Systèmes de Référence Temps-Espace

Variation des constantes
Progrès des méthodes astrophysiques et en laboratoire

Jean-Philippe UZAN, Sébastien BIZE

Séminaire GreCO-SYRTE, 7 février 2008, Observatoire de Paris

Tests de variation des constantes fondamentales utilisant les horloges atomiques

Outline

- Sensibility of atomic transitions to varying constants.
- Principle of atomic clocks and review of some experimental methods.
- Comparisons of Rb and Cs hyperfine frequency at LNE-SYRTE. Recent results.
- Summary of clock results.
- Variation of constants with gravity.

TRANSITIONS ATOMIQUES ET CONSTANTES FONDAMENTALES (1)

- Atomic transitions and fundamental constants
  - Hyperfine transition
    $$\nu_{\rm hfs}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\rm hfs}^{(i)} \times g^{(i)} \left(\frac{m_e}{m_p}\right) \alpha^2 F_{\rm hfs}^{(i)}(\alpha)$$
  - Electronic transition
    $$\nu_{\rm elec}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\rm elec}^{(i)} \times F_{\rm elec}^{(i)}(\alpha).$$
  - See also, molecular vibrational and rotation => $(m_e/m_p)^{1/2}$, m_e/m_p

- Actual measurements: ratio of frequencies

$$\frac{\nu_{\rm elec}^{(ii)}}{\nu_{\rm elec}^{(i)}} \propto \frac{F_{\rm elec}^{(ii)}(\alpha)}{F_{\rm elec}^{(i)}(\alpha)}$$
$$\frac{\nu_{\rm hfs}^{(ii)}}{\nu_{\rm elec}^{(i)}} \propto g^{(ii)} \frac{m_e}{m_p} \alpha^2 \frac{F_{\rm hfs}^{(ii)}(\alpha)}{F_{\rm elec}^{(i)}(\alpha)}$$
$$\frac{\nu_{\rm hfs}^{(ii)}}{\nu_{\rm hfs}^{(i)}} \propto \frac{g^{(ii)}}{g^{(i)}} \frac{F_{\rm hfs}^{(ii)}(\alpha)}{F_{\rm hfs}^{(i)}(\alpha)}.$$

- Electronic transitions test α alone (electroweak interaction)
- Hyperfine and molecular transitions bring sensitivity to the strong interaction

TRANSITIONS ATOMIQUES ET CONSTANTES FONDAMENTALES (2)

- ✓ m_p , $g^{(i)}$ are not fundamental parameters of the Standard Model

- ✓ m_p , $g^{(i)}$, can be related to fundamental parameters of the Standard Model (m_q/Λ_{QCD}, m_s/Λ_{QCD}, $m_q=(m_u+m_d)/2$)

It is often assumed that : $\frac{\delta(m_s/\Lambda_{QCD})}{(m_s/\Lambda_{QCD})} = \frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})}$

*V. V. Flambaum et al., PR **D69**, 115006 (2004)*

- ✓ Recent accurate calculations have been done for some relevant transitions

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

- ✓ Any atomic transition (i) has a sensitivity to one particular combination of only 3 parameters (α, m_e/Λ_{QCD}, m_q/Λ_{QCD})

$$\delta \ln\left(\frac{\nu^{(i)}}{R_\infty c}\right) \simeq K_\alpha^{(i)} \times \frac{\delta\alpha}{\alpha} + K_q^{(i)} \times \frac{\delta(m_q/\Lambda_{\rm QCD})}{(m_q/\Lambda_{\rm QCD})} + K_e^{(i)} \times \frac{\delta(m_e/\Lambda_{\rm QCD})}{(m_e/\Lambda_{\rm QCD})}$$

COEFFICIENT DE SENSIBILITE DE QUELQUES TRANSITIONS

	κ_α	κ_q	κ_e
Rb hfs	2.34	-0.064	1
Cs hfs	2.83	-0.039	1
H opt	0	0	0
Yb^+ opt	0.88	0	0
Hg^+ opt	-3.2	0	0
Dy comb.	1.5 10^7	0	0

K_α, K_e : accuracy at the percent level or better

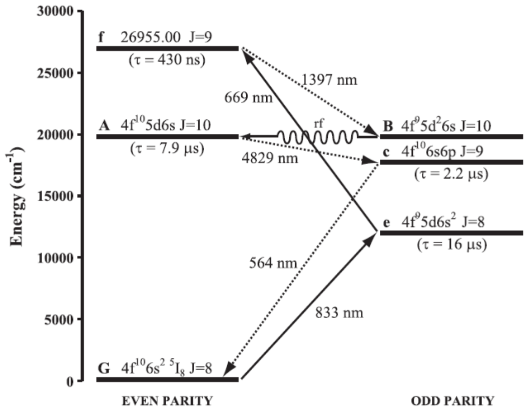
K_q : accuracy ?

Atom	^{87}Rb	^{133}Cs
Method A	−0.074	0.127
Method B	−0.056	0.044
Method C	−0.016	0.009

*PR **C73**, 055501 (2006)*

Dysprosium : RF transition between 2 accidentally degenerated electronic states

*Dzuba et al., PRL **82**, 888 (1999)*



In some diatomic molecules: cancellation between hyperfine and rotational energies also leads to large (2-3 orders of magnitude enhancement)

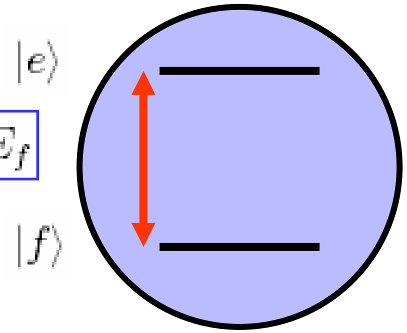
*Flambaum, PRA **73**, 034101 (2006)*

Principle of atomic clocks (1)

