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Next-generation frequency standards

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National Measurement Institute, Australia

with acknowledgments to many colleagues, including:
Peter Fisk, Michael Wouters and Magnus Hsu, NMIA
Andre Luiten, UWA
Patrick Gill and Helen Margolis, NPL
Tanja Mehlstäubler, PTB

measurement.gov.au

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Overview

- Introduction
- Building blocks
- Systematic frequency shifts
- Trapped ion frequency standards
- Optical lattice frequency standards
- Comparing optical frequency standards
- Time and frequency transfer
- Atomic Clock Ensemble in Space
- The future

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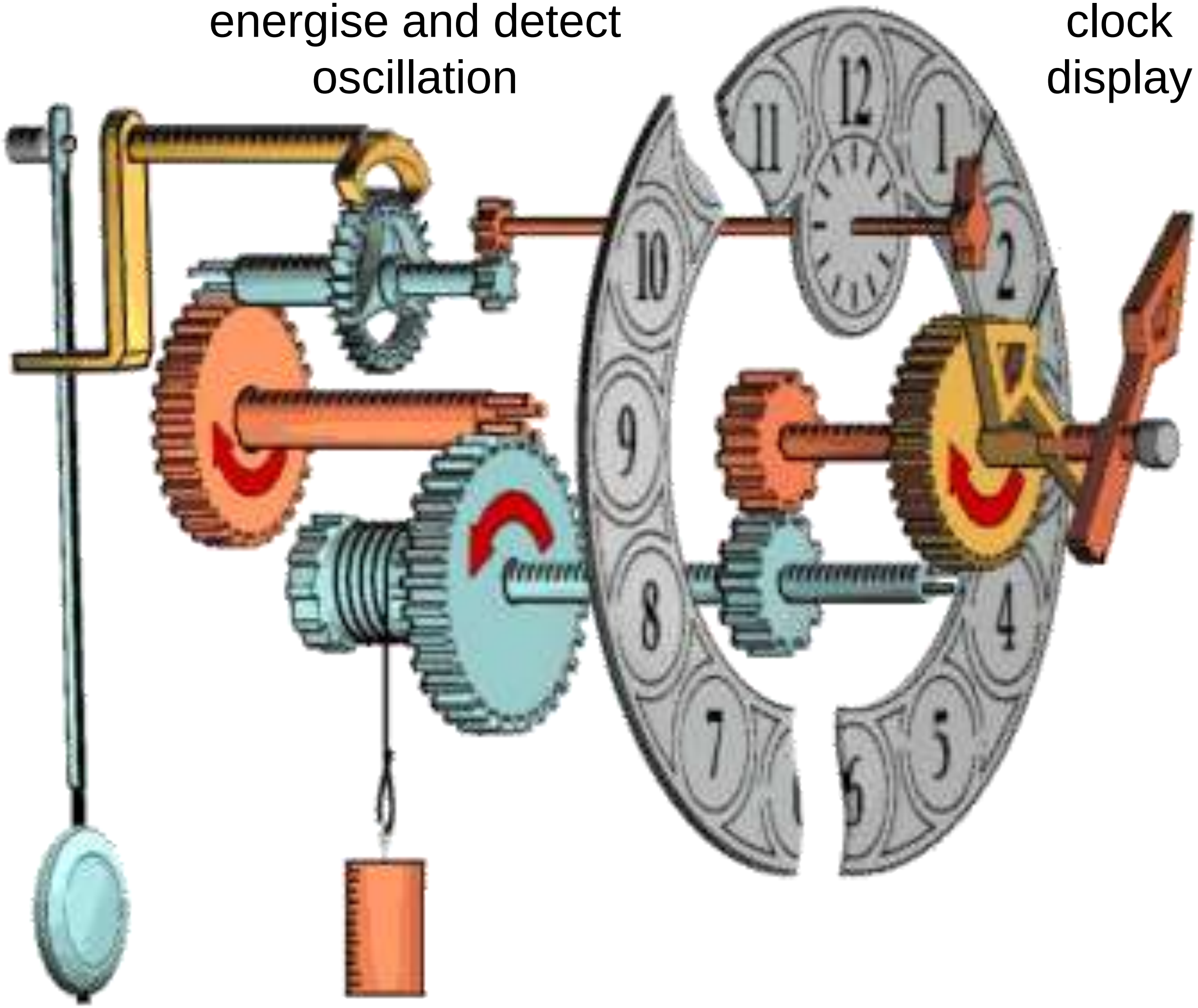
What is a clock?

energise and detect oscillation

clock display



periodic oscillation energy supply **clockwork: divide oscillations**

www.britannica.com/clockworks

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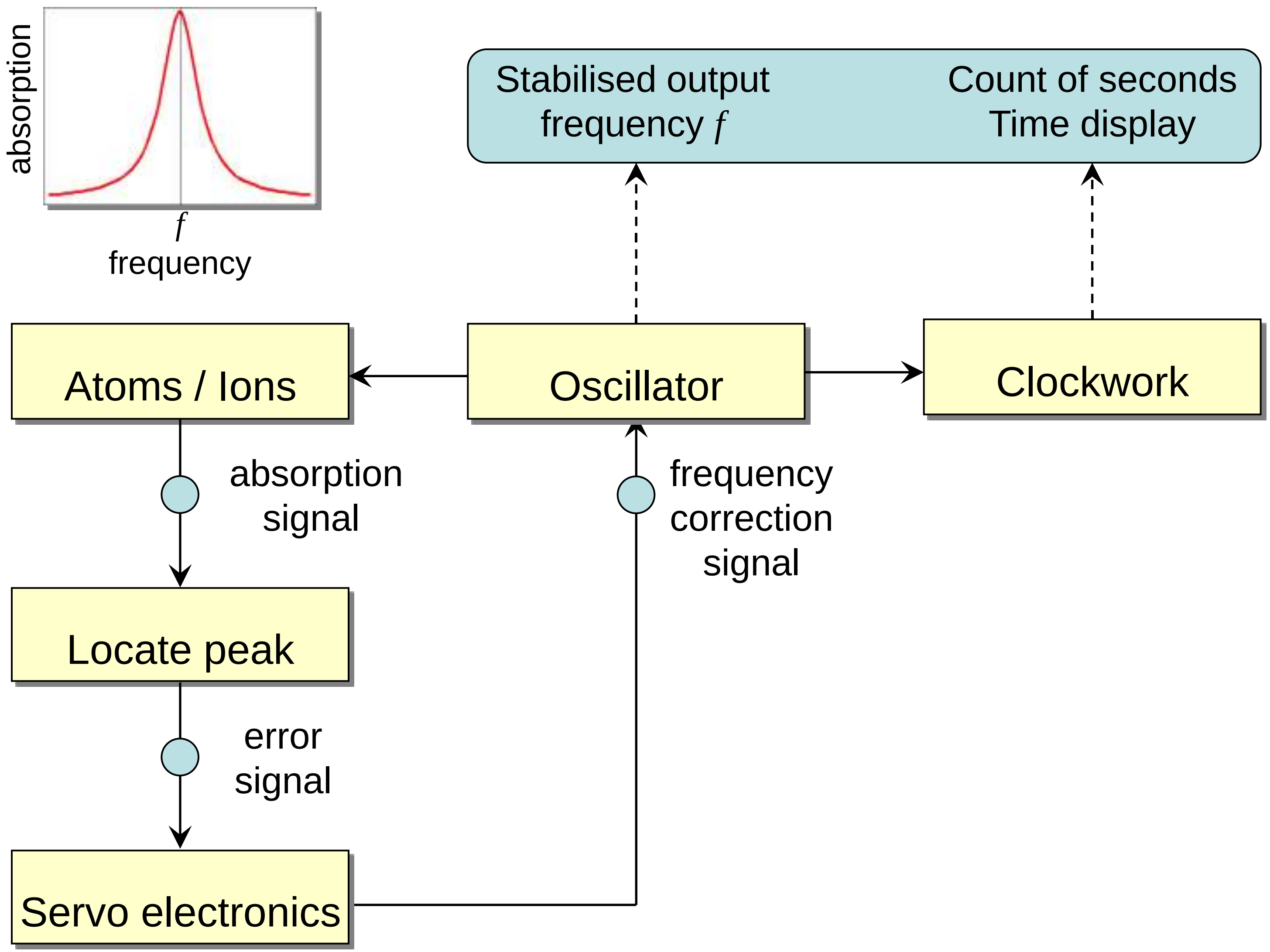
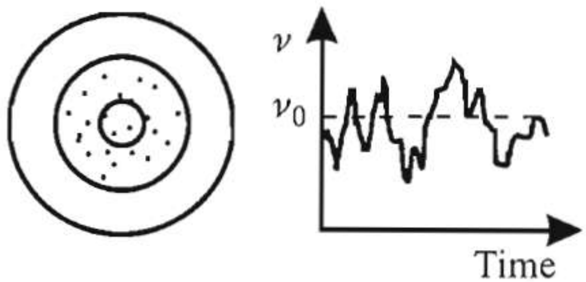
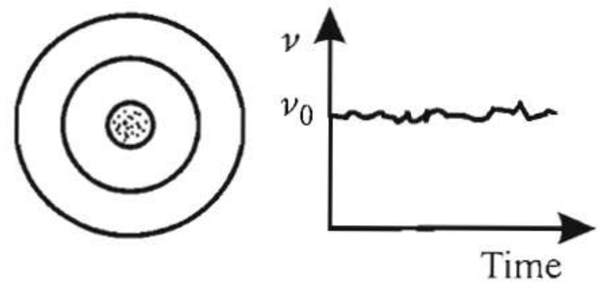
Generic atomic clock



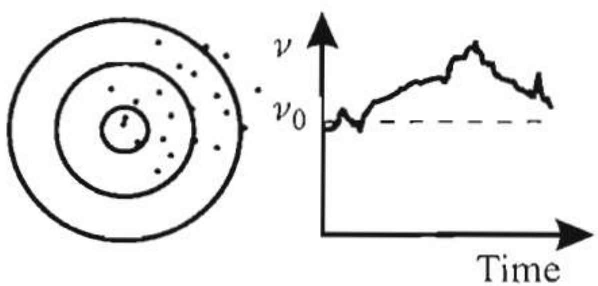
Accuracy and stability



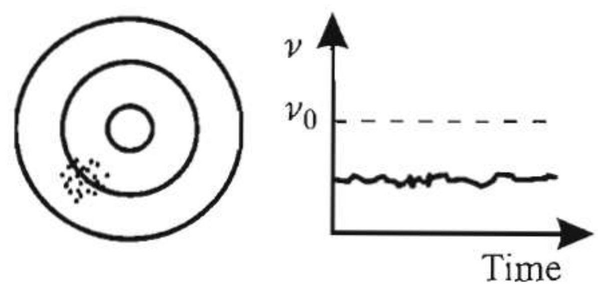
high accuracy
low stability



high accuracy
high stability



low accuracy
low stability



low accuracy
high stability

Adapted from J. Vig, 'Introduction to Quartz Frequency Standards', IEEE FCS tutorial (available online) as in Riehle [1, Fig 1.4]

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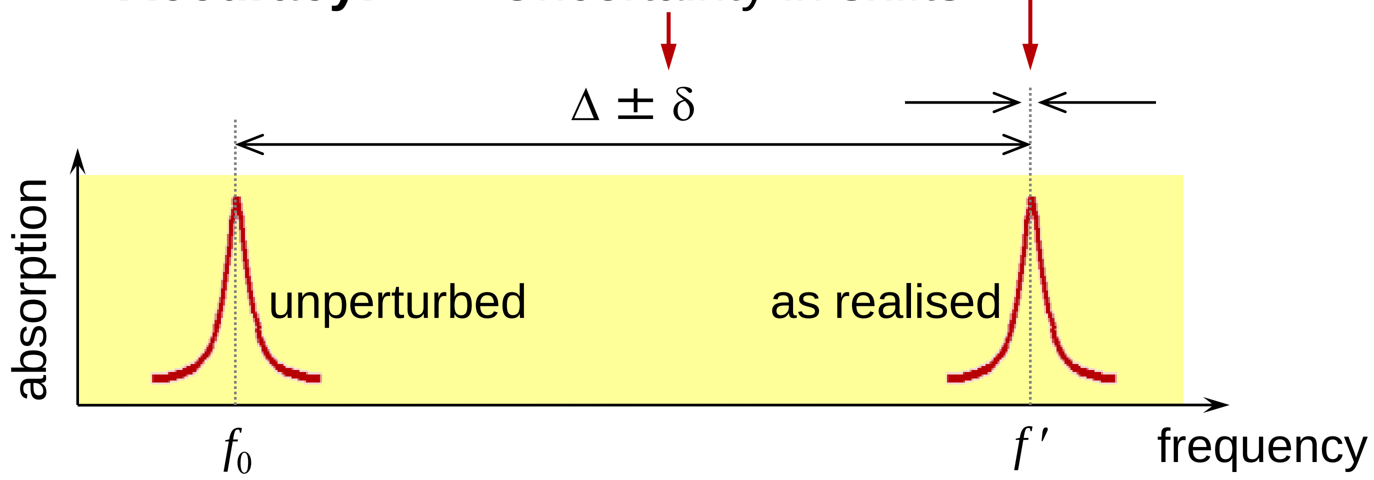
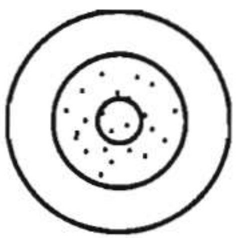
Accuracy and stability: key issues

Stability: Shot-to-shot reproducibility

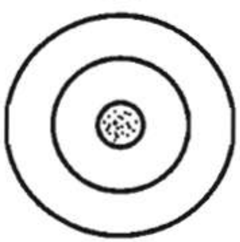
Accuracy: Uncertainty in shifts





high accuracy
low stability

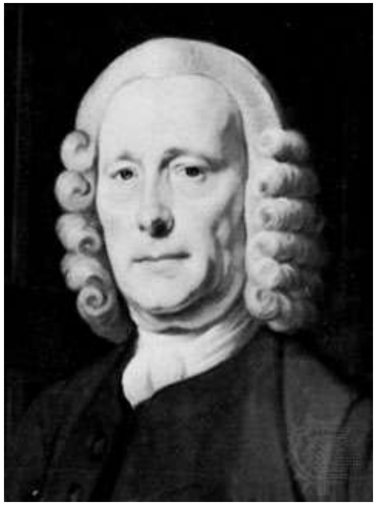
requires longer averaging time to *verify* accuracy and then subsequently to *use* it



high accuracy
high stability

accuracy available at shorter averaging times — potentially *significantly* shorter

Accuracy: controlling systematic shifts
John Harrison and temperature

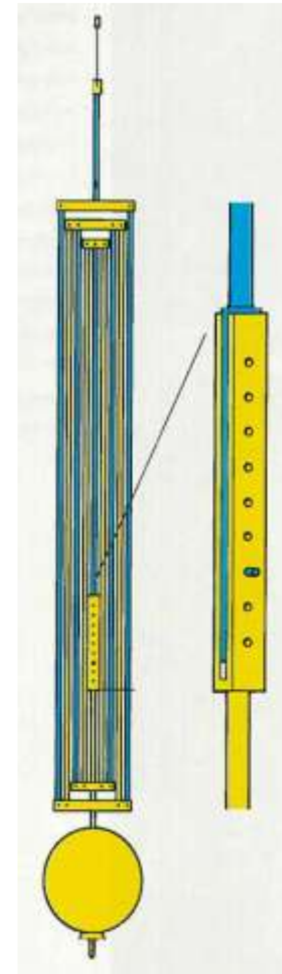


Harrison

"two Clocks [are] plac'd one in one Room & the other in another, yet so, that I can stand in the Doorstead, & hear the beats of both the Pendulums… by which means I can have difference of the Clocks to a small part of a second"

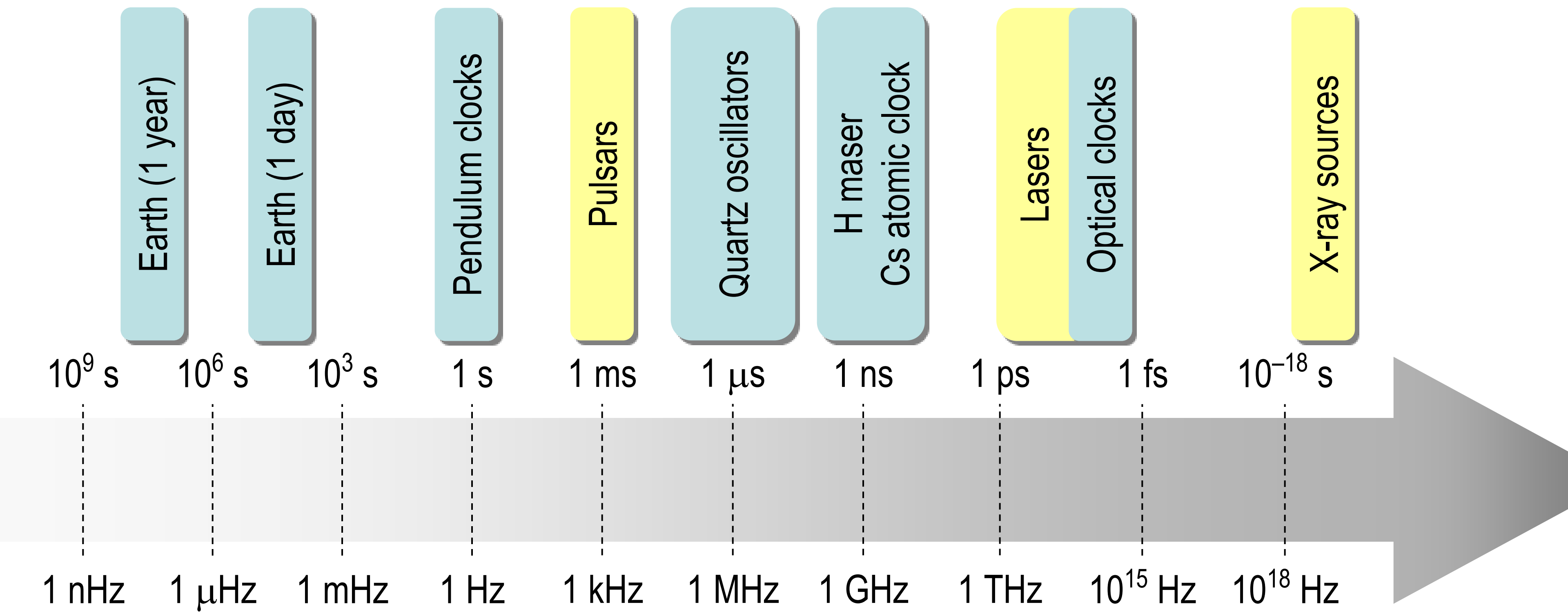
"And in very Cold and Frosty Weather I sometimes make one Room very warm, with a great Fire, whilst the other is very Cold. And again the Contrary."

L=1m$\rightarrow T$=2s; dL= 10μm (1 in 10^5) gives a rate of 1s per day; this dL from dt of 2ºC using thermal expansion of brass 19×10^{-6}



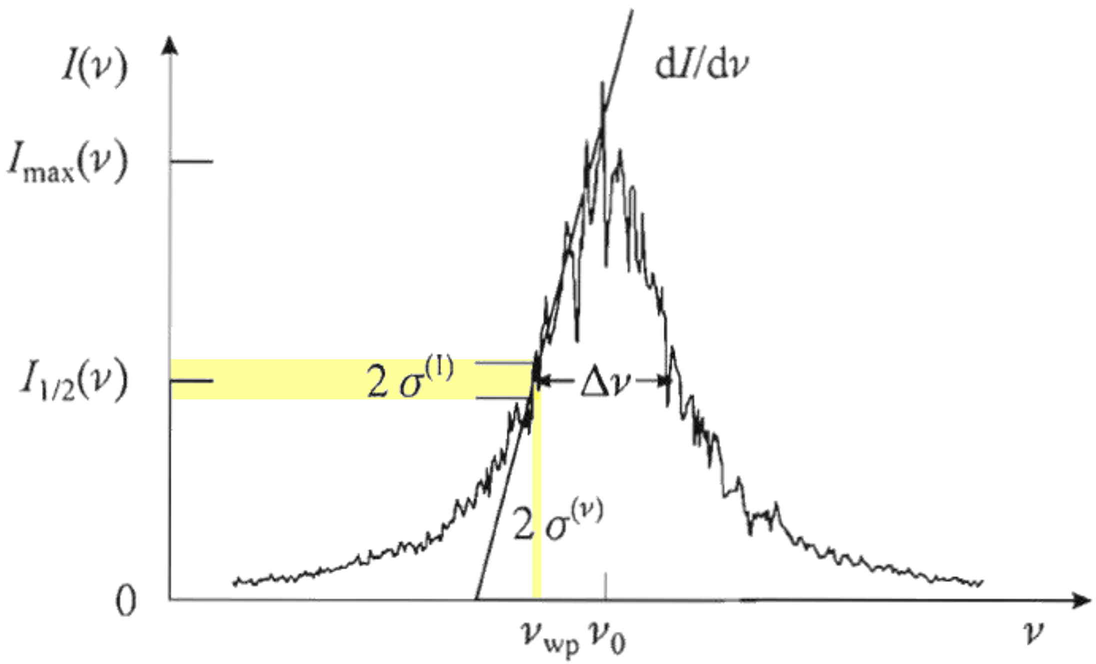
Longcase regulator and gridiron pendulum, 1727

Stability: A brief history (i)



Adapted from Riehle [1, Fig 1.1]

Stability: fundamental limits



$$\sigma_y(\tau) \propto \frac{1}{Q}\frac{1}{S/N}\frac{1}{\sqrt{\tau}}$$

$$Q = \nu_0 / \Delta\nu$$

$$S/N \propto \frac{1}{\sqrt{n}}$$

High ν_0
Low $\Delta\nu$
High n

Adapted from Riehle [1, Fig 3.19]

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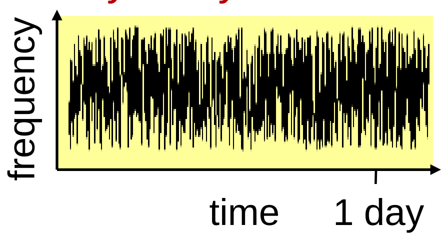
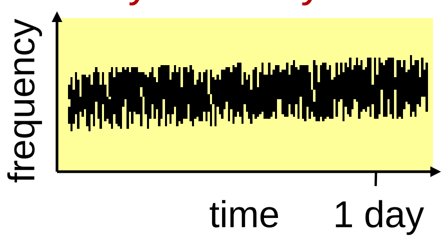
Stability: Allan deviation $\sigma_y(\tau)$

Allan Deviation $\sigma_y(\tau)$: instability *as a function of averaging time*

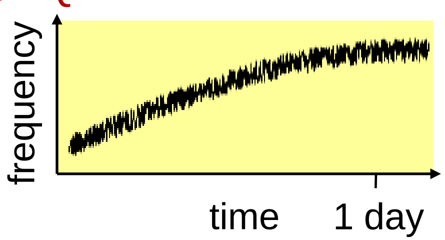
❶ Very noisy but stable



❷ Noisy but fairly stable

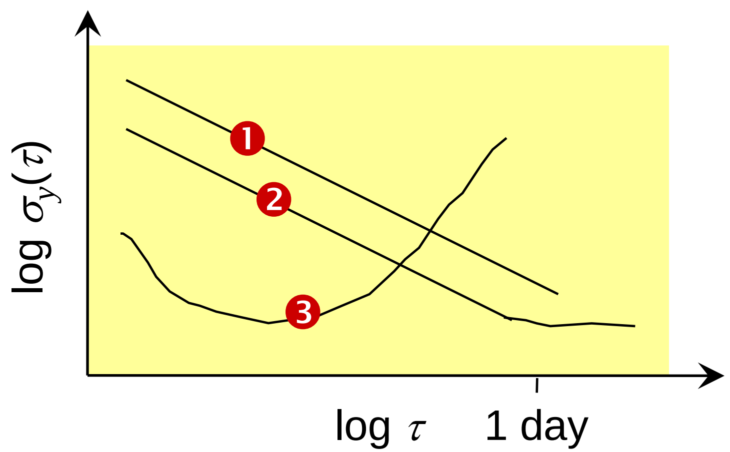


❸ Quiet but unstable

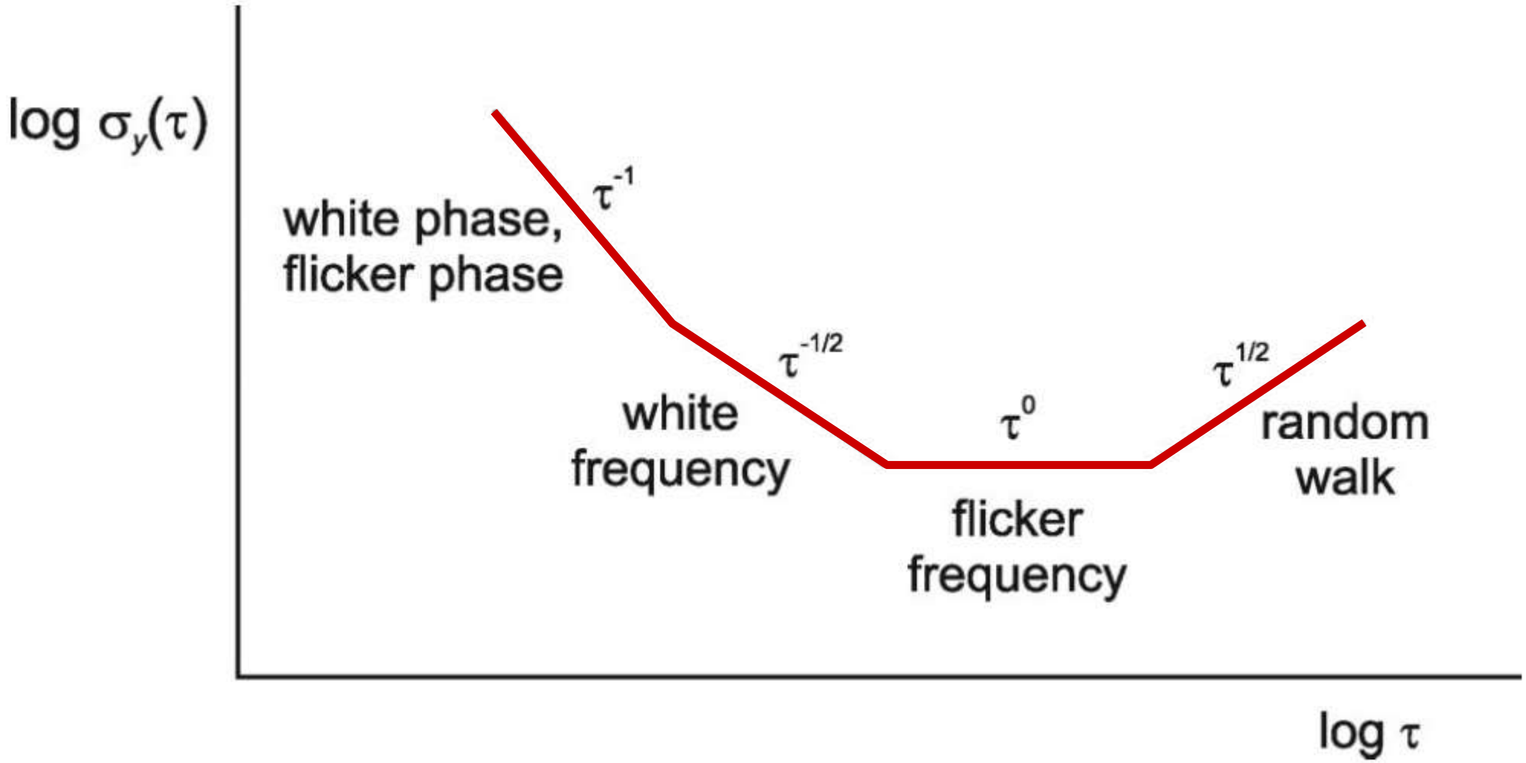


$$\sigma_y(\tau) = \sqrt{\frac{1}{2}\left\langle \left(\bar{y}_{k+1} - \bar{y}_k\right)^2 \right\rangle}$$

$$\bar{y}_k = \frac{1}{\tau}\int_{t_k}^{t_k+\tau} \frac{\nu(t) - \nu_0}{\nu_0}\, dt$$

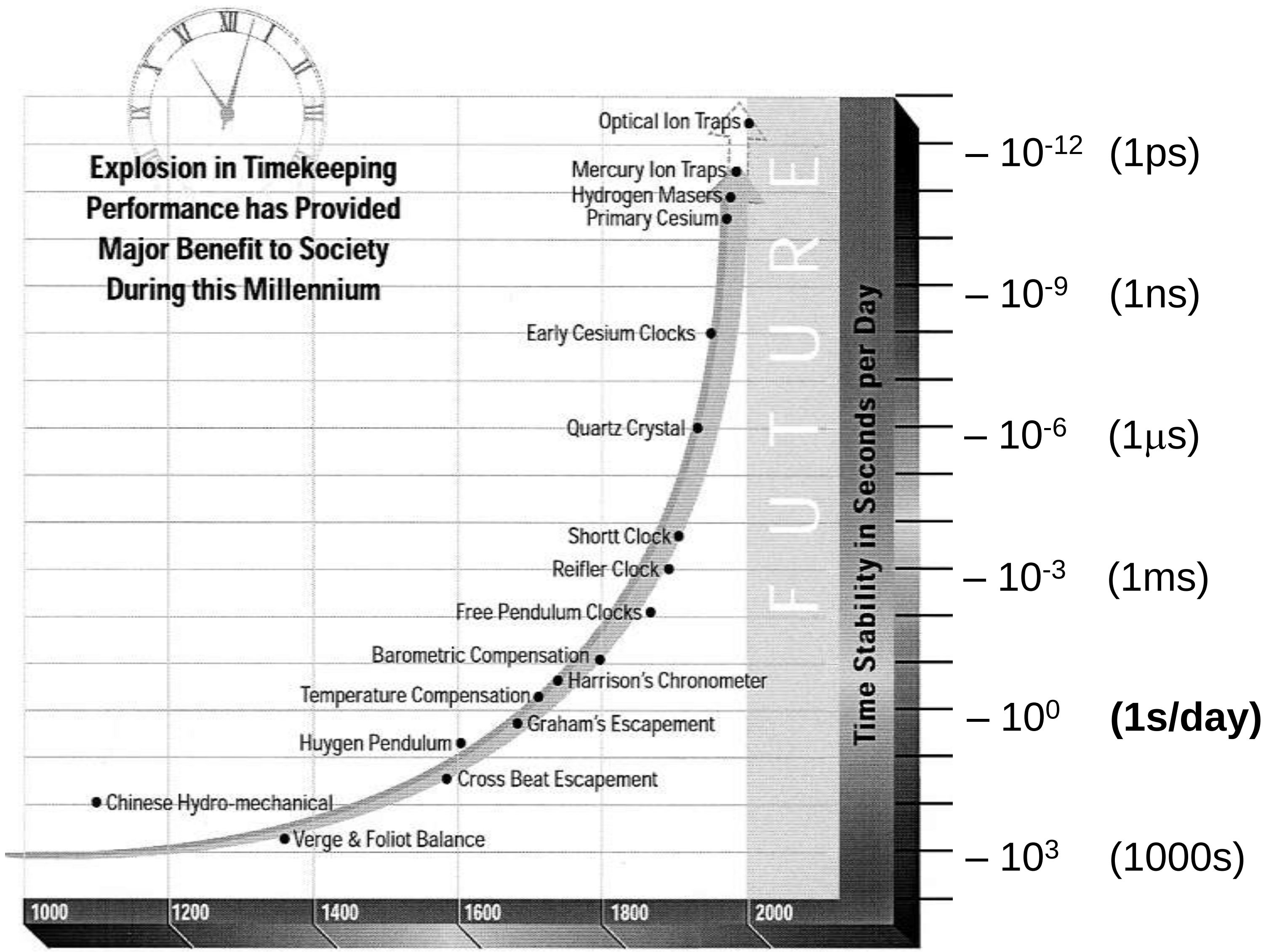


Stability: identifying noise processes



H. S. Margolis, Contemporary Physics ***51*** *37 (2010) [4]*

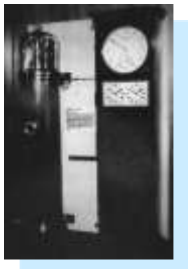
Stability: A brief history (ii)



