ATOMIC CLOCK ENSEMBLE IN SPACE

Mission status

Luigi Cacciapuoti

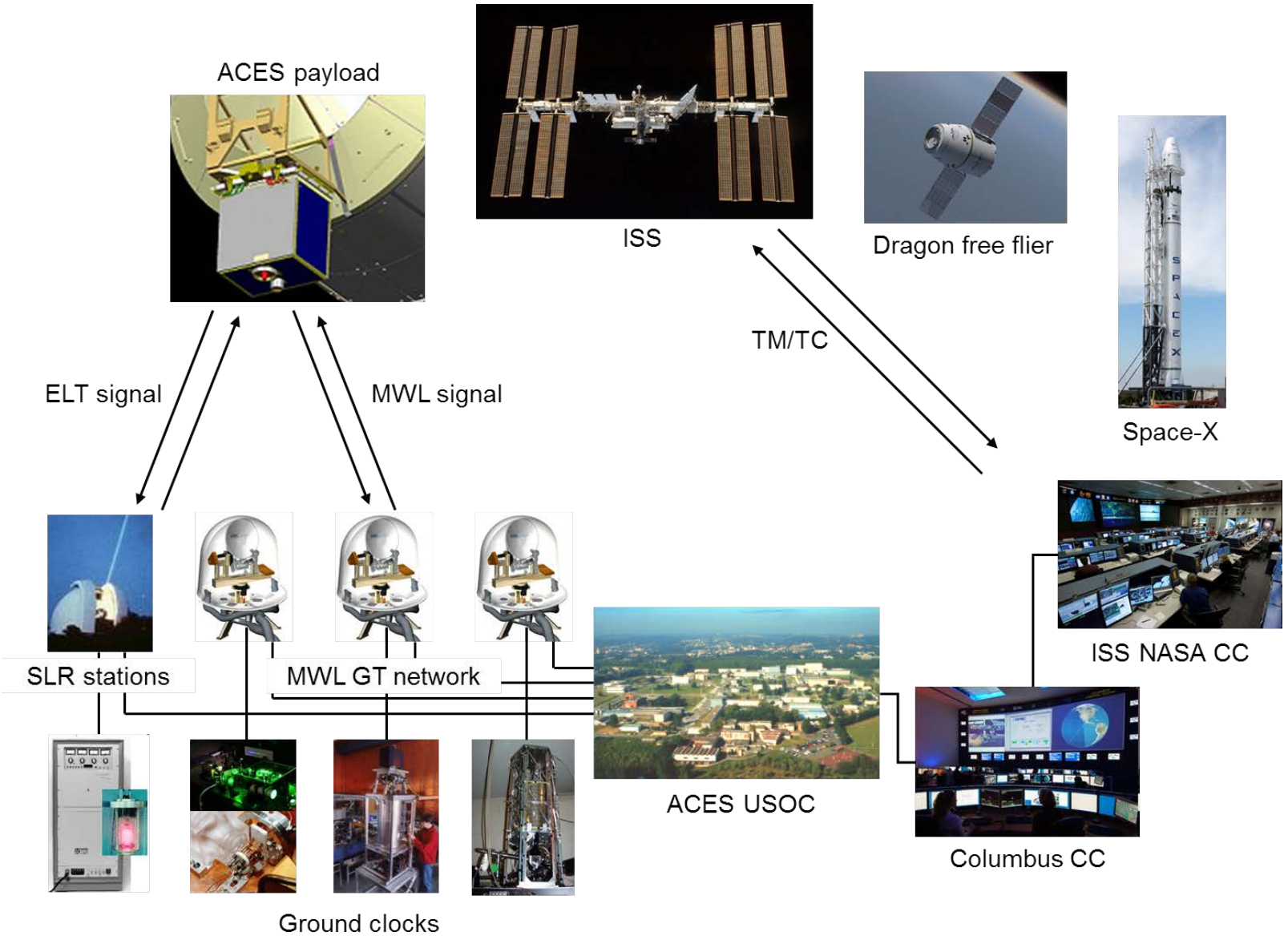
on behalf of the ACES team

29/06/2017

ACES Workshop 2017 - Zurich

ESA UNCLASSIFIED - For Official Use

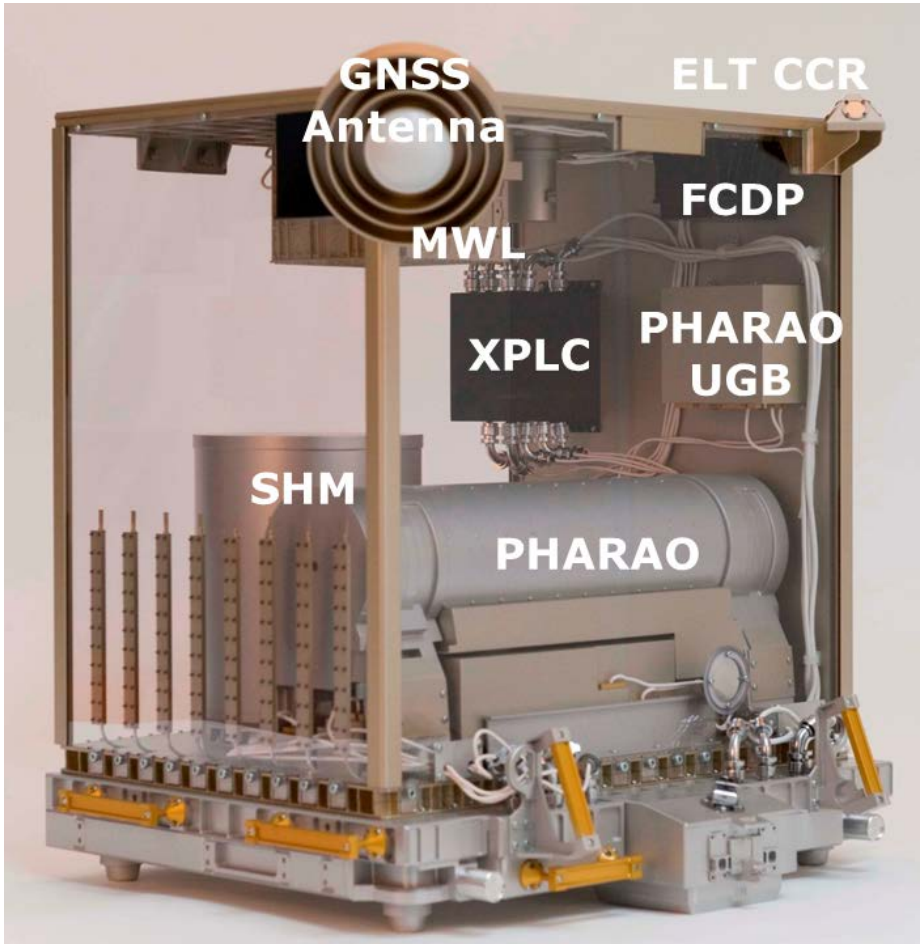
ACES


ACES payload
ISS
Dragon free flier
Space-X
TM/TC
ELT signal
MWL signal
SLR stations
MWL GT network
ISS NASA CC
ACES USOC
Columbus CC
Ground clocks

The Columbus module

The ACES Payload

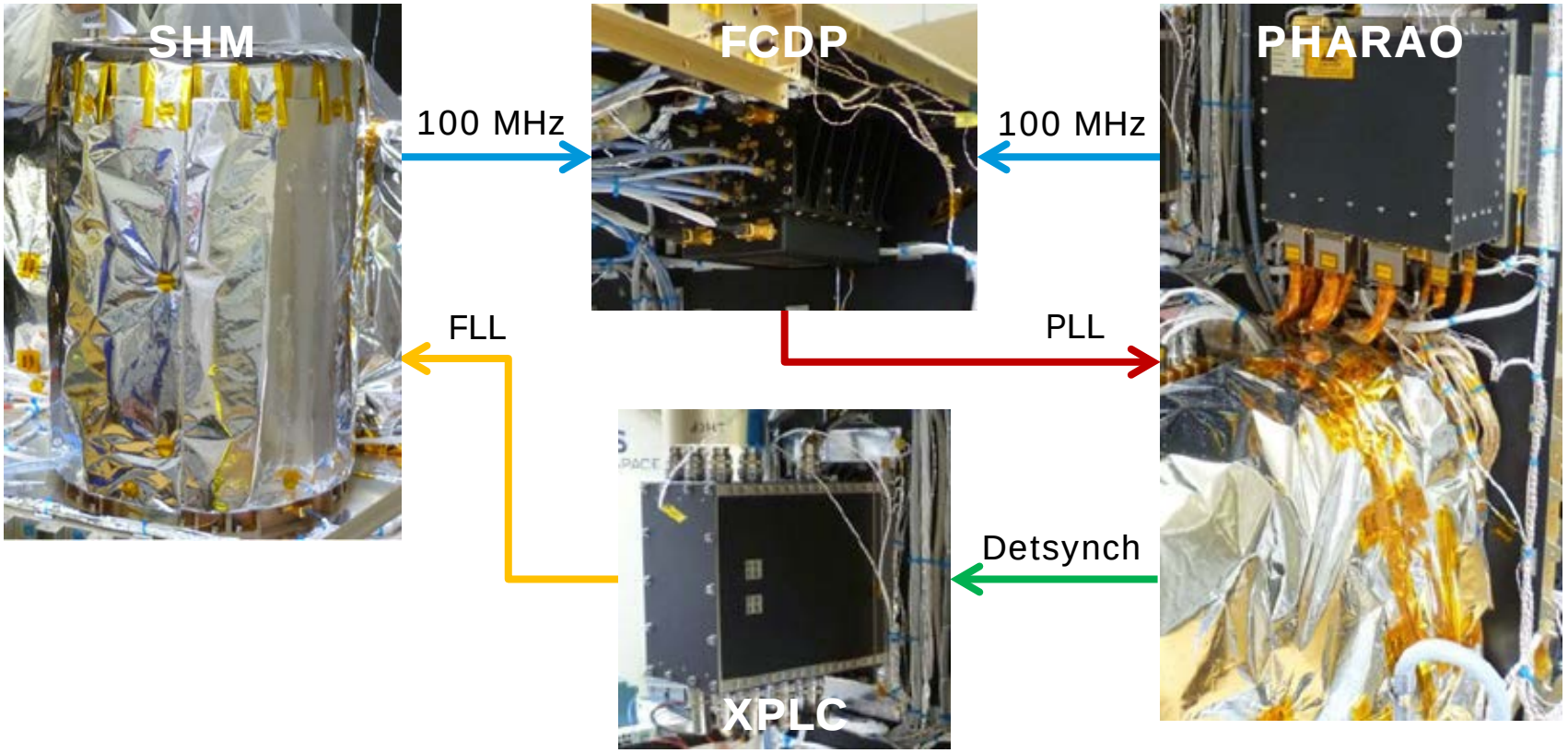
- PHARAO (CNES): Atomic clock based on laser cooled Cs atoms
- SHM (ESA): Active hydrogen maser
- FCDP (ESA): Clocks comparison and distribution
- MWL (ESA): T&F transfer link
- GNSS receiver (ESA)
- ELT (ESA): Optical link
- Support subsystems (ESA)
  - XPLC: External PL computer
  - PDU: Power distribution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



