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FROM INERTIAL NAVIGATION TO OPTICAL COMMUNICATION LINKS IN SPACE

CLEMENT GUYOT
SPACE PRODUCT LINE MANAGER

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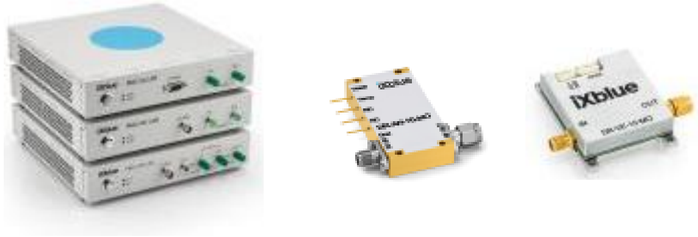
Photonics and Quantum COTS solutions, from components to instruments

› Scalable technologies to address a full range of applications

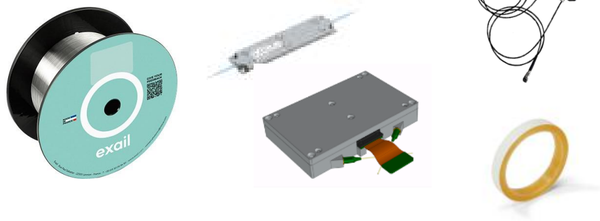
Components

$LiNbO_3$ Phase, Amplitude, IQ Modulators (COTS, Space model)

Modulators Matching components (RF Amplifier, Low Noise Electronic)



Fibers and fiber solutions (Fiber, FBG, coils)



Turn-key devices and systems

µoptics and passive optics integration

Transmitters, transceivers, laser pilot, coherent regeneration station

Lasers (Narrow-linewidth, high-power) Optical Low Noise & Power amplifiers

Instruments

Absolute Quantum Gravimeter

Cold atom frequency metrology

Inertial Measurement Unit

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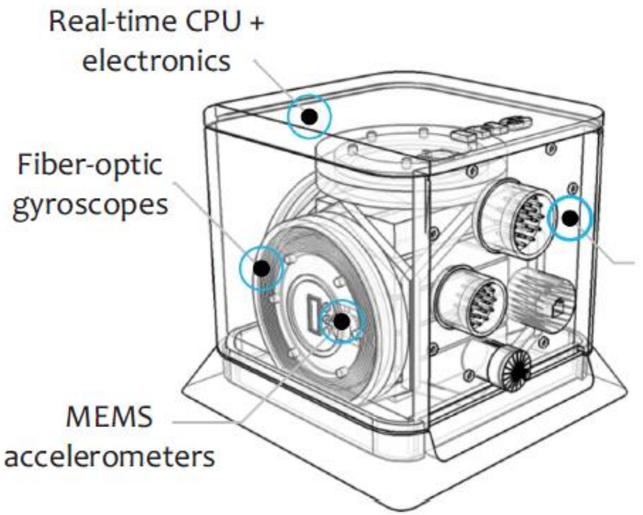
INERTIAL NAVIGATION IN SPACE

Inertial Navigation System

Aim to know the exact position of an object by measuring inertia



Composition of an INS

- 3 accelerometers
- 3 gyroscopes
- Signal processing (Strapdown algorithm, Kalman filter…)

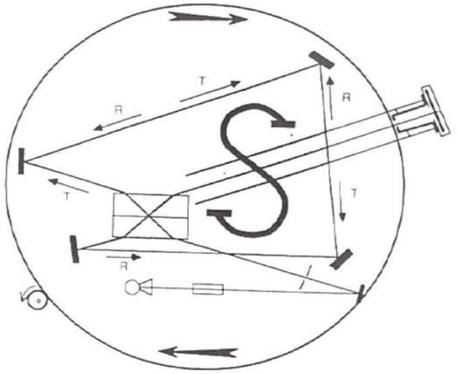
Different technologies & precision ranges

- MEMS gyroscopes
- Microresonator based gyroscopes
- Ring laser gyroscopes - RLG
- Fiber optic gyroscopes - FOG

Performance Grade	Bias Stability	Applications	Gyro Technology
Consumer	30–1000°/h	Motion interface	MEMS
Industrial & Low-end Tactical	1–30°/h	Ammunitions & rockets guidance	MEMS
Tactical	0.1–30°/h	Platform stabilization	FOG/RLG
High-end Tactical	0.1–1°/h	Missile navigation	RLG/FOG
Navigation	0.01–0.1°/h	Aeronautics navigation	RLG/FOG
Strategic	0.0001–0.01°/h	Submarine navigation	RLG/FOG

Vittorio M. N. Passaro et al. , Gyroscope Technology and Applications: A Review in the Industrial Perspective, Sensors 17, 2284

The fiber optic gyroscope

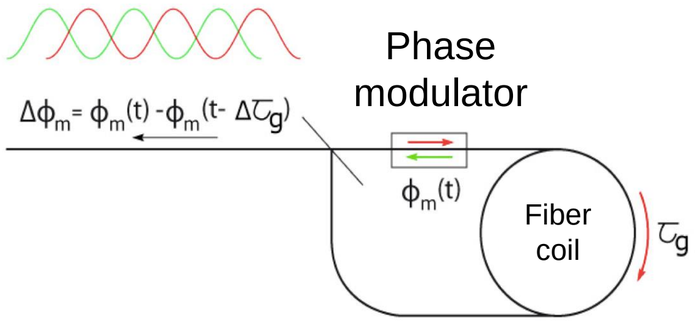


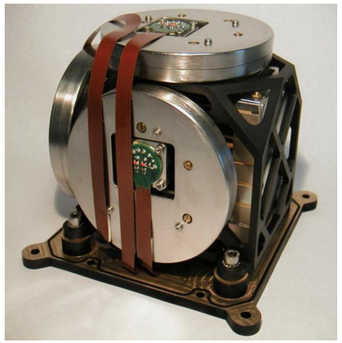
Based on Sagnac effect

- Measurement of the phase difference between two counter propagating waves along optical path length during interferometer rotation
- Phase difference proportional to rotation rate