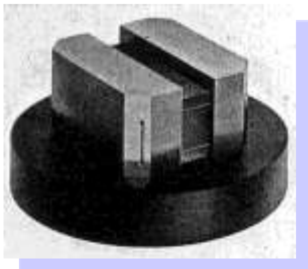
D. W. Allan, N. Ashby and C. C. Hodge, 'The Science of Timekeeping', Agilent Application Note 1289

A brief history of the second

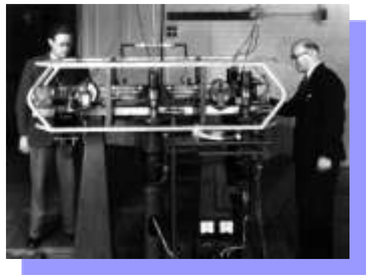
Pendulum clocks



Quartz clocks

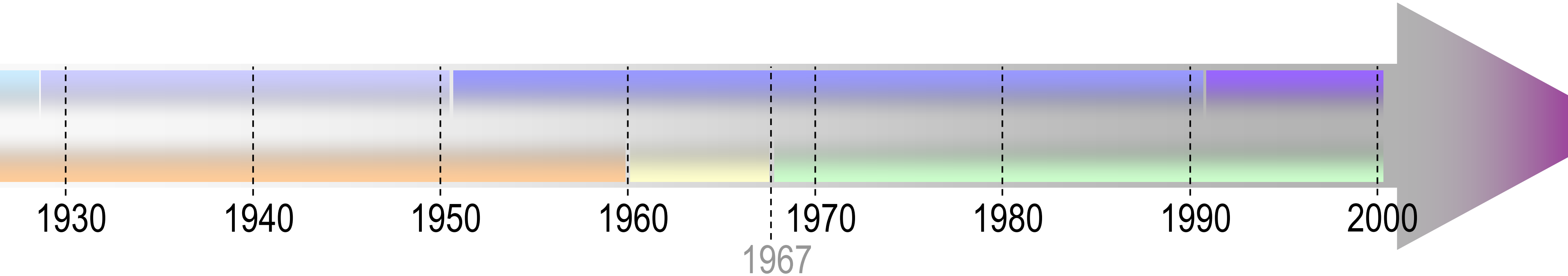


Atomic clocks



Fountain clocks

Optical clocks



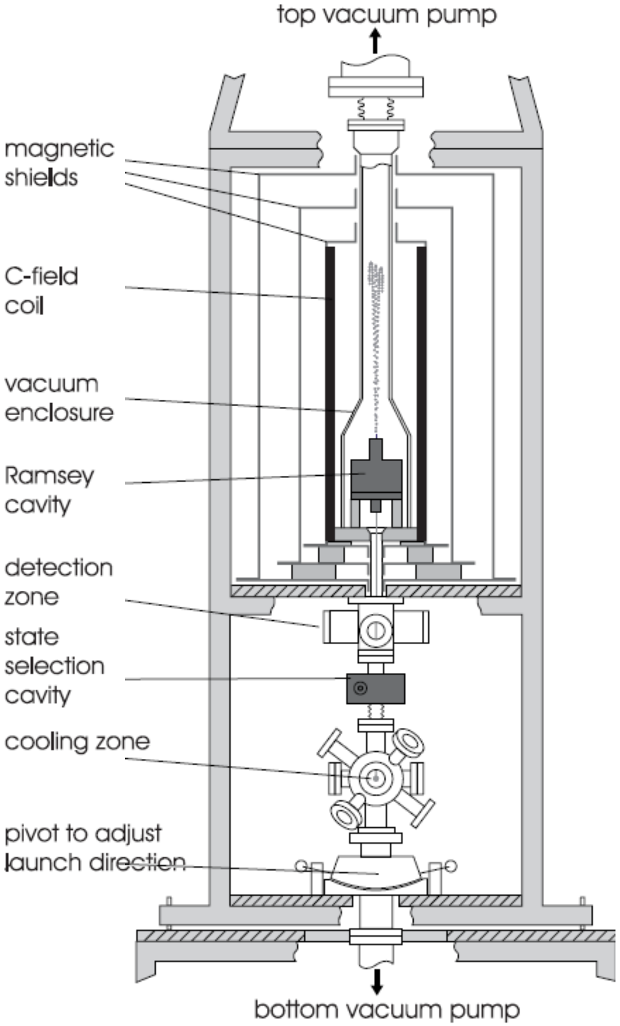
1/86400 of the time taken for the Earth to rotate on its axis

1/31355925.9747 of the time taken for the Earth to orbit the Sun in 1900

The time taken by 9 192 631 770 cycles of the radiation corresponding to the ground-state hyperfine transition of the ^{133}Cs atom

The Cs second: accuracy ~5×10^{-16}

eg PTB CSF2:

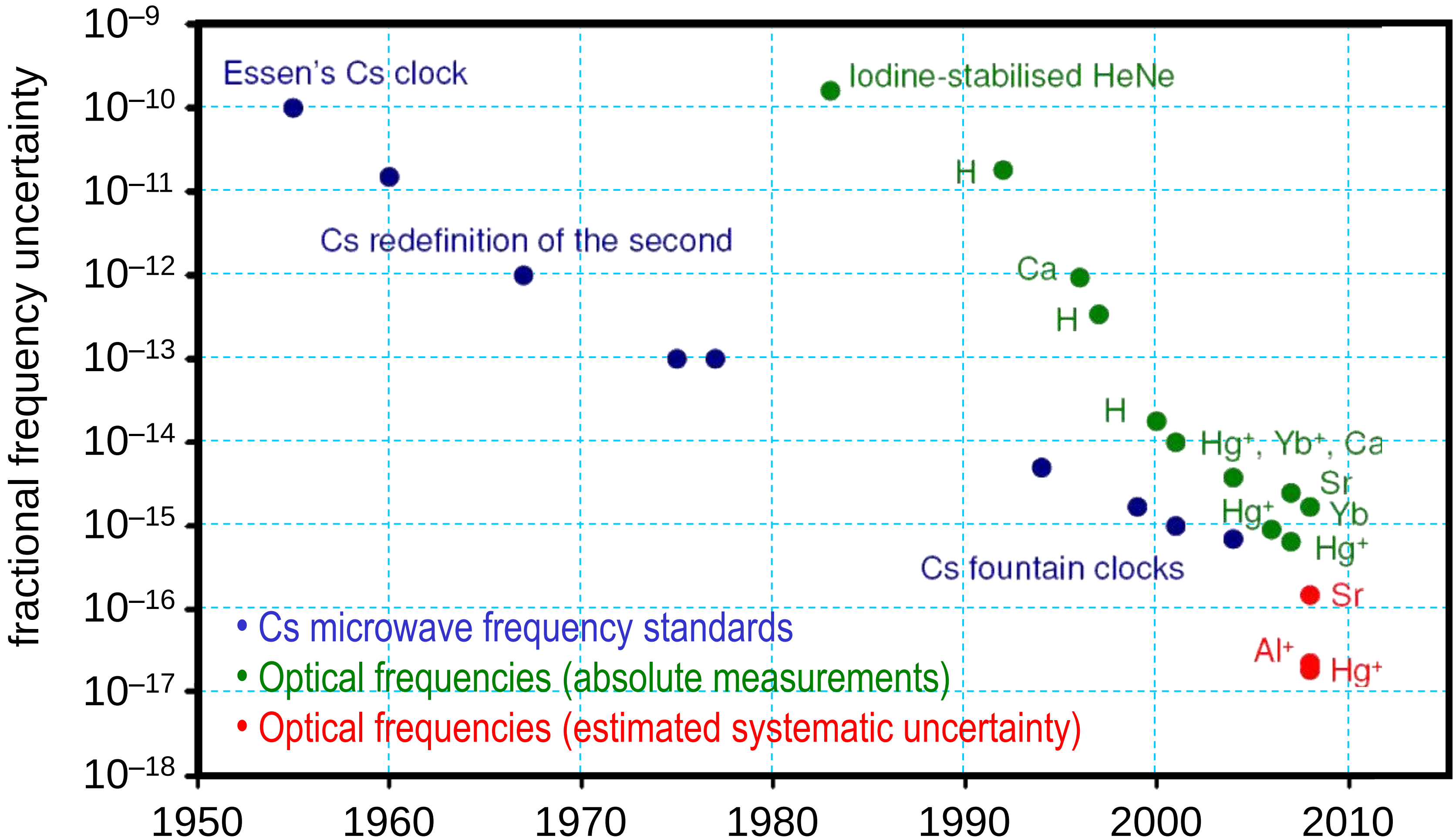


Frequency shift (parts in 10^{15})	Correction	Uncertainty
Quadratic Zeeman shift	−99.85	0.06
Blackbody radiation shift	16.60	0.06
Gravity + relativistic Doppler effect	−8.567	0.006
Collisional shift	0.32	0.62
Cavity phase shift	0.0	0.15
Light shift	0.0	0.001
Majorana transitions	0.0	0.0001
Rabi pulling	0.0	0.0002
Ramsey pulling	0.0	0.001
Electronics	0.0	0.20
Microwave leakage	0.0	0.10
Microwave power dependence	0.0	0.40
Background pressure	0.0	0.05
Total	−91.50	0.80

- SYRTE, NIST, NPL, INRIM similar and many other institutions active
- Limited prospects for significant further improvement

V Gerginov, N Nemitz, S Weyers, R Schröder, D Griebsch and R Wynands, Metrologia ***47*** *65–79 (2010)*

A brief history of frequency standards



Adapted from P. Gill et al., 'Optical Atomic Clocks for Space' (2008) [3]

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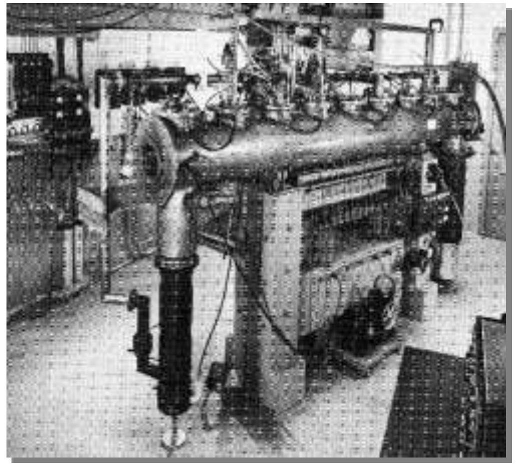
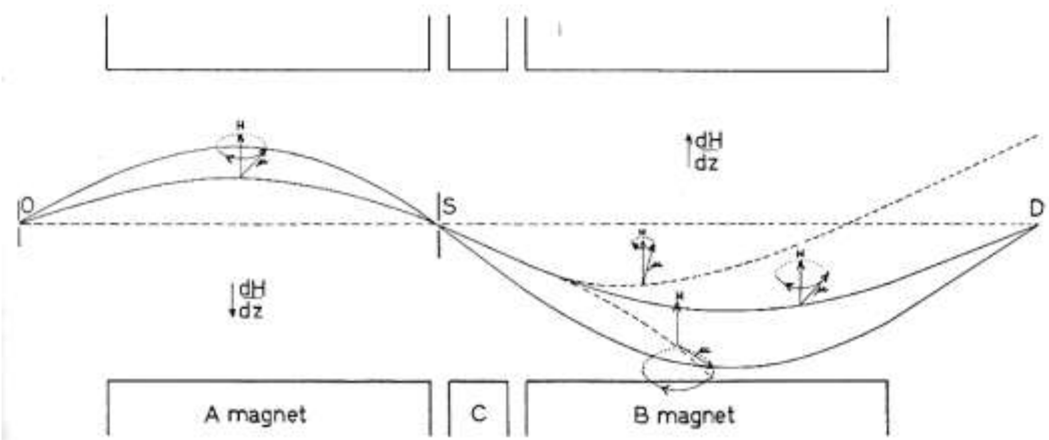
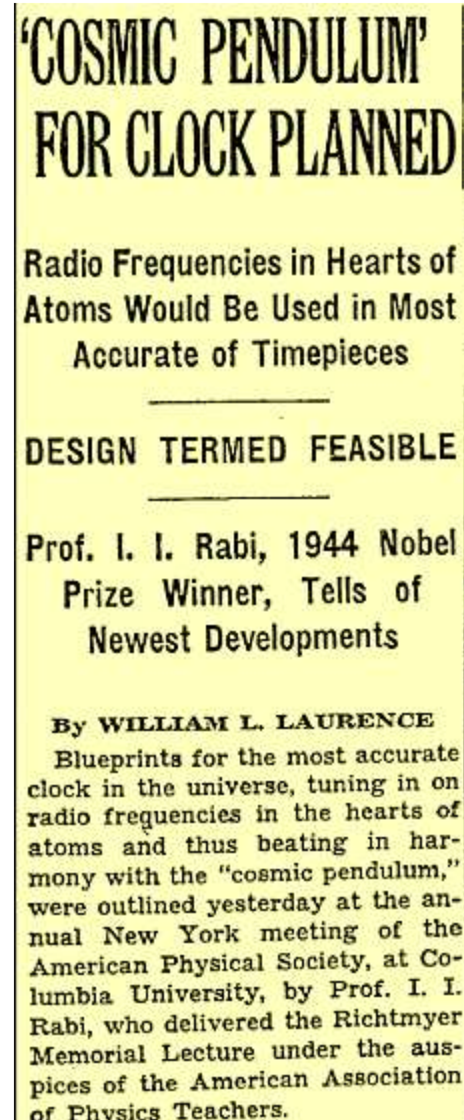
Molecular beam resonance (1937)

Rabi

1944







'COSMIC PENDULUM' FOR CLOCK PLANNED

Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces

DESIGN TERMED FEASIBLE

Prof. I. I. Rabi, 1944 Nobel Prize Winner, Tells of Newest Developments

By WILLIAM L. LAURENCE

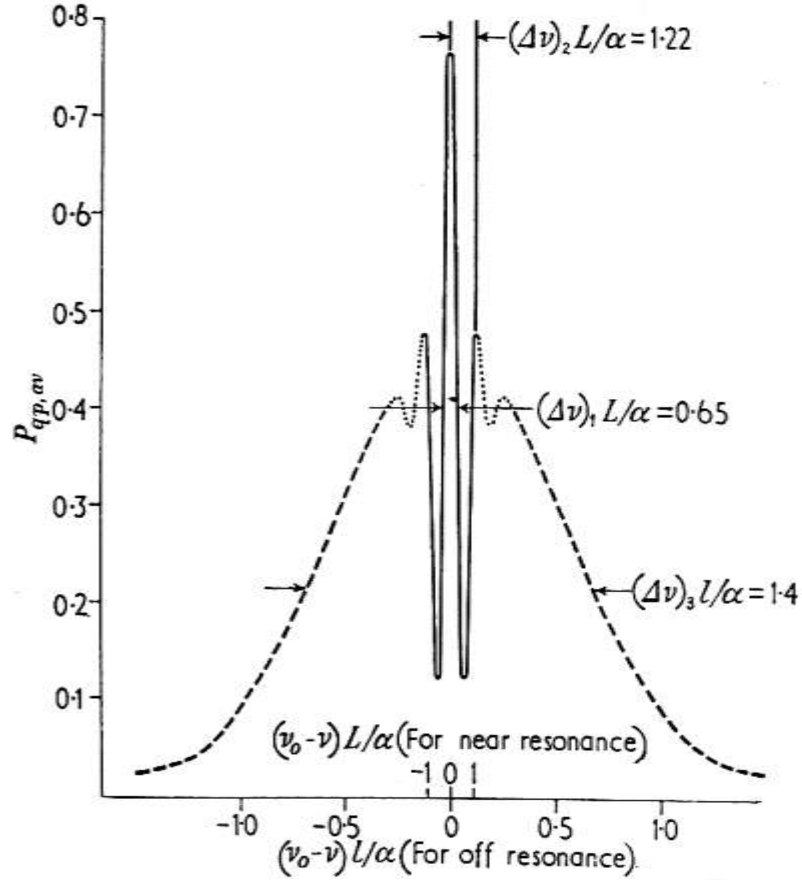
Blueprints for the most accurate clock in the universe, tuning in on radio frequencies in the hearts of atoms and thus beating in harmony with the "cosmic pendulum," were outlined yesterday at the annual New York meeting of the American Physical Society, at Columbia University, by Prof. I. I. Rabi, who delivered the Richtmyer Memorial Lecture under the auspices of the American Association of Physics Teachers.

New York Times, Jan 21, 1945

Separated oscillatory fields (1949)

Ramsey

1989



Resonance lineshape

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

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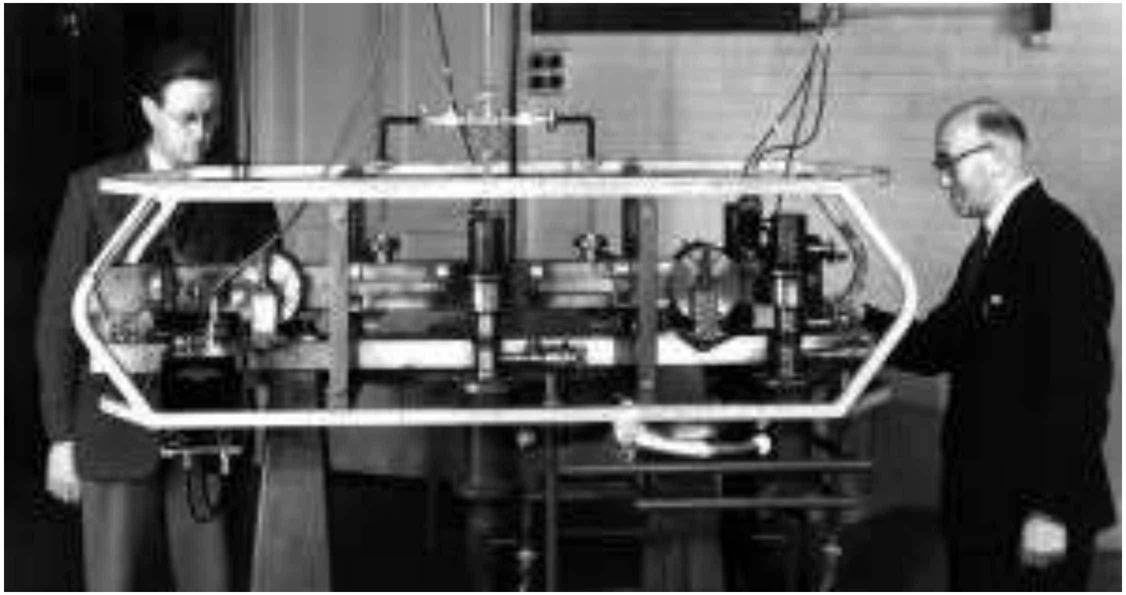
‘The birth of atomic time’ (1955)

Louis Essen

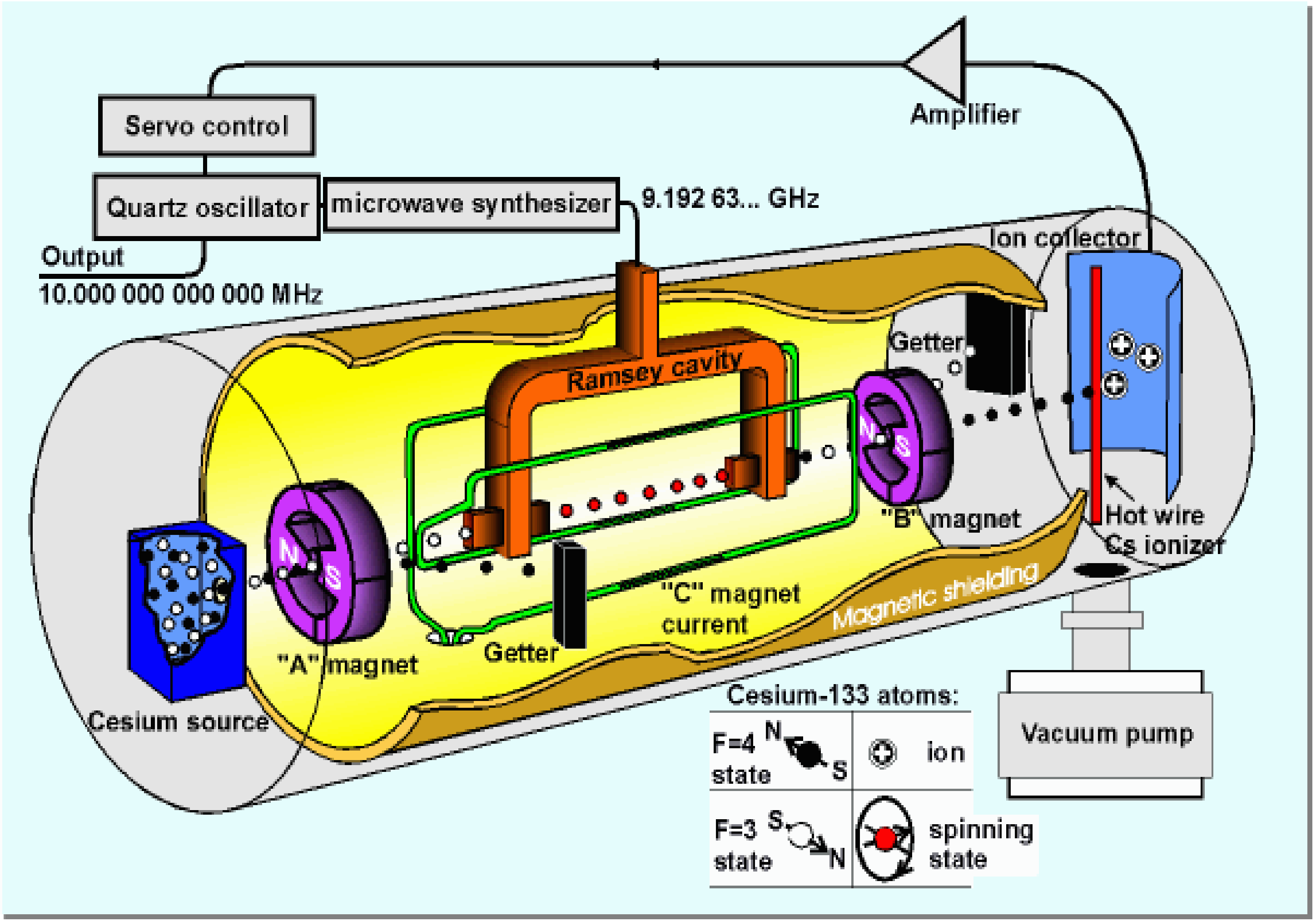


Parry and Essen with Caesium-1 at NPL

‘In less than two years the equipment was installed and the beam detected… there was the resonance exactly as sharp as predicted. We invited the Director to come and witness the death of the astronomical second and the birth of atomic time. … It was obvious from this very first moment of operation that we could set the quartz clocks with a far greater accuracy than could be obtained by astronomical means.’

Louis Essen, Time for Reflection (autobiographical, 1996)

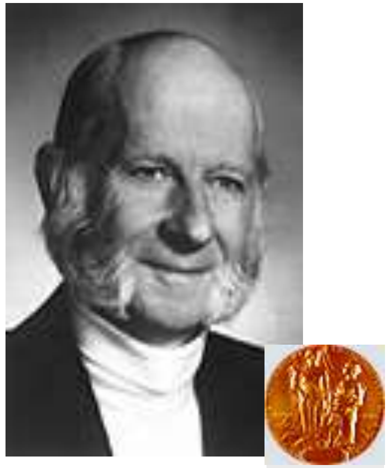
Cesium beam frequency standard



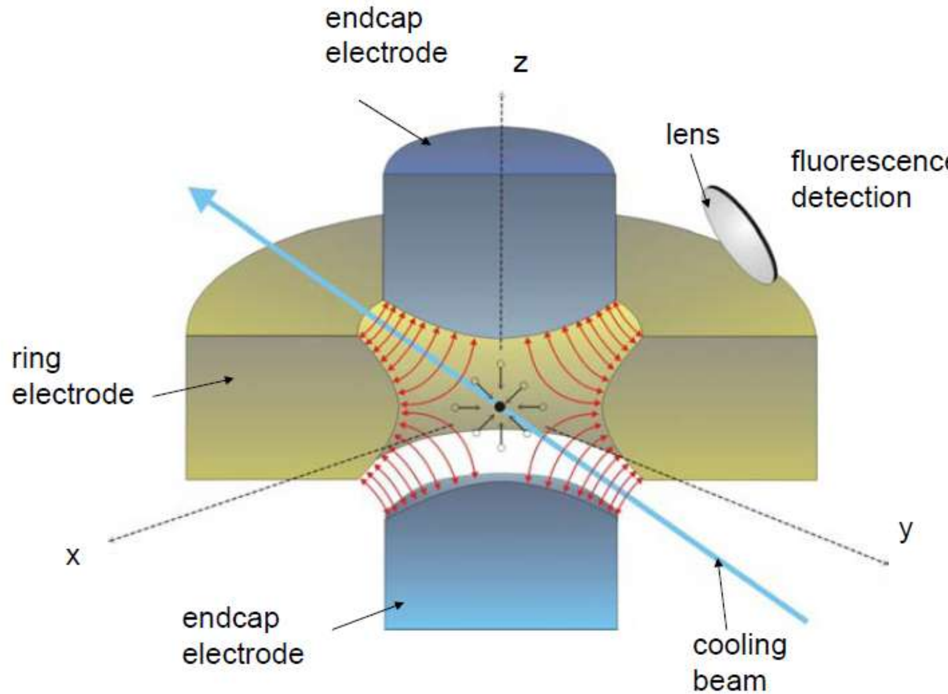
"Time and Frequency Metrology Course", National Research Council, Canada

Ion trapping

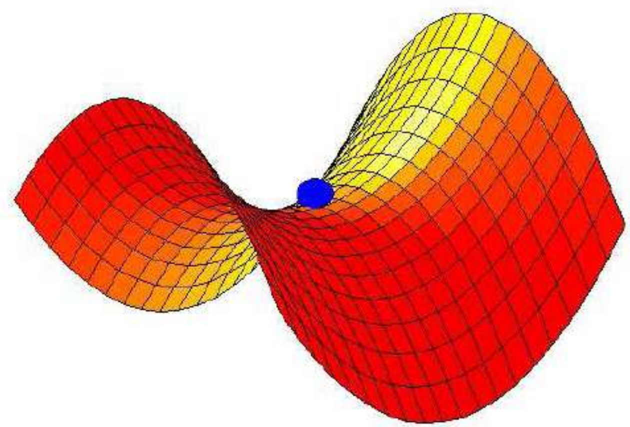
Paul



Dehmelt **1989**



Itano and Ramsey, Scientific American ***269*** *46 (1993)*



W. Lange, in Mehlstäubler [2]

Motion of a trapped ion

$$\Phi = \frac{\Phi_0}{r_0^2}(x^2 + y^2 - 2z^2)$$

quadrupole potential

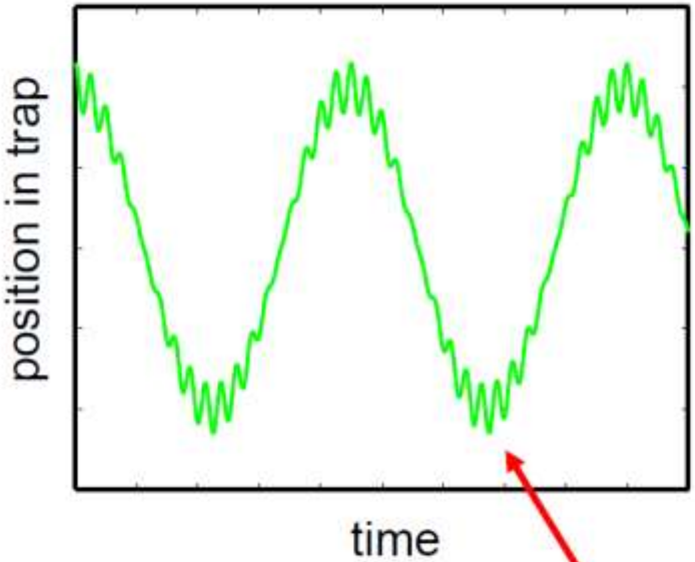
$$\Phi_0 = U_0 + V_0 \cos\Omega t$$

$$\ddot{x} + (a - 2q\cos\Omega t)\frac{\Omega^2}{4}x = 0$$

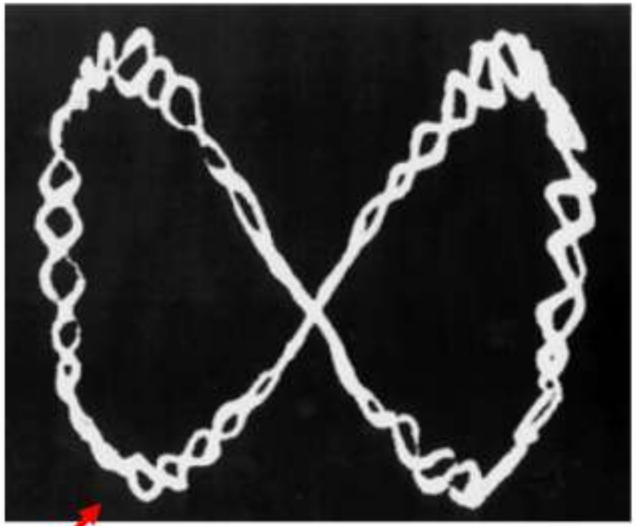
equation of motion in a Paul trap

Mathieu equation

1D-solution of Mathieu equation



single Al dust particle in trap

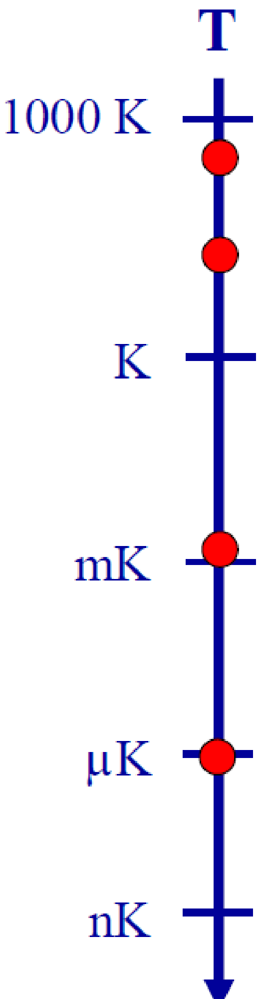


micromotion

Wuerker, Shelton, Langmuir, J. Appl. Phys. **30**, 342 (1959)