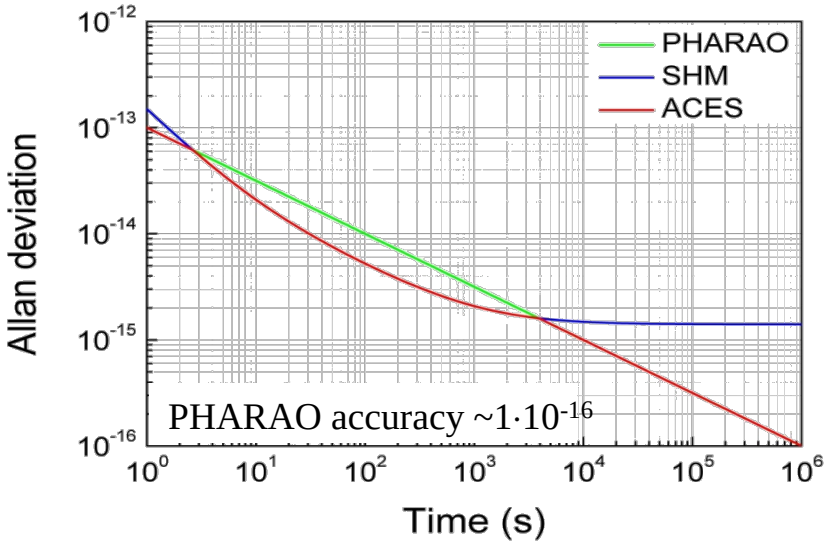
Volume: 1172x867x1246 mm^3
Mass: 227 kg
Power: 450 W