Principle of FOG

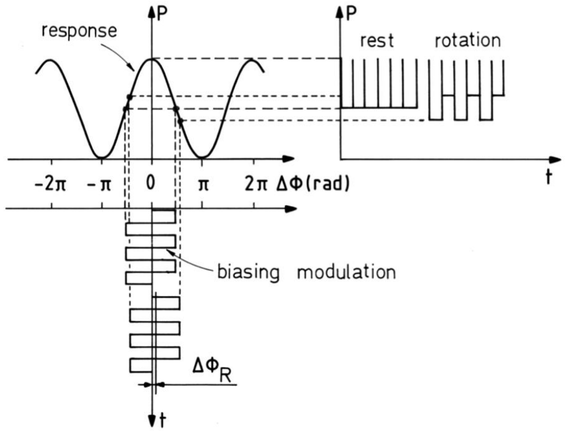
- Free space interferometer replaced by optical fiber coil
- Coil diameter & length determine the rotation precision
- Phase modulation used to bias the system





Advantages

- Reciprocity
- No acoustical noise
- Low maintenance
- Close to theoretical performances → **high performance reachable**
  - **Submarine or space for instance**



H Lefevre, The Fiber Optic Gyroscope, 2nd Edition, Artech House, 2014

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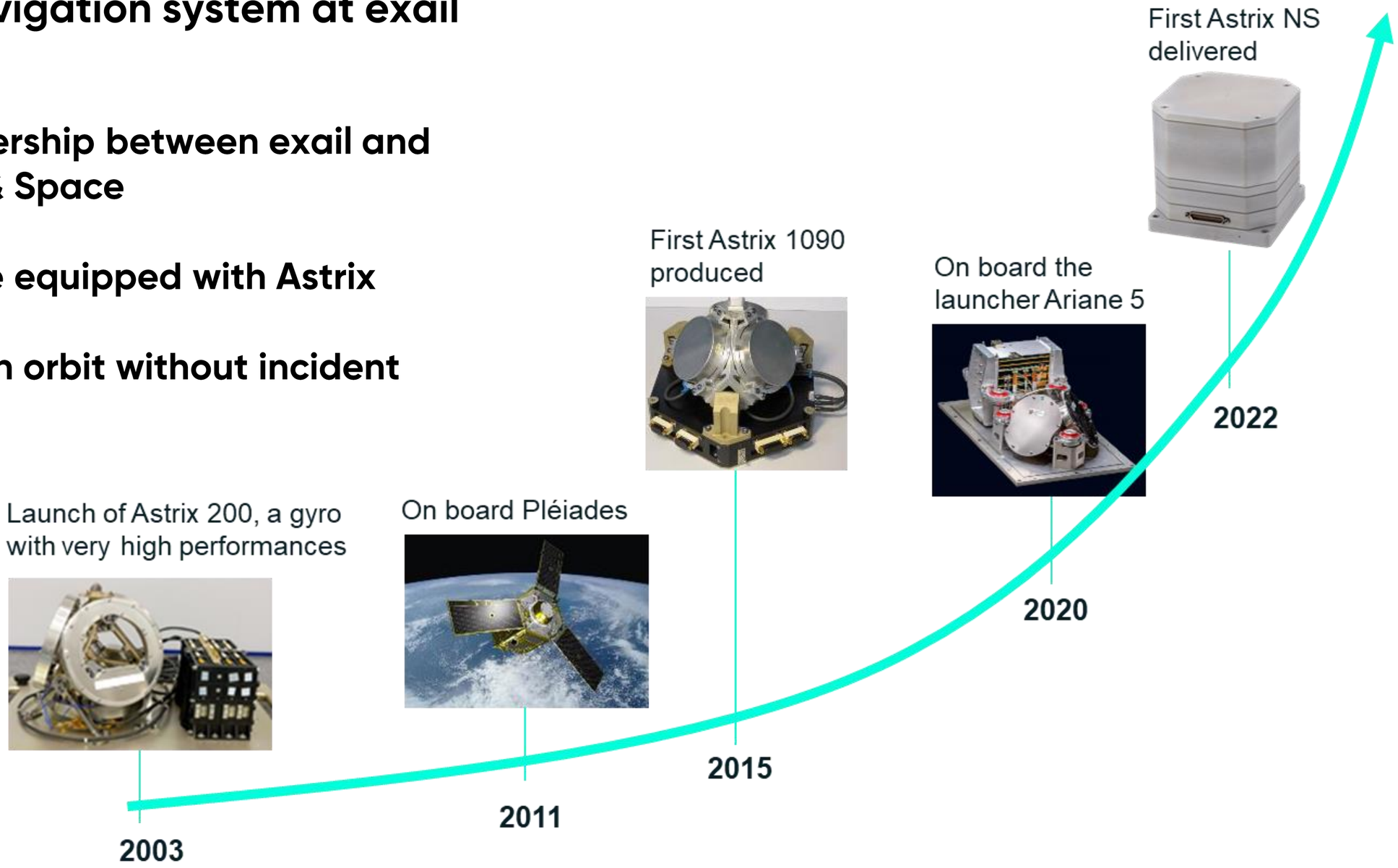
Space inertial navigation system at exail

- +20-years partnership between exail and Airbus Defence & Space
- +30 satellites are equipped with Astrix
- +6 million hours in orbit without incident



