Optical Frequency Standards

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

http://www.gocomics.com/nonsequitur/1994/07/21

What are they and what are they good for?

E.A.ALDEN
Leanhardt Lab
Department of Physics, University of Michigan

This talk

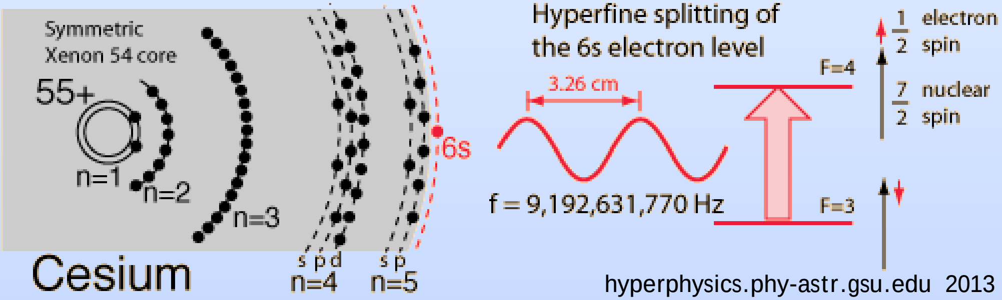
- Define Optical Frequency Standards
- Compare Frequency Standards
- Describe structure of an atomic clock

Units

80 $^1S_0$
Hg
Mercury
200.59
[Xe]$4f^{14}5d^{10}6s^2$
10.4375

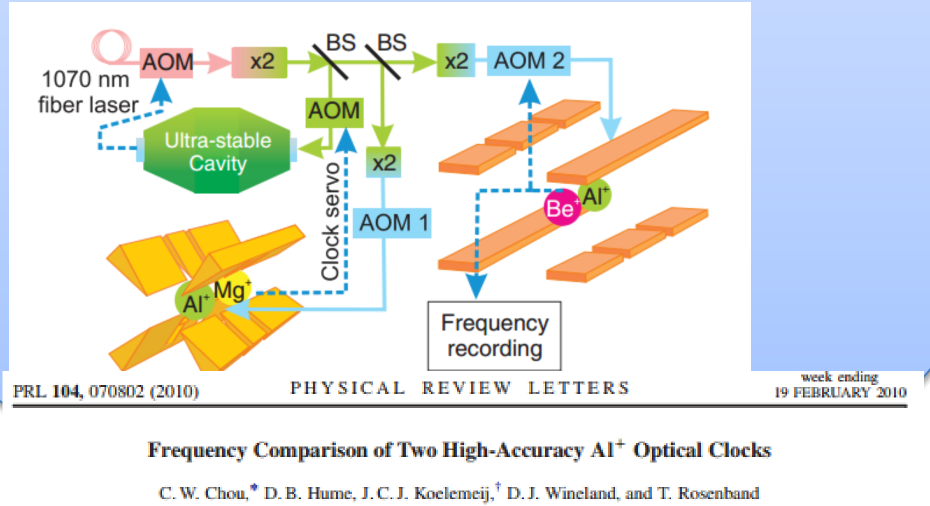
Time

Current standard:



hyperphysics.phy-astr.gsu.edu 2013

Future standard?



PRL **104,** 070802 (2010) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2010

Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks

C. W. Chou,* D. B. Hume, J. C. J. Koelemeij,† D. J. Wineland, and T. Rosenband

Mass

Current standard:

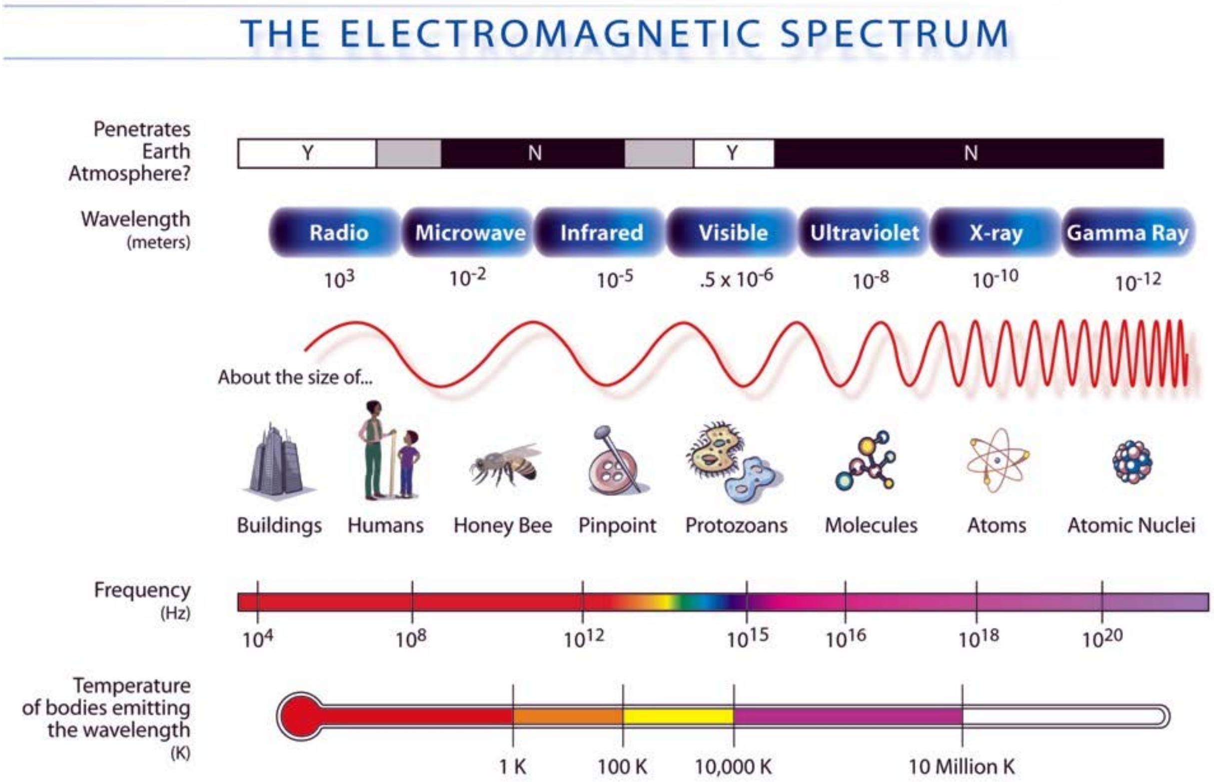
http://www.bipm.org/en/scientific/mass/pictures_mass/prototype.html

