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Engineering Model of Optical Space Cs Clock

R.Schmeissner, F.Favard, A.Douahi, P.Dufreche, N.Mestre, P.Perez, M.Baldy
Thales Electron Devices, France

F.Loiseau, A.Romer, C.Roth, F.Chastellain, W.W.Coppolse
OEI Opto AG (Thales), Switzerland

Support from
Thales Nokia III-V Lab, Thales Research & Technology,
Thales TCS, Thales Alenia Space, Thales Optronique SA

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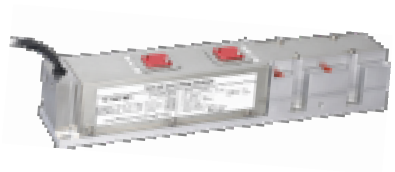
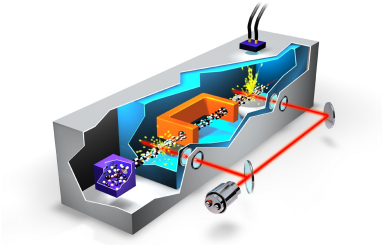
Introduction

Thales Electron Devices

- World leader in Travelling Wave Tubes (TWT)
  - Vacuum and RF-technologies
- Diversification on Cs-tubes for atomic clocks
  - ➢ Ground: Tube production line
  - ➢ Space: Clock System Development





- **Optical Space Cs Clock (OSCC)**
  - ➢ Galileo 2nd Generation > 2020

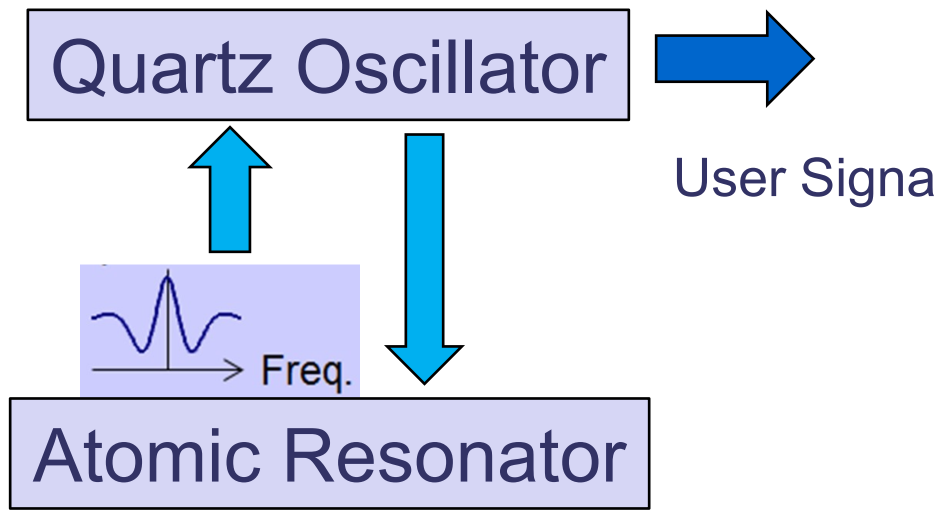
Atomic Clocks

Clock Properties

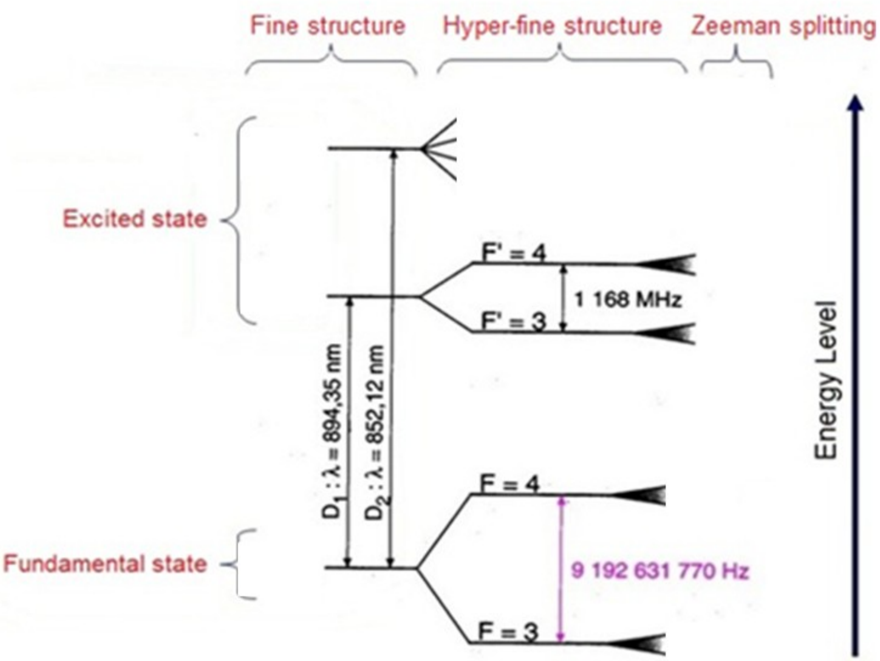
- Exactitude
- Stability
- User signal 10MHz, 1pps

