Launch your Vision

From lidar to optical atomic clocks

Building blocks for optical frequency references in space

SpaceTech GmbH
Hanjo Schäfer

12.09.2019
EPIC Meeting on New Space at European Space Agency

Outline

- Introduction of SpaceTech
  - Company heritage
  - Company profile
- Space activities and developments on frequency metrology in the frame of lidars
  - High stability lasers for ranging applications
  - Absolute frequency references for green house gas detection
- Final steps towards optical atomic clocks
  - Present state and perspective

In Orbit on

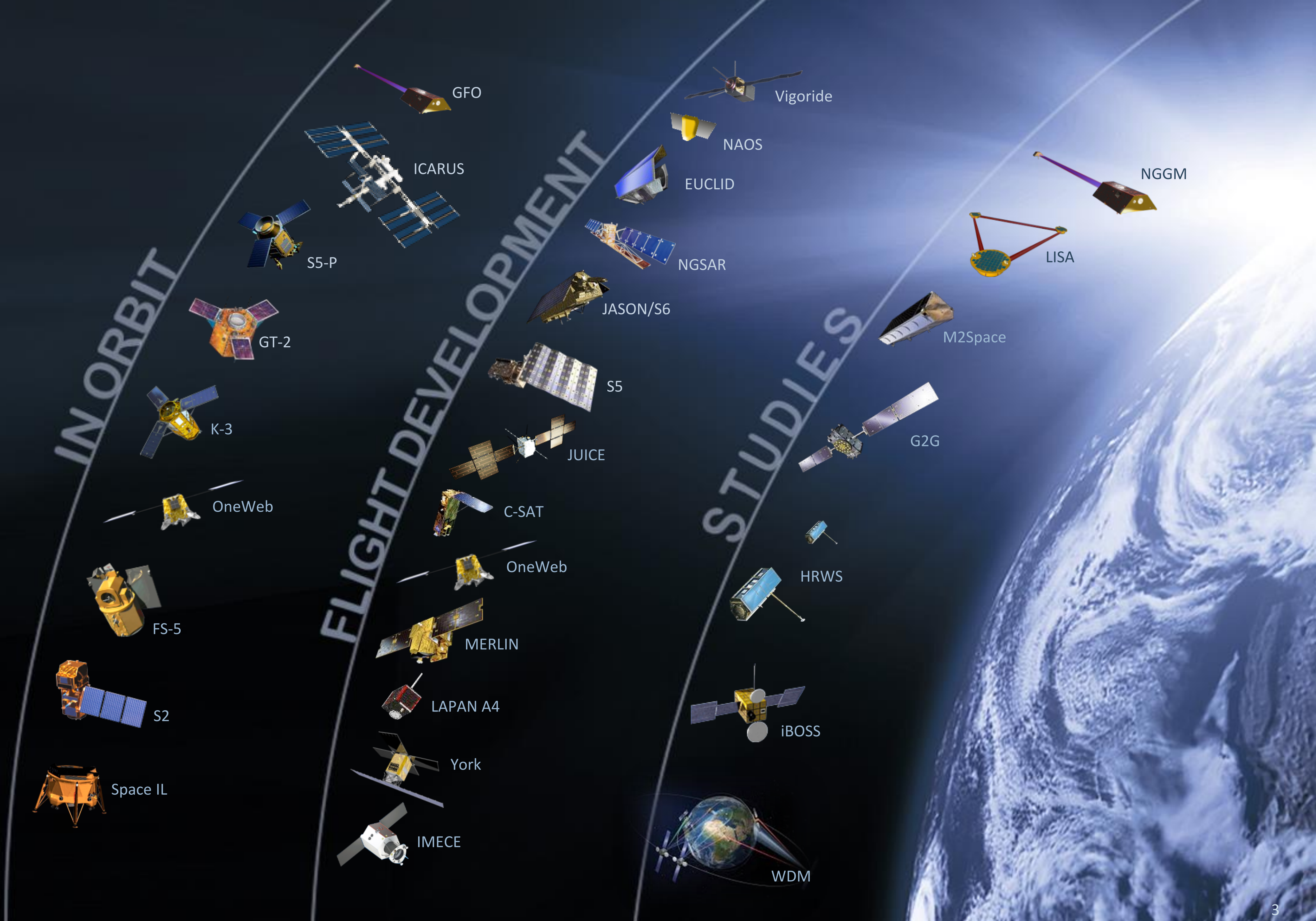
- 9 Missions
- 15 Satellites
- 38 Equipments

Development for

- 15 Missions
- 916 Satellites
- 1819 Equipments

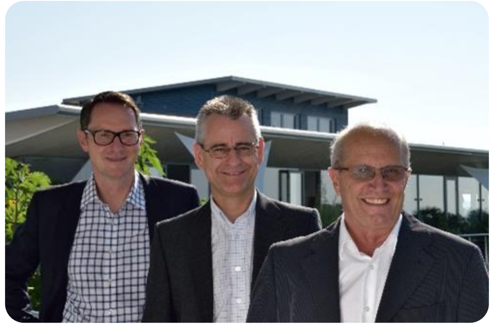
And more

to come …



Company Profile

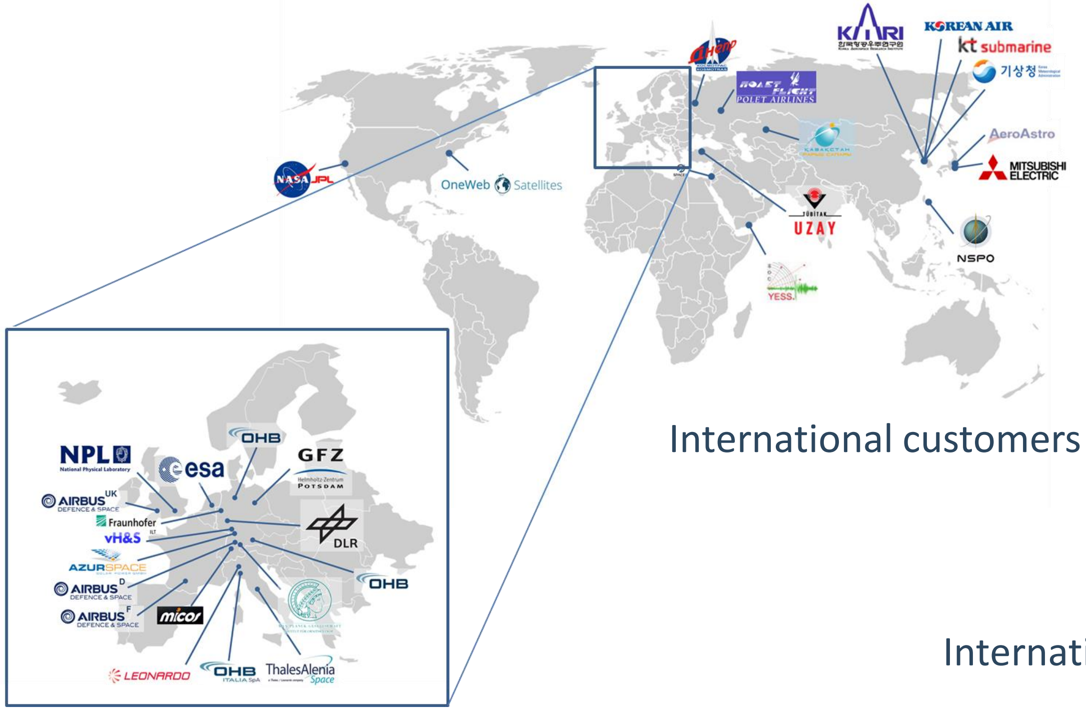
- **Business Areas**
  - Small Sat. Missions
  - Optical Instruments
  - Satellite Equipment
- **Facts & Figures**
  - Foundation: 2004
  - Staff: 90 (avg. age 39)
  - Yearly Turnover: 20 M€
- **We stand for**
  - Smart & Reliable Designs
  - High Cost Efficiency



Man. Directors: W. Pitz (CEO), F. Gilles, B. Doll

SpaceTech GmbH

Seelbachstrasse 9-11-13
88090 Immenstaad
www.spacetech-i.com



International customers

International workforce

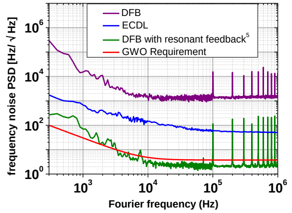
Laser & QT Building Block developments at STI

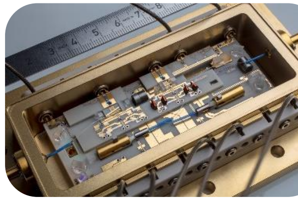
Laser Building Blocks

Laser developments at STI with the potential to act as “laser building blocks” for many missions

1. Micro-integrated seed laser platform

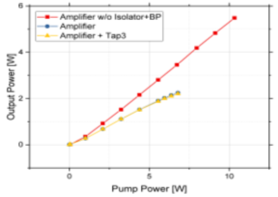
- Wide laser wavelength range
- Customized frequency stability
- High output power and low noise





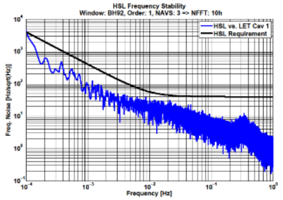
2. Fiber amplifier

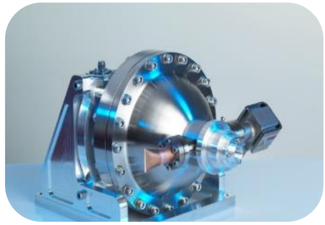
- Optimized for low nonlinearities
- 10 W of optical output power and low noise



3. Optical cavities/gas cells

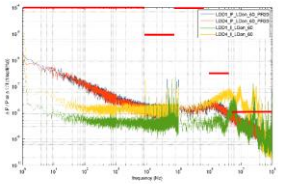
- Hz to MHz stability





4. Associated drive and control electronics

- Low noise laser drivers
- Flexible control electronics



Application in

- Navigation (Galileo)
- Science (LISA, BECCAL, optical clocks)
- EO (NGGM, LIDAR seeder,…)
- Optical communication

Developments at STI for

- LISA –GWO (ESA,CTP)
- NGGM - HSL1 & 2 (ESA, TRP&GSTP)
- DWDM (ESA, ARTES)
- (Optical Clock for G2G – DLR)

Our partners

TESAT, NPL National Physical Laboratory, JPL, ONERA THE FRENCH AEROSPACE LAB, DELOS Space, FBH Ferdinand Braun Institut, DLR, Fraunhofer ILT, AIRBUS, MenloSystems, GFZ Helmholtz Centre Potsdam

Laser Instrument Activities – Examples 1/2

From lidar to optical atomic clocks

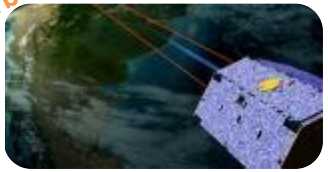
SpaceTech develops optical systems with a focus on earth observation and science missions.