Future standard?

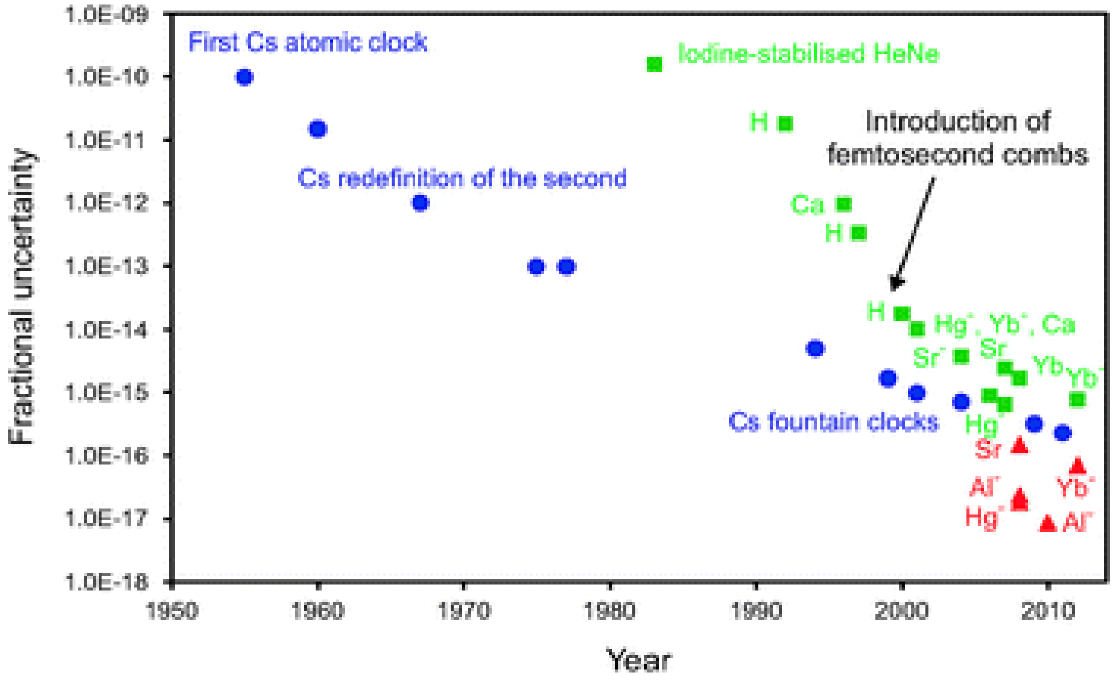
Avogadro Project

Make ν big

$$\sigma(\tau) = \left\langle \frac{\Delta\nu}{\nu} \right\rangle_{\tau}$$



Brief History of Time

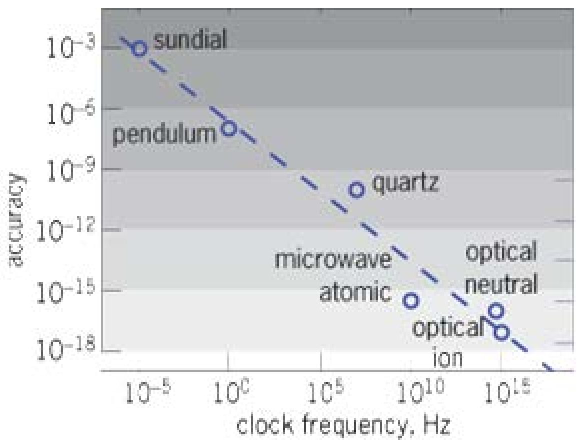


http://pubs.rsc.org/en/content/articlehtml/2012/cs/c2cs35163c
Accessed 2013

What is a clock?

