Cold Atom Clocks and Fundamental Tests

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1) What is an atomic clock?
   - Frequency stability
   - Accuracy

2) Atomic fountains and optical clocks
   - Performances

3) Fundamental tests with space clocks
   - Redshift measurement
   - Search for drift of fundamental constants

4) ACES applications
   - Geodesy, GNSS
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

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

Quartz oscillator,… vibration of crystal coupled to an electrical circuit

Atomic Clock:

Intrinsic stability of energy levels (Quantum Mechanics)
Control of atomic motion
Laser cooling: low velocities : 1 cm/s
  Long measurement time:
  Narrow atomic resonance
  Better clocks
Precision of Time

- 100 ps/day
- 10 ps/day

Timeline:
- 1600 to 1700: Astronomical and mechanical era
- 1800: Shortt clock
- 1900: First Cs clock
- 2000: Cs fountain clock

Key events:
- Crossing of Atlantic
- Variation of Earth's rotation rate
- Ephemeris time
- Millisecond pulsars
- GPS time
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 lock system.
**Atomic clock**

**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 electronic state of cesium 133.

**Intrinsic stability of atomic energy levels**

**Laser cooling to 1 µK**

Corresponding to rms velocity of 7mm/s

1) **Fountain geometry**
2) **Microgravity environment**

1. **Stability**
2. **Accuracy**

\[
\begin{align*}
F=4 & \quad 6 S_{1/2} \\
F=3 & \quad \nu_0 = 9,192,631,770 \text{ Hz}
\end{align*}
\]
Ramsey fringes in atomic fountain

S/N = 5000 per point
Cesium clock Stability/Accuracy: State of the art

\[ \nu_{\text{clock}}(t) = \nu_{\text{cesium}}(1 + \varepsilon + y(t)) \]

Where \( \nu_{\text{cesium}} \) is the transition frequency of a cesium atom at rest in absence of perturbation

\( \varepsilon \) : frequency shift, \( \varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \ldots \)

\( y(t) \): frequency fluctuations with zero mean value.

Accuracy: \( \varepsilon \)
To what extent does the clock realize the definition of the second?

Cesium and rubidium fountains: \( \varepsilon \sim 3 \times 10^{-16} \)

Frequency stability
Measurement duration \( \tau \): \( y(\tau) \) averaged frequency instability
For \( \tau = 1s \), \( y(\tau) = 1.4 \times 10^{-14} \) fundamental quantum limit
For \( \tau = 50 000 \text{ s} \), \( y(\tau) \sim 1.4 \times 10^{-16} \)
Atomic Fountains

14 fountains in operation at SYRTE, PTB, NIST, USNO, JPL, Penn St, INRIM, NPL, ON. 6 with accuracy at $1 \times 10^{-15}$. More than 10 under construction.
Comparison between two Cesium Fountains FO1 and FO2 (Paris)

S. Bize et al. C. Rendus Acad. Sciences 2004 SYRTE

Measured Stability: $1.4 \times 10^{-16}$ at 50 000 s
Best measured stability for fountains! Factor 5-10/Hydrogen Maser
Agreement between the Cesium frequencies: $4 \times 10^{-16}$
A transportable cold atom clock

Transport to Bordeaux: 1997
PTB: 2002
Innsbruck 2007
PHARAO in parabolic flights in ZeroG Airbus
Frequency Comb

J. Reichert et al. PRL 84, 3232 (2000),
S. Diddams et al. PRL 84, 5102 (2000)
Connecting microwaves to optical frequencies

Measurement of 1S-2S transition of Hydrogen at MPQ in Hänsch lab
Using the mobile cold atom fountain

\[ \nu_{1S-2S} = 2\,466\,061\,413\,187\,103 \pm 46 \text{ Hz} \]
Accuracy : \(1.8 \times 10^{-14}\)

M. Fischer et al., PRL, 92 (2004)

Multiplication by 250 000 of the cesium frequency to the UV range, 243 nm

New limits on time change of fundamental constants, \(\alpha\) and strong interaction constant
Search for variations of fundamental constants and Einstein Equivalence Principle

In any free falling local reference frame, the result of a non gravitational measurement should not depend upon when it is performed and where it is performed.

