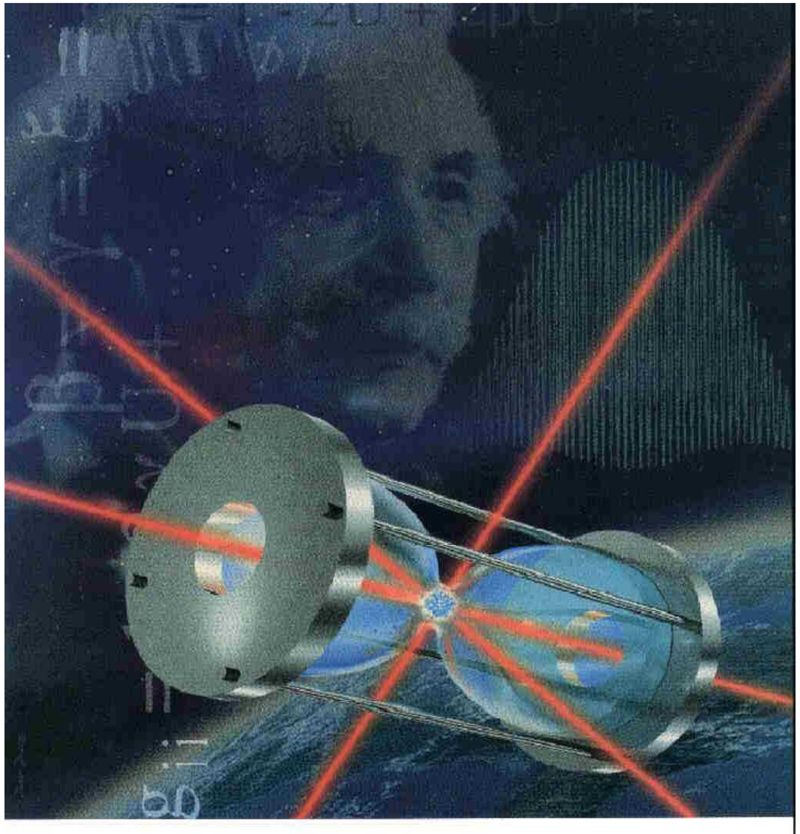
The ACES/PHARAO Space Mission
Fundamental Physics Tests with Space Clocks



Peter Wolf and C. Salomon
LNE-SYRTE and Laboratoire Kastler Brossel, Paris

Workshop « Atomes Froids et Applications Embarquées »

CNES-Toulouse, December 9th, 2015

Participants

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J. Guéna, J. Lodewyk, F. Meynadier, A. Clairon

M. Tobar, J. Hartnett, A. Luiten, J. Mc Ferran, C. Vale
F. Riehle, E. Peik, D. Piester, A. Bauch
O. Montenbruck, G. Beyerle,
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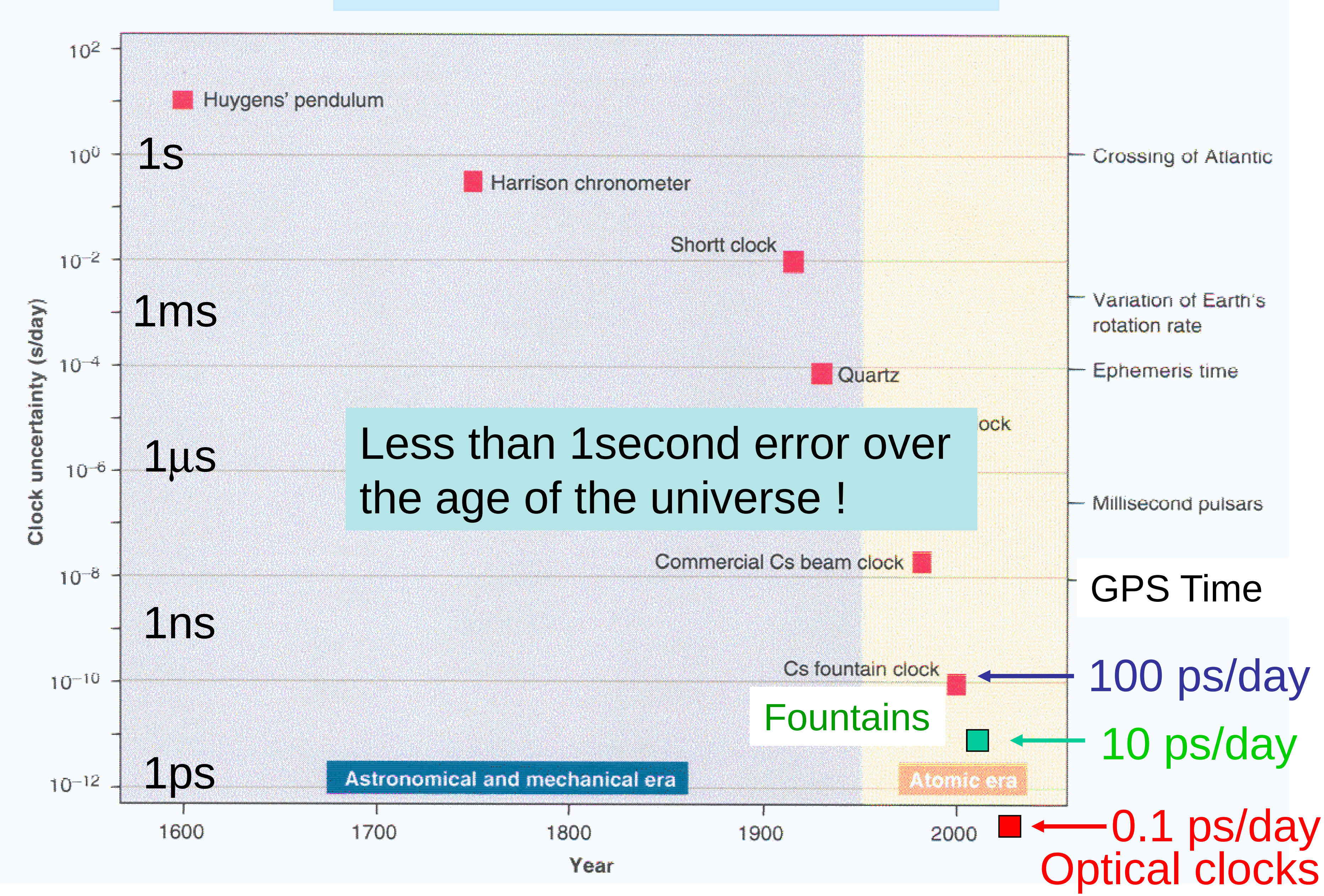
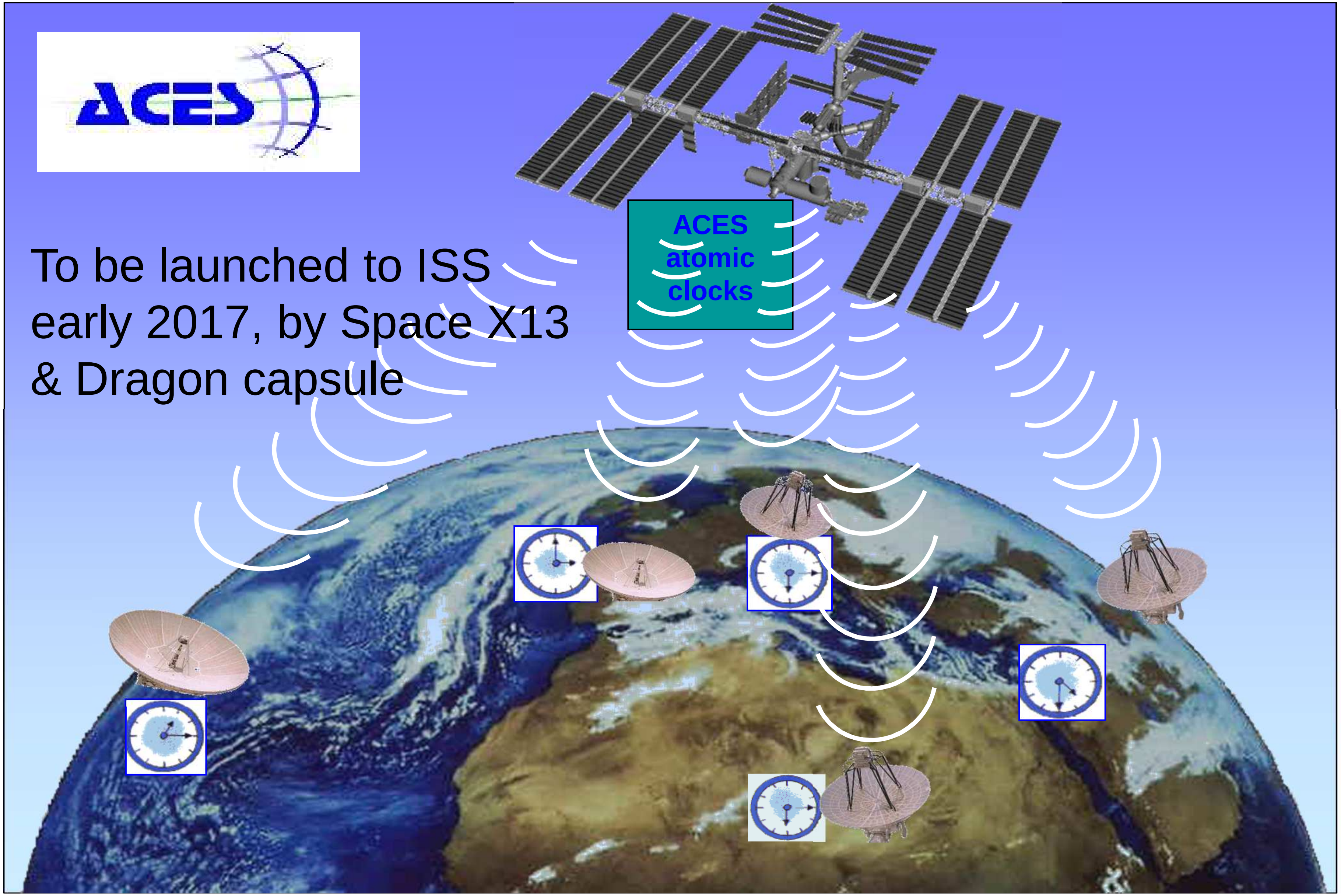
G. Tino, P. Thomann, S. Schiller, D. Calonico, S. Weyers
L. Cacciapuoti, R. Nasca, S. Feltham, F. Levi
R. Much, O. Minster, P. Gill, K. Szymaniec,
S. Jefferts, J. Ye, D. Wineland, H. Katori, M. Fujieda,
Y. Hanado, S. Watabe, Nan Yu, R. Toelkjer, K. Gibble
L. Hollberg, S. Léon, D. Massonnet and 15 engineers at CNES
L. Blanchet, C. Bordé, C. Cohen -Tannoudji,
C. Guerlin, S. Reynaud

Precision of Time





- **A cold atom Cesium clock in space**
- **Fundamental physics tests**
- **Worldwide access**

esa

cnes
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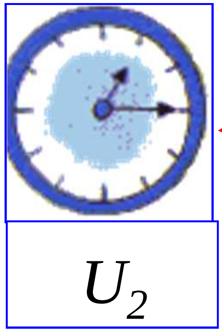
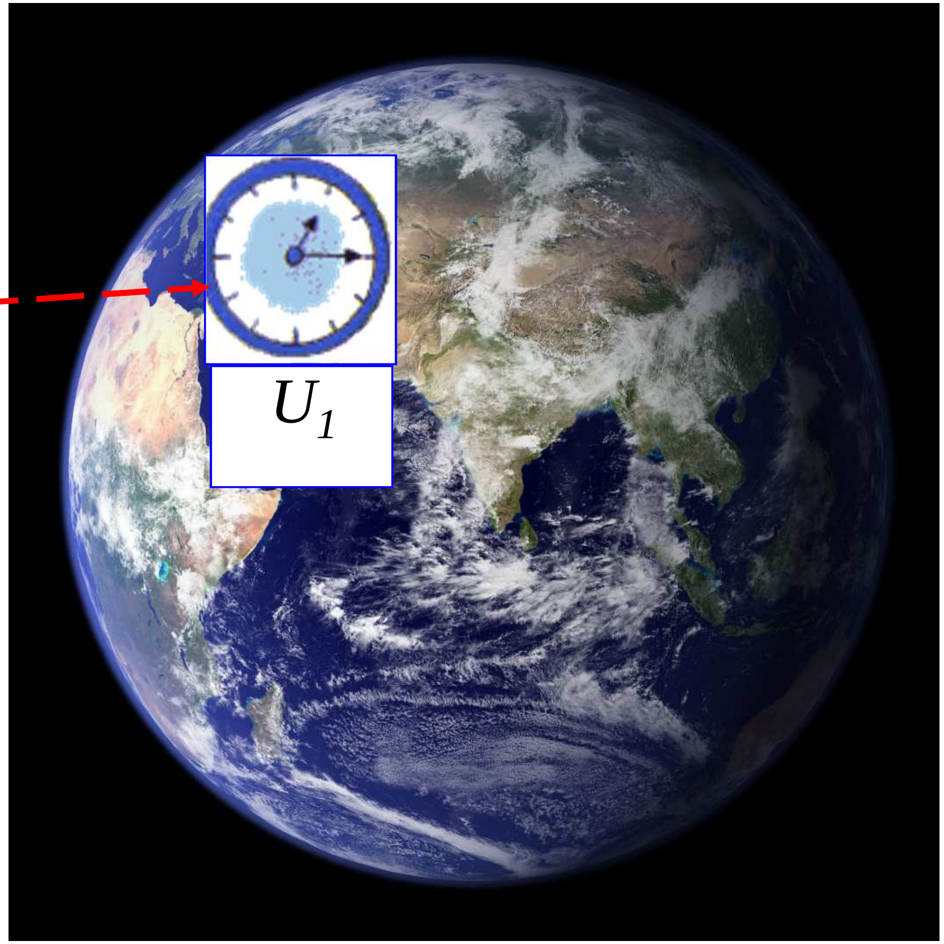
A Prediction of General Relativity

