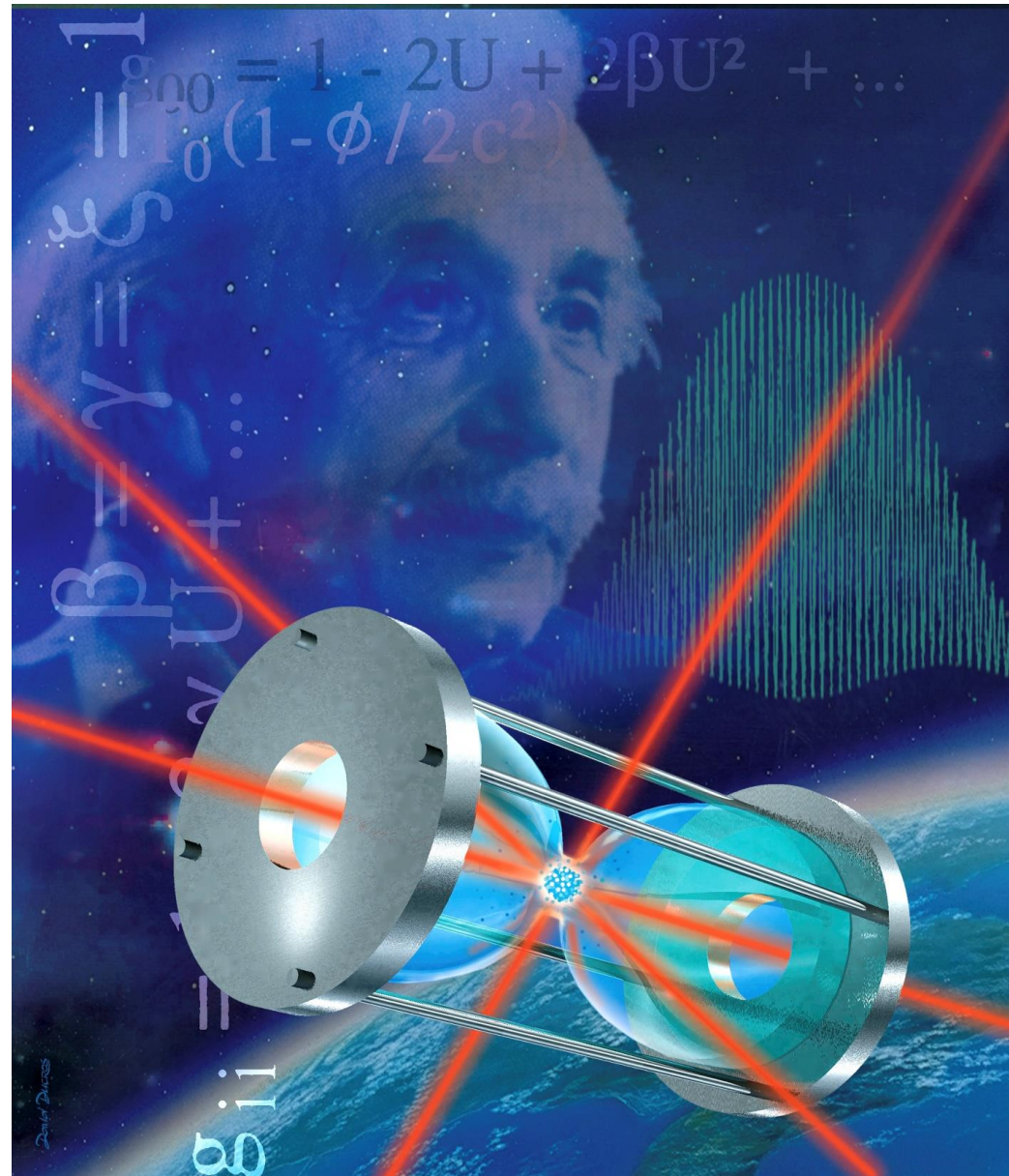




Atomic Clock Ensemble in Space: 14 months after launch

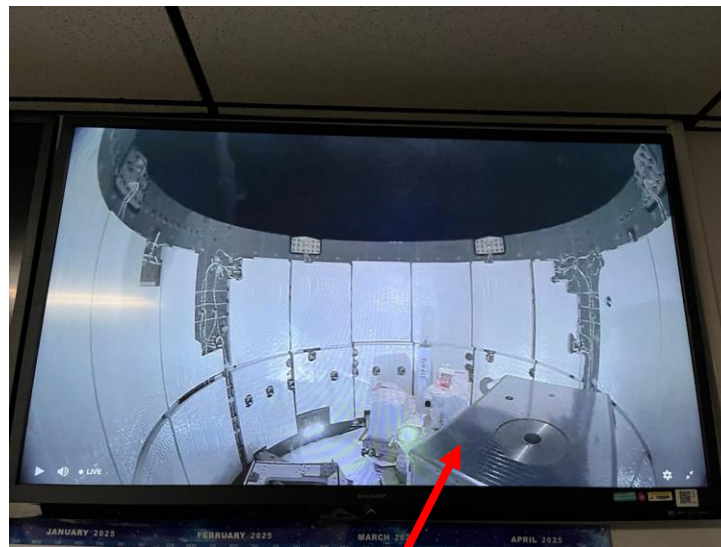
*Peter Wolf
on behalf of the ACES collaboration*

Journées SF2A
Grenoble
Juin 22-2, 2026

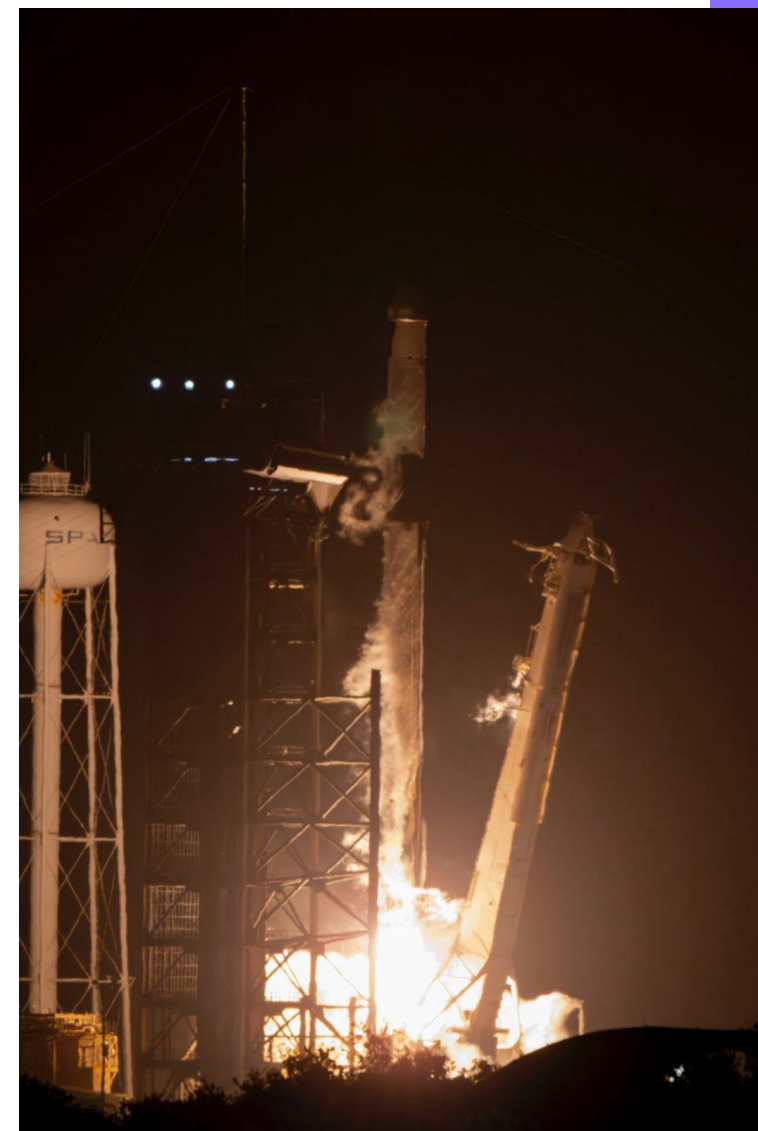
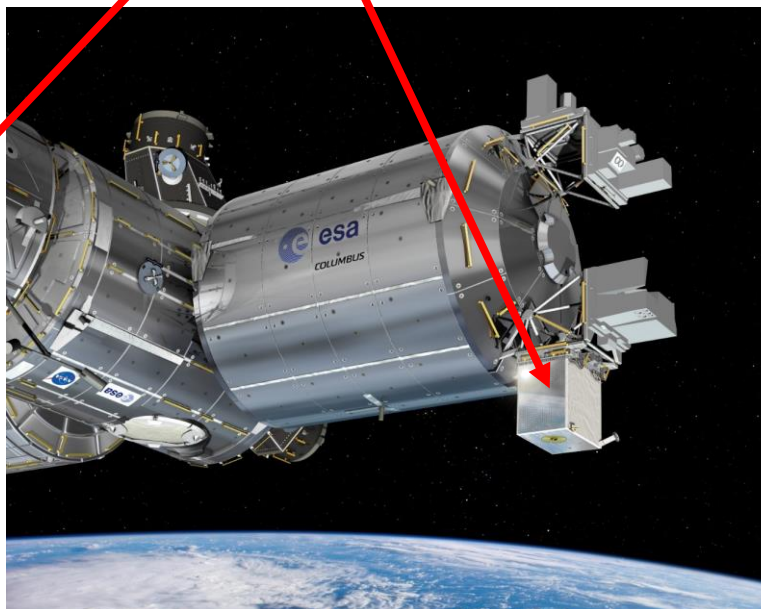




Arrival at Kennedy space center,
March 10, 2025



ACES



Launch on April 21, 2025
on Space-X Dragon capsule

ACES collaboration

Wolf P², Abgrall M², Allart E³, Bauch A⁴, Bize S², Cacciapuoti L¹, Clairon A², Crescence P³, Delva P², Diener WA⁵, Eckl J⁶, Enzer DG⁵, Esnault FX⁷, Fuijeda M⁸, Gibble K⁹, Goujon D¹⁰, Guerlin C¹¹, Heimbach F⁴, Helm A³, Ichikawa R.⁸, Kannanthara J¹², Kehrer J³, Kodet J¹³, Lachaud R³, Laurent P², Léger B⁷, Le Poncin-Lafitte C², Lilley M², Liu S¹⁴, Lorini L², Mamoru S⁸, Marz S¹³, Massonnet D⁷, McKelvy J⁵, Montenbruck O¹⁵, Niedermaier T³, Pataria S¹, Patla B¹⁶, Peignier T¹, Peik E⁴, Perri A¹⁰, Piester D⁴, Pittet J¹⁰, Plumaris M¹, Prochazka I¹⁷, Rahm J⁴, Roze J², Salomon C¹¹, Savalle E¹⁸, Schaefer W¹⁴, Schlicht A¹³, Schreiber U¹³, Schwall T¹⁴, Schwatke C¹³, Shemar S¹², Thulliez E⁷, Tjoelker R⁵, Tunesi J¹², Vollmair P¹³, Wang Q¹⁰, Weinberg S¹, Wermuth M¹⁵, Weyers S⁴, Yu N⁵

¹European Space Agency, ESTEC, Noordwijk, The Netherlands,

²LTE, Observatoire de Paris-PSL, CNRS, LNE, Sorbonne Université, Université de Lille, Paris, France

³Airbus Defence and Space, Friedrichshafen, Germany, ⁴Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

⁵Jet Propulsion Laboratory, California Institute of Technology, USA,

⁶Bundesamt für Kartographie und Geodäsie, Geodetic Observatory Wettzell, Bad Kötzing, Germany

⁷CNES, Toulouse, France, ⁸National Institute of Information and Communications Technology, Koganei, Tokyo, Japan

⁹The Pennsylvania State University, University Park, USA, ¹⁰Safran Timing Technologies SA, Neuchâtel, Switzerland

¹¹Laboratoire Kastler Brossel, ENS-PSL, Paris, France, ¹²National Physical Laboratory, Teddington, United Kingdom

¹³Technical University of Munich, Munich, Germany, ¹⁴Timetech, Stuttgart, Germany

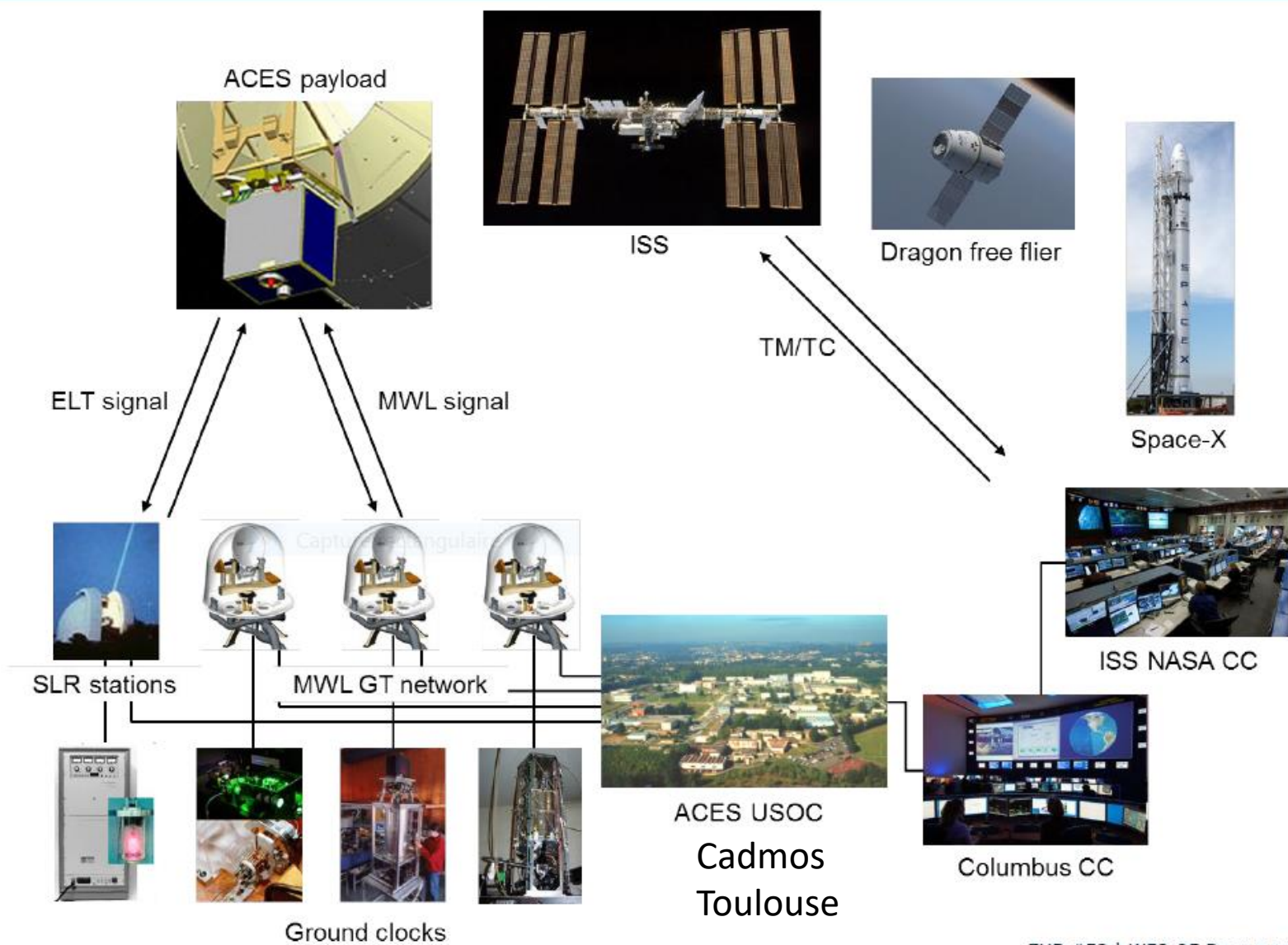
¹⁵German Space Operations Center, DLR, Weßling, Germany, ¹⁶National Institute of Standards and Technology, Boulder, USA

