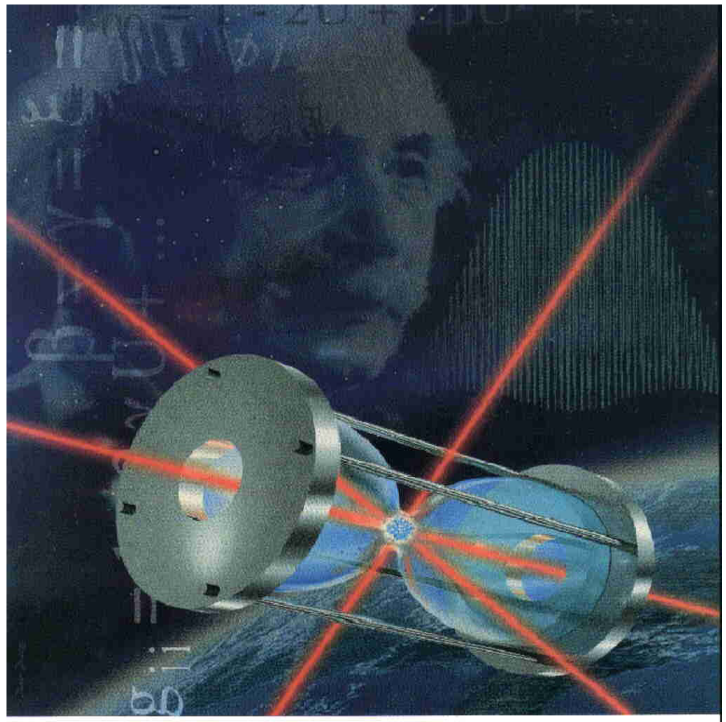
ACES: Atomic Clock Ensemble in Space

1997



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Physique quantique et applications

Ecole Normale Supérieure, Paris, France

Q2C6 Nice, Parc Valrose, October 15th, 2013

Participants

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R. Much, O. Minster,
S. Jefferts, J. Ye, D. Wineland, H. Katori, M. Fujieda,
Y. Hanado, S. Watabe, Nan Yu, R. Toelkjer, K. Gibble
S. Léon, D. Massonnet and 15 engineers at CNES
L. Blanchet, C. Bordé, C. Cohen -Tannoudji,
C. Guerlin, S. Reynaud

Fundamental Questions

1) Missing mass in the Universe

Dark matter and dark energy represent 95% of the mass of the Universe but have unknown origin !

New particles and/or change of the laws of gravity ?

2) Atomic quantum sensors can tests fundamental laws with exquisite precision

Einstein's equivalence principle and Universality of Free Fall

Tests of gravity in Earth orbit or at solar system scale

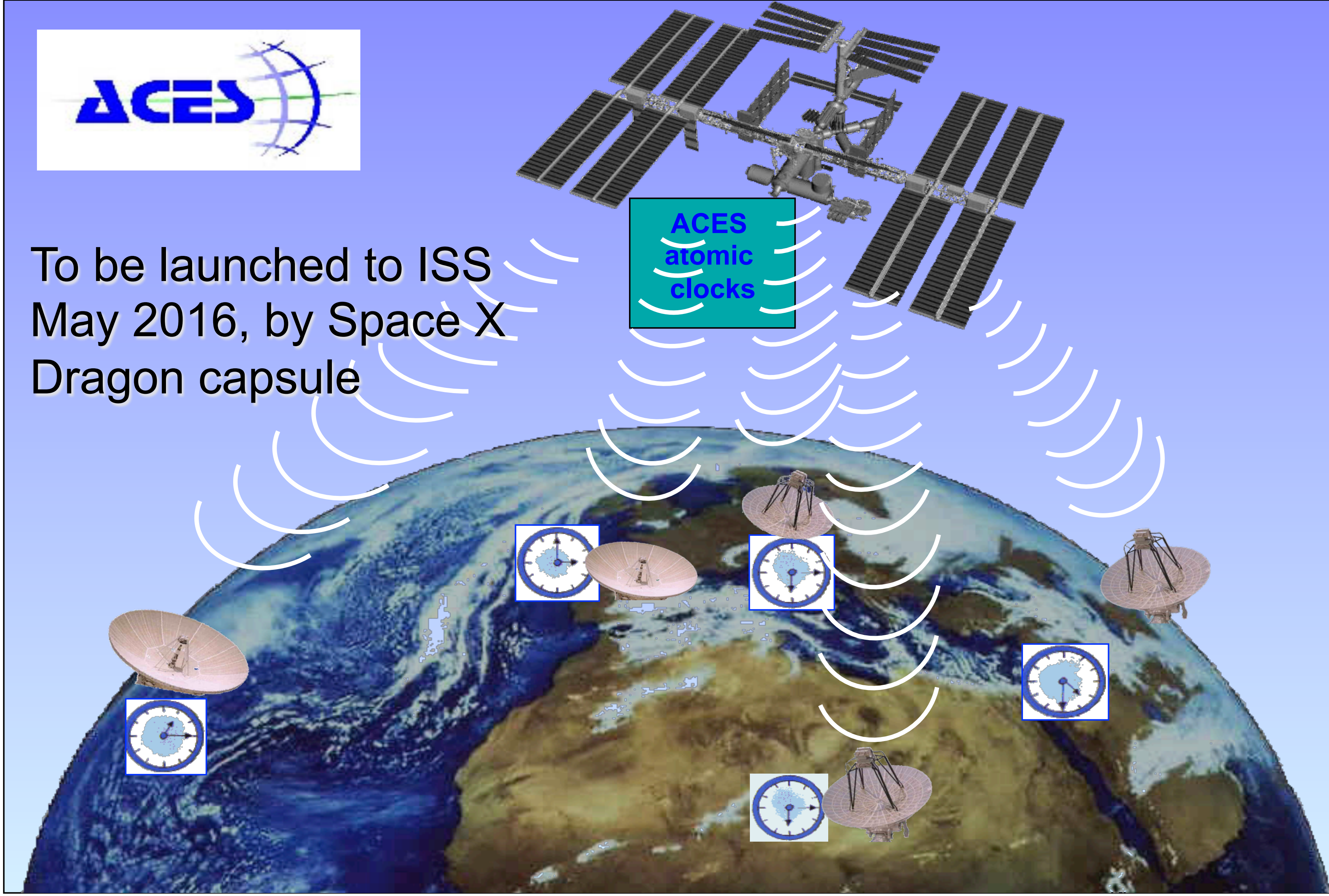
Precision redshift measurement

Variability of fundamental constants

3) Quantum sensors have societal applications

Accelerometry, Gravimetry, Navigation, GPS, GALILEO, Geodesy, Earth monitoring,…

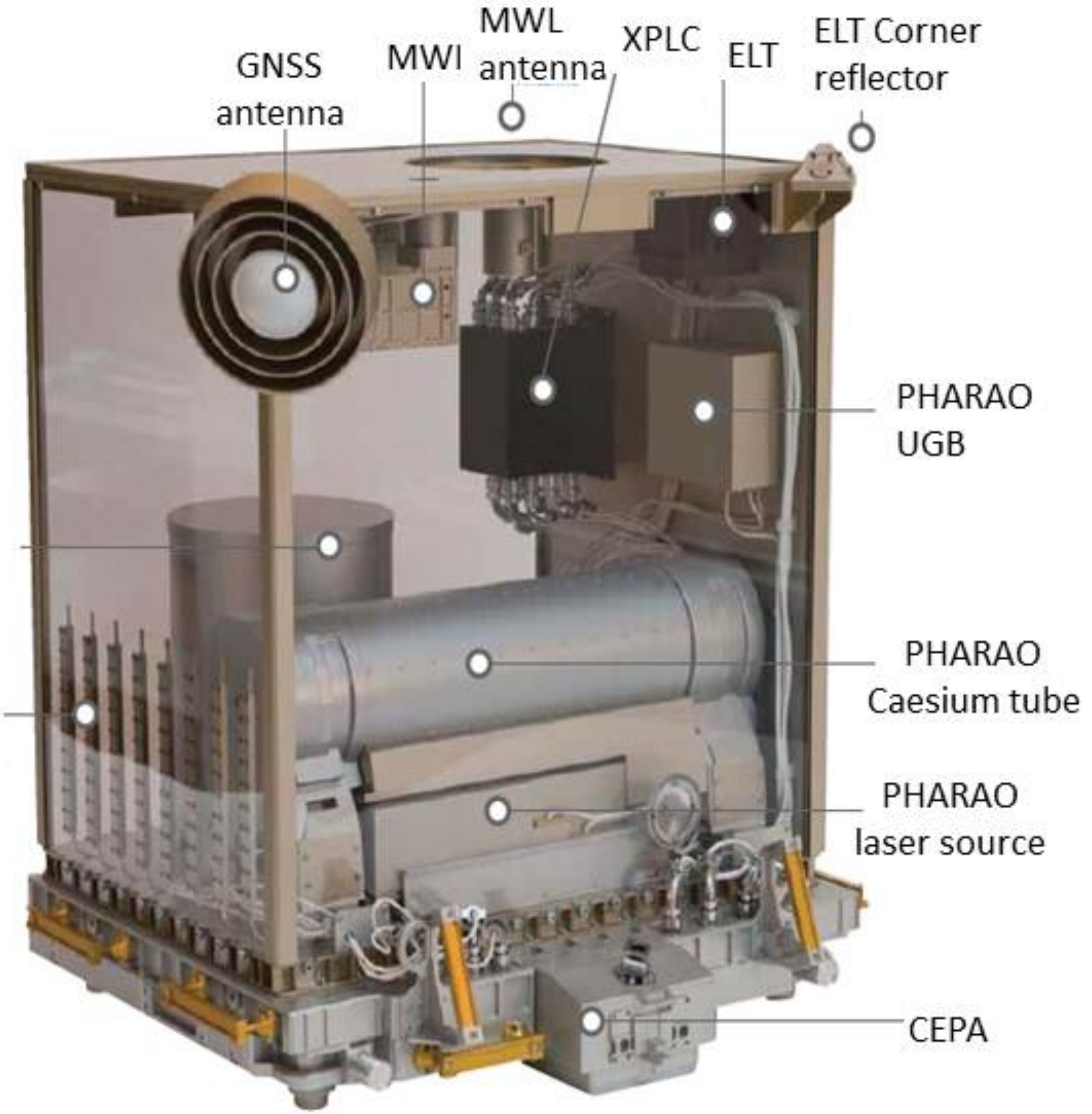
To be launched to ISS May 2016, by Space X Dragon capsule