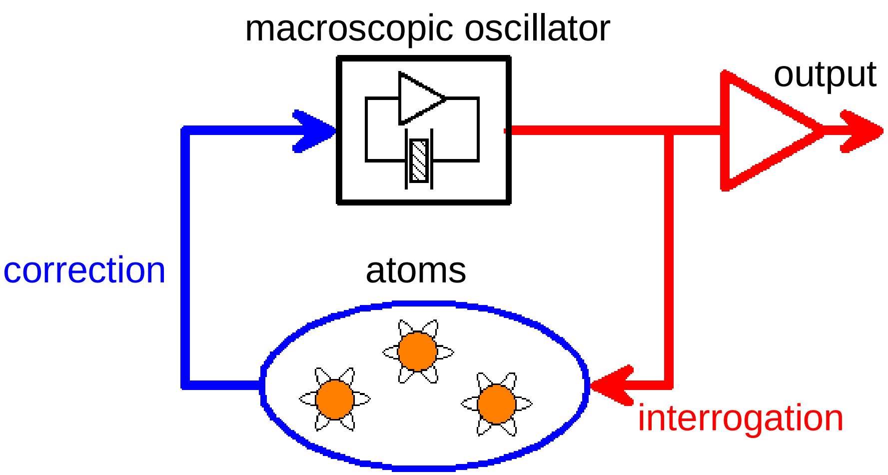
Goal: deliver a signal with stable and universal frequency

Bohr frequencies of unperturbed atoms are expected to be stable and universal

$$\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f$$



Building blocks of an atomic clock



$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

ε : fractional frequency offset

Accuracy: overall uncertainty on ε

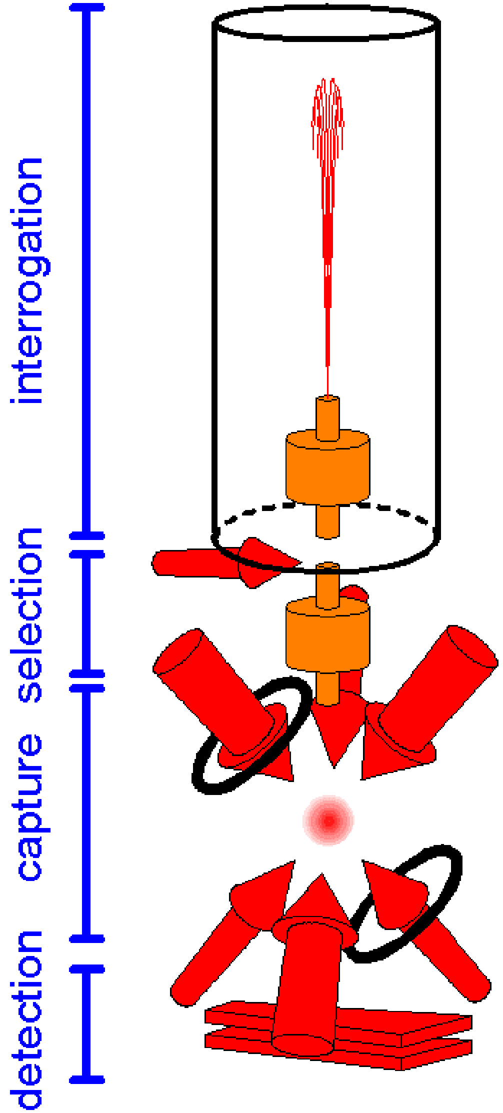
y(t) : fractional frequency fluctuations

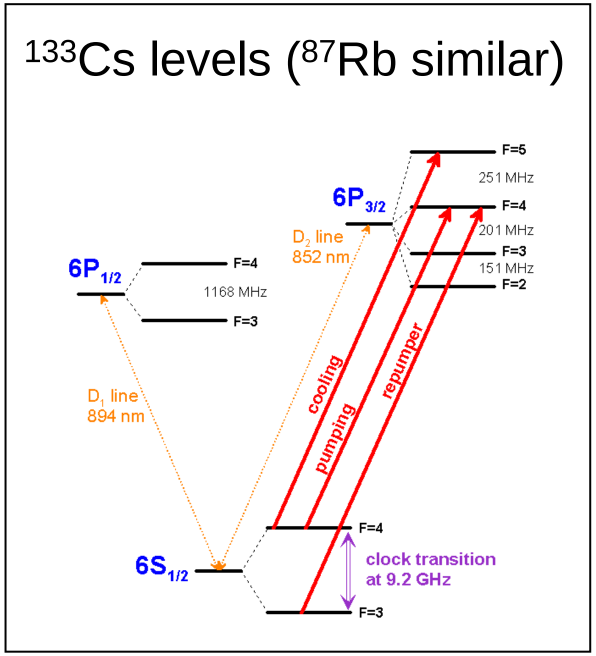
Stability: statistical properties of *y(t)*, characterized by the Allan variance $\sigma_y^2(\tau)$

Can be done with microwave or optical frequencies, with neutral atoms, ions or molecules

