Advances in atomic fountains and local comparisons at SYRTE

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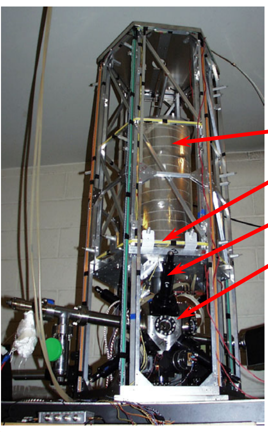
l'Observatoire de Paris — BNM-SYRTE
Systèmes de Référence Temps-Espace

Motivations

- ☐ **Improvement of the realization the SI unit of time**
  - Primary frequency standards with **better stability and accuracy**
  - **Calibration** of national and international **atomic timescales**
  - **Comparisons** with other primary labs
- ☐ **Fundamental tests**
  - Test of Local Position Invariance / test of the **stability of fundamental constants** through the comparison of clocks with different atomic species and/or type of transitions
  - Test of **Local Lorentz Invariance**
  - Measurement of the gravitational redshift with **PHARAO/ACES**
- ☐ **Investigation of atomic properties relevant to atomic clocks**
  - **Cold collision** properties of Cs and Rb
  - **Feshbach resonances** in Cs
  - Stark shift and **black body radiation** shift

Atomic fountains: Principles of operation

SYRTE Rb and Cs fountain FO2



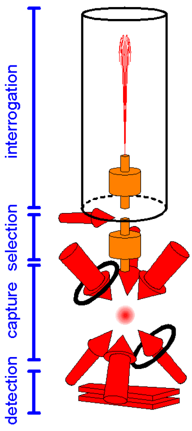
The 2 outermost shields are removed

Interrogation region with magnetic and thermal shields

Compensation coils

Collimator for molasses beams

Optical molasses



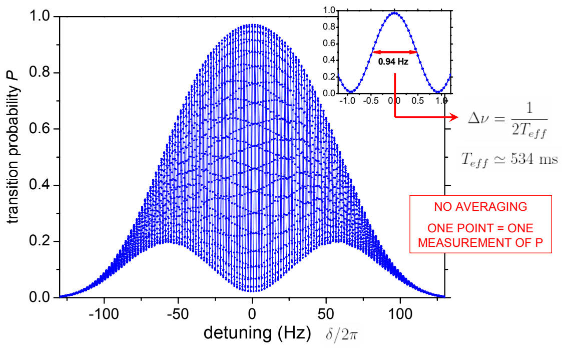
N_{at} ~2×10⁹
σ_r ~1.5–3mm
T ~1μK
ΔV ~2 cm.s⁻¹

V_{launch} ~ 4m.s⁻¹
H ~1m
T ~500ms

T_c ~0.8-2s

A. Clairon et al., Europhys. Lett. **16**, *165 (1991)*
A. Clairon et al., IEEE-IM **44**, *128 (1995)*
S. Ghezali et al., Europhys. Lett. **36**, *25 (1996)*
Ph. Laurent et al., Eur. Phys. J. D **3**, *201 (1998)*
E. Simon et al., Phys. Rev. A **57**, *436 (1998)*
S. Bize et al., Europhys. Lett. **45**, *558 (1999)*
G. Santarelli et al., Phys. Rev. Lett. **82**, *4619 (1999)*
Y. Sortais et al., Phys. Rev. Lett. **85**, *3117 (2000)*
M. Niering et al., Phys. Rev. Lett **84**, *5496 (2000)*
F. Pereira Dos Santos et al., Phys. Rev. Lett **89**, *233004 (2002)*
H. Marion et al., Phys. Rev. Lett **90**, *150801 (2003)*

Ramsey fringes in atomic fountain



$$\Delta\nu = \frac{1}{2T_{eff}}$$

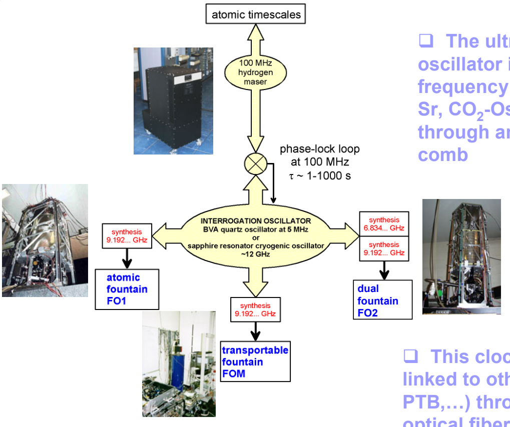
$$T_{eff} \simeq 534 \text{ ms}$$

NO AVERAGING
ONE POINT = ONE MEASUREMENT OF P

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

Fluctuations of the transition probability: $\sigma_{\delta P} \simeq 2\times 10^{-4}$