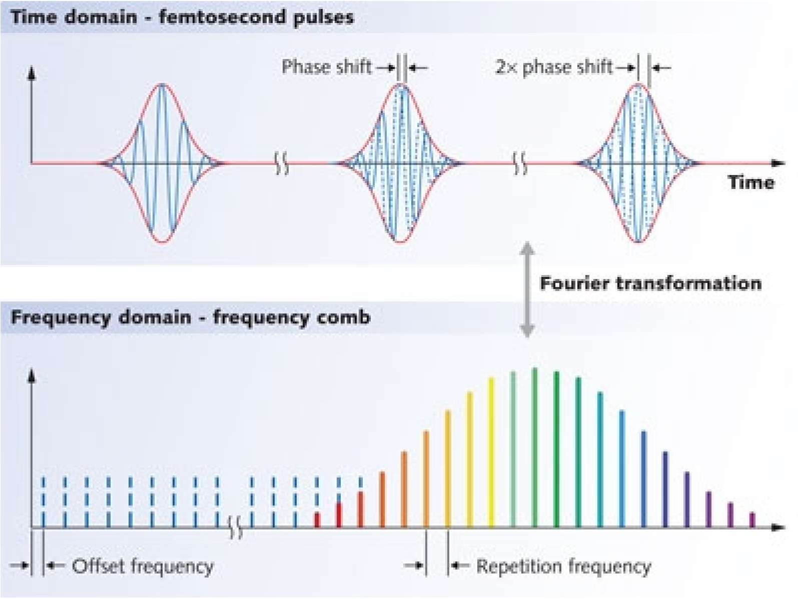
What is a good clock?

- Doesn’t lose many seconds?



Why is an atom a good clock?

- Assumption:
  - – atoms are equivalent
  - – α is constant
  - – light has constrained properties



www.laserfocusworld.com
Accessed 2013

Lingua Franca

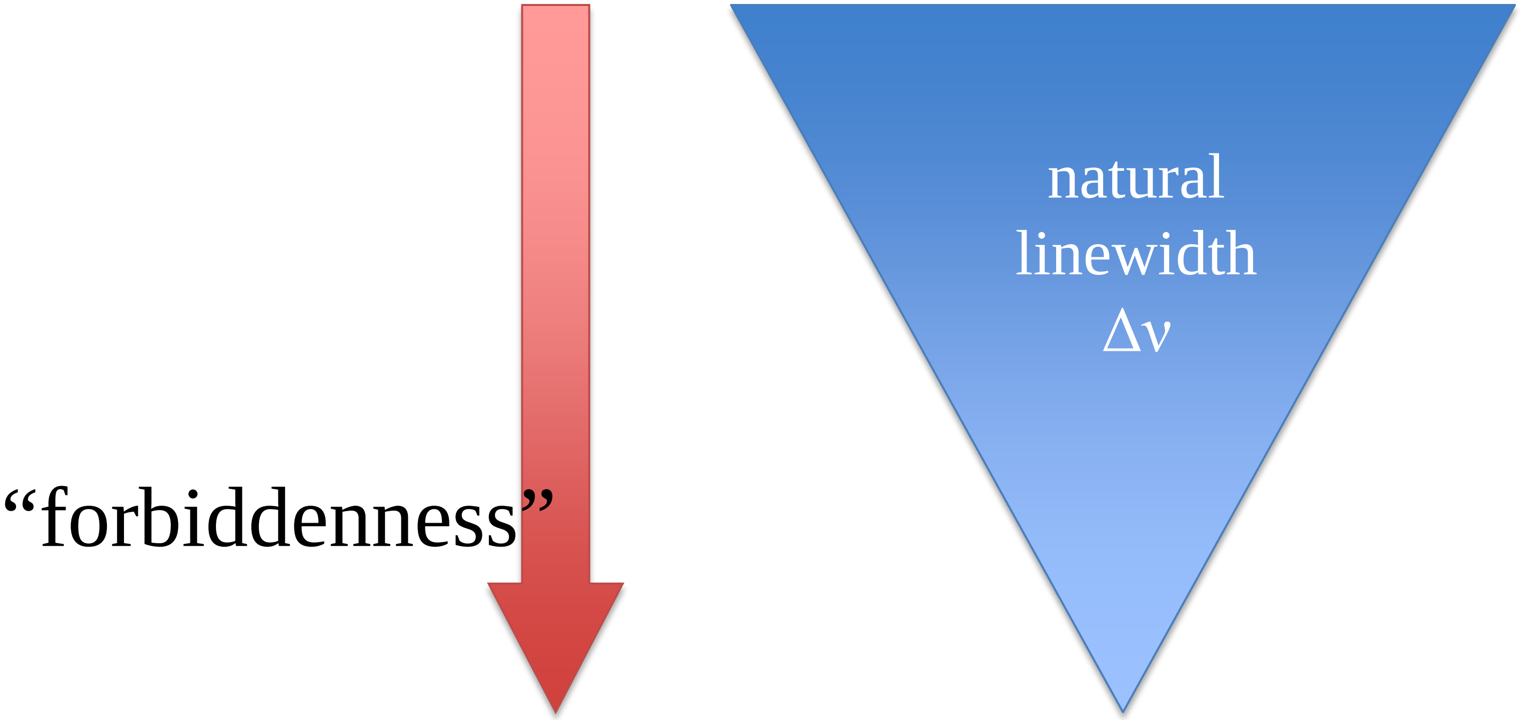
- Fractional frequency uncertainty

Theory Limit -

$$\sigma_\nu = \frac{\Delta\nu}{\nu}\sqrt{\frac{T}{\tau N}}$$

$\Delta\nu$ is the linewidth of the system
ν is the frequency of the sampling probe
T is the duty cycle of the experiment
τ is the total experiment time
N is the sample size per duty cycle