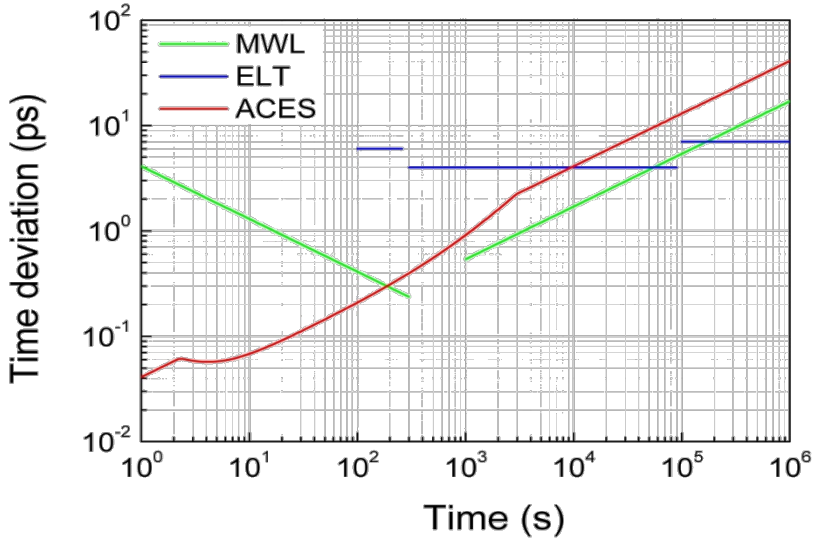
AIRBUS DEFENCE & SPACE

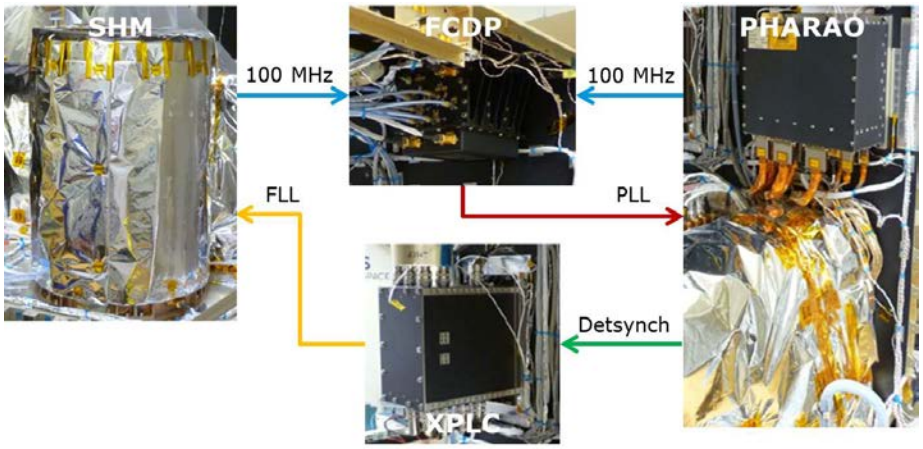
ACES Servo-loops

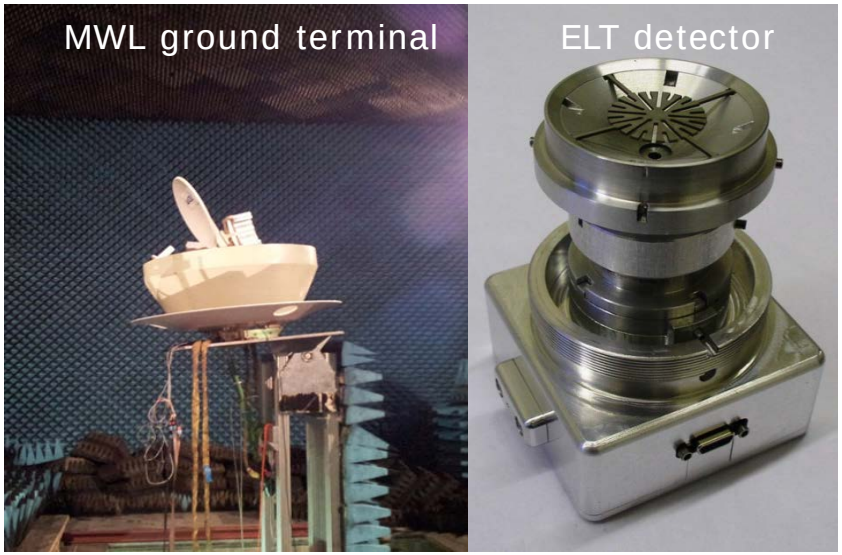


ACES Clocks and Links Performance

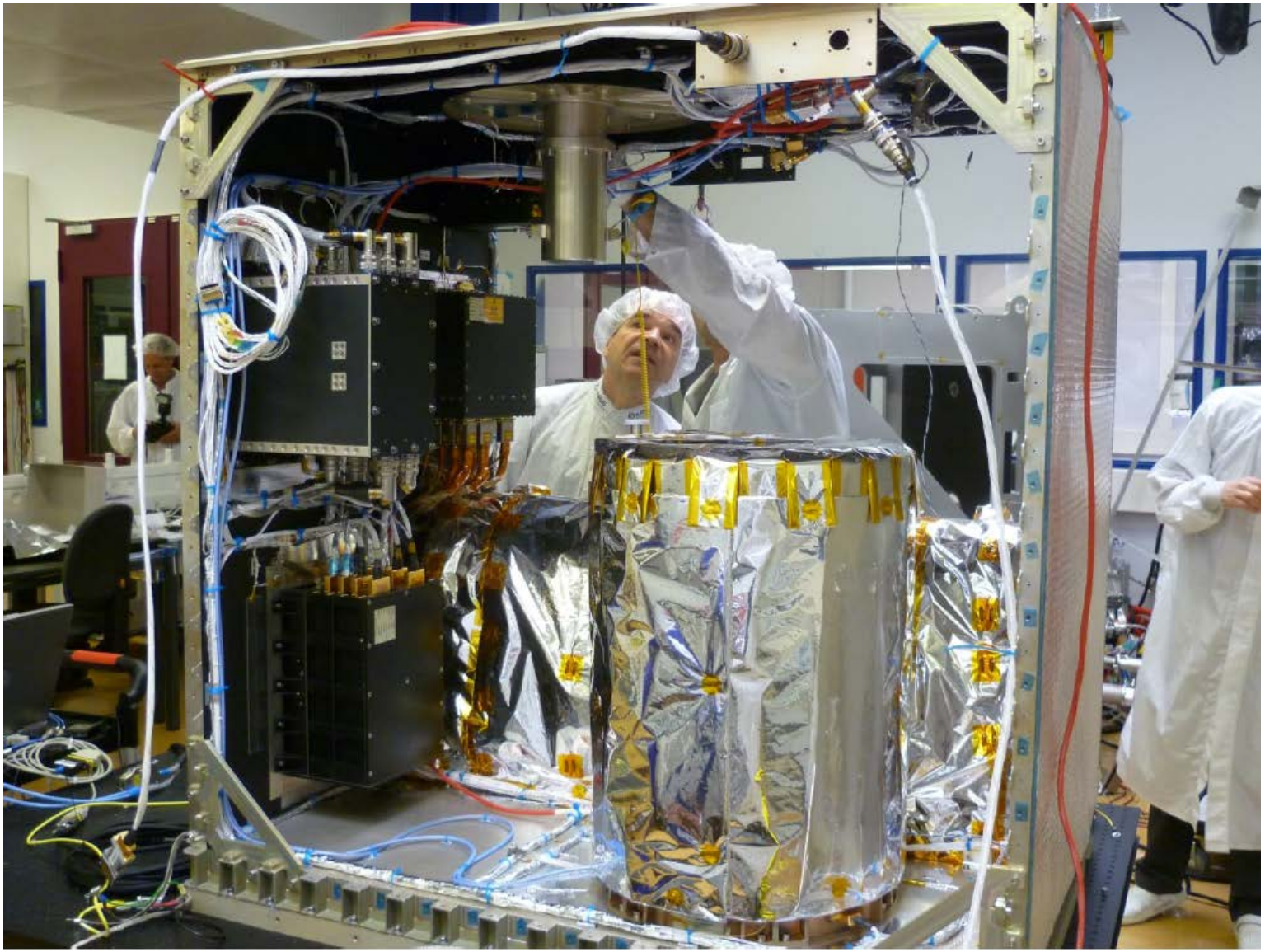




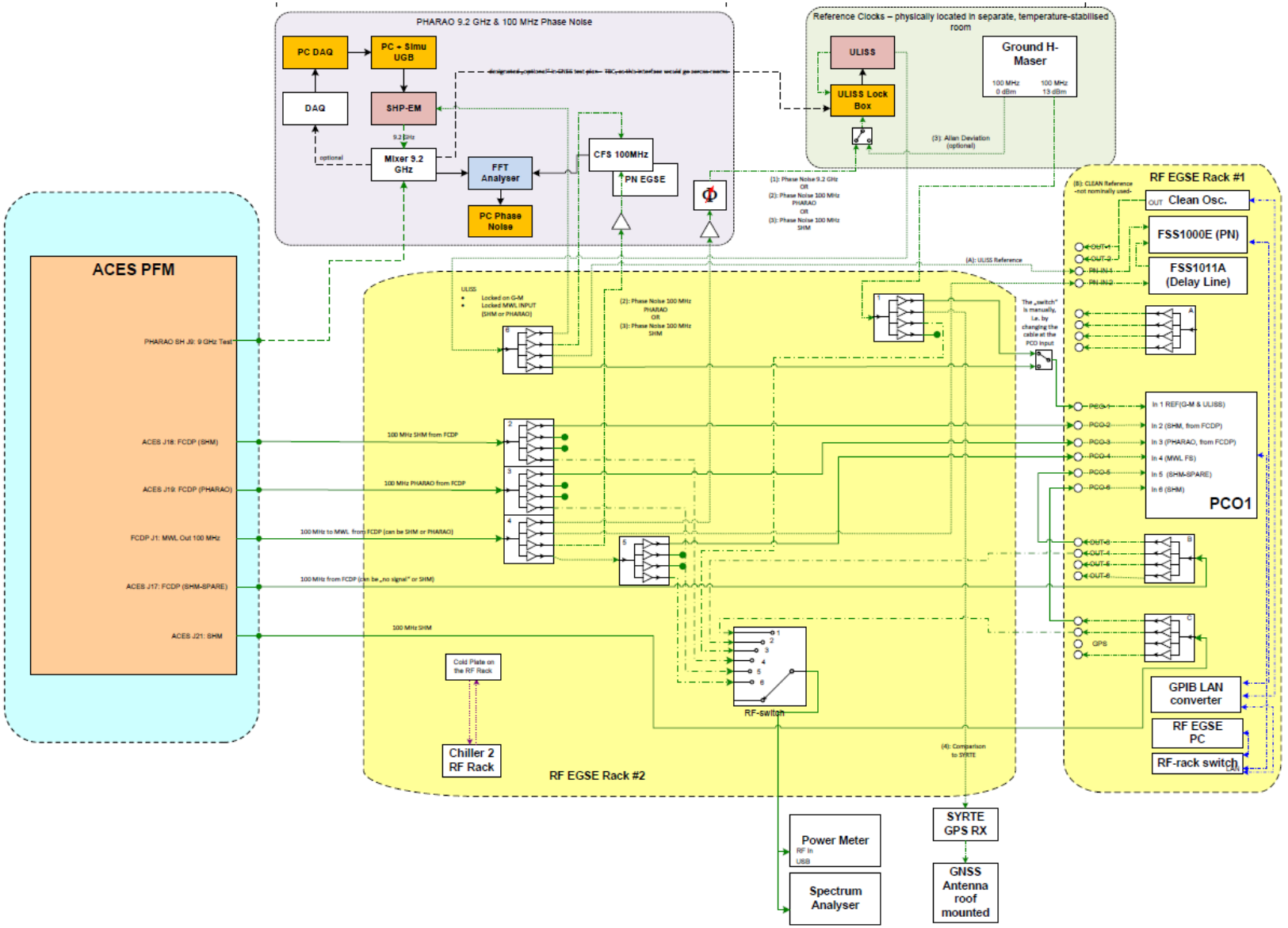




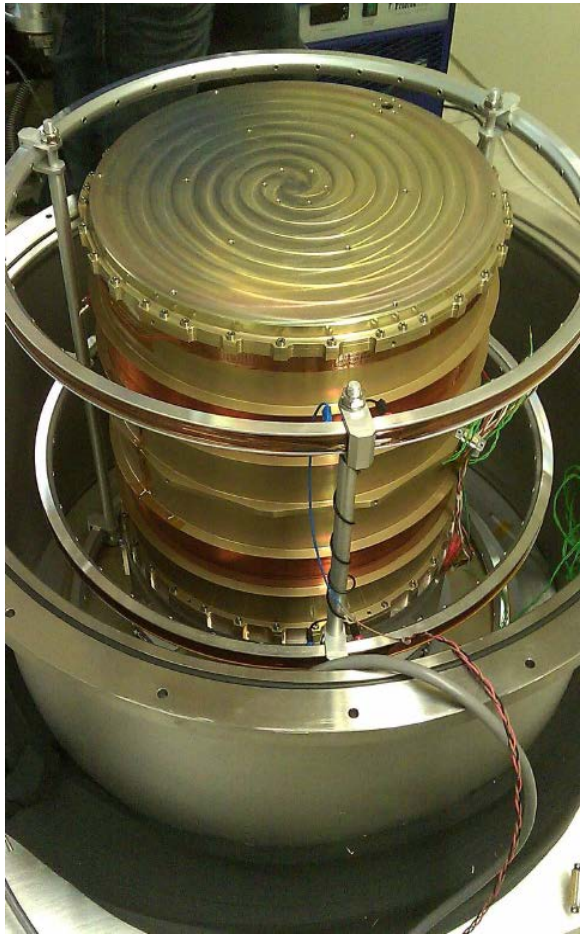
ACES Integration Activities



ACES Pre-IST (Integrated System Tests)



SHM: An Active H-maser for Space

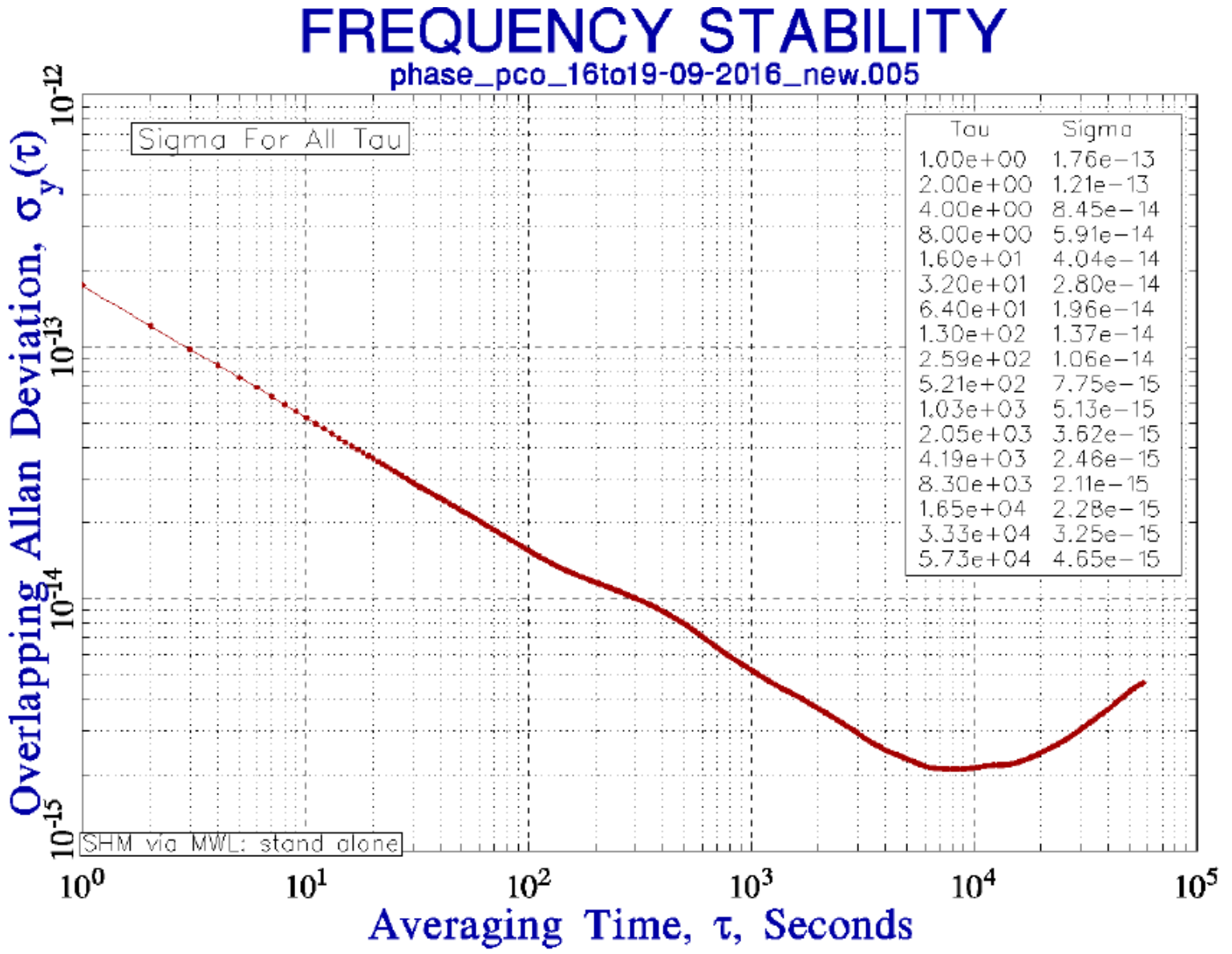


Volume: 390x390x590 mm^3
Mass: 42 kg

- 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
  - Automatic Cavity Tuning System (ACT)

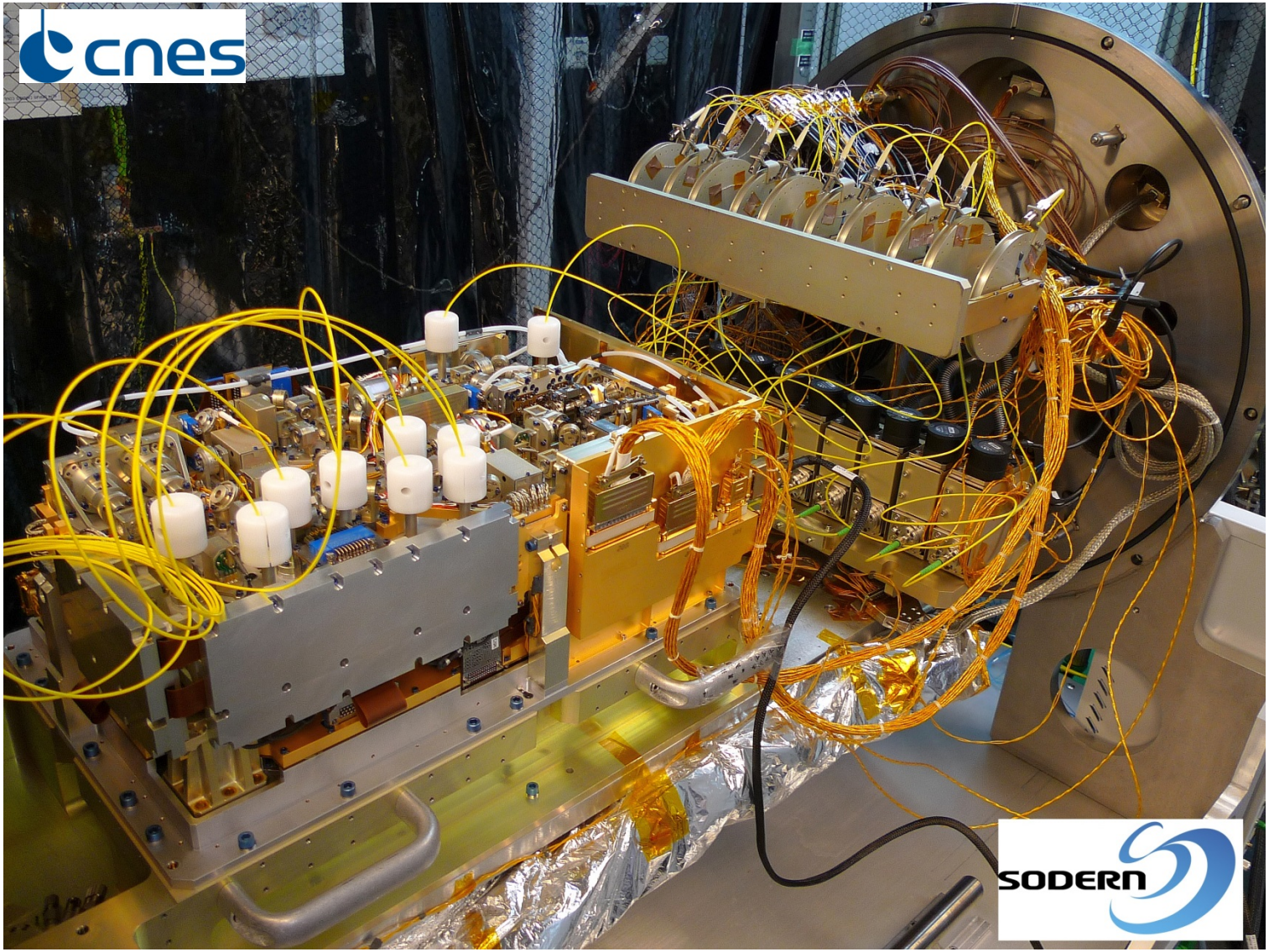
SpectraTime iPrecision Timing Solutions™

