Atomic Clock Ensemble in Space

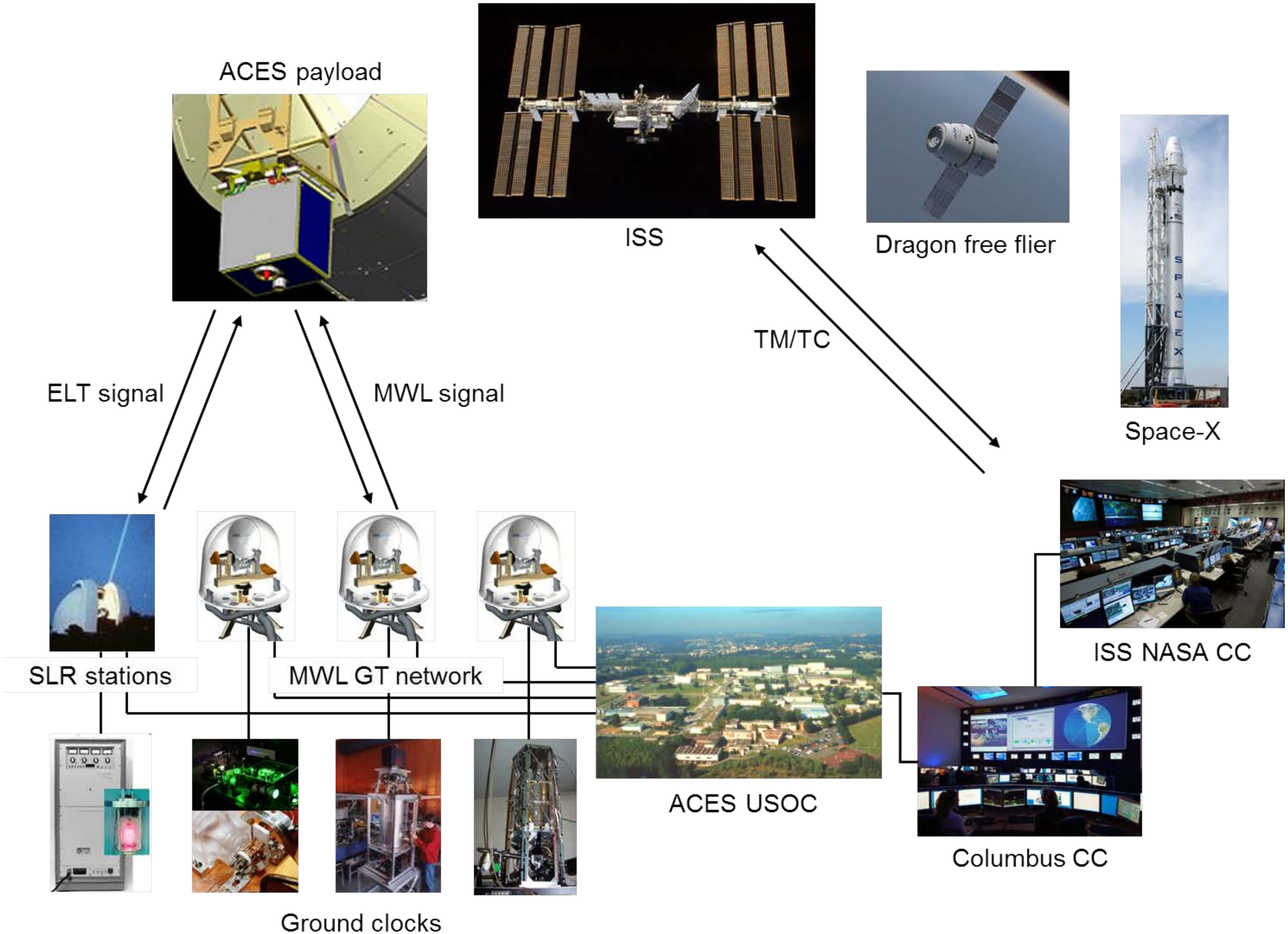
Luigi Cacciapuoti

On behalf of the ACES Team

23/10/2018

ACES Workshop 2018 - Munich

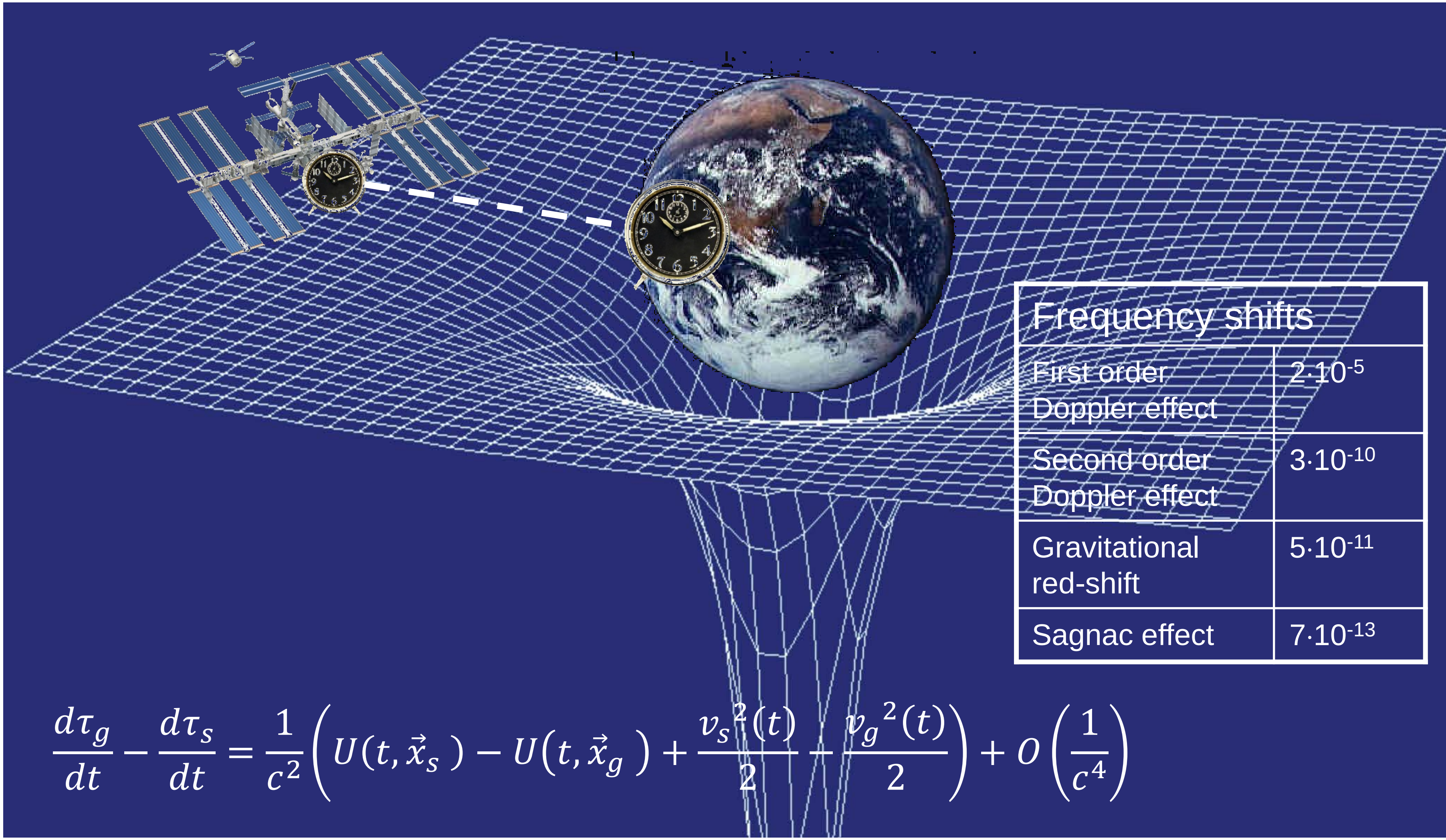
ACES


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

Fundamental Physics Tests

ACES Mission Objectives	ACES performances	Scientific background and recent results
	Fundamental physics tests	
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level $< 50 \cdot 10^{-6}$ after 300 s and $< 2 \cdot 10^{-6}$ after 10 days of integration time.	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 70 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-17}$ year $^{-1}$ down to $3 \cdot 10^{-18}$ year $^{-1}$ in case of a mission duration of 3 years	Optical clocks progress will allow clock-to-clock comparisons below the 10^{-17} level. Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of α, m_e / Λ_{QCD} , and m_u / 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 to two orders of magnitude.

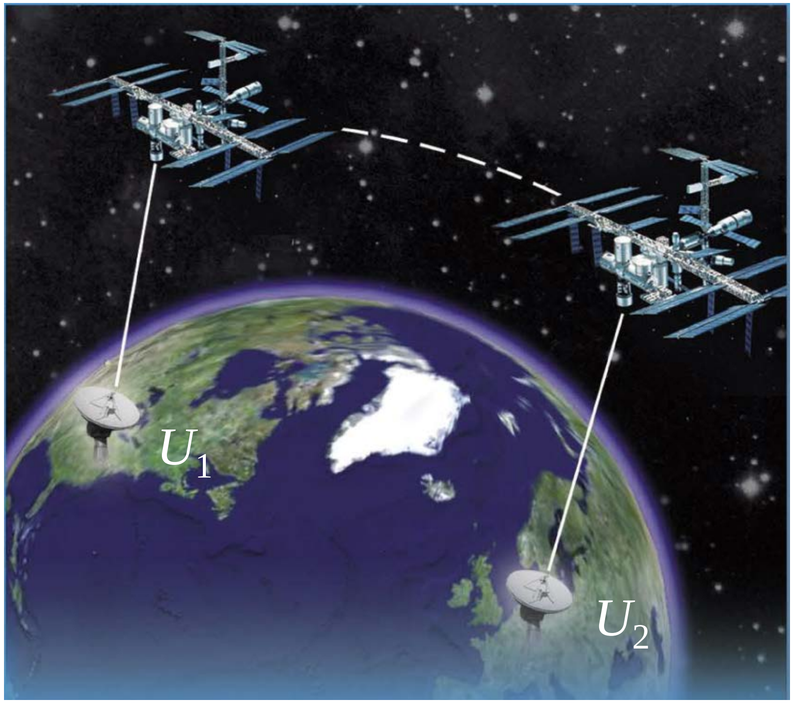
Gravitational Redshift Test

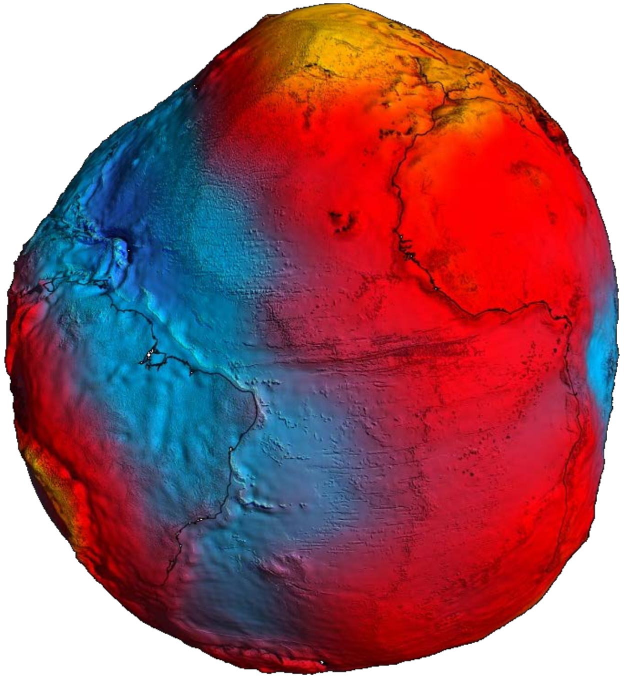


Frequency shifts	
First order Doppler effect	$2 \cdot 10^{-5}$
Second order Doppler effect	$3 \cdot 10^{-10}$
Gravitational red-shift	$5 \cdot 10^{-11}$
Sagnac effect	$7 \cdot 10^{-13}$

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

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 1 week 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.

Fundamental Physics Tests

ACES Mission Objectives	ACES performances	Scientific background and recent results
Fundamental physics tests		
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level < $50 \cdot 10^{-6}$ after 300 s and < $2 \cdot 10^{-6}$ after 10 days of integration time.	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 70 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1{\cdot}10^{-17}$ year $^{-1}$ down to $3{\cdot}10^{-18}$ year $^{-1}$ in case of a mission duration of 3 years	Optical clocks progress will allow clock-to-clock comparisons below the 10^{-17} level. Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of α, m_e / Λ_{QCD}, and m_u / 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 to two orders of magnitude.

Fundamental Constants

Frequency of hyperfine transitions: $$\nu_{\text{hfs}}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\text{hfs}}^{(i)} \times g^{(i)} \left(\frac{m_e}{m_p}\right) \alpha^2 F_{\text{hfs}}^{(i)}(\alpha)$$

Frequency of electronic transitions: $$\nu_{\text{elec}}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\text{elec}}^{(i)} \times F_{\text{elec}}^{(i)}(\alpha)$$

Ratios between atomic frequencies:

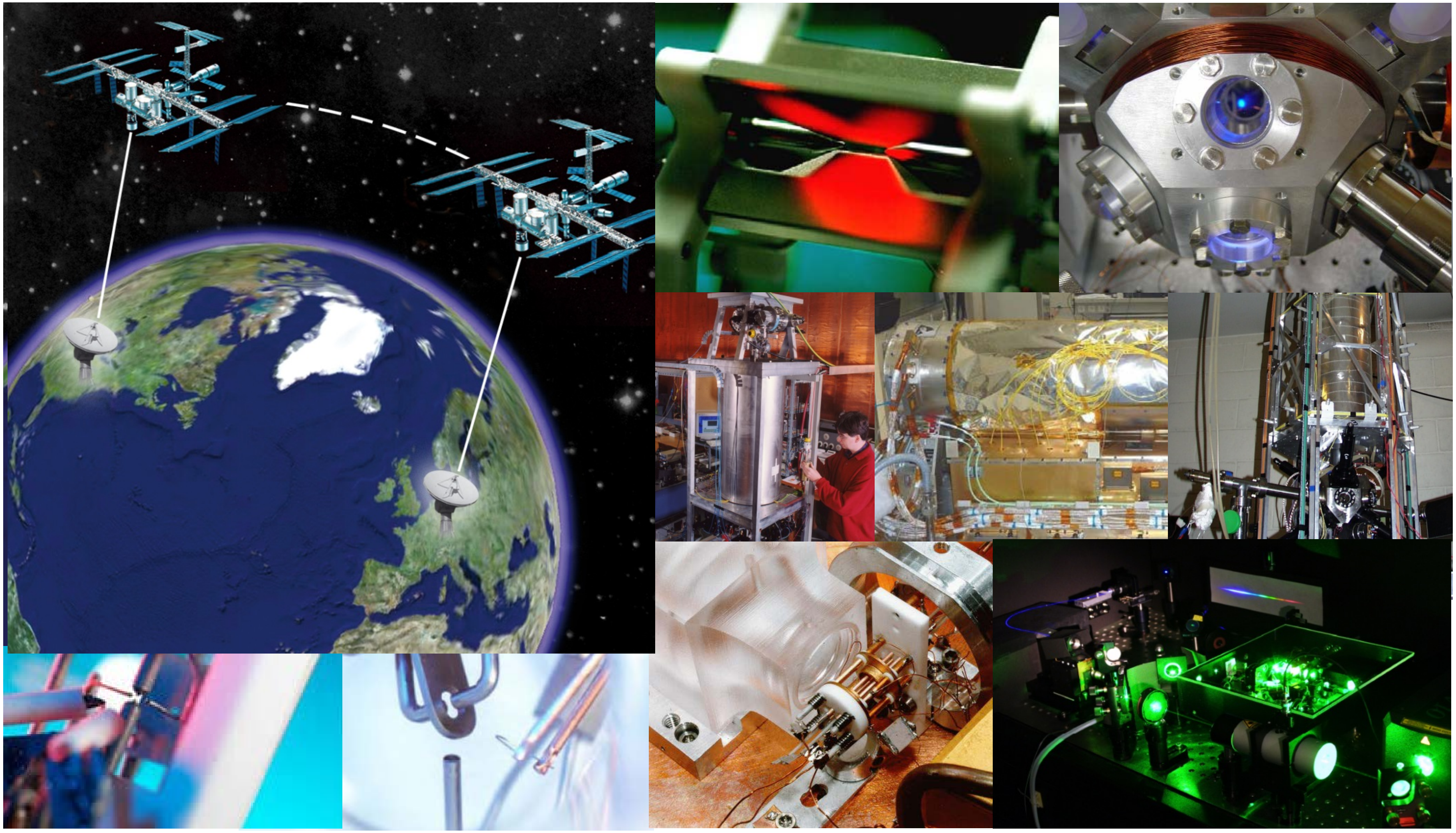
$$\frac{\nu_{\text{elec}}^{(ii)}}{\nu_{\text{elec}}^{(i)}} \propto \frac{F_{\text{elec}}^{(ii)}(\alpha)}{F_{\text{elec}}^{(i)}(\alpha)} \qquad \frac{\nu_{\text{hfs}}^{(ii)}}{\nu_{\text{elec}}^{(i)}} \propto g^{(ii)} \frac{m_e}{m_p} \alpha^2 \frac{F_{\text{hfs}}^{(ii)}(\alpha)}{F_{\text{elec}}^{(i)}(\alpha)} \qquad \frac{\nu_{\text{hfs}}^{(ii)}}{\nu_{\text{hfs}}^{(i)}} \propto \frac{g^{(ii)}}{g^{(i)}} \frac{F_{\text{hfs}}^{(ii)}(\alpha)}{F_{\text{hfs}}^{(i)}(\alpha)}$$

