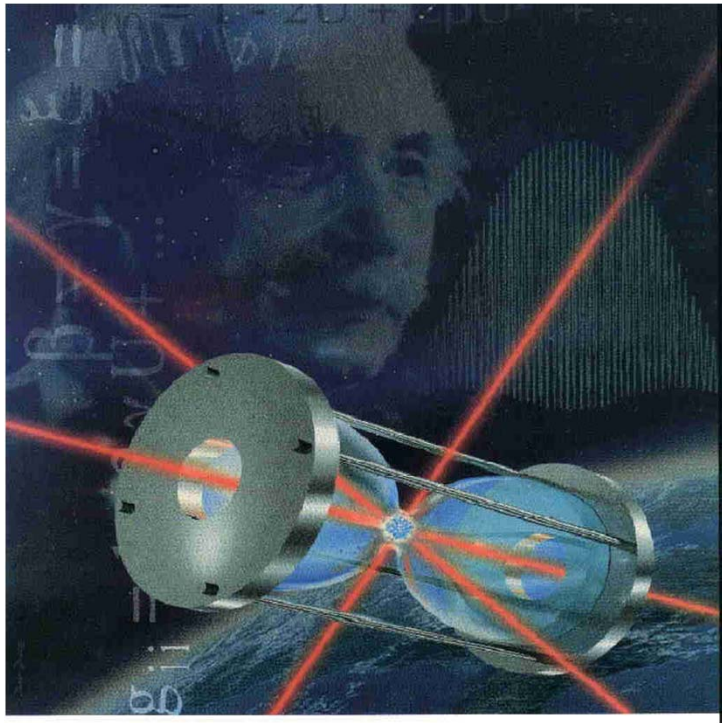
Fundamental Physics tests with space clocks

1997

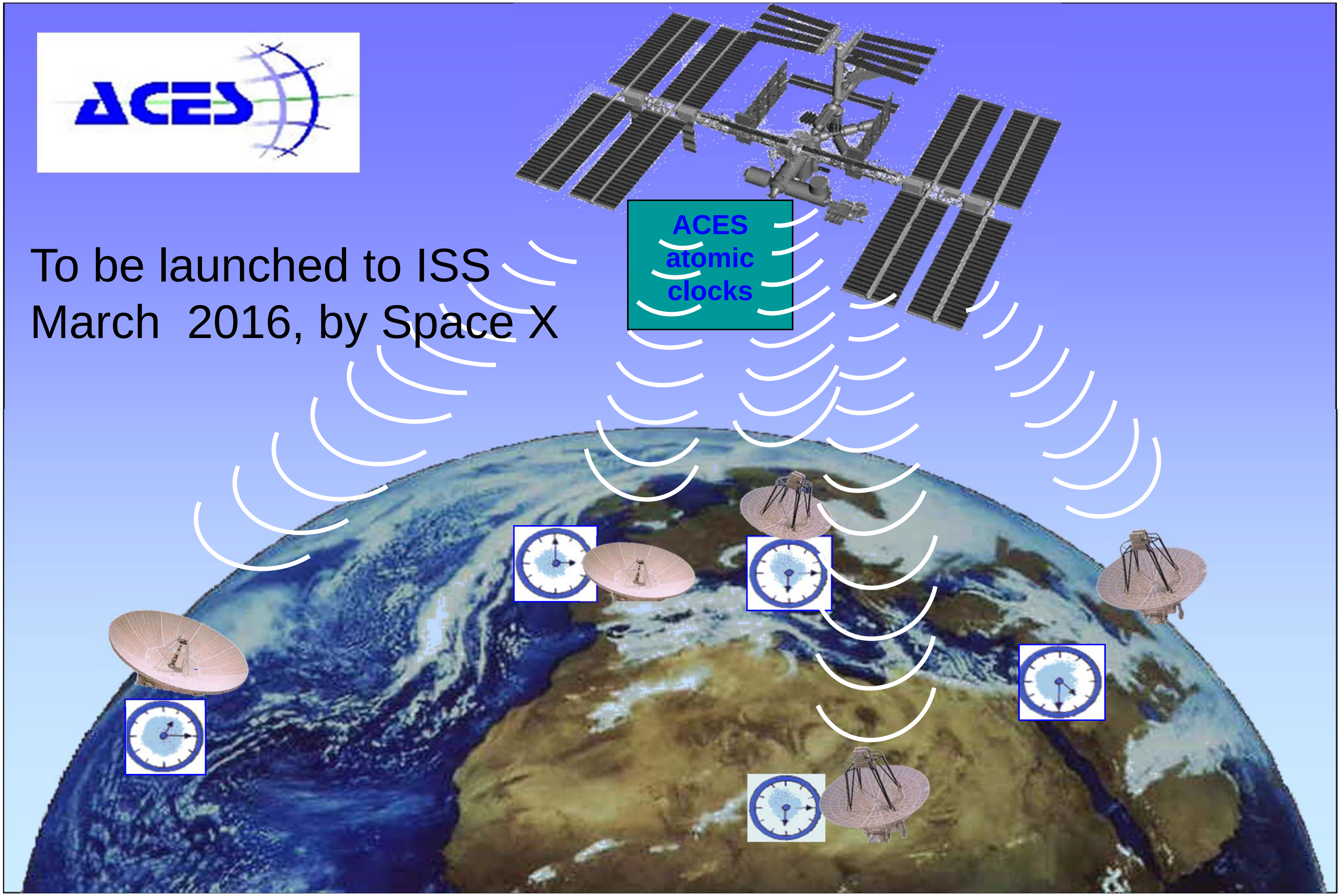


C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

Ecole Normale Supérieure, Paris, France

STE-QUEST workshop
ESTEC, May 22, 2013



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

esa

cnes
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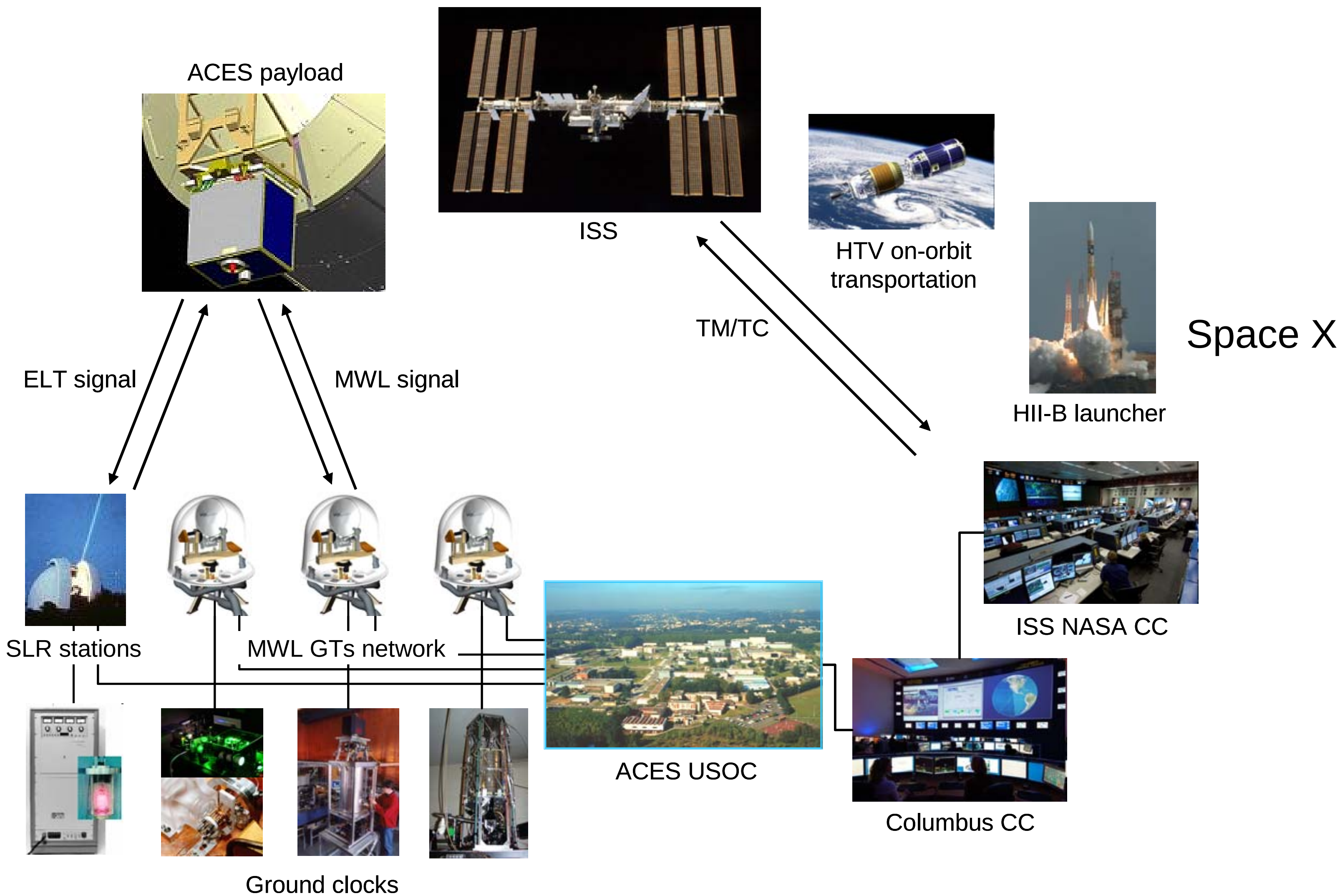
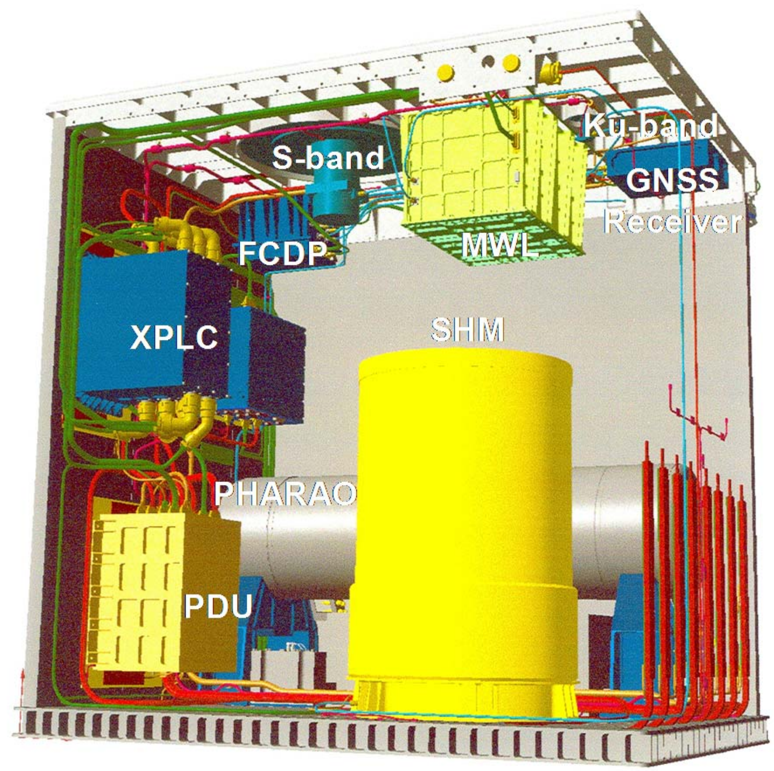
ACES Mission Concept



