**Time, Frequency and atomic clocks**

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**Outline**

1) Introduction on oscillators and atomic clocks  
2) Vapor-cell atomic clocks (Rubidium)  
3) Atomic beam standards (Cesium and laser cooling)  
4) Hydrogen Masers  
5) Optical frequency synthesizers and clocks (combs)  
6) Summary

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**“Clock = Oscillator + Counter”**

- **“Oscillator”**  
  Based on a periodical event, supposedly “regular” and having a period $T$ (earth, pendulum, spring, quartz, etc.)  
  Frequency $f = 1 / T$  

- **“Counter”**  
  Able to count the oscillations and display the result in some manner (escapement, gear, dial, hands, etc.)

**“Reference”:**  
Sometimes used to stabilize the oscillator and/or the clock

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1) What is a clock?

- **“Oscillator”**  
  Black box having an input (power supply) and an “ideal” output: for instance an absolutely pure (accurate and stable) sinus with amplitude $A$ and frequency $\nu_0$  
  $A\cos(2\pi\nu t)$

- **“Counter”**  
  Able to count the oscillations and display the result in some manner (escapement, gear, dial, hands, etc.)

**Reference**:  
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**Ideal and real oscillators**

- **Ideal “oscillator”** (or frequency standard)  
  Black box having an input (power supply) and an “ideal” output: for instance an absolutely pure (accurate and stable) sinus with amplitude $A$ and frequency $\nu_0$  
  $A\cos(2\pi\nu t)$

- **Real “oscillator”**  
  The amplitude and the frequency of the output fluctuate. These instabilities are observed and described by various techniques in the “time domain” and in the “frequency domain”.  
  $A(2\pi\nu t)$

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Annual meeting of the Swiss Physical Society, UNI-Geneva, 27 March 2008
G. Mileti, Laboratoire Temps – Fréquence, Time, Frequency and Atomic Clocks

Oscillator model

\[
\text{Signal}(t) = Re\left(\frac{\gamma(t)}{2} e^{i\Phi(t)}\right)
\]

where \( \gamma(t) = \phi(t) + j \cdot q(t) = (1 + e(t)) e^{i\Phi(t)} \)

Time error: \( \frac{\Phi(t)}{2\pi} \)

\[
\text{Normalized frequency error: } \frac{\gamma(t)}{\Phi(t)} = \frac{1}{2\pi} \frac{\delta\Phi(t)}{\Phi(t)} = \frac{\delta\gamma}{\gamma} = 10^{-4} - 10^{-6}
\]

Measured frequency: \( v(t) = v_0 + \delta v(t) \)

\( \delta v(t) \): deterministic + random fluctuations

In general \( \frac{1}{\tau} \int_0^\tau \delta v(t) dt \) diverges

Allan deviation (\( \tau \)) and noise processes (\( f \))

\( \sigma_f(\tau) \)

tells us how our oscillator 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

Stabilized oscillators

Example 1 of a stabilized oscillator:
pendulum periodically stabilized after earth rotation observation

Example 2 of a stabilized oscillator:
wrist-watch periodically stabilized after comparison to a more stable / accurate clock (tower clock)

Examples 3 of a stabilized oscillator:
quartz oscillator locked to a GNSS signal (GPS, GLONASS, GALILEO ...)

Atomic clock (stabilized quartz)

Reference for the user (5 MHz)

Quartz oscillator

Feed-back

Atoms

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)

Frequency \( v_0 = \frac{E_e - E_i}{h} = 9192631770 \text{ Hz} \)

This would be the frequency of an atomic clock in which the atomic transition is not perturbed and the stabilization "perfect"

Atomic time (TAI) and astronomical time (UTC)

UTC-6

Leap second

Leap second
Magnetic resonance allows spin flip.

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.

Resonance line-width, line Q, signal-to-noise ratio and frequency stability

\[ \Delta \omega_0 \propto \frac{1}{\tau} \]

\[ Q = \frac{\omega_0}{\Delta \omega_0} \]

\[ \sigma_i = \frac{0.2}{Q(S/N)^{1/2}} \]

Optical pumping (in Rb clocks)

Lamp Rb\(^{87}\)

Filter Rb\(^{85}\)

Cell Rb\(^{87}\)

Why Rb? Isotopic filtering

Excitation of a Rb lamp with an RF oscillator (~120 MHz).

