First results of a high performance optically-pumped cesium beam clock

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Outline

• Motivation and applications
• Clock sub-systems development
• Clock integration results
• Conclusion and acknowledgment
Identified markets

- **Telecommunication** network reference
  - Telecom operators, railways, utilities, ...

- **Science**
  - Astronomy, nuclear and quantum physics, ...

- **Metrology**
  - Time scale, fund. units measurement

- **Professional mobile radio**
  - Emergency, fire, police

- **Defense**
  - Secured telecom, inertial navigation

- **Space** (on-board and ground segments)
  - Satellite mission tracking, GNSS systems
Available Cs clock commercial products

• **Long life magnetic** Cs clock
  • Stability : $2.7 \times 10^{-11} \tau^{-1/2}$, floor = $5 \times 10^{-14}$
  • Lifetime : 10 years
  • Availability : commercial product

• **High performance magnetic** Cs clock
  • Stability : $8.5 \times 10^{-12} \tau^{-1/2}$, floor = $5 \times 10^{-15}$
  • Lifetime : 5 years
  • Availability : commercial product

• **High performance and long life optical** Cs clock
  • Stability : $3.0 \times 10^{-12} \tau^{-1/2}$, floor = $5 \times 10^{-15}$
  • Lifetime : 10 years
  • Availability : under development
Motivation for an Optical Cs clock

• **Improved performance (short and long-term stability)** for:
  • Metrology and time scales
  • Science (long-term stability of fundamental constants)
  • Inertial navigation (sub-marine, GNSS)
  • Telecom (ePRTC = enhanced Primary Reference Time Clock)

• **No compromise between lifetime and performance**
  • Low temperature operation of the Cs oven
  • Standard vacuum pumping capacity
  • Large increase of the Cs beam flux by laser optical pumping
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Optical Cesium clock operation

- Cs beam generated in the Cs oven (vacuum operation)
- Cs atoms state selection by laser
- Cs clock frequency probing (9.192 GHz) in the Ramsey cavity
- Atoms detection and amplification by photodetector (air)
- Laser and RF sources servo loops using atomic signals
Optical pumping: principle of operation

- Stable ground states (F=3 and F=4)

- Switching between ground states F by RF interaction 9.192 GHz

- Unstable excited states (F’=2,3,4,5)

- Switching between ground states F and excited states F’ by laser interaction 852 nm (optical domain)

133Cs atomic energy levels

\[
v_{hf} = 9.192 \text{ GHz}
\]
Cesium clock: Magnetic vs. Optical

- **Weak flux**
  - Strong **velocity selection** (bent)
  - Magnetic deflection (atoms kicked off)
- **Typical performances:**
  - $2.7 \times 10^{-11} \tau^{-1/2}$
  - 10 years
- **Stringent** alignment (bent beam)
- **Critical component** under vacuum (electron multiplier)

- **High flux (x100)**
  - **No velocity selection** (straight)
  - Optical pumping (atoms reused)
- **Typical performances:**
  - $2.7 \times 10^{-12} \tau^{-1/2}$
  - 10 years
- **Relaxed** alignment (straight beam)
- **Critical component** outside vacuum (laser)
Clock functional bloc diagram

- **Cs tube**
  - Generate **Cs atomic beam** in ultra high vacuum enclosure

- **Optics**
  - Generate **2 optical beams** from 1 **single frequency laser**

- **Electronics**
  - **Cs core electronics** for driving the Optics and the Cs tube
  - **External modules** for power supplies, management, signals I/O

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**Optics**
- Laser
- Splitter
- Mirror
- **Cs tube**
- Magnetic field and shields
- Cs Oven
- Collect
- Ramsey cavity
- Collect

**Clock electronics**
- Photo Detect
- RF Source
- Photo Detect
- Clock Ctrl
- Power Supply
- **Expansion electronics**
- Manage
- PPS
- Metrology
- DC/DC
- AC/DC
- Battery
- **Expansion electronics**
- Remote (TCP/IP)
- Serial (RS232)
- Display
- 4xSync.out (1PPS)
- 10MHz sine
- 10 or 50MHz sine (option)
- External DC supply
- External AC supply

**Metrology**
- Manage
- PPS
- Metrology
- DC/DC
- AC/DC
- Battery
- **Metrology**
- Remote (TCP/IP)
- Serial (RS232)
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Clock architecture (top view)

- **Cs core** is not customizable
- **External modules** are customizable:
  - Power supplies
  - Signal outputs
  - Management
Cs tube sub-assembly
Optics sub-assembly

- Optical sub-system
  - Free space propagation
  - Single optical frequency (no acousto-optic modulator)
  - Redundant laser modules (2)
  - No optical isolator
  - Ambient light protection by cover and sealing (not shown here)

- Laser module
  - DFB 852 nm, TO3 package
  - Narrow linewidth (<1MHz)
Physics Package

- Laser modules
- Optics
- Cs tube
- Photo-detectors modules
Complete Cs clock

- Front view
  - LCD touchscreen
- Top view
  - Optics + Cs tube in front
  - Core electronics
- Rear view
  - **Power supplies** (AC, DC, Battery)
  - **Sinus Outputs** (5, 10, 100 MHz)
  - **Sync 1PPS** (1x In, 4x Out)
  - **Management** (RS 232, Ethernet, Alarms)
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Laser frequency synchronous detector

- **Green curve:**
laser current (ramp + AM modulation)

- **Blue curve:**
modulated atomic fluorescence zone A (before Ramsey cavity)

- **Pink curve:**
demodulated atomic fluorescence in zone A

- Phase optimization for synchronous detector (max signal, positive slope on peak)
Laser frequency lock

- Automatic laser lock
  - Atomic line identification by correlation in micro-controller
  - Laser optical frequency centering (center of laser current ramp)
  - At mid height of next ramp, automatic closing of frequency lock loop

- Optimization of laser lock loop
  - Tuning parameters: amplitude of modulation, PID parameters
  - Criterion: min PSD of laser current
  - Reliability of laser lock
Ramsey fringes (Preliminary)

- **Dark fringe** behavior (minimum at resonance)
- **Central fringe**
  - Amplitude = 200 pA
  - Linewidth = 800 Hz (FWHM)
  - Background = 600 pA
- **Noise PSD** $[1E-28*A^2/Hz]$
  - Photo-detector = 1.6
  - Background light = 1.9
  - Atomic shot noise = 0.5
  - Extra noise = 6.2
  - Total = 10.2
  - SNR = $6'090 \text{ Hz}^{1/2}$
Frequency stability (Preliminary)

- **Measured** frequency stability
  - $ADEV = 7.5 \times 10^{-12} \tau^{-1/2}$
  - Compared to H-maser

- **Calculated** frequency stability
  - $ADEV = 7.1 \times 10^{-12} \tau^{-1/2}$
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Conclusion and acknowledgment

• Development of an industrial Optical Cesium Clock for ground applications

• All sub-systems are functional (Cs tube, Optics, Electronics)

• Preliminary frequency stability measurement ADEV = 7.5E-12 recorded for long life operation (10 years target)

• Present performance limitations: laser lock quality (extra noise)

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Thank You