The gravitational clock shift





$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

Gravity- probe A:

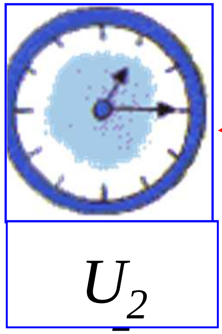
- Space H maser on a sounding rocket: 10 000 kms, 2 hour flight
- Ground maser
- orbit determination by radio station tracking

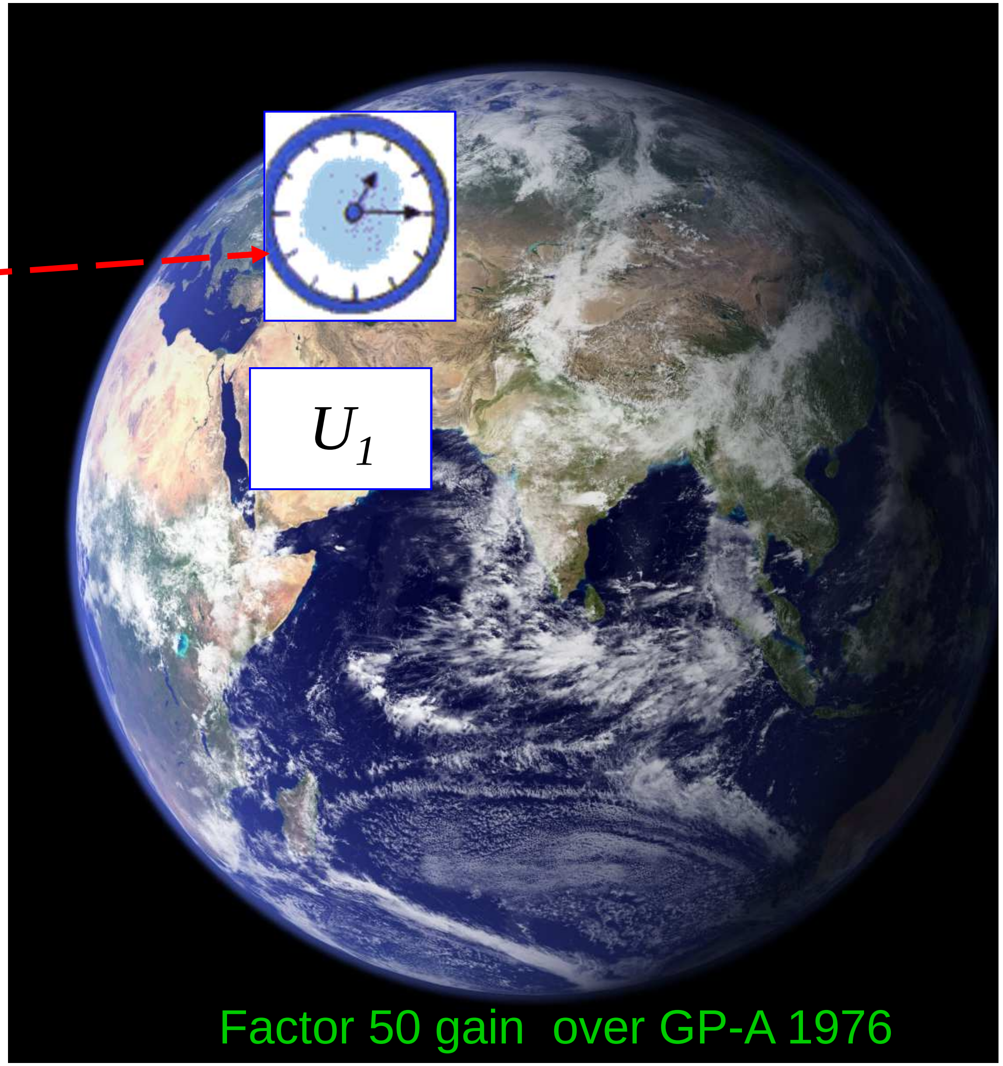
Also seen in lab with optical clocks !