¹⁷Czech Technical University in Prague, Prague, Czech Republic, ¹⁸IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

Contents

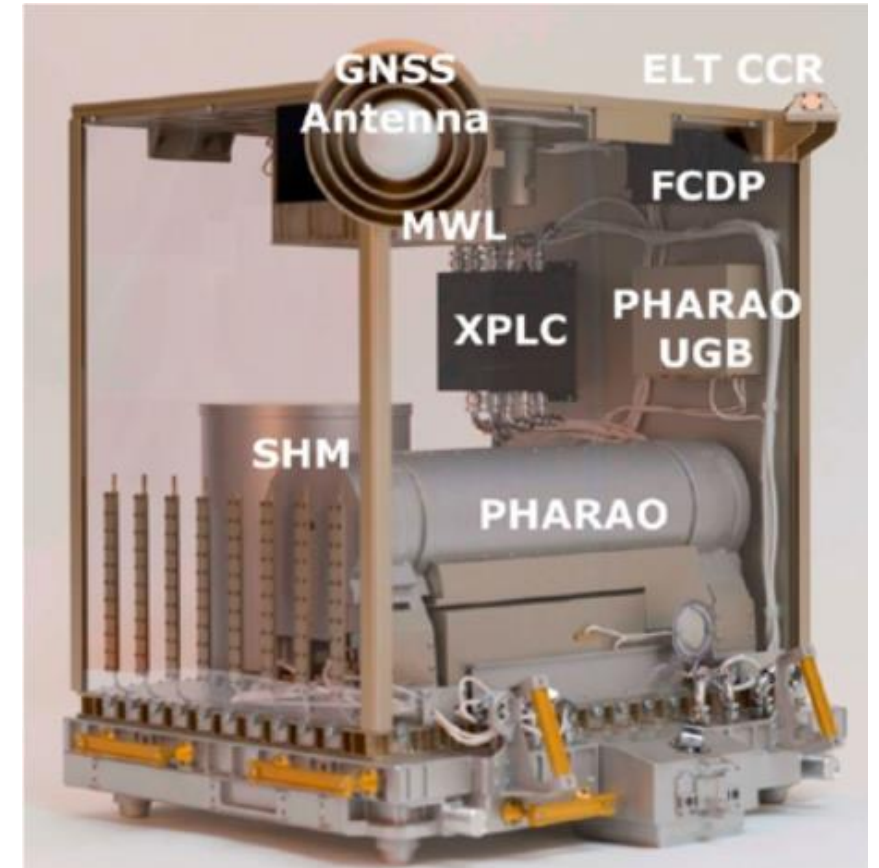
- Mission Concept
- ACES Payload (good/bad news)
- Science Objectives
- First in-orbit results
- The reality of space (on the ISS)
- Conclusion

ACES Mission Concept



ACES Payload (good/bad news)

- PHARAO (LTE/CNES): Laser cooled Cs atomic clock
- SHM: Active Space Hydrogen Maser
- FCDP: Clock comparison and distribution
- MWL: MicroWave Link for T/F transfer
- GNSS: geodetic grade GNSS receiver
- ELT: Optical link for T/F comparison



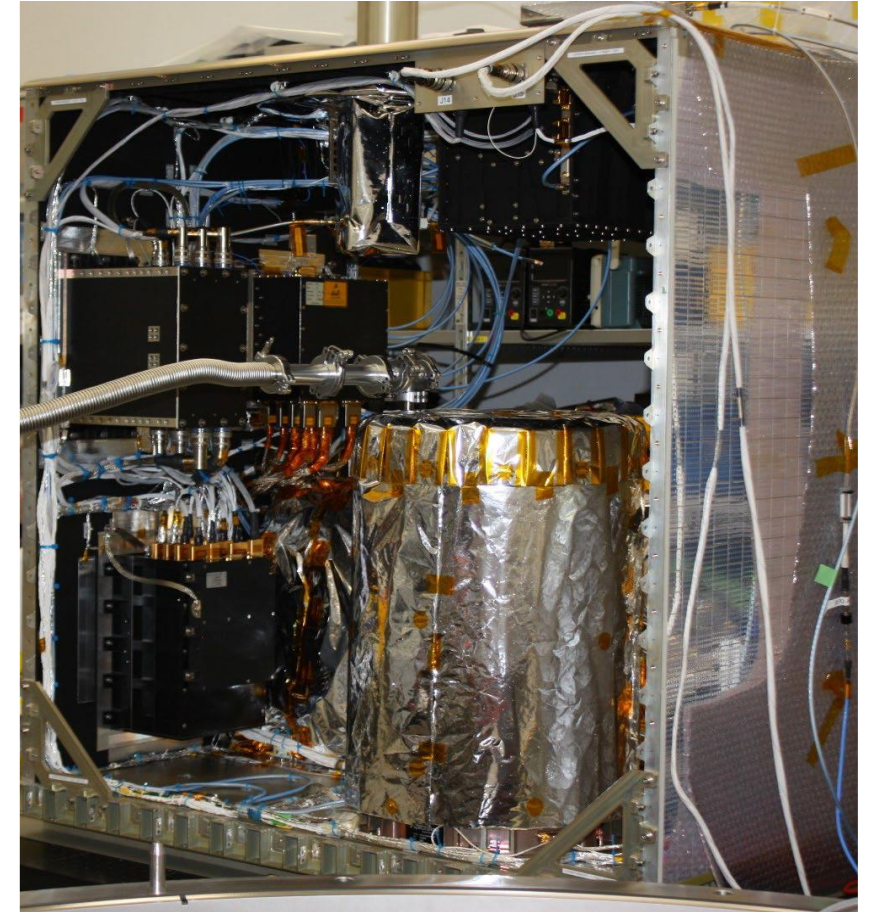
Volume: 1172x867x1246 mm

Mass: 240 kg

Power: 600 W

ACES Payload (good/bad news)

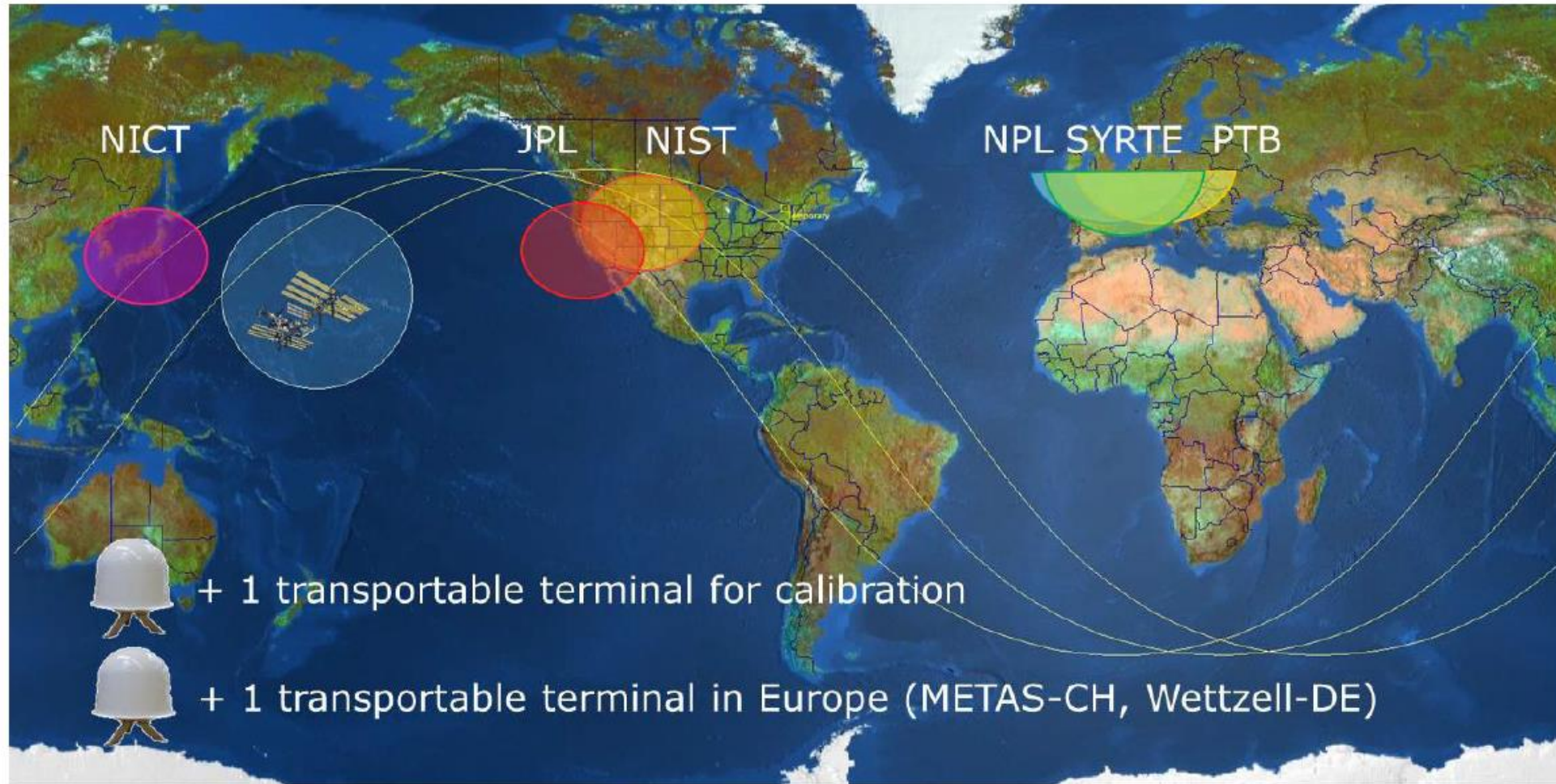
- PHARAO (LTE/CNES): Laser cooled Cs atomic clock
- SHM: Active Space Hydrogen Maser
- FCDP: Clock comparison and distribution
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- ELT: Optical link for T/F comparison