Adapted from J. Eschner et al., Experimental Quantum Optics and Quantum Information (2005) [online]

Laser cooling and trapping of atoms



atomic beam v ~ 700 m/s

300 K: room temperature
v ~ some 100 m/s

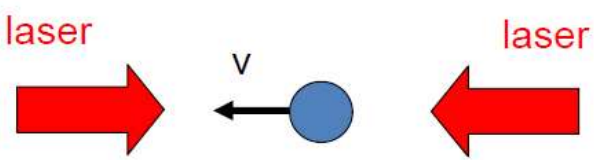
Doppler cooling / MOT:

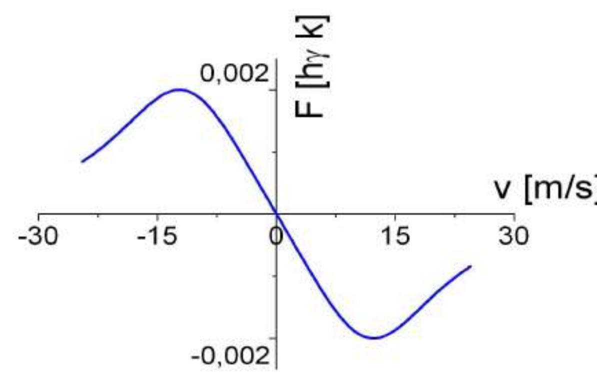
$T_{Dopp} = h\gamma/2k_B = 1$ mK
v ~ 1 m/s

sub-Doppler-cooling:
T_{rec} recoil !
v ~ 1 cm/s

evaporation

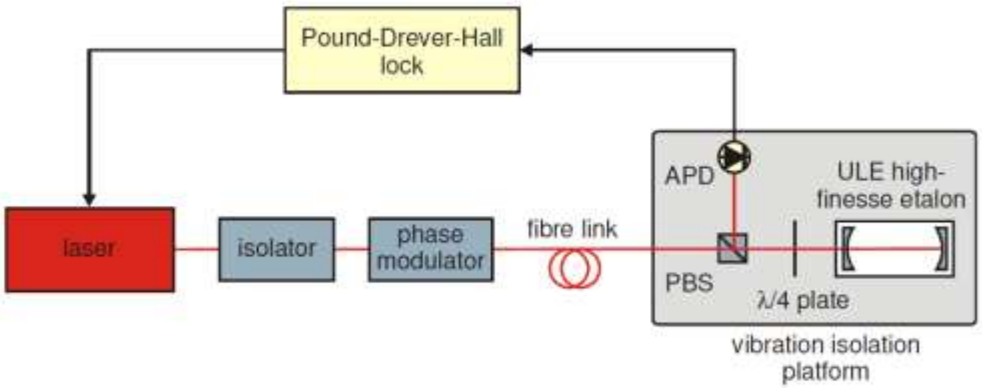
Chu Cohen-Tannoudji Phillips





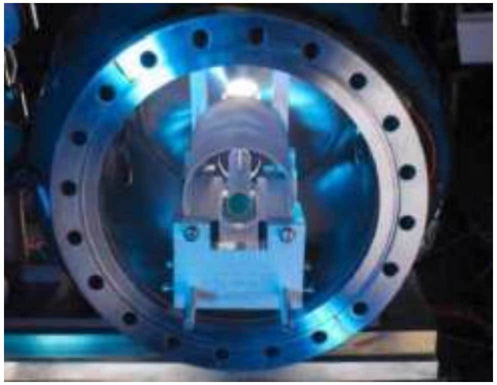
Adapted from Mehlstäubler [2]

Ultrastable lasers



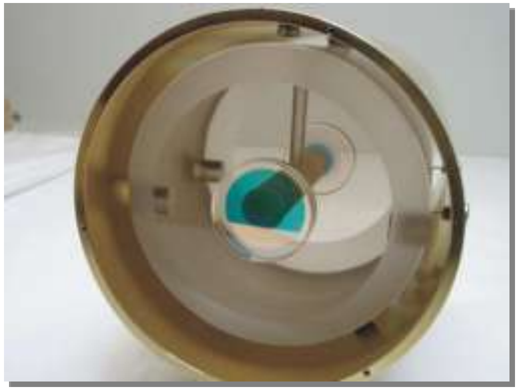
P. Gill et al., *'Optical Atomic Clocks for Space' (2008) [3]*

- Mirrors contacted to ULE substrate (*F*>100 000)
- T stability to 1 mK and expansion <30 ppb/K
- Optimise design to minimise vibration sensitivity
- Isothermal drift remains (~0.1 Hz/s)



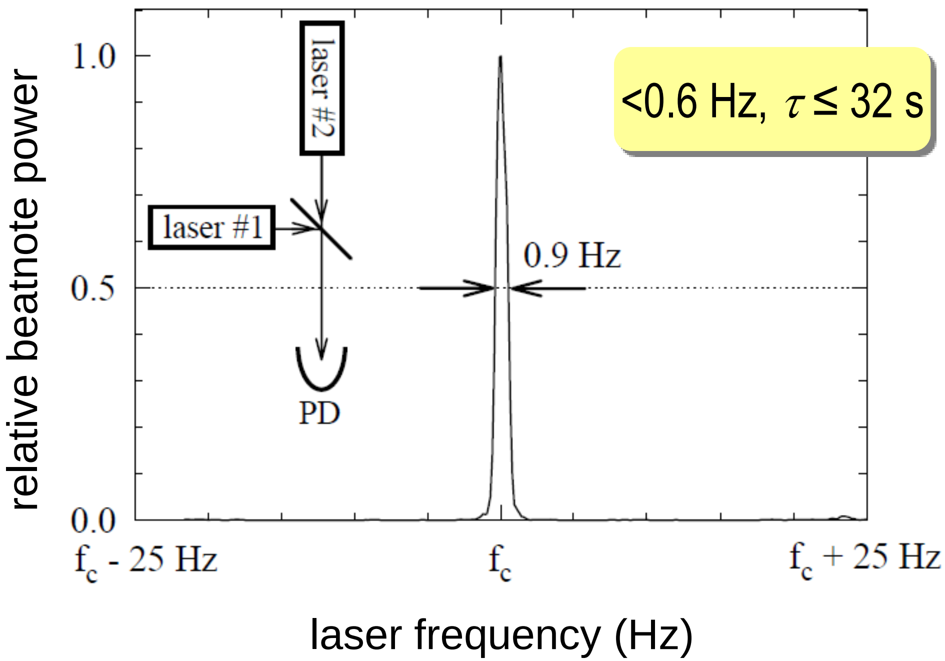
S. A. Webster et al.,
Phys. Rev. A ***71*** *011801 (2007)*

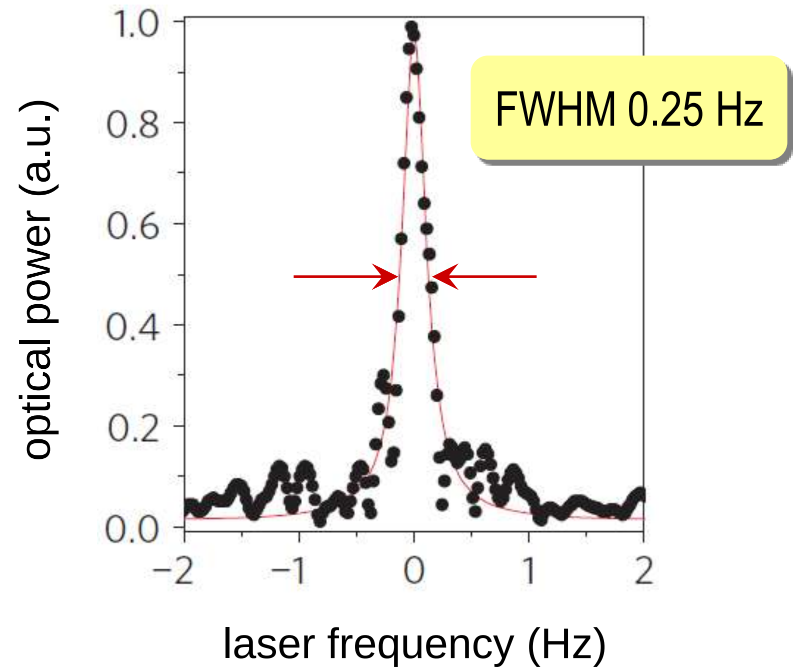
A. D. Ludlow et al.,
Opt. Lett. ***32*** *641 (2007)*



T. Nazarova et al.,
Appl. Phys. B ***83*** *531 (2006)*

Ultrastable lasers: state of the art

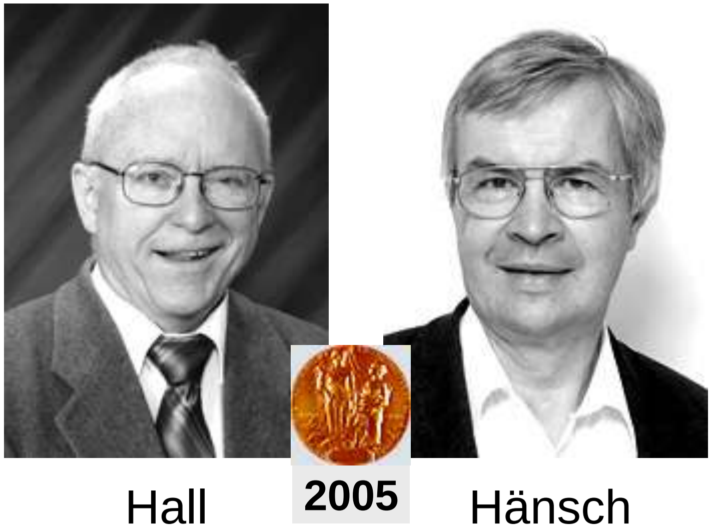


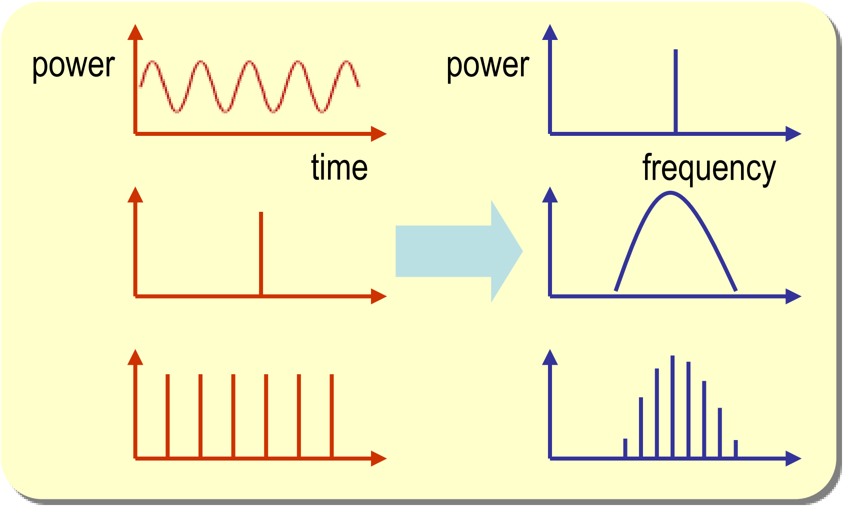


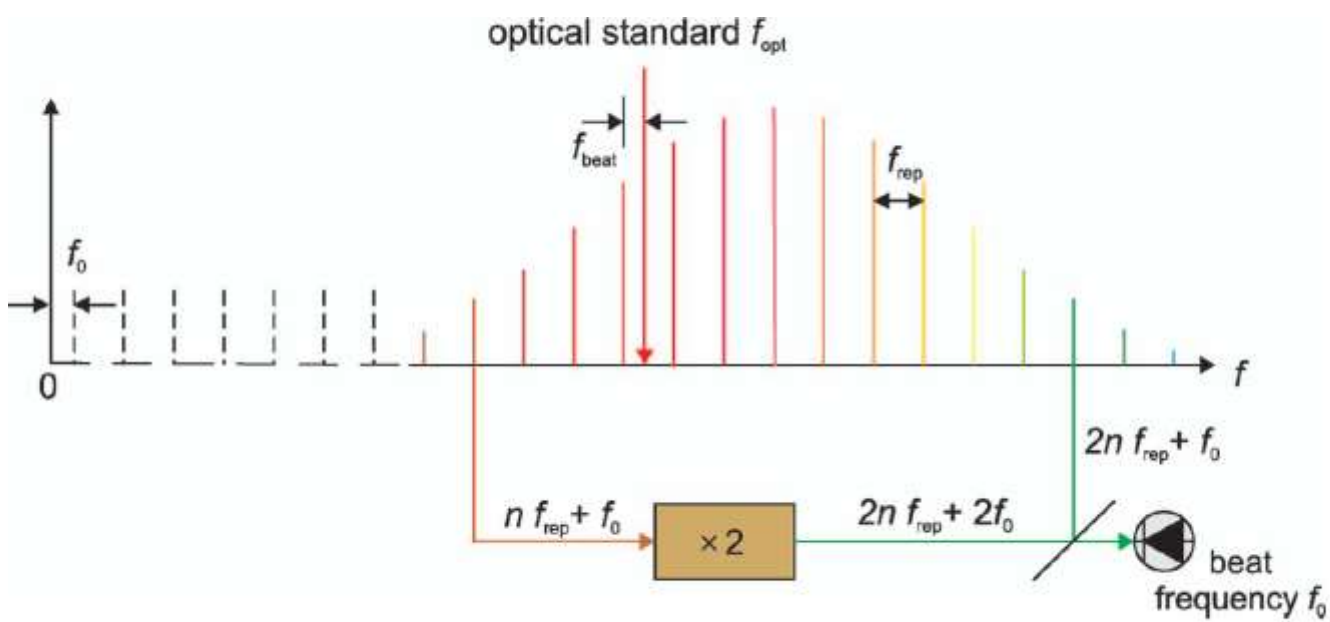
B. C. Young et al., Phys. Rev. Lett. ***82*** *2799 (199)*
563 nm, for Hg^+ single-ion clock
(below quantum limit for τ <10 s)

Y. Y. Jiang et al., Nature Photonics ***5*** *158 (2011)*
578 nm, for Yb lattice clock

Optical frequency combs







H. S. Margolis, Contemporary Physics ***51*** *37 (2010) [4]*

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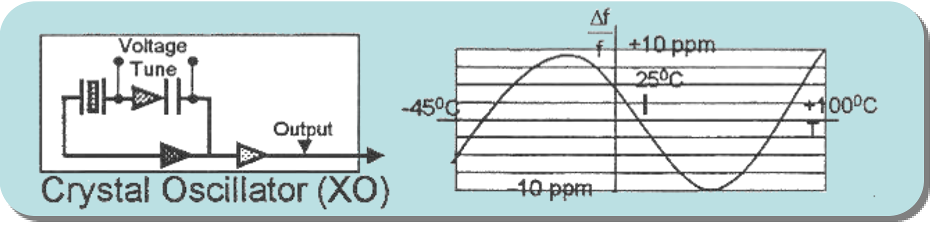
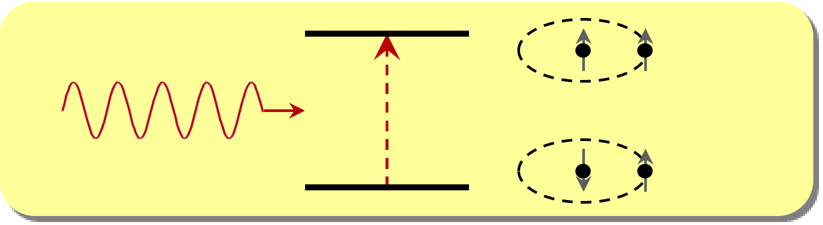
Accuracy: systematic shifts

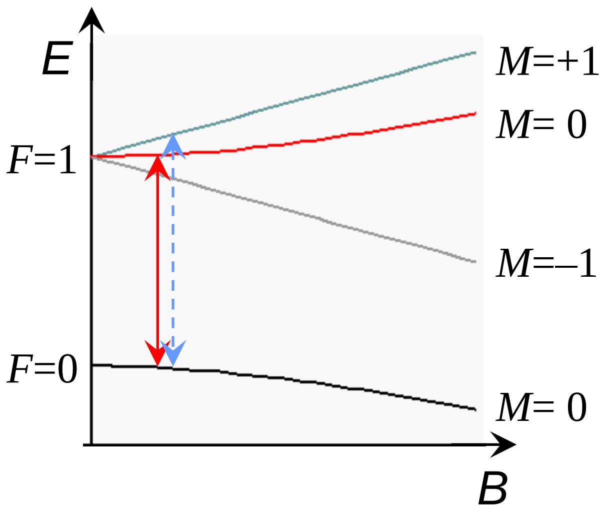




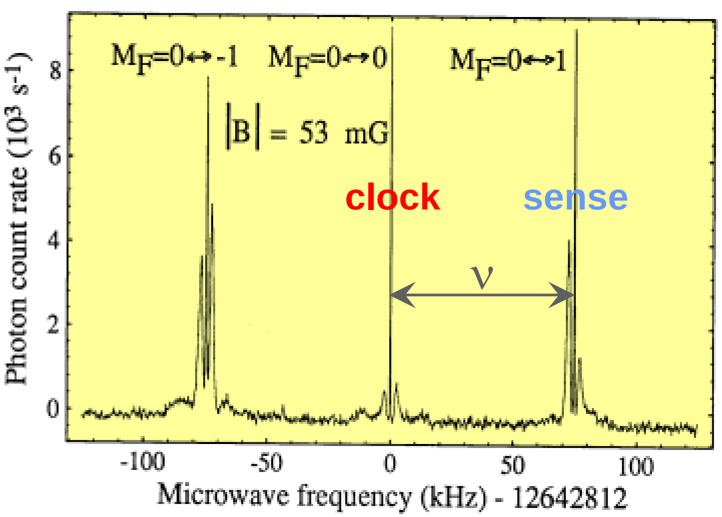
- Temperature
  thermal characteristic, component variations
- Electric field
  $\Delta f/f \sim 10^{-8}$/V for a 5 MHz SC-cut oscillator
- Pressure
  deformation of sealed resonator packages
- Humidity
  can affect dielectric constants of circuit components
- Power supply voltage and impedance
  $\Delta f/f \sim 10^{-11}$/V for a high-quality oscillator
- Gas permeation
  mechanical thickness variation :
  1 ppm=1 monolayer of contamination=10^3 s at 10^{-9} Torr if every molecule sticks
- Aging
  Chemical or photo-chemical effects

- Electric field
  Stark shifts, including from stray DC fields
- Magnetic field
  Zeeman shifts
- Interrogating field
  eg microwave field: phase uniformity, phase shifts, sidebands
- Temperature: blackbody radiation
  AC Stark shifts of atomic energy levels
- Collisions
  Phase shifts, interatomic potential
- Relativistic shifts
  Special relativity: motional shifts
  General relativity: gravitational potential

Zeeman effect: frequency shift with *B* field



- energy of atomic states varies with magnetic field ***B***
- apply small field to lift degeneracy and select *M*=0→*M*=0 clock transition
- no first-order Zeeman shift, but small second-order correction
- measure applied *B* by measuring frequency of *M*=0→*M*=1 sense transition



Blackbody radiation (i)

Quadratic Stark shift (DC):

$$\hat{H}' = -\boldsymbol{\mathcal{E}} \cdot \mathbf{D} = e\boldsymbol{\mathcal{E}} \cdot \mathbf{r}$$

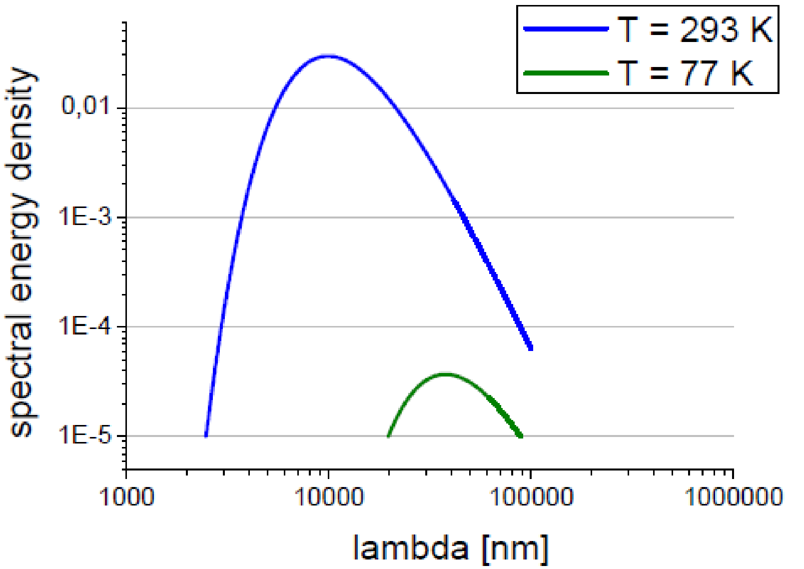
$$\delta\nu_{\gamma J} = -\frac{1}{2h}\alpha_{\gamma J}\mathcal{E}^2$$

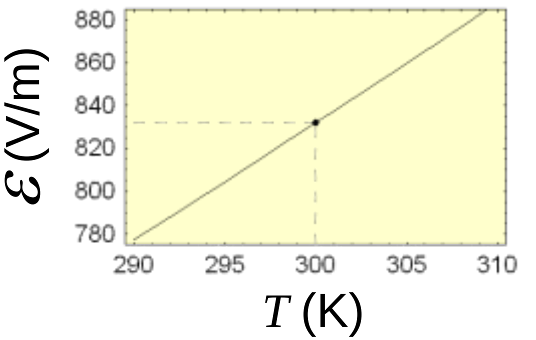
$$\alpha_{\gamma J} = -\frac{2}{3}\frac{1}{2J+1}\sum_{\gamma' J'}\frac{\left|\langle \gamma J \| D \| \gamma' J' \rangle\right|^2}{E_{\gamma J} - E_{\gamma' J'}}$$

$$= \frac{e^2\hbar^2}{m}\sum_{\gamma' J'}\frac{f_{\gamma J, \gamma' J'}}{(E_{\gamma J} - E_{\gamma' J'})^2}$$

so $\delta\nu \propto \sum f\lambda^2$

and $\mathcal{E}^2 = \dfrac{8\pi^5}{15\varepsilon_0}\dfrac{(kT)^4}{(hc)^3}$





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Blackbody radiation (ii)

- Itano *et al.* observed in 1982 that this shift is of practical consequence for atomic frequency standards, and predicted fractional shifts of order 10^{-14} in Cs.
  W. M. Itano, L. L. Lewis and D. J. Wineland, Phys. Rev. A ***25*** *1233 (1982)*

- The shift was confirmed experimentally in 1997 using Cs beam standards at PTB.
  A. Bauch and R. Schröder, Phys. Rev. Lett. ***78*** *622 (1997)*

- The CIPM affirmed in 1997 that '[the SI definition of the second] refers to a caesium atom at rest at a temperature of 0 K'.
  BIPM, 'The SI System of Units', 8^{th} ed. *(2006)*

- Frequency standards must therefore correct for the shift due to ambient radiation (usually calculated, based on atomic theory), and/or minimise the shift by operating at cryogenic temperatures.

species	transition	$\lvert\Delta\nu/\nu\rvert \times 10^{18}$
Al^+	${}^1S_0 \rightarrow {}^3P_0$	8(3)
In^+	${}^1S_0 \rightarrow {}^3P_0$	< 70
Ag	${}^2S_{1/2} \rightarrow {}^2D_{5/2}$	190
Yb^+	${}^2S_{1/2} \rightarrow {}^2F_{7/2}$	234(110)
Hg	${}^1S_0 \rightarrow {}^3P_0$	240
Mg	${}^1S_0 \rightarrow {}^3P_0$	394(11)
Yb^+	${}^2S_{1/2} \rightarrow {}^2D_{3/2}$	580(30)
Sr^+	${}^2S_{1/2} \rightarrow {}^2D_{5/2}$	670(250)
Ca	${}^1S_0 \rightarrow {}^3P_1$	2210(50)
Yb	${}^1S_0 \rightarrow {}^3P_0$	2400(250)
Sr	${}^1S_0 \rightarrow {}^3P_0$	5500(70)
Cs	$F=4 \rightarrow F=3$	21210(260)

Calculated blackbody shifts
T. Rosenband et al., *Proc 20th EFTF 289 (2006)*

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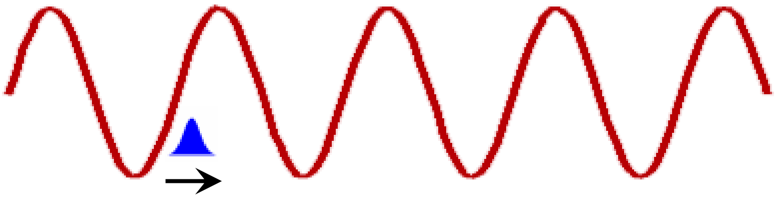
Motional shifts

- Lamb-Dicke limit: confinement within a wavelength avoids first-order Doppler shift

$$\sqrt{\langle x^2 \rangle} << \frac{\lambda}{2\pi}$$



- Second-order Doppler shift: time dilation shift

$$\left.\frac{\Delta f}{f}\right|_{\mathrm{2OD}} = -\frac{3kT}{2mc^2}$$

$\Delta f/f$ ~ 2×10^{-13} at T~300K

$\Delta f/f < 1 \times 10^{-15}$ at T<1K

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Overview

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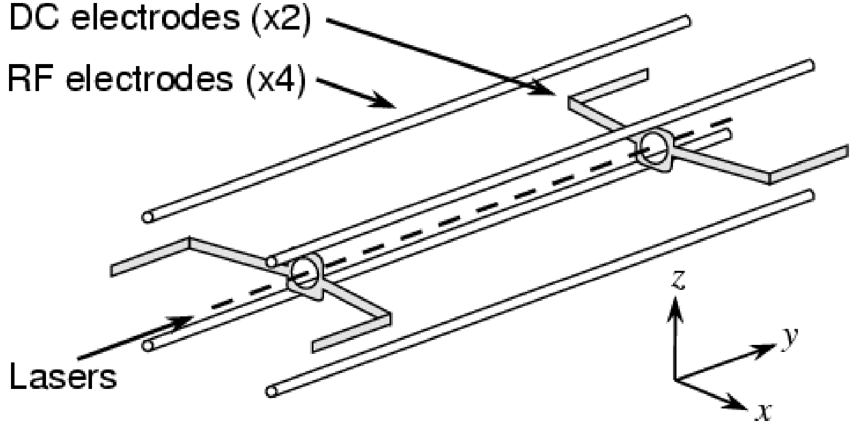
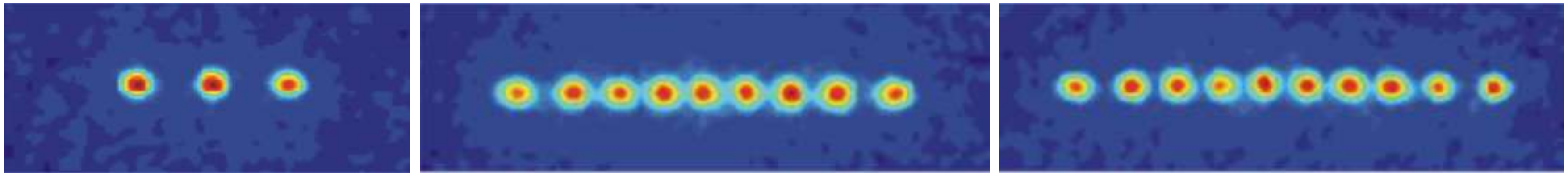
- Trapped ion frequency standards
- Optical lattice frequency standards
- Comparing optical frequency standards
- Time and frequency transfer
- Atomic Clock Ensemble in Space
- The future

Linear ion trap



Linear quadrupole RF trap

Trap for dust particles

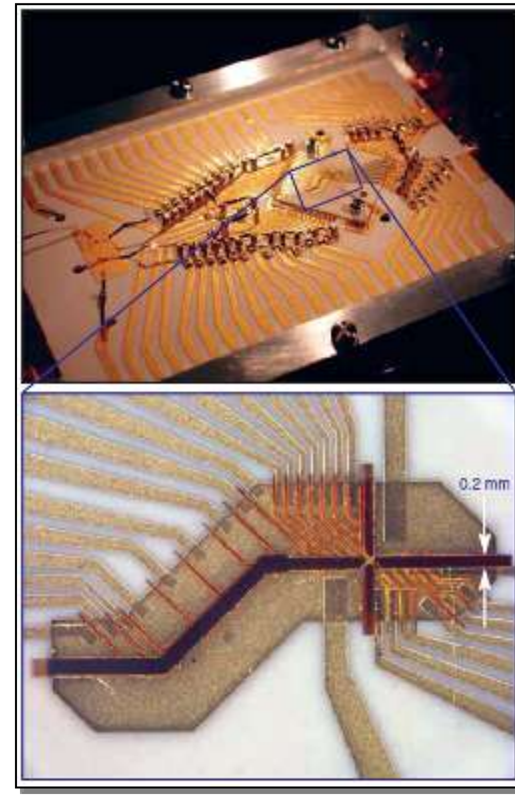


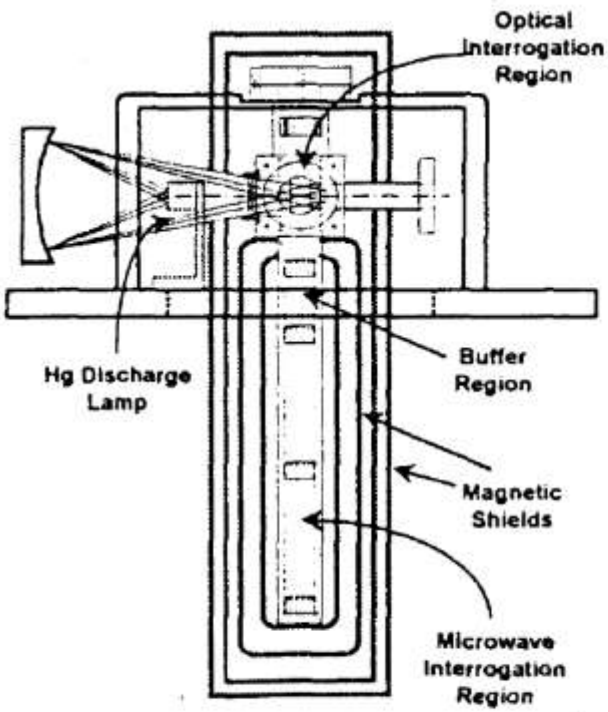
$^{40}Ca^{+}$ ion strings along the nodal line of a linear ion trap