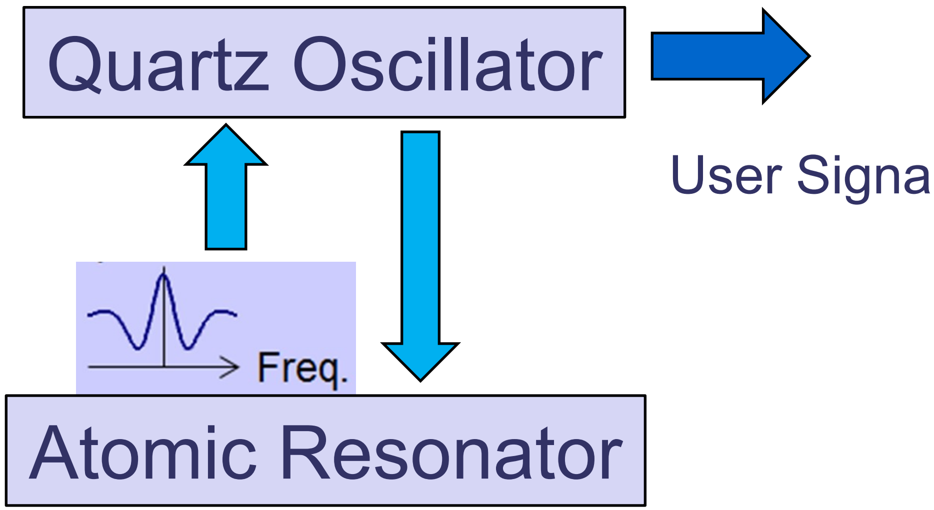
Physical Properties

- Quality factor Q
- Signal-to-Noise ratio



Atomic Clocks

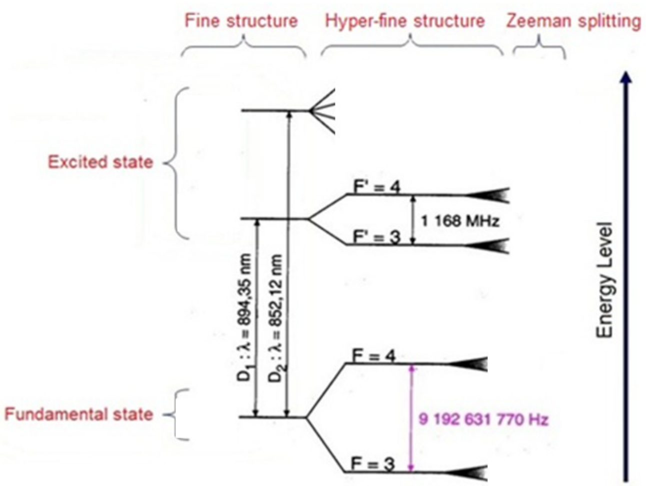


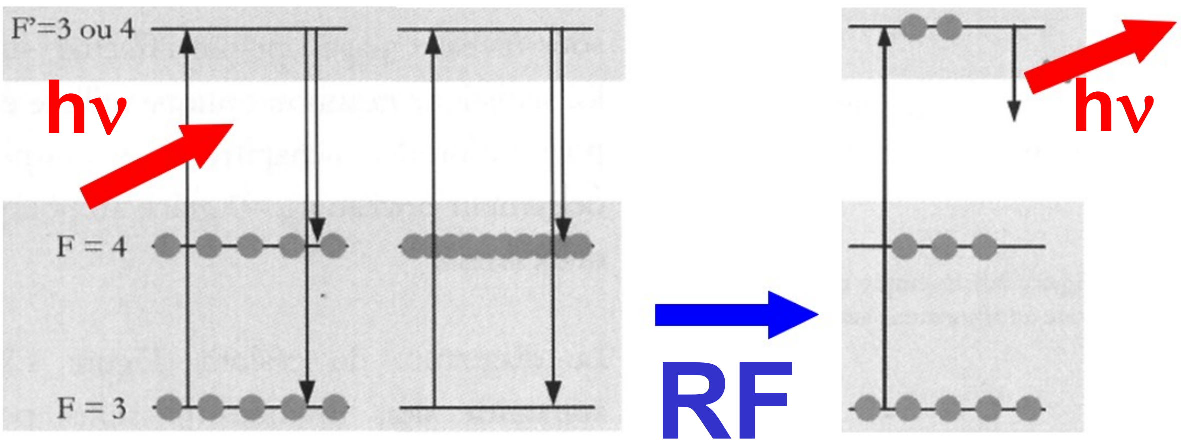


Cs Atom as Frequency Reference

- Ground State Hyperfine Splitting at 9.19 GHz
- Definition of the second

The Optically Pumped Cs Clock





Physical Principle

- Optical pumping of a hyperfine level of the Cs ground state
- Resonant atom interaction with 9.19GHz
- Optical detection of the hyperfine level via fluorescence

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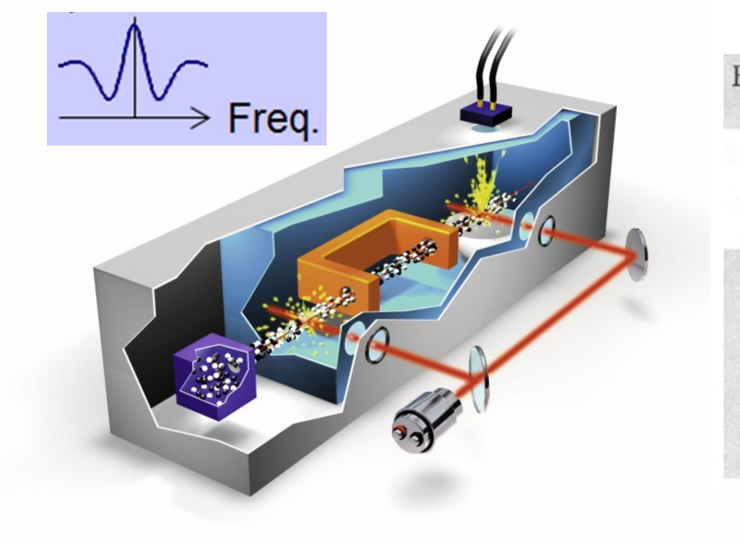