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

ACES General View

Earth

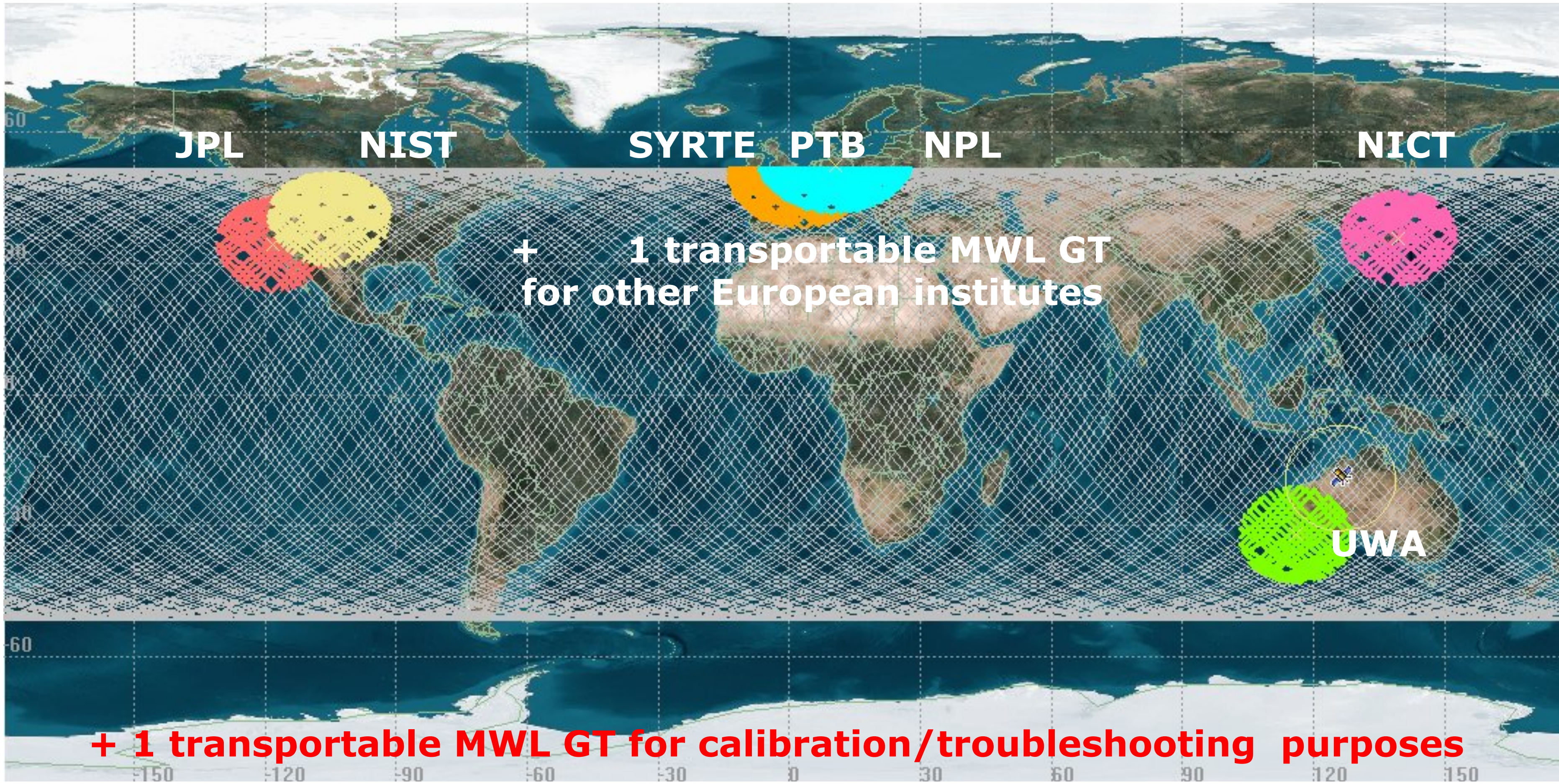


ACES ON COLUMBUS EXTERNAL PLATFORM

ACES

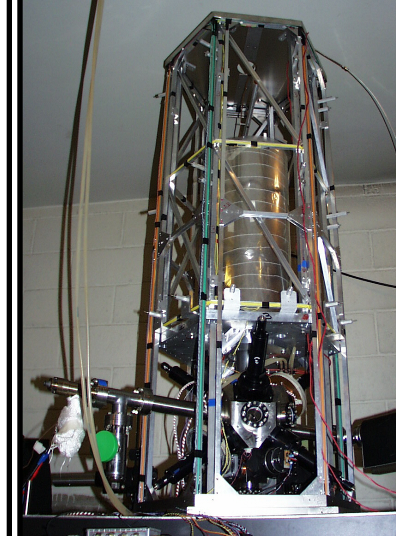
Current launch date : May 2016
Mission duration : 18 months to 3 years

Current Network of Ground Institutes



Delivery of first two MWL GT units is planned in June-July 2014

Do fundamental physical constants vary with time ?



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

α_{elm}, m_e / m_p…

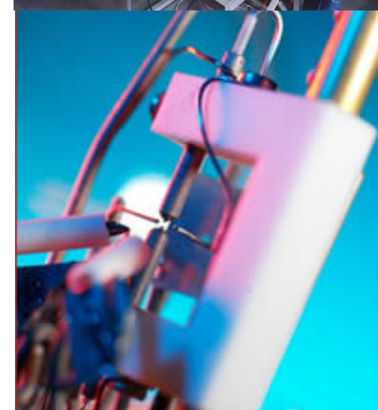
Principle : Compare two or several clocks of different nature as a function of time

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

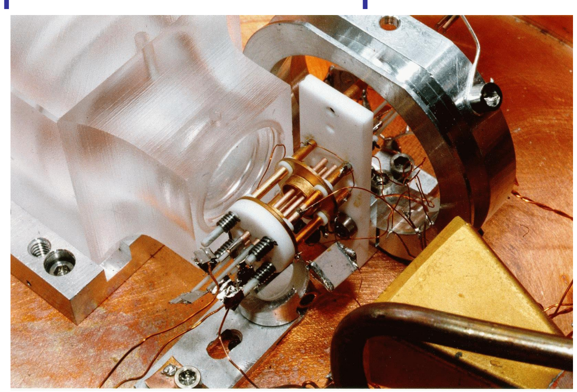
rubidium and cesium

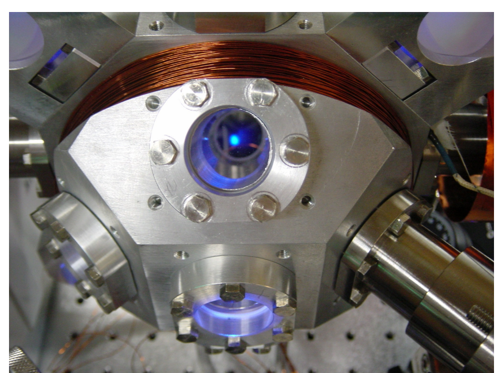
Microwave/Optical clock : α, m_e/m_p, $g^{(i)}$

