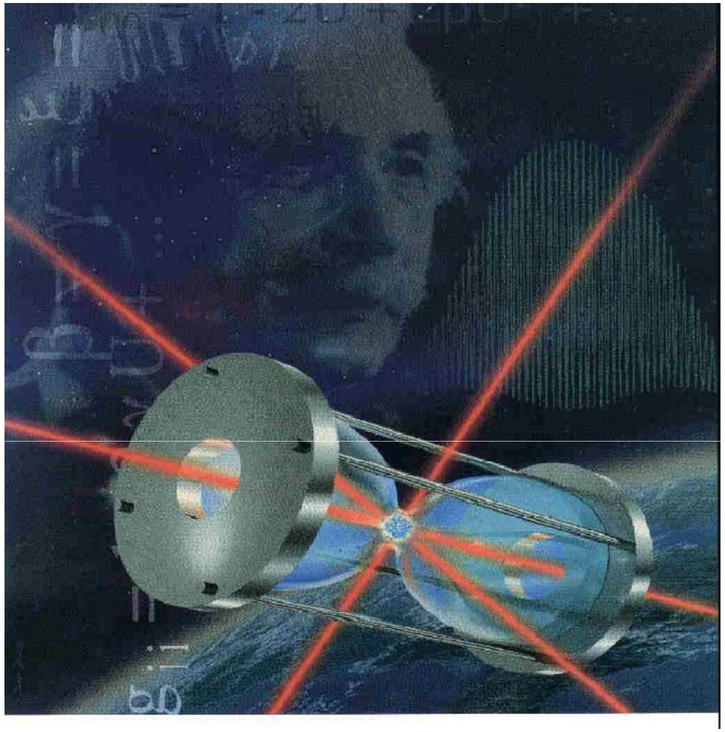
Metrology of Time
From fundamental tests to applications



C. Salomon

Laboratoire Kastler Brossel
Physique quantique et applications

Ecole Normale Supérieure, Paris, France

Euramet GA, Cavtat, Croatia, June 4, 2014

Never measure anything but frequency !

Arthur Schawlow advice to his students at Stanford

1981 Nobel prize laureate

Examples

Distance: through speed of light with c fixed: $d = c\,\Delta t$

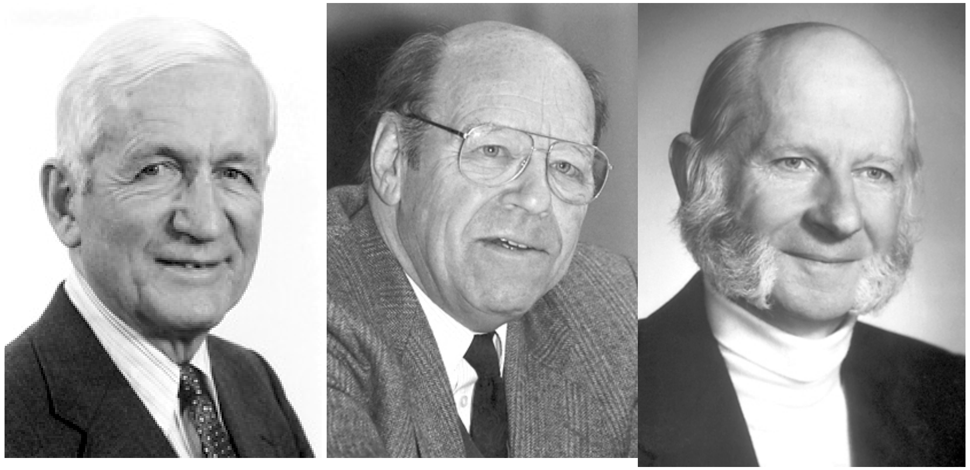
Boltmann constant k_B: Doppler width in a dilute gas

Rydberg constant: hydrogen spectroscopy

Fine structure constant: $\alpha = (1/4\pi\varepsilon_0)\,e^2/hc$
Cyclotron frequency of a single electron in magnetic field
or atomic recoil frequency shift

Charge to mass ratio through cyclotron motion

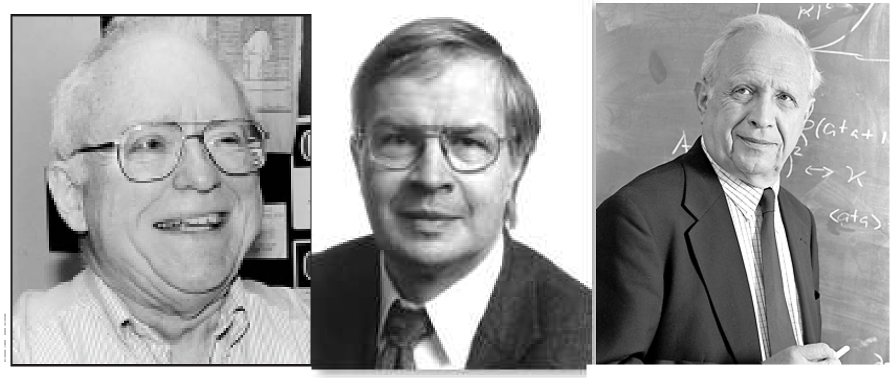
……….



1989: N. Ramsey, W. Paul, H. Dehmelt

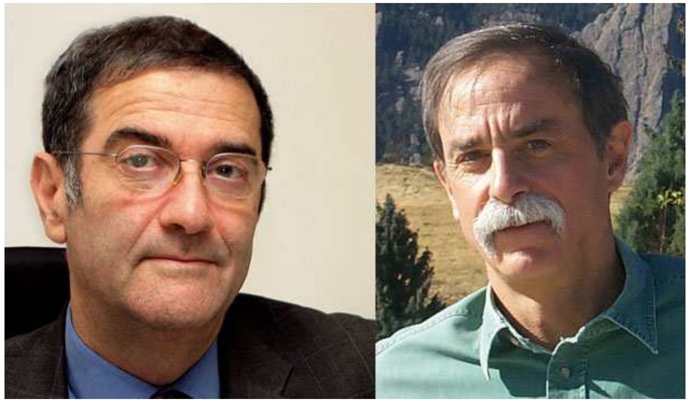
Separated oscillatory fields method
for atomic clocks, ion trap techniques

S. Chu, C. Cohen-Tannoudji, W. Phillips
1997: Laser manipulation of atoms



2005: J. Hall, T. Haensch, R. Glauber

Laser precision spectroscopy
Optical frequency comb
Quantum optics



2012: S. Haroche, D. Wineland

Control of individual quantum objects
Photons and atoms

Discovery of integer quantum Hall effect

2 dimensional electron gas in a strong magnetic field
Metal oxyde semicond field effect transistor : Resistivity is quantized

K. Von Klitzing, G. Dorda, M. Pepper, Phys. Rev. Lett, 45, 494, 1980

Klaus von Klitzing
Nobel laureate 1985

$$R_H = n\, h/e^2$$

$$R_H = \mu_0\, c\, /\, 2\, \alpha\, n$$

→ Standard of electrical resistance ~25 kΩ for n =1

Time measurement

Find a periodic phenomenon:

1) Nature:

observation: Earth rotation, moon rotation, orbit of pulsars,..

2) Human realization: egyptian sandstone, Galileo pendulum….

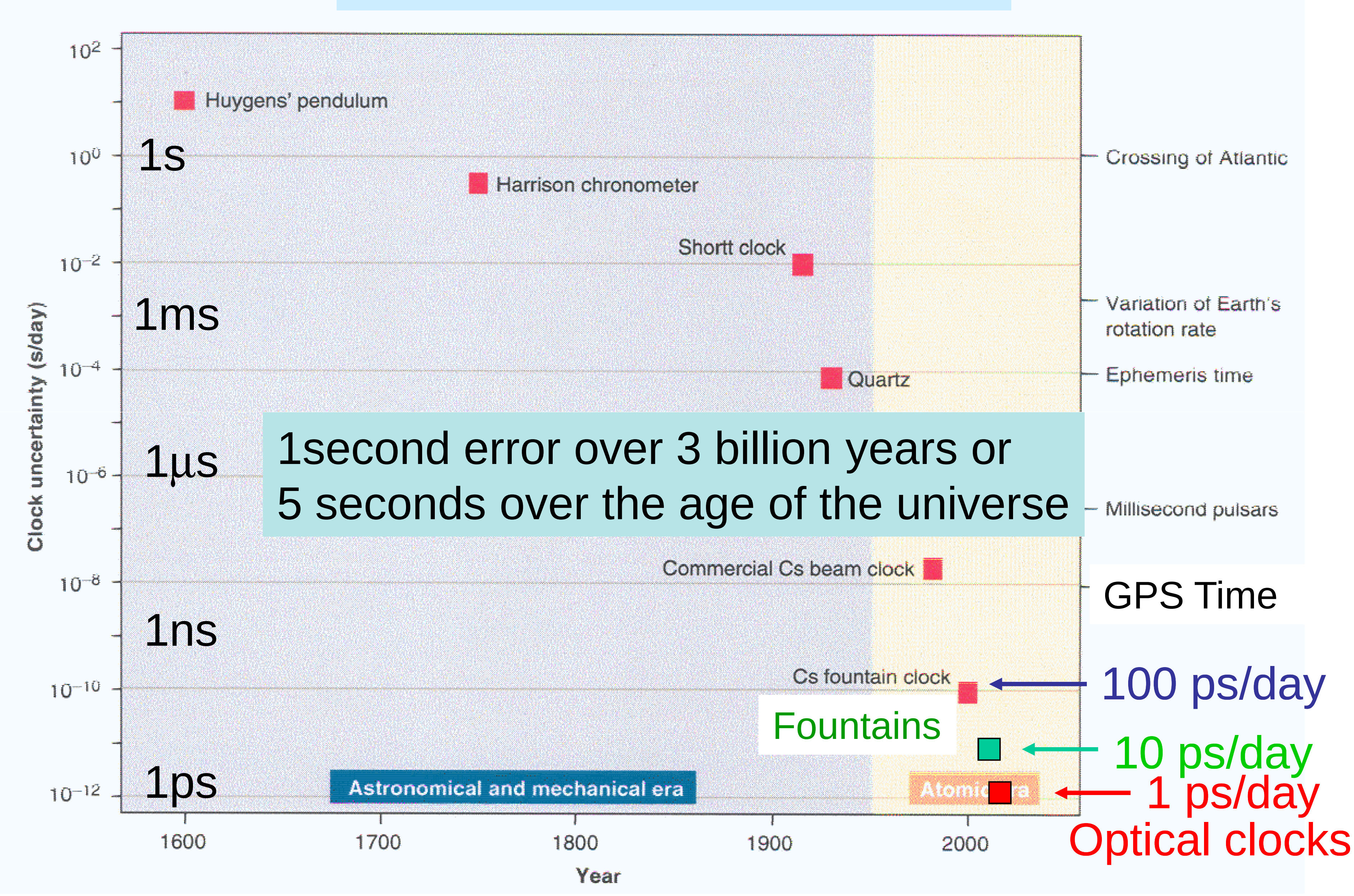
simple phenomenon described by a small number of parameters

The faster the pendulum,
The better is time resolution

$$T = 2\pi\sqrt{l/g}$$

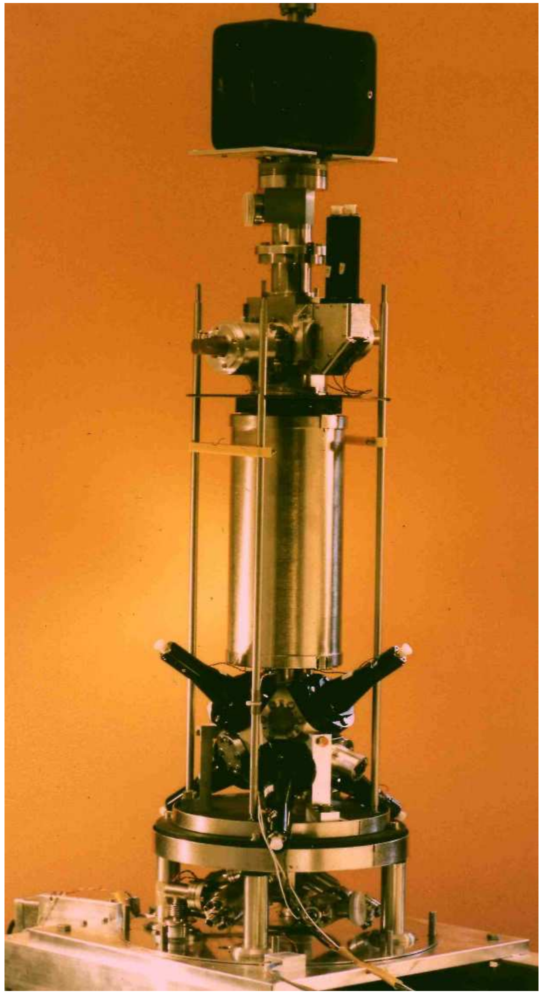
3) Modern clocks use electromagnetic signals locked to atomic lines

Precision of Time



1second error over 3 billion years or
5 seconds over the age of the universe

Atomic Clock



Definition of the second:

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine states of the ground electronic state of cesium 133.