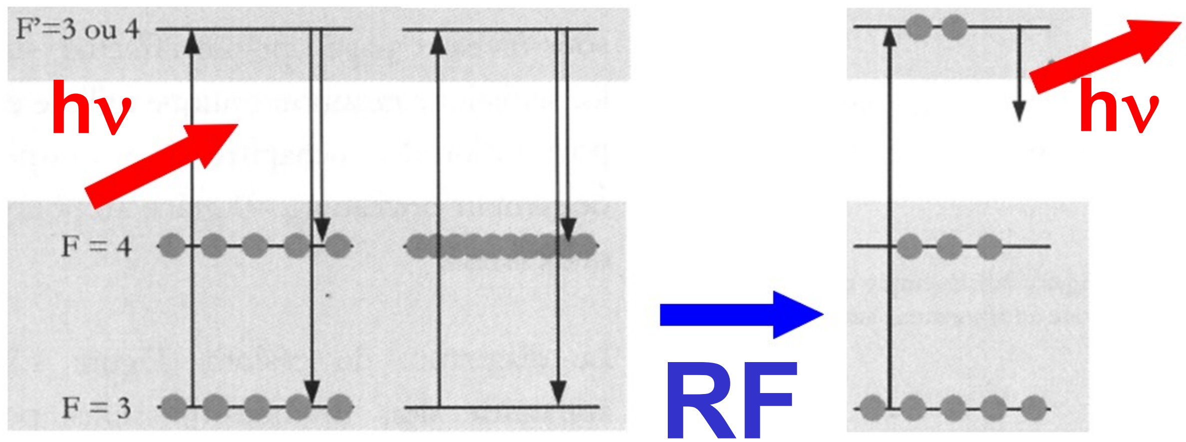

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OSCC Optical Space Cs Clock

- Possible Clock Technology for Galileo 2nd Generation, after 2020
- Engineering Model development 2015-2017
- ESA/CNES contract

Consortium

Prime contractor: Thales Electron Devices (TED)

OEI Opto AG (former RUAG, Thales by end of 2016)

- Swiss high technolgy company in space segment,
- strong heritage in domains of electronics and optics

Technical Support from

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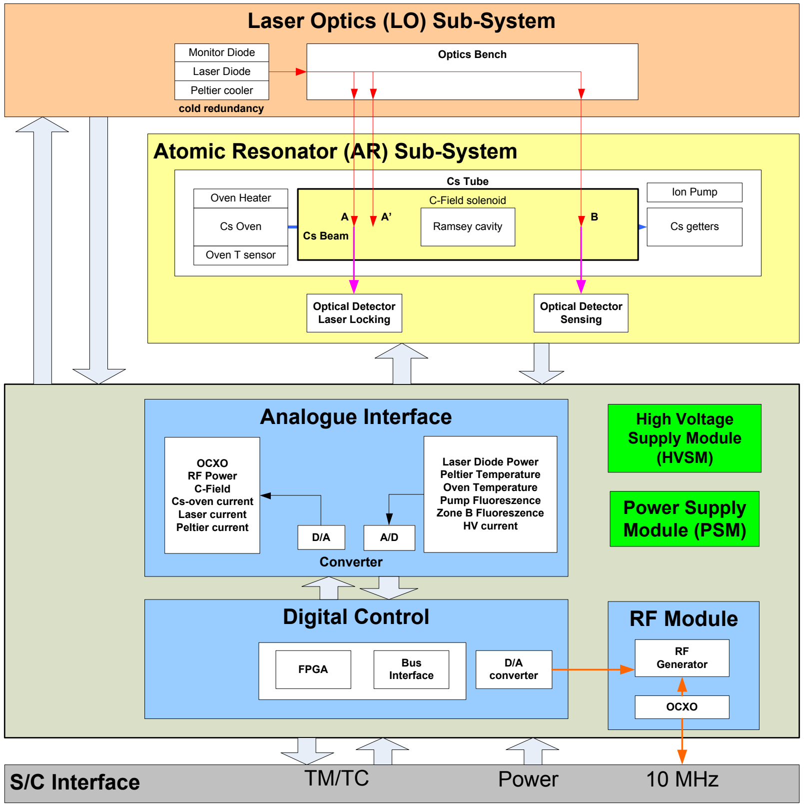
OSCC: Engineering Model



Functional Architecture

- Consolidated in previous phases

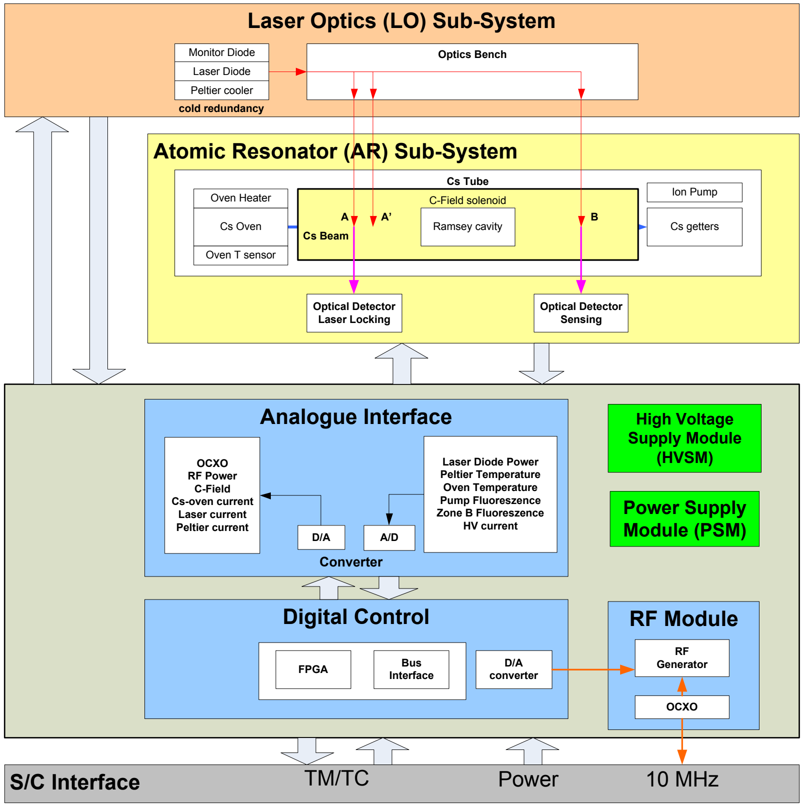
Three Sub-systems

- Atomic-Resonator Vacuum Tube (TED)
- Laser and Optics sub-system (TED)
- Electronics sub-system (OEI Opto)