Volume: 1172x867x1246 mm

Mass: 240 kg

Power: 600 W



ACES GT Network



Observatoire de Paris

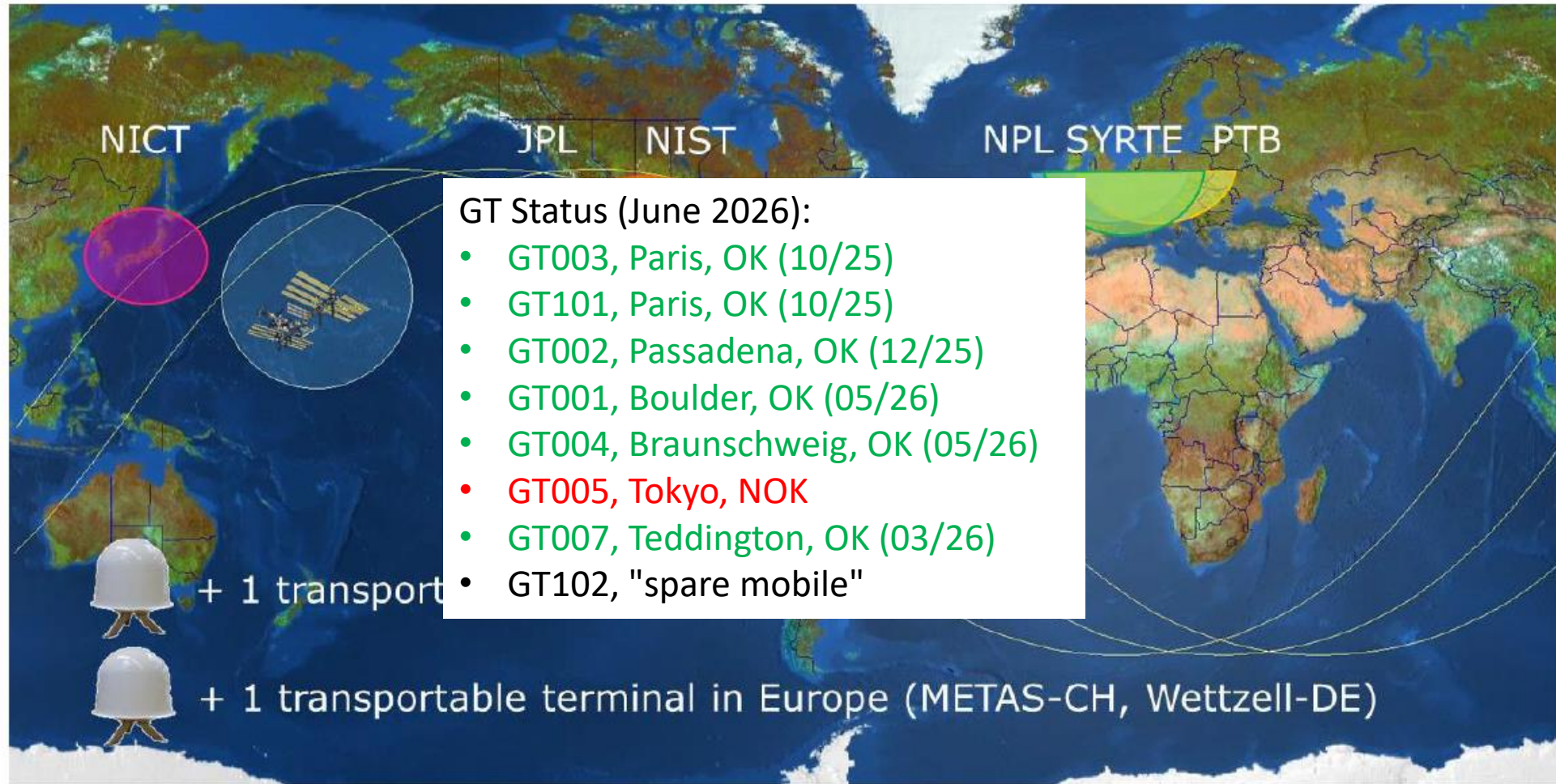
ACES GT Network



NPL, Teddington, UK



JPL, Pasadena, USA

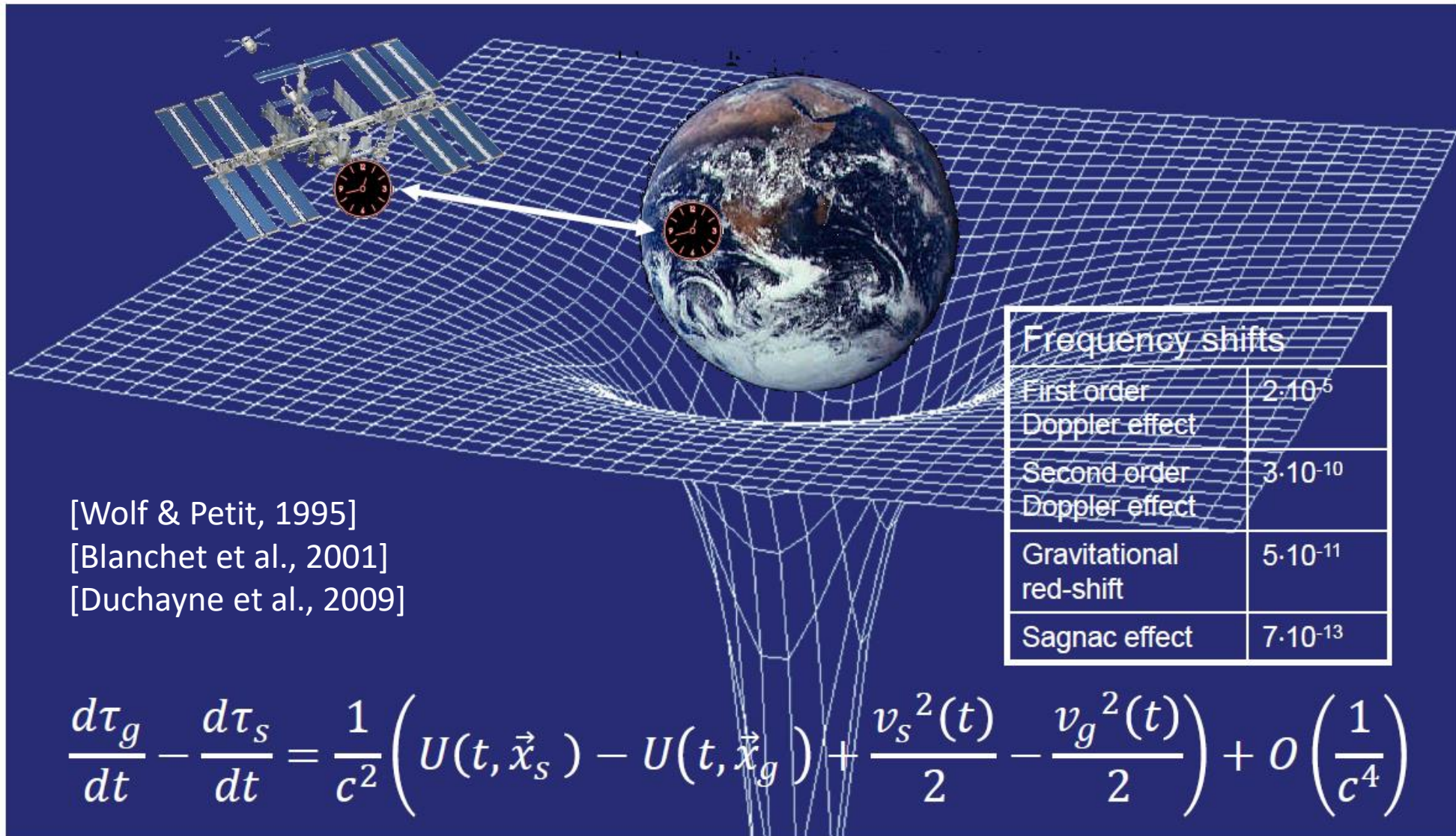




ACES science objectives

- **Test of the gravitational redshift**
 - part of the Einstein Equivalence Principle (EEP)
 - theory of gravitation is metric iff EEP is satisfied
- Comparison of ground clocks world wide and associated science
 - space-time variations of fundamental constants, DM searches
 - chronometric geodesy
 - contribution to global time scales (TAI), SI-second
- Demonstrate and study cold atom clock operation in space

Gravitational redshift test



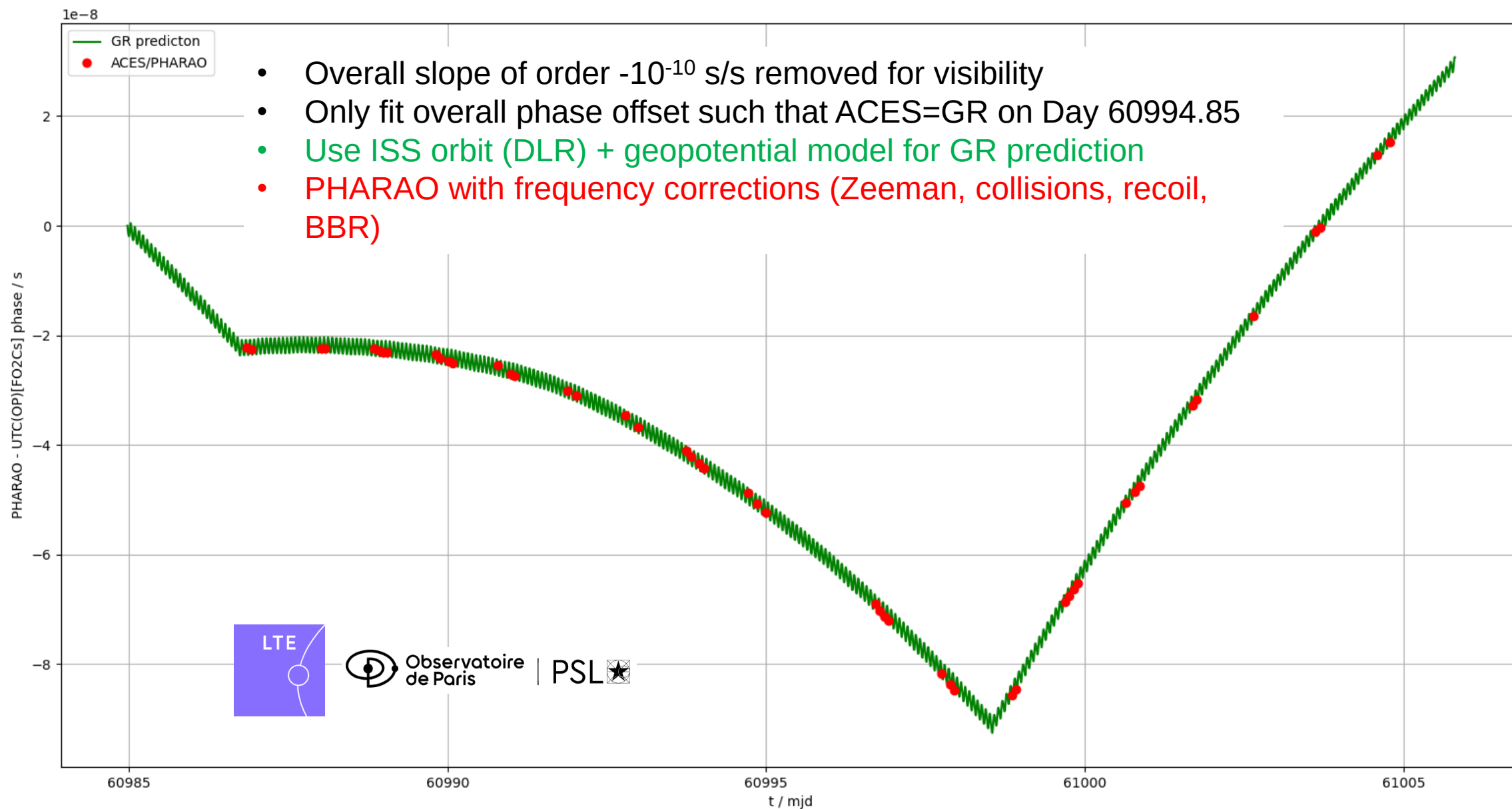
Gravitational redshift test

$$\frac{d\tau_g}{dt} - \frac{d\tau_s}{dt} = \frac{(1 + \alpha)}{c^2} (U_s - U_g)$$

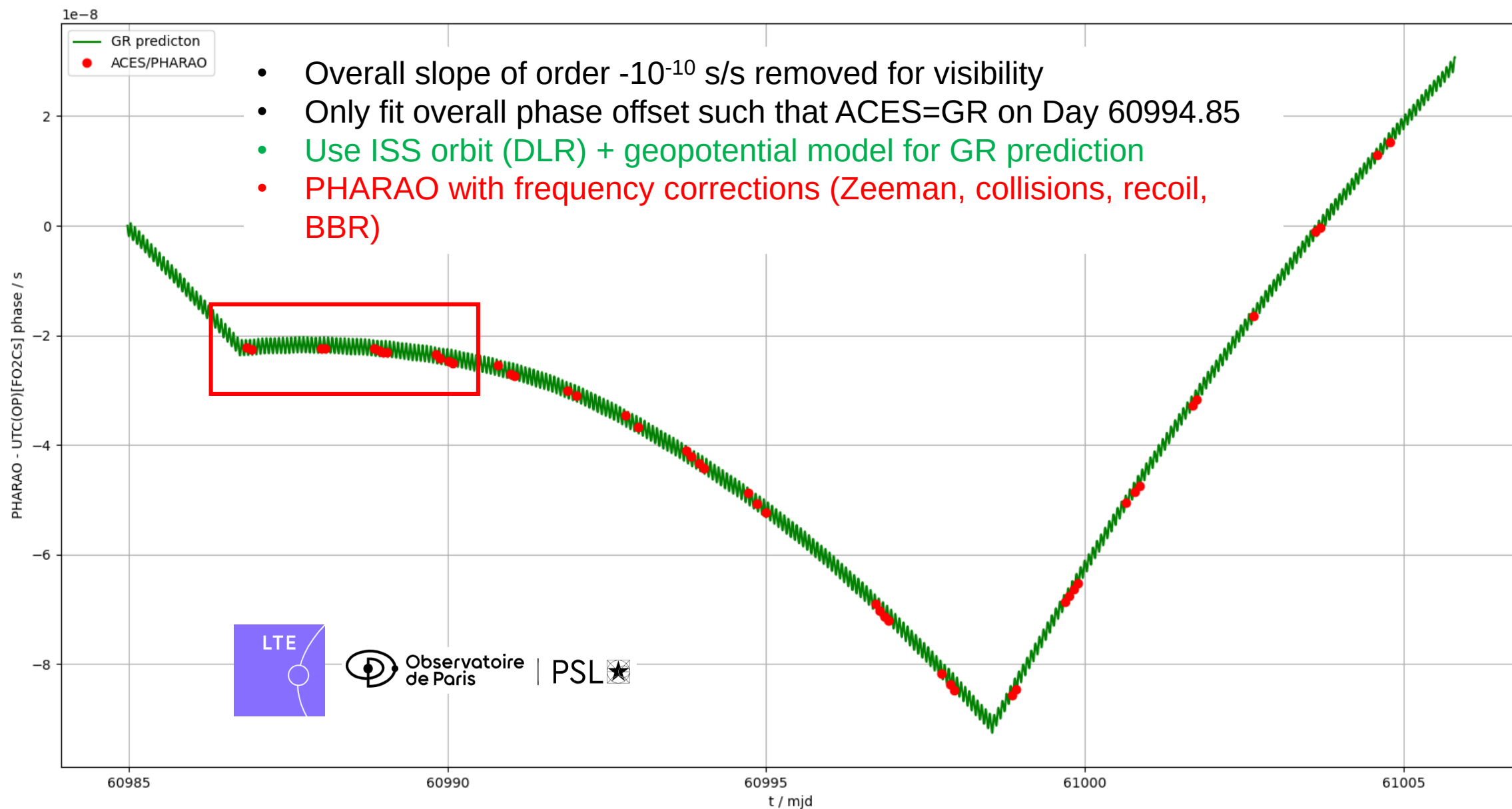
- Harvard tower, Pound & Rebka, 1964: $|\alpha| \leq 10^{-1}, 10^{-2}$
- Gravity Probe-A on sounding rocket, Vessot et al., PRL 1980 : $|\alpha| \leq 1.4 \cdot 10^{-4}$
- Galileo 5&6 on eccentric orbits, Delva et al./Hermann et al., PRL 2018: $|\alpha| \leq 2.5 \cdot 10^{-5}$
- Optical clocks on Tokyo skytree, Takamoto et al., Nature Phot. 2020: $|\alpha| \leq 9.1 \cdot 10^{-5}$
- Optical "clocks" on mm scale, Bothwell et al., Nature 2022: $|\alpha| \leq 10^{-1}$
- ACES estimation, Savalle et al., CQG 2019: $|\alpha| \leq 2\text{-}3 \cdot 10^{-6}$
confirmed recently by Enzer & Yu, CQG 2025

For that space/ground clocks and space-ground links need to be **accurate** to $1\text{-}2 \cdot 10^{-16}$ in fractional frequency.

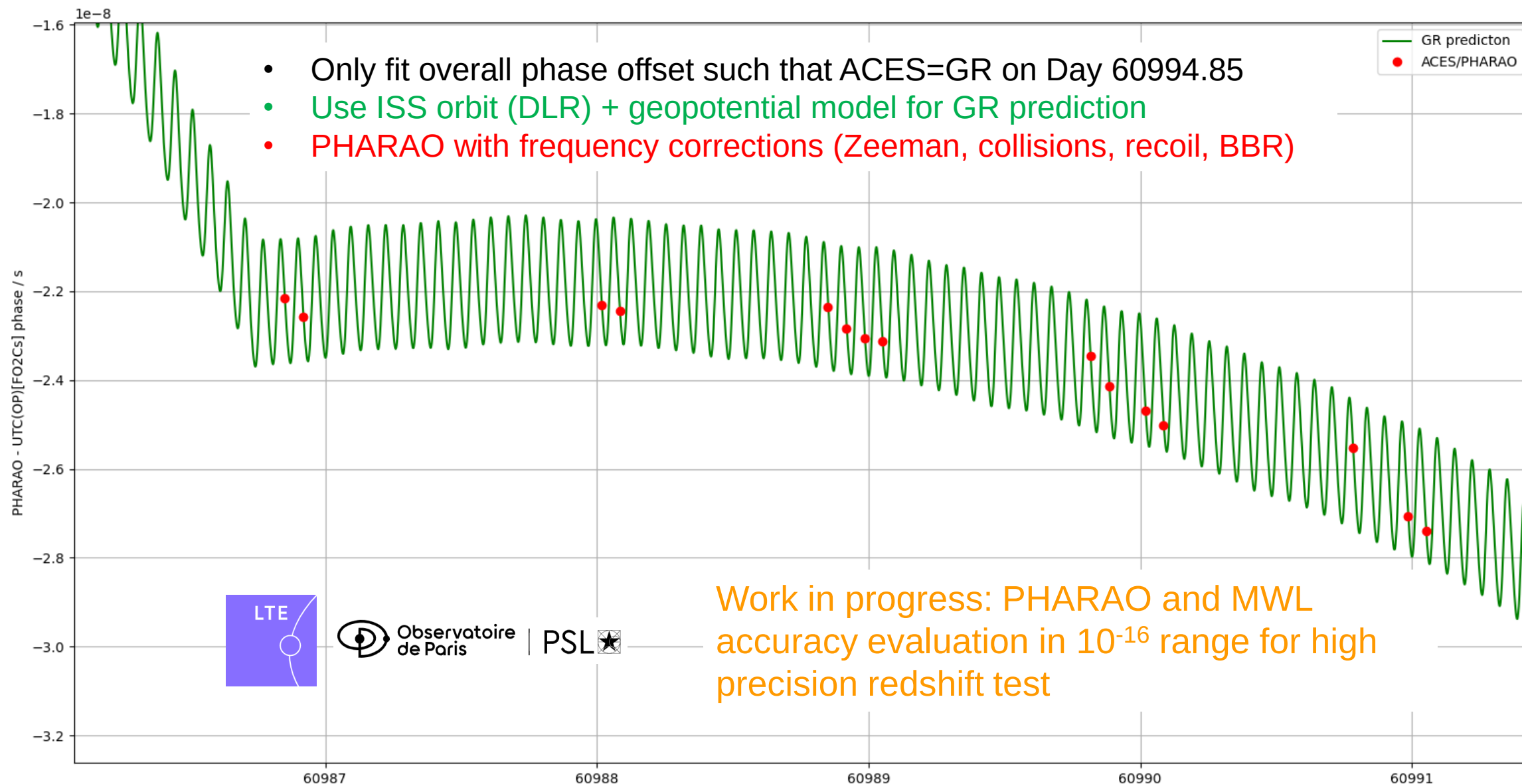
First in-orbit results: PHARAO vs LTE FO2 Cs fountain



