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Development of a high performance optical cesium beam clock for ground applications

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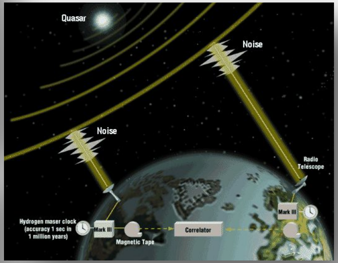
Outline

- 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



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Available Cs clock commercial products

- **Long life magnetic** Cs clock
  - Stability : **$2.7^{E}\text{-}11\ \tau^{-1/2}$, floor = $5^{E}\text{-}14$**
  - Lifetime : **10 years**
  - Availability : commercial product
- **High performance magnetic** Cs clock
  - Stability : **$8.5^{E}\text{-}12\ \tau^{-1/2}$, floor = $5^{E}\text{-}15$**
  - Lifetime : **5 years**
  - Availability : commercial product
- **High performance and long life optical** Cs clock
  - Stability : **$3.0^{E}\text{-}12\ \tau^{-1/2}$, floor = $5^{E}\text{-}15$**
  - 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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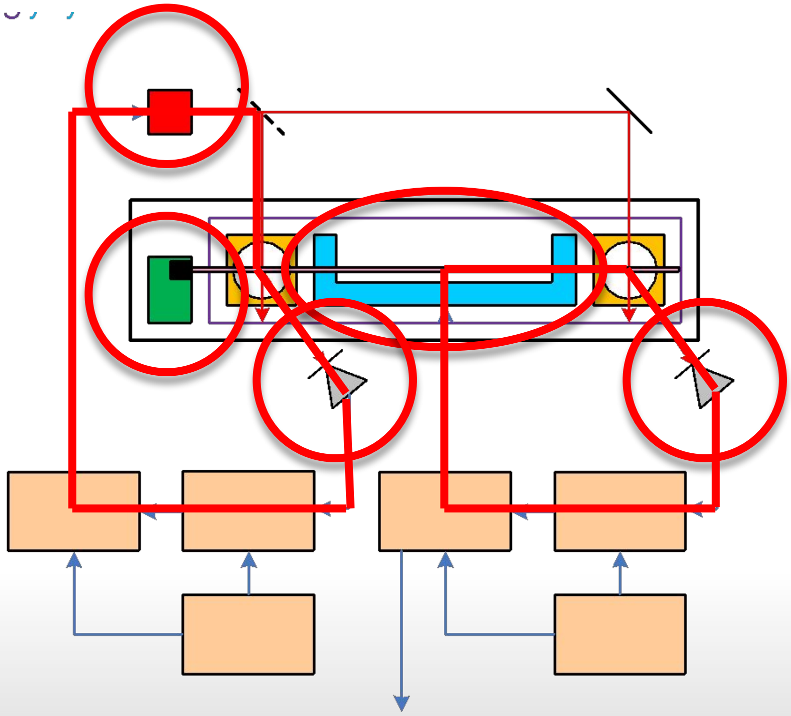
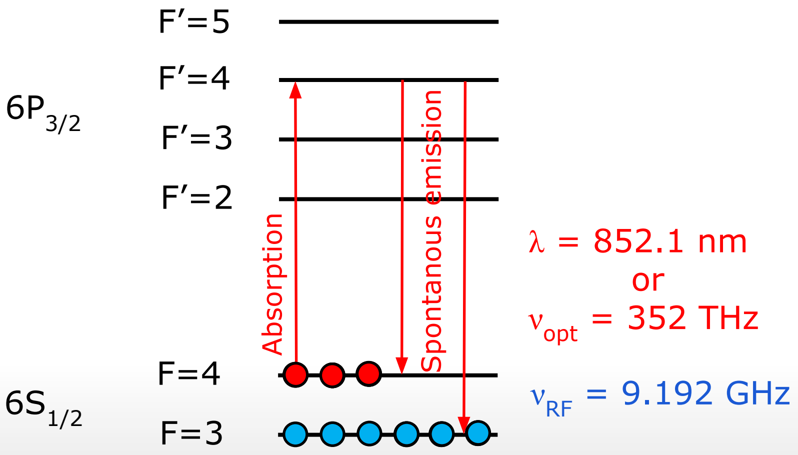
Optical Cesium clock architecture