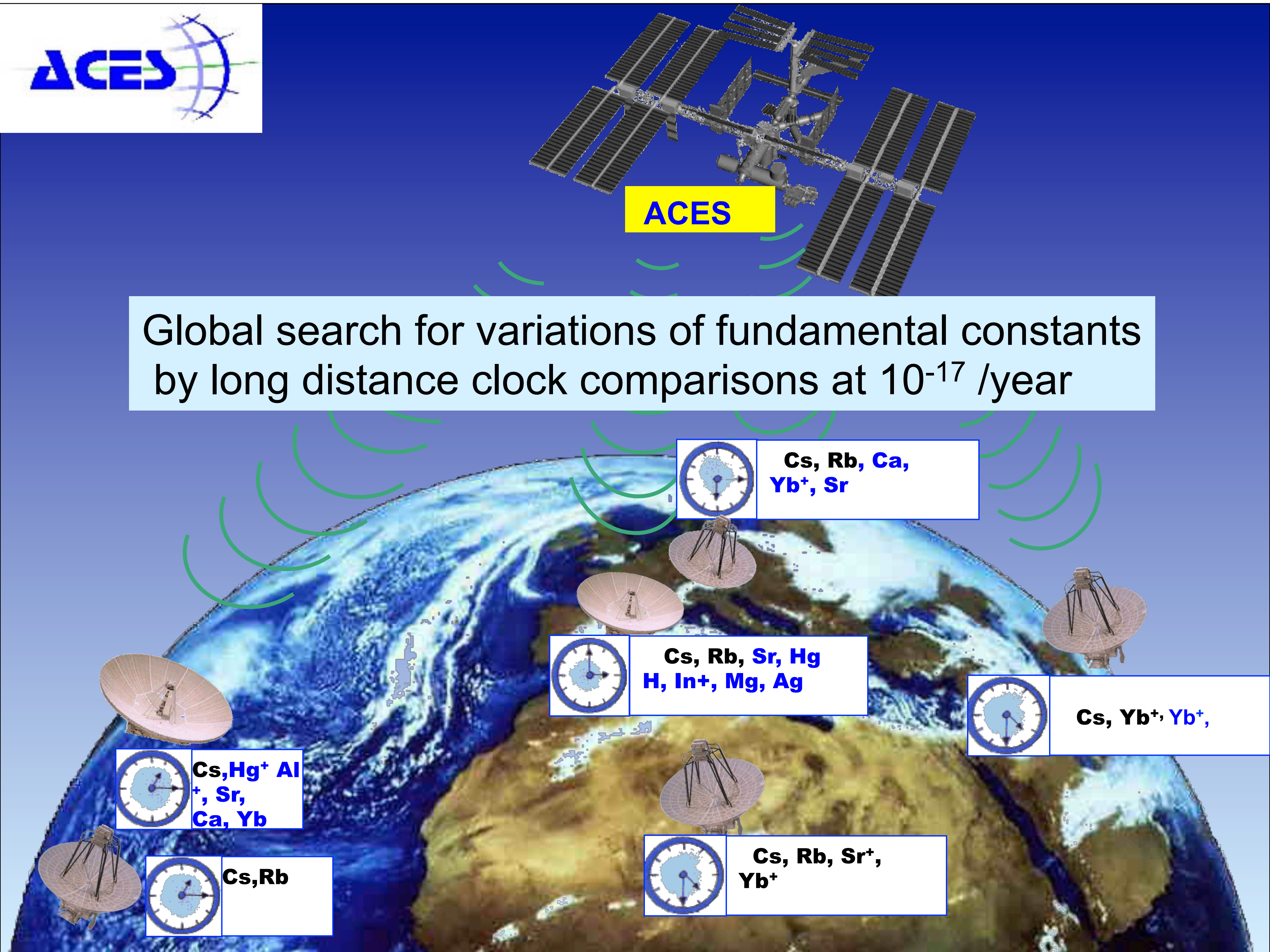
Optical Clock / Optical clock: α



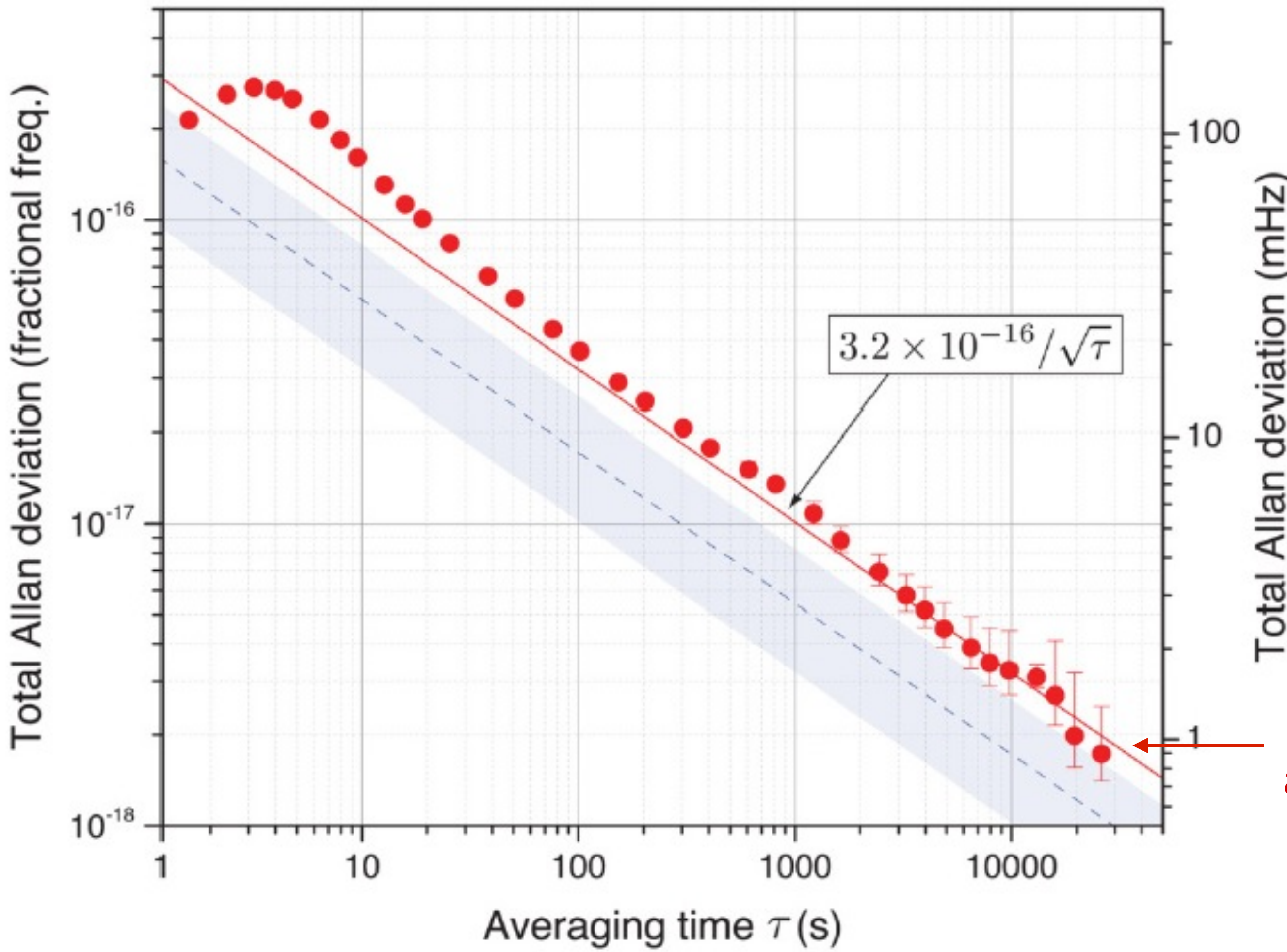
The ovens and electrodes of the NPL strontium ion end-cap trap.






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^+

^{171}Yb Optical Lattice Clocks

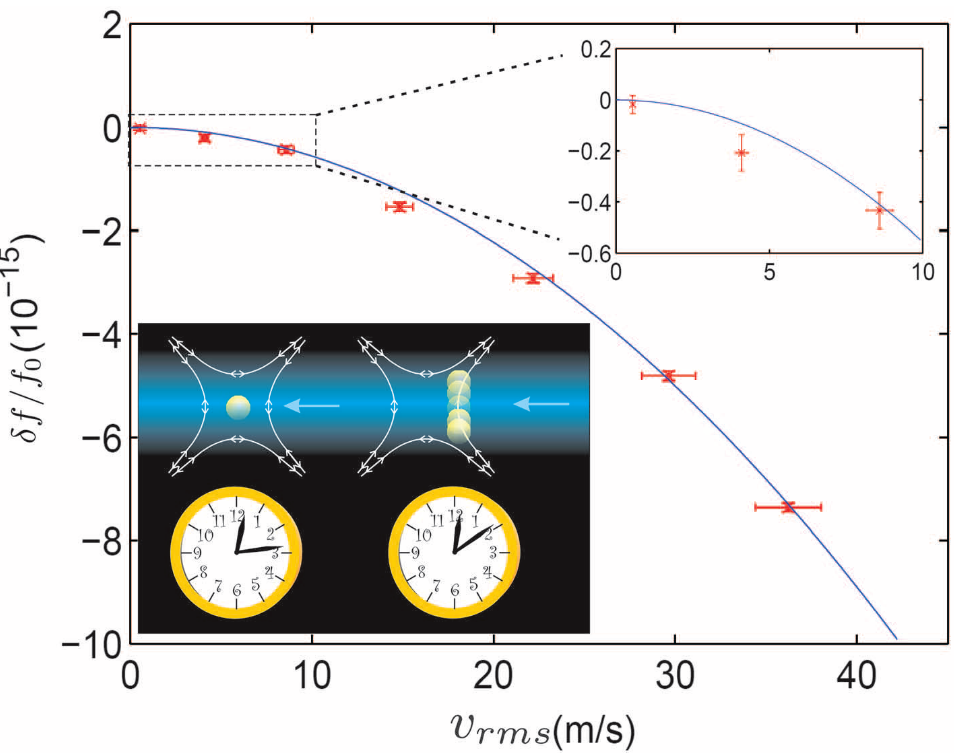


1.6 10^{-18}
at 25 000 s

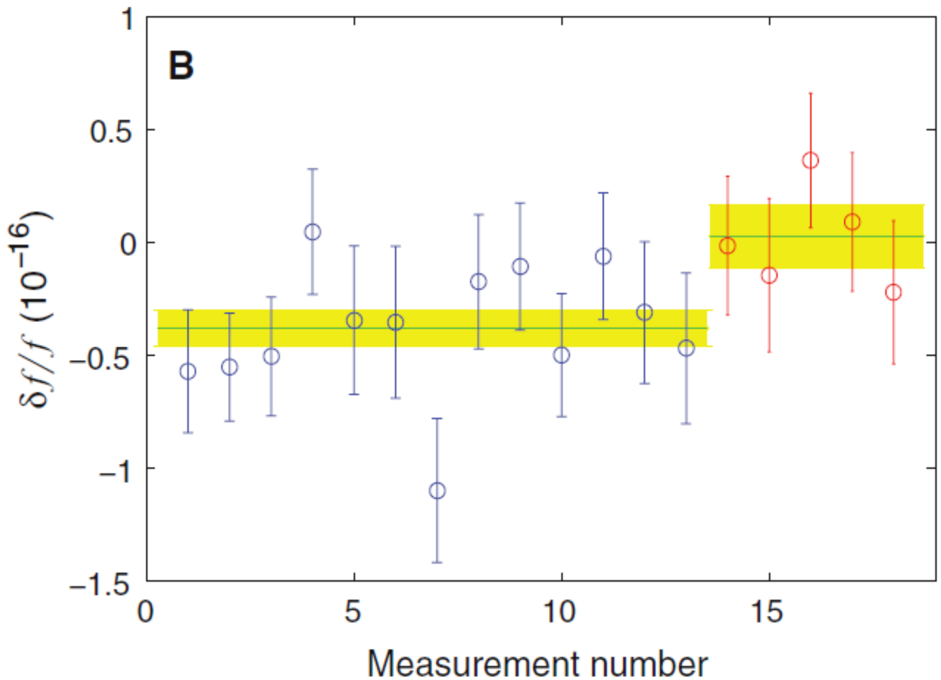
N. Hinkley,J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lemke,1, K. Beloy, M. Pizzocaro, C. W. Oates, A. D. Ludlow, Science '13

Relativity with optical clocks in the Lab

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland, Science 329, 1630, (2010)