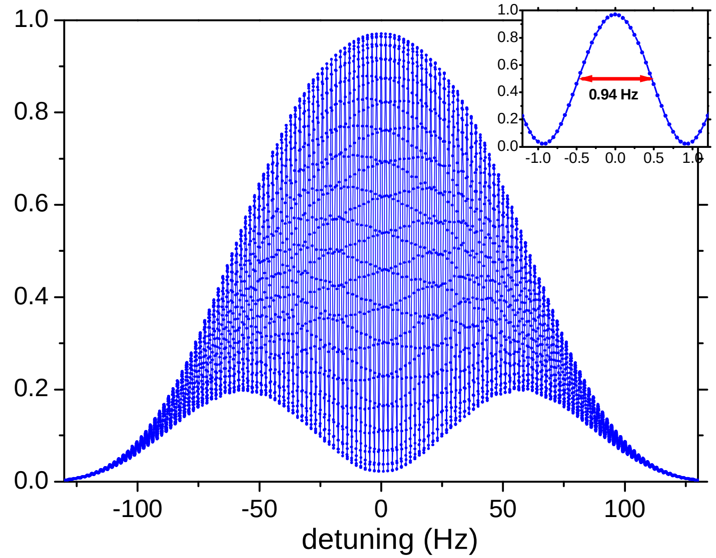
=> THESE GOALS CLOSELY MATCH THE NEED OF FUNDAMENTAL TESTS

Atomic fountain clocks





Ramsey fringes



Atomic quality factor:

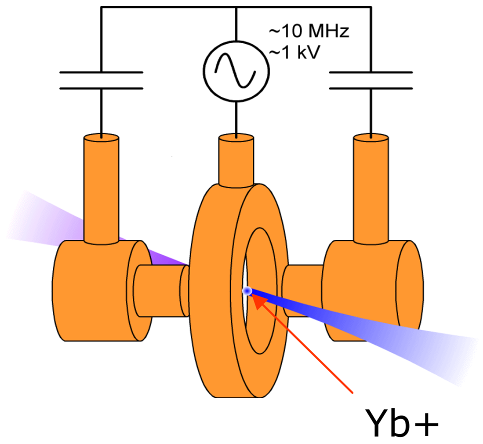
$$Q_{at} = \nu_{ef}/\Delta\nu \simeq 9.8 \times 10^9$$

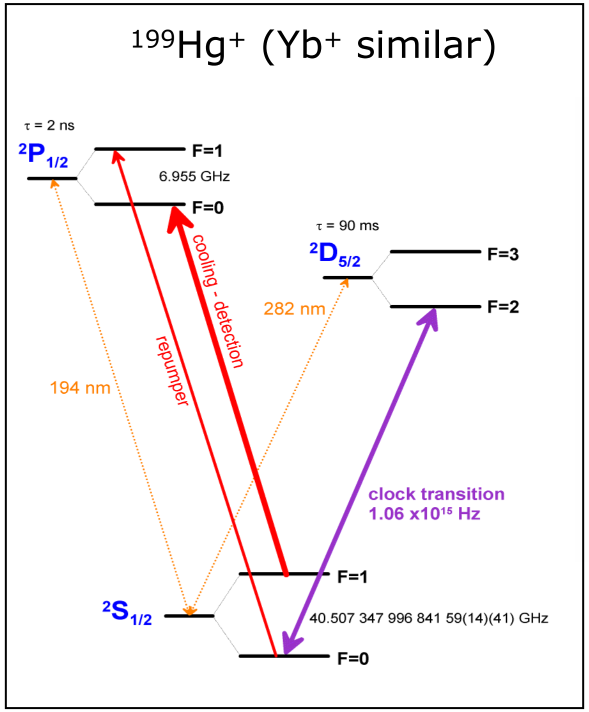
Best frequency stability: 1.6×10^{-14} @1s

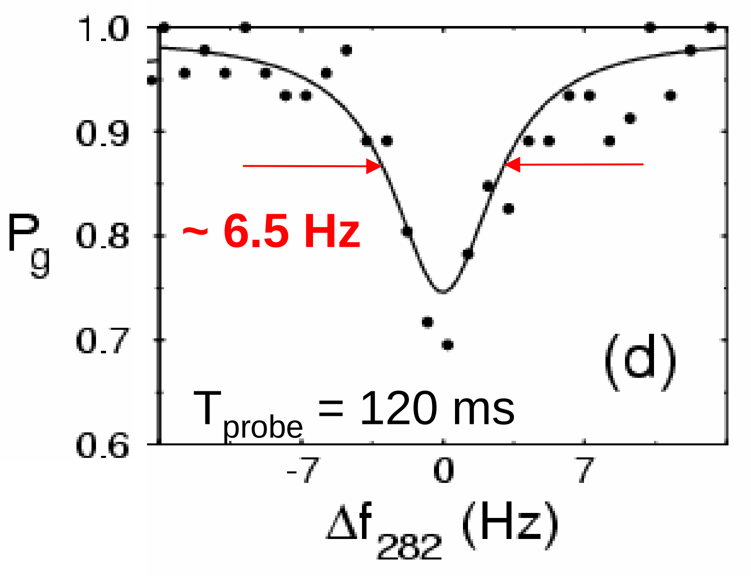
Best accuracy: 4×10^{-16}

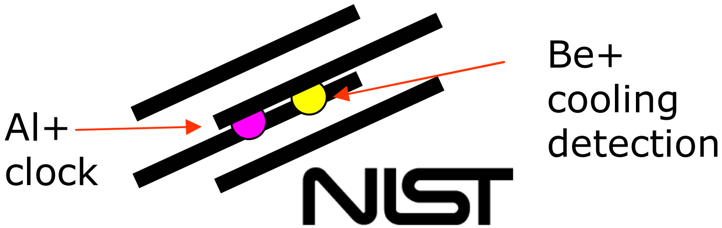
~ 10 fountains in operation (LNE-SYRTE, PTB, NIST, USNO, ON, INRIM, NPL, USP,…) with an accuracy ~10^{-15} and <10^{-15} for a few of them.