C. W. Chou et al., Science 329, 1630, 2010

Gravitational Redshift tested at 1,4 10^{-4}

Gravitational redshift with ACES



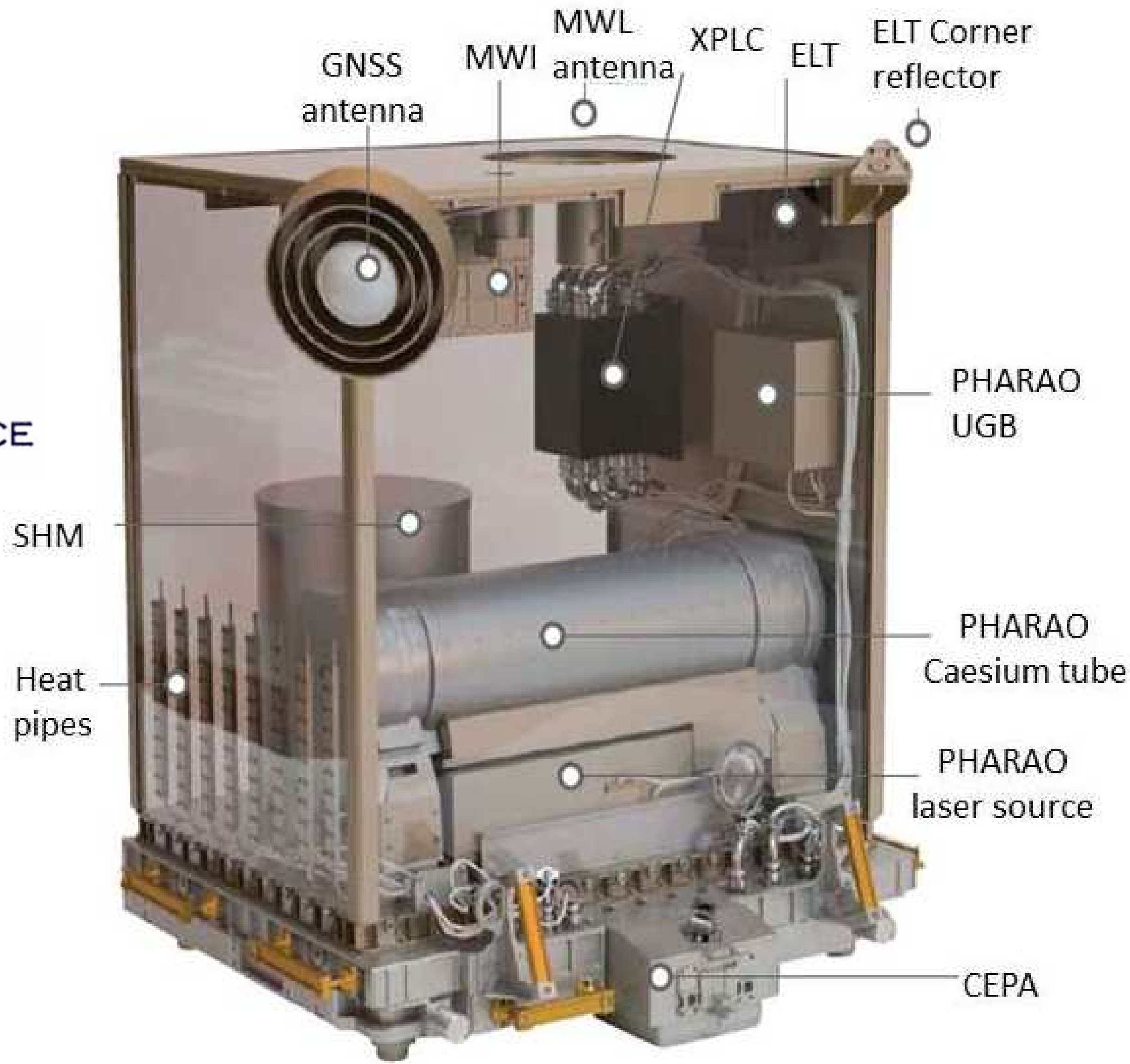


$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

Redshift : $4.6\ 10^{-11}$
With 10^{-16} clock
ACES: $\sim 2\ 10^{-6}$

ACES General View

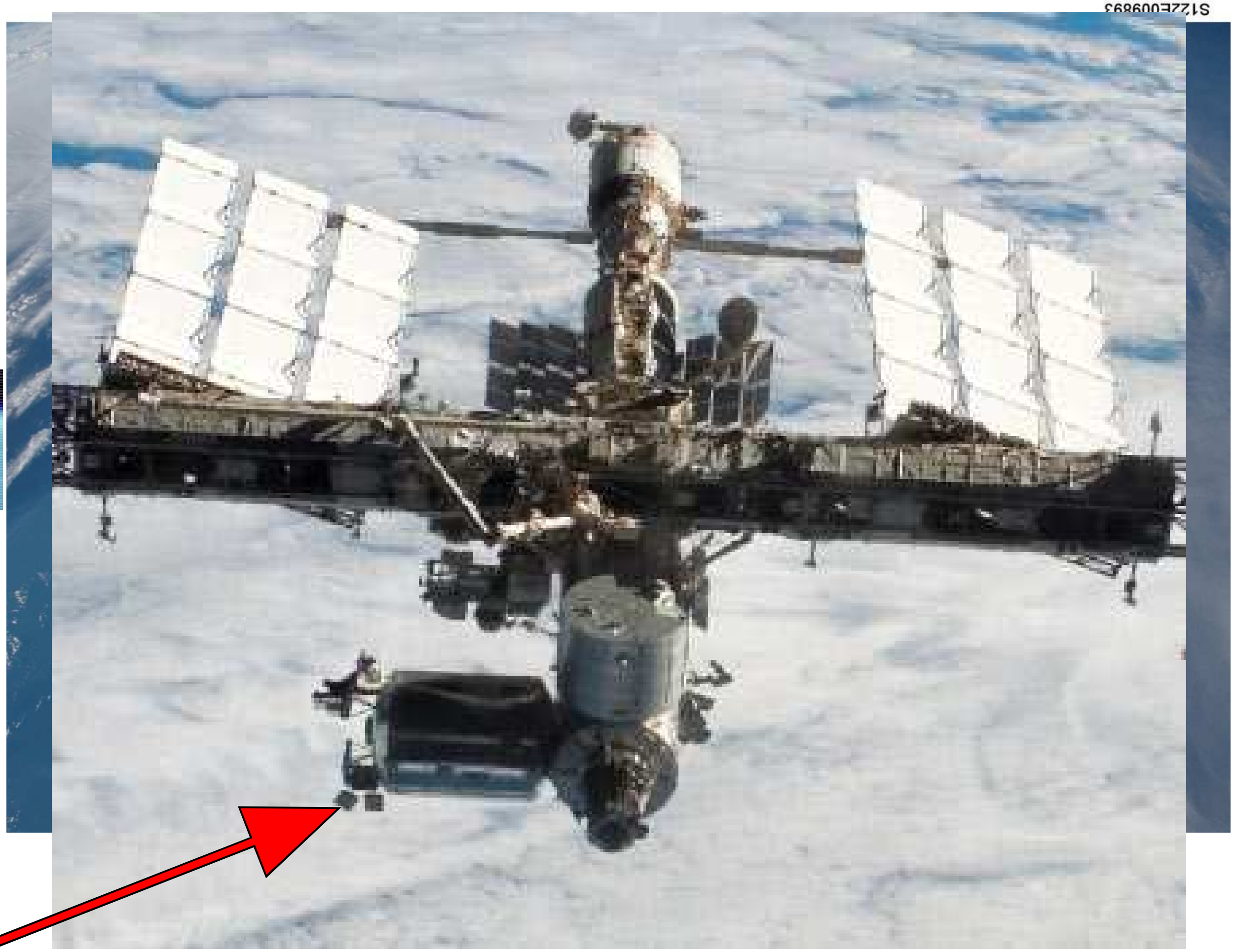
Earth



Mass: 227 kg,
Power: 450 W

Challenges: thermo-mechanical stability, three year operation

ACES ON COLUMBUS EXTERNAL PLATFORM on ISS

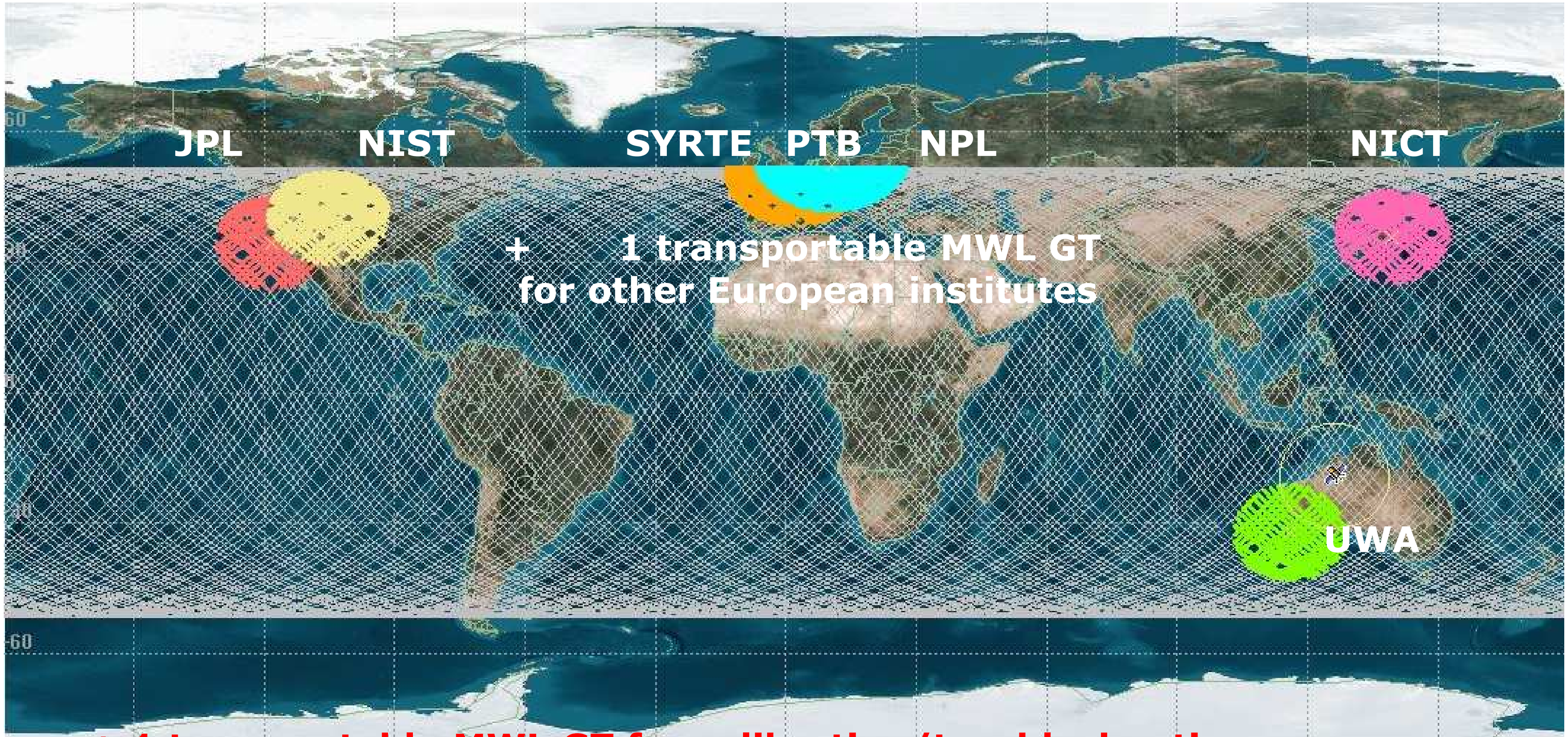


ACES

Current launch date : first semester 2017

Mission duration : 18 months to 3 years

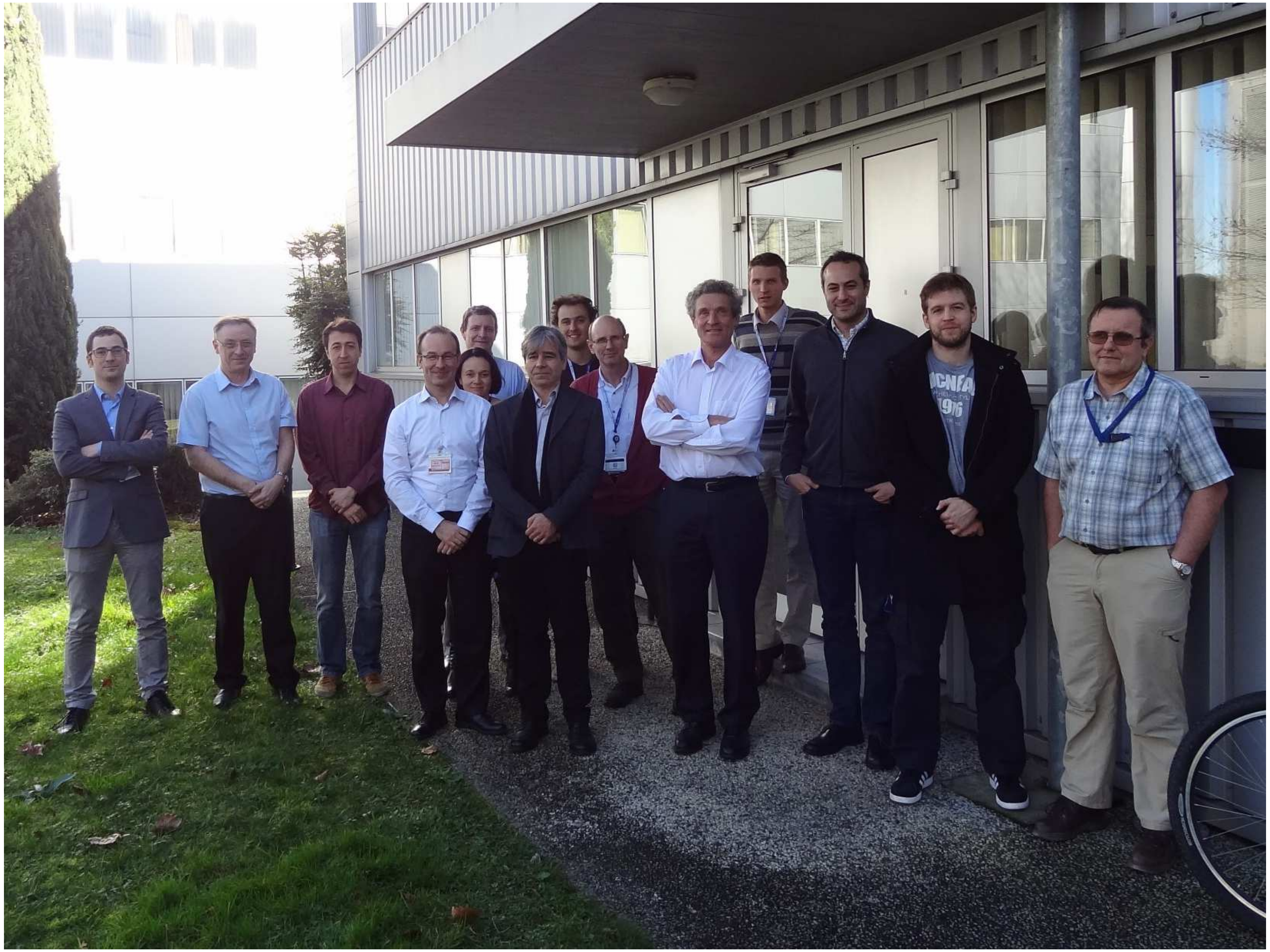
Current Network of Ground Institutes



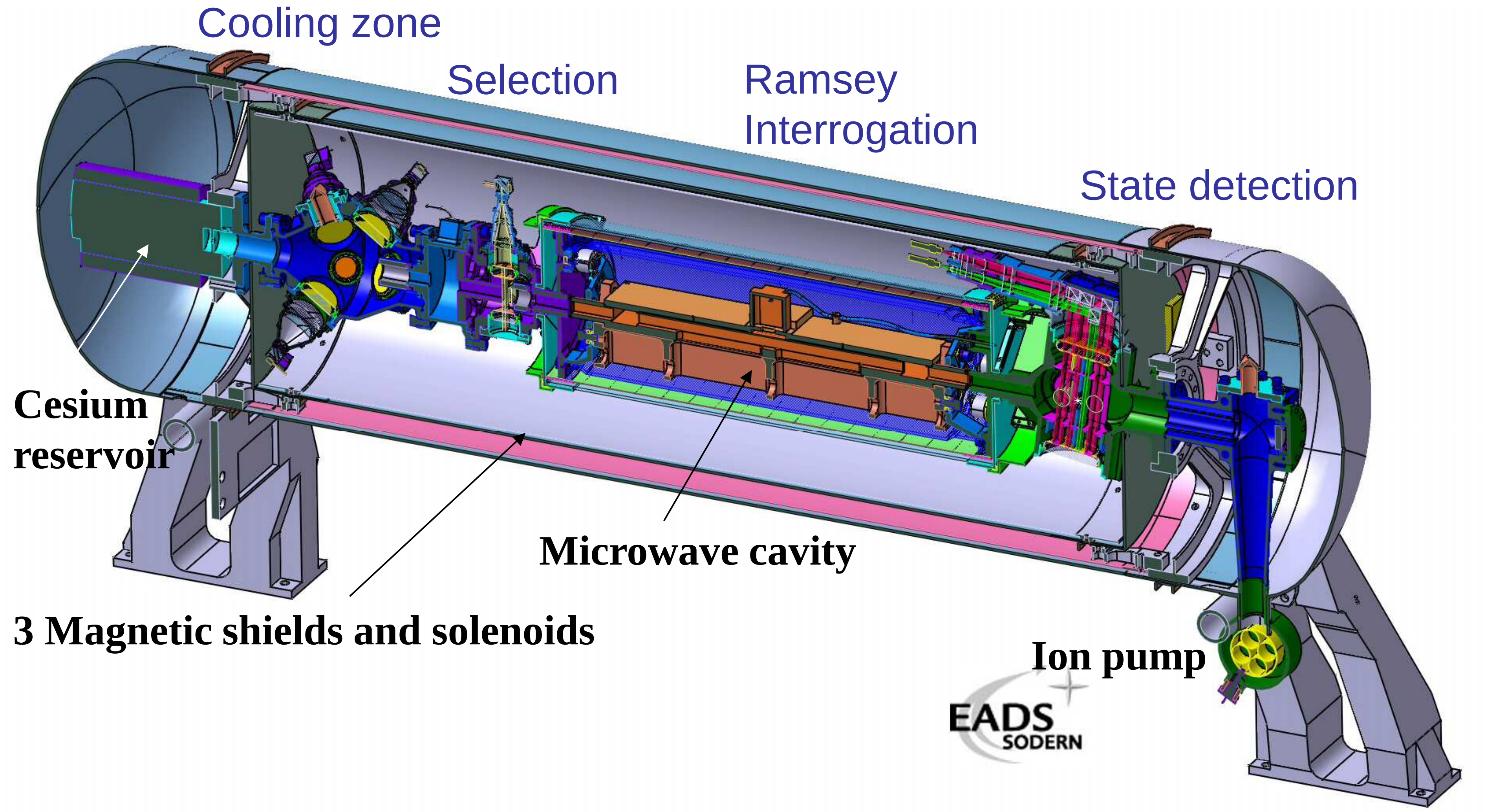
+ 1 transportable MWL GT for calibration/troubleshooting purposes
METAS, INRIM,…