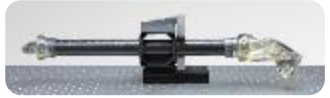
- Laser Instruments
- Quantum Technology Instruments
- Structures & Mechanisms
- Optical Components

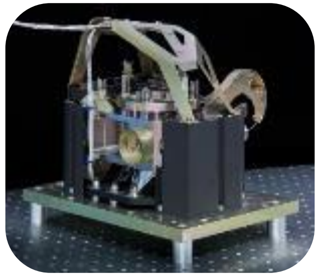
- **GRACE Follow-On LRI**
  - Prime for German Laser Ranging Interferometer part
  - Cooperation with JPL/NASA
  - Launched 5/2018
- **MERLIN Frequency Reference Unit**
  - German-French mission on methane gas measurement
  - Subsystem for absolute frequency reference
  - FM delivery in 2020
- **High Stability Laser**
  - Laser system for NGGM, GRACE 2, LISA…
  - TLR6 model completed
- **Laser Interferometer Space Antenna**
  - STI selected by ESA as prime for the development of the LISA Laser (Phase 1: BB, Phase 2: EM)
- **LEMON FRUit**
  - H2020 activity for a multi-species lidar
  - Subsystem for absolute frequency reference

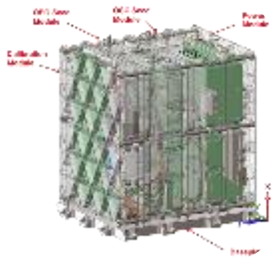
In more detail in the next section of the talk

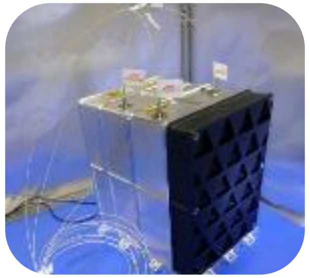
In Orbit

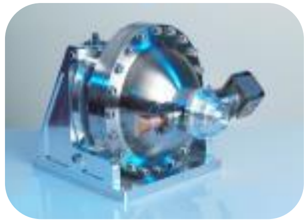












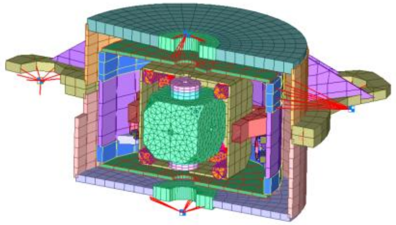
Laser Instrument Activities – Examples 2/2

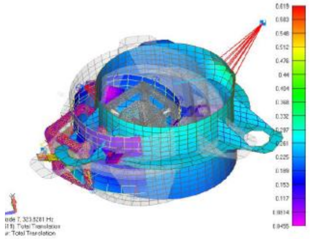
From lidar to optical atomic clocks

SpaceTech develops optical systems with a focus on earth observation and science missions.

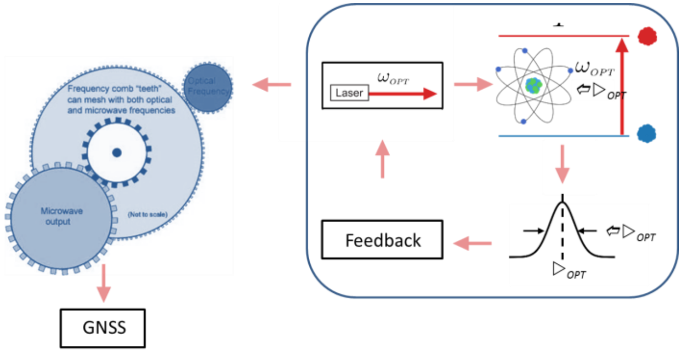
- Laser Instruments
- Quantum Technology Instruments
- Structures & Mechanisms
- Optical Components

- **OSRC – optical stabilising reference cavity**
  - Cavity Development for Optical clocks & LISA
  - STI responsible for thermal & structural Analysis

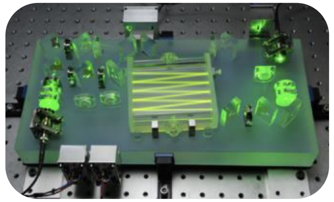




- **Optical Clock for Galileo 2nd generation**
  - DLR funded Study for optical clock technology
  - STI responsible for System requirements, Space Design & DDV-Plan



- **CaLas**
  - QUTEGA funded activity for laser system for Ca-Ion clocks
  - STI responsible for optical isolator and space design of laser system



- **ACES MWL**
  - Integration & testing of ground terminal electronic

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SpaceTech is the

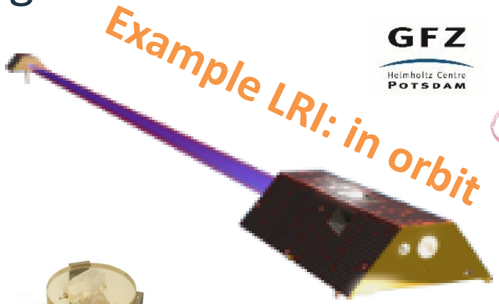
Gateway to Space

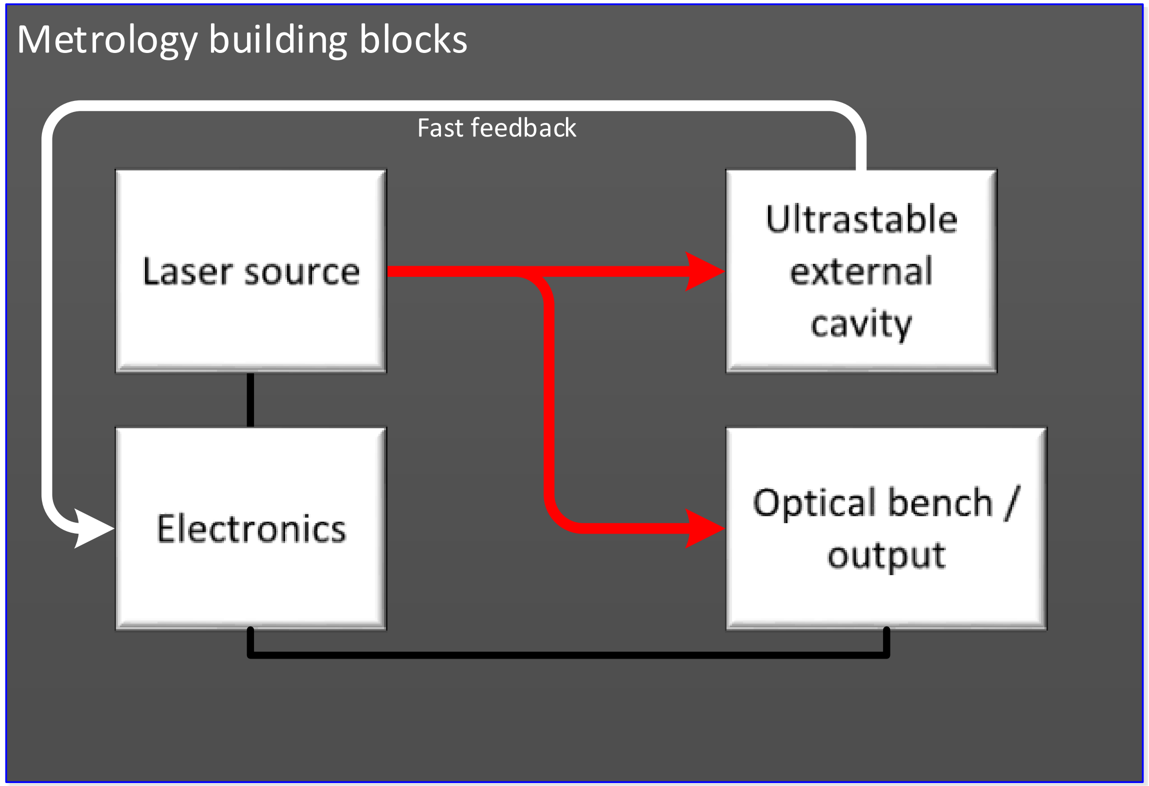
for your commercial products.

