OSCILLOQUARTZ
An ADVA Optical Networking Company

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

Berthoud Patrick, Chief Scientist Time & Frequency

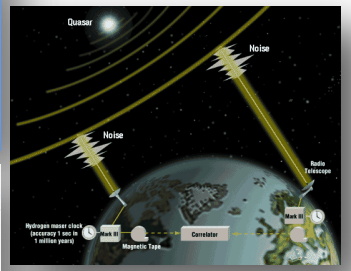
Workshop on Synchronization and Timing Systems, WSTS 2016, San Jose CA, USA, June 2016

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



OSCILLOQUARTZ
An ADVA Optical Networking Company

Available Cs clock commercial products

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

Motivation for an Optical Cs clock

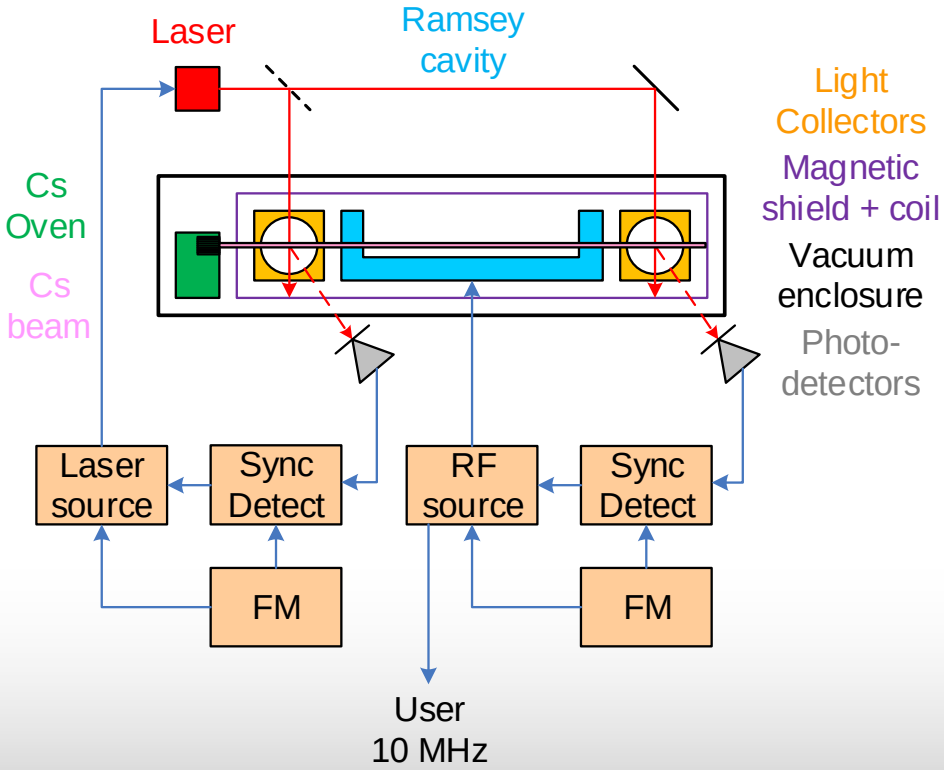
- **Improved performance (short and long-term stability)** for:
  - Metrology and time scales
  - Science (long-term stability of fundamental constants)
  - Inertial navigation (sub-marine, GNSS)
  - Telecom (ePRTC = enhanced Primary Reference Time Clock)

- **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

Outline

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

Optical Cesium clock operation

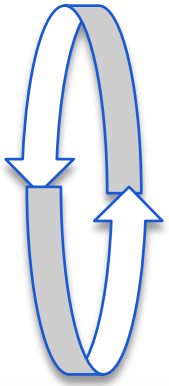


- **Cs beam** generated in the Cs oven (vacuum operation)
- Cs atoms state selection by **laser**
- Cs clock frequency probing (9.192 GHz) in the **Ramsey cavity**
- Atoms detection and amplification by **photodetector** (air)
- Laser and RF sources servo loops using **atomic signals**