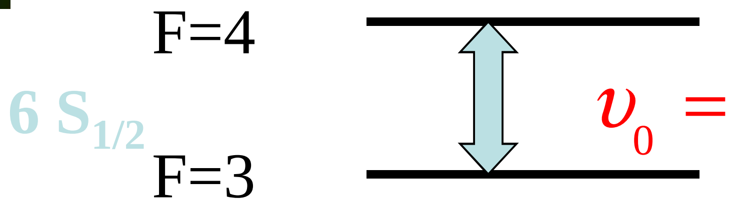
intrinsic stability of atomic energy levels

Laser cooling to 1 µK

rms velocity: 7mm/s

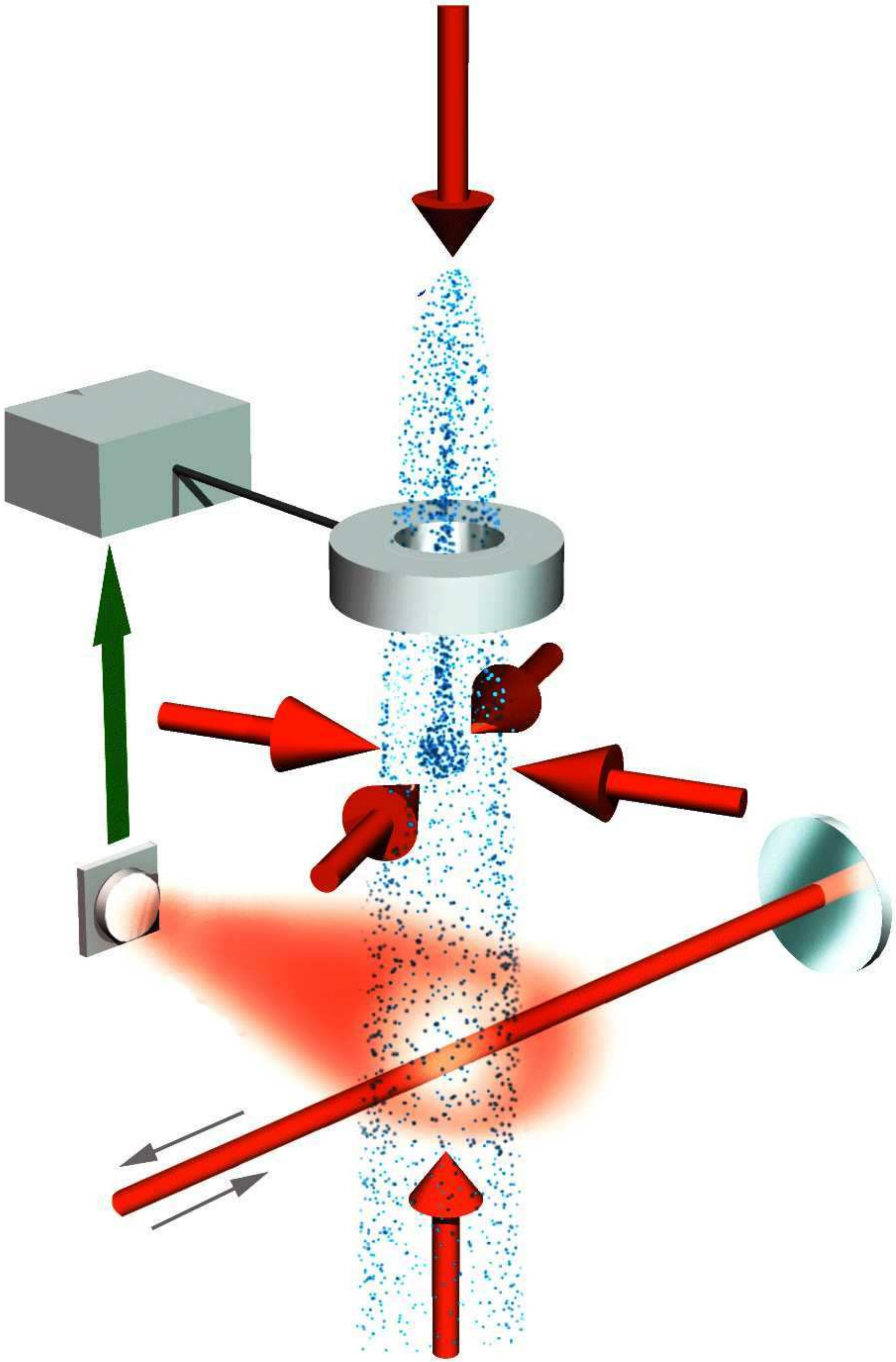
1) Fountain
2) Microgravity

1. **Stability**
2. **Accuracy**

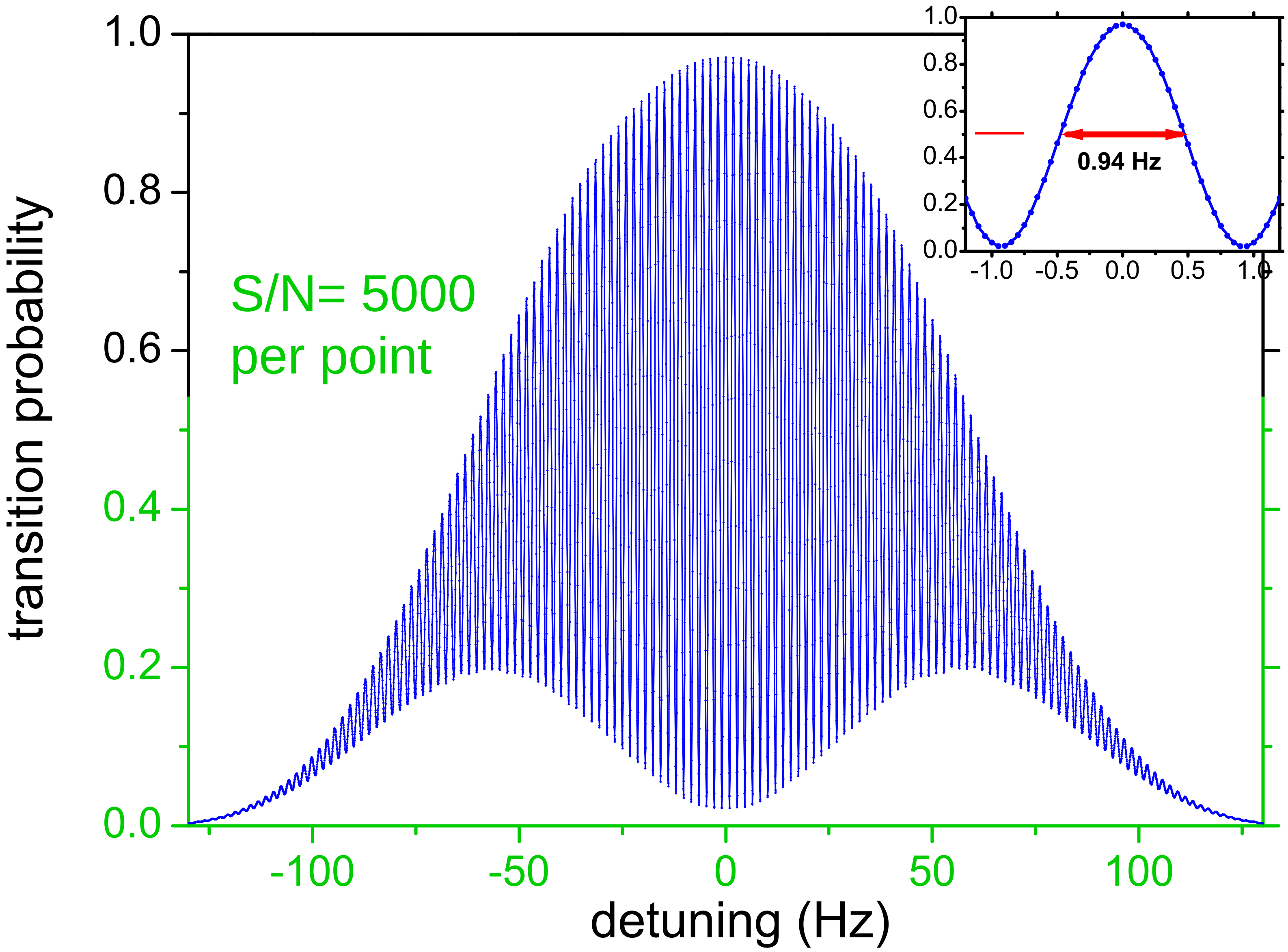


$$\upsilon_0 = 9\,192\,631\,770\ \mathbf{Hz}$$

Atomic fountain

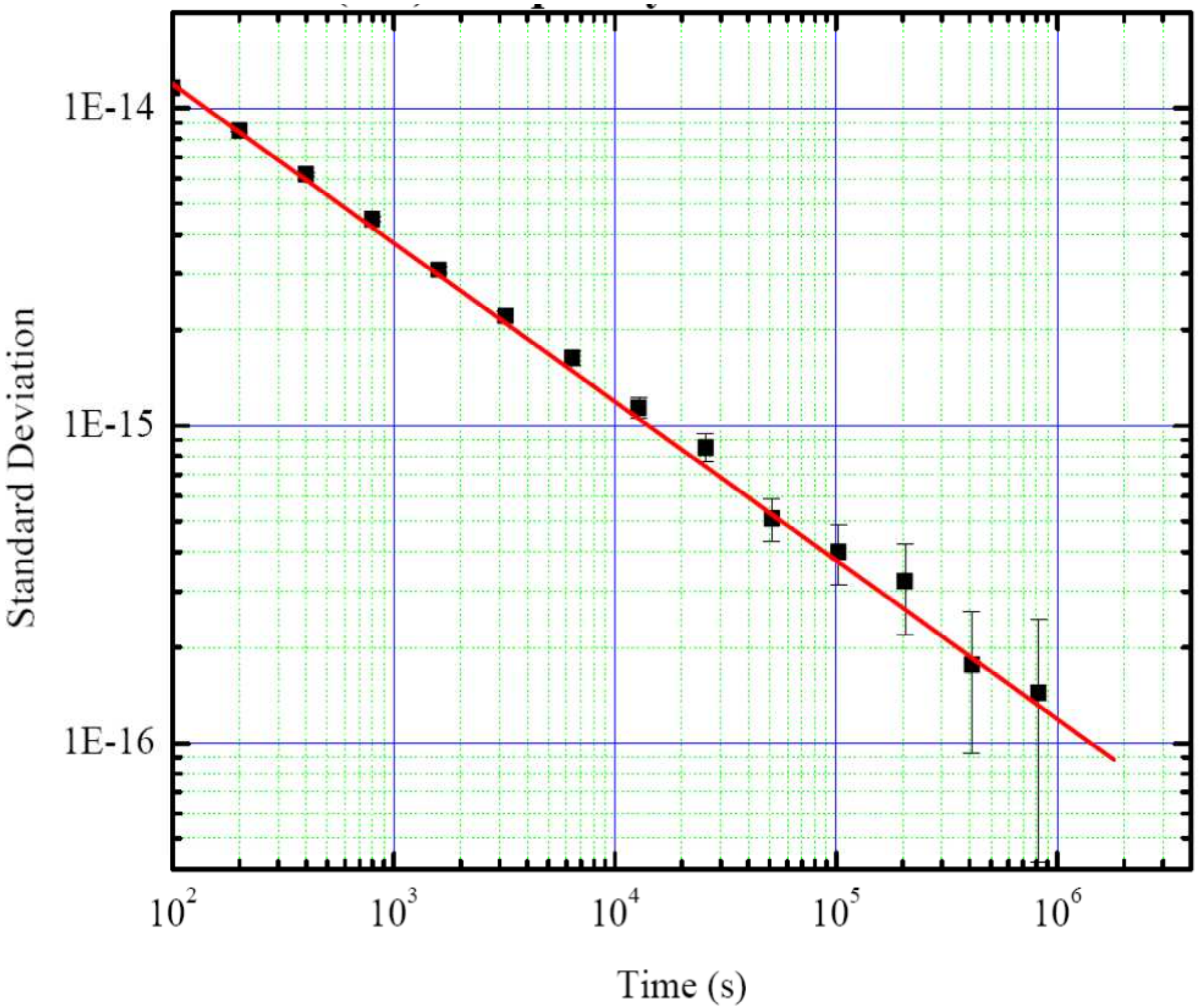


Ramsey fringes in atomic fountain



Comparison between two Fountains FOM and FO2 (Paris Observatory)

cs1



S. Bize
et al.
EFTF’08
J. Phys. B 2005
SYRTE

Frequency stability below 10^{-16} after 5 to10 days of averaging
Accuracy: agreement between the Cesium frequencies: 4 10^{-16}

cs1 Each fountain is measuring its collisional shift in real time at 2 part in 103 and it will be very difficult to go much beyond these values. Rubidium, on the other hand has much reduced colisional shift and will lead to better stability and accuracy.

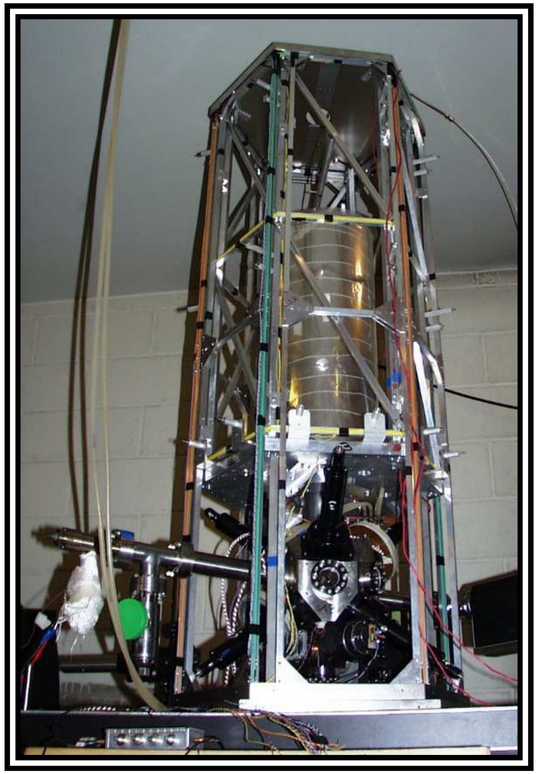
Christophe SALOMON; 13.02.2005

Atomic Fountains and TAI

15 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, INRIM, NPL, METAS, JPL, NIM, NMIJ, NICT, Sao Carlos,….