SHM EM Stability

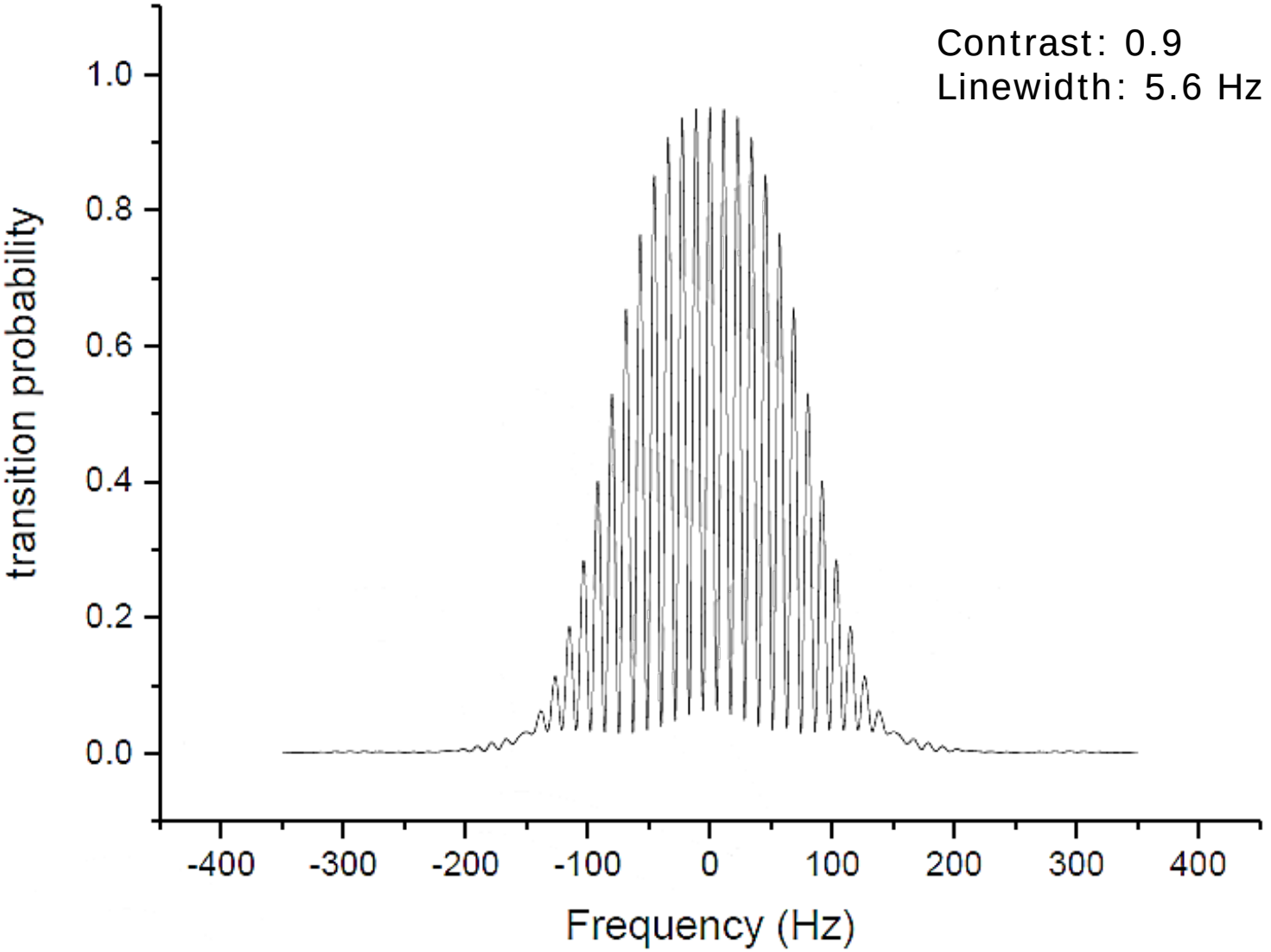


PHARAO FM Integration

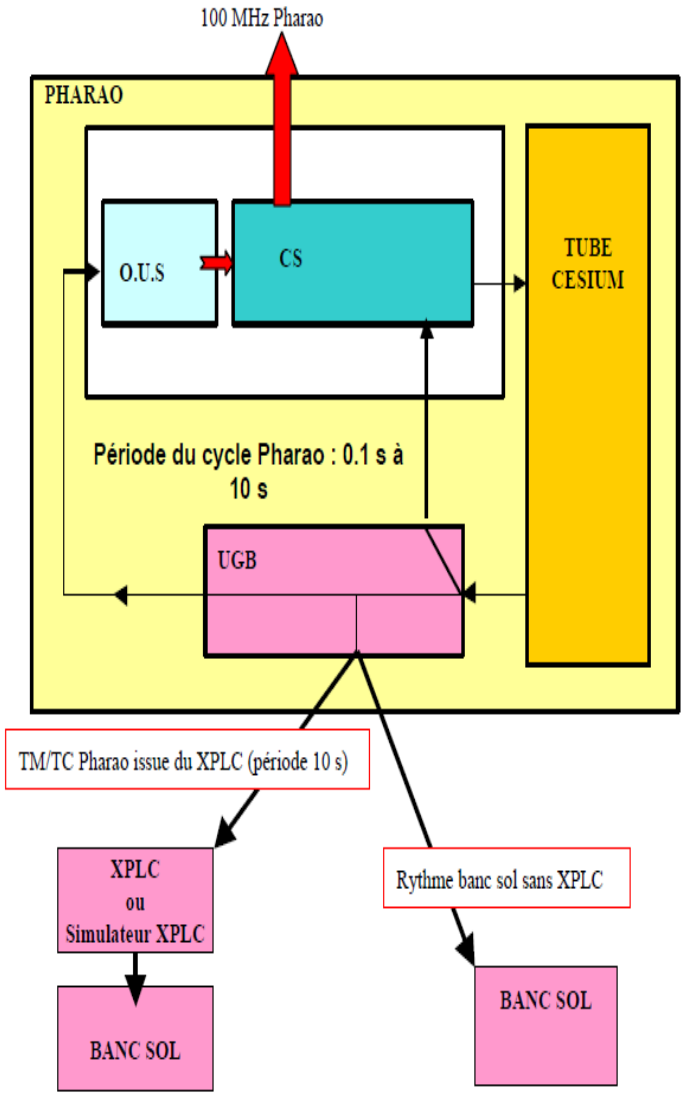
Flight Model of the PHARAO Lasers Source

