Atomic Clock Ensemble in Space

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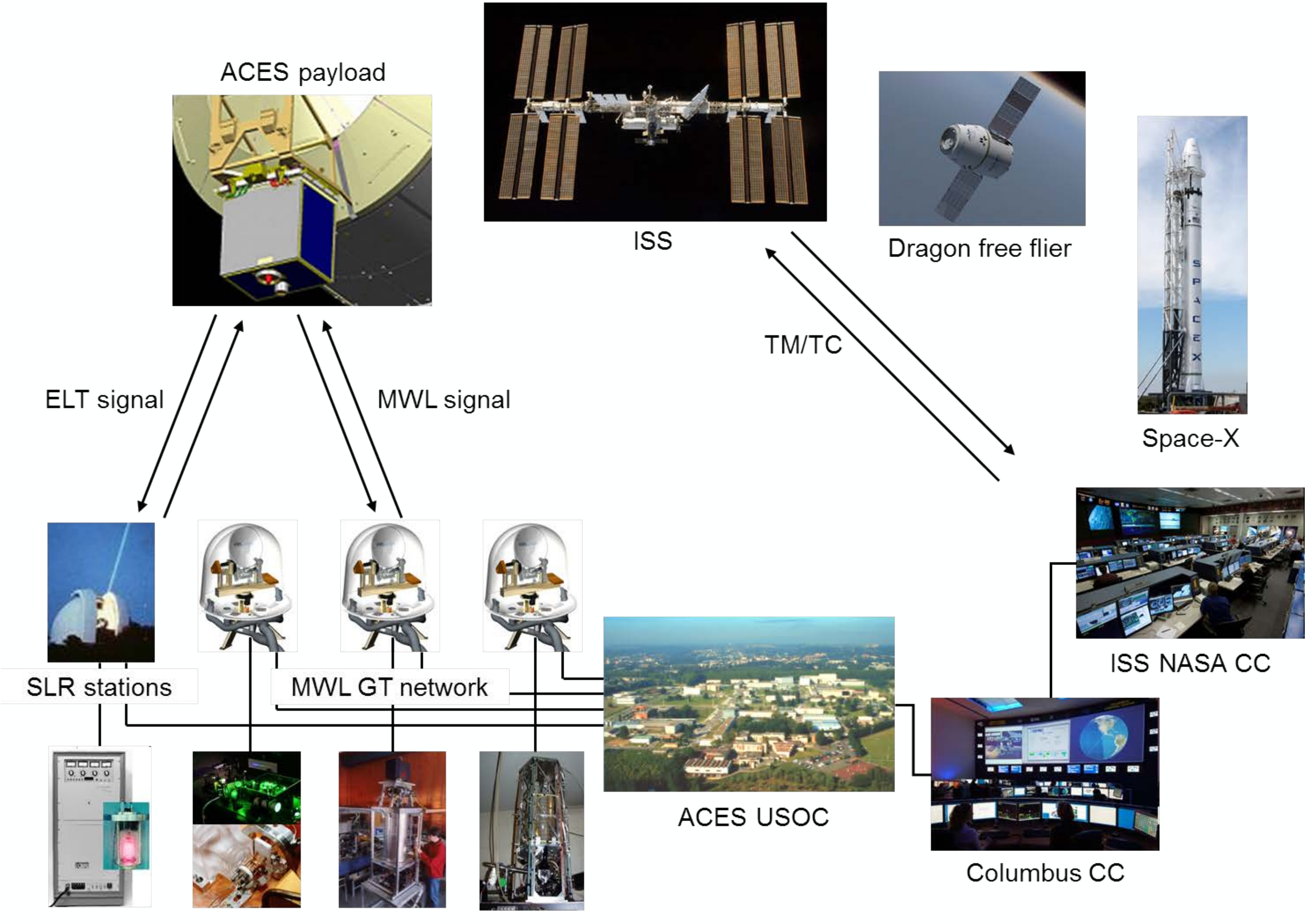
Second EPS Conference on Gravitation, 06/07/2021

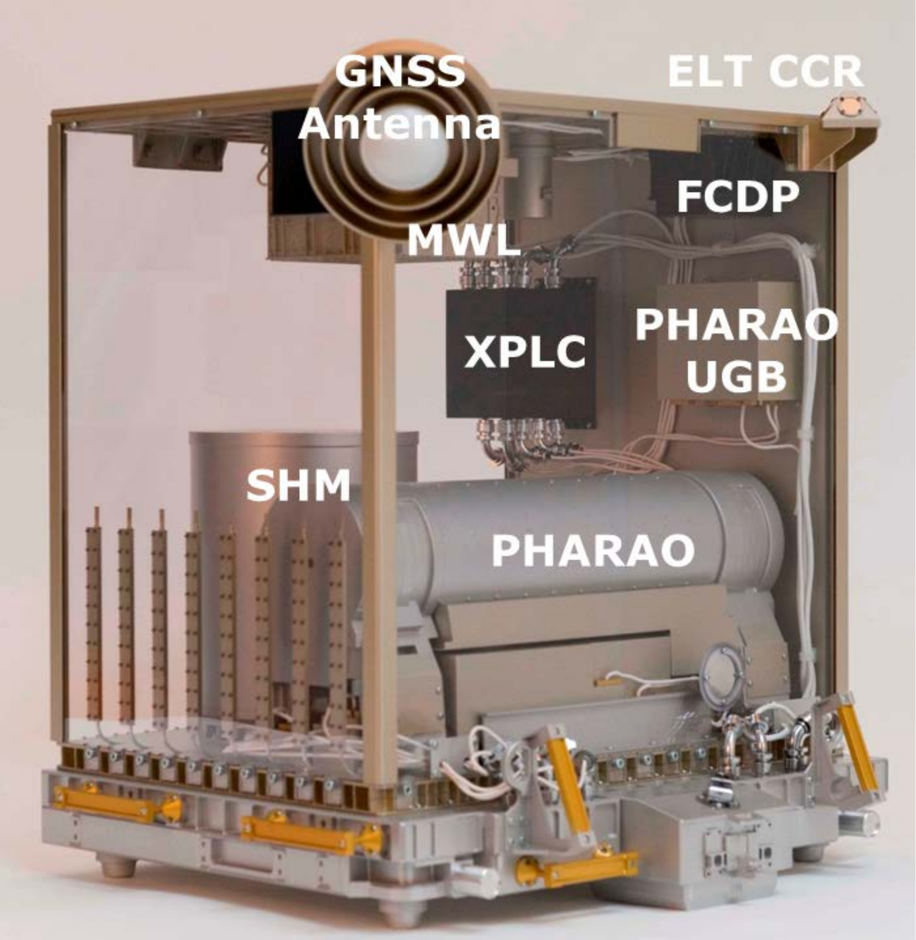
ACES mission concept



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

AIRBUS DEFENCE & SPACE

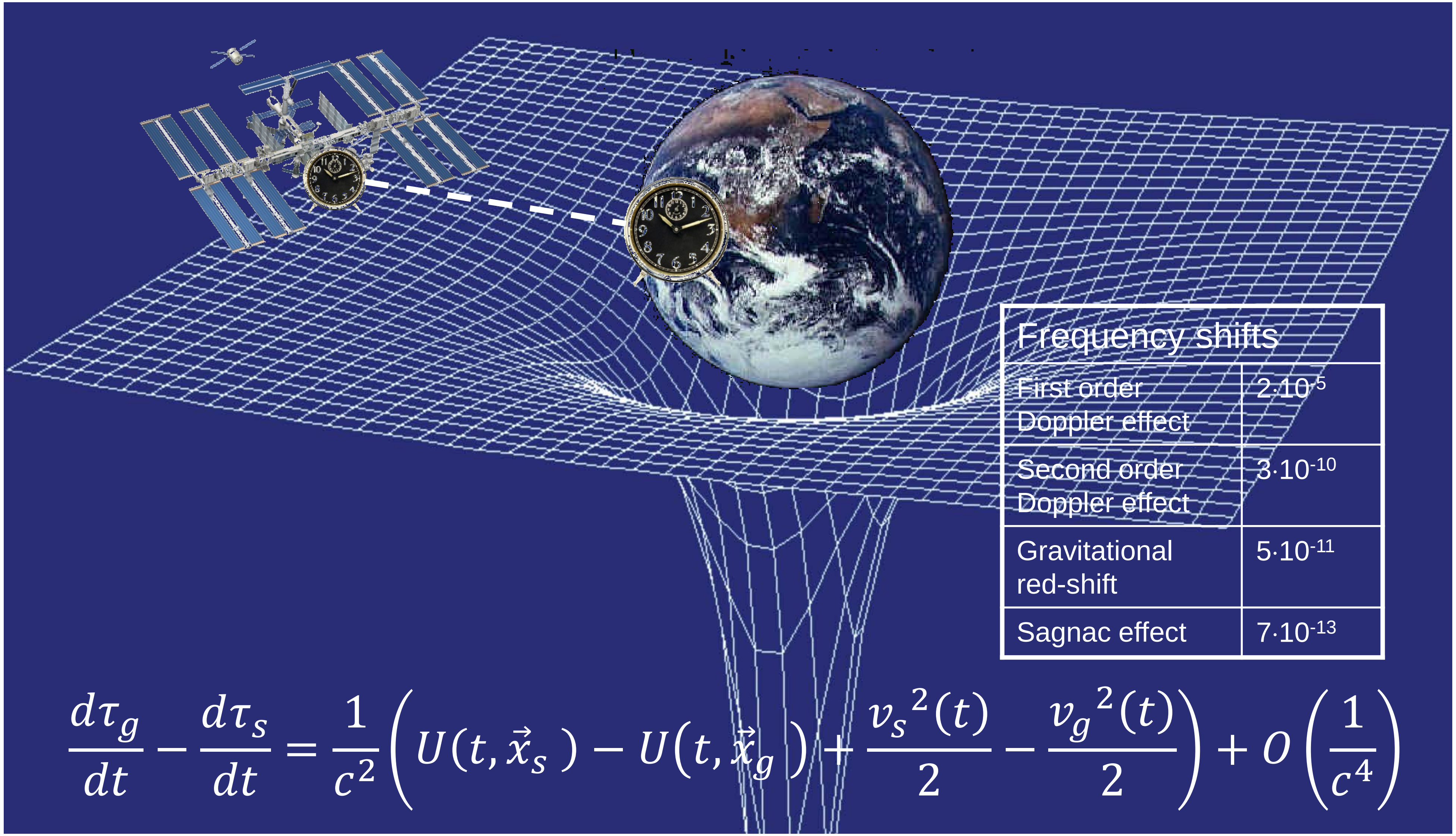
Atomic Clock Ensemble in Space

Science

Fundamental physics tests

ACES Mission Objectives	ACES specified performances	Scientific background and recent results
Fundamental physics tests		
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at a precision < $50 \cdot 10^{-6}$ after 300 s and < $2 \cdot 10^{-6}$ after 10 days of integration time.	ACES will yield an improvement of a factor 70 over the GPA experiment and a factor 10 over recent tests involving Galileo 5 and 6 satellites.
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1{\cdot}10^{-17}$ yr $^{-1}$ down to $3{\cdot}10^{-18}$ yr $^{-1}$ in case of a mission duration of 3 years.	The α drift has been constrained to $1{\cdot}10^{-18}$ yr $^{-1}$ based on a comparison of the electric quadrupole and octupole transition frequencies in $^{171}Yb^{+}$. ACES will perform crossed comparisons of clocks based on different atomic elements on a worldwide scale thus constraining the time drift 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 $\delta c / c < 10^{-10}$.	ACES results will improve present limits on the RMS parameter α based on GPS satellites by one order magnitude. Best limits today are reaching $\delta c / c < 2.6{\cdot}10^{-11}$, a factor 4 better than the ACES results.