FOG & INS applications in space

Inertial measurement unit for Exomars mission

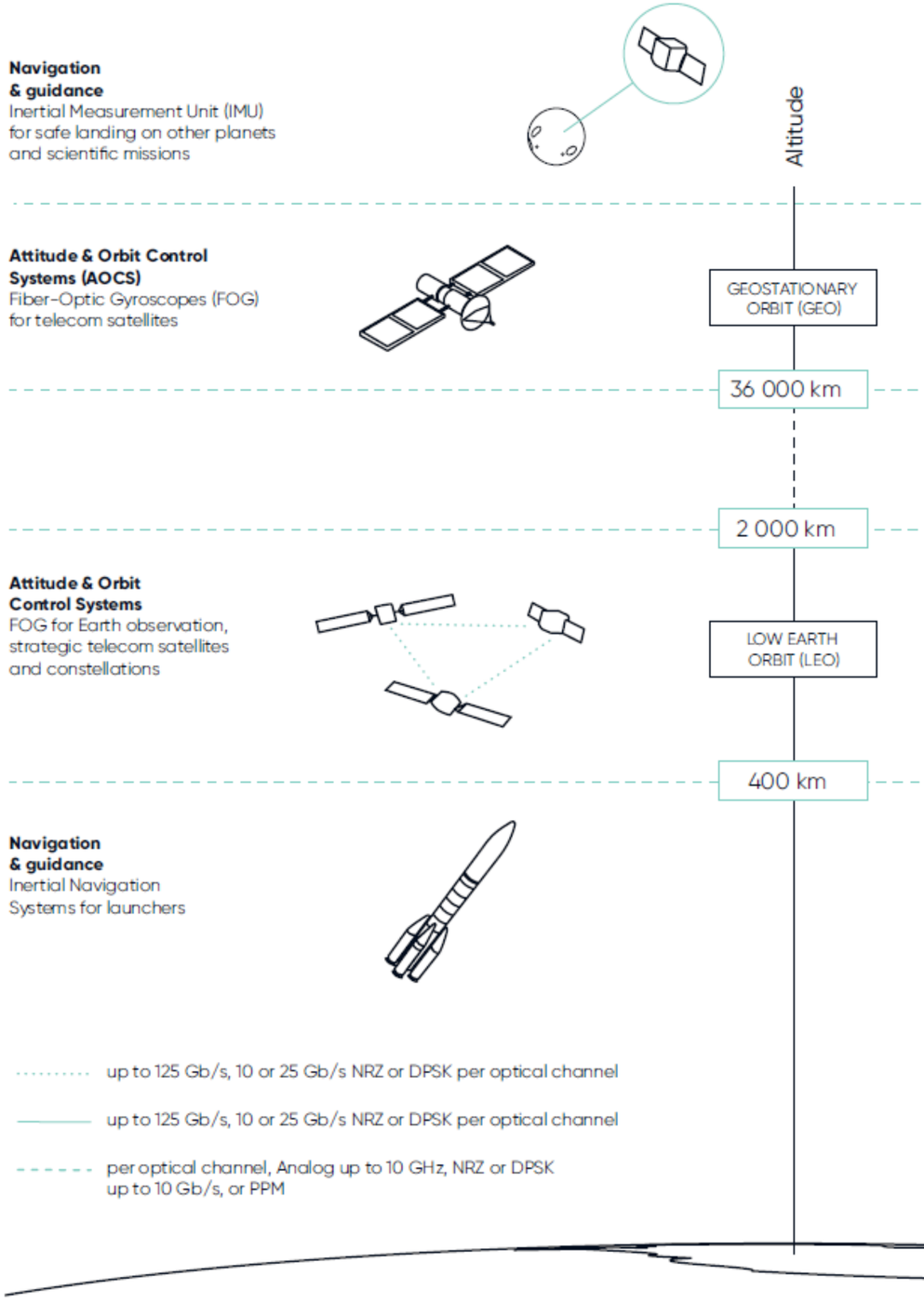
- Astrix 90 IMU will be placed on exomars rover to manage difficult and sensitive **landing** phase on Mars.

Fiber Optic Gyroscope on satellites

- Used for **attitude & orbit control**
- Compensation of micromovements of the satellites for precise satellite attitude (earth observation)

Safety inertial navigation for Ariane 5 & 6 launchers

- Used to indicate the **precise position** of the launcher. Help for decision to make the launcher explode in case of wrong destination
- Full performance under **vibrations (27 g rms), shocks 5000g, vacuum and very high speed**