H. C. Nägerl et al., Appl. Phys. B ***66*** *603 (1998)*

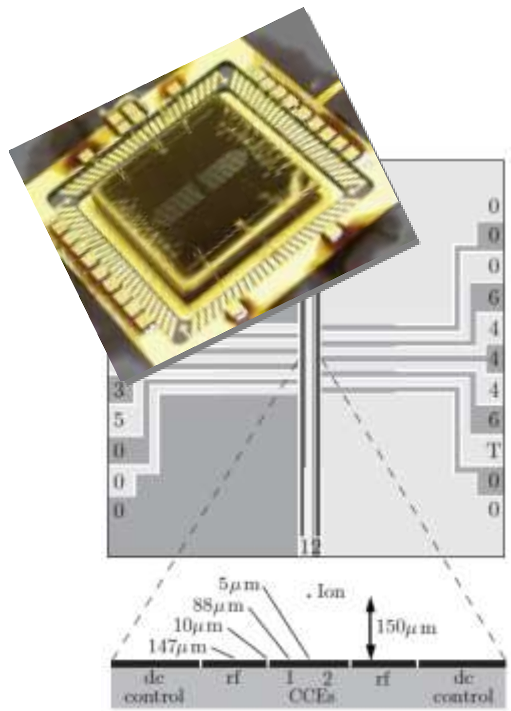
$^{171}Yb^{+}$, NMI Australia (1995)

$^{40}Ca^{+}$, Innsbruck (2000)

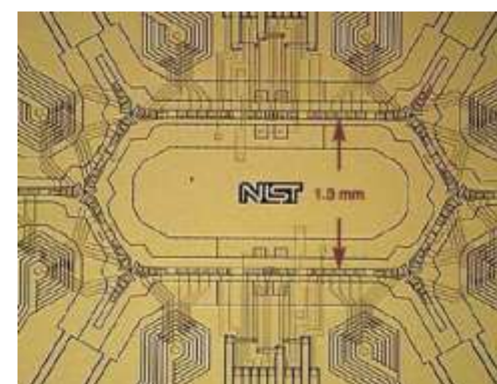




J. D. Prestage et al.,
Proc. Joint IEEE FCS/EFTF *(1999)*

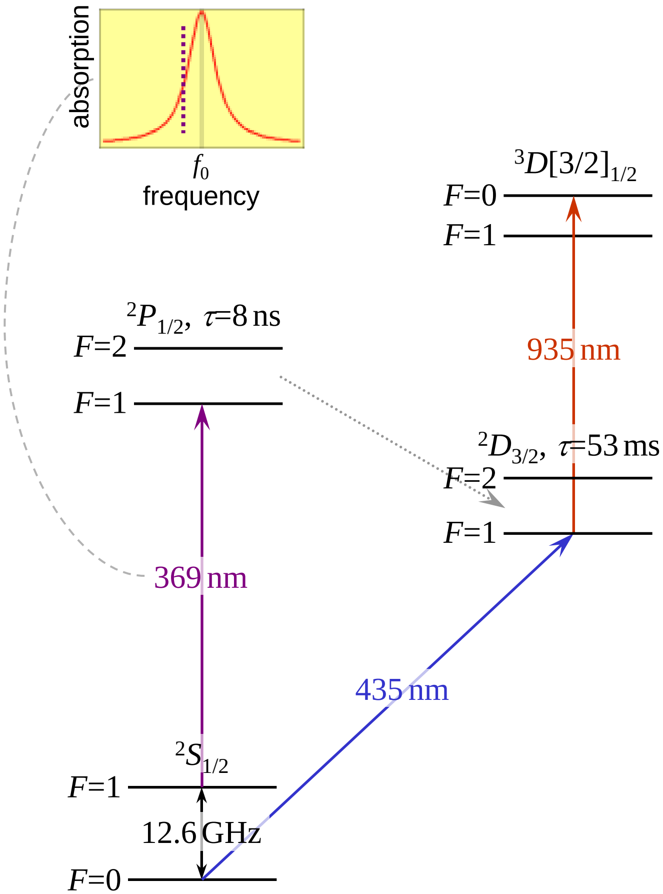


D. T. C. Allcock et al.,
arXiv:0909.3272v2 (2009)

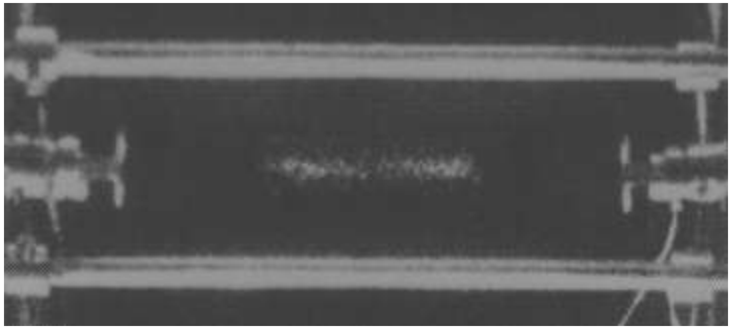


D J. Wineland and D. Liebfried,
Laser Phys. Lett. ***8*** *175 (2011)*

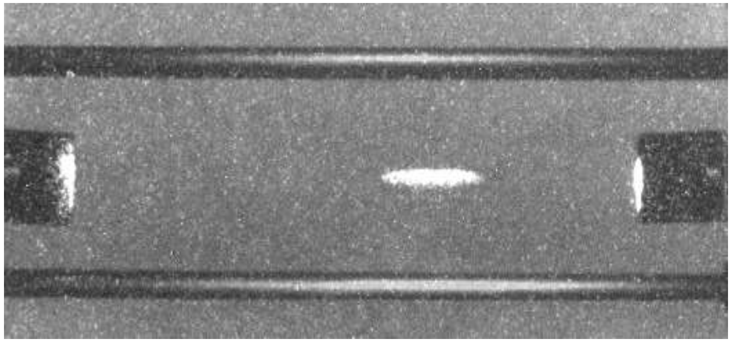
Laser cooling of $^{171}Yb^{+}$ in a linear trap



$^{171}Yb^{+}$ energy levels



warm cloud: T ~ 380 K



laser-cooled cloud: T < 200 mK

radius	~	1 mm
length	~	10 mm
ions	~	10^4
temperature	<	200 mK

$$\nabla^2\Psi = -\frac{\rho}{\varepsilon_0}$$

P. Fisk and R. B. Warrington et al., *NMIA*

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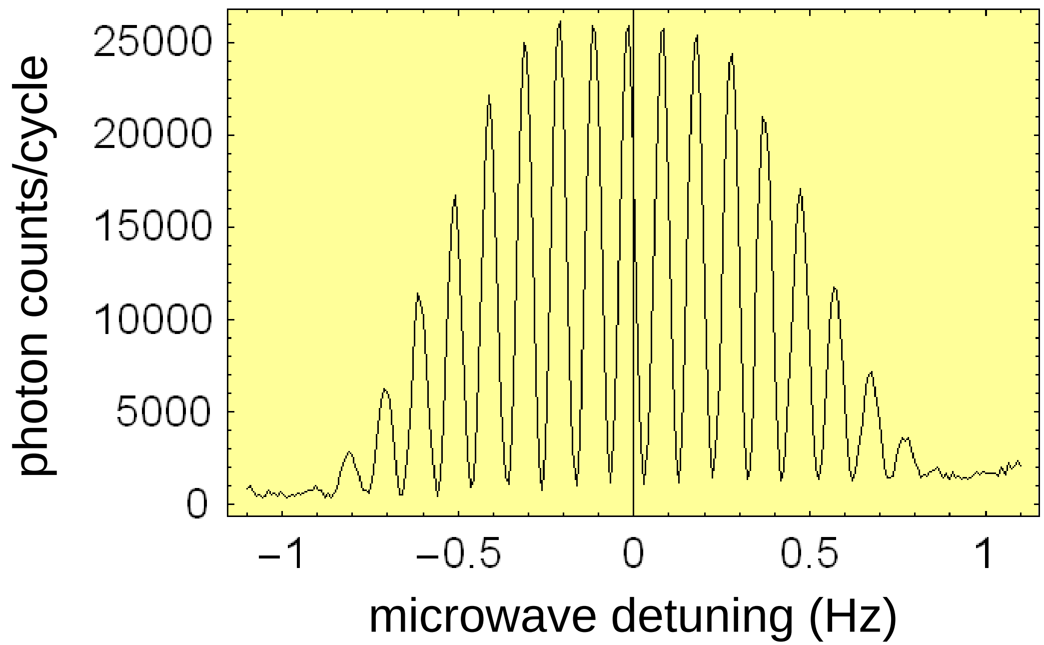
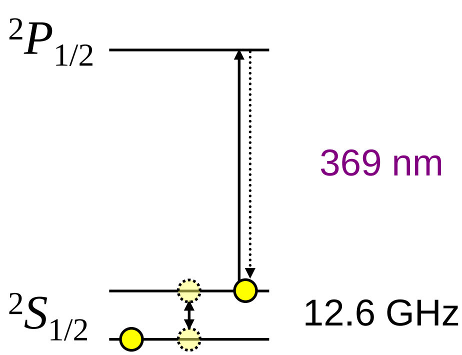
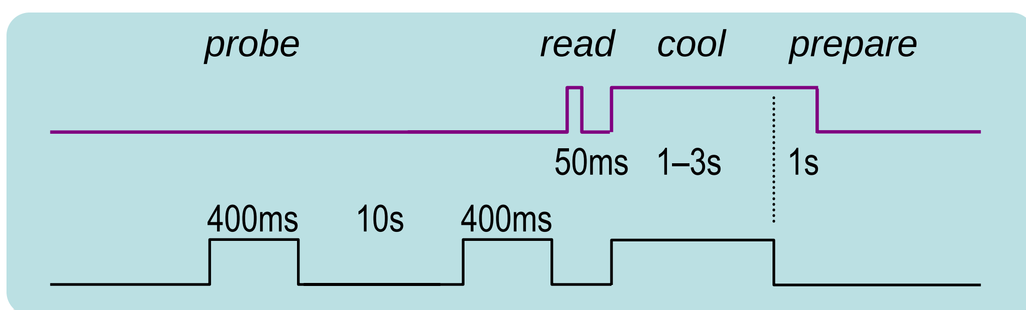
Ramsey fringes (t_R=10s) for $^{171}Yb^+$







P. Fisk and R. B. Warrington et al., *NMIA*

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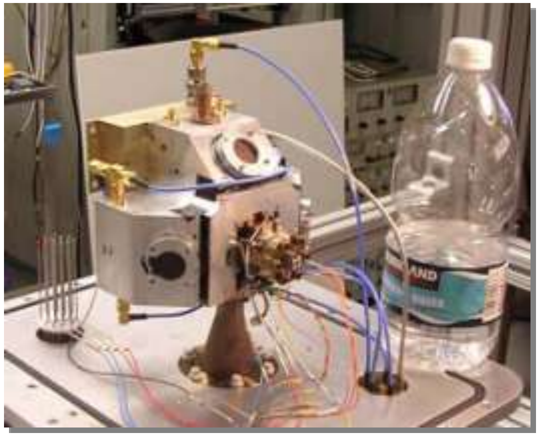
Compact low-power multipole traps…

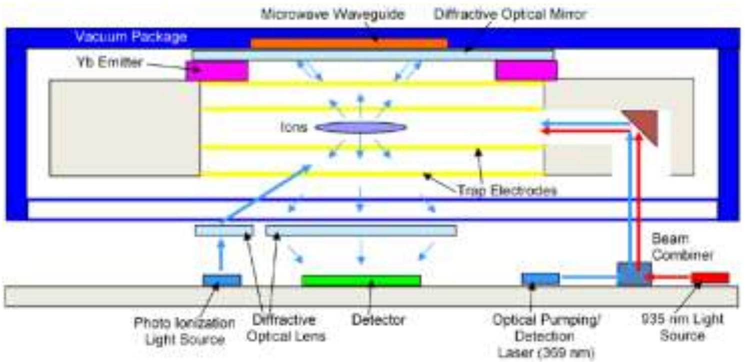
…for space applications [JPL]

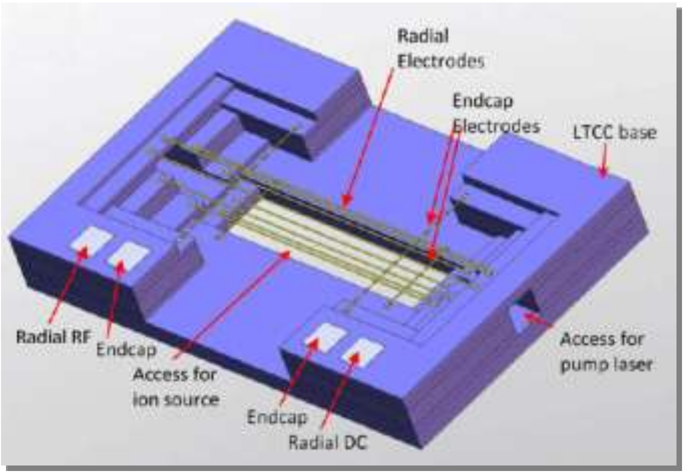
R. L. Tjoelker et al., Proc 33rd PTTI *(2001)*



J. D. Prestage et al., Proc IEEE FCS and 37th PTTI *(2005)*

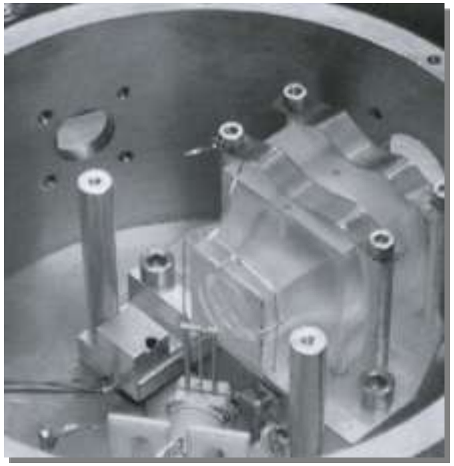
…as a stable reference [Sandia]



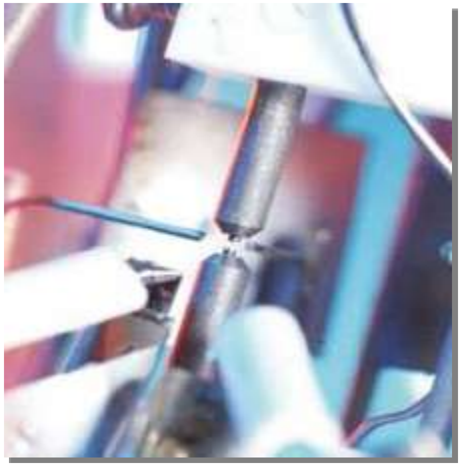


P. D. D. Schwindt et al., Proc 41st PTTI *(2009)*

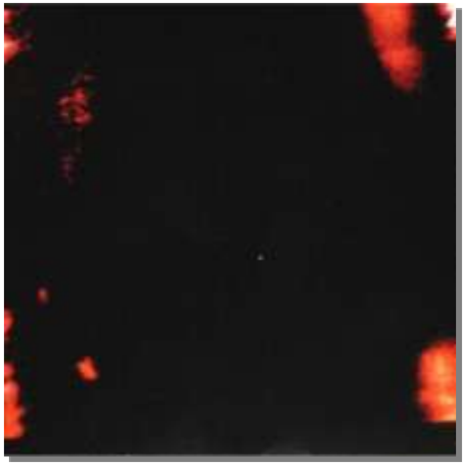
Single ion traps



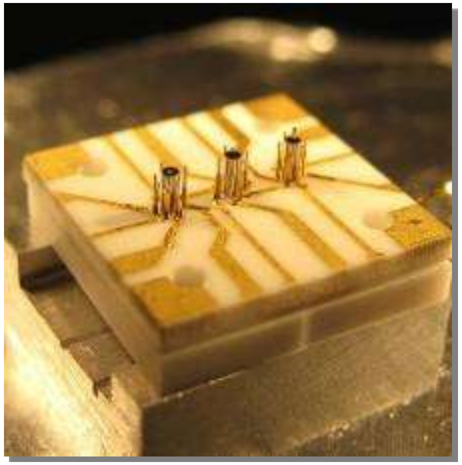
Cryogenic Paul trap, NIST, Hg^+



Endcap trap, NPL, $^{88}Sr^+$



Ba^+, UWA (Nagourney)

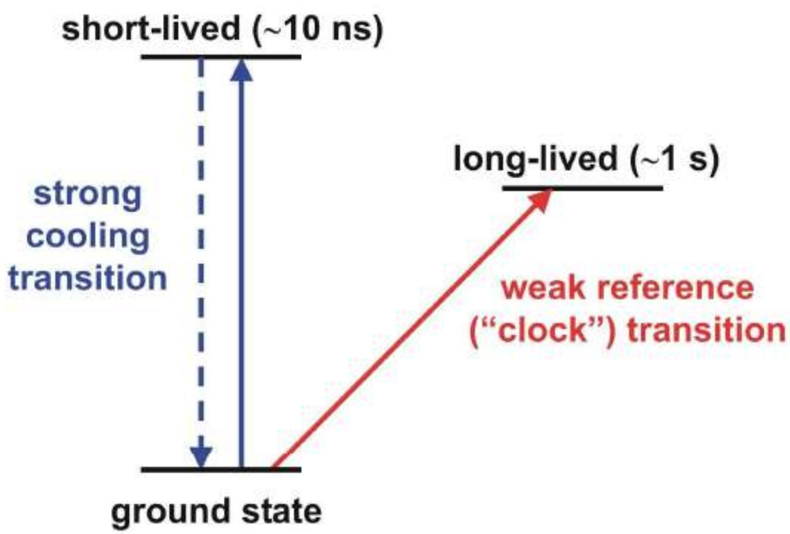


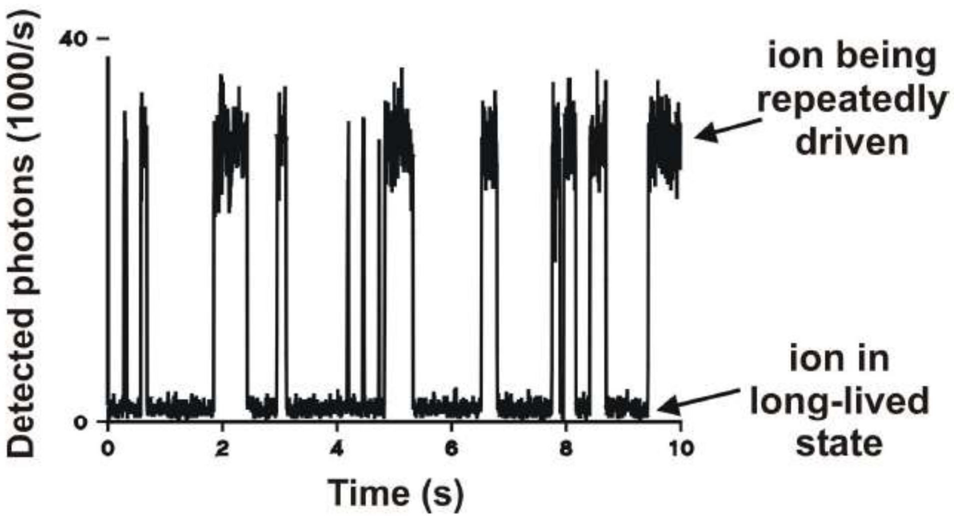
Stylus trap, NIST, Mg^+

Paul-Straubel trap, PTB, $^{171}Yb^+$

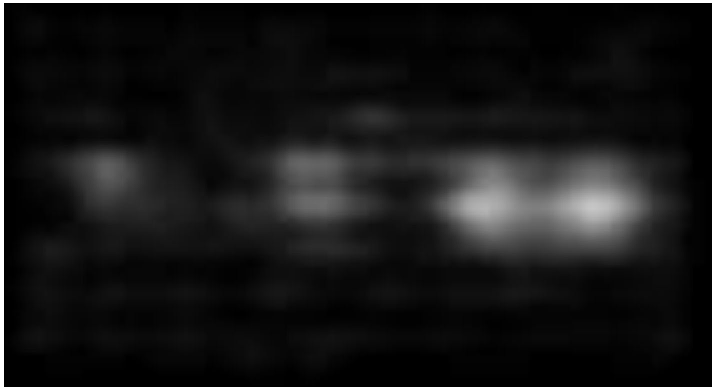
$^{171}Yb^+$, PTB (Mehlstäuber [2])

State detection by ‘electron shelving’





NPL, as in P. Gill et al., *‘Optical Atomic Clocks for Space’ (2008) [3]*



Courtesy Steane/Lucas/Stacey group, Oxford

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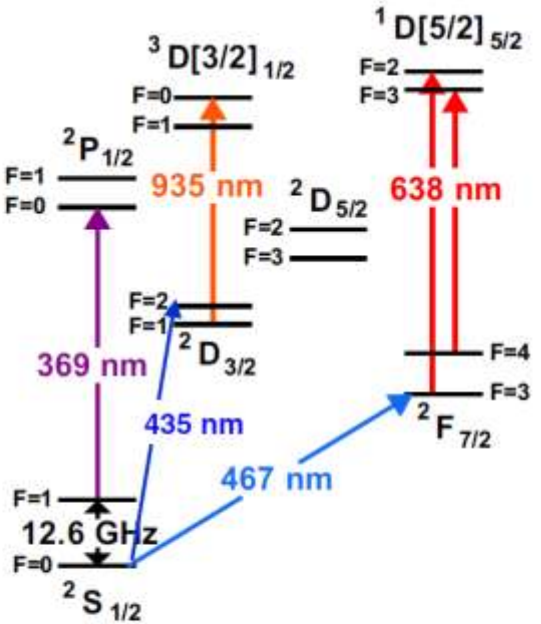
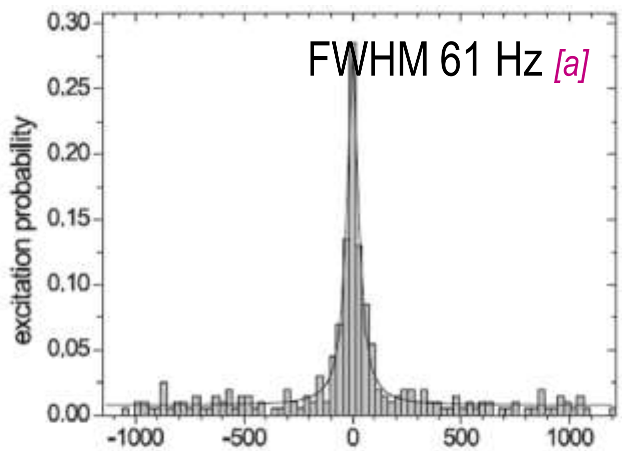
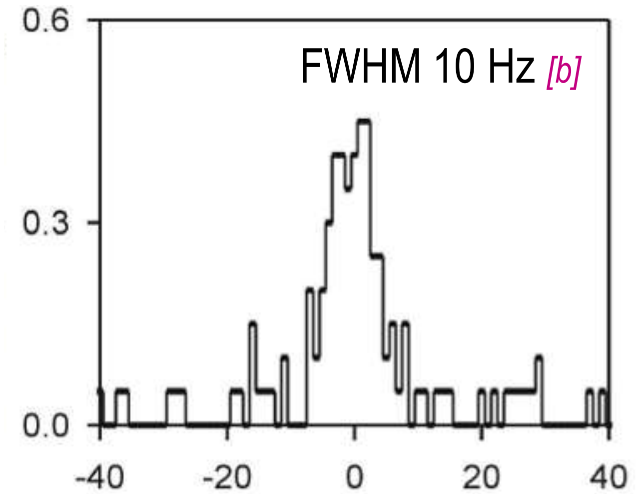
$^{171}Yb^+$ $^2S_{1/2} \rightarrow {}^2D_{3/2}$ (688 THz, 435 nm)







lineshape: excitation probability vs detuning at 435 nm (Hz)

ν_0 = 688 358 979 309 309.9 (8.9) Hz
S. Webster et al., IEEE Trans. UFFC ***57*** *592 (2010) [a]*

ν_0 = 688 358 979 309 306.62(73) Hz
Chr. Tamm et al., Phys. Rev. A ***80*** *043403 (2009) [b]*

- Electric quadrupole shift: averaged over 3 $\perp$ ***B***; systematic uncertainty ~0.3 Hz (5×10^{-16})
- Fiber comb to PTB CSF1: $\sigma(\tau) \sim 10^{-13}\ \tau^{-1/2}$, averaging time 25–90 hours
- ν_0 determined at 300 K; blackbody shift –0.35(7) Hz

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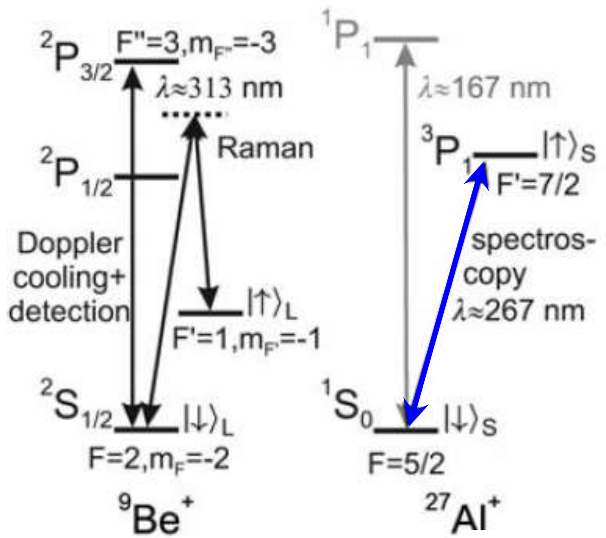
$^{27}\mathrm{Al}^+\ {}^1S_0 \rightarrow {}^3P_1$ (267 nm)



- Al^+ cooling transition at 167 nm inaccessible. Load $^{27}Al^+$ and auxiliary $^9Be^+$ in a linear ion trap: cooling Be^+ cools Al^+ by Coulomb coupling
- Coulomb coupling also used for quantum logic: map Al^+ clock state to Be^+ hyperfine state

$$\left(\alpha|S\rangle + \beta|P\rangle\right) \rightarrow \left(\alpha|1\rangle + \beta|2\rangle\right)$$

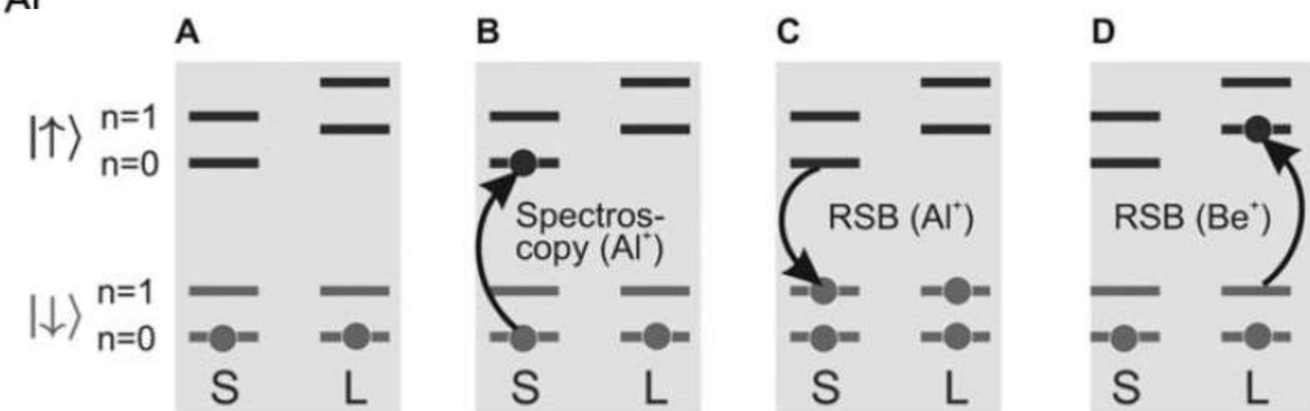
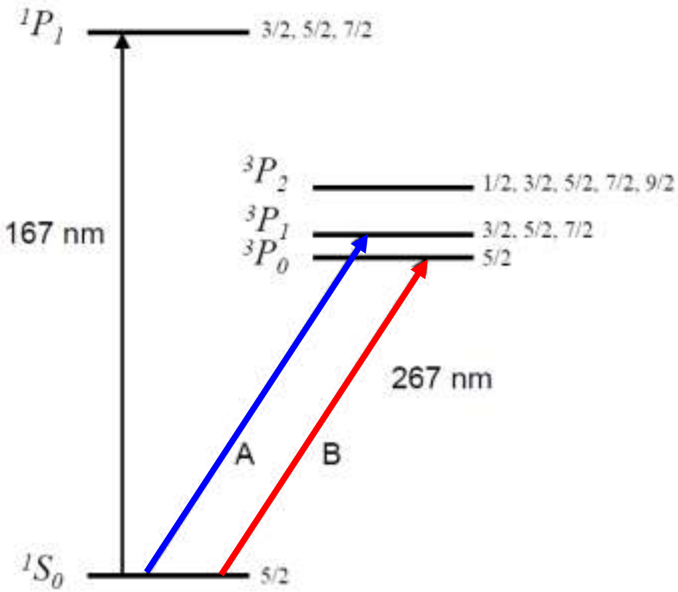


Fig. 1. Spectroscopy and transfer scheme for spectroscopy (S) and logic (L) ions sharing a common normal mode of motion, the transfer mode, with excitation n. (Only the ground and first excited states of the transfer mode are shown.) (A) Initialization to the ground internal and transfer-mode states. (B) Interrogation of the spectroscopy transition. (C) Coherent transfer of the internal superposition state of the spectroscopy ion into a motional superposition state by use of an RSB π pulse on the spectroscopy ion. (D) Coherent transfer of the motional superposition state into an internal superposition state of the logic ion by use of an RSB π pulse on the logic ion.