Isotopic filtering with a \(^{85}\)Rb cell.
Microwave / optical double resonance

Swiss (Neuchâtel) Rubidium clocks

Worldwide space clocks (navigation)

Other applications of Rb clocks

New Rb clocks: laser optical pumping

Coherent Population Trapping (CPT)

Potential advantages of using CPT:
- No microwave cavity
- Reduced light-shift

Potential advantages:
- More efficient pumping
- Improved S/N
- Long term stability
- Power / Weight / Volume
- Redundancy

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Coherent Population Trapping (CPT)
Chip-scale (vapor cell) atomic clocks

Examples of (US) prototypes

Activities in UNINE

Miniature alkali vapour cells

Potential applications:
- Chip-scale frequency references
- Chip-scale atomic clocks (microwave and optical)
- Chip-scale atomic magnetometers
- Chip-scale gyroscopes

In the future:
- Atom chips
- Quantum computing
- Quantum communication

3) Atomic beam frequency standards

Potential applications:

Destruction of fringes contrast due to atomic velocity distribution
Laser-pumped beam standards

Extended-cavity and other diode lasers

Laser trapping and cooling

Application of laser cooling: atomic fountains

Pulsed fountain

Continuous fountain (Swiss primary standard)
**Fundamental physics in space**

**Why in space?**
- Long free fall conditions, long interaction times
- Large potential differences, large velocity changes, availability of long distances
- Absence of atmosphere, low noise / vibration environment

**What fundamental physics?**
- Probe the foundations of general relativity (equivalence principle, Lorentz invariances, universality of a free fall and gravitational redshift, constancy of gravitational and fine-structure constants, etc.) -- new physics!
- Key instruments (payload)
  - Atomic clocks (H-Masers, fountains, ion clocks, resonators) and gyroscopes
  - High stability lasers (ex: LISA), optical combs and optical synthesizers
  - Cold atoms, Bose-Einstein Condensates BEC (ex: HYPER)

For more details see: H. Dittus et al., “Lasers, clocks and drag-free control”, Springer.

**ACES mission scientific goals**

**Cold atom clock in microgravity:**
- Linewidth ≤ 100 mHz
- Frequency stability ≤ 10^{-13} ω^{1/2} and <3·10^{-14} / day
- Ultimate stability and accuracy in space: ~ 10^{-14}

**Ultra-stable time-scale comparison on a worldwide basis:**
- 30 ps accuracy and clock synchronisation @ 10^{-16} level
- Contribution to TAI
- Test General Relativity:
  - Red shift (improve sensitivity by a factor of 25, target: 2·10^{-6})
  - Search for a drift of the fine structure constant α: 10^{-16} / year (x 20 or more)
  - Search for an anisotropy of the speed of light (10 times more sensitivity)


**Active space Hydrogen Maser**

ACES Maser prototype (Neuchâtel)

Sapphire bulb to reduce the dimensions of the cavity

**Passive space Hydrogen Maser**

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, 7·10^{-13} @ 1 s
**GALILEO**

In space: Rubidium, passive Hydrogen Maser (1st generation)
On earth: (quartz), Rubidium, Cesium beams, H Masers (1st generation)


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**VLBI (Very Long Base Interferometry)**

H-Masers (10^{-19} \to 1000-10,000 s) are used to increase the resolution

Angular resolution: \( \sim \lambda / \text{Diameter} \)

1 radio-telescope: \( \sim 1 \text{ mrad} \) (10^{-9} rad)

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

Earth rotation: 1 mrad \( \sim 6 \text{ km} \to 14 \text{ s} \)

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**RADIOASTRON Mission (Space VLBI)**

Increase the Baseline B from 30'000 to 300'000 km, by putting one of the telescope (and one Maser!) in space.

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**4) Optical frequency synthesizers and clocks**

5) Optical frequency synthesizers and clocks

\[ \Delta \omega = Q \rightarrow \text{Laser cooling to increase } \Delta \omega \rightarrow \text{Cold atoms clock} \]

\[ \Delta \omega = Q \rightarrow \text{Optical clock } (\nu_0: 10^{10} \to 10^{15} \text{ Hz}) \]

Problem: link the 10 MHz oscillator (user) and the 10^{14} Hz reference frequency

Solution: use an optical comb (for the optical frequency synthesis)

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**Optical clocks**

Basic components
Optical comb (to make the link between \( \nu_0 \) and the user frequency)
Narrow and stable atomic, molecular or ion reference (typically 1 Hz)
Ultra stable laser to probe the transition \( \nu_0 \) (Local Oscillator): \( \Delta \nu < 1 \text{ Hz} \)

Possible approaches (reference)
Trapped ions Cold atoms

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6) 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;

$$\text{(in)stability} = \frac{\Delta \omega}{\omega_0} = \frac{1}{\tau_0 - \tau}$$

- 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.)