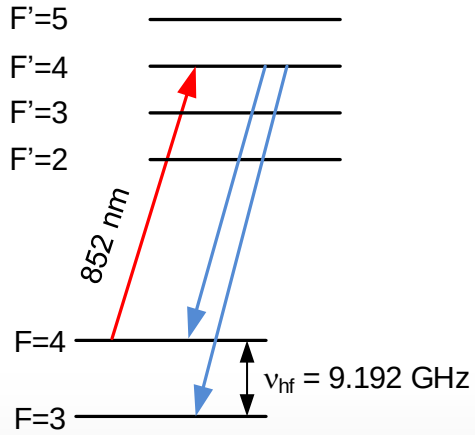
OSCILLOQUARTZ
An ADVA Optical Networking Company

Optical pumping: principle of operation

^{133}Cs atomic energy levels



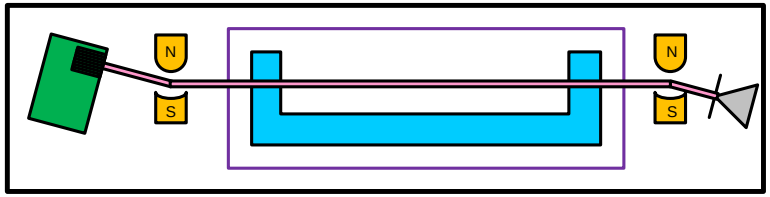
Optical pumping



- 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)

OSCILLOQUARTZ
An ADVA Optical Networking Company

Cesium clock: Magnetic vs. Optical



F=3,4

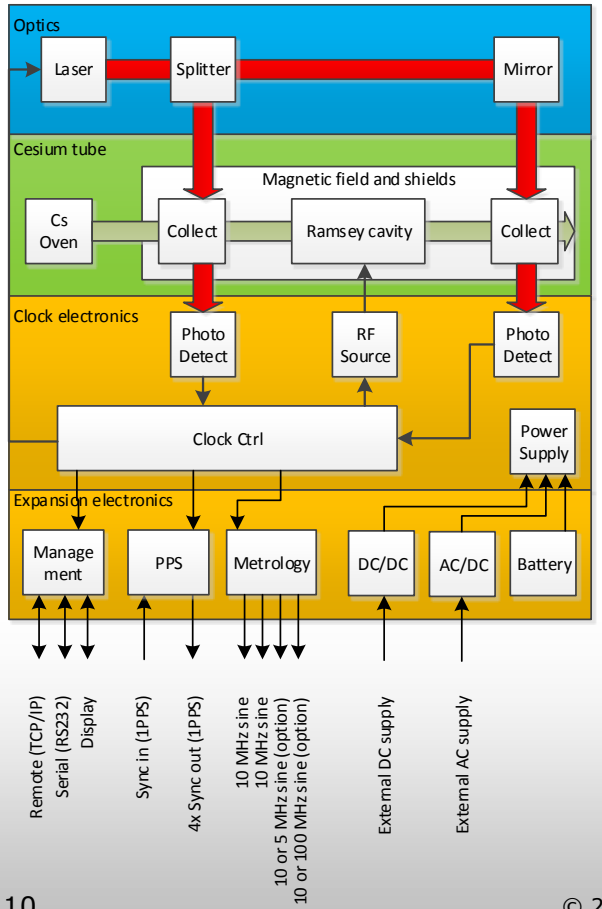
- Weak flux
  - Strong **velocity selection** (bent)
  - Magnetic deflection (**atoms kicked off**)
- Typical performances:
  - **2.7^{E}-11 $\tau^{-1/2}$**
  - 10 years
- **Stringent** alignment (bent beam)
- Critical component **under vacuum** (electron multiplier)

F=3,4

- 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)