Gravitational redshift test

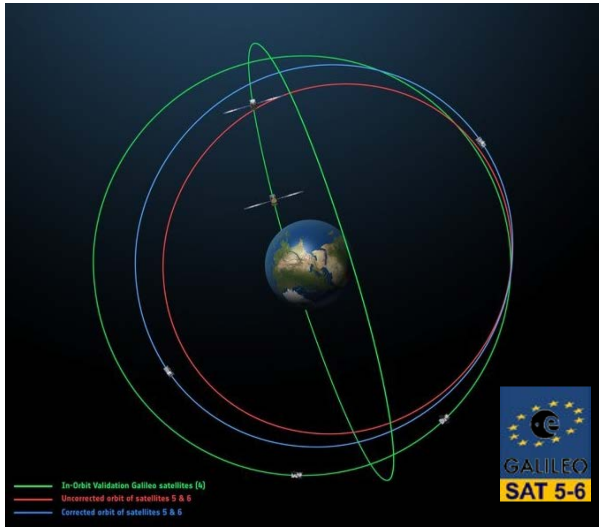


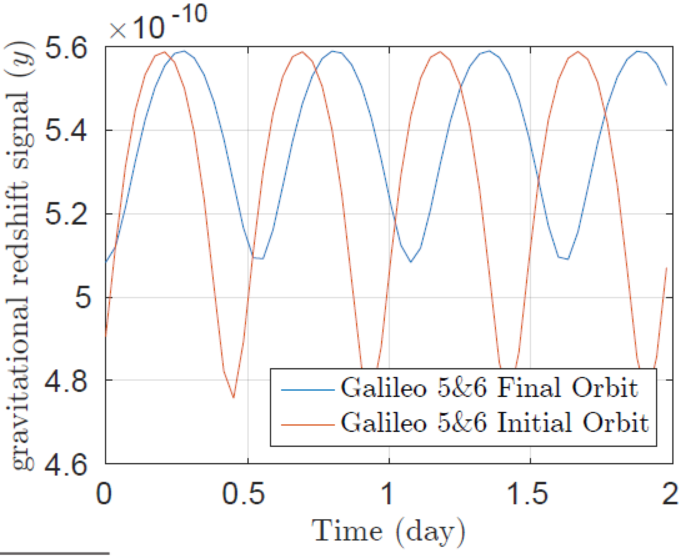
Frequency shifts	
First order Doppler effect	$2 \cdot 10^{-5}$
Second order Doppler effect	$3 \cdot 10^{-10}$
Gravitational red-shift	$5 \cdot 10^{-11}$
Sagnac effect	$7 \cdot 10^{-13}$

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

Gravitational redshift test

Redshift tests on Galileo 5 and 6 satellites





$\alpha \pm \Delta\alpha (\times 10^{-5})$	Clock 1	Clock 3	Clock 5
Days included	414	167	510
Statistics	-0.7 ± 0.5	8.4 ± 1.2	3.7 ± 0.4
Orbit model	-2.2 ± 0.5	-8.1 ± 0.9	-1.5 ± 0.9
Temperature	0 ± 2.0	0 ± 2.0	0 ± 2.0
Magnetic field	0 ± 0.8	0 ± 0.8	0 ± 0.8
Total	-2.9 ± 1.4	0.3 ± 1.9	2.2 ± 1.6

PRL 121, 231102 (2018)
PRL 121, 231101 (2018)

	LPI violation $[\times 10^{-5}]$	Total uncertainty $[\times 10^{-5}]$	Stat. unc. $[\times 10^{-5}]$	Orbit unc. $[\times 10^{-5}]$	Temperature unc. $[\times 10^{-5}]$	Magnetic field tot. unc. (X, Y, Z) $[\times 10^{-5}]$
GSAT0201	−0.77	2.73	1.48	1.09	0.59	1.93 (0.52, −0.36, 1.82)
GSAT0202	6.75	5.62	1.41	5.09	0.13	1.92 (−0.07, 0.58, 1.83)
Combined	0.19	2.48	1.32	0.70	0.55	1.91 (0.48, −0.29, 1.82)

ACES redshift tests

- ACES will perform an absolute measurement of the gravitational redshift between the PHARAO clocks and a network of Cs clocks on the ground.
- In this measurement, the accuracy of both PHARAO and clocks on the ground allows to test the redshift effect to 2ppm.
- With a network of 8 ground clocks, this accuracy level can be reached in 20 days.
- However, the accuracy evaluation of the PHARAO clock will require the whole mission, particularly for what concerns the cavity phase, the microwave lensing and the collisional frequency shifts.

ACES is expected to improve this result by a factor 10, down to 2 ppm.

Fundamental physics tests

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Time variations of fundamental constants

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:

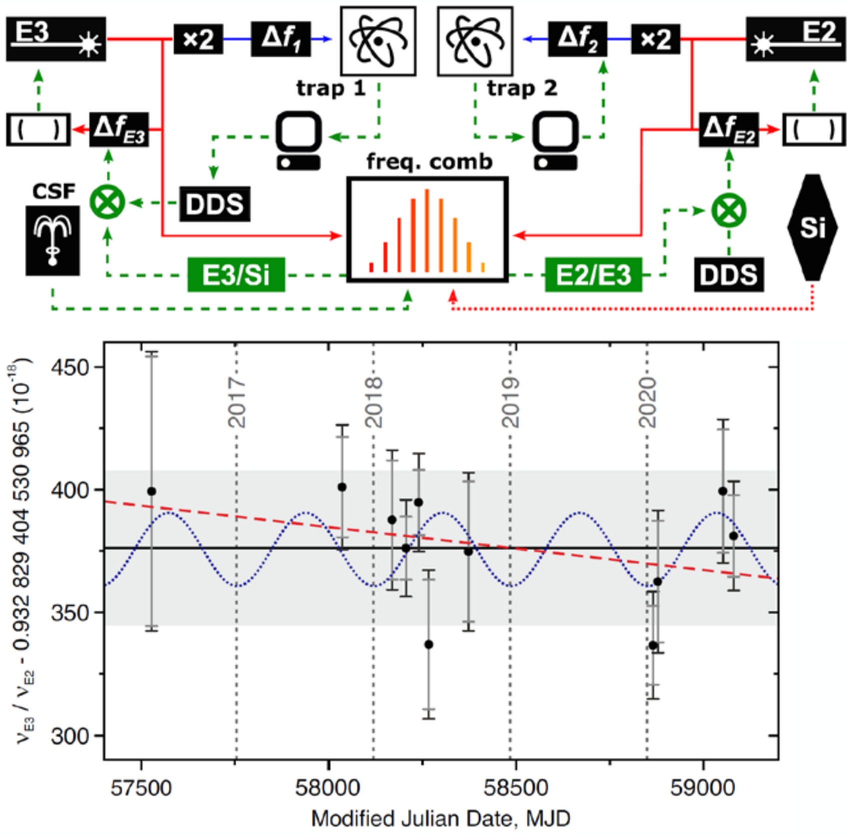
$$\delta \ln\left(\frac{\nu_{\mathrm{hfs}}^{(i)}}{R_\infty c}\right) \simeq \frac{\delta g^{(i)}}{g^{(i)}} + \frac{\delta(m_e/m_p)}{(m_e/m_p)} + \left(2 + \alpha \frac{\partial}{\partial \alpha} \ln F_{\mathrm{hfs}}^{(i)}(\alpha)\right) \times \frac{\delta \alpha}{\alpha}$$

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

Time variations of fundamental constants

α drift measurement at PTB

- Constrained to $1.1 \cdot 10^{-18}$ yr $^{-1}$ based on a comparison of the frequencies of the electric quadrupole and electric octupole transitions in $^{171}Yb^{+}$.



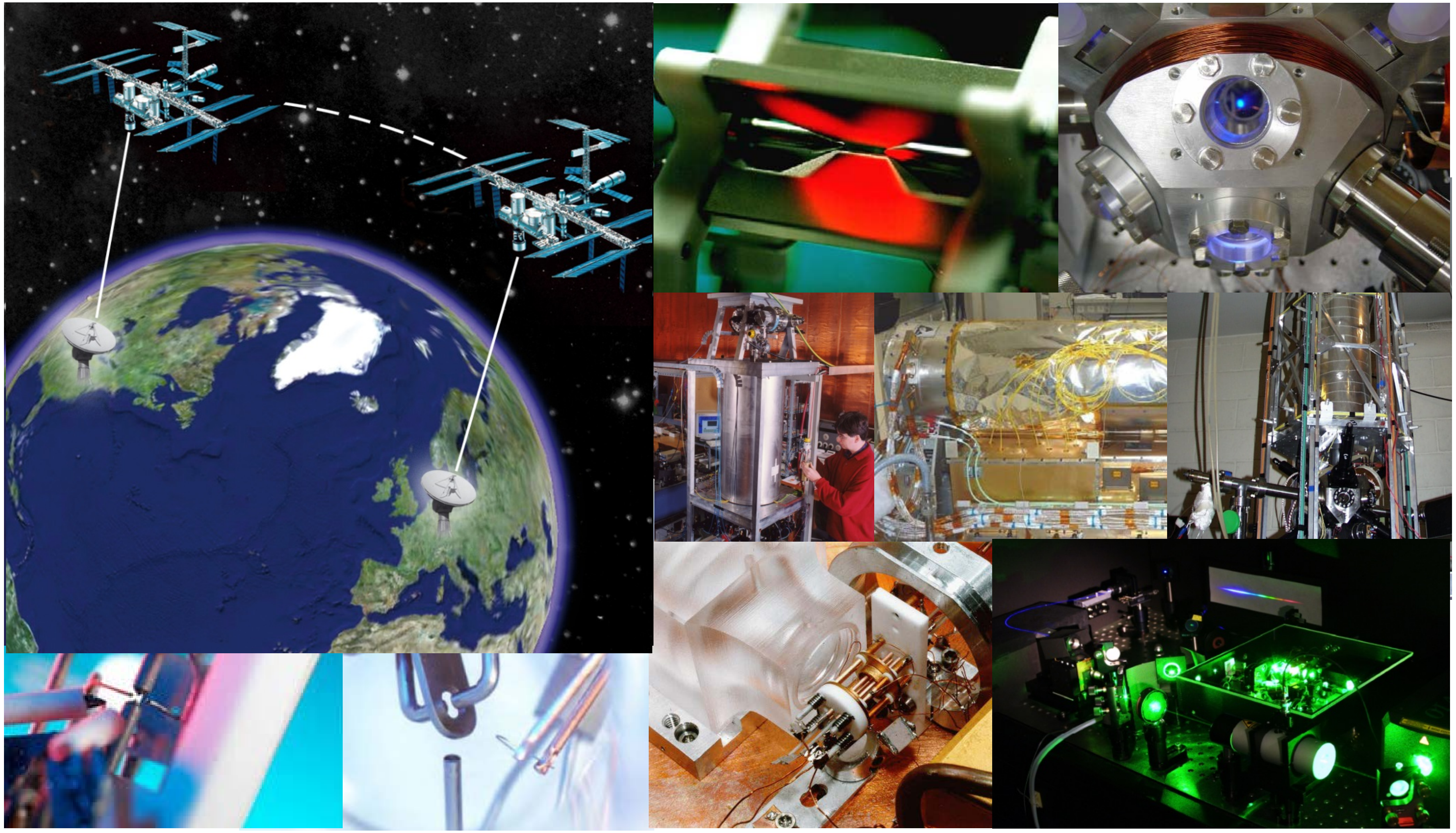
PRL 126, 011102 (2021)

Time variations of fundamental constants with ACES

- ACES will perform crossed comparisons of clocks based on different atomic transitions connecting the best clocks available worldwide.
- Frequency comparisons to $1 \cdot 10^{-17}$ will be possible, corresponding to $1 \cdot 10^{-17}$ yr $^{-1}$ after 1 yr of mission, $3 \cdot 10^{-18}$ yr $^{-1}$ after 3 yr.
- Such measurements will allow constraining the time drift of α, m_e/Λ_{QCD} and m_u/Λ_{QCD}. Depending on the sensitivity of the atomic transitions to the 3 fundamental constants, it will be possible to constrain them at the $1 \cdot 10^{-18}$ yr $^{-1}$ level.