ACES Payload

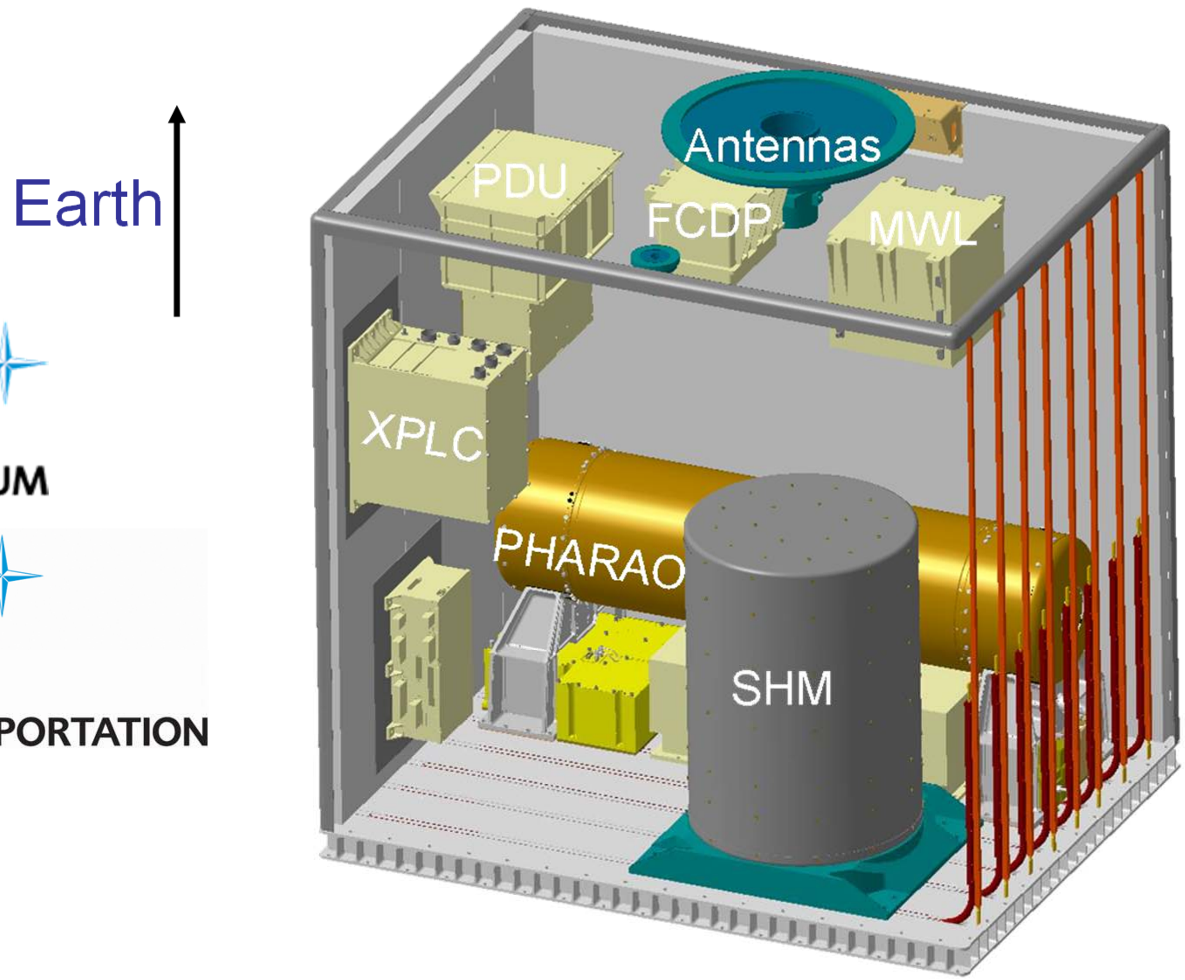
– CNES): PHARAO (Atomic clock based on laser cooled Cs atoms
– SHM (ESA): Active hydrogen maser
– FCDP (ESA): Clocks comparison and distribution
– MWL (ESA): T&F transfer link
– GNSS receiver (ESA)
– European Laser Timing (ELT) optical link (ESA)
– Support subsystems (ESA)
    - XPLC: External PL computer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



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

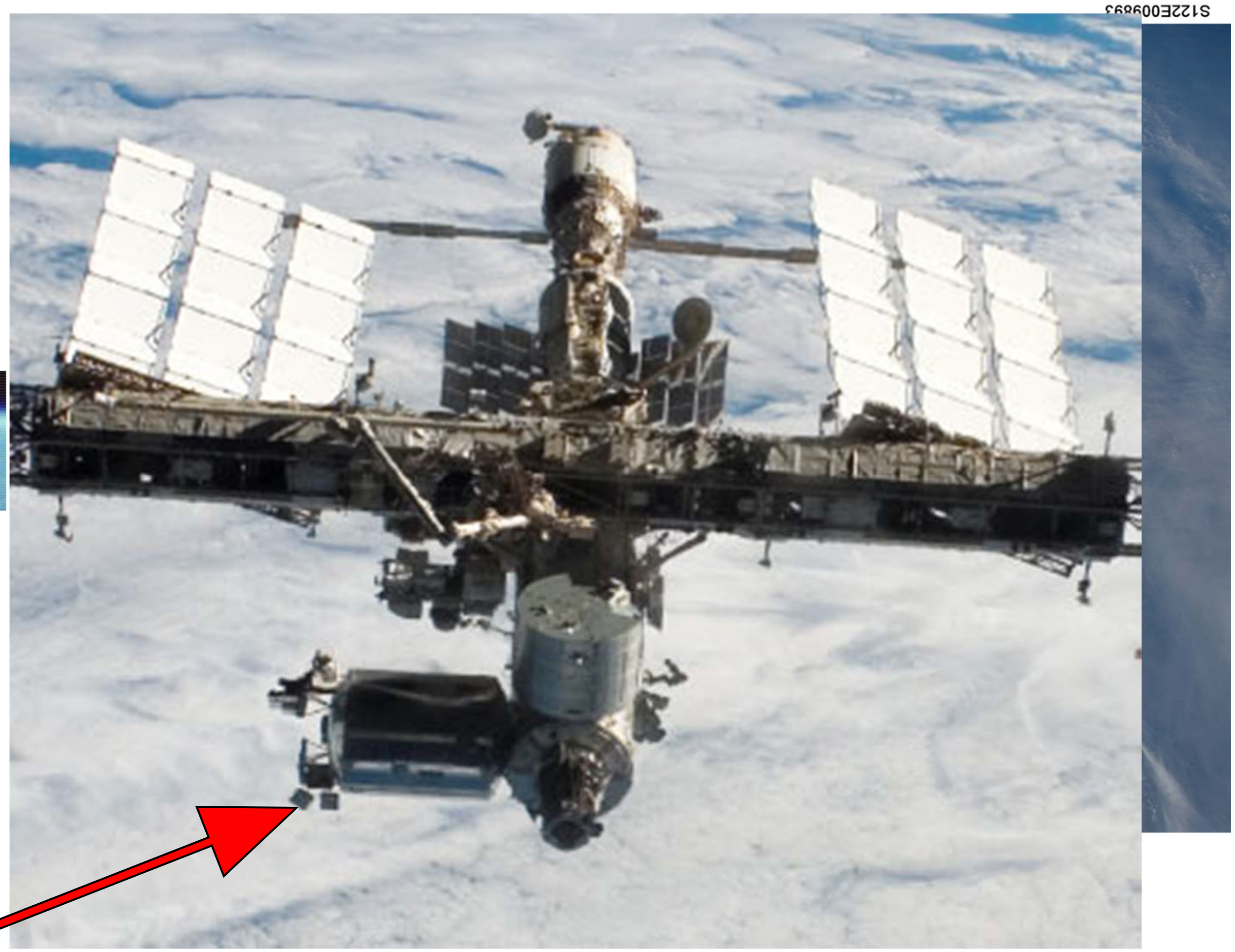
ASTRIUM

ACES General View



Mass: 227 kg, Power 450 W
Challenge: thermo-mechanical stability
Three year operation

ACES ON COLUMBUS EXTERNAL PLATFORM



ACES

Current launch date : March 2016

Mission duration : 18 months to 3 years

Do fundamental physical constants vary with time ?

Motivation: unification theories, string theory,…
Damour, Polyakov, Marciano,….

α_{elm}, m_e/ m_p…

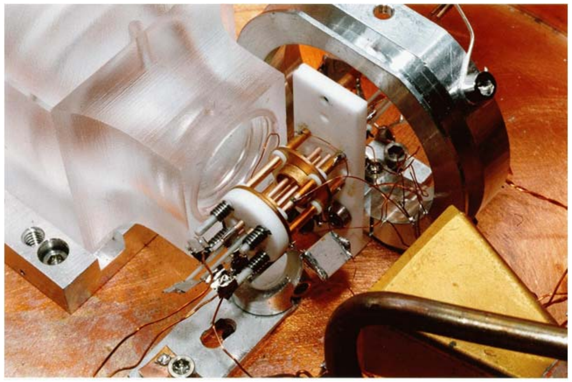
Principle : Compare two or several clocks of different nature as a function of time

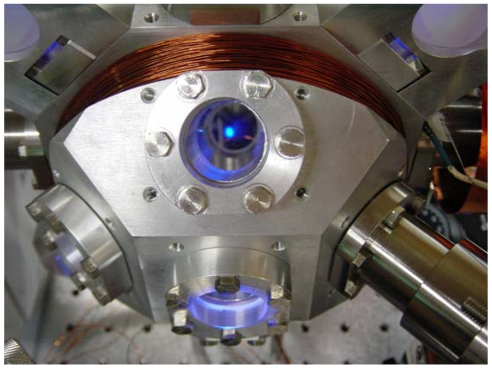
Microwave clock/Microwave clock: α, m_e/m_p, $g^{(i)}$