- **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**

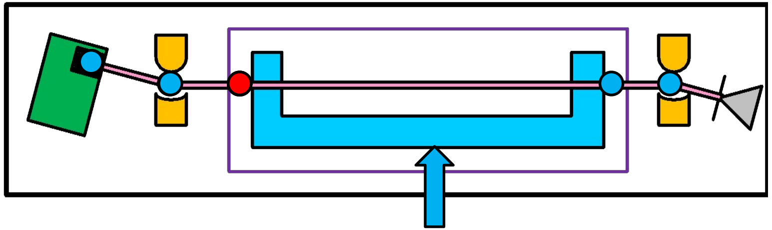
Optical Pumping vs Magnetic Selection

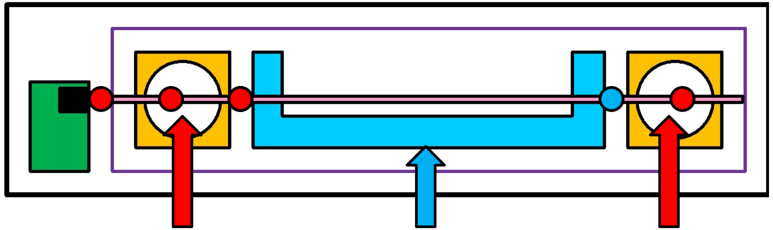
^{133}Cs atomic energy levels



- Atomic energy states
  - **Ground states** (F=3,4) equally populated
  - **Excited states** (F'=2,3,4,5) empty
- Switching between ground states F by **RF interaction 9.192 GHz** without atomic selection (no useful differential signal)
- Atomic preparation by **magnetic deflection** (loss of atoms)
- Atomic preparation by **optical pumping** with laser tuned to F=4 →F'=4 transition (gain of atoms)

Cesium clock: Magnetic vs. Optical





- Weak flux
  - Strong **velocity selection** (bent)
  - Magnetic deflection (**atoms kicked off**)
- Typical performances:
  - **2.7^{E}-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^{E}-12 $\tau^{-1/2}$**
  - 10 years
- **Relaxed** alignment (straight beam)
- Critical component **outside vacuum** (laser)