OSCILLOQUARTZ
An ADVA Optical Networking Company

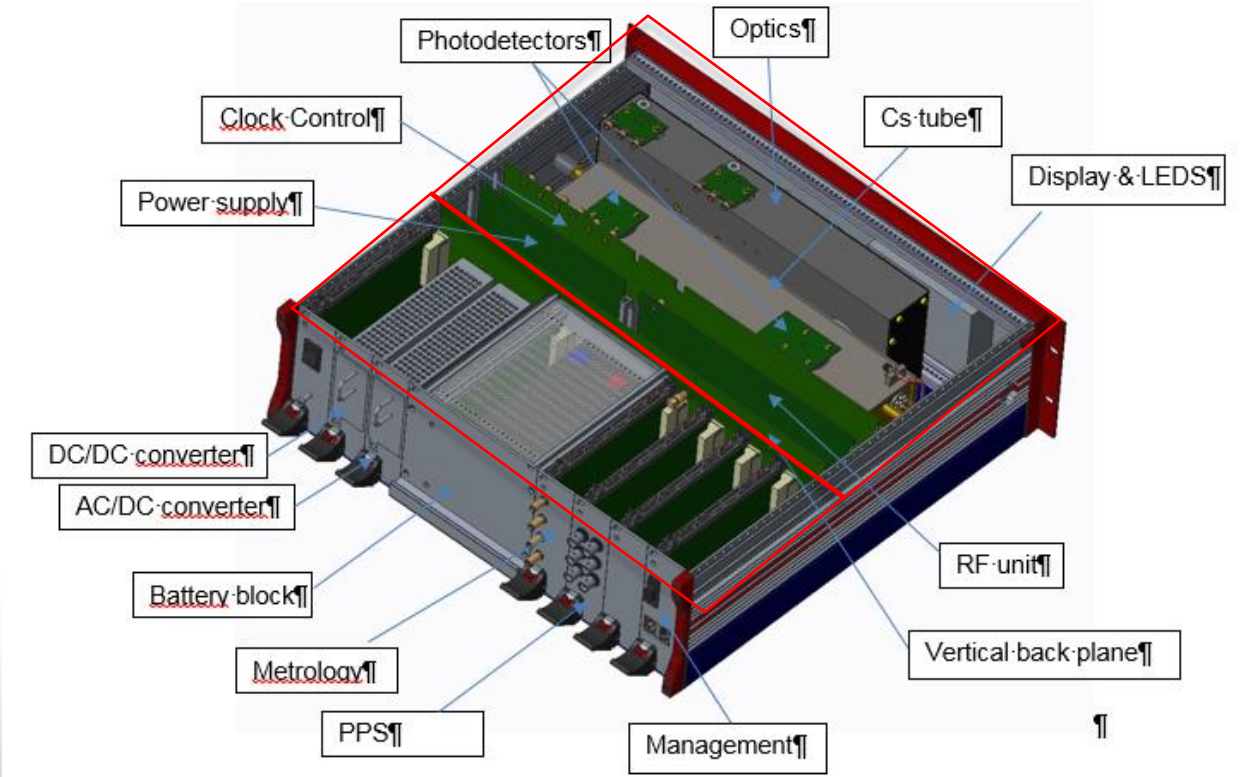
Clock functional bloc diagram



- 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

OSCILLOQUARTZ
An ADVA Optical Networking Company

Clock architecture (top view)



