ATOMIC CLOCKS: BASIC PRINCIPLES, APPLICATIONS AND CURRENT TRENDS

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LABORATOIRE TEMPS – FRÉQUENCE (LTF)

Time & Frequency metrology
Atomic spectroscopy
Primary standards
Optical clocks
Cell standards
Space clocks

Optical metrology
Optical combs
XUV frequency combs
Stabilized lasers
Laser characterisation
Laser instruments
OUTLINE OF THE TALK

1) Introduction to atomic frequency standards
Basic (functional and physical) principles
Examples and applications of frequency standards

2) Current trends in the field
Optical frequency standards
Chip-scale atomic clocks
RECENT NOBEL PRIZES IN PHYSICS RELATED TO THE FIELD

2012: S. Haroche, D. Wineland
Control of individual quantum objects. Photons and atoms

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

1997: S. Chu, C. Cohen-Tannoudji, W. Philips
Laser manipulation of atoms

1989: N. Ramsey, W. Paul, H. Dehmelt
Separated oscillatory fields method for atomic clocks.
Ion trap techniques

And several others in the previous years (Kastler, optical pumping, etc.)
OUTLINE OF THE TALK

1) Introduction to atomic frequency standards
   Basic (functional and physical) principles
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2) Current trends in the field
   Optical frequency standards
   Chip-scale atomic clocks
**Definition in SI system**

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 cesium 133 (1967)

\[
\text{Frequency } \nu_0 = \frac{E_2 - E_1}{h} = 9192631770 \text{ Hz}
\]

\[
\text{Period } T_0 = \frac{1}{\nu_0}
\]

This would be the frequency of an atomic clock in which the atomic transition is not perturbed and the stabilisation “perfect”

**Quartz oscillator**

**Atoms**

Reference for the user (5 MHz)
WHY DO WE NEED TO STABILIZE THE QUARTZ?

Slide from: John Vig, tutorial on «Quartz crystal resonators and oscillators»
### FIRST OVERVIEW OF APPLICATIONS AND NEEDS

<table>
<thead>
<tr>
<th>Application</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture (seasons)</td>
<td>(~ 1’000’000 ) s</td>
</tr>
<tr>
<td>Calendar (solstices, equinoxes)</td>
<td>(~ 100 ) ’000 s</td>
</tr>
<tr>
<td>Daily activities (professional, social, etc.)</td>
<td>(~ 1’000 ) s</td>
</tr>
<tr>
<td>Determination of the longitude (sea navigation)</td>
<td>(~ 1 ) s</td>
</tr>
<tr>
<td>Common electronic and telecommunication devices</td>
<td>(~ 0.01 ) s</td>
</tr>
<tr>
<td>Advanced telecommunication devices</td>
<td>(~ 0.000’001 ) s 10^{-11}</td>
</tr>
<tr>
<td>Satellite navigation</td>
<td>(~ 0.000’000’001 ) s 10^{-14}</td>
</tr>
<tr>
<td>Scientific research and primary metrology</td>
<td>&lt; 0.000’000’000’1 s &lt; 10^{-14}</td>
</tr>
</tbody>
</table>

**Need of atomic clocks** (in the device or to calibrate the device)
Typically 5 or 10 MHz

How to measure / evaluate the stability and accuracy?

- By comparing to a more stable and/or accurate oscillator
- Statistical and non-statistical analysis
Frequency of the oscillator: \( \nu(t) = \nu_0 [1 + \epsilon + y(t)] \)

\[ y_K = \frac{1}{\tau} \int_{t_k}^{t_{k+\tau}} y(t) \, dt \]

"True variance": \( \sigma_y^2 = \overline{y_k^2} \) diverges in general

\[ \sigma_y^2(\tau) = \frac{1}{2} (y_{k+1} - y_k)^2 \]

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

**\( \sigma_y(\tau) \)** tells us how the oscillator under test compares to an ideal one over the timescale \( \tau \)

- Different types of noise processes affect differently the Allan deviation;
- Different applications require different (in)stabilities at given time scales
**Magnetic resonance** allows “spin flip”.