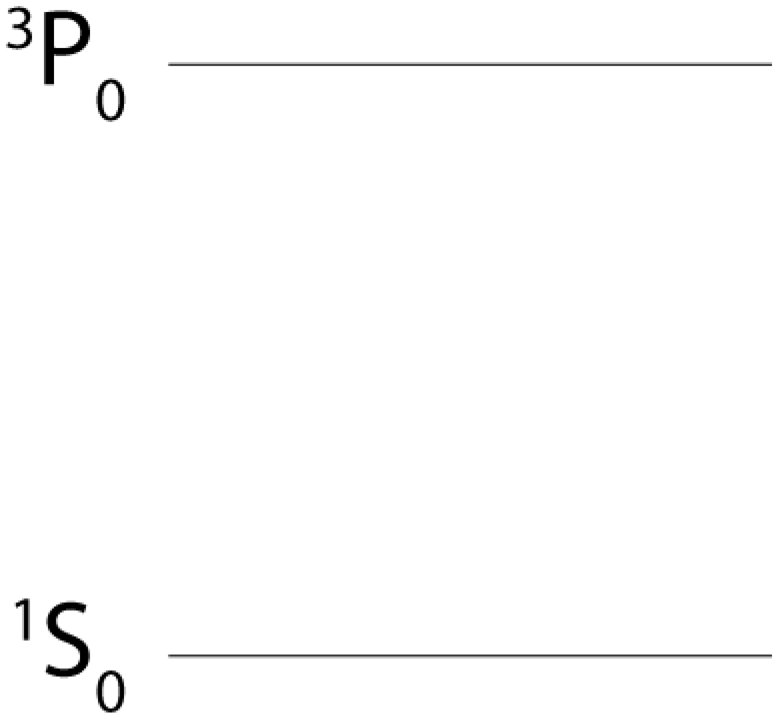
Choose Transition Wisely



“forbiddenness”

