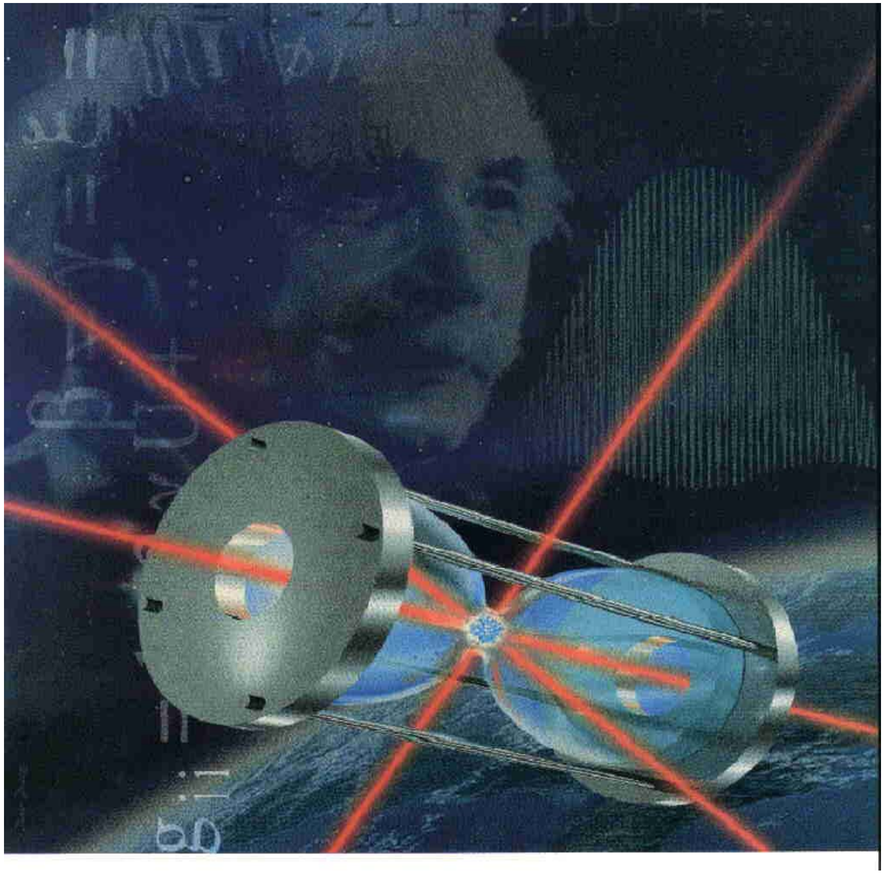
La Mesure du Temps au $21^{\text{ième}}$ Siècle

Recherche sur les Atomes Froids
Institut Francilien de
IFRAF



LETTRES SCIENCES
ECOLE NORMALE SUPERIEURE

cnrs

Séminaire Poincaré XV
IHP, Paris

C. Salomon

December 4, 2010

Laboratoire Kastler Brossel
Physique quantique et applications

Ecole Normale Supérieure, Paris, France

Participants

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S. Léon, D. Massonnet and 15 engineers at CNES
L. Blanchet, C. Bordé
C. Cohen-Tannoudji, S. Reynaud, C. Salomon

Summary

1) Atomic clocks

    Frequency stability

    Accuracy

    Pulsar Time

2) Fundamental tests

    Search for drift of fundamental constants

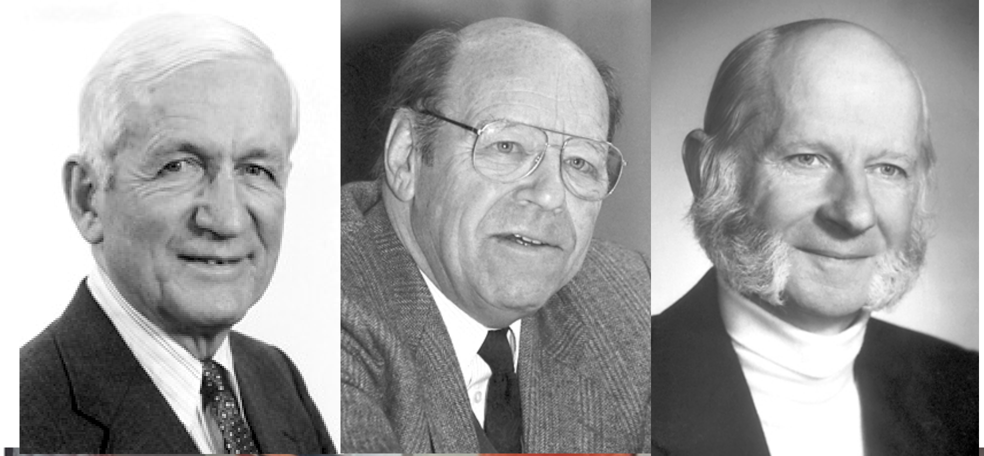
    Precision redshift measurement

3) Perspectives

    Space clocks, PHARAO/ACES

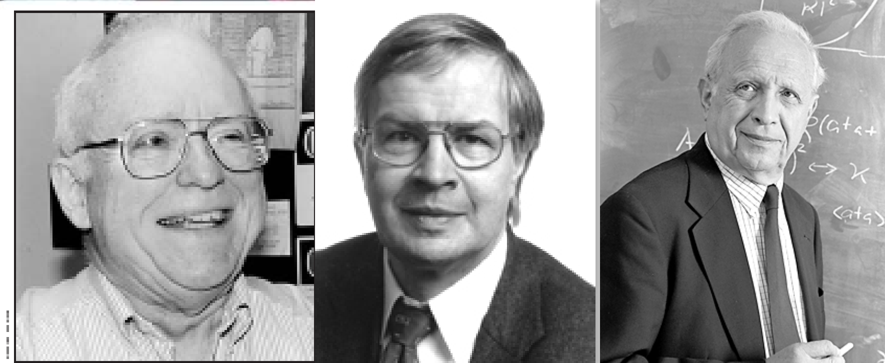
1989 Nobel Prize in Physics
N. Ramsey, H. Dehmelt, W. Paul

separated oscillatory fields method
for atomic clocks, ion trap techniques



1997 Nobel prize in physics
S. Chu, C. Cohen-Tannoudji, W. Phillips
Laser manipulation of atoms

2005 Nobel prize in physics
J. Hall, T. Haensch, R. Glauber
Laser precision spectroscopy
Optical frequency comb
Quantum optics



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

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

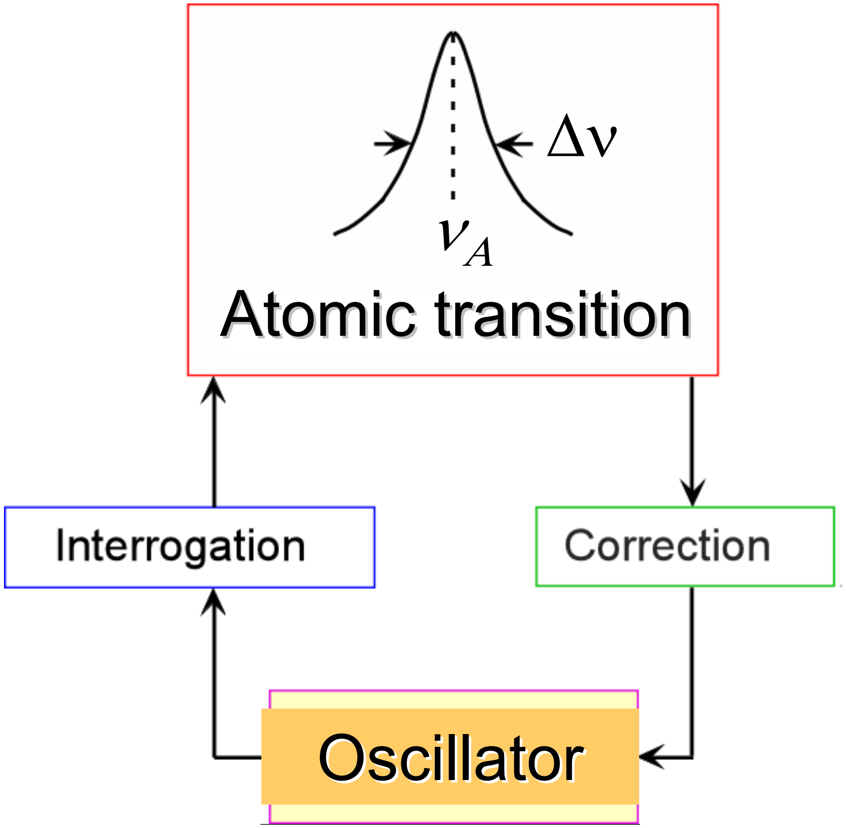
3) Modern clocks use electromagnetic signals locked to atomic lines

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 $\Delta\nu$

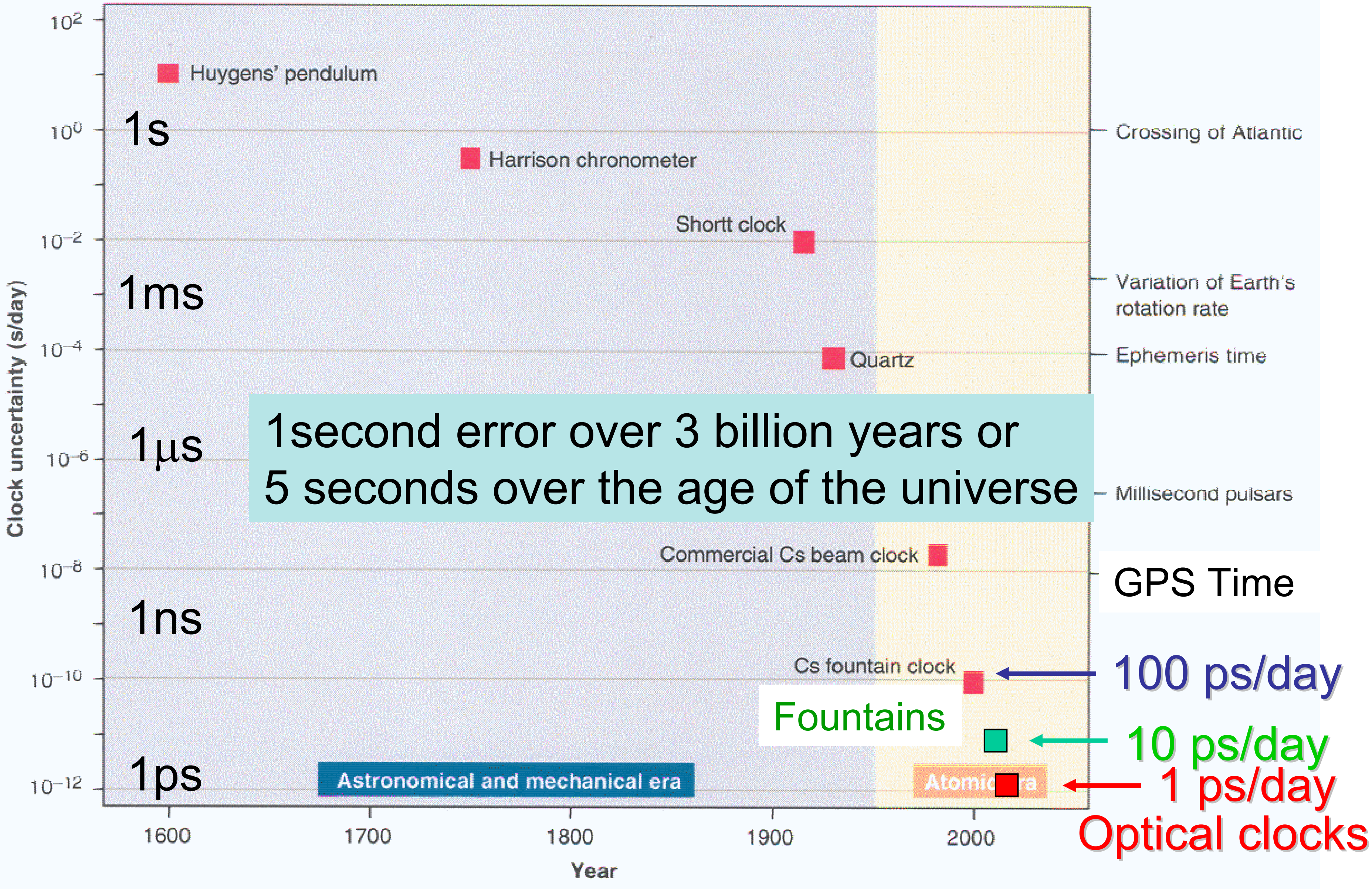
A servo system forces ν to stay equal to the atomic frequency ν_A