~10 report to BIPM with accuracy of a few 1 10^{-16}

Realize the International Atomic Time, TAI



LNE-SYRTE, FR

PTB, D

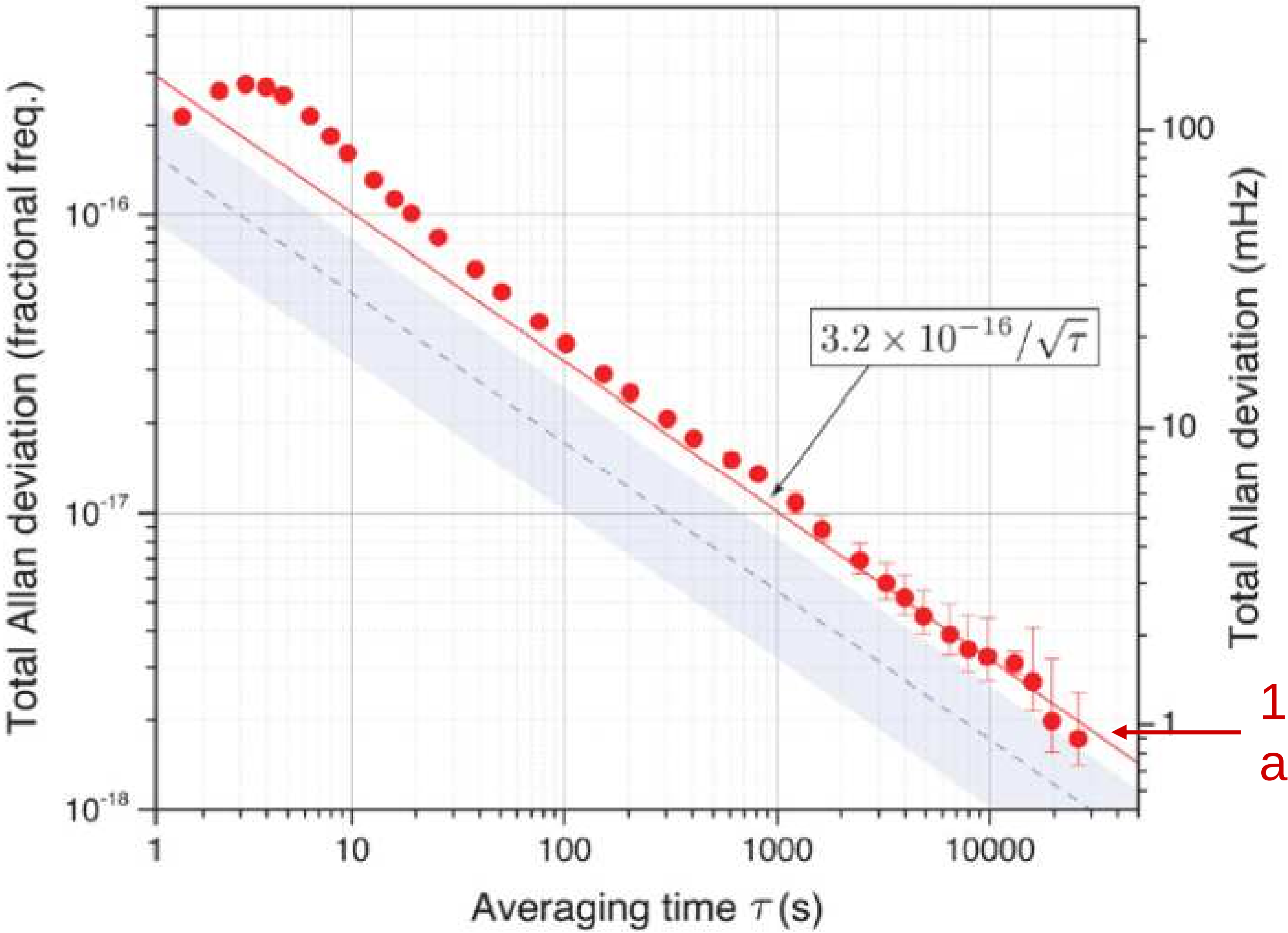
NIST, USA

CS1

Folie 12

CS1 Christophe Salomon; 22.11.2007

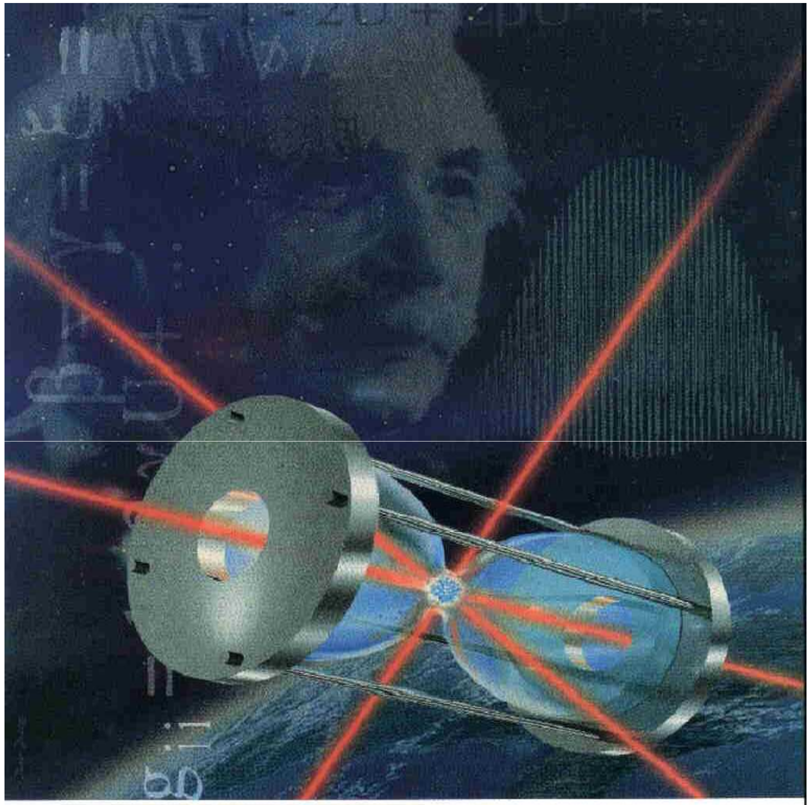
^{171}Yb Optical Lattice Clocks



1.6 10^{-18}
at 25 000 s

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

The space clock mission ACES

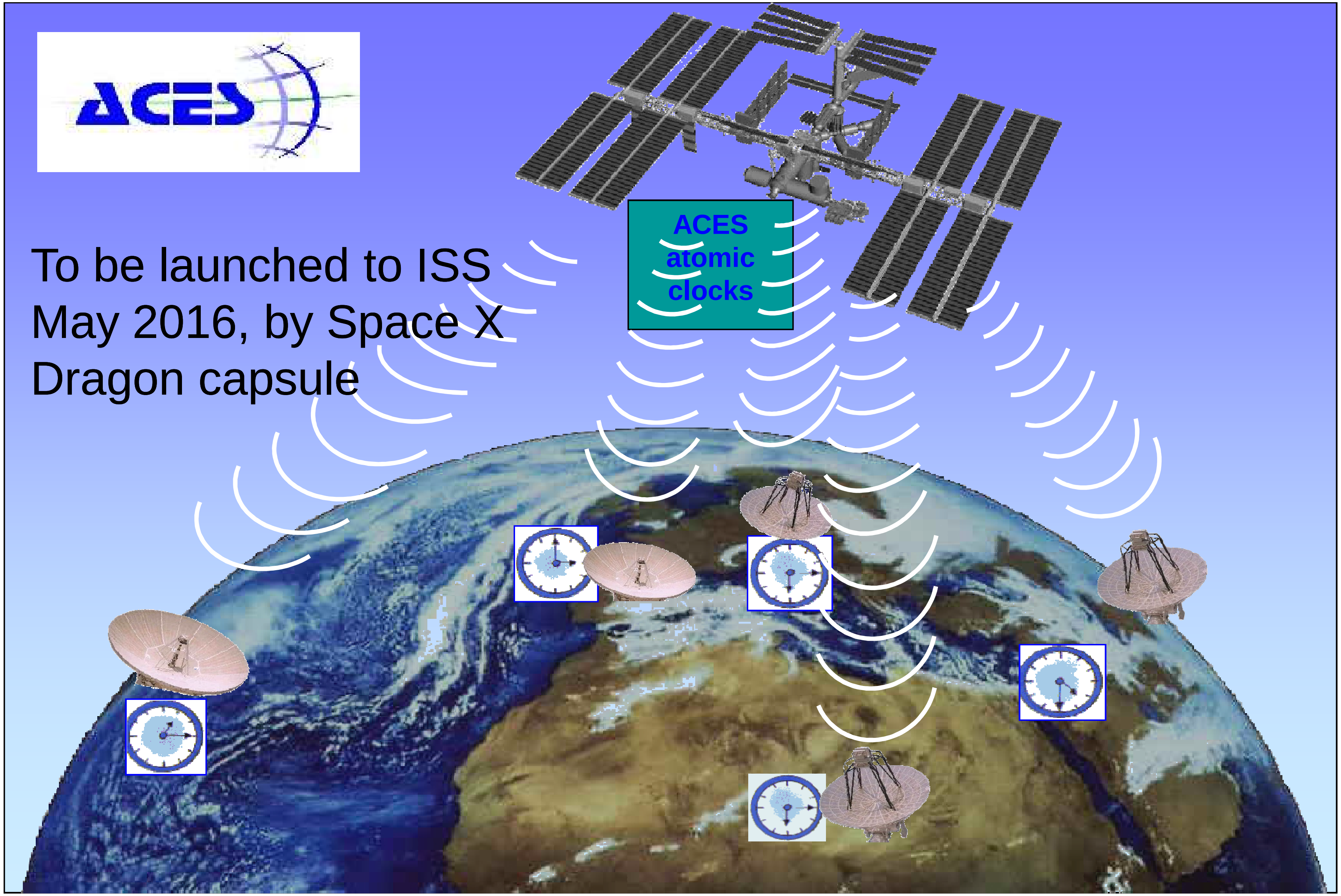


Proposal:1997

Participants

L. Duchayne, X. Baillard, D. Magalhaes ,C. Mandache, P. G. Westergaard, A. Lecallier, F. Chapelet, M. Petersen, J. Millo, S. Dawkins, R.Chicireanu,
S. Bize, P. Lemonde, P. Laurent, M. Lours,
G. Santarelli, P. Rosenbusch, D. Rovera,
M. Abgrall, R. Le Targat, Y. Lecoq, P. Delva,
P. Wolf, 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,
Y. Prochazka, U. Schreiber, W. Bosch, A. Schlicht
G. Tino, P. Thomann, S. Schiller,
L. Cacciapuoti, R. Nasca, S. Feltham,
R. Much, O. Minster,
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