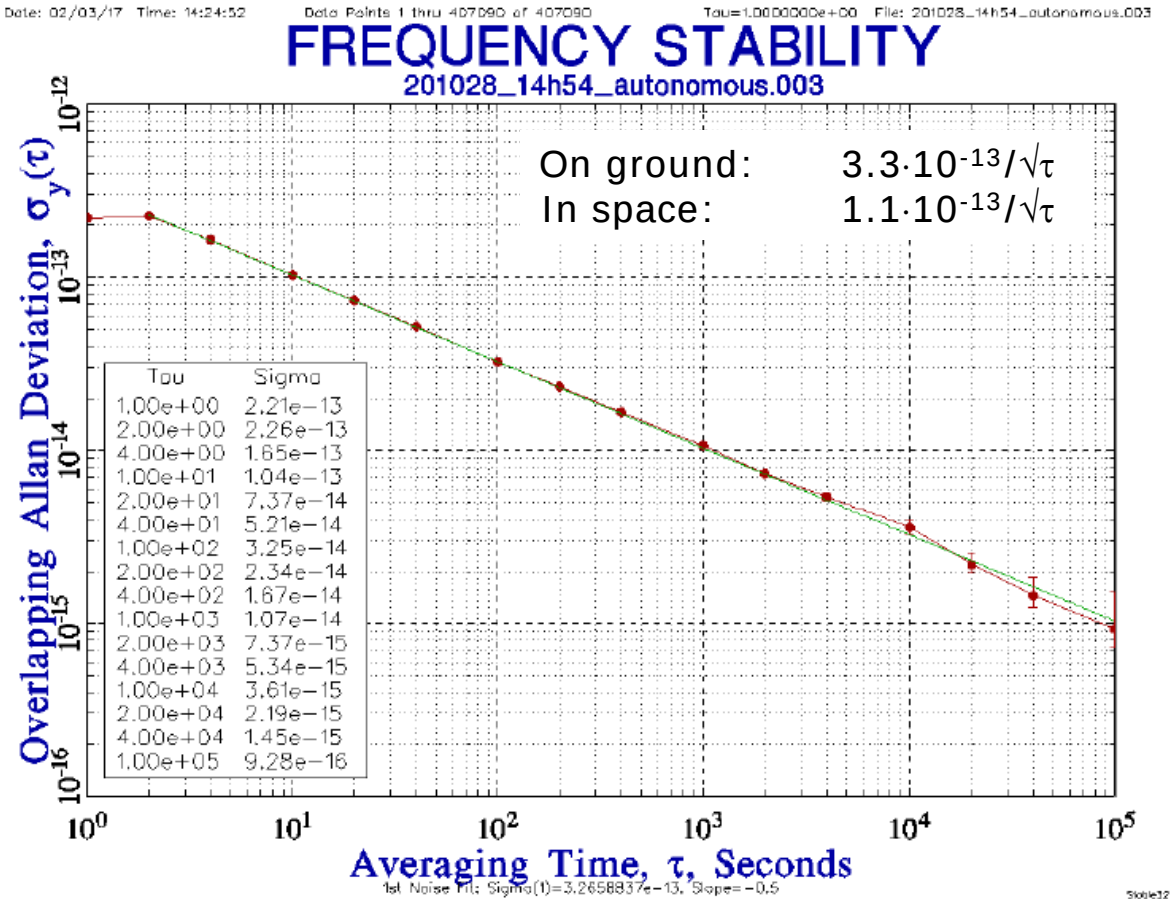


PHARAO FM Ramsey Fringes

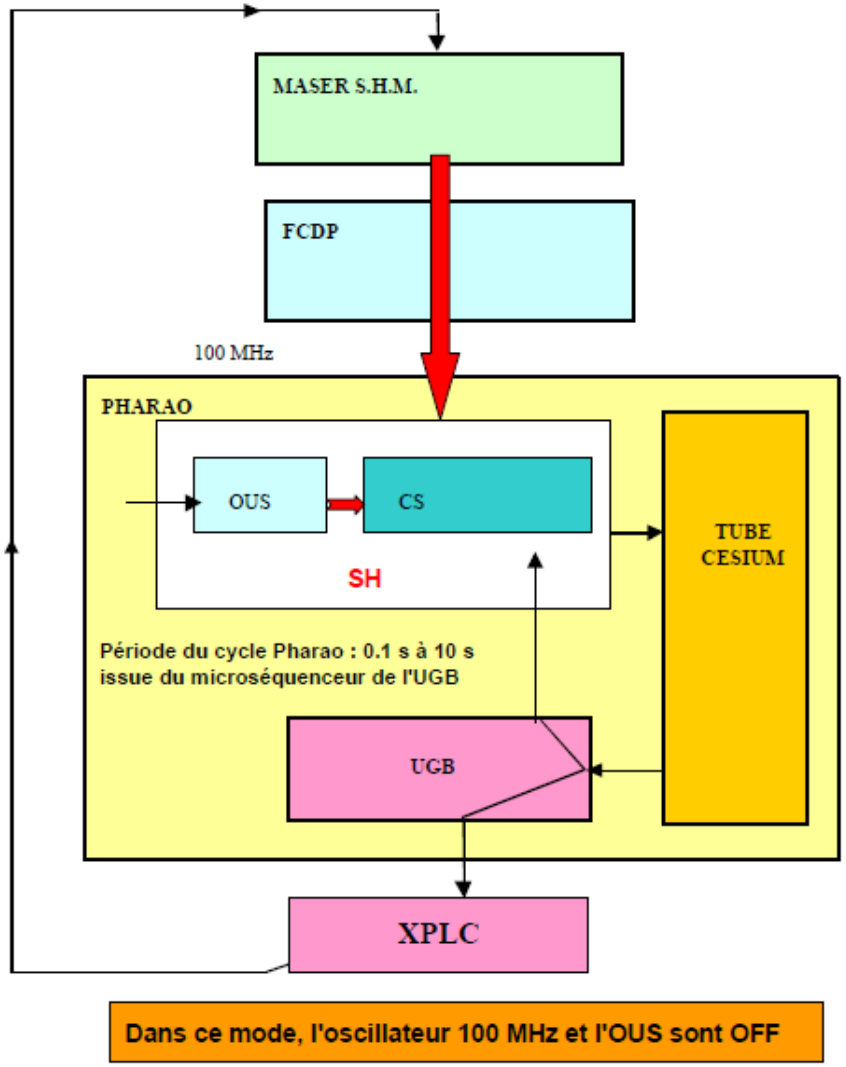


PHARAO FM Stability – Autonomous Mode

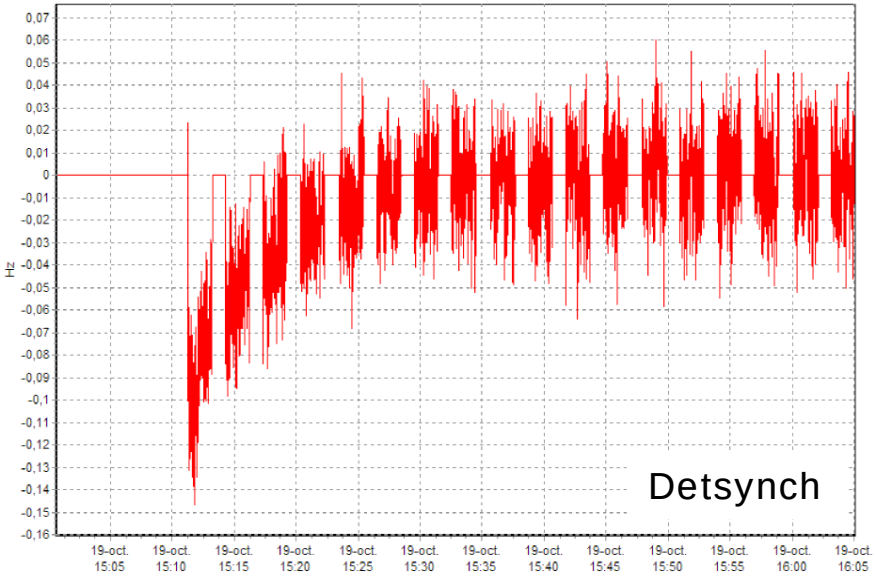


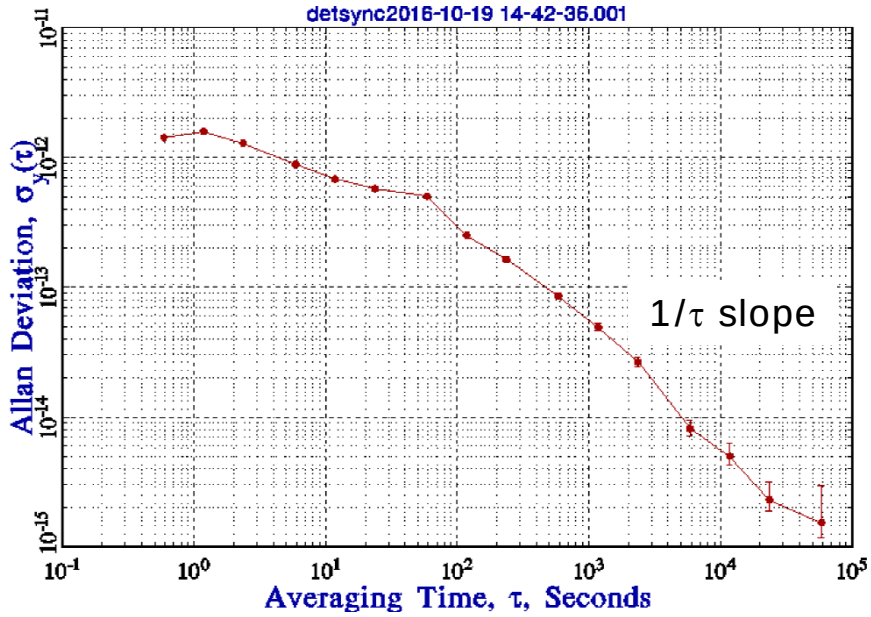


ACES Backup Mode



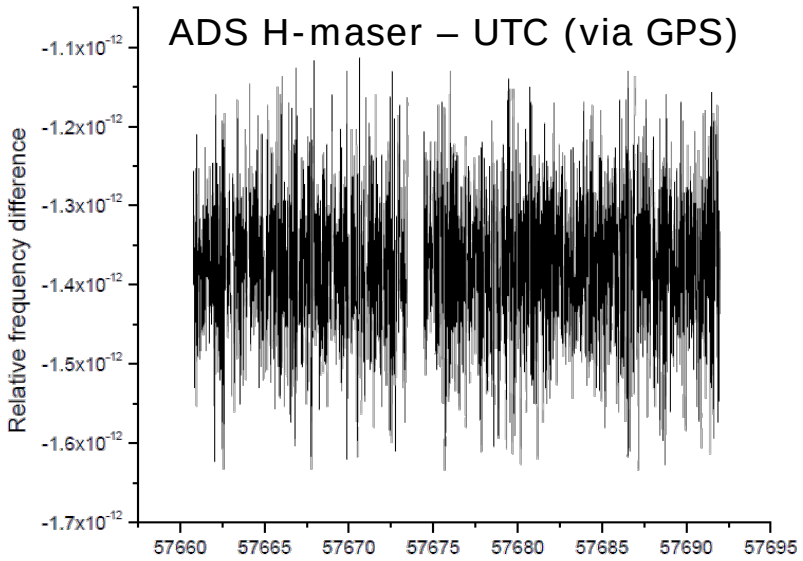
Dans ce mode, l'oscillateur 100 MHz et l'OUS sont OFF

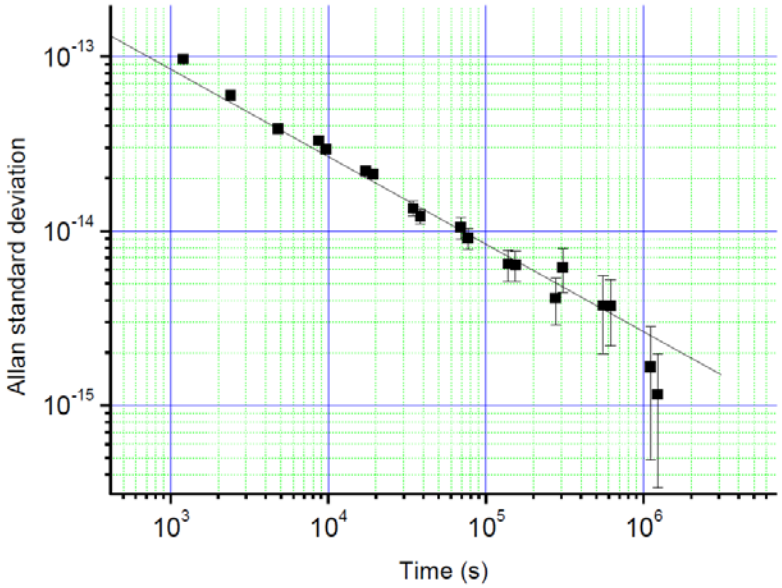




PHARAO FM Frequency Shift and Accuracy

	Main frequency shifts ($\cdot 10^{-15}$)
2nd order Zeeman effect ($\Delta\nu$=1372 Hz)	178
Blackbody radiation (T=24.999 mK)	-17
Cold collisions ($N=1.47\cdot10^6$)	-6.3
1st order Doppler effect	2.7
Gravitational redshift (410 m)	47.3
Total	205

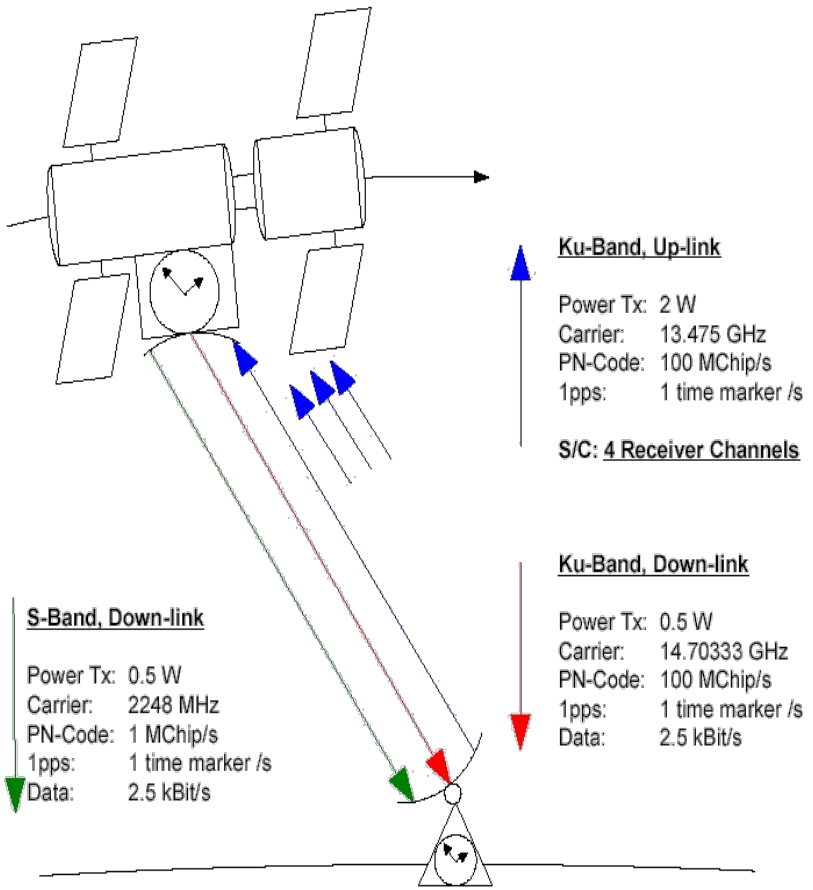




PHARAO Accuracy (evaluated @ CNES):