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

The smaller $\Delta\nu$, the better is the precision of the locked system

Precision of Time



1s

1ms

1μs

1ns

1ps

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

GPS Time

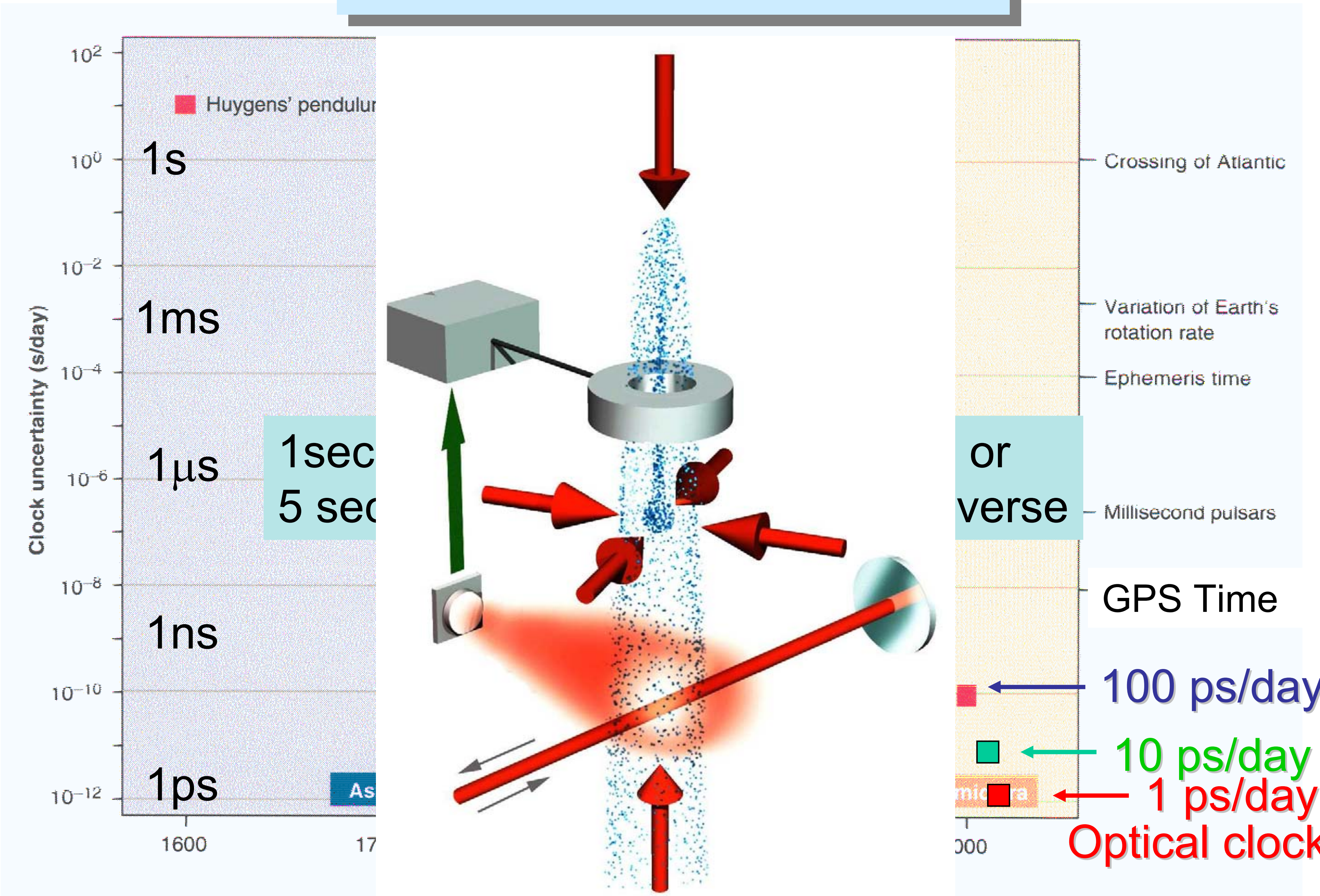
100 ps/day

Fountains

10 ps/day

1 ps/day
Optical clocks

Precision of Time



1s

1ms

1µs

1ns

1ps

1sec
5 sec

or
verse

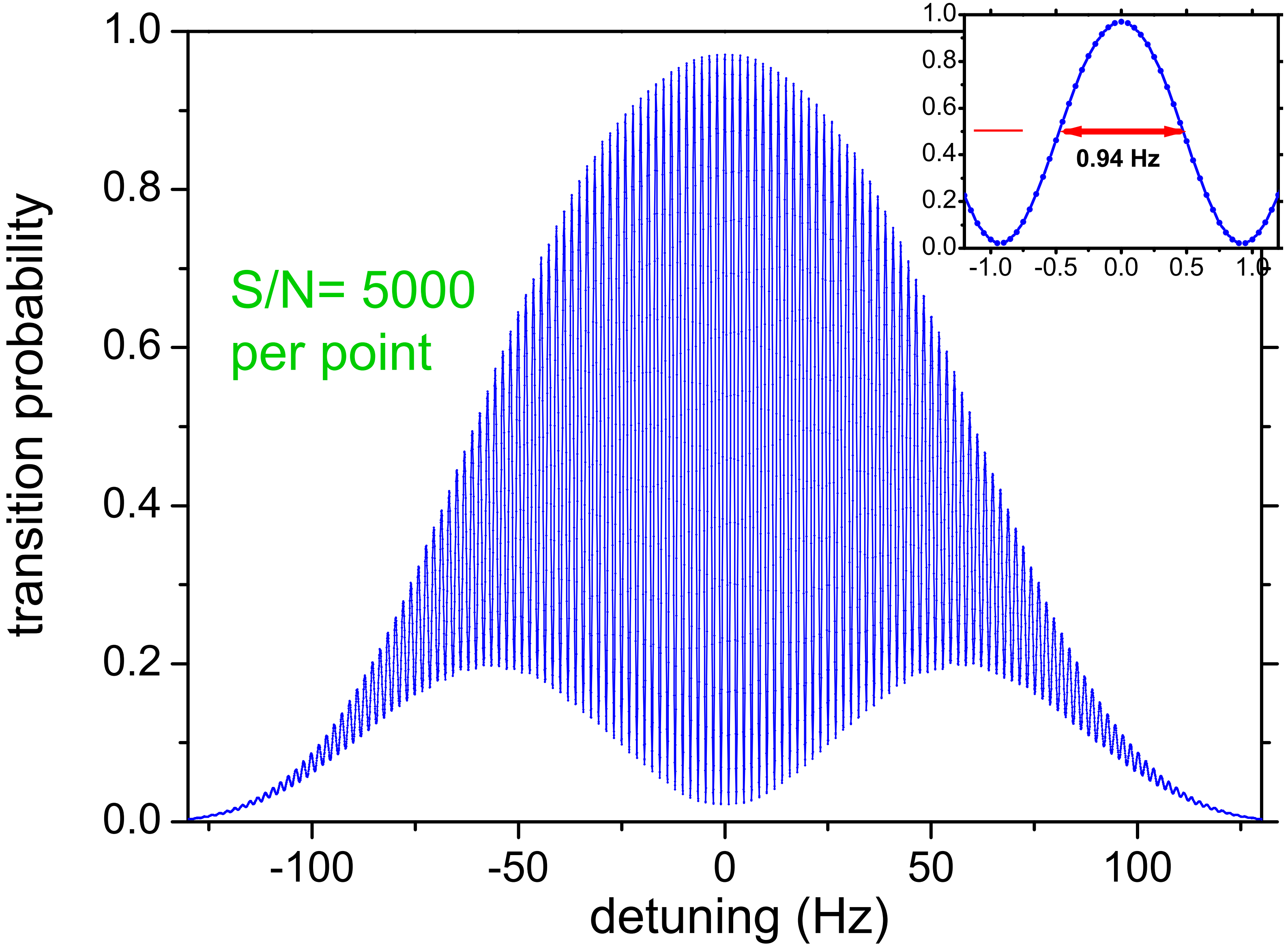
GPS Time

100 ps/day

10 ps/day

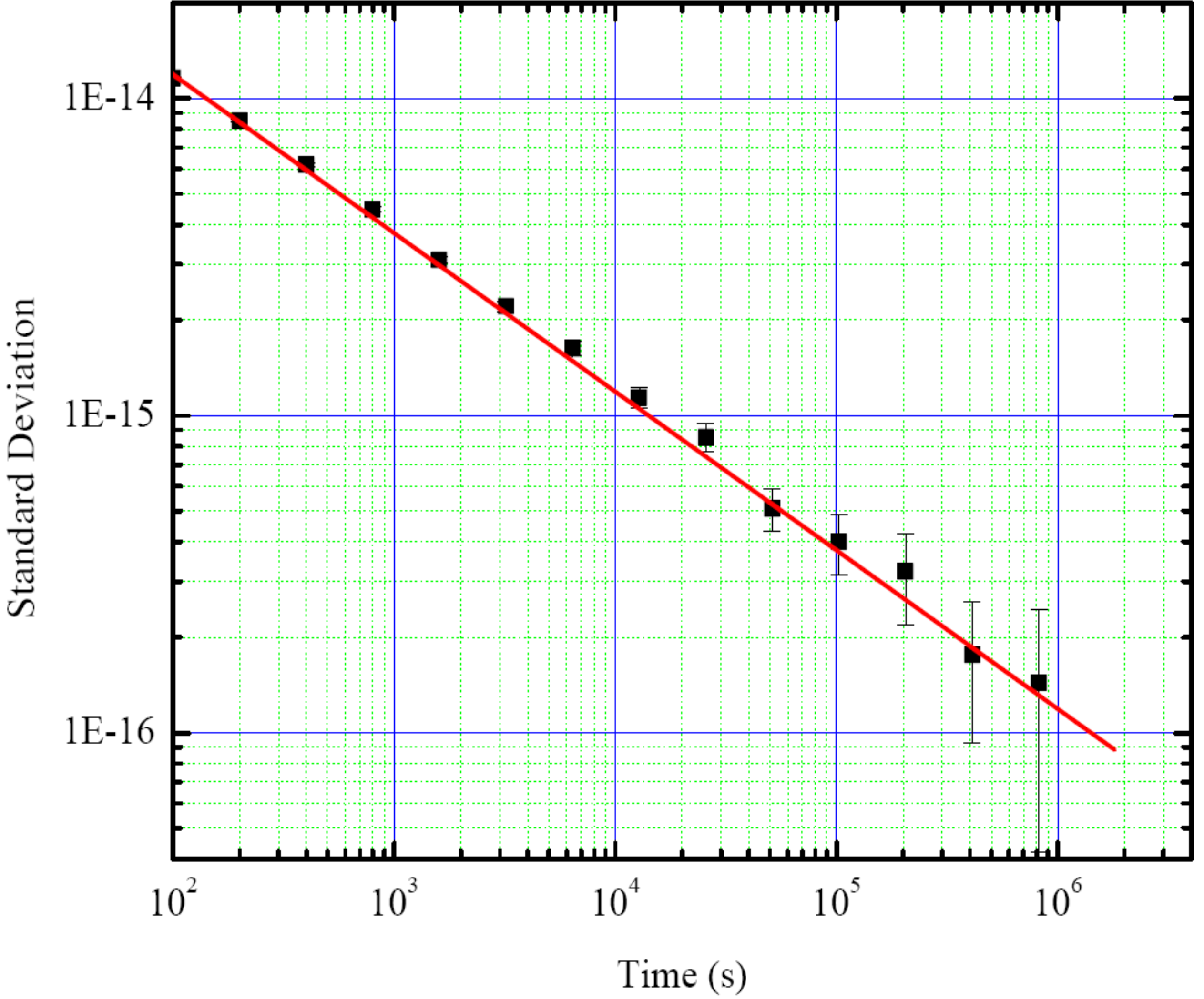
1 ps/day
Optical clocks

Ramsey fringes in atomic fountain



S/N= 5000
per point

Comparison between two Fountains FOM and FO2 (Paris Observatory)

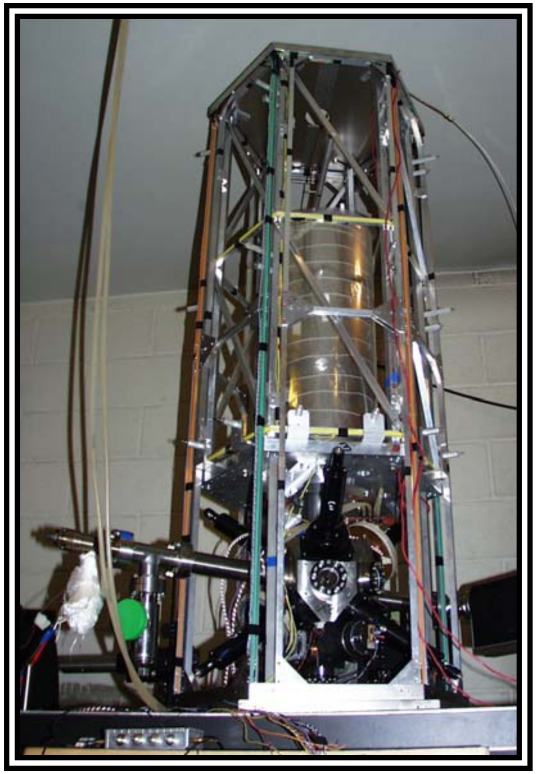


S. Bize
et al.
EFTF’08
J. Phys. B 2005
SYRTE

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

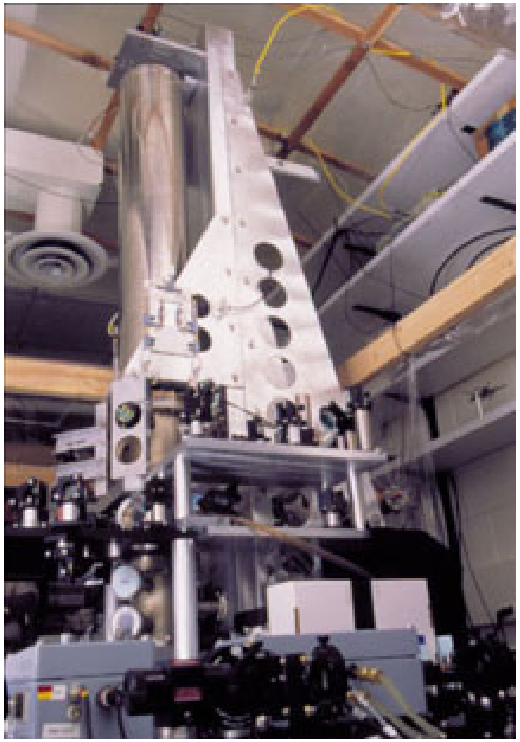
Atomic Fountains

15 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, IEN, NPL, Neuchatel, JPL, NIM, Sao Carlos,…. 10 with accuracy at or below 1 10^{-15} .