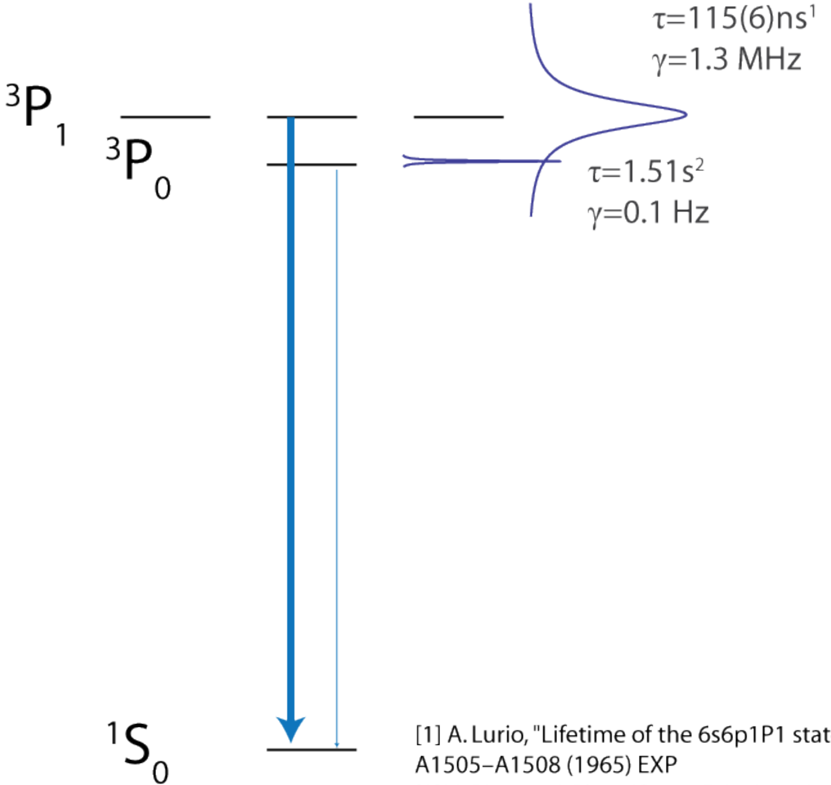
natural
linewidth
$\Delta\nu$

Optical Clock Level Structure



Narrow Linewidth Transition

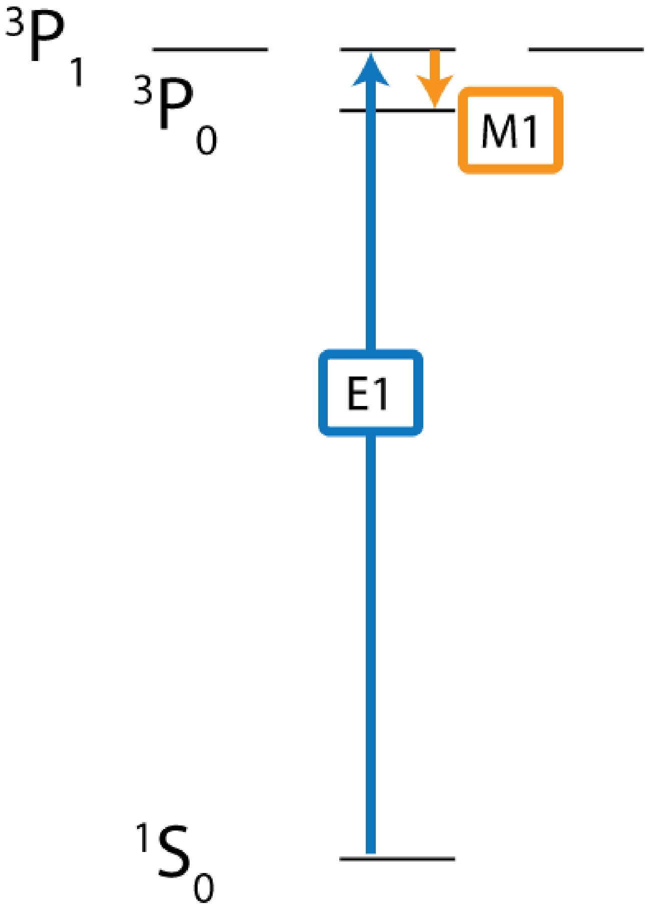
^{199}Hg I=1/2



[1] A. Lurio, "Lifetime of the 6s6p1P1 state of mercury," Phys. Rev. 140, A1505–A1508 (1965) EXP
[2]M. Bigeon, J. Phys. (Orsay, Fr.) 28, 51 (1967). THEORY

Even Narrower Transition?

80 $^1S_0$
Hg
Mercury
200.59
[Xe]$4f^{14}5d^{10}6s^2$
10.4375



Make Δν small

80 $^1S_0$
Hg
Mercury
200.59
$[Xe]4f^{14}5d^{10}6s^2$
10.4375

$$\sigma(\tau) = \left\langle \frac{\Delta\nu}{\nu} \right\rangle_\tau$$

- Narrow linewidth transition
- Narrow linewidth laser
- Large number of addressed resonators
- Long coherence times
- Long measurement times
- Laser excitation geometry (transit broadening)
- So on….

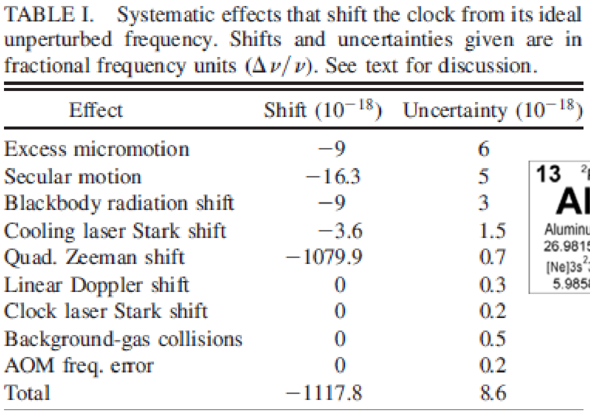
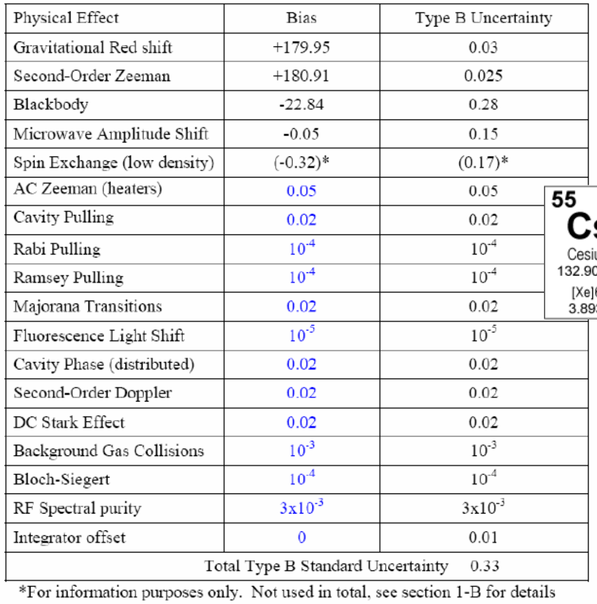


TABLE I. Systematic effects that shift the clock from its ideal unperturbed frequency. Shifts and uncertainties given are in fractional frequency units ($\Delta\nu/\nu$). See text for discussion.

Effect	Shift (10^{-18})	Uncertainty (10^{-18})
Excess micromotion	−9	6
Secular motion	−16.3	5
Blackbody radiation shift	−9	3
Cooling laser Stark shift	−3.6	1.5
Quad. Zeeman shift	−1079.9	0.7
Linear Doppler shift	0	0.3
Clock laser Stark shift	0	0.2
Background-gas collisions	0	0.5
AOM freq. error	0	0.2
Total	−1117.8	8.6

