Optical Clocks at $10^{-18}$ accuracy: challenges and applications

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Never measure anything but frequency!

Arthur Schawlow advice to his students at Stanford

1981 Nobel prize laureate
Clock concept

Find a periodic phenomenon
1) Nature:
   observation: Earth rotation, pulsars,…
2) Human realization: example Galileo pendulum
   simple phenomenon described by a small number of parameters

\[ T = 2\pi \sqrt{\frac{l}{g}} \]

Counting oscillations!
The shorter the period, the better is the precision of a time interval measurement

3) Optical clocks use electromagnetic signals oscillating with \(10^{15}\) cycles per second.

The physical signal is locked onto an atomic transition
The oscillator of frequency $\nu$ is locked to the frequency $\nu_A$ of a transition between two energy levels in an atom.
Current definition of the second: Cesium atomic fountain

\[ E_e - E_f = h\nu_A \]

Planck –Einstein relation

Hyperfine transition at 9.2 GHz
Atoms at 1 microKelvin

Comparison between two fountains
Paris Observatory

Frequency stability at $10^{-16}$ after 5 to 10 days of averaging
Accuracy: agreement between the cesium frequencies: $2 \times 10^{-16}$
~ 12 fountains in the world are compared by GPS and optical fibers. Steer TAI computed by BIPM with an accuracy of $2 \times 10^{-16}$
Clock Figure of Merit

- Frequency: $\nu$
- Resonance width and interaction time $T$
  $\Delta\nu = 1/2T$
- Signal to Noise ratio: $S/N \sim N_{at}^{1/2}$

$$\mathcal{F} = \frac{\nu}{\Delta\nu} \times S/N = 2 \nu T S/N$$

Microwave cesium fountain: $\mathcal{F} = 2 \times 10^{10} \times 0.5 \times 5000 = 5 \times 10^{13}$

Optical clocks: $\mathcal{F} = 2 \times 5 \times 10^{14} \times 1 \times 100 = 5 \times 10^{17}$

Trapped ion: $\text{Al}^+, \text{Yb}^+, \text{Hg}^+$, $\text{Ca}^+, \text{Lu}^+$,…..

Neutral atoms: $\text{Sr}, \text{Yb}, \text{Hg}, \text{Ca}, \text{Cd}$

NIST, PTB, NPL, SYRTE, NPL, RIKEN, NICT, Innsbruck, Seoul, Singapore,…..
Optical Clocks surpass cesium clocks by two orders of magnitude.
87 Strontium Optical Clocks

Non-perturbing lattice trap at magic wavelength: light shift of the clock transition vanishes


Magic wavelength $\lambda_{\text{magic}}$: polarizabilities are equal for both clock states

Clock transition: 698 nm
Lifetime $\sim$20 s

Nature, 602 420, 2022
Ye’s group
JILA

Laser cooled, atoms in lattice
Laser beam

3.1 second probe time

87 Strontium

Optical Clocks

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Frequency Stability of Optical Atomic Clocks

Graph from C. Oates, NIST, Oct '19

1 cm of gravitational red shift

Applications in Earth geodesy
JILA $^{87}\text{Sr}$ OLC: measuring the differential gravitational shift over 1 mm sample

Two trap areas on same image: laser noise is common mode

Differential sensibility: $4.4 \times 10^{-18}$ @1 s and $1 \times 10^{-19}$ @2000 s

T. Bothwell,…
J. Ye, JILA, Nature, 602 420, 2022
Testing the Einstein effect with transportable optical clocks

\[ \frac{\nu_2}{\nu_1} = \left( 1 + \frac{U_2 - U_1}{c^2} \right) \]

Tokyo skytree
450 m radio tower

Katori et al., 2020
Testing the Einstein effect with transportable optical clocks

\[
\frac{v_2}{v_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)
\]

\[10^{-4}\] test near Earth surface
Quantum metrology: towards Heisenberg limit

The signal to noise ratio in fountains and OL clocks is at the quantum projection noise:

Uncorrelated atoms: frequency instability scales as $I/N^{1/2}$

N two-level atoms: spin $1/2$ ensemble forming a collective spin $|J| = N/2$

$$\Delta J_z, \Delta J_y \geq |J_x/2|$$

Spin squeezing: reduce variance in one direction, useful for measurement sensitivity
Kitagawa et Ueda, 1993, Wineland et al. 1994, approach $I/N$

LETTER Nature 2016

doi:10.1038/nature16176

Non destructive measurement of index of refraction of atoms in cavity mode: $J_z$
Quantum metrology

Gain in signal to noise: factor 10 for $5 \times 10^5$ atoms

Phase sensitivity: 147 microradians per cycle

This implies that at least 680 particles are entangled
20 dB noise reduction on variance
Towards an optical clock with correlated atoms

The current challenge: increase interaction time beyond 228 μs while preserving quantum correlations

Entanglement-Enhanced $^{171}$Yb Optical Atomic Clock


Vuletic, MIT  Metrological gain: 4.4 dB
Optical clocks surpass microwave clocks by two orders of magnitude. They have daily fluctuations ~ 0.1 - 1 picosecond. New definition of the second is required.

3 options:

- One atomic species

- A combination of atomic transitions

  See J. Lodewyck, Metrologia 56, 055009 (2019)

- Fixing another fundamental constant such as electron mass

  See presentation of draft resolution E by N. Dimarcq
1) Optical fiber links and frequency combs enable *continental* optical clock comparisons at adequate level. Satellite missions like ACES will enable in 2025 *intercontinental* clock comparisons at $10^{-17} - 10^{-18}$.

2) Einstein effect: a new relativistic geodesy with optical clocks.

3) Earth potential fluctuations will limit the precision of time on ground at $10^{-18} - 10^{-19}$ (ie. cm - mm). Solution: have reference clock(s) in high Earth orbit where fluctuations are reduced.

4) Quantum Metrology will improve clock performance through quantum correlations.