LNE-SYRTE, FR

PTB, D



NIST, USA

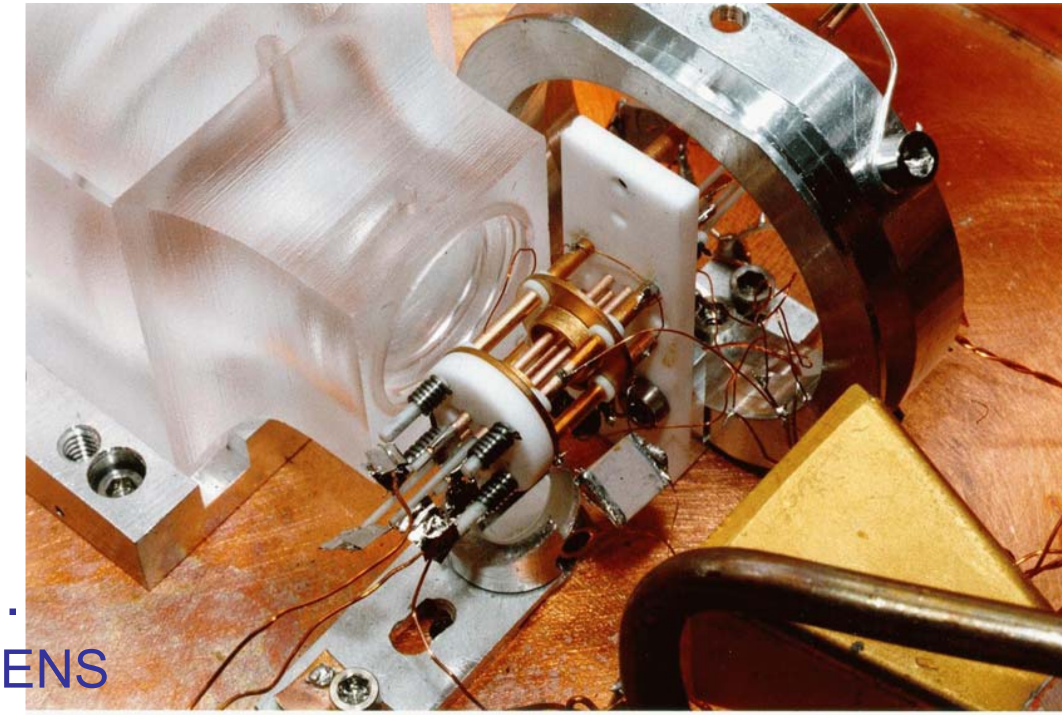
Optical Clocks
Trapped Ions and Neutral Atoms

- Quality of the clock: $\nu/\Delta\nu \times S/N = 2\,\nu\,T \times S/N$
- Increase the frequency, increase T, increase S/N
- Trapped ions : T very long but only one ion in the trap.
- Neutral atoms: T long and large numbers: improved stability

NIST : Bergquist, Rosenband, Wineland et al.

- Hg^+:optical transition
- stability: 4 $10^{-15}\ \tau^{-1/2}$
- Accuracy: 1.9 10^{-17}
- Al^+: 8.6 10^{-18}

A factor of 30 beyond the cesium accuracy !

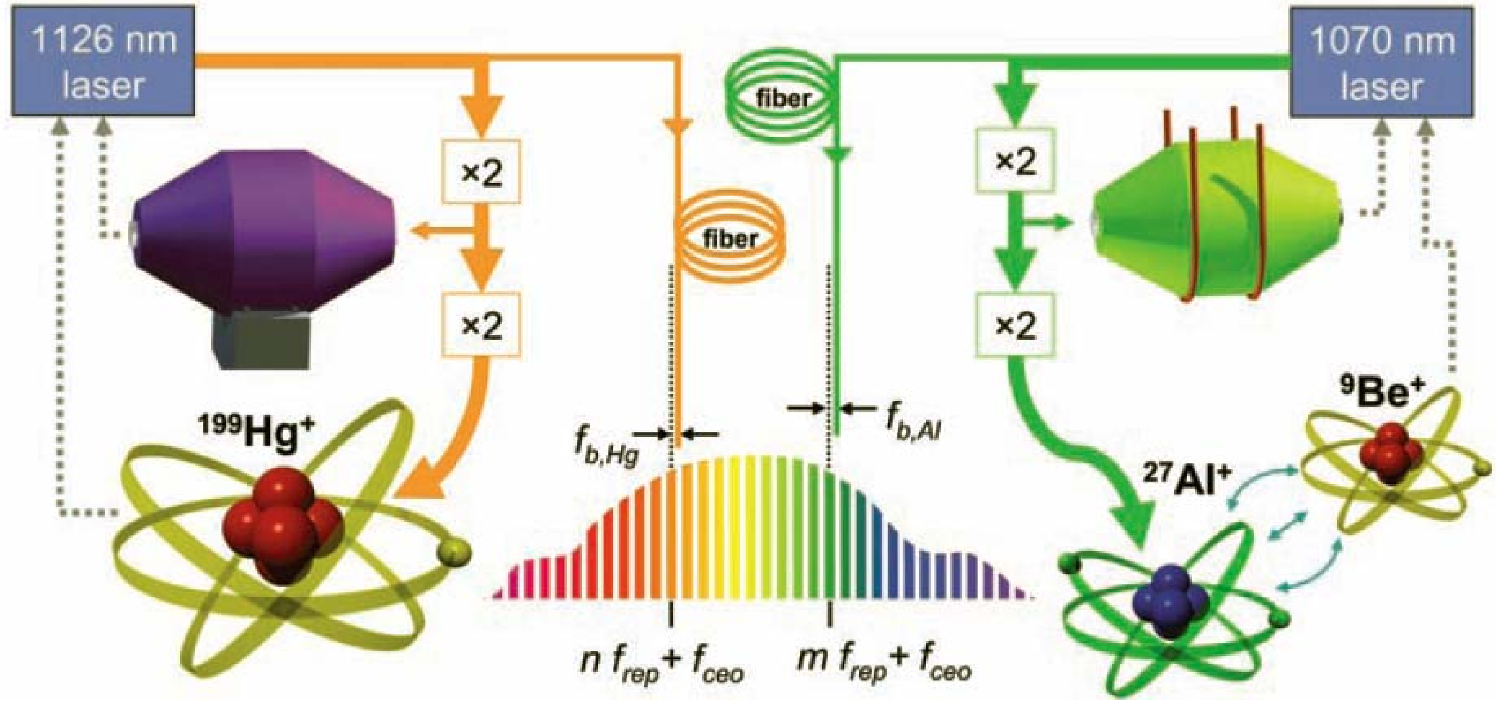


- Neutral Sr, lattice clocks
- 10^{-16} accuracy, J. Ye et al.
- TOKYO, JILA, SYRTE, PTB, LENS

NIST

Accuracy: state of the art

Rosenband *et al.*,
Science 319, 1808 (2008)



$$\frac{f_{\mathrm{Al+}}}{f_{\mathrm{Hg+}}} = 1.052\,871\,833\,148\,990\,438\,(55)$$

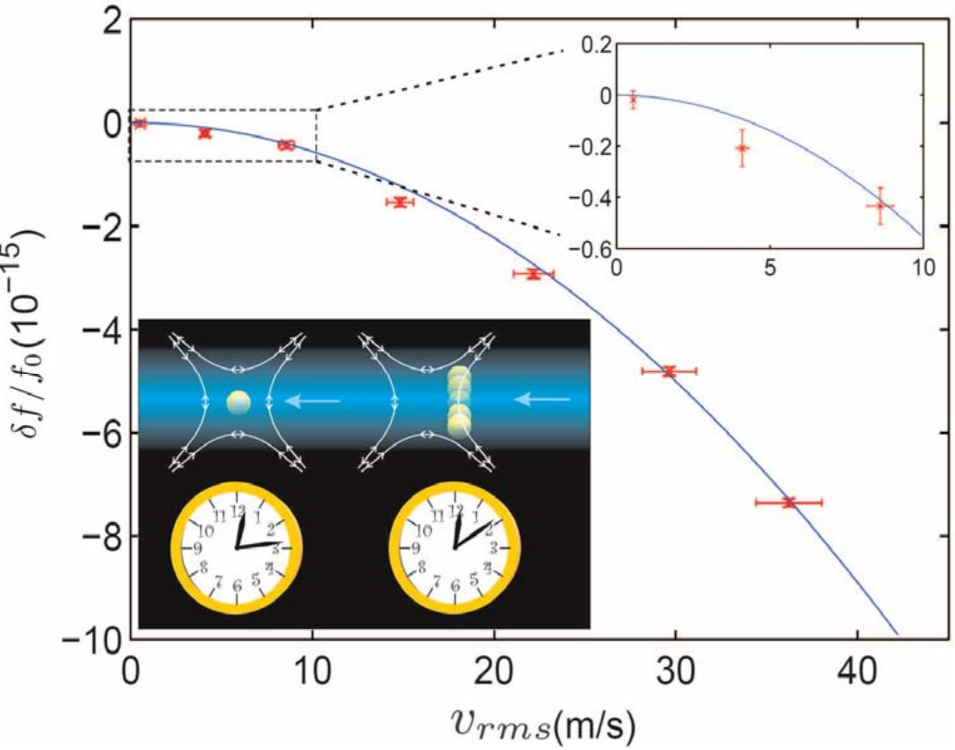
Relative uncertainty: 5.2 x 10^{-17}

Hg^+ systematics: 1.9 10^{-17}

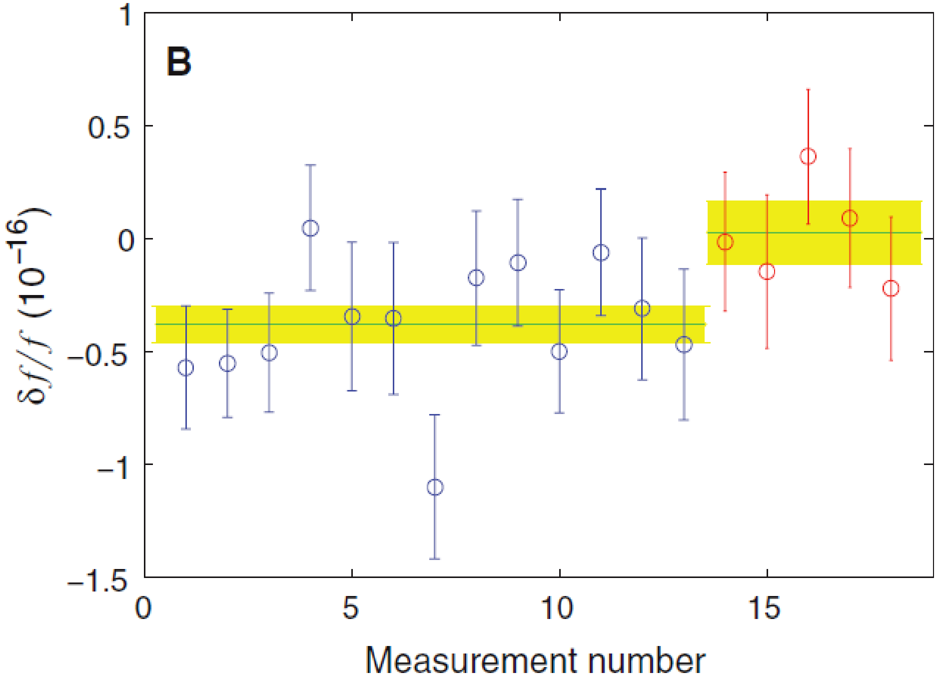
Al^+ systematics: 8 10^{-18} (2010)