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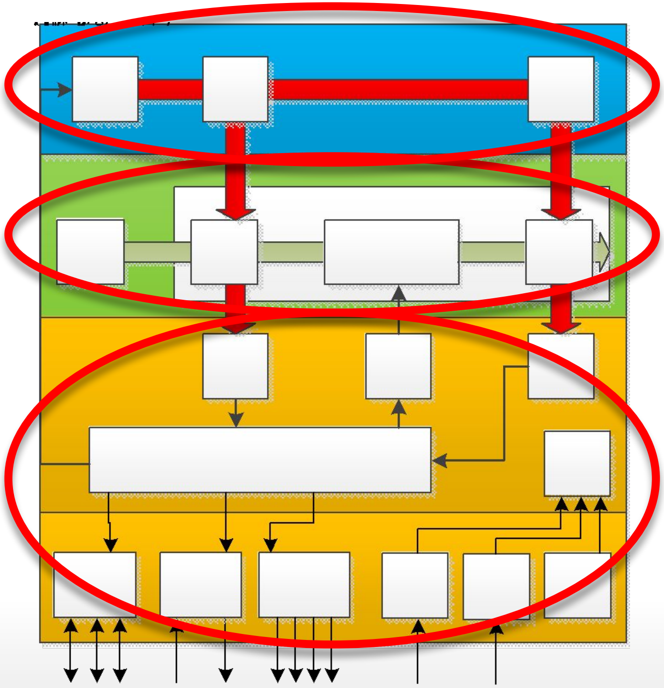
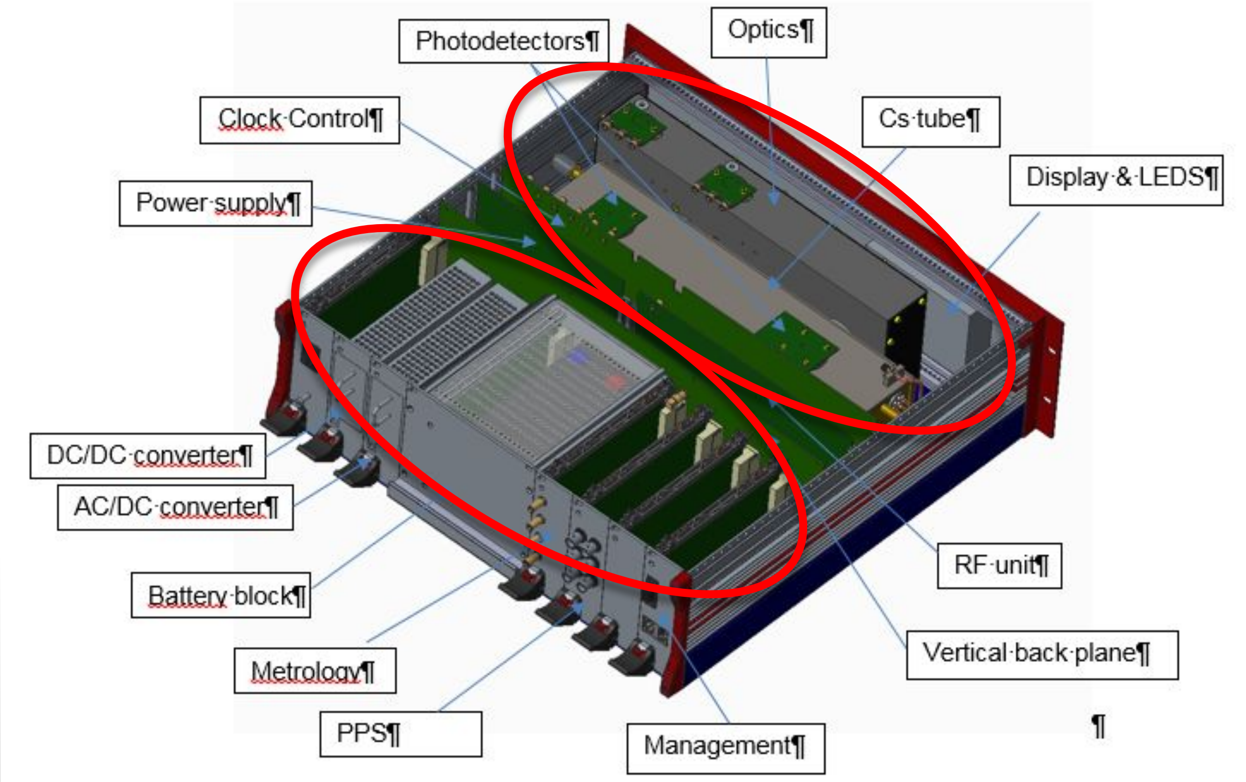
Clock functional bloc diagram



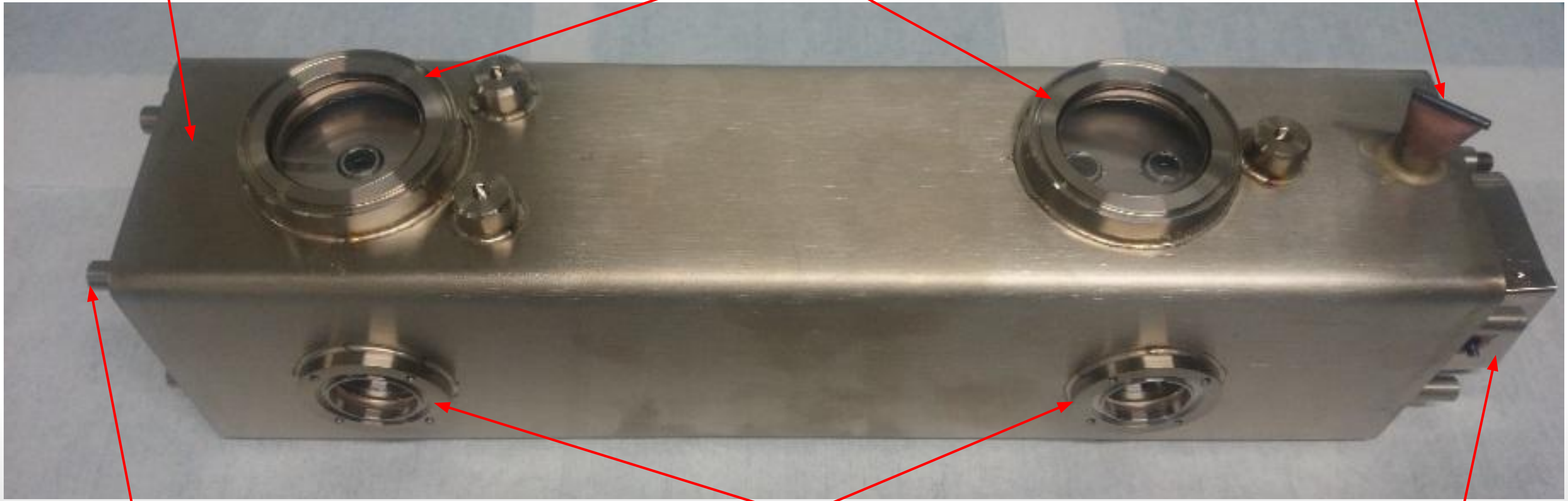
- Cs tube
  - Generate **Cs atomic beam** in ultra high vacuum enclosure
- Optics
  - Generate **2 optical beams** from 1 **single frequency laser** (no acousto-optic modulator)
- Electronics
  - **Cs core electronics** for driving the Optics and the Cs tube
  - **External modules** for power supplies, management, signals I/O