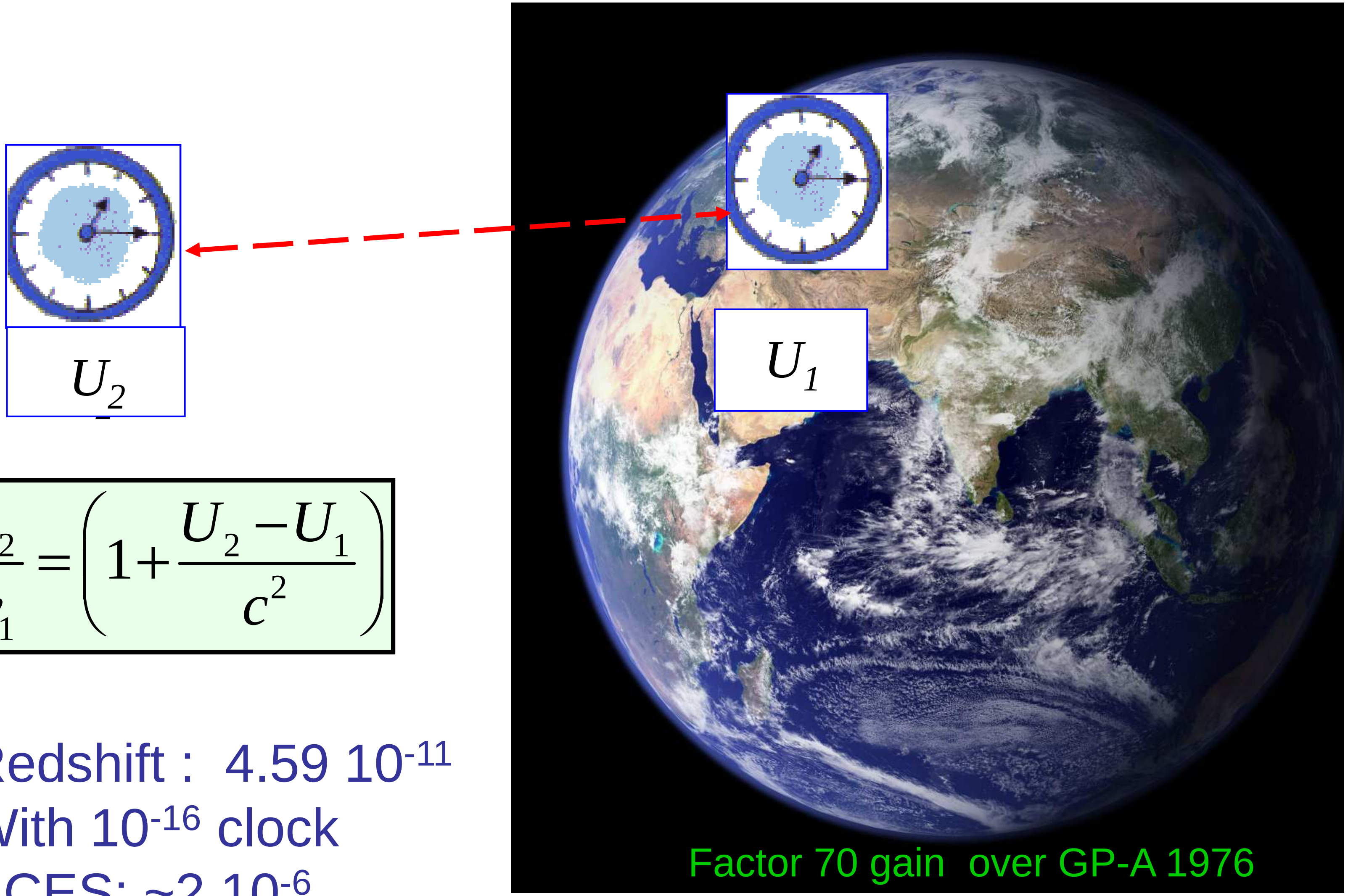


To be launched to ISS
May 2016, by Space X
Dragon capsule

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

CENTRE NATIONAL D'ETUDES SPATIALES

Gravitational redshift with ACES

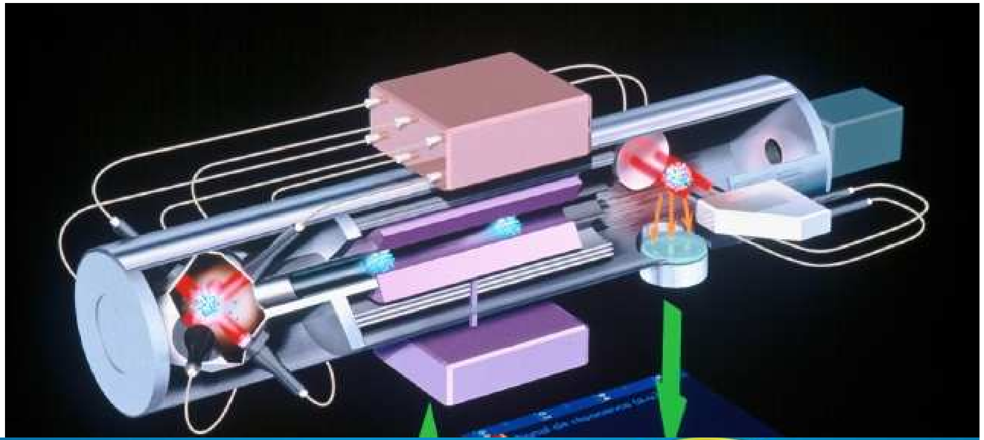


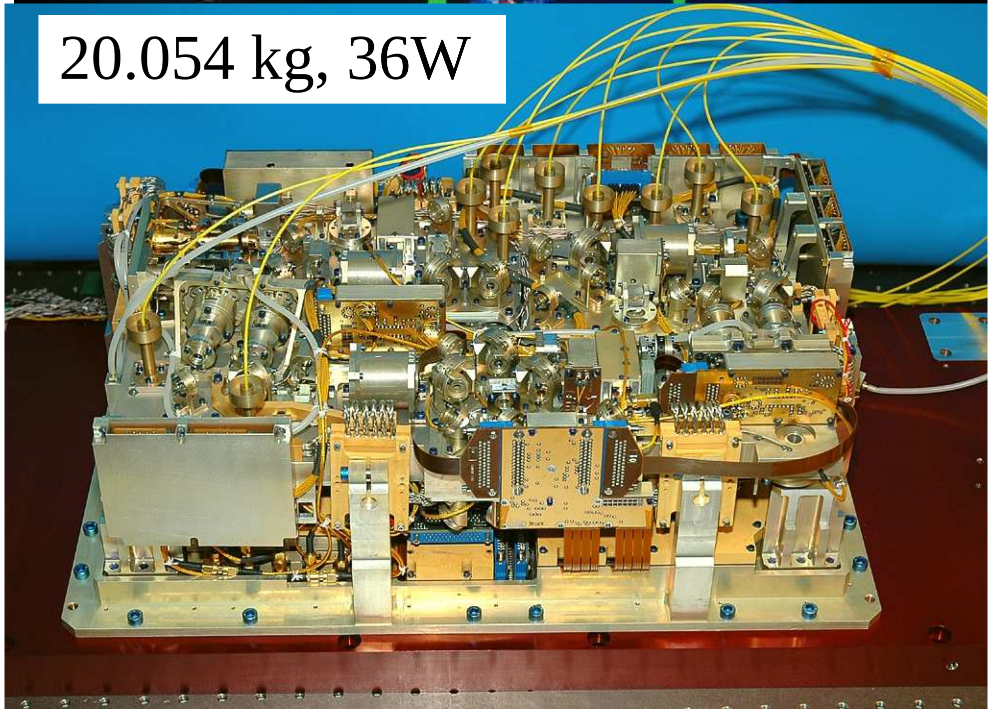
Factor 70 gain over GP-A 1976

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

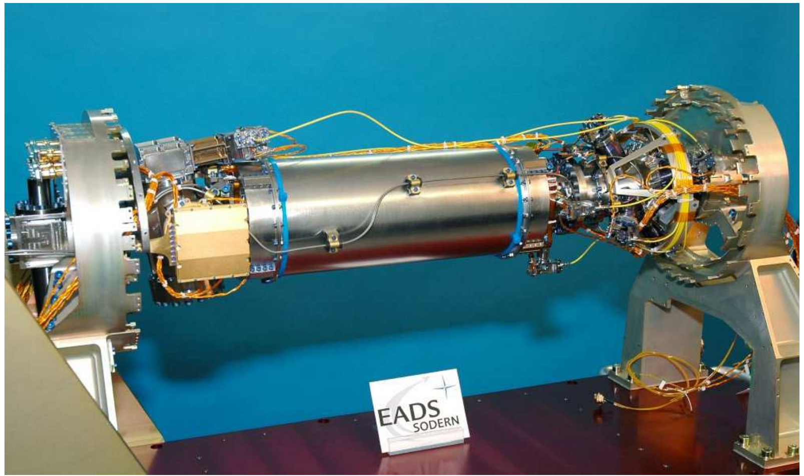
Redshift : 4.59 10^{-11}
With 10^{-16} clock
ACES: ~2 10^{-6}

Cold Atom Clock in μ-gravity : PHARAO/ACES



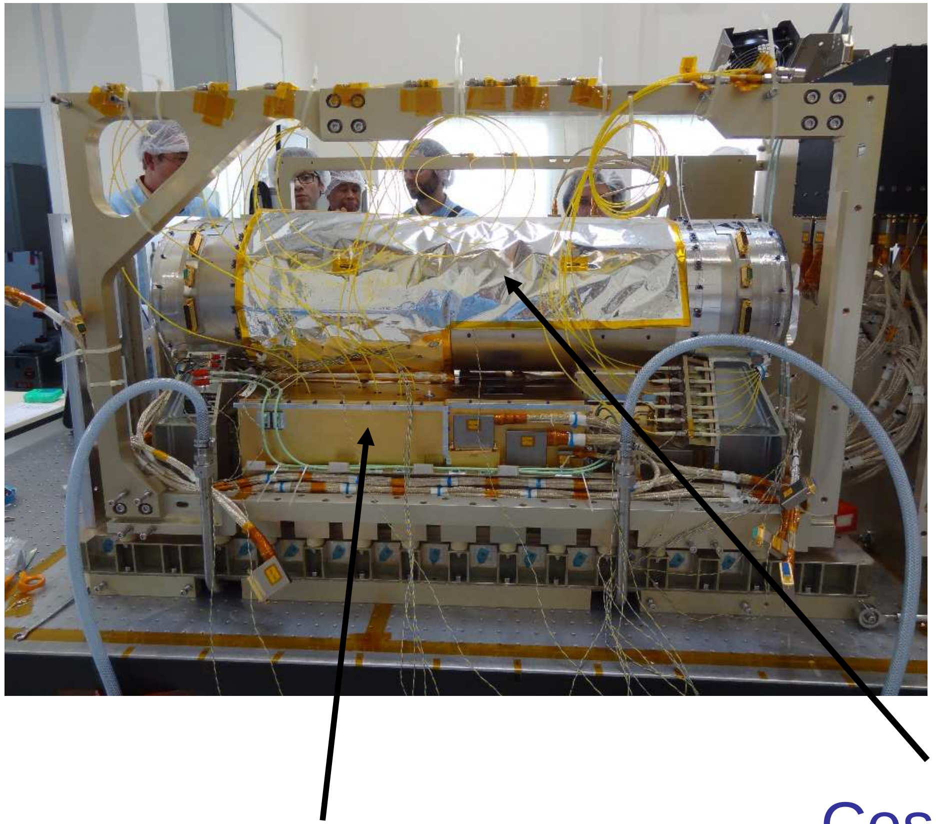


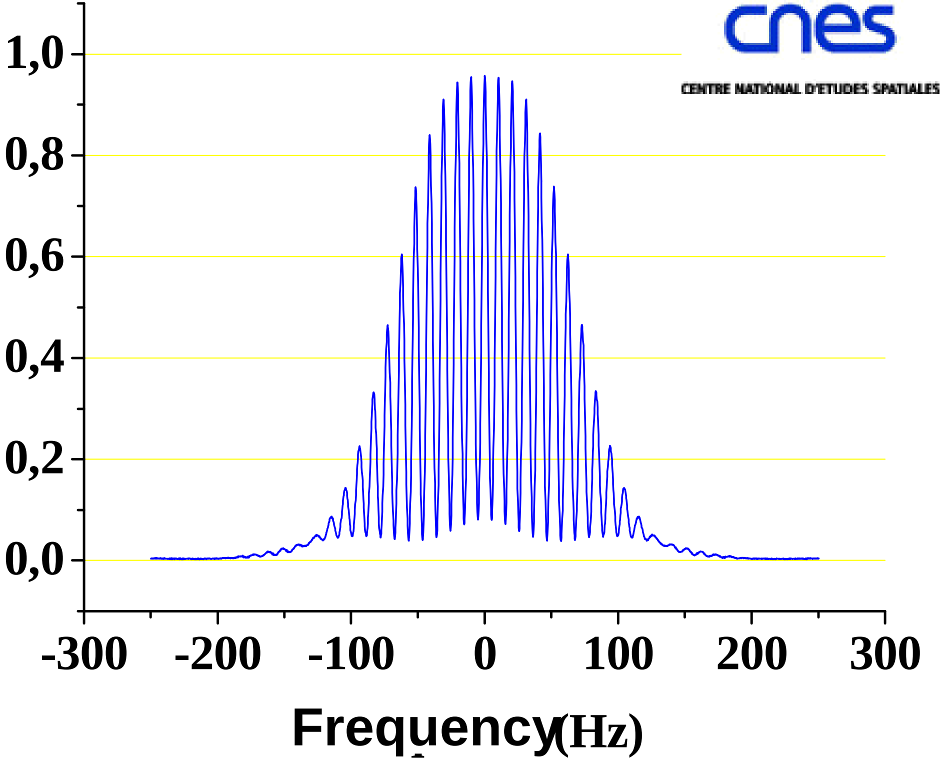
20.054 kg, 36W



Total volume: 990x336x444 mm^3
Mass: 44 kg

PHARAO Space Clock



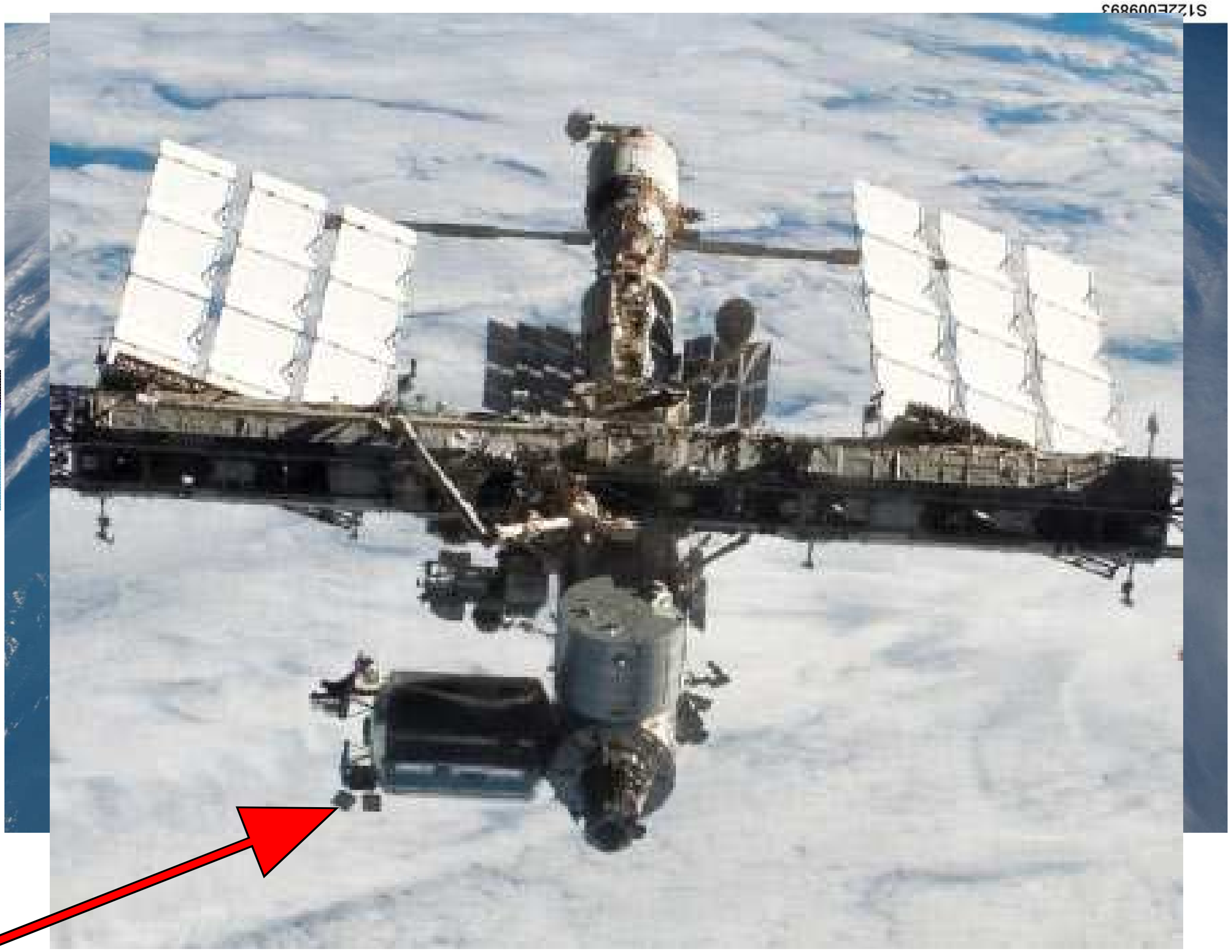


Flight model tests completed in Toulouse

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

Delivery to ESA: June 18, 2014

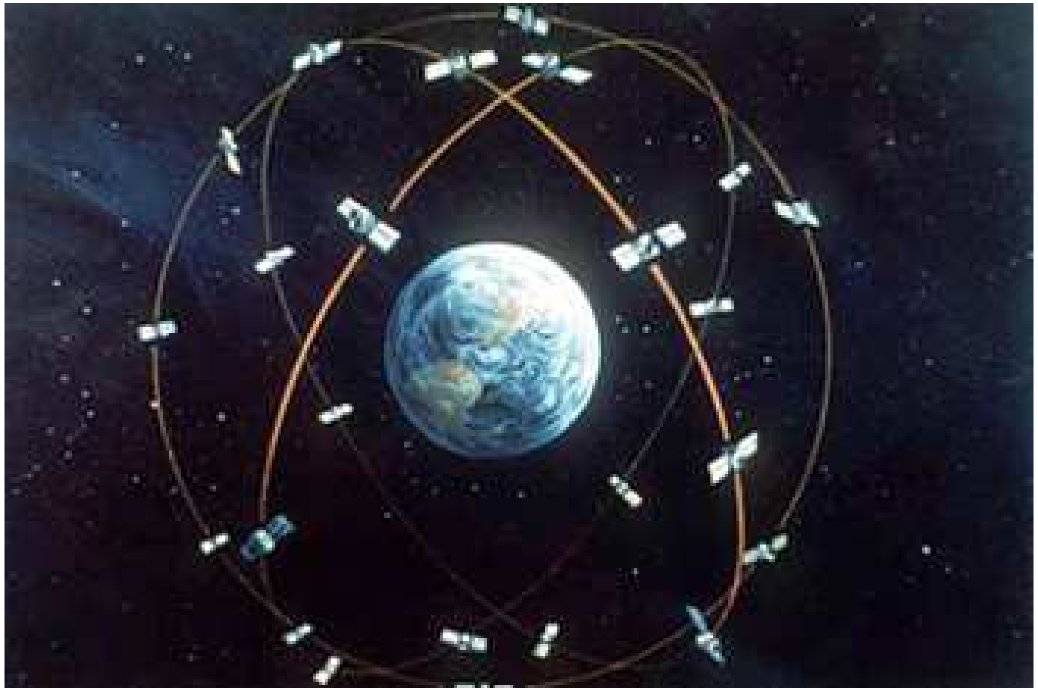
ACES ON COLUMBUS EXTERNAL PLATFORM



Current launch date : May 2016

Mission duration : 18 months to 3 years

Global Positioning System

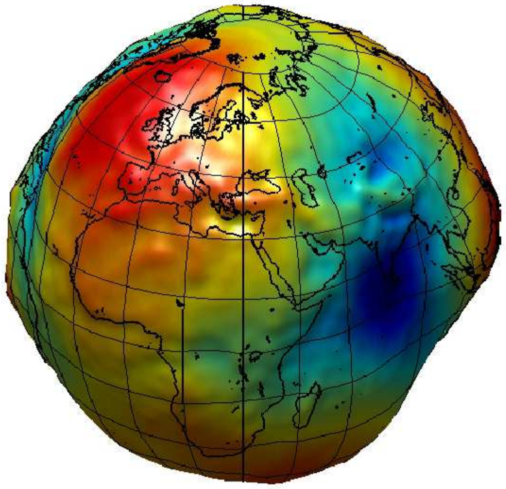


24 satellites
In 20 000 kms orbit
12 hour period

Each satellite transmits a message with:
Time of emission and satellite position at time of emission
Propagation of signal from 4 or more satellites at speed of light provides distances.
Receiver computes its 3 D position (and clock offset) from intersection of 4 spheres.
Precision of a few meters and even centimeters with additional systems

