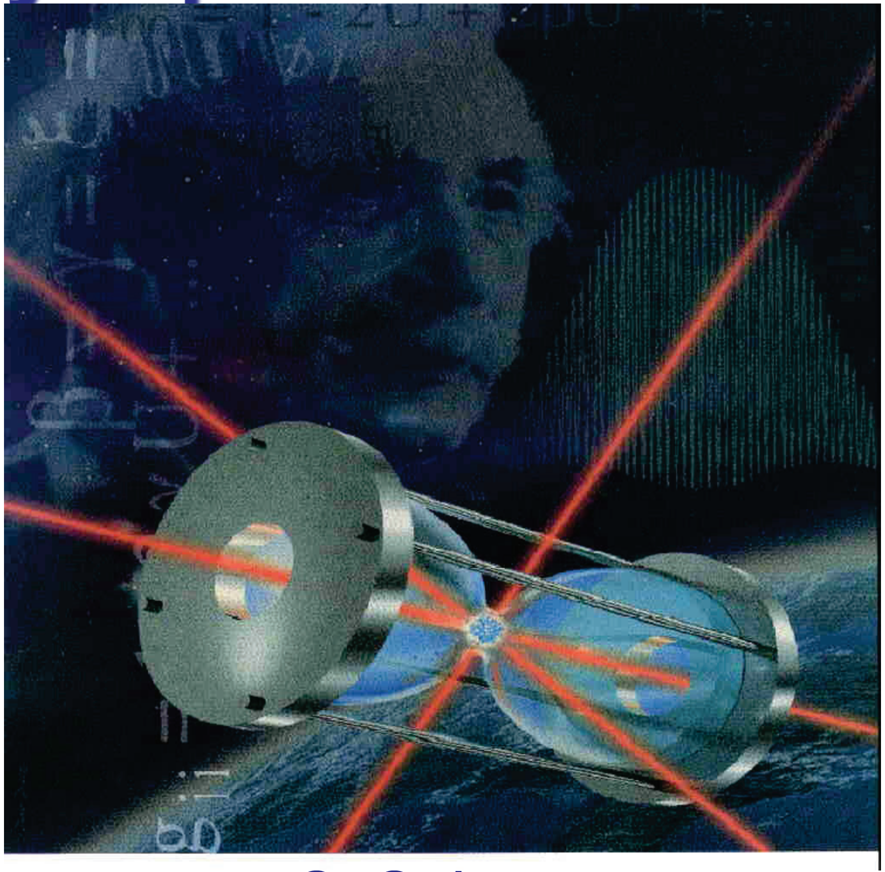
Horloges atomiques et physique fondamentale



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GRAM, Nice
November 29th, 2010

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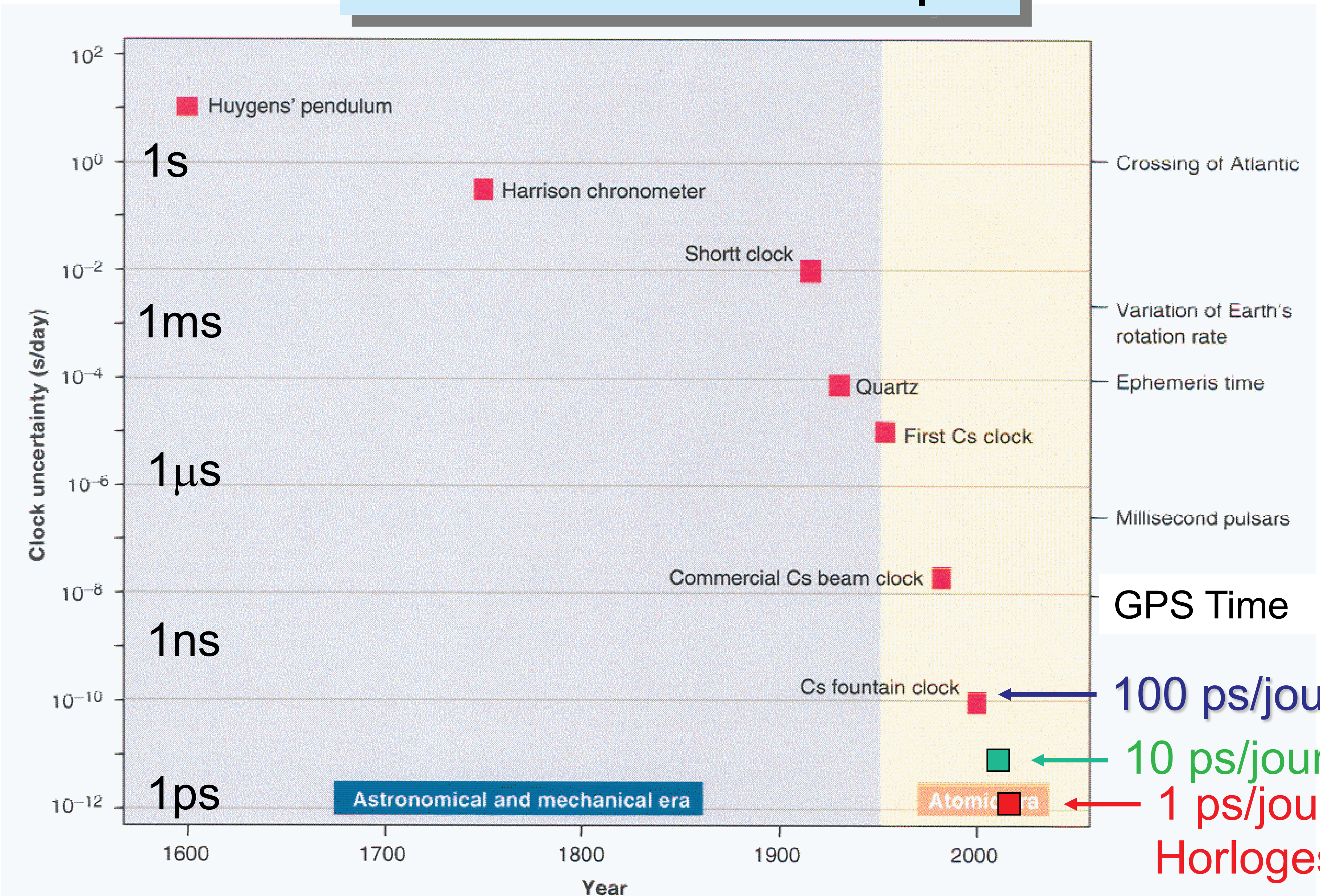
L. Blanchet, C. Bordé
C. Cohen-Tannoudji, S. Reynaud, C. Salomon