RISE OF SPACE OPTICAL COMMUNICATION

Optical link between ground and space

Replacement of conventional electrical approach by photonic components & systems

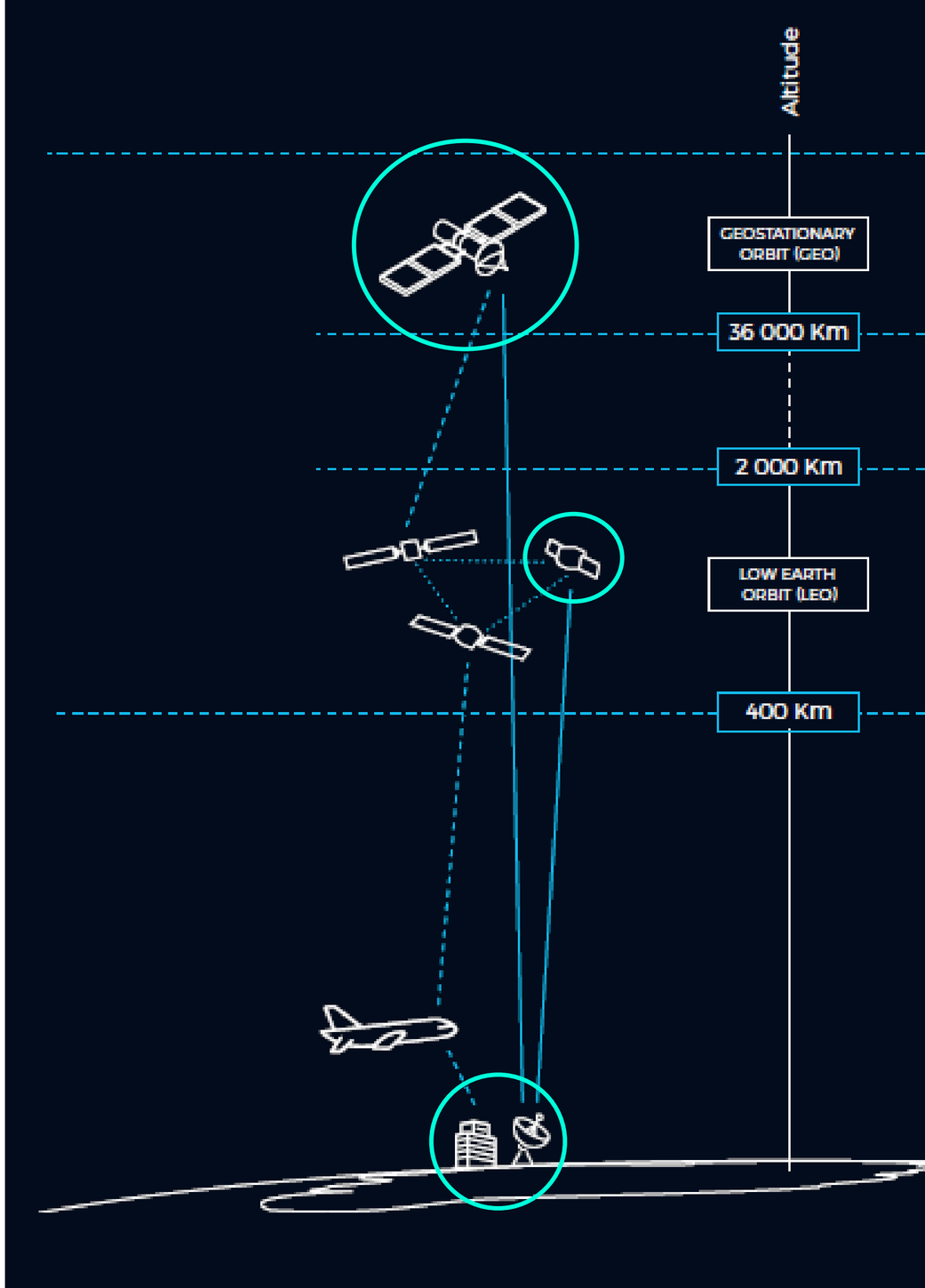
- More compact, lighter and cost-effective satellites
- Increase of data rate to hundreds of Gb/s and higher than Tb/s
- No frequency authorization requirement
- Secure transmission with reduced beam diameter

LEO-LEO inter & intra satellite constellation communication:

- Different strategies depending on satellite lifetime: 2-3 years vs up to 7 years on-flight. **COTS vs high reliability parts**
- **Radiation environment** very different depending on orbit altitude
- Few attenuation → **no amplification needed**.

Optical link on GEO Feeder satellite implies :

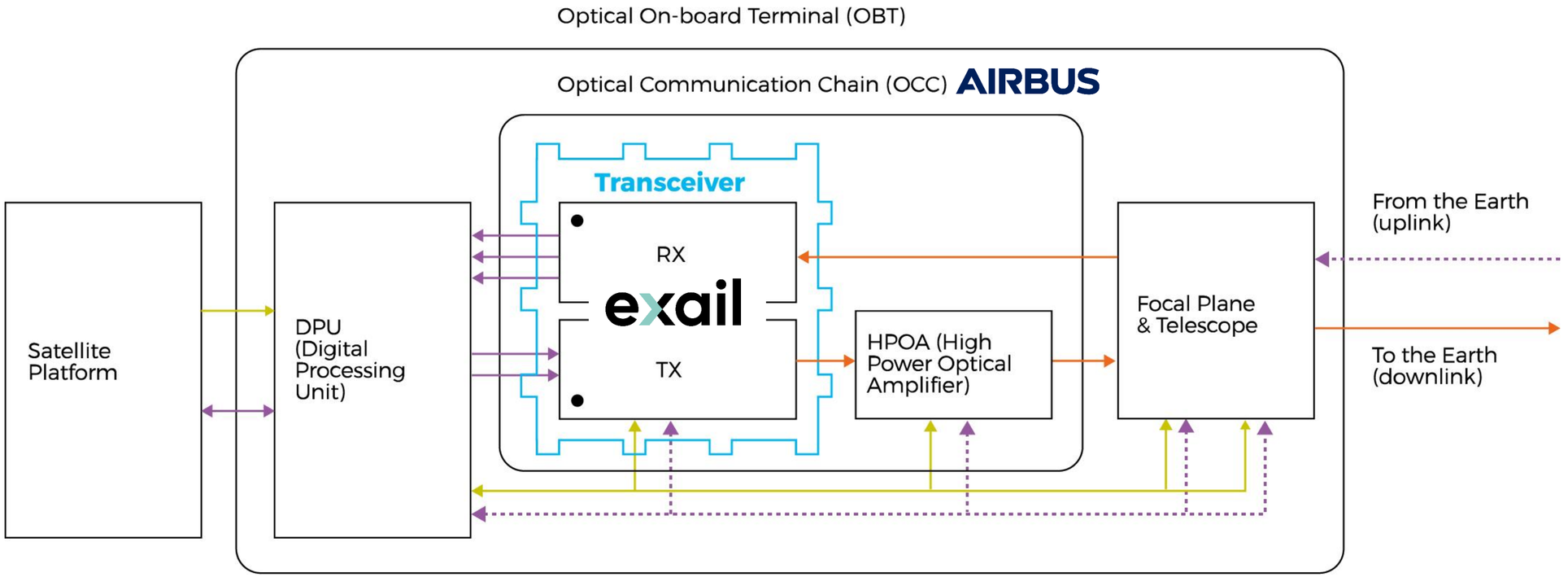
- equipment design that can handle up to **15-year lifetime under harsh environment** (radiations, vacuum, thermal cycling…)
- Signal power and contrast sufficient enough to compensate **atmospheric attenuation**