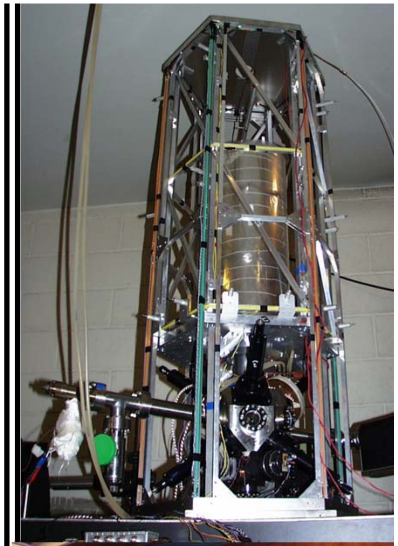
rubidium and cesium

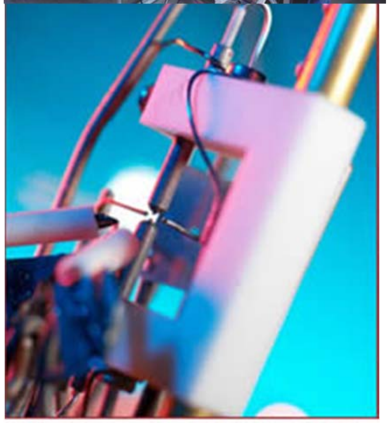
Microwave/Optical clock : α, m_e/m_p, $g^{(i)}$

Optical Clock / Optical clock: α

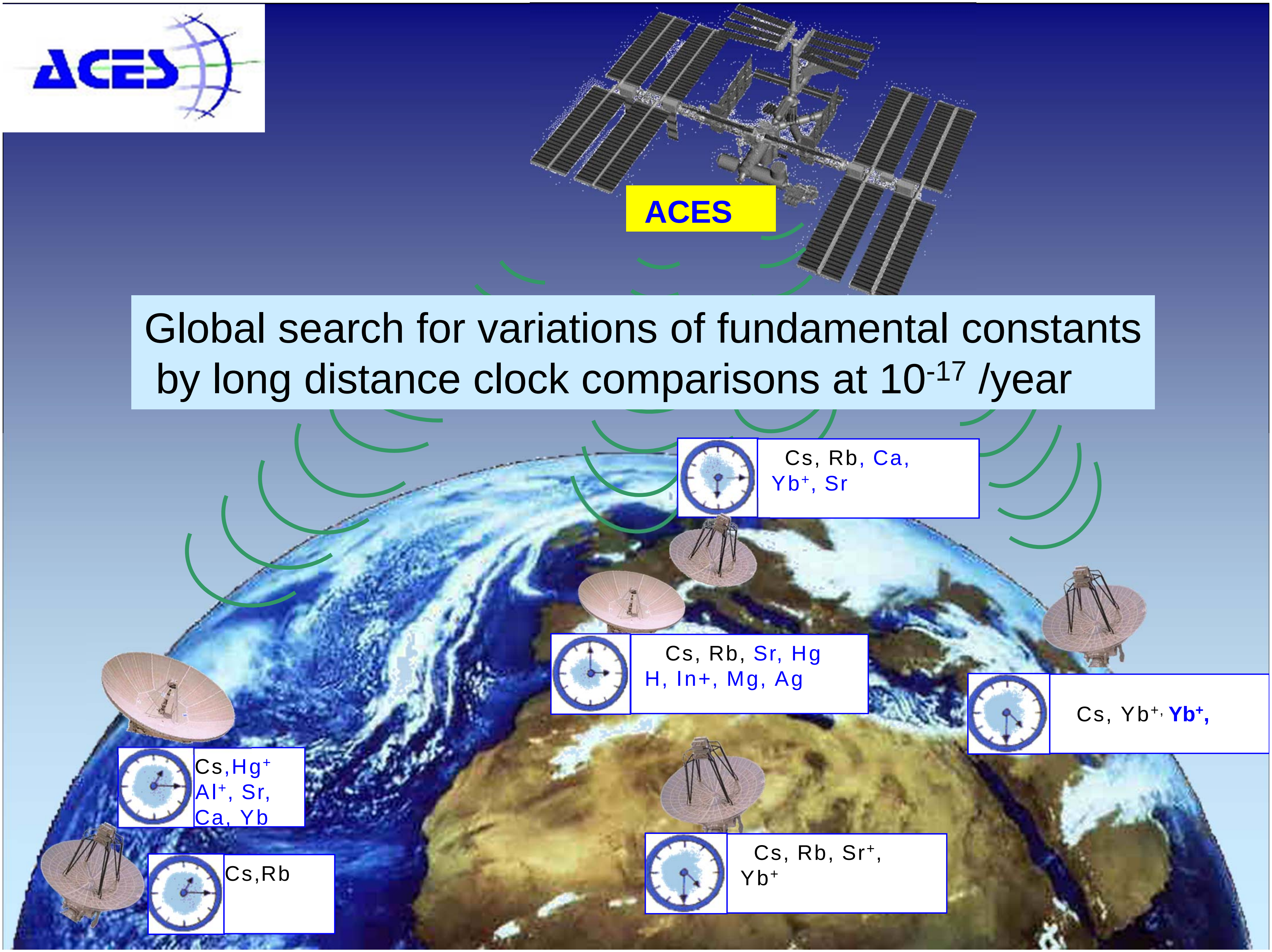




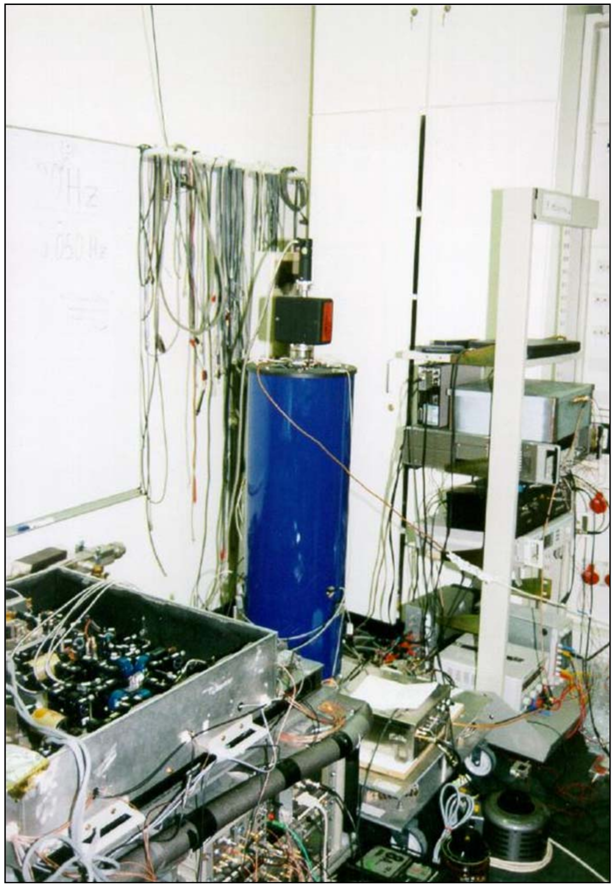




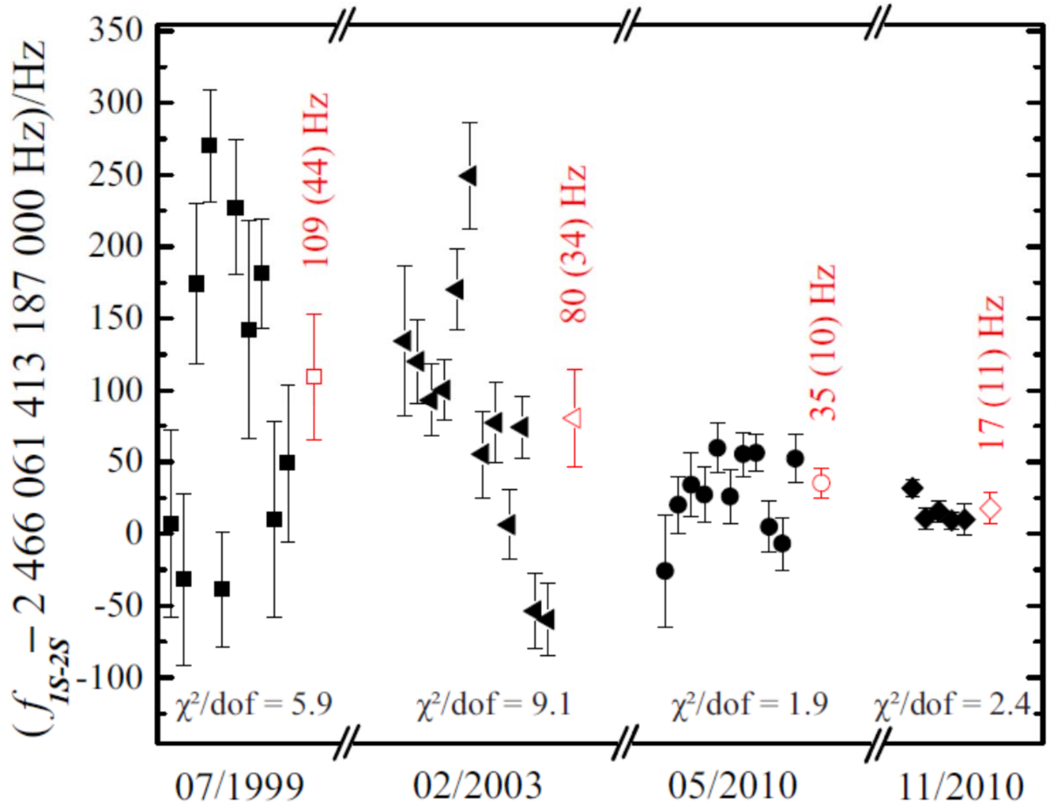
The ovens and electrodes of the NPL strontium ion end-cap trap.