P. O. Schmidt et al., Science ***309*** *749 (2005)*

$^{27}Al^+$ $^1S_0 \rightarrow$ $^3P_0$ (1121 THz, 267 nm)



W. M. Itano et al., Proc. SPIE ***6673***, *667301-1 (2007)*

ν_0 = 1 121 015 393 207 851(6) Hz
T. Rosenband et al., Phys. Rev. Lett. ***98*** *220801 (2007)*

- $^1S_0 \rightarrow$ $^3P_0$ of $^{27}Al^+$ and other group IIIA ions originally proposed by Dehmelt : very high Q, minimal systematic effects
- $^3P_0$ state has no electric quadrupole moment to first order, only due to hyperfine mixing: quadrupole shifts below 1×10^{-18}
- Blackbody shift has fortuitous cancellation for $^1S_0$ and $^3P_0$ states: shift at 300 K = $8(5) \times 10^{-18}$
- Linear Zeeman shift cancelled (by averaging $m_F = +5/2 \rightarrow +5/2$ and $m_F = -5/2 \rightarrow -5/2$) and quadratic Zeeman shift below 1×10^{-18}
- Combined systematic uncertainty **below 5×10^{-17}**, dominated by residual second-order Doppler shift (thermal and micromotion)

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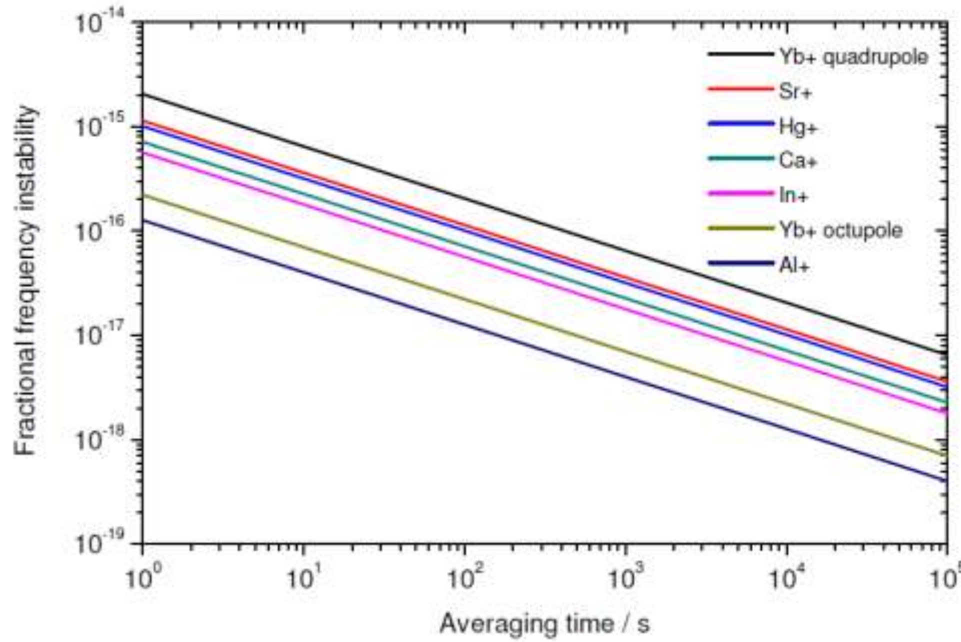
Single-ion optical frequency standards

Ion	Clock transition	λ/nm	$\Delta\nu_{nat}$/Hz	$10^{15}(\delta\nu/\nu)$
$^{27}Al^{+}$	$^{1}S_0$–$^{3}P_0$	267	8×10^{-3}	0.65
$^{40}Ca^{+}$	$^{2}S_{1/2}$–$^{2}D_{5/2}$	729	0.14	2.4
$^{88}Sr^{+}$	$^{2}S_{1/2}$–$^{2}D_{5/2}$	674	0.4	3.8
$^{115}In^{+}$	$^{1}S_0$–$^{3}P_0$	237	0.8	180*
				260*
$^{171}Yb^{+}$	$^{2}S_{1/2}$–$^{2}D_{3/2}$	436	3.1	3.2
$^{171}Yb^{+}$	$^{2}S_{1/2}$–$^{2}F_{7/2}$	467	$\sim 10^{-9}$	20
$^{199}Hg^{+}$	$^{2}S_{1/2}$–$^{2}D_{5/2}$	282	1.8	0.65



A summary of single-ion optical frequency standards

Theoretical quantum-limited stability for single-ion optical frequency standards

H. S. Margolis, Contemporary Physics ***51*** *37 (2010) [4]*

P. Gill et al., *'Optical Atomic Clocks for Space' (2008) [3]*

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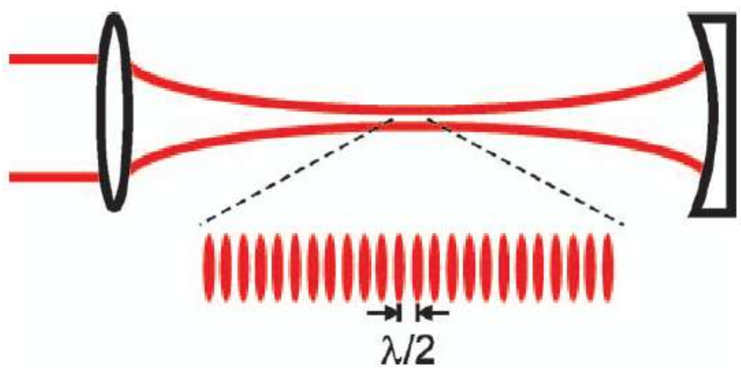
Optical lattices

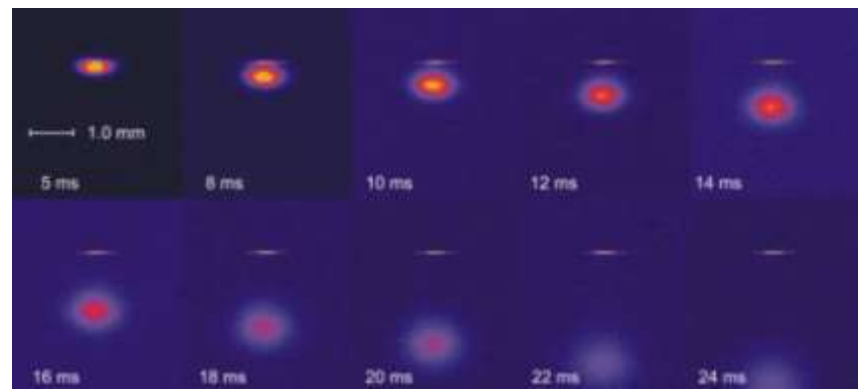
Single-ion traps achieve high accuracy (confinement, isolation) but n=1

Cold neutral clouds have high stability (high n) but motional and collisional shifts

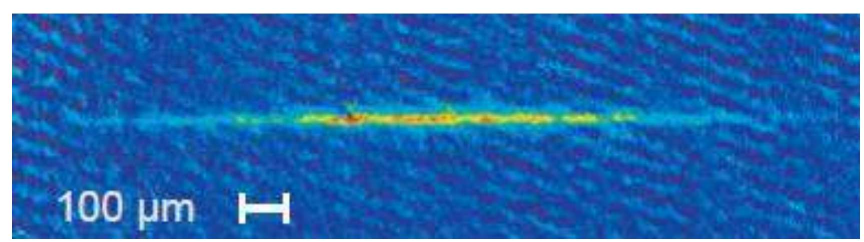
→ Use an *optical lattice* for Lamb-Dicke confinement of n ‘individual’ cold atoms



optical interference of red-detuned light →
localisation in regions of high intensity
(blue-detuned → low intensity)



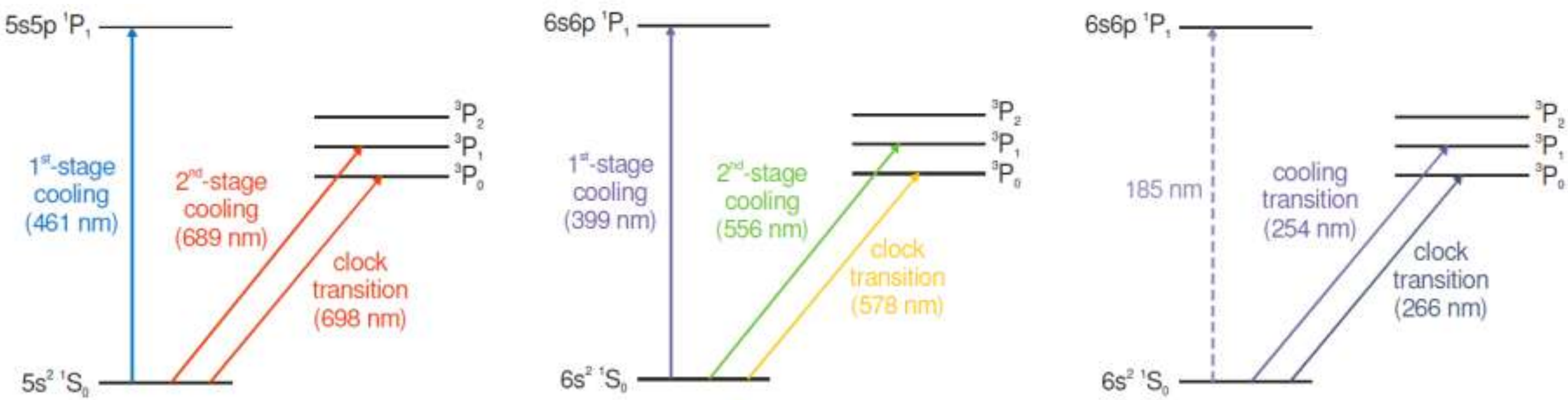
loading of cold Sr atoms into 1D lattice *PTB*



Yb atoms in optical trap at 40 μK *HHUD Düsseldorf*

Candidates for an optical lattice clock

^{87}Sr, ^{88}Sr | ^{171}Yb, ^{174}Yb | ^{199}Hg



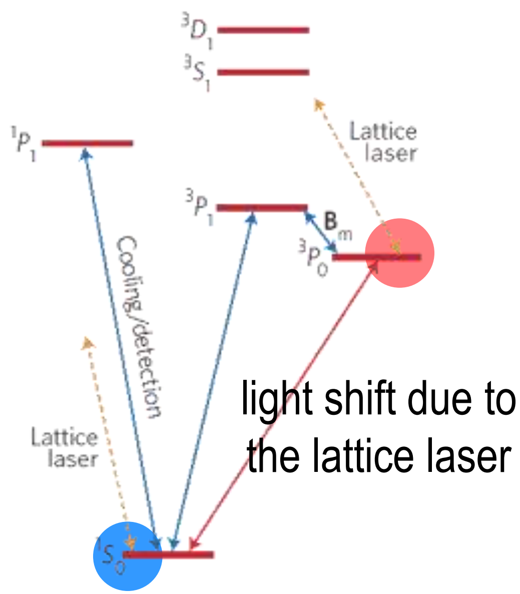
strong cooling transitions and narrow (forbidden) clock transitions

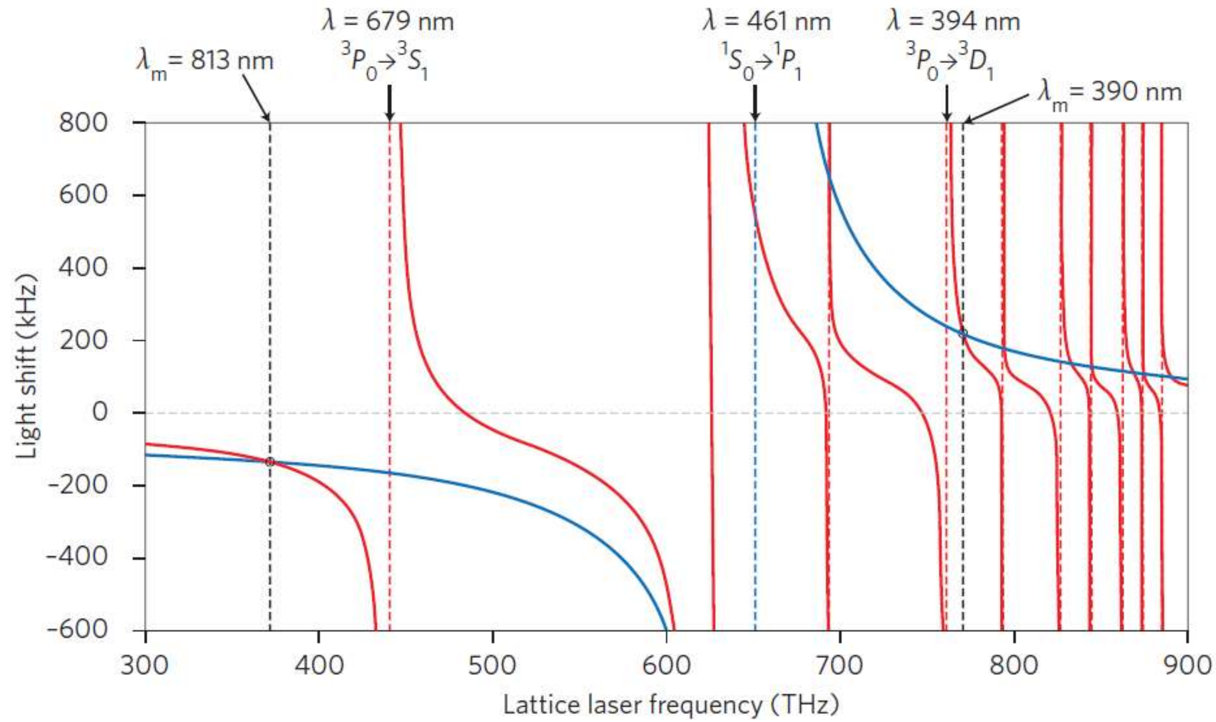
'second stage' cooling on intercombination line → lower Doppler limit

both bosonic and fermionic isotopes available

P. Gill et al., *'Optical Atomic Clocks for Space' (2008) [3]*

Cancelling the lattice light shift





H. Katori, Nature Photonics ***5*** *203 (2011) [6]*

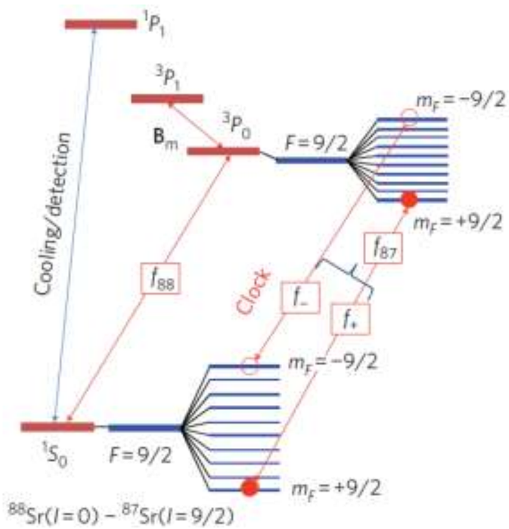
→ at a 'magic wavelength' for the lattice laser, the light shifts of the lower and upper levels of the clock transition cancel

eg Sr: 813 nm (red-detuned from clock transition) and 390 nm (blue-detuned)

Atom	Magic wavelength / nm
Mg	432
Ca	680
^{87}Sr	813.428(1), 389.889(9)
^{174}Yb	759.35374(7)
Hg	362.53(21)

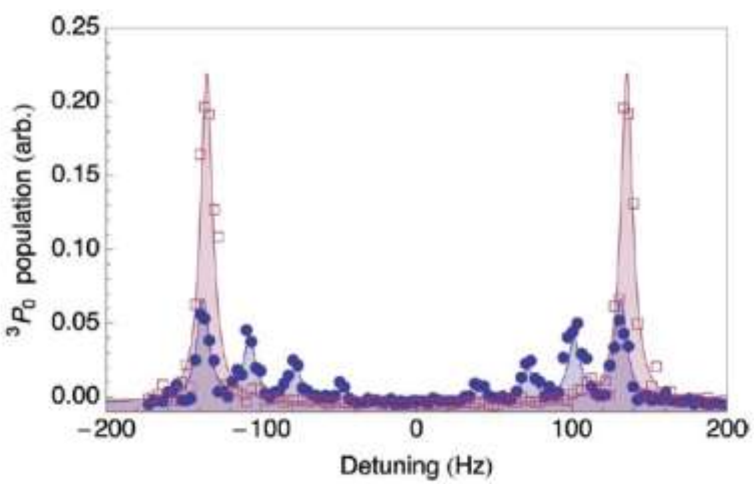
P. Gill et al., *'Optical Atomic Clocks for Space' (2008) [3]*
L. Yi et al., Phys. Rev. Lett. ***106*** *073005 (2011)*

^{87}Sr lattice clock (*eg* JILA)



- Two-stage MOT (T~1 mK), 10^4 atoms loaded into vertical lattice; optically pump into $m_F=\pm 9/2$ (average linear Zeeman shift)
- FWHM Fourier-limited at 2 Hz (480 ms probe time, limited by clock laser noise)
- Lock fibre frequency comb to clock laser, then compare comb spacing with NIST-F1 (via intermediate maser and fibre link)

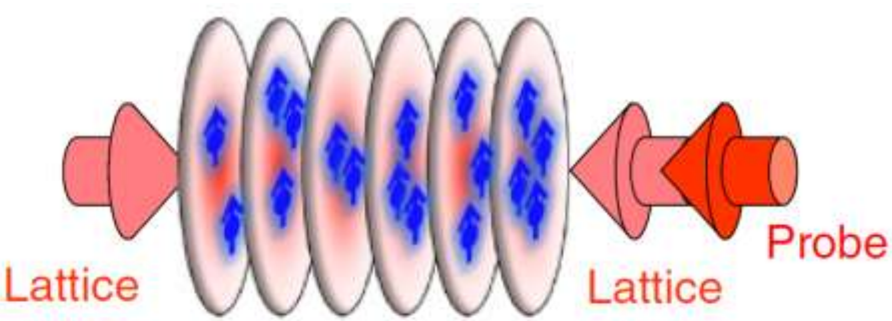
ν_0 = 429 228 004 229 873.65(37) Hz
G. K. Campbell et al., Metrologia ***45*** *439 (2008)*

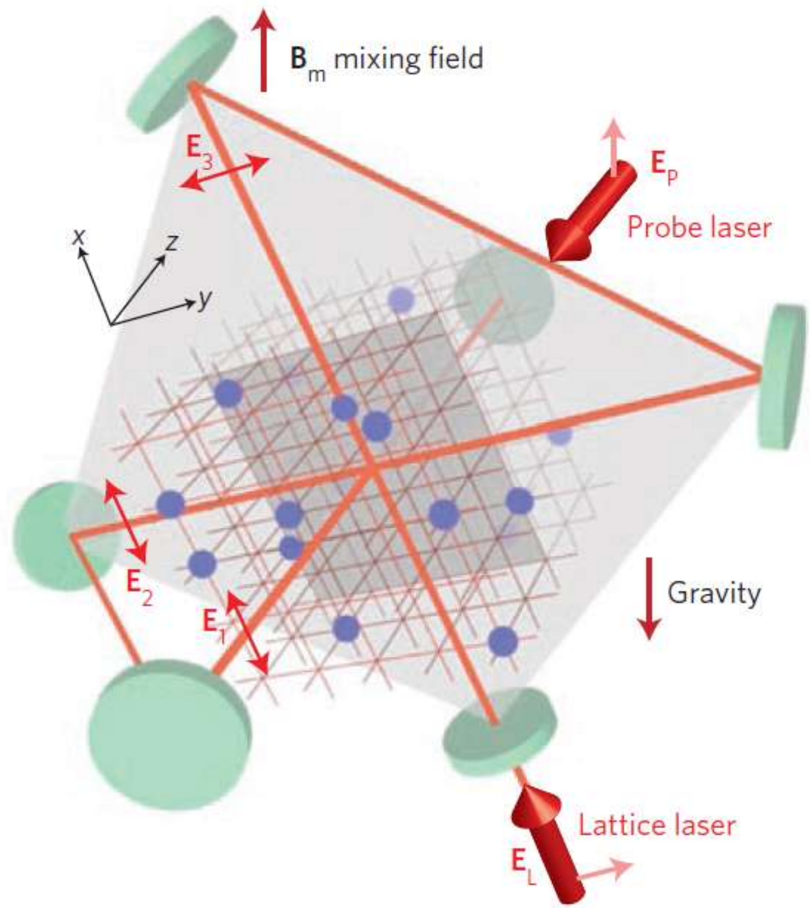


- Evaluate systematic uncertainty by comparing Sr to NIST neutral Ca standard
- Combined systematic uncertainty **1.4x10^{-16}**, dominated by blackbody shift 54(1)x10^{-16}

M. D. Swallows et al., IEEE Trans. UFFC ***57*** *574 (2010)*

Optical lattices in 1D and 3D





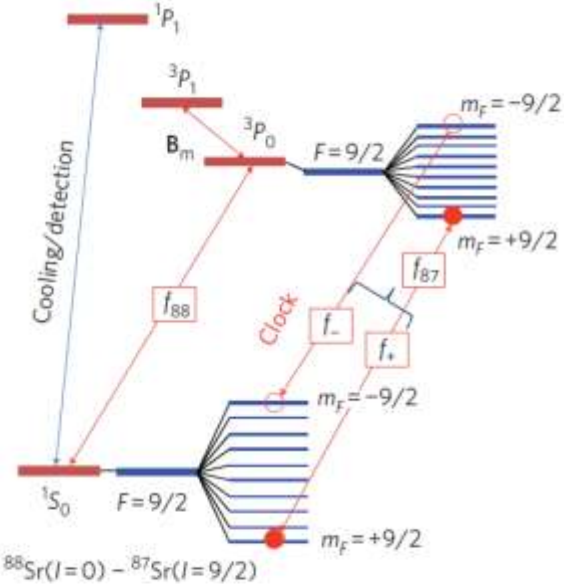
1D: suppress collisions by using spin-polarized fermions such as ^{87}Sr (Pauli exclusion); uniform light polarization → cancel vector light shift

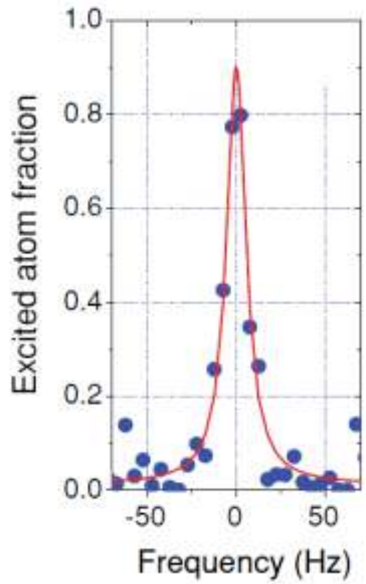
3D: reduce collisional shifts (≤1 atom per lattice site), but hard to control polarization → use bosonic atoms (eg ^{88}Sr, F=0)

H. Katori, Nature Photonics ***5*** *203 (2011) [6]*
F.-L. Hong and H. Katori [7]

Australian Government
National Measurement Institute

^{88}Sr lattice clock (eg Tokyo)

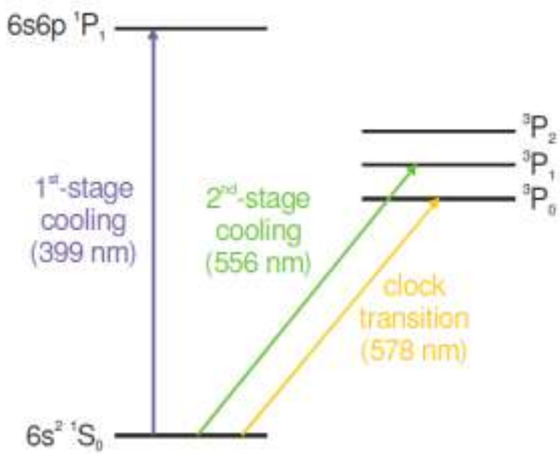




- Bosonic ^{88}Sr: must now apply larger **B** field, to mix in $^3P_1$ (otherwise 0→0 transition strictly forbidden); this gives larger Zeeman shifts (~100 Hz)
- Also must increase clock laser intensity (low transition rate); this gives larger light shift (few Hz)
- Drive photoassociation after lattice loading to eliminate sites with more than one atom
- Evaluate uncertainty by comparing to ^{87}Sr; systematic uncertainty for ^{88}Sr **2×10^{-15}**, due to lattice scalar light shift (different magic wavelength)

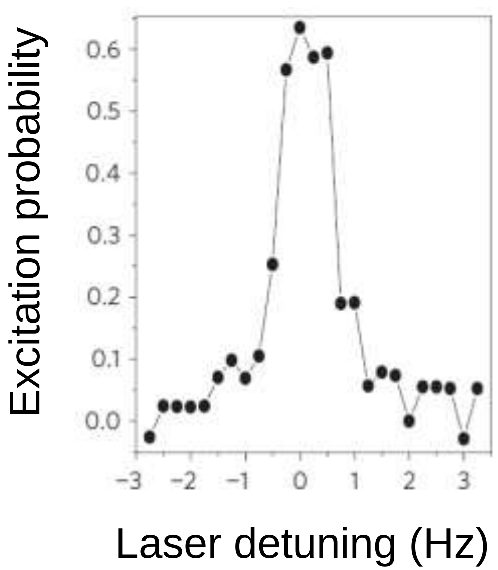
T. Akatsuka, M. Takamoto and H. Katori, Phys. Rev. A ***81*** *023402 (2010)*

^{171}Yb lattice clock (*eg* NIST)



- Fermionic ^{171}Yb: two-stage MOT, 1D lattice at magic wavelength of 759 nm
- Evaluate uncertainty by comparing to neutral Ca; systematic uncertainty **3.4x10^{-16}**, dominated by blackbody shift and higher-order lattice light shifts

ν_0 = 518 295 836 590 865.2(7) Hz
N. D. Lemke et al., Phys. Rev. Lett. ***103*** *063001 (2009)*



- Clock laser recently improved to ~0.25 Hz linewidth, using new reference cavity (ULE spacer with silica mirror substrates, reduced thermal noise)
- Use ^{171}Yb lattice clock transition as a frequency discriminant: clock laser instability ~ 5x10^{-16} $\tau^{-1/2}$
- FWHM Fourier-limited at 1 Hz (0.9 s probe time); Q > 5**x**10^{14} (1 Hz @ 518 THz)

Y. Y. Jiang et al., Nature Photonics ***5*** *158 (2011)*

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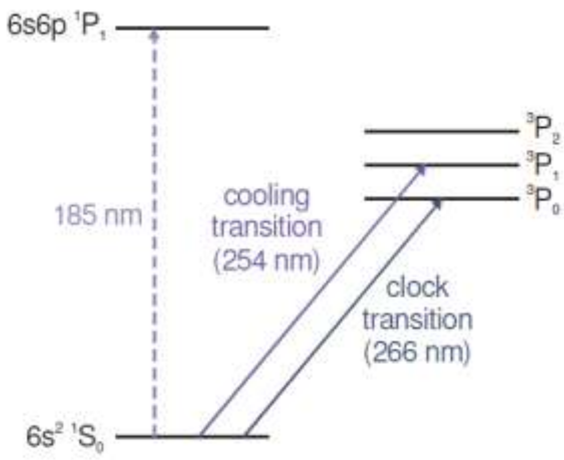
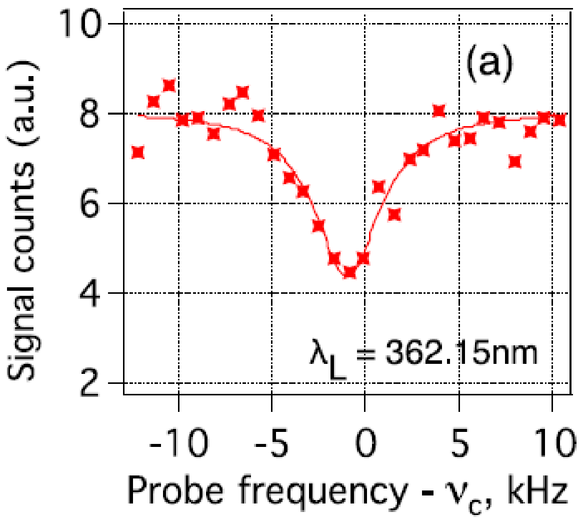
^{199}Hg lattice spectroscopy (SYRTE)





- Fermionic ^{199}Hg: single stage cooling on intercombination line to ~60 μK in MOT, ~500 atoms transferred into 1D vertical lattice
- Lattice wavelength ~363 nm also in the UV, and power limited to avoid mirror damage; measured λ=362.53(21) nm
- Thermal occupation of lattice vibrational states → broadened lineshape (sum over different transition frequencies)
- Dominant systematic uncertainty for ^{87}Sr and ^{171}Yb the blackbody shift; lower polarizability means ^{199}Hg shift should be an order of magnitude lower

ν_0 = 1 128 575 290 808 400 Hz

L. Yi et al., Phys. Rev. Lett. ***106*** *073005 (2011)*

Overview

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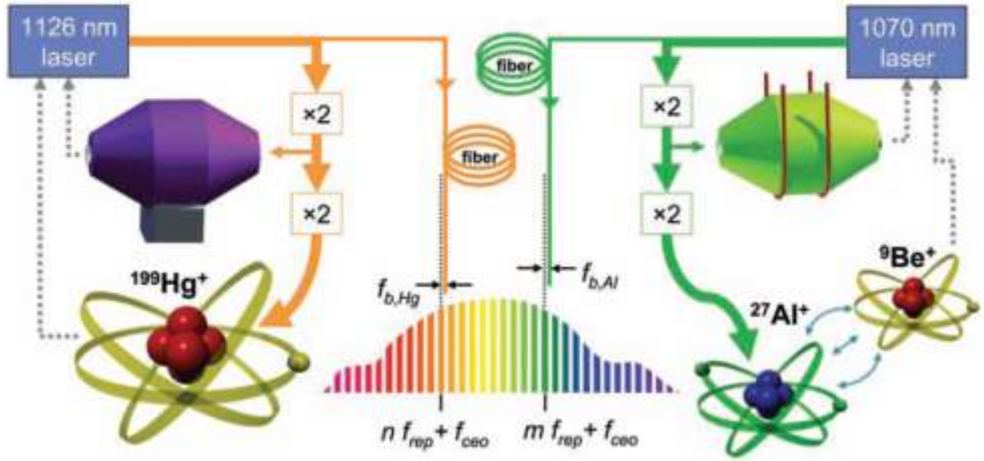
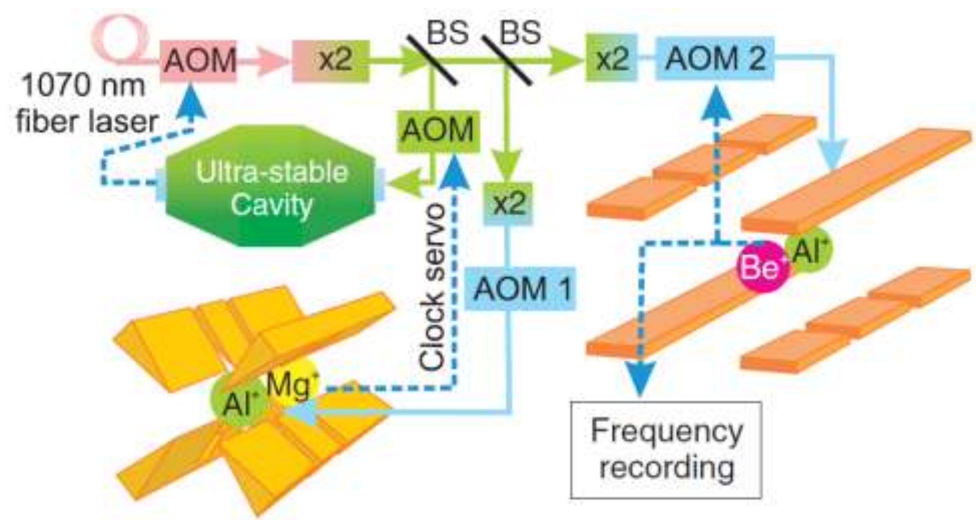
Comparisons between optical clocks (i)

- evaluating uncertainty needs comparisons between two clocks of similar performance
- *eg* $^{199}Hg^{+}$ 1.9×10^{-17}
  $^{27}Al^{+}$–$^{9}Be^{+}$ 2.3×10^{-17}
  $\sigma_y(\tau) \sim$ $3.9 \times 10^{-15}\ \tau^{-1/2}$
- also Sr-Ca, Yb-Hg^{+}, Sr-Yb…



T. Rosenband et al., Science ***319*** *1808 (2008)*

- *eg* $^{27}Al^{+}$–$^{25}Mg^{+}$ 8.6×10^{-18}
  $^{27}Al^{+}$–$^{9}Be^{+}$ 2.3×10^{-17}
  $\sigma_y(\tau) \sim$ $2.8 \times 10^{-15}\ \tau^{-1/2}$
- testbed with unprecedented accuracy and stability: fundamental physics, relativity, gravimetry…



