic time scales (TAI)

- The PHARAO clock is accurate to $1-2 \times 10^{-16}$.
- 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.

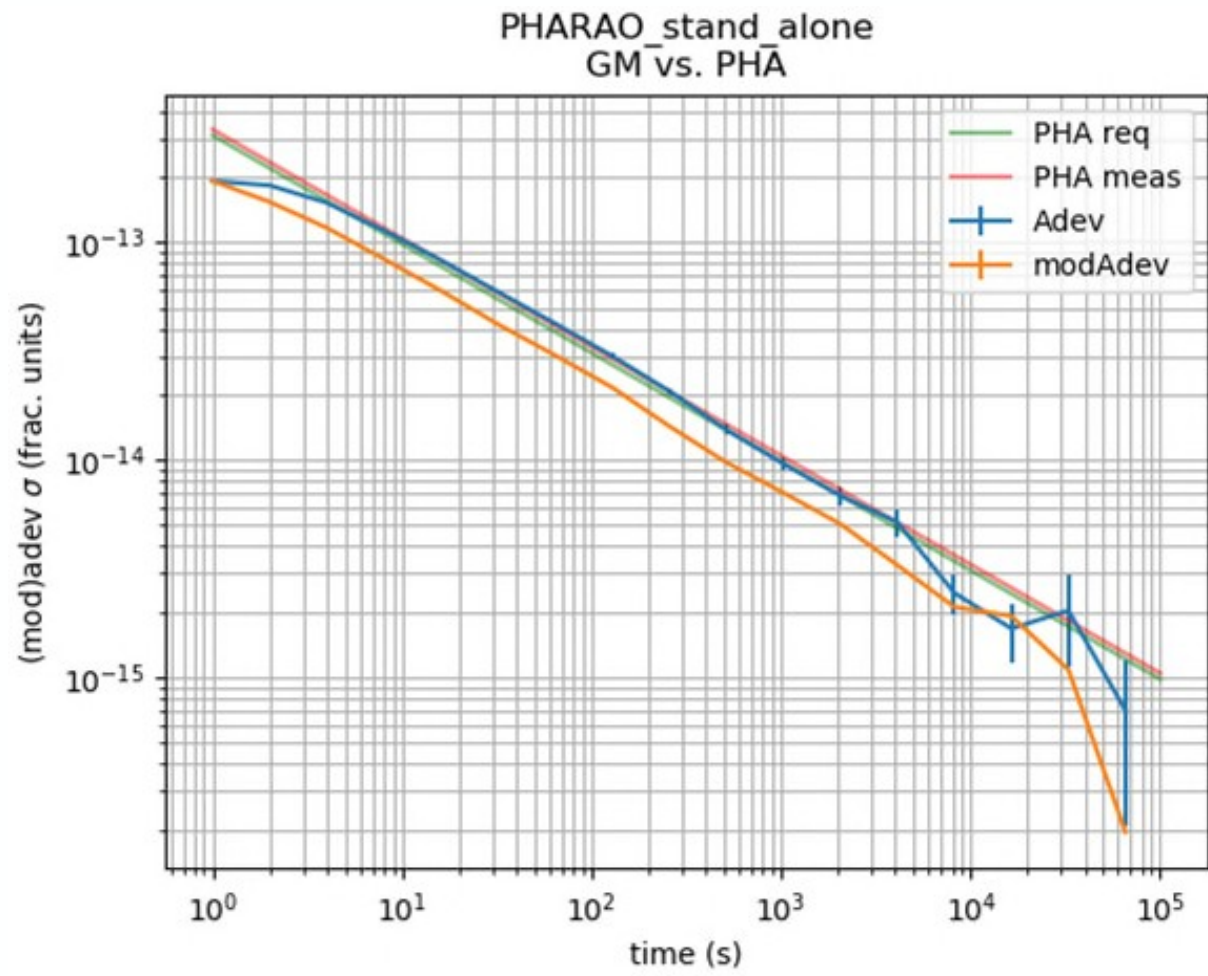


The ACES clock signal

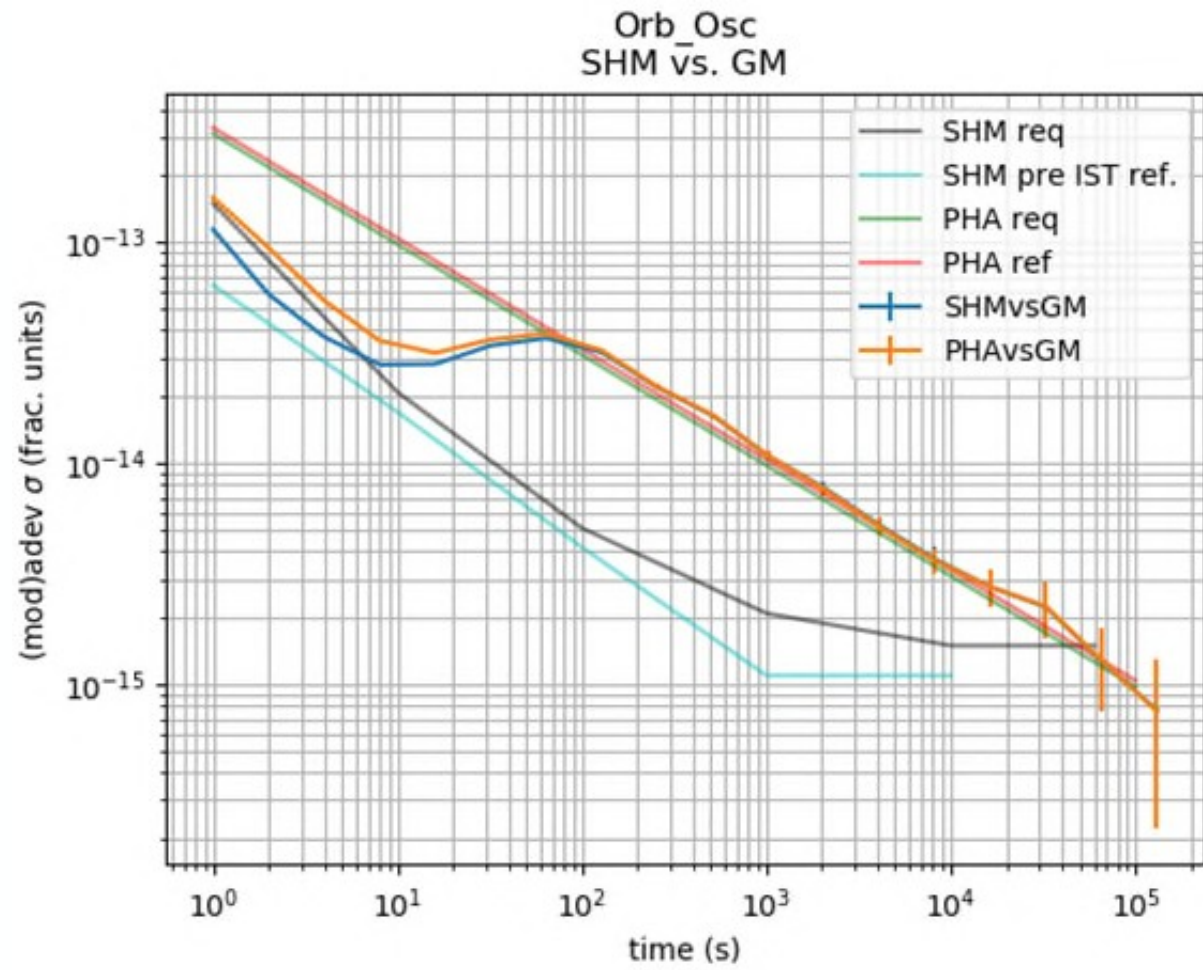


- The ACES clock signal (red curve) combines the good short-to-medium term frequency stability of the active H-maser SHM with the long term stability and accuracy of the Cs clock PHARAO.
- Two servo-loops control the clocks with two different time constants: the short-term servo-loop (PLL) steers PHARAO local oscillator on SHM (1-2 s time constant); the long-term servo-loop (FLL) corrects SHM against long term drifts (100-500 s time constant).