Sensitivity to time variations of fundamental constants:

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

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

Fundamental Constants



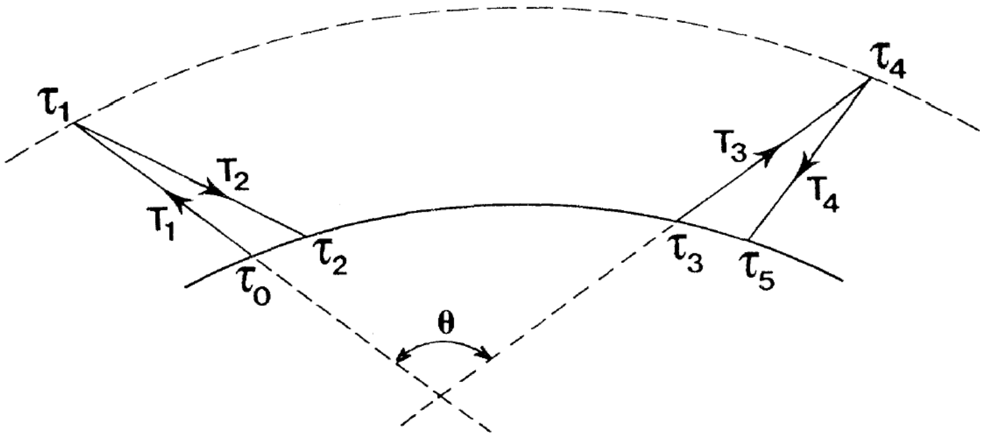
Fundamental Physics Tests

ACES Mission Objectives	ACES performances	Scientific background and recent results
Fundamental physics tests		
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level $< 50 \cdot 10^{-6}$ after 300 s and $< 2 \cdot 10^{-6}$ after 10 days of integration time.	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 70 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-17}$ year $^{-1}$ down to $3 \cdot 10^{-18}$ year $^{-1}$ in case of a mission duration of 3 years	Optical clocks progress will allow clock-to-clock comparisons below the 10^{-17} level. Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of α, m_e / Λ_{QCD} , *and* m_u / 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 to two orders of magnitude.

Special Relativity Tests

Kinematic test theories (RMS framework): Preferred reference frame (CMB) in which light is assumed to propagate isotropically

Dynamic test theories (SME framework): Lorentz transformations violating terms in the Hamiltonian of the system



$$T_1 - T_2 = \Delta_s + \Delta_l + 2\frac{\delta c}{c} T \cos\theta$$

$$(T_1 - T_2) - (T_3 - T_4) + \Delta_a = 2\frac{\delta c}{c} T (1 - \cos\theta)$$

Measurement principle:

- Exchange of microwave signals between ACES clocks and ground clocks along the ISS orbit
- Difference of measured reception and emission times provides the one-way travel time of the signal plus some unknown constant offset (desynchronization, path asymmetries, propagation delay ...)
- Difference of the up and down travel times sensitive to a non zero value of $\delta c/c$

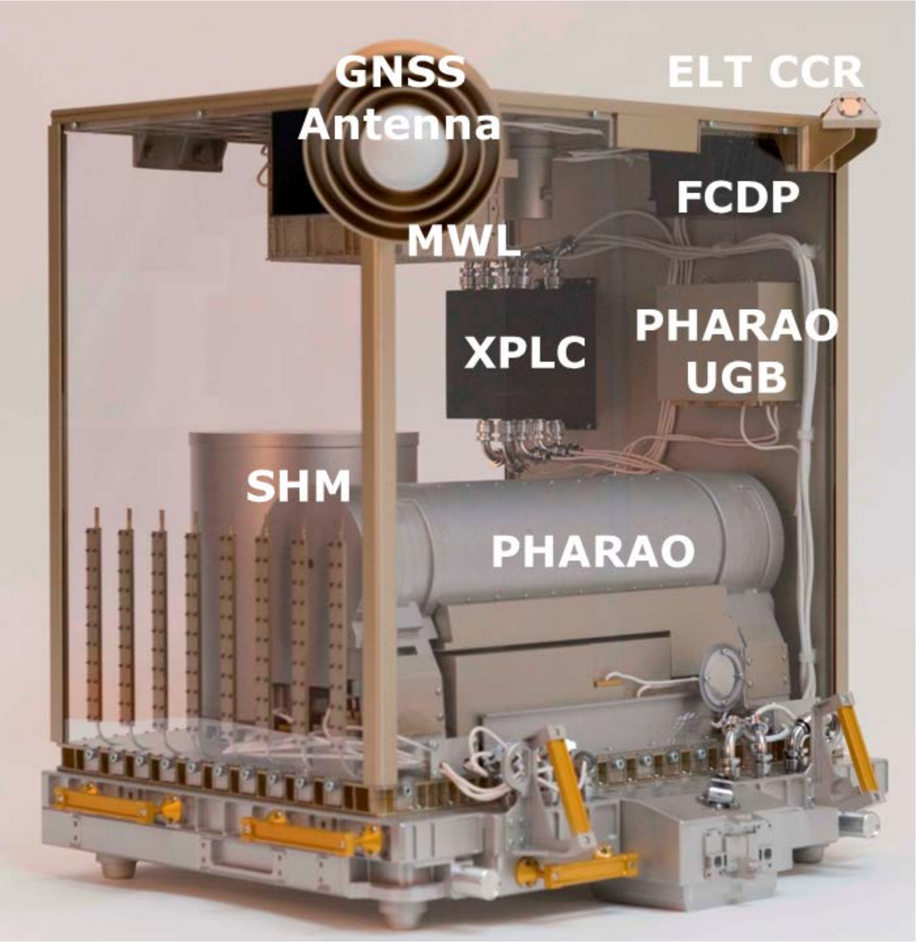
P. Wolf, PRA **56**, 4405 (1997)

Applications

- 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

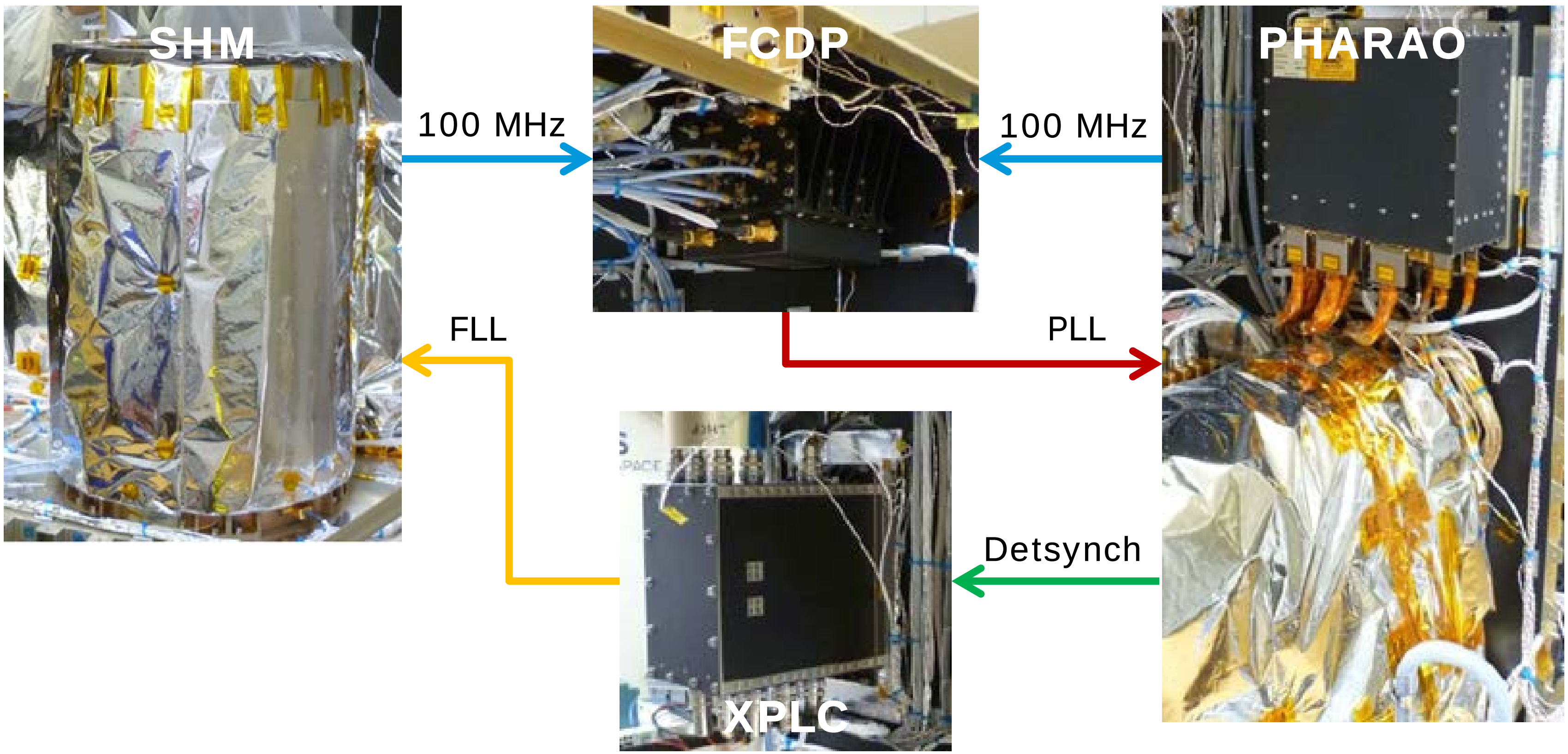
The ACES Payload

- 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)

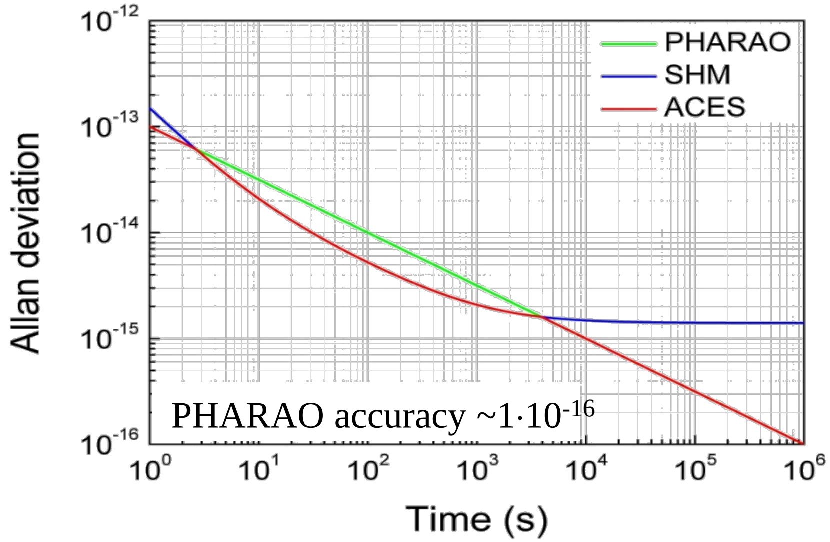


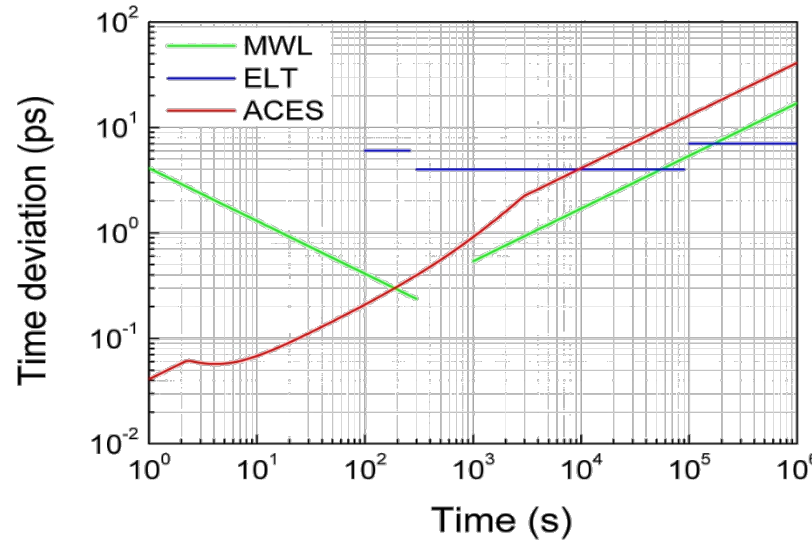
Volume: 1172x867x1246 mm^3
Mass: 227 kg
Power: 450 W