Précision du temps



1s

1ms

1µs

1ns

1ps

GPS Time

100 ps/jour

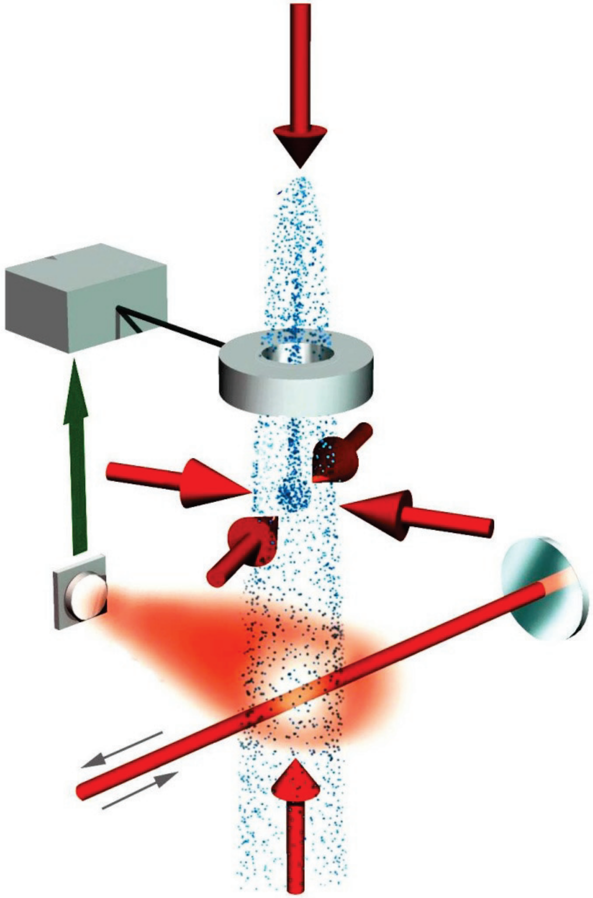
10 ps/jour

1 ps/jour
Horloges optiques

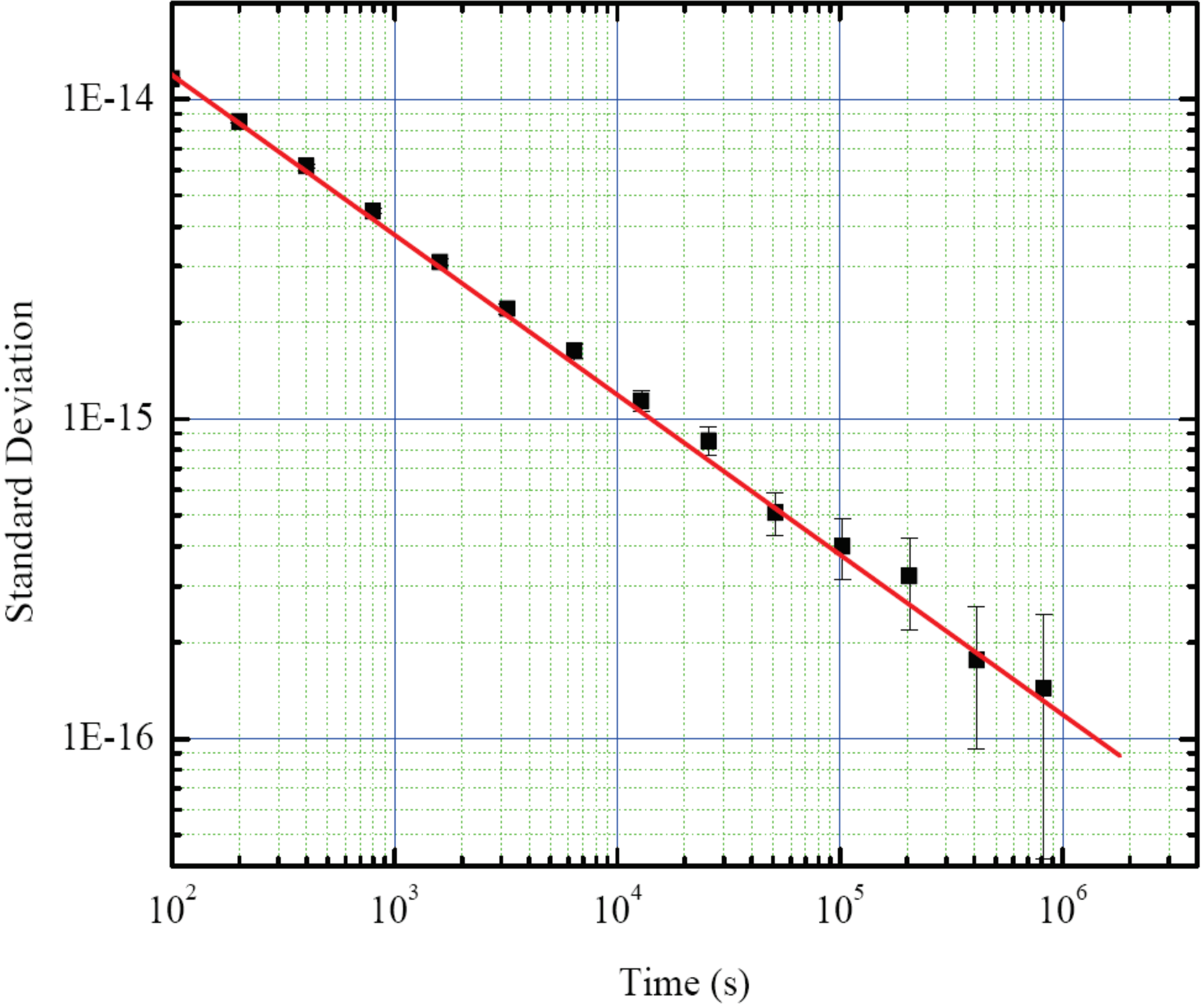
Précision du temps

Une seconde d’erreur tout les 3 milliards d’années !
soit 5 secondes sur l’âge de l’univers