PHARAO and ACES stability



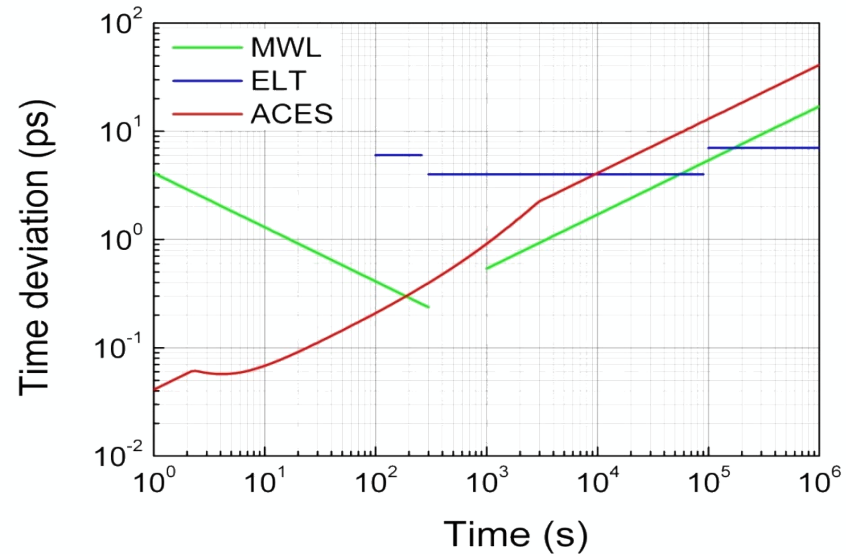
PHARAO stability in autonomous mode



ACES stability with STSL and LTSL closed and in the presence of magnetic and thermal perturbations

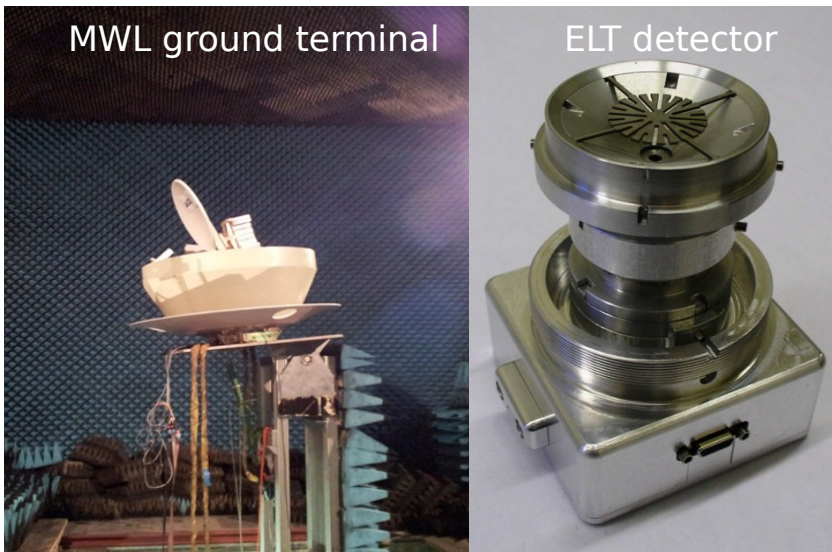


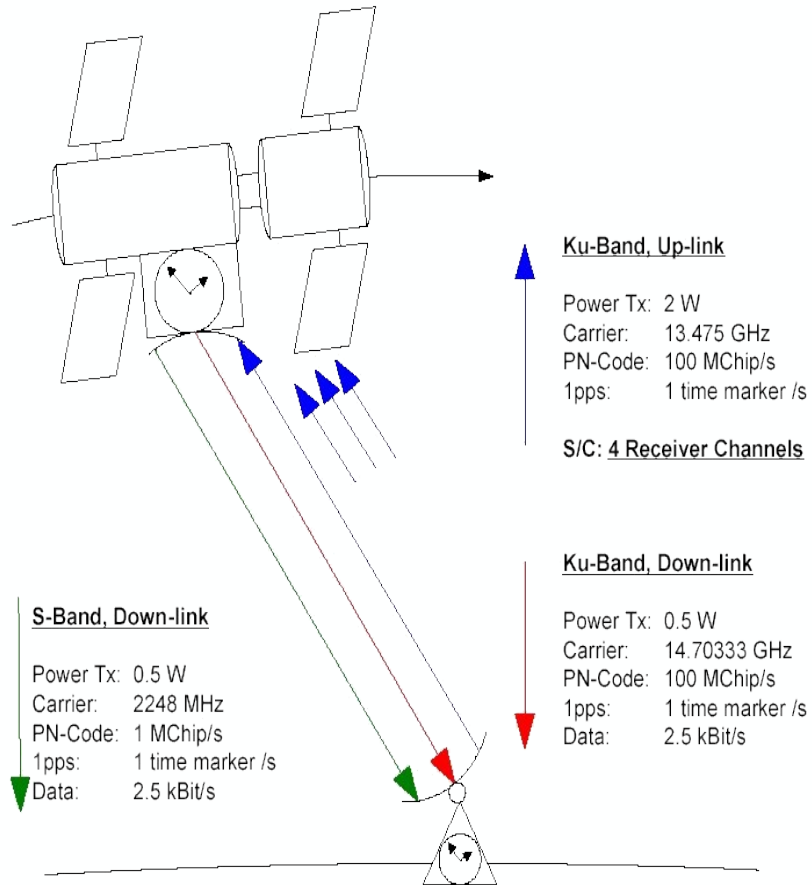
Space-to-ground clock comparisons



- MWL specifications defined not to degrade the clock performance in the space-to-ground comparison.
- Under static conditions (no signal dynamics), MWL noise reaches a flicker floor below 100 fs after 100 s of integration time.
- ELT detector noise averages down to a flicker floor below 1 ps after 10⁴ s of integration time at 100 Hz firing rate.
- Test results give large margins with respect to specifications and provide good confidence in the capability of limiting long term drifts of both MWL and ELT below 1-2 ps.