First in-orbit results: PHARAO vs LTE FO2 Cs fountain



First in-orbit results: PHARAO vs LTE FO2 Cs fountain



LTE

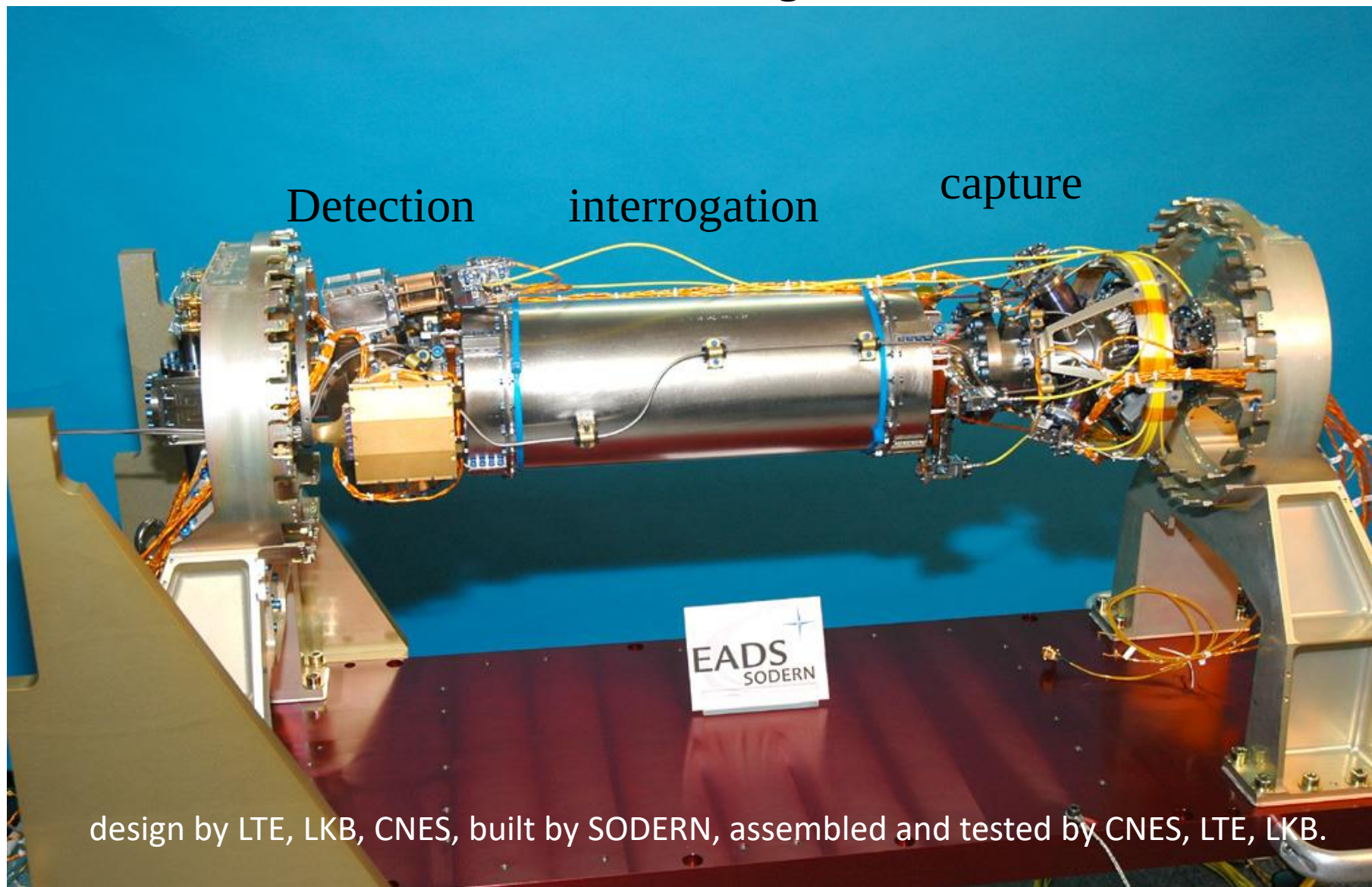
PHARAO

L=900 mm, M= 45 kg, P= 5 W

LTE



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design by LTE, LKB, CNES, built by SODERN, assembled and tested by CNES, LTE, LKB.

LTE

PHARAO

L=900 mm, M= 45 kg, P= 5 W

LTE

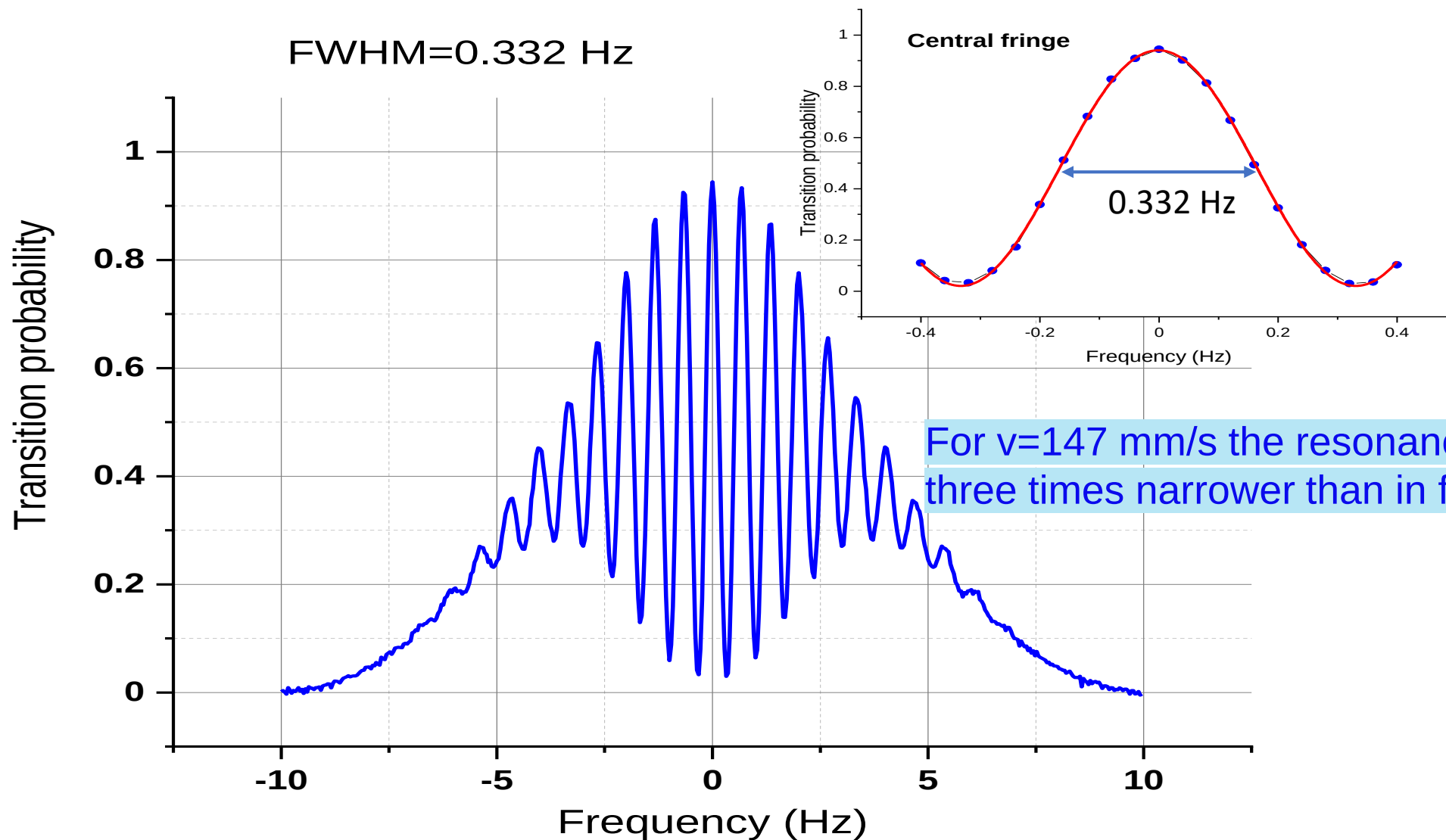


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Detection Interrogation capture
Ramsey cavity
Tested in fountain

design by LTE, LKB, CNES, built by SODERN, assembled and tested by CNES, LTE, LKB.

1.5 s coherence time: narrowest fringe!



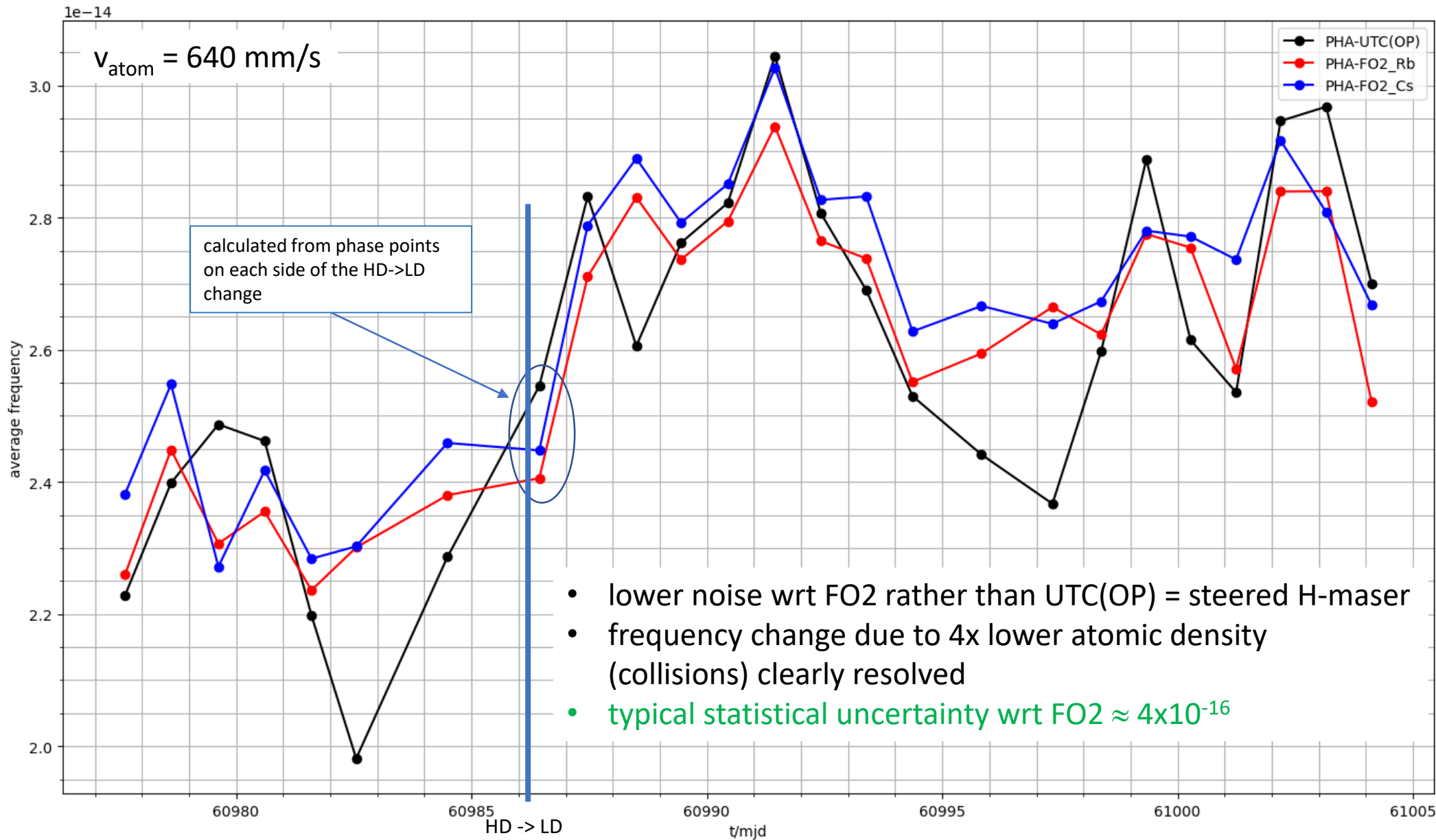
Towards 10^{-16} stat. and syst. uncertainty

- Need to operate PHARAO at different densities and atomic velocities to be able to correct for collisional shift and cavity phase shift. Since SHM is not operational this needs to be done using ground clocks with a frequency stability degradation of PHARAO (no USO/SHM servo-loop) => significantly longer measurement sequences!
- Need to run long enough to reach 10^{-16} overall statistical uncertainty.
- Need to correct for all frequency shifts (Magnetic, Temperature, Recoil, ...).
- Need to correct/estimate any MWL induced phase drifts (= frequency offsets).
- Need to correct/estimate effect of orbitography errors.
- Need 10^{-16} accuracy Cs ground clocks, and/or 10^{-16} confidence in Cs/X frequency ratios when using other ground clocks (X = Rb, Sr, Yb, Al⁺, Yb⁺, ...).

