Atomic fountain as frequency standard

Seminari Dottorandi XXXII ciclo 08/06/17

Umberto Giacomelli

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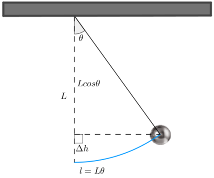
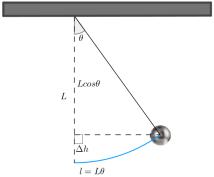
Why frequency standard

- Metrology
- Physcics experiment
- Navigation system



Why frequency standard

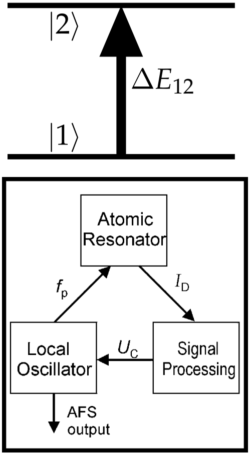
- Metrology
- Physcics experiment
- Navigation system



Kind of frequency standard

- Radio-frequency
- Optic

ATOMIC FREQUENCY STANDARD (AFS)

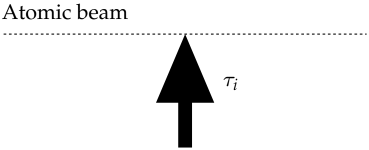


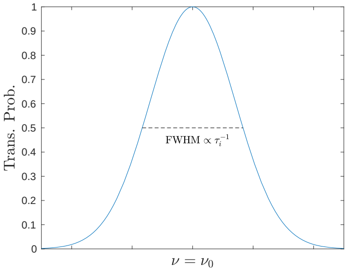
Scheme of the function of an AFS
Fig 5 from A. Bauch, H. R. Telle, Rep. Prog. Phys. **65** 789 (2002)

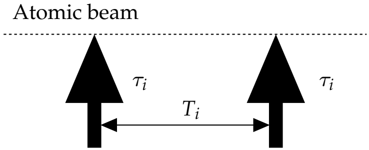
$$f = \frac{\Delta E_{12}}{h}$$

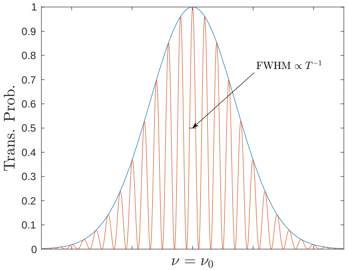
- f_p: probing frequency
- I_D: delivered response of atomic resonator in dependence of f_p
- U_C: LO Control signal generated by processing I_D

RAMSEY'S IDEA

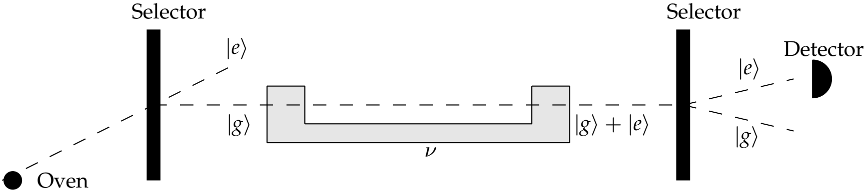








RAMSEY CAVITY



Readapted from Fig 18.1 of C. Cohen-Tannoudji, D. Guery-Odelin *Advances in Atomic Physics: An Overview*

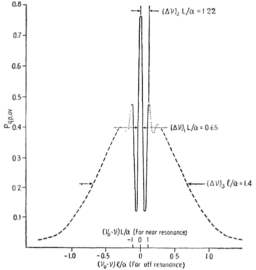


Fig 18.1 of N. F. Ramsey, Phys. Rev. **78** 695 (1950)

Using a thermal beam of cesium athoms with a mean velocity of $\sim 100\ \mathrm{ms}^{-1}$ we get a FWHM of 100 Hz with respect to a theorical central frequency $\nu_0 = 9.192631770$ GHz