Compatible with space-to-ground clock comparisons at the $1 \cdot 10^{-17}$ level after 1 day of integration time.

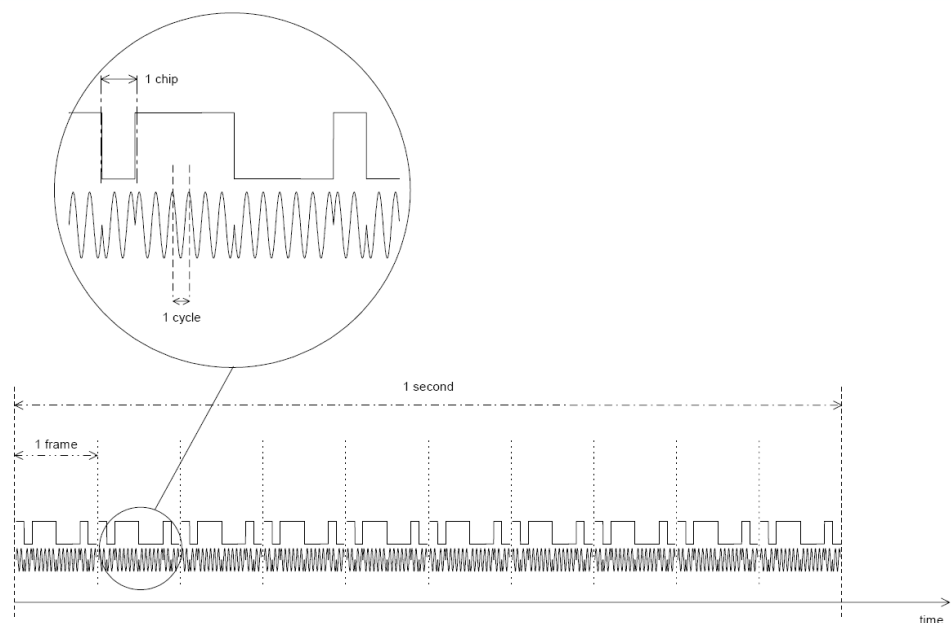




- Two-way link:
 - Removal of the troposphere time delay (8.3-103 ns)
 - Removal of 1st order Doppler effect
 - Removal of instrumental delays and common mode effects
- Additional down-link in the S-band:
 - Determination of the ionosphere TEC
 - Correction of the ionosphere time delay (0.3-40 ns in 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 (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