C. W. Chou et al., Phys. Rev. Lett. ***104*** *070802 (2010)*

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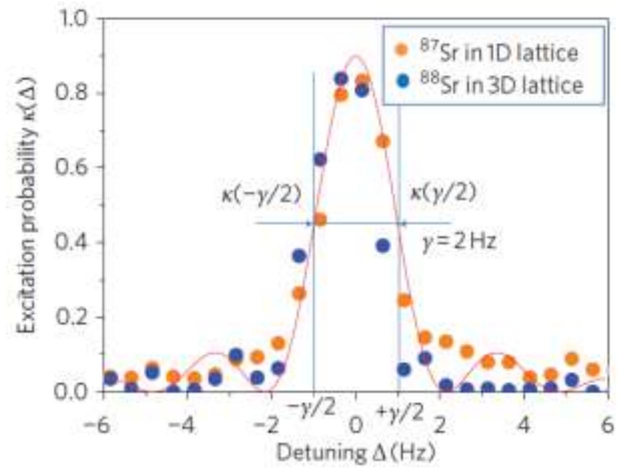
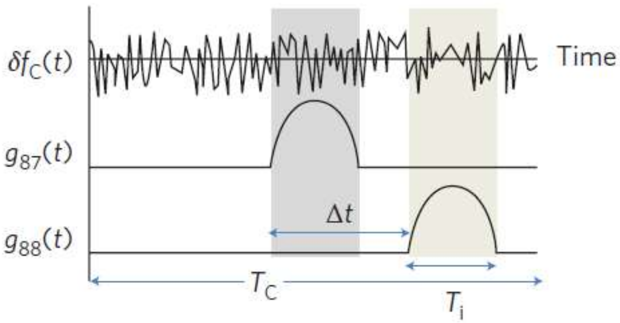
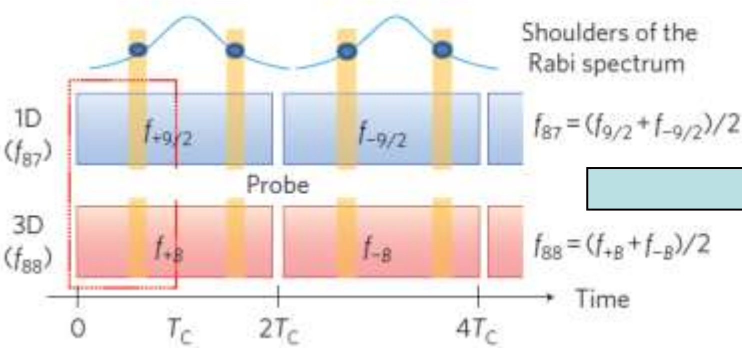
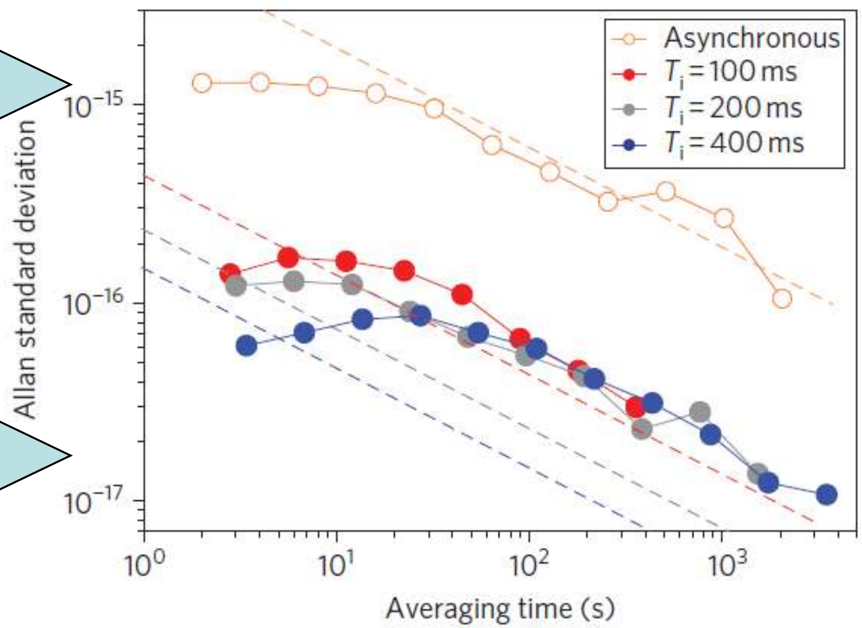
Comparisons between optical clocks (ii)

- Compare ^{87}Sr (1D) and ^{88}Sr (3D) lattice clocks
- Use synchronous probing to mitigate Dick effect (previously demonstrated for fountain standards with microwave local oscillator)



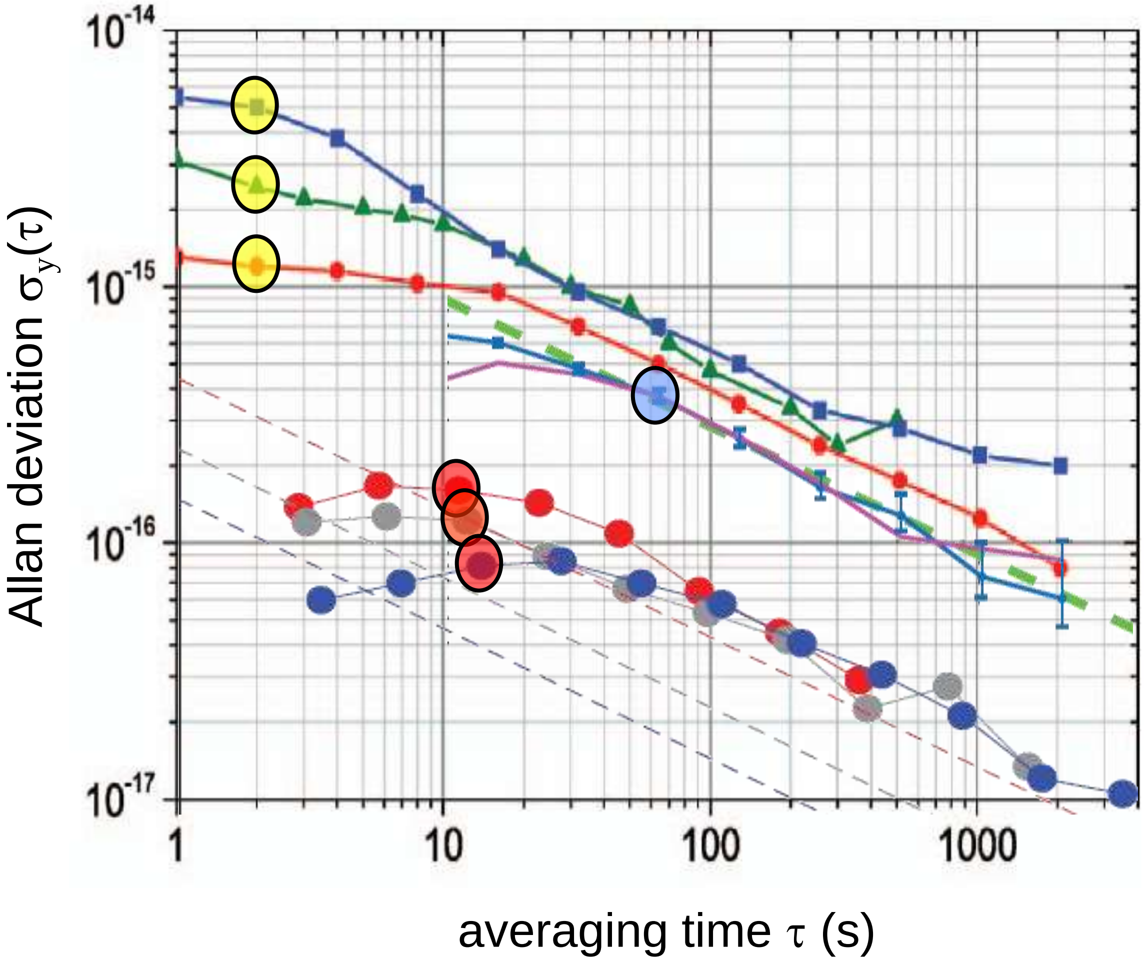






H. Katori, Nature Photonics ***5*** *203 (2011) [6]; M. Takamoto* et al., Nature Photonics *online 3 April 2011 (DOI:10.1038/nphoton.2011.34)*

Stability of optical clock comparisons



$^{199}Hg – ^{27}Al^+$

$^{87}Sr – ^{40}Ca$

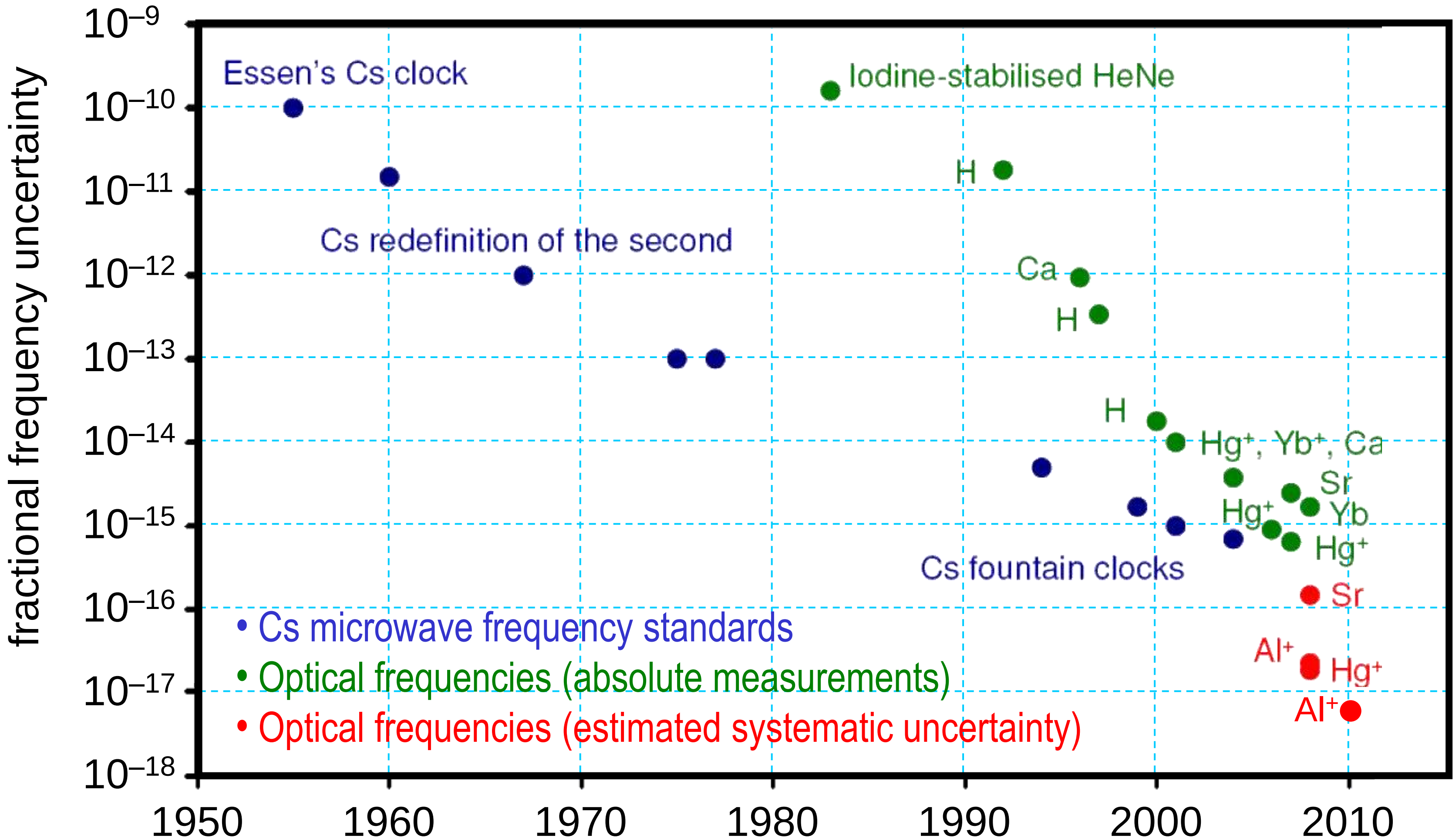
$^{174}Yb – ^{199}Hg^+$

$^{27}Al^+ – ^{27}Al^+$

$^{87}Sr – ^{88}Sr$

Composite plot: H. Margolis [3], C. W. Chou et al. *(2010); M. Takamoto* et al. Nature Photonics *(2011)*

A brief history of frequency standards



C. Chou et al., *Phys. Rev. Lett.* ***104*** *070802 (2010)*
Adapted from P. Gill et al., *'Optical Atomic Clocks for Space' (2008) [3]*

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‘Flying clock’ trips

HEWLETT·PACKARD
JOURNAL

TECHNICAL INFORMATION FROM THE -hp- LABORATORIES

Vol. 15, No. 11

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JULY, 1964

A New Performance of the "Flying Clock" Experiment

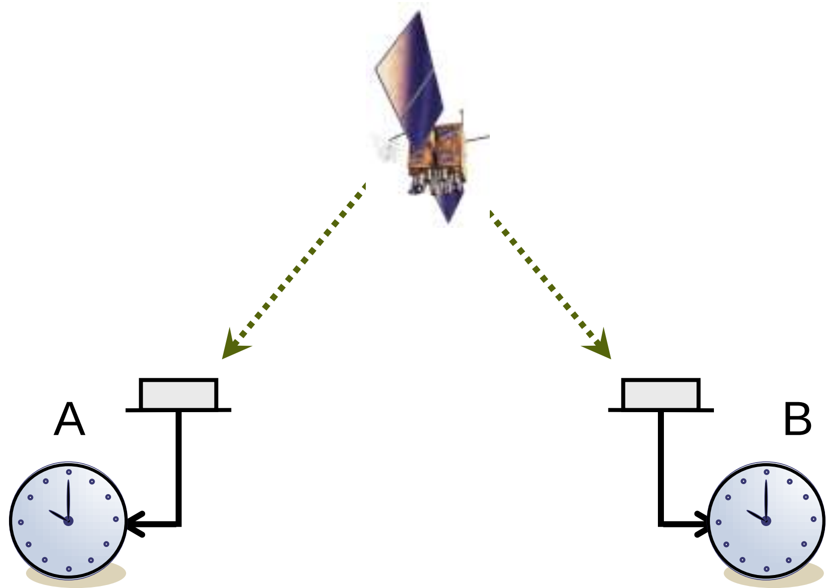
A new experiment has been made to compare clocks in the U.S. and Europe to higher precision. The results will be used by the various official agencies of the two continents in improving their time synchronization.

Fig. 2. *The two atomic clocks being fastened in passenger seats aboard airliner. Operating power in flight was supplied by plane.*

Courtesy Hewlett-Packard, www.hpmemory.org

HF radio	1 ms
‘Flying clock’ [FCS 1961]	5 μs
‘Flying clock’ [HP 1964]	1 μs
Telstar-1 [CPEM 1964]	1 μs

GPS common-view time transfer



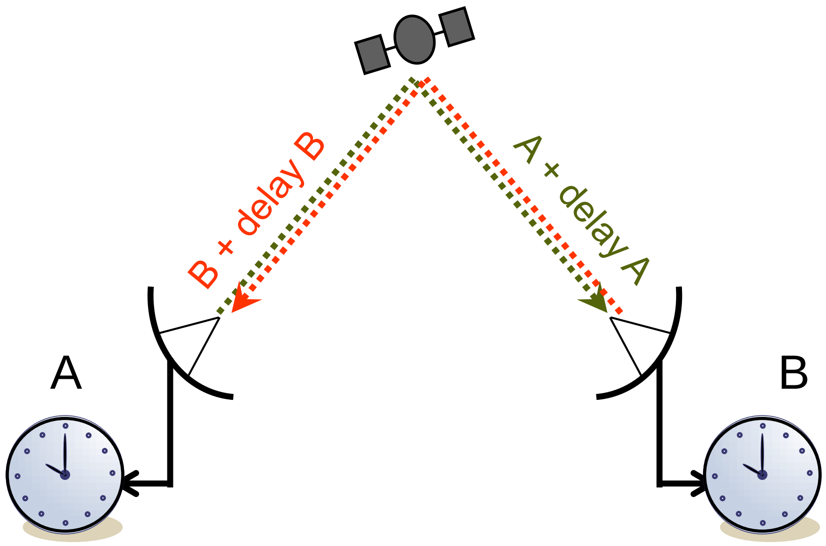
$\Delta_A = REF_A - GPS$

$\Delta_B = REF_B - GPS$

$$REF_A - REF_B = (REF_A - GPS) - (REF_B - GPS)$$

- ‘common view’ GPS time transfer: same satellite tracked from both A and B
- GPS time transfer follows an internationally agreed protocol, and is the main method used to compare atomic clocks around the world

Two-Way Satellite Time Transfer



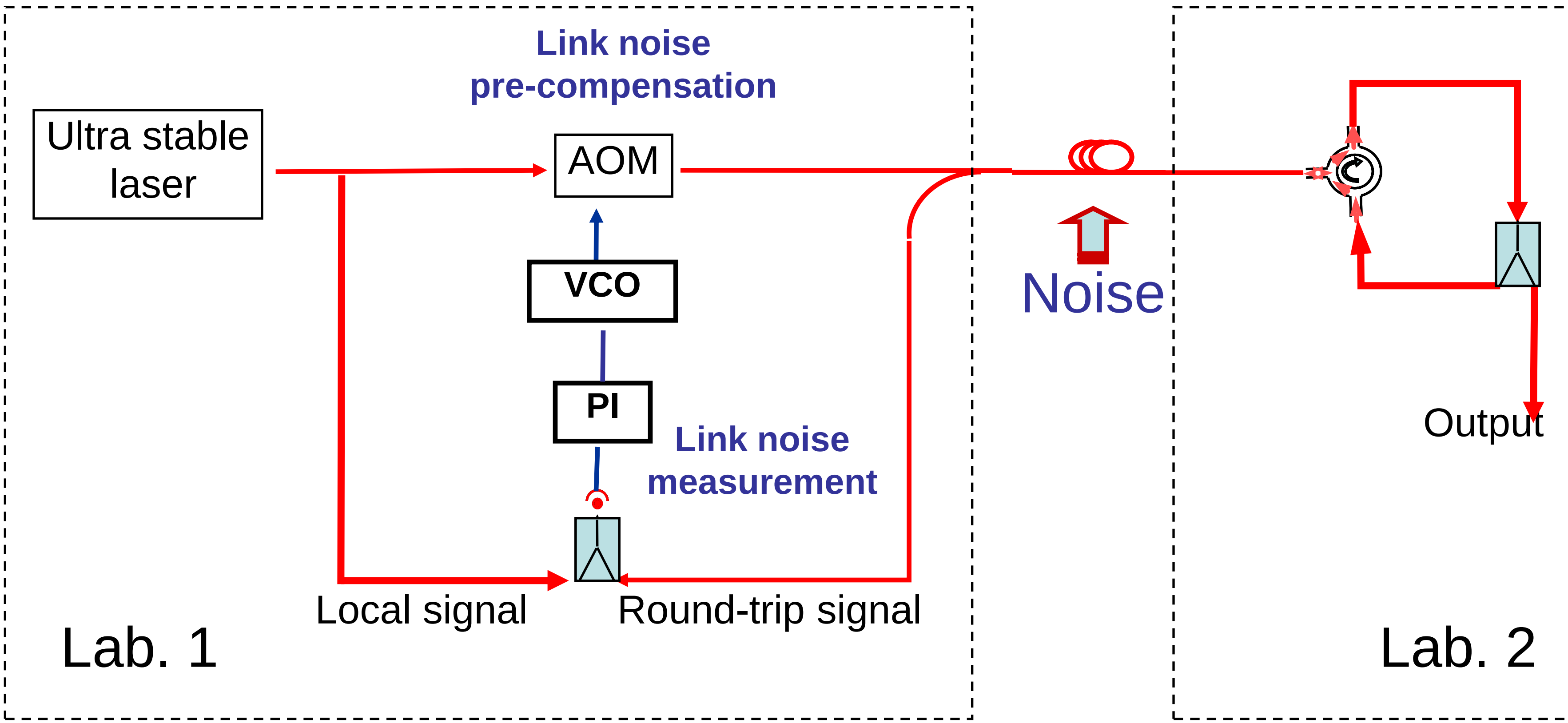
Δ_A = A – (B+delay B)

Δ_B = B – (A+delay A)

$$A - B = \tfrac{1}{2}(\Delta_A - \Delta_B) \quad \textit{if} \text{ delay A = delay B}$$

two-way communication allows direct measurement of propagation delay

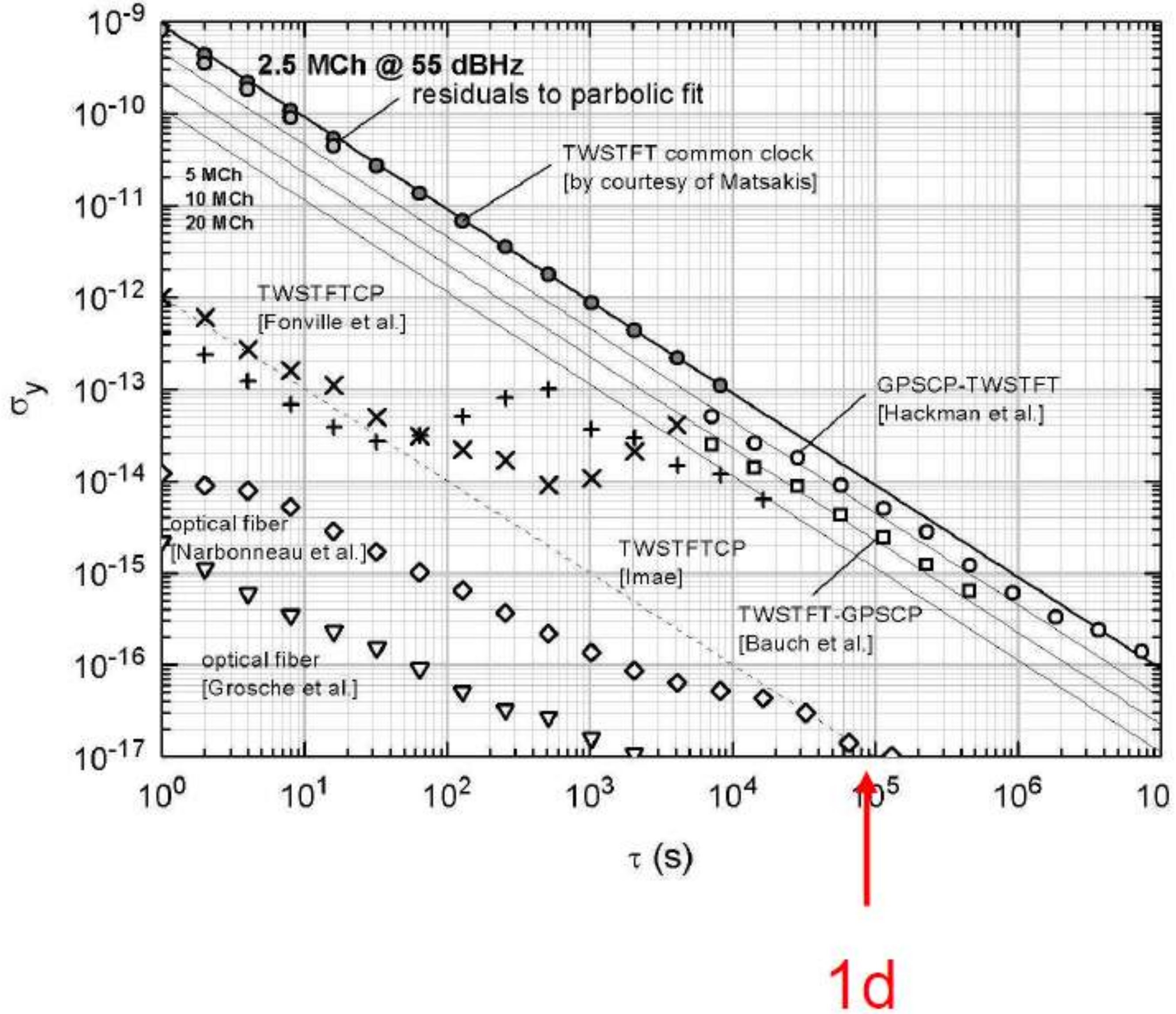
Optical fibre transfer: simplified scheme



Andre Luiten, UWA

Australian Government
National Measurement Institute

Transfer methods: performance



PTB compilation, in Mehlstäubler [2]

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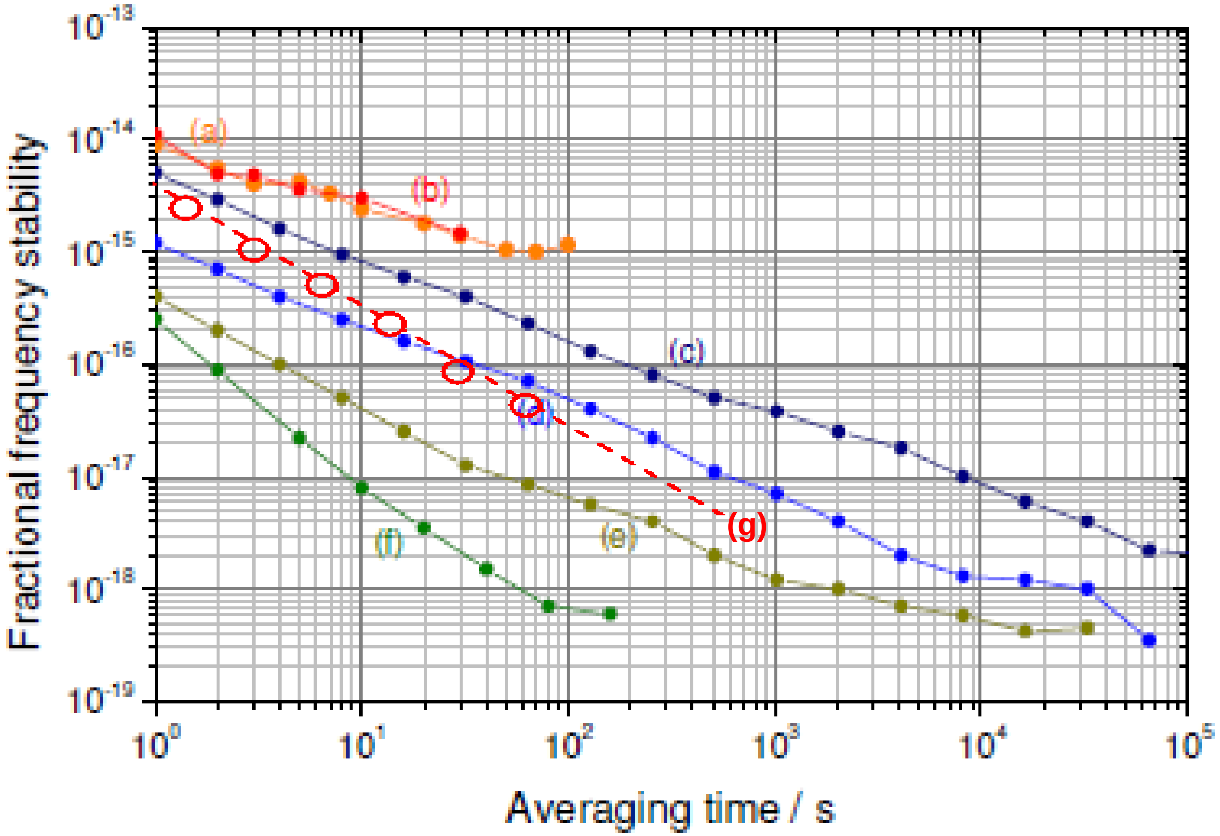
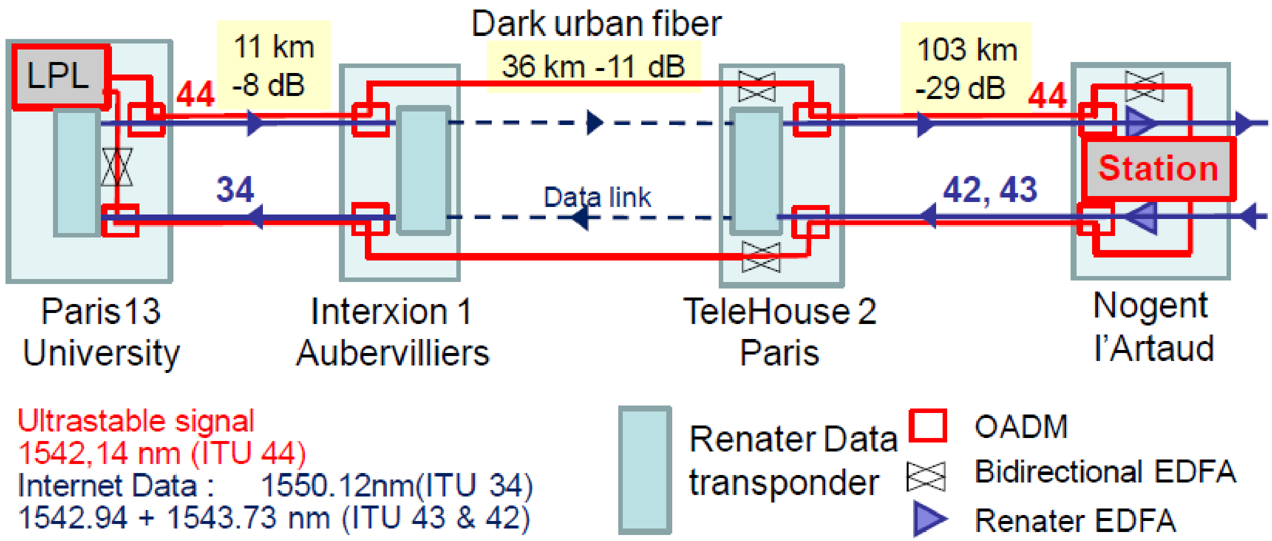
Optical fibre transfer: performance

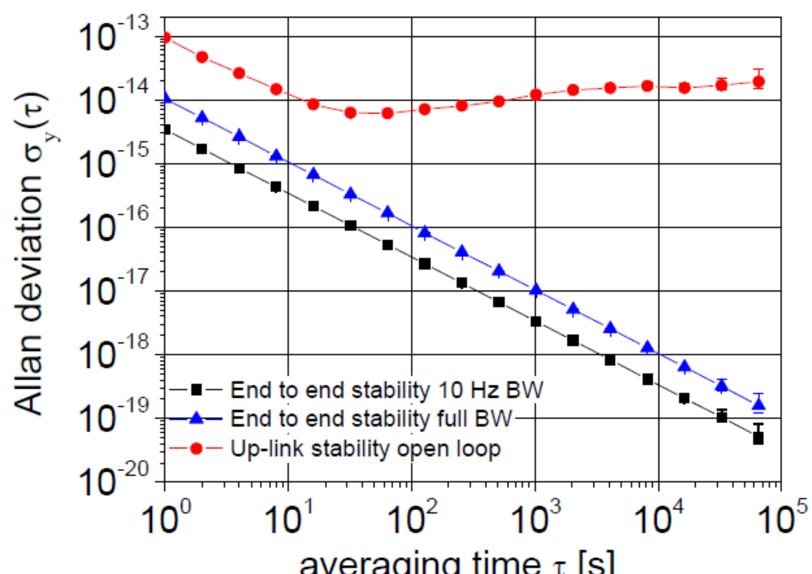


(a) microwave (774 MHz), 6.9 km, mode-locked fibre laser *[Holman 2005]*
(b) microwave (1.5 GHz), 100 km fibre spool *[Marra 2008]*
(c) microwave (1.5 GHz), 86 km *[Lopez 2008]*
(d) microwave (9.2 GHz), 86 km *[Jiang 2008]*
(e) optical (1.5 μm), 172 km *[Jiang 2008]*
(f) optical (1.5 μm), 76 km + 175 km spool *[Newbury 2007]*
(g) optical (1.5 μm), 146 km *[Terra 2009]*