**EEP ensures the universality of the definition of the second**

It implies the stability of fundamental constants: \( \alpha = \frac{e^2}{4 \pi \varepsilon_0 \hbar c} \), \( m_e \), \( m_p \),…

In particular: the ratio of the transition frequencies in different atoms and molecules should not vary with space and time.

The EEP can be tested by high resolution frequency measurements regardless of any theoretical assumption.

EEP revisited by modern theories: \( g_{\mu\nu} \Rightarrow g_{\mu\nu}, \phi, \ldots \)

Fundamental constants depend upon local value of \( \phi : \alpha(\phi), m(\phi), \ldots \)

**Violations of EEP are expected at some level!!**

For instance: T. Damour, G. Veneziano, PRL 2002
\[ \frac{d}{dt} \ln \left( \frac{v_{Rb}}{v_{Cs}} \right) = (-0.5 \pm 5.3) \times 10^{-16} / \text{year} \]

\[ \frac{\dot{\alpha}}{\alpha} = (1.0 \pm 12) \times 10^{-16} / \text{year} \]

Within Prestage et al.

theoretical framework:

H. Marion et al.,
PRL (2003),
Bize 2004
Applications of atomic clocks

• Navigation, Positioning
  GPS, GLONASS, deep space probes
• Datation of millisecond pulsars
• VLBI
• Synchronisation of distant clocks
  TAI
• Geodesy
• Fundamental physics tests  Ex : general relativity
  Einstein effect, gravitational red-shift : $10^{-4}$ → $10^{-6}$
  Shapiro delay : $10^{-3}$ → $10^{-7}$

Search for a drift of fundamental constants such as the fine structure constant $\alpha$ :

\[ \alpha^{-1} \frac{d\alpha}{dt} \text{ a t } 10^{-17}/\text{year} \]
Fundamental Tests with space Clocks

1997

ACES

CNES

PHARAO
• A cold atom Cesium clock in space
• Fundamental physics tests
• Worldwide access
ACES on the ISS

H = 400 km
V = 7 km/s
T = 5400 s
A Prediction of General Relativity

Einstein gravitational shift

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

Redshift: \(+4.59 \times 10^{-11}\)

with \(10^{-16}\) clocks

ACES: \(2 \times 10^{-6}\)

Factor 35 gain over GP-A 1976
ACES and variations of fundamental physical constants

\[ G, \alpha_{\text{elm}}, \alpha_{\text{strong}}, m_e, \ldots \]

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

Microwave clock/Microwave clock

Very stringent limits on variations of \( \alpha_{\text{elm}}, \alpha_{\text{strong}}, \frac{m_e}{m_p} \)

Sensitivity: \( 10^{-17}/\text{year} \)

Optical Clock / Optical clock

Today: \( \alpha / \alpha < 1 - 3 \times 10^{-16} / \text{year} \), Fortier et al. 2007
MWL Ku- and S-band antennas
FCDP
PHARAO SHM cavity assembly
PHARAO laser source
PHARAO tube
Heat pipes
MWL UGB
XPLC
ACES base-plate
PHARAO accelerometer and coils control unit
CEPA

Volume: 1172x867x1246 mm³
Total mass: 227 kg
Power: 450 W
ACES ON COLUMBUS EXTERNAL PLATFORM

Current launch date: end 2013
Mission duration: 18 months to 3 years
Launch of European Columbus Module: end 2007- early 2008 by US shuttle
ACES launch by Japan HTV
**PHARAO cold atom clock**

- **Cooling zone**
- **Selection**
- **Ramsey Interrogation**
- **State detection**

**Cesium reservoir**

**Microwave cavity**

**3 Magnetic shields and solenoids**

**Ion pump**

**Fountain**:
\[ v = 4 \text{ m/s}, \ T = 0.5 \text{ s} \quad \Delta \nu = 1 \text{ Hz} \]

- **PHARAO**:
\[ v = 0.05 \text{ m/s}, \ T = 5 \text{ s} \quad \Delta \nu = 0.1 \text{ Hz} \]
PHARAO Space Clock