- On ground: $1.4\cdot10^{-15}$
- In space: $< 2\cdot10^{-16}$

MWL



AIRBUS DEFENCE & SPACE

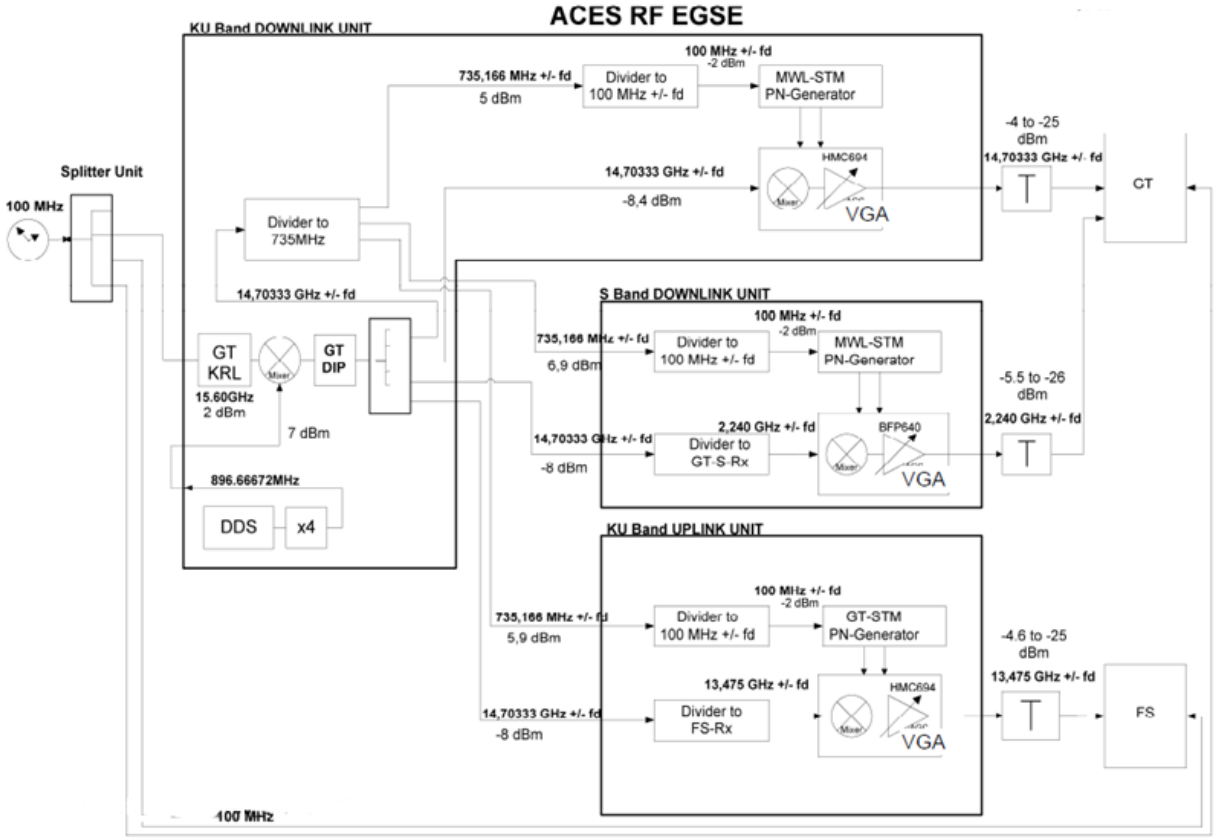
TIMETECH

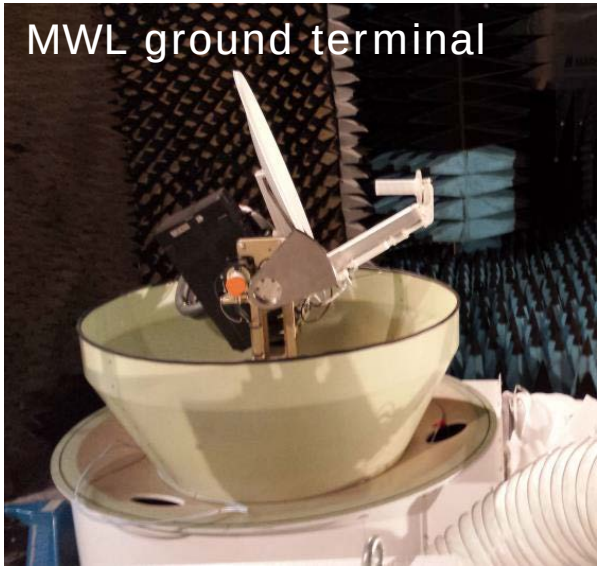
TZR

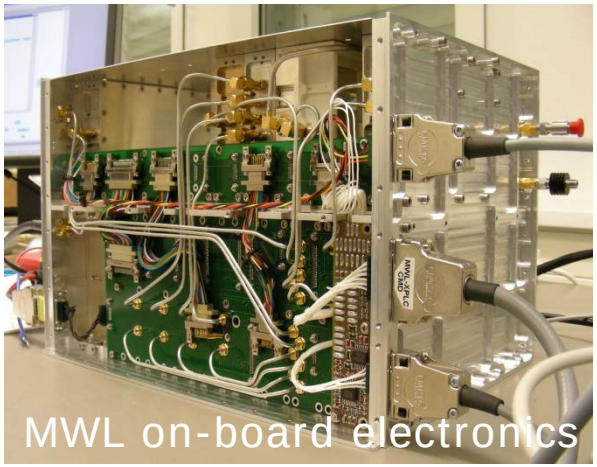
EREMS

- 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 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