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

OSCILLOQUARTZ
An ADVA Optical Networking Company

Cs tube sub-assembly

OSCILLOQUARTZ
An ADVA Optical Networking Company

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

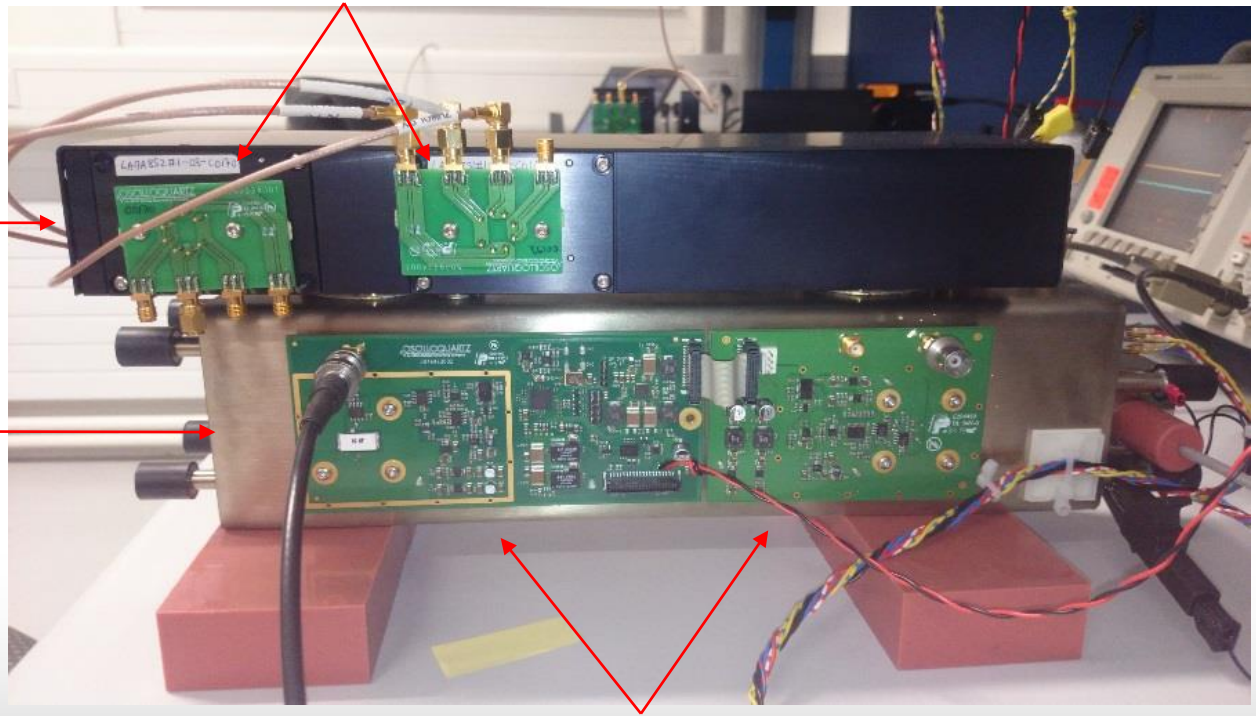
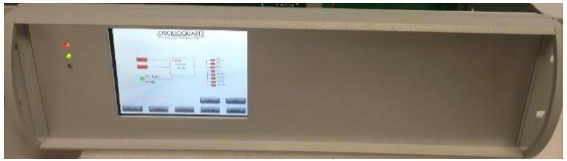
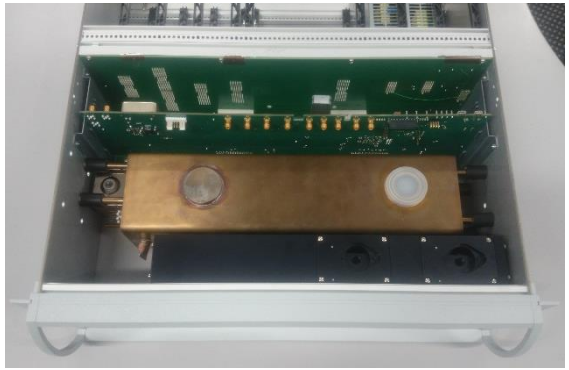