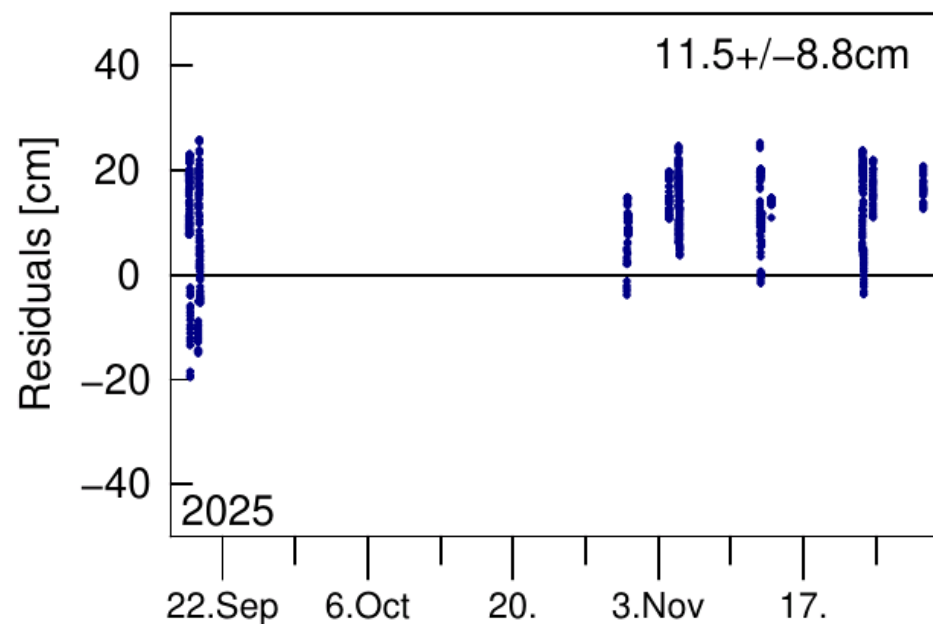
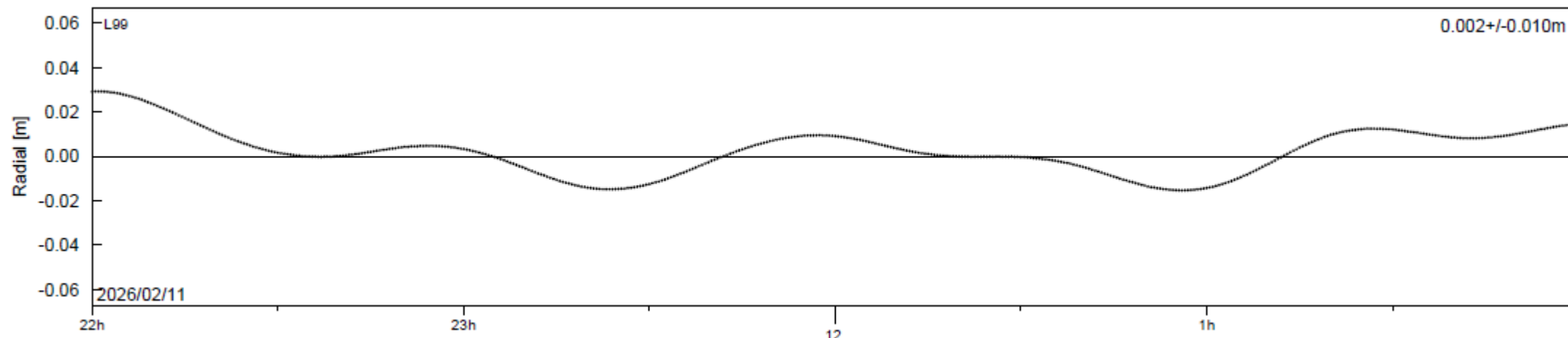
All of these points are "under control" (so far) but will require long measurement periods for full evaluation and confidence => mission extension?

Some examples:

Example: collisional shift



Example: orbit uncertainties

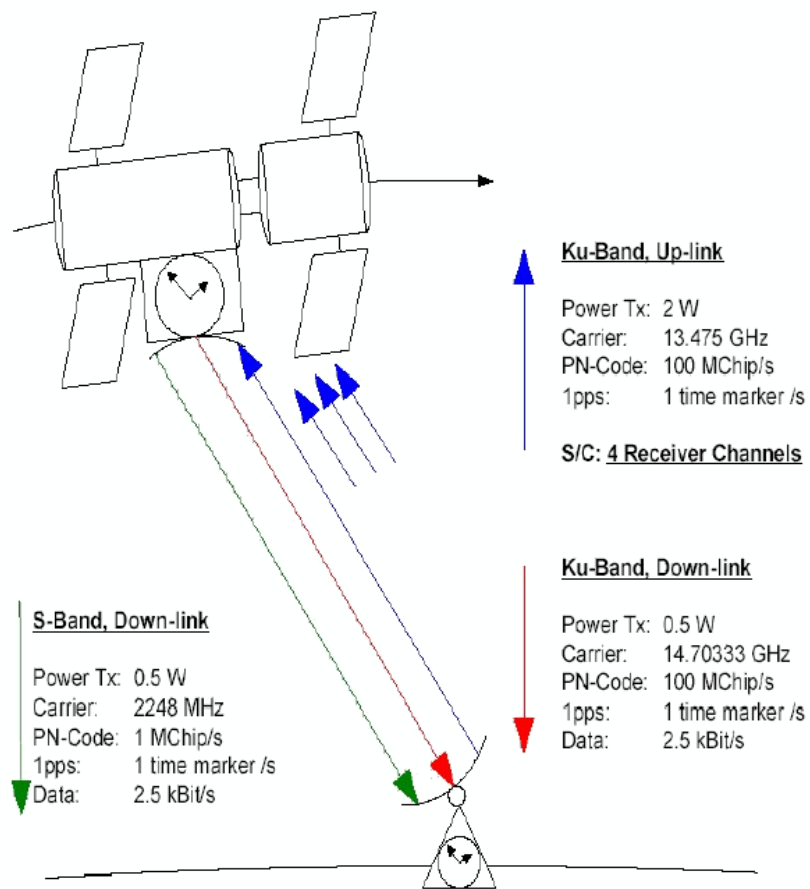


Results provided by Martin Wermuth, DLR



- Requirements are $\delta R < 8$ m [Duchayne et al. 2009]
- GNSS performance well within that bound (overlap and SLR comparison).
- Orbits are delivered regularly and continuously without gaps, even across reboost/docking.

The ACES Microwave Link (MWL)

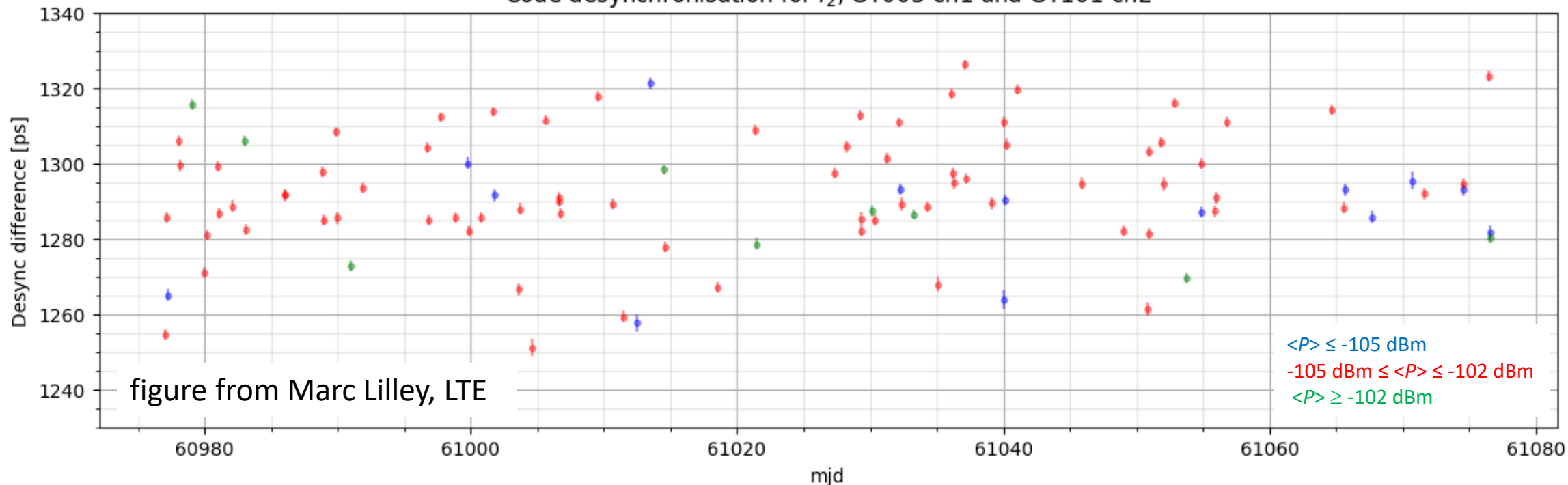


- Two-way link: First order insensitive to Range and troposphere.
- Dual frequency downlink => ionospheric effect removal
- Carrier and code measurements
=> phase coherence between passes
- 4 channels on board => simultaneous common-views
- Space and ground terminals are equipped with Test Loop Transponders (TLT) allowing monitoring of internal delays

Phase drift can be controlled by TLT, by common view of GT-channels/collocated GTs, or by comparison to other links (fibres, GNSS, TWSTFT).

Example: GT003 - GT101 common views

Code desynchronisation for f_2 , GT003-ch1 and GT101-ch2



- Corrected for many effects (AM/PM, temperature, antenna corrections, ...)
- Only passes > 160 s (max pass duration 400 s)
- Over 100 days GT003-GT101 difference is ≈ 60 ps pk to pk., standard deviation = 16 ps.
- Over a 10 day interval, frequency error ≈ 16 ps/10 days $\approx 2 \times 10^{-17}$.
- But of course correlated => need long baseline common views with parallel fibre link!

The reality of space (on the ISS)

Space experiments bring many, often unforeseen, problems. In the case of ACES on the ISS:

- Vibrations from human activity, limited μg environment
- Radiation effects (South Atlantic Anomaly)
- Multipath effects from ISS structure
- Numerous reboosts and attitude manoeuvres
- Visiting vehicles (obstruction and multipath)

<https://artsandculture.google.com/asset/international-space-station-3d-model-nasa/1wEkLGp7VFjRvw?hl=en>

Example: HTV obstruction and multipath

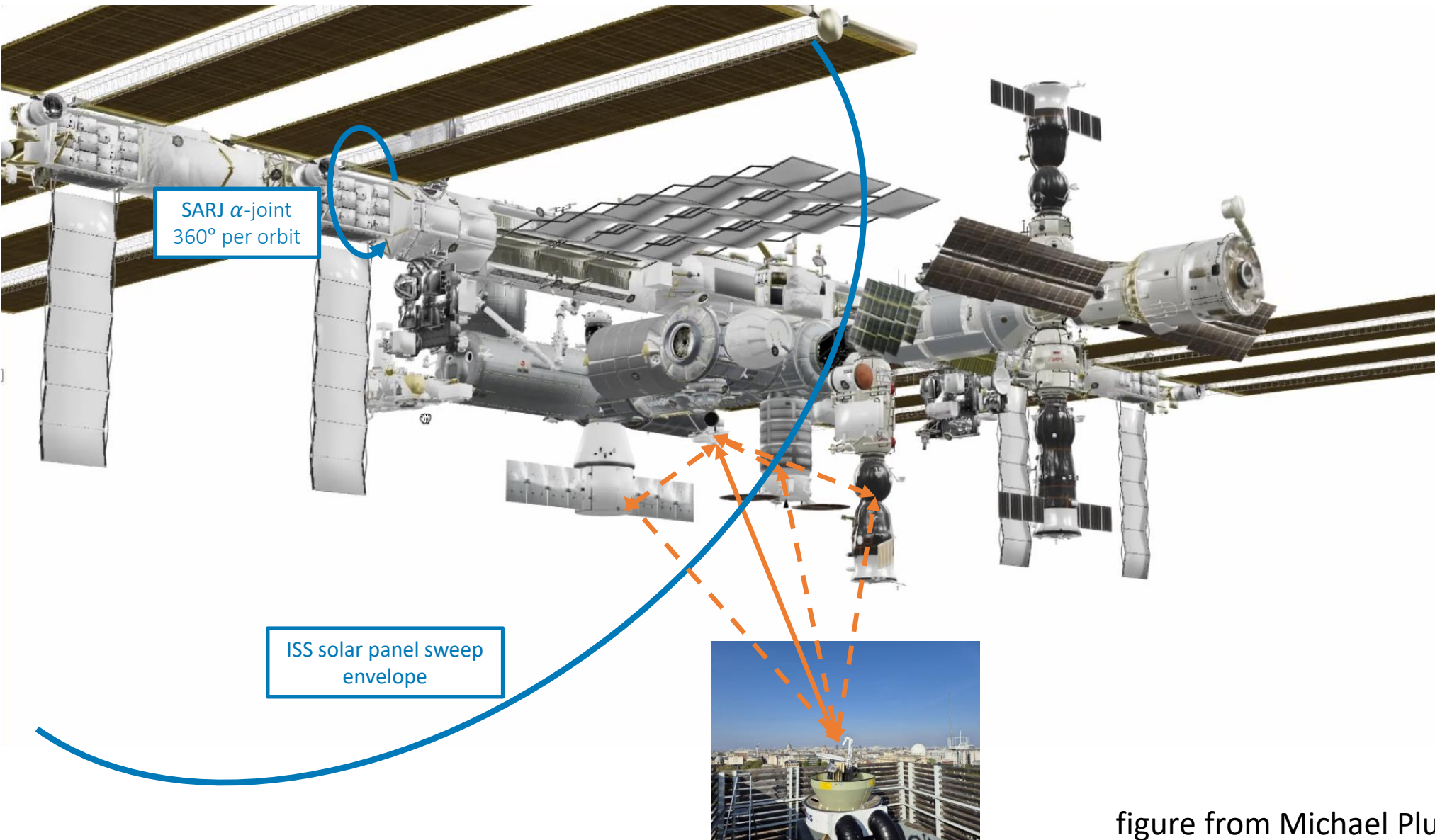
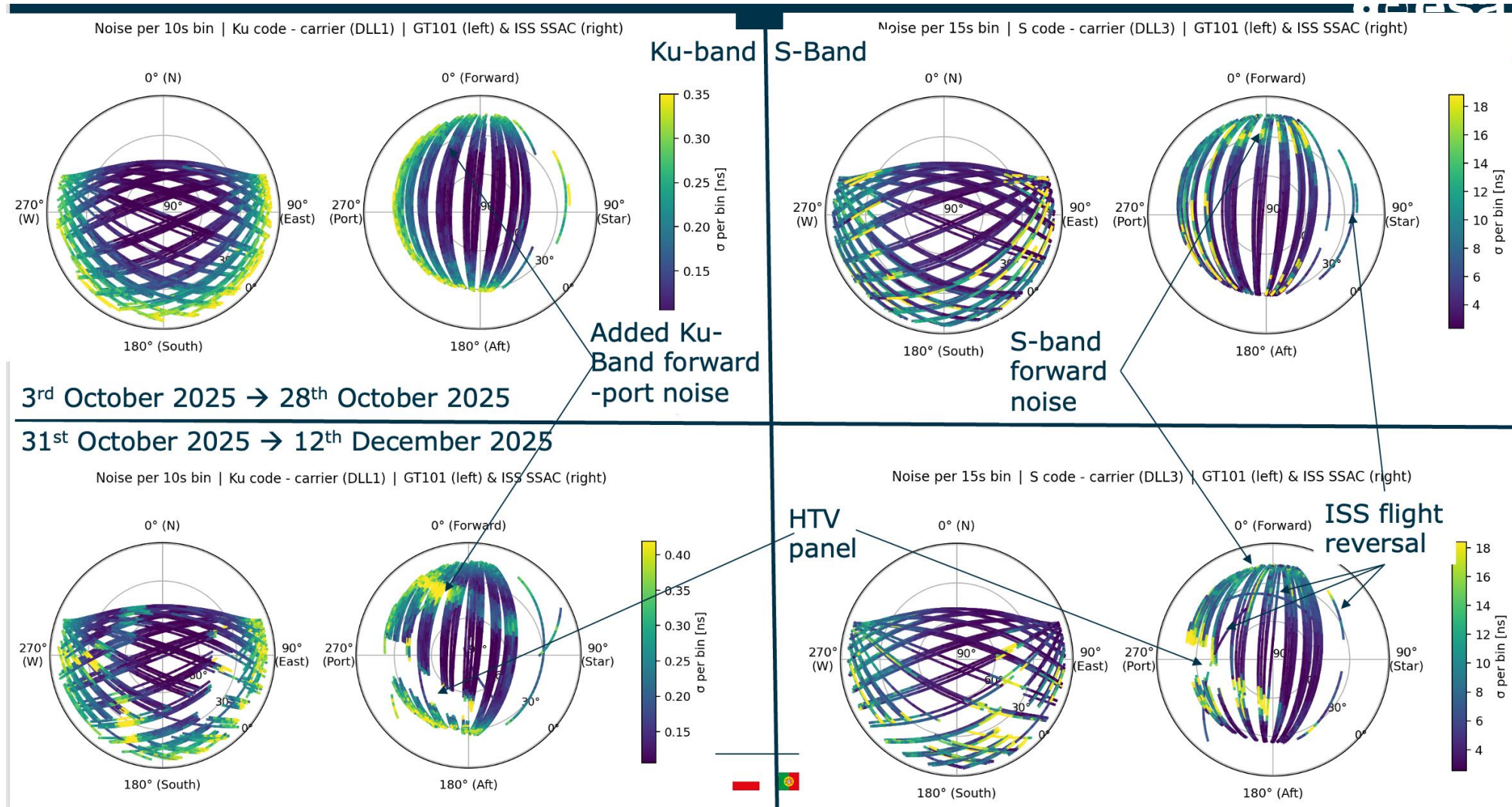