Trapped ion clocks









Atomic quality factor: ~1.5×10^{14}

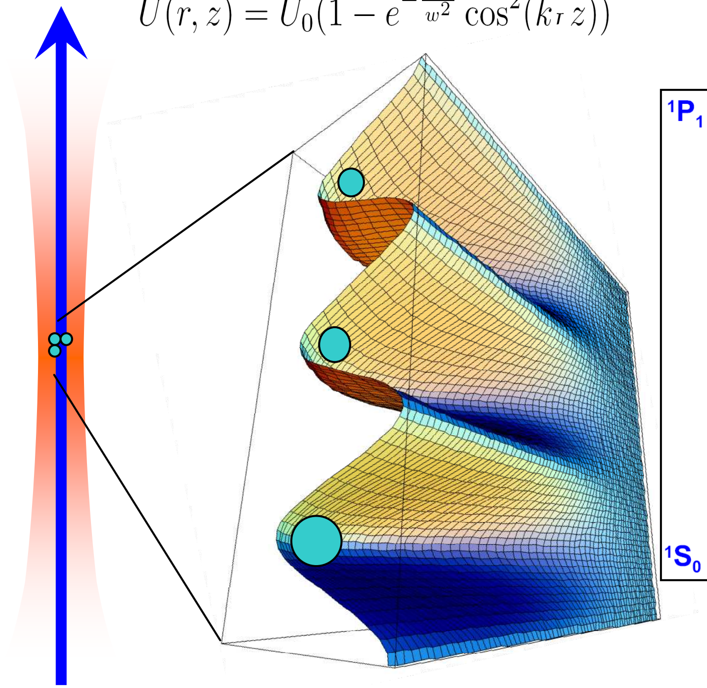
Best frequency stability: ~2×10^{-15} @1s

Best accuracy : ~2×10^{-17}

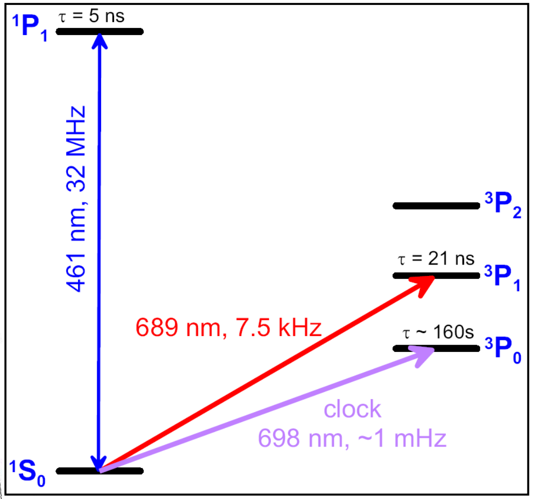
Work on trapped ion clock at NIST, PTB, NPL, Innsbruck,…

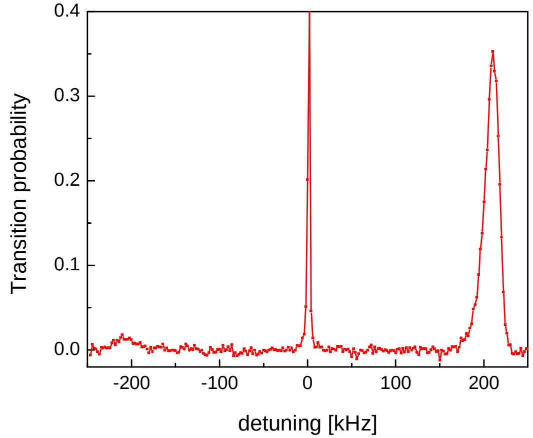
Optical lattice clocks

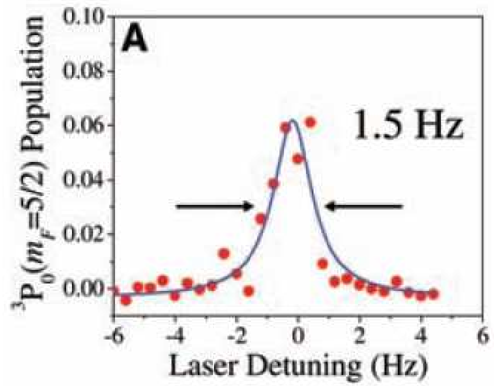
$$U(r,z) = U_0(1 - e^{-\frac{2r^2}{w^2}} \cos^2(k_l z))$$



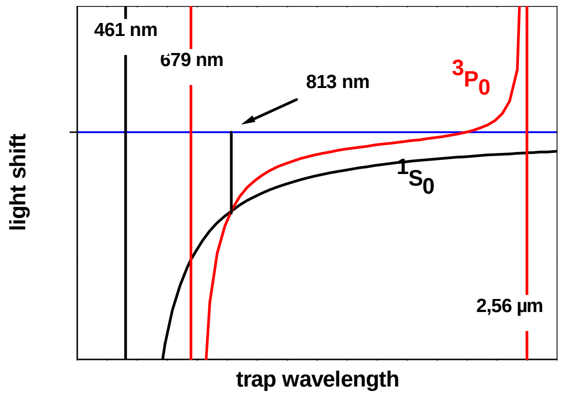
^{87}Sr (Yb, Hg similar)