Magnetic resonance is a **frequency selective** phenomenon

**Signal**

- Probing frequency
- Linewidth $\Delta \omega_0$

Allan deviation:

$$\sigma_y^I = \frac{0.2}{Q \cdot (S/N)} \tau^{-1/2}$$

$Q = \frac{\omega_0}{\Delta \omega_0}$

$$\Delta \omega_0 \propto \frac{1}{T_R}$$

$T_R$: resonance «duration»


**BASIC PHYSICAL PRINCIPLE: MAGNETIC RESONANCE**
The most important parameters for the clock performances are:

- The resonance quality factor $Q$
- The signal to noise ratio $S/N$

**Relevant Parameters of the Resonance Signal**

The error signal is related to the frequency noise by:

$$\sigma_y(\tau) \propto \frac{\tau^{-\frac{1}{2}}}{Q(S/N)}$$

The quality factor $Q$ is defined as:

$$Q = \frac{\omega_0}{\Delta \omega}$$

The frequency offset $\Delta \omega$ is related to the observation time $T_{\text{observation}}$ by:

$$\Delta \omega \propto \frac{1}{T_{\text{observation}}}$$
The state of an atom (2 levels) may be represented with a vector \( \vec{S} \) ("Bloch vector", or "Fictitious spin") and its behavior when interacting with a resonant field as a magnetic moment in a magnetic field.

Microwave transitions, optical transitions, \( \pi/2 \) pulses, etc.

\[ e^{i\omega t} \approx \frac{E_2 - E_1}{\hbar} \]

\[ \left( \begin{array}{c} u \\ v \\ w \end{array} \right) \propto \left( \begin{array}{c} \text{atomic dipole in phase} \\ \text{atomic dipole in quadrature} \\ \text{difference of populations} \end{array} \right) \]

WHAT HAPPENS IN AN ATOMIC CLOCK

*Generalised magnetic resonance* allows “spin flips”

It is a *frequency selective* phenomenon

In an *atomic clock* you exploit this phenomenon to frequency stabilise a quartz oscillator

In each *type of clock* it is realised on different species, in various configurations and with different detection techniques
GENERAL SCHEME (OR SEQUENCE) IN ATOMIC CLOCKS

- Have the atoms available and as isolated as possible from the “outside” undesired interactions / perturbations;

- Put (or select) as many atoms as possible atoms in one (of the two) levels;

- Perform the “magnetic resonance” (in one or more steps);

- Detect the result of the “magnetic resonance” (level transition);

- Apply the necessary correction to the quartz oscillator

\[ \tilde{S} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \]
Stern-Gerlach (State selection) and Ramsey interrogation

\[
\vec{s} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}
\begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}
\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}
\begin{pmatrix} \sin(\omega_0 t) \\ \cos(\omega_0 t) \\ 0 \end{pmatrix}
\begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix}
\]
CATEGORIES OF ATOMIC CLOCKS

- Primary (Cs) – Secondary
- Passive – Active (H-Maser)
- Commercial (Rb, Cs, H)
- Ground or Space applications
- Laboratory – “In development”
- Microwave – Optical
- Neutral atoms – Ions – Molecules – Nuclear - …

\[ \nu(t) = \nu_0 \left[ 1 + \epsilon + y(t) \right] \]
MAIN FIELDS OF APPLICATIONS OF ATOMIC CLOCKS

- **Radioastronomy, Geodesy**
  (VLBI, Radioastron, etc.)

- **Scientific Research, Instrumentation**
  (Microgravity, ACES, HYPER, etc.)

- **Navigation & Positioning**
  (Galileo, GPS, GLONASS, etc.)

- **Telecommunications**
  (Networks synchronisation, etc.)

- **Power distribution networks**
  (Smart power grids.)