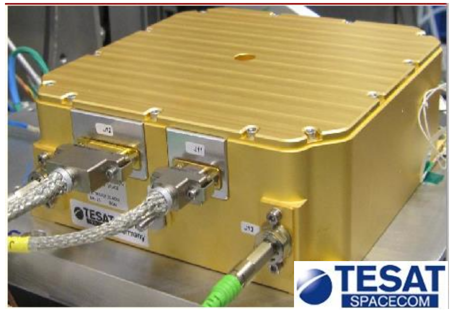
Frequency metrology for laser ranging applications

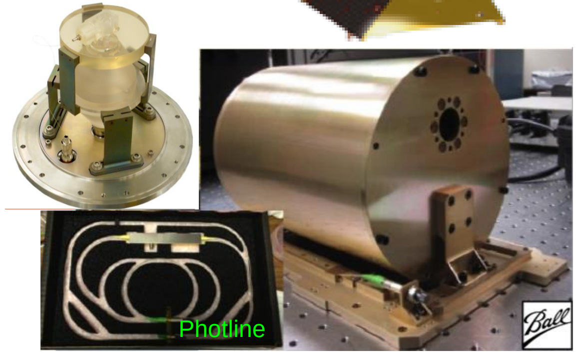
Space developments on frequency metrology

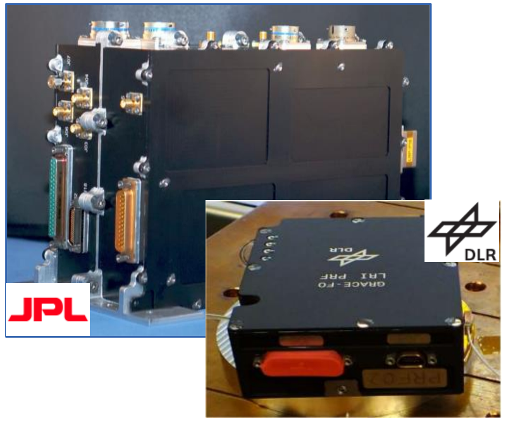
- For geodesy applications and gravitational wave detection only relative changes over limited time intervals are needed
  - Implementation of narrow linewidth cw laser source for measurement of relative phase changes
  - Ranging information obtained from two unreferenced laser sources in master-slave configuration
  - LRI: Laser frequency noise < 30 Hz / √ Hz x NSF(f) @10 – 100 mHz

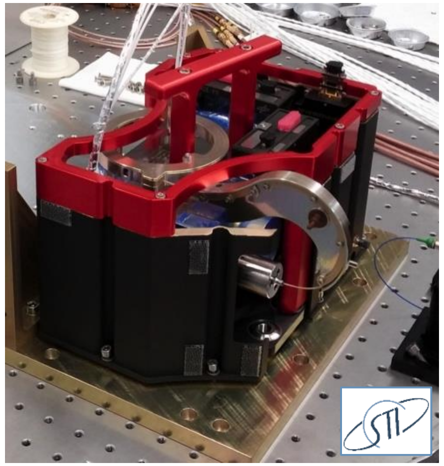






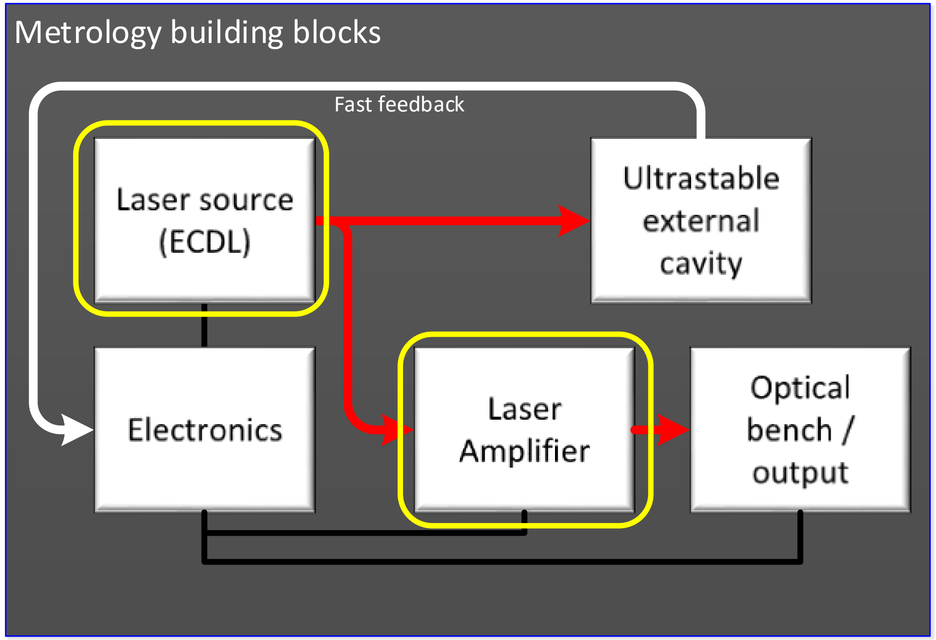


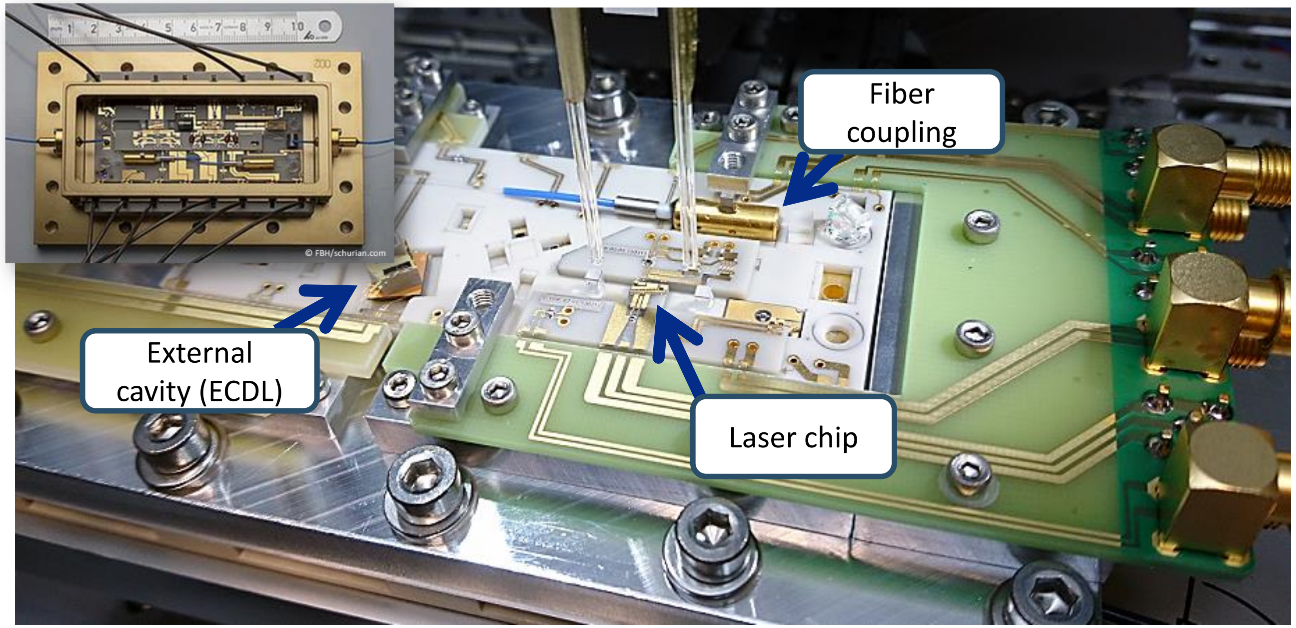




Frequency metrology for laser ranging applications

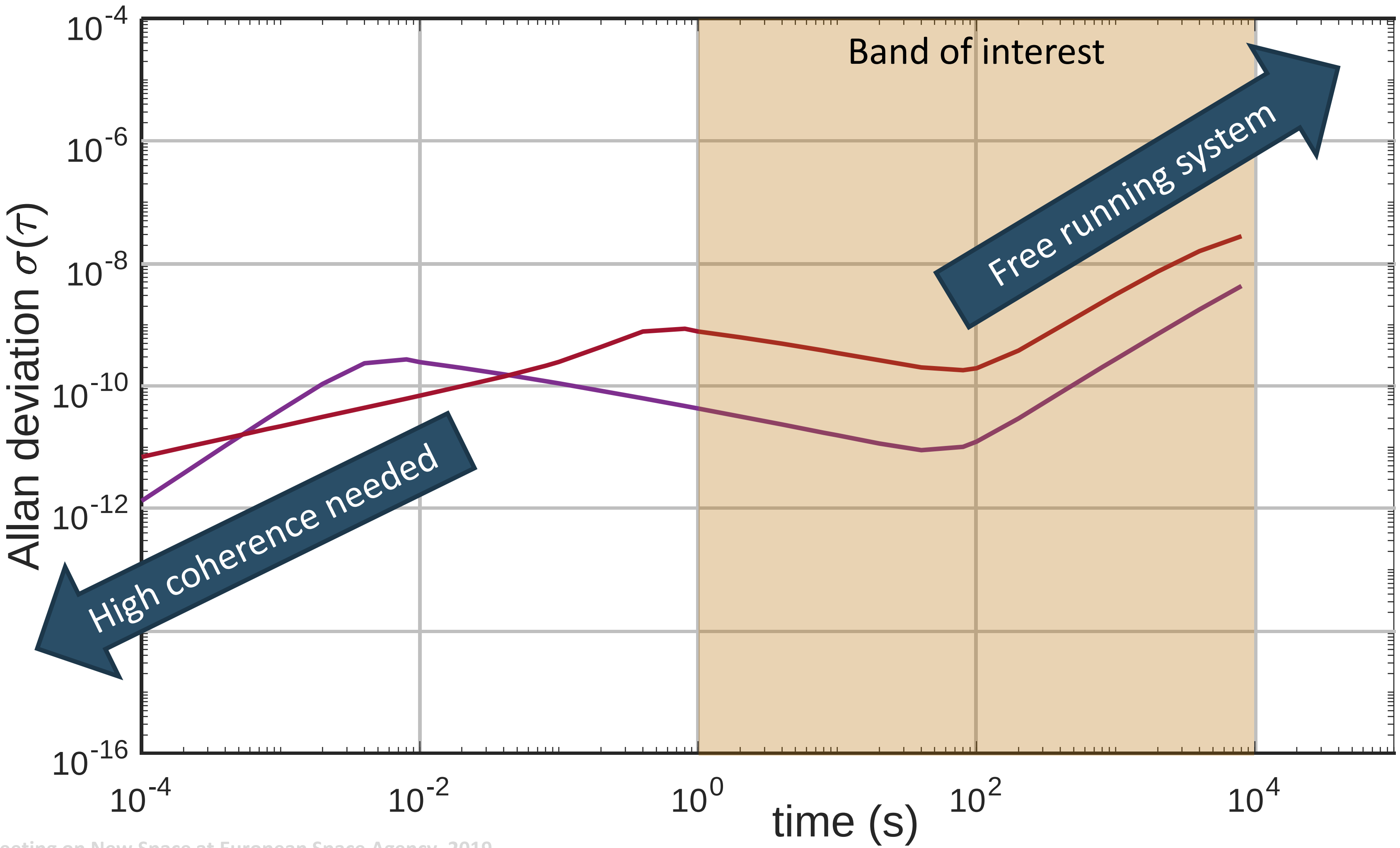
- Ongoing developments for the LISA laser
  - Semiconductor based ECDL laser source
  - Further integration of the laser source
  - Boosting the laser power by an fiber amplifier
  - Laser frequency noise < 300 Hz / √ Hz x NSF(f) @ 0.1 mHz – 1 Hz
  - Laser RIN < 1e-8 @MHz