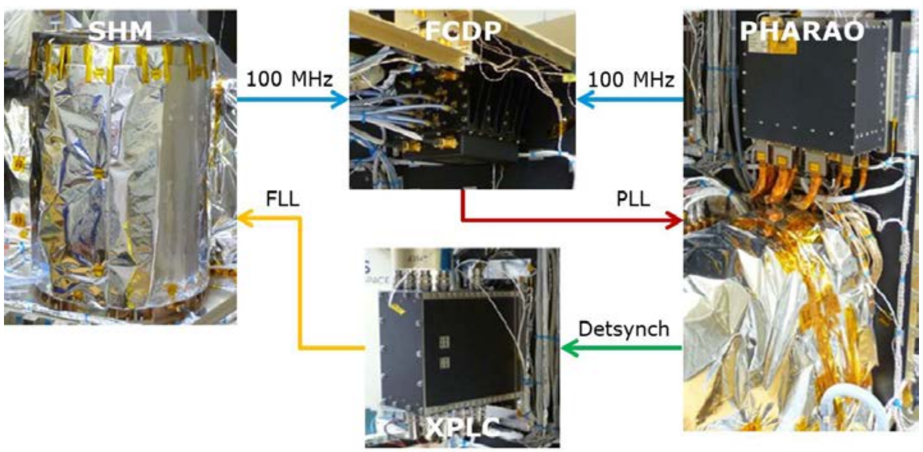
ACES Servo-loops

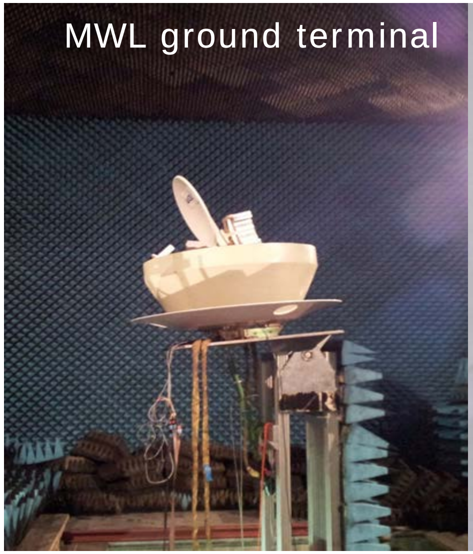


ACES Clocks and Links Performance

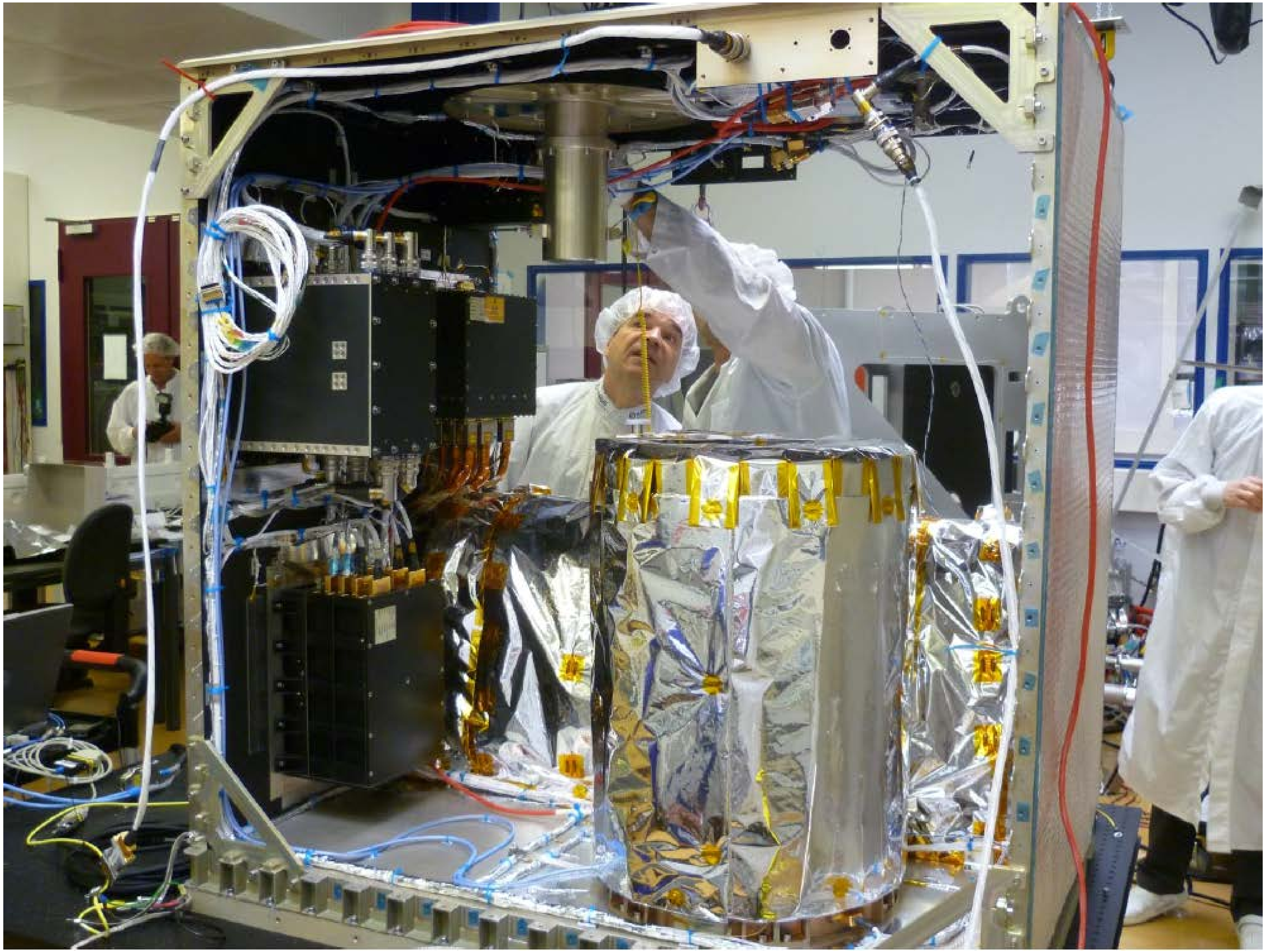




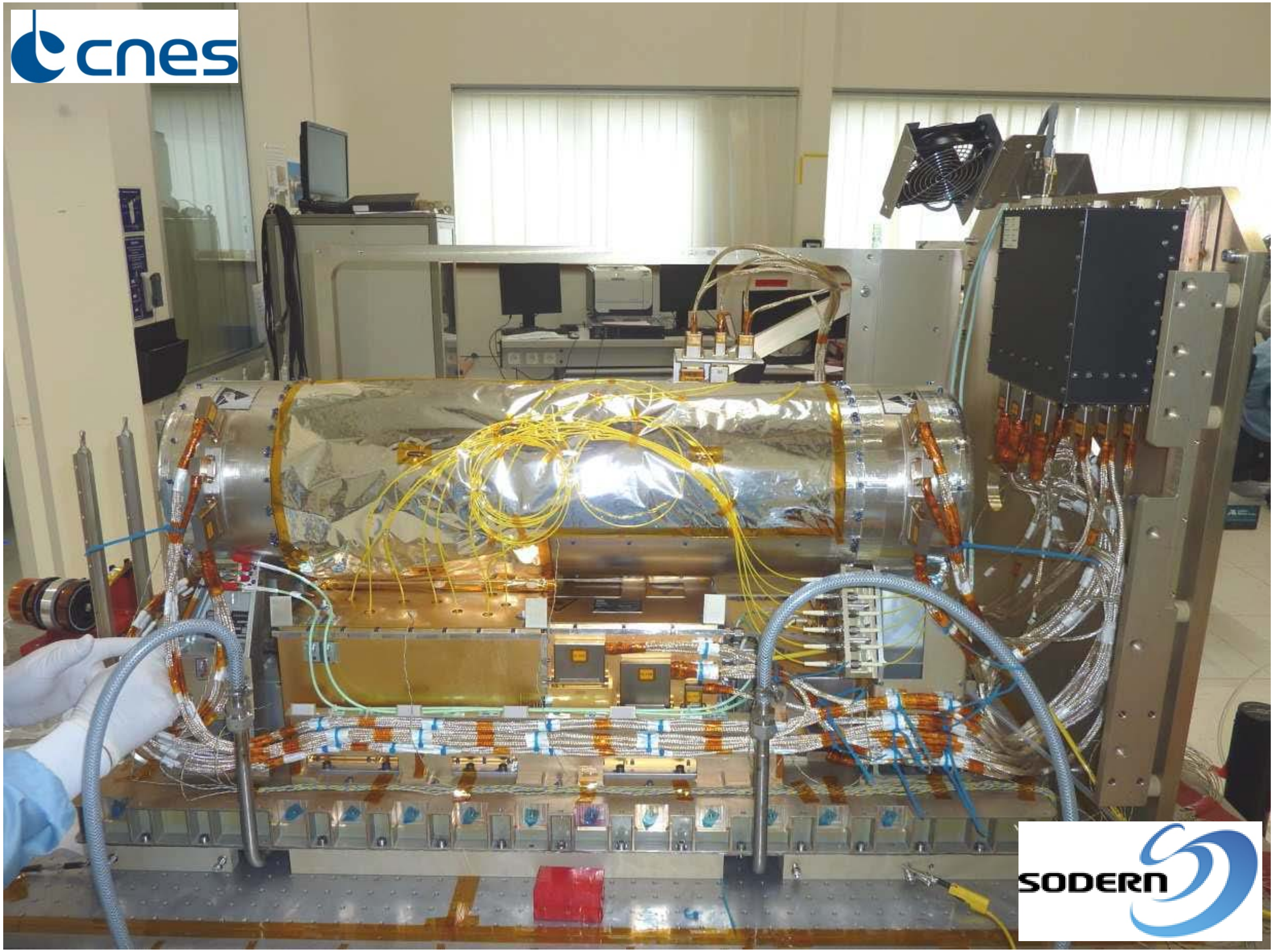




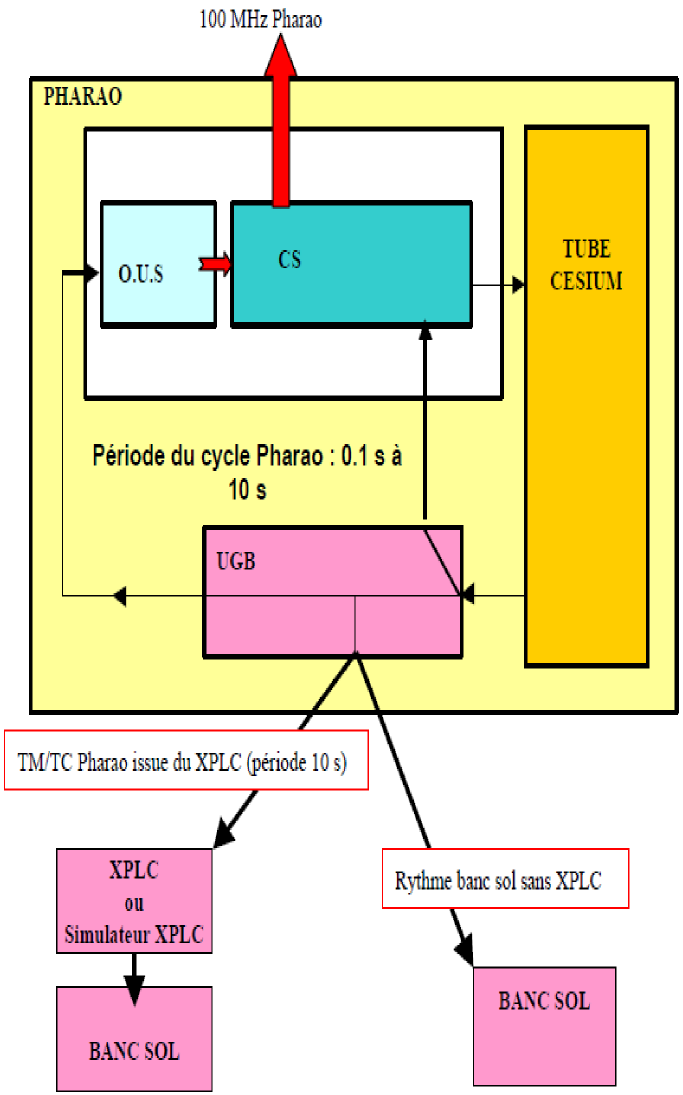
ACES Integration Activities

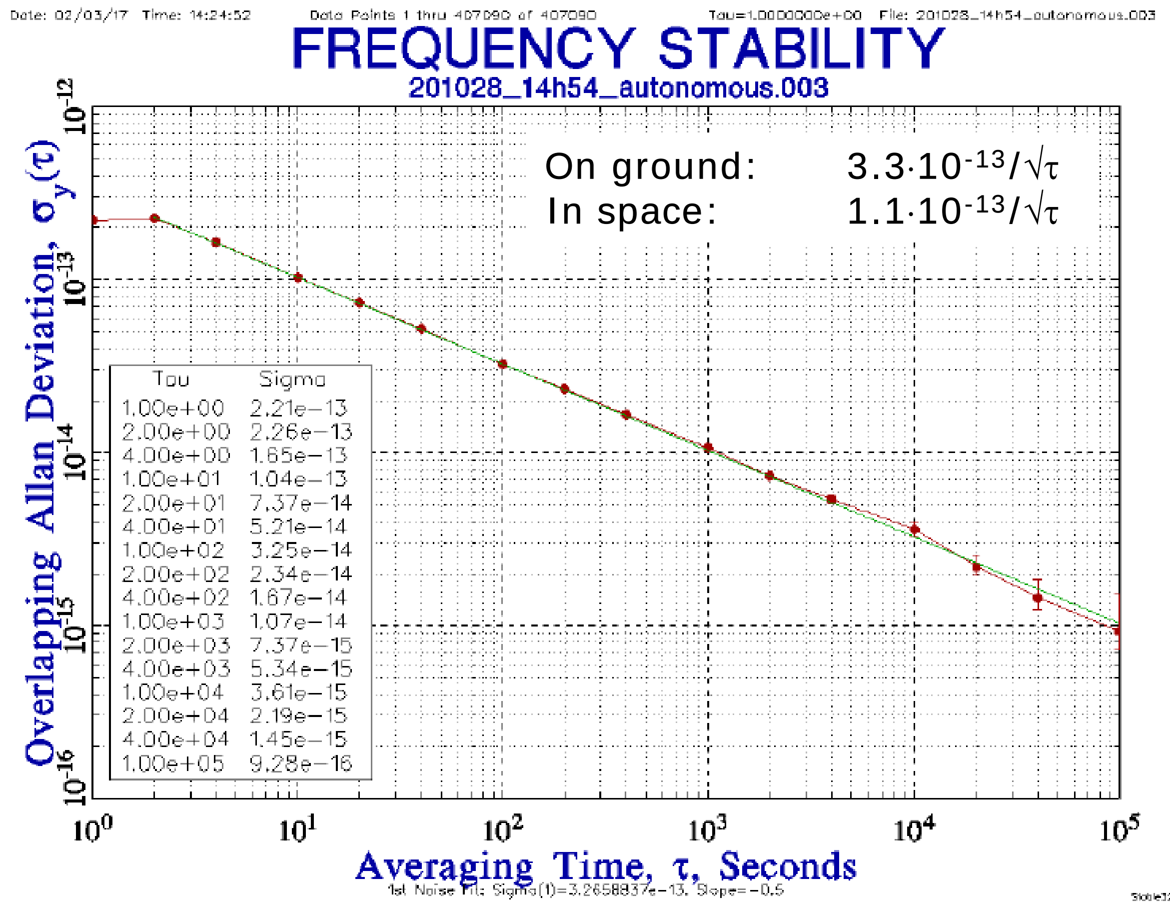


PHARAO FM



PHARAO FM Stability – Autonomous Mode

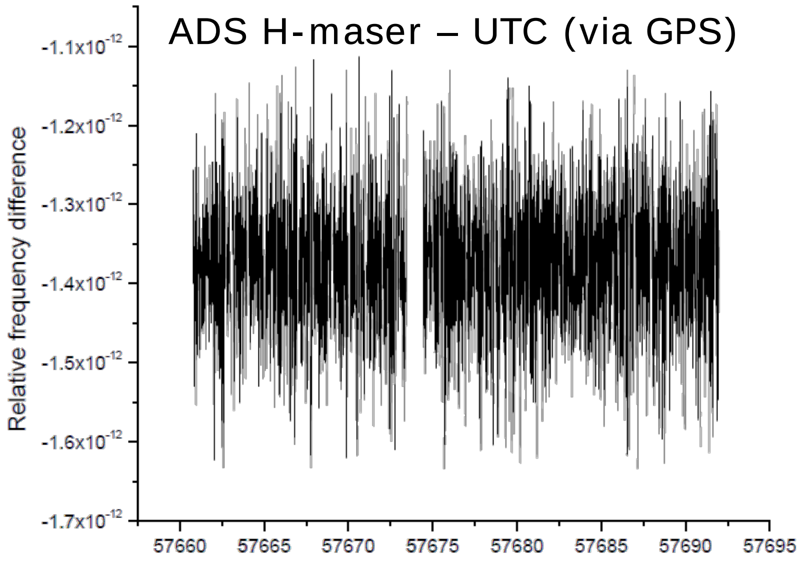


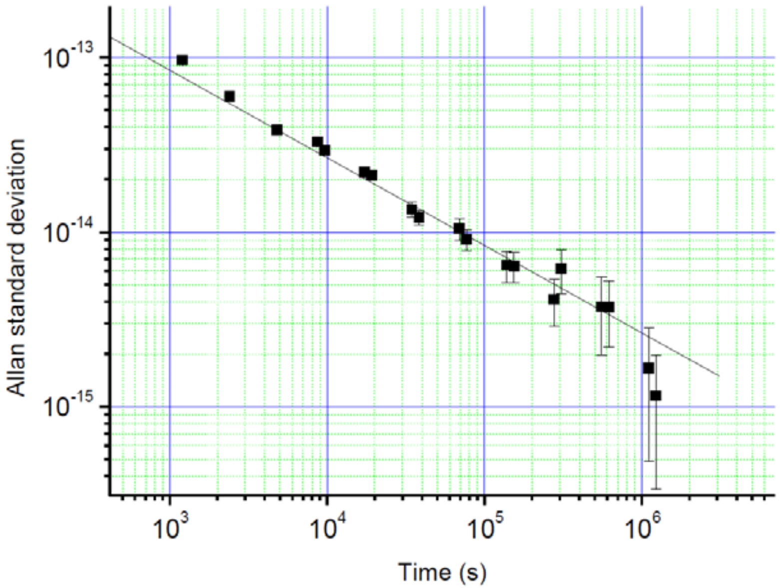


PHARAO FM Frequency Shift and Accuracy

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

Gravitational redshift (410 m)	47.3
Total	205

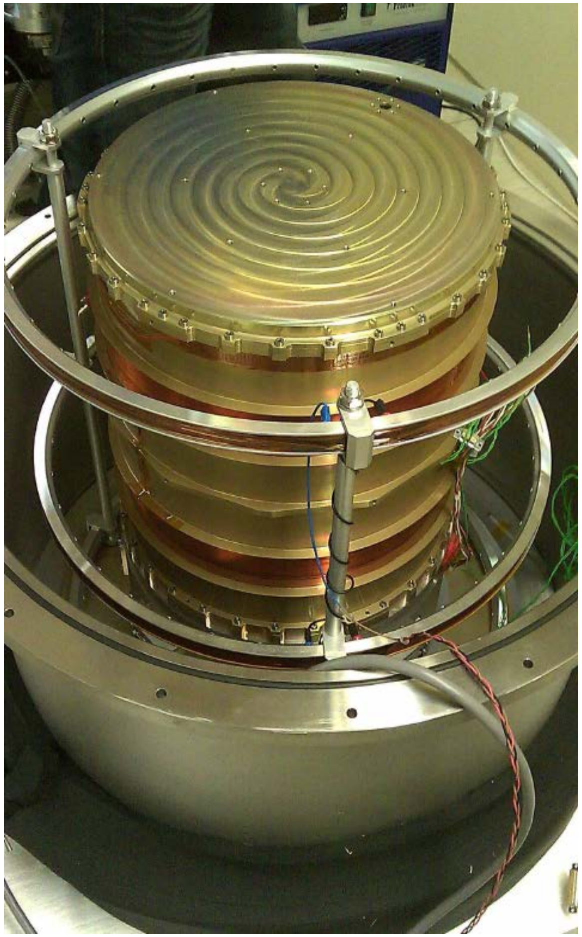




PHARAO Accuracy (evaluated @ CNES):