- **Metrology, Time scales**
  (Primary and secondary standards, H-Masers)
CESIUM BEAM STANDARD

$10^{-11}$ @ 1s but accurate and very stable in the long term

$$
\text{Linewidth } \Delta \omega_0 \propto \frac{1}{T_R}
$$

$$
T_R = \frac{L}{v} = \frac{\text{Length of cavity}}{\text{speed of atoms}}
$$
RAMSEY SCHEME (SEPARATED OSCILLATORY FIELDS METHOD)

For a monokinetic beam

\[ P_{12}(\delta) = \frac{1}{2} \sin^2 \Omega_1 \tau (1 + \cos \delta \tau) \]

\[ (\omega_{RF} - \omega_0)T = 2n\pi \quad (\omega_{RF} - \omega_0)T = (2n+1)\pi \]

\[ \Delta \nu \approx \frac{1}{T} \quad \Delta \nu = \frac{1}{2T} \]
1st Rabi ($\pi/2$) pulse

Free precession

2nd Rabi ($\pi/2$) pulse

Detection

Optical pumping
LASER RADIATIVE FORCES

\[
\vec{E}(r,t) = \hat{e} \cdot E_0 \cdot \cos[\omega_L t + \phi(r)]
\]

\[
\vec{F} = \hat{e} \cdot d_{ab} \cdot u_{st} \cdot \nabla E_0(r) + \hat{e} \cdot d_{ab} \cdot v_{st} \cdot E_0(r) \cdot \nabla \phi(r)
\]

- **reactive or dipolar force**  
  \(\sim\) light-shift

- **dissipative or radiation pressure force**  
  \(\sim\) absorption

Motivations: reduce the Doppler effect, increase interaction time, etc. \(\Delta \omega_0 \propto \frac{1}{T_R}\)

Optical trapping (lattice, tweezers, etc.)

Optical molasses
Linewidth: $\Delta \omega_0 \propto \frac{1}{T_R}$

- Thermal beam: $v = 100$ m/s, $T_R = 5$ ms
  $\Delta \omega_0 = 100$ Hz

- Cold fountain: $v = 4$ m/s, $T_R = 0.5$ s
  $\Delta \omega_0 = 1$ Hz

- Next step: microgravity ($T_R = 10$ s, $\Delta \omega_0 = 0.1$ Hz)
Frequency: \( \nu(t) = \nu_0 \left[ 1 + \epsilon + y(t) \right] \)

\begin{align*}
\text{Systematic bias} & \quad \text{Statistical fluctuations} \\
\end{align*}

<table>
<thead>
<tr>
<th>Type of shift</th>
<th>Freq. shift</th>
<th>Uncertainty</th>
<th>Type of shift</th>
<th>Freq. shift</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd order Zeeman</td>
<td>3.3 \times 10^{-10}</td>
<td>1 \times 10^{-15}</td>
<td>CS fountain</td>
<td>4.5 \times 10^{-14}</td>
<td>1 \times 10^{-16}</td>
</tr>
<tr>
<td>2nd order Doppler</td>
<td>5 \times 10^{-14}</td>
<td>5 \times 10^{-16}</td>
<td></td>
<td>&lt; 1 \times 10^{-16}</td>
<td>&lt; 1 \times 10^{-16}</td>
</tr>
<tr>
<td>Cavity phase-shift</td>
<td>2.5 \times 10^{-13}</td>
<td>6 \times 10^{-15}</td>
<td></td>
<td>&lt; 1 \times 10^{-16}</td>
<td>&lt; 3 \times 10^{-16}</td>
</tr>
<tr>
<td>Gravitational pot.</td>
<td>8 \times 10^{-15}</td>
<td>2 \times 10^{-16}</td>
<td></td>
<td>1.8 \times 10^{-13}</td>
<td>1 \times 10^{-16}</td>
</tr>
<tr>
<td>Spin-exchange</td>
<td>-</td>
<td>-</td>
<td></td>
<td>1 \times 10^{-14}</td>
<td>3 \times 10^{-16}</td>
</tr>
<tr>
<td>Black body (AC Stark)</td>
<td>2 \times 10^{-14}</td>
<td>5 \times 10^{-16}</td>
<td></td>
<td>2 \times 10^{-14}</td>
<td>3 \times 10^{-16}</td>
</tr>
<tr>
<td>Other effects</td>
<td>4 \times 10^{-15}</td>
<td>&lt; 4 \times 10^{-16}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total uncertainty D</td>
<td>7 \times 10^{-15}</td>
<td>7 \times 10^{-16}</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ATOMIC TIME (TAI) AND ASTRONOMICAL TIME (UTC)