ACES will complement the results from local comparisons of clocks in the lab or via a fiber link constraining the 3 fundamental constants.

Time variations of fundamental constants



Fundamental physics tests

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Fundamental physics tests

ACES Mission Objectives	ACES specified performances	Scientific background and recent results
Fundamental physics tests		
Dark matter search with atomic clocks	Establish bounds on topological dark matter models based on the comparisons of clocks in the ACES network.	The ACES network can ensure comparisons of atomic clocks based on different atomic transitions down to $1 \cdot 10^{-17}$. 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 Λ_α, Λ_e, and Λ_q. Clock comparisons can be performed continuously on 20 d intervals thanks to the ACES MWL thus extending the analysis on the interval T between encounters by one order of magnitude.

Note: Currently under investigation.

Dark matter search with the ACES network-Preliminary

- 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 (New J. Phys. 22, 093010 (2020), Nat. Comm. 8, 1195 (2017)).
- The ACES network can ensure comparisons of atomic clocks based on different atomic transitions down to $1 \cdot 10^{-17}$, 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 Λ_α, Λ_e, and Λ_q.
- 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. MWL operation is based on the time scale coherently generated with respect to the local clocks on the ground and in space thus ensuring phase continuity in the comparisons of clocks (both in common and non common view) across deadtimes.

The ACES clocks network will contribute to dark matter searches

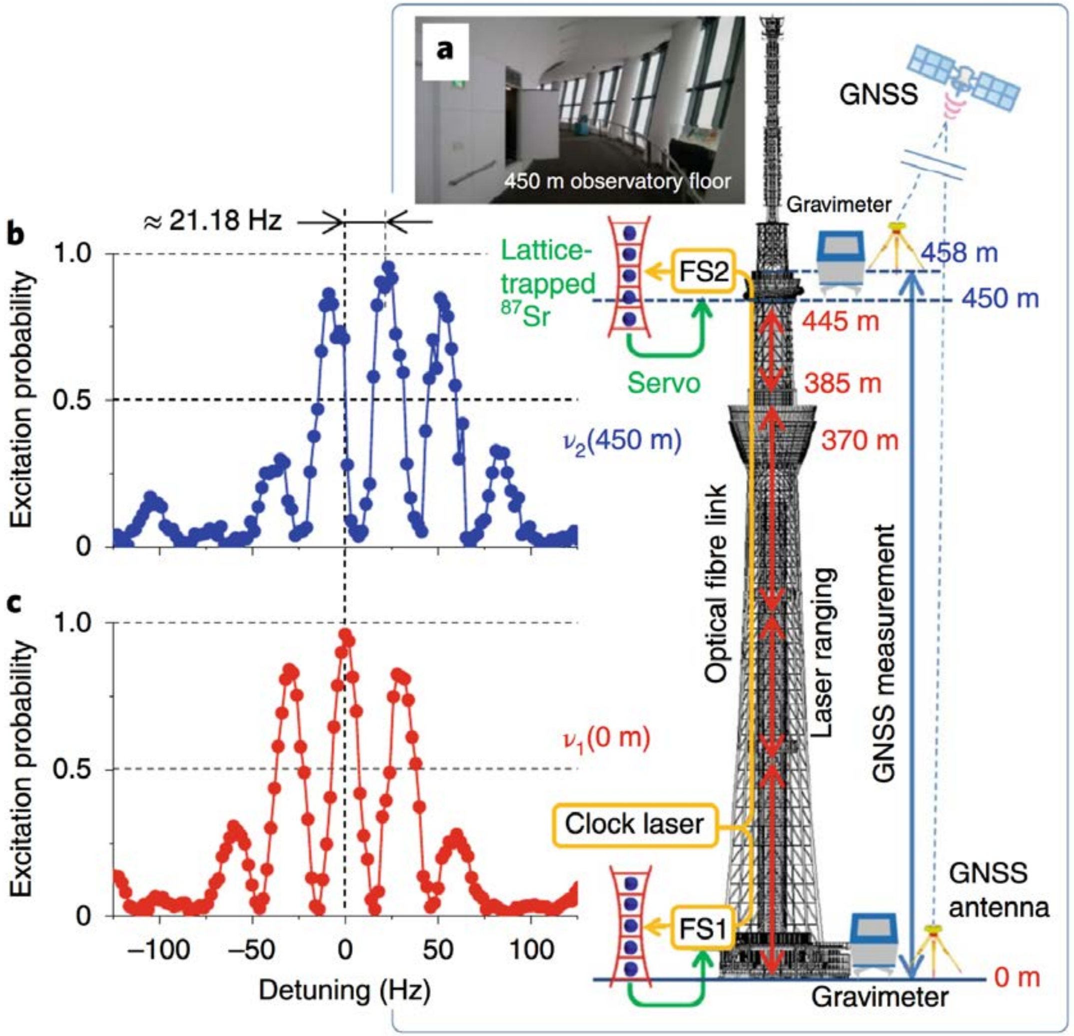
Applications

ACES Mission Objectives	ACES specified performances	Scientific background and recent results
Applications		
Relativistic geodesy	Differential geopotential measurements to a resolution of 1 m.	Geopotential differences have been measured with optical clocks to 4 cm. Based on the measured performance of MWL and ELT, ACES can reach 10 cm resolution on the geoid and it can offer a worldwide coverage over long baselines and between continents.

Relativistic geodesy

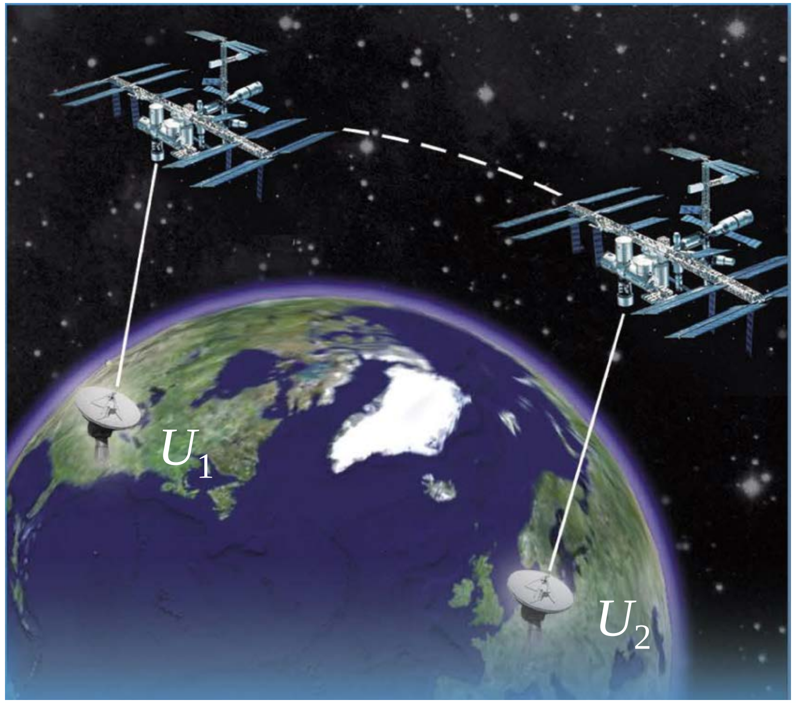
Tokyo skytree experiment:

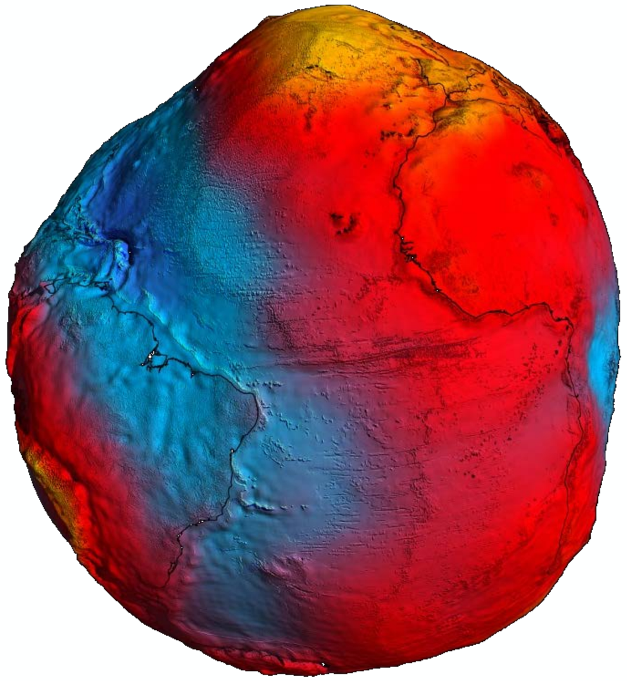
- Two Sr optical lattice clocks compared through a fiber link over a height difference of 458 m.
- Clock-to-clock comparison to a frequency uncertainty of $4{\cdot}10^{-18}$, corresponding to a 4 cm height resolution.
- Geopotential difference measured through gravimetric measurements at the location of the two clocks and a laser ranging measurement of the distance.
- The experiment also tests the gravitational redshift to $9{\cdot}10^{-5}$, a factor 50 above the ACES target accuracy.
- The next step might be a comparisons between a clock at sea level and a clock on top of mount Fuji. The redshift test could reach an accuracy at the ACES level, but estimating the gravitational potential difference at the level of a few cm is a major challenge.



Nat. Photonics 14, 411–415 (2020)

Relativistic geodesy





- Relativistic geodesy: mapping of the Earth gravitational potential based on the precision measurement of the red-shift experienced by two clocks at two different locations
- ACES will perform intercontinental comparisons of optical clocks at the 10^{-17} level after 4 days of integration time, measuring the local height of the geoid at the 10 cm level.

The global coverage offered by ACES will complement the results of the CHAMP, GRACE, and GOCE missions.