Fontaine atomique

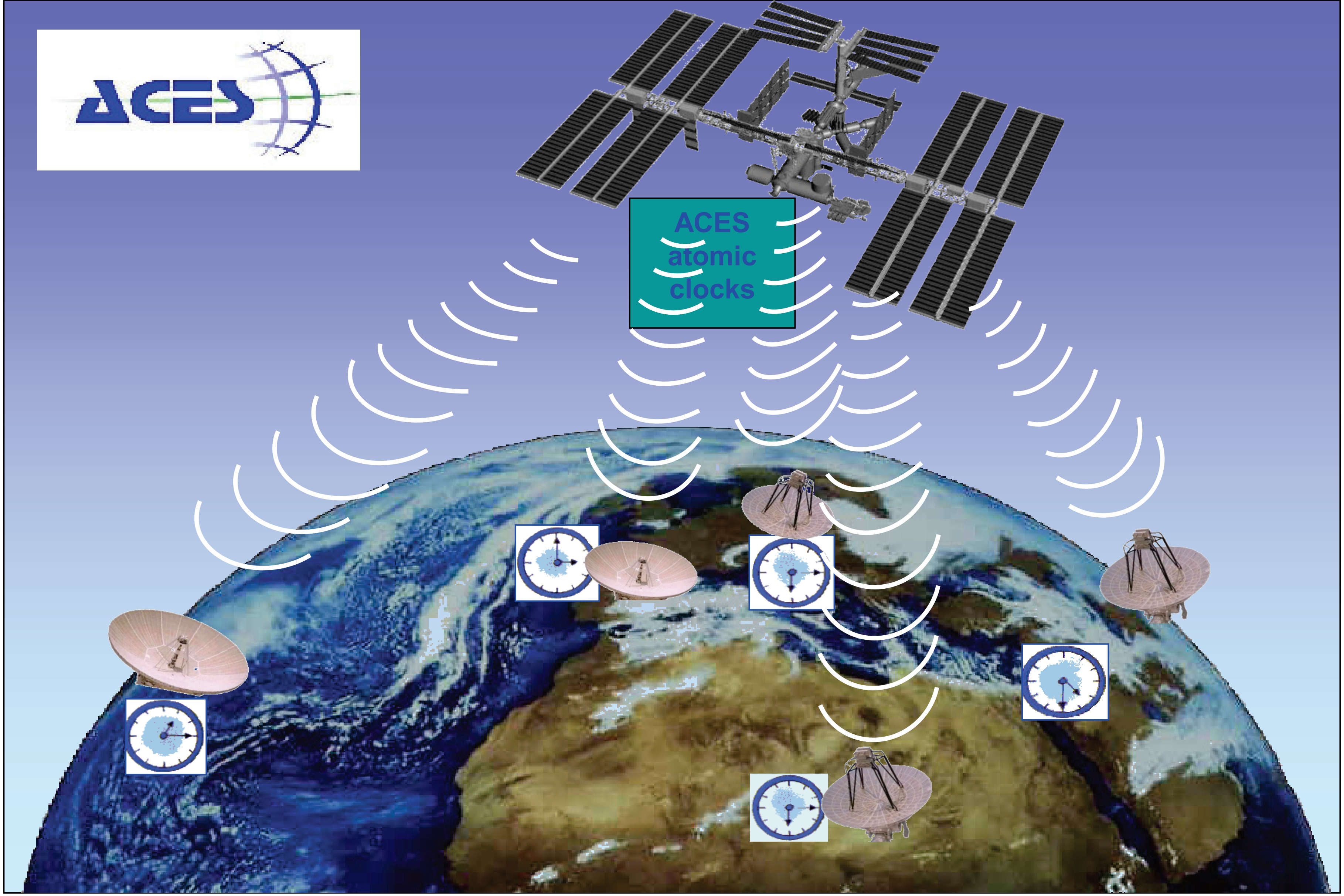


Comparison between two Fountains FOM and FO2 (Paris Observatory)