Relativity with slow ions and at 30 cm level

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



Time dilation



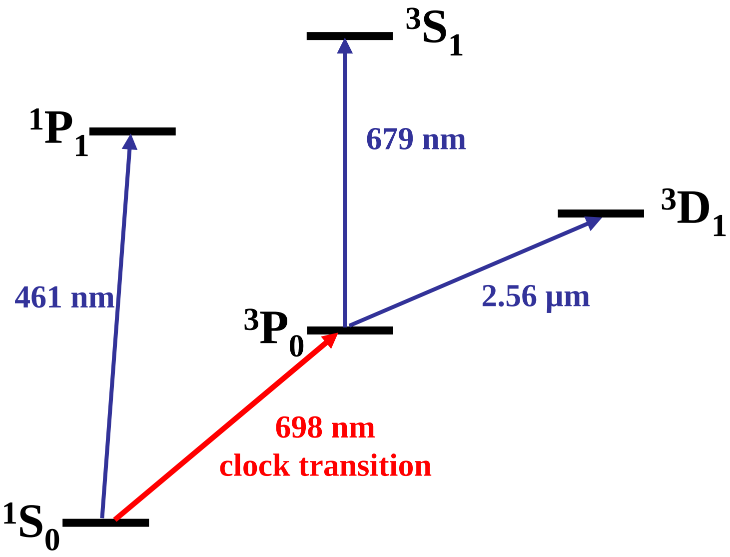
Gravitational shift

Clock B is lifted up by 33 cm

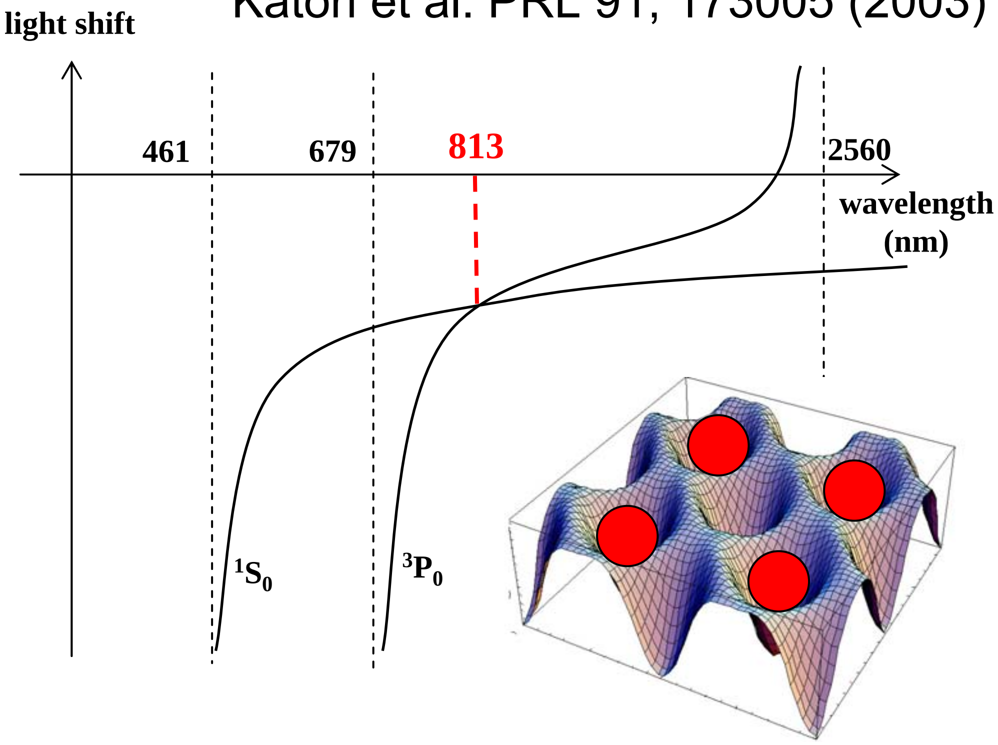
its rate is increased by 3. 4 10^{-17}

Optical lattice clocks

- Atoms trapped in Lamb-Dicke regime using an optical lattice
- Strong trapping field : large light shift induced (at least several tens of kHz) (10 kHz=2.10^{-11} for Sr)
- But: cancellation of the light shift is possible with Sr



Katori et al. PRL 91, 173005 (2003)



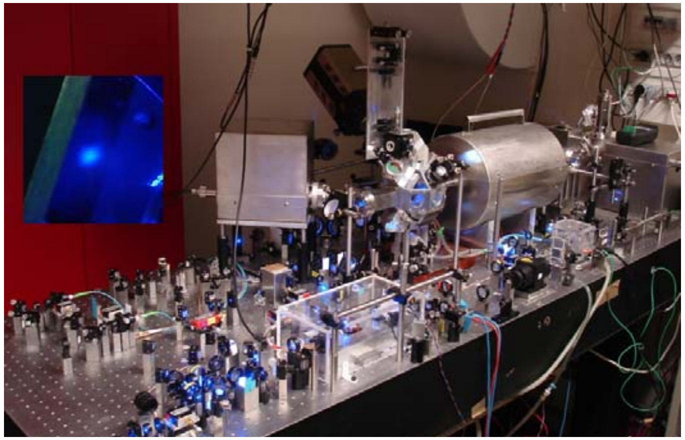
Potential accuracy ≤ mHz

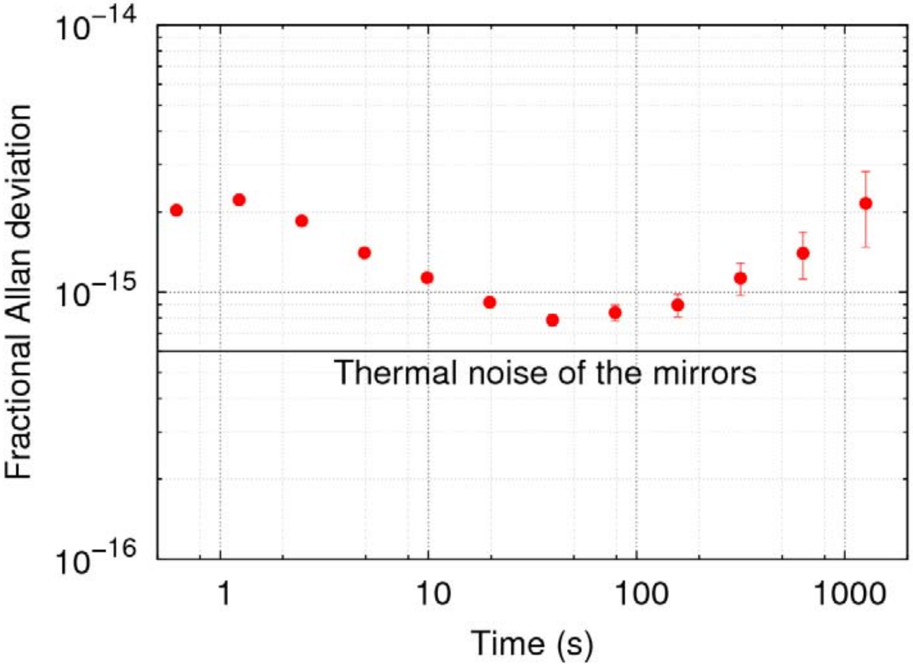
$\delta f / f \approx 10^{-17}$-$10^{-18}$

2 Strontium lattice optical clocks

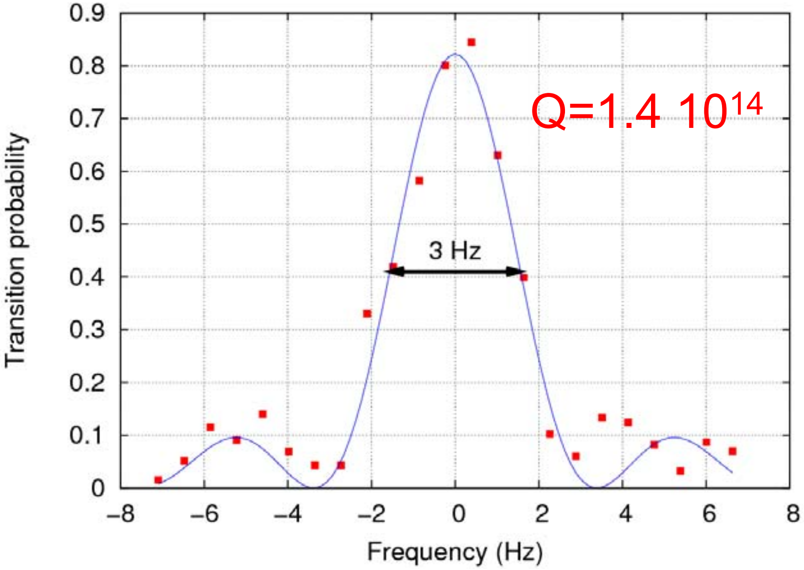
l'Observatoire de Paris | SYRTE

- 2 Sr lattice clocks at SYRTE
- Clock laser: Ultra-stable cavity with silica mirrors





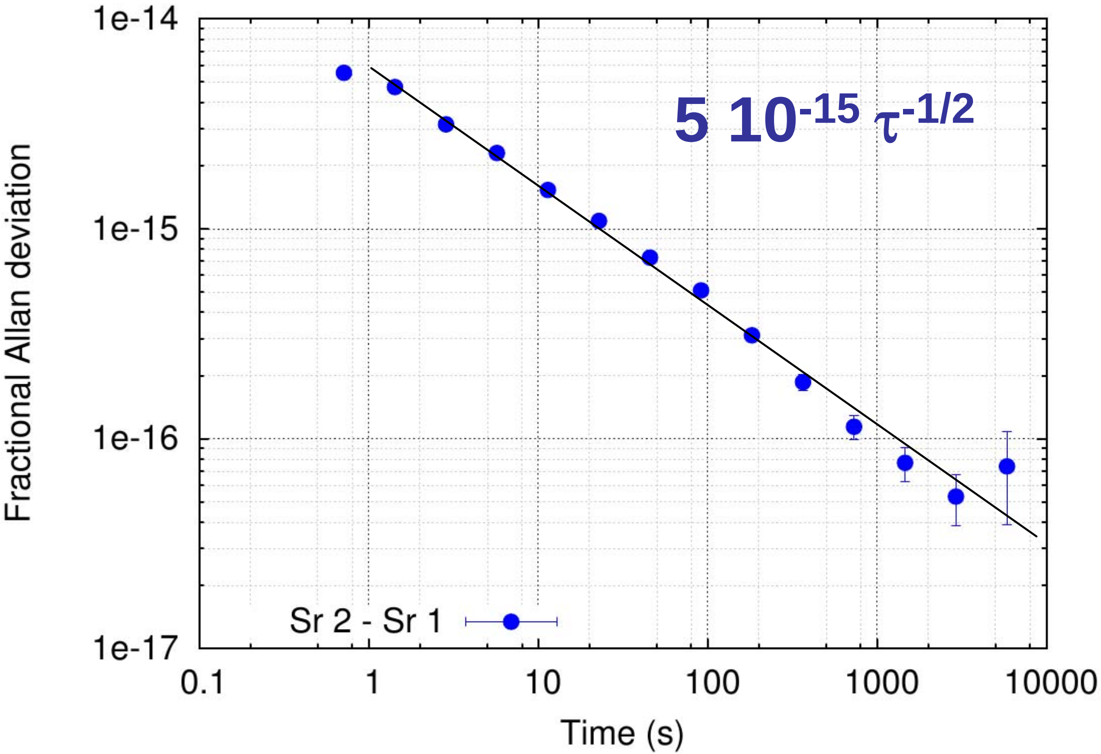
Stabilized clock laser vs. Sr 2



Clock resonance on Strontium 1

Strontium optical clocks frequency stability

- Stability of Sr vs Sr
- 10^{-16} after 1000 s
- Expected stability with an optimized sequence :
  a few 10^{-16} at 1 s



- Accuracy budget at the 10^{-16} level in progress
- Frequency measurement

P. Westergaard, J. Lodewyck, L. Lorini, A. Lecallier, P. Lemonde, LNE-SYRTE

Pulsar Time

Millisecond Pulsars discovered by Hulse and Taylor, 1973, Nobel prize1993
> 2000 pulsars observed; 20 of them are precisely monitored in a search for stochastic gravitational wave background
J. P. W. Verbiest et al, 2009