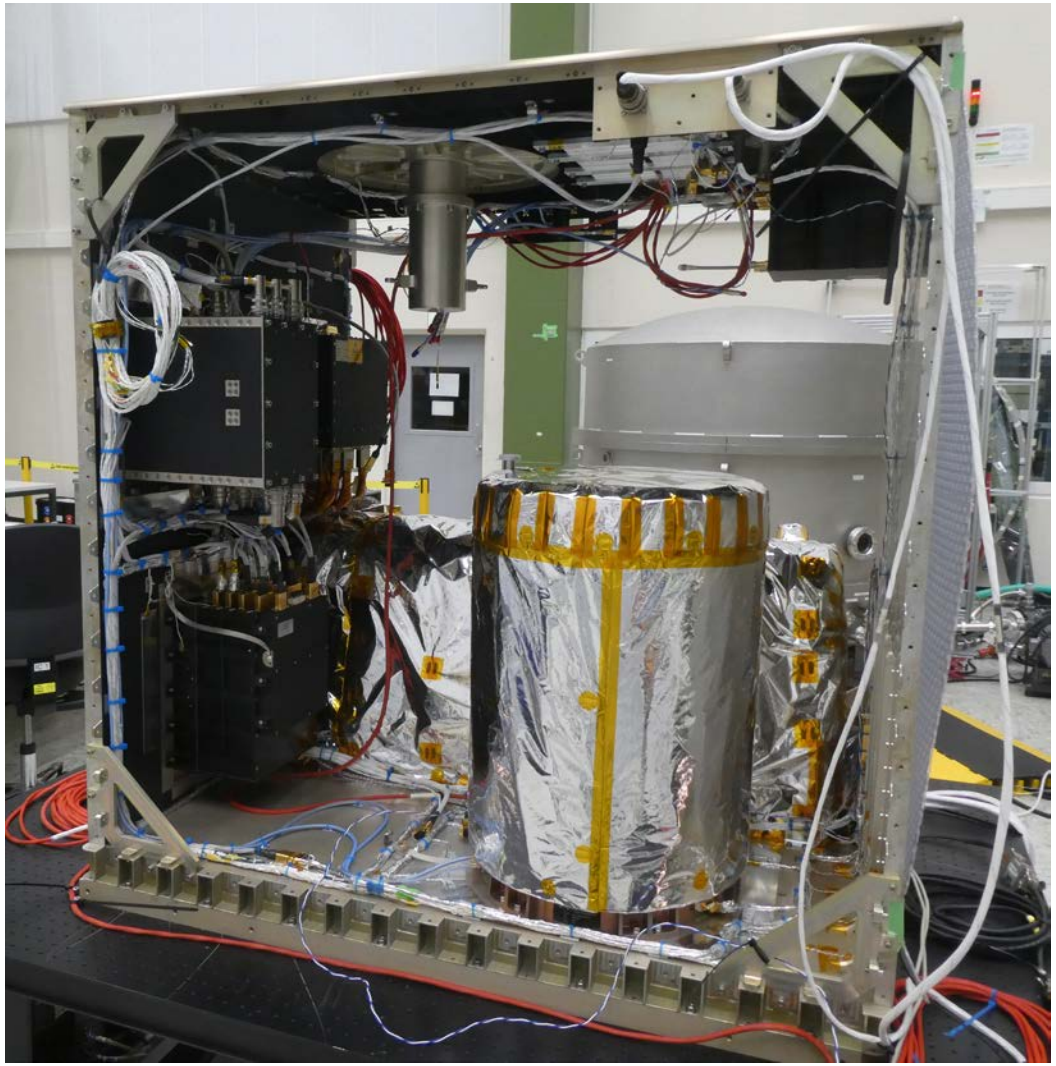
Applications

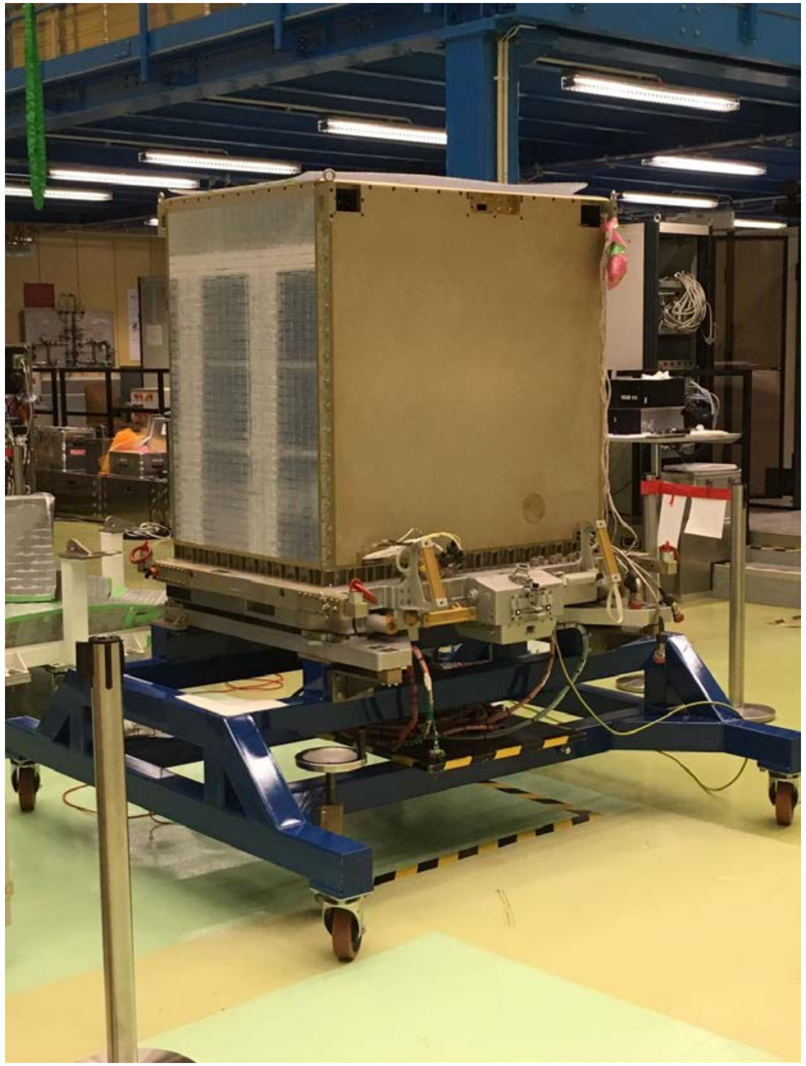
- Differential geopotential measurements to 10 cm resolution over the geoid.
- Clock comparisons over intercontinental distances: 10^{-17} in less than 1 week.
- Absolute time transfer and time synchronization of remote clocks: 100 ps via MWL and 50 ps via ELT .
- Universal time scales: UTC, TAI…
- Ranging: optical vs microwave and 1-way vs 2-way.
- Atmospheric propagation delays: optical and microwave.
- Monitoring of clocks in the GNSS network (GPS and Galileo) + test bed for technology towards future GNSS systems.

Atomic Clock Ensemble in Space

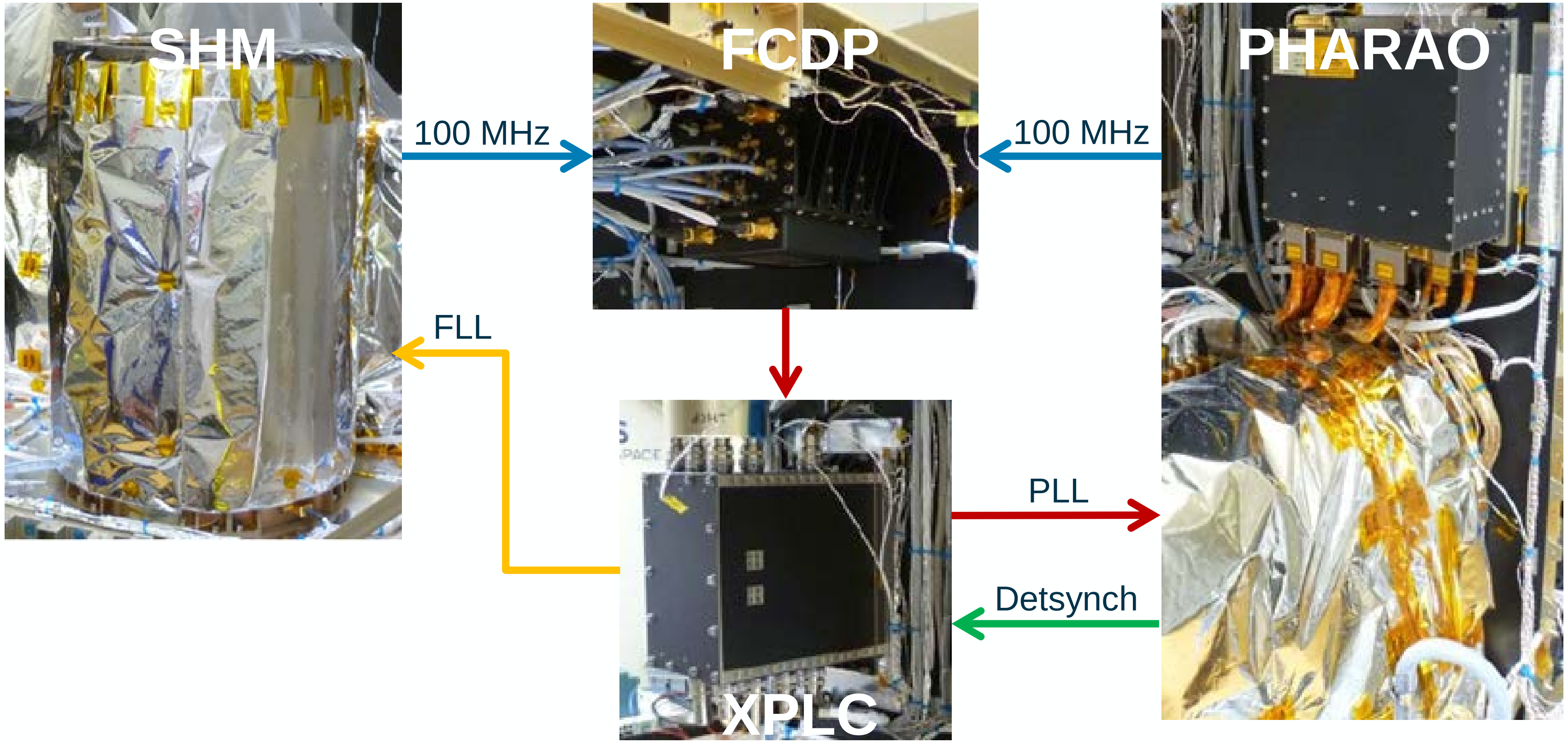
Status

ACES Integrated System Tests (IST)