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}

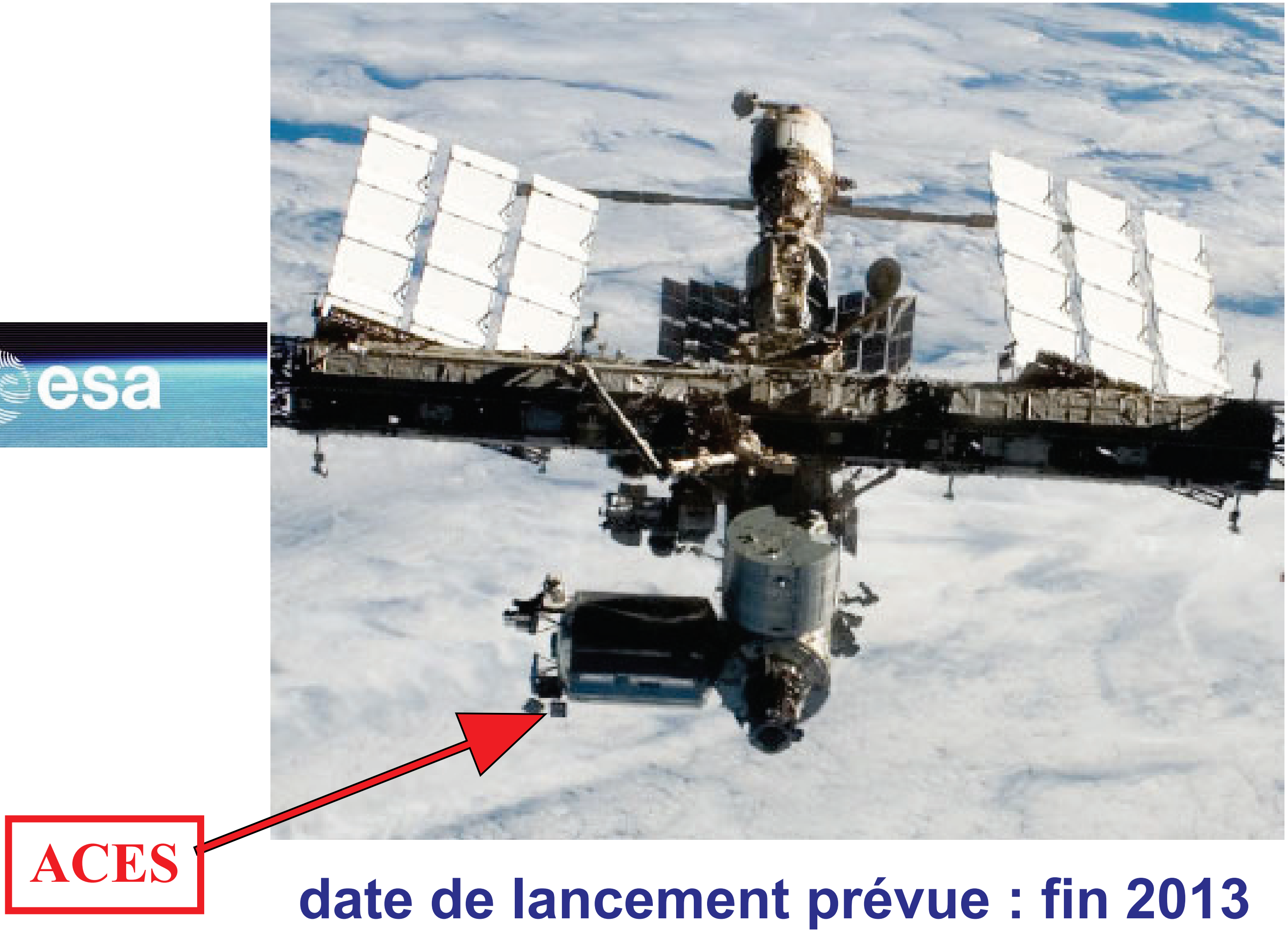


Une horloge à atomes froids en microgravité

Tests de la relativité générale

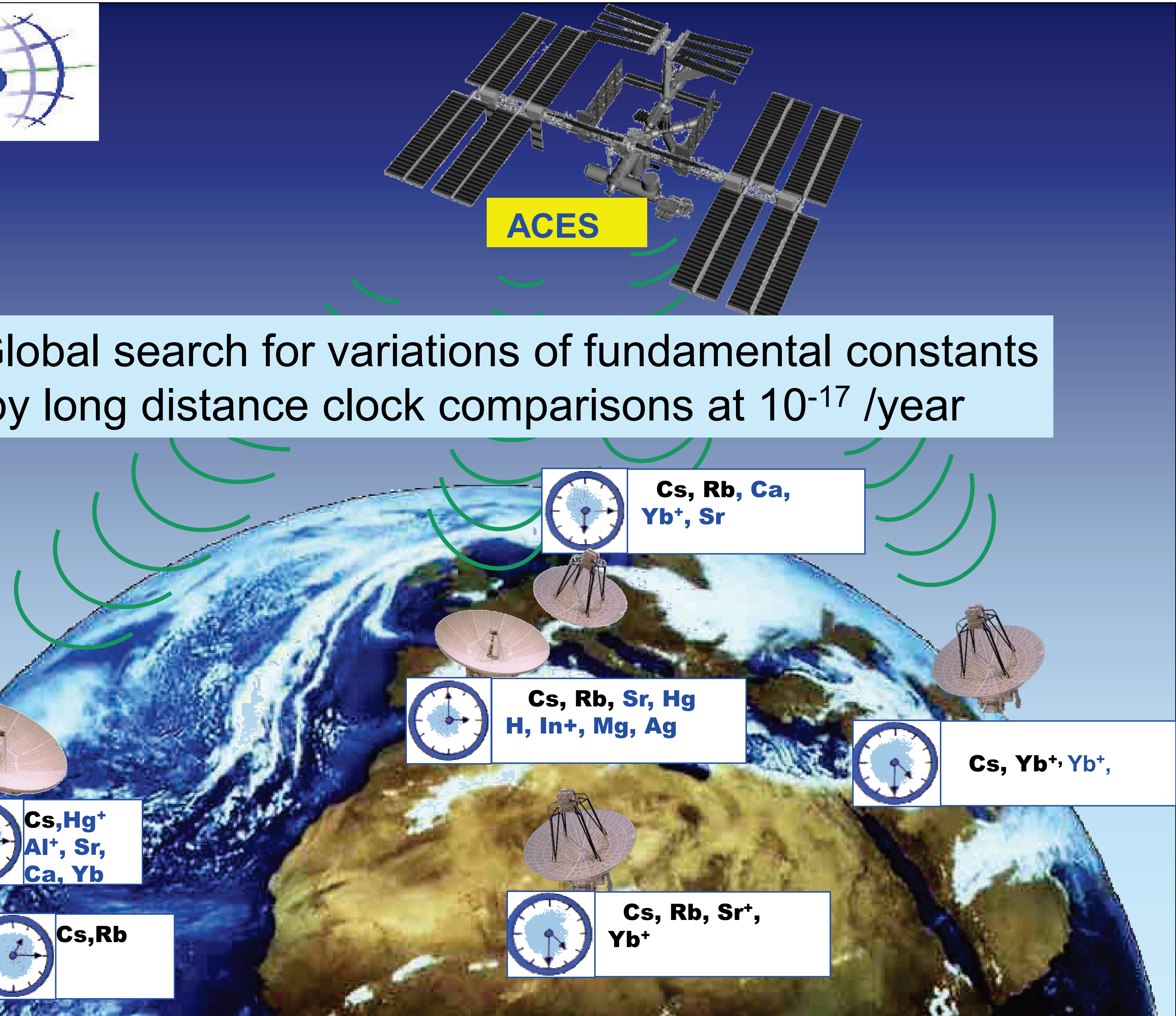
Accès mondial

ACES sur la station spatiale internationale



date de lancement prévue : fin 2013
durée de la mission : 18 mois /3 ans

Global search for variations of fundamental constants by long distance clock comparisons at 10^{-17} /year