figure from Michael Plumaris, ESA

Example: HTV obstruction and multipath



Conclusion

- After a long wait (since 1997) ACES is finally operating in space.
- The atomic clock (PHARAO) is working like a charm.
- GNSS orbit determination is way better and reliable than expected.
- Commissioning is still incomplete, still 1 MWL ground terminal not operational.
- Some payload elements are, so far, not functioning correctly (SHM, ELT).
- Nonetheless, we are already taking science data and starting to be cautiously optimistic on overall performance.

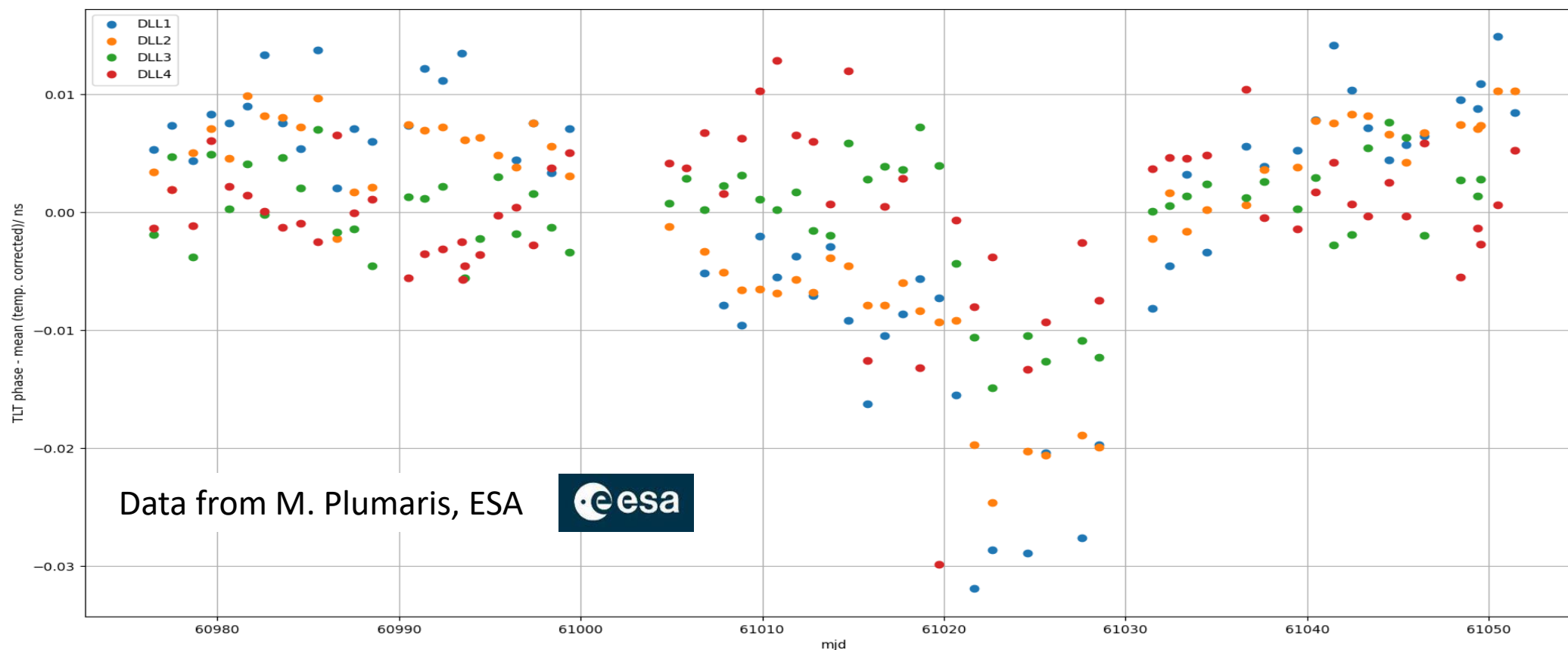
Much work remains to be done:

- Assess PHARAO accuracy at 10^{-16} level: different launch velocities and several densities
- Improve MWL operation, reliability and performance
- Assess MWL long term performance (e.g. compare to fibre link)
- Full test of the gravitational redshift
- Continental and intercontinental comparison of clocks
- Science phase for two years => more results to come!

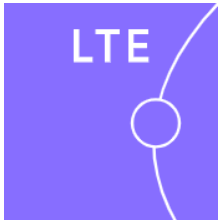


Back Up

Example: Flight segment TLT measurements



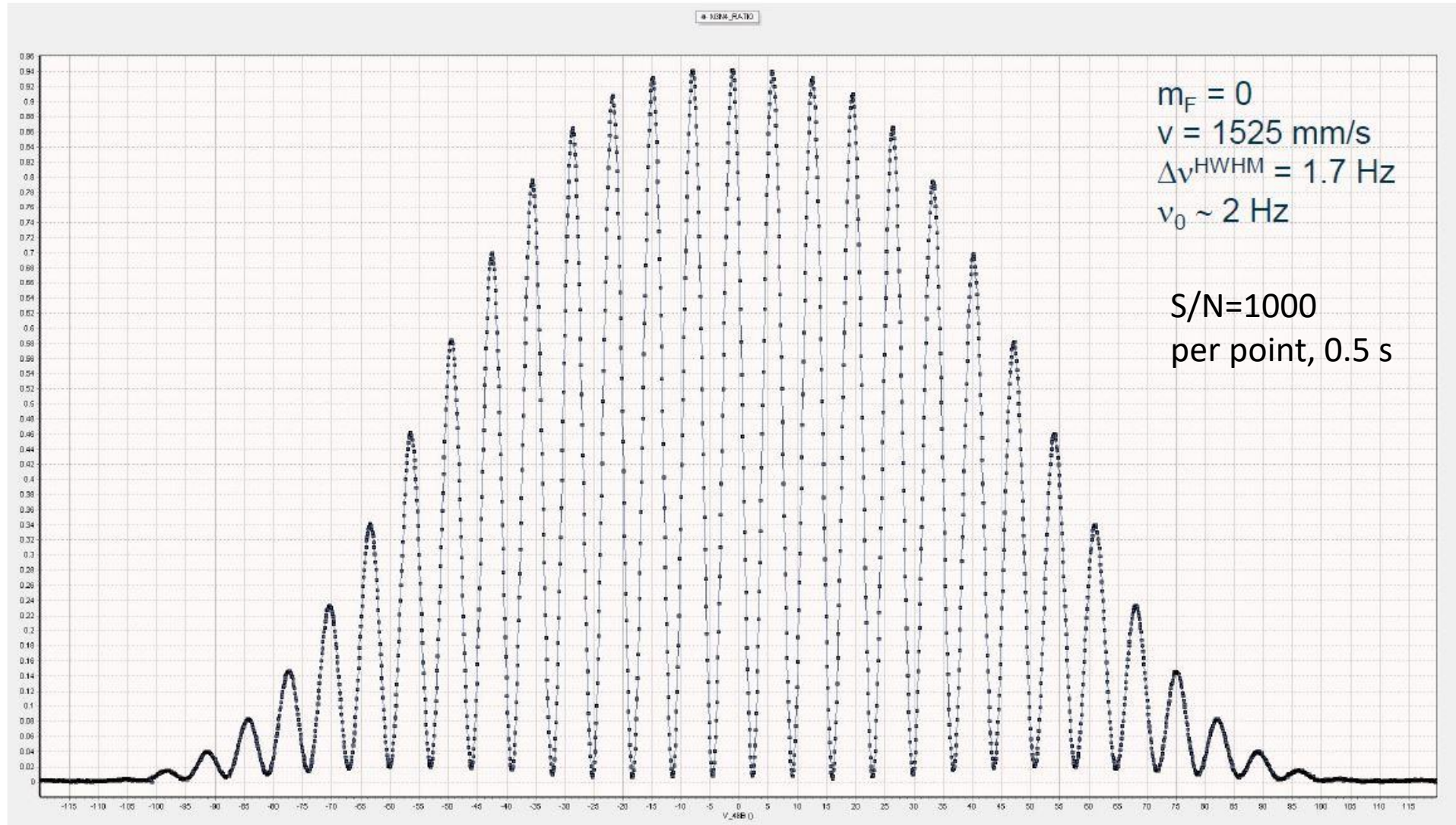
- Corrected for temperature
- Over 100 days TLT variation is ≈ 20 ps pk to pk., except over 10 days (max beta angle? ISS manoeuvres?)
- Overall standard deviation = 12/9/5/7 ps for the four DLLs.
- Over a 10 day interval, frequency error ≈ 8 ps/10 days $\approx 1 \times 10^{-17}$.
- But only part of the story => need common views!