TAI is generated from an ensemble of various clocks:
- ~ 10 fountains
- > 300 commercial clocks
  (cesium clocks, rubidium clocks, H-masers)

Leap second
Double resonance

Discharge lamp

vapour cell

microwave resonator & source

Quartz LO

Transmitted light

Microwave frequency

$10^{-11} @ 1s$

$10^{-13} @ 10'000s$
DOUBLE RESONANCE (WITH A DISCHARGE LAMP)

Double resonance

P
S
light
µ-wave

Microwave cavity

détector

Rb\textsuperscript{87} Lamp
Rb\textsuperscript{85} filter
Rb\textsuperscript{87} resonance cell

Transmitted light [V on 10kΩ] vs. Synthesiser frequency [Hz]

5.304x10\textsuperscript{6}  5.306x10\textsuperscript{6}  5.308x10\textsuperscript{6}  5.310x10\textsuperscript{6}  5.312x10\textsuperscript{6}

0.108  0.110  0.112  0.114  0.116  0.118  0.120  0.122  0.124  0.126  0.128
EXAMPLES OF RB CLOCKS (OBSERVATOIRE NE 1985-1995)

Currently commercialized by Spectratime-Orolia. Used in the GALILEO navigation system
Next generation: replace the discharge lamp with a laser for a more efficient optical pumping
HYDROGEN MASER

\[ \sigma(\tau) \sim \frac{1}{\tau} \]

\[ 10^{-13} @ 1s \]

\[ 10^{-15} @ 100s \]

100 kg
VLBI (VERY LONG BASE INTERFEROMETRY)

H-Masers ($10^{-15}$ @ $\sim 1000-10’000$ s) are used to increase the resolution

Angular resolution: $\sim \lambda / \text{Diameter}$

1 radio-telescope: $\sim 1 \text{ mrad} (10^{-3} \text{ rad})$

2 radio-telescopes: $\sim 1 \text{ nrad} (10^{-9} \text{ rad})$

*Earth rotation*: 1 mrad $\rightarrow$ 6 km $\rightarrow$ 14 s
Increase the Baseline B from 30’000 to 300’000 km, by putting one of the telescope (and one Maser!) in space.
FUNDAMENTAL PHYSICS IN SPACE

STE-QUEST
(Space-Time Explorer and Quantum Equivalence Principle Space Test)
A class M mission proposal for Cosmic Vision 2015-2025

FUNDAMENTAL PHYSICS IN SPACE

Atomic Clock Ensemble in Space

Micro-gravity

Relativity

$1 \propto \frac{1}{Q} \cdot \frac{1}{\omega_0 \cdot \tau}$
Application: GALILEO

1 ns ($10^{-14}$) time error
↓
30 cm position error

Goal: $10^{-14}$ stability @ 10'000 s (keeping 1 ns over one orbit)
↓
$10^{-12}$ @ 1 s

18 kg, 28 L, $7 \cdot 10^{-13}$ @ 1 s
GALILEO (EUROPEAN SATELLITE NAVIGATION SYSTEM)

In space: Rubidium, passive Hydrogen Maser (1° generation)

On earth: (quartz), Rubidium, Cesium beams, active H Masers (1° generation)

GIOVE-A (launched 28 Dec 2005)  GIOVE-B (launched 26 April 08)

2011 and 2012: launch of first operational satellites (IOV – In Orbit Validation)
WHY RB CLOCK AND PASSIVE H MASER ON GALILEO?