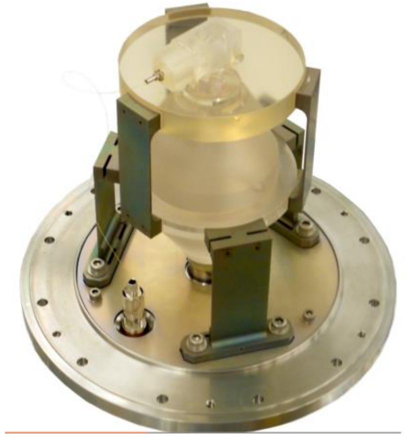


Frequency metrology for laser ranging applications

- Allen deviation (ADEV) as a general measure of frequency stability
  - Ranging requirements are typically provided in power spectral densities (PSD)
  - For comparison stability requirements can be transferred from frequency noise PSD to ADEV



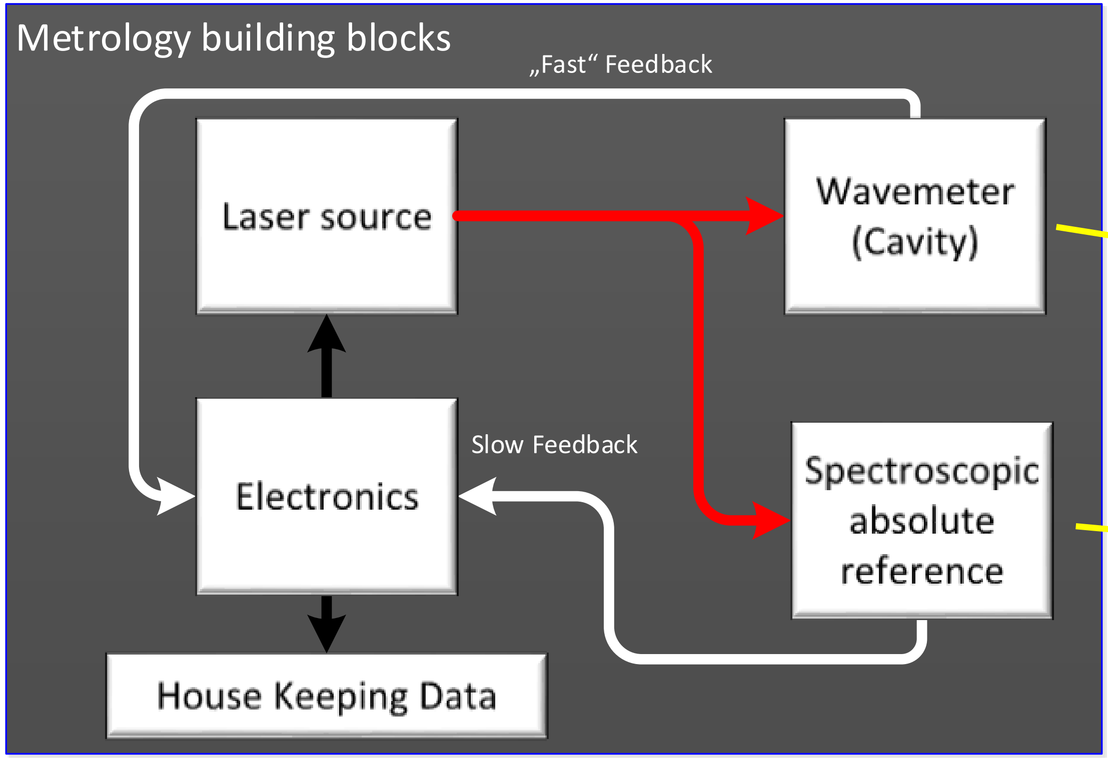
Cavity based systems

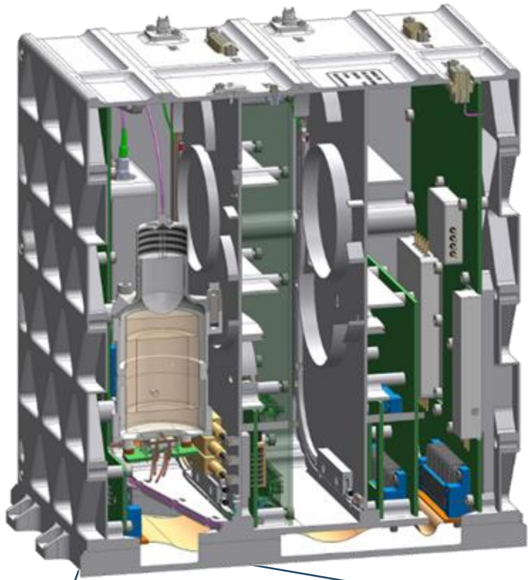


Frequency metrology for trace gas detection

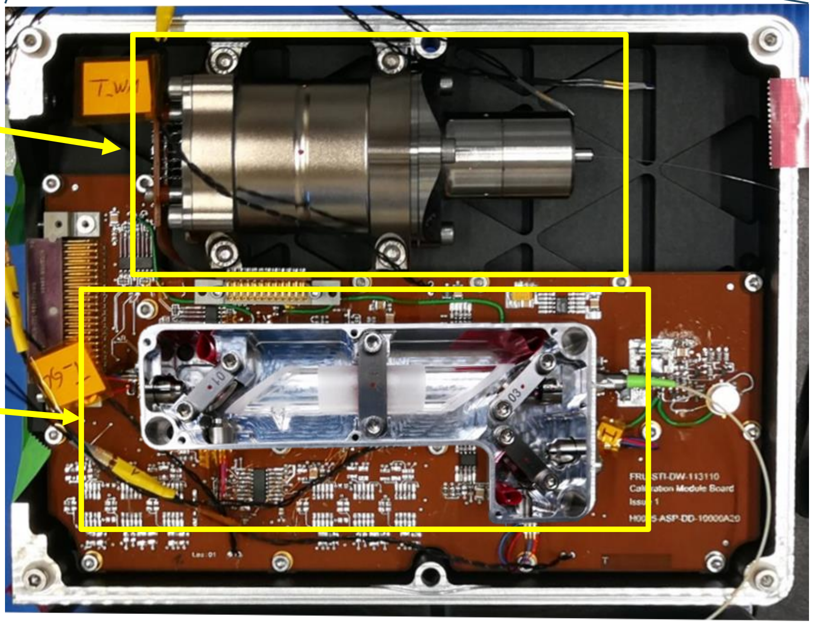
Space developments on frequency metrology

- Frequency reference unit (FRU) for the MERLIN mission
  - Global detection of atmospheric CH_4 concentration
  - Absolute calibration and stability needed
  - $3x10^{-4}$ spectral coverage (0.5 nm) needed at 1645.7 nm





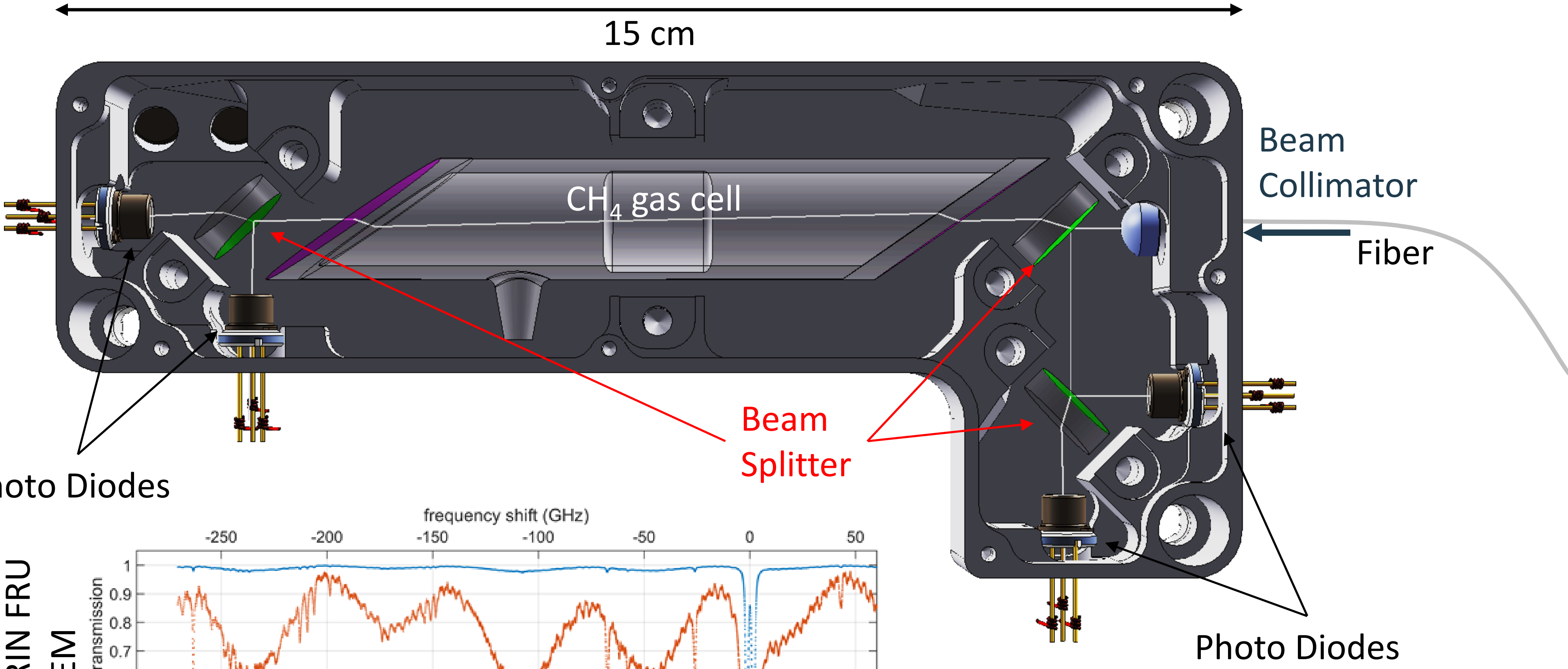
Heinecke, D., Liebherr, T., Battles, D. et al. CEAS Space J (2019) https://doi.org/10.1007/s12567-019-00268-6