Delivery of first MWL GT unit to PTB just made, end of 2015

PHARAO Team in Toulouse



PHARAO cold atom clock



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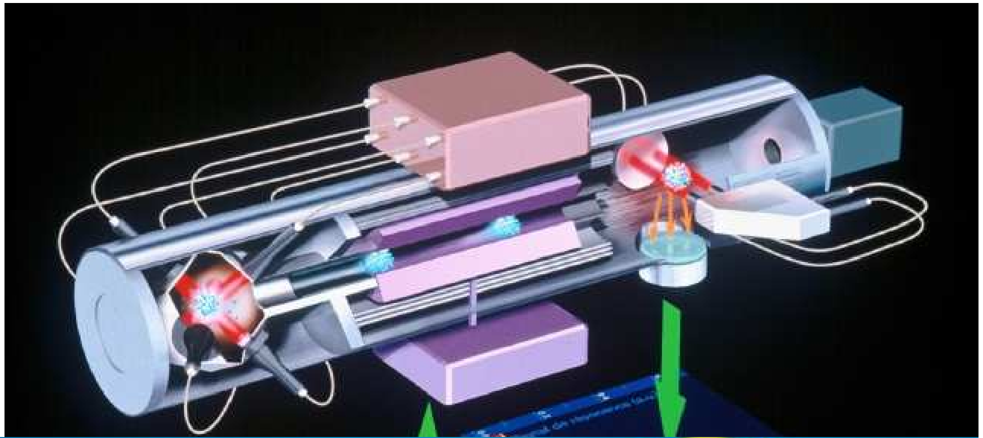
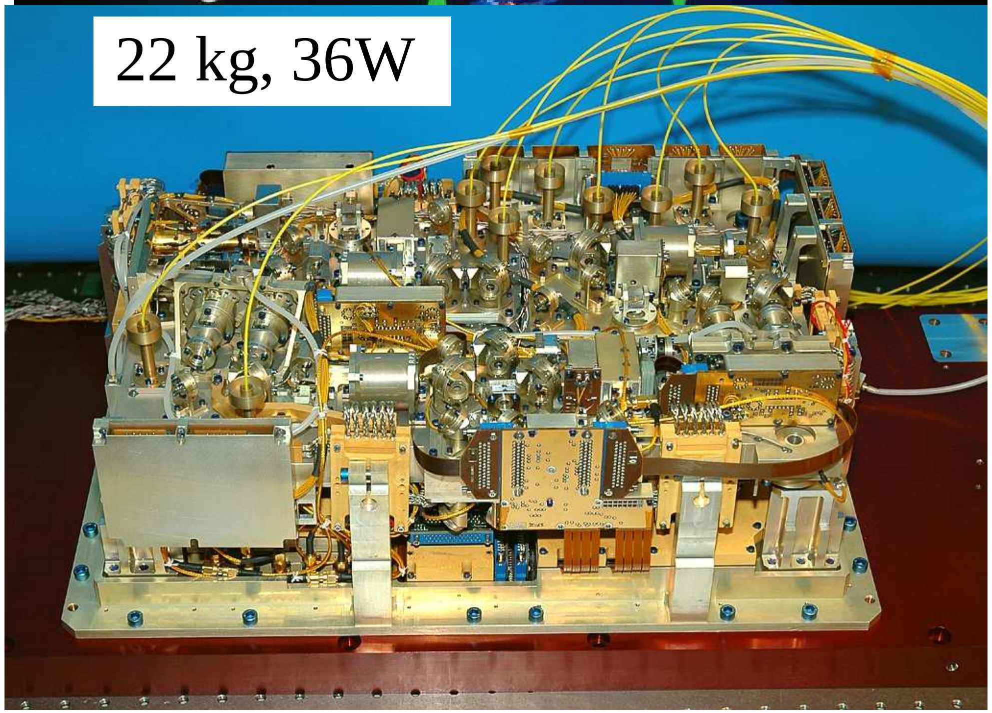
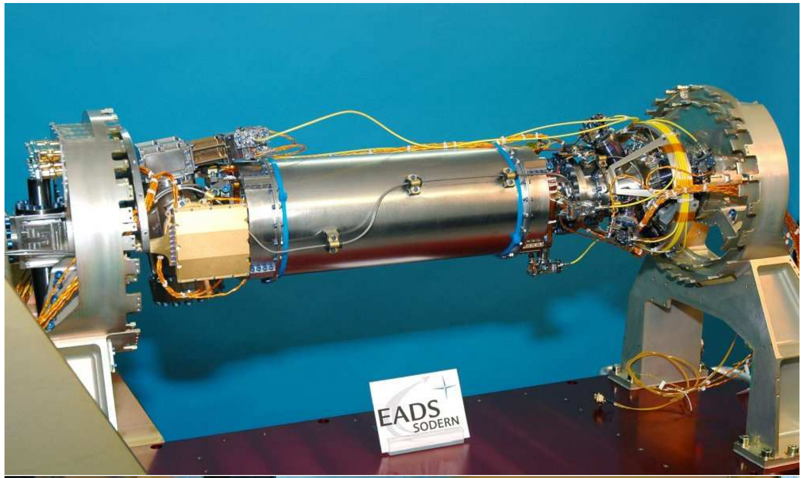
Cold Atom Clock in μ-gravity : PHARAO/ACES



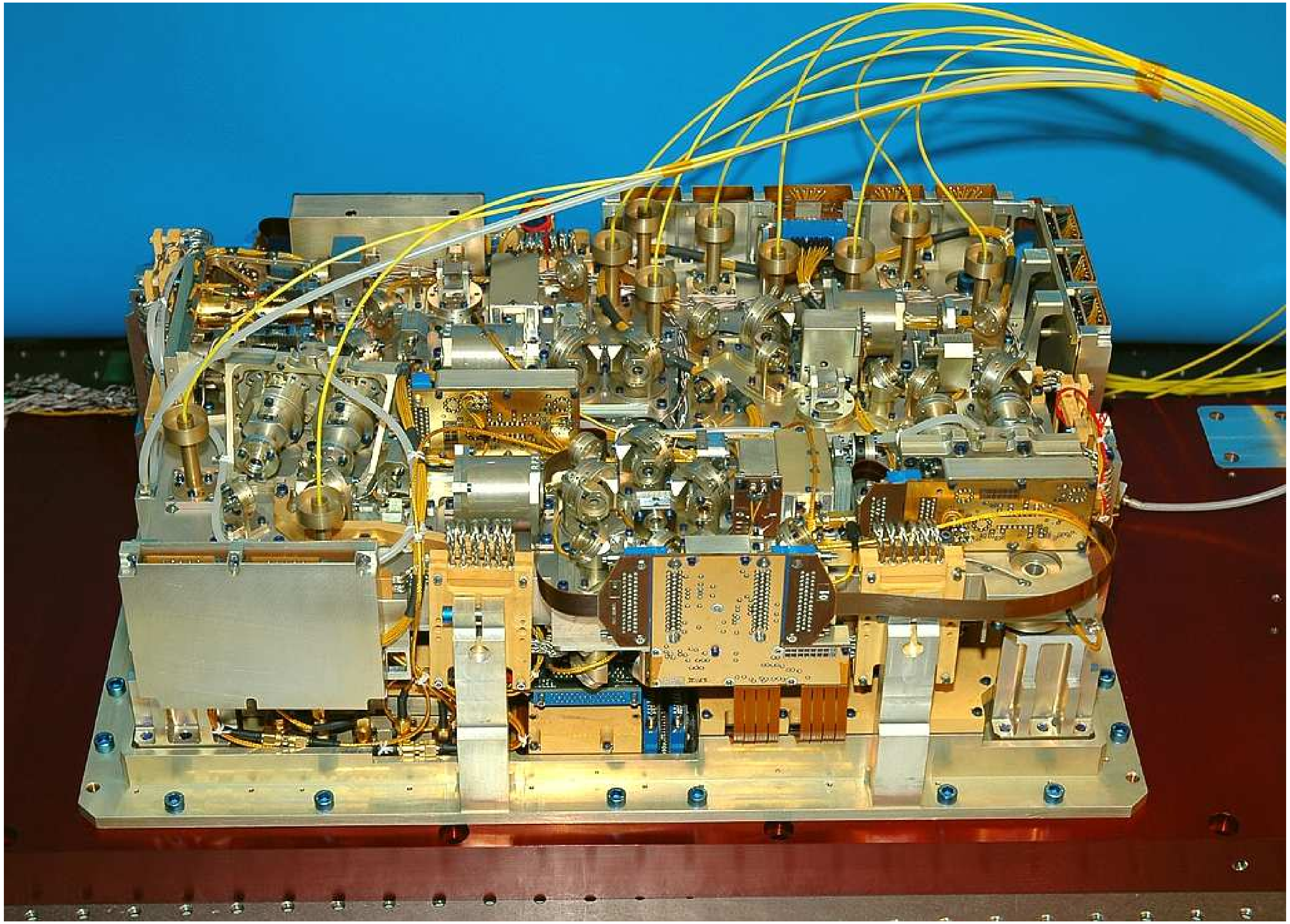




Laser Source

22 kg, 36W, 30 liters, Vacuum and Air operation, T=10-35 deg.

Engineering model: 7 years of operation without manual adjustment



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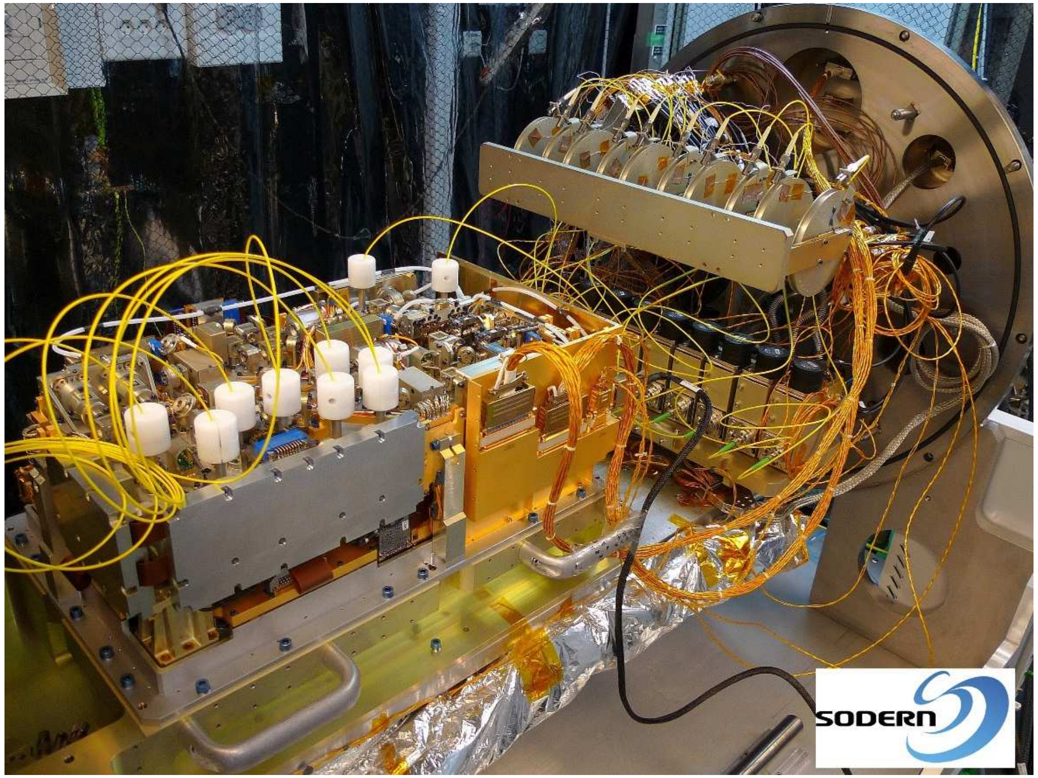
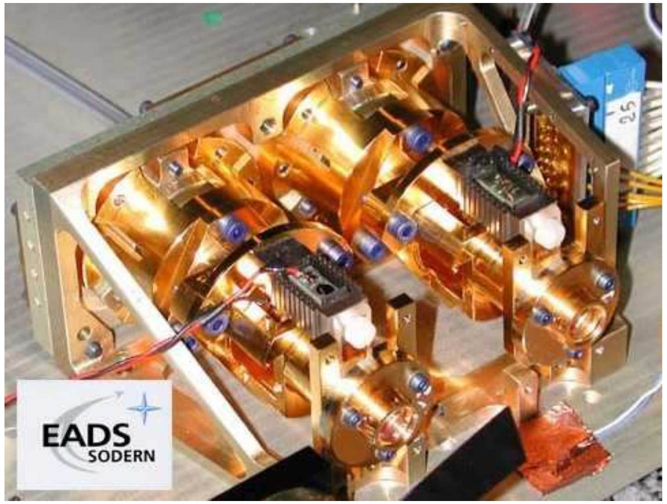
Main active components:
4 ECDL
4 DL
6 AOM
30 PZT
11 motors
6 photodiodes
8 peltier coolers