PSR B1534+12
Period, P= 3.790444080643456(3) ms

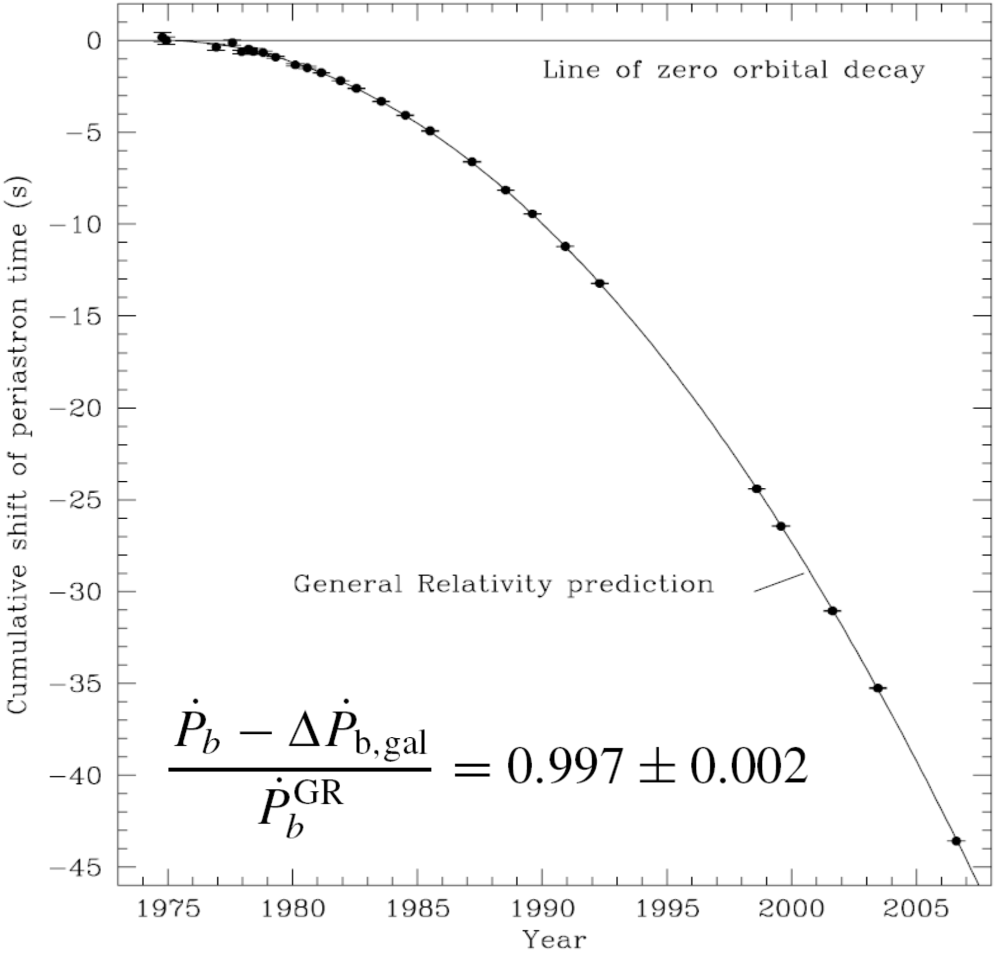
Orbital period, Pb =0.420737299153(4)

PSR B1913+16

Period P=59.0299952695(8) ms

Orbital period Pb =0.322997448930 (4)

Orbital decay



$$\frac{\dot{P}_b - \Delta\dot{P}_{\mathrm{b,gal}}}{\dot{P}_b^{\mathrm{GR}}} = 0.997 \pm 0.002$$

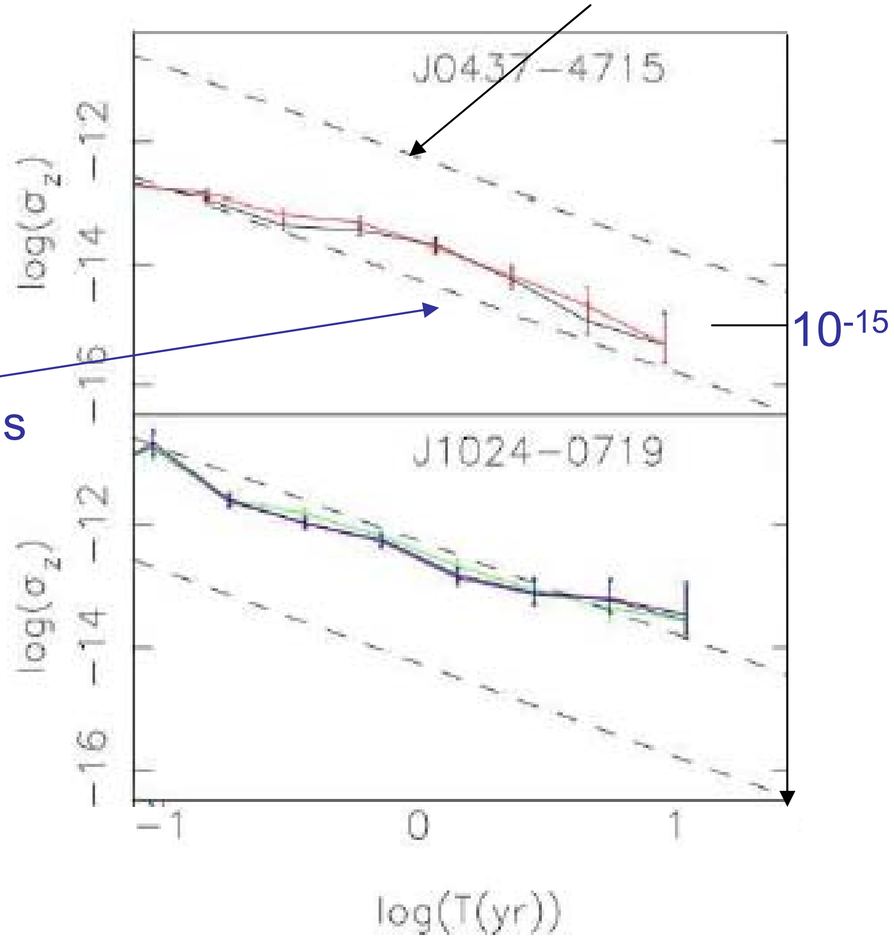
Pulsar Time scales

Guinot & Petit 1991, Petit & Tavella 1996, Foster & Backer 1990 and Rodin 2008

J. P. W. Verbiest et al, 2009

A few pulsars have rms residuals of ~150 ns over 10 years

Pulsar name	rms (μs)	T (yr)
J1909−3744	0.166	5.2
J1713+0747	0.198	14.0
J0437−4715	0.199	9.9
J1744−1134	0.617	13.2
J1939+2134	0.679	12.5



White noise, 10μs

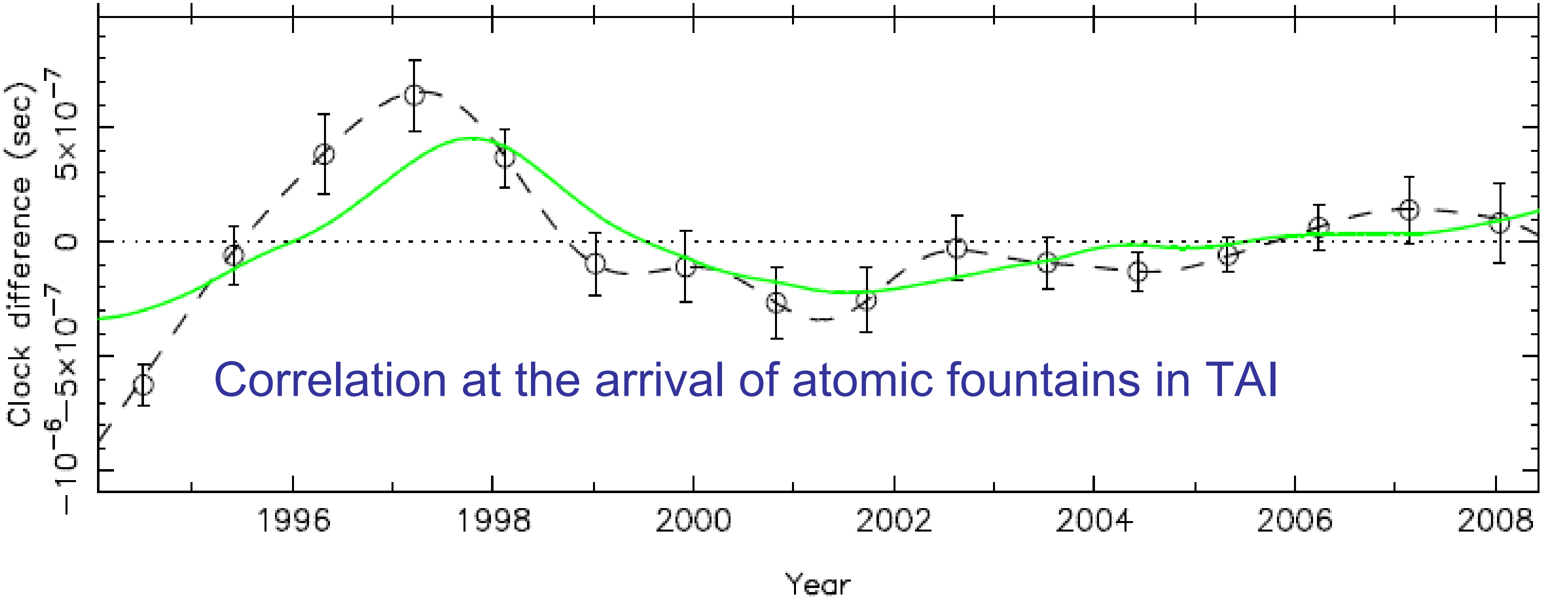
White noise, 100ns

10^{-15}

Pulsars probe long term behaviour of time scales realized by atomic clocks

Pulsar Time scales vs TAI

G. Hobbs et al; 2010


Correlation at the arrival of atomic fountains in TAI

pulsar time scale with respect to TT(TAI). TAI is steered by atomic fountains

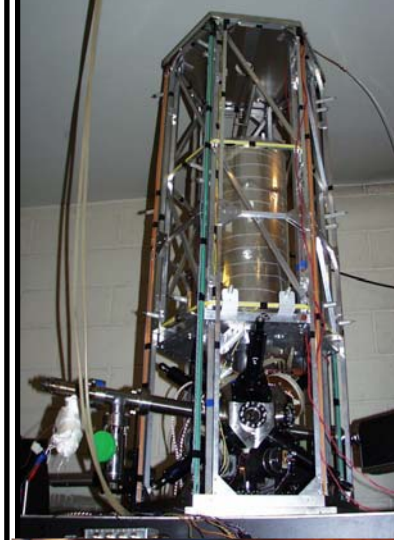
The solid green line indicates TT(TAI)-TT(BIPM2010) with a quadratic polynomial fitted and removed. TT (BIPM2010) is a recalculated time towards the past that includes the applied corrections to TAI.

Messages:

1) long term monitoring of pulsar vs atomic clocks is highly interesting
2) Distant Clock comparison methods are not up to par with fountains and optical clocks
3) Deliver best TAI to PSR telescopes !

Fundamental physics Tests using ultra-stable clocks

Do fundamental physical constants vary with time ?



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

G, α_{elm}, m_e/ m_p…

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

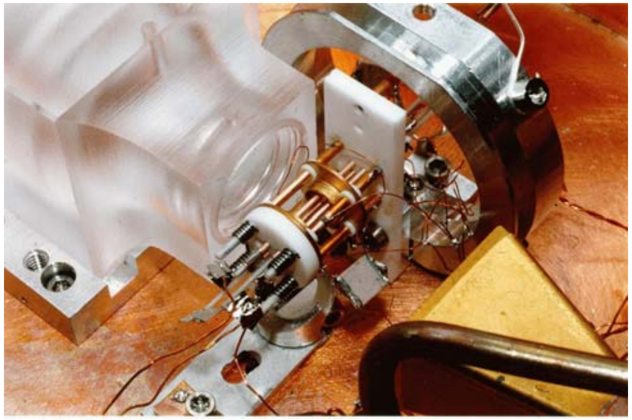
ex:

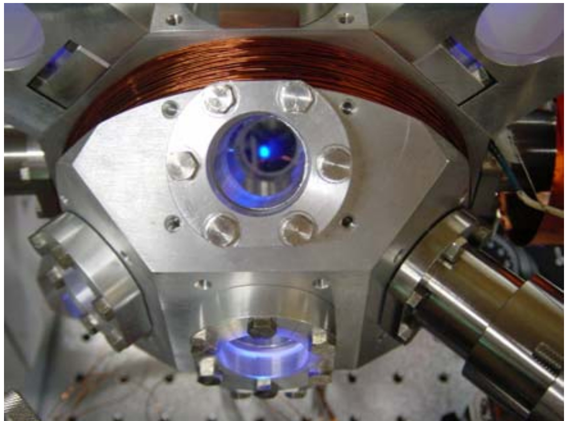
Microwave clock/Microwave clock: α, m_e/m_p, $g^{(i)}$

rubidium and cesium

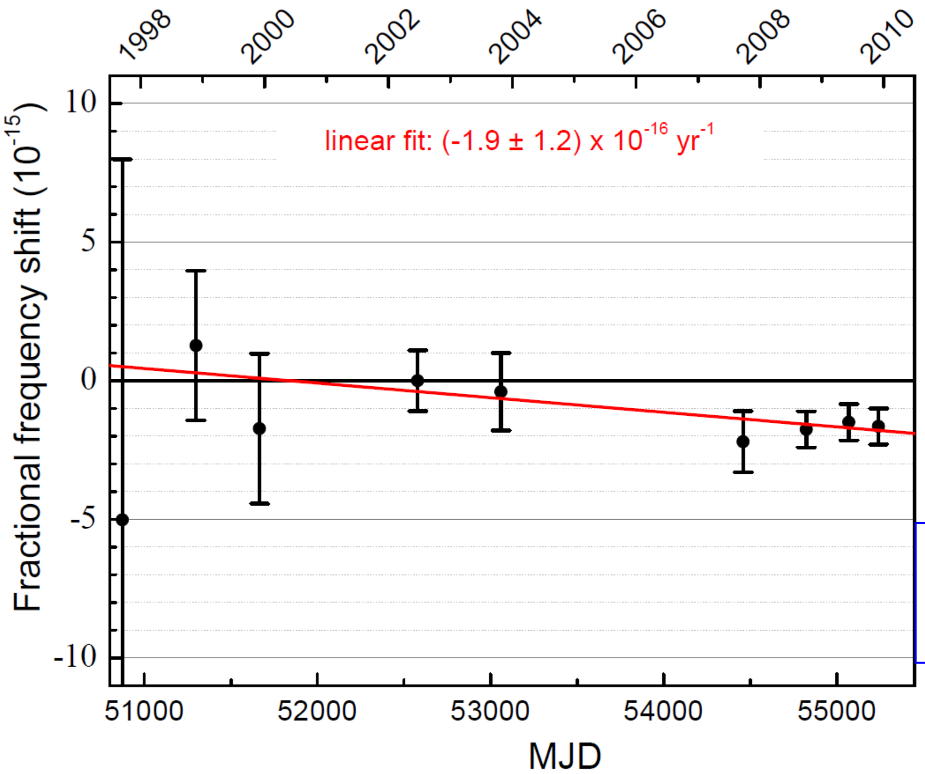
Microwave/Optical clock : α, m_e/m_p, $g^{(i)}$