- On ground: $1.4\cdot 10^{-15}$
- In space: $< 2\cdot 10^{-16}$

SHM: An Active H-maser for Space

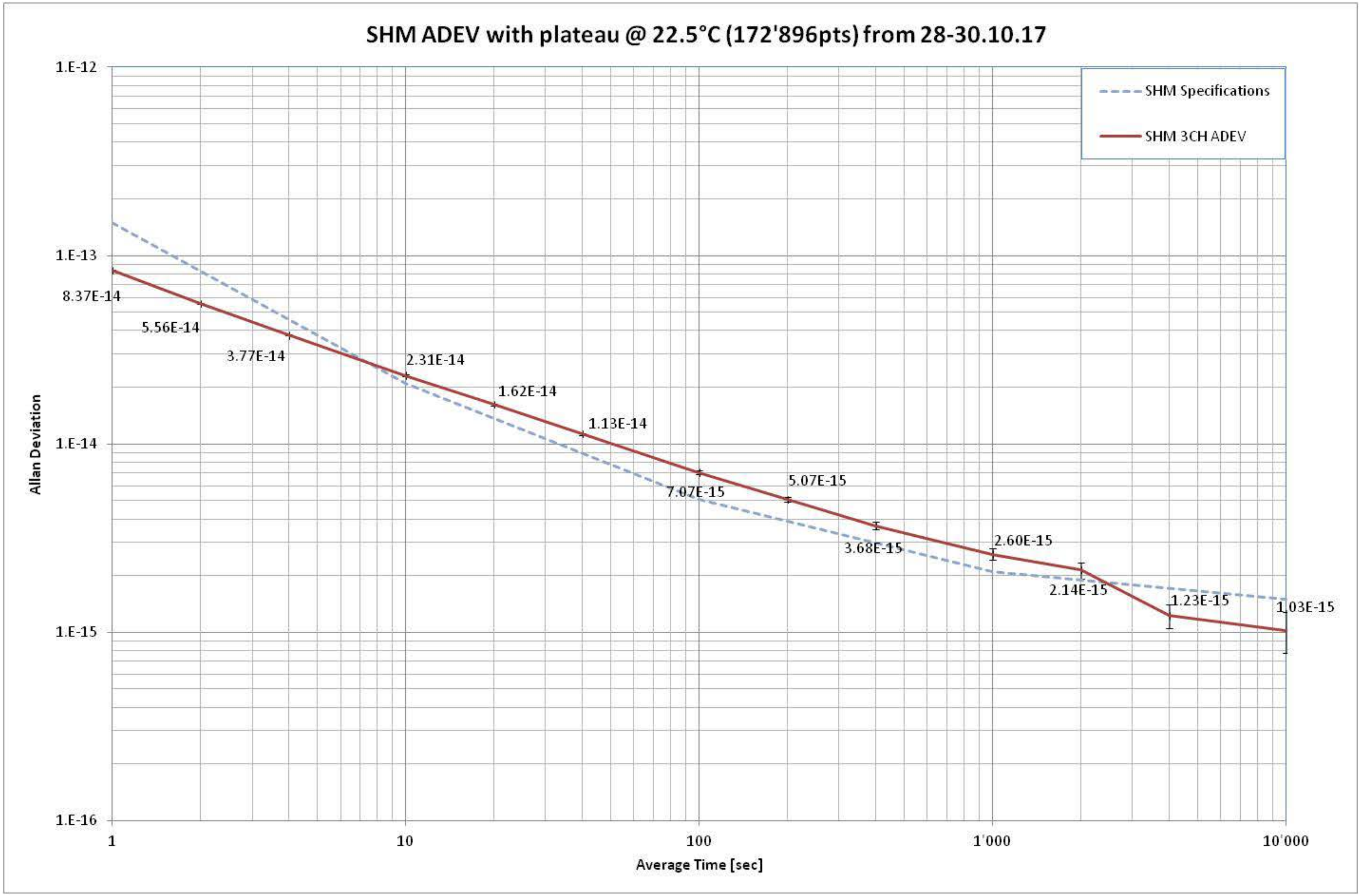


Volume: 390x390x590 mm^3
Mass: 42 kg

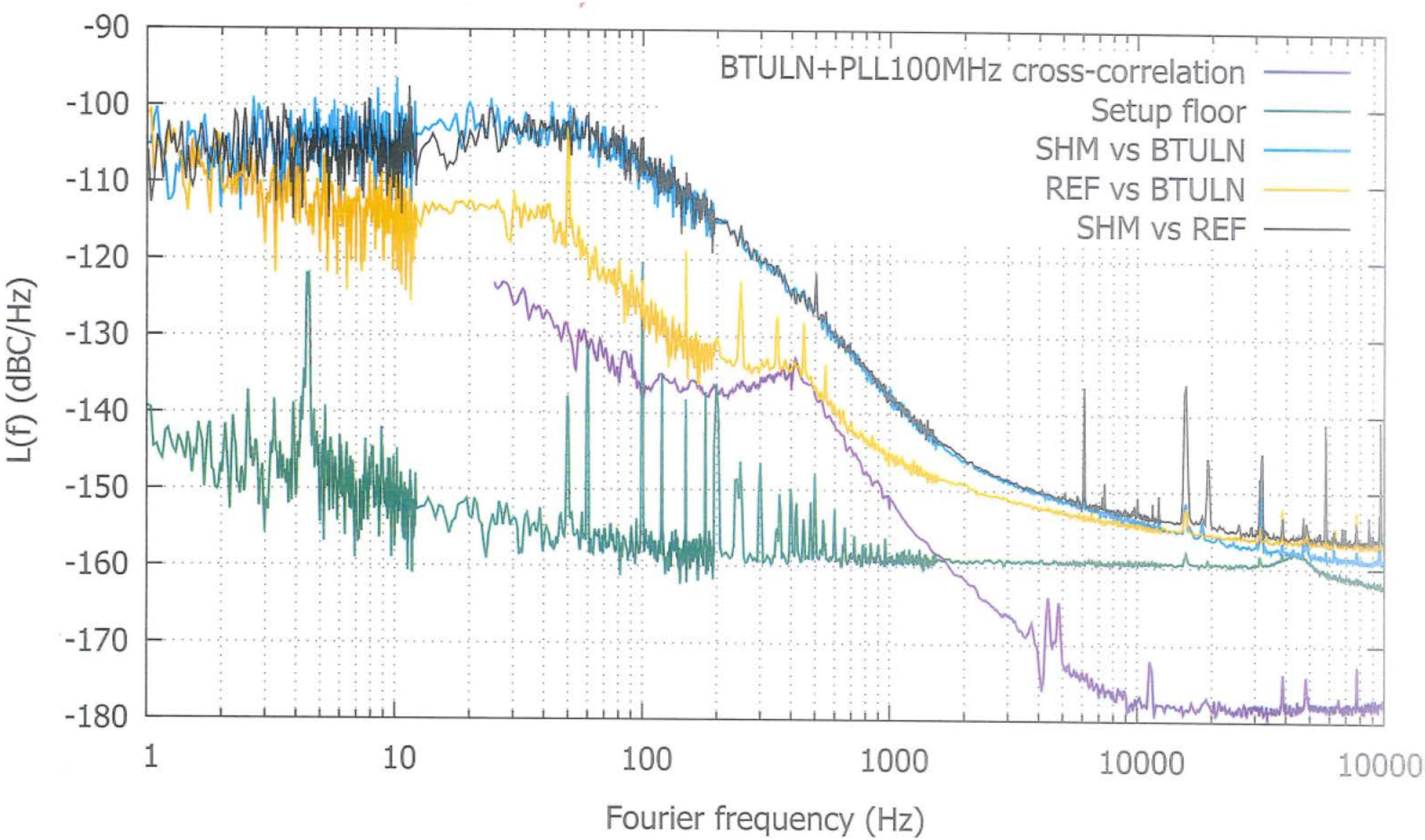
- SHM role in ACES
  - ACES flywheel oscillator
  - PHARAO characterization
- Technical challenges
  - Low mass, volume, and power consumption
  - Full performances:
    - $1.5 \cdot 10^{-13}$ @ 1 s
    - $1.5 \cdot 10^{-15}$ @ 10^4 s
  - Design solution
    - Full size Al cavity
    - Automatic Cavity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

SpectraTime
iPrecision Timing Solutions™

SHM PFM Stability



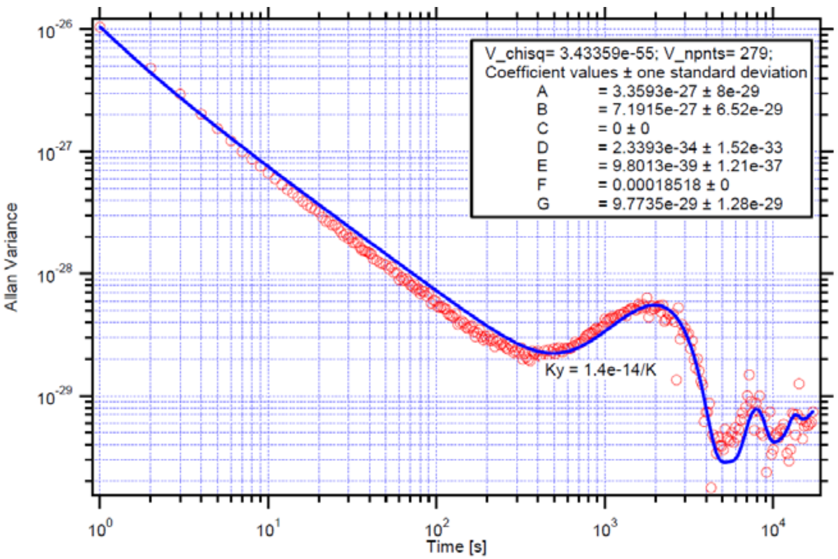
SHM PFM Phase Noise PSD



SHM Thermal Sensitivity

Overall Thermal Sensitivity

		Allan Variance Fit	FFT Analysis
Period	ΔT_{pp}	K_T	K_T
5400 s	1.45 K	$1.4{\cdot}10^{-14}$/K	$1.2{\cdot}10^{-14}$/K
2000 s	1.36 K	$9.1{\cdot}10^{-15}$/K	$9.6{\cdot}10^{-14}$/K
600 s	0.94 K	---	---
300 s	0.35 K	---	---

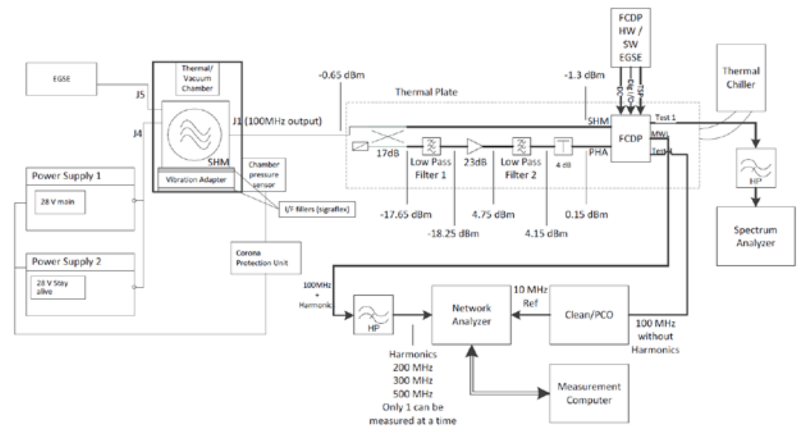


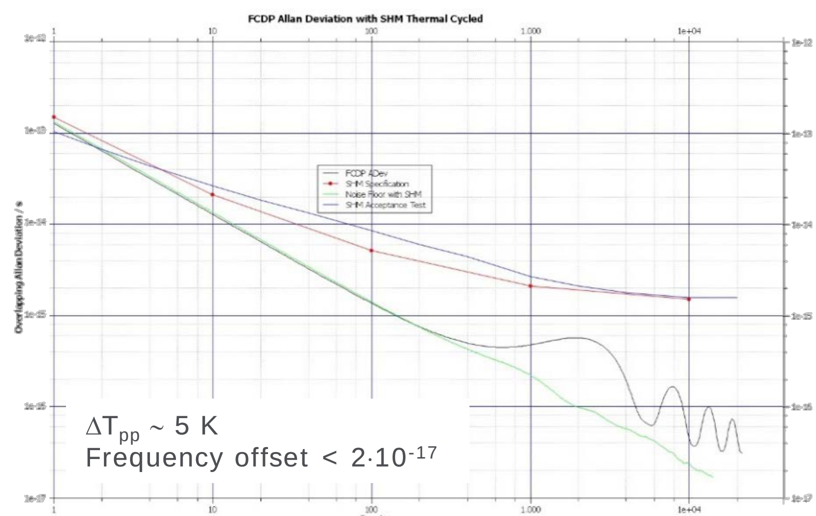
↓

Calibration of the SHM output frequency vs temperature

Effect of 100 MHz Harmonics

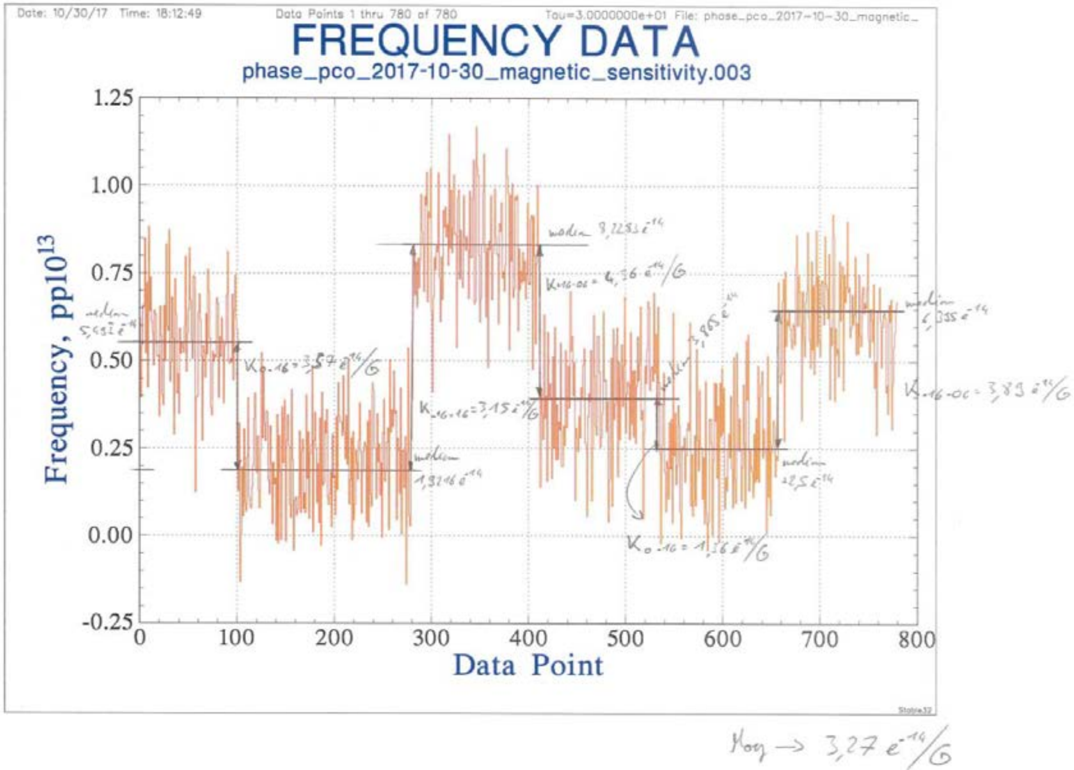
Harmonics content of the SHM output frequency too high: e.g. -41 dBc @ 200 MHz (vs -70 dBc spec)