PHARAO Laser Source





Extende cavity lasers
Autolock on cesium saturated absorption lines

Mass: 22 Kg, Power 36 W
Flight model assembly: January 2014

PHARAO Cesium Tube on the Shaker

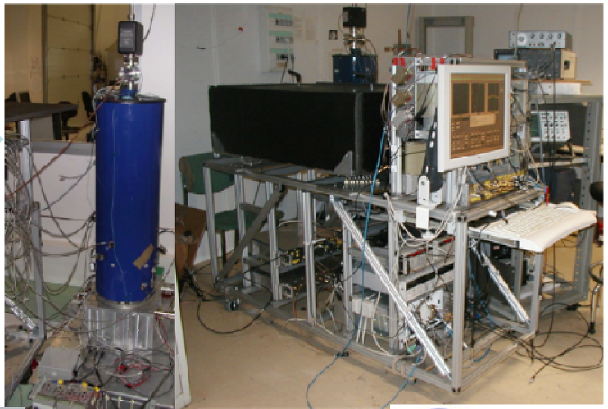
PHARAO Flight Model Performance Tests

Cryo-oscillator

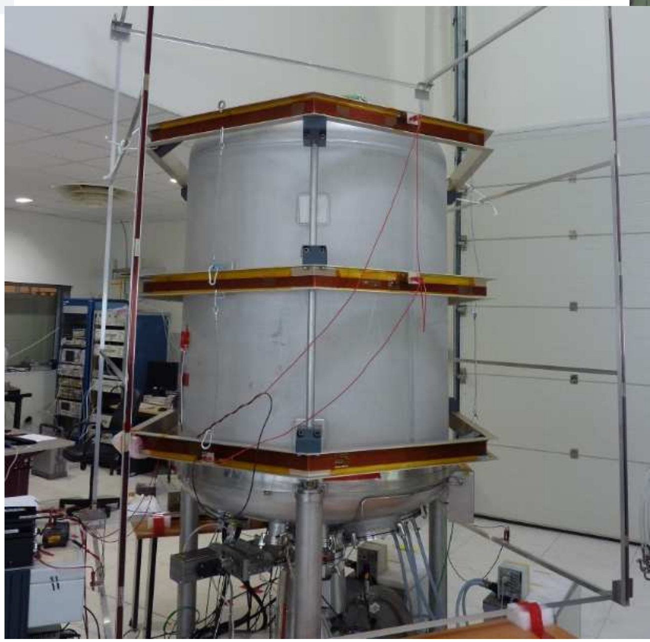
+ CNES H-MASER frequency stability

100MHz

Mobile Fountain FOM



Frequency comparison accuracy



Ground Commands

- Orbital simulations in vacuum
- Temperature and Magnetism

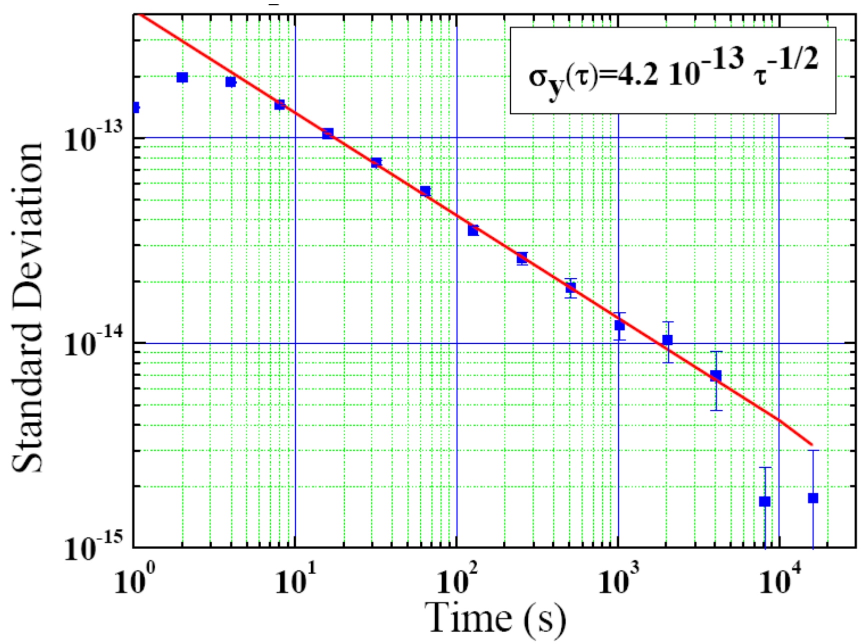
PHARAO Frequency Stability and Accuracy

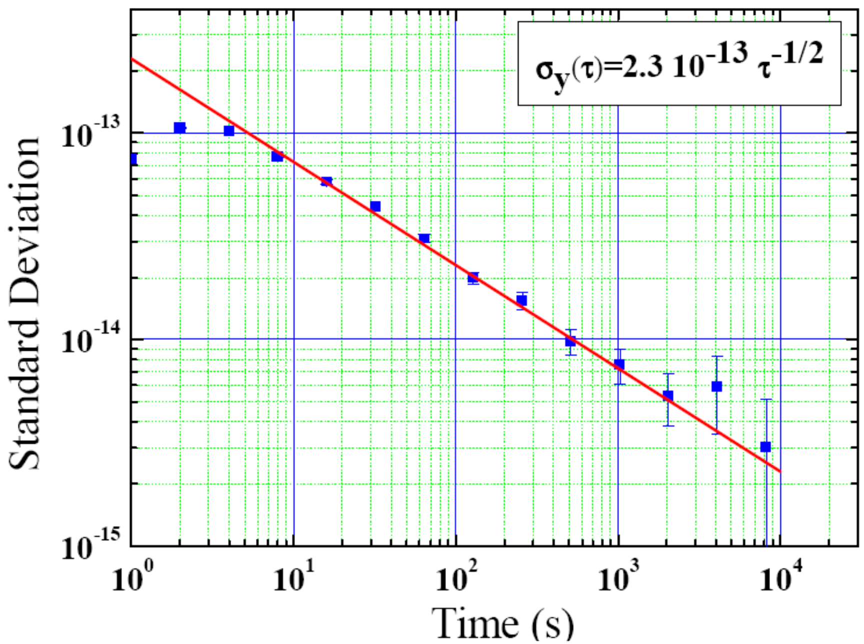
$$\sigma_y(\tau) = 4.2\ 10^{-13}\ \tau^{-1/2}$$

With ultra-stable Quartz
Limited by gravity !

$$\sigma_y(\tau) = 2.3\ 10^{-13}\ \tau^{-1/2}$$

With Cryo. Oscillator

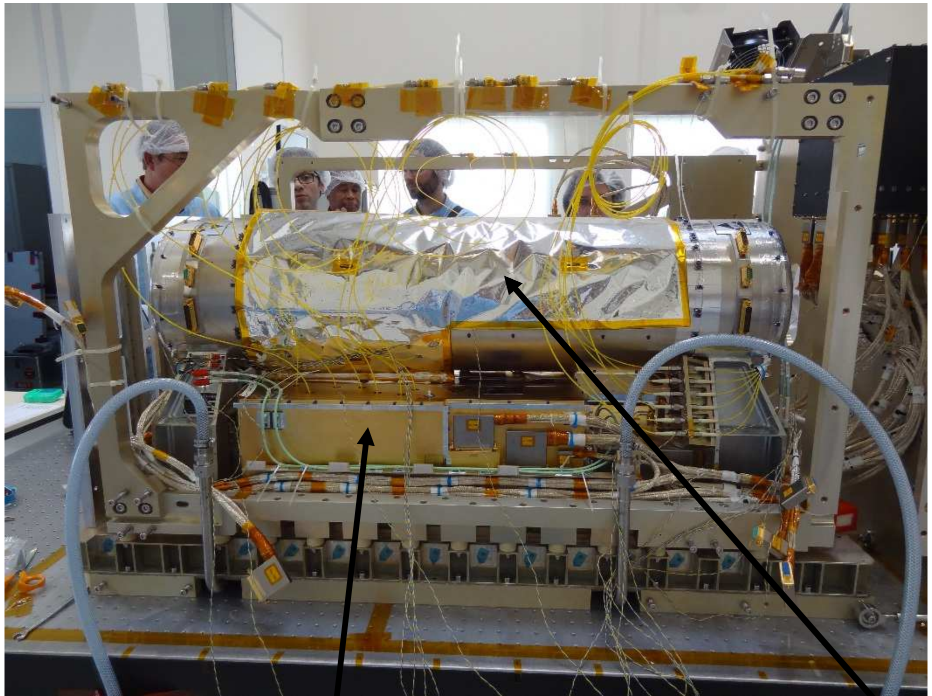


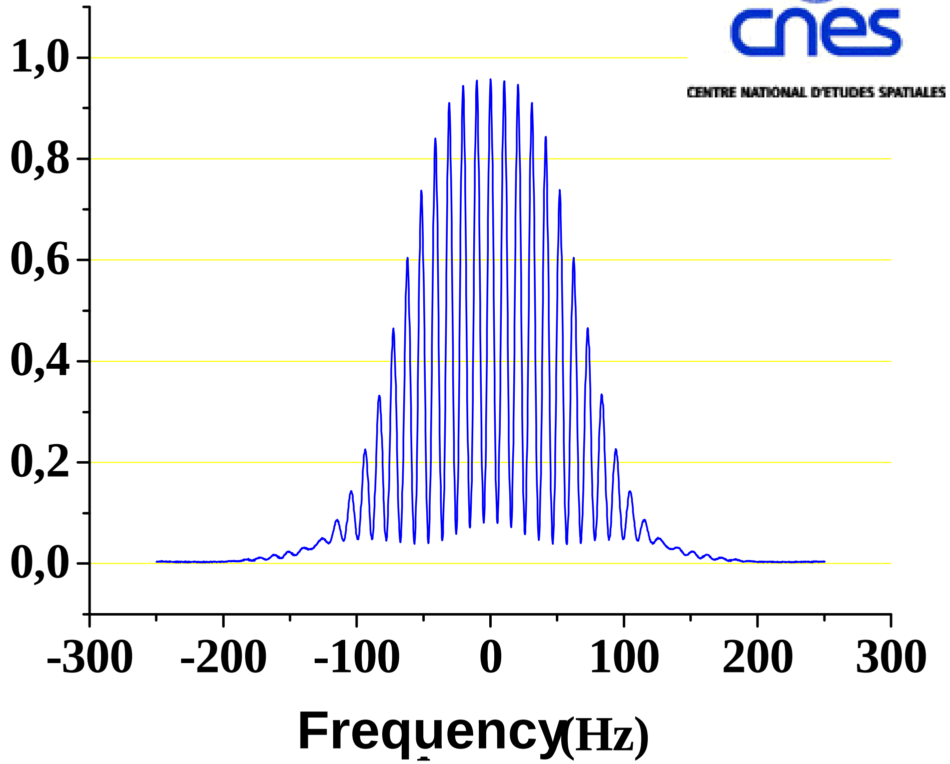


Will enable $8\ 10^{-14}\ \tau^{-1/2}$
in space with narrower line

Accuracy evaluation :
Currently $1.4\ 10^{-15}$ on the ground.
Should enable 10^{-16} in space.

PHARAO cold atom Space Clock





Cesium tube

Laser source

Flight model tests completed in Toulouse

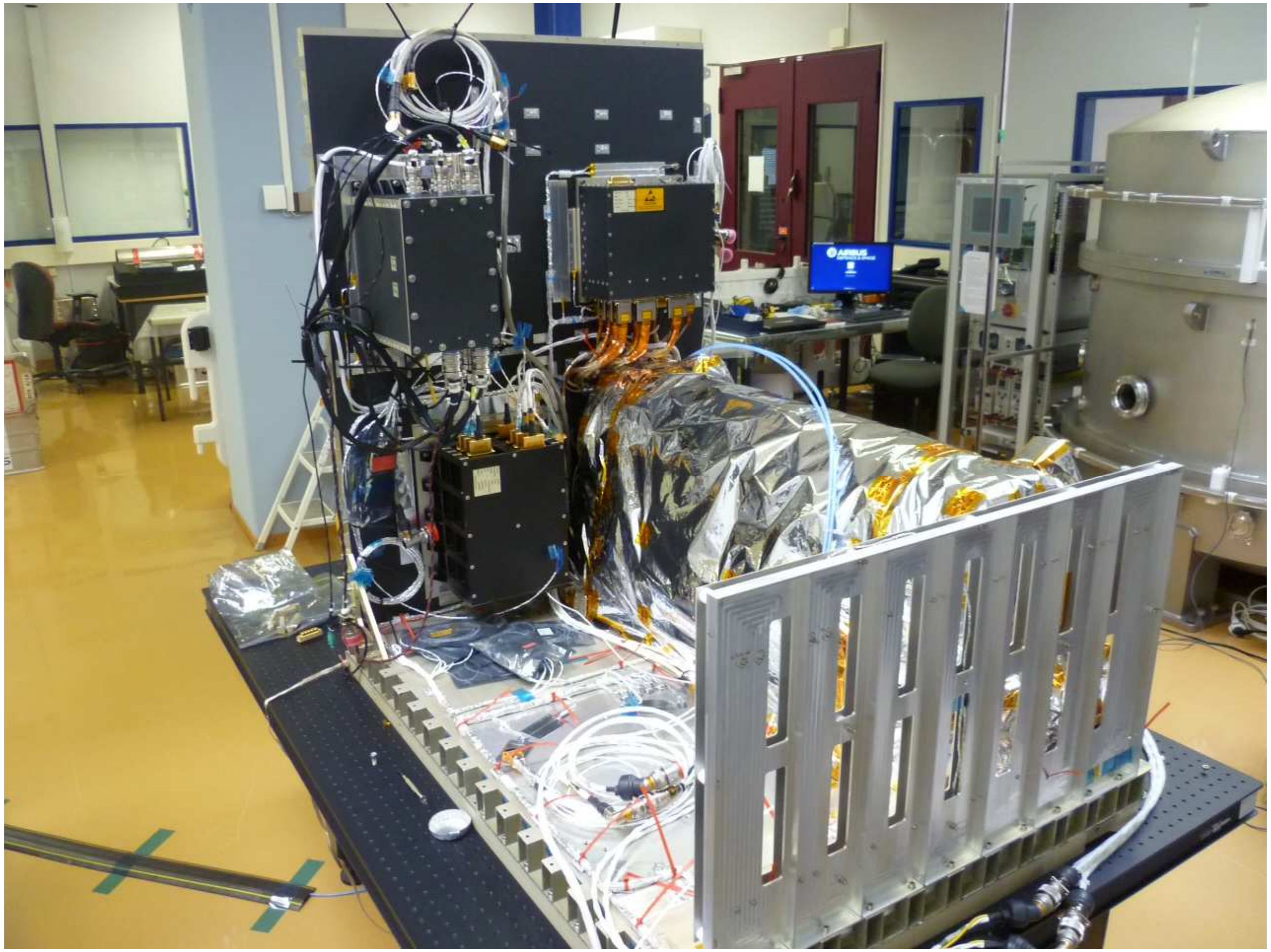
Expected accuracy and stability:10^{-16} in space