Started in 1973 by US army
Developped into a spectacular open worldwide service
European Galileo system operational before 2020

Relativistic Geodesy



The clock frequency depends on the Earth gravitational potential

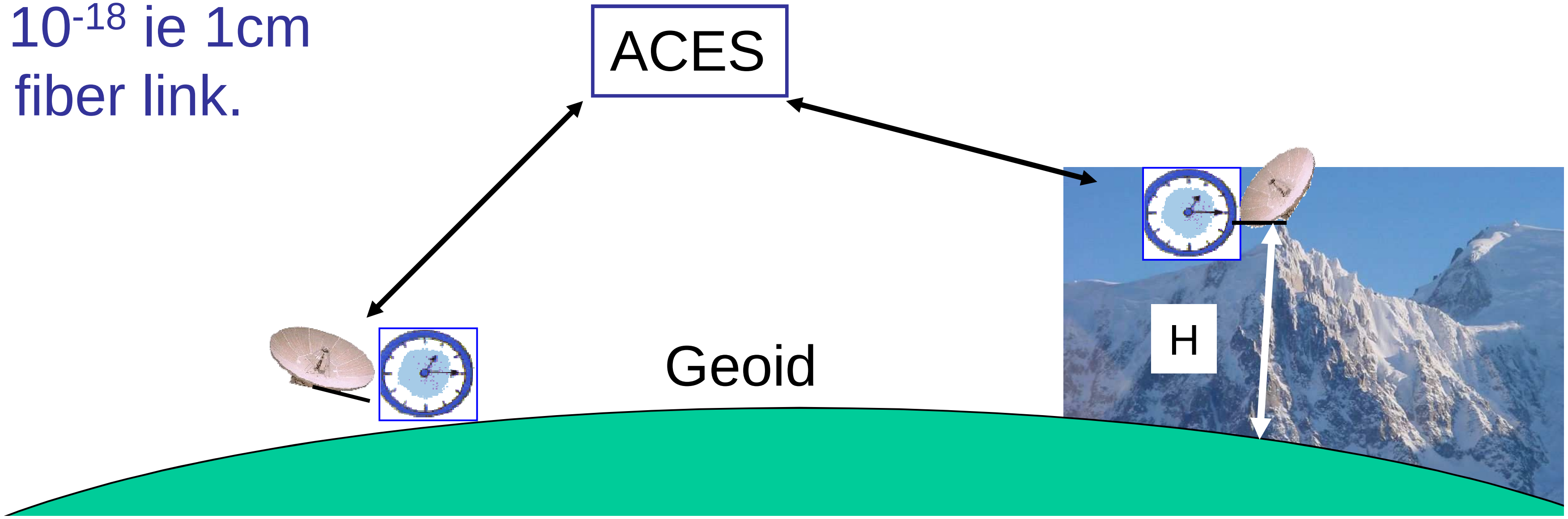
10^{-16} per meter

Best ground clocks have accuracy of 6 10^{-18} and will improve !

Competitive with satellite + levelling techniques at ~ 20 cm level

Applications in Earth Science, Earth ressources monitoring,….

between the two clock locations at 10^{-17} level ie 10 cm and 10^{-18} ie 1cm with fiber link.



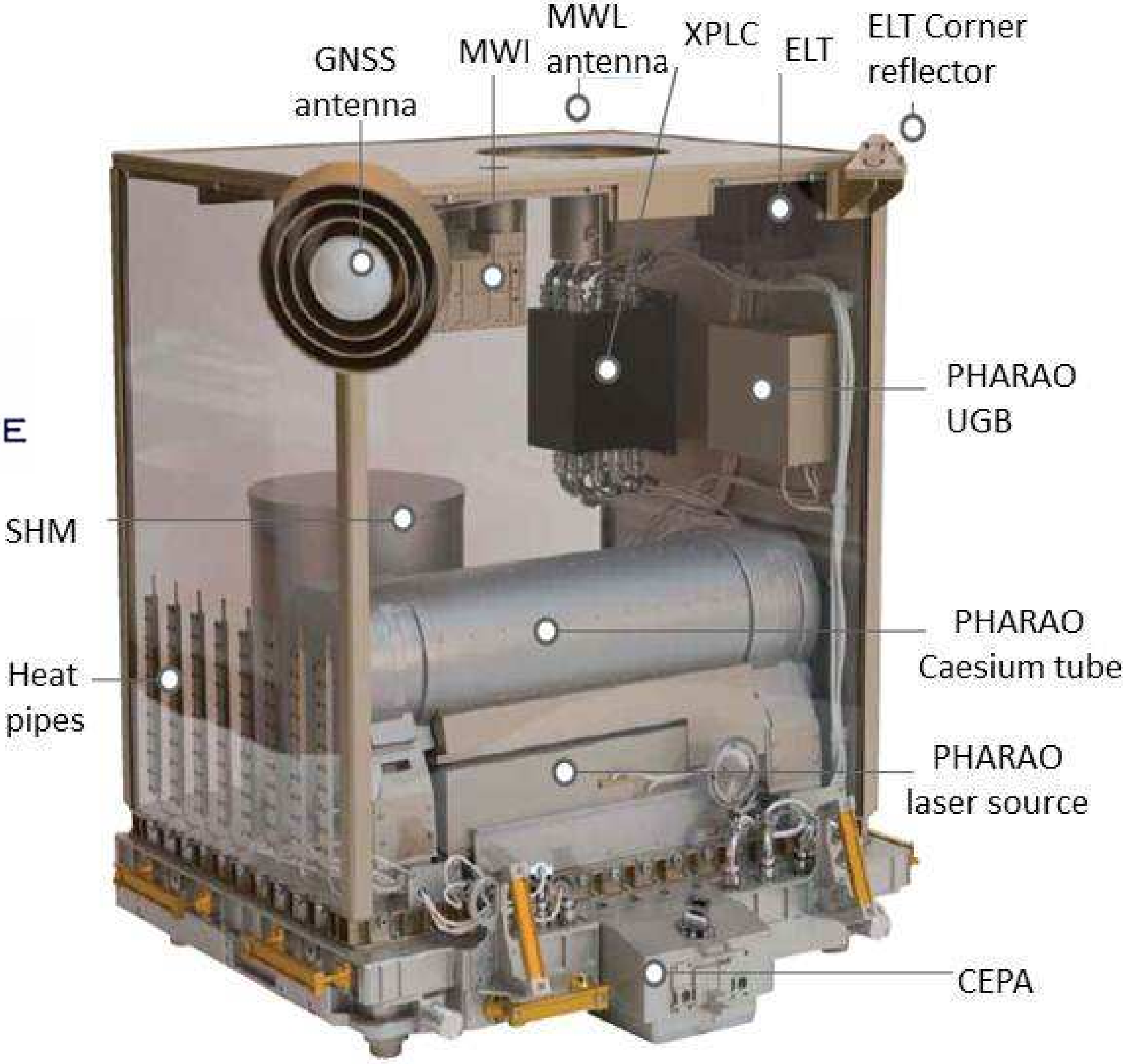
Future Time Definition from Space

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

Towards a space-time reference frame in Earth orbit

ACES General View

Earth ↑



Mass: 227 kg,
Power 450 W

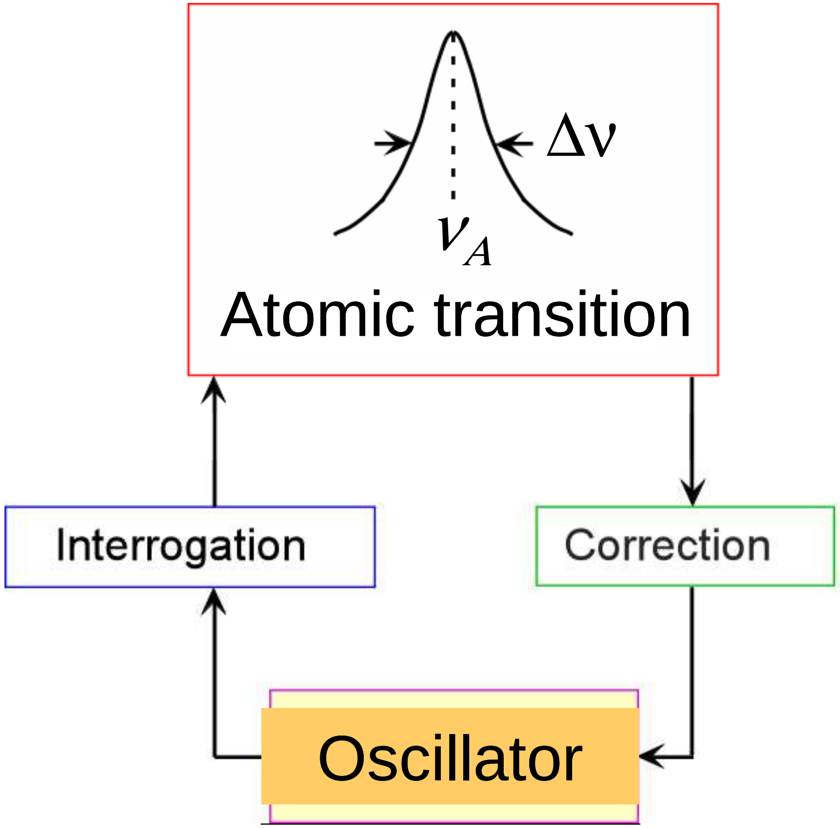
Challenges: thermo-mechanical stability, three year operation

Atomic Clock

An oscillator of frequency ν produces an electromagnetic wave which excites a transition a - b

The transition probability a→b as a function of ν has the shape of a resonance curve centred in $\nu_A = (E_b - E_a) / h$ and of width Δν

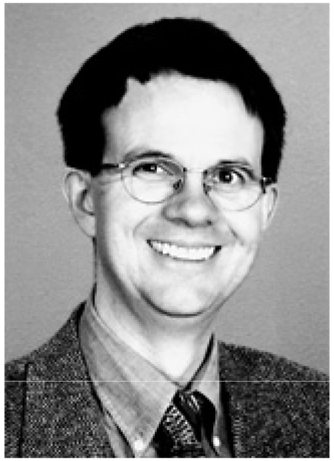
A servo system forces ν to stay equal to the atomic frequency ν_A



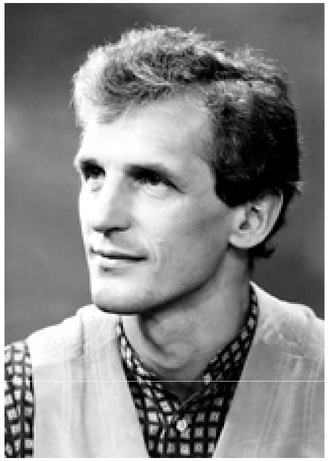
An atomic clock is an oscillator whose frequency is locked to that of an atomic transition

The smaller Δν, the better is the precision of the locked system

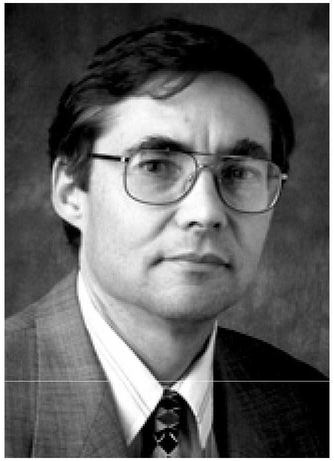
A new frontier: connecting precision measurements and many-body physics



E. Cornell



W. Ketterle



C. Wieman

2001: Bose-Einstein Condensation

Atom-Atom interaction are a limit to sensor precision,
Example: Cesium fountain clocks, Rubidium is much better !

Spin squeezing

Continuous atom lasers ?

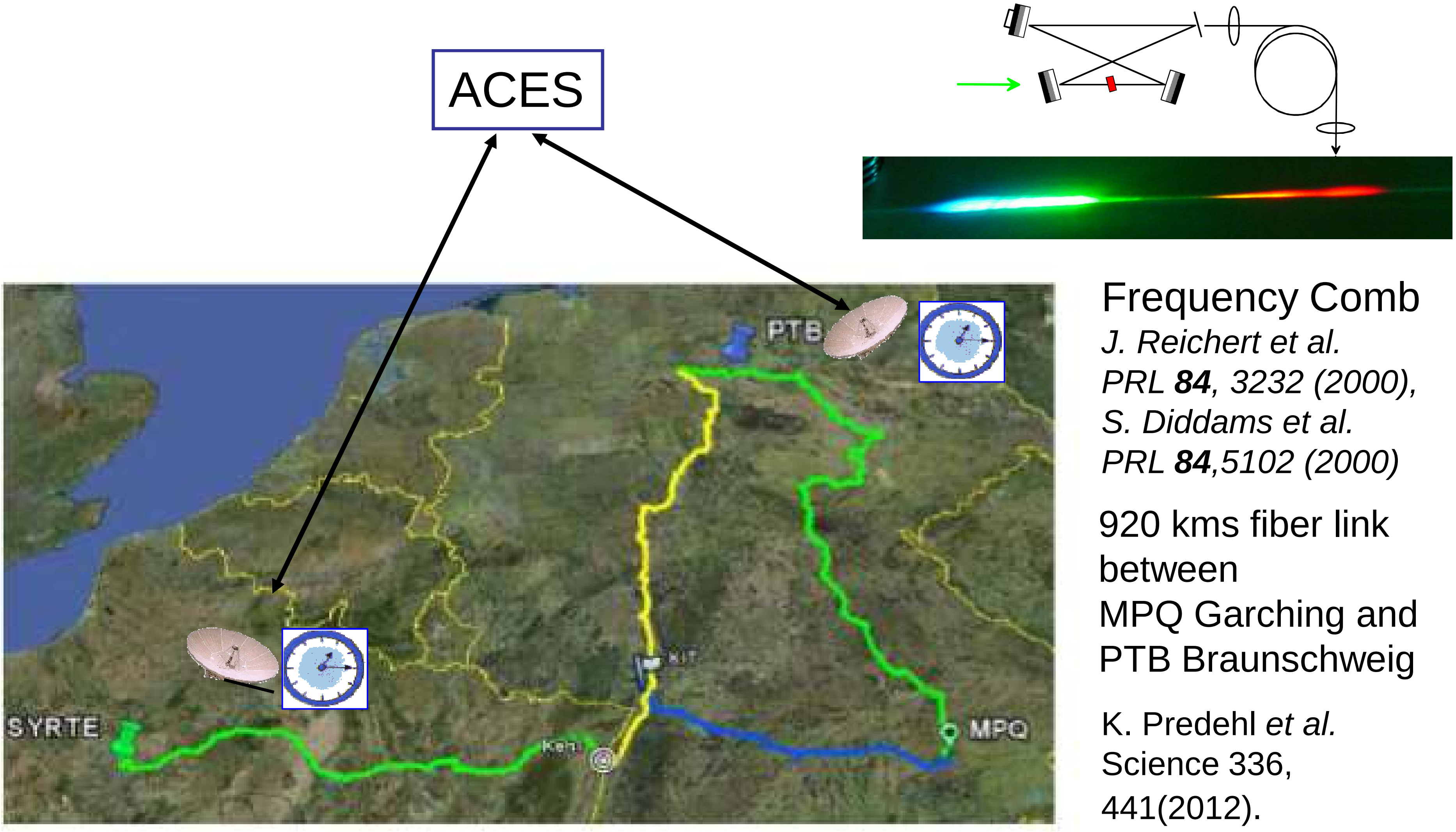
Clock Figure of Merit

- Quality of the clock: $\nu/\Delta\nu \times S/N = 2\,\nu\, T \times S/N$
- Microwave cesium fountain: ~$2\;10^{10}$ x 0.5 x 5000 =$5\;10^{13}$
- Increase clock frequency to optical or UV domain

- Trapped ions: T very long but only one ion in the trap.
- stability: $4\;10^{-15}\;\tau^{-1/2}$
- Accuracy: Al^{+}: $8.6\;10^{-18}$

- Trapped neutral atoms: T long and large numbers: improved stability
- Optical clocks : ~$2\;10^{15}$ x 0.5 x 100= 10^{17}
- Stability: $3.2\;10^{-16}\;\tau^{-1/2}$
- Accuracy: $6\;10^{-18}$, J. Ye et al., 2014
- TOKYO, SYRTE, PTB, JILA, NIST, LENS, INRIM, DÜSSELDORF ….