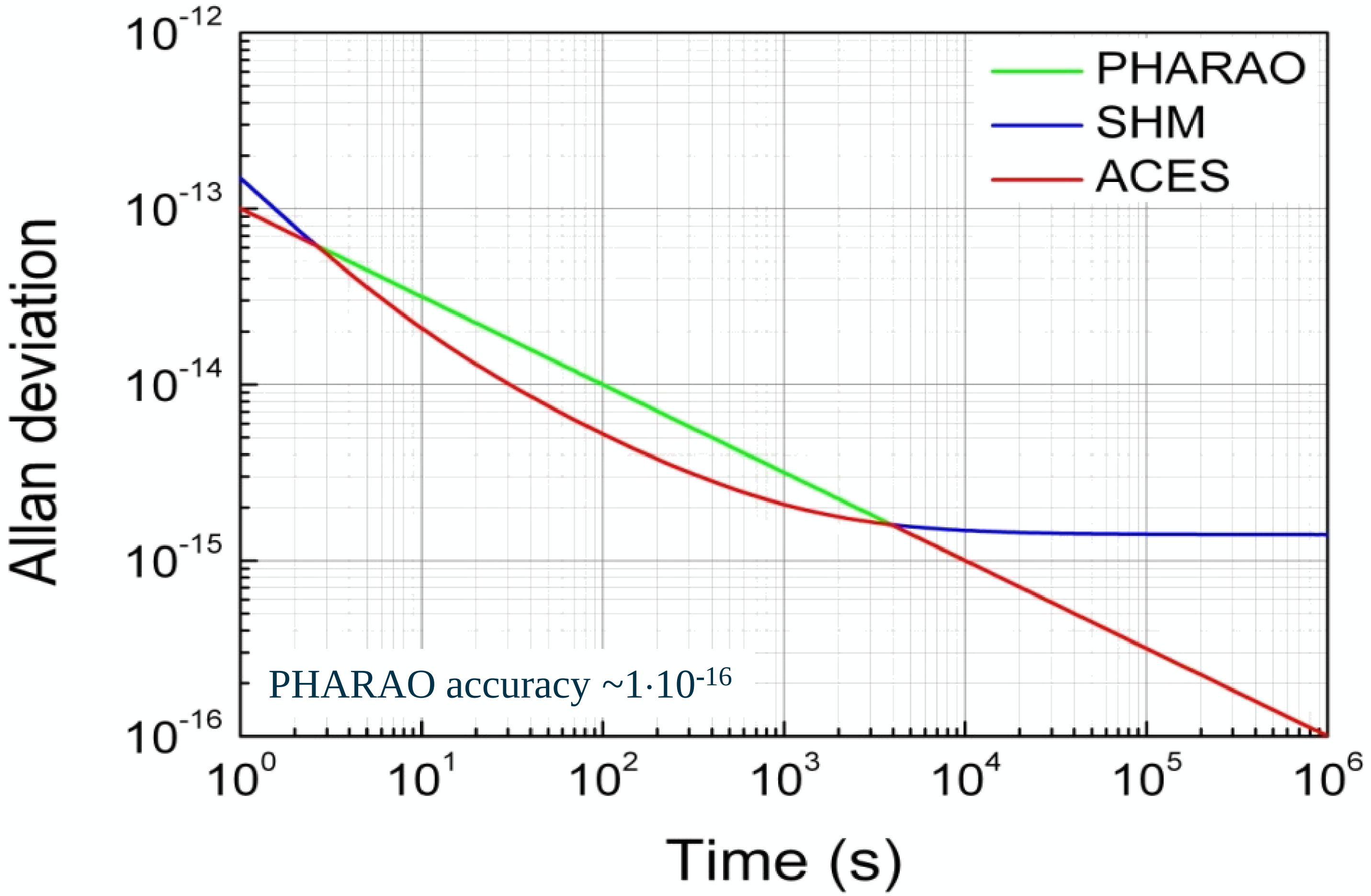




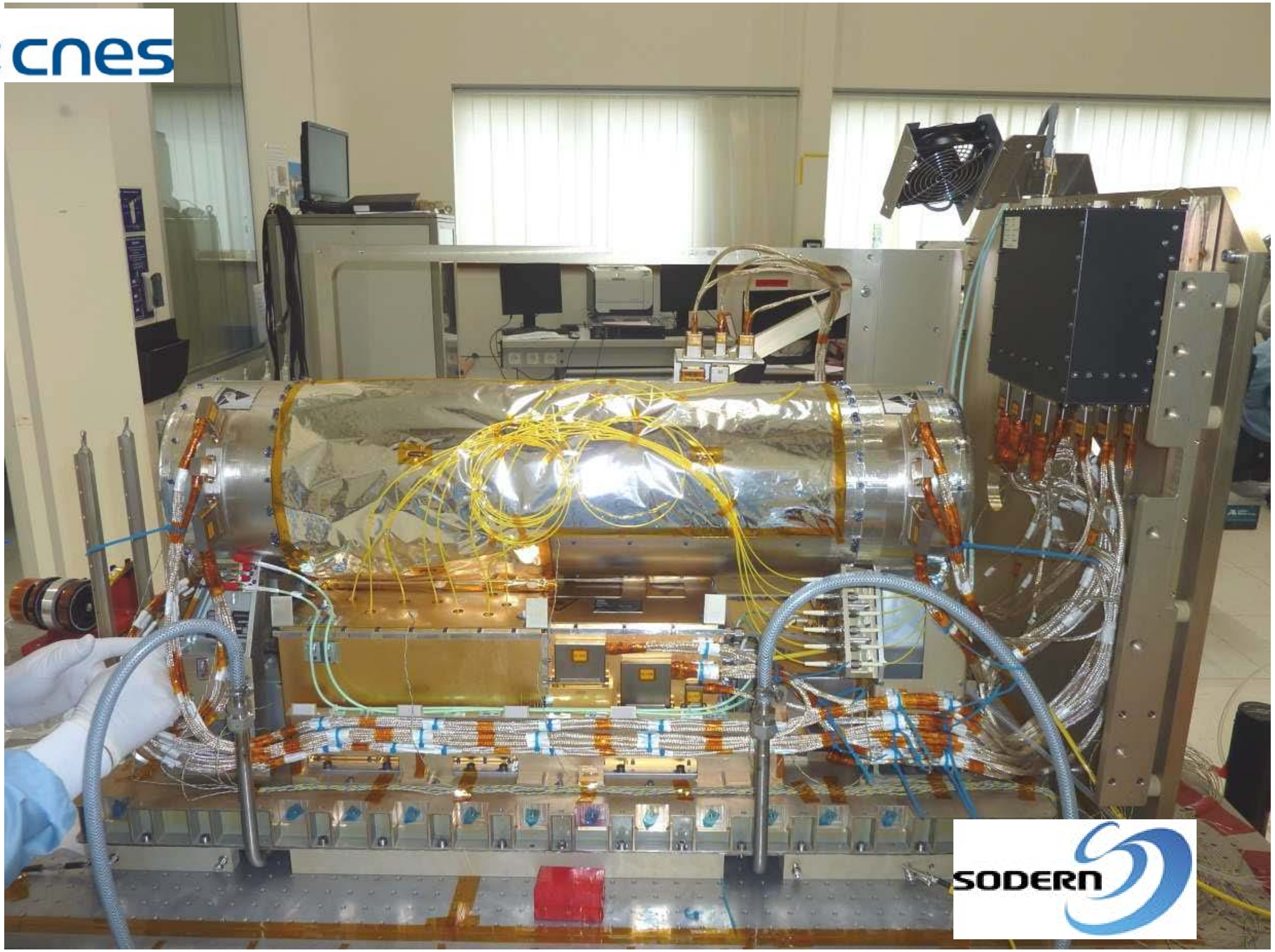
ACES servo loops



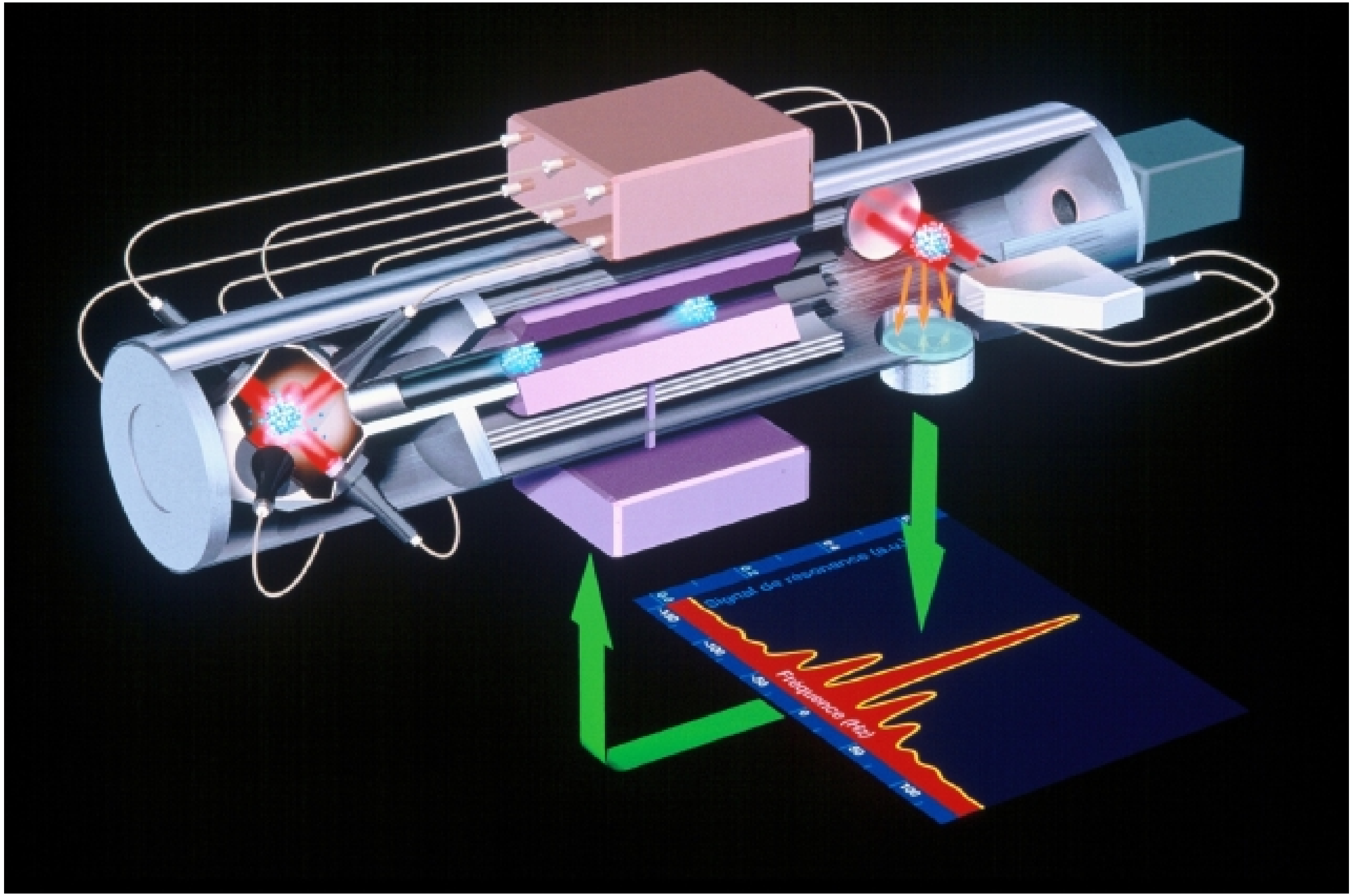
ACES servo loops



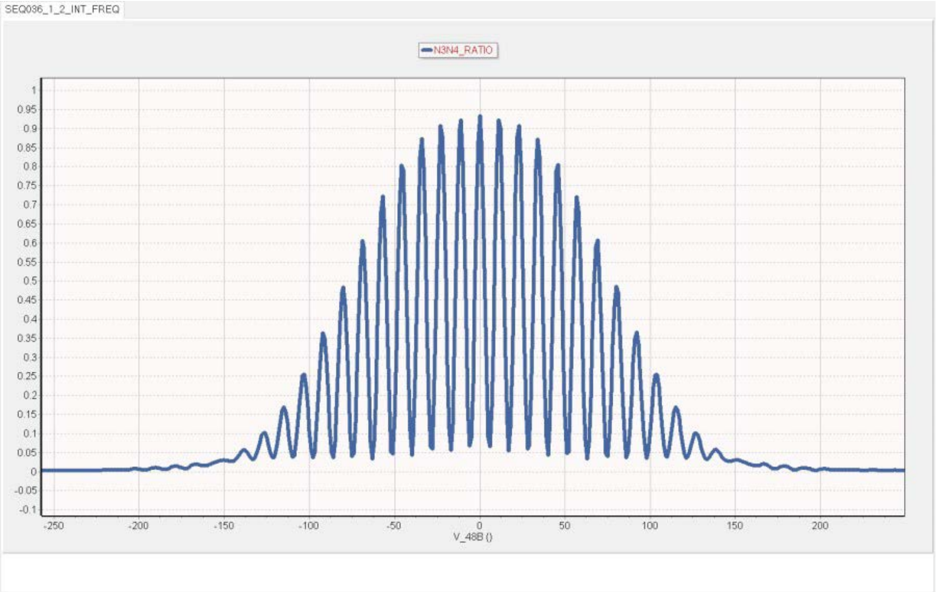
PHARAO FM

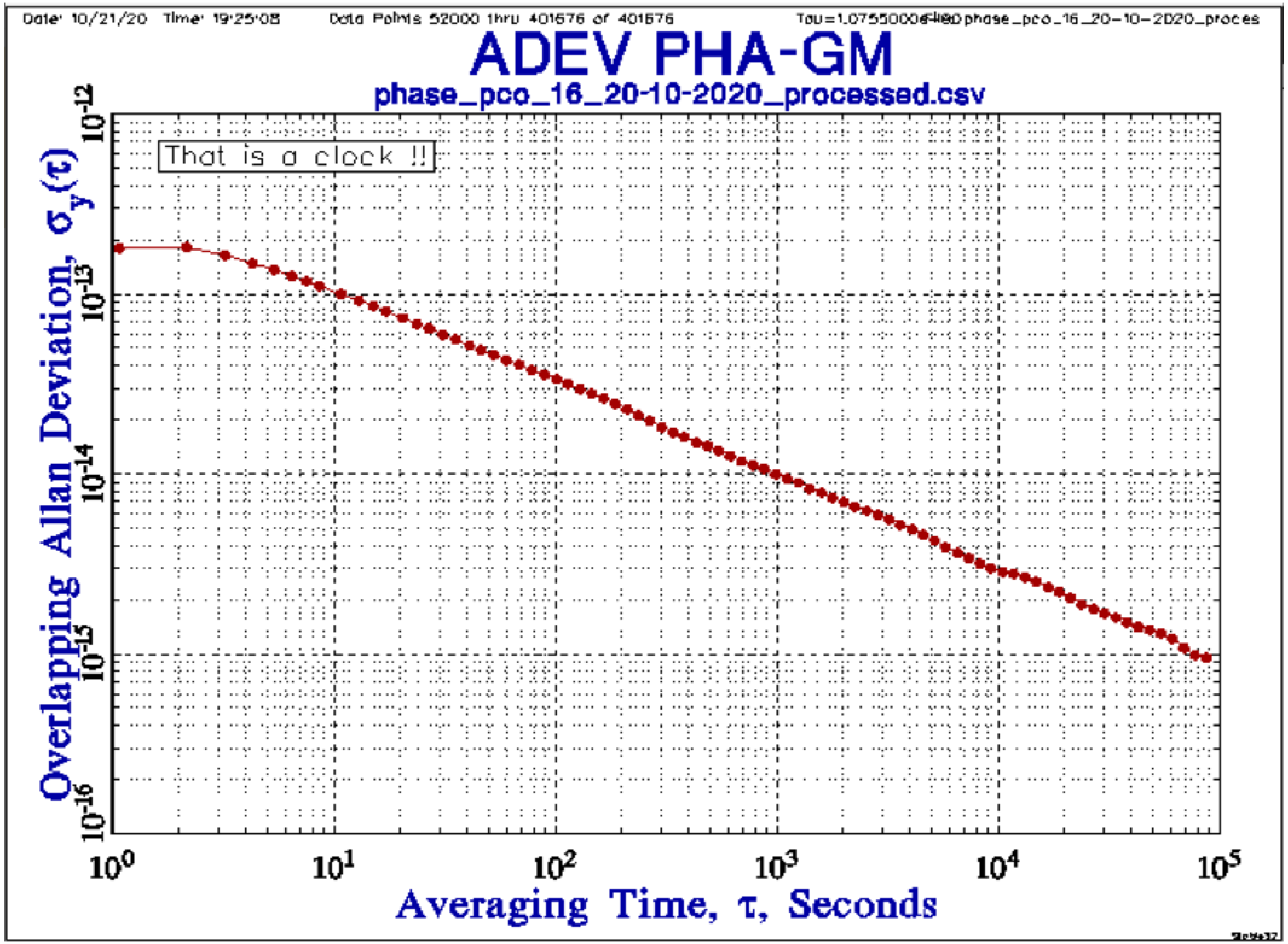


PHARAO clock cycle



PHARAO stability





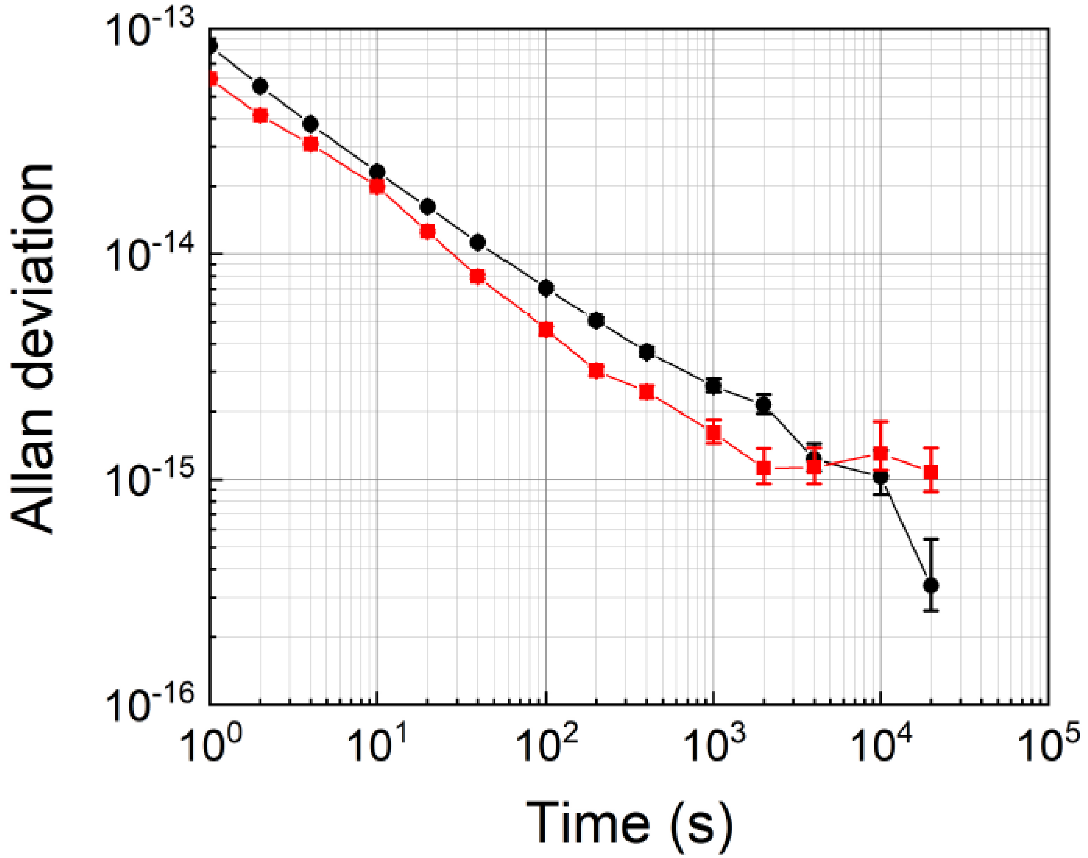
SHM: An active H-maser for space

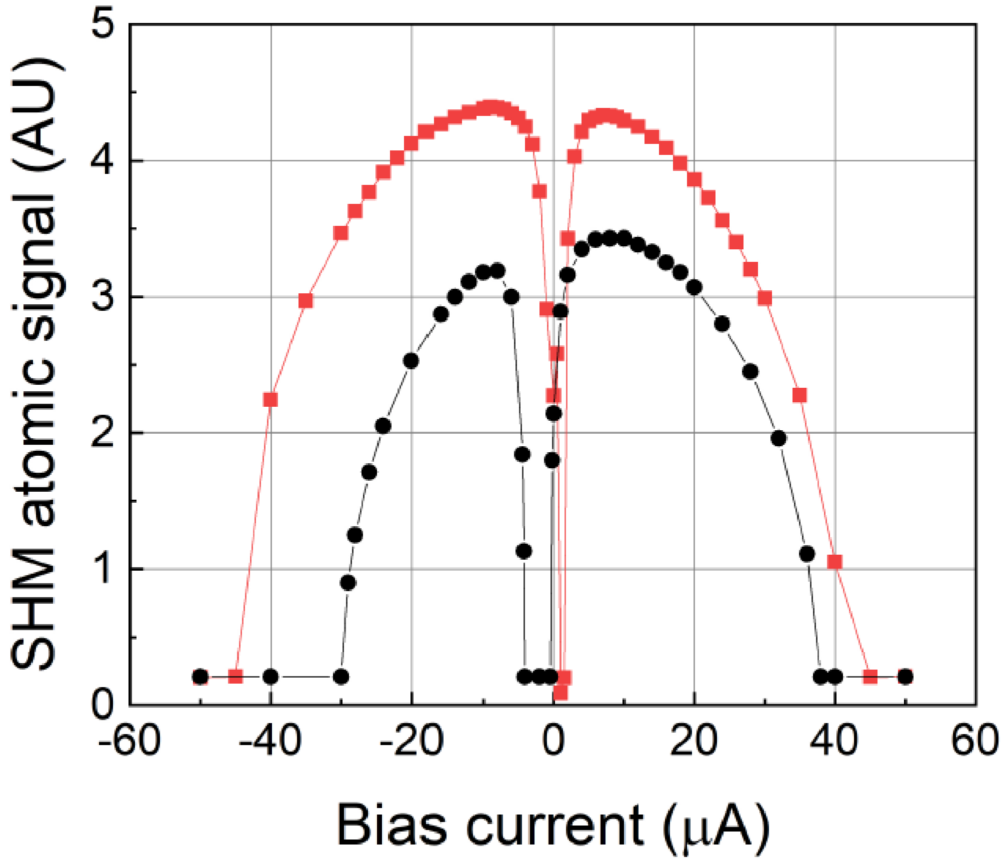
Volume: 390x390x590 mm^3
Mass: 42 kg

- SHM role in ACES