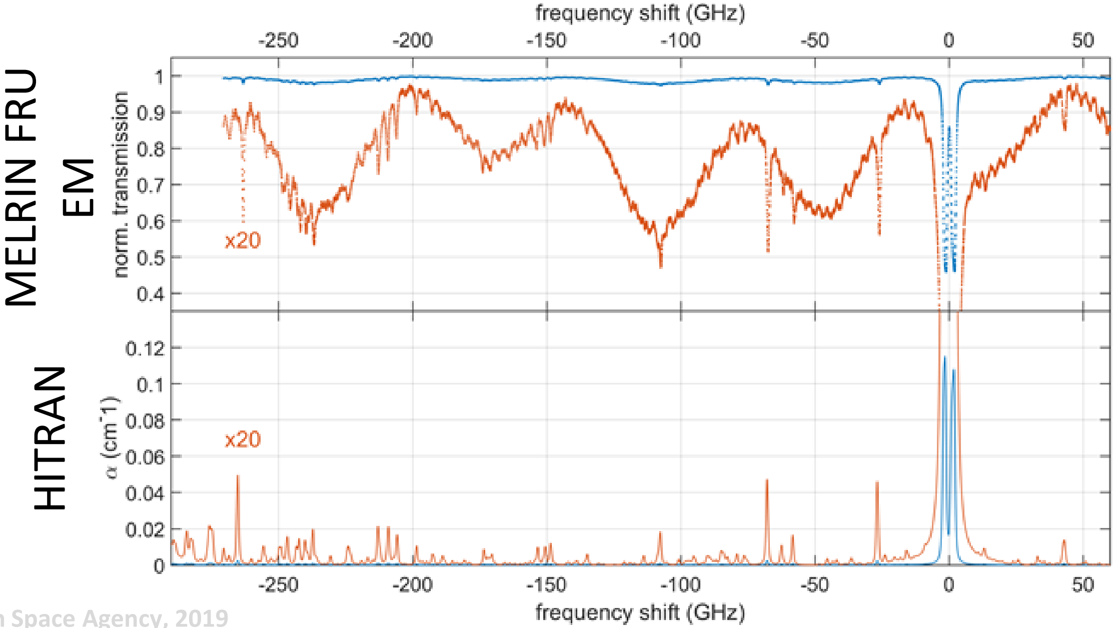


Calibration Module (Engineering Model)

The absolute frequency reference assembly

Design, Assembly and Qualification by STI

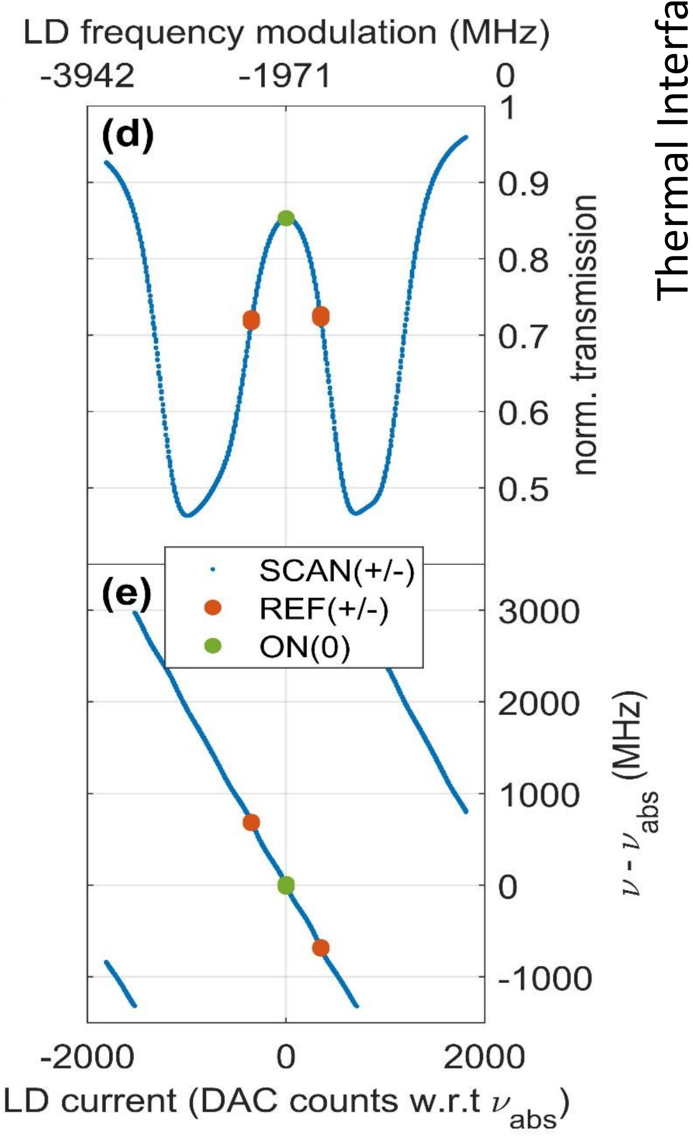




Heinecke, D., Liebherr, T., Battles, D. et al. CEAS Space J (2019)

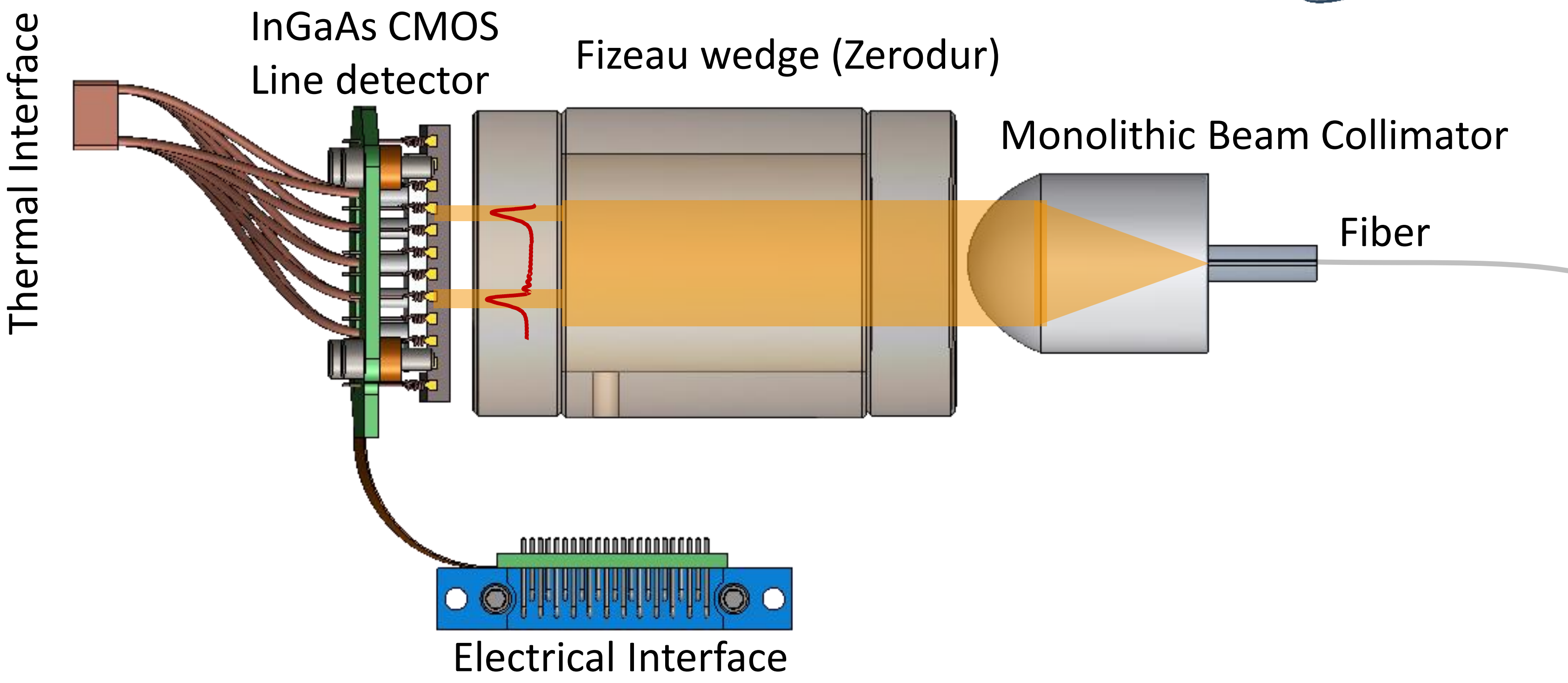
The wavemeter

Space developments on frequency metrology



Heinecke, D., Liebherr, T., Battles, D. et al. CEAS Space J (2019)