Time dilation

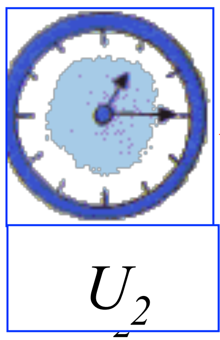


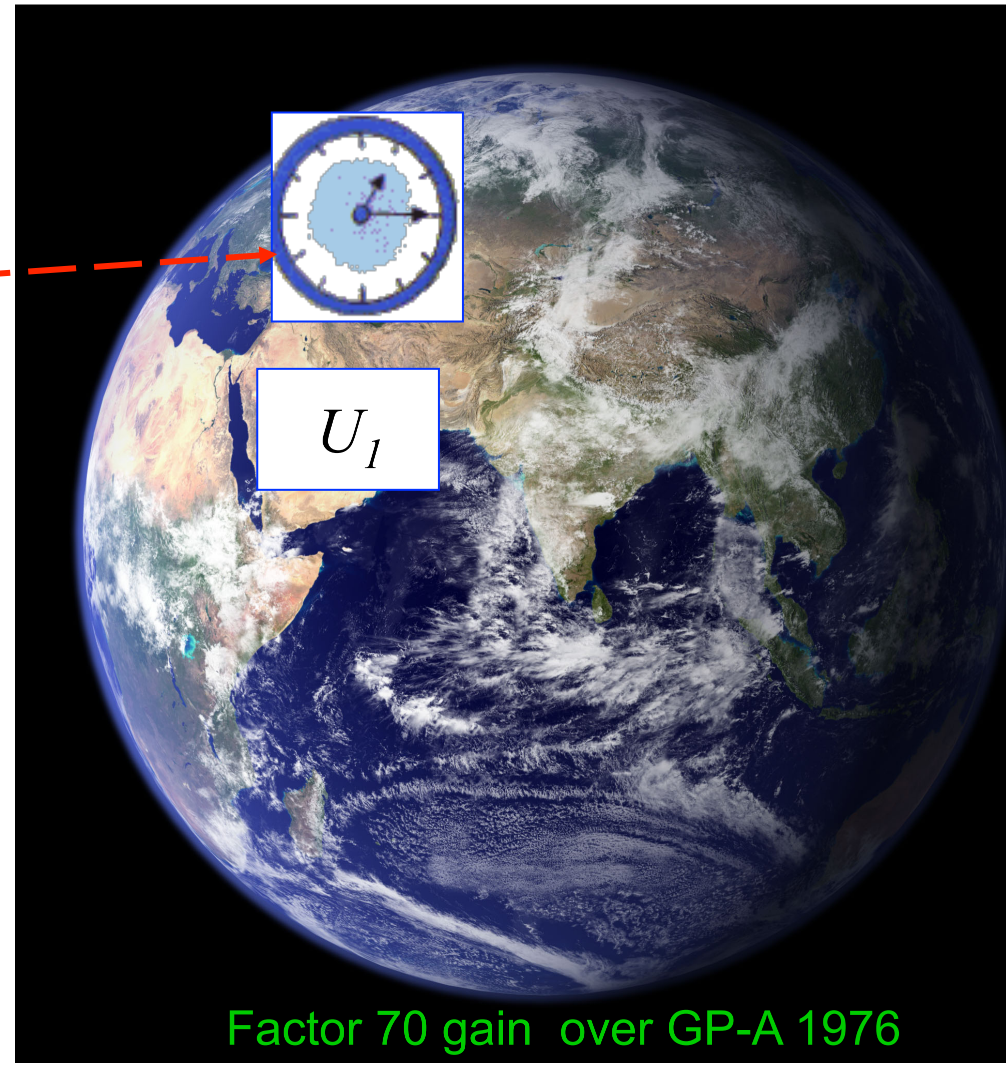
Gravitational shift

Clock B is lifted up by 33 cm

its rate is increased by 3. 4 10^{-17}

Gravitational redshift with ACES

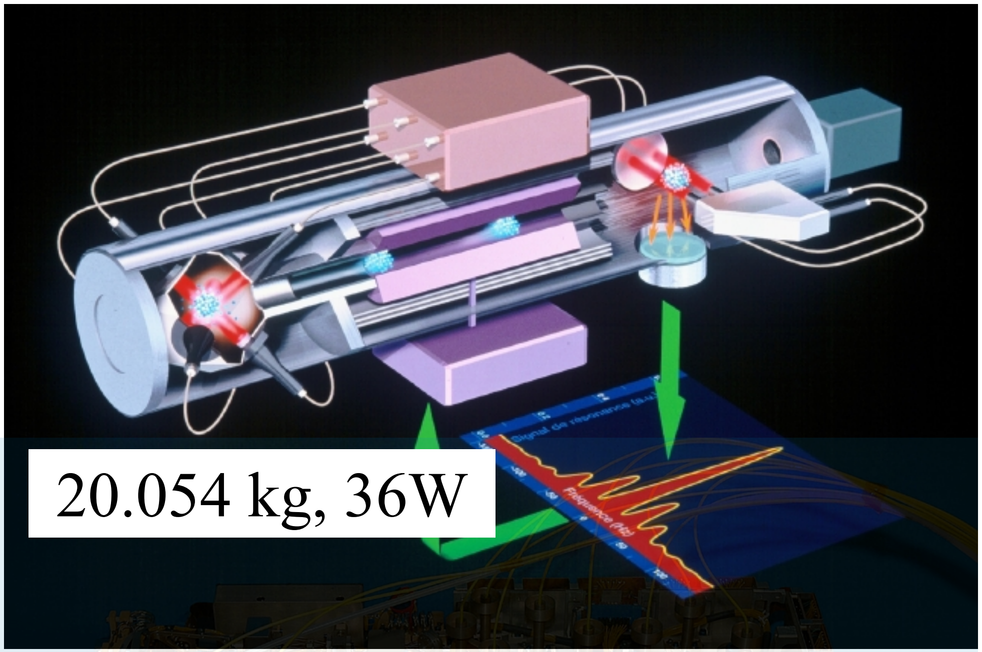


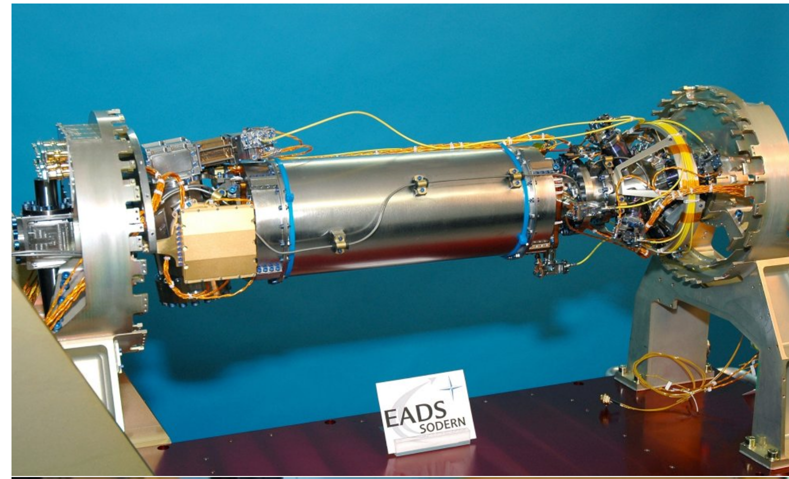


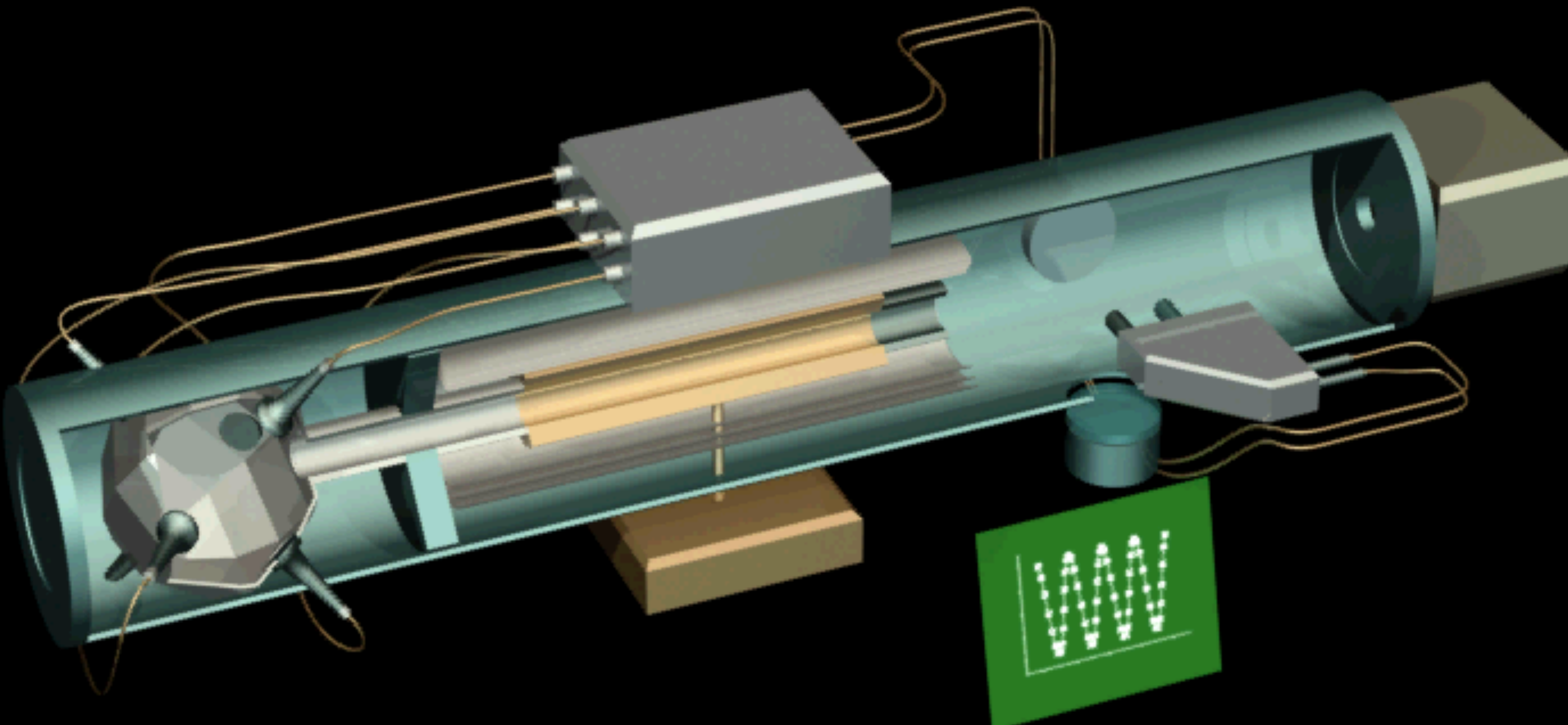
$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

