Metrology of Time
From fundamental tests to applications

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Never measure anything but frequency!

Arthur Schawlow advice to his students at Stanford

1981 Nobel prize laureate
Distance: through speed of light with c fixed: \( d = c \Delta t \)

Boltmann constant \( k_B \): Doppler width in a dilute gas

Rydberg constant: hydrogen spectroscopy

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

Charge to mass ratio through cyclotron motion
1989: N. Ramsey, W. Paul, H. Dehmelt
Separated oscillatory fields method for atomic clocks, ion trap techniques

1997: S. Chu, C. Cohen-Tannoudji, W. Phillips
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
Discovery of integer quantum Hall effect

2 dimensional electron gas in a strong magnetic field
Metal oxide semiconductor field effect transistor: Resistivity is quantized


Klaus von Klitzing
Nobel laureate 1985

$R_H = n\frac{h}{e^2}$

$R_H = \mu_0 \frac{c}{2\alpha n}$

Standard of electrical resistance $\sim 25 \text{k}\Omega$ for $n = 1$
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
Precision of Time

1 ms

1 s

1 ms

1 µs

1 second error over 3 billion years or 5 seconds over the age of the universe

1 µs

1 ns

1 ps

GPS Time

100 ps/day

10 ps/day

1 ps/day

Optical clocks

Commercial Cs beam clock

Huygens’ pendulum

GPS Time

Earth’s rotation rate

Ephemeris time

Millisecond pulsars

Crossing of Atlantic

Harrison chronometer

Shortt clock

Quartz

Fountains

Astronomical and mechanical era

Atomic Era
**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 states of the ground electronic state of cesium 133.

**Intrinsic stability of atomic energy levels**

Laser cooling to 1 µK
rms velocity: 7mm/s

1) **Fountain**
2) **Microgravity**

\[ F = 4 \quad 6 S_{1/2} \quad F = 3 \]

\[ v_0 = 9 192 631 770 \text{ Hz} \]
Atomic fountain
Ramsey fringes in atomic fountain

S/N = 5000 per point

detuning (Hz)
Comparison between two Fountains FOM and FO2 (Paris Observatory)

Frequency stability below $10^{-16}$ after 5 to 10 days of averaging

Accuracy: agreement between the Cesium frequencies: $4 \times 10^{-16}$
Each fountain is measuring its collisional shift in real time at 2 part in 103 and it will be very difficult to go much beyond these values. Rubidium, on the other hand has much reduced collisional shift and will lead to better stability and accuracy.

Christophe SALOMON; 13.02.2005
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
$^{171}$Yb Optical Lattice Clocks


$3.2 \times 10^{-10}/\sqrt{\tau}$

1.6 $10^{-18}$ at 25 000 s
The space clock mission ACES

Proposal: 1997
Participants

To be launched to ISS May 2016, by Space X Dragon capsule

- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access
Gravitational redshift with ACES

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

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

Factor 70 gain over GP-A 1976
Cold Atom Clock in μ-gravity: PHARAO/ACES

20.054 kg, 36W

Total volume: 990x336x444 mm³
Mass: 44 kg
Flight model tests completed in Toulouse
Expected accuracy and stability: $10^{-16}$ in space
Delivery to ESA: June 18, 2014
ACES ON COLUMBUS EXTERNAL PLATFORM

Current launch date: May 2016
Mission duration: 18 months to 3 years
Each satellite transmits a message with:
- Time of emission
- 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.

Started in 1973 by US army
Developed into a spectacular open worldwide service
European Galileo system operational before 2020
The clock frequency depends on the Earth gravitational potential $10^{-16}$ per meter

Best ground clocks have accuracy of $6 \times 10^{-18}$ and will improve!