Design, Assembly and Qualification by



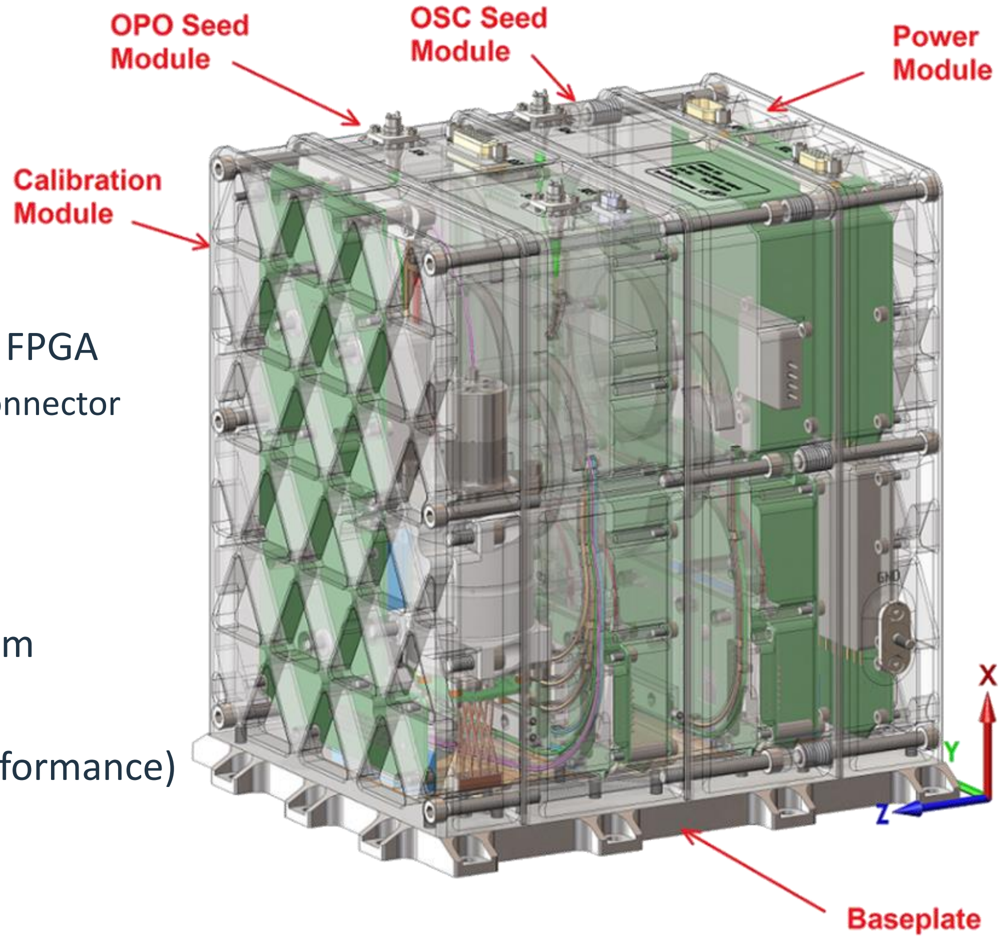
- **Technical Data**
  - < 1 MHz resolution
  - 4.28 GHz FSR
  - 6.6 GHz spectral window
  - 12.5 mm beam diameter
- **Environment**
  - 1000 g shock
  - > 50 g_{rms} vibration
  - > 20 krad TID
  - 0-40 °C full performance

Optomechanical Design of MERLIN FRU

Space developments on frequency metrology

Modular Design

- Power Module – DC/DC Converters & Filters
  - Power & signal (trigger) connector
- OSC Module – 1064 nm seeders
  - 1064 output connector
- OPO Module – 1645 nm seeders & harness & FPGA
  - 1645 output and input connector, SpW & test connector
- Calibration Module – spectroscopy



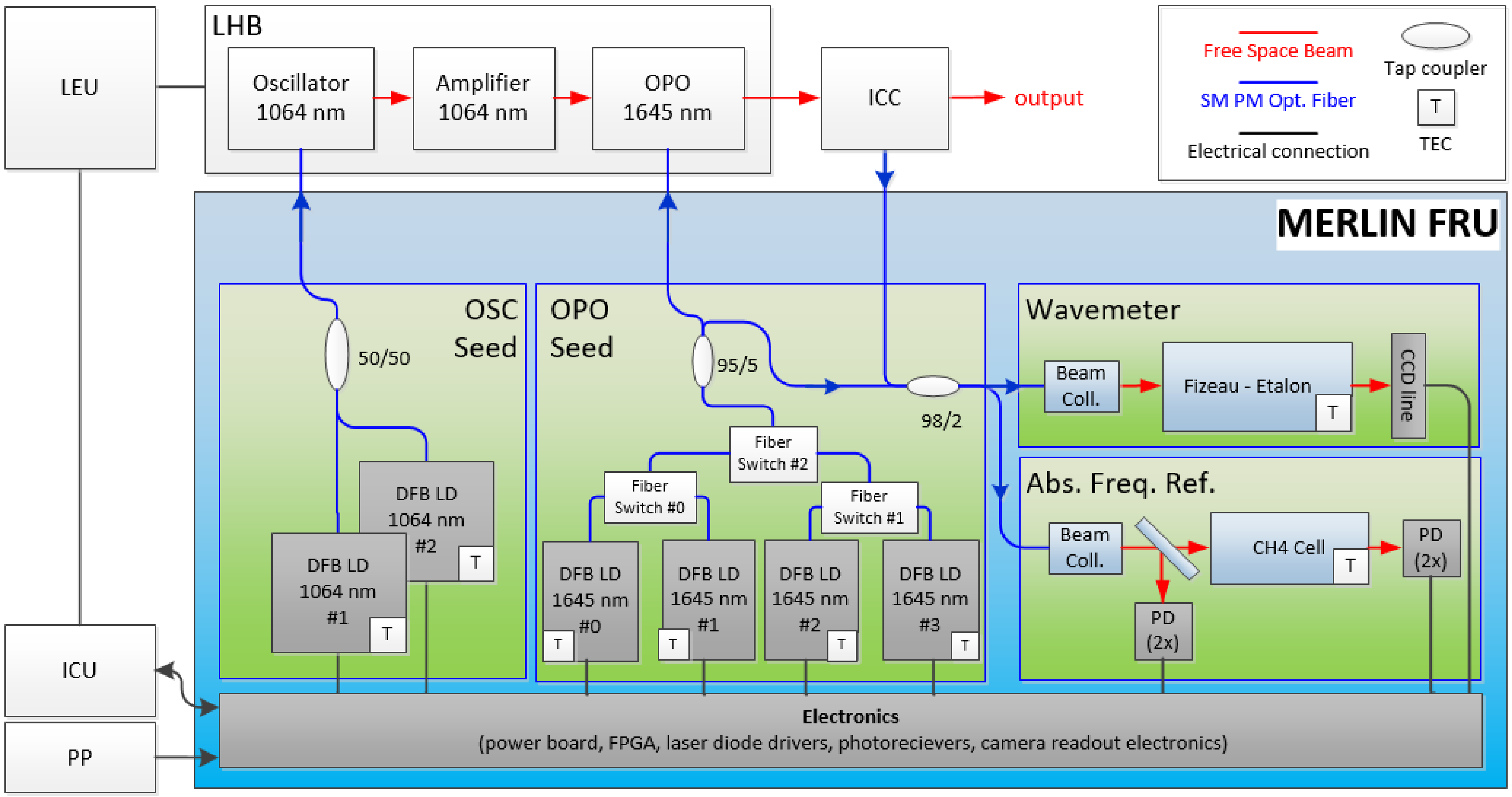
Technical Data

Envelope:	190x 232 x 237 mm
Total mass:	≤ 6.3 kg
Op. temp. range:	0 to 40°C (full performance)
Power consumption :	≤ 24 W

Functional Design of MERLIN FRU

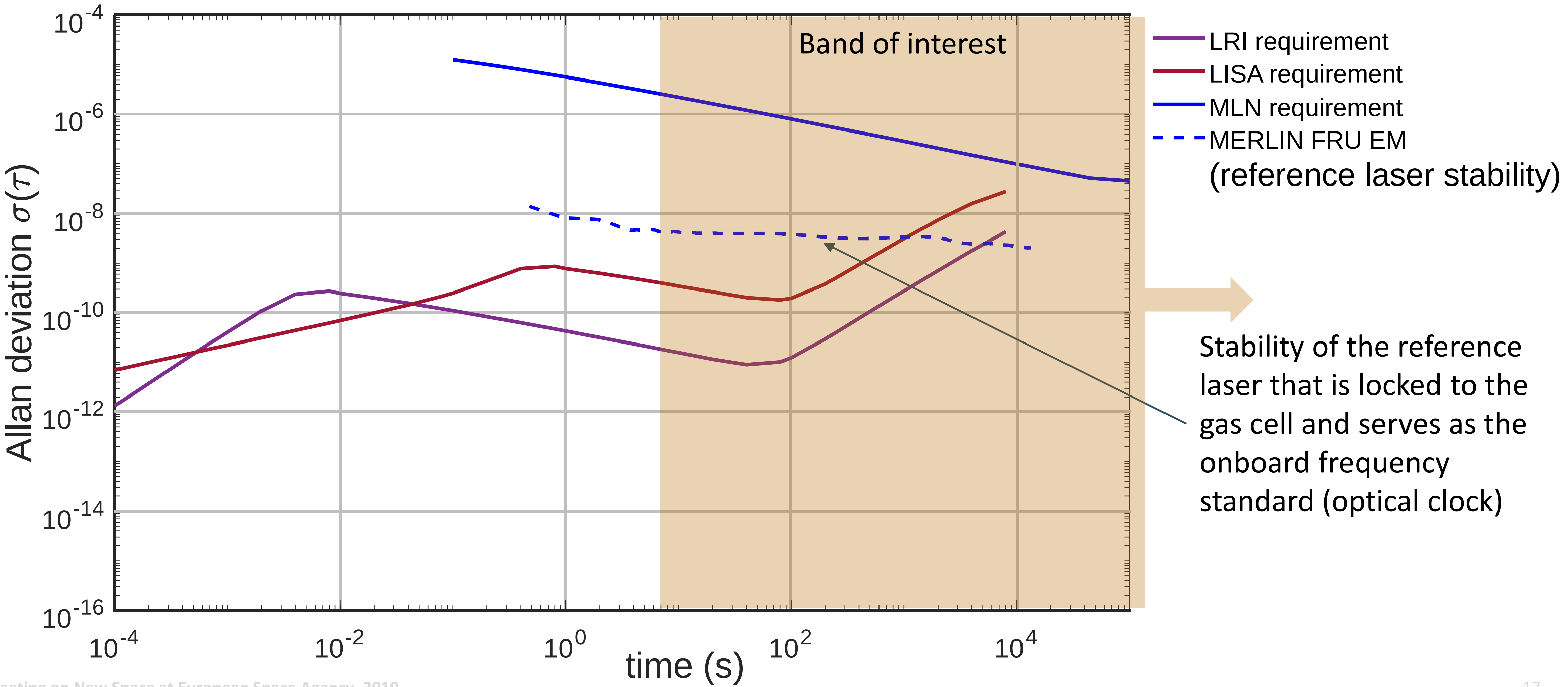
Space developments on frequency metrology