"non-perturbing" dipole lattice trap



Atomic quality factor: ~2.8x10^{14}

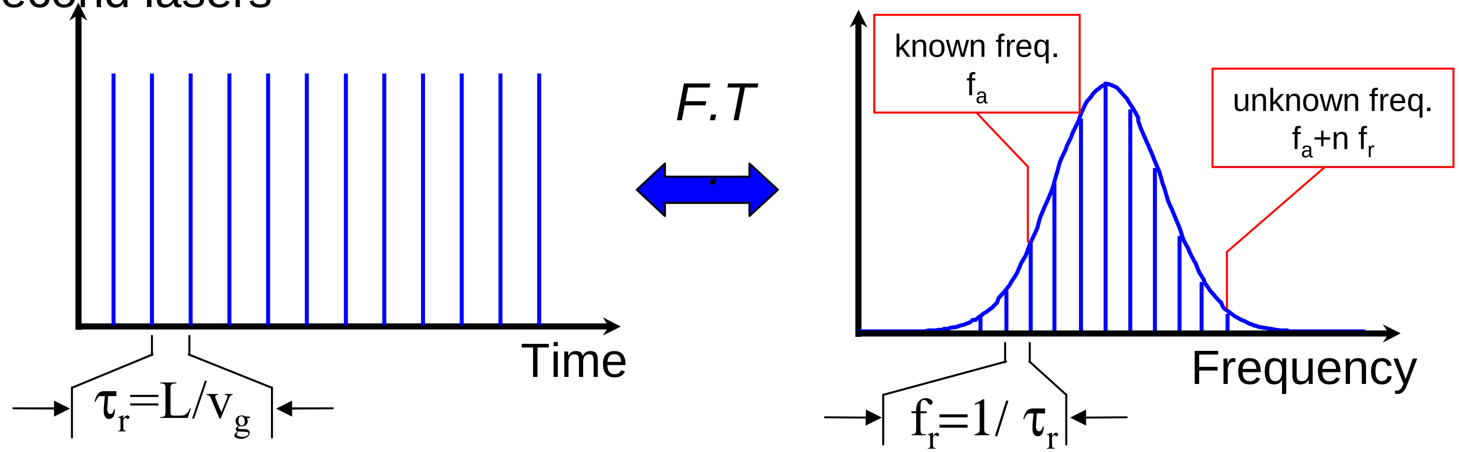
Best frequency stability: ~2x10^{-15} @1s

Best accuracy : ~1x10^{-16}

Work on optical lattice clocks at Tokyo university, LNE-SYRTE, JILA, NIST, INRIM,…

Comparison methods

Between several regions of electromagnetic spectrum (MHz to 10^{15} Hz): ultra low noise RF and microwave synthesizers and optical frequency combs generated by femtosecond lasers



Between remote clocks:

Satellite systems : GPS phase, TWSTFT : ~ 10^{-15} @1d, PHARAO/ACES when available

Telecom fibers :

Dissemination of RF frequency reference : few 10^{-15} @1s on <100 km scale

Dissemination of optical frequency reference : few 10^{-15} @1s on <100 km scale

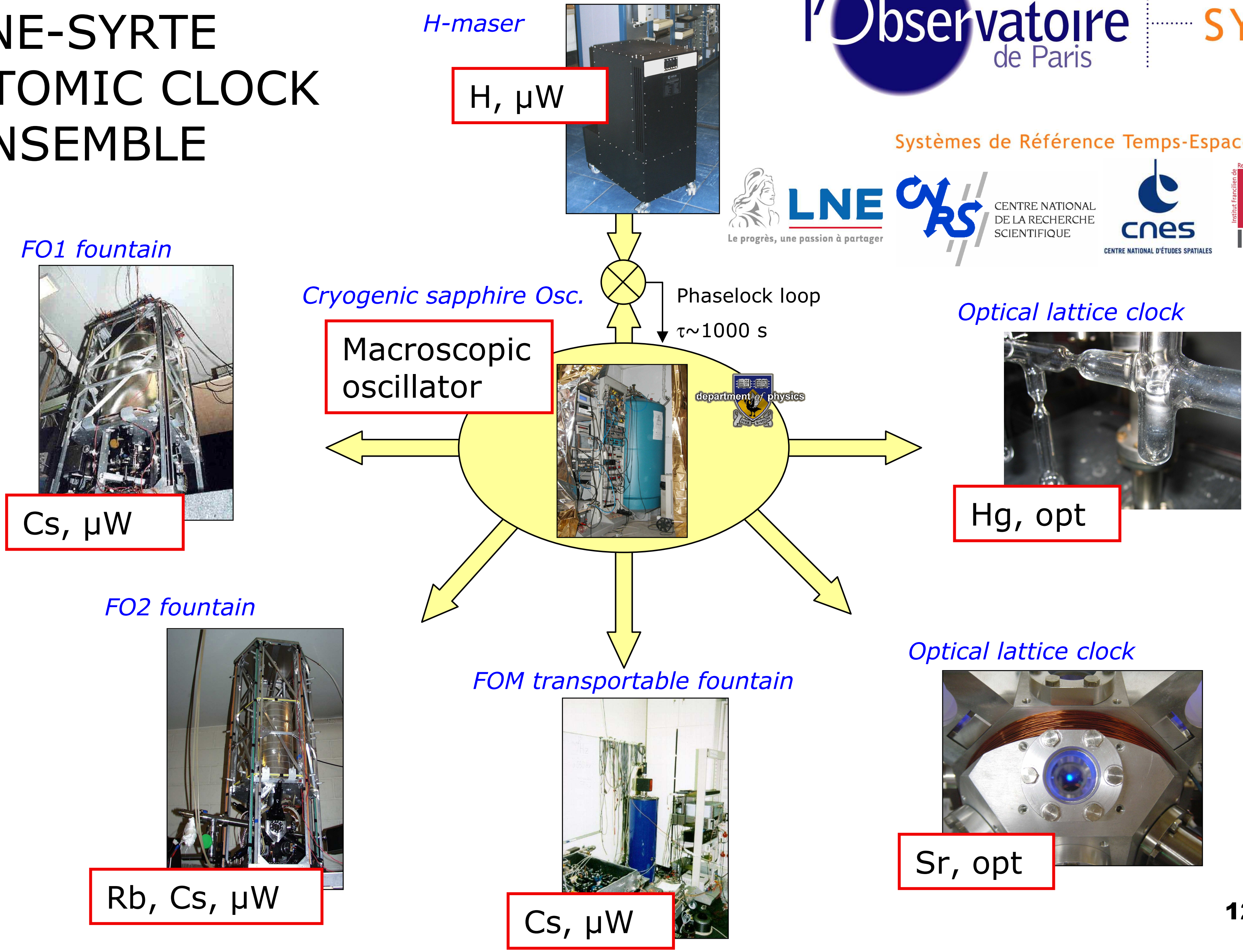
Dissemination of optical frequency reference on continental scale under study