Transceiver for on-board terminal

Transceiver is part of an optical board terminal

- Aims to generate downlink modulated optical signal (**Tx - transmitter**)
- And to detect and convert optical uplink modulated signal (**Rx - receiver**)



C. Guyot et al., “WDM Optical Front End for GEO-Ground Digital and Analog Telecommunications”, ICSO 2022.

P. Berceau et al., “Space Optical Instrument for GEO – Ground Laser communications”, ICSO 2022.

S. Poulenard et al., “10 Gbauds digital optical link and analog link from/to geostationary satellite”, ICSO 2022.

Space grade solutions, telecom, and scientific

TRL9 Fibers, $LiNbO_3$ Modulators and free space optical assemblies

- **Space Grade PM Gyro Fibers & RadHard Space Grade Doped Fibers**
  - +10 references in stock with guaranteed Radiation Induced Attenuation (RIA)
  - +1000 km space qualified fibers delivered
  - Guaranteed Radiation Induced Gain Variation (RIGV) on Er, Yb and Er/Yb fibers

- **On-board Amplitude and Phase $LiNbO_3$ modulators**
  - 850 nm & 1064 nm & 1550 nm, High Extinction Ratio, TRL9 modulators
  - more than 30 projects delivered, and 10 on-going projects involved
  - +300 Flight Models modulators delivered

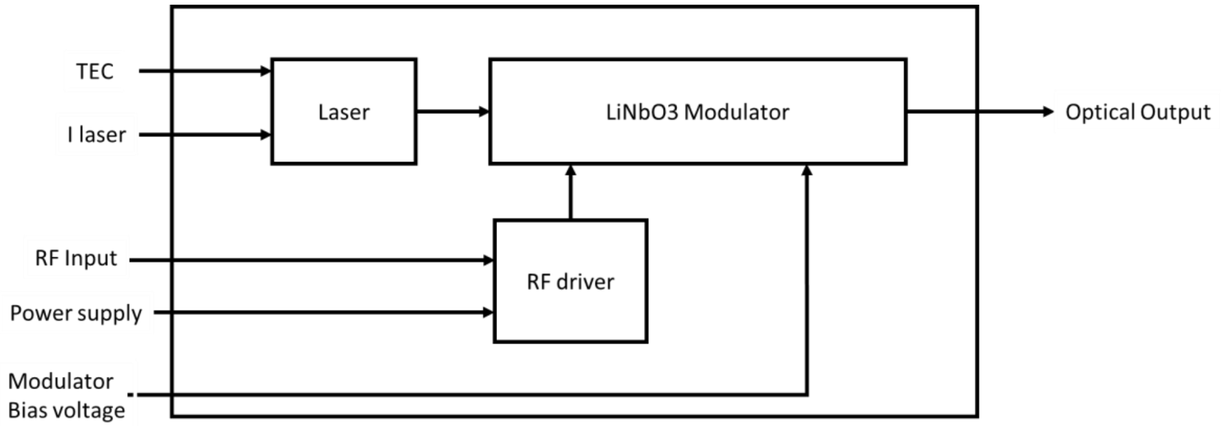
- **On-board free space optical assemblies**
  - TRL9 hybrid coherent mixers
  - TRL6 Multiplexers & Demultiplexers
  - TRL9 custom free space optical assemblies

Space grade sub-systems

Optical Channel Emitter - OCE

OCE highlight:

- Autonomous optical modulated channel composed by a laser, a modulator and a RF driver
- Single electrical connector to control laser, Modulator bias and RF driver

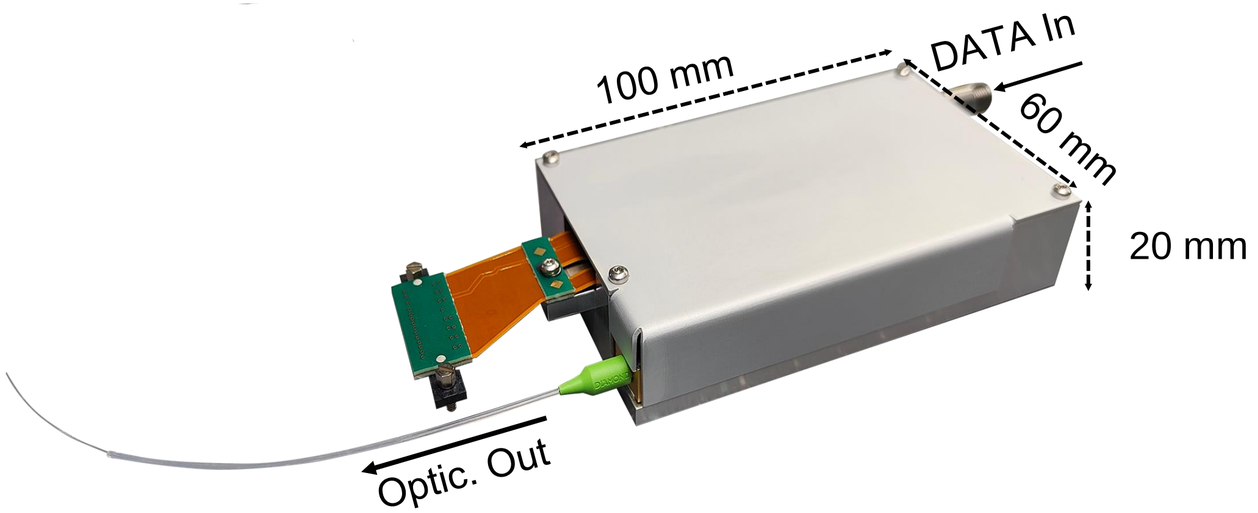


Main performances:

- Data rate up to 10 Gb/s
- NRZ-OOK or DPSK
- Output power > 10 mW
- RF input: 150 mVpp to 400 mVpp