MERLIN frequency reference unit
- 61064 nm & 1645 nm)
- 3 Tap Couplers
- 3 Fiber Optical Switches (no mechanics)
- 4 Photodiodes (InGaAs)
- 1 InGaAs CMOS line detector
- Laser Diodes (Free space optics (gas cell, Fizeau etalon)
- Electronics



Frequency metrology for trace gas detection

- Allen deviation of MERLIN frequency reference unit
  - Requirement and performance of Engineering Model (EM) measured against a GPS referenced frequency comb



Stability of the reference laser that is locked to the gas cell and serves as the onboard frequency standard (optical clock)

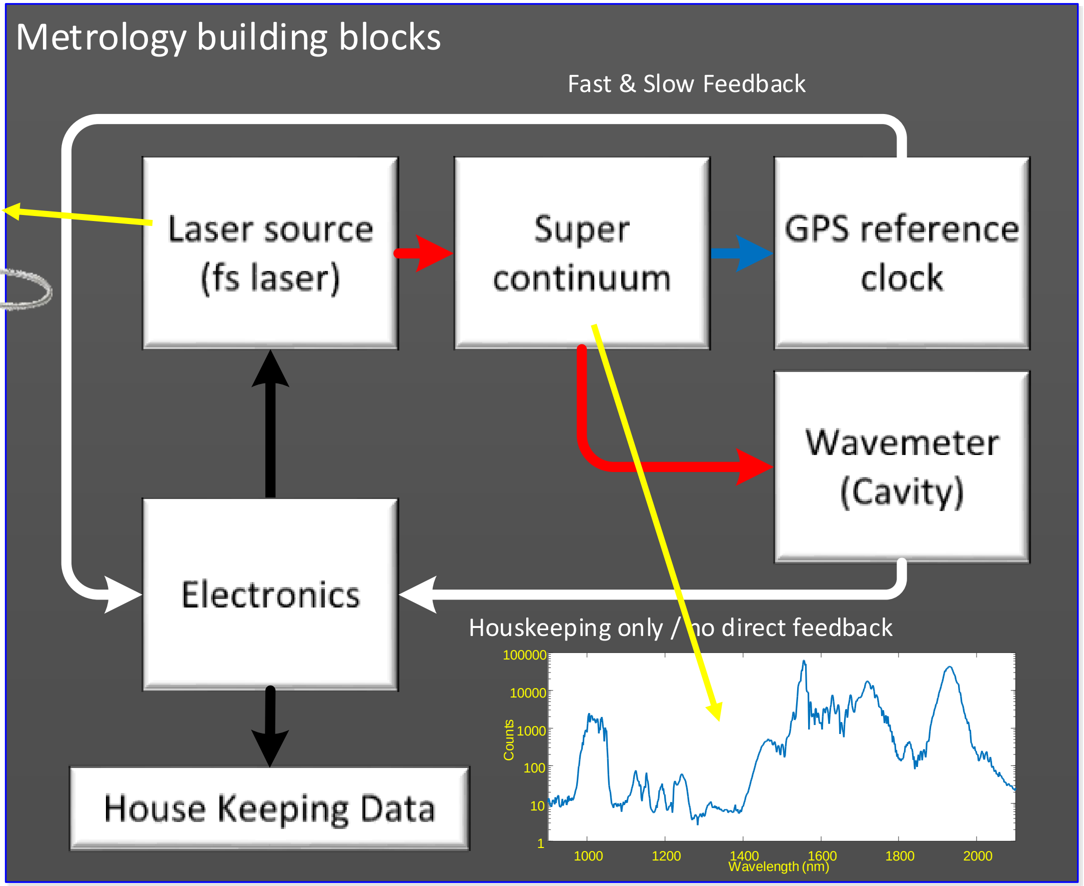
Frequency metrology for trace gas detection

EU's Horizon 2020

ONERA THE FRENCH AEROSPACE LAB

Frequency reference unit for LEMON

- Dual absorption lidar system addressing multiple species (CO_2, H_20, HDO, CH_4) at 2 µm
- Airborne demonstrator (full fiber optic / electronic stabilization)
- 7 % spectral coverage needed around 1 µm – the second harmonic of the OPO
  - ➢ **Tunable absolute frequency reference needed**



- **Laser**
  - fs light source
  - 1 GHz repetition rate (comb mode spacing)
  - 1550 nm telecom wavelength

Menhir Photonics covesion

- **Super continuum**
  - Octave spanning for f-2f detection
  - Covering 1 µm region for OPO detection & stabilization
- **GPS stabilized reference clock**
  - Easy to implement
  - Sufficient stability (<3x10-11)
- **Wavemeter**
  - Used for coarse calibration
  - ➢ comb mode identification
  - < 250 MHz absolute accuracy

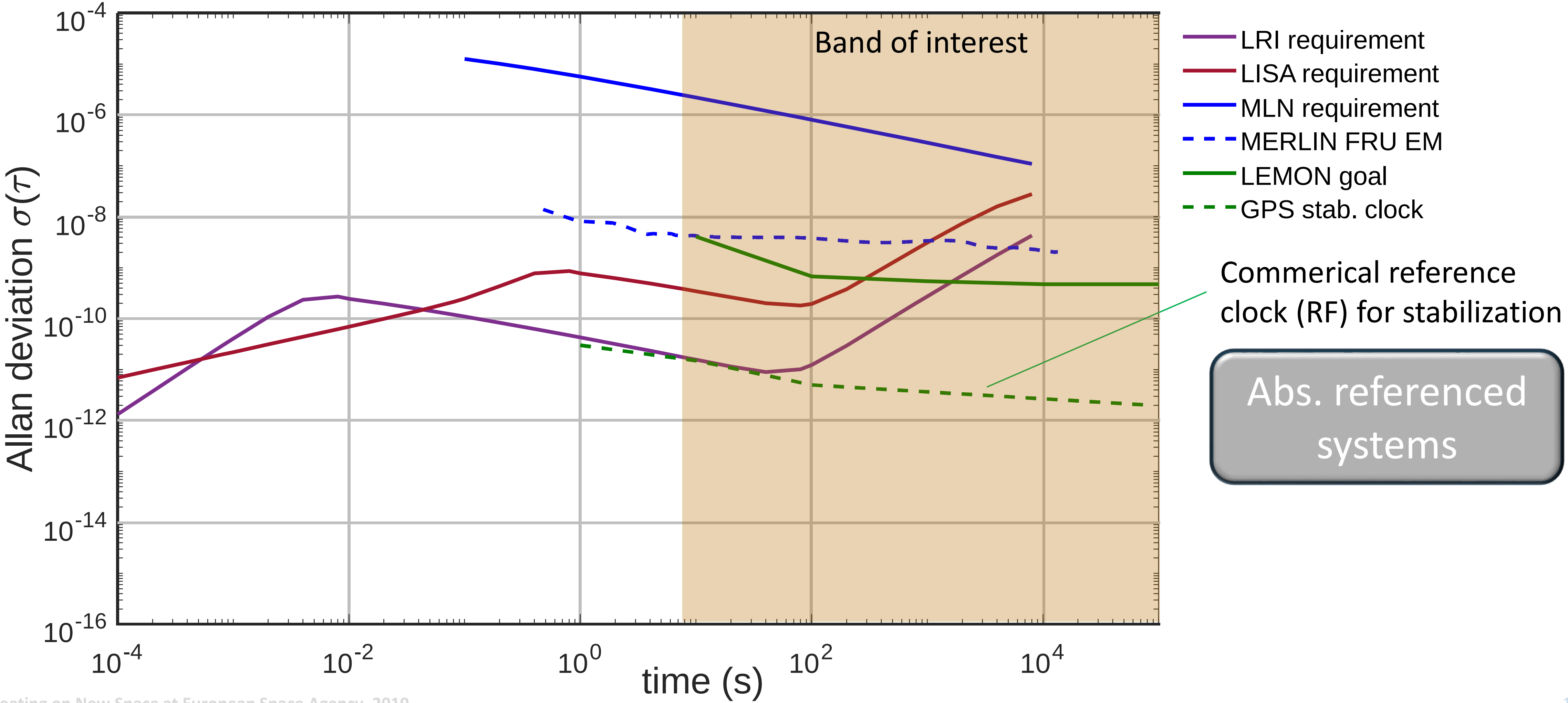
lemon

lemon-dial-project.eu

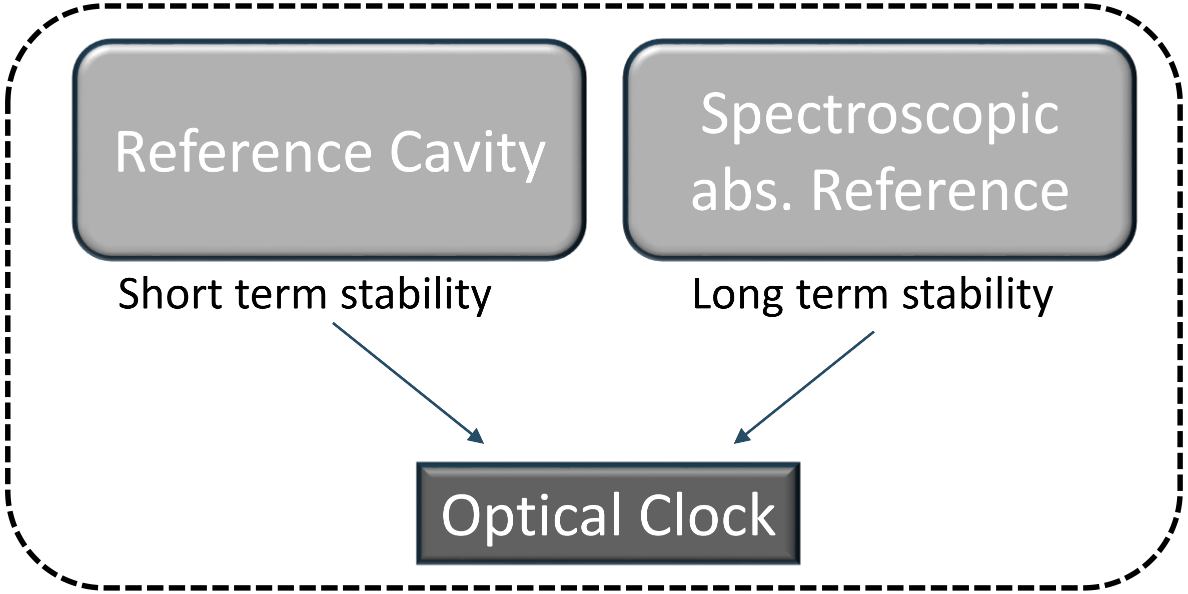
Frequency metrology for trace gas detection