REQUIREMENTS FOR A GOOD AFS

- Small natural linewidth of the transition
- Long interaction time of the atomic absorber with the probing radiation (or low velocity of the probed atoms)
- High signal-to-noise ratio in order to minimize statistical fluctuations in the signal used for control of the LO
- Minimal dependency of the atomic eigenstates energy to electric and magnetic fields

COOLING

Doopler

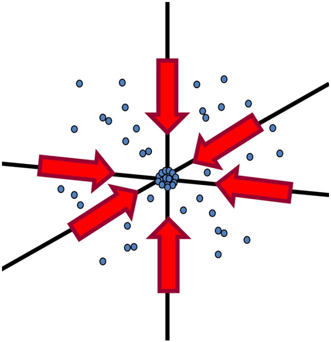


Fig 4.1 from D. L. Andrews, D. S. Bradshaw, Optical Nanomanipulation

Sisyphus

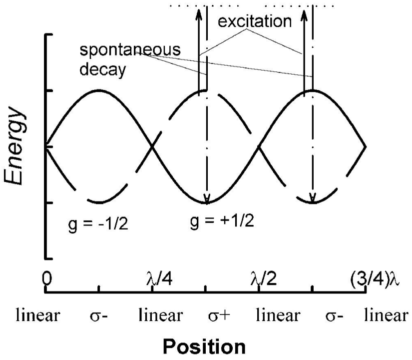


Fig 5 from A. Bauch, H. R. Telle, Rep. Prog. Phys. **65** 789 (2002)

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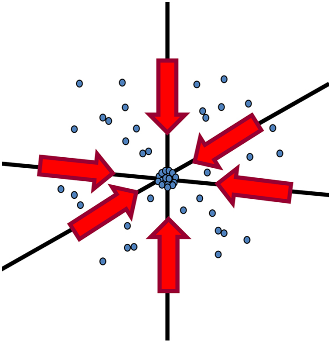

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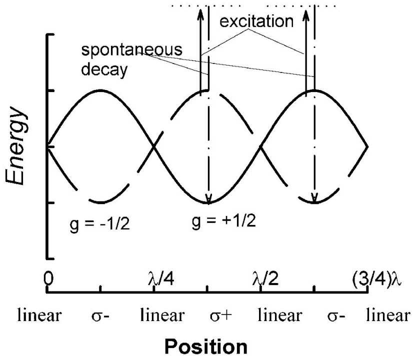


Fig 5 from A. Bauch, H. R. Telle, Rep. Prog. Phys. **65** 789 (2002)

In the case of cesium the final temperature is $\sim 2\mu$K corresponding to speed of 11mms^{-1}

FOUNTAIN CONFIGURATION

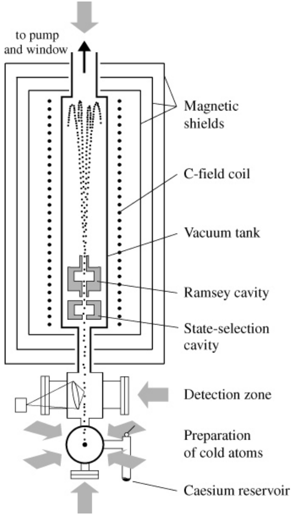


Fig 3 from R. Wynands, S. Weyers, Metrologia **42** (3) S64 (2005)