Delivery to ESA: July 2014

Test of Einstein effect at 2 ppm

ACES Status

Payload at ADS
Friedrichshafen



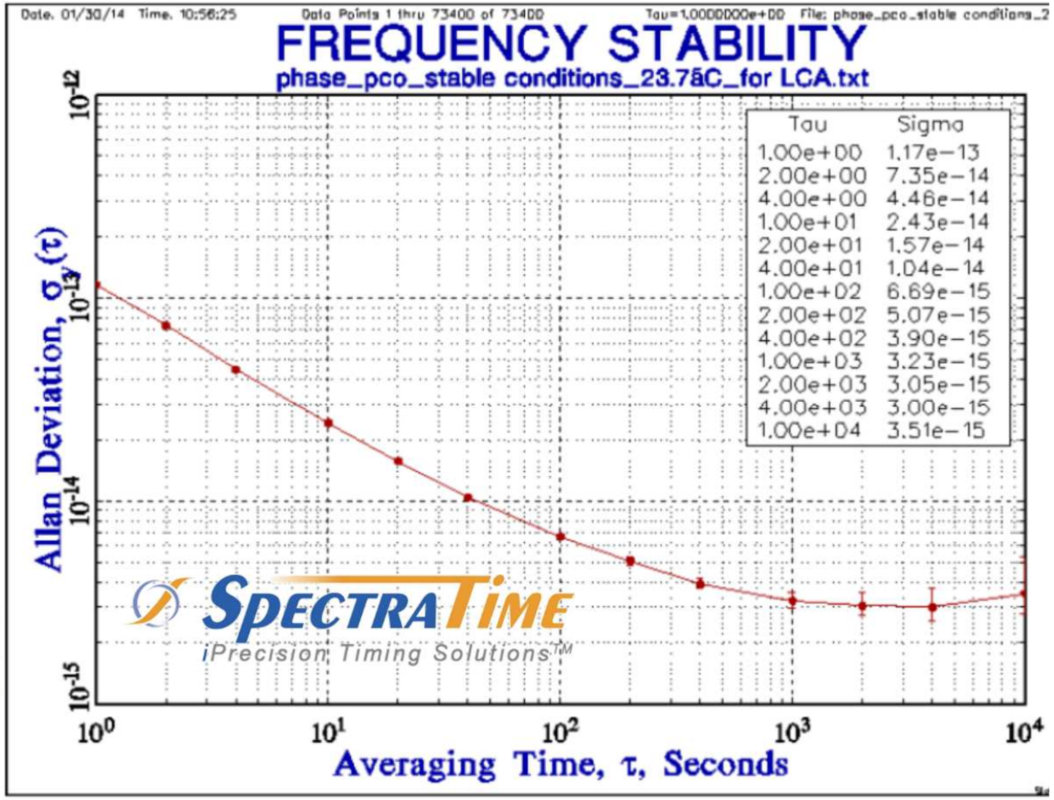
PHARAO clock mounted on base plate
PDU mounted on –X panel
FCDP passed environmental tests and delivered
ELT : repair after EMC test damage

ACES Visitors at ADS Friedrichshafen

Claude Cohen-Tannoudji Ted Hänsch

ACES Status: Space Hydrogen Maser

SHM stability in stable environmental conditions.
Magnetic sensitivity coefficient: 6 10^{-14}/Gauss
Degradation of stability at half ISS period



SHM EM2B on shaker: passed vibrations !
SHM PFM delivery to ADS: March 2016
Final configuration and performance tests

ACES TIME Transfer

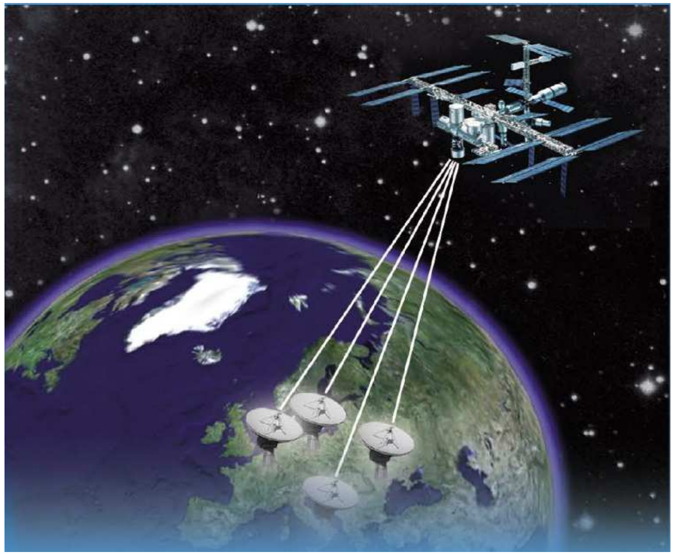
Ultra-stable frequency comparisons on a worldwide basis :

Ground Clock comparisons@ 10^{-17} over one week

Contribution to TAI

Gain: x 20 wrt current GPS

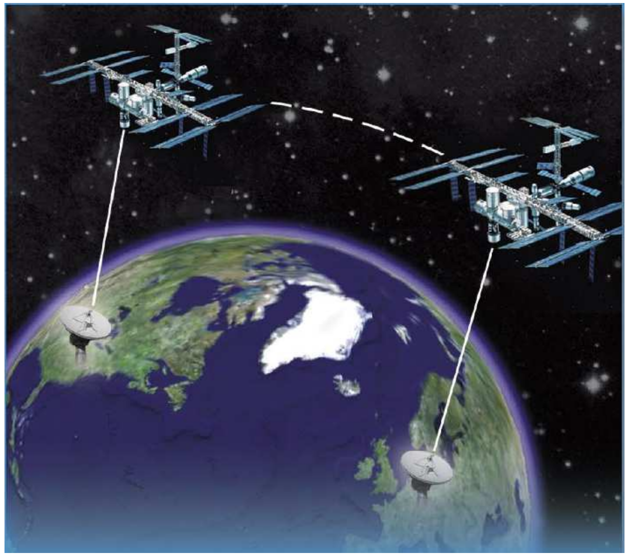
Common view



Error < 0.3ps over 300 s

To be checked by fiber-link

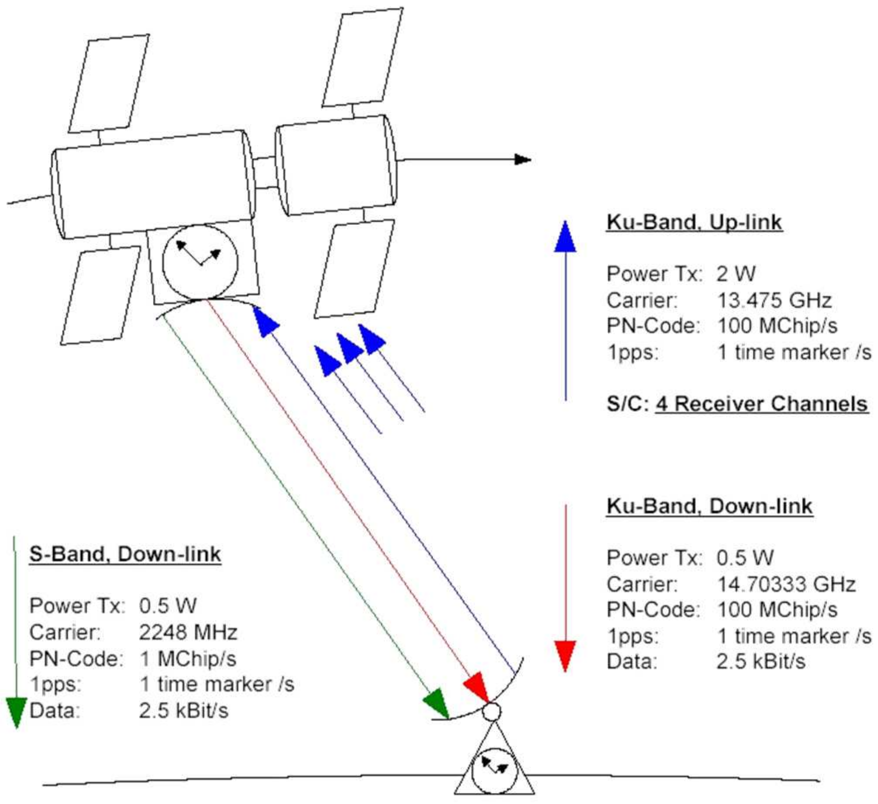
non common view



Error < 3ps over 3000 s

Frequency comparisons at 10^{-17} over 4-5 days

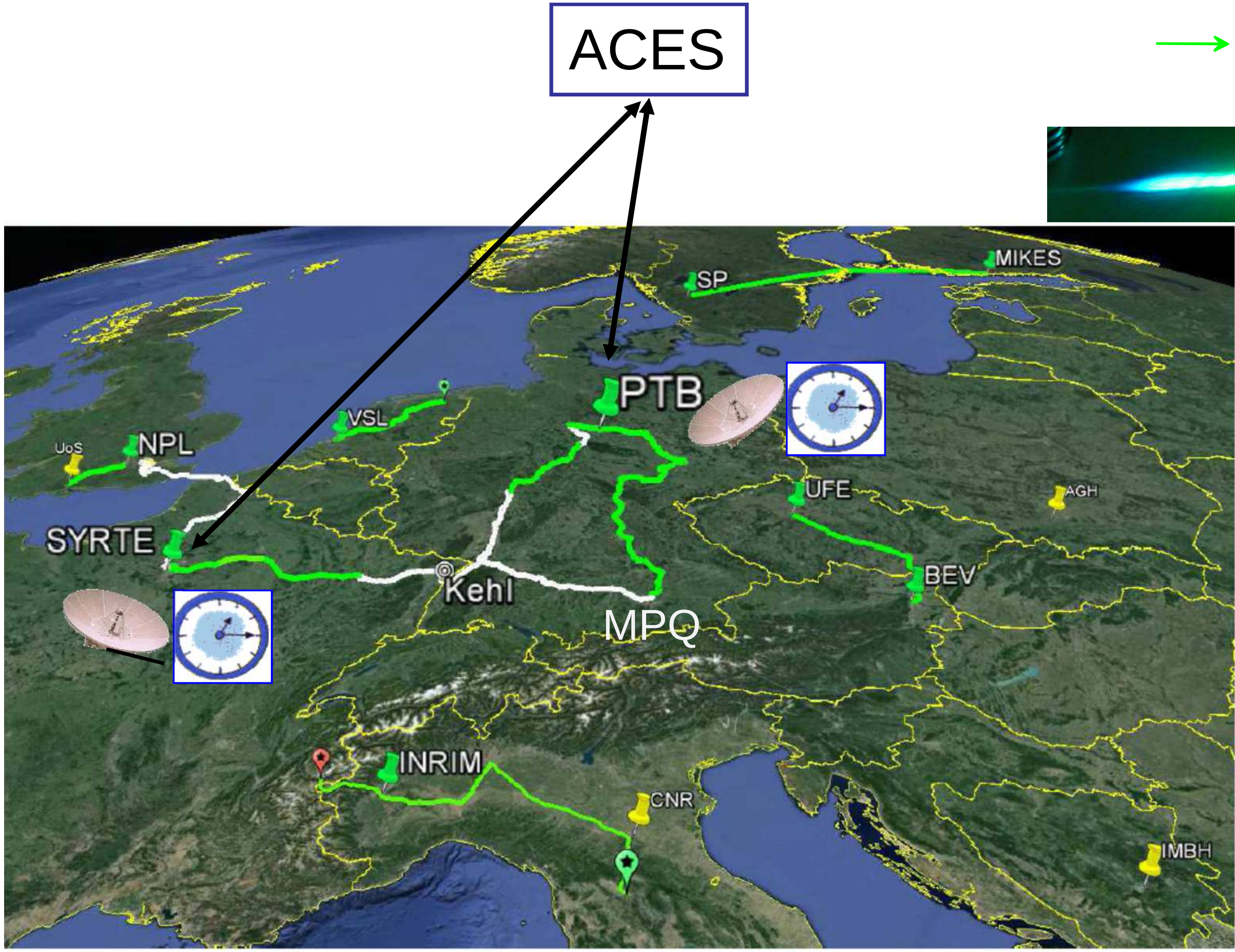
ACES Microwave Link (MWL)

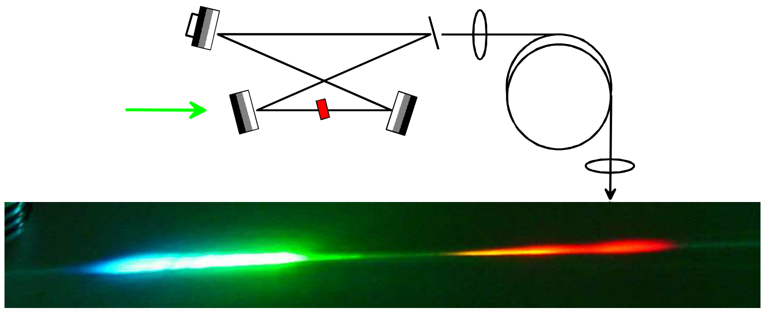


ASTRIUM TIMETECH TZR EREMS

- Two-way link:
  - Removal of the troposphere time delay (8-10 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 (0.3-4 ns in S-band, 6-10 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: 2.5 kbit/s on the S-band down-link to obtain clock comparison results in real time
- Up to 4 simultaneous space-to-ground clock comparisons