Photo-detectors modules

OSCILLOQUARTZ
An ADVA Optical Networking Company

Complete Cs clock



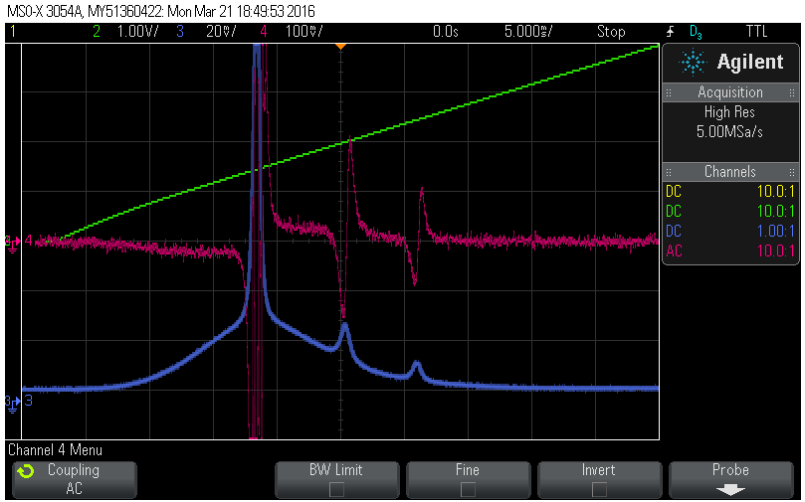


- Front view
  - **LCD touchscreen**
- Top view
  - Optics + Cs tube in front
  - Core electronics
- Rear view
  - **Power supplies** (AC, DC, Battery)
  - **Sinus Outputs** (5, 10, 100 MHz)
  - **Sync 1PPS** (1x In, 4x Out)
  - **Management** (RS 232, Ethernet, Alarms)

Outline

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

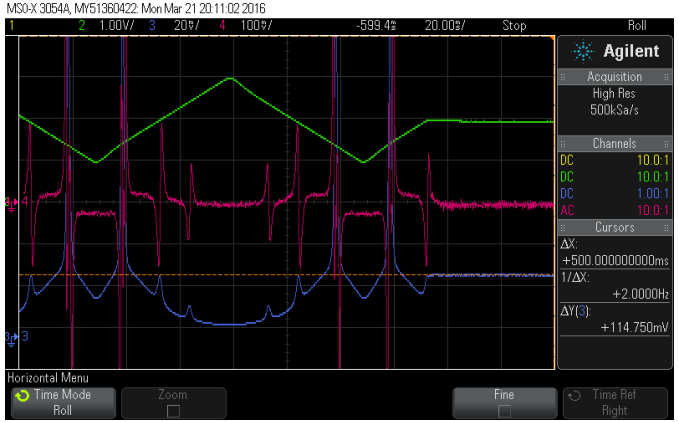
Laser frequency synchronous detector

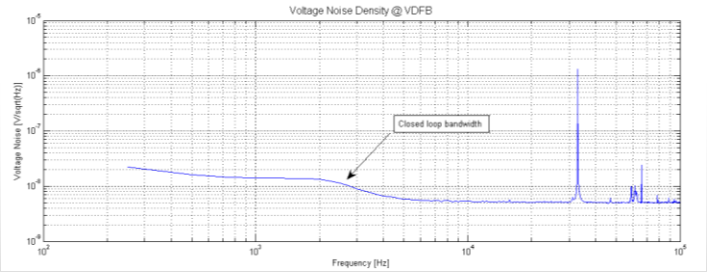


- Green curve:
  laser current (ramp + AM modulation)
- Blue curve:
  modulated atomic fluorescence zone A (before Ramsey cavity)
- Pink curve:
  demodulated atomic fluorescence in zone A
- Phase optimization for synchronous detector (max signal, positive slope on peak)