13 $^2P^\circ_{1/2}$
Al
Aluminum
26.981538
$[Ne]3s^23p$
5.9858

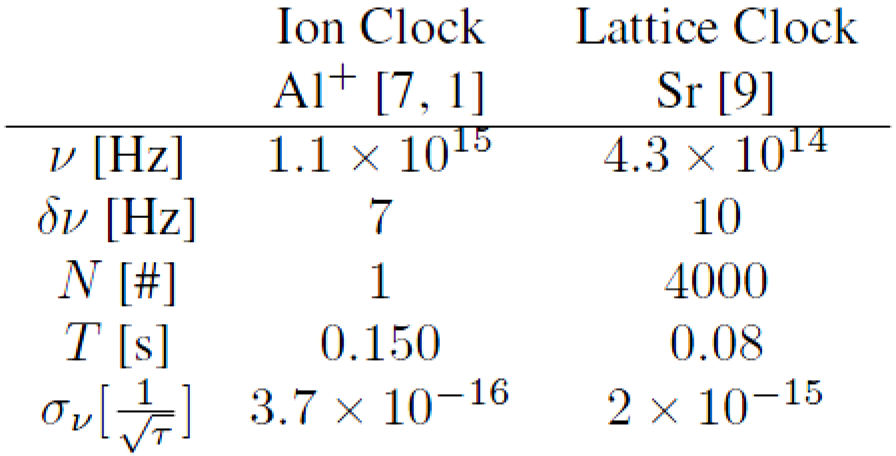


Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+180.91	0.025
Blackbody	-22.84	0.28
Microwave Amplitude Shift	-0.05	0.15
Spin Exchange (low density)	(-0.32)*	(0.17)*
AC Zeeman (heaters)	0.05	0.05
Cavity Pulling	0.02	0.02
Rabi Pulling	10^{-4}	10^{-4}
Ramsey Pulling	10^{-4}	10^{-4}
Majorana Transitions	0.02	0.02
Fluorescence Light Shift	10^{-5}	10^{-5}
Cavity Phase (distributed)	0.02	0.02
Second-Order Doppler	0.02	0.02
DC Stark Effect	0.02	0.02
Background Gas Collisions	10^{-3}	10^{-3}
Bloch-Siegert	10^{-4}	10^{-4}
RF Spectral purity	$3\text{x}10^{-3}$	$3\text{x}10^{-3}$
Integrator offset	0	0.01
	Total Type B Standard Uncertainty	0.33

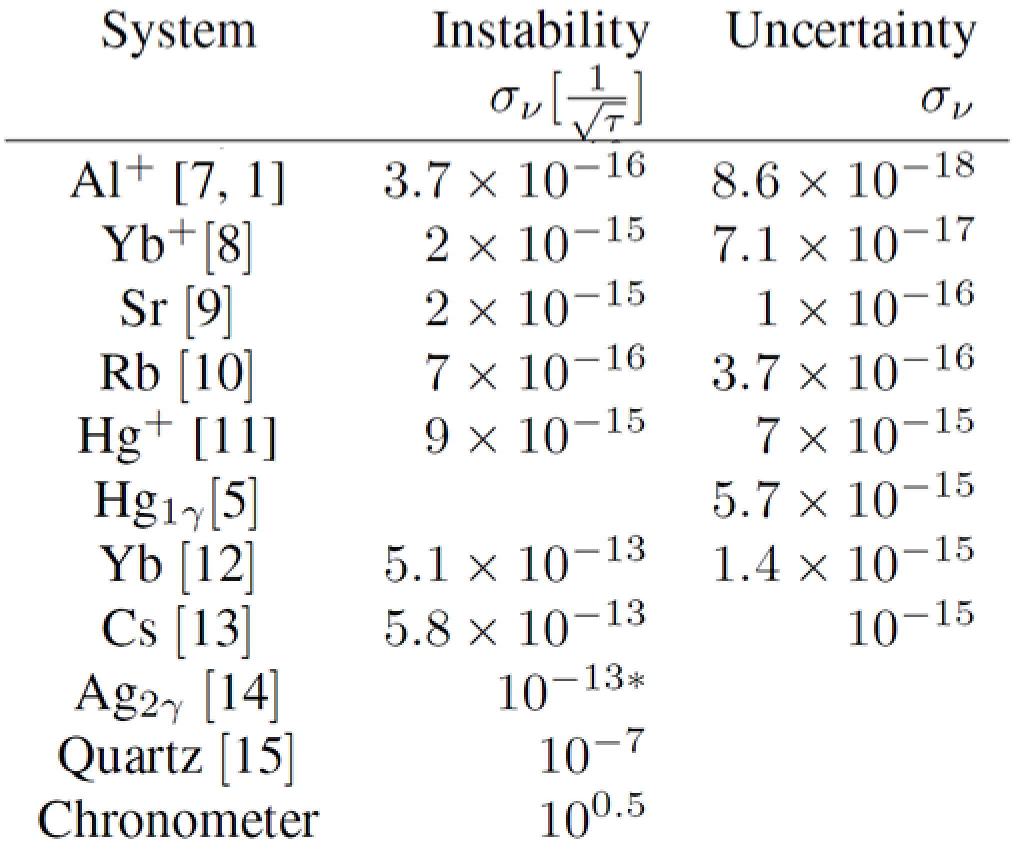
*For information purposes only. Not used in total, see section 1-B for details

55 $^2S_{1/2}$
Cs
Cesium
132.90545
[Xe]6s
3.8939

__Table 1__ – The list of known frequency biases for NIST-F1. This includes both the magnitude of the biases as well as the uncertainty of each individual contribution to the final uncertainty.