Validation of the satellite time transfer with continental fiber link



Frequency Comb

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

920 kms fiber link between MPQ Garching and PTB Braunschweig

K. Predehl *et al.*
Science 336,
441(2012).

Discovery of integer quantum Hall effect

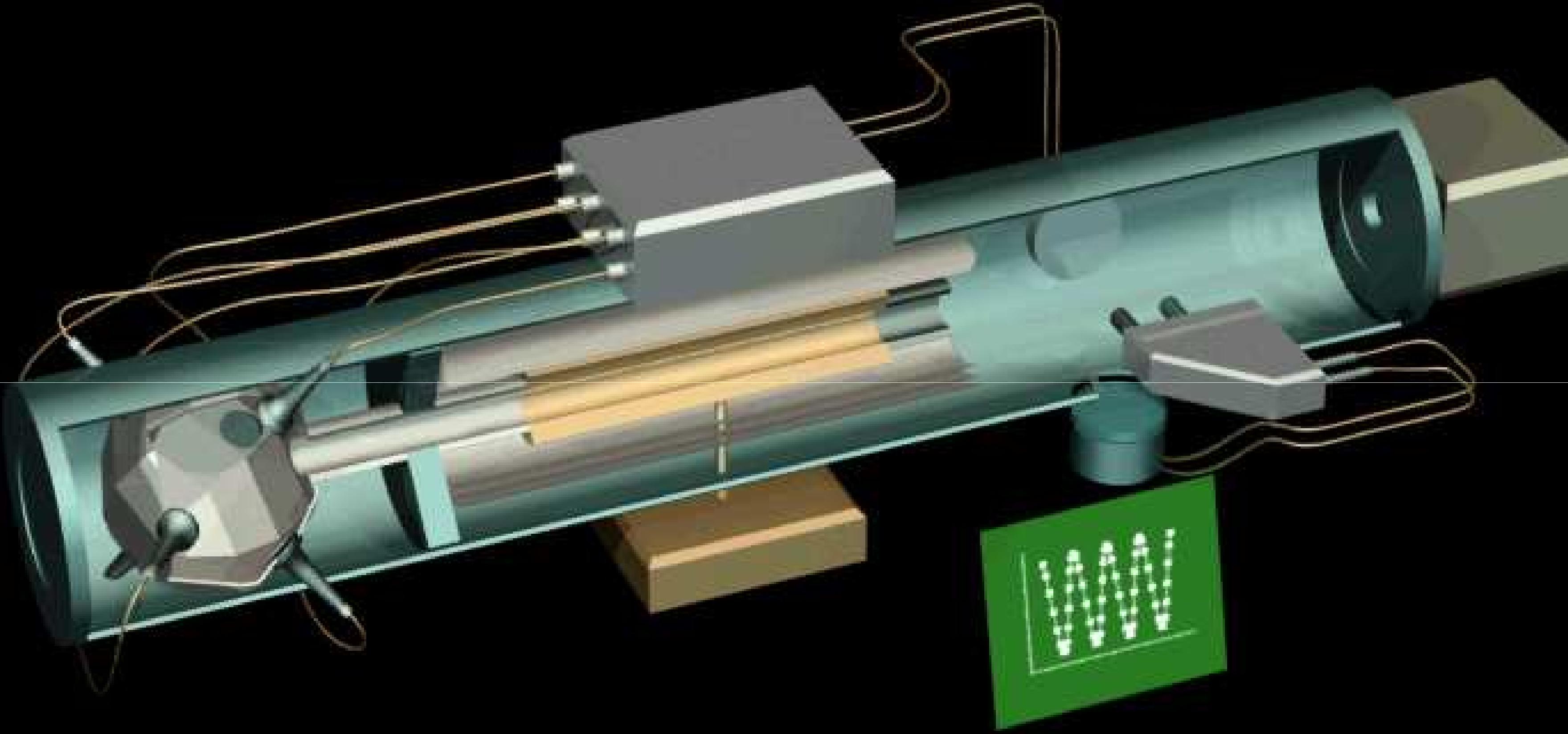
2 dimensional electron gas in a strong magnetic field

Klaus von Klitzing
Nobel laureate 1985

$$R_H = n\, h/e^2$$

$$R_H = \mu_0\, c\, /\, 2\, \alpha\, n$$

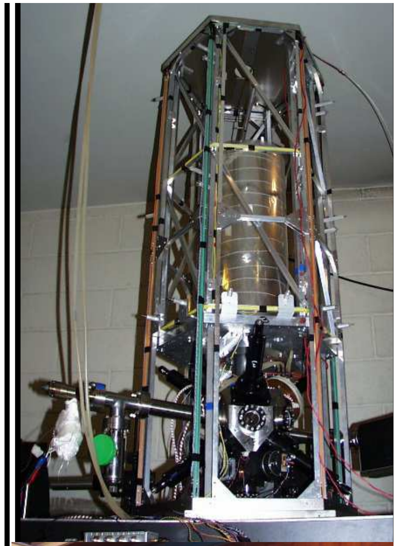
Standard of electrical resistance



Current Network of Ground Institutes

Delivery of first two MWL GT units is planned in second half of 2014

Do fundamental physical constants vary with time ?



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

α_{elm}, m_e/ m_p…

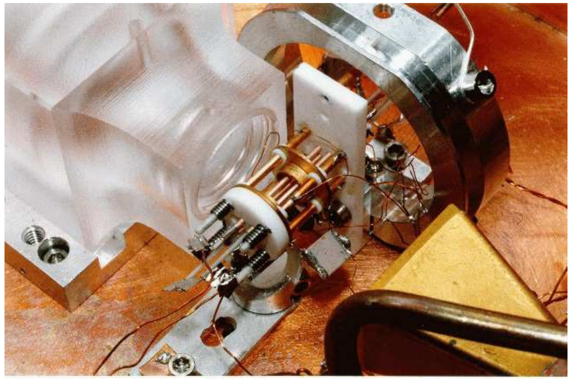
Principle : Compare two or several clocks of different nature as a function of time

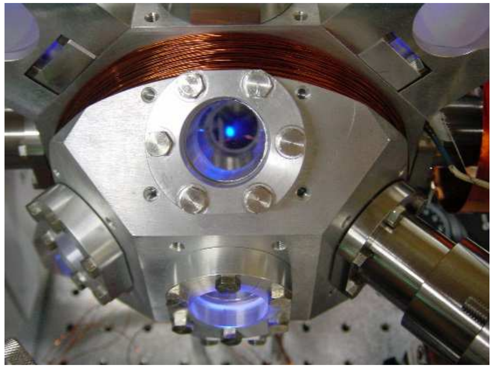
Microwave clock/Microwave clock: α, m_e/m_p, $g^{(i)}$

rubidium and cesium

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

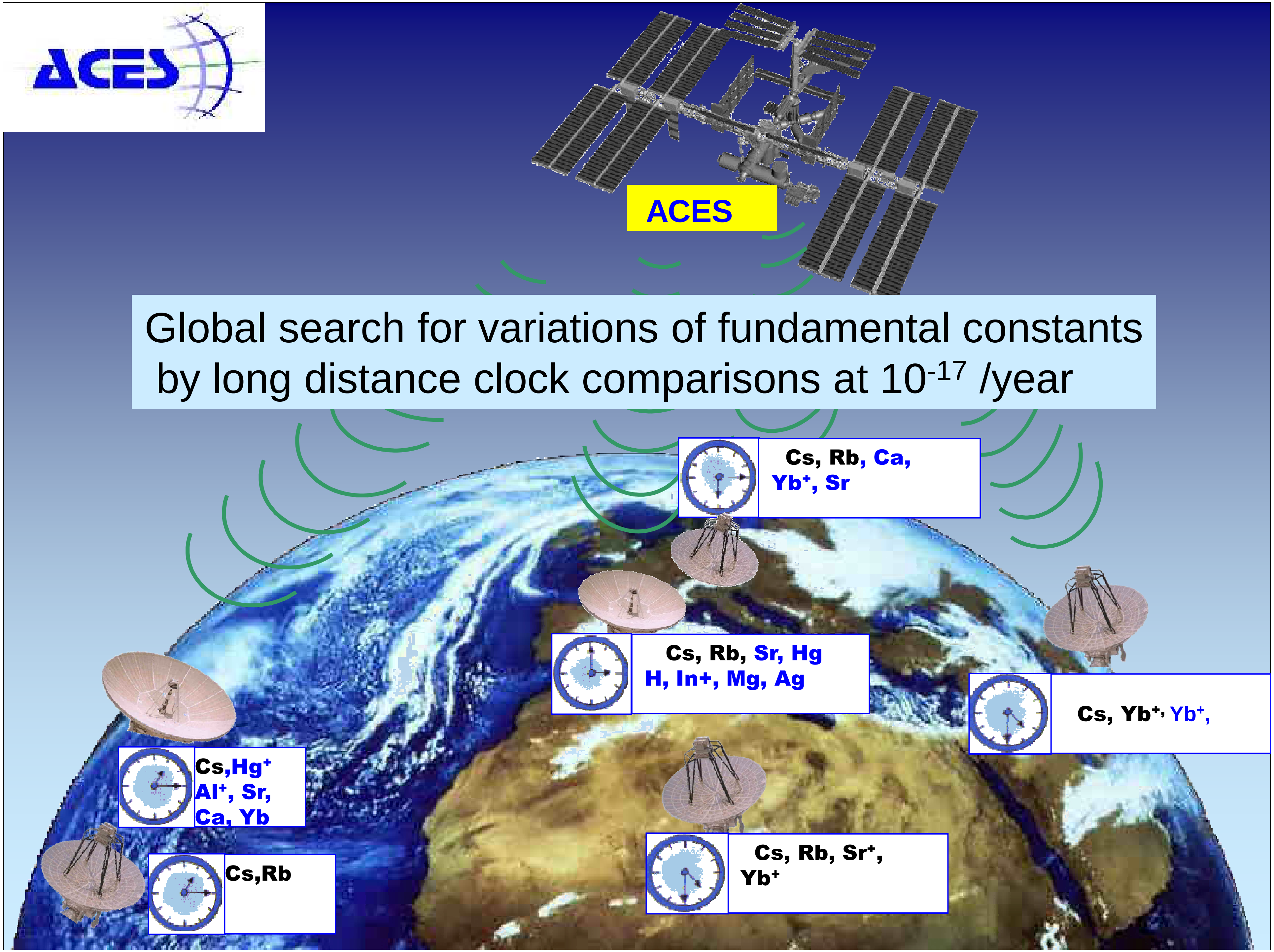
Optical Clock / Optical clock: α





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

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^+

ACES TIME Transfer

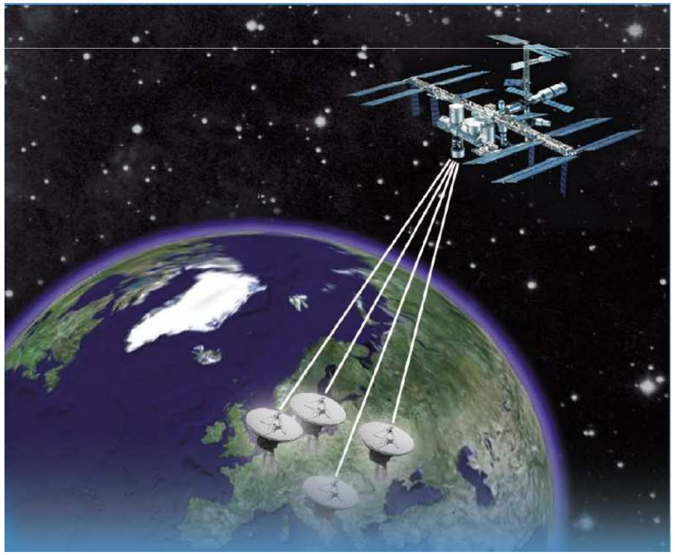
Ultra-stable frequency comparisons on a worldwide basis :