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^+,
Cs, Hg^+ Al^+, Sr, Ca, Yb
Cs,Rb
Cs, Rb, Sr^+, Yb^+

Direct link Cs Microwave to 1s-2s Hydrogen frequency with optical Frequency comb at MPQ



Mobile fountain at MPQ
P. Laurent, D. Rovera



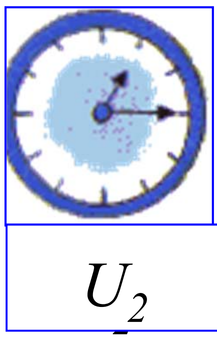
$f_{1s\text{-}2s}$= 2 466 061 413 187 017 (11) Hz

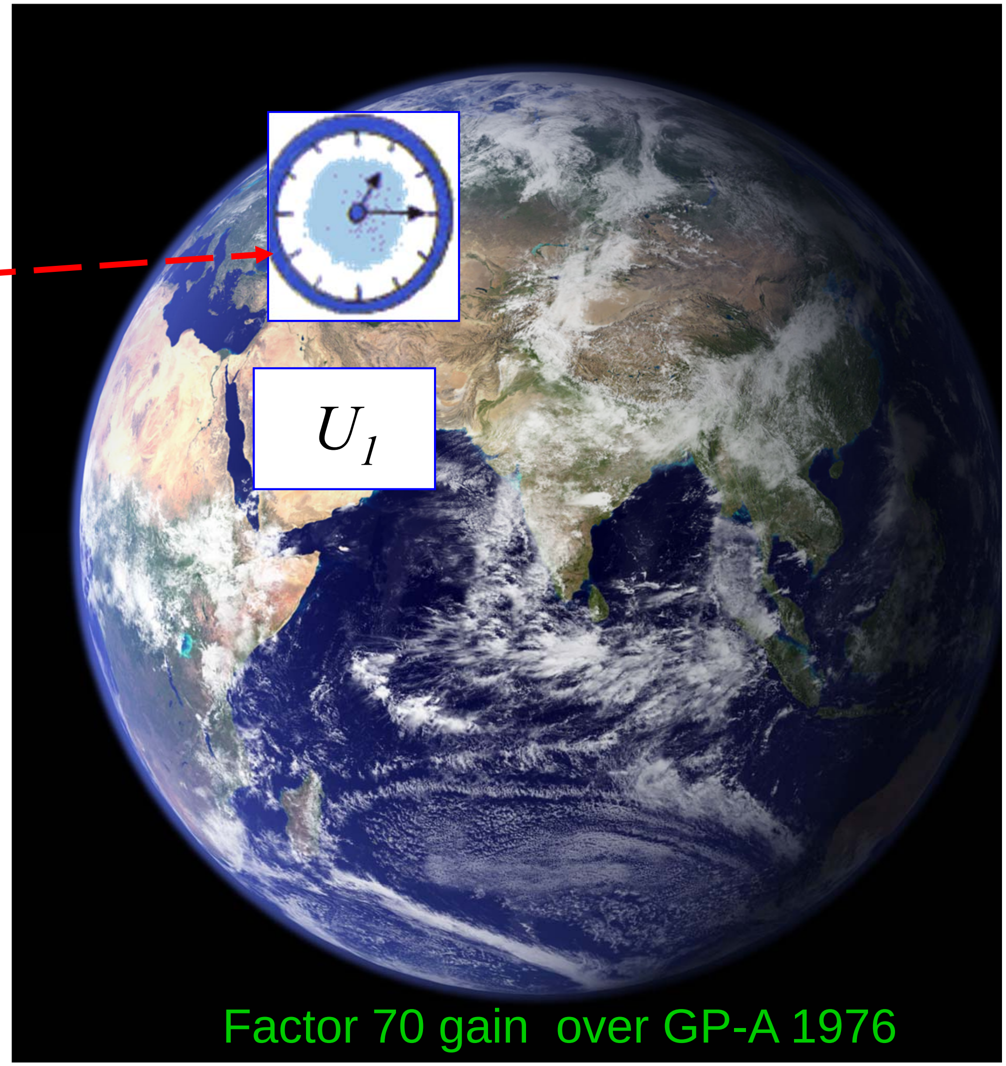
A. Matveev et al., PRL 2013

C. Parthey et al., PRL 2011, Hänsch group

Now: 920 kms fiber link to PTB

A Prediction of General Relativity: the gravitational redshift

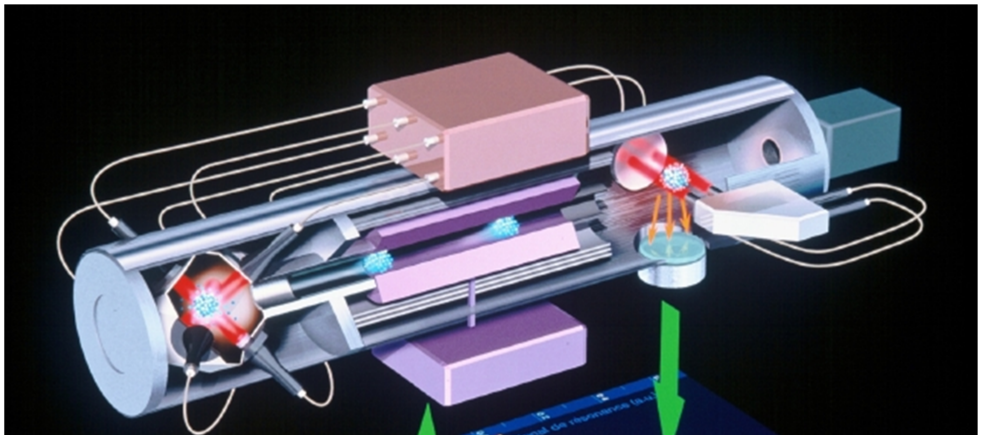


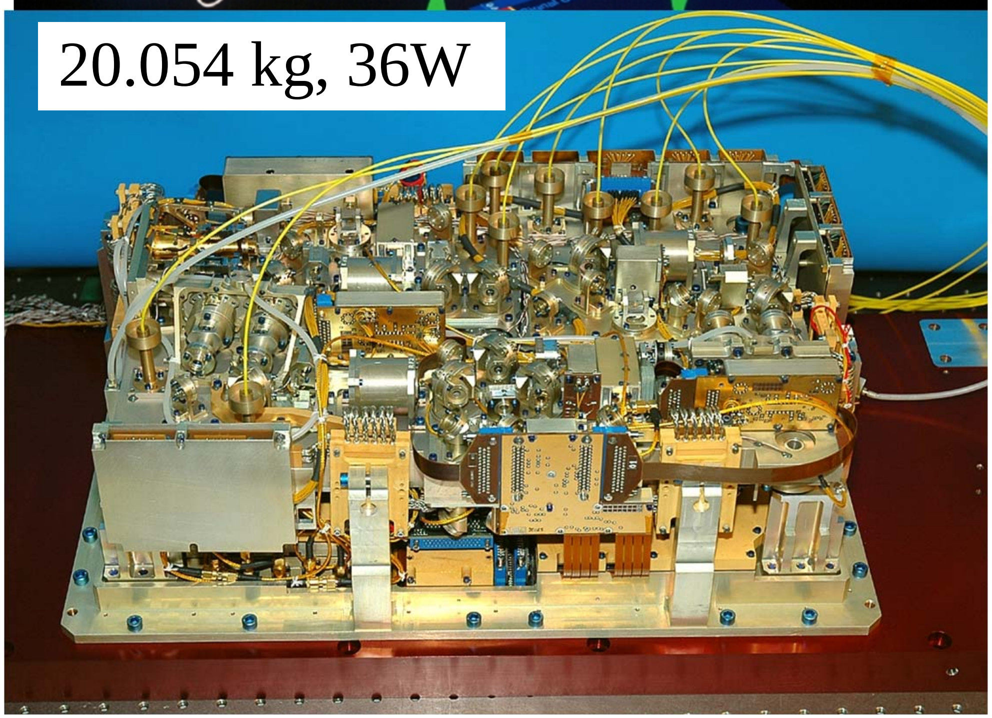


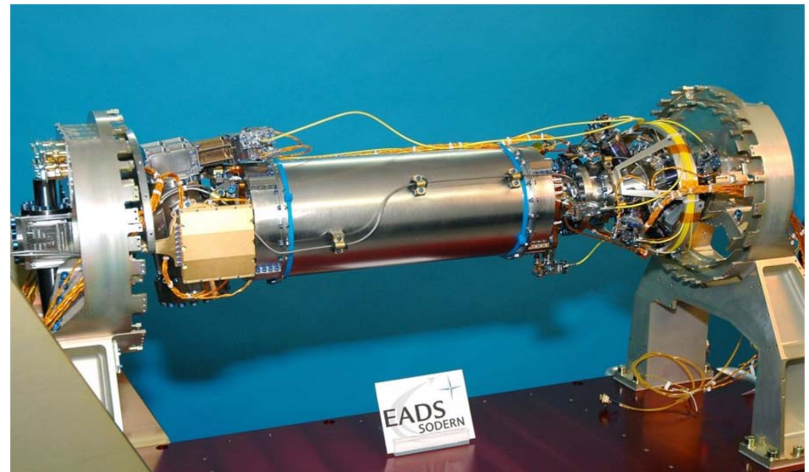
$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

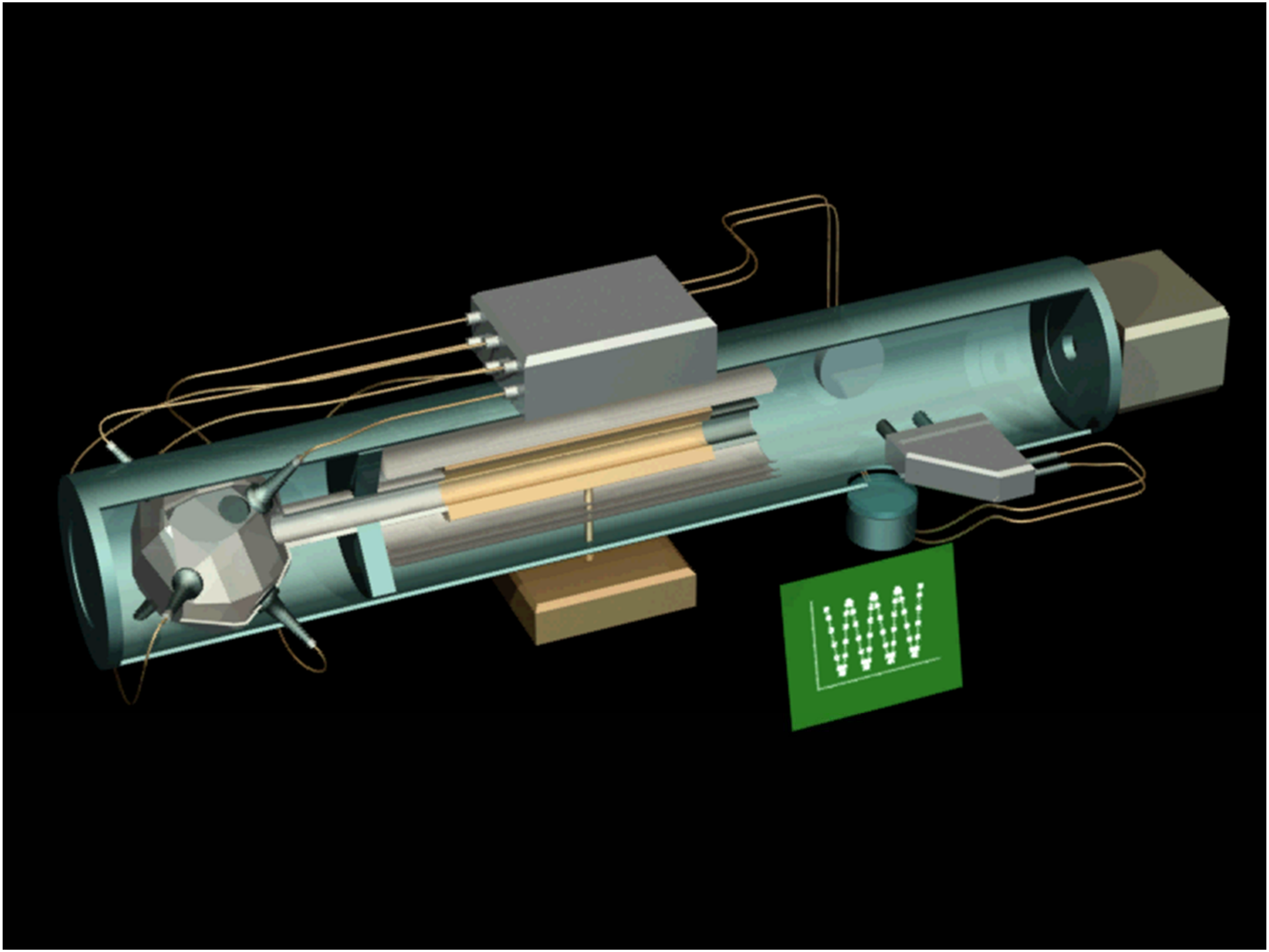
Redshift : 4.59 10^{-11}
With 10^{-16} clock
ACES: ~2 10^{-6}