LNE-SYRTE ATOMIC CLOCK ENSEMBLE

l'Observatoire de Paris — SYRTE

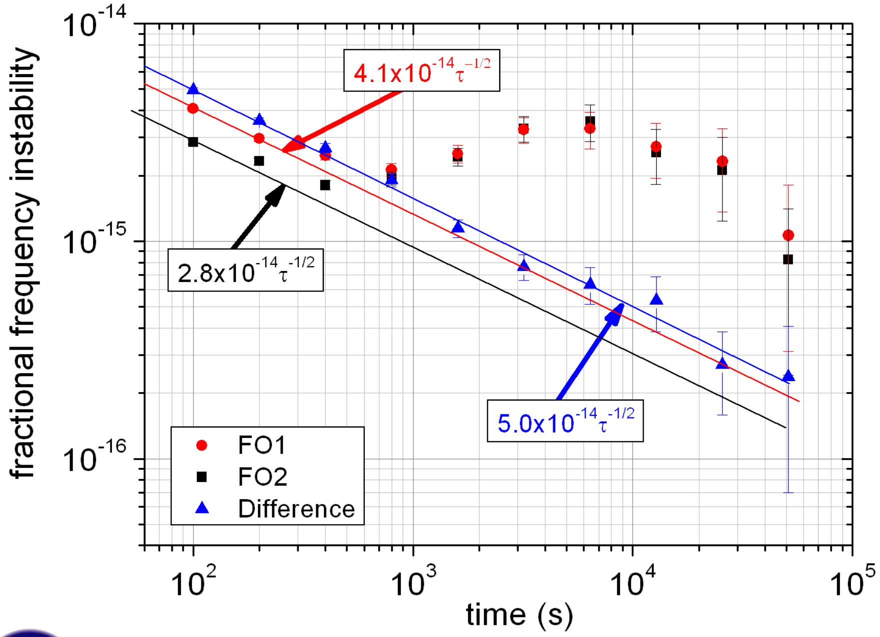
Systèmes de Référence Temps-Espace

LNE Le progrès, une passion à partager — CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE — cnes CENTRE NATIONAL D'ÉTUDES SPATIALES — IFRAF Institut Francilien de Recherche sur les Atomes Froids

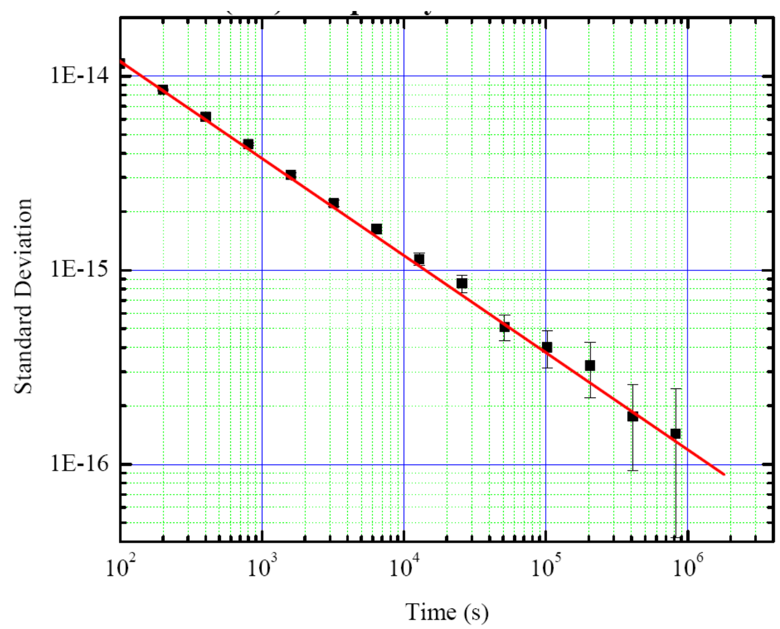


LNE-SYRTE FOUTAINS: FREQUENCY STABILITY AND ACCURACY

FO1 vs FO2-Cs (2004)



FOM vs FO2-Rb (Nov. 2007)