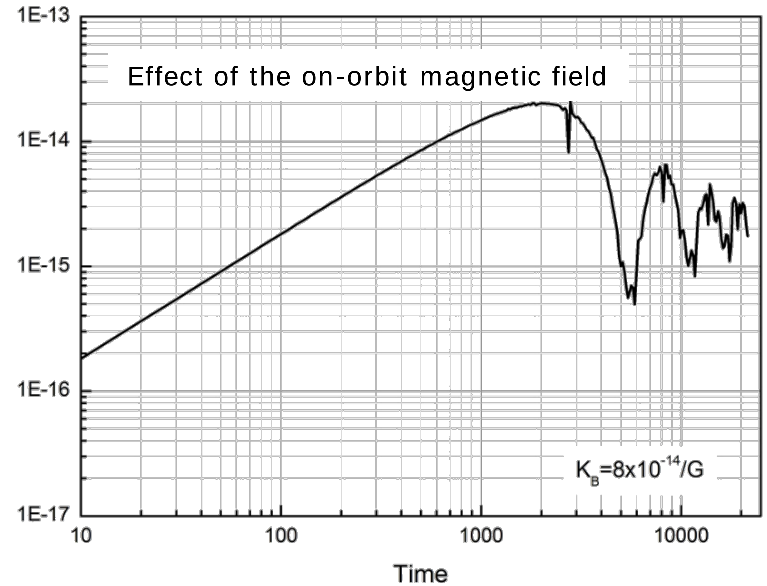


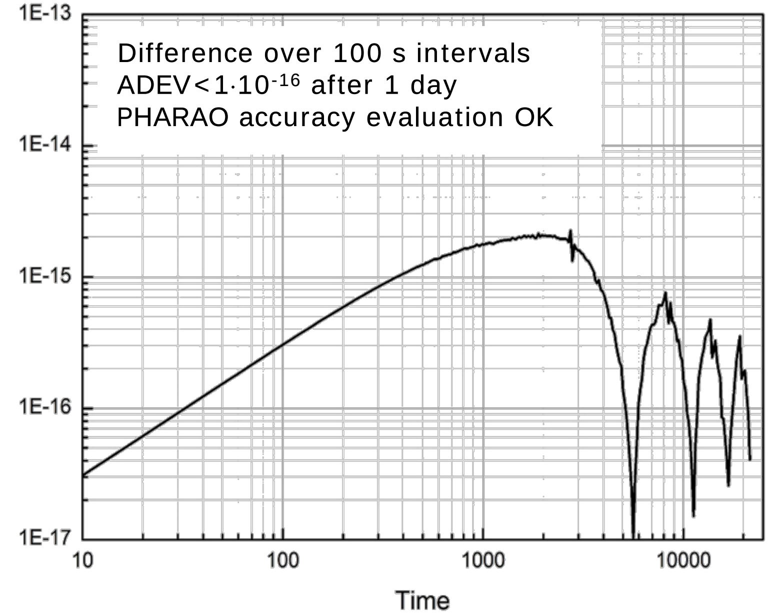


ΔT_{pp} ~ 5 K
Frequency offset < $2{\cdot}10^{-17}$

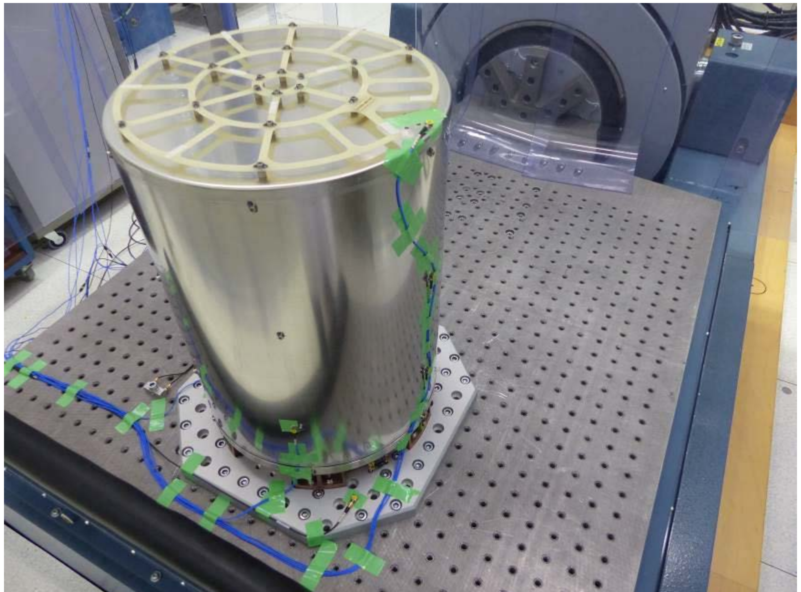
SHM Magnetic Sensitivity

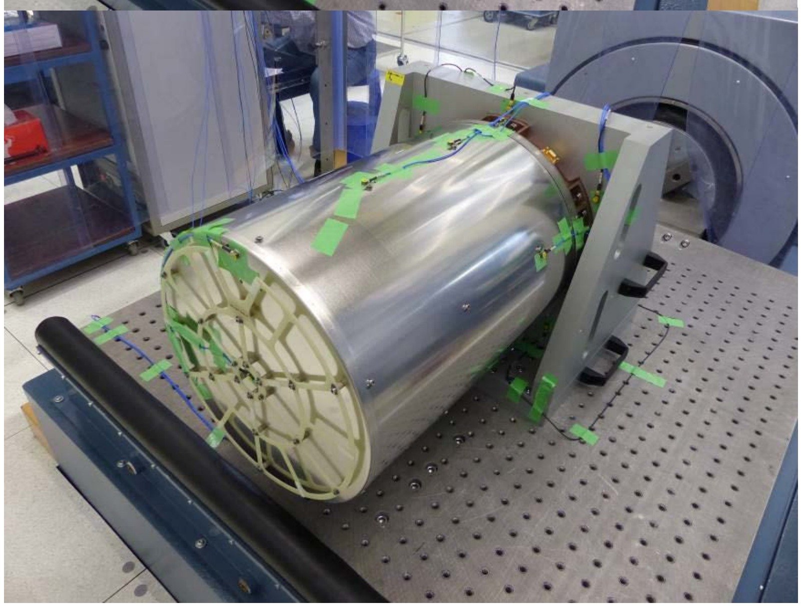






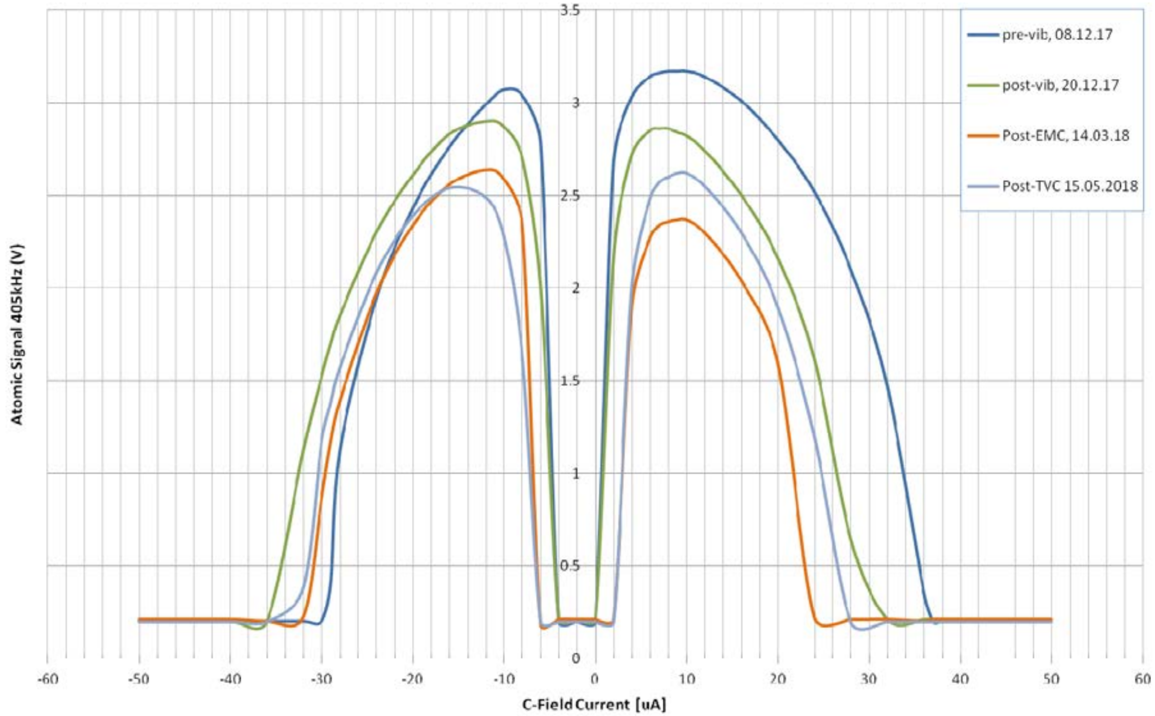
SHM PFM Environmental Test Campaign





Performance through Environmental Tests

	Post-Shipment (cleanroom)
Signal level (at highest c-field point)	3.51V (+10uA)
ADEV (contribution removed) 1s (requ. 1.5e-13) 10s (requ. 2.5e-14) 100s (requ. 7.5e-15)	 7.5e-14 2.16e-14 6.63e-15
Atomic signal linewidth	2.34Hz
Varactor	7V
Magnetic sensitivity	2.5e-14/G
	Post-Vibration (cleanroom)
Signal level (at highest c-field point)	2.86V (-12uA)
ADEV (contribution removed) 1s (requ. 1.5e-13) 10s (requ. 2.5e-14) 100s (requ. 7.5e-15)	 9.72e-14 2.92e-14 6.7e-15
Atomic signal linewidth	2.55Hz
Varactor	9.6V
Magnetic sensitivity	1.4e-14/G (max. measured level)
	Post-EMC (cleanroom)
Signal level (at highest c-field point)	2.7V (-12uA)
ADEV (contribution removed) 1s (requ. 1.5e-13) 10s (requ. 2.5e-14) 100s (requ. 7.5e-15)	 9.72e-14 2.65e-14 7.76e-15
Atomic signal linewidth	2.61Hz
Varactor	9.23V
Magnetic sensitivity	3.4e-14/G
	Post-TVC Tuning (cleanroom)
Signal level (at highest c-field point)	2.8V (+9uA)
ADEV (contribution removed) 1s (requ. 1.5e-13) 10s (requ. 2.5e-14) 100s (requ. 7.5e-15)	 9.72e-14 2.49e-14 8.54e-15
Varactor	4.3V
Magnetic sensitivity	1.22e-14/G
ACT	0x0239

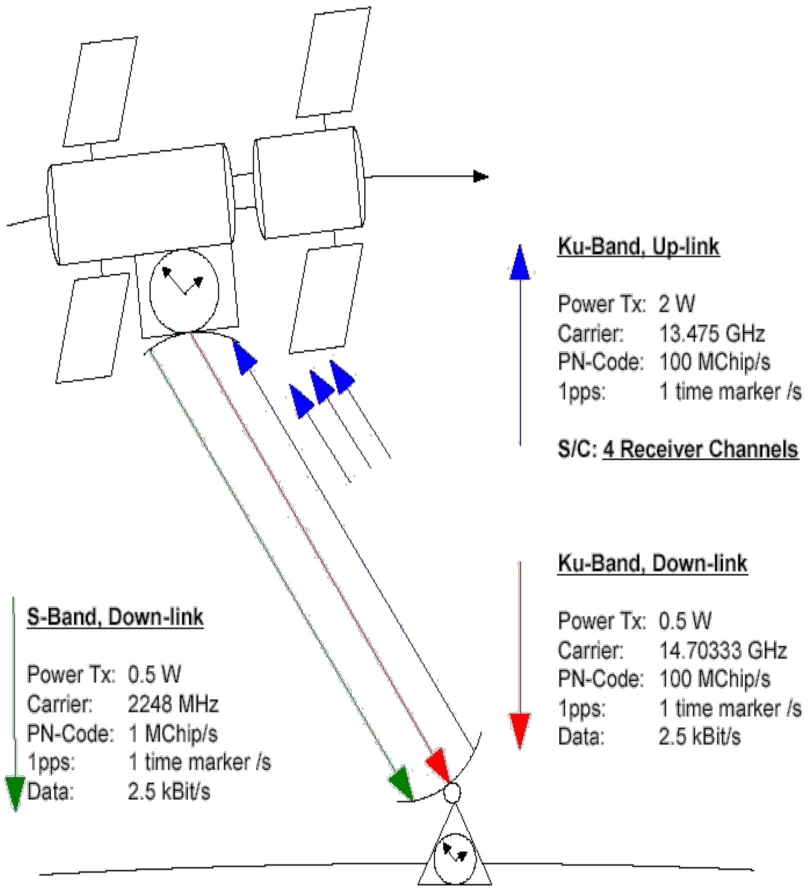


Next step

↓

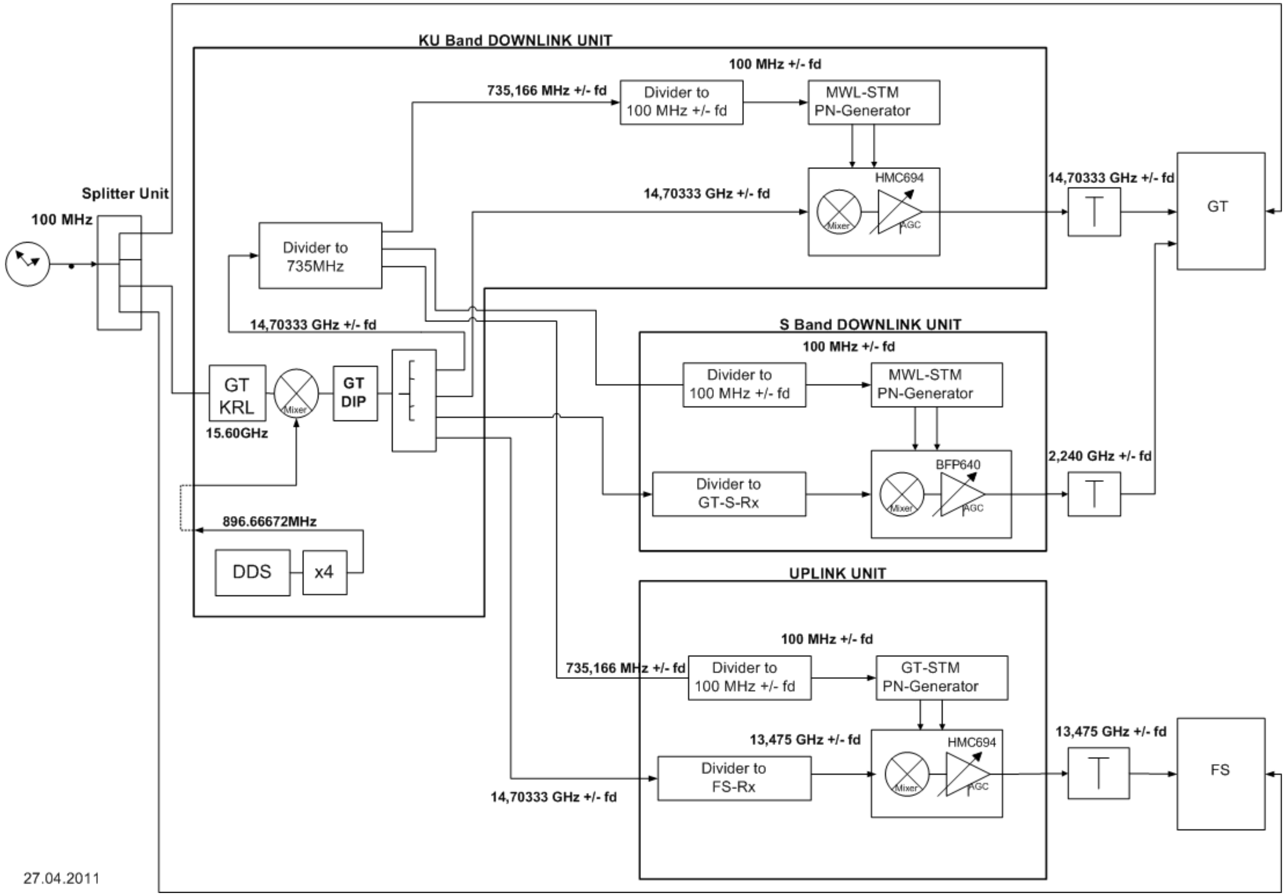
SHM degaussing + performance tests

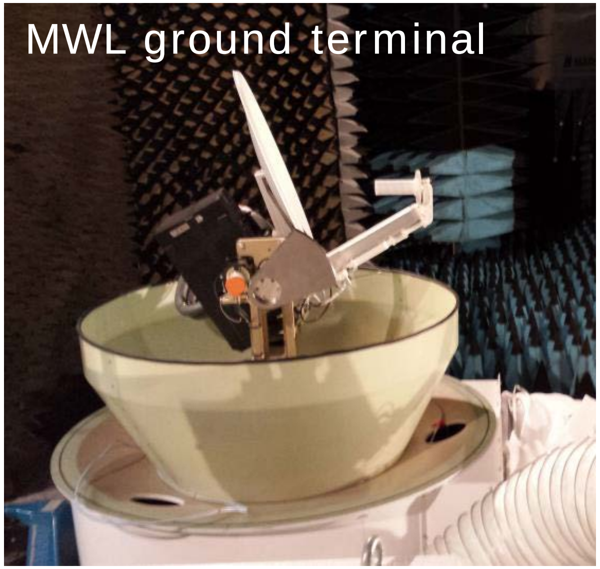
MWL

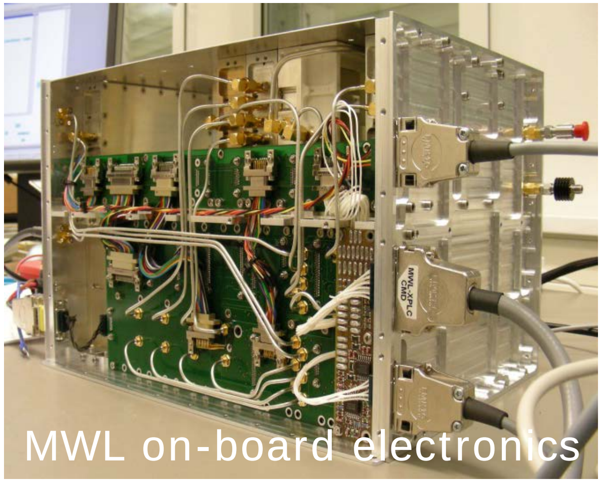


- Two-way link:
  - Removal of the troposphere time delay (8.3-103 ns)
  - Removal of 1st order Doppler effect
  - Removal of instrumental delays and common mode effects
- Additional down-link in the S-band:
  - Determination of the ionosphere TEC
  - Correction of the ionosphere time delay (0.3-40 ns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