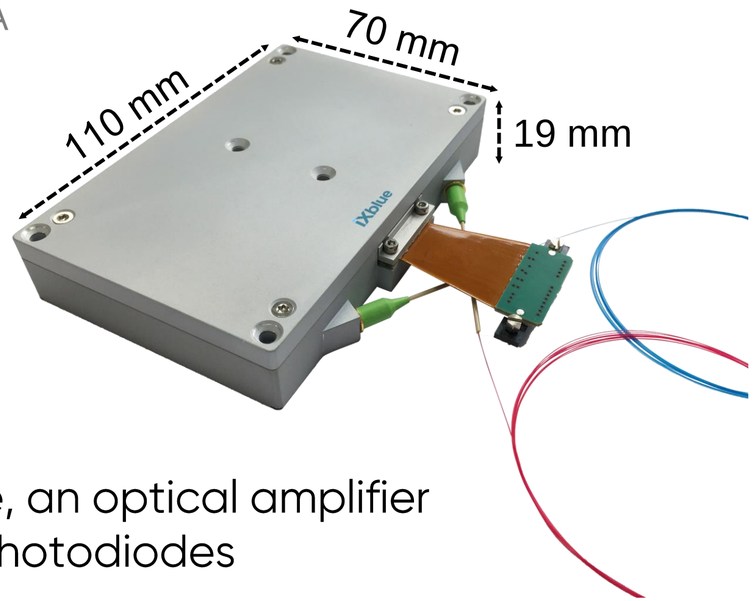
Environment:

- Assembly using Astrix legacy
- Spage qualified (lifetest, mechanical, thermal cycling, ESD)



Space grade sub-systems

Low Noise Optical Amplifier- LNOA



LNOA highlight:

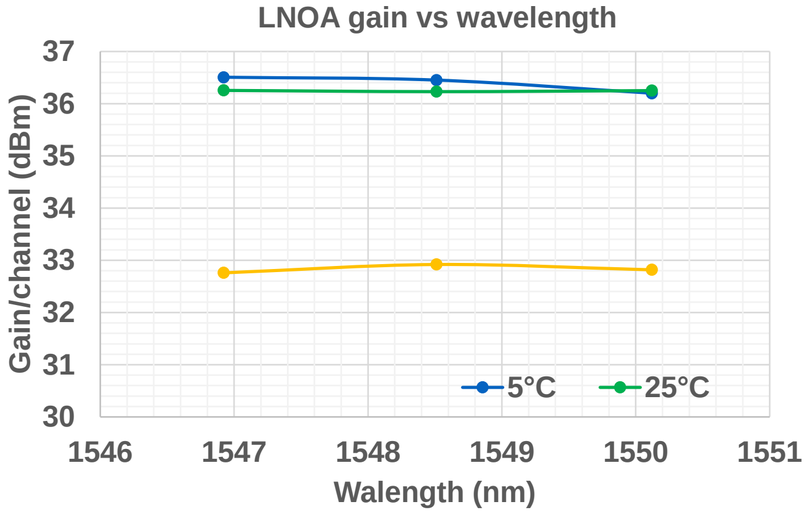
- Composed by a pump diode, an optical amplifier and one or two monitoring photodiodes
- Single channel or WDM

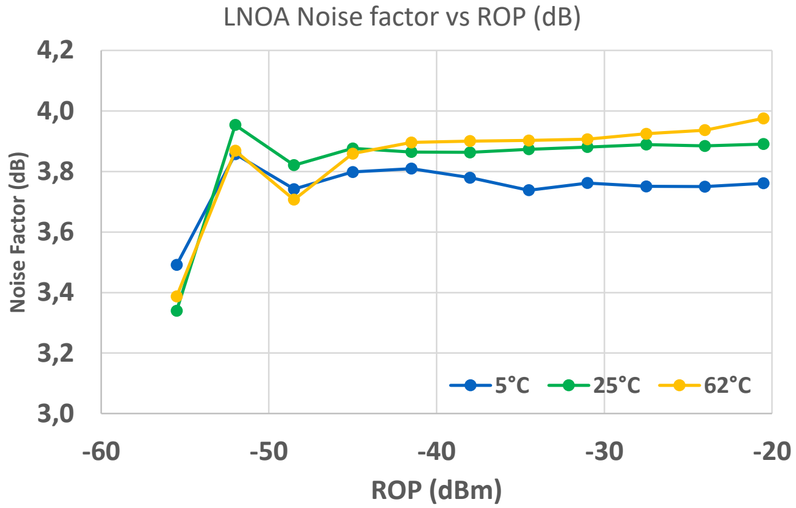
Typical performances at 25°C:

- Gain flatness < 1 dB for Pin [-55 dBm ; -20 dBm]
- Noise figure < 6 dB for Pin [-55 dBm ; -20 dBm]

Environment:

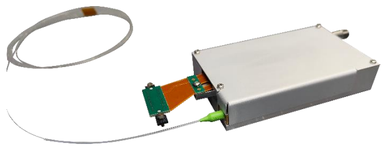
- Assembly using Astrix legacy
- Space qualified (radiation, mechanical tests)



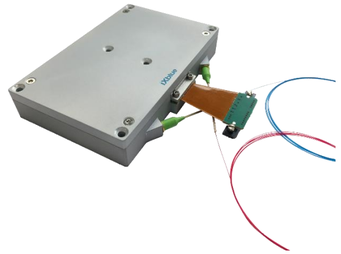


Space grade solutions, telecom, and scientific

Development of optical transceiver for GEO-Ground & LEO-ground telecommunications