l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

LNE

Le progrès, une passion à partager

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

Institut Francilien de Recherche sur les Atomes Froids IFRAF

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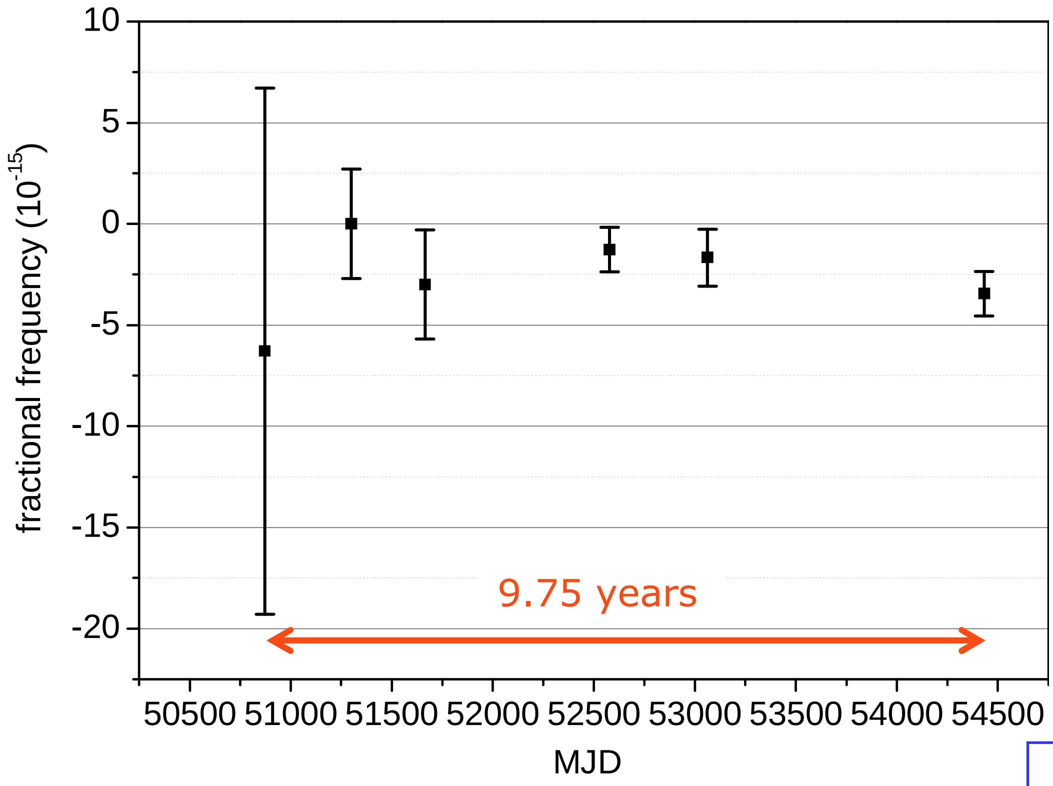
	FO1	FO2	FOM
Quadratic Zeeman	1927.3 +/- 0.3	1927.3 +/- 0.3	210.2 +/- 1.1
Blackbody radiation	-165.0 +/- 1.0	-168.2 +/- 0.6	-160.45 +/- 0.6
Collision and cavity pulling	-201.4 +/- 2.4	-357.5 +/- 1.0	-39.5 +/- 6.7
Microwave spectral purity & leakage	0 +/- 0.6	0 +/- 0.5	0 +/- 10.0
First order Doppler	< 3.2	< 3.0	< 3.2
Ramsey & Rabi pulling	< 0.1	< 1	< 0.1
Quantized motion ("microwave recoil")	< 1.4	< 1.4	< 1.4
Background collisions	< 0.3	< 1	< 1
TOTAL UNCERTAINTY	**4**	**4**	**12**

COMPARISON OF Rb and Cs HFS at LNE-SYRTE



one data point ⇔ ~1 to 2 months of measurements, with many checks of systematic shifts

Weighted least squares fit gives:

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

(improvement by ~2.3)

⇩

$$\frac{d}{dt}\ln\left(\frac{g_{\mathrm{Rb}}}{g_{\mathrm{Cs}}}\alpha^{-0.49}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

With further theory, nuclear g-factors can be related to m_q/Λ_{QCD}:

⇩

$$\frac{d}{dt}\ln\left(\alpha^{-0.49}\left[m_q/\Lambda_{\mathrm{QCD}}\right]^{-0.025}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

OVERVIEW OF MEASUREMENTS

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-3.2\pm2.3)\times10^{-16}\,\mathrm{yr}^{-1} = -0.49\frac{d}{dt}\ln(\alpha) - 0.025\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}})$$

LNE-SYRTE, JPB (2004)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Hg+}}}{\nu_{\mathrm{Cs}}}\right) = (3.7\pm3.9)\times10^{-16}\,\mathrm{yr}^{-1} = -6.03\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

NIST, PRL (2007)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Yb+}}}{\nu_{\mathrm{Cs}}}\right) = (-7.8\pm14)\times10^{-16}\,\mathrm{yr}^{-1} = -1.95\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

PTB, arXiv (2006)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{H}}}{\nu_{\mathrm{Cs}}}\right) = (-32\pm63)\times10^{-16}\,\mathrm{yr}^{-1} = -2.83\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

MPQ
+ LNE-SYRTE
PRL (2004)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Dy}}}{\nu_{\mathrm{Cs}}}\right) = (-4\pm3.9)\times10^{-8}\,\mathrm{yr}^{-1} = 1.5\times10^{7}\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

Berkley,
PRL (2007)

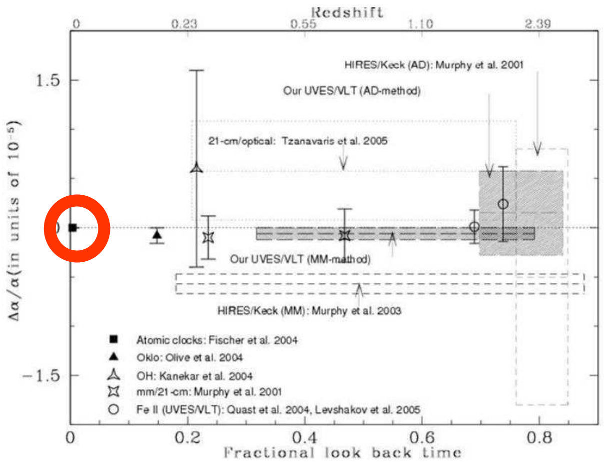
$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Sr}}}{\nu_{\mathrm{Cs}}}\right) = (-7\pm18)\times10^{-16}\,\mathrm{yr}^{-1} = -2.77\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

Tokyo
JILA
LNE-SYRTE
arXiv (2008)

- All optical frequency measurements are against Cs
- Only 2 hyperfine transitions Rb and Cs
- Direct optical vs optical measurements to come