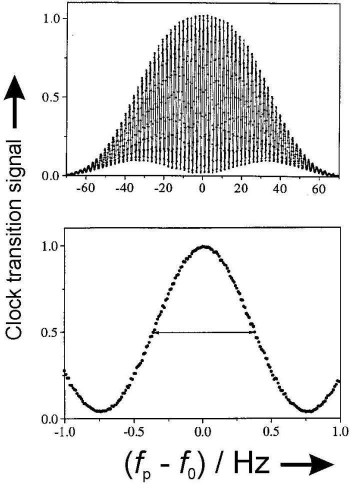
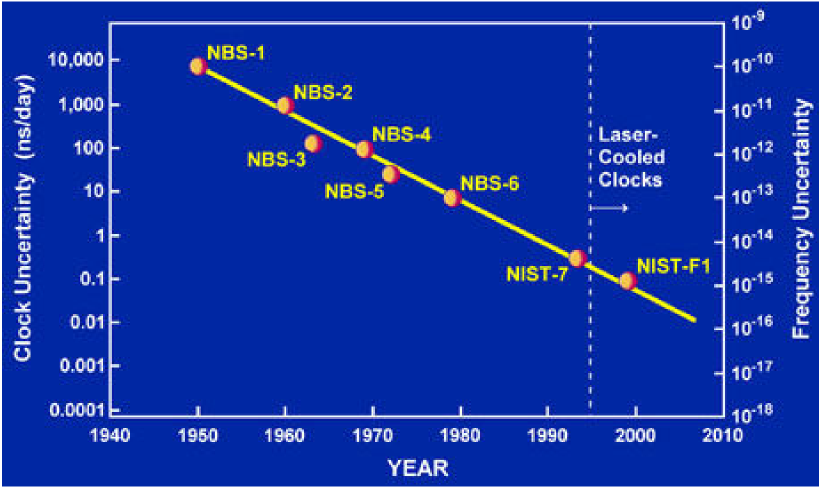


Fig 8 from A. Bauch, H. R. Telle, Rep. Prog. Phys. **65** 789 (2002)

COMPARISON


NBS-1
NBS-2
NBS-3
NBS-4
NBS-5
NBS-6
NIST-7
NIST-F1
Laser-
Cooled
Clocks
Clock Uncertainty (ns/day)
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
1940
1950
1960
1970
1980
1990
2000
2010
YEAR
Frequency Uncertainty
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18

NIST-F2 Apparatus

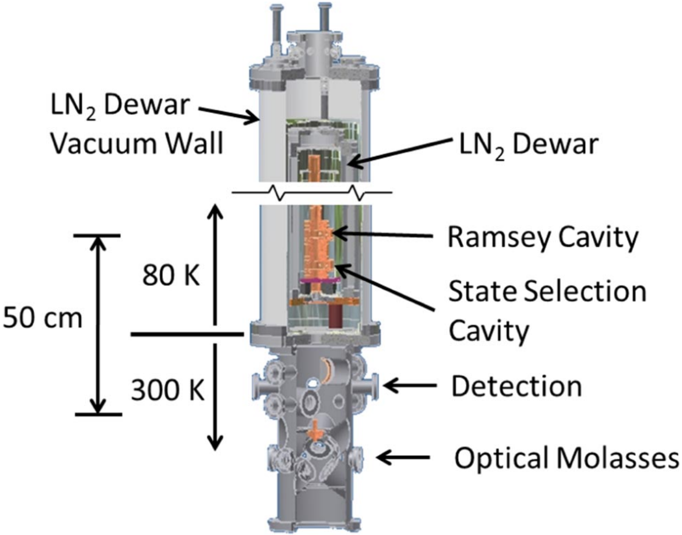


Fig 2 from T. P. Heavner et al Metrologia **51** (3) 174 (2014)

NIST-F2 UNCERTAINTIES AND STABILITY

Fractional Uncertainties type A $0.44 \cdot 10^{-15}$ type B $0.16 \cdot 10^{-15}$