Design Targets

- **Stability of 1E-12$\tau^{-1/2}$, 12 years lifetime in orbit**
- **12 liter volume, 10kg mass, 30W power consumption**

OSCC: Engineering Model



Functional Architecture

- ➢ Consolidated in previous phases

Electronic Architecture

Power consumption, Sensitivity & Noise

- ➢ Multiplexing approach
- ➢ Oversampling to reduce physical bit-number of ADC/DAC

Design Targets

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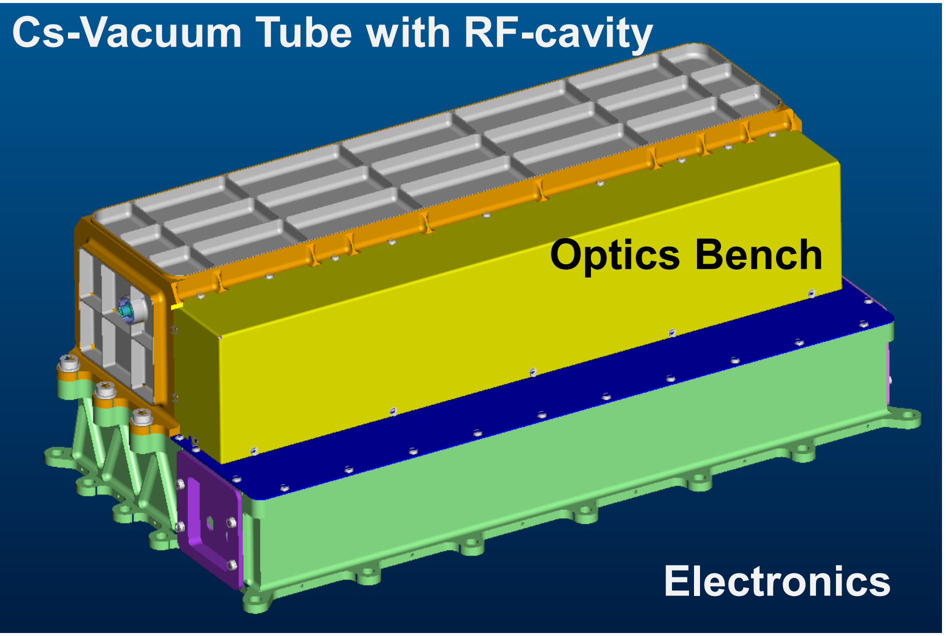
OSCC: Engineering Model



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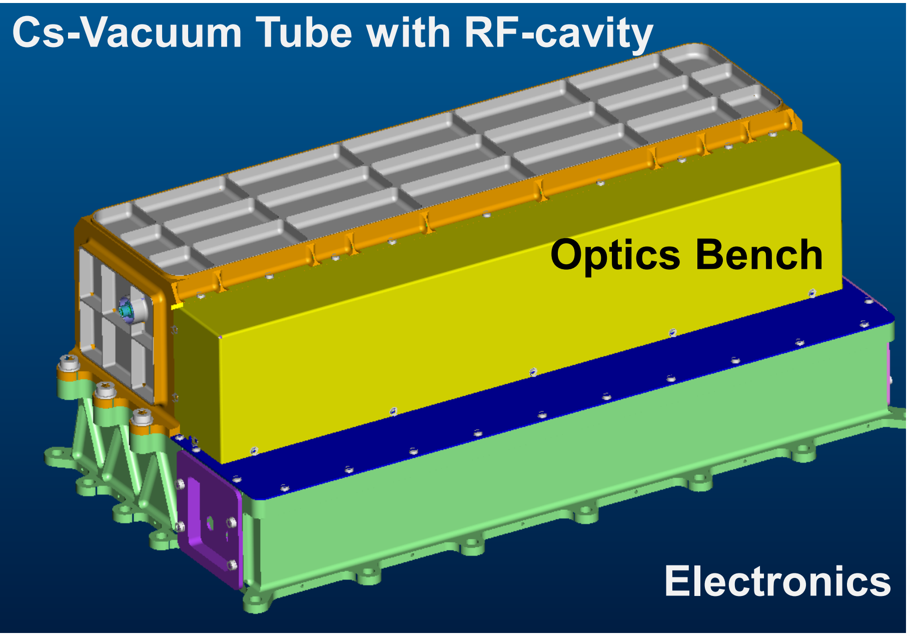
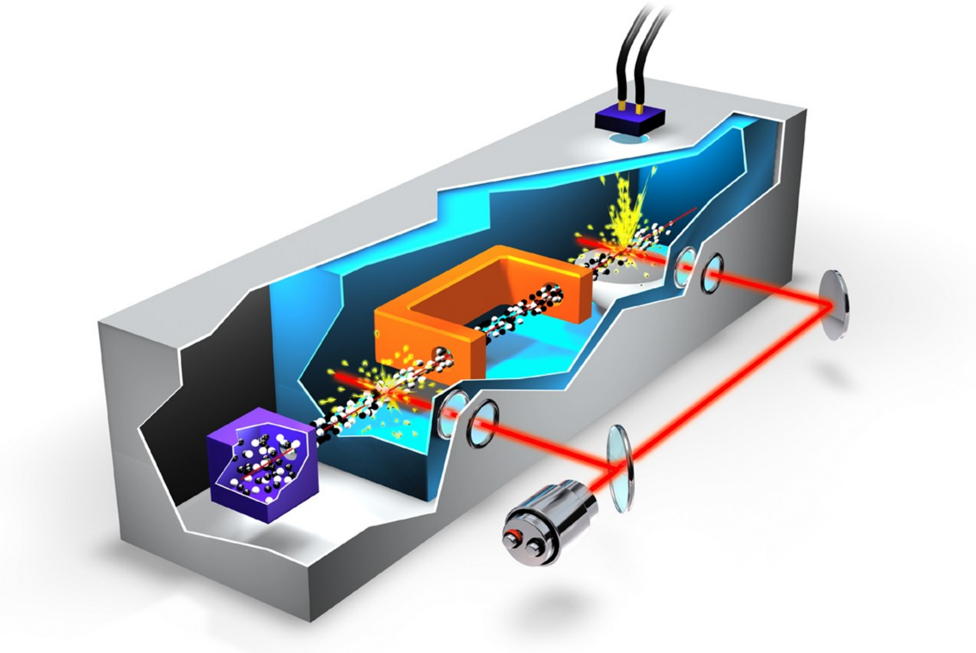