Clock architecture (top view)

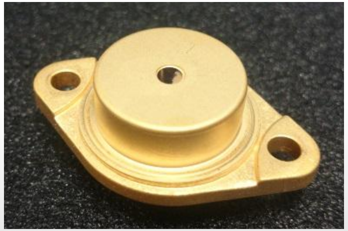


- **Cesium core** is not customizable
- **External modules** are customizable:
  - Power supplies
  - Signal outputs
  - Management

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 (redundant)

Optics

Cs tube

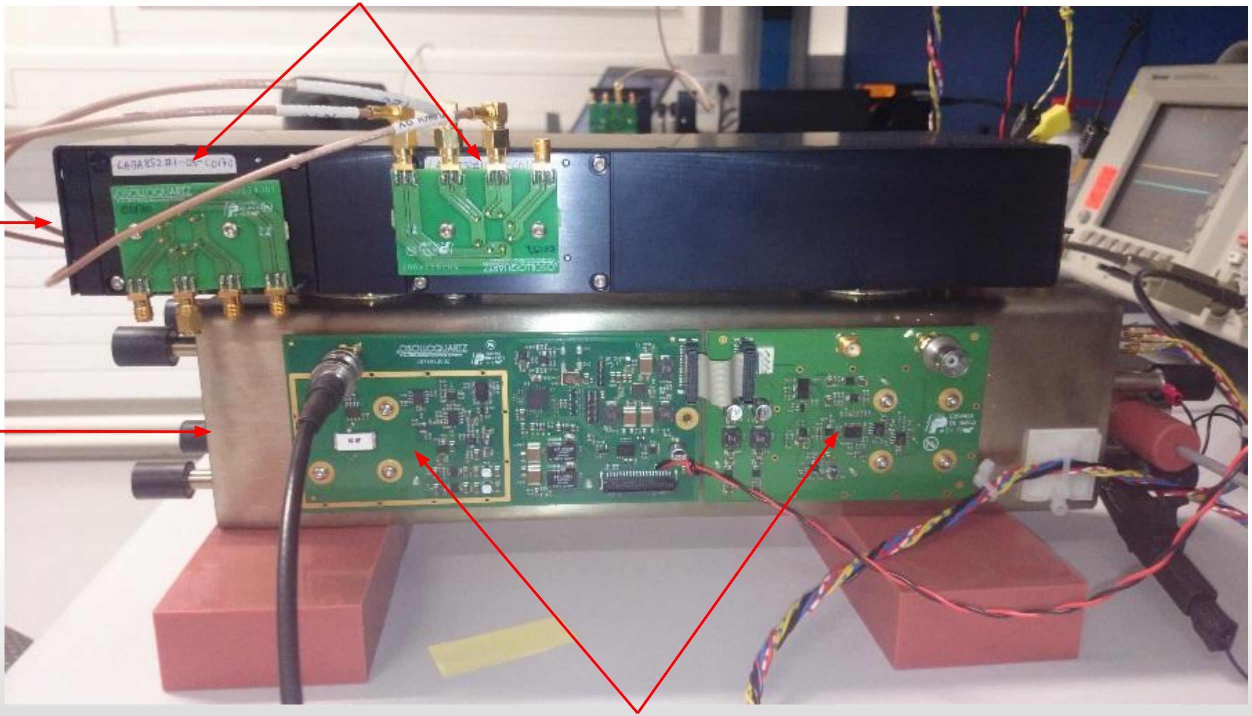


Photo-detectors modules

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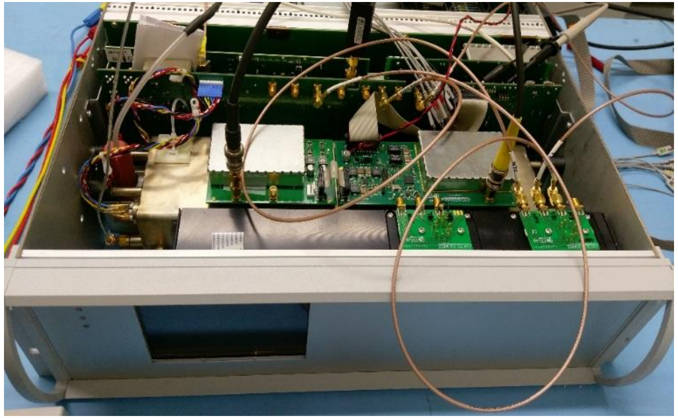
Complete Cs clock



- Front and top view
  - **LCD touchscreen**
  - 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)
- Dimensions: **standard 19” rack** (450 x 133 x 460 mm3)
- Mass:**17.5 kg**
- Power consumption: **35 W**

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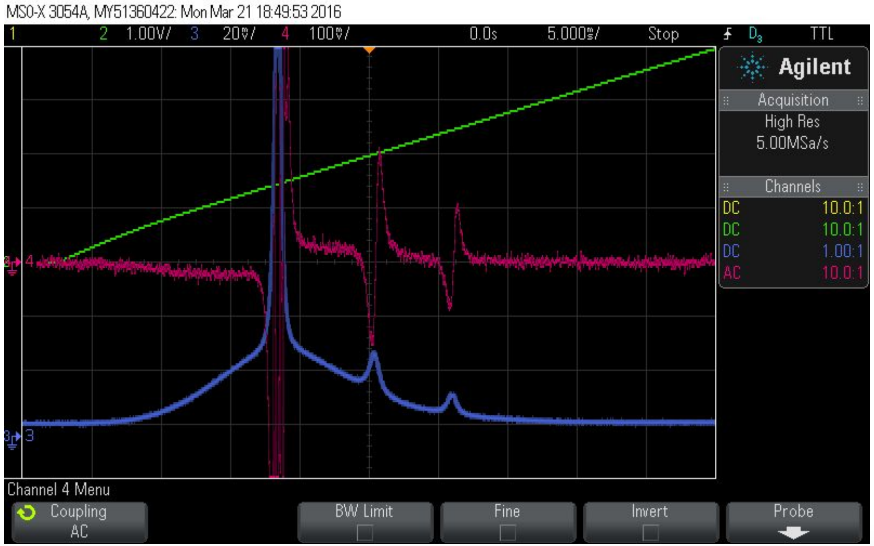
Laser frequency synchronous detector



- 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)