For 30 cm accuracy
Maximal Time error:
1 nanosecond for
1s < \( \tau \) < 20'000 s

\( \sigma_y (20'000 \text{s}) \approx 10^{-14} \)

![Graph showing Allan deviation for different clock types](image)
OUTLINE OF THE TALK

1) Introduction to atomic frequency standards
   Basic (functional and physical) principles
   Examples and applications of frequency standards

2) Current trends in the field
   Optical frequency standards
   Chip-scale atomic clocks
OPTICAL FREQUENCY STANDARDS

\[ \frac{1}{Q} \propto \frac{1}{\omega_0 \cdot T_R} \]

\( \omega_0 : 10^{10} \rightarrow 10^{15} \text{ Hz} \)
MICROWAVE AND OPTICAL CLOCKS

RIVISTA DEL NUOVO CIMENTO
Vol. 36, N. 12
DOI 10.1393/ncr/i2013-10095-x

Optical atomic clocks

N. Poli(1), C. W. Oates(2), P. Gill(3) and G. M. Tino(1)(*)

13th PSI Summer School
Zug, August 9-15 2014

Atomic clocks: basic principles, applications and current trends
Gaetano Mileti, UniNe, 10.08.2014
Frequency Ratio of Al\(^+\) and Hg\(^+\) Single-Ion Optical Clocks; Metrology at the 17th Decimal Place

EXAMPLE OF MORE RECENT ACHIEVEMENTS

An Atomic Clock with $10^{-18}$ Instability

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Atomic clocks have been instrumental in science and technology, leading to innovations such as global positioning, advanced communications, and tests of fundamental constant variation. Timekeeping precision at 1 part in $10^{18}$ enables new timing applications in relativistic geodesy, enhanced Earth- and space-based navigation and telescope, and new tests of physics beyond the Standard Model. Here, we describe the development and operation of two optical lattice clocks, both utilizing spin-polarized, ultracold atomic ytterbium. A measurement comparing these systems demonstrates an unprecedented atomic clock instability of $1.6 \times 10^{-18}$ after only 7 hours of averaging.

Scienceexpress / http://www.sciencemag.org/content/early/recent / 22 August 2013 / Page 1 / 10.1126/science.1240420
STABILISED LASERS & COMB FOR A (SPACE) CO2 LIDAR

DFB master laser

FP-EOM

RF

SHG

Rb FRU

system output

DFB slave laser

SHG: second-harmonic generation

FP: Fabry Perot

EOM: electro-optical modulator


**RAMSEY INTERROGATION IN A CELL STANDARD**

Time-domain Ramsey scheme:

- Optical pumping ($T_p$)
- Microwave pulse interrogation ($T_1$, $T_{\text{Ramsey}}$)
- Optical Detection ($T_d$)

Advantages:

- Compactness
- Narrow linewidth
- Negligible light shift

---

Bring atomic timing precision to the size and power range previously covered by quartz oscillators.

New clocks!

<table>
<thead>
<tr>
<th></th>
<th>Primary Standard</th>
<th>Commercial Beam Clock</th>
<th>Compact Atomic Clock</th>
<th>Miniature Atomic Clock</th>
<th>Precision Quartz</th>
<th>Wristwatch Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>$10^{-15}$</td>
<td>$10^{-13}$</td>
<td>$10^{-11}$</td>
<td>$10^{-10}$</td>
<td>$10^{-7}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Timing error</td>
<td>10ns/yr</td>
<td>1µs/yr</td>
<td>0.1µs/day</td>
<td>1µs/day</td>
<td>100µs/day</td>
<td>1s/day</td>
</tr>
<tr>
<td>Size</td>
<td>$10^7$ cm$^3$</td>
<td>$10^4$ cm$^3$</td>
<td>100 cm$^3$</td>
<td>10 cm$^3$</td>
<td>1-10 cm$^3$</td>
<td>10 mm$^3$</td>
</tr>
<tr>
<td>Power</td>
<td>kW</td>
<td>100's W</td>
<td>1 W</td>
<td>120mW</td>
<td>100 mW</td>
<td>10 µW</td>
</tr>
<tr>
<td>Cost</td>
<td>&gt;$1 M</td>
<td>$50 k</td>
<td>$2,000</td>
<td>$300</td>
<td>$100</td>
<td>$1</td>
</tr>
</tbody>
</table>