TED Hardware Development for Space Application:

- ➢ Cs Vacuum Tube with specific components:
  - Cs, RF, Optics, Photodetectors
- ➢ Optics sub-system

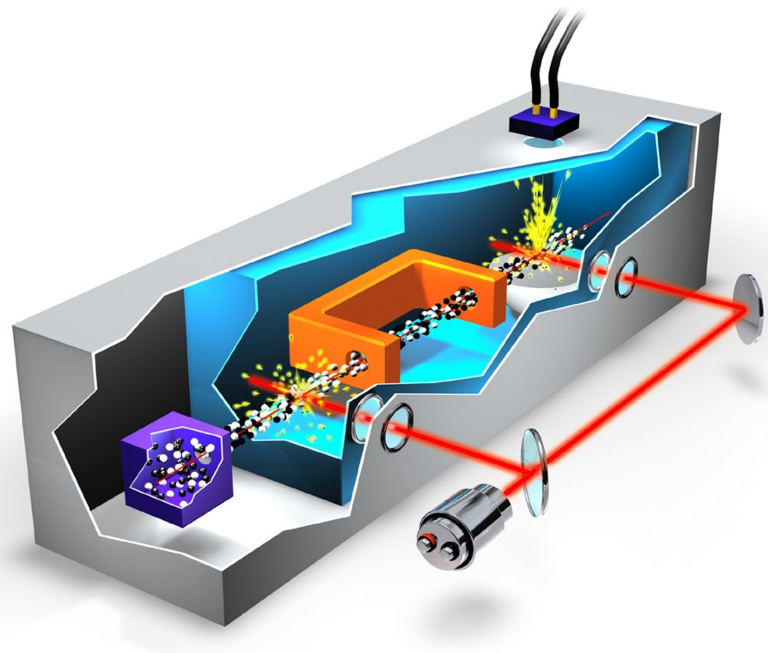
OSCC: Engineering Model

Atomic Resonator Tube

- Titanium, Aluminium, Glass
- Welding, Soldering, Screwing

- Cs Oven and Graphite beam shaping
- Resonant RF-cavity
- Mu-Metal magnetic shielding
- Helmholz Coil C-Field

- Fluorescence collection optics
- Stray light absorption



Space application

- Mass, Volume, Vibration

Atomic Resonator Tube

- Titanium, Aluminium, Glass
- Welding, Soldering, Screwing

- Cs Oven and Graphite beam shaping
- Resonant RF-cavity
- Mu-Metal magnetic shielding
- Helmholz Coil C-Field

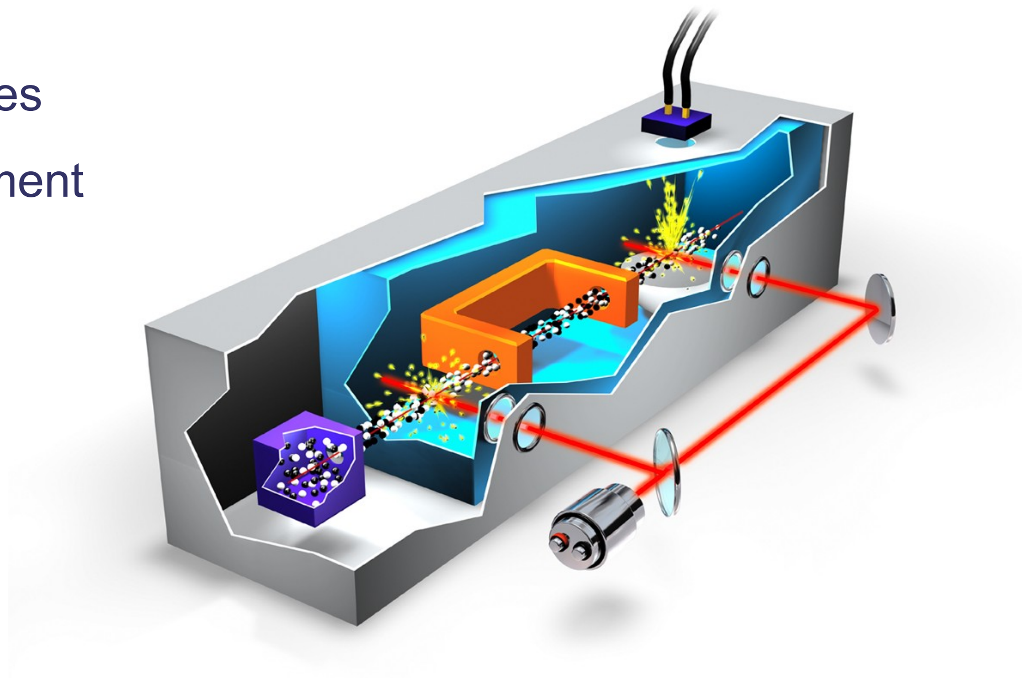
- Fluorescence collection optics
- Stray light absorption