Competitive with satellite + levelling techniques at ~ 20 cm level

Applications in Earth Science, Earth resources monitoring, ....

between the two clock locations at $10^{-17}$ level ie 10 cm
and $10^{-18}$ ie 1cm
with fiber link.
1) The Earth gravitational potential fluctuations will limit the precision of time on the ground at $10^{-18}$-$10^{-19}$ (ie: cm to mm level)

2) The only solution: set the reference clocks in space where potential fluctuations are vastly reduced

3) Improved Navigation, Earth Monitoring and Geodesy

Towards a space-time reference frame in Earth orbit
Mass: 227 kg, Power 450 W

Challenges: thermo-mechanical stability, three year operation
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
A new frontier: connecting precision measurements and many-body physics

Spin squeezing
Continuous atom lasers?

2001: Bose-Einstein Condensation

Atom-Atom interaction are a limit to sensor precision,
Example: Cesium fountain clocks, Rubidium is much better!

E. Cornell  W. Ketterle  C. Wieman
Clock Figure of Merit

- **Quality of the clock:** \( \nu/\Delta\nu \times S/N = 2 \nu \times T \times S/N \)
- **Microwave cesium fountain:** \( \sim 2 \times 10^{10} \times 0.5 \times 5000 = 5 \times 10^{13} \)
- **Increase clock frequency to optical or UV domain**

- **Trapped ions:** T very long but only **one** ion in the trap.
  - **stability:** \( 4 \times 10^{-15} \times \tau^{-1/2} \)
  - **Accuracy:** Al\(^+\): \( 8.6 \times 10^{-18} \)

- **Trapped neutral atoms:** T long and large numbers: improved stability
  - **Optical clocks:** \( \sim 2 \times 10^{15} \times 0.5 \times 100 = 10^{17} \)
  - **Stability:** \( 3.2 \times 10^{-16} \times \tau^{-1/2} \)
  - **Accuracy:** \( 6 \times 10^{-18} \), J. Ye et al., 2014
  - **TOKYO, SYRTE, PTB, JILA, NIST, LENS, INRIM, DÜSSELDORF**
Validation of the satellite time transfer with continental fiber link

Frequency Comb

\[ J. \text{Reichert et al.} \]
\[ \text{PRL} \text{ 84}, 3232 (2000), \]
\[ S. \text{Diddams et al.} \]
\[ \text{PRL} \text{ 84}, 5102 (2000) \]

920 kms fiber link between
MPQ Garching and
PTB Braunschweig

K. Predehl et al.
Science 336,
441(2012).
Discovery of integer quantum Hall effect

2 dimensional electron gas in a strong magnetic field

Klaus von Klitzing
Nobel laureate 1985

\[ R_H = n \frac{h}{e^2} \]
\[ R_H = \mu_0 \frac{c}{2} \alpha n \]

Standard of electrical resistance
Current Network of Ground Institutes

+ 1 transportable MWL GT for calibration/troubleshooting purposes

Delivery of first two MWL GT units is planned in second half of 2014
Do fundamental physical constants vary with time?

Motivation: unification theories, string theory,… Damour, Polyakov, Marciano,….

\[ \alpha_{\text{elm}}, \frac{m_e}{m_p} \ldots \]

**Principle**: Compare two or several clocks of different nature as a function of time

Microwave clock/Microwave clock: \( \alpha, \frac{m_e}{m_p}, g^{(i)} \)

rubidium and cesium

Microwave/Optical clock : \( \alpha, \frac{m_e}{m_p}, g^{(i)} \)

Optical Clock / Optical clock: \( \alpha \)
Global search for variations of fundamental constants by long distance clock comparisons at $10^{-17}$/year
Ultra-stable frequency comparisons on a worldwide basis:
Ground Clock comparisons@ $10^{-17}$ over one week
Contribution to TAI
Gain: x 20 wrt current GPS

Common view
Error < 0.3ps over 300 s
Can be checked by fiber-link

Non common view
Error < 3ps over 3000 s
• GPS
• Pulsars
• Klaus Von Klitzing
• Arthur Schawlow
PHARAO Cesium Tube on the Shaker
PHARAO Team in Toulouse
SYRTE Comparison between Rubidium and Cesium
Hyperfine Structure over ~15 years