Global satellite time transfer and continental fiber links



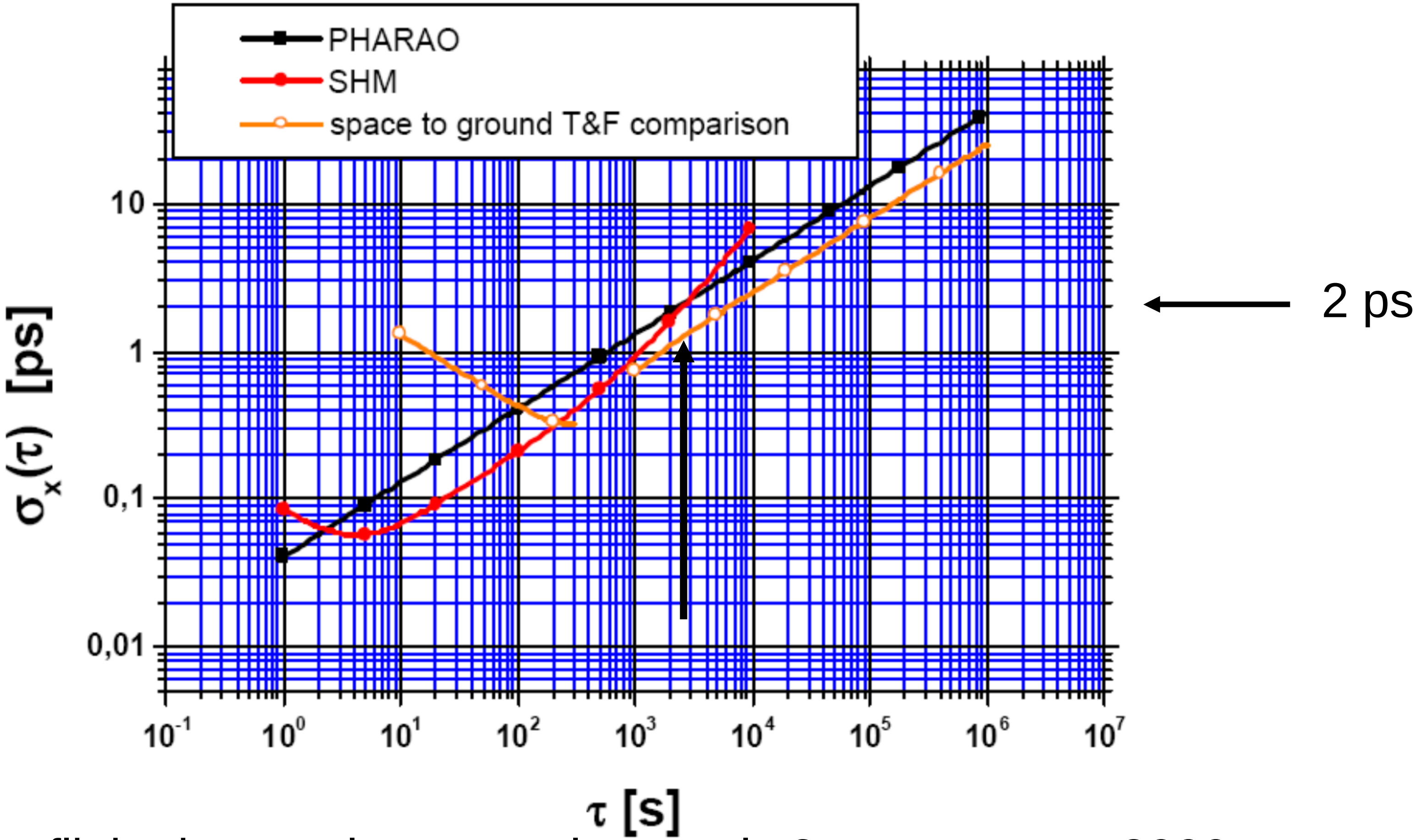


Frequency Comb
J. Reichert et al.
*PRL **84**, 3232 (2000),*
S. Diddams et al.
*PRL **84**,5102 (2000)*

Test of ACES MWL
by fiber links between
PTB, MPQ, SYRTE,
NPL, INRIM,VSL,…

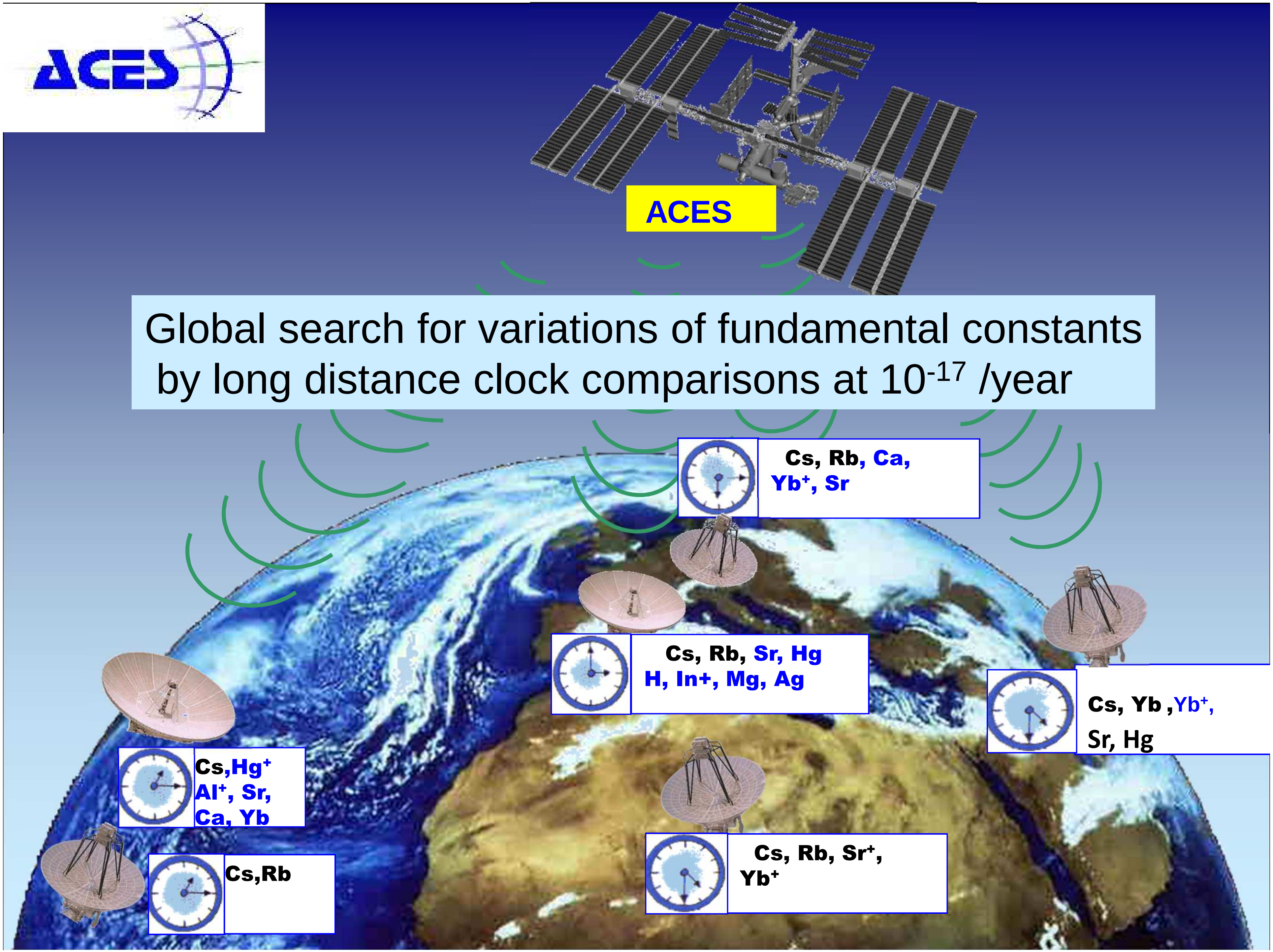
Talk by S. Bize

Time stability of Microwave link: Non Common View (intercontinental)



The flight time scale accumulates only 2 ps error over 3000 s
i.e. half an orbital period. 2-5 comparisons per day.

Frequency comparisons at 10^{-17} over 4-5 days
a factor > 20 gain vs GPS and TWSTFT


ACES
ACES
Global search for variations of fundamental constants
by long distance clock comparisons at 10^{-17} /year
Cs, Rb, Ca, Yb$^+$, Sr
Cs, Rb, Sr, Hg H, In+, Mg, Ag
Cs, Yb ,Yb$^+$, Sr, Hg
Cs,Hg$^+$ Al$^+$, Sr, Ca, Yb
Cs,Rb
Cs, Rb, Sr$^+$, Yb$^+$

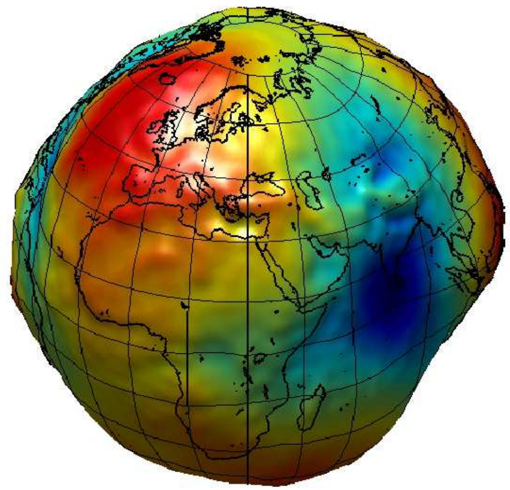
c3

Relativistic Geodesy

The clock frequency depends on the Earth gravitational potential

10^{-16} per meter

Best ground clocks have accuracy of 2 10^{-18} and will improve !

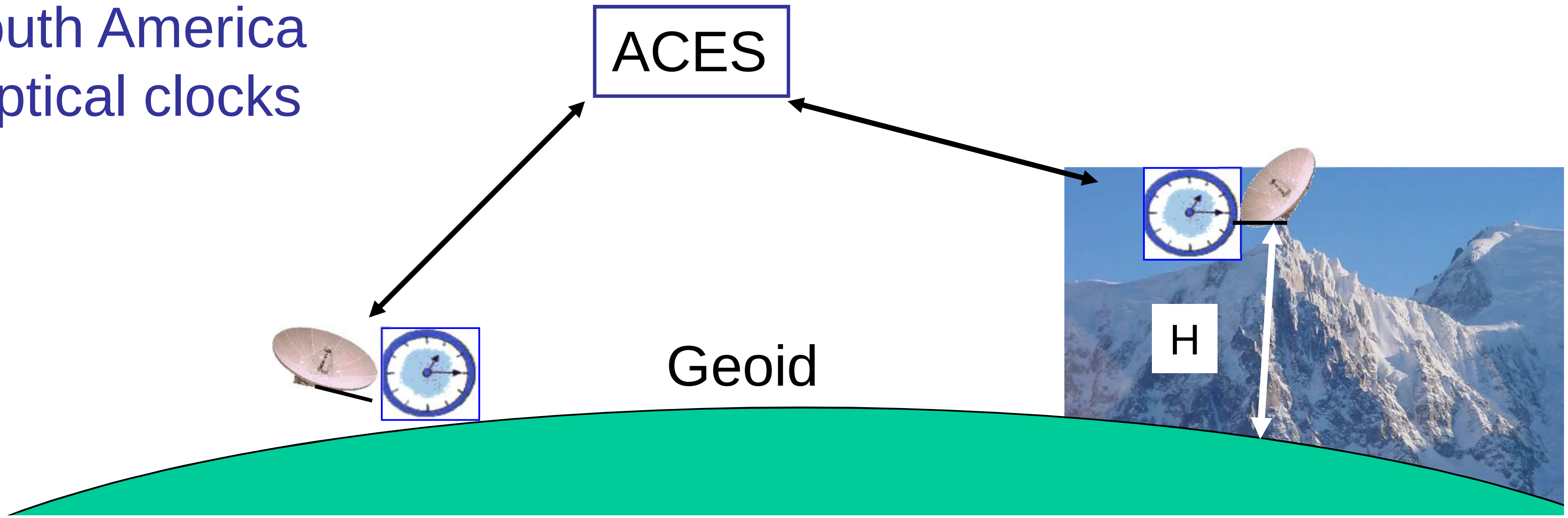


With ACES:

Possibility to measure the **potential difference** between the two clock locations at 10^{-17} level ie 10 cm

- South America

+ Optical clocks



ACES in flight preparation activities

ACES assembly and Tests in Friedrichshafen
(software, performances, vibrations)

Delivery to Kennedy Space center for launch
on Space X 13 Dragon module

ACES in flight commissioning plan

ACES operation team at CNES Toulouse

Microwave link ground terminals delivery and tests

ACES Data base and Transmission of the
clock status file to the ACES data base.

Preparation of Data analysis with DPC at SYRTE, (NPL).