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

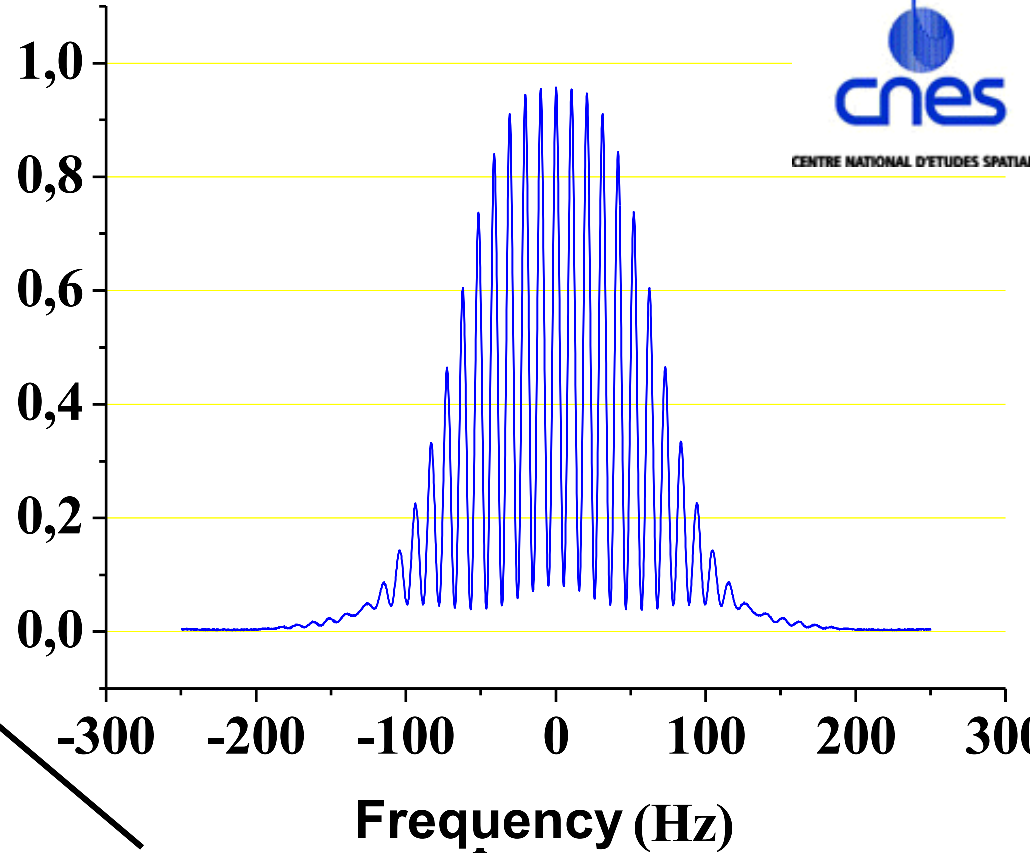
Cold Atom Clock in μ-gravity : PHARAO/ACES







PHARAO Space Clock



Cesium tube

Laser source

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

PHARAO Frequency Stability and Accuracy

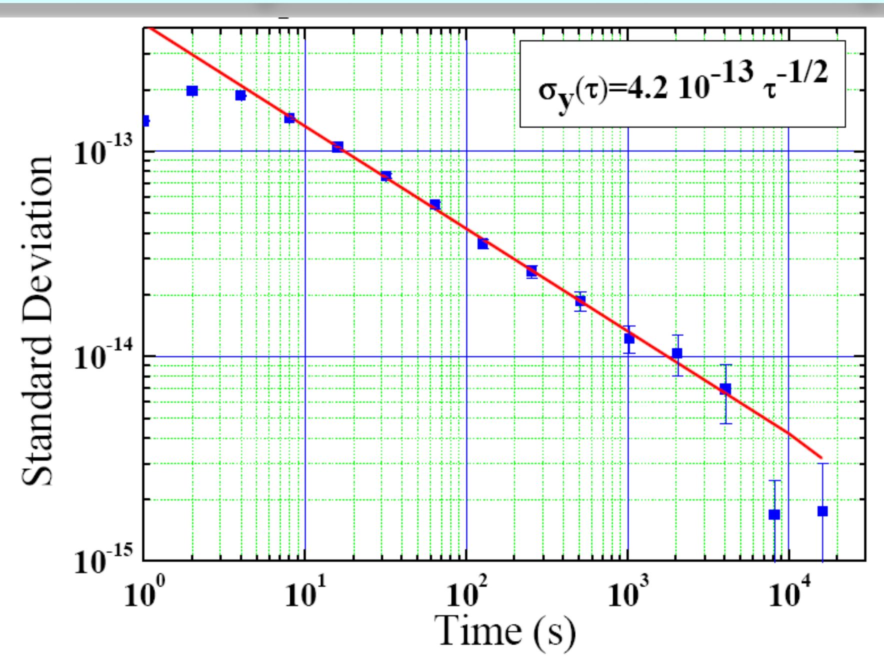
$$\sigma_y(\tau) = 4\ 10^{-13}\ \tau^{-1/2}$$

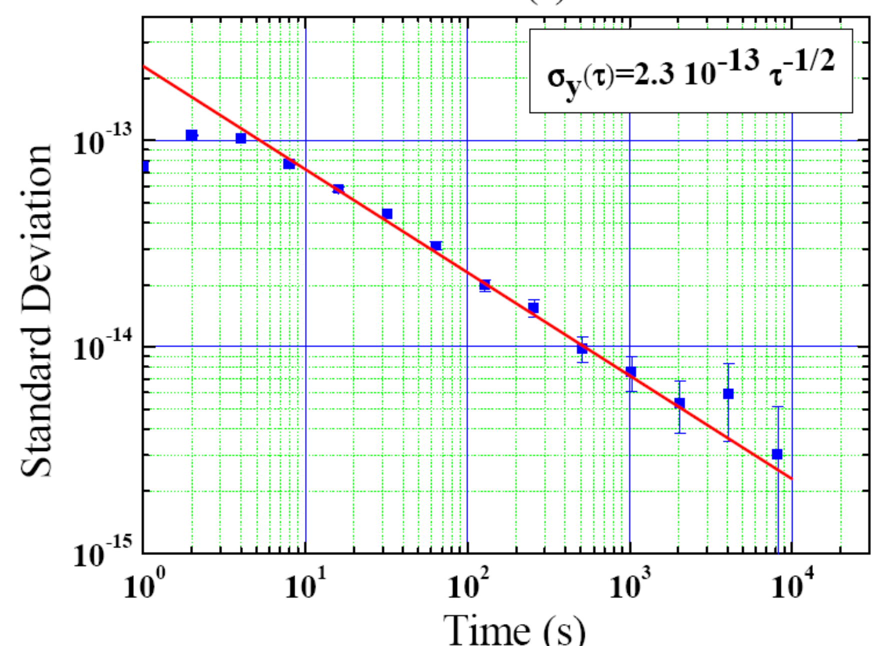
With ultra-stable Quartz
Limited by gravity !

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

With Cryo. Oscillator

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

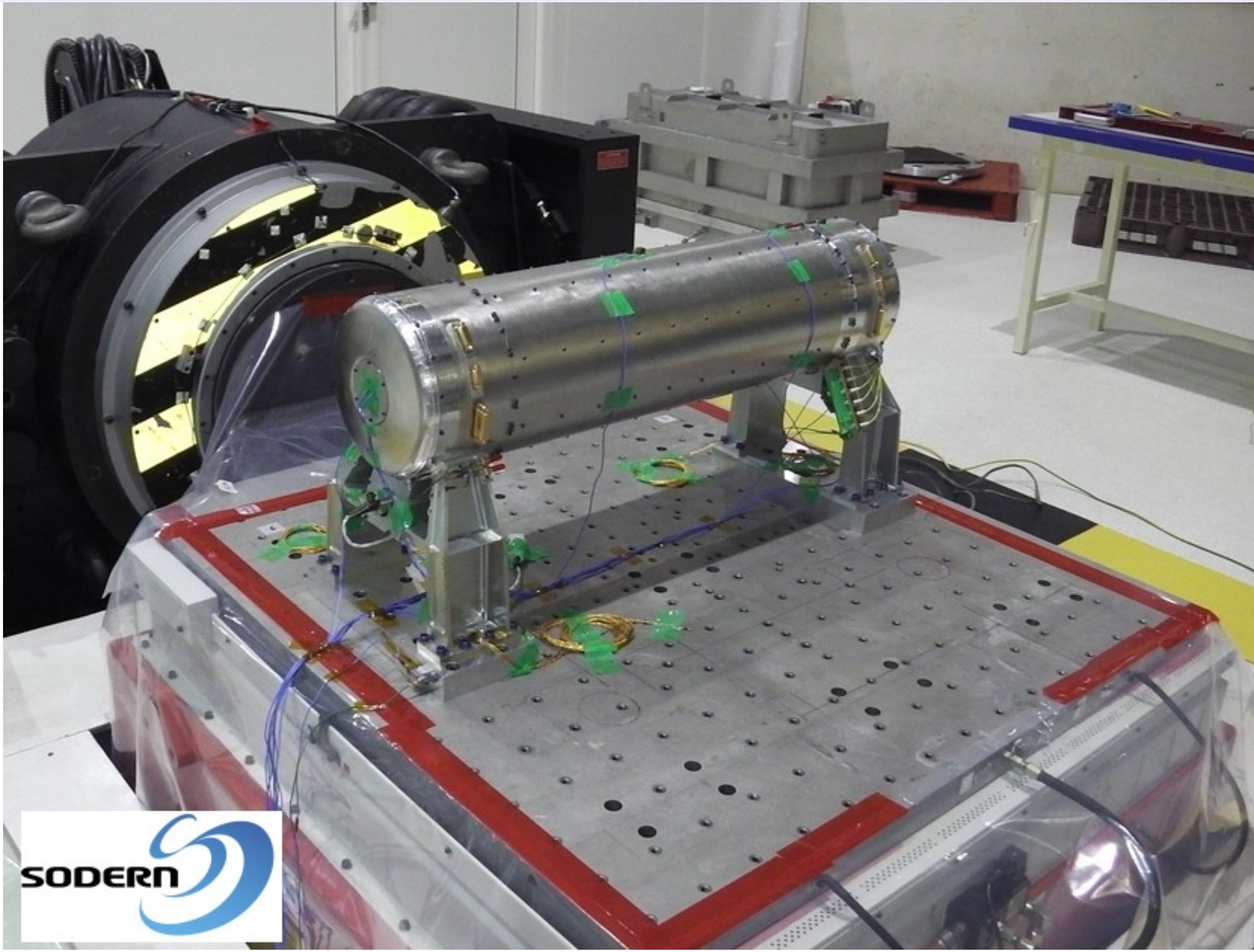




Accuracy evaluation :
Currently 2 10^{-15} on the ground.
Should enable 10^{-16} in space