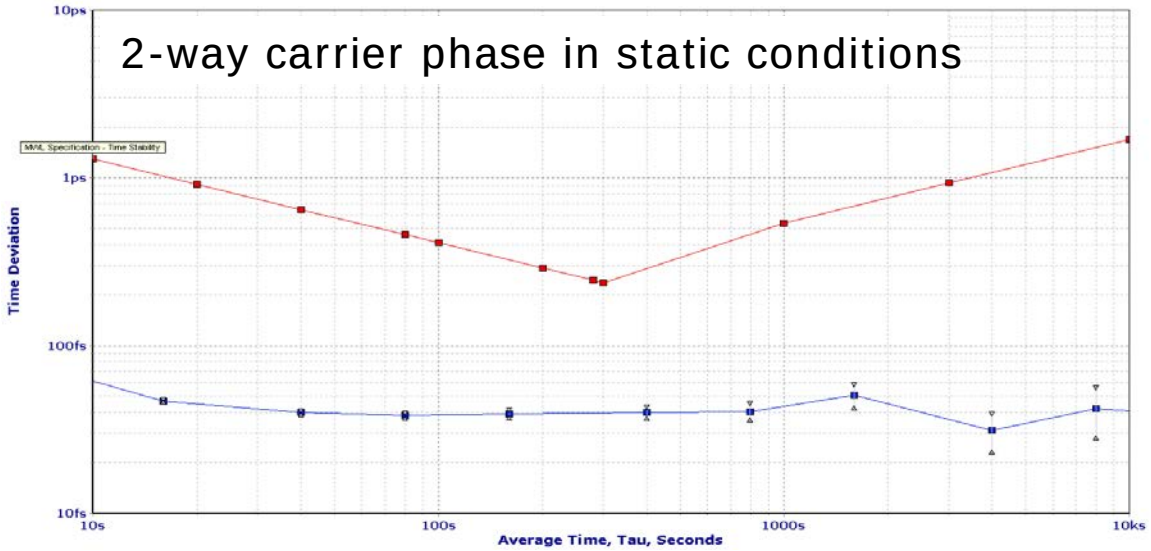
MWL EM End-to-end Test

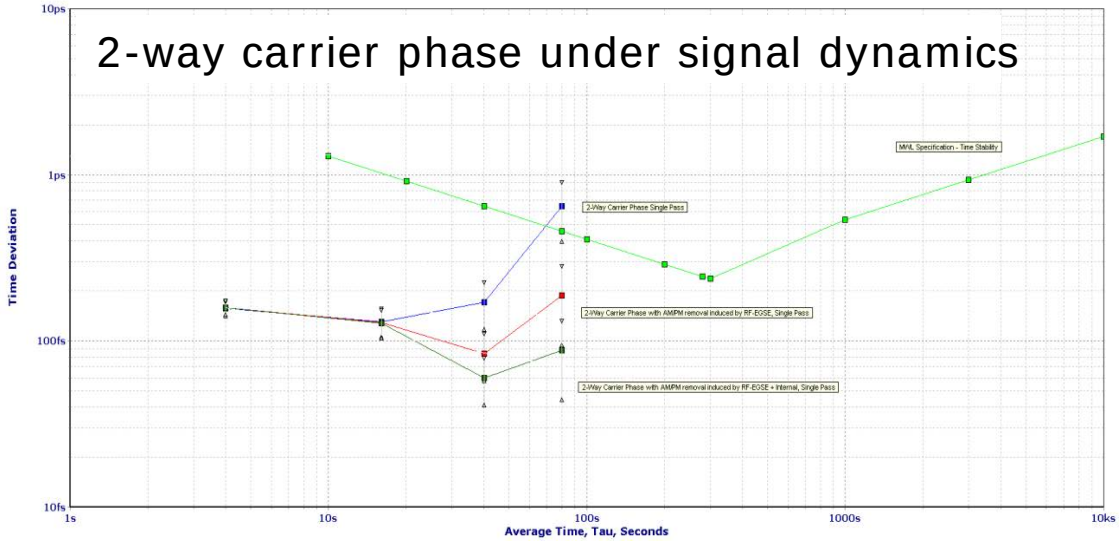




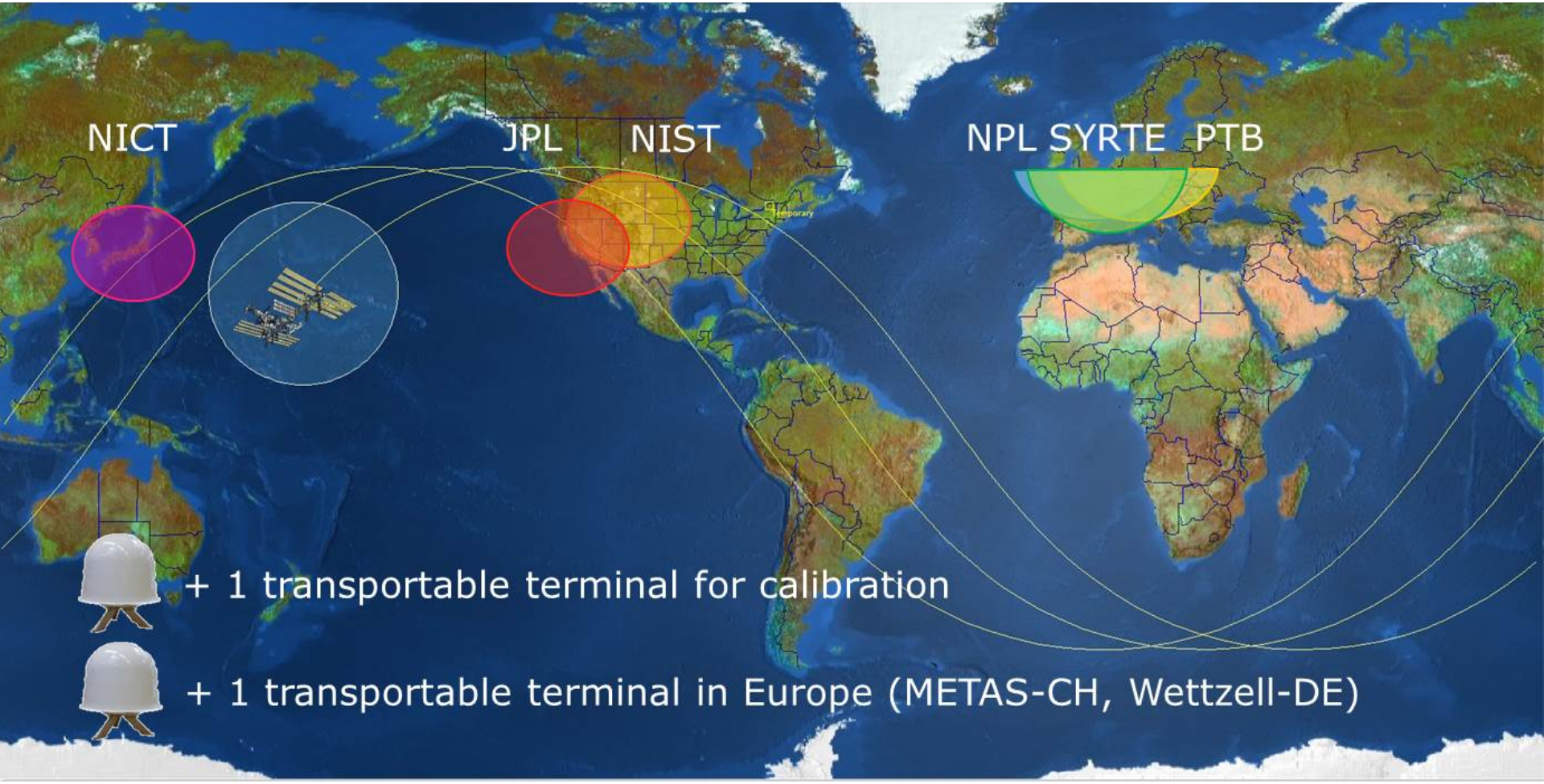


MWL EM Results

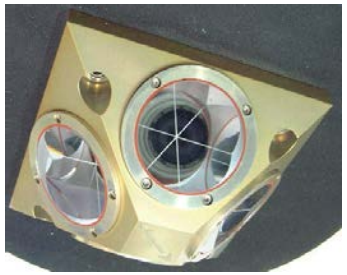


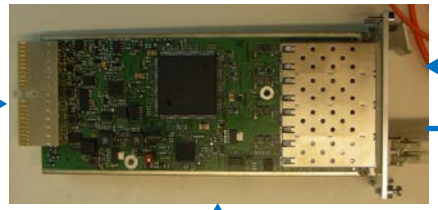


ACES MWL Network



European Laser Timing (ELT)





TM/TC

Power

ACES

t_{space}

ACES Time Scale (MWL)

Detector package
500 grams
0.6 Watt

t_{stop} t_{start}

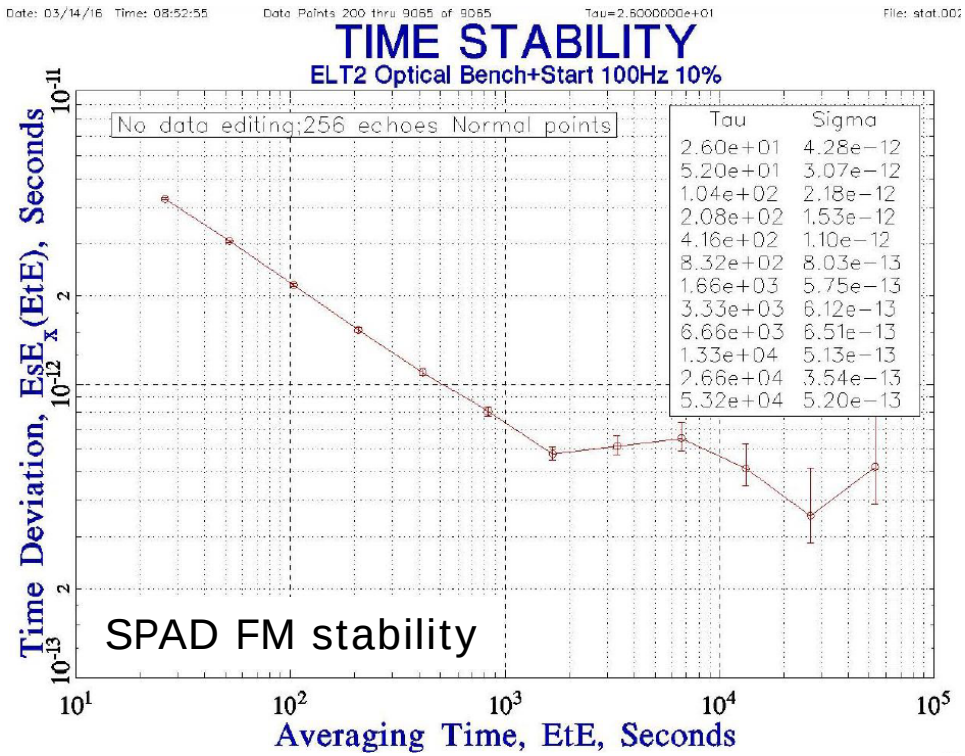
$$\tau_g(t) - \tau_s(t) = \frac{t_{start} + t_{stop}}{2} - t_{space} + \\ + \tau_{relativity} + \tau_{atmosphere} + \tau_{geometry}$$