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

Contribution to TAI

Gain: x 20 wrt current GPS

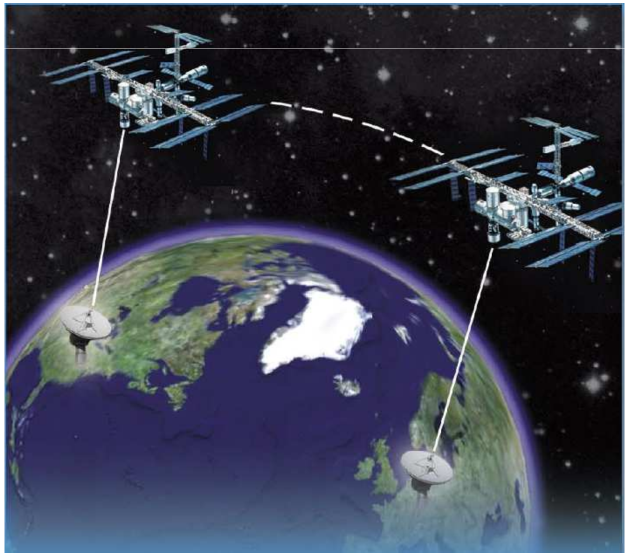
Common view



Error < 0.3ps over 300 s

Can be checked by fiber-link

non common view

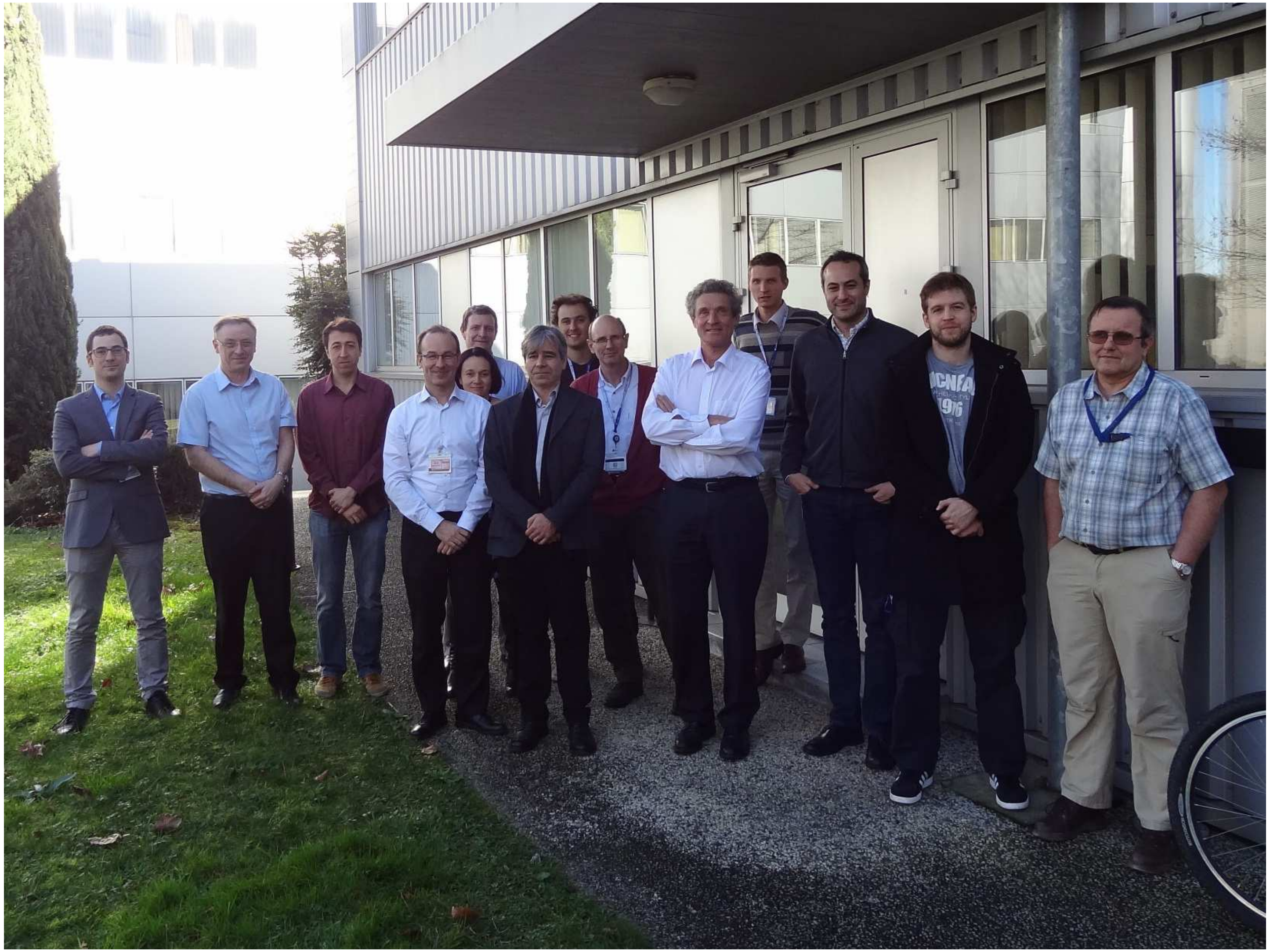


Error < 3ps over 3000 s

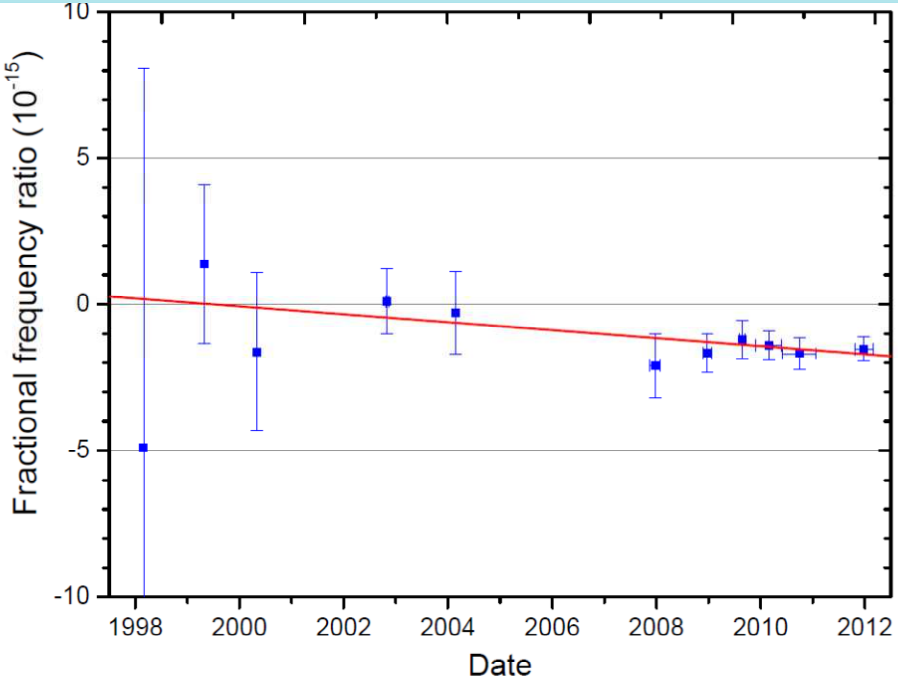
- GPS
- Pulsars
- Klaus Von Klitzing
- Arthur Schawlow

PHARAO Cesium Tube on the Shaker

PHARAO Team in Toulouse



SYRTE Comparison between Rubidium and Cesium Hyperfine Structure over ~15 years



Weighted least square fit to a line

$$\frac{d}{dt}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right)=(-1.36\pm 0.91)\times 10^{-16}\,yr^{-1}$$

- The yearly drift deviates from zero by 1.5 standard deviation: not statistically significant.
- The uncertainty improves by a factor of 7.7 over last report [PRL 90,150801 (2003).

J. Guéna et al., Phys. Rev.Lett.109 (2012)

- With QED calculations: *J. Prestage, et al., PRL (1995), V. Dzuba, et al., PRA (1999)*

$$\frac{d}{dt}\ln\left(\frac{g_{Rb}}{g_{Cs}}\alpha^{-0.49}\right)=(-1.36\pm 0.91)\times 10^{-16}\,yr^{-1}$$

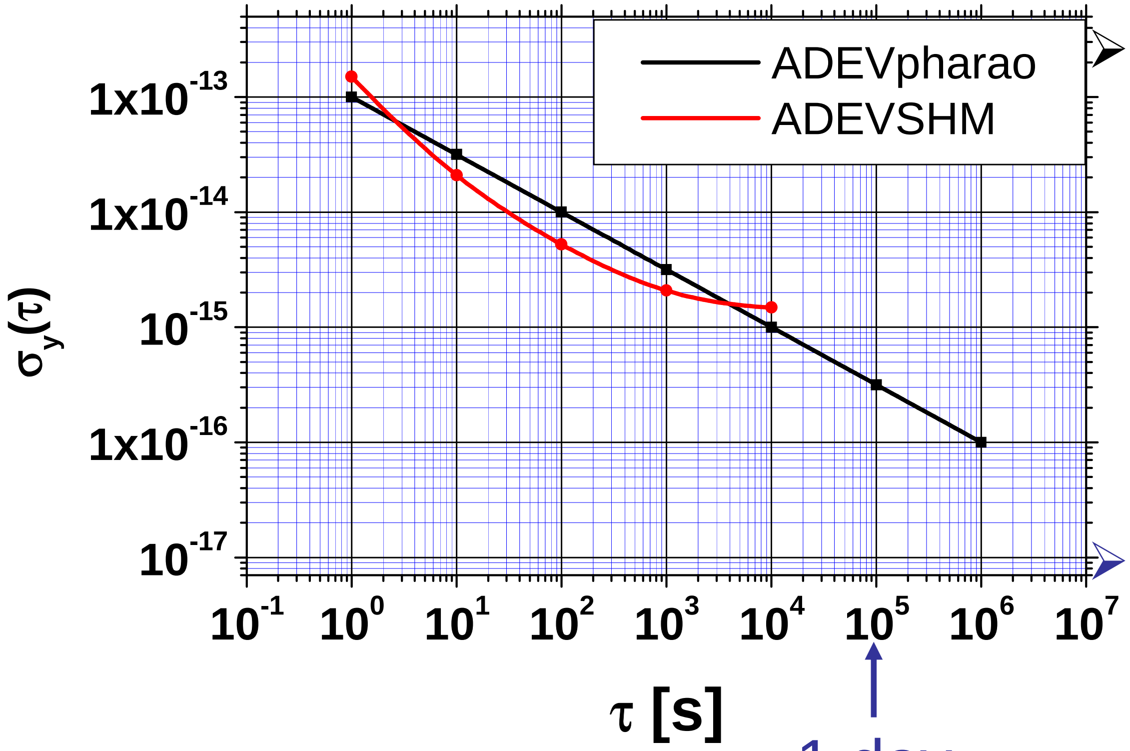
‘ NIST’08 T. Rosenband et al., Science Express, 2008

Al^{+} -Hg^{+} optical frequency comparison over 18 months:

$d\alpha/\alpha dt = (-1.6+-2.4)\times 10^{-17}$/year

Frequency stability of ACES Clocks

Allan deviation of the 2 clocks:



1 day

Stability at one day: 3 10^{-16}

at 10 days: 1 10^{-16}

- Stability of SHM in time intervals of 3 to 3000 s, well adapted to:
  - ISS single pass (duration: 200-400 s)
  - evaluation and optimization of PHARAO
- ACES: slow servo of SHM onto PHARAO

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

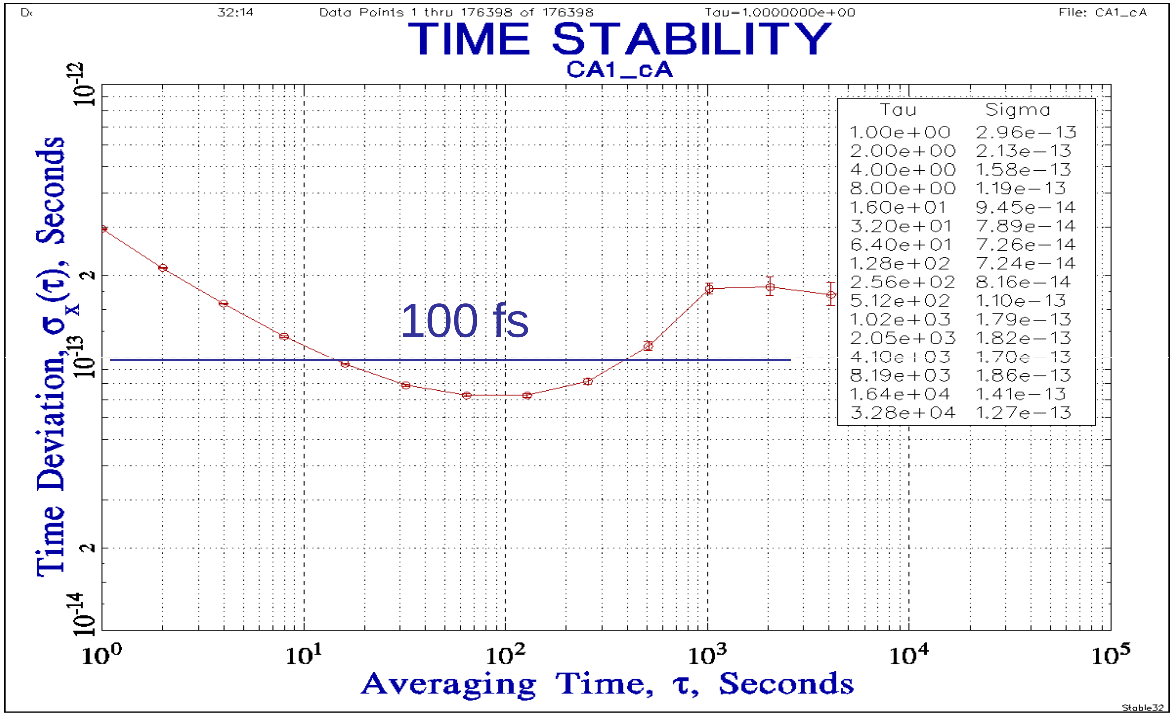
Comparisons between distant clocks at 10^{-17}
Large improvements on relativity tests
Stringent limits for variations of α, g_p, M_e / M_p

Proposed ACES mission follow-on with microwave/optical clocks:

STE-QUEST, SOC on ISS, SAGAS,..