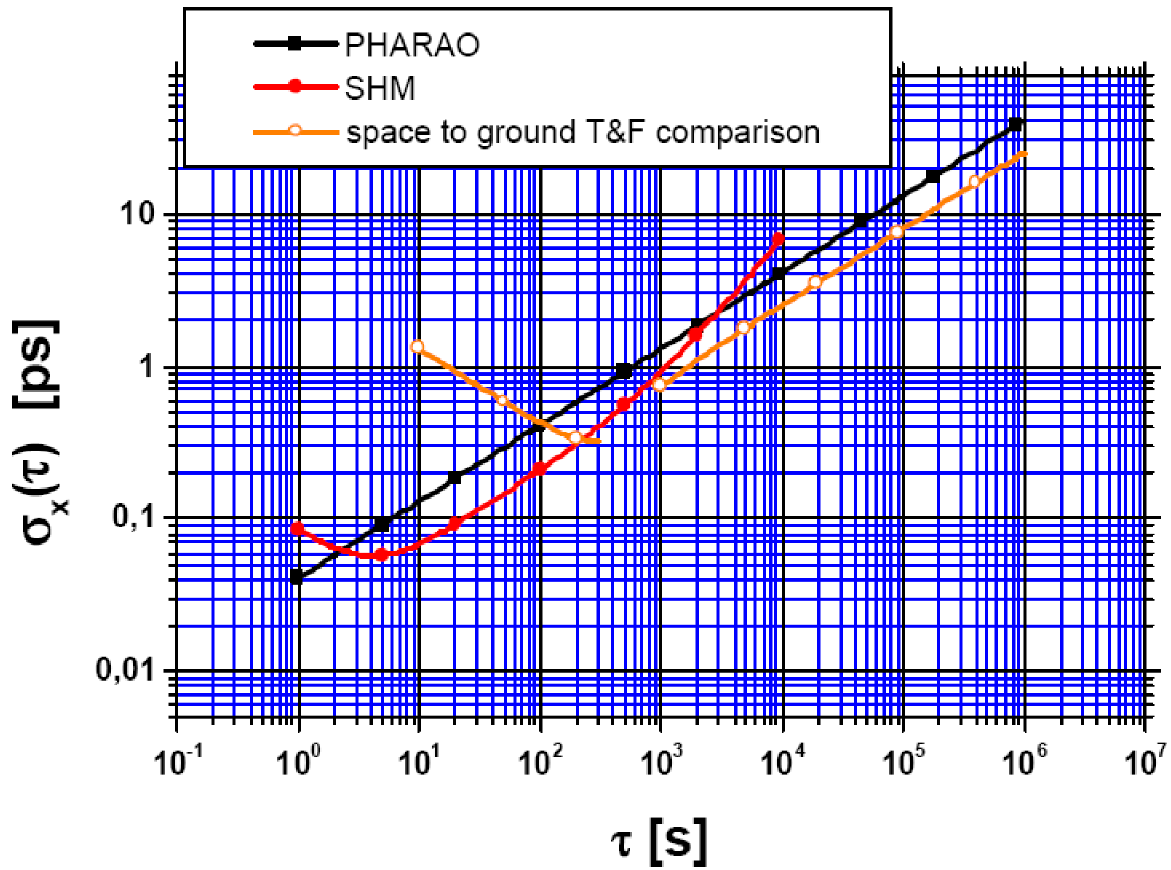
See talk by Ph. Laurent et al.

PHARAO Cesium Tube on the Shaker



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

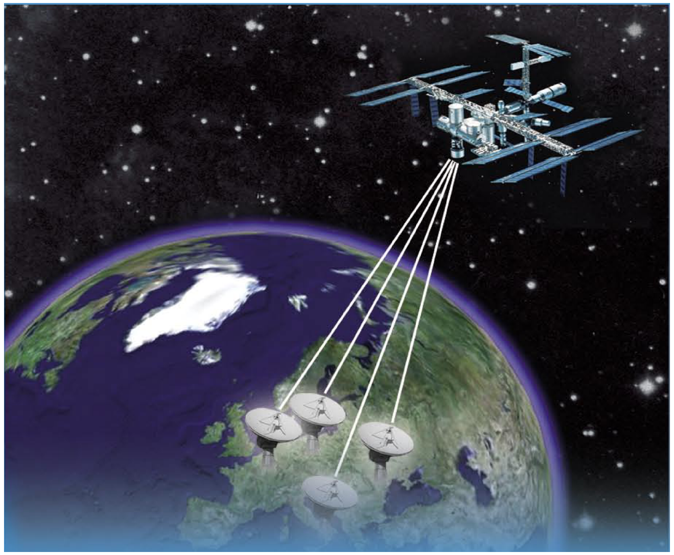
Ultra-stable frequency comparisons on a worldwide basis :