  - ACES flywheel oscillator
  - PHARAO characterization
- Technical challenges
  - Low mass, volume, and power consumption
  - Full performances:
    - $1.5 \cdot 10^{-13}$ @ 1 s
    - $1.5 \cdot 10^{-15}$ @ 10^4 s
  - Design solution: Full size Al cavity and Automatic Cavity Tuning System (ACT)

SpectraTime
iPrecision Timing Solutions™

SHM stability

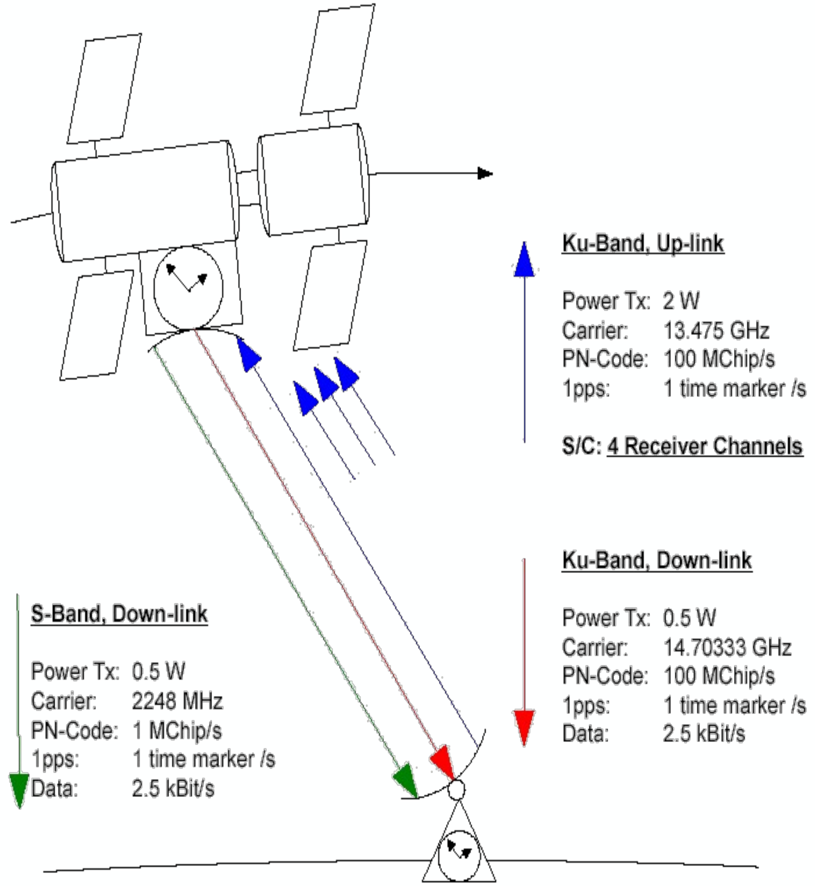




SHM frequency stability **before** and **after** degaussing.