ACES

Cs, Rb, Ca, Yb^+, Sr

Cs, Rb, Sr, Hg
H, In+, Mg, Ag

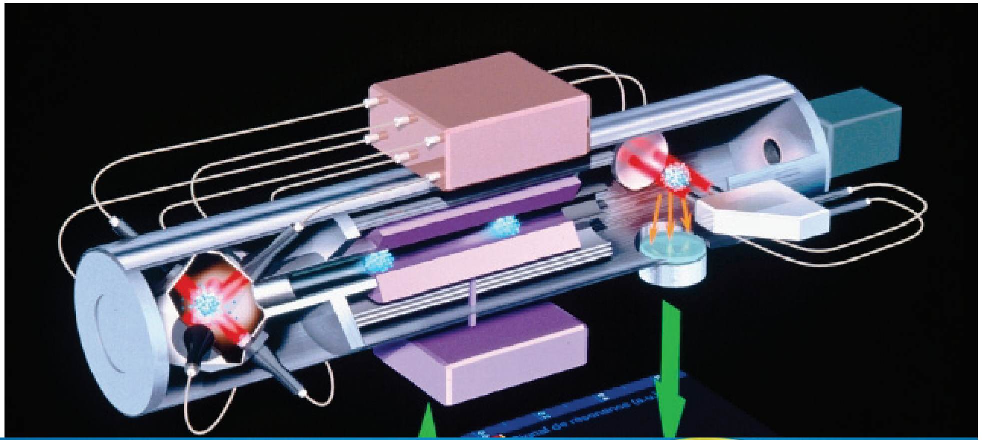
Cs, Yb^+, Yb^+,

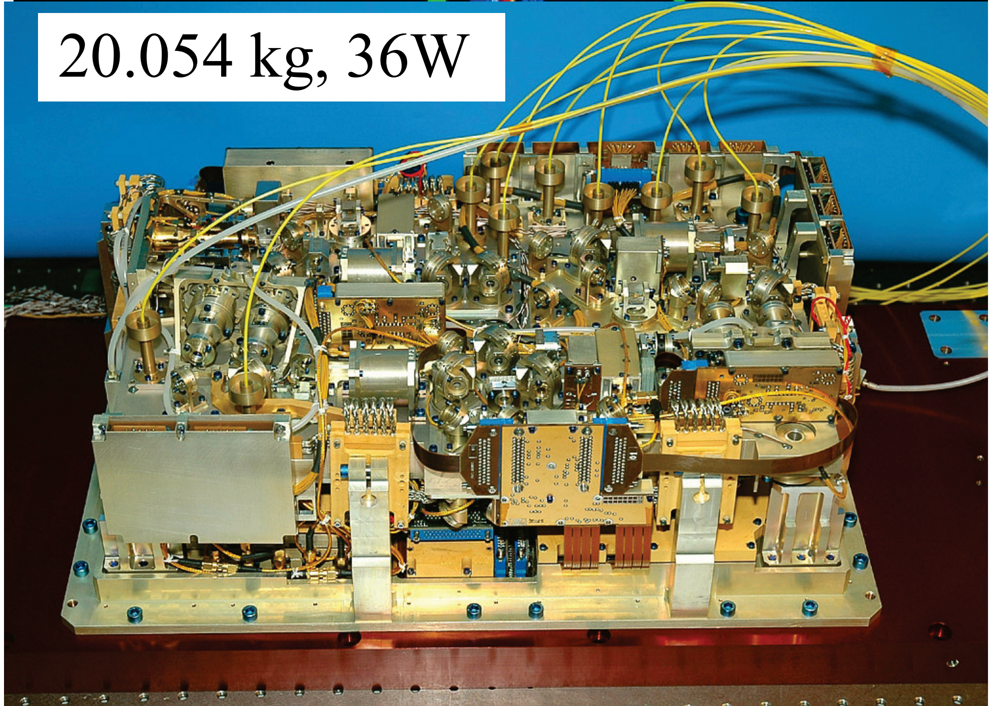
Cs, Hg^+
Al^+, Sr,
Ca, Yb

Cs,Rb

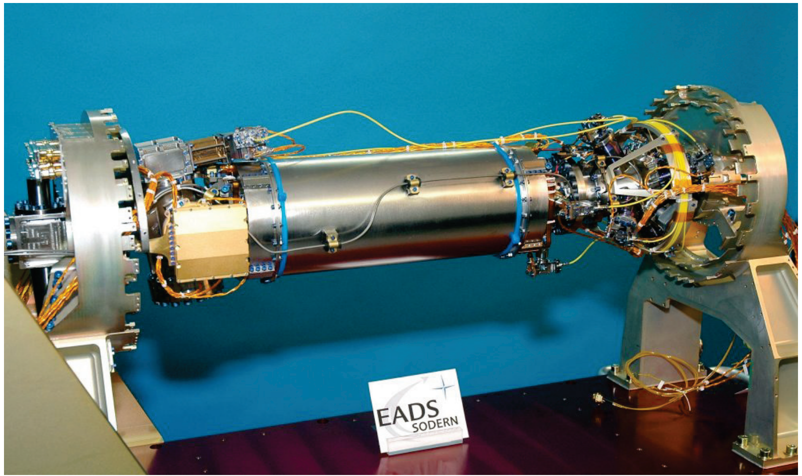
Cs, Rb, Sr^+,
Yb^+

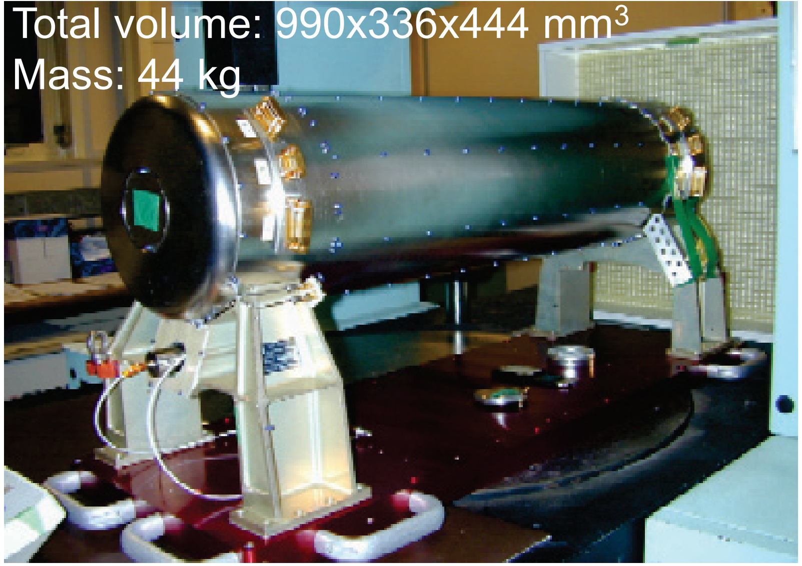
Cold Atom Clock in μ-gravity : PHARAO/ACES