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

Contribution to TAI

Gain: x 20 wrt current GPS

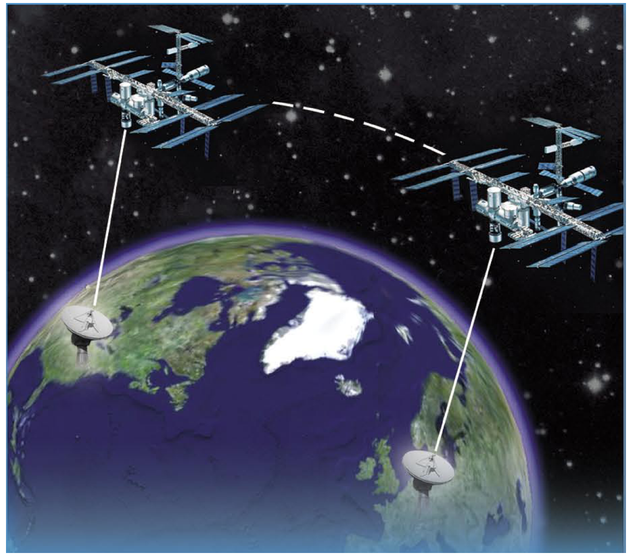
Common view



Error < 0.3ps over 300 s

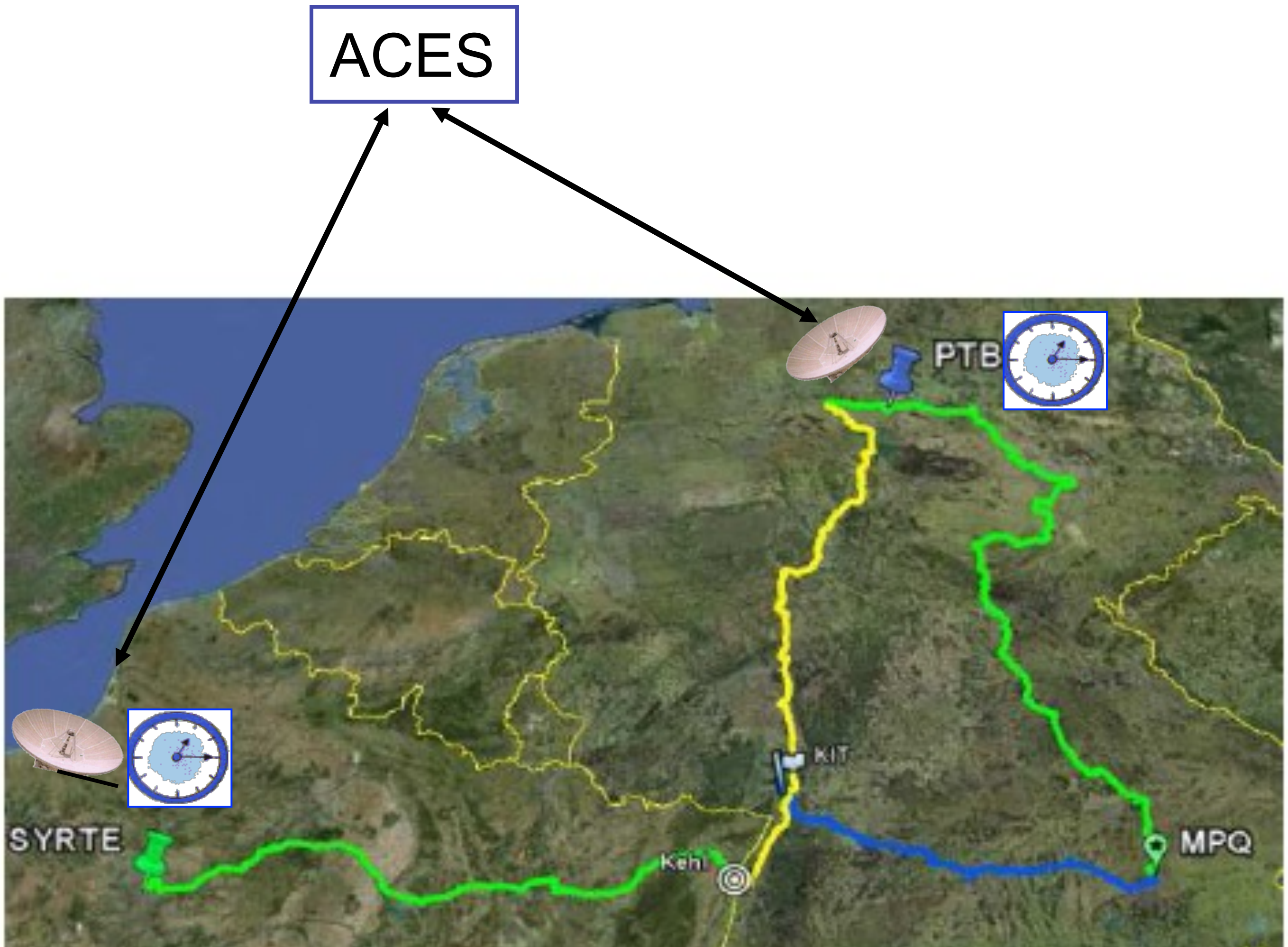
Can be checked by fiber-link

non common view

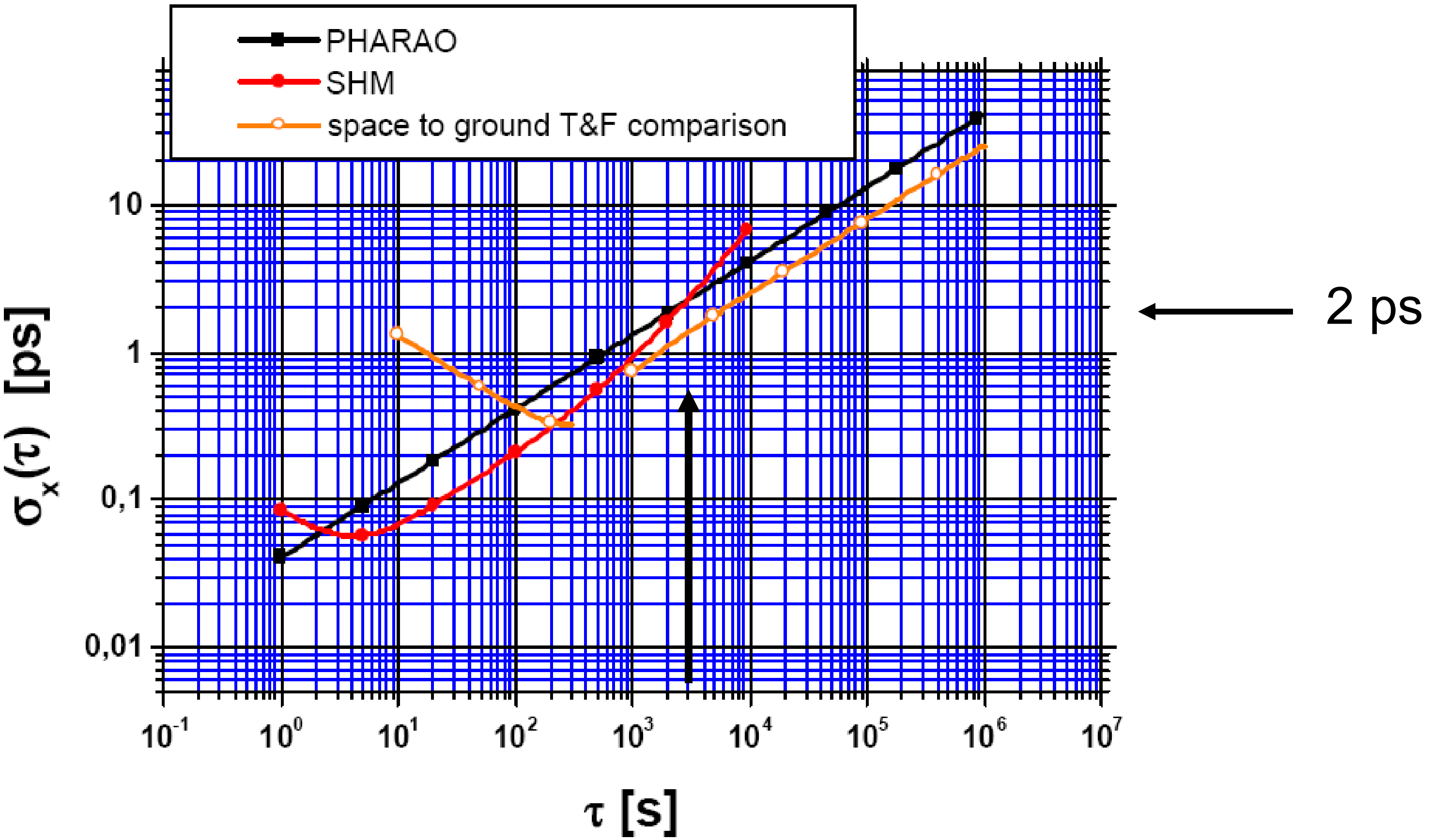


Error < 3ps over 3000 s

Validation of the satellite time transfer with continental fiber link



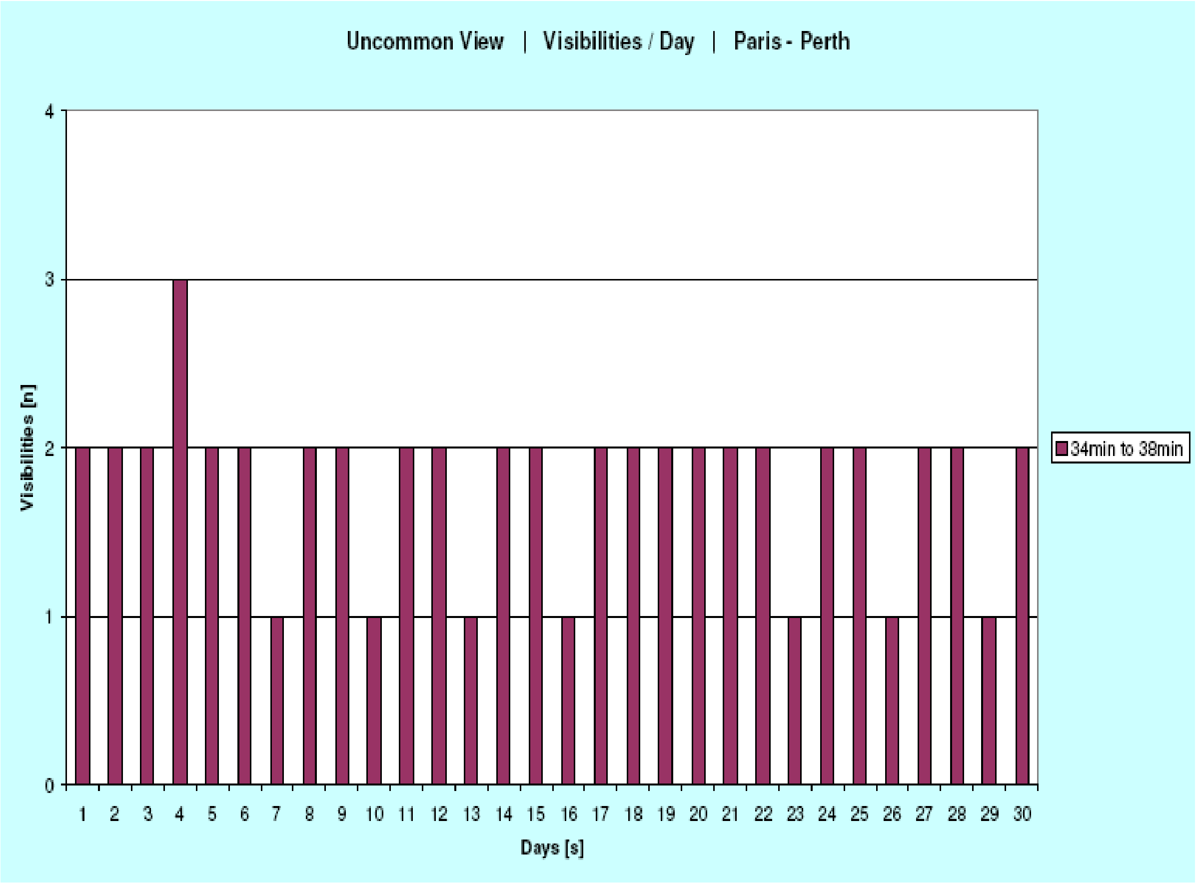
Non Common View



The flight time scale accumulates only 2 ps error over 3000 s i.e. half an orbital period.