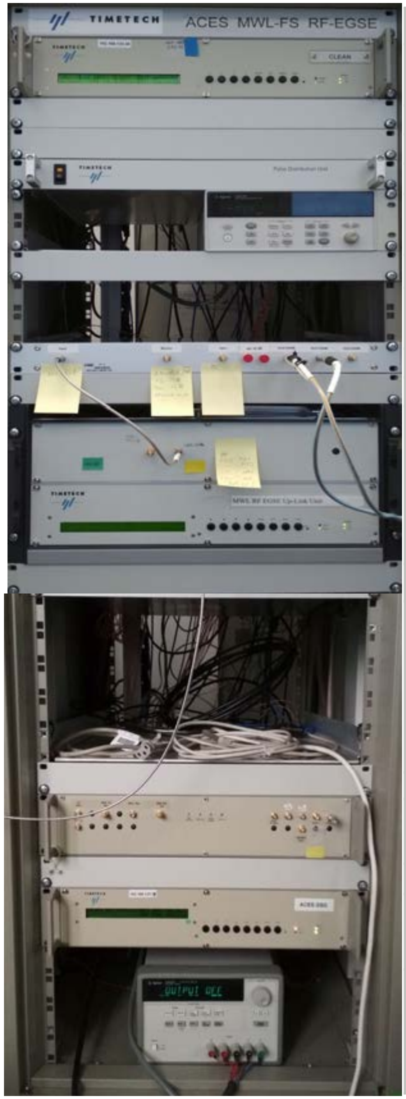
MWL End-to-end Test Configuration







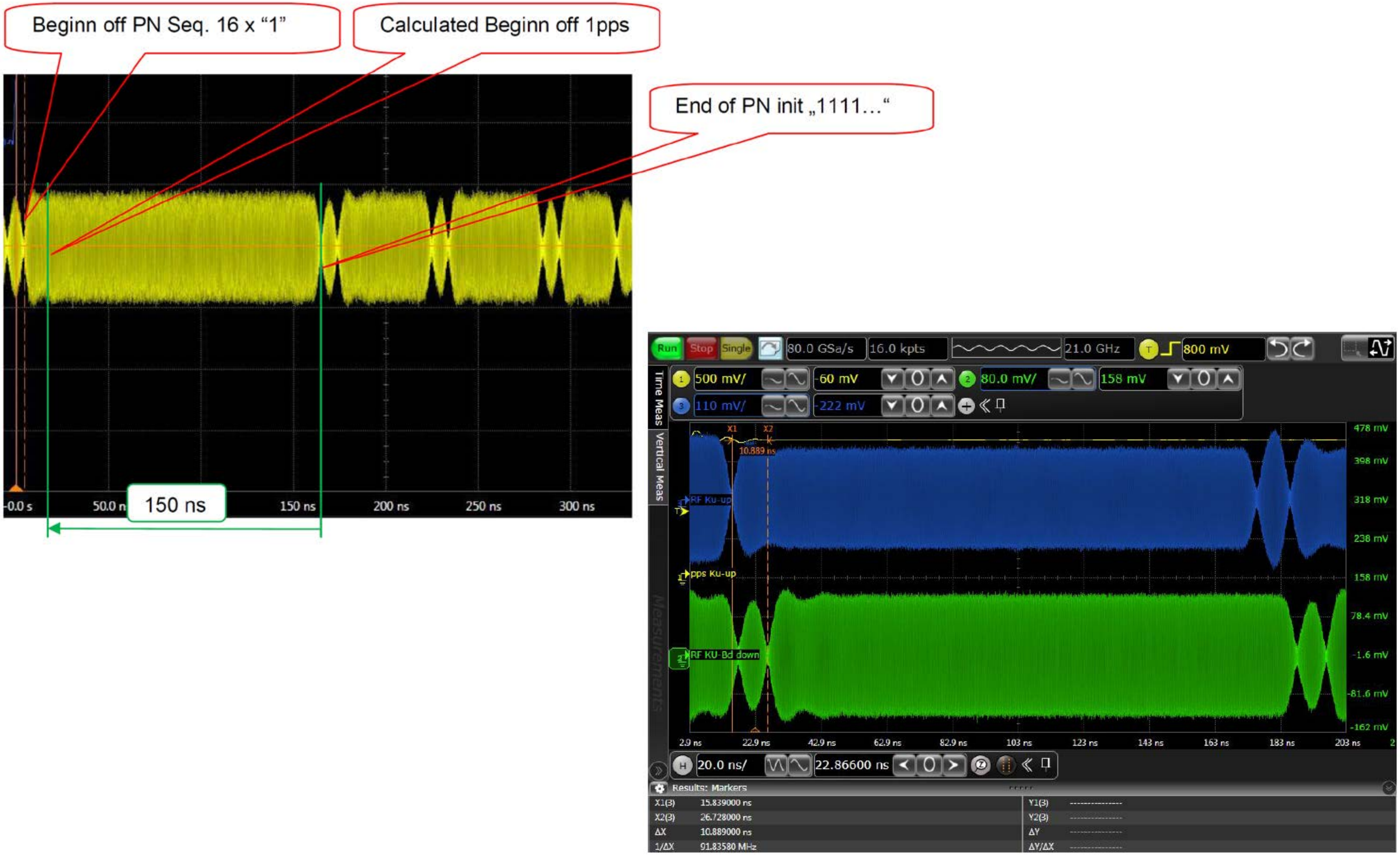
MWL RF EGSE



FS RF- EGSE
Clean (TimeTech Synos) 100MHz + 10 MHz Reference Frequency Generation
Cooler
Freq. Distr. Amp. (100 MHz)
Puls Distribution Unit
Agilent 34970A
Cooler
2- way Splitter
Cooler
RF EGSE Uplink Simulator and Doppler Generation Unit
Cooler
Cooler
Not used
Cooler
TimeTech 4-fach Relais for FS-EU Status TM

GT RF- EGSE
Agilent Power Supply not connected
Time Interval Counter TIC
Cooler
Freq. Distr. Amp. (10 MHz)
Master 100 MHz Freq. Generator
RF - Network Fa. SatService
S-Band Down Link Unit and Doppler Generation Unit
cooler
Ku-Band Down Link Unit and Doppler Generation Unit
4-way Splitter
Agilent Power Supply

MWL Signals

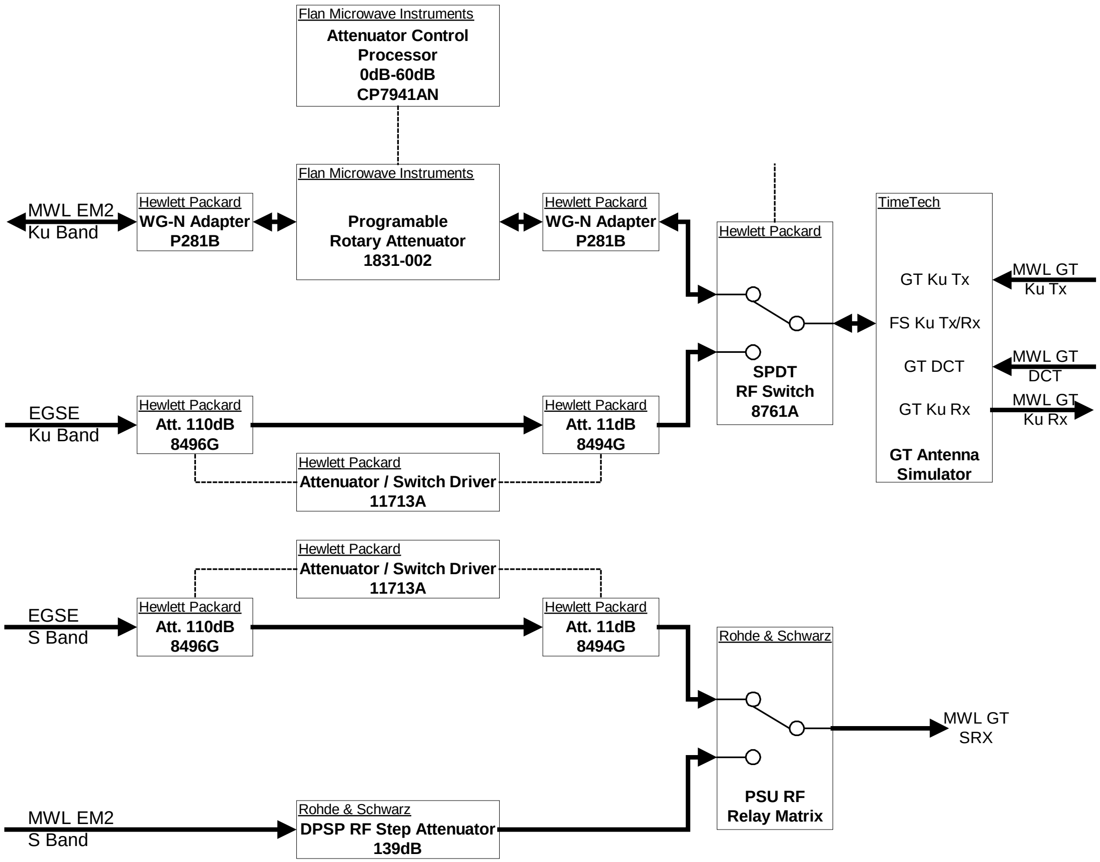


Beginn off PN Seq. 16 x "1"
Calculated Beginn off 1pps
End of PN init „1111…"
150 ns
-0.0 s
50.0 n
150 ns
200 ns
250 ns
300 ns
Run
Stop
Single
80.0 GSa/s
16.0 kpts
21.0 GHz
800 mV
500 mV/
-60 mV
80.0 mV/
158 mV
110 mV/
-222 mV
Time Meas
Vertical Meas
RF Ku-up
pps Ku-up
RF KU-Bd down
10.889 ns
20.0 ns/
22.86600 ns
Results: Markers
X1(3) 15.839000 ns
X2(3) 26.728000 ns
ΔX 10.889000 ns
1/ΔX 91.83580 MHz
Y1(3)
Y2(3)
ΔY
ΔY/ΔX

MWL Delays Calibration

Delays combination	Uncertainty	Note
Ionosphere modelling		
$(\Delta_{Tx2}^{co} - \Delta_{Tx3}^{co}) + (\Delta_{Rx2}^{co} - \Delta_{Rx3}^{co})$	600 ps	Up to a constant offset over the mission lifetime or at least between on/off cycles
$(\Delta_{Tx2}^{co} - \Delta_{Tx3}^{co}) + (\Delta_{Rx2}^{co} - \Delta_{Rx3}^{co})$	$400 \cdot \sigma_x(\tau)_{MWL}$	Stability requirement
$(\Delta_{Tx2}^{co} - \Delta_{Tx3}^{co}) + (\Delta_{Rx2}^{co} - \Delta_{Rx3}^{co})$	40 ns	Accuracy requirement
$(\Delta_{Tx2}^{co} - \Delta_{Tx3}^{co}) + (\Delta_{Rx2}^{co} - \Delta_{Rx3}^{co})$	1.3 ns	Accuracy goal
Carrier cycle ambiguity resolution		
$(\Delta_{Tx1}^{co} - \Delta_{Tx1}^{ca}) + (\Delta_{Rx1}^{co} - \Delta_{Rx1}^{ca})$	34 ps	Up to a constant offset over the mission lifetime or at least between on/off cycles
$(\Delta_{Tx2}^{co} - \Delta_{Tx2}^{ca}) + (\Delta_{Rx2}^{co} - \Delta_{Rx2}^{ca})$	34 ps	Up to a constant offset over the mission lifetime or at least between on/off cycles
Lambda configuration		
$\Delta_{Rx1}^{co} + \Delta_{Tx2}^{co}$	40 ns	Accuracy requirement
$\Delta_{Rx1}^{ca} + \Delta_{Tx2}^{ca}$	34 ps (TBC)	Stability requirement
$\Delta_{Tx1}^{co} + \Delta_{Rx2}^{co}$	40 ns	Accuracy requirement
$\Delta_{Tx1}^{ca} + \Delta_{Rx2}^{ca}$	34 ps (TBC)	Stability requirement
Time transfer		
$\frac{1}{2}[(\Delta_{Rx1}^{co} - \Delta_{Tx2}^{co}) + (\Delta_{Tx1}^{co} - \Delta_{Rx2}^{co})]$	100 ps	Accuracy requirement
$\frac{1}{2}[(\Delta_{Rx1}^{ca} - \Delta_{Tx2}^{ca}) + (\Delta_{Tx1}^{ca} - \Delta_{Rx2}^{ca})]$	$\sigma_x(\tau)_{MWL}$	Stability requirement

MWL GT2 Tests and Calibrations

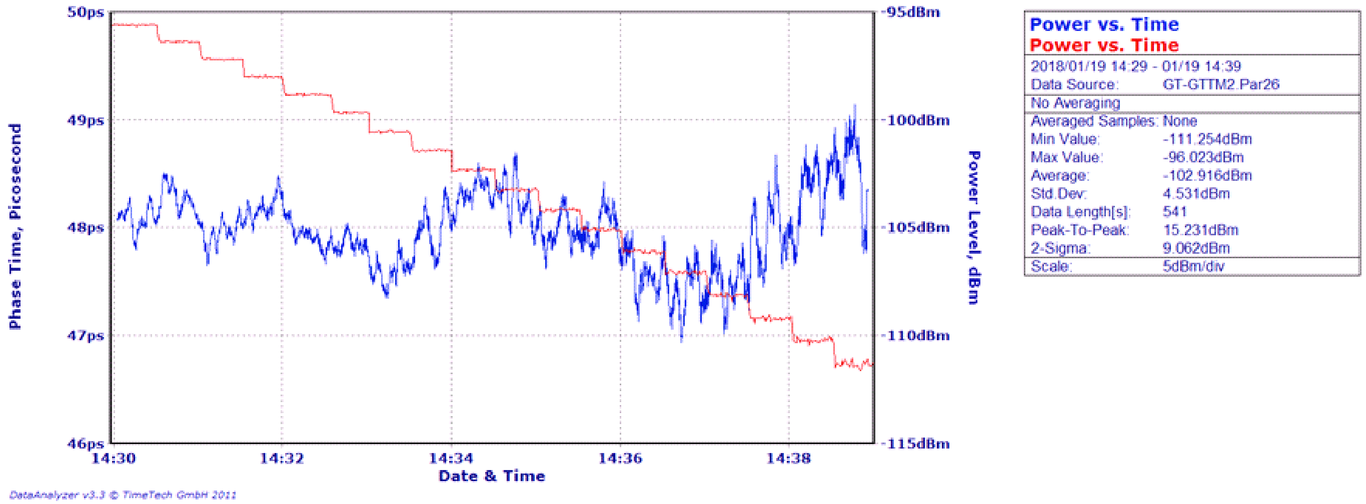


RF Switch matrix and attenuators, connecting

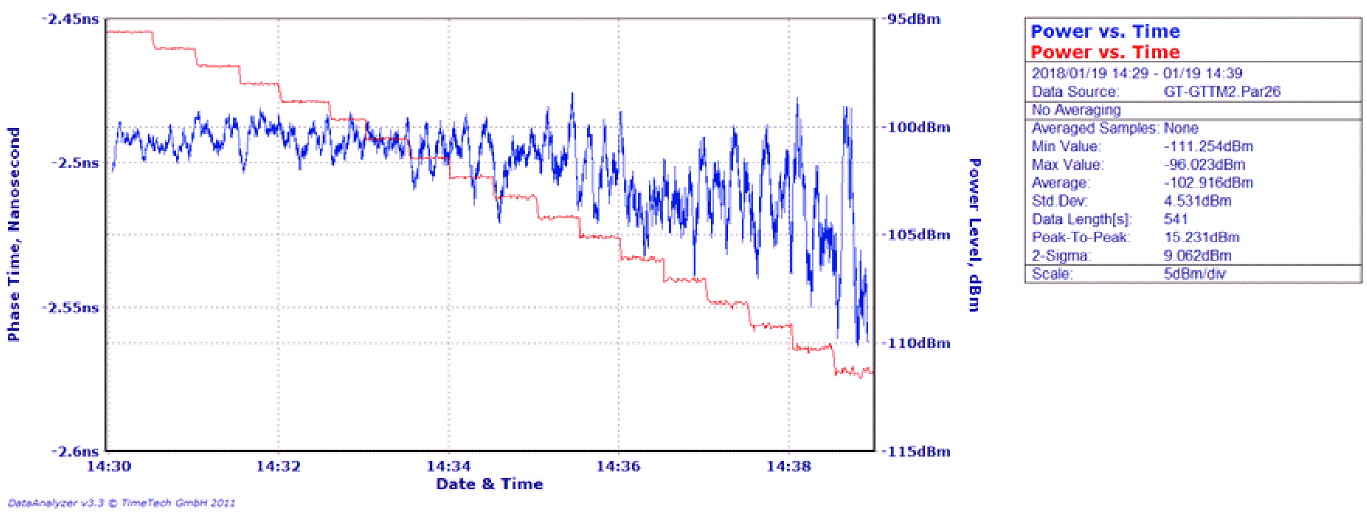
- MWL Engineering Model, Ku & S, fixed Doppler
- MWL RF EGSE, with Doppler and AM capability
- GT Antenna simulator and return loop