Optical Clock/Optical clock: α





SYRTE Comparison between Rubidium and Cesium Hyperfine Structure over ~12 years



J. Guéna et al., IEEE Trans. UFFC 57, 647 (2010)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-1.9\pm1.2)\times 10^{-16}\,\mathrm{yr}^{-1}$$

Improvement by 5.8 wrt PRL 90,150801 (2003)

With QED calculations:

J. Prestage, et al., PRL (1995), V. Dzuba, et al., PRL (1999)

$$\frac{d}{dt}\ln\left(\frac{g_{\mathrm{Rb}}}{g_{\mathrm{Cs}}}\alpha^{-0.49}\right) = (-1.9\pm1.2)\times 10^{-16}\,\mathrm{yr}^{-1}$$

With QCD calculations:

V. V. Flambaum and A. F. Tedesco, PR C73, 055501 (2006)

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

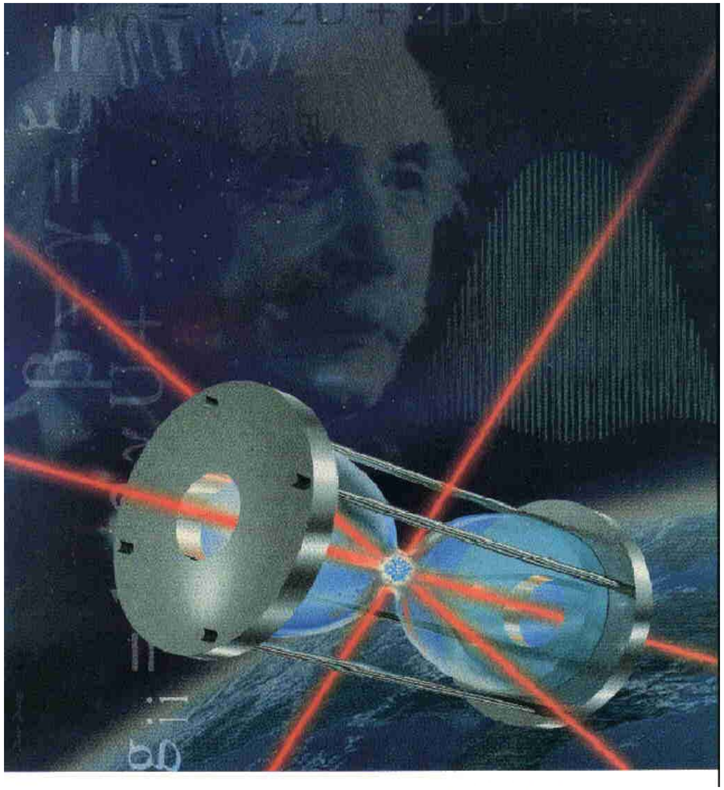
Al^{+} -Hg^{+} optical frequency comparison over 18 months:

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

Fundamental Physics tests with space clocks

1997

esa



cnes

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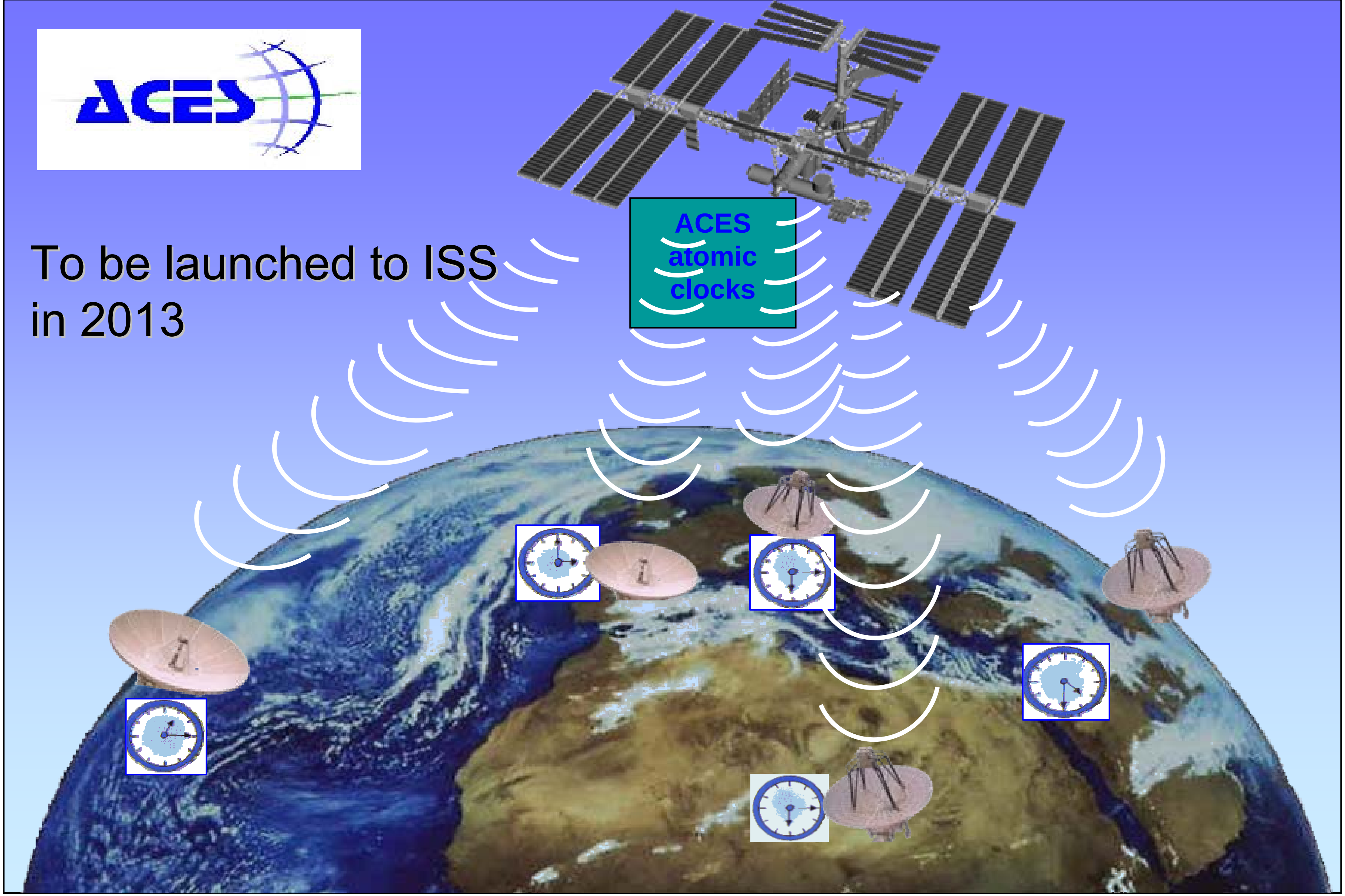
PHARAO