Frequency comparisons at 10^{-17} over one week

Non Common View: Paris - Perth



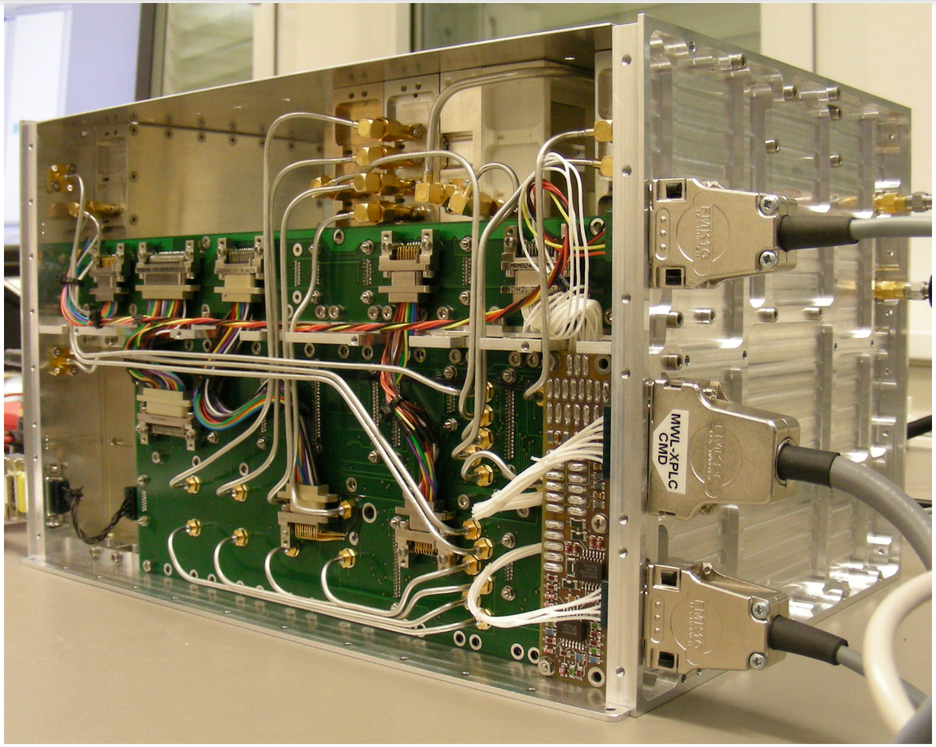
Most distant stations: Paris-Perth

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

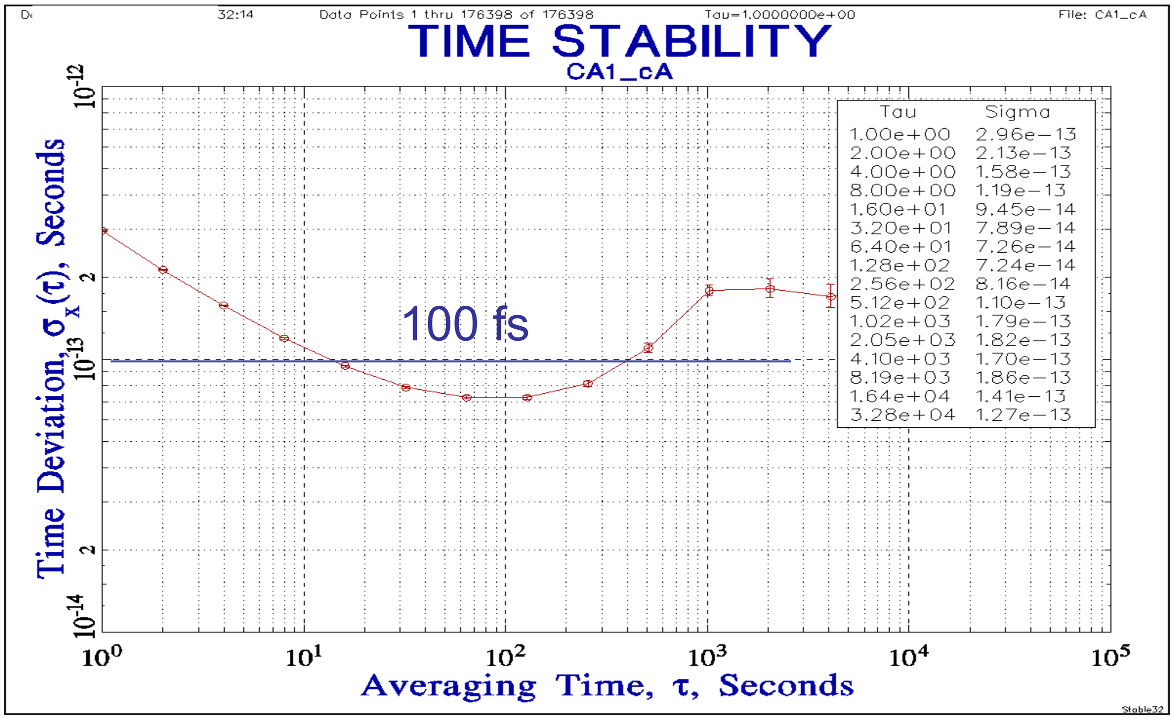
ACES Time Transfer Engineering Model



Onboard receiver

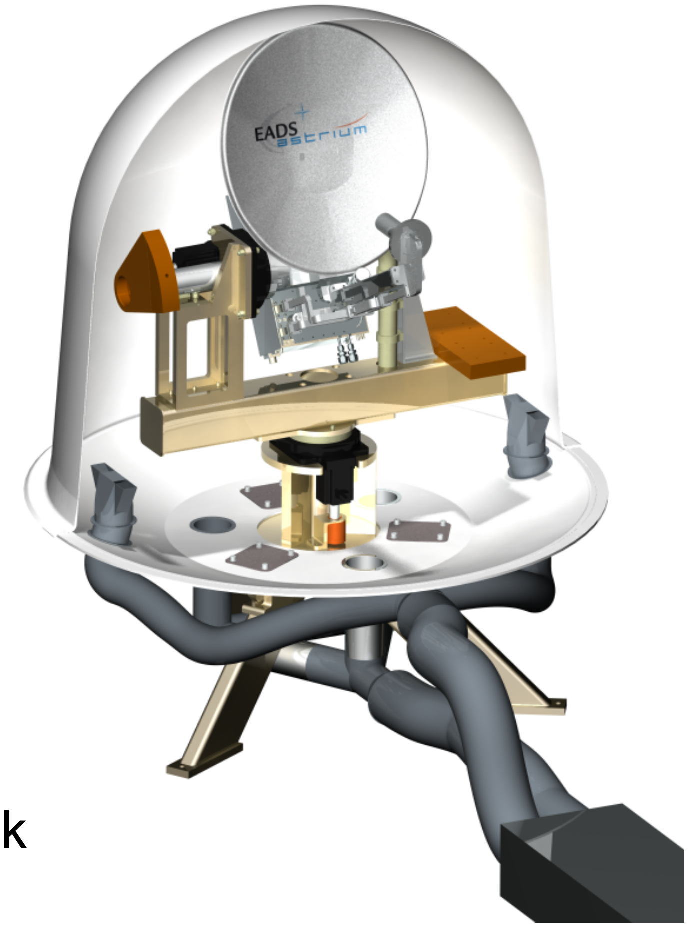
TimeTech and EADS

ACES Time Transfer



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

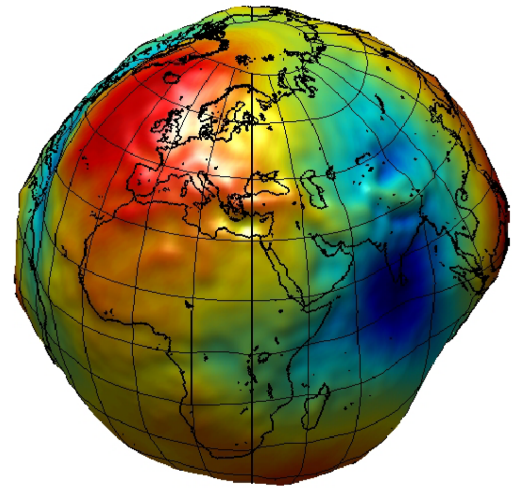
The microwave link ground terminal



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

MWL End to End tests are ongoing
Recent progress on solving NCR

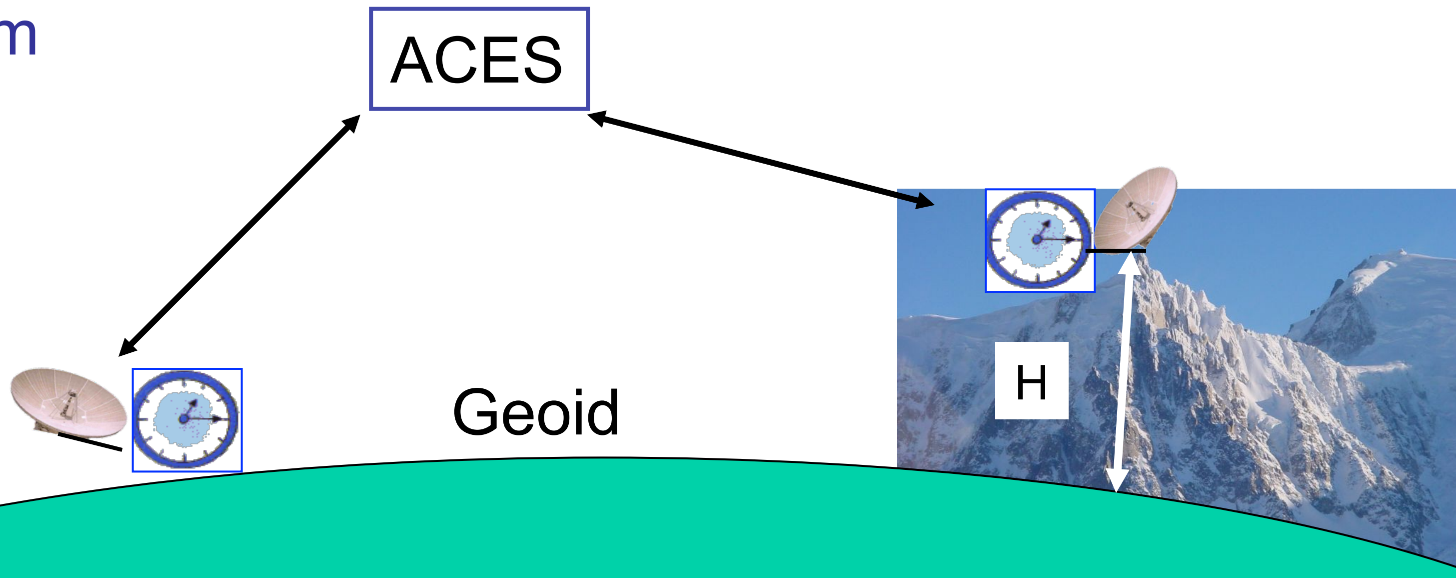
Relativistic Geodesy



The clock frequency depends on the Earth gravitational potential
10^{-16} per meter
Best ground clocks have accuracy of $7\ 10^{-18}$ and will improve ! (NIST, JILA)

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 and 10^{-18} ie1cm with fiber link.



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, JILA,' 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,..

See talks by Peter Wolf and Ernst Rasel

ACES and Beyond

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

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

ACES
Comparisons between distant clocks at 10^{-17} in 2016
Large improvements on relativity tests
Stringent limits for variations of α, g_p, M_e / M_p

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

See next talk by S. Schiller