P. Laurent
F. X Esnault



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

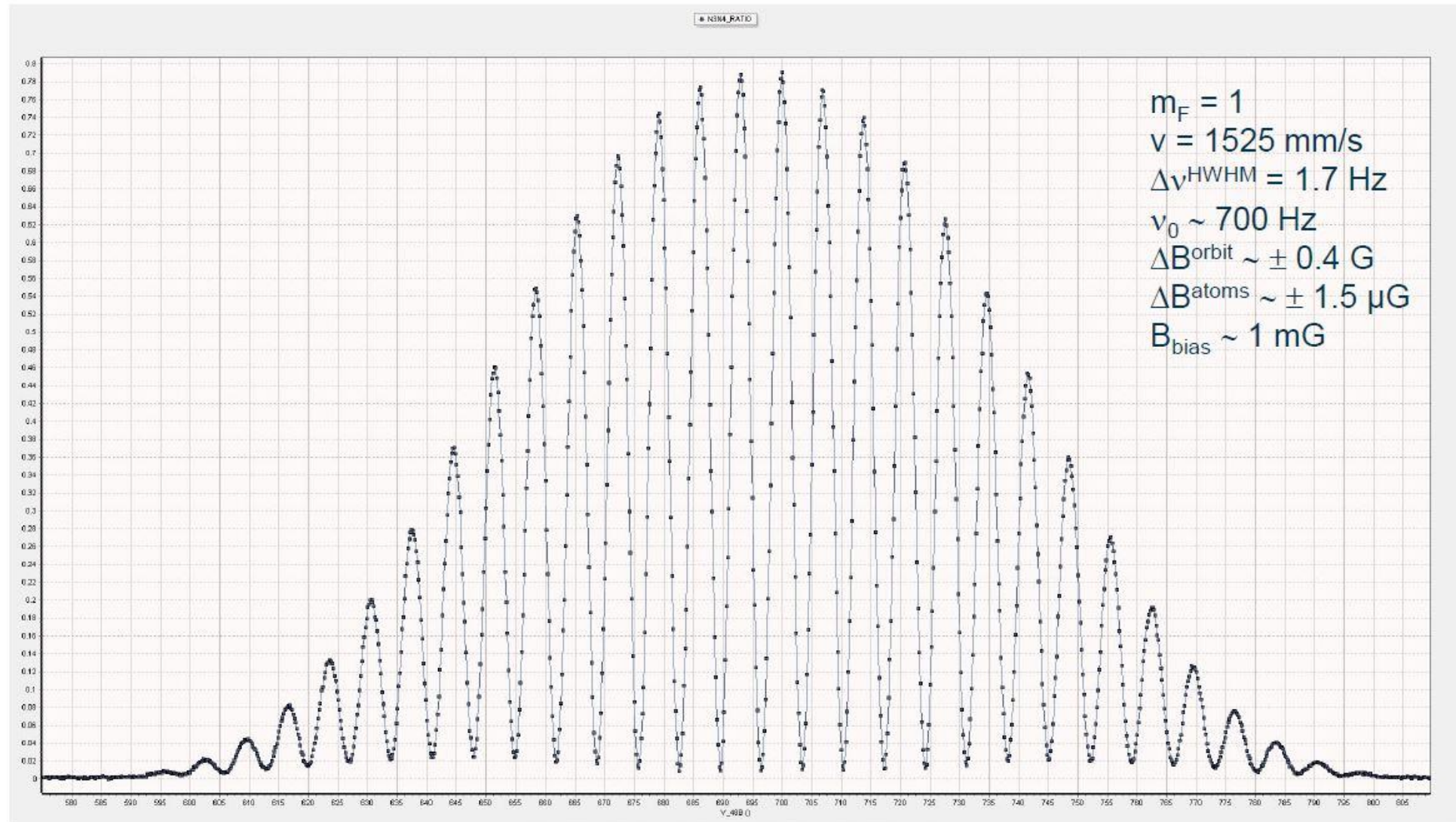
PHARAO Ramsey fringes II



P. Laurent
F X Esnault



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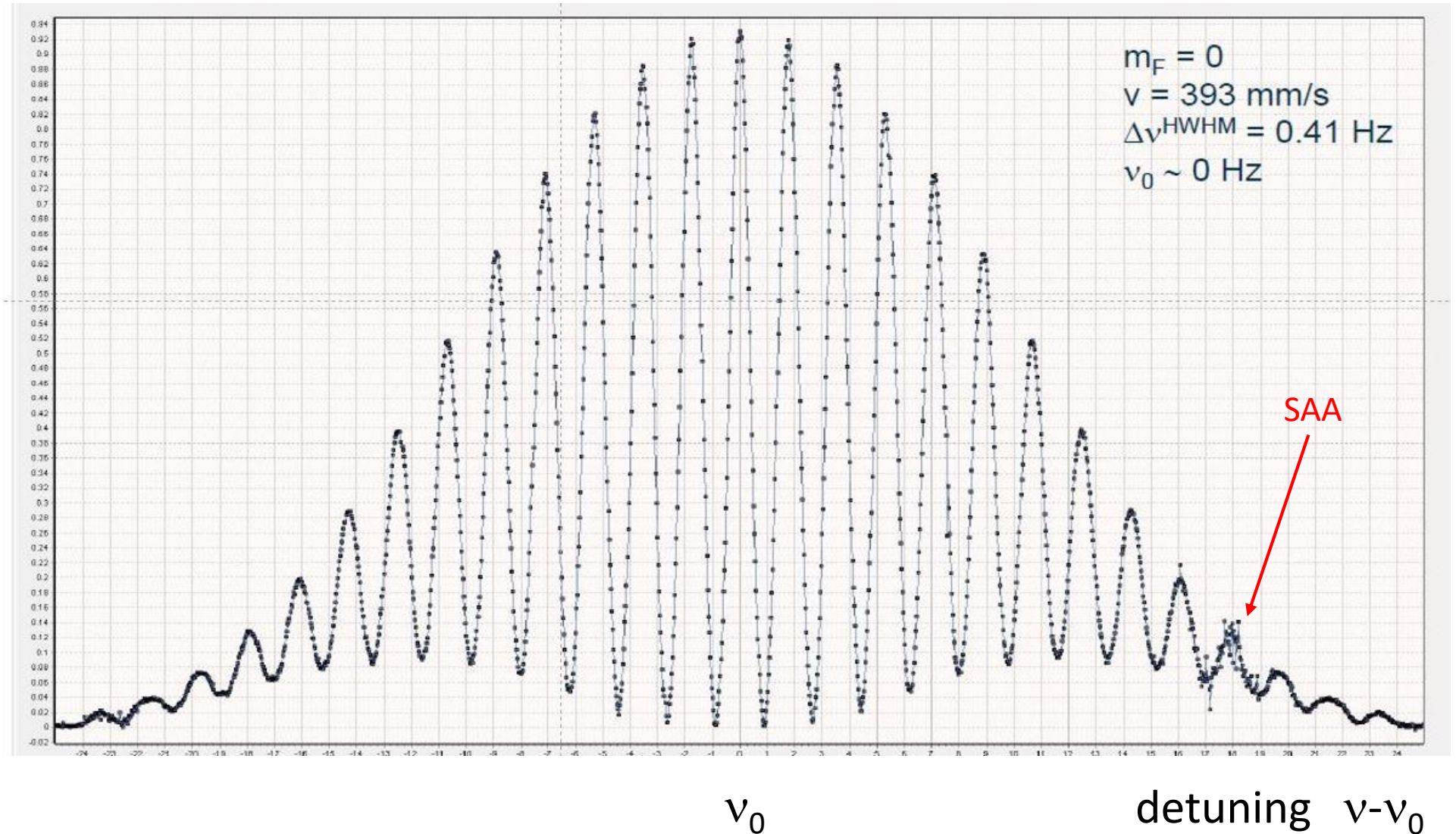
PhL, LTE/CNES, ESA, OP, LNE, PSL, SU

Space problems: South Atlantic Anomaly

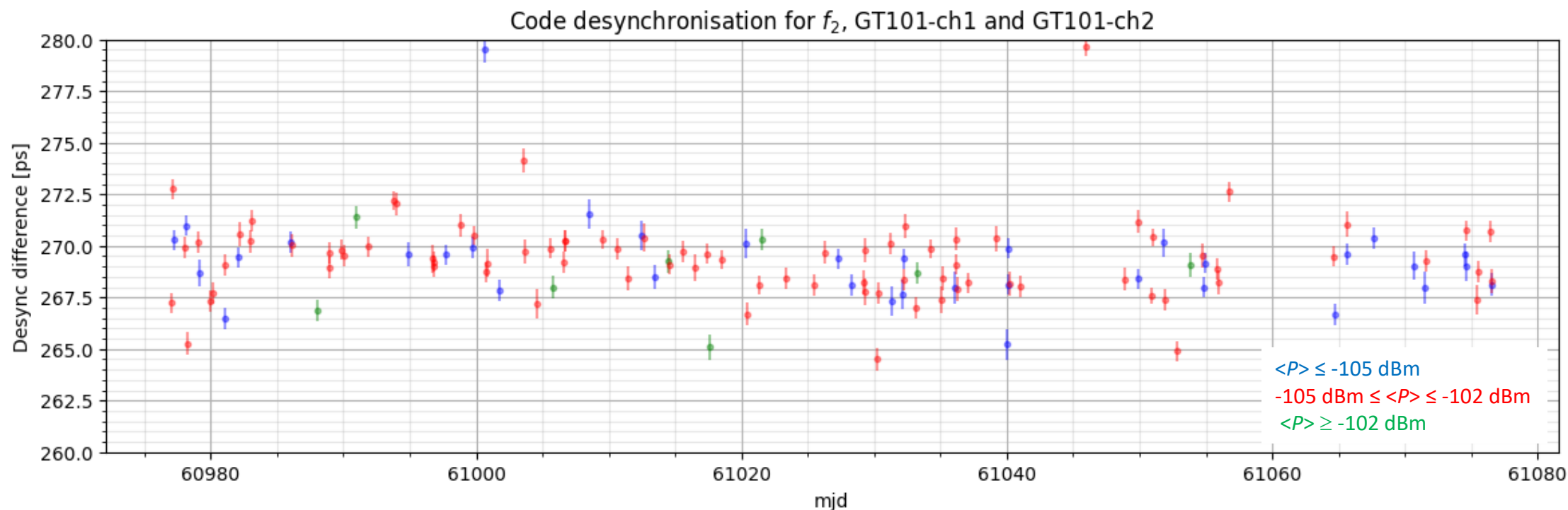


Transition probability

P. Laurent et al.
LTE, Obs. Paris,
LKB

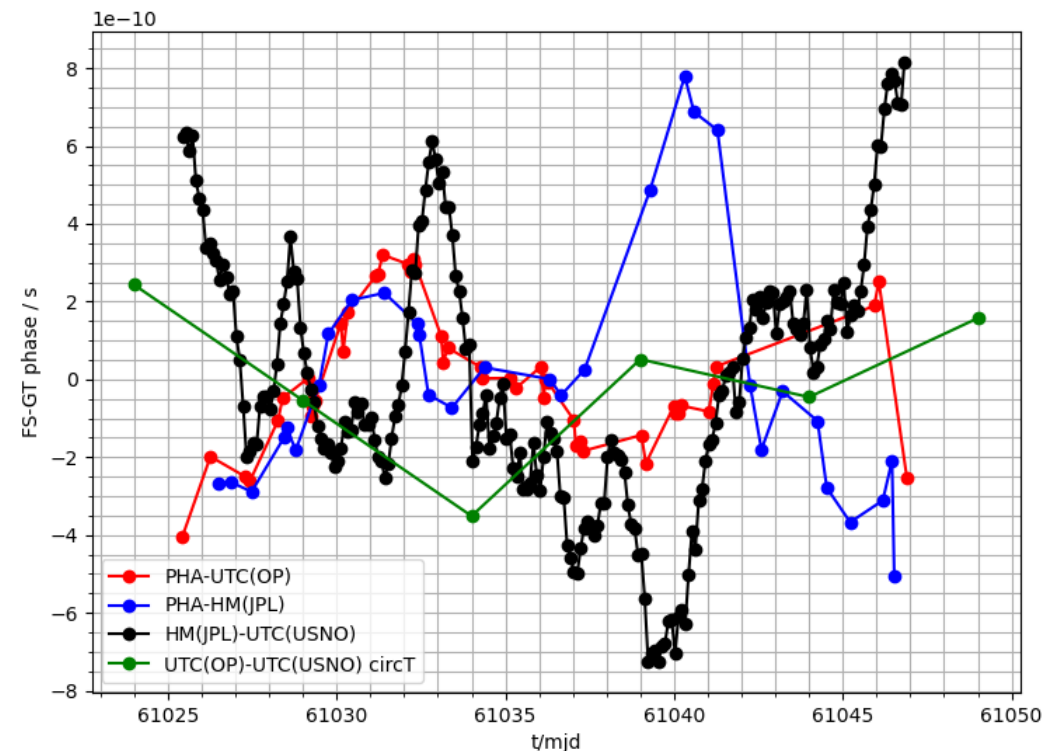
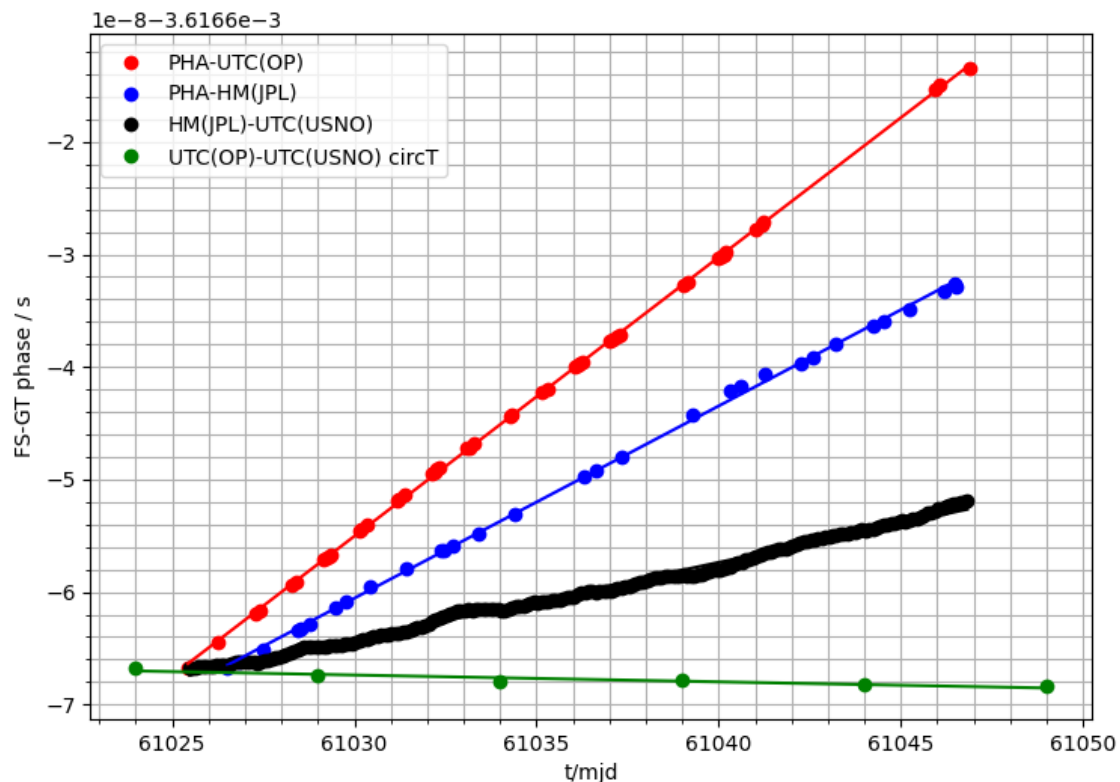


Example: GT101_ch1 - GT101_ch2 common views



- Corrected for many effects (AM/PM, temperature, antenna corrections, ...)
- Over 100 days GT003-GT101 difference is ≈ 10 ps pk to pk., standard deviation = 2 ps.
- Over a 10 day interval, frequency error ≈ 2 ps/10 days $\approx 0.2 \times 10^{-17}$.
- But of course correlated => need long baseline common views with parallel fibre link!

Example: Transatlantic link comparison

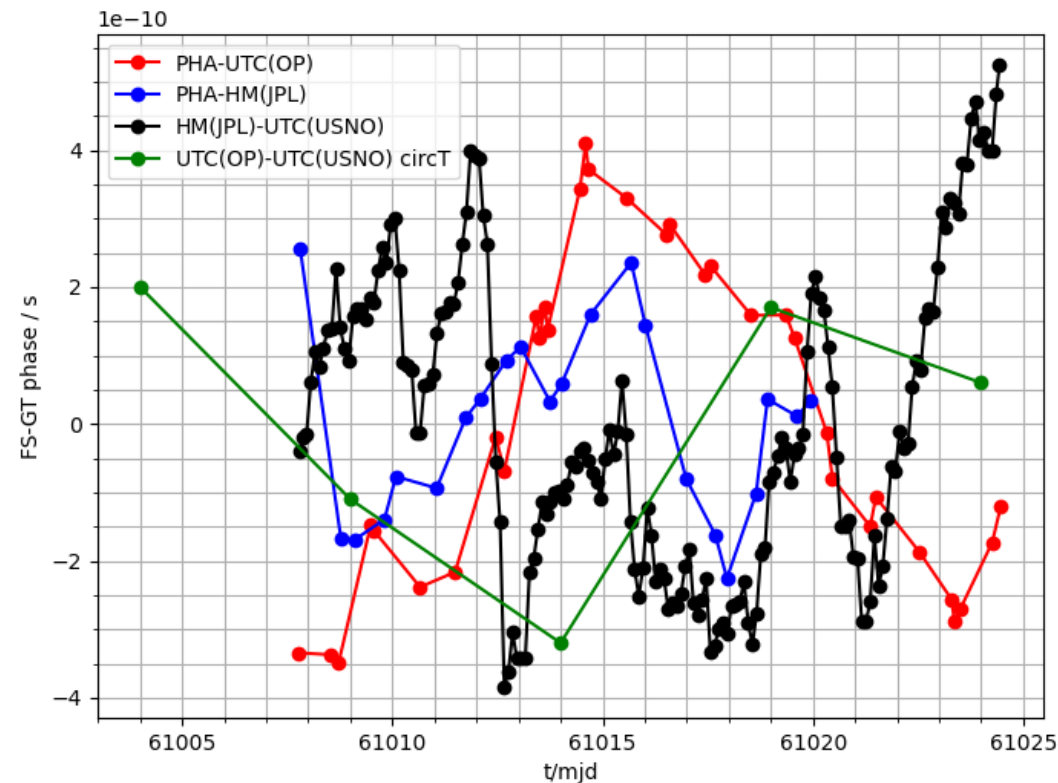
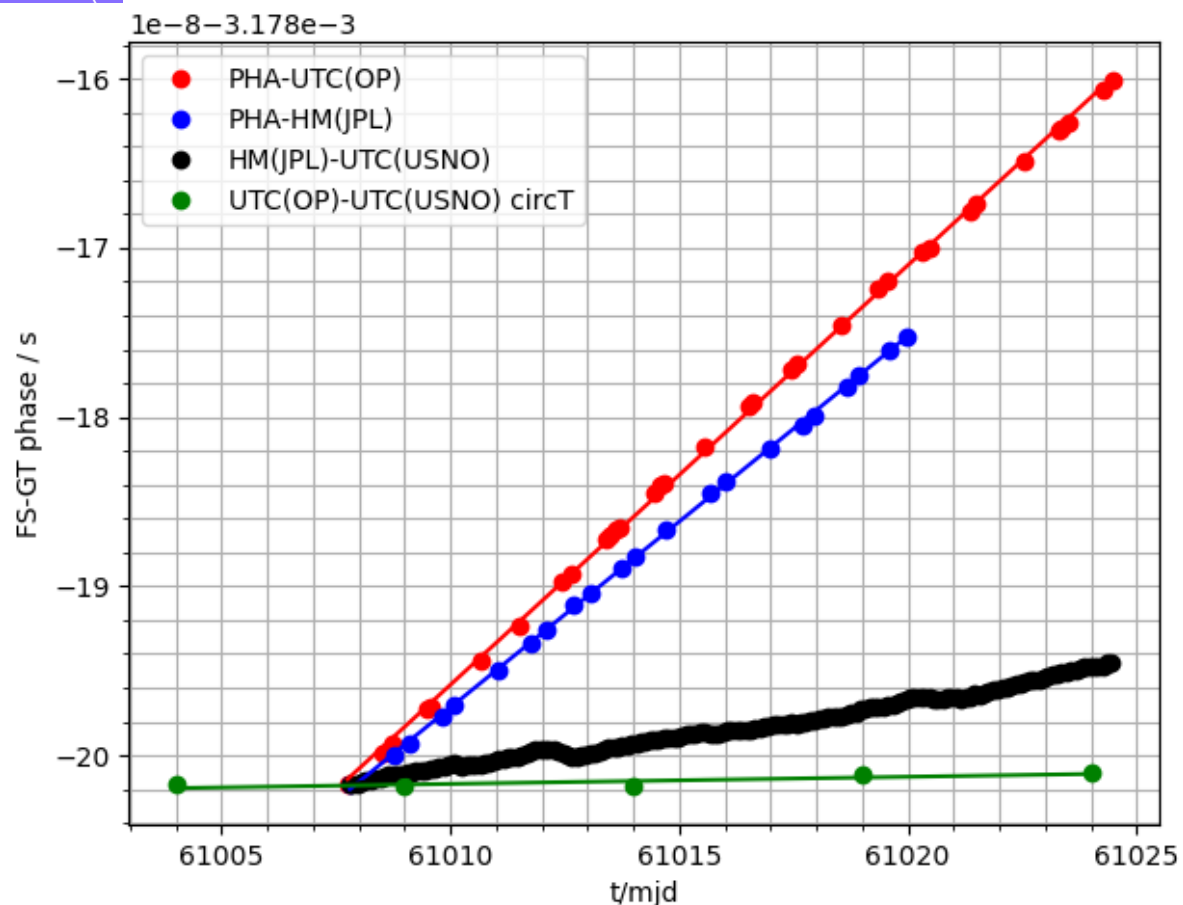