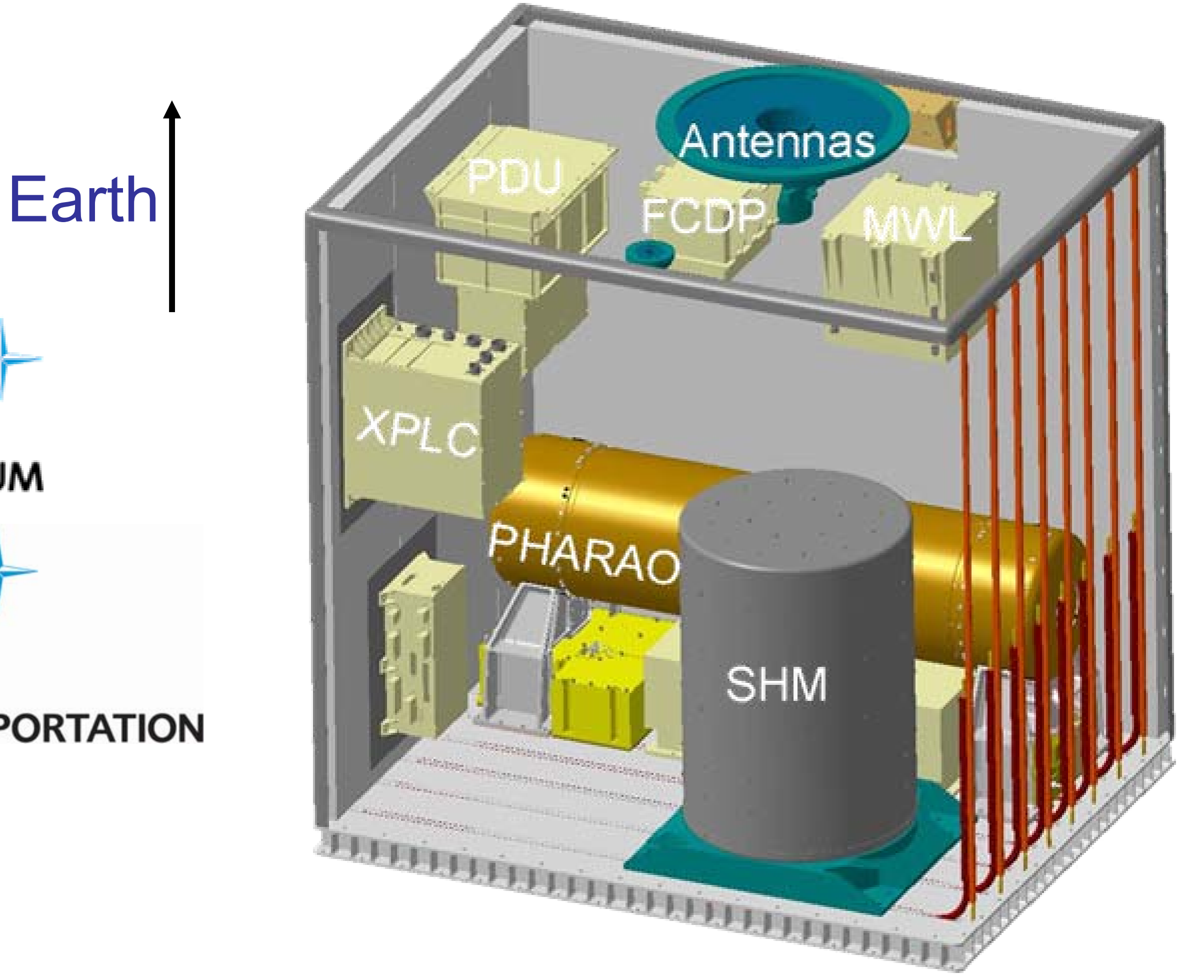
ACES



To be launched to ISS in 2013

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

ACES General View



EADS ASTRIUM

EADS SPACE TRANSPORTATION

ACES

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

esa

ACES ON COLUMBUS EXTERNAL PLATFORM

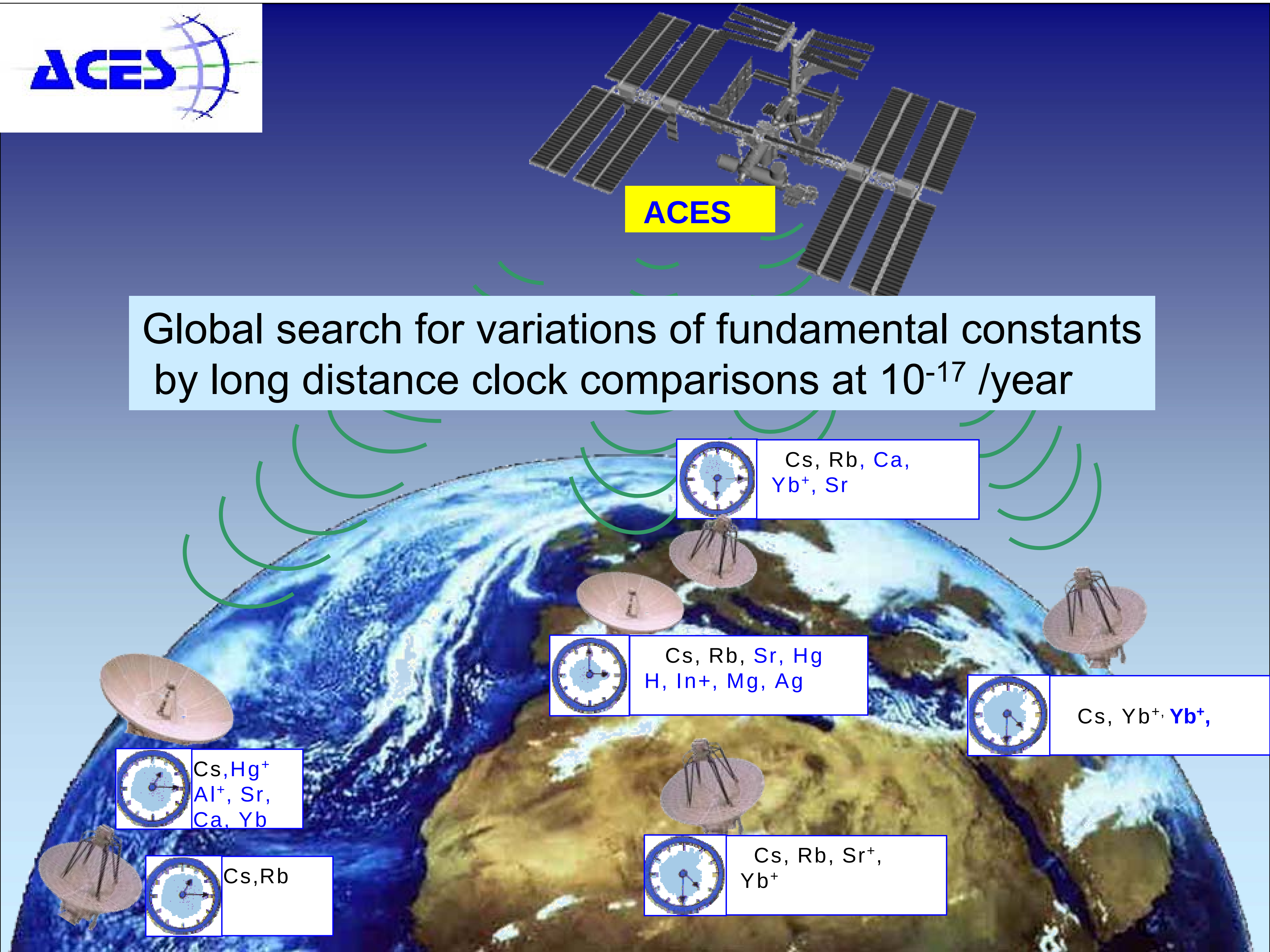
ACES

Current launch date : end 2013
Mission duration : 18 months to 3 years

ACES Ground laboratories (June 2010)

Australia: UWA, CSIRO(Sydney)
Austria: Univ. Innsbruck
Brazil: Univ. Sao Carlos
Canada: NRC
China: Shangai Obs, NIM, NTSC
Germany: PTB, MPQ, Univ. Hannover, Univ. Düsseldorf, TU Muenchen, Univ. Erlangen
France: SYRTE, CNES, Obs. Besançon, OCA, LPL
Italy: INRIM, Univ. Firenze
Japan: Tokyo Univ., NMIJ, CRL
Russia: Vniftri, ILS Novosibirsk
Swiss: METAS, ON
United King: NPL
USA: JPL, NIST, Penn St. Univ., USNO, JILA
Taiwan: Telecom research lab
Int. Agency: BIPM