20.054 kg, 36W



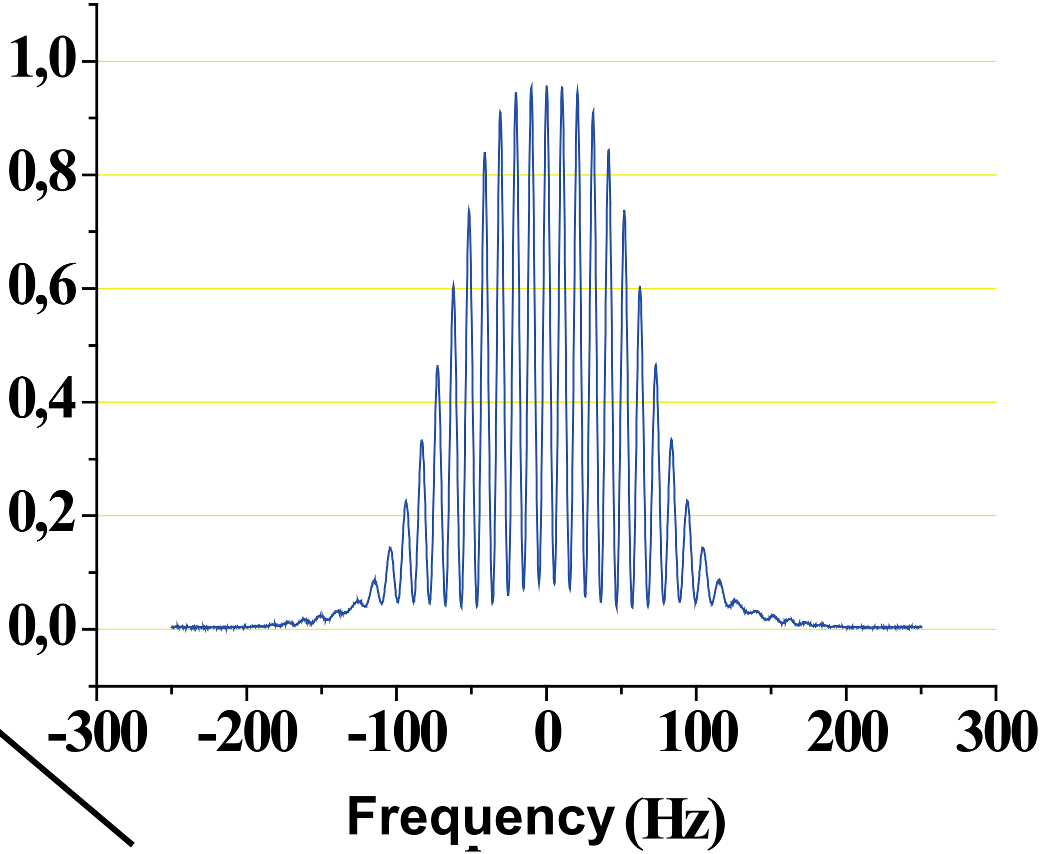


Total volume: 990x336x444 mm^3
Mass: 44 kg

PHARAO: modèle d'ingéniérie

Laser source

Cesium tube



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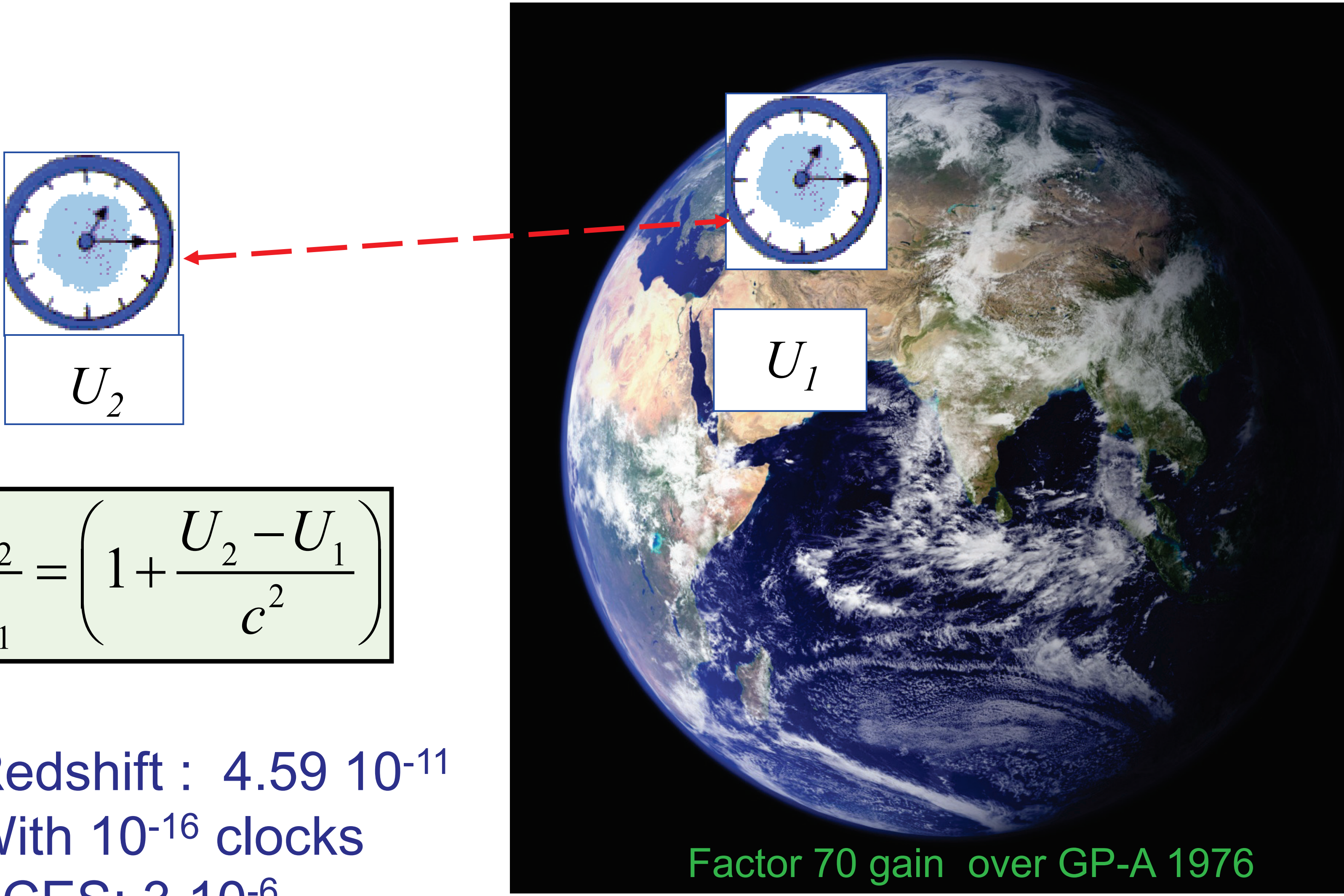
Tests de performances terminés
modèle de vol en construction