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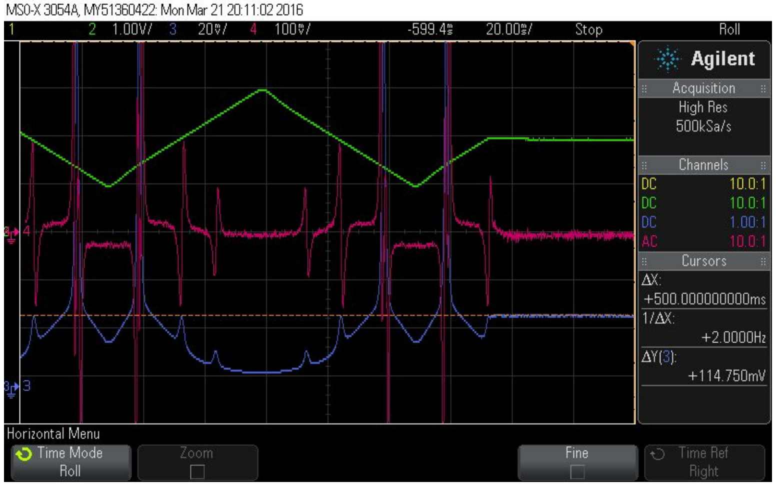
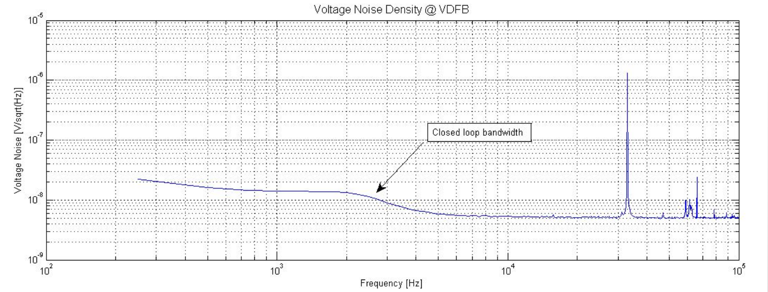
Laser frequency lock





- 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
  - **Criteria:**
    - min **PSD of laser current**
    - max **reliability** of laser lock

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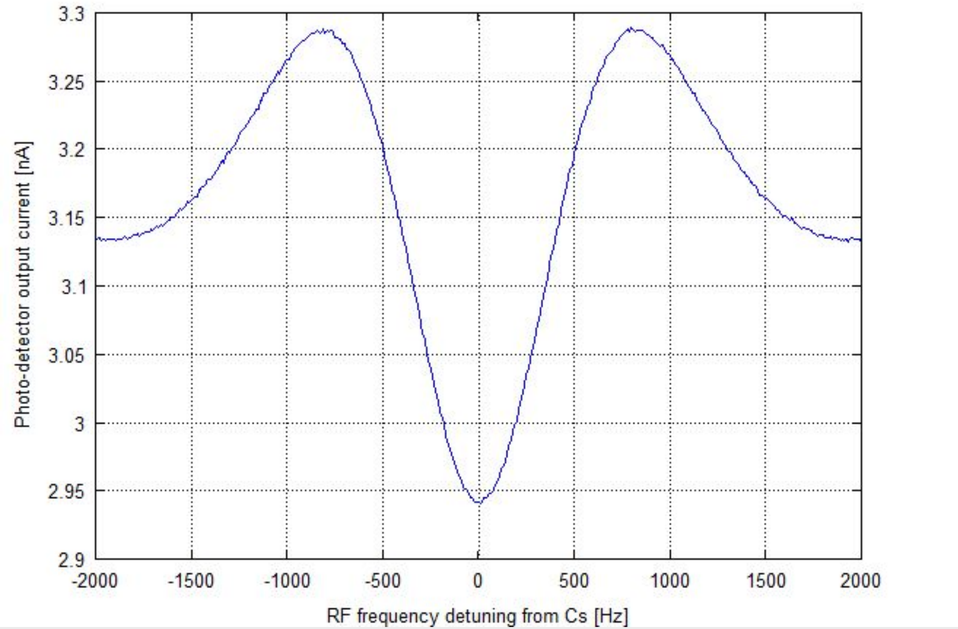
Ramsey fringes



Performance limiting factors

- **Dark fringe** behavior (minimum at resonance)
- **Central fringe**
  - Amplitude = **345 pA**
  - Linewidth = **730 Hz** (FWHM)
  - Background = **2940 pA**
- **Noise PSD** [1E-28*A²/Hz]
  - Photo-detector = 1.44
  - Background light = 9.42
  - Atomic shot noise = 0.53
  - Extra noise = 2.44
  - Total = 13.8
  - SNR= **9’250 Hz$^{1/2}$**