Total : 35 institutes + theory groups
> 350 researchers



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

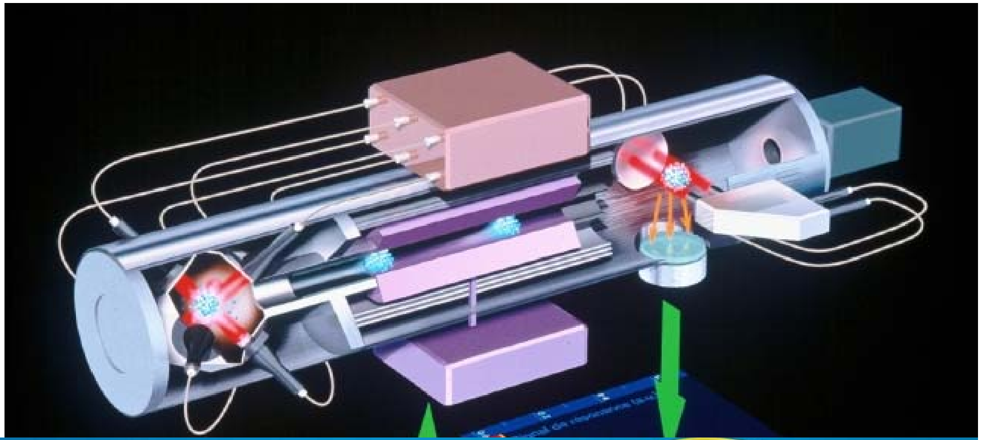
Cs, Yb^{+}, **Yb^{+},**

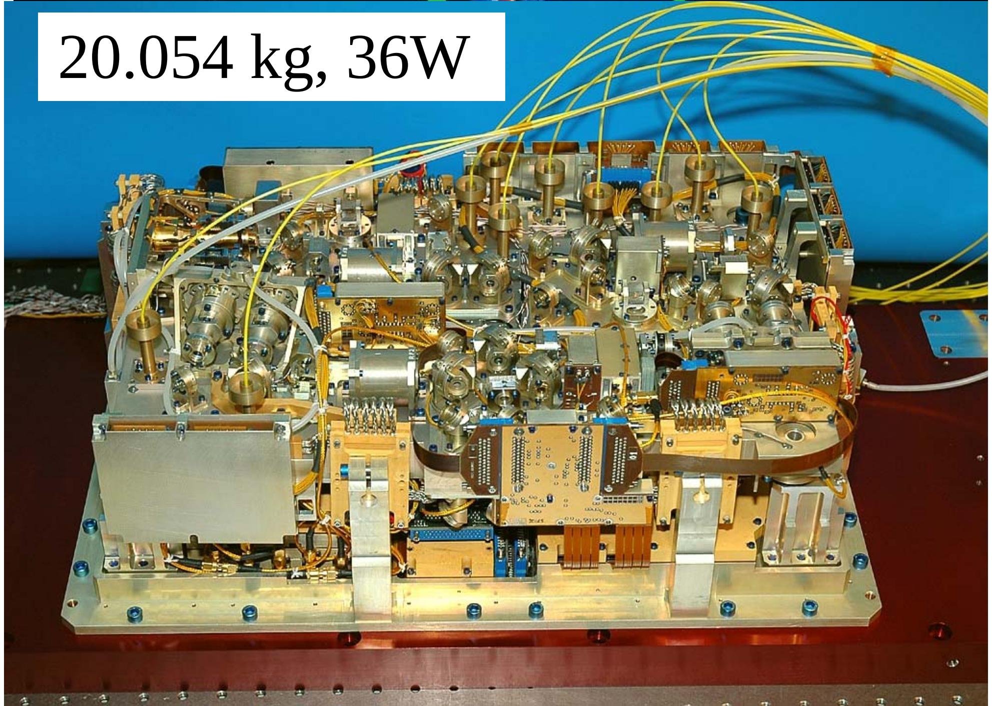
Cs, Hg^{+}
Al^{+}, Sr,
Ca, Yb

Cs,Rb

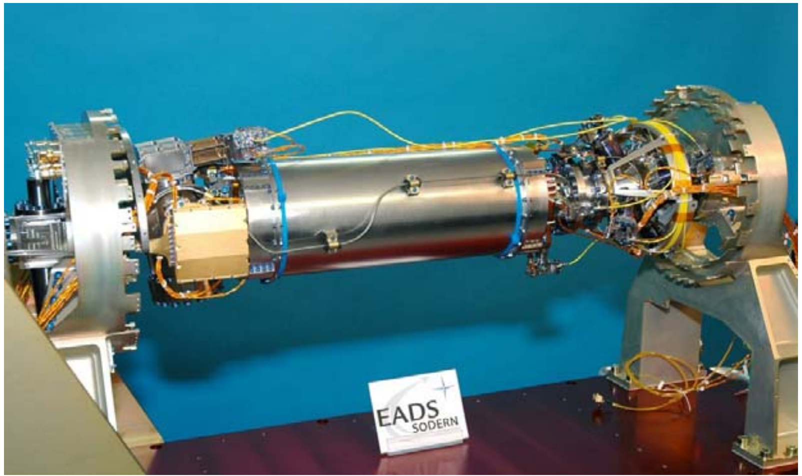
Cs, Rb, Sr^{+},
Yb^{+}

Cold Atom Clock in μ-gravity : PHARAO/ACES





20.054 kg, 36W

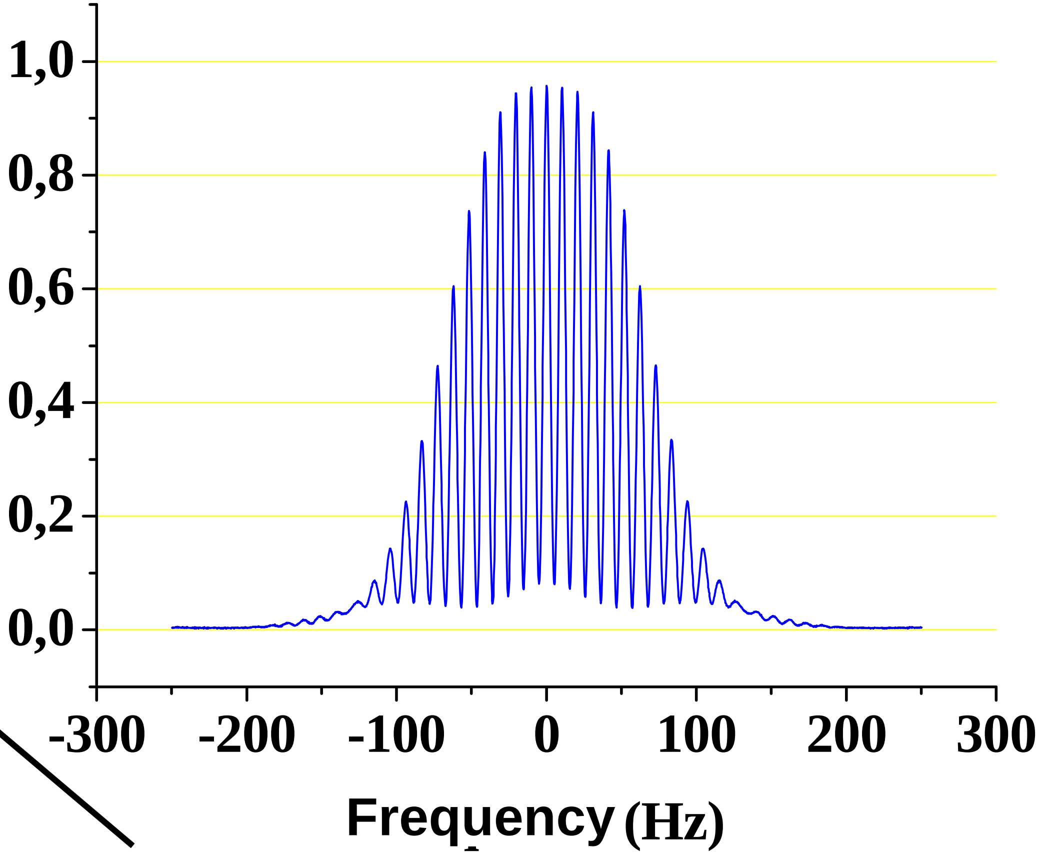


Total volume: 990x336x444 mm^3
Mass: 44 kg

PHARAO Space Clock

Cesium tube

Laser source



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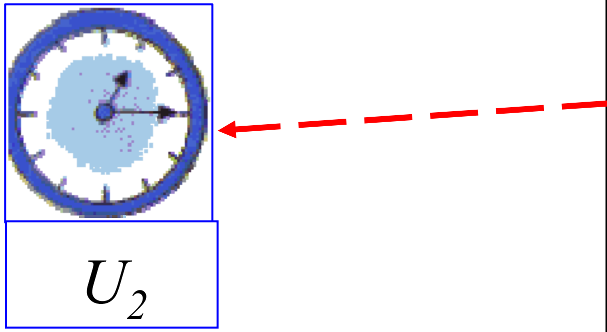
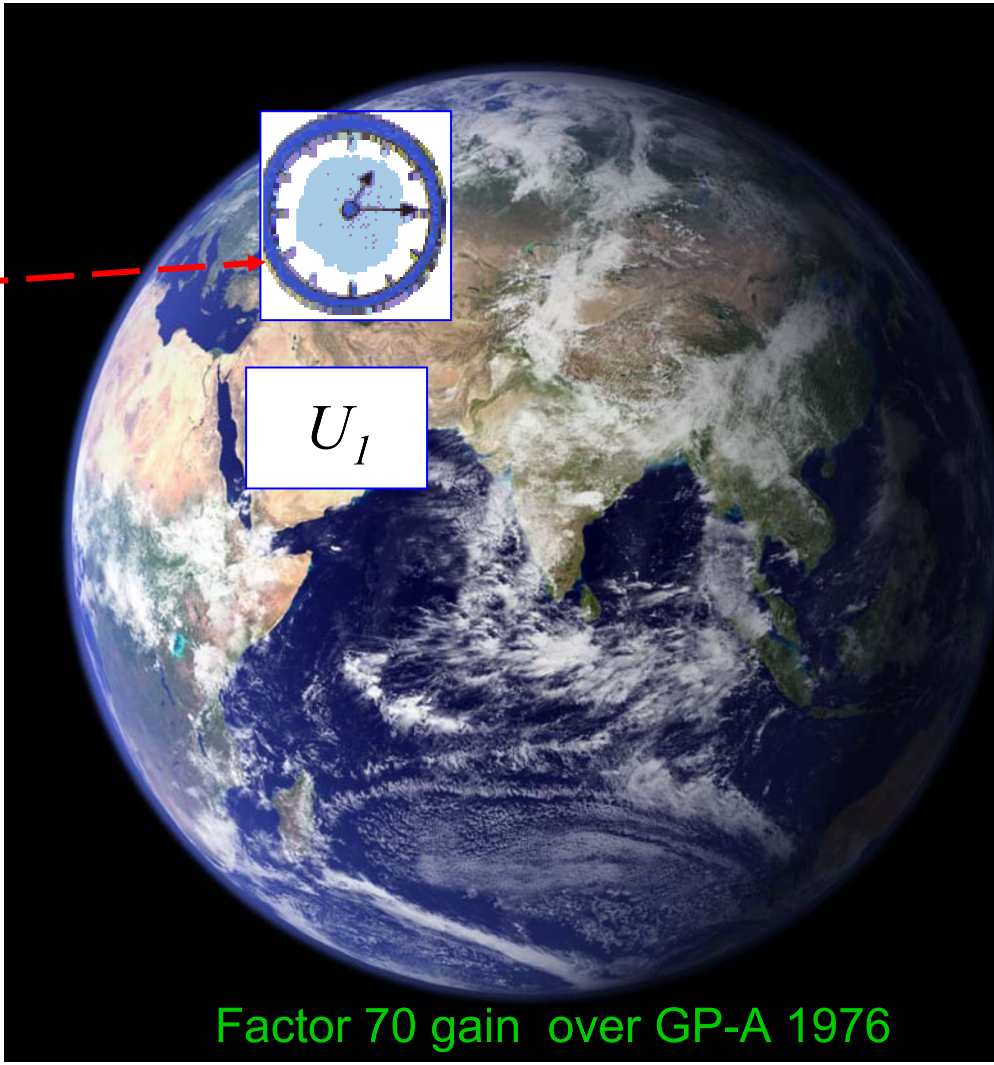
Performance tests completed
Flight model under construction

A Prediction of General Relativity: the gravitational redshift





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} clocks

ACES: 3 10^{-6}

ACES TIME Transfer

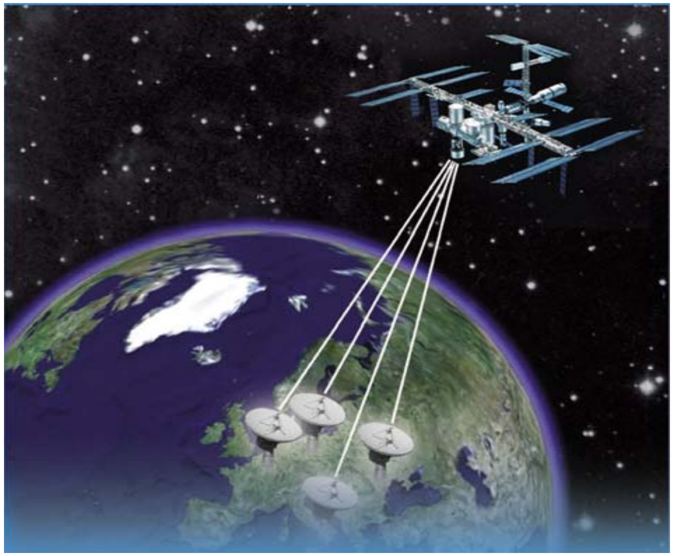
Ultra-stable frequency comparisons on a worldwide basis :

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

Contribution to TAI

Gain: x 20 wrt current GPS

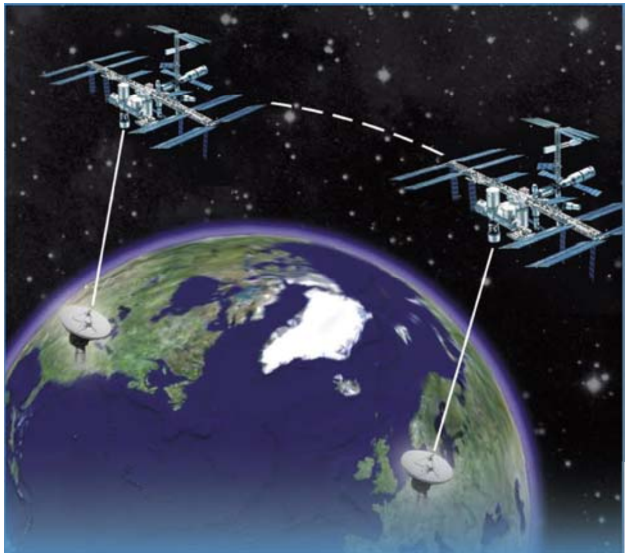
Common view



Error < 0.3ps over 300 s

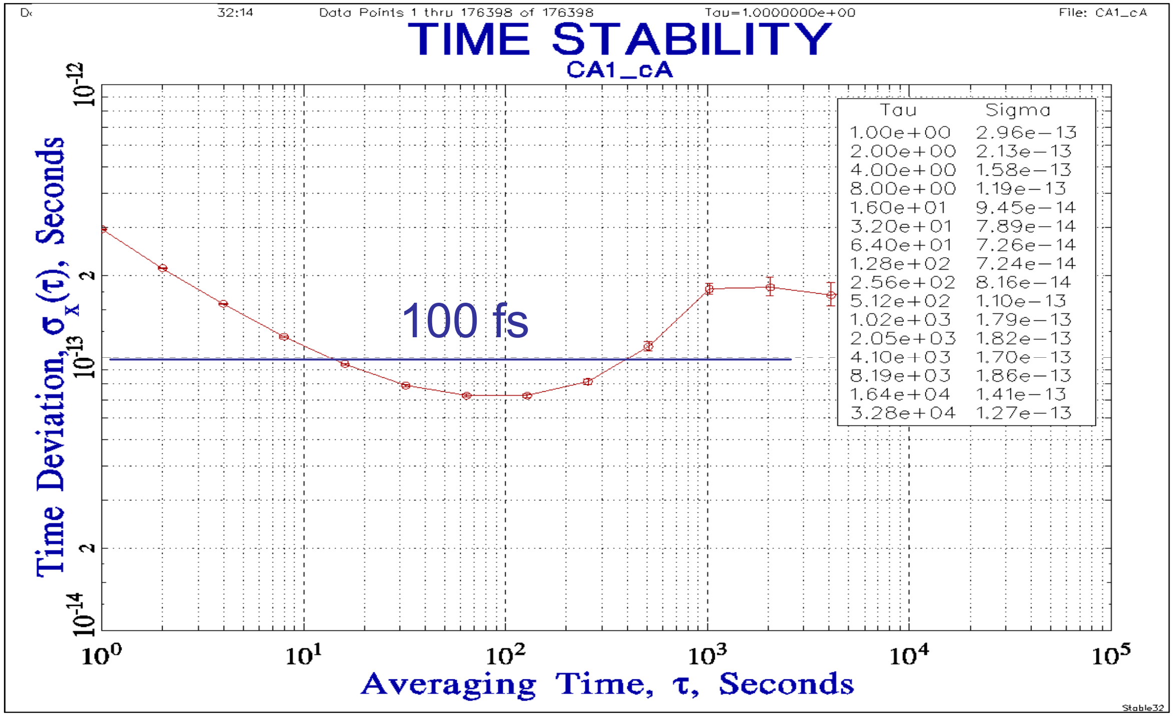
Can be checked by fiber-link

non common view



Error < 3ps over 3000 s

ACES Time Transfer



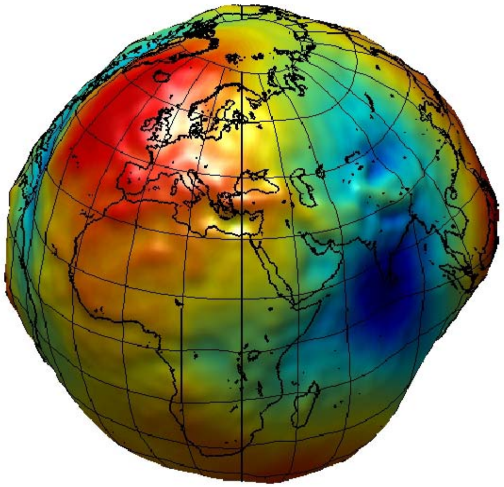
Tau	Sigma
1.00e+00	2.96e−13
2.00e+00	2.13e−13
4.00e+00	1.58e−13
8.00e+00	1.19e−13
1.60e+01	9.45e−14
3.20e+01	7.89e−14
6.40e+01	7.26e−14
1.28e+02	7.24e−14
2.56e+02	8.16e−14
5.12e+02	1.10e−13
1.02e+03	1.79e−13
2.05e+03	1.82e−13
4.10e+03	1.70e−13
8.19e+03	1.86e−13
1.64e+04	1.41e−13
3.28e+04	1.27e−13

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

The microwave link ground terminal

End to End tests are ongoing

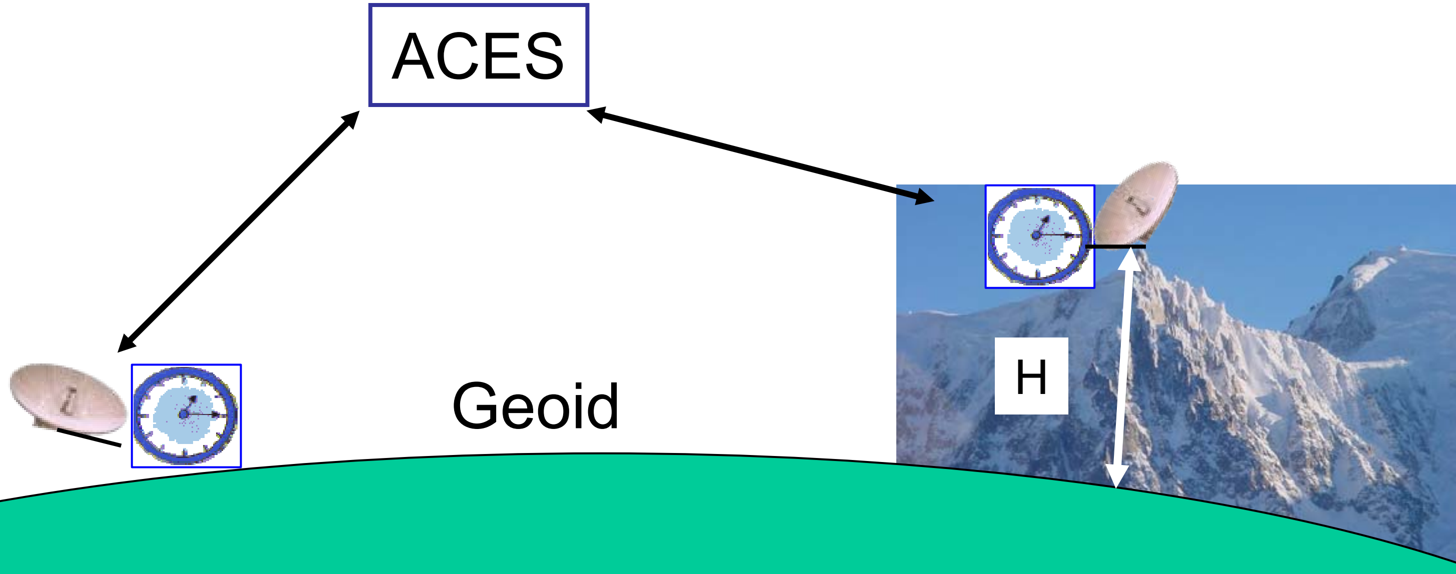
Relativistic Geodesy



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

ACES and Beyond

Microwave clocks:

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

Optical clocks:

10^{-18} range (NIST'09-10)

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

Applications to GPS & GALILEO monitoring and in Earth Science

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

SOC, STE-QUEST, SAGAS,..