- Phase data on left, residuals wrt linear fit on right
- The slopes should add to zero (closure via Circ. T)
- They do, to $< 10^{-15}$
- "Quick 'n dirty analysis" to check consistency, no rigorous statistical analysis, no uncertainty evaluation yet !!
- ultimately limited by GNSS/TWSTFT/non-CV => fibres!

```
In [7]: runfile('D:/dataPW/ACES/InFlight/Data/Ground-ground
InFlight/Data')
slope PHA-UTC(OP) = 2.868985876304303e-14
slope PHA-HM(JPL) = 1.977067670960678e-14
slope HM(JPL)-UTC(USNO) = 7.993036775886354e-15

slope UTC(OP)-UTC(USNO) circT = -7.010582010582008e-16
slope UTC(OP)-UTC(USNO) ACES = -9.261452775498946e-16
```

Example: Transatlantic link comparison



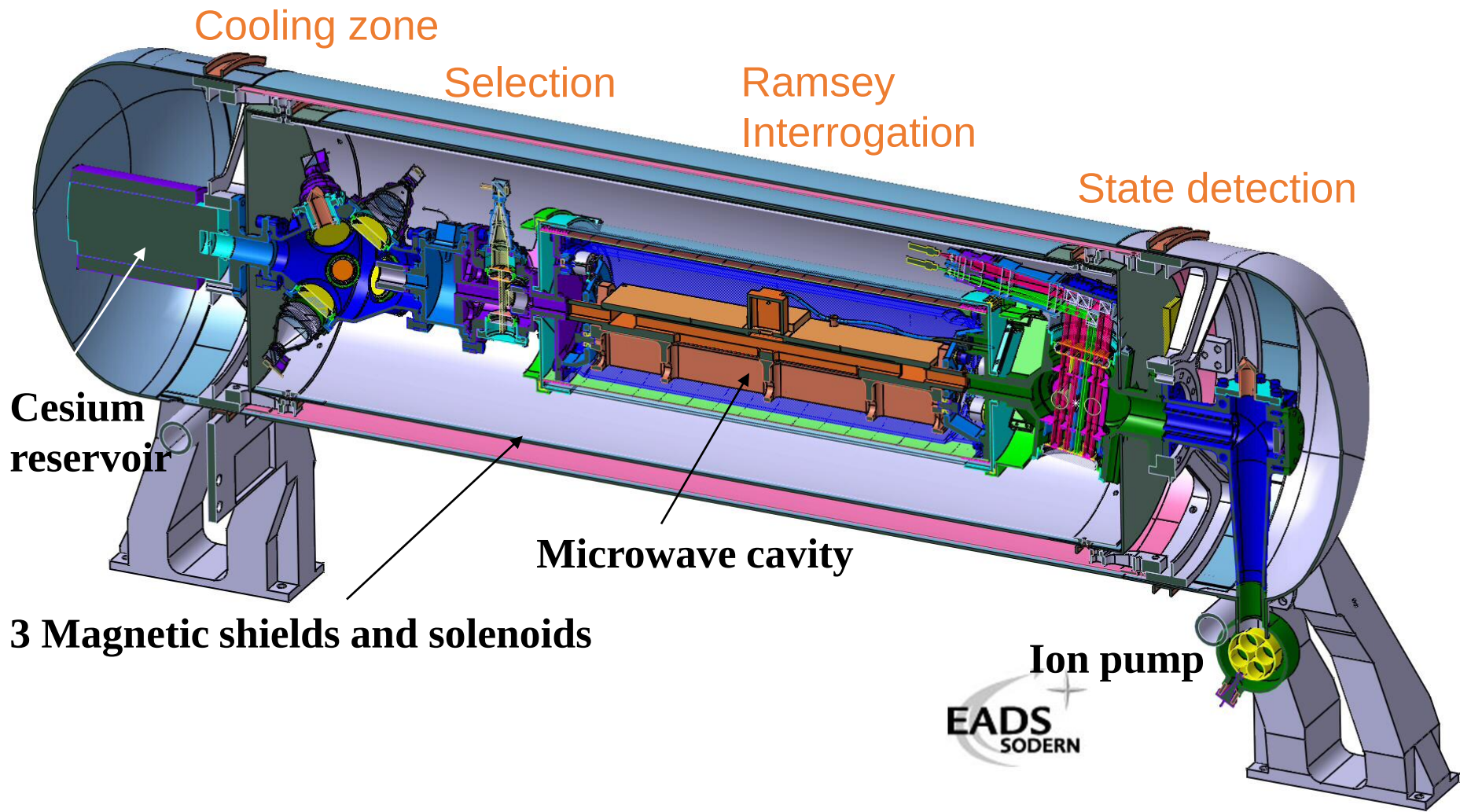
- Phase data on left, residuals wrt linear fit on right
- The slopes should add to zero (closure via Circ. T)
- They do to $< 10^{-15}$
- "Quick 'n dirty analysis" to check consistency, no rigorous statistical analysis, no uncertainty evaluation yet !!

```
In [30]: runfile('D:/dataPW/ACES/InFlight/Data/Ground-ground.py',
InFlight/Data')
slope PHA-UTC(OP) = 2.872237890312364e-14
slope PHA-HM(JPL) = 2.544088623068075e-14
slope HM(JPL)-UTC(USNO) = 4.646462613363625e-15

slope UTC(OP)-UTC(USNO) circT = 4.861111111111111e-16
slope UTC(OP)-UTC(USNO) ACES = 1.364969940920737e-15
```



PHARAO cold atom clock



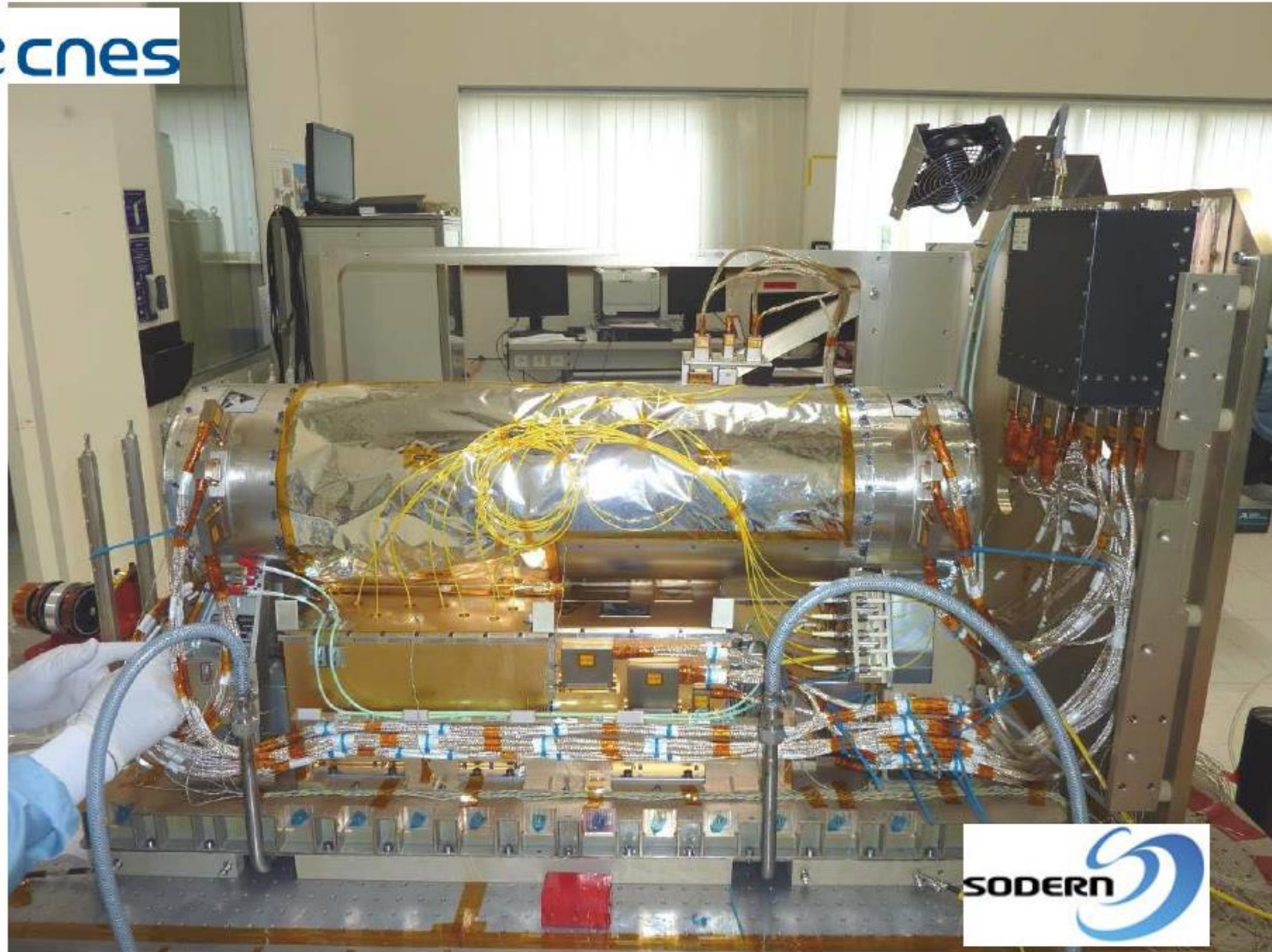
Stability and accuracy goal: 10^{-16} in space



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LTE

cnes



Cold atom cesium clock designed for microgravity operation

See P. Laurent et al.,
Metrologia 2020

Talk by P. Laurent

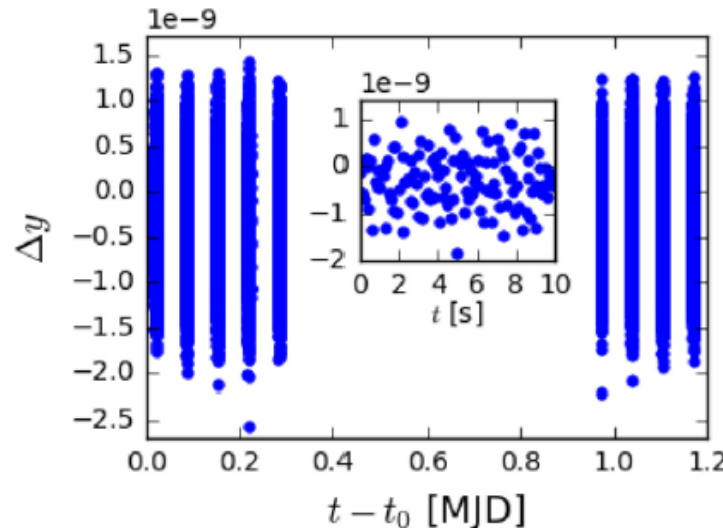
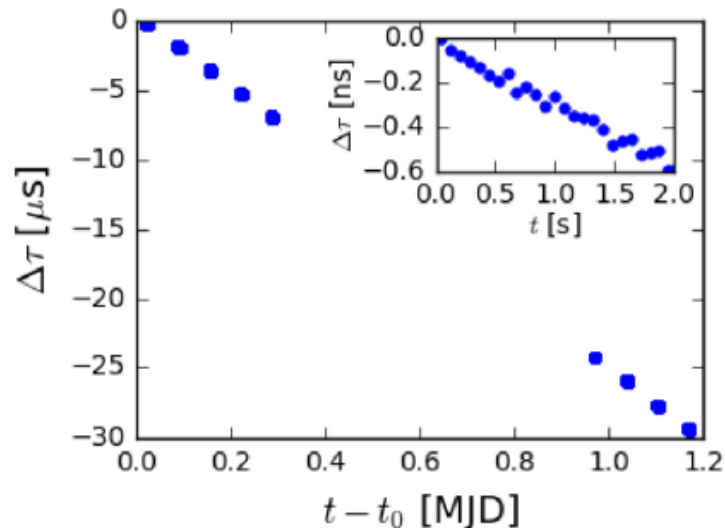
Flight model tested and delivered to ESA in July 2014

Still working nicely during 2024 ACES Science tests in Friedrichshafen

Gravitational redshift test, simulation

How to get there with ACES:

- Space and ground clocks need to be **accurate** to $1\text{--}2 \cdot 10^{-16}$ in fractional frequency (PHARAO)
- Absolute phase comparisons (up to an overall constant) to deal with dead times (MWL, ELT)
- Two-way links to remove 1st order Doppler (Range)
- ISS orbitography (< 10 m) to remove 2nd order Doppler
- Remove or calibrate all perturbing effects (troposphere, ionosphere, instrumental delays, PHARAO frequency shifts, ...). $10^{-16} = 80$ ps over 10 days.



Simulated ISS passes over Paris
[Savalle et al., CQG **36**, 245004, 2019]