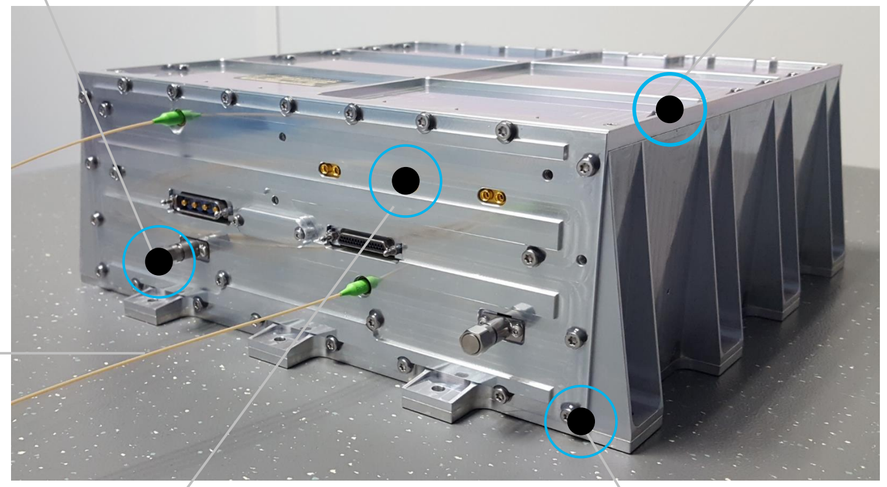


OCE / Optical Channel Emitter
Laser + Modulator + RF amplifier



LNOA /
Low noise amplifier

OCR / Optical Channel Receiver



Receiver stage
3 multiplexed channels
10 Gb/s OOK modulation
analog modulations
> -40dBm input power allowed

Transmitter stage
2 multiplexed channels
10 Gb/s DPSK modulation
> 7dBm output power/channel

- **First Demonstration Model integrated into BADR-8 GEO satellite. Launch planned in a few weeks.**
- **Transposable design for LEO feeder links. Ongoing manufacture of DM model for LASIN mission**

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TOWARD QUANTUM OPTICS

FOR DATA SECURING

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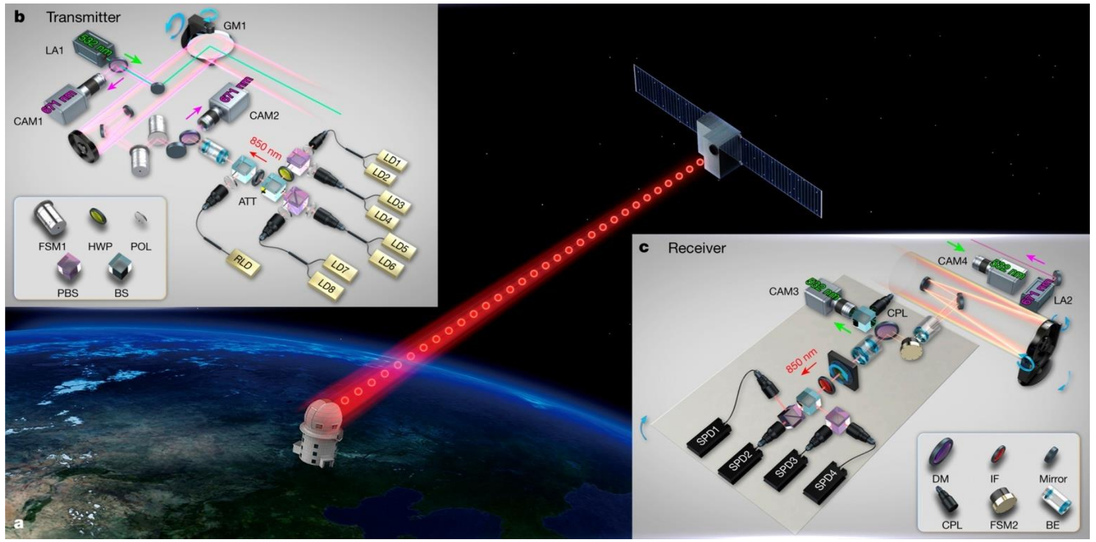
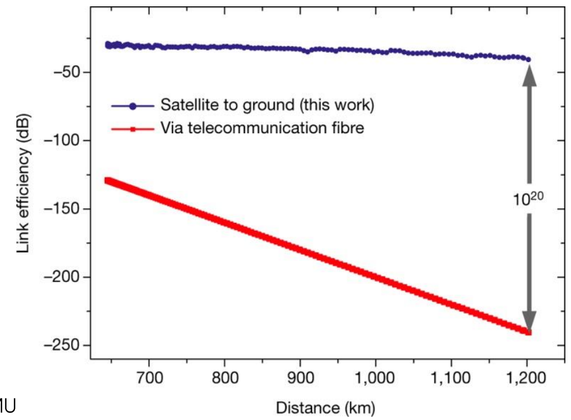
Space quantum cryptography