SYRTE fountain ensemble



- ☐ The ultra-stable cryogenic oscillator is also linked to optical frequency standards (laser cooled Sr, CO_2-OsO_4 stabilized laser) through an optical frequency comb
- ☐ This clock ensemble is also linked to other labs (LKB, LPL, PTB,…) through GPS, TWTFT and optical fibers

Improved microwave synthesis-Improved frequency stability

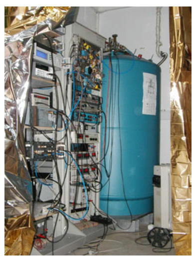
Sapphire cryogenic oscillator from the **University of Western Australia**

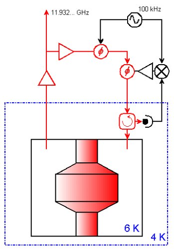
High quality factor sapphire resonator (Q ~ 4×10⁹) at 12 GHz

Turning point of temperature sensibility: dν/dT = 0 near T=6K

CSO has **extremely good short term stability** (measured at UWA against a second CSO)

$$\sigma_y(\tau = 1\text{s}) = 5\times 10^{-16}$$
$$\sigma_y(\tau = 10-100\text{s}) \sim 3\times 10^{-16}$$



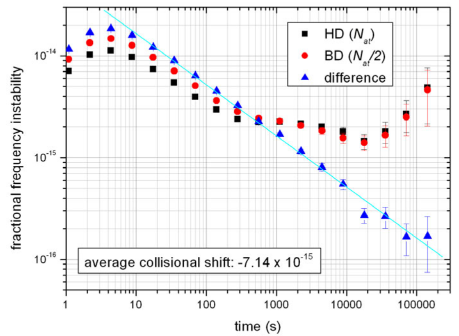


The CSO signal is divided to generate 9.2 GHz instead of multiplying a 100 MHz reference

This leads to an interrogation source with **very low phase noise** (stability of ~3×10⁻¹⁵ at 1s) and **less spurious 50 Hz sidebands**

G. Santarelli et al., Phys. Rev. Lett. **82**, *4619 (1999)*
A. Mann et al., IEEE-IM **50**, *519 (2001)*
P. Wolf et al., Phys. Rev. Lett. **90**, *060402 (2003)*

Typical measurement session with the CSO



FO2-Cs fountain vs CSO best fractional frequency stability: $\sigma_y(\tau) = 1.6\times 10^{-14}\tau^{-1/2}$

Almost **10 times better** than regular synthesis (based on quartz oscillator)

A fractional frequency resolution of 10⁻¹⁶ is achieved in ~6 hours of integration

Controlling the cold collision shift at the 10⁻³ level

"Adiabatic passage method": Principle

F. Pereira Dos Santos et al., Phys. Rev. Lett ***89****, 233004 (2002)*

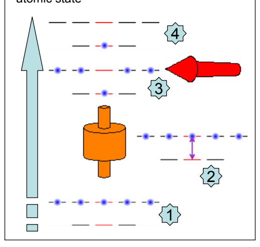
Goals: -Vary the atomic density with good relative precision

-Combine this method with the « differential measurement method » to precisely measure the cold collision shift *(the biggest limitation to Cs fountain)*

In a first configuration, the selection is done using adiabatic transfer to move 100% of the F=4,m_F=0 atoms in F=3, m_F=0

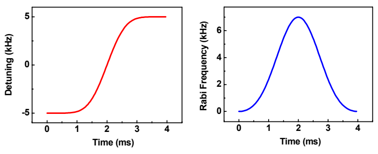
In a second configuration, the same adiabatic transfer is used but it is interrupted when the detuning is zero, leading to transfer of 50% of the F=4, m_F=0 atoms in F=3, m_F=0

Selection sequence and evolution of the atomic state



A B field is applied to split Zeeman sub-levels

Blackman pulses are used to minimize off-resonant excitation



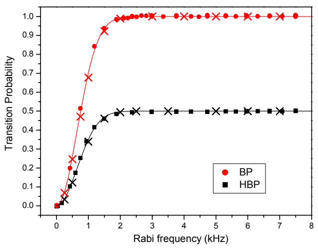
In both cases (50% and 100% transfer), the final transition probability does not depend on the field amplitude

In our condition, the final transition probability of the 50% transfer changes by 7×10⁻⁵ per Hz detuning

"Adiabatic passage method": Experiments

The final detuning of interrupted adiabatic passage (only critical parameter) is well controlled by generating the selection pulse with a DDS synthesizer.