Cold Atom Clock in μ-gravity : PHARAO/ACES



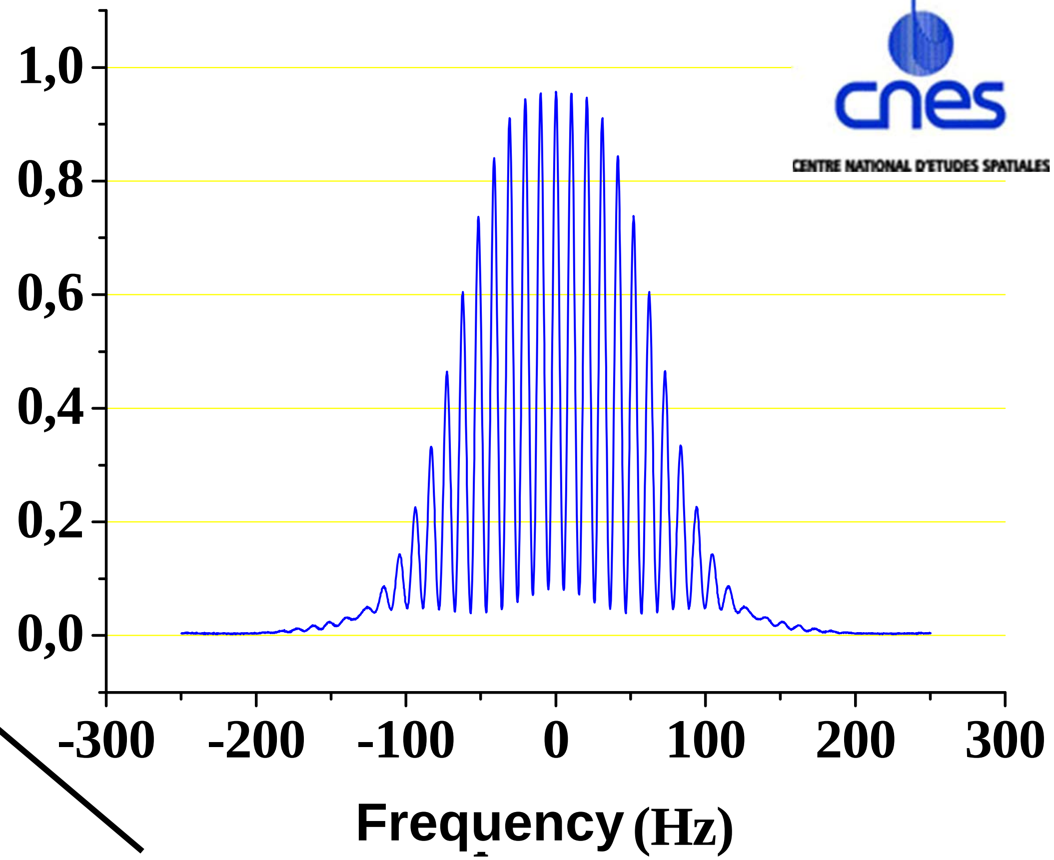






PHARAO Space Clock

Laser source



Cesium tube

EM performance tests completed
Flight model under construction
Expected accuracy and stability:
10^{-16} in space

PHARAO Frequency Stability and Accuracy

$$\sigma_y(\tau) = 4\ 10^{-13}\ \tau^{-1/2}$$

With ultra-stable Quartz
Limited by gravity !

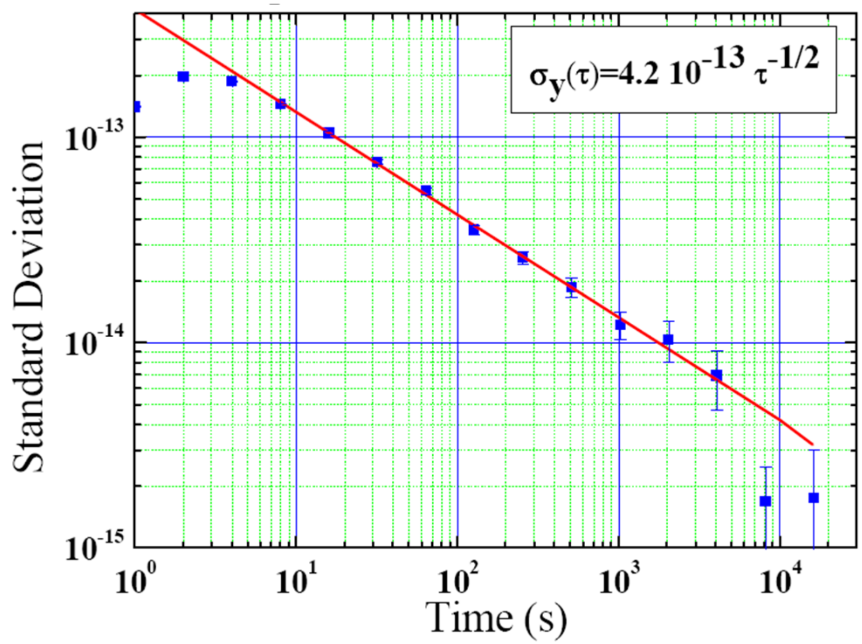
$$\sigma_y(\tau) = 2.5\ 10^{-13}\ \tau^{-1/2}$$

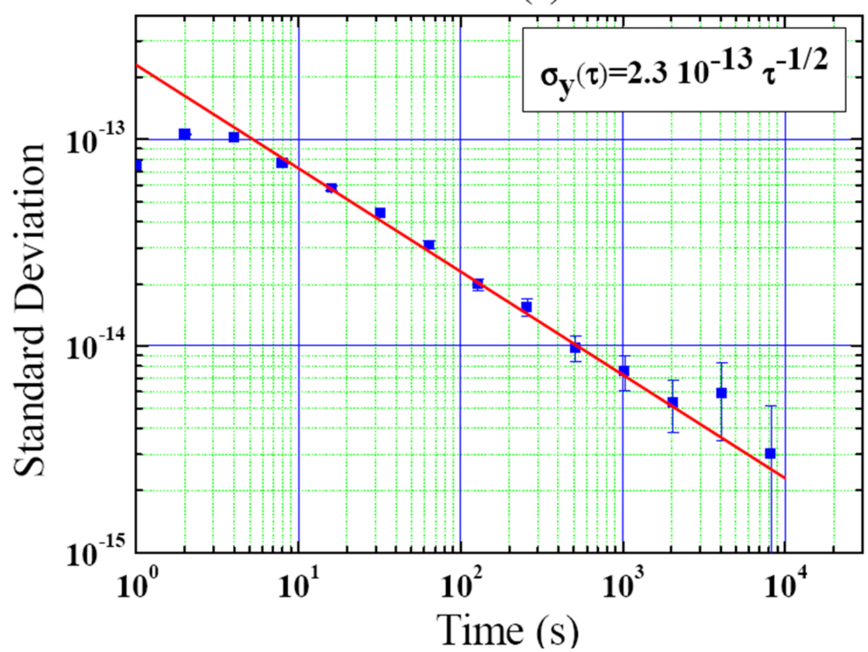
With Cryo. Oscillator

Will enable 7 10^{-14} $\tau^{-1/2}$
in space

Accuracy evaluation :
Currently 2 10^{-15} on the ground.
Should enable 10^{-16} in space

