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Never measure anything but frequency!

Arthur Schawlow advice to his students at Stanford

1981 Nobel prize laureate

Frequency and Time are the most precise measurable quantities
All SI units can be derived from the second
Examples

Distance: through speed of light with c fixed: \( d = c \Delta t \)

Charge to mass ratio: cyclotron motion frequency

Mass: \( h/M \): atomic recoil frequency shift
Kg: from Planck’s constant and Watt balance

Fine structure constant: \( \alpha = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{hc} \)
Cyclotron frequency of a single electron in magnetic field

Boltzmann constant \( k_B \):
Acoustic mode frequency in Helium gas
Doppler width in a dilute gas

Electrical units
Josephson and Quantum Hall effects

K. Von Klitzing
Nobel 1985
1989: N. Ramsey, W. Paul, H. Dehmelt
Separated oscillatory fields method for atomic clocks, ion trap techniques

1997: Laser manipulation of atoms

2005: J. Hall, T. Haensch, R. Glauber
Laser precision spectroscopy
Optical frequency comb
Quantum optics

2012: S. Haroche, D. Wineland
Control of individual quantum objects
Photons and atoms
A new frontier: connecting precision measurements and many-body physics

Atom-Atom interaction are both:
- a limit to sensor precision
  example: Cesium fountain clocks, Rubidium is much better!
- a resource for quantum metrology using correlated atoms
  Spin squeezing, continuous atom lasers?
Time measurement

Find a periodic phenomenon:

1) Nature:
   observation: Earth rotation, moon rotation, orbit of pulsars,..

2) Human realization: egyptian sandstone, Galileo pendulum....
   simple phenomenon described by a small number of parameters

The faster the pendulum,
The better is time resolution

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

3) Modern clocks use electromagnetic signals locked to atomic lines
Atomic Clock

An oscillator of frequency $\nu$ produces an electromagnetic wave which excites a transition $a \rightarrow b$.

The transition probability $a \rightarrow b$ as a function of $\nu$ has the shape of a resonance curve centred in $\nu_A = (E_b - E_a) / h$ and of width $\Delta \nu$.

A servo system forces $\nu$ to stay equal to the atomic frequency $\nu_A$.

An atomic clock is an oscillator whose frequency is locked to that of an atomic transition.

The smaller $\Delta \nu$, the better is the precision of the locked system.
Precision of Time

100 ps/day

GPS Time

10 ps/day

Optical clocks

0.5 ps/day

Fountains

Less than 1 second error over 5 billion years or 3 seconds over the age of the universe
Global Positioning System

Each satellite transmits a message with:
- Time of emission and satellite position at time of emission
- Propagation of signal from 4 or more satellites at speed of light provides distances.
- Receiver computes its 3D position (and clock offset) from intersection of 4 spheres.
- Precision of a few meters and even centimeters with additional systems

GPS: started in 1973 by US army
Developed into a spectacular open worldwide service
GLONASS, GALILEO: operational before 2020; BEIDOU,…

24 satellites
In 20 000 kms orbit
12 hour period
Current definition of the second:
Cesium Atomic fountain
Ramsey resonance in an atomic fountain

transition probability

S/N = 5000 per point

S/N = 5000 per point

0.94 Hz

detuning (Hz)
Comparison between two fountains
Paris Observatory

S. Bize et al. EFTF’08
J. Phys. B 2005
SYRTE

Frequency stability below $10^{-16}$ after 5 to 10 days of averaging
Accuracy: agreement between the Cesium frequencies: $4 \times 10^{-16}$
Atomic Fountains and TAI

15 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, INRIM, NPL, METAS, JPL, NIM, NMIJ, NICT, Sao Carlos,….
~10 report to BIPM with accuracy of a few $1 \times 10^{-16}$
Realize the International Atomic Time, TAI

LNE-SYRTE, FR

PTB, D

NIST, USA
Optical Lattice Clocks: $^{171}\text{Yb, }^{87}\text{Sr}$

Accuracy: $\sim 6 \times 10^{-18}$

JILA, NIST, TOKYO, SYRTE, PTB, LENS, INRIM, DÜSSELDORF ….

Riken: I. Ushijima, ArXiv 1405. 1471 (2014), cryogenic clock
The space clock mission ACES 1997
To be launched to ISS July 2016, by Space X Dragon capsule

- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access
Worldwide Network of Ground Institutes

+ 1 transportable MWL GT for calibration/troubleshooting purposes

+ 1 transportable MWL GT for other European institutes INRIM, METAS,....

Delivery of first two MWL GT units: end of 2014
Gravitational redshift with ACES

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

Redshift: \(4.59 \times 10^{-11}\)
With \(10^{-16}\) clock
ACES: \(\sim 2 \times 10^{-6}\)

Factor 70 gain over GP-A 1976
PHARAO cold atom Space Clock

Flight model tests completed in Toulouse
Expected accuracy and stability: $10^{-16}$ in space
Delivery to ESA: July 2014
ACES ON COLUMBUS EXTERNAL PLATFORM on ISS

Current launch date: July 2016
Mission duration: 18 months to 3 years
Global satellite time transfer and continental fiber links

Frequency Comb
J. Reichert et al.
PRL 84, 3232 (2000),
S. Diddams et al.
PRL 84, 5102 (2000)

920 kms fiber link between
MPQ Garching and
PTB Braunschweig

K. Predehl et al.
Science 336, 441(2012).
1) Optical clocks have less than a picosecond per day timing fluctuations: new definition of the SI second

2) Precise Time is delivered by satellites and fiber links to any interested user with capability of ~ picosecond

3) Einstein effect: the Earth gravitational potential fluctuations will limit the precision of time on the ground at $10^{-18}$-$10^{-19}$ (ie: cm to mm level)

4) Solution: set the reference clocks in space where potential fluctuations are vastly reduced

5) Improved Navigation, Earth Monitoring and Geodesy

Towards a space-time reference frame in Earth orbit