P. Gill et al. *[3]*
O. Terra et al., Appl. Phys. B ***97*** *541 (2009)*

Optical frequency transfer with data





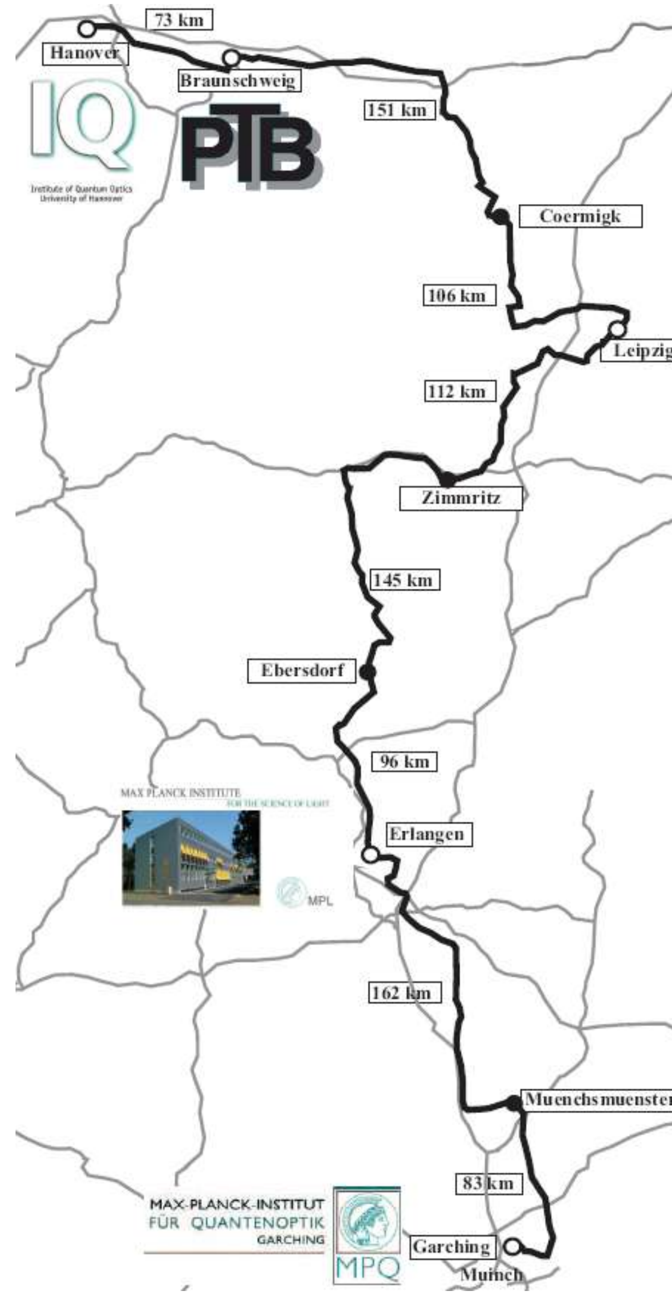
O. Lopez et al., Optics Express ***18*** *16849 (2010)*

IQ Hanover to PTB Braunschweig (76 km)

O. Terra et al., Appl. Phys. B ***97*** *541 (2009)*

PTB Braunschweig to MPQ Garching (~900 km)

H. Schnatz et al., IEEE Trans. UFFC ***57*** *175 (2010)*



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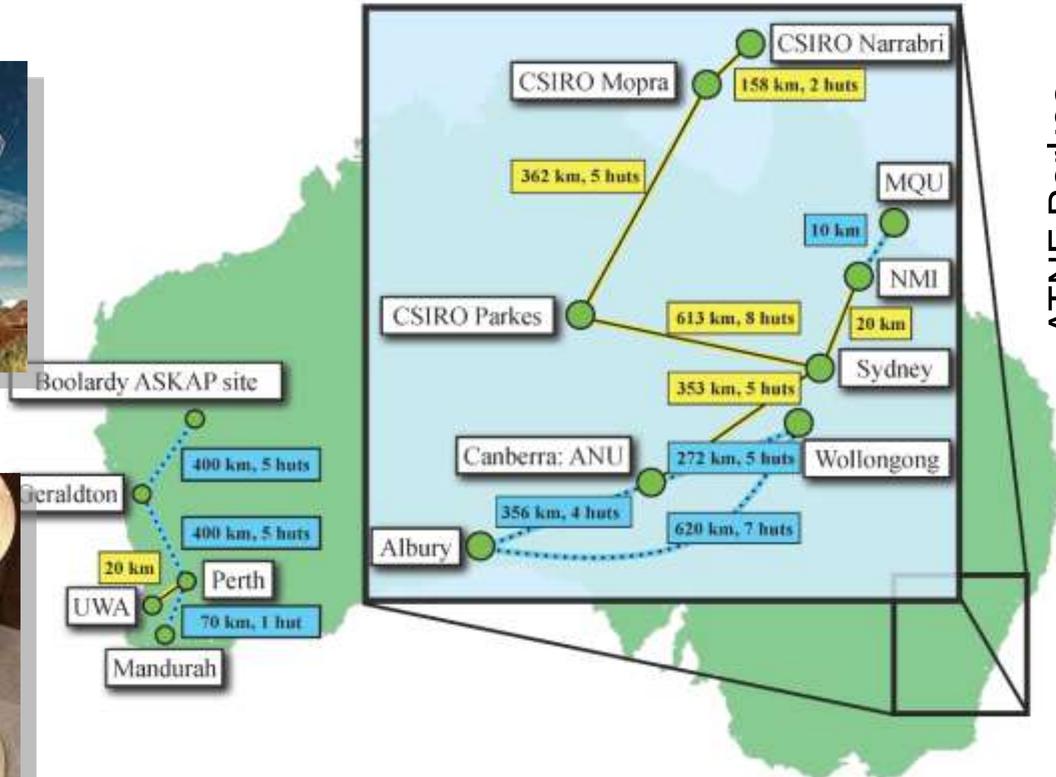
Towards an Australian network

ASKAP

UWA



ATNF Parkes

Australian Government
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MACQUARIE UNIVERSITY

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA

aarnet

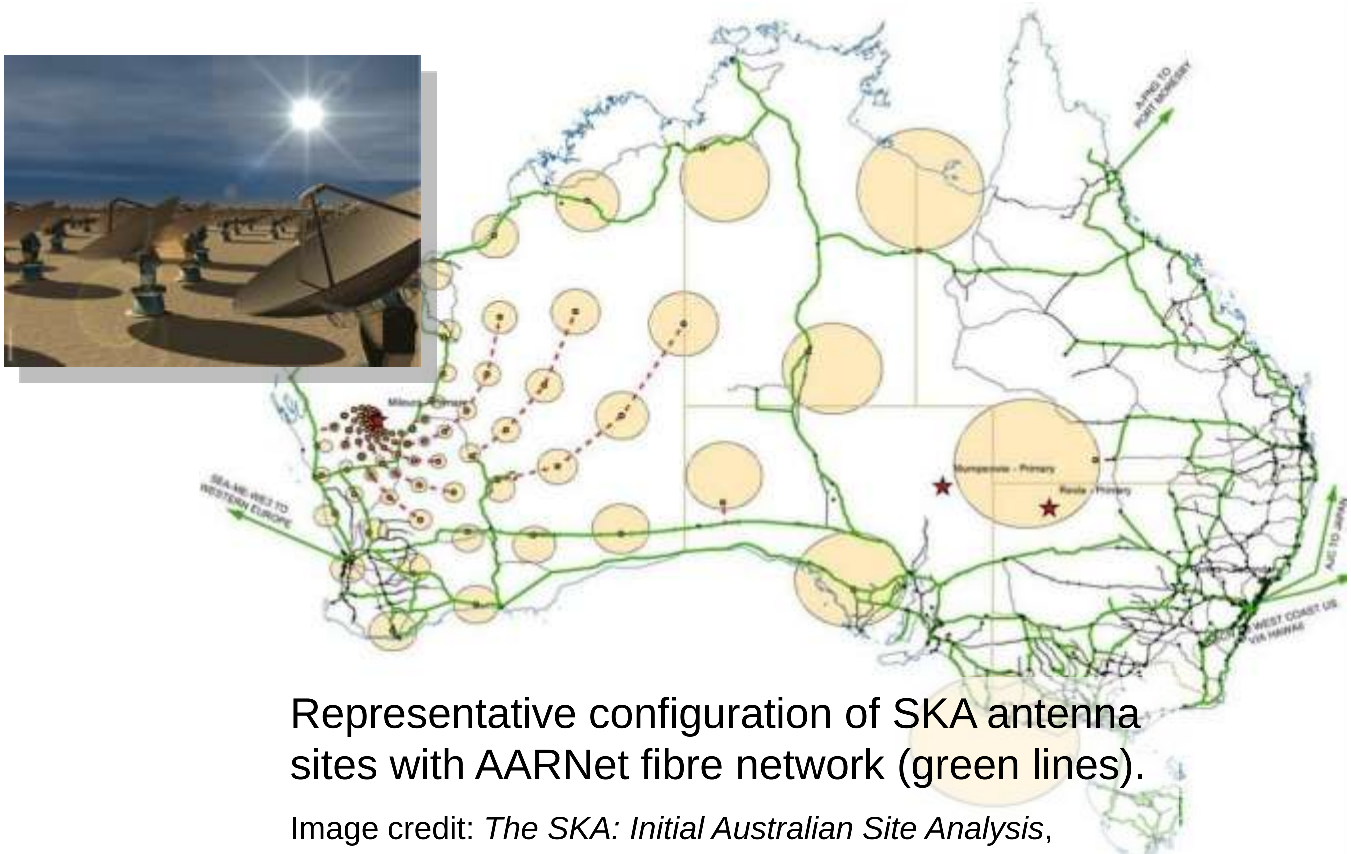
Brian Orr
Yabai He

Ken Baldwin
David McClelland

Andre Luiten
John Hartnett

Guido Aben
John Nicholls

Supporting the Square Kilometre Array



Representative configuration of SKA antenna sites with AARNet fibre network (green lines).

Image credit: *The SKA: Initial Australian Site Analysis*, Appendix F, p. 61 (May 2003).

- SKA antenna sites need tight synchronization, either by installing many reference hydrogen masers or by linking over optical fibre
- New fibre links planned, with additional support from the National Broadband Network

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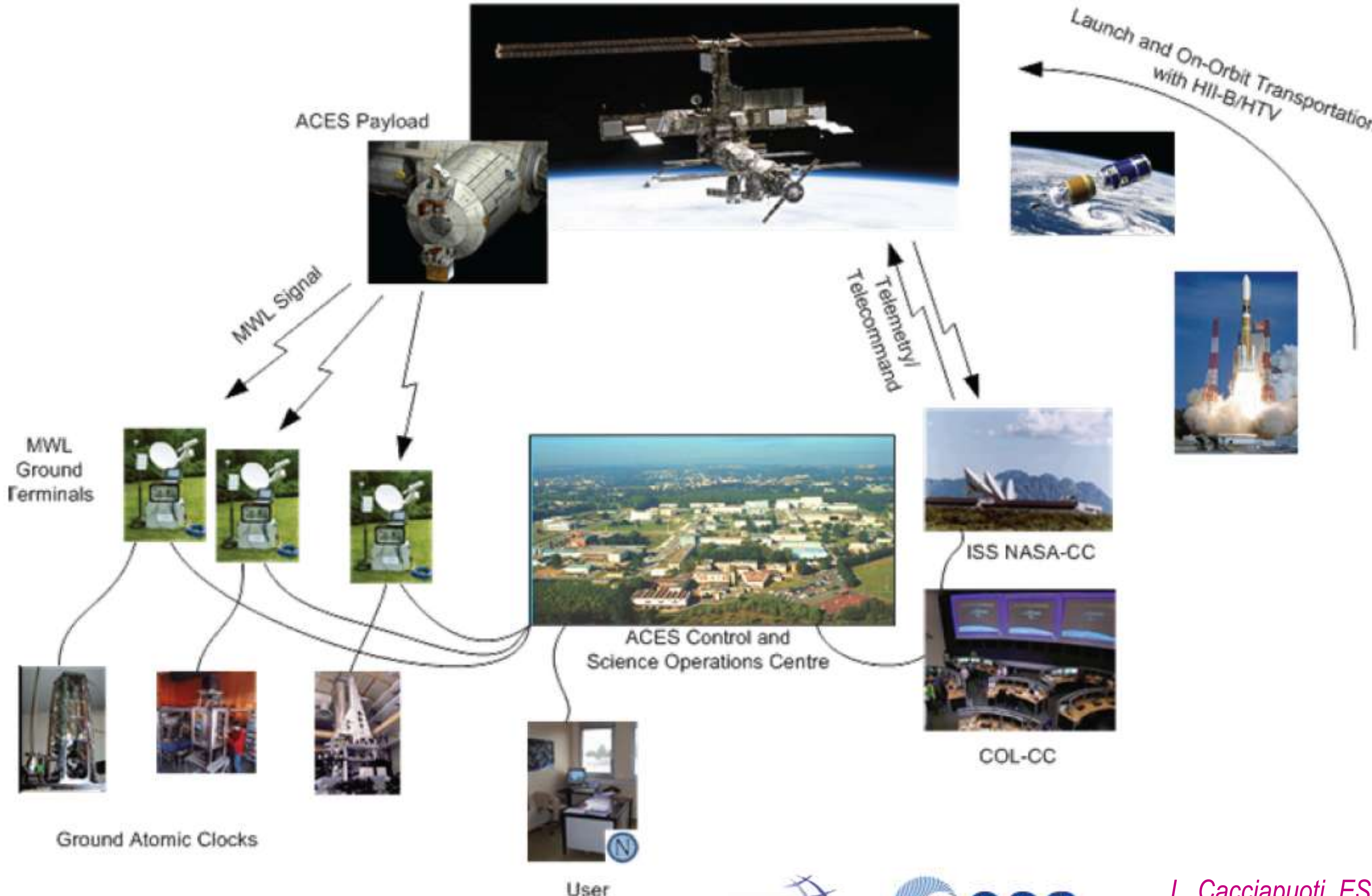
Atomic Clock Ensemble in Space (2013)



L. Cacciapuoti, ESA [8]
www.iapg.bv.tum.de/aces.html

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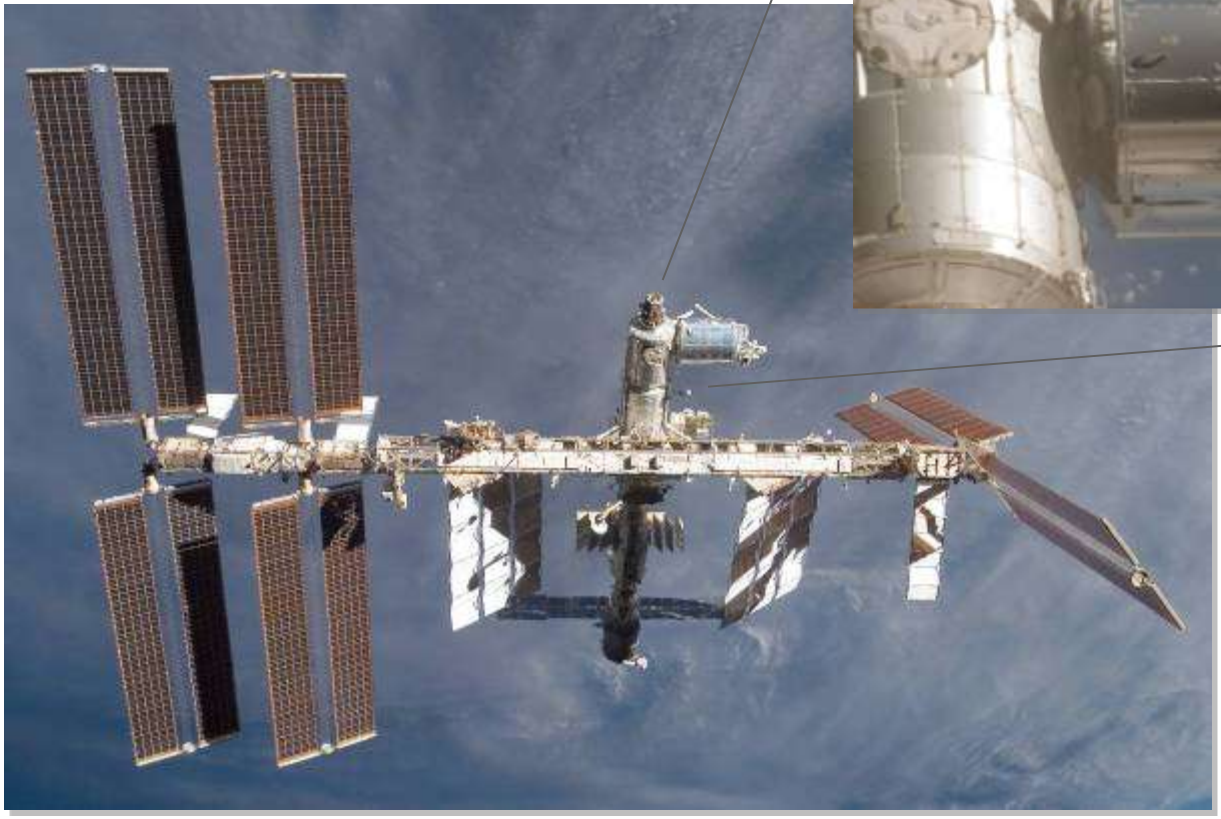
ISS and Columbus

Columbus laboratory and external payload facility
STS-122, February 2008

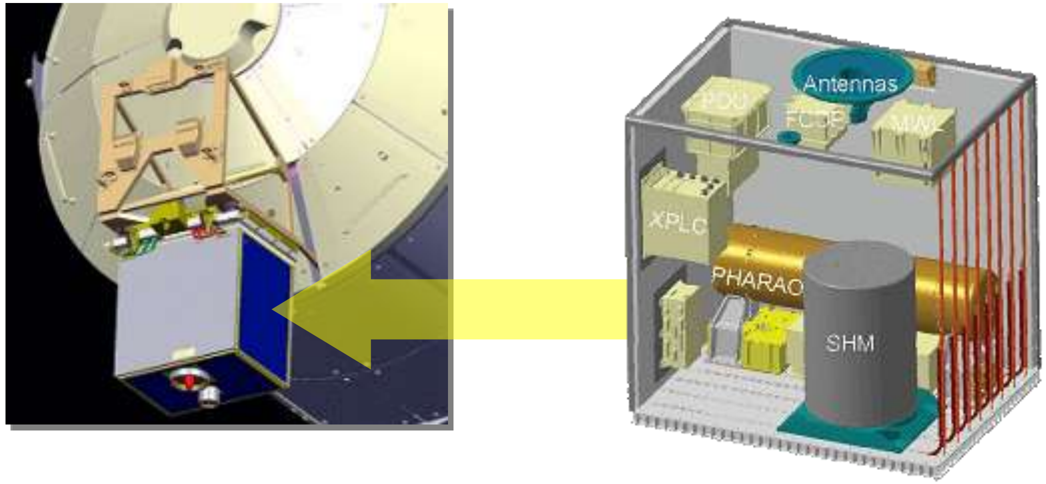


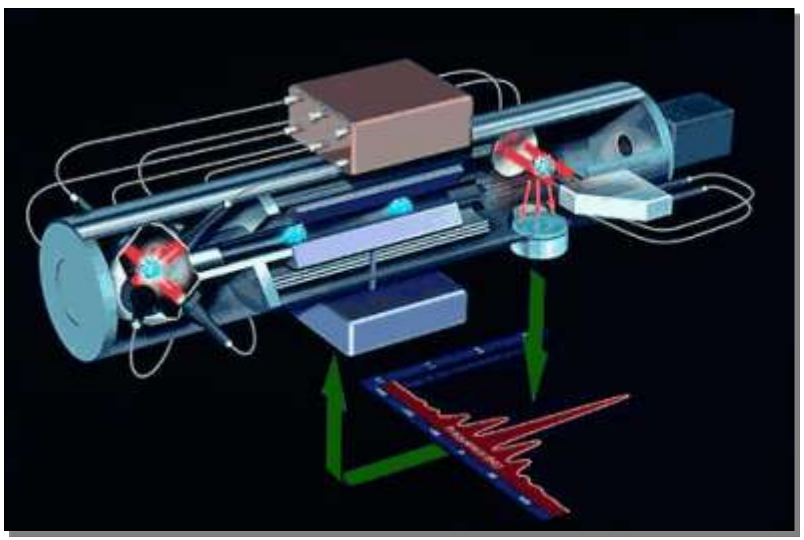
International Space Station (ISS)
STS-122, February 2008

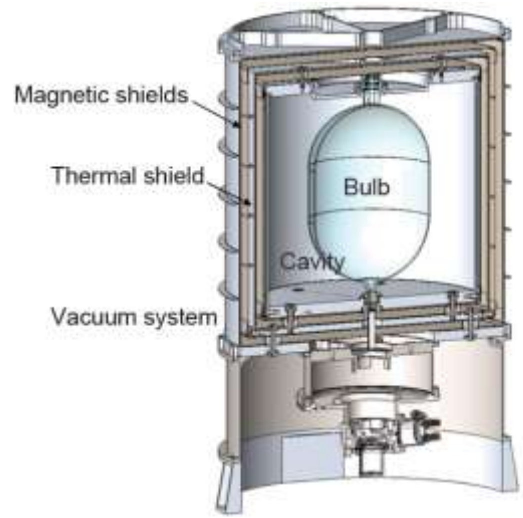
ACES NASA esa JAXA

Australian Government
National Measurement Institute

ACES payload





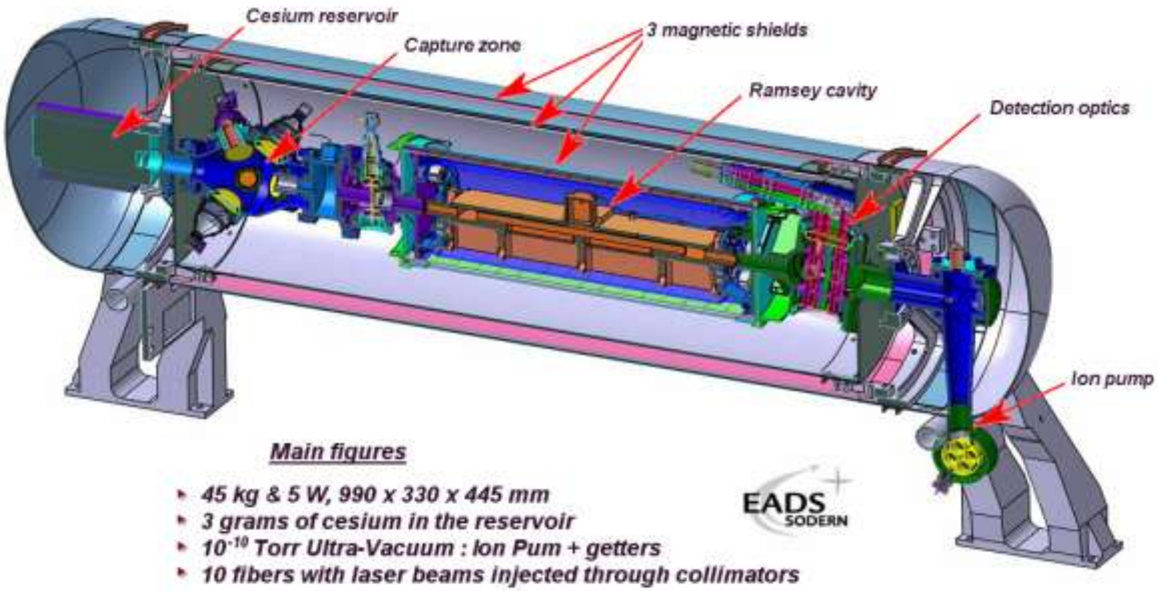


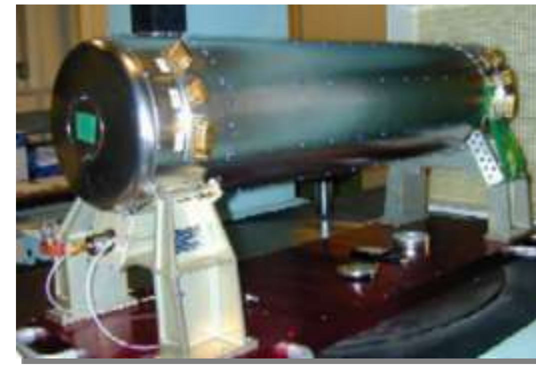
PHARAO – microgravity Cs clock

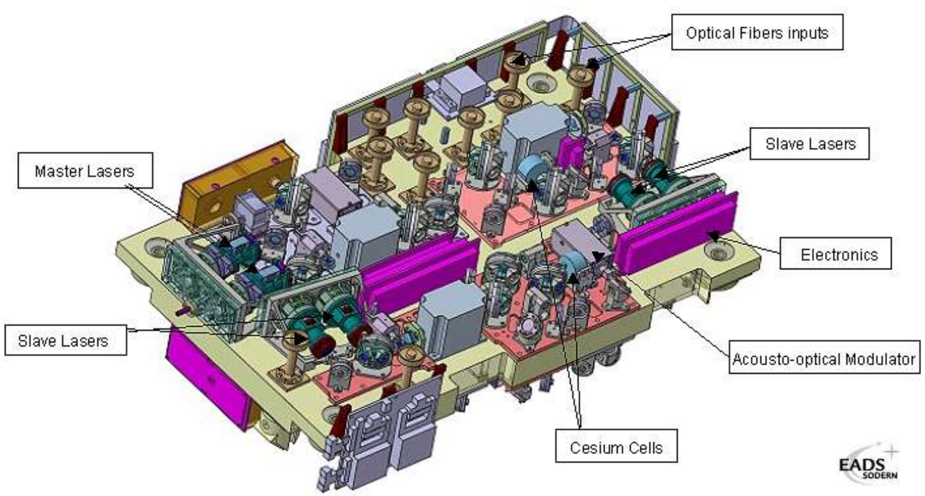
SHM – active H maser

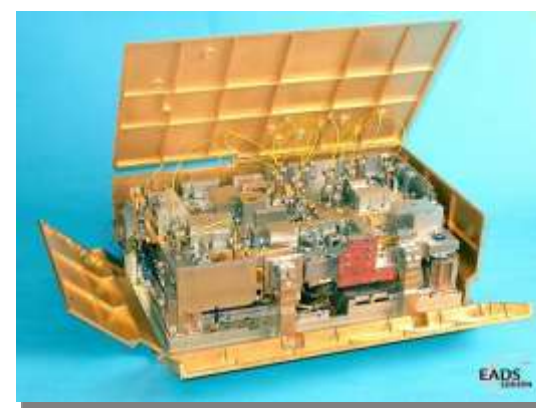
L. Cacciapuoti, ESA [8]
www.iapg.bv.tum.de/aces.html

PHARAO microgravity Cs clock

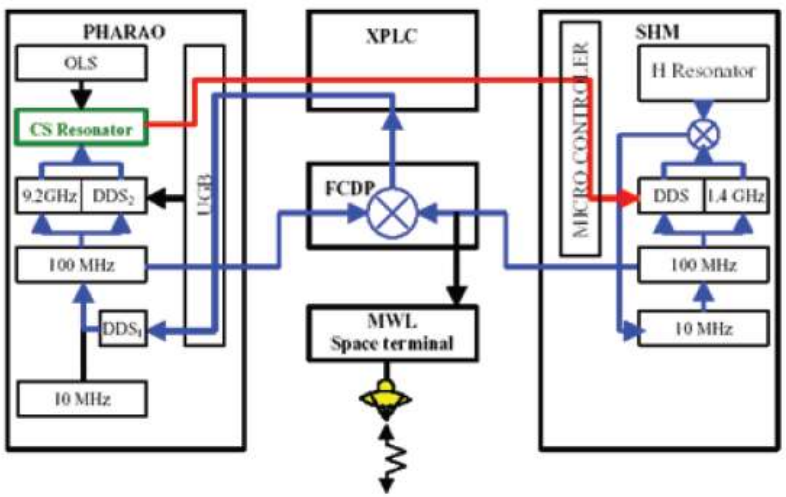


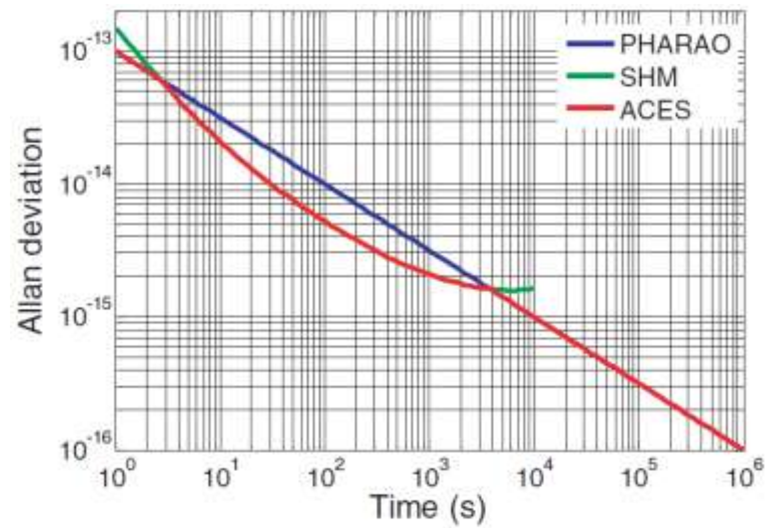






ACES clock signal





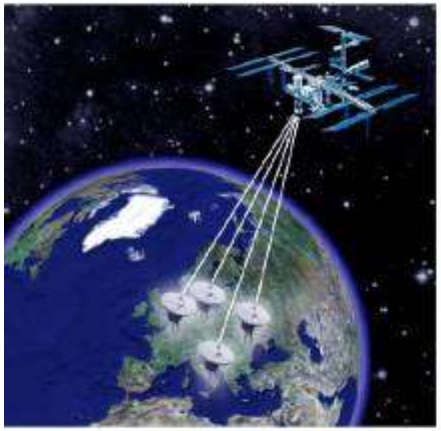
Stability of the ACES clock signal:

- $3 \cdot 10^{-15}$ at 300 s (ISS pass)
- $3 \cdot 10^{-16}$ at 1 day
- $1 \cdot 10^{-16}$ at 10 days