Laser source

Frequency stability validated
Functional tests ongoing in CNES Toulouse
Laser Source

20.054 kg, 36W, 30 liters, Vacuum and Air operation, T=10-35 deg. Operation for 18 months without manual adjustment

Main active components:
- 4 ECDL
- 4 DL
- 6 AOM
- 30 PZT
- 11 motors
- 6 photodiodes
- 8 peltier coolers
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.
Ground Clock Frequency Comparison

ACES microwave link: two way system

Common View

Non Common View

Error < 0.3ps over 300 s

Error < 3ps over 3000 s
ACES versus GPS

Note: Allan Deviation
The clock frequency depends on the Earth gravitational potential $10^{-16}$ per meter.
Best ground clocks have accuracy of $3 \times 10^{-17}$ and will improve!

With ACES link: Possibility to measure the potential difference between the two clock locations at $10^{-17}$ level i.e. 10 cm.

In 2013-2015
ACES Ground laboratories (March 07)

Australia: UWA, CSIRO (Sydney)
Austria: Univ. Innsbruck
Brazil: Univ. Sao Carlos
Canada: NRC
China: Shangai Obs, NIM, NTSC
Germany: PTB, MPQ, Univ. Hannover, Univ. Düsseldorf, TU Muenchen, Univ. Erlangen
France: SYRTE, CNES, Obs. Besançon, OCA, LPL
Italy: INRIM, Univ. Firenze
Japan: Tokyo Univ., NMIJ, CRL
Russia: Vniftri, ILS Novosibirsk
Swiss: METAS, ON
United King: NPL
USA: JPL, NIST, Penn St. Univ., USNO, JILA
Taiwan: Telecom research lab
Int. Agency: BIPM

Total: 35 institutes + theory groups
> 300 researchers
Accuracy of the atomic time

ACCURACY OF THE ATOMIC TIME

ACCURACY OF THE ATOMIC TIME

Relative Accuracy vs. Year

Cesium Microwave clocks
Slope: gain of 10 every 10 years

Optical Clocks

Current accuracy:
Microwave: $3 \times 10^{-16}$
Optical: $3 \times 10^{-17}$

10^{-17} and below

ACES


NIST, 06

Cold atoms

ACES
**Optical Clocks with Cold Neutral Atoms**

Quality of the clock: \( \frac{\nu}{\Delta \nu} \times \text{S/N} = 2 \times \nu \times T \times \text{S/N} \)

Increase the frequency, \( T \), and \( \text{S/N} \)

A lot of atoms at the same time,

hence good \( \text{S/N} \)

Excellent short term stability

- Microwave domain: Cs, Rb,
- Optical domain: H, Ca, Mg, Sr, Ag,…
- Trapped in optical lattice at magic wavelength (Katori),

Increased \( T \)

JILA 2007: current linewidth: 2 Hz; stability at 1s: \( 3 \times 10^{-15} \)!

Target: \( 10^{-16} \) at 1s and \( 10^{-18} \) at 10 000 seconds

Tokyo, JILA, SYRTE, NIST, PTB, KRISS,….
Perspectives: 10^{-18}

Microwave clocks: Cs, Rb: stability 10^{-16} per day, accuracy: ~ 1 \times 10^{-16}
On Earth and in space
Optical clocks: 4 \times 10^{-17} today and towards 10^{-18} range

**ACES: Comparisons between distant clocks at 10^{-17}**
Clocks at 10^{-17} or below will probe time-dependent Earth potential
Currently, clock transport and progress with telecom fiber networks!!

Large improvements on tests of variations of $\alpha$, $g_p$, $M_e/M_p$

Links with GNSS navigation GPS, GALILEO, GLONASS,…

**Dedicated satellite for global time dissemination**
without Earth potential variations

Clocks with quantum correlated states
Demonstrated with 6 ions at NIST: Stability as $1/N$ instead of $1/N^{1/2}$