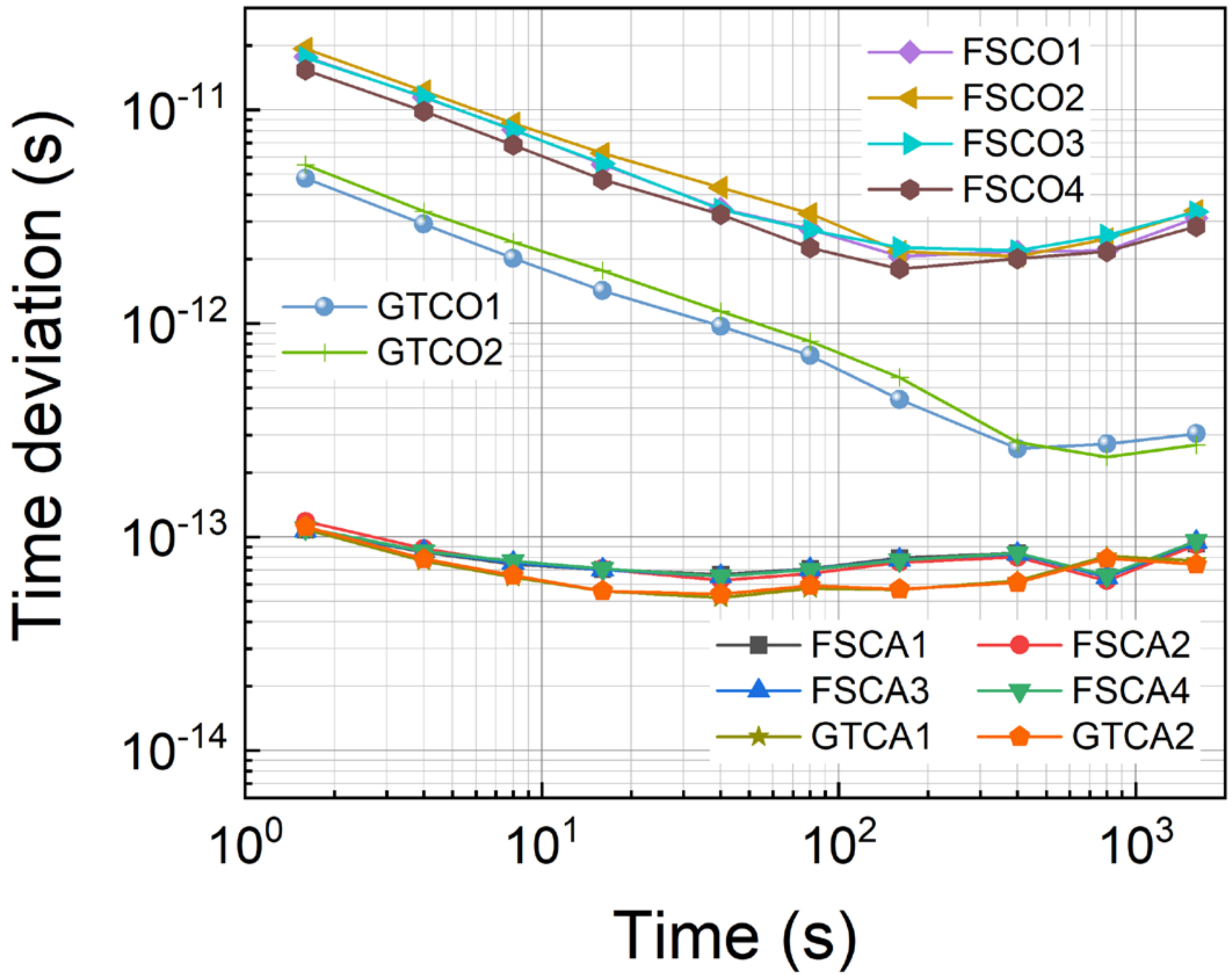
SHM degaussing works correctly, improving the atomic signal and the magnetic field homogeneity.

MWL



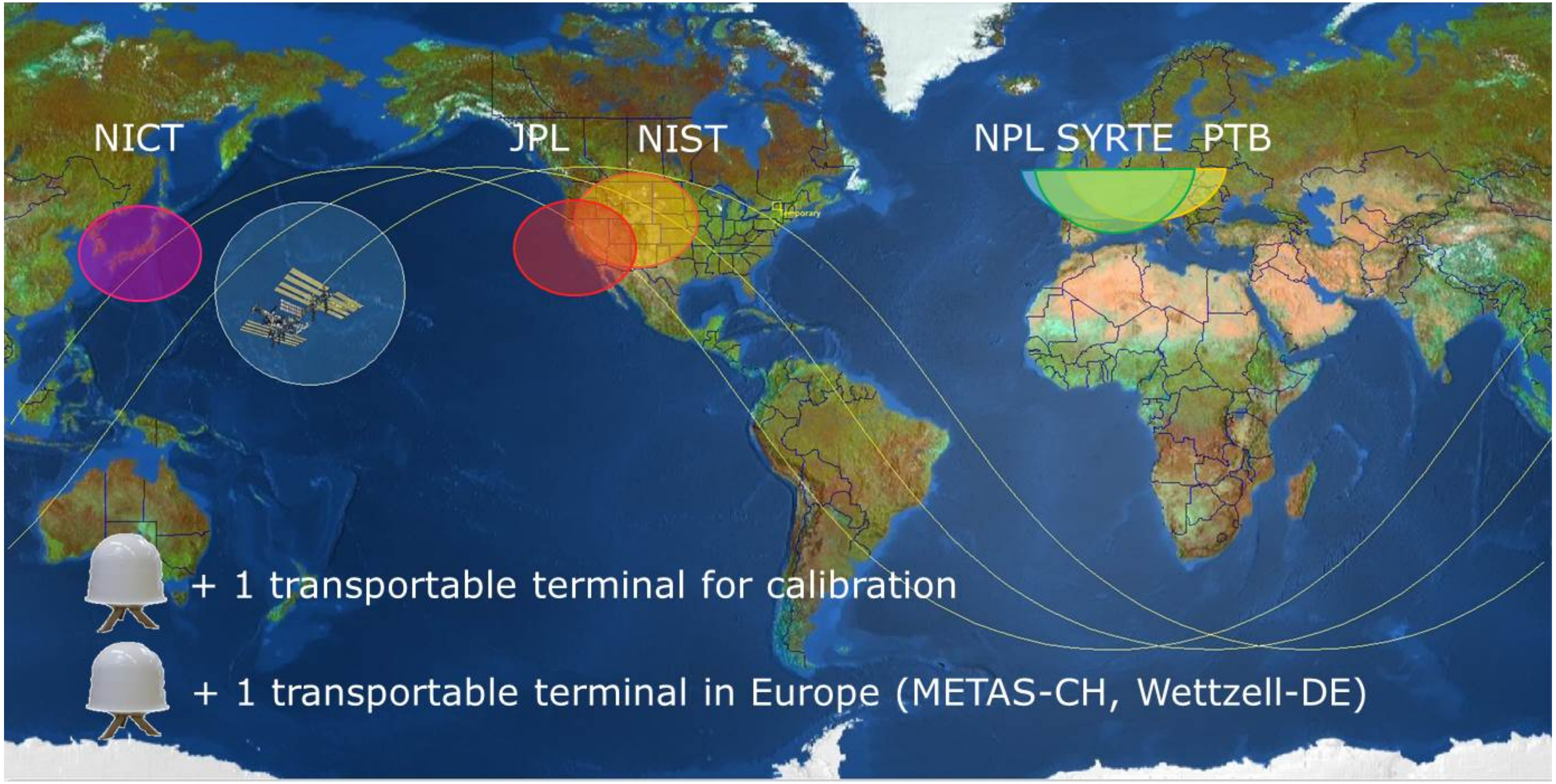
- Two-way link:
  - Removal of the troposphere time delay (8.3-103 ns)
  - Removal of 1st order Doppler effect
  - Removal of instrumental delays and common mode effects
- Additional down-link in the S-band:
  - Determination of the ionosphere TEC
  - Correction of the ionosphere time delay (0.3-40 ns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