	Ion Clock Al^+ [7, 1]	Lattice Clock Sr [9]
ν [Hz]	1.1×10^{15}	4.3×10^{14}
$\delta\nu$ [Hz]	7	10
N [#]	1	4000
T [s]	0.150	0.08
$\sigma_\nu[\frac{1}{\sqrt{\tau}}]$	3.7×10^{-16}	2×10^{-15}



System	Instability $\sigma_\nu[\frac{1}{\sqrt{\tau}}]$	Uncertainty σ_ν
Al^+ [7, 1]	3.7×10^{-16}	8.6×10^{-18}
Yb^+[8]	2×10^{-15}	7.1×10^{-17}
Sr [9]	2×10^{-15}	1×10^{-16}
Rb [10]	7×10^{-16}	3.7×10^{-16}
Hg^+ [11]	9×10^{-15}	7×10^{-15}
$Hg_{1\gamma}$[5]		5.7×10^{-15}
Yb [12]	5.1×10^{-13}	1.4×10^{-15}
Cs [13]	5.8×10^{-13}	10^{-15}
$Ag_{2\gamma}$ [14]	10^{-13*}	
Quartz [15]	10^{-7}	
Chronometer	$10^{0.5}$	

Measurement of FFU

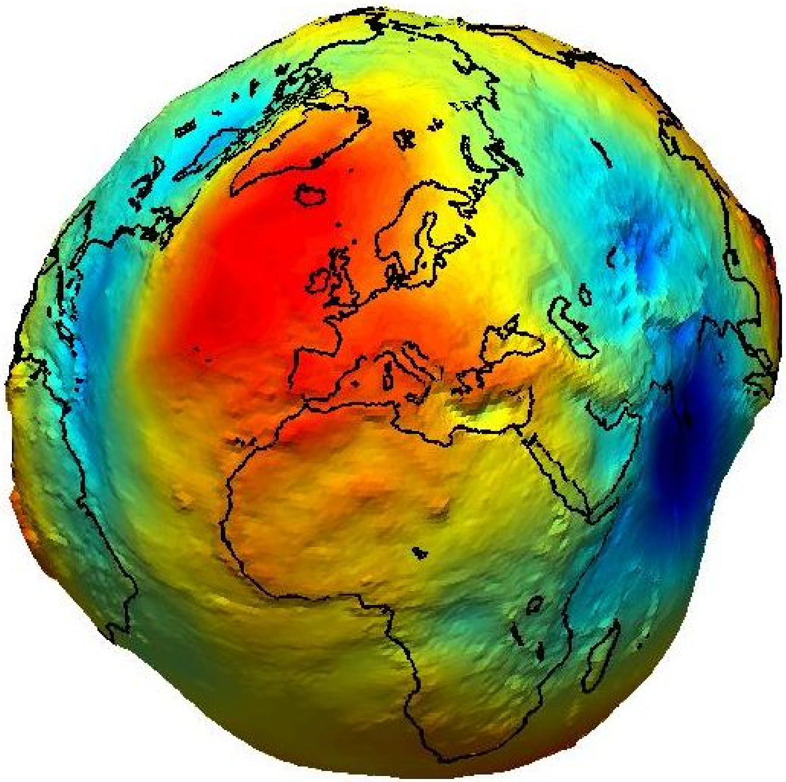
- Frequency comb
- Another clock

And the point of all this…

when ↔ where

Recalculating

Geoid



phys.org Accessed 2013

OFS: What is it good for? Absolutely Something

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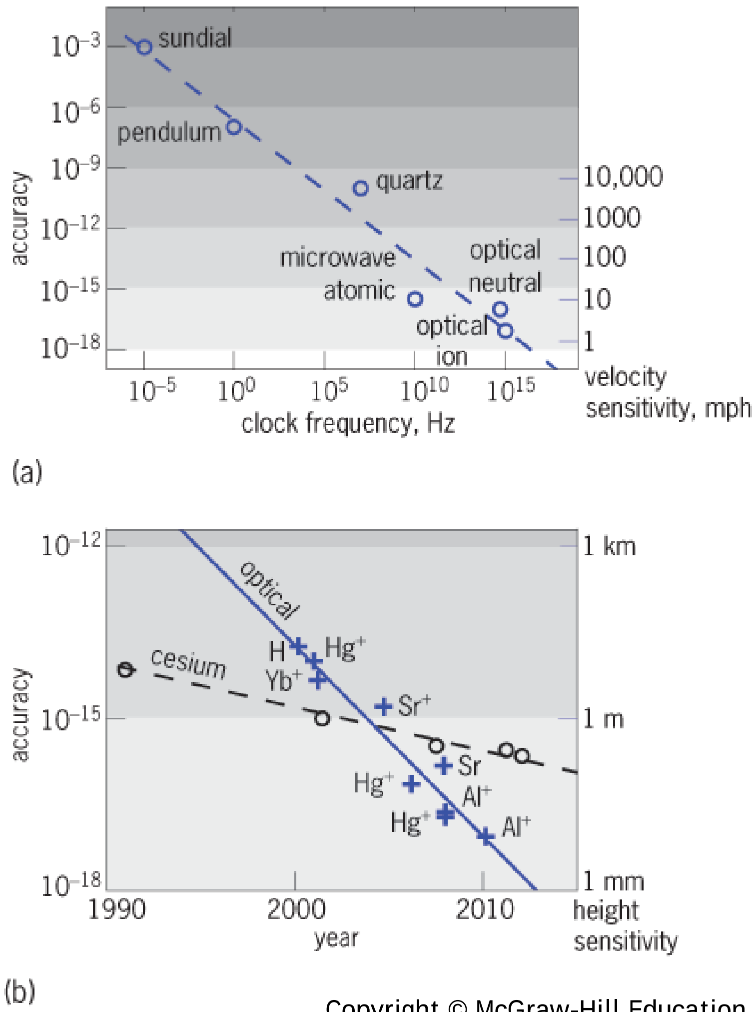