LABORATORY TESTS: RESULTS

Using a weighted least squares fit to previous data:



$$\frac{d}{dt}\ln(\alpha) = (-3.5 \pm 3.0) \times 10^{-16}\,\mathrm{yr}^{-1}$$

$$\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) = (195 \pm 110) \times 10^{-16}\,\mathrm{yr}^{-1}$$

$$\frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}}) = (24.6 \pm 20) \times 10^{-16}\,\mathrm{yr}^{-1}$$

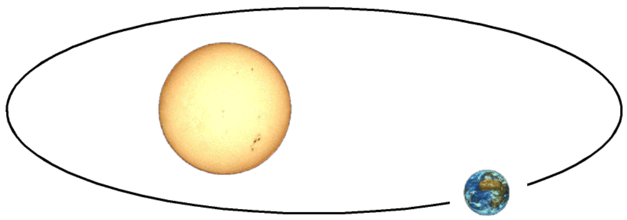
INDEPENDENT OF COSMOLOGICAL MODELS

- Limit on α var. is becoming competitive with Oklo ($\sim 10^{-17} yr^{-1}$) and Quasar limits ($\sim 10^{-16} yr^{-1}$) assuming linear change.
- Assuming linear change, limits on m_q and m_e do not exclude the positive result on m_e/m_p (Reinhold et al. 2006)

- However, still difficult to decorrelate variations of the different constants (correlation coefficients = -0.53, -0.96, 0.67).
- More accurate, and more diverse measurements are required!!

VARIATION OF CONSTANTS WITH GRAVITY

Annual modulation of the Sun gravitation potential at the Earth :



$$\frac{\Delta U(t)}{c^2} = -\underbrace{\frac{GM_S}{c^2 a}}_{\sim 1.6\ 10^{-10}} \epsilon \cos \phi(t).$$

Correlations with varying potential are searched in atomic clock data. Sensitivity of atomic transitions to α, m_q/Λ_{QCD} and m_e/Λ_{QCD} are as before.

Putative sensitivities of α, m_q/Λ_{QCD} and m_e/Λ_{QCD} to $\Delta U/c^2$ are defined: $\frac{\delta\alpha}{\alpha} = k_\alpha \frac{\Delta U(t)}{c^2}$,

*PR A **76**, 062104 (2007)*

Dy/Cs (Berkley)
Hg^+/Cs (NIST)
Cs/H(hfs) (NIST, SYRTE, PTB)

Parameter	Constraint
$k_\alpha + 0.17 k_e$	$(-3.5 \pm 6) \times 10^{-7}$
$\lvert k_\alpha + 0.13 k_q \rvert$	$< 2.5 \times 10^{-5}$
$k_\alpha + 0.13 k_q$	$(-1 \pm 17) \times 10^{-7}$
k_α	$(-8.7 \pm 6.6) \times 10^{-6}$
k_e	$(4.9 \pm 3.9) \times 10^{-5}$
k_q	$(6.6 \pm 5.2) \times 10^{-5}$

arxiv:0801.1874 (2008)

Sr/Cs (SYRTE,Tokyo,JILA)
Hg^+/Cs (NIST)
Cs/H(hfs) (NIST, SYRTE, PTB)

$$k_\alpha = (-2.3 \pm 3.1) \times 10^{-6}$$
$$k_\mu = (1.1 \pm 1.7) \times 10^{-5}$$
$$k_q = (1.7 \pm 2.7) \times 10^{-5}.$$

OTHER FUNDAMENTAL TESTS USING CLOCKS AND ULTRA STABLE OSCILLATORS

- ✓ LLI in the photon sector using CSO vs H-maser (SYRTE)

Wolf et al., Phys. Rev. Lett. 90, 060402 (2003)
Wolf et al., Gen. Rel. Grav. 36, 2351 (2004)
Wolf et al., Phys. Rev. D 70, 051902(R) (2004)

Most stringent Kennedy-Thorndicke experiment to date

$|\beta-\alpha-1<4.7\text{x}10^{-7}$

- ✓ LLI in the photon sector using rotating CORE and rotating CSO (UWA and Berlin Univ., Düsseldorf Univ.)

*Antonini et al., Phys. Rev. A **71**, 050101 (2005)*
*Stanwix et al., Phys. Rev. Lett. **95**, 040404 (2005)*

*Müller et al., Phys. Rev. Lett. **99**, 050401 (2007)*

Most stringent Michelson-Morley experiment to date

$(\delta-\beta+1/2)=9.4(8.1)\times10^{-11}$

- ✓ LLI in the matter sector using Zeeman transitions in Cs-hfs in atomic fountains (SYRTE)

P. Wolf et al., Phys. Rev. Lett. 96, 060801 (2006)

FUNDAMENTAL TESTS WITH PHARAO/ACES

- ✓ FM is being developed, yet with strong uncertainty on the development of the project
- ✓ If development continues, current launch schedule is 2014

- ✓ Measurement of the gravitational redshift

At *H*= 450km, gravitational redshift is 4.59 10^{-11}

With clock accuracy of 10^{-16}, the red-shift can be measured at 3×10^{-6}

Improvement by ~30 over GPA, R. Vessot et al. (1976).

- ✓ Enhanced comparisons between ground clocks through common view comparisons with PHARAO/ACES, down to the 10^{-17} level

Acknowledgments

J. Guéna, F. Chapelet, P. Rosenbusch, P. Laurent, G. Santarelli, M. Abgrall, D. Rovera, C. Salomon, A. Clairon, M.E. Tobar, A. Luiten, P. Wolf, D. Rovera, Y. Lecoq, X. Baillard, M. Fouché, R. Le Targat, P. Westergaard, A. Lecallier, J. Lodewyck, P. Lemonde, M. Petersen, D. Magalhães, C. Mandache, O. Acef, S. Dawkins, R. Chicireanu,…

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LNE
Le progrès, une passion à partager

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