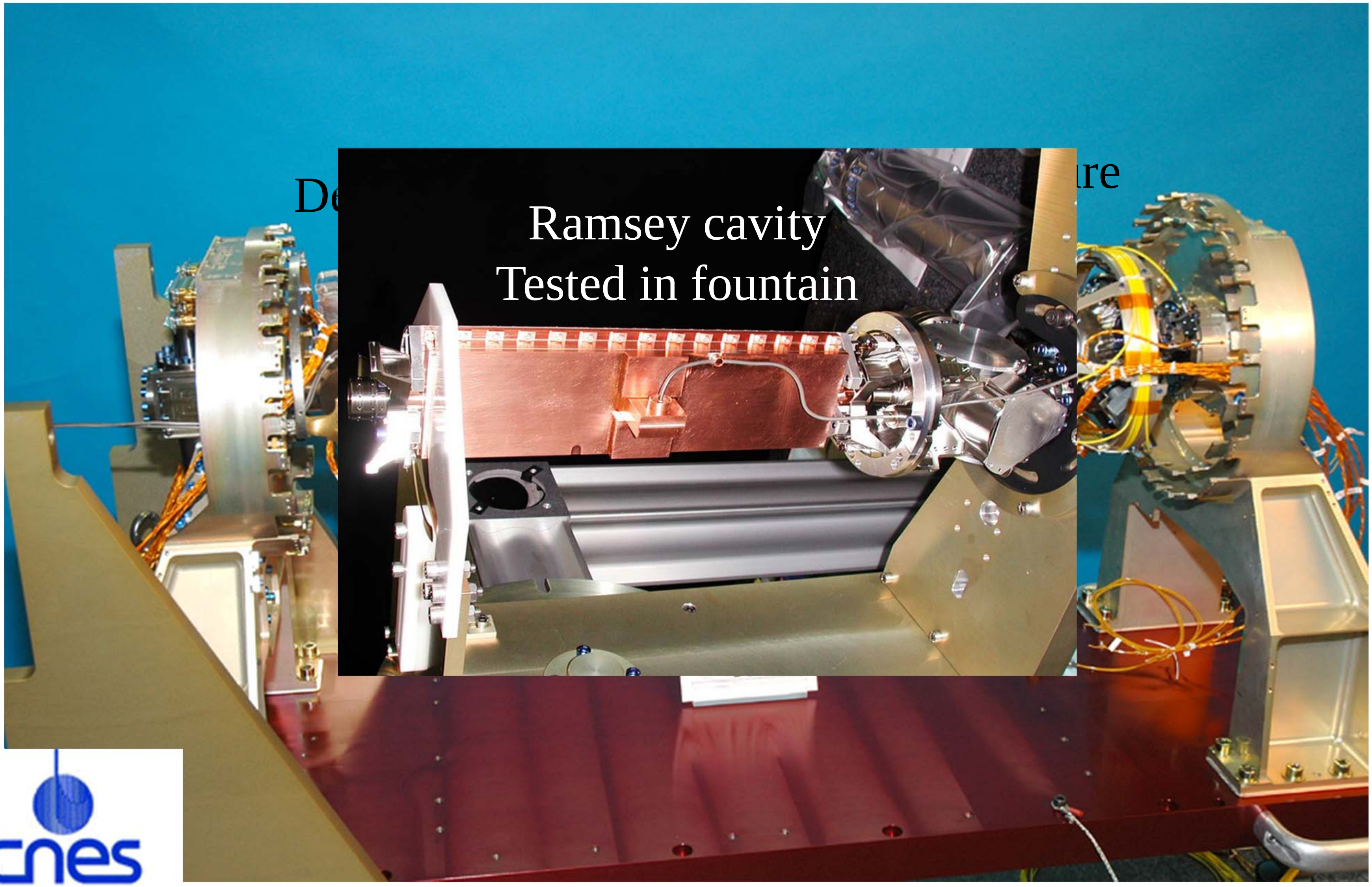
See Poster by Ph. Laurent et al.





Cesium Tube

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



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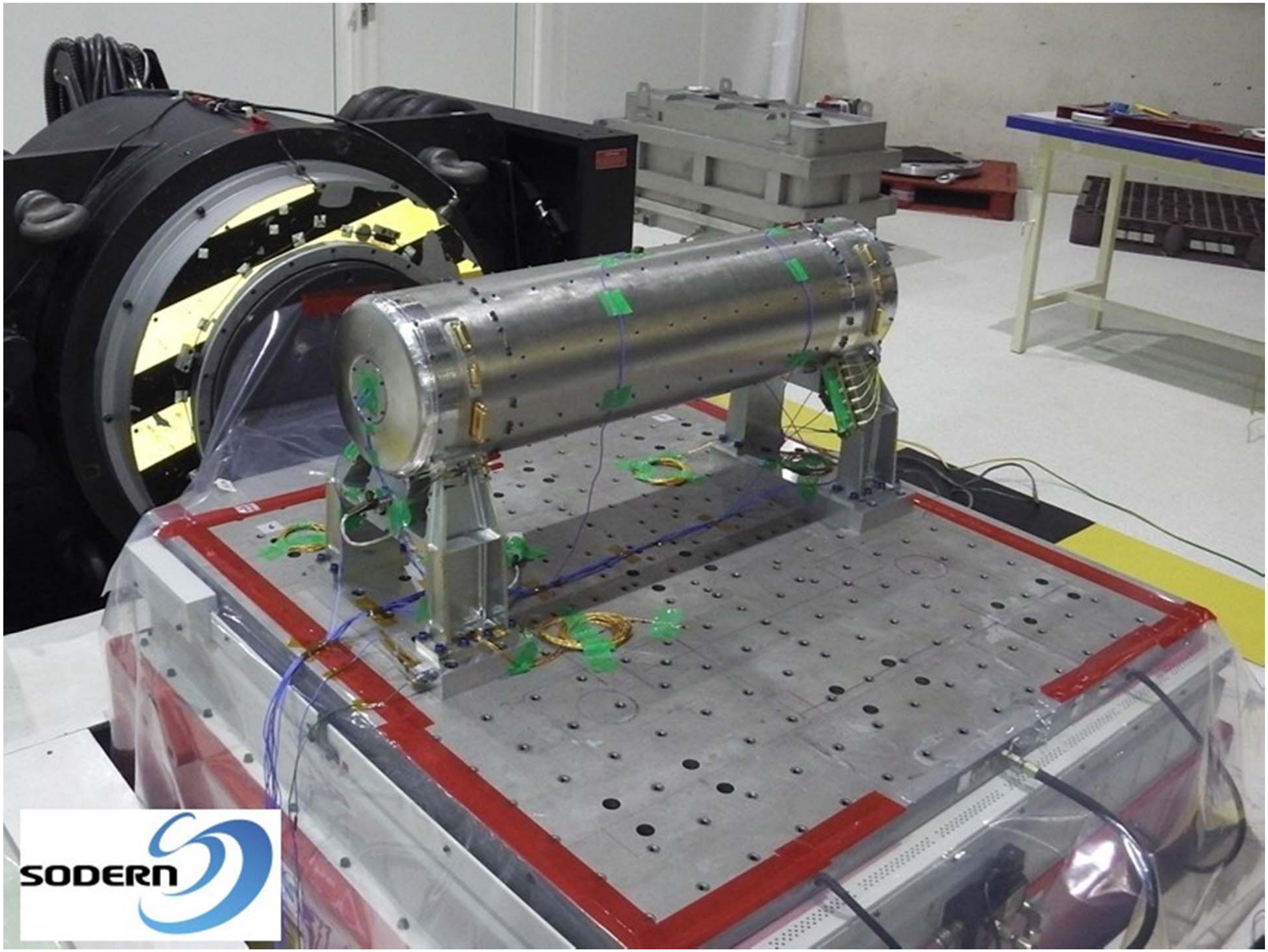
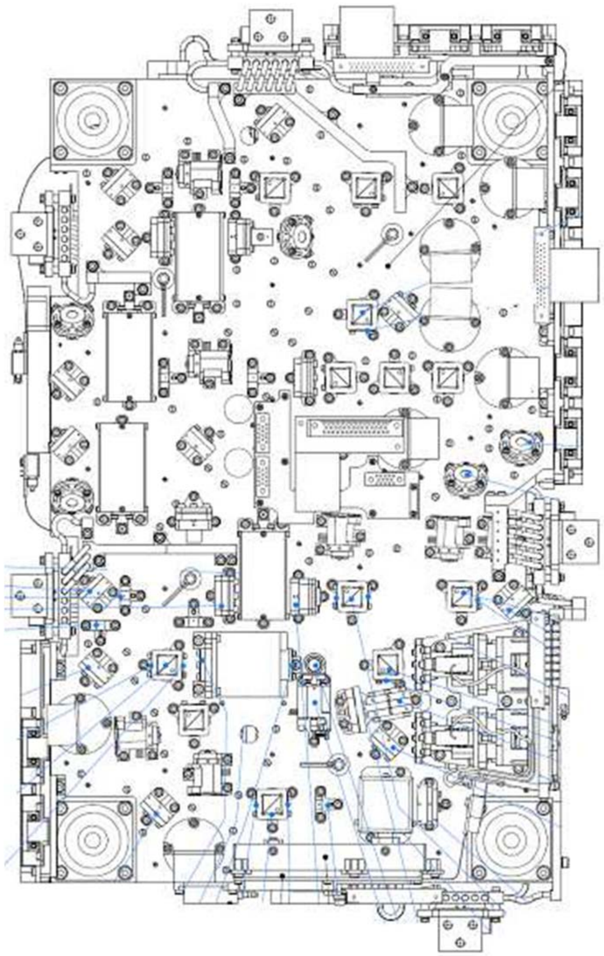
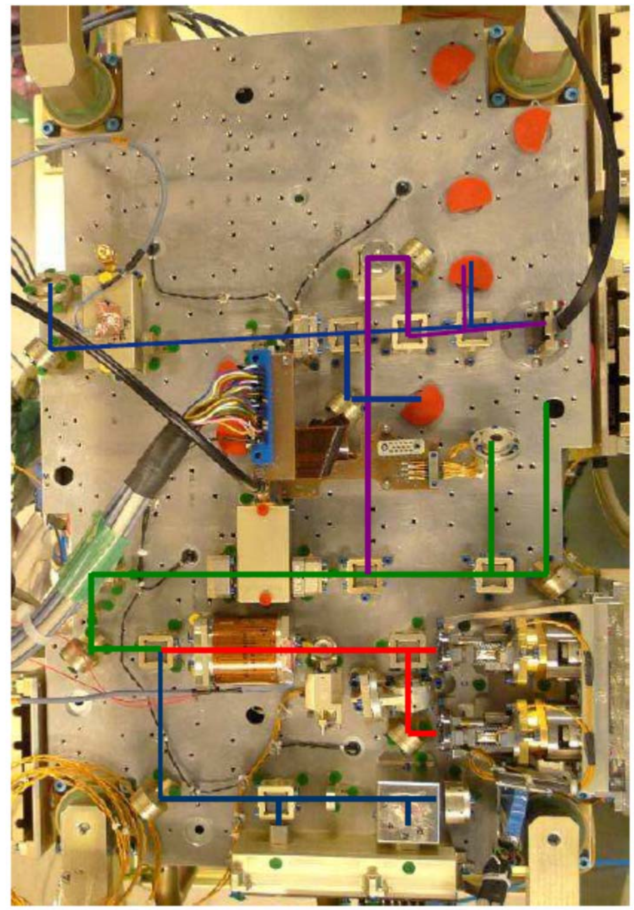
PHARAO Cesium Tube on the Shaker