Summary

1) Optical clocks have less than 1 picosecond per day timing fluctuations: redefinition of the SI second

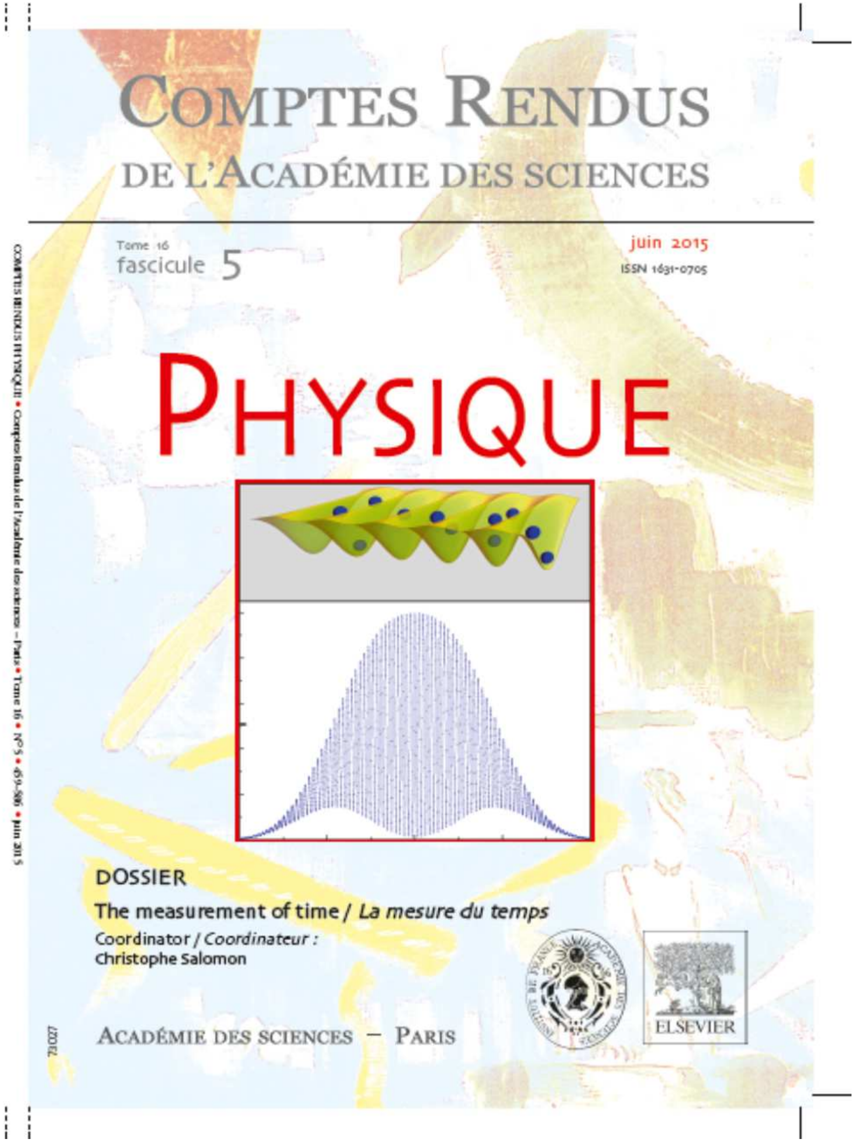
2) Precise Time can be delivered by satellites and fiber links to any interested user with capability of ~ a few picoseconds

3) ACES will perform a test of the Einstein effect at 2 ppm and enable distant clock comparisons at 10^{-17} .

4) This will advance new applications like chronometric geodesy, on continental and (more importantly) intercontinental scales.

5) ACES is also a pre-curser for cold atoms in space, opening the way for missions in fundamental physics, Earth/planetary gravity (e.g. STE-QUEST, space-gradiometer, ….)

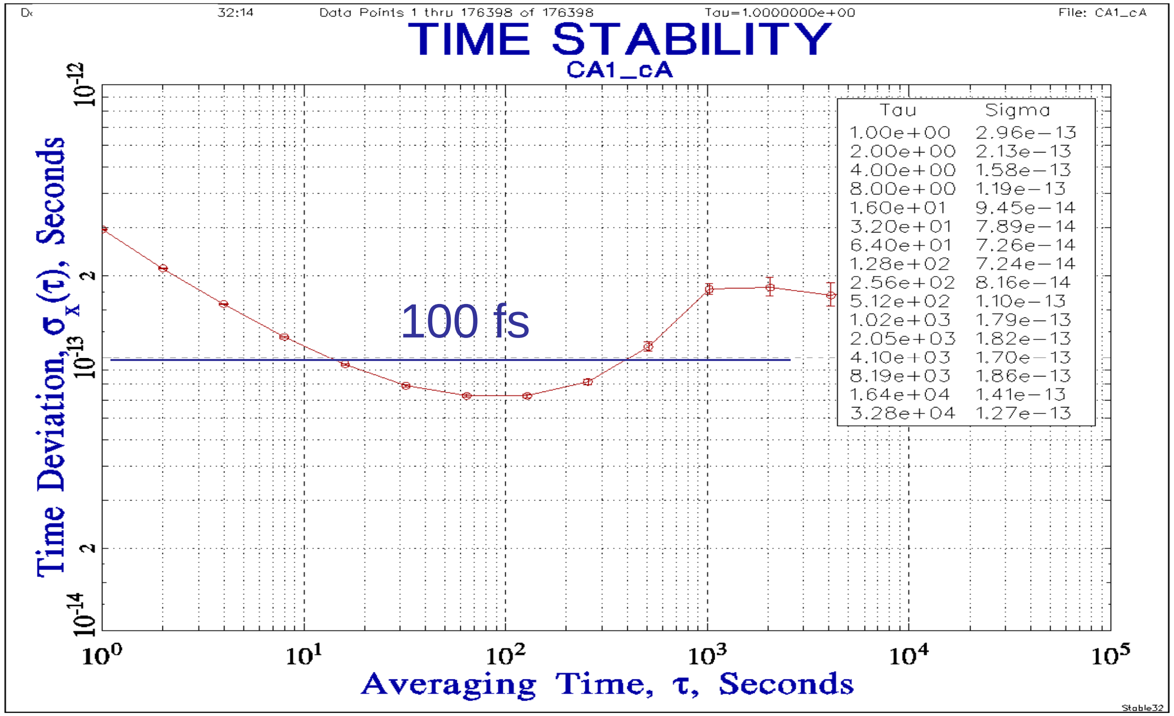
Special Issue of Comptes-Rendus Physique
The Measurement of Time



A good reading !

ACES Time Transfer

The microwave link ground terminal



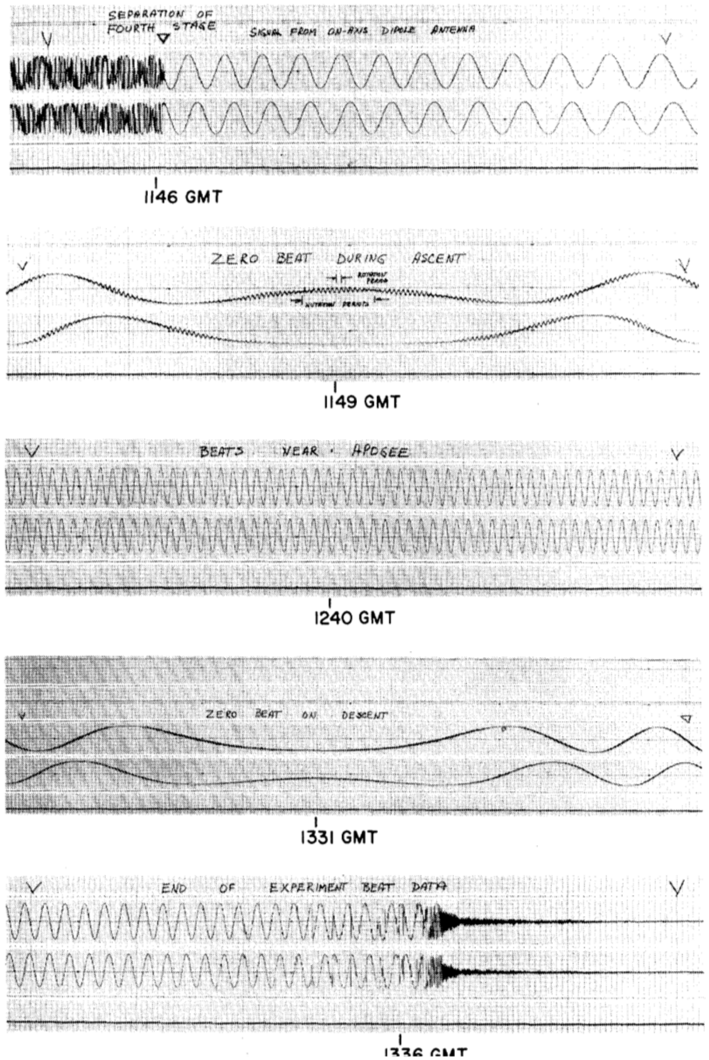
Time stability of carrier with 10 Kelvin peak to peak temperature variation

PTB, SYRTE, NPL, JPL,
NIST, NICT, UWA, INRIM, METAS,…

MWL flight models
under construction

3rd FSM Aussois 1981, R. Vessot
Test of the gravitational redshift with Masers

GP A: R. Vessot et al., PRL, 45, 2081 (1980)



Max redshift: 0.9 Hz

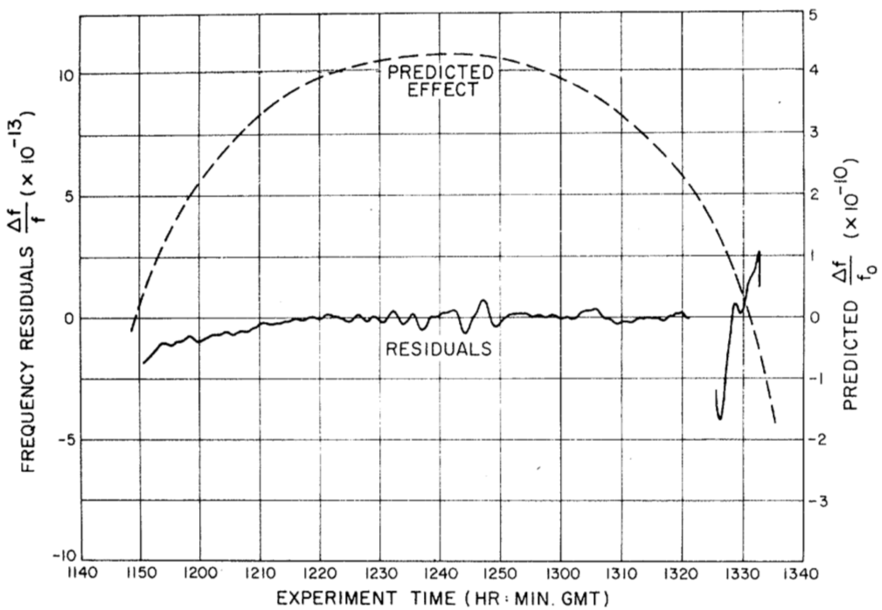
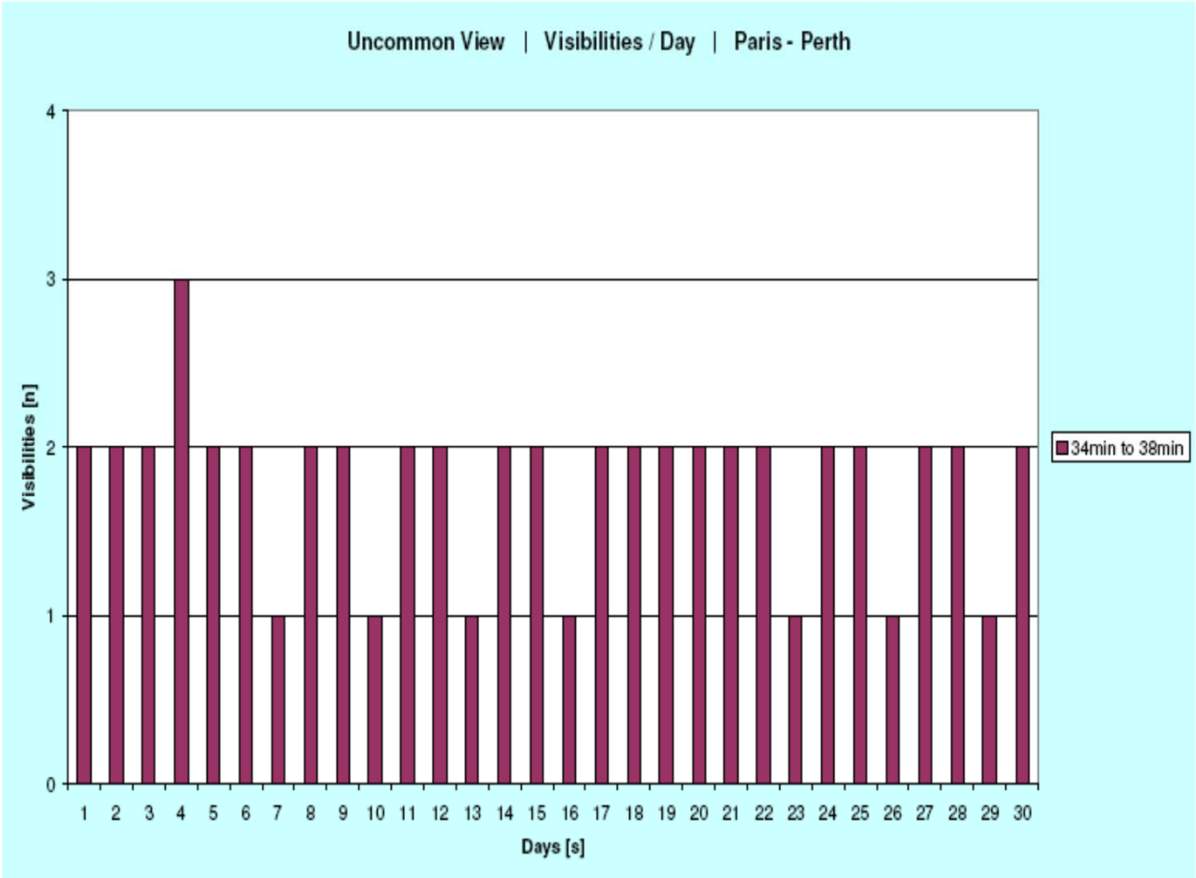


FIG. 3. Frequency residuals and predicted effect during mission.

$$\frac{\varphi_s - \varphi_e}{c^2} - \frac{|\vec{v}_e - \vec{v}_s|^2}{2c^2} - \frac{\vec{r}_{se} \cdot \vec{a}_e}{c^2} .$$

Non Common View: Paris - Perth



Most distant stations: Paris-Perth

Between 1 and 2 non common views per day within less than 3000 seconds

Several NC Views within 10 000 seconds,

Overall: less than 10 ps at half day, ie 2 10^{-16} and 1 10^{-17} at one week