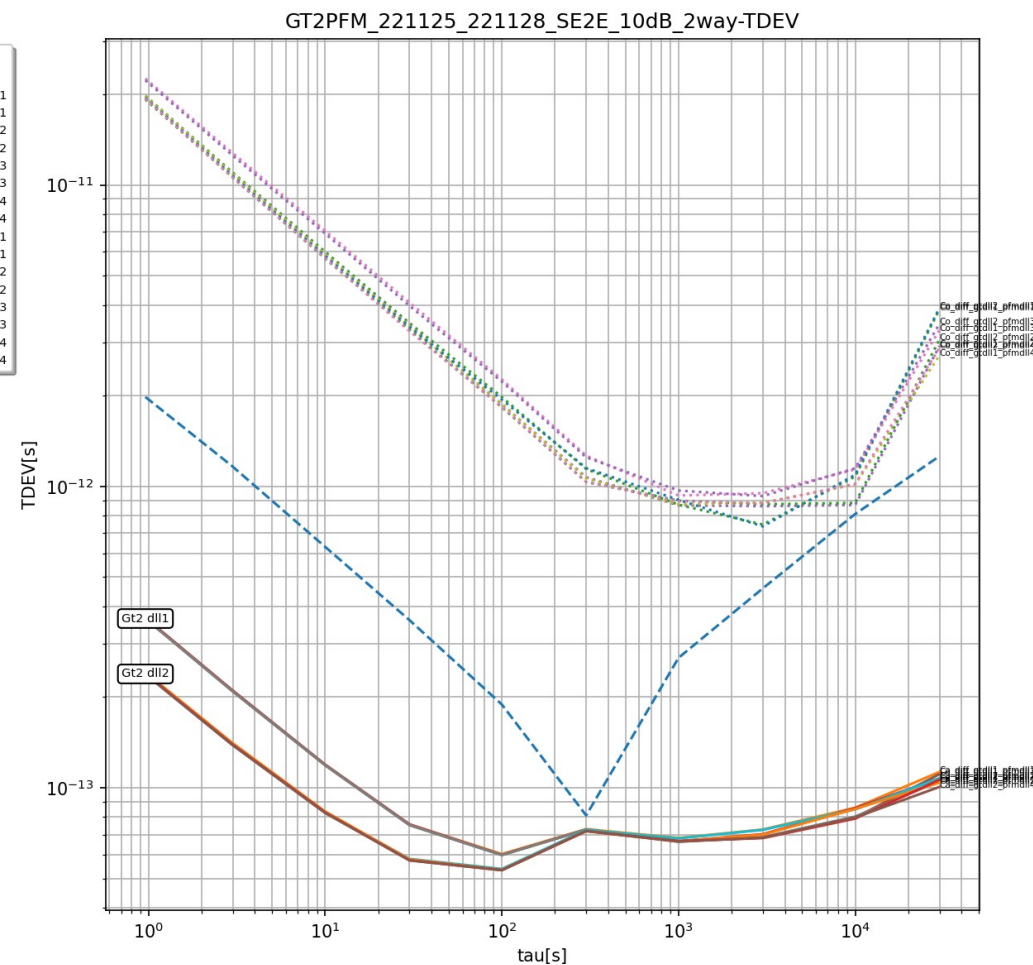


MWL PFM performance - Preliminary

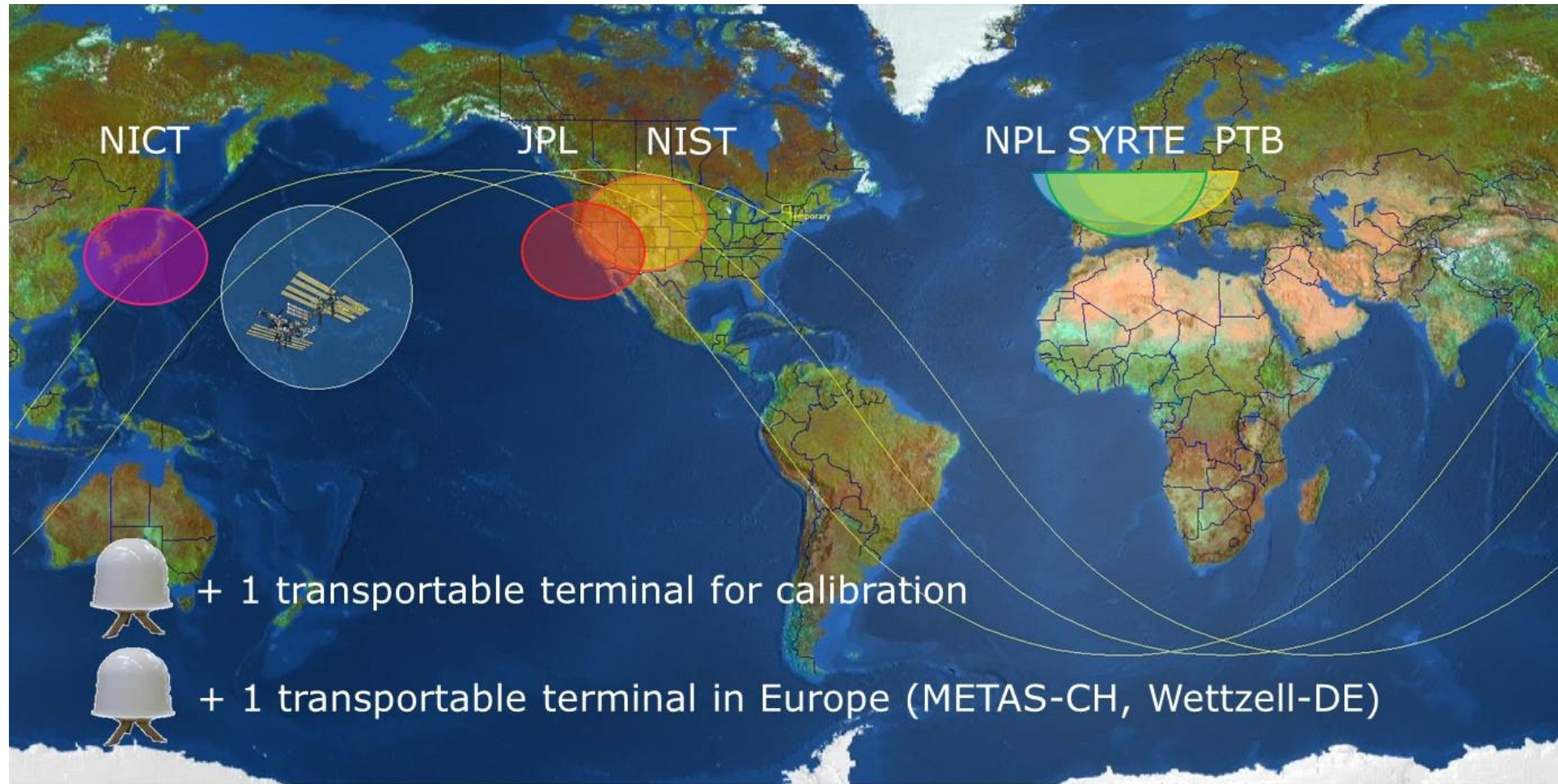


MWL signal

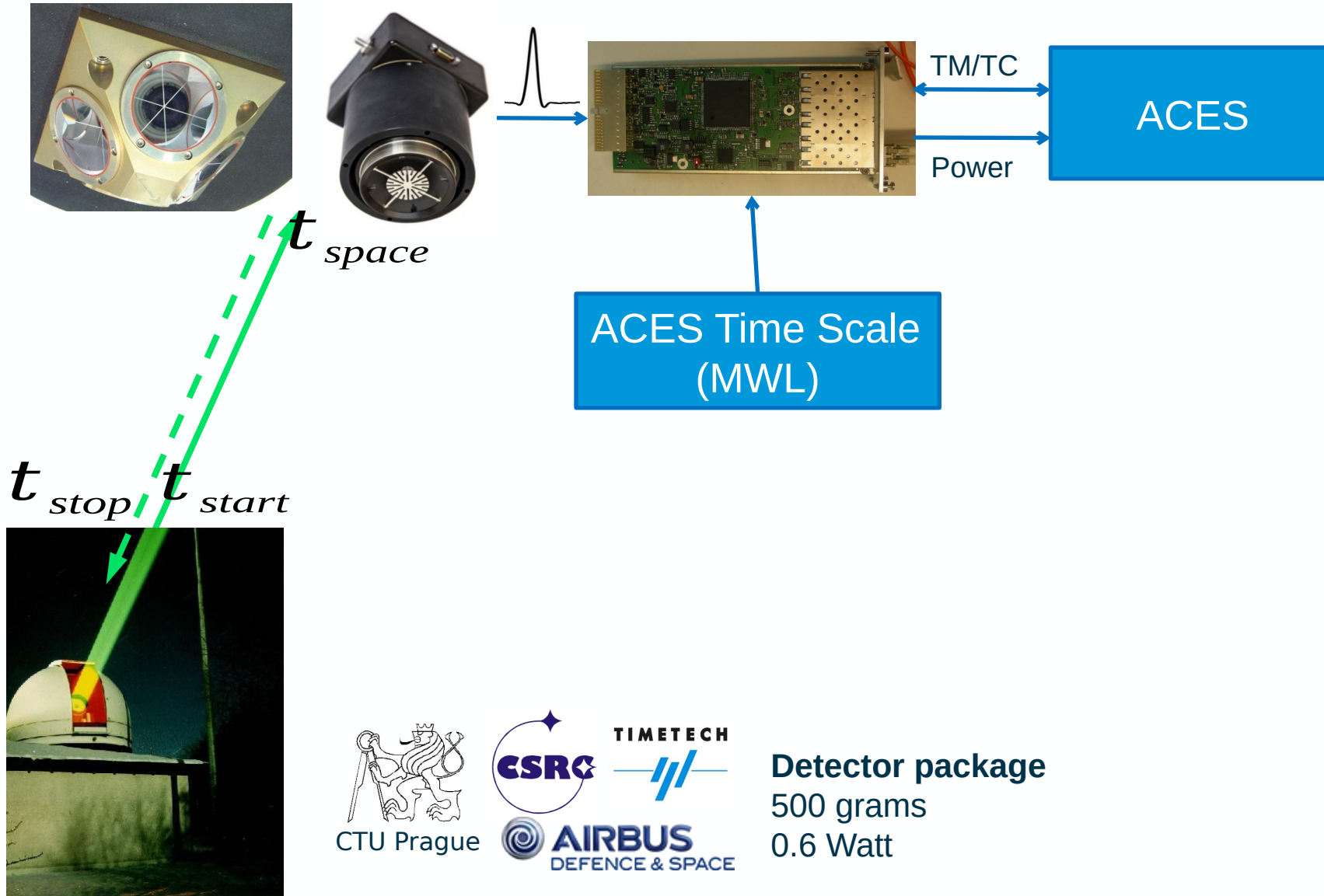
- 2 way TDEV[s]
- spect1wvayTdev[s]
 - Ca_diff_gtd11_pfm11
 - Co_diff_gtd11_pfm11
 - Ca_diff_gtd11_pfm12
 - Co_diff_gtd11_pfm12
 - Ca_diff_gtd11_pfm13
 - Co_diff_gtd11_pfm13
 - Ca_diff_gtd11_pfm14
 - Co_diff_gtd11_pfm14
 - Ca_diff_gtd12_pfm11
 - Co_diff_gtd12_pfm11
 - Ca_diff_gtd12_pfm12
 - Co_diff_gtd12_pfm12
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 - Co_diff_gtd12_pfm14