Risk-reduction

- **Prototyping**

Laser and Optics

- Distributed Feedback Laser Diodes
- Polarization and stray-light managment
- Specific optical coatings



- Photodetection:

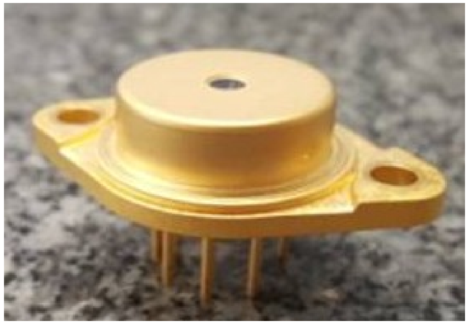
High sensitivity & low noise

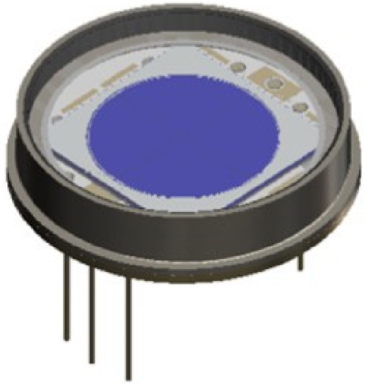
Space application

- Harsh environment: Vacuum, Vibration & Shock, Temperature Radiation
- Space Evaluation Program for Laser Diode & Photodiode

Space evaluation of most critical components 2016-2017

- Risk reduction for later space qualification
- First step: assessment of most critical degradation modes





➢ **Laser Diode**

- III-V Lab & eagleyard, DFB, TO3
- Specific development:

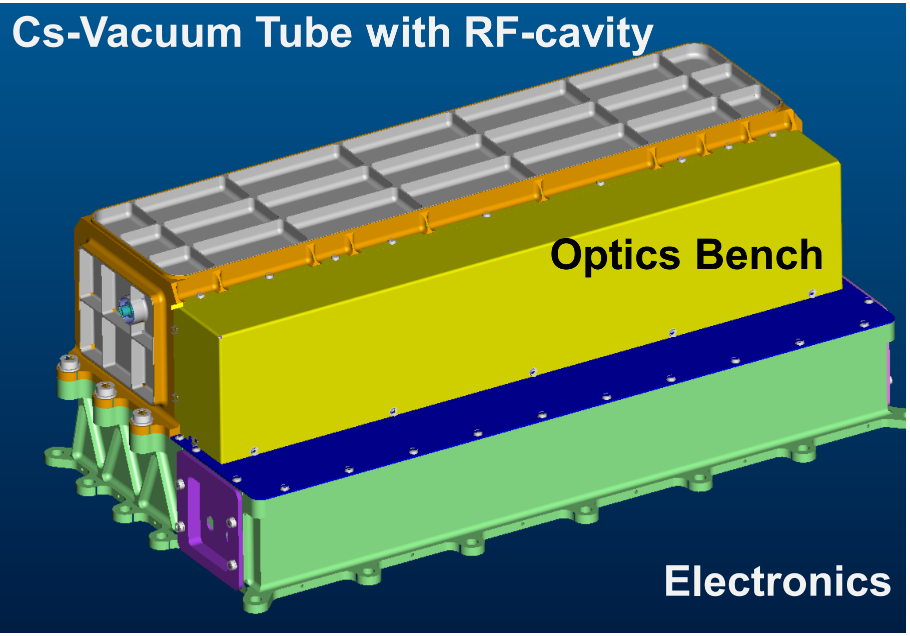
Low noise, address optimal Cs transition

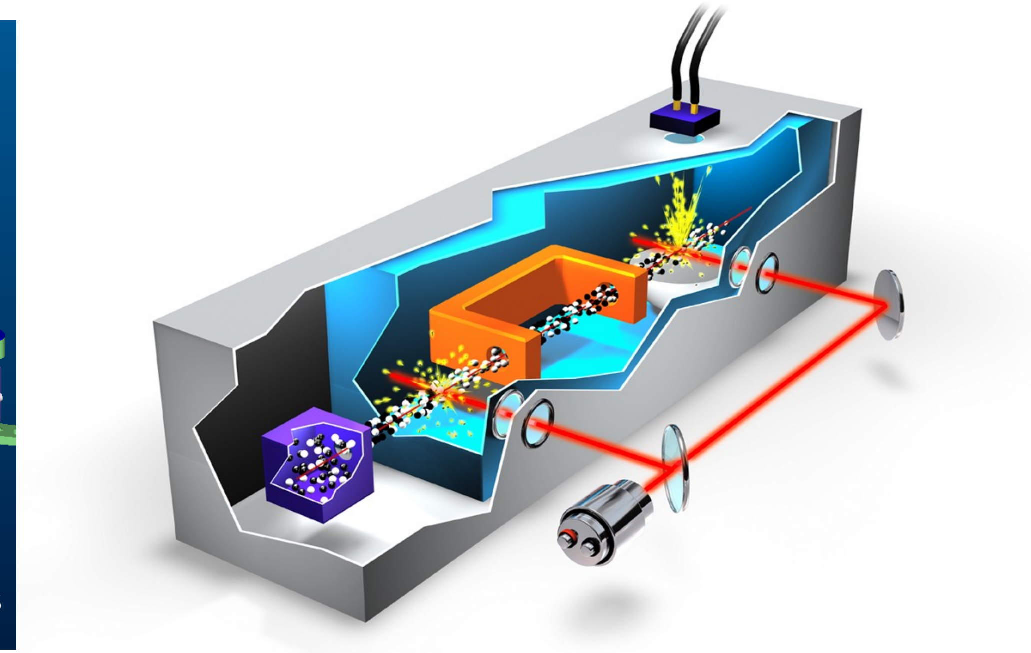
- Lifetime, Hermeticity, Construction (vibration)