Decreasing performance and size/power/cost.
NEUCHÂTEL ANODIC BONDING TECHNOLOGY

SPECIAL MINIATURE CELLS

4-mm size Rb cells
Micro-fabrication technology for precise control of cell geometry

Multi-stack anodic bonding:
⇒ Thick glass core wafer
⇒ 2 Si layers + 2 glass windows
⇒ 4 steps of anodic bonding

Indium cell sealing
Low-temperature sealing (≤ 140°C)
⇒ alkali control & wall coatings


Miniature cesium atomic clock
CPT (Coherent population trapping) technique

Applications
Telecom (4G LTE base stations)
Smart grid (power distribution)

Product specifications
Superior frequency and time stability: 1 µs/day
Compact size: 51x51x18 mm3
Low power: 2W
Lower price: 400 CHF
OTHER RECENT DEVELOPMENTS

Imaging of microwave field and atoms relaxation time

Microfabricated discharge lamps

Microfabricated cells with wall coating

Double resonance with miniature microwave cavity and Rb cell
Summary

• Thanks to the latest discoveries in atomic physics and photonics (or photon engineering) the precision of atomic clocks is being improved down to $10^{-16}$ and beyond;

• More precisely, it is the manipulation of atoms photons and the availability of tunable laser sources and optical combs which is allowing such dramatic improvements:

$$(In)stability \propto \frac{\Delta \omega_0}{\omega_0} \propto \frac{1}{\omega_0 \cdot T_R}$$

- $T_R$: cooling
- $\omega_0$: going optical

• Atomic clocks (and stabilized lasers) are key instruments for fundamental physics experiments on ground and in space;

• Compact high performance and miniature atomic clocks find many applications in every day life (positioning, telecoms, etc.)

• Micro-fabrication techniques are crucial for extreme miniaturization

• With its tradition in Time keeping, precision mechanics, micro-technology, optical metrology and space science & technology, Switzerland makes crucial contributions to this domain
ESSENTIAL BIBLIOGRAPHY


Time & Frequency conferences proceedings (including tutorials)
www.eftf.org (free) → EFTF-2014 in Neuchâtel (June 23-26 2014)
www.pptimeeting.org (on subscription)
www.ieee-uffc.org/main/publications/fcs/index.asp (on subscription)

European Time and Frequency Seminar (EFTS) – July 2014 in Besançon (F)
NIST Time & Frequency Seminar – June 2014 in Boulder (CO, USA)
CUSO doctoral school on atomic clocks (2010, 2012 & 2014)
The metamorphosis of time measurement

Marine chronometers

Space atomic clocks

Earth rotation

10 ps

100 ps

1 ns

10 ns

1 μs

1 ms

1 s

10 s

1000 s

-3000 -1500 -170 800 1300 1600 1700 1900 2000

Tower clocks (1300) verge-and-foliot mechanism

Marine chronometers (1750), Harrison

Huygens Pendulum (1650) pendulum

Quartz oscillators (1930)

Atomic clocks (1950)

Hydrogen Maser, Caesium beam, Rubidium clock

Precision / Stability in seconds per day

1 ns

100 ps

10 ns

1 μs

1 ms

1 s

10 s

1000 s
THANK YOU FOR YOUR ATTENTION!

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