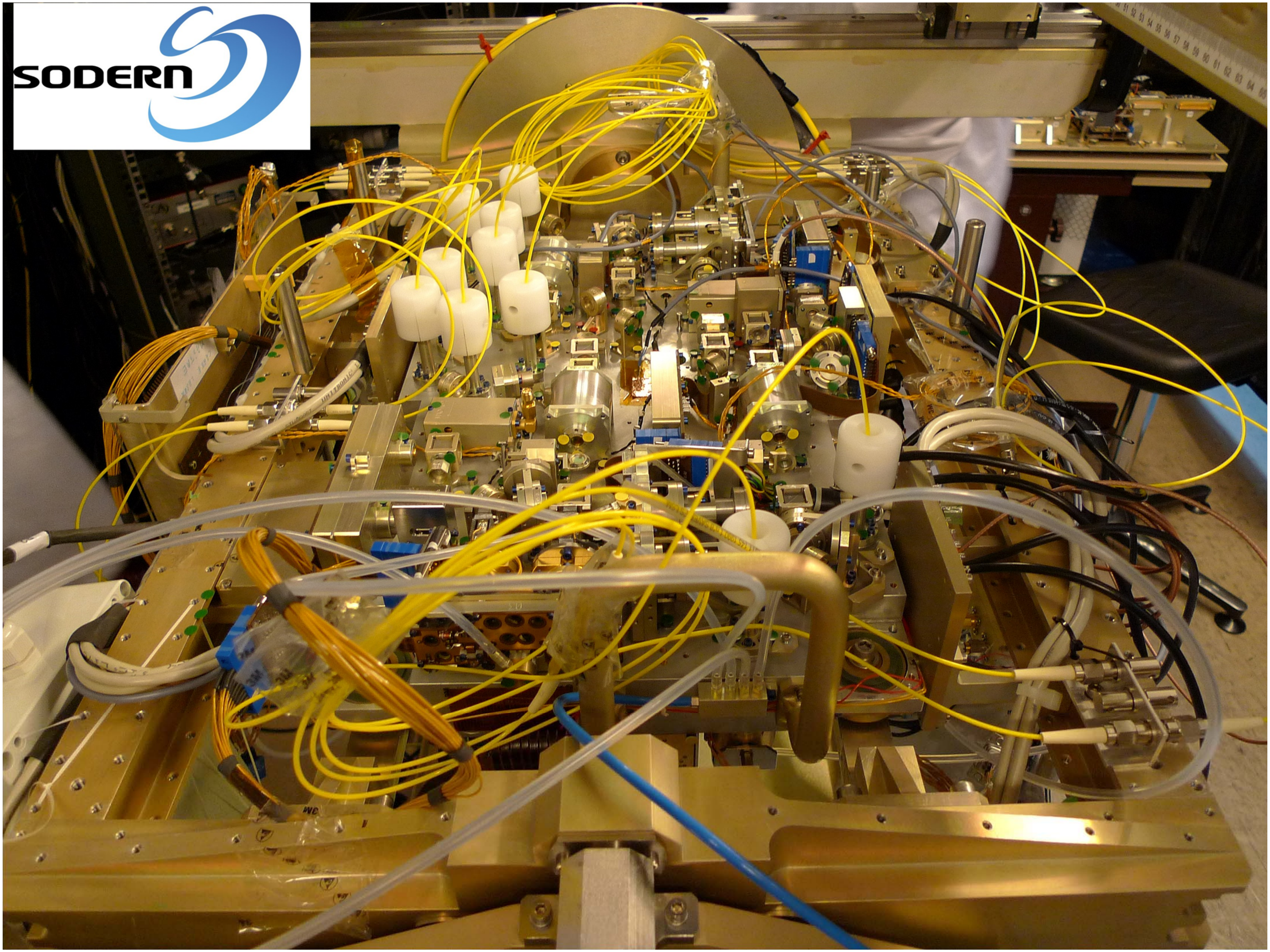
Laser bench FM assembly

Optical bench lower rside



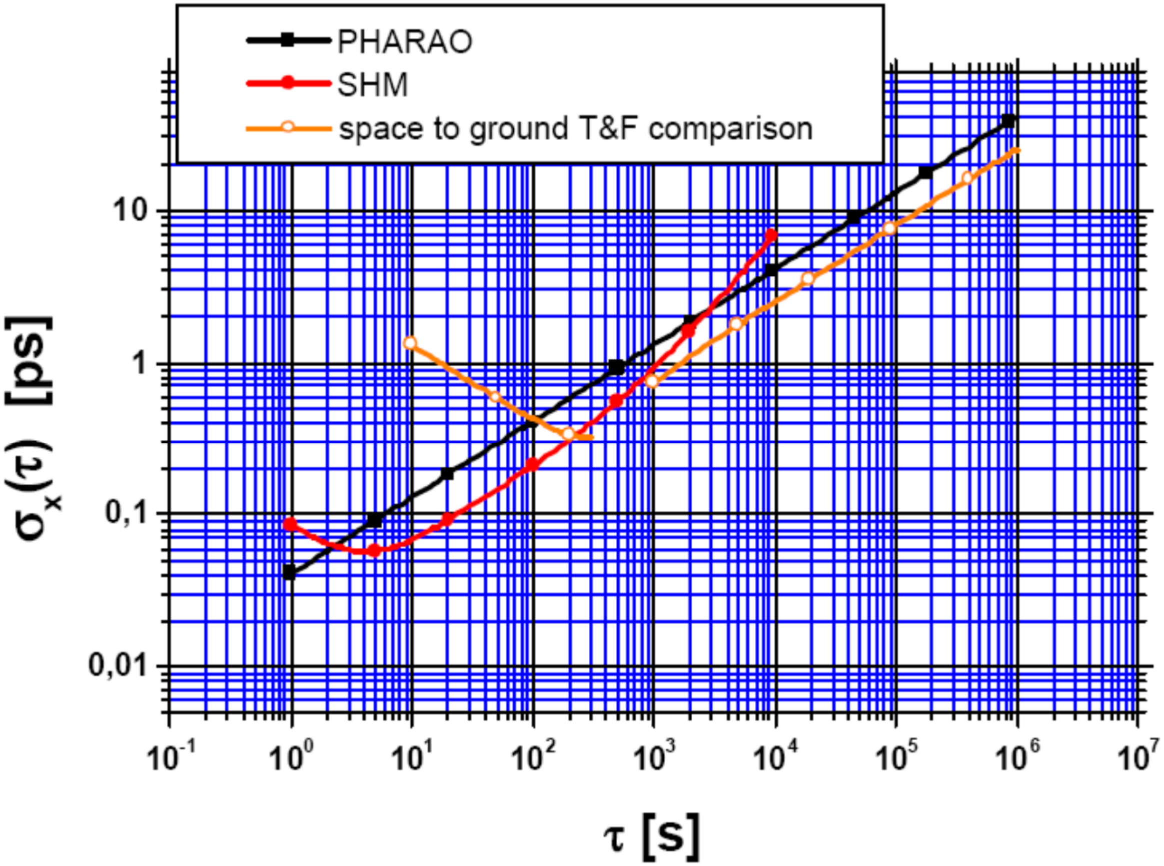


Flight Model optical bench near completion


SODERN

Time stability of ACES clocks and link to ground

The ACES Mission will demonstrate the capability to perform phase/frequency comparison between space and ground clocks with a resolution at the level of 0.3 ps over one ISS pass (300 s), 7 ps over 1 day and 23 ps over 10 days.



ACES TIME Transfer

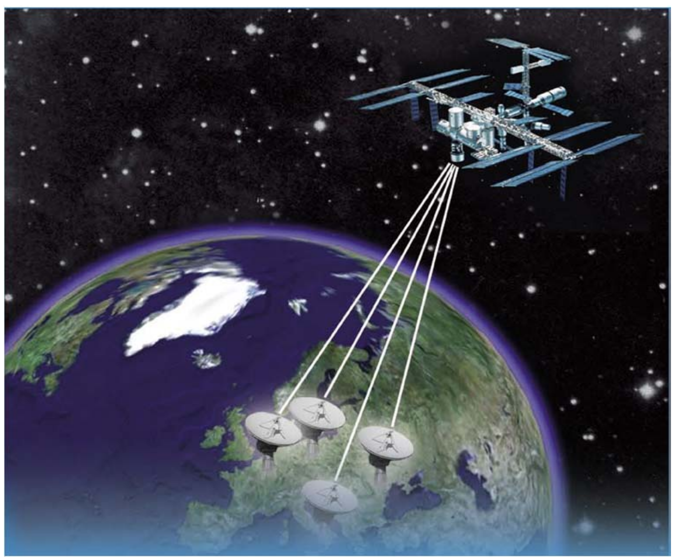
Ultra-stable frequency comparisons on a worldwide basis :