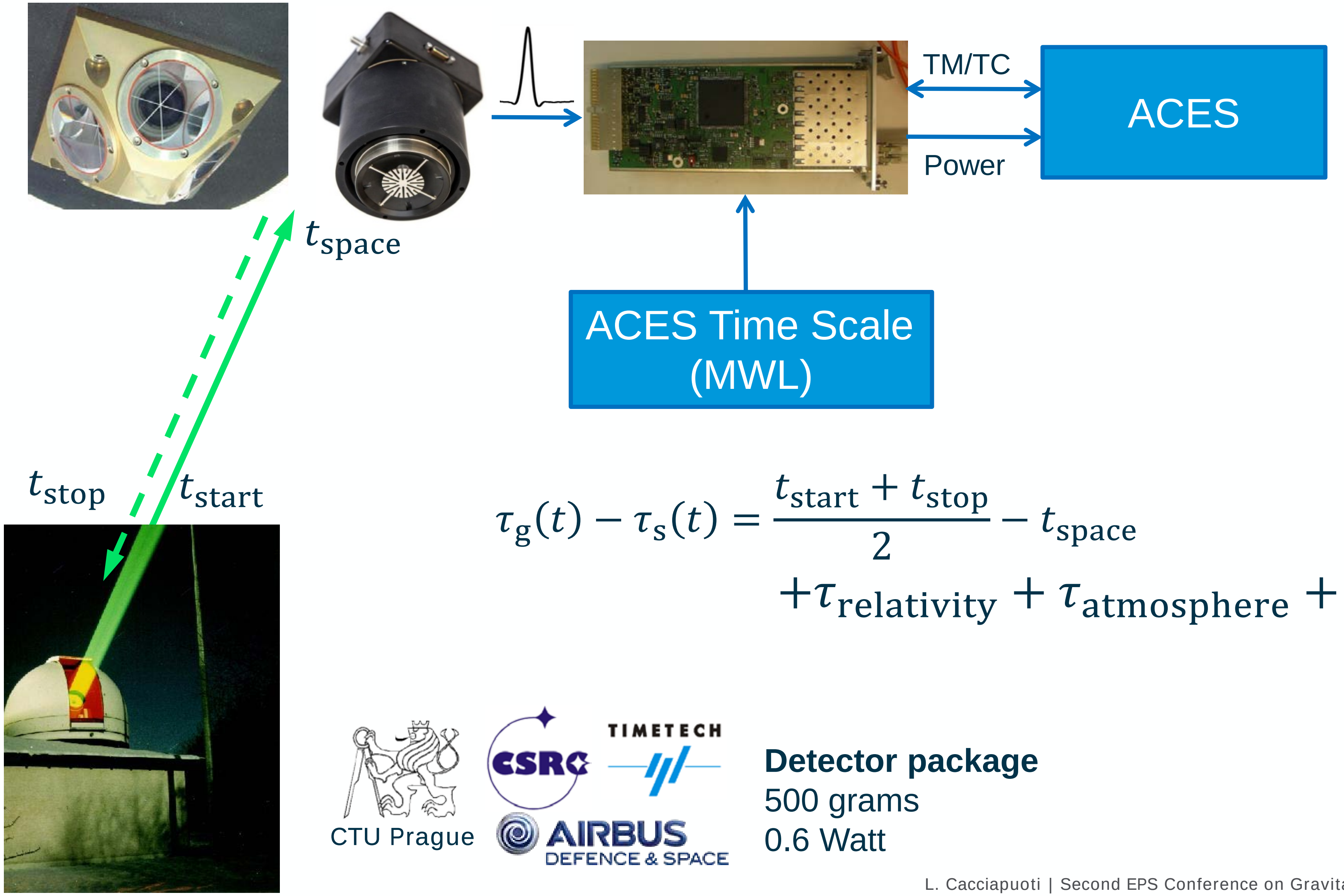
- Time deviation of code (CO) and carrier (CA) phase measurements at the MLW flight segment (FS) and ground terminal (GT) electronics.
- The test is performed in end-to-end configuration under static conditions (no signal dynamics).

ACES MWL network



First MWL GT deployed @ PTB

European Laser Timing (ELT)

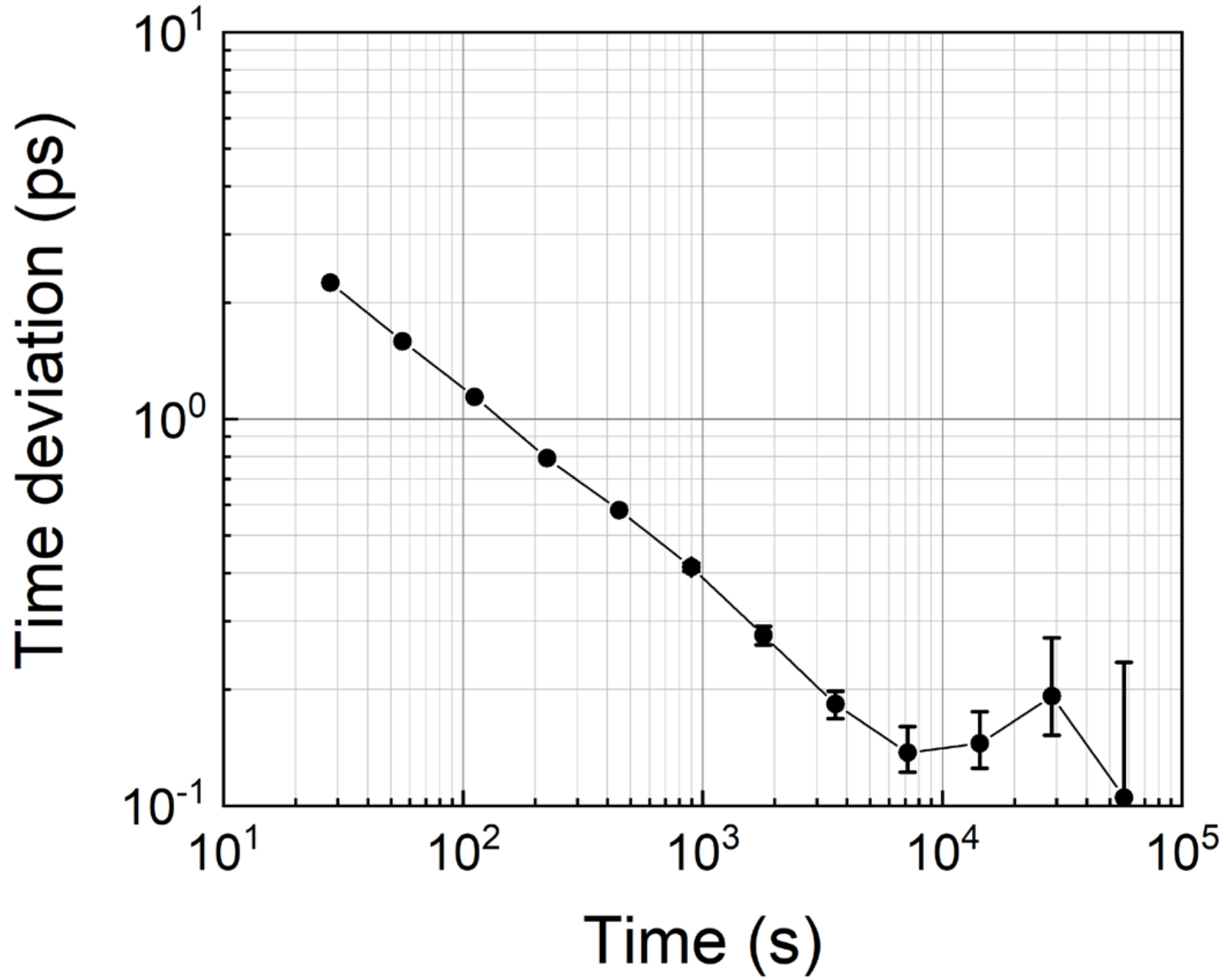


$$\tau_g(t) - \tau_s(t) = \frac{t_{\text{start}} + t_{\text{stop}}}{2} - t_{\text{space}}$$
$$+\tau_{\text{relativity}} + \tau_{\text{atmosphere}} + \tau_{\text{geometry}}$$

CTU Prague

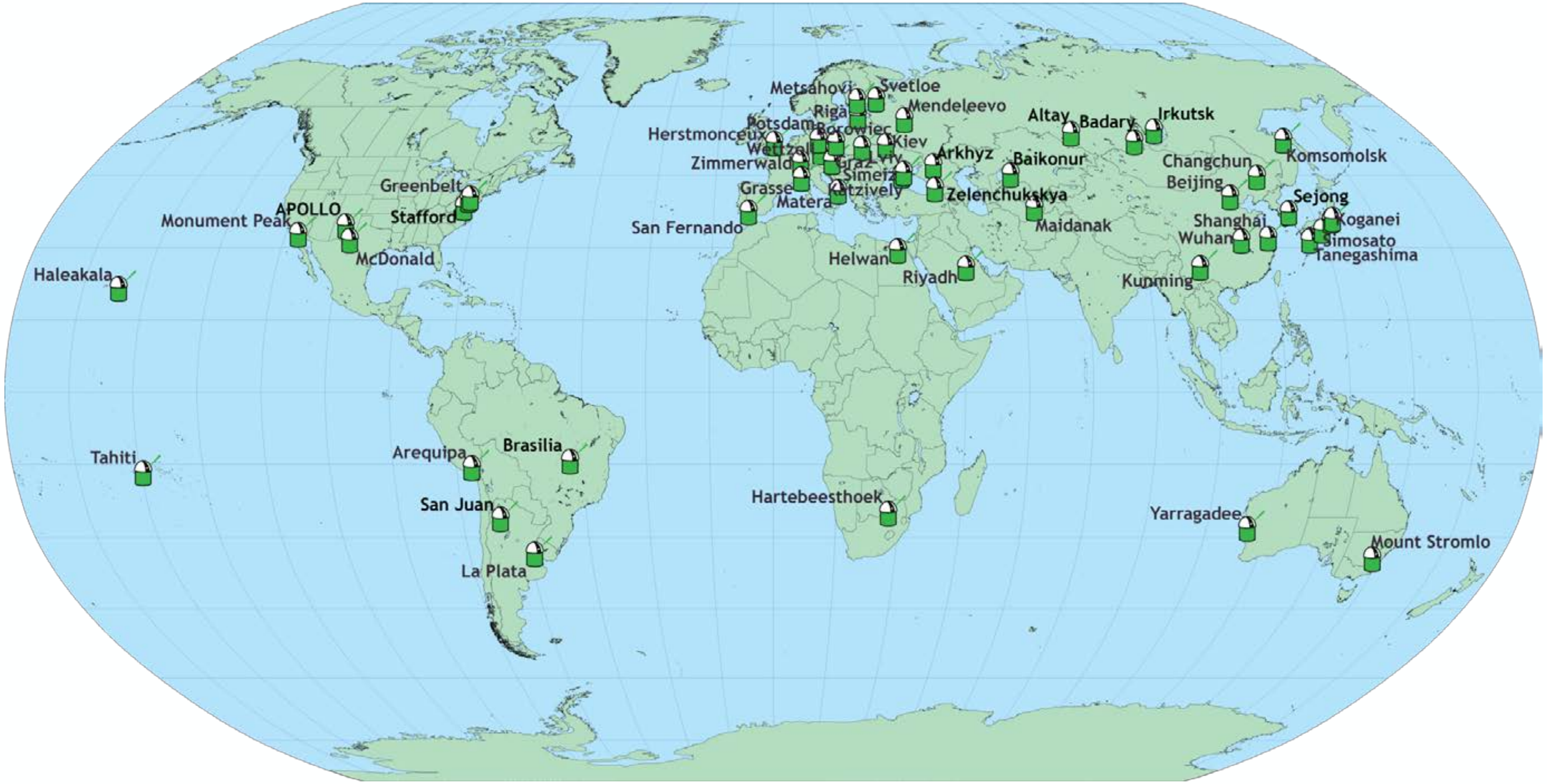
Detector package
500 grams
0.6 Watt

ELT FM performance



- TDEV of the entire optical chain consisting of the picosecond laser source, the start detector package, the timing system and the ELT detector package.
- 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.

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Conclusions

Way-forward to the ACES launch

- ACES is the pathfinder of a new class of missions using atomic sensors to perform precision measurements of the space-time metric to test general relativity and alternative theories of gravitation.
- The last Integrated System Tests (IST) confirmed the clocks and servo-loops performance, but they unfortunately revealed 3 major anomalies that will require resolution:
  - Temperature dependence of the PHARAO pump power at detection.
    Solution: ACES and PHARAO temperature control to be optimized.
  - Degradation of the SHM inner vacuum.
    Solution: SHM getters will have to be replaced and activated; SHM storage time under air to be reduced.
  - On-board phase comparator FCDP sensitive to AM/PM conversion effects.
  - **Solution:** Tuning of the FCDP hardware or calibration and correction of the effect.
- The anomalies will require further investigations. Their resolution will introduce major delays that at the moment are difficult to evaluate.
- MWL calibration and performance tests to be completed.
- The ACES schedule and launch date are currently being consolidated.

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Thanks for your attention