Transition probability as a function of microwave amplitude
(calculation and measurement)



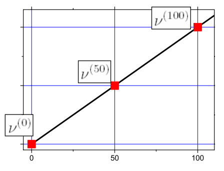
The value and the stability of the ratio between 50% and 100% configurations is monitored during each measurement. We find:

MEASURED

$$\frac{A_e^{(50)}}{A_e^{(100)}} = \frac{1}{2}\times\left(1+5\times 10^{-5}\right)$$

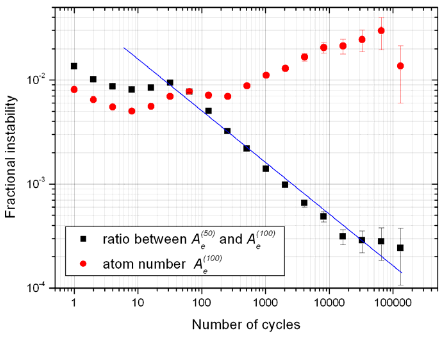
Extrapolation of the collision shift:

$$\nu^{(0)} = \nu^{(50)} - \left(\nu^{(100)} - \nu^{(50)}\right) = 2\times\nu^{(50)} - \nu^{(100)}$$



Limitation: residual populations in F=3, m_F states: ~3×10⁻³

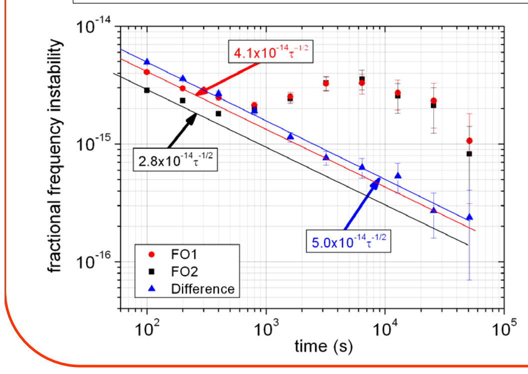
We have a practical realization of two atomic samples with a density ratio precisely equal to 1/2



Frequency comparisons between two ¹³³Cs fountains below 10⁻¹⁵

S. Bize et al., C.R. Physique 5 (2004)

Fractional frequency instability (Allan deviation) between FO1 and FO2 fountains & fractional frequency instability of **FO1** and **FO2** against the CSO locked to a hydrogen maser



For the first time: frequency comparisons in the low 10⁻¹⁶ range

This has been allowed by the routine operation of two atomic fountains near the quantum noise limit using the CSO as an interrogation oscillator

Each fountain is operated in differential mode ⇒ permanent evaluation of the collision shift

Stability

Direct comparison eliminates the local oscillator

After 50 000 s of averaging, the stability between the two fountains is $\sigma_y(\tau = 50\,000\text{s}) = 2.2\times 10^{-16}$

⇒ At least one of the two fountain has a stability below (2.2/√2) x 10⁻¹⁶ = 1.6 x 10⁻¹⁶

This very good stability sets a new challenge for time and frequency transfer systems between remote clocks

Current developments:
Long distance frequency comparisons with GPS and TWSTFT,
between primary frequency standards all over the world (NIST, PTB, NPL, IEN,…)

Accuracy

The **mean fractional frequency difference between the two fountains** is **4 x 10⁻¹⁶** fully compatible with the accuracy of each of the two clocks.

Systematic fractional frequency shifts for FO1 and FO2 ¹³³Cs fountains

	FO1 (×10¹⁶)	**FO2** (×10¹⁶)
Quadratic Zeeman effect	1199.7 ± 4.5	1927.3 ± 0.3
Blackbody radiation	-162.8 ± 2.5	-162.8 ± 2.5
Collisions and cavity pulling	-197.9 ± 2.4	-357.5 ± 2.0
Microwave spectral purity & leakage	0.0 ± 3.3	0.0 ± 4.3
First order Doppler effect	< 3	< 3
Ramsey & Rabi pulling	< 1	< 1
Microwave recoil	< 1.4	< 1.4
Second order Doppler effect	< 0.08	< 0.08
Background collisions	< 1	< 1
Total uncertainty	± 7.5	± 6.5

Stability fundamental constants

[Following the work of Prestage *et al.*, (1995)]

Frequency of hyperfine transitions as a function of fundamental constants (at lowest order):

$$\nu^{(i)}_{\text{hfs}} \simeq \underbrace{R_\infty c}_{\text{atomic unit of frequency}} \times \underbrace{\mathcal{A}^{(i)}_{\text{hfs}}}_{\text{purely numerical factor}} \times \underbrace{g^{(i)}}_{\text{nuclear g-factor}} \underbrace{\left(\frac{m_e}{m_p}\right)}_{\text{electron to proton mass ratio}} \alpha^2 \underbrace{F^{(i)}_{\text{hfs}}(\alpha)}_{\text{relativistic « correction » factor, function of the fine structure constant } \alpha}$$