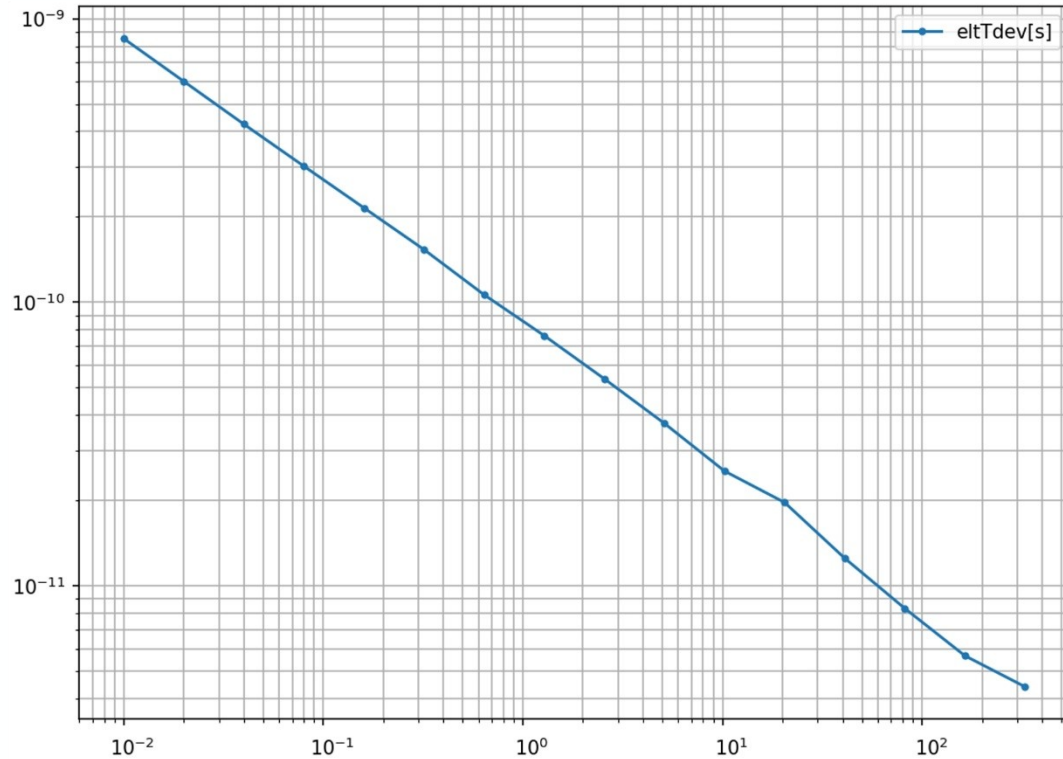


MWL Time Stability [s]: 2-way combination of common clock measurements (no signal dynamics)



European Laser Timing (ELT)