➢ **Photodiode**

- First Sensor customized assembly of COTS components
- Radiation, Hermeticity, Construction (vibration)

OSCC: Engineering Model





Optical Space Cs Clock Development:

- Highly complex, numerous different technologies
- All core expertise in Thales Group

Conclusions

- **OSCC engineering model design completed (Sept. 2016, on time)**
Electronics and Optics hardware to be manufactured in 2017

- **Successful de-risking of a new optics hardware through prototyping**
short term stability better than $2.8E\text{-}12\tau^{-1/2}$

- **Compliance to Requirements:**
Mass, Volume, Performance and Power Consumption

- **Space evaluation of laser diode and photodiode:**
Starting end of 2016, important REX expected

Aknowledgements

Financial Support

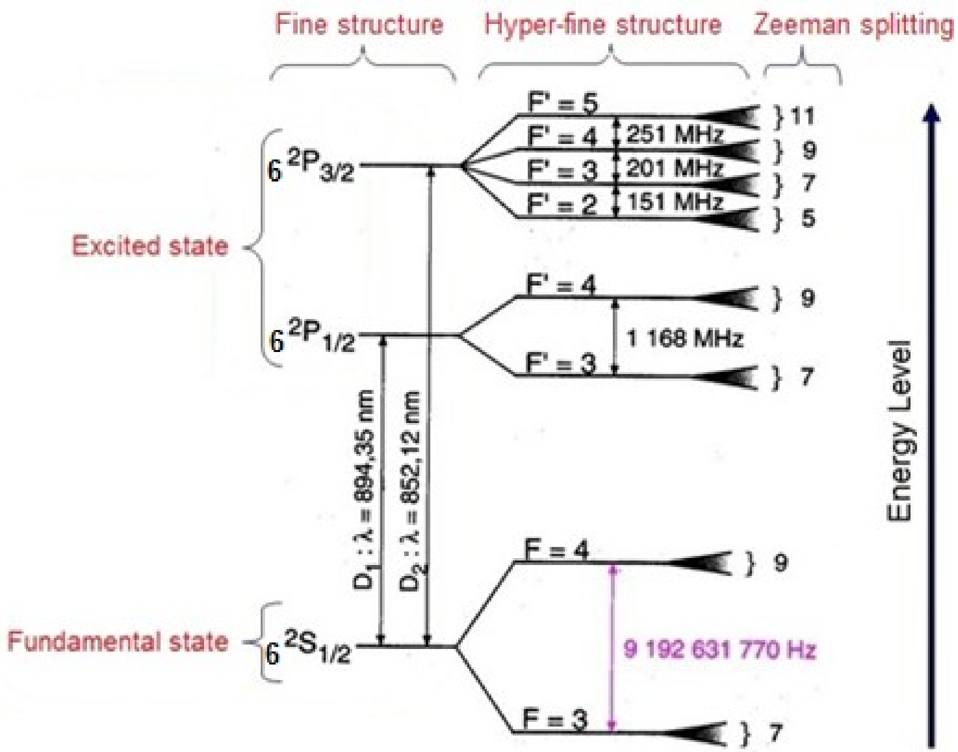
European Space Agency (ESA)
Centre National d'Etudes Spatiales (CNES)
EURIPIDES
Thales Electron Devices

Technical Contributions

M.Kauffmann, V.Hermann, G.Corridor and G.Gauthier at Thales Electron Devices
S.Guérandel at SYRTE, Paris
G.Baily and L.Morvan at Thales Research and Technology, Palaiseau,
G.Guibaud at Thales Communication and Security, Toulouse,
Y.Folco at Thales Alenia Space, Cannes
Thales Optronique SA, Elancourt
J.Delporte, F-X Esnault, O.Gilard and J.Mekki at CNES, Toulouse
C.Bringer and P.Waller at ESA-ESTEC, Noordwijk

The suppliers First Sensor and eagleyard Photonics.

Introduction: Optically Pumped Cs Clock



- **Operational Principle**

Adressing the Cs D1 (894nm) and D2 (852nm)

Line	*Transition*	*Photons/atom*
D1	**4-3'σ**	**4**
D2	**3-3'σ**	**4**
D2	**4-4'σ**	**2,4**

SNR in $Hz^{1/2}$ on OSCC tube at 96°C Cs oven			
DFB Laser	**D1 4-3'**	**D2 4-4'**	**D2 3-3'**
Eagleyard	**n/a**	**15000**	**15500**
III-V Lab	**20000**	**15000**	**16500**

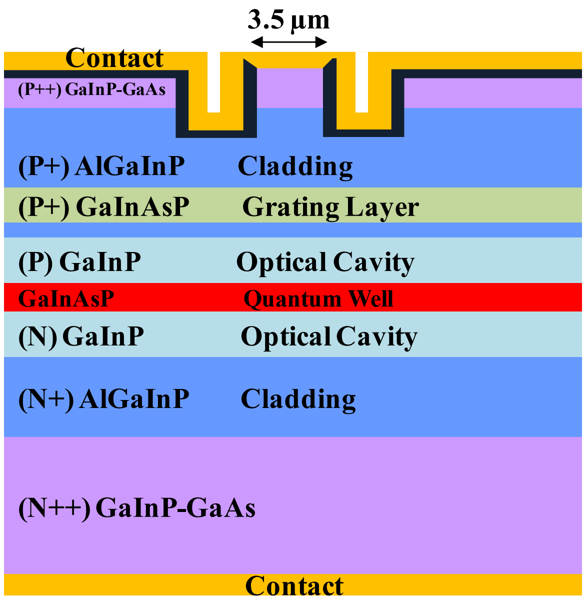
Pumping transition comparison

- Best performances expected & measured for Cs D1 4-3'
- Best performance SNR 24500 $Hz^{1/2}$ at 100°C Cs oven
- Theoretical OSCC stability better than $2E\text{-}12\tau^{-1/2}$