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

Contribution to TAI

Gain: x 20 wrt current GPS

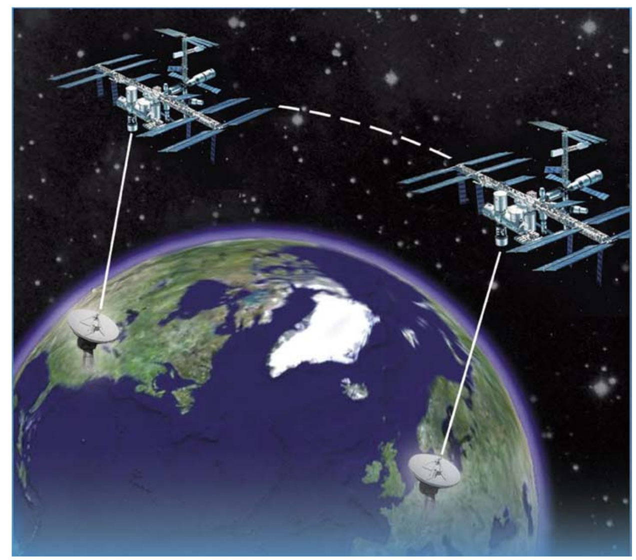
Common view



Error < 0.3ps over 300 s

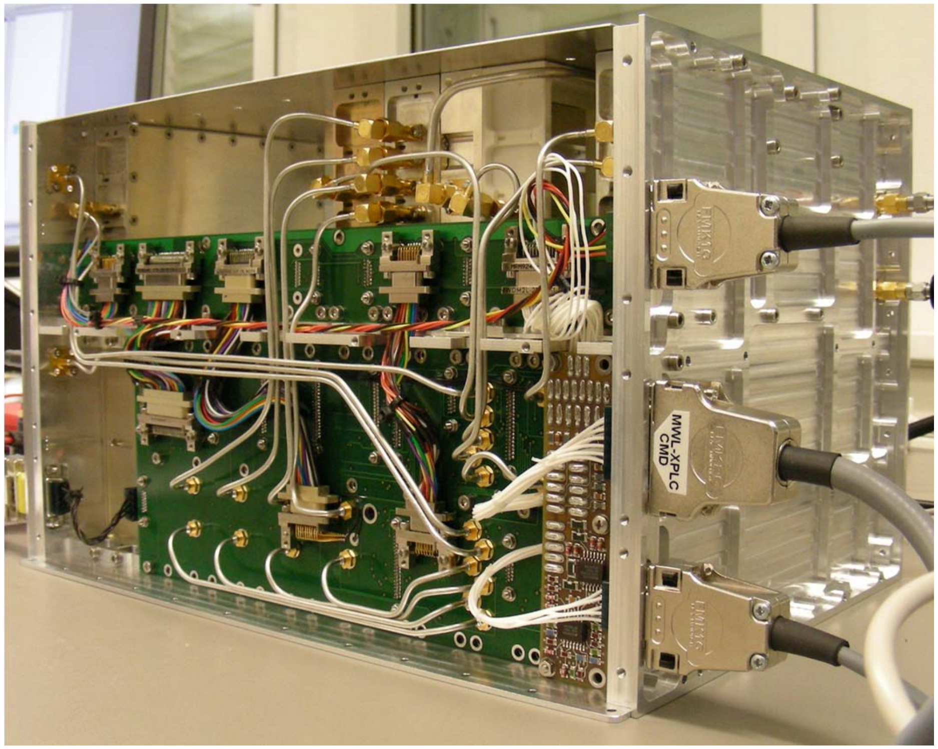
Can be checked by fiber-link

non common view



Error < 3ps over 3000 s

ACES Time transfer Engineering Model

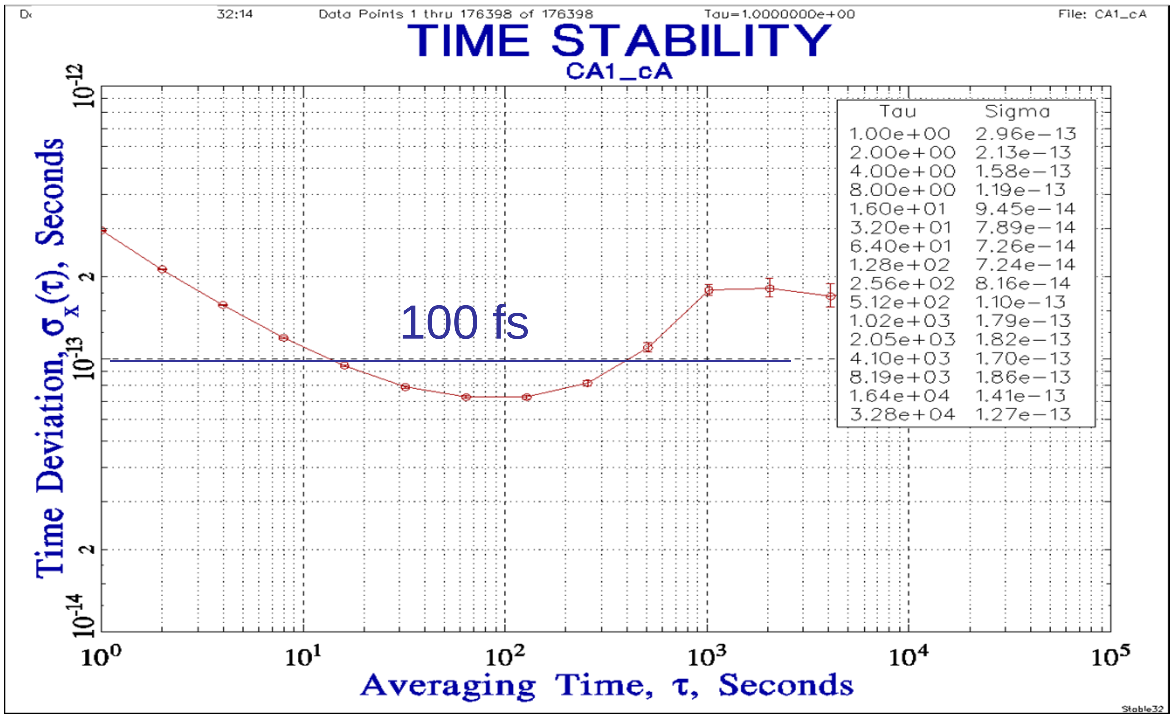


Onboard receiver

TimeTech and EADS
See Poster by T. Feldmann

ACES Time Transfer

The microwave link ground terminal



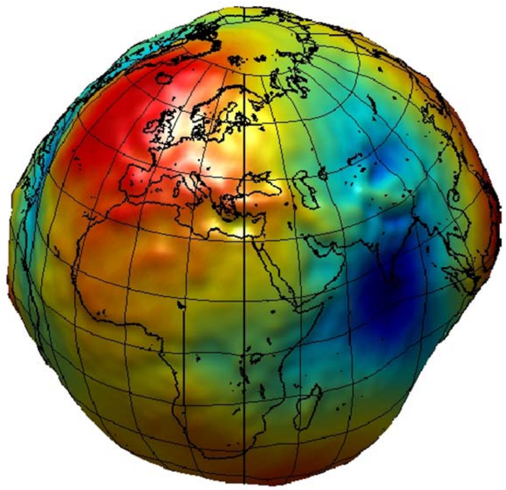
Time stability of carrier with 10 Kelvin peak to peak temperature variation

PTB, SYRTE, NPL, JPL, NIST, Tokyo, UWA,…

End to End tests are ongoing
See Poster by P. Delva et al.

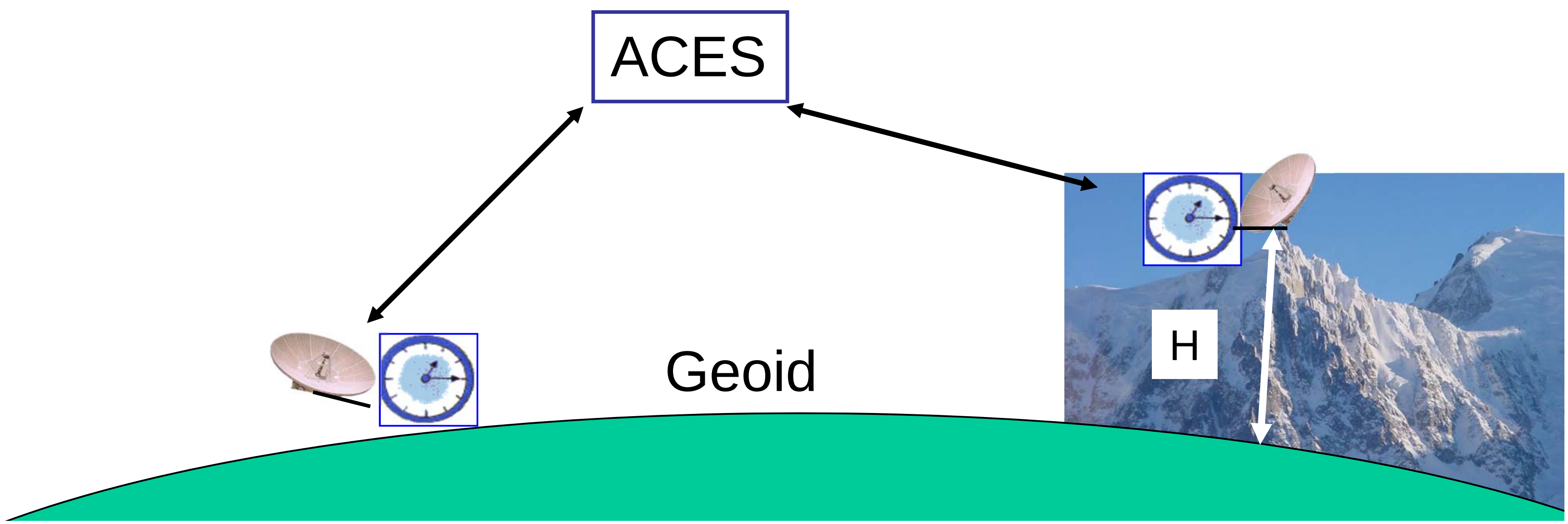
Relativistic Geodesy

The clock frequency depends on
the Earth gravitational potential
10^{-16} per meter
Best ground clocks have accuracy
of 9 10^{-18} and will improve ! (NIST '10)



Competitive with satellite + levelling techniques at ~ 20 cm level

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



Future Time Definition from Space

1) The Earth gravitational potential fluctuations will limit the precision of time on the ground at 10^{-18}-10^{-19} (ie: cm to mm level)
2) The only solution: set the reference clocks in space where potential fluctuations are vastly reduced
3) Improved Navigation, Earth Monitoring and Geodesy

Beyond ACES

Microwave clocks:
stability 10^{-16} per day, accuracy: ~ 1 10^{-16} on Earth and in Space

Optical clocks:
10^{-18} range (NIST'09-13)
Towards a redefinition of the SI second

ACES
Comparisons between distant clocks at 10^{-17}
Large improvements on relativity tests
Stringent limits for variations of α, g_p, M_e/ M_p

ACES mission follow-on with microwave/optical clocks:
STE-QUEST, SOC on ISS, SAGAS,..

ACES contributors

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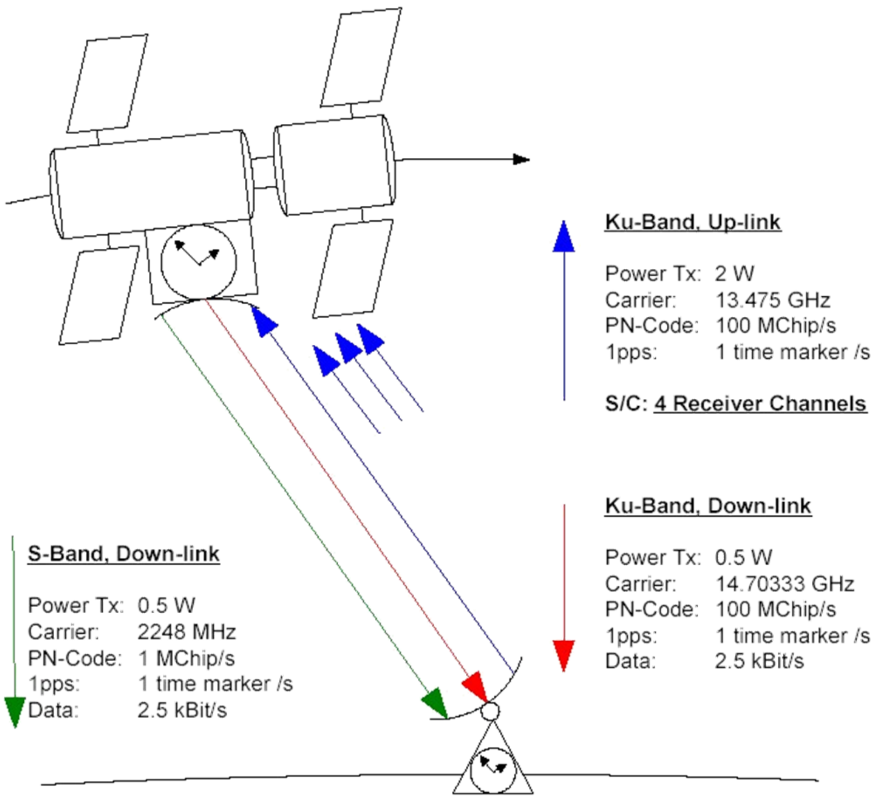
ACES Microwave Link (MWL)



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