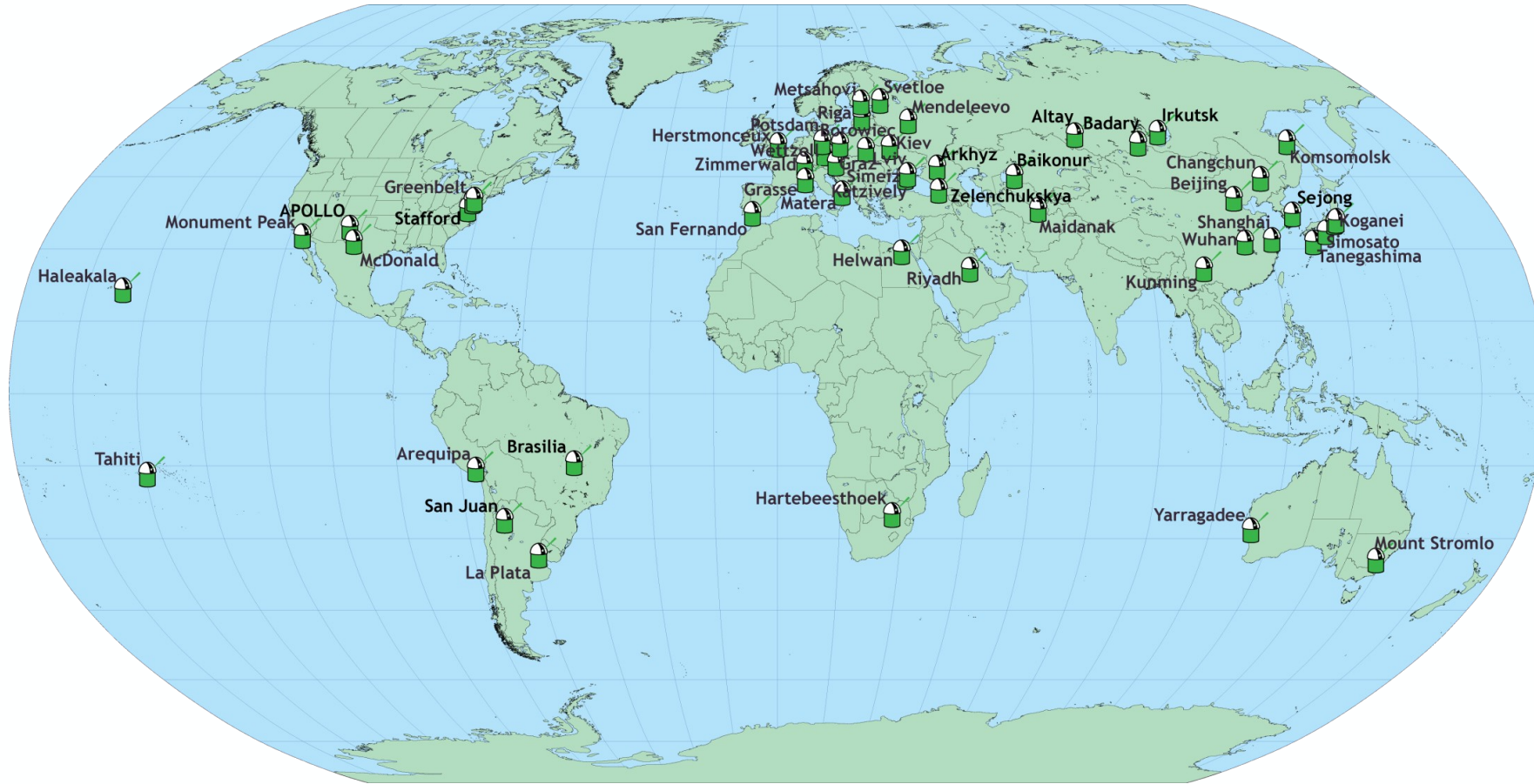




ELT Time Stability [s]: dark counts detection events vs NPET time tagging measurements

- ELT detector package tested from -55°C to +60°C.
- Temperature sensitivity coefficient: 1 ps/K

ILRS network of SLR stations



ACES as official ILRS target: **Wettzell** (primary station), **Graz**, **Herstmonceaux**, **Potsdam**, and **Zimmerwald** SLR stations already calibrated; other stations can join provided they comply with ISS safety requirements.

- A first run of the ACES Integrated System Tests (IST) tests has been completed. They included:
 - Clocks characterization tests in standalone configuration
 - ACES servo-loops performance
 - ACES clock signal performance evaluation
 - Sensitivity under temperature and magnetic field variations
- IST revealed a major anomaly: SHM getters got passivated and needed replacement, introducing a major delay in the ACES schedule.
- Acceptance status of ACES:
 - PHARAO clock PFM and ELT detector package are accepted. ACES GNSS system and FCDP PFM are completing their acceptance process.
 - SHM PFM getters have been refurbished. Acceptance tests are expected to be completed by this summer.
 - MWL PFM is completing qualification tests and calibration before final acceptance (by autumn 2023).
 - ACES payload acceptance planned for summer 2024.
- ACES PFM delivered for launch on SpaceX in December 2024.
- MWL GTs deployment will start in mid 2024 (SYRTE, PTB and Wettzell); the other institutes will follow.

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