With QED calculations:  
\[ \frac{d}{dt} \ln \left( \frac{g_{Rb}}{g_{Cs}} \alpha^{-0.49} \right) = (-1.36 \pm 0.91) \times 10^{-16} \text{ yr}^{-1} \]

With QCD calculations:  
\[ \frac{d}{dt} \ln \left( \frac{g_{Rb}}{g_{Cs}} \alpha^{-0.49} \right) = (-1.36 \pm 0.91) \times 10^{-16} \text{ yr}^{-1} \]

\[ d\alpha/\alpha dt = (-1.6\pm2.4) \times 10^{-17}/\text{year} \]

\[ \frac{d}{dt} \ln \left( \frac{V_{Rb}}{V_{Cs}} \right) = (-1.36 \pm 0.91) \times 10^{-16} \text{ yr}^{-1} \]
Stability of SHM in time intervals of 3 to 3000 s, well adapted to:

- ISS single pass (duration: 200-400 s)
- Evaluation and optimization of PHARAO

ACES: slow servo of SHM onto PHARAO

Allan deviation of the 2 clocks:

- Stability of SHM in time intervals of 3 to 3000 s, well adapted to:
  - ISS single pass (duration: 200-400 s)
  - Evaluation and optimization of PHARAO

ACES: slow servo of SHM onto PHARAO

Stability at one day: $3 \times 10^{-16}$

at 10 days: $1 \times 10^{-16}$
Beyond ACES

Microwave clocks:
stability $10^{-16}$ per day, accuracy: $\sim 1 \times 10^{-16}$ on Earth and in Space

Optical clocks:
$10^{-18}$ range (NIST, JILA,’13)
Towards a redefinition of the SI second

**ACES**
Comparisons between distant clocks at $10^{-17}$
Large improvements on relativity tests
Stringent limits for variations of $\alpha$, $g_p$, $M_e/M_p$

Proposed ACES mission follow-on with microwave/optical clocks:
STE-QUEST, SOC on ISS, SAGAS,..
The microwave link ground terminal

Time stability of carrier with 10 Kelvin peak to peak temperature variation

PTB, SYRTE, NPL, JPL, NIST, Tokyo, UWA, METAS,…

MWL End to End tests are ongoing
The flight time scale accumulates only 2 ps error over 3000 s i.e. half an orbital period.
Frequency comparisons at $10^{-17}$ over one week
\[ \sigma_y(\tau) = 4 \times 10^{-13} \, \tau^{-1/2} \]

With ultra-stable Quartz
Limited by gravity!

\[ \sigma_y(\tau) = 2.5 \times 10^{-13} \, \tau^{-1/2} \]

With Cryo. Oscillator
Will enable \(7 \times 10^{-14} \, \tau^{-1/2}\)
in space

Accuracy evaluation:
Currently \(2 \times 10^{-15}\) on the ground.
Should enable \(10^{-16}\) in space
Most distant stations: Paris-Perth
Between 1 and 2 non common views per day within less than 3000 seconds
Several NC Views within 10 000 seconds,
Overall: less than 10 ps at half day, ie $2 \times 10^{-16}$ and $1 \times 10^{-17}$ at one week
ACES Time Transfer Engineering Model

Onboard receiver

TimeTech and EADS
The ACES Mission will demonstrate the capability to perform phase/frequency comparison between space and ground clocks with a resolution at the level of 0.3 ps over one ISS pass (300 s), 7 ps over 1 day and 23 ps over 10 days.
Fundamental Questions

1) **Missing mass in the Universe**

   Dark matter and dark energy represent 95% of the mass of the Universe but have unknown origin!

   New particles and/or change of the laws of gravity?

2) **Atomic quantum sensors can test fundamental laws with exquisite precision**

   - Einstein’s equivalence principle and Universality of Free Fall
   - Proposal for detection of gravitational waves
   - Precision redshift measurement
   - Variability of fundamental constants

3) **Quantum sensors have societal applications**

   - Accelerometry, Gravimetry, Navigation, GPS, GALILEO, GLONASS, Geodesy, Earth monitoring,…