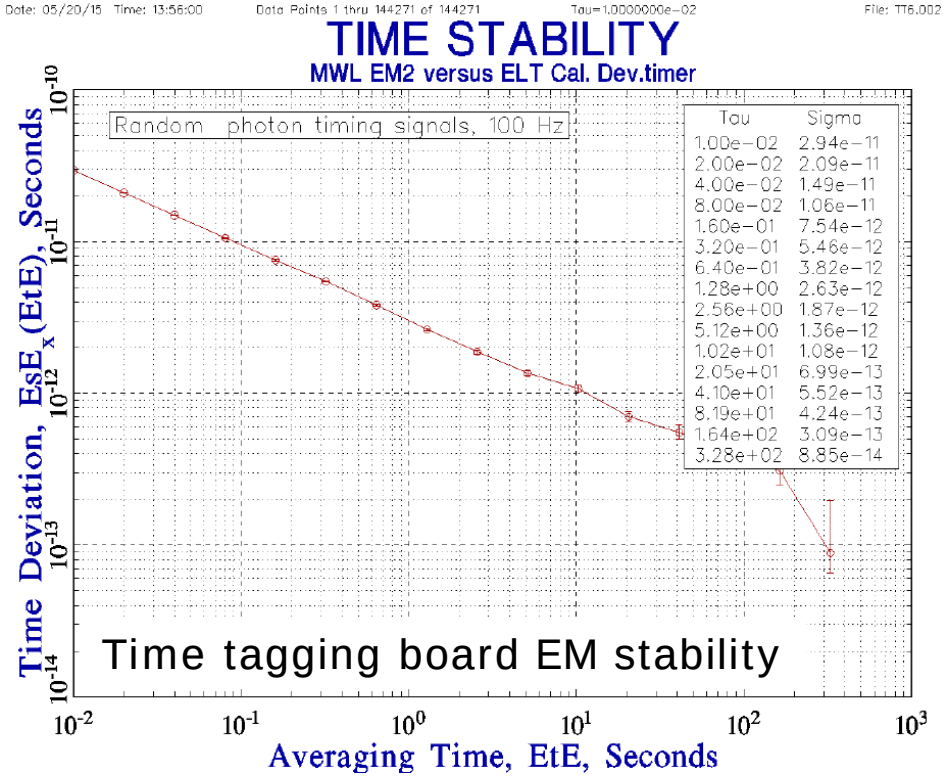
CTU Prague

TIMETECH

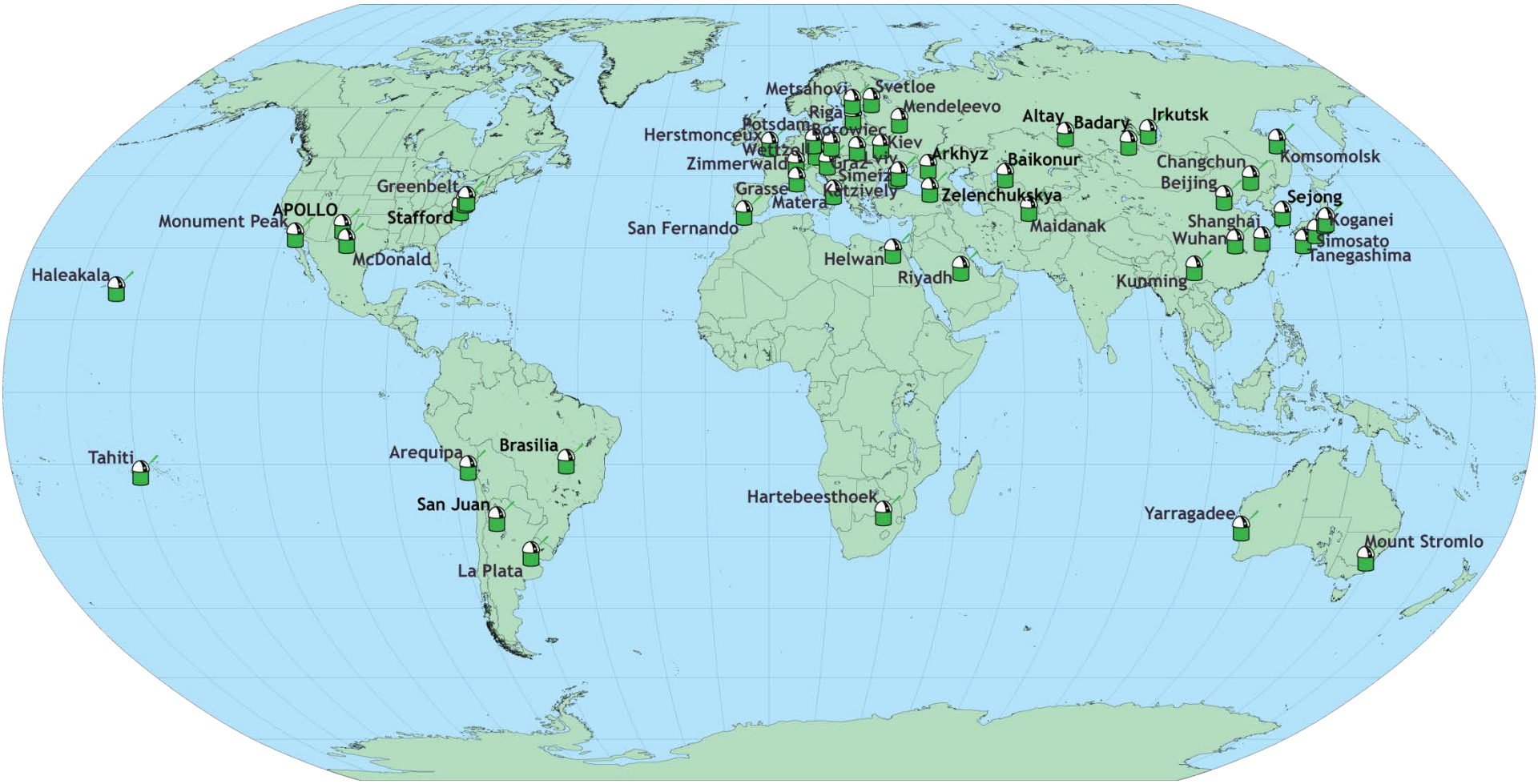
AIRBUS DEFENCE & SPACE

ELT FM Performance





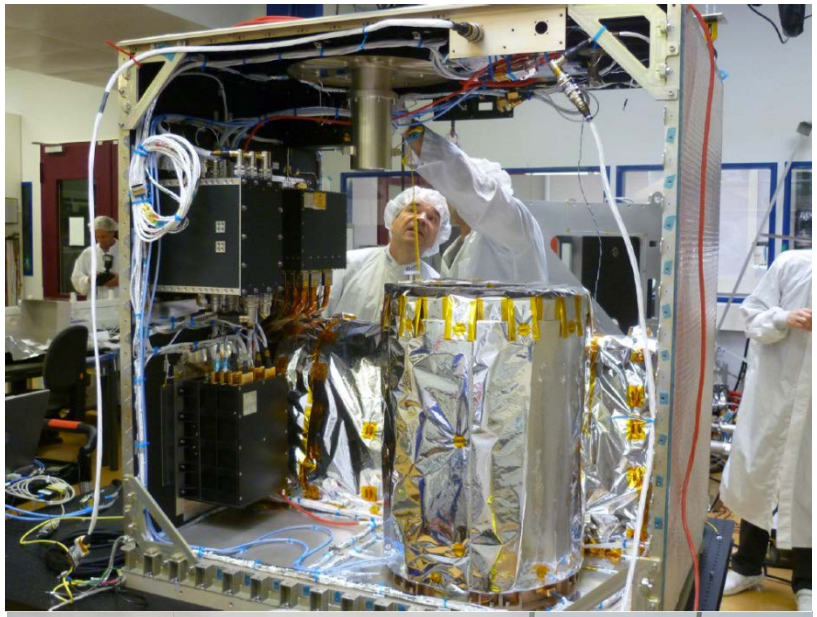
ILRS Network of SLR Stations



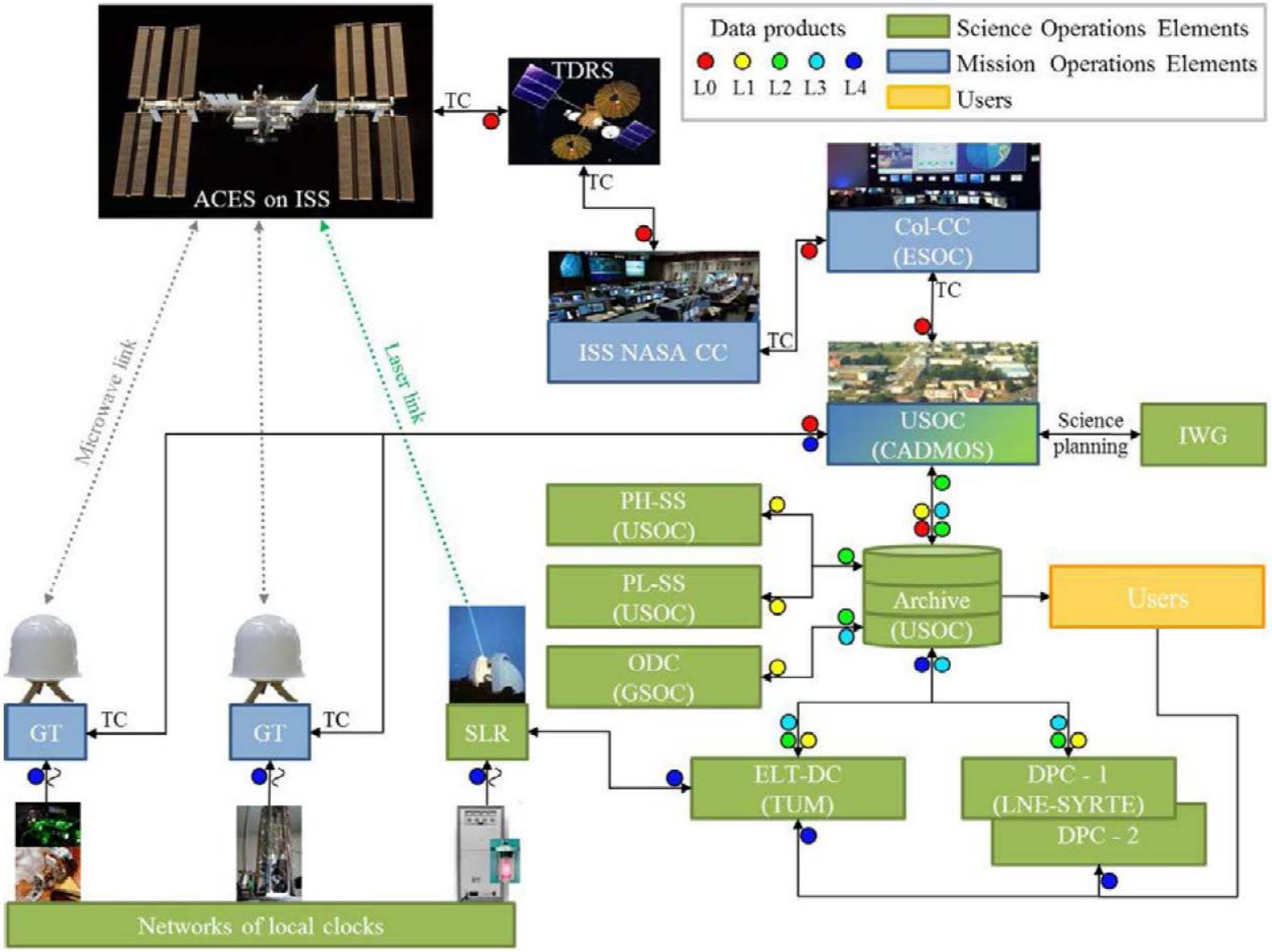
ACES submitted to ILRS as target: Wettzell, the ACES primary station already calibrated; Gratz and Herstmonceaux will follow; other stations can join provided they comply with ISS safety requirements.

ACES Status

- PHARAO FM delivered and integrated on the ACES baseplate
- FCDP, ELT, and on-board GNSS receiver FMs delivered for integration
- MWL FM and SHM PFM will be completed, tested and delivered by end 2017
- Pre-IST tests completed in Nov. 2016
- ACES FM tests already started and continued all across 2017 and 2018
- MWL GTs:
  - First terminal deployed in PTB in Nov. 2015 and remotely monitored since then
  - Remaining fixed terminals to be deployed by mid 2018
- ACES ready for launch not earlier than August 2018
  - 6 months: commissioning/calibration
  - 12 to 30 months: routine science phase



ACES Data and Science Ground Segment



ACES Investigators Working Group

ACES Science Coordinators	C. Salomon (*IWG co-chair*, ENS, FR) F. Riehle (PTB, DE) G. Tino (Firenze University, IT) S. Schiller (Düsseldorf University, DE) M. Tobar (UWA, AU) T. Südmeyer (Neuchâtel University, CH)
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PHARAO Instrument Science Coordinators	P. Laurent (LNE-SYRTE, FR) A. Clairon (LNE-SYRTE, FR)
MWL Instrument Science Coordinators	M. Prevedelli (Bologna University, IT) D. Piester (PTB, DE)
GNSS Instrument Science Coordinator	O. Montenbruck (DLR, DE)
ELT Instrument Science Coordinator	I. Procházka (CTU Prague, CZ)
Data Analysis Coordinators *T&F Transfer and Fundamental Physics* *Geodesy* *European Laser Timing*	 P. Wolf (LNE-SYRTE, FR) W. Bosch (DGFI, DE) U. Schreiber (TUM, DE)
Ground Clocks Coordinator	TBD
On-site Ground Clock Responsible *SYRTE* *PTB* *NPL* *NIST* *JPL* *NICT*	 M. Abgrall (SYRTE, FR) D. Piester (PTB, DE) S. Shemar (NPL, UK) S. Jefferts (NIST, US) N. Yu (JPL, US) M. Fuijeda (NICT, JP)
Topical Team Coordinators *Cold Atom Sensors in Space* *Relativity and Fundamental Physics* *Geodesy, Clocks, and Time Transfer*	 W. Ertmer (IQ Hannover, DE) P. Jetzer (Zurich University, CH) U. Schreiber (TUM, DE)

ACES Data Policy

The ACES data policy has been shaped considering:

- Specific aspects of the ACES mission;
- ESA data policy as described in the documents:
  - ESA/PB-HSR(2004)29 rev. 2 corr.1 on “Human Spaceflight Data Policy”;
  - ESA/C(2002)3 corr.1 on “Rules on Information, Data and Intellectual Property”.

Through the basic principles below, the Human Spaceflight Data Policy has been adapted to the specific case of ACES:

- ACES data will be provided by ESA to the ACES IWG for analysis and publication of the scientific results.
- The ACES IWG will coordinate along with the Topical Teams an optimal plan of utilization of the ACES data.
- Scientists that are not members of the ACES IWG and are interested in participating to the ACES data analysis:
  - They shall apply to ESA by submitting a proposal to the ACES Project Scientist.
  - Upon positive evaluation of the data analysis proposal by the ACES IWG and ESA approval, the scientist can be entitled to access all ACES data or part of it.

ACES Data Policy

- ACES User shall mean IWG scientist(s) or scientist(s) entitled to access all ACES data or part of it (as specified in point 4) for analysis and publication of the scientific results.
- Right of Prior Access
  - ESA grants the ACES Users a right of Prior Access to the Raw and Calibrated Data for scientific analysis and first publication rights for a period of one year (Period of Prior Access) beginning on the date of receipt by the Users of such Raw and Calibrated Data, and any associated data, in a form suitable for analysis, and after their validation by the ACES IWG.
  - Users wishing to publish the results obtained in the Period of Prior Access shall first submit them to the ACES IWG for internal review. However, such a review shall not unduly withhold the publication and shall be carried out within a reasonable time.
- All data shall be protected, distributed, stored and handled by the responsible USOC, under mandate of ESA.
- Arrangements shall be made with the Users so that they:
  - Are obligated to furnish expeditiously to ESA an analysis of the results obtained in the execution of their respective experiments;
  - Will take all reasonable steps to make these results available to the scientific community, or alternatively, authorize ESA to do so, through publication in appropriate journals or other established channels as soon as practicable and consistent with good scientific practice.
- The ACES data will become publicly available (directly accessible or made available upon request) after the Period of Prior Access

...looking forward to receiving your research proposals

Thanks for your attention