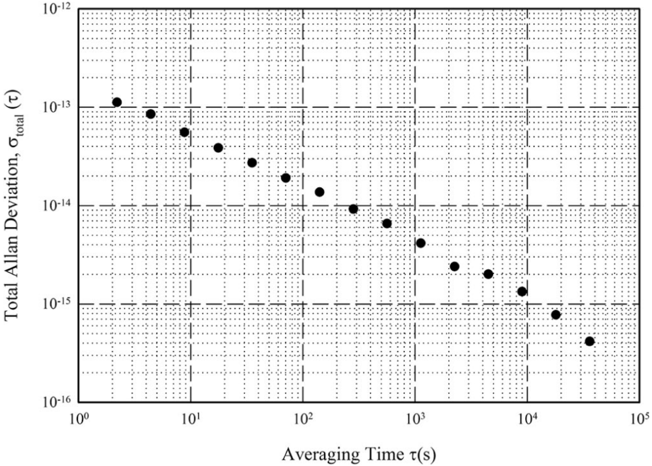
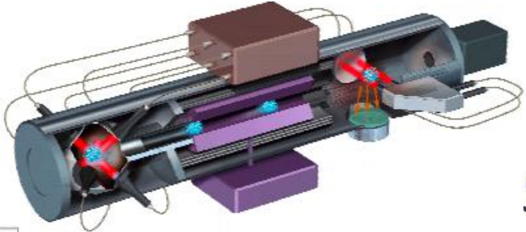
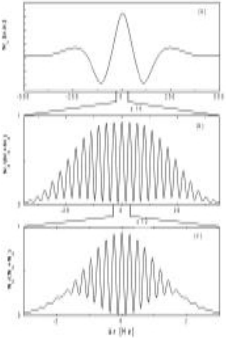


Fig 1 from T. P. Heavner et al Metrologia **51** (3) 174 (2014)

Atomic Clock Ensemble in Space (ACES)





- Thermal beam :
  v = 100 m/s, T = 5 ms Δν = 100 Hz
- Fountain :
  v = 4 m/s, T = 0.5 s Δν = 1 Hz
- PHARAO :
  v = 0.05 m/s, T = 5 s Δν = 0.1 Hz

THANK YOU FOR YOUR ATTENTION

REFERENCES

T. P. Heavner et al Metrologia **51** (3) 174 (2014)

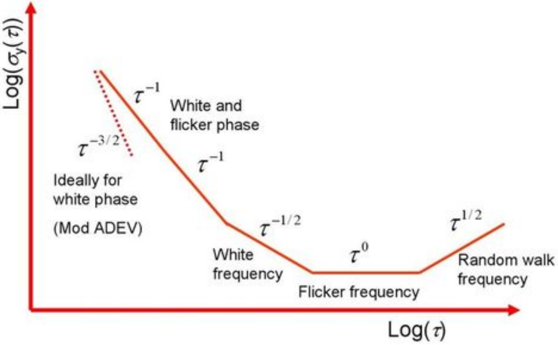
A. Bauch, H. R. Telle, Rep. Prog. Phys. **65** 789 (2002)

C. Cohen-Tannoudji, D. Guery-Odelin *Advances in Atomic Physics: An Overview*

Allan Deviation

$$\sigma_y(\tau) = \sqrt{\frac{1}{2(M-1)} \sum_{i=1}^{M-1} (\bar{y}_{i+1} - \bar{y}_i)^2}$$

where τ is the observation period, $\bar{y}_i$ is the ith fractional frequency average over τ, M is the number of values in the $\bar{y}_i$ series



Physical effect	Magnitude	Uncertainty
Gravitational redshift	179.87	0.03
Second-order Zeeman	286.06	0.02
Blackbody radiation	-0.087	0.005
Spin-exchange (low density)	-0.71	0.24
Spin-exchange non-linearity	0	0.02
Microwave amplitude effects		
Distributed cavity phase shift (DCPS)		
m = 0	<0.01	<0.01
m = 1	0	0.028
m = 2	0	0.02
Microwave power	<0.01	0.08
Microwave spurious	0	0.05
Cavity pulling	0.015	0.015
Rabi pulling	<0.01	<0.01
Ramsey pulling	<0.01	<0.01
Majorana transitions	<0.01	<0.01
Fluorescence light shift	<0.01	<0.01
Dc Stark effect	<0.01	<0.01
Background gas collisions	<0.01	<0.01
Bloch-Siegert	<0.01	<0.01
Integrator offset	<0.01	<0.01

Tab 1 from T. P. Heavner et al Metrologia **51** (3) 174 (2014)