Frequency of electronic transitions as a function of fundamental constants (at lowest order):

$$\nu^{(i)}_{\text{elec}} \simeq R_\infty c \times \mathcal{A}^{(i)}_{\text{elec}} \times F^{(i)}_{\text{elec}}(\alpha)$$

Sensitivity to variation of fundamental constants:

$$\delta\ln\left(\frac{\nu^{(i)}_{\text{hfs}}}{R_\infty c}\right) \simeq \frac{\delta g^{(i)}}{g^{(i)}} + \frac{\delta(m_e/m_p)}{(m_e/m_p)} + \left(2 + \alpha\frac{\partial}{\partial\alpha}\ln F^{(i)}_{\text{hfs}}(\alpha)\right)\times\frac{\delta\alpha}{\alpha}$$

$$\delta\ln\left(\frac{\nu^{(i)}_{\text{elec}}}{R_\infty c}\right) \simeq \left(\alpha\frac{\partial}{\partial\alpha}\ln F^{(i)}_{\text{elec}}(\alpha)\right)\times\frac{\delta\alpha}{\alpha}$$

[Following the work of V.V. Flambaum, arXiv:physics/0302015 (2003) and arXiv:hep-ph/0402098 (2004)]

$$\delta\ln\left(\frac{\nu^{(i)}}{R_\infty c}\right) \simeq K^{(i)}_\alpha\times\frac{\delta\alpha}{\alpha} + K^{(i)}_q\times\frac{\delta(m_q/\Lambda_{\text{QCD}})}{(m_q/\Lambda_{\text{QCD}})} + K^{(i)}_e\times\frac{\delta(m_e/\Lambda_{\text{QCD}})}{(m_e/\Lambda_{\text{QCD}})}$$

hfs: $K^{(i)}_\alpha \neq 0, K^{(i)}_q \neq 0, K^{(i)}_e \simeq 1$
elec: $K^{(i)}_\alpha \neq 0, K^{(i)}_q \simeq 0, K^{(i)}_e \simeq 0$
molecular vibration: $K^{(i)}_\alpha \simeq 0, K^{(i)}_q \simeq 0, K^{(i)}_e \simeq 1/2$

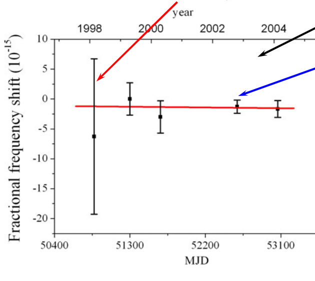
The $K^{(i)}$ are sensitivity coefficients for a particular clock comparison

Experiments at BNM-SYRTE: Comparisons between ⁸⁷Rb and ¹³³Cs hyperfine frequencies in atomic fountains over 7 years *H. Marion et al., Phys. Rev. Lett* ***90****, 150801 (2003)*

early measurement with a fractional uncertainty 1.3×10⁻¹⁴. Improvement by 10⁴ at the time.

one data point on this graph corresponds to ~2 months of measurements, with many checks on systematic shifts

best measurements with a fractional uncertainty of 1.3×10⁻¹⁵:



$$\nu_{\text{Rb}}(2002) = 6\ 834\ 682\ 610.904\ 324(4)(7)\ \text{Hz}$$

The most precisely known atomic frequency

$$\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = (-0.5\pm 5.3)\times 10^{-16}\,\text{yr}^{-1}$$

Stability of fundamental constants:

$$\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\alpha^{0.49}\left[m_q/\Lambda_{QCD}\right]^{0.174}\left[m_s/\Lambda_{QCD}\right]^{0.027}\right) = (0.5\pm 5.3)\times 10^{-16}\,\text{yr}^{-1}$$

H(1S-2S) absolute frequency measurements at MPQ with the BNM-SYRTE transportable fountain FOM
M. Niering et al., Phys. Rev. Lett ***84****, 5496 (2000) and M. Fischer et al., arXiv:physcics/0312086 (2003)*

Future work

- ☐ **Investigation of systematic effects at the 10⁻¹⁶ level**
  - Residual phase gradients
  - Recoil
  - ...
- ☐ **Tests of some components of the PHARAO space clock**
  - Microwave synthesizer (FO2)
  - Microwave cavity (FO1)
- ☐ **Improvements of the Rb part of FO2**
  - New Rb optical bench with improved reliability
  - 2D MOT
- ☐ **Rb vs Cs comparisons at the 10⁻¹⁶ level**
- ☐ **High stability and high accuracy comparisons with optical frequency standards (CO_2-OsO_4 stabilized laser, Sr optical clock,…)**