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}

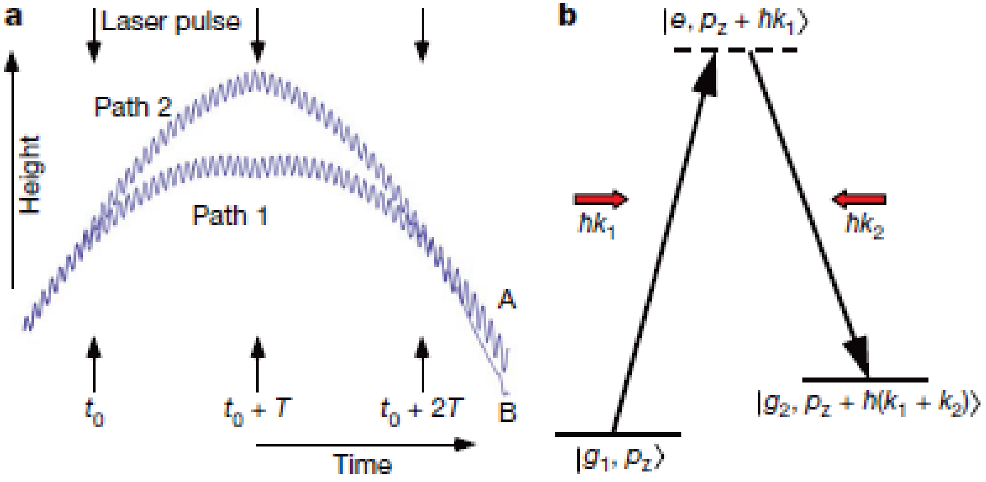
Does an atom interferometer measure the redshift at Compton frequency ?

nature Vol 463|18 February 2010|doi:10.1038/nature08776

LETTERS

A precision measurement of the gravitational redshift by the interference of matter waves

Holger Müller[1,2], Achim Peters[3] & Steven Chu[1,2,4]



Idea: describe the interferometer as beat note between two clocks at Compton frequency:

$$\omega_c = mc^2 / \hbar$$

ω_c=3.2 10^{25} Hz

Phase shift calculation in General Relativity

See, C. Bordé, 2008, and P. Storey and C. Cohen-Tannoudji, 1994

$$\Delta S = \oint L(\vec{x},\dot{\vec{x}})dt = \int_{1} L(\vec{x},\dot{\vec{x}})dt - \int_{2} L(\vec{x},\dot{\vec{x}})dt \quad \Longrightarrow \quad \Delta\varphi_s = \frac{\Delta S}{\hbar}$$

$$\Delta\varphi = \Delta\varphi_s + \Delta\varphi_L$$

Lagrangian in GR: $L_{GR}(z,\dot{z}) = -mc^2 \dfrac{d\tau}{dt} = -mc^2 + \dfrac{GMm}{r_{Earth}} - mgz + \dfrac{1}{2}m\dot{z}^2 + \mathrm{O}(1/c^2)$

One finds: $\Delta\varphi_s = \Delta\varphi_{red\,shit} + \Delta\varphi_{time\,dilation} = 0$

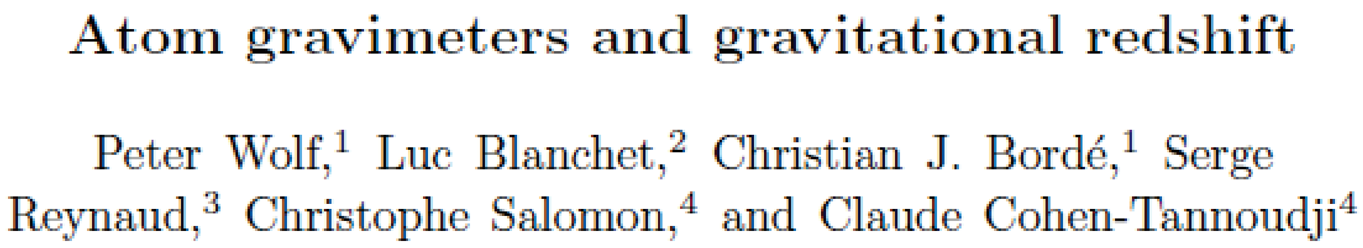
The 2 terms that depend on m cancel out !

The difference in the action integrals that involve the Compton frequency is zero
One cannot disentangle the sole contribution of the red shift.

One is left with: $\Delta\varphi = \Delta\varphi_L = kgT^2$

This instrument is a gravimeter !
Comparing g measured by atomic interferometry with the falling corner cube provides an interesting test of the universalitry of free fall at 7 10^{-9}

Beyond General Relativity



Atom gravimeters and gravitational redshift

Peter Wolf,[1] Luc Blanchet,[2] Christian J. Bordé,[1] Serge Reynaud,[3] Christophe Salomon,[4] and Claude Cohen-Tannoudji[4]

Comment in Nature 467,E1, September 2010,
and arXiv to be posted this week.

Modified Lagrangian frameworks: see C. Will book
Some versions of string theories,
THεμ
Lorentz-violating standard model extension (Kostelecky et al.)

The same conclusion $\Delta\varphi_s = 0$ is true when using the same Lagrangian for calculating the phase shift of matter waves and the atomic trajectories.

When does an atom interferometer provide a test of redshift ?

Only when multiple Lagrangians are used, does one get a non-zero effect. This means using a different Lagrangian for the atomic phase:

$$L_a(z,\dot{z}) = -mc^2 + \frac{GMm}{r_{Earth}} - (1+\beta)mgz + \frac{1}{2}m\dot{z}^2$$

and for the atomic trajectories:

$$L_b(z,\dot{z}) = -mc^2 + \frac{GMm}{r_{Earth}} - mgz + \frac{1}{2}m\dot{z}^2$$

But these theories violate:

- Feynman’s formulation of quantum mechanics, Schrödinger equation
- The principle of least action,
- Energy conservation
- Schiff’s conjecture !

The theory of the interferometer in this alternative to QM remains to be done !