Conclusion

- Cs D1 transition new target for OSCC implementation

Adressing the Cs D1 (894nm)



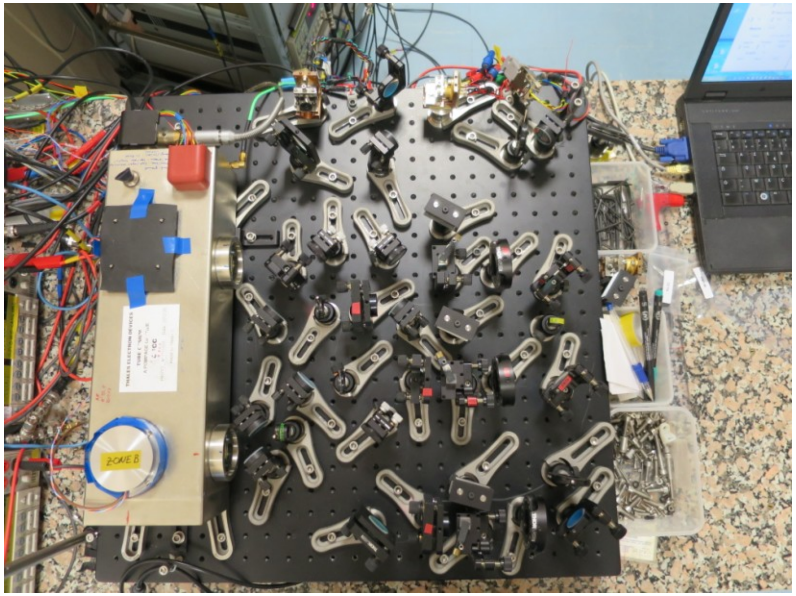
III-V Lab development

- Separate Confinement Heterostructure
- Al free active region
- More than 45 dB Side Mode Suppression
- Small linewidth below 1 MHz
- TO3 hermetic packaging

Thales Group secures the Laser Diode supply chain

- additional source with respect to eagleyard

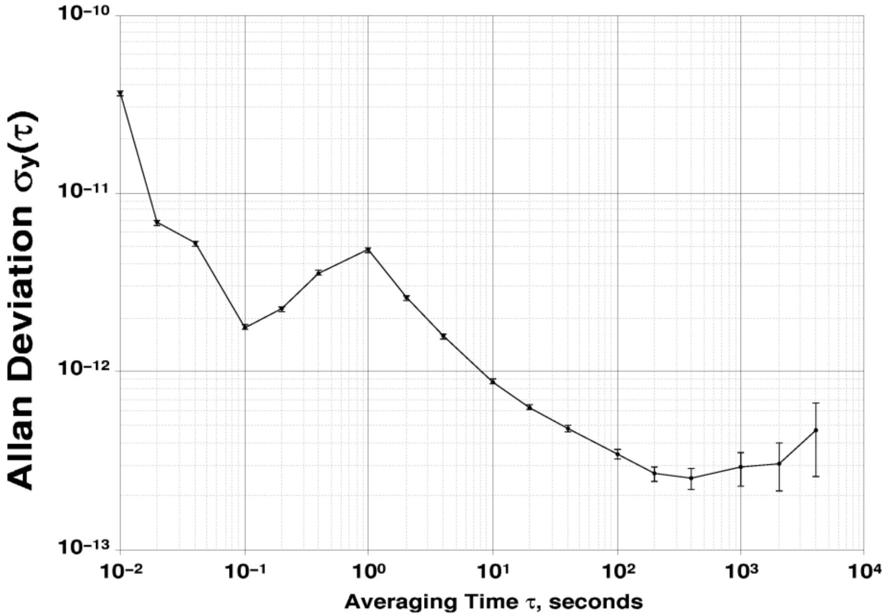
Adressing the Cs D1 (894nm)



Dedicated opics test bench

- Successful test of III-V Lab laser diode functionality on clock Cs tube
- Quantitative perfomance comparison to eagleyard

Optics bench preliminary design: concept validation



- Partially representative optics bench prototype & dedicated Cs tube
  - Clock short term stability better than $2.8E\text{-}12\tau^{-1/2}$
    - Using III-V Lab TO3 laser diode at 894nm
      - Robust Cs tube manufacturing files

Selection of the Cs electronic transition

Clock performance target: Stability of 1E-12$\tau^{-1/2}$

Line	*Transition*	*Photons/atom*
D1	**4-3'σ**	**4**
D2	**3-3'σ**	**4**
D2	**4-4'σ**	**2,4**

Clock (year)	*Oven temp °C*	*Transition*	*Laser*	*1/Q*SNR*
Tekelec (2000)	110	D2 3-3'σ	DBR	< 1E-11
Cs4 (2000)	90	D2 3-3'σ	DBR	6E-12
PHACS (2003)	**110**	**D1 3-4'π**	**ECDL**	**2.5E-11**
ECO (2012)	95	D2 4-4'depolarized	DFB	6.1E-12
OSCC (2013)	**95**	**D2 4-4'depolarized**	**DFB**	**4.8E-12**

Numerous former developments since two decades

- OSCC Elegant Breadboard (2013) highest maturity and performace

Main purposes

- Consolidate the choice of Cs transition
- Cs D1 not yet considered in OSCC

Adressing the Cs D1 (894nm)

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