OSCILLOQUARTZ
An ADVA Optical Networking Company

Laser frequency lock

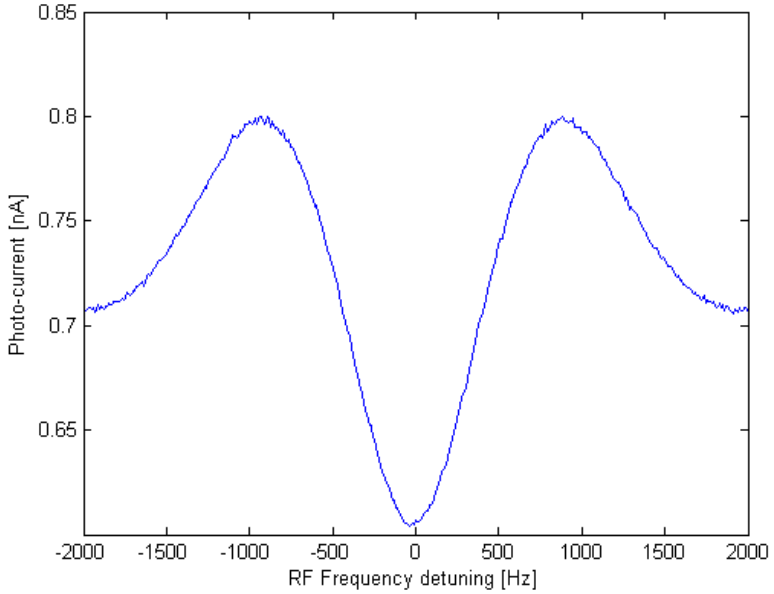




- Automatic laser lock
  - **Atomic line identification** by correlation in micro-controller
  - Laser **optical frequency centering** (center of laser current ramp)
  - At mid height of next ramp, **automatic closing** of frequency lock loop
- Optimization of laser lock loop
  - **Tuning parameters**: amplitude of modulation, PID parameters
  - Criterion: min **PSD of laser current**
  - **Reliability** of laser lock

OSCILLOQUARTZ
An ADVA Optical Networking Company

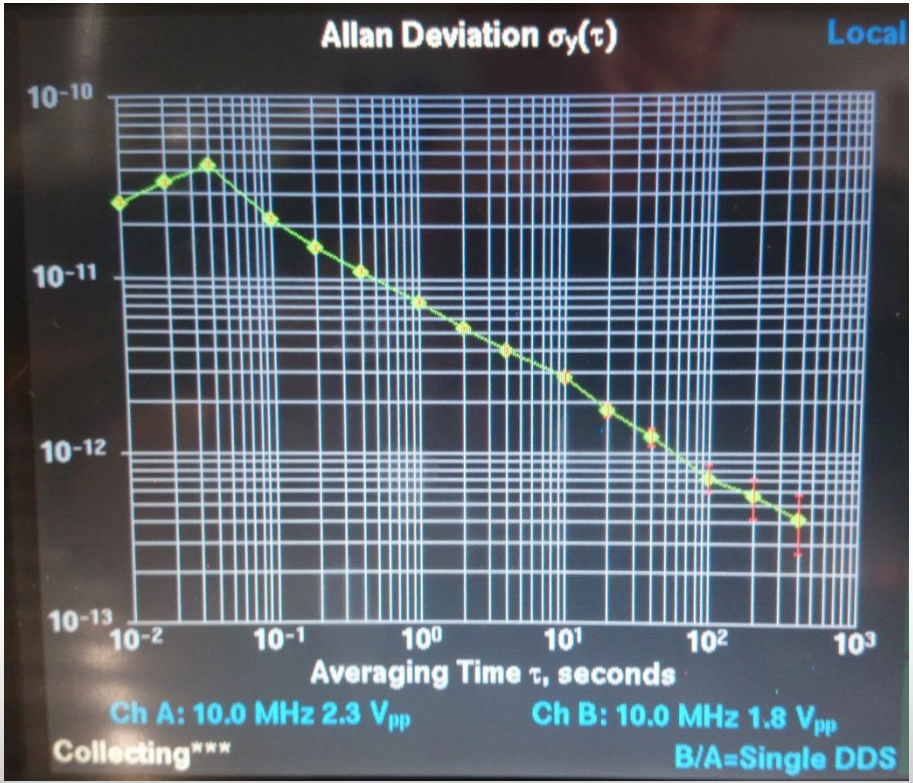
Ramsey fringes (Preliminary)



- **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 $Hz^{1/2}$**

OSCILLOQUARTZ
An ADVA Optical Networking Company

Frequency stability (Preliminary)



- **Measured** frequency stability
  - **ADEV = 7.5E-12 $\tau^{-1/2}$**
  - Compared to H-maser
- **Calculated** frequency stability
  - **ADEV = 7.1E-12 $\tau^{-1/2}$**
  - Using SYRTE model (S. Guérandel at al, Proc. of the Joint Meeting EFTF & IEEE - IFCS, 2007, 1050-1055)

OSCILLOQUARTZ
An ADVA Optical Networking Company

Outline

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

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)

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

OSCILLOQUARTZ
An ADVA Optical Networking Company

Thank You