ACES Time Transfer

The microwave link ground terminal



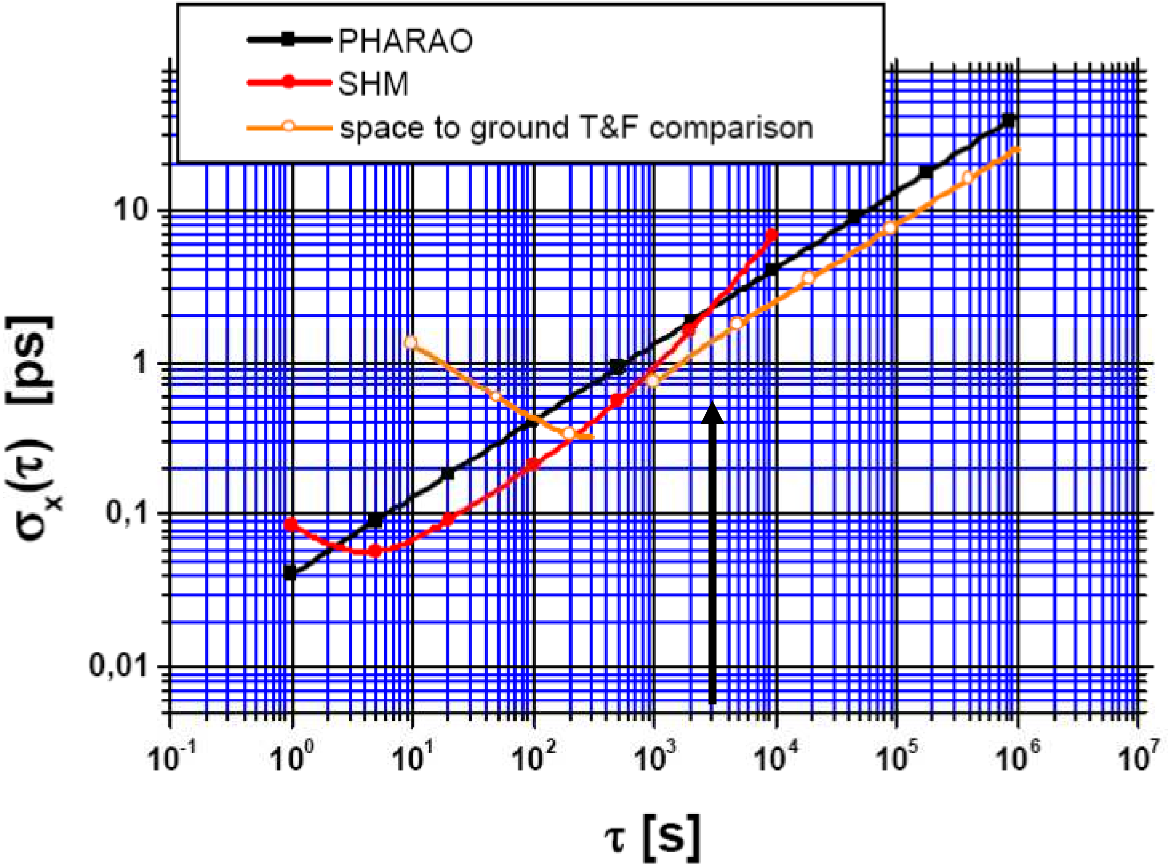
Tau	Sigma
1.00e+00	2.96e−13
2.00e+00	2.13e−13
4.00e+00	1.58e−13
8.00e+00	1.19e−13
1.60e+01	9.45e−14
3.20e+01	7.89e−14
6.40e+01	7.26e−14
1.28e+02	7.24e−14
2.56e+02	8.16e−14
5.12e+02	1.10e−13
1.02e+03	1.79e−13
2.05e+03	1.82e−13
4.10e+03	1.70e−13
8.19e+03	1.86e−13
1.64e+04	1.41e−13
3.28e+04	1.27e−13

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

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

MWL End to End tests are ongoing

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

PHARAO Frequency Stability and Accuracy

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

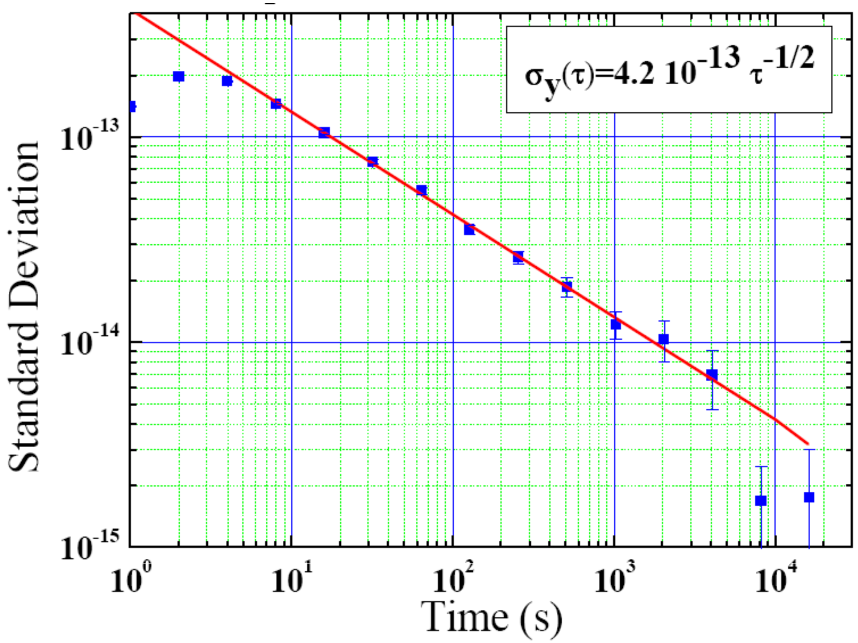
With ultra-stable Quartz
Limited by gravity !

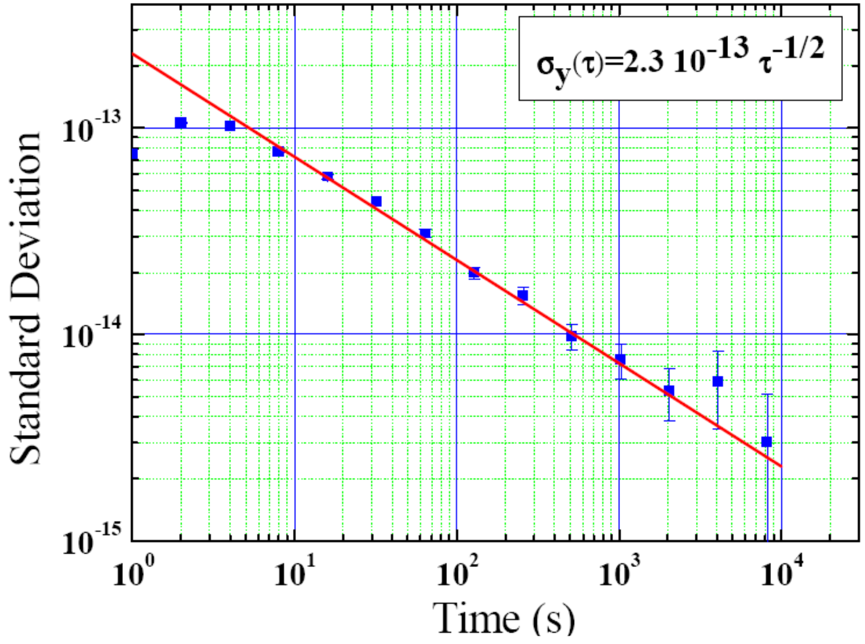
$$\sigma_y(\tau) = 2.5\ 10^{-13}\ \tau^{-1/2}$$

With Cryo. Oscillator

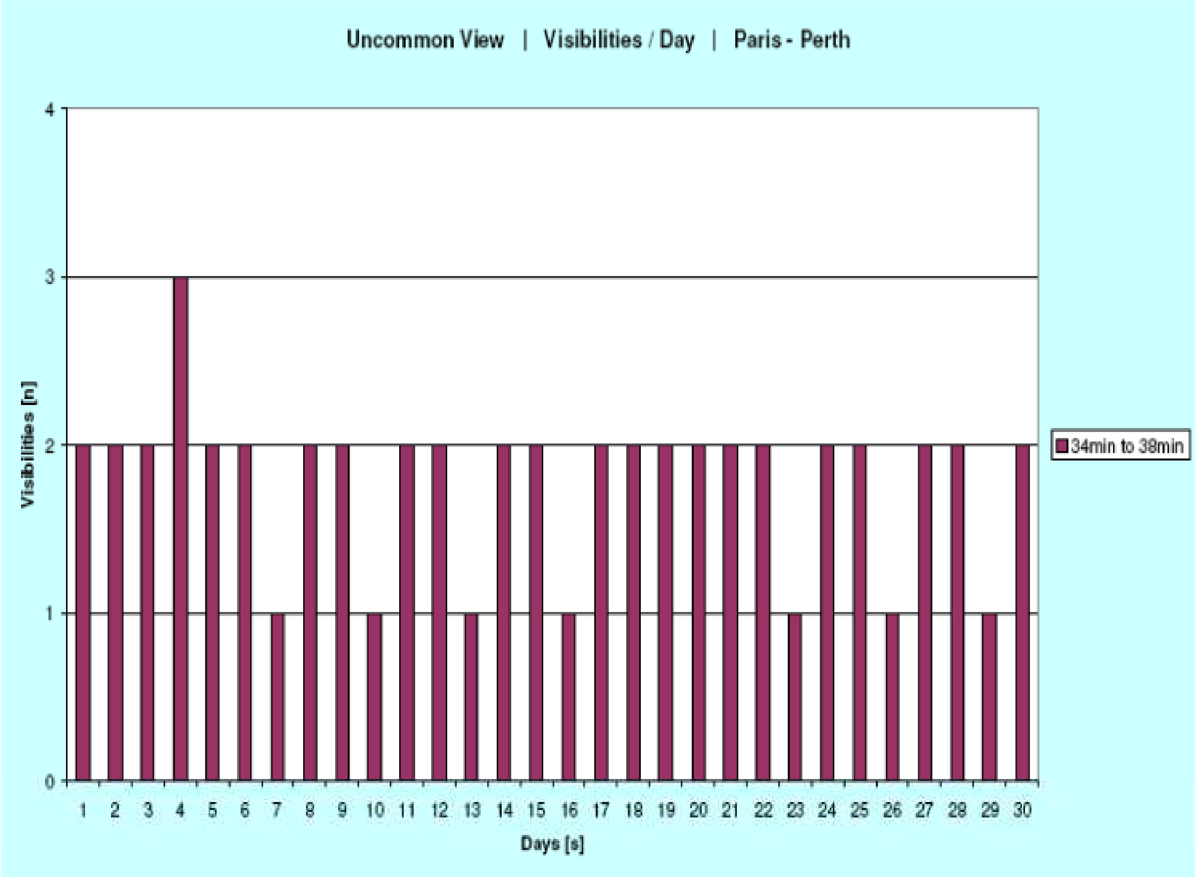
Will enable 7 10^{-14} $\tau^{-1/2}$
in space

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





Non Common View: Paris - Perth



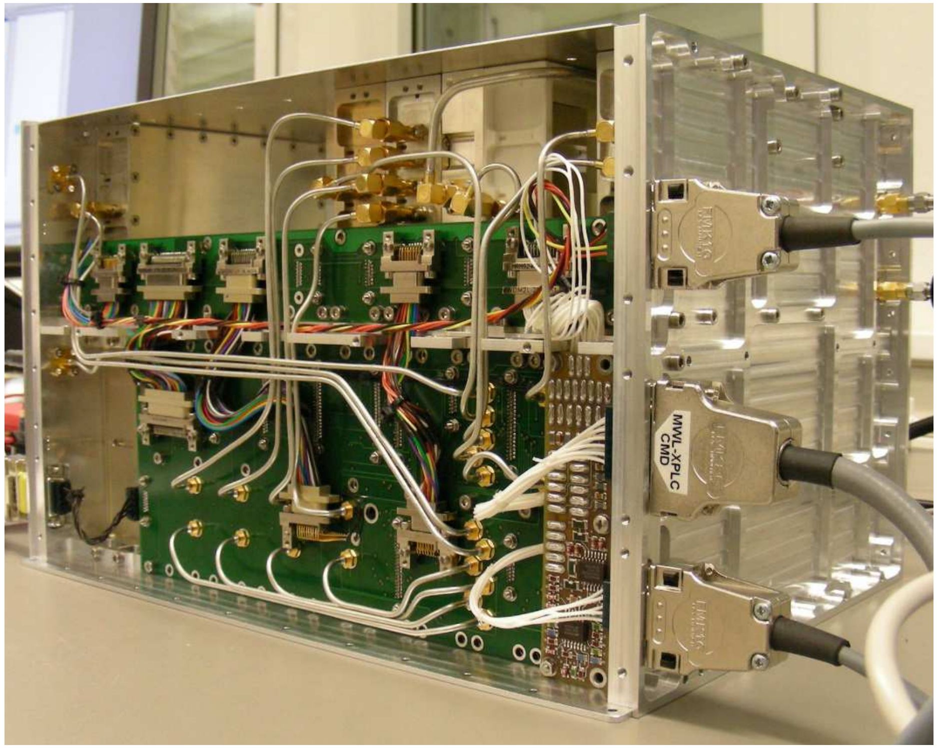
Most distant stations: Paris-Perth

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

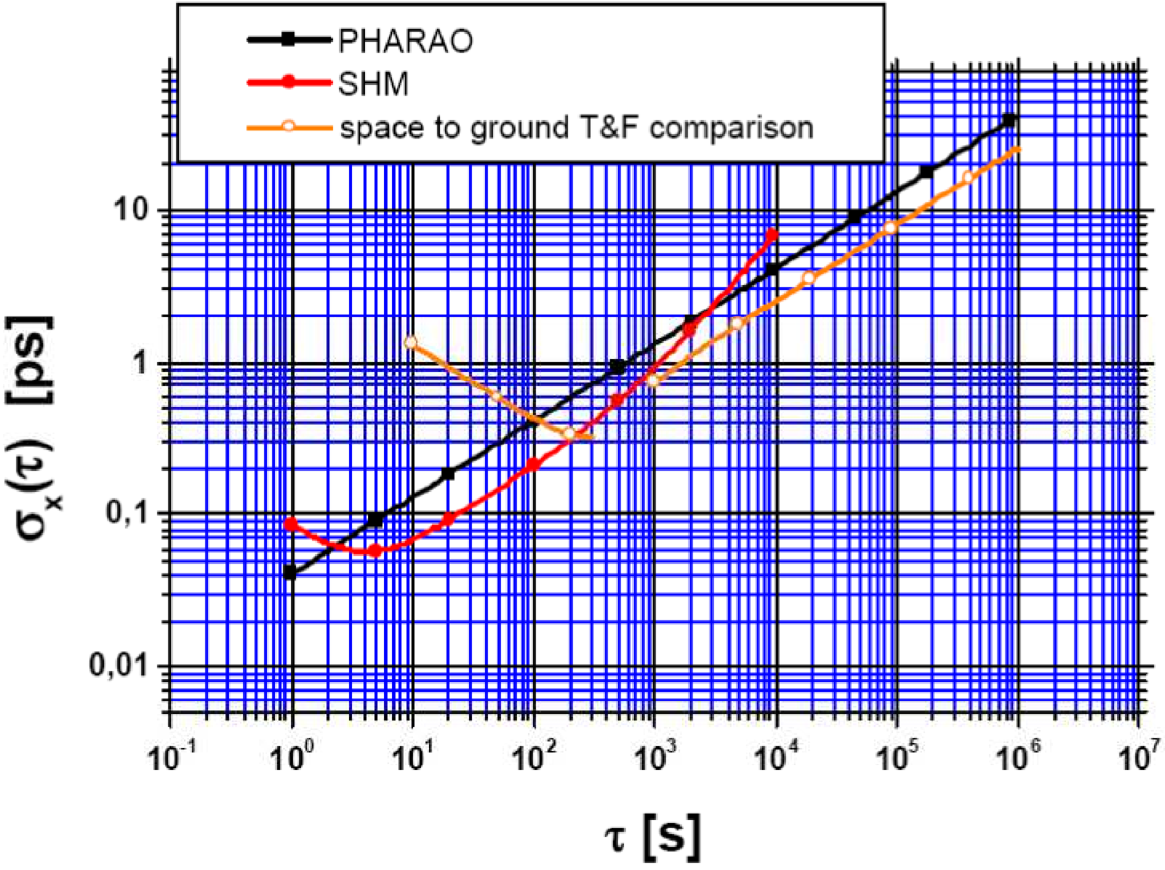


Onboard receiver

TimeTech and EADS

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.



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

Proposal for detection of gravitational waves

→ Precision redshift measurement

→ Variability of fundamental constants

3) Quantum sensors have societal applications

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