Space developments on frequency metrology

- Allen deviation of LEMON frequency reference unit
  - Requirement and foreseen reference clock



Outline



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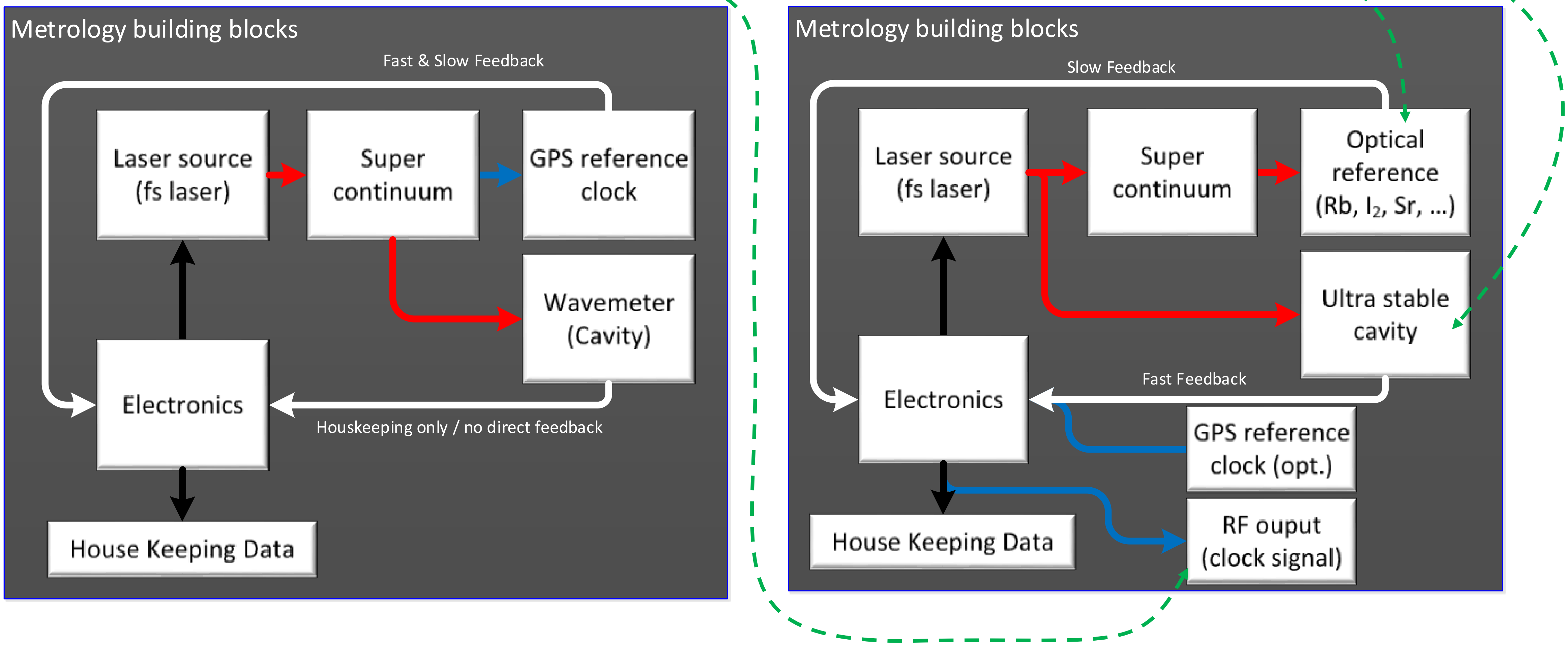
From a frequency reference to an optical atomic clock

The final step towards optical atomic clocks

- Steps to be done
  - Integration of an ultra stable cavity
  - Replacement of the RF reference by an optical reference
  - Highly stabilized output provides clock signal to RF



Development timeline from Spacetech's view

TRL 1-3 4-6 7-9

Photonic integration wherever possible

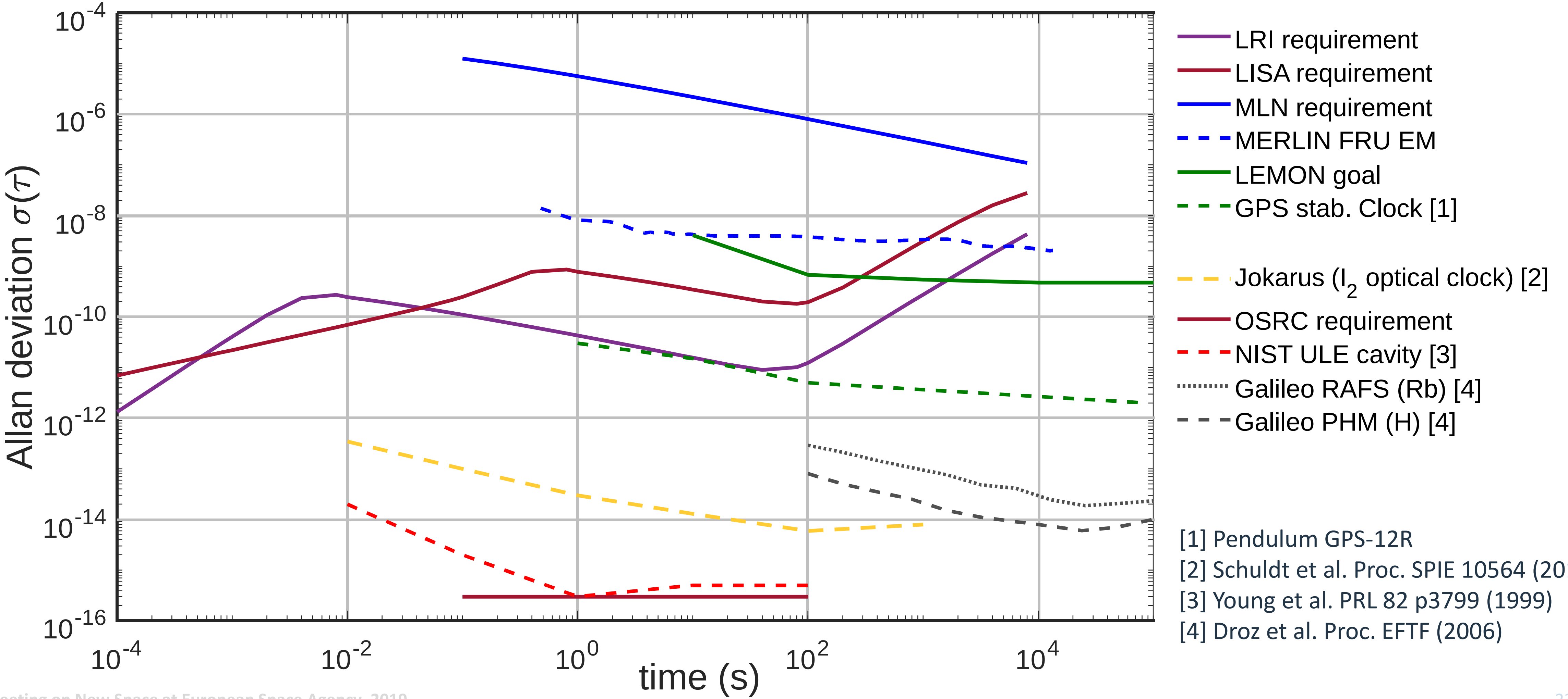
The final step towards optical atomic clocks

	Flight hardware in AIT: MERLIN FRU	Ongoing development: LEMON FRUit	1. compact optical clock: DLR Study, G2G	Perspective for higher accuracy solutions
Laser source	DFB	1 GHz fs Oscillator	ECDL	ECDL / ECDL ROF
Absolute reference	Simple gas cell	GPS reference	Doppler free gas cell	Cold atoms reference
External cavity	Not required	Not required	HSL/OSRC cavity (opt.)	HSL/OSRC cavity
Transfer	Not required	GHz comb	Comb	Comb
	10^{-8} @ 1s	3×10^{-11} @ 1s	$<10^{-14}$ @ 1s	$<10^{-16}$ @ 1s

Overview over achieved performances

From lidar to optical atomic clocks

- Technologies for the next step have been demonstrated
  - ➢ Make them compact and robust for the space environment



[1] Pendulum GPS-12R
[2] Schuldt et al. Proc. SPIE 10564 (2012)
[3] Young et al. PRL 82 p3799 (1999)
[4] Droz et al. Proc. EFTF (2006)

Summary

- SpaceTech is a dynamic and experienced partner for space developments
  - New space is a central topic at SpaceTech
  - Gateway to space for commercial photonic products
  - New partners are welcome
- SpaceTech has developed building blocks for key elements of optical clocks
  - Stable and reliable laser sources
  - Stabilization on cavity and spectroscopic references
- Next step is to get an optical clock to space on satellite level
  - Shrinking by higher integration levels and modern technologies
  - Space qualification

SpaceTech GmbH

- Systems
- Instruments
- Equipment

Thank you very much for your attention!

Many thanks to our partners

TESAT, NPL National Physical Laboratory, JPL, DELOS Space, FBH Ferdinand Braun Institut, DLR, ONERA THE FRENCH AEROSPACE LAB, GFZ Helmholtz Centre Potsdam, Fraunhofer ILT, AIRBUS, MenloSystems

and more…

Seelbachstr. 13
D-88090 Immenstaad
Tel: +49 7454 932 84 86
www.spacetech-i.com

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