Remark: if one uses the same term $(1+\beta)mgz$ in both Lagrangians, one always finds: $\Delta\varphi_s = 0$

Transfert de temps par ACES

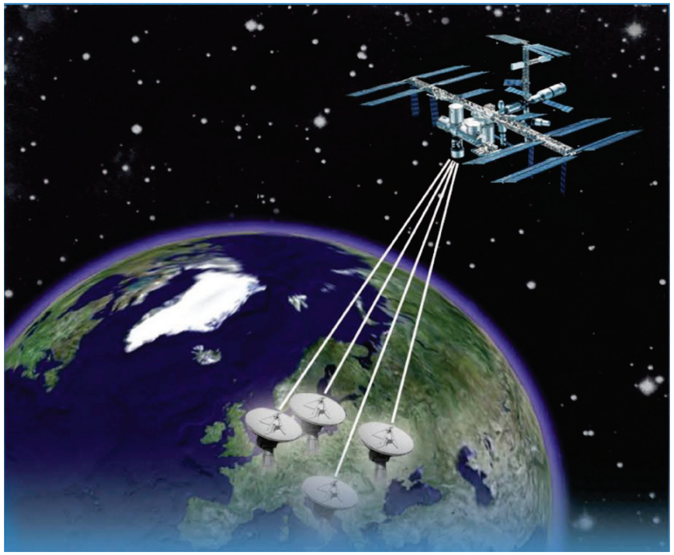
Ultra-stable frequency comparisons on a worldwide basis :

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

Contribution to TAI

Gain: x 20 wrt current GPS

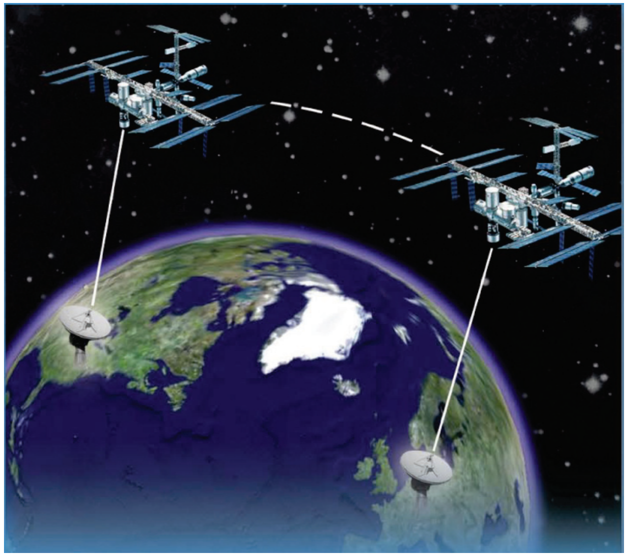
Common view



Error < 0.3ps over 300 s

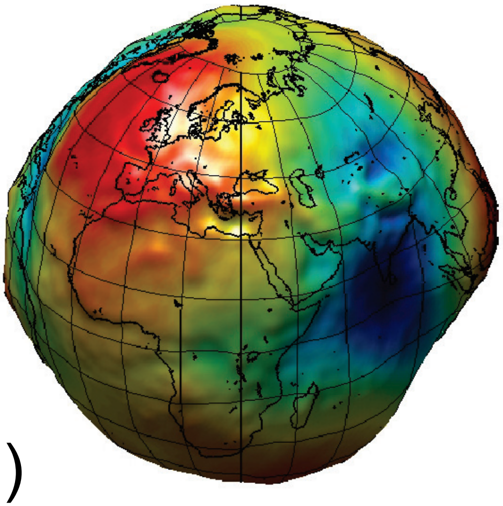
Can be checked by fiber-link

non common view



Error < 3ps over 3000 s

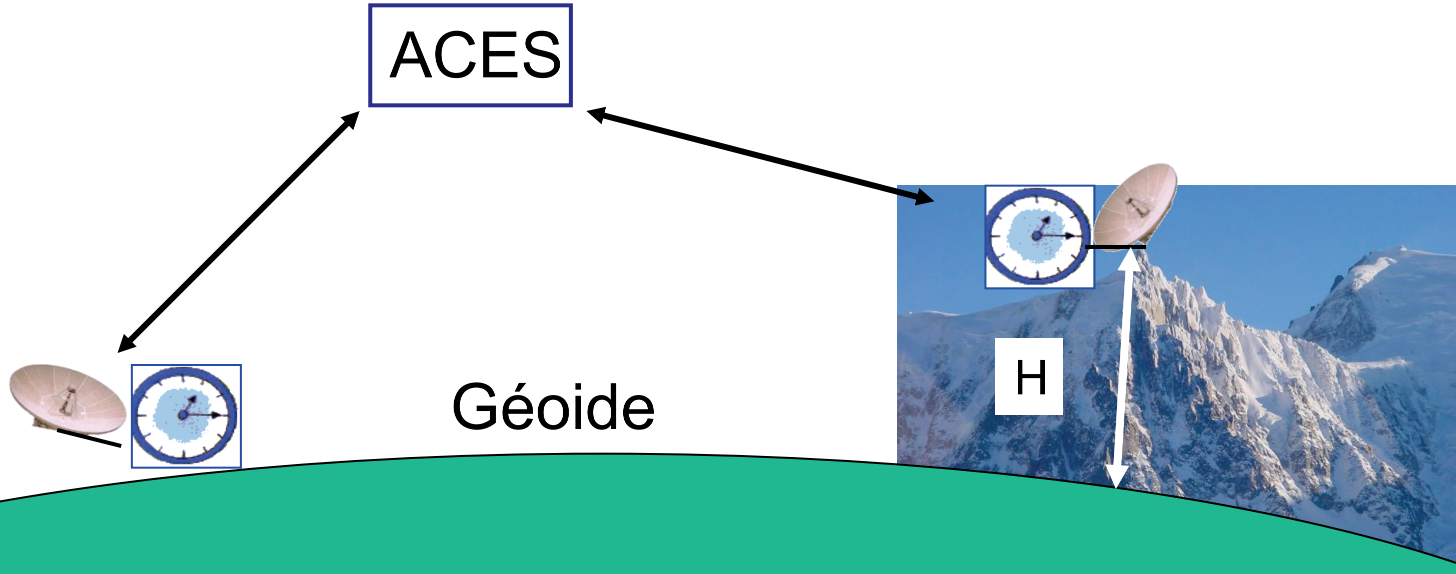
Géodésie relativiste



La fréquence de l'horloge dépend du potentiel gravitationnel, 10^{-16} par mètre

Horloges optiques: exactitude de 1 10^{-17} soit l'équivalent de 10 cm de hauteur (NIST'10)

Avec ACES:
Possibilité de mesurer la différence de potentiel entre les sites des deux horloges distantes à 10^{-17} soit 10 cm



Conclusions et perspectives

Les horloges permettent d'effectuer des tests des lois fondamentales de la physique

Décalage gravitationnel
Recherche d'une dérive des constantes fondamentales

Quelles limites pour les horloges atomiques ?

Les fluctuations du potentiel gravitationnel vont limiter la précision du temps à la surface de la la terre à 10^{-18} --10^{-19} cad 1cm à 1mm.

Vers une référence de temps spatiale