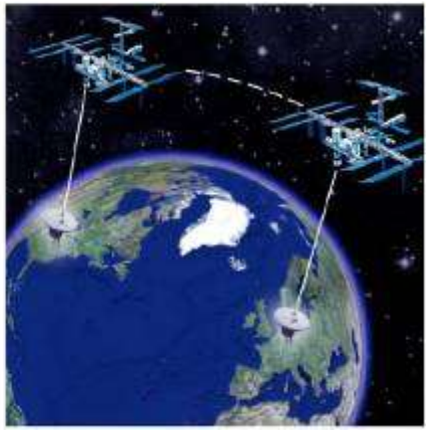
Accuracy: $\sim 1 \cdot 10^{-16}$

L. Cacciapuoti, ESA [8]
www.iapg.bv.tum.de/aces.html

ACES time transfer



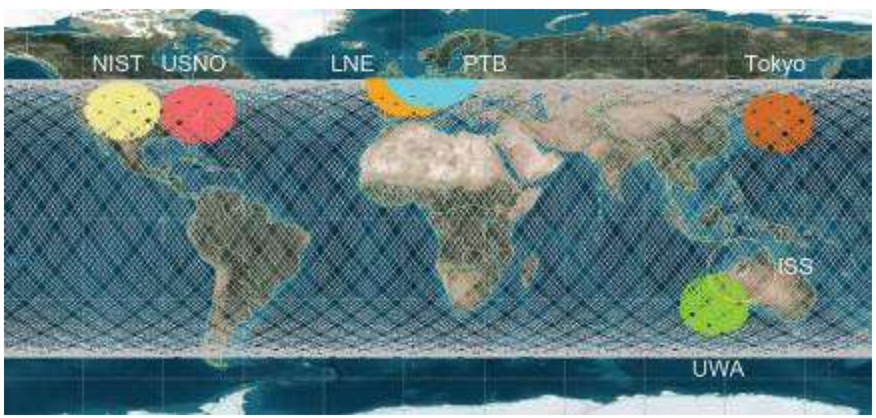
common view

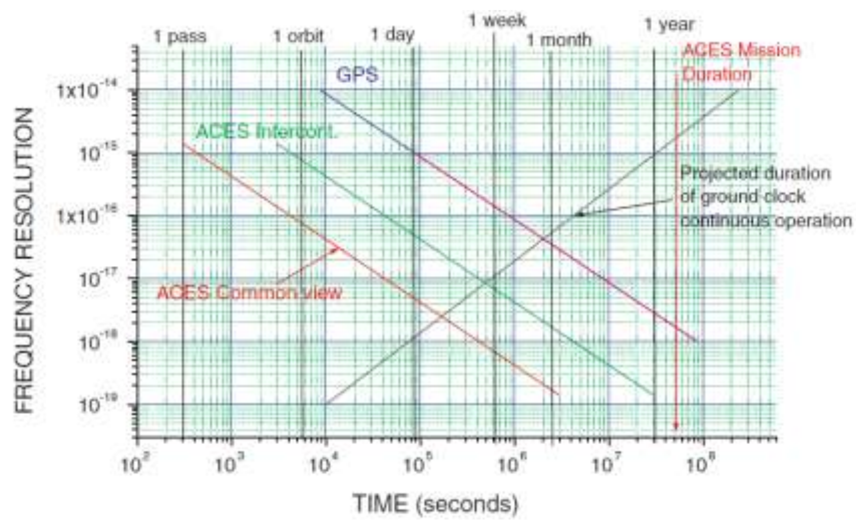


non-common view

common view:
  below 1 ps in one ISS pass

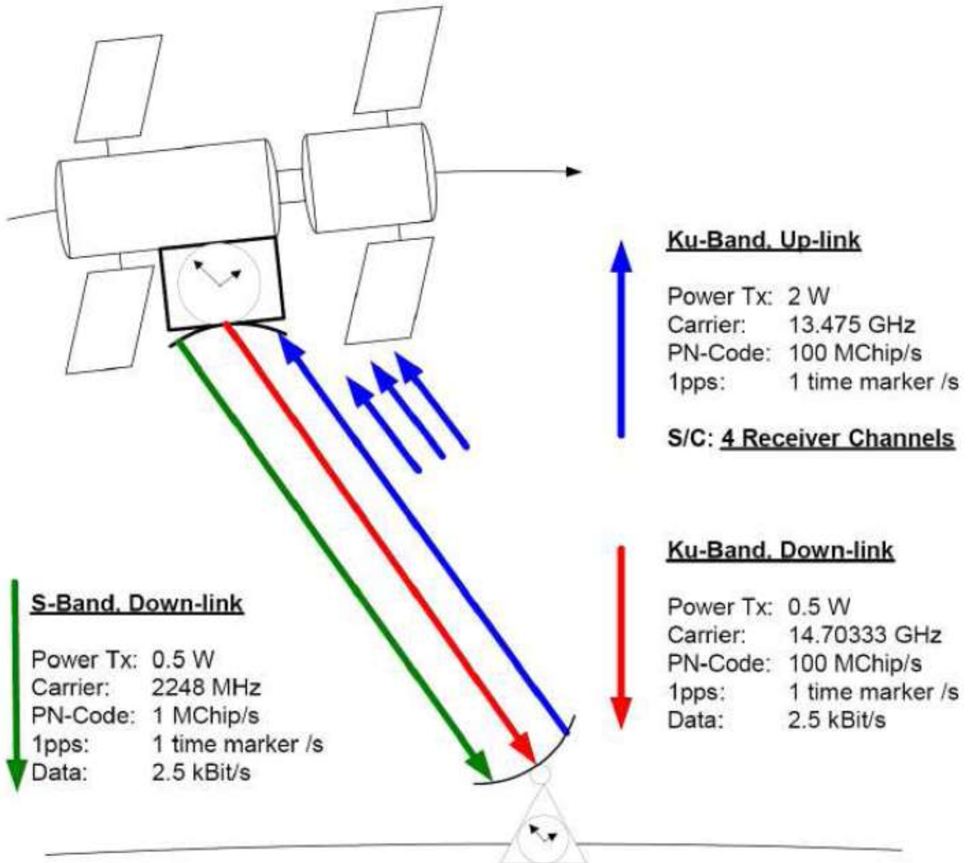
non-common view:
  2 ps for τ = 1,000 s
  5 ps for τ = 10,000 s
  20 ps for τ = 1 day





L. Cacciapuoti, ESA [8]
www.iapg.bv.tum.de/aces.html

ACES microwave link

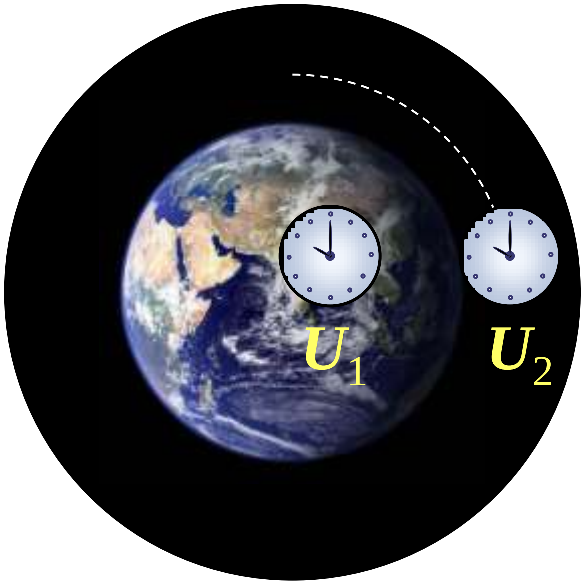


- time transfer based on Vessot technique
- two-way Ku-band transfer: remove troposphere delay, first-order Doppler
- high chip rate (100 MChip/s)
- multiple channels to compare ground clocks in common view
- additional S-band downlink: determine TEC and Ku-band ionospheric delay (up to 1 ns)
- data downlink (S, Ku 2.5 kBit/s) for real-time clock comparison

L. Cacciapuoti, ESA [8]
www.iapg.bv.tum.de/aces.html

ACES fundamental physics

- **General relativity:** test clock rate dependence on gravitational potential



$$\frac{\nu_1 - \nu_2}{\nu_1} = \frac{U_2 - U_1}{c^2}(1+\delta) = \frac{gH}{c^2}(1+\delta)$$

Vessot *et al.* 1976: $|\delta| < 7\times10^{-5}$
ACES on ISS: δ to 2×10^{-6}
(H=450 km, shift $+4.59\times10^{-11}$, 10^{-16} clocks)

- **Time variation of fundamental constants** to $\Delta\alpha/\alpha \sim 10^{-16}$ per year, by precision comparison of primary clocks referenced to different atoms

- **Other tests of relativity:** *eg* violation of Lorentz invariance to $\Delta c/c \sim 10^{-10}$, using stability of ground and ACES clocks over an ISS pass

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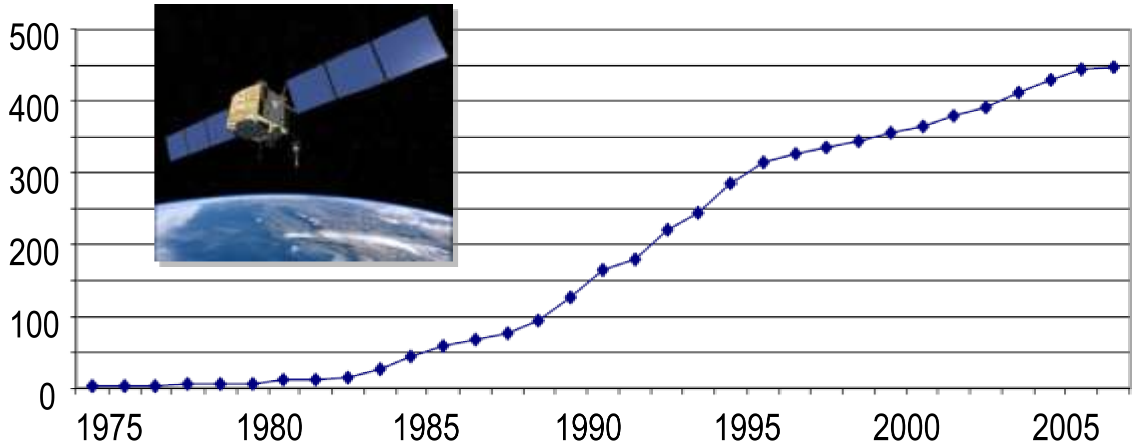
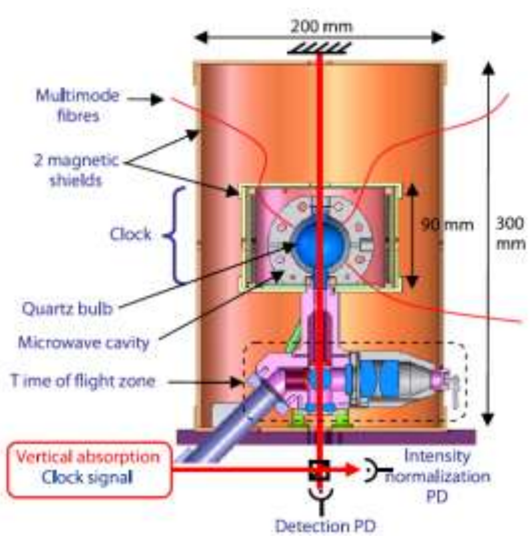
Clocks in space



J. White et al., Proc. 38th PTTI *(2006)*

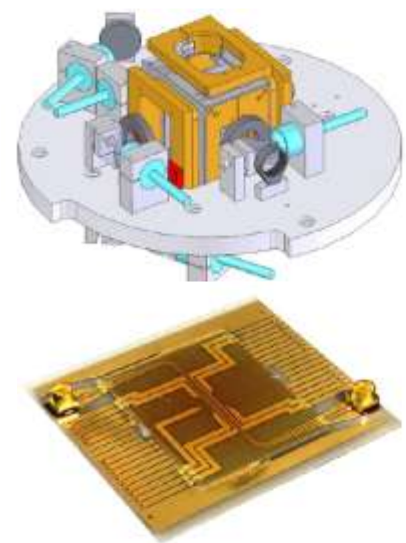
linear ion trap clocks

J. D. Prestage et al., Proc. 38th PTTI *(2006)*



compact cold-atom clocks

J. D. Prestage et al., Proc. 38th PTTI *(2006)*



chip-based cold-atom clocks

Ramírez-Martínez et al., Adv. Space Res. ***47*** *247 (2011)*

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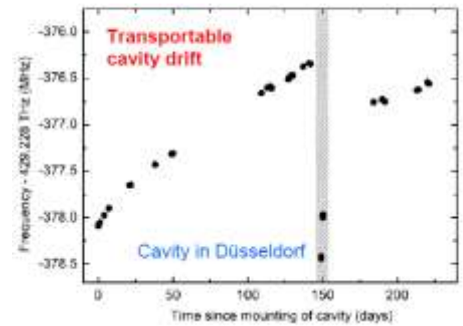
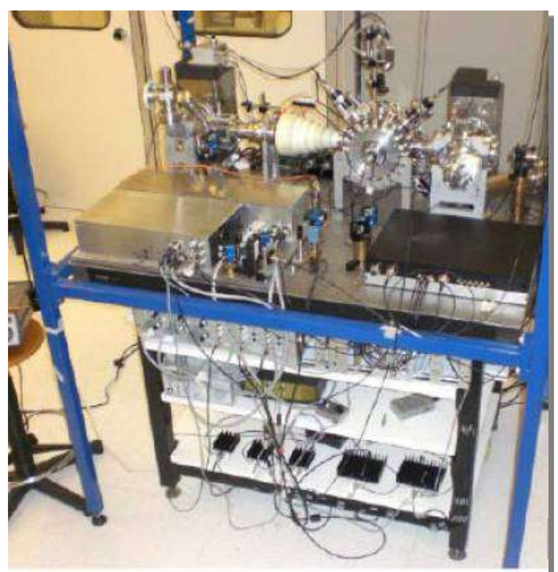
Back to ‘flying clock’ trips?

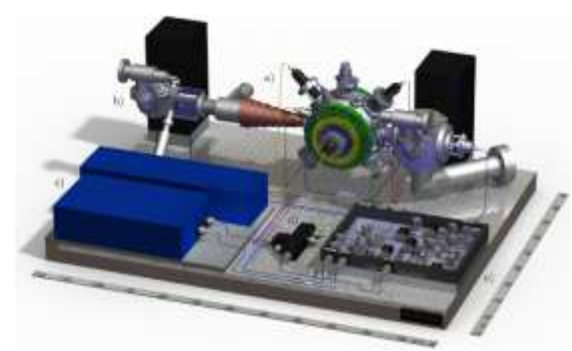
Hewlett-Packard, www.hpmemory.org

transportable clock laser (698 nm, 1 Hz)
PTB Braunschweig ↔ HHUD Düsseldorf
without degrading performance



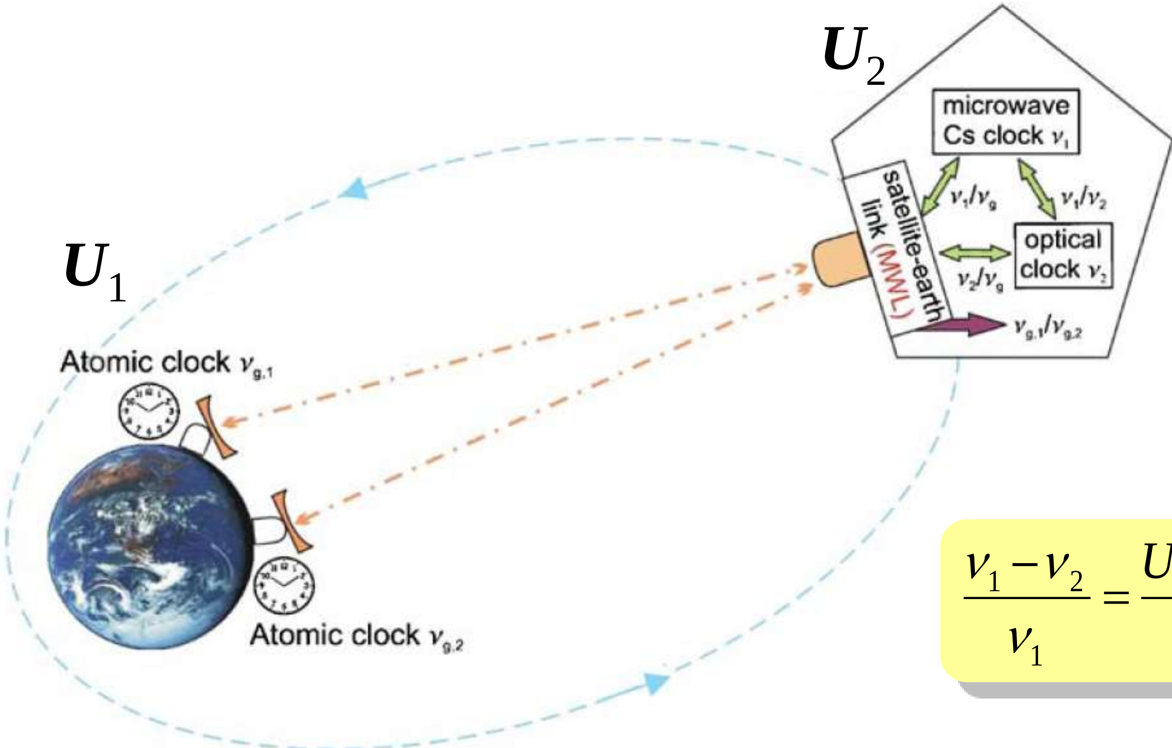


transportable laser-cooled Sr source
‘physics package’ 210 L, 120 kg, 110 W



M. Schioppo et al., Proc. EFTF *(2010)*
ESA project ‘Space Optical Clocks’; EU-FP7 SOC2: ‘Towards Neutral-atom Space Optical Clocks’

Einstein Gravity Explorer



$$\frac{\nu_1 - \nu_2}{\nu_1} = \frac{U_2 - U_1}{c^2}(1+\delta) = \frac{gH}{c^2}(1+\delta)$$

Vessot *et al.* 1976: $|\delta| < 7\times10^{-5}$
ACES on ISS: δ to 2×10^{-6}
EGE, highly elliptic orbit: δ to 2.5×10^{-8}

Challenging clock and link targets
Projected: 200 W, 155 L, 125 kg

S. Schiller et al., Exp Astron ***23*** *573 (2009)*

Measuring gravitational potential shift

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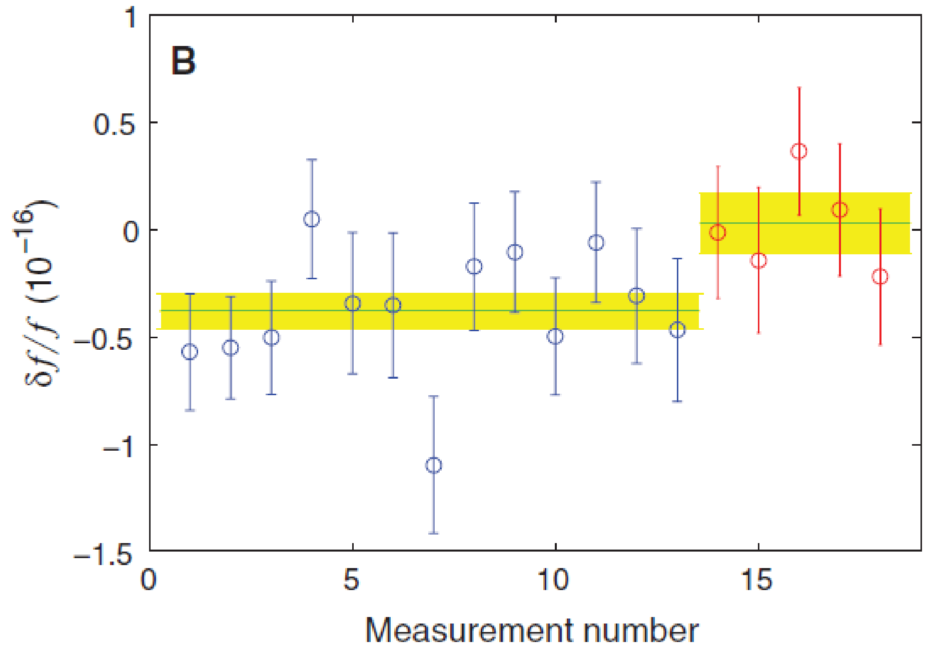
$$\frac{\Delta f}{f_0} = \frac{g\Delta H}{c^2}$$

$10^{-17} \Leftrightarrow 1$ cm



'NIST physicists compared a pair of the world's best atomic clocks to demonstrate that you age faster when you stand just a couple of steps higher on a staircase' *NIST*

- Two single-ion optical standards (Al^+-Mg^+ and Al^+-Be^+) compared over 75-m noise-cancelled fibre link
- Accuracy 8.6×10^{-18} (Al^+-Mg^+) and 2.3×10^{-17} (Al^+-Be^+), and stability $\sim3\times10^{-15}\,\tau^{-1/2}$ enables high resolution within practical averaging times (~2 hours per point)
- ΔH = 33 cm gives measurable frequency difference of $4.1(1.6)\times10^{-17}$, equivalent to 37(15) cm

C. W. Chou et al., Science ***329*** *1630 (2010)*

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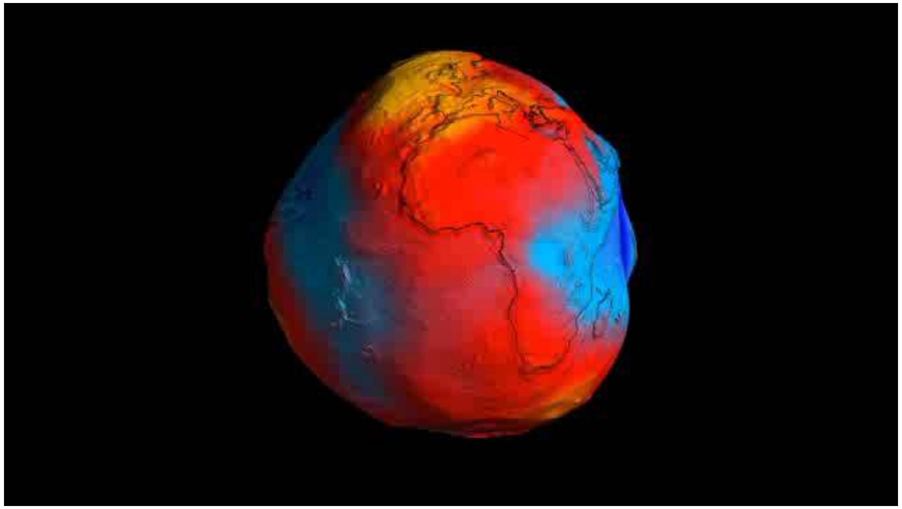
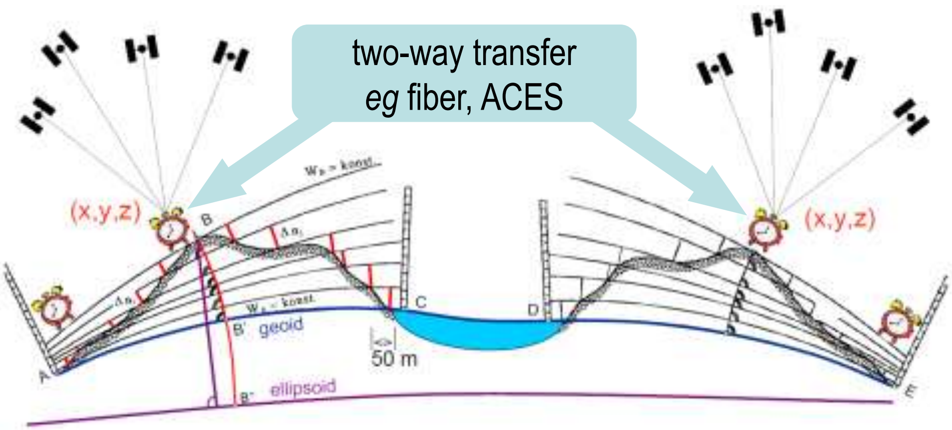
Gravimetry



GOCE (ESA/HPF/DLR)



D. Svehla, TU München, www.iapg.bv.tum.de/aces.html

- Height difference between geoid [gravimetry] and ellipsoid [surveying] varies over the Earth's surface
- Relevant for atomic clocks and timekeeping but also *eg* monitoring of global sea levels
- Comparison of optical clocks could determine unified global reference datum to high precision ($10^{-18} \longrightarrow$ cm level)
- High temporal and spatial resolution complements geodetic levelling and satellite surveys
- Optical clock in space could act as 'master clock' reference for comparison to ground clocks

D. Kleppner, Physics Today ***59*** *10 (2006); P. Gill [3]*

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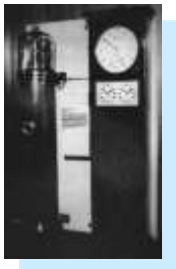
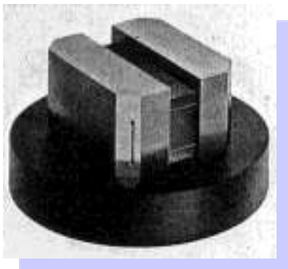
A brief history of the second

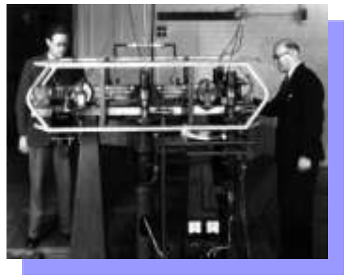
Pendulum clocks



Quartz clocks

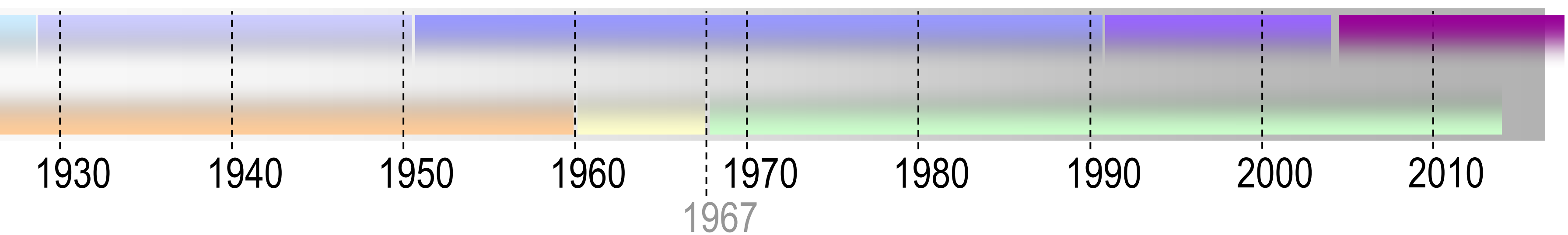


Atomic clocks



Fountain clocks

Optical clocks



1/86400 of
the time taken for the Earth
to rotate on its axis

1/31355925.9747 of
the time taken for the Earth
to orbit the Sun in 1900

The time taken by 9 192 631 770 cycles of the radiation corresponding to the ground-state hyperfine transition of the ^{133}Cs atom

?

Towards a new definition of the second

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom.

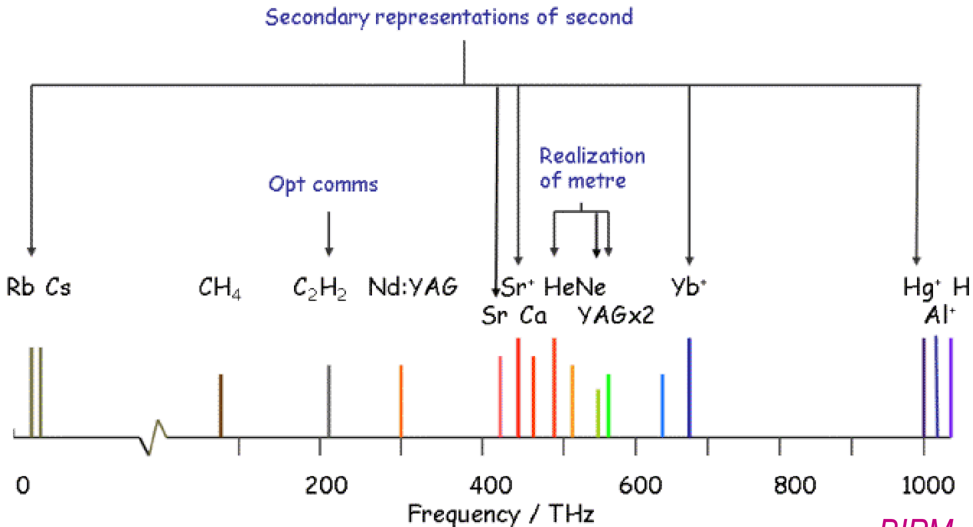
13th CGPM (1967/68, Resolution 1)
'The International System of Units (SI)' 2.1.1.3, 8th edition, BIPM 2006

"The existing SI definition of the second based on Cs will serve the needs of industry for some time, with Secondary Representations serving the needs of the scientific community. It is not yet clear whether the best approach is to adopt standards based on single trapped ions or on neutral atoms in an optical lattice, with further work required for consensus. The time will be right for a new definition when the current progress in optical standards slows, and when the current limitations of frequency transfer have been solved: 2015 may be too early, and 2019 may be possible."

CCL-CCTF Joint Working Group on Frequency Standards:
Presentation to CCU, 'On a new definition of the second' (F. Riehle and P. Gill)
Report of the 18th CCTF (B. Warrington and F. Arias, 2009, available online)

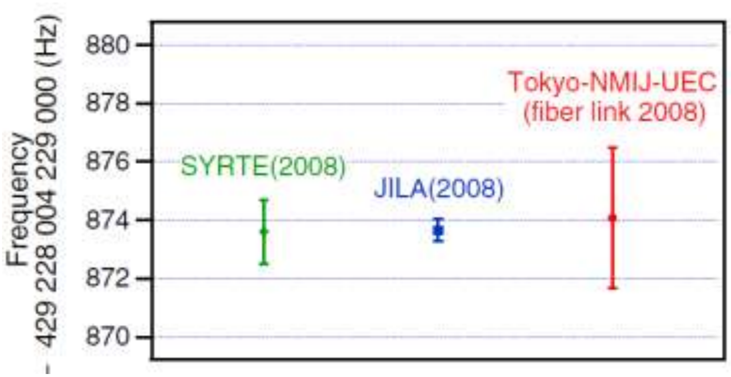
Standard frequencies

for applications including the practical realization of the metre and secondary representations of the second



BIPM

- First published by the CIPM in 1983 in the *mise en pratique* of the definition of the metre
- Updated by approval of the CIPM, based on recommendations of CCL and CCTF working groups
- *eg* updates at CCTF 2009— $^{40}Ca^+$, $^{171}Yb^+$ E3, ^{88}Sr and ^{87}Sr:



F.-L. Hong and H. Katori [7]

"the unperturbed optical transition $5s^2\ ^1S_0 - 5s5p\ ^3P_0$ of the ^{87}Sr neutral atom, with a frequency of 429 228 004 229 873.7 Hz and an uncertainty of 1×10^{-15}"

Recommendation CCTF1(2009), Report of the 18th CCTF

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[2] T. E. Mehlstäubler, 'Atomic Clocks', at *Varying Fundamental Constants*, Lorentz Centre, Leiden, May 2009 (available online)

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[4] H. S. Margolis, 'Optical frequency standards and clocks', *Contemporary Physics* **51** 37–58, 2010 (available online)

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[6] H. Katori, 'Optical lattice clocks and quantum metrology', *Nature Photonics* **5** 203 (April 2011)

[7] F.-L. Hong and H. Katori, 'Frequency metrology with optical lattice clocks', *Japanese Journal of Applied Physics* **49** 080001 (2010)

[8] L. Cacciapuoti, 'ACES mission status', at *ACES and future GNSS-based Earth observation and navigation*, Munich, May 2008 (available online); also L. Cacciapuoti and Ch. Salomon, *European Physical Journal Special Topics* **172** 57 (2009)

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