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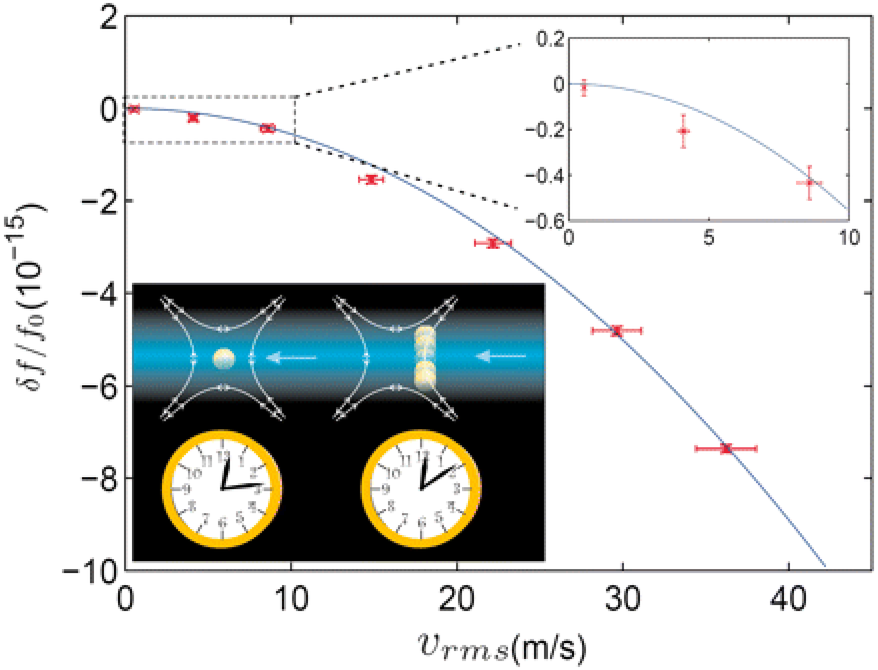
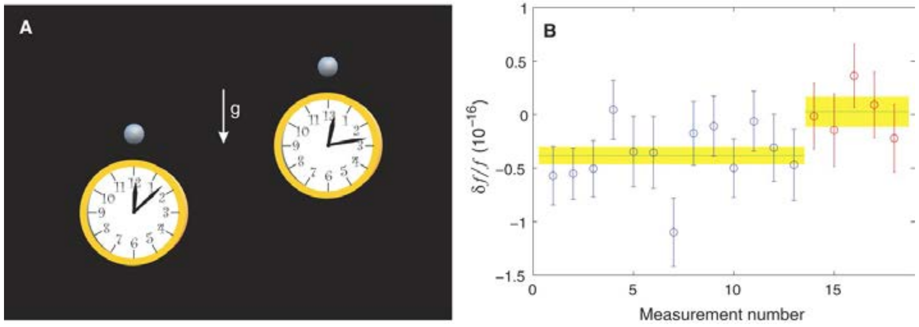
Proximity to mass and motion

The paper





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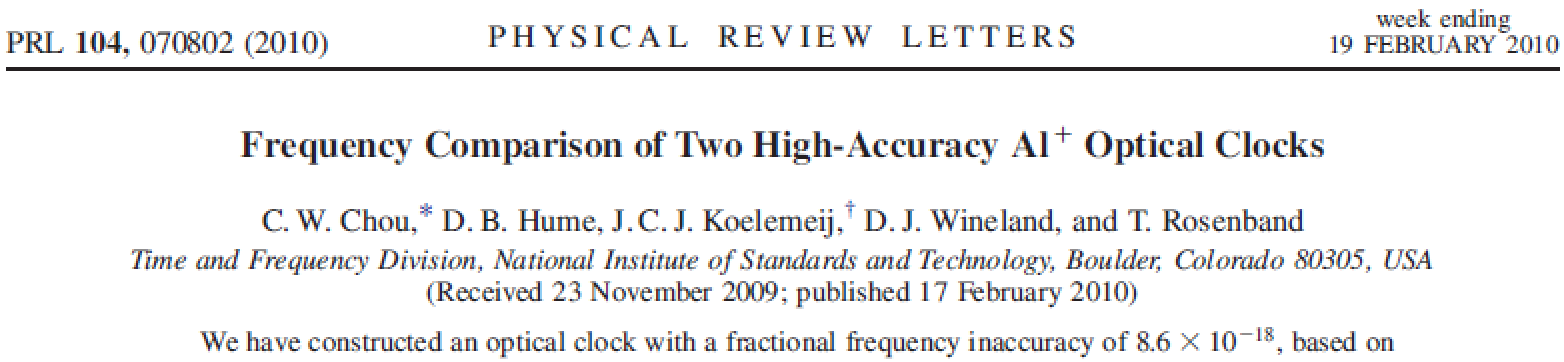
The Best in the World



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Frequency Comparison of Two High-Accuracy Al$^+$ Optical Clocks

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Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA

(Received 23 November 2009; published 17 February 2010)

We have constructed an optical clock with a fractional frequency inaccuracy of 8.6×10^{-18}, based on

$$\frac{\Delta \nu}{\nu} = 8.6 \times 10^{-18}$$

The End

Mike Mosedale

Even Narrower Transition?