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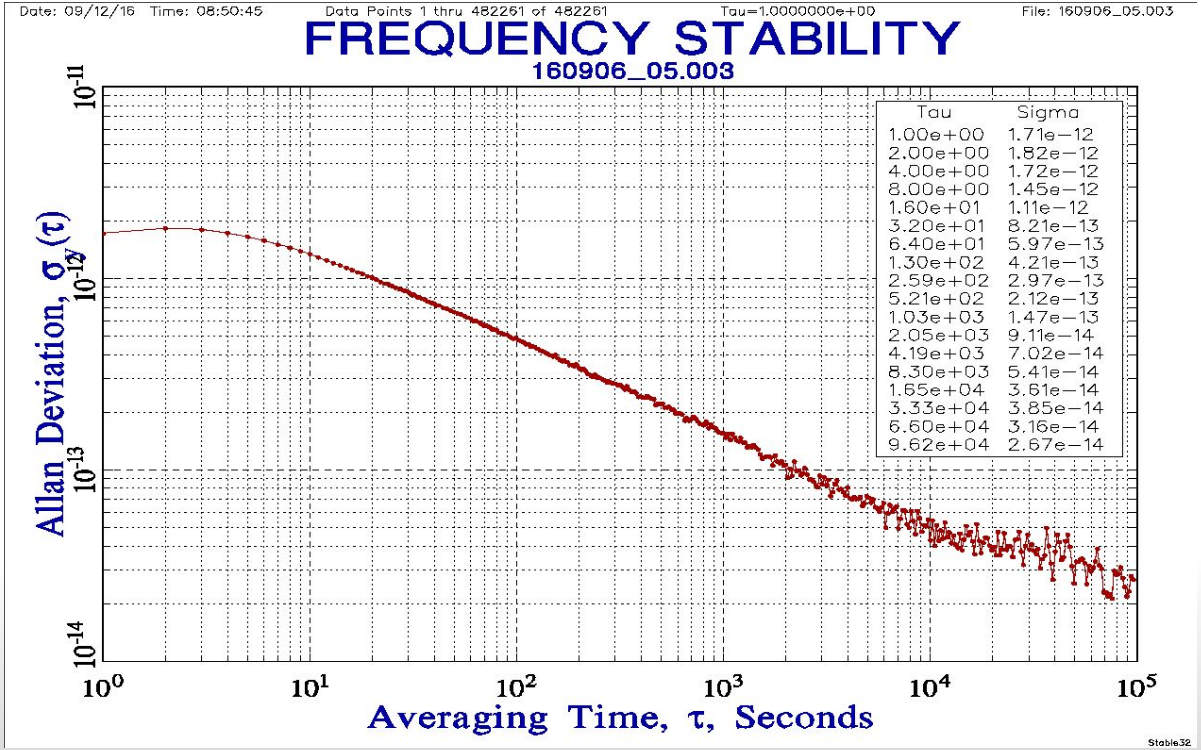
Frequency stability



Tau	Sigma
1.00e+00	1.71e−12
2.00e+00	1.82e−12
4.00e+00	1.72e−12
8.00e+00	1.45e−12
1.60e+01	1.11e−12
3.20e+01	8.21e−13
6.40e+01	5.97e−13
1.30e+02	4.21e−13
2.59e+02	2.97e−13
5.21e+02	2.12e−13
1.03e+03	1.47e−13
2.05e+03	9.11e−14
4.19e+03	7.02e−14
8.30e+03	5.41e−14
1.65e+04	3.61e−14
3.33e+04	3.85e−14
6.60e+04	3.16e−14
9.62e+04	2.67e−14

- **Measured**
  - ADEV = **4.8E-12** $\tau^{-1/2}$
  - Compared to active H-maser
- **Best prediction**
  - ADEV = **4.6E-12** $\tau^{-1/2}$
  - Using SYRTE model [REF1]
  - Very good agreement

[REF1] S. Guérandel at al, Proc. of the Joint Meeting EFTF & IEEE - IFCS, 2007, 1050-1055

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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)
- **1st prototype** frequency stability measurement ADEV = **4.8E-12** $\tau^{-1/2}$ recorded for **long life** operation (10 years target)
- Identified performance limitations (correction action **under progress**):
  - Too weak **atomic flux** in the Cs tube
  - Too high **background light**

- **Acknowledgment**: this work is being supported by the **European Space Agency**

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Thank You