AM / PM Calibration on GT2 (WG attenuator)

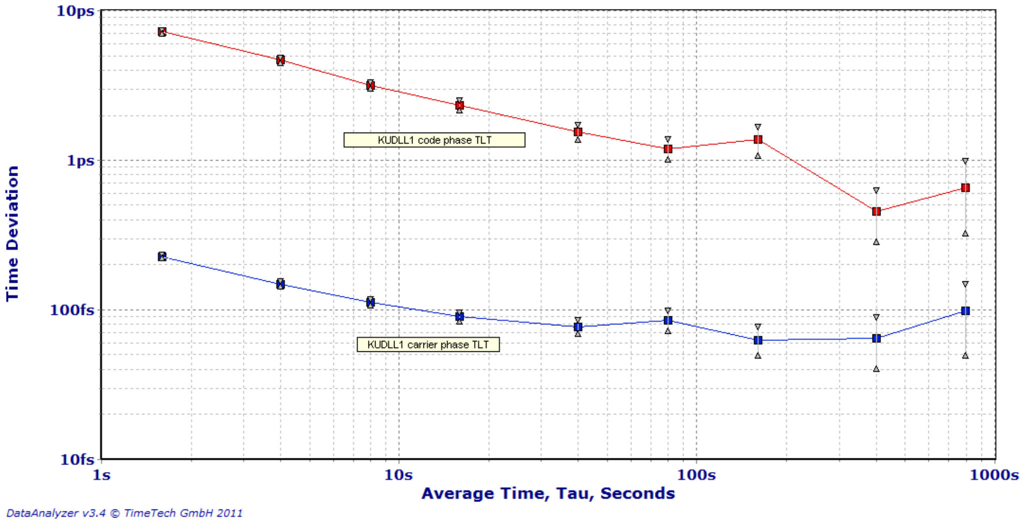
2s-smoothed carrier phase vs Input signal power readout (range 15dB)



2s-smoothed code phase vs Input signal power readout (range 15dB)



MWL GT2 Test Loop Translator



Time Deviation vs. Tau

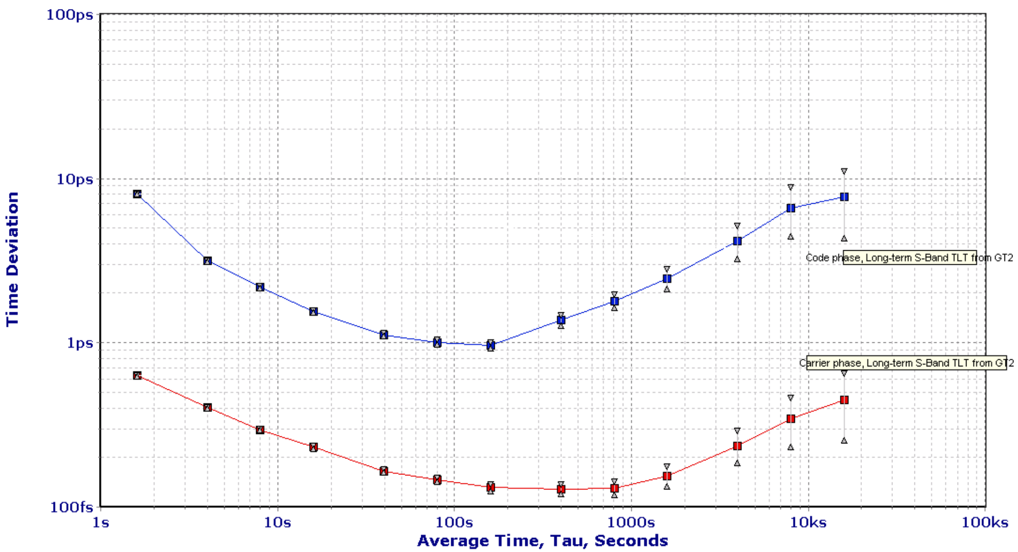
2018/10/11 12:50 - 10/11 13:49

Data Source: GT-GTCA1.lns

No Averaging

Noise:	White PM
2s	2.27E-13
4s	1.49E-13
8s	1.12E-13
16s	9.01E-14
40s	7.72E-14
80s	8.50E-14
160s	6.29E-14
400s	6.48E-14
800s	9.91E-14

Ku-TLT



Time Deviation vs. Tau

2017/11/26 00:00 - 11/26 23:58

Data Source A: GT-GTCA3.lns

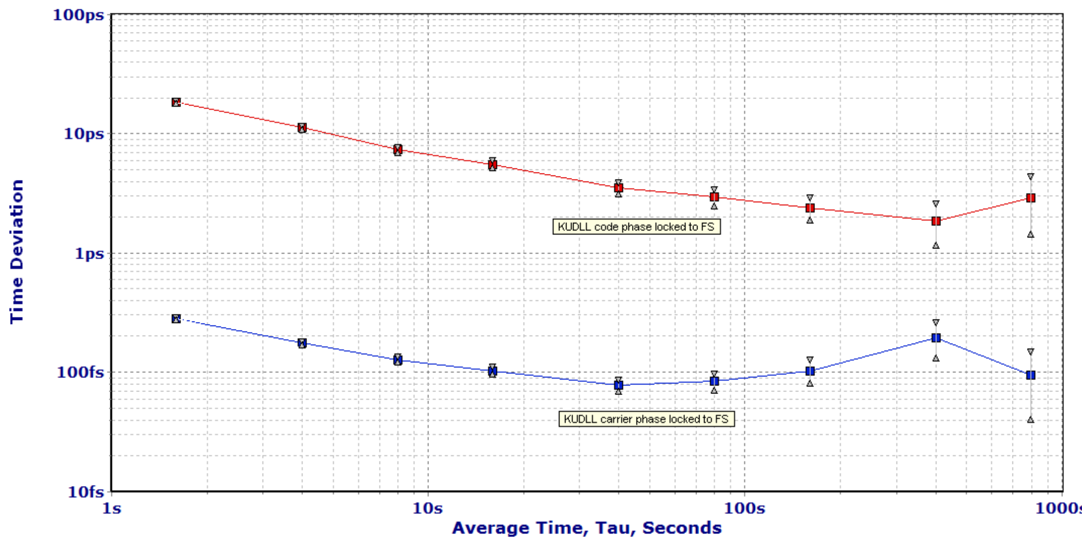
Data Source B: GT-GTCO3.lns

No Averaging

Noise:	White PM
2s	6.29E-13
4s	4.02E-13
8s	2.96E-13
16s	2.31E-13
40s	1.66E-13
80s	1.46E-13
160s	1.31E-13
400s	1.28E-13
800s	1.31E-13
1600s	1.55E-13
4000s	2.37E-13
8000s	3.45E-13
16000s	4.50E-13

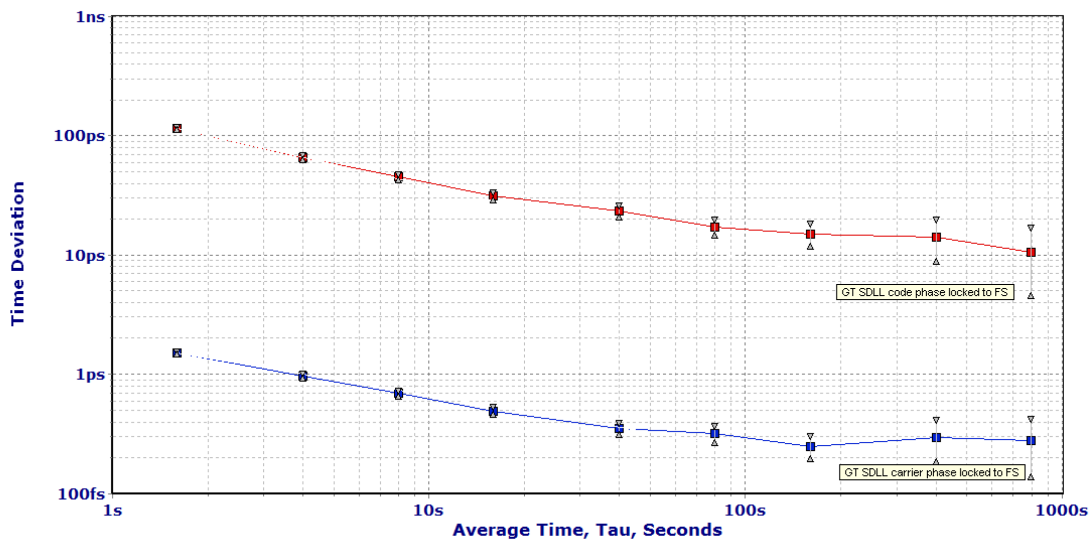
S-TLT

MWL FS EM2 vs GT2



Time Deviation vs. Tau	
2018/10/11 12:50 - 10/11 13:49	
Data Source: GT-GTCA2.Ins	
No Averaging	
Noise:	White PM
2s	2.82E-13
4s	1.76E-13
8s	1.28E-13
16s	1.04E-13
40s	7.79E-14
80s	8.38E-14
160s	1.04E-13
400s	1.95E-13
800s	9.47E-14

Ku: EM2 to GT2



Time Deviation vs. Tau	
2018/10/11 12:50 - 10/11 13:49	
Data Source: GT-GTCA3.Ins	
No Averaging	
Noise:	White PM
2s	1.52E-12
4s	9.69E-13
8s	6.95E-13
16s	4.94E-13
40s	3.50E-13
80s	3.19E-13
160s	2.50E-13
400s	2.99E-13
800s	2.81E-13

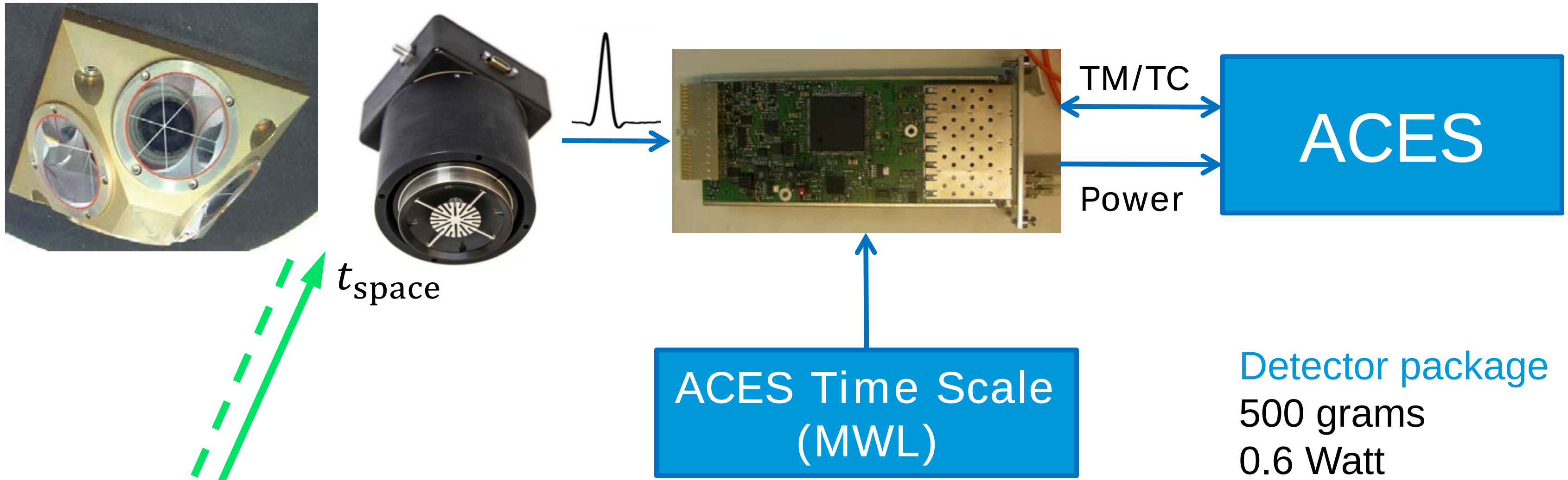
S: EM2 to GT2

DataAnalyzer v3.4 © TimeTech GmbH 2011

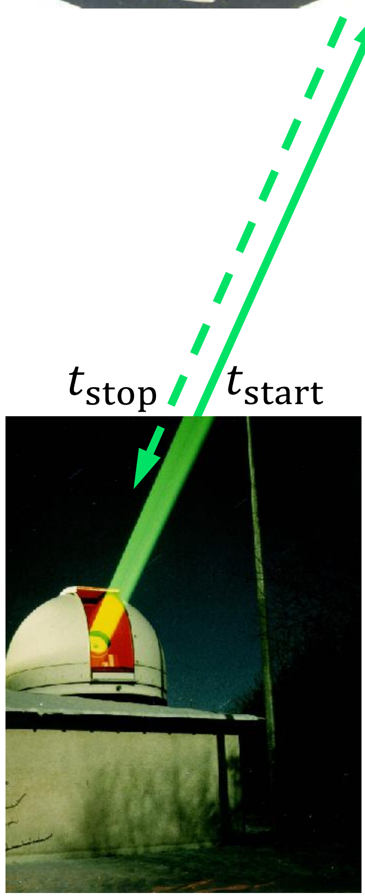
MWL: Next Steps

- Complete FM firmware and software testing
- Lock-in sensitivity tests under dynamic conditions
- Test and calibration of MWL FS in end-to-end configuration with GT2
- MWL FS environmental tests
- MWL FS integration on the ACES baseplate

European Laser Timing (ELT)



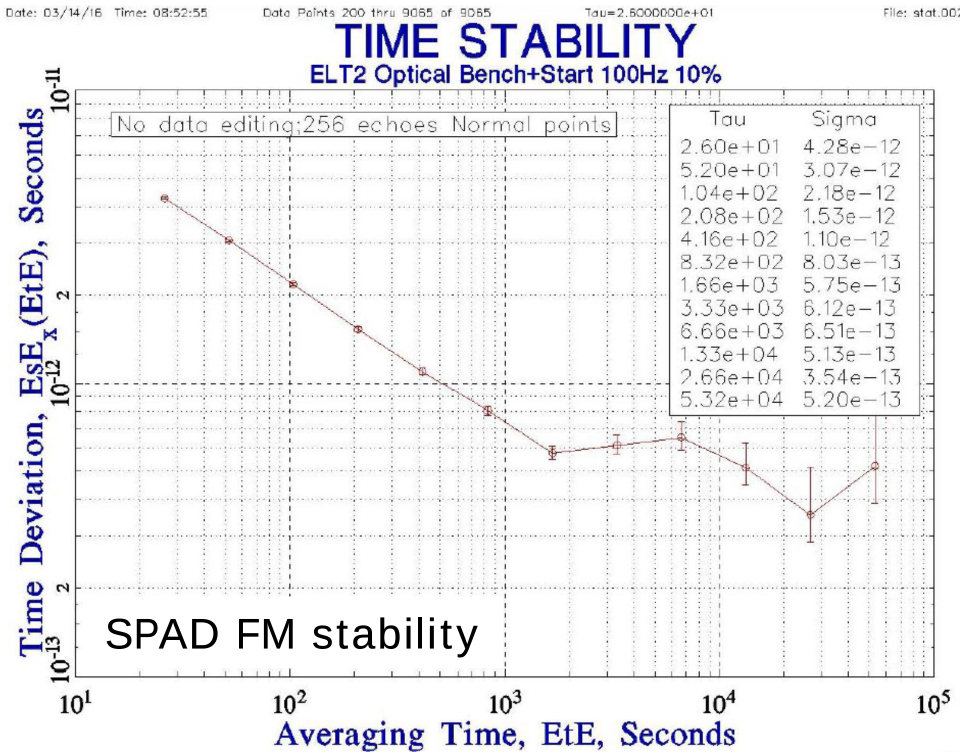
Detector package
500 grams
0.6 Watt

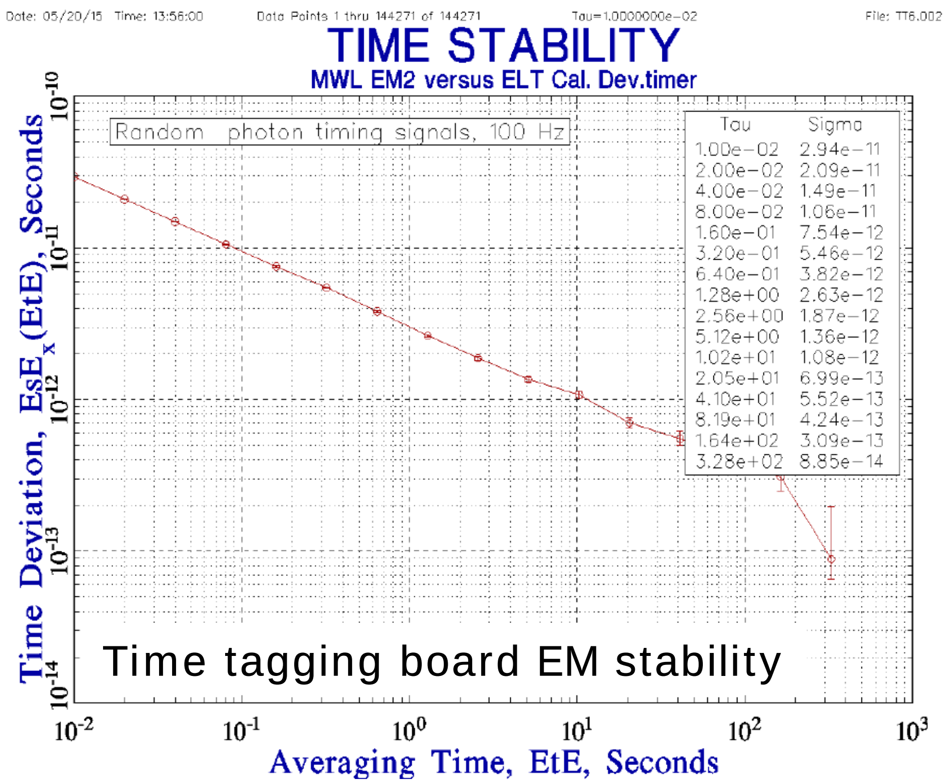


$$\tau_g(t) - \tau_s(t) = \frac{t_{start} + t_{stop}}{2} - t_{space} + $$
$$+\tau_{relativity} + \tau_{atmosphere} + \tau_{geometry}$$

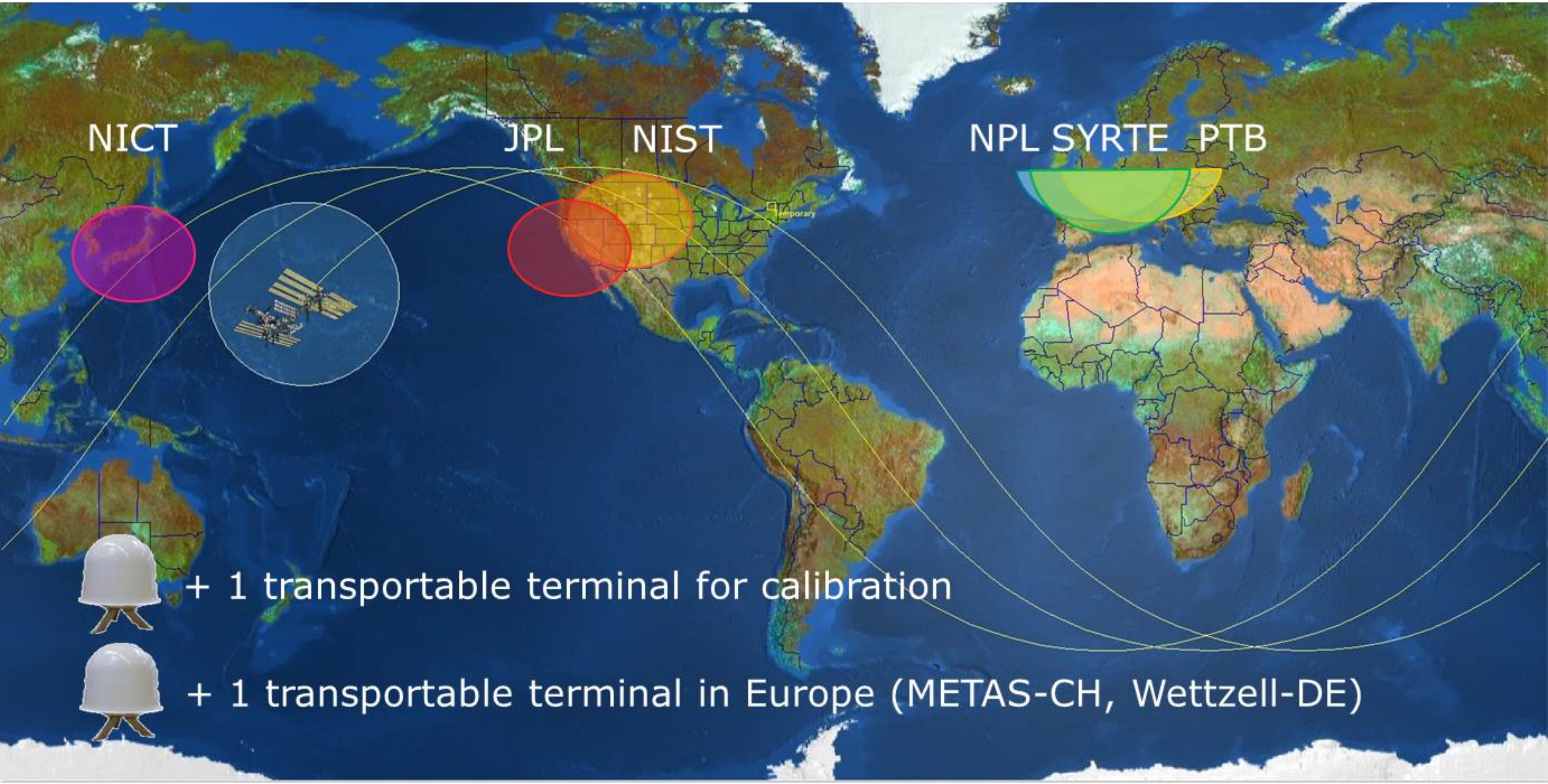
CTU Prague

ELT FM Performance

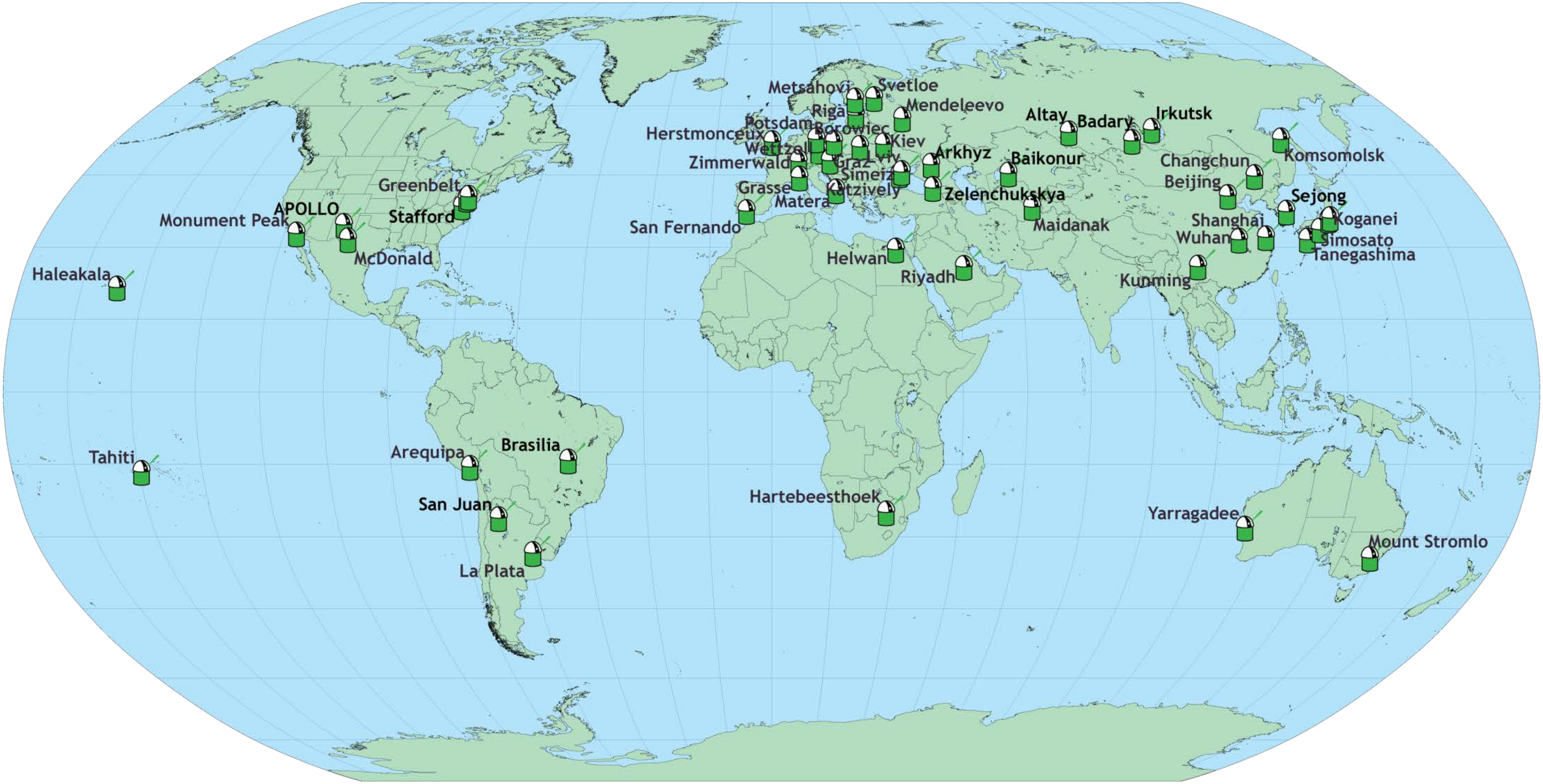




ACES MWL Network

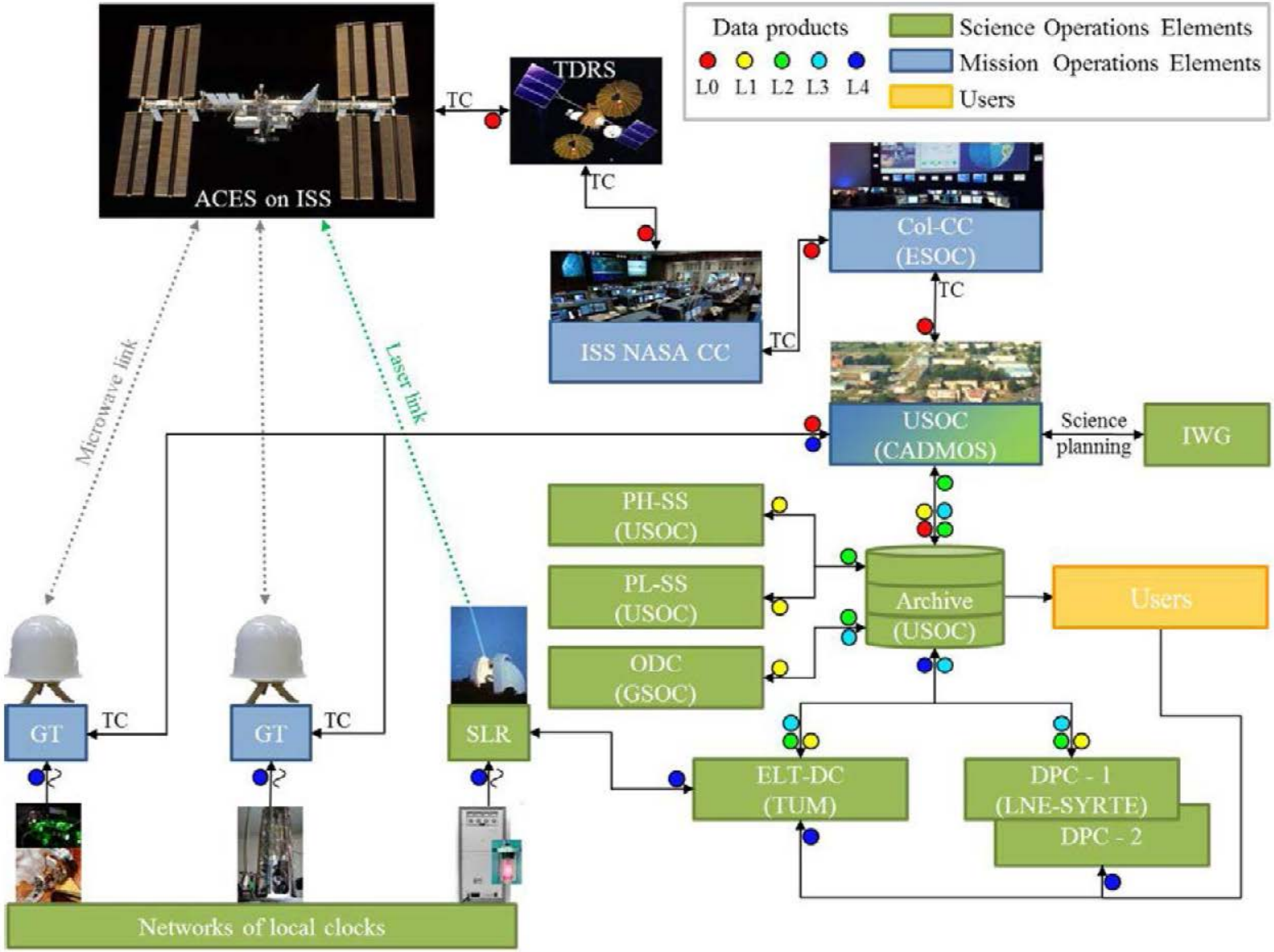


ILRS Network of SLR Stations



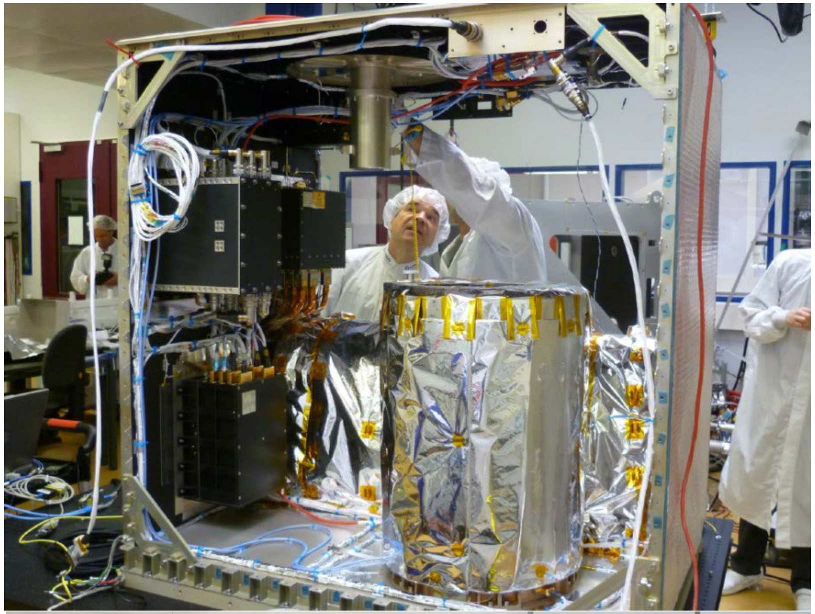
ACES as official ILRS target: Wettzell (primary station), Gratz and Herstmonceaux SLR stations already calibrated; other stations can join provided they comply with ISS safety requirements.

ACES Data and Science Ground Segment



ACES Status

- o PHARAO FM delivered and integrated on the ACES baseplate
- o FCDP, ELT, and on-board GNSS receiver FMs delivered to Airbus
- o SHM PFM ready for integration at the end of November
- o MWL FM completed, tested and delivered by May 2019
- o ACES FM tests already started and continued until summer 2019
- o MWL GTs:
  - First terminal deployed in PTB in Nov. 2015 and remotely monitored since then
  - Remaining fixed terminals to be deployed in the course of 2019
- o ACES ready for shipment to launch site on December 2019
- o ACES bookmarked for launch on SpaceX 21
  - 6 months: commissioning/calibration
  - 12 to 30 months: routine science phase



Thanks for your attention