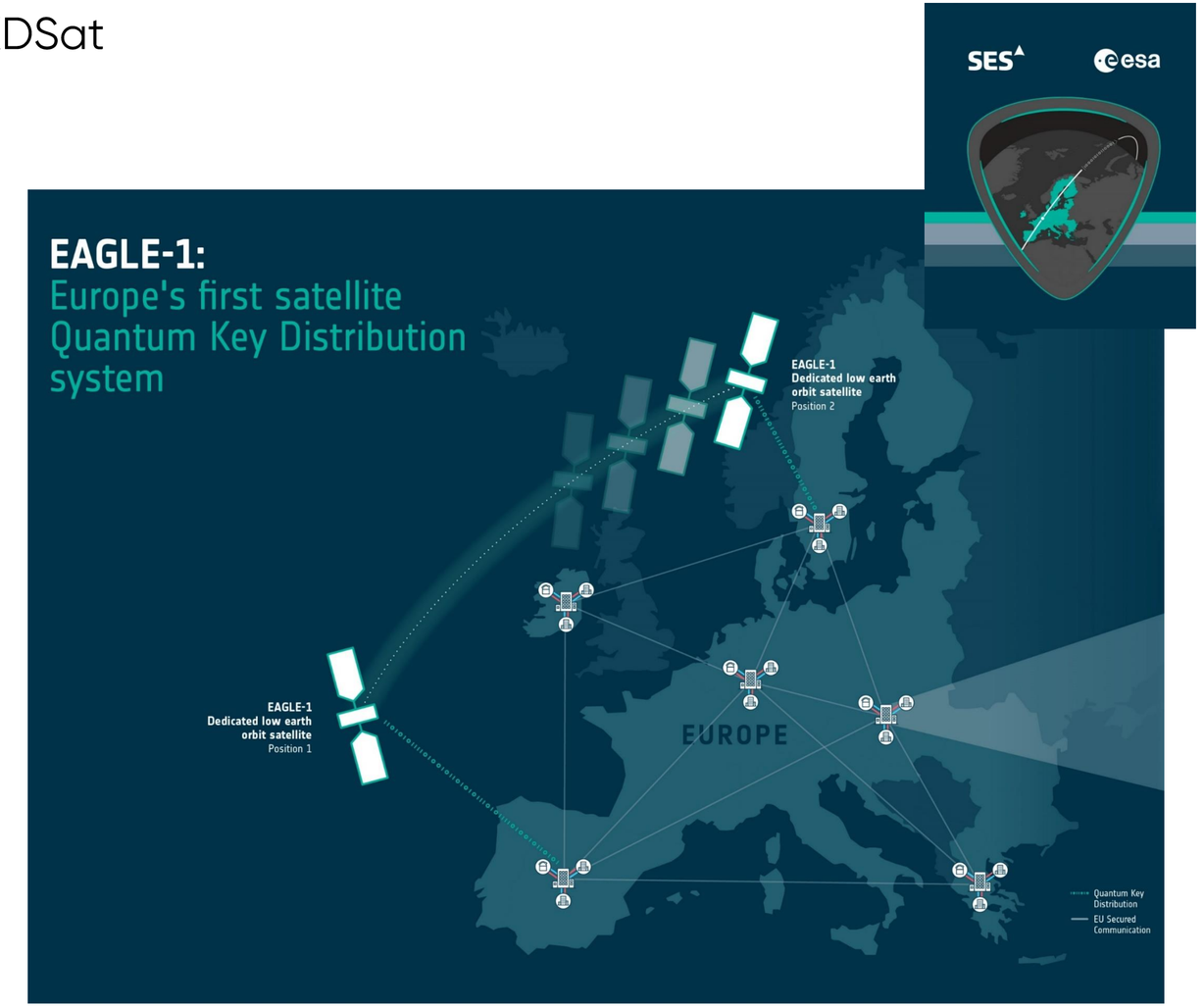
Quantum key distribution between two ground stations by the mean of a satelitte.

- First demonstration by Micius Chinese satellite in 2016
- Ongoing European response with projects Eagle-1 & QKDSat





Liao, SK., Cai, WQ., Liu, WY. *et al.* Satellite-to-ground quantum key distribution. *Nature* **549**, 43–47 (2017) nature



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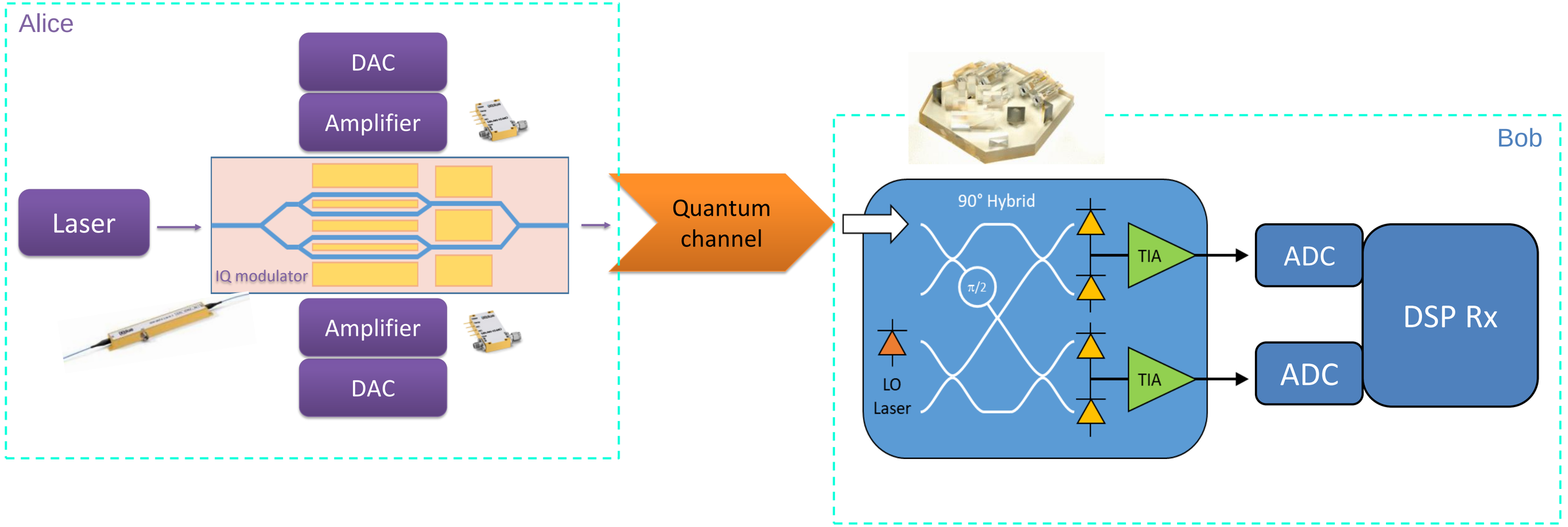
Quantum project in exail

- **CVQKD systems development with Thales & CNRS (for terrestrial market)**
  - Information encoded in amplitude and phase (phase & intensity modulators or IQ modulator)
  - use standard telecom components and DSP techniques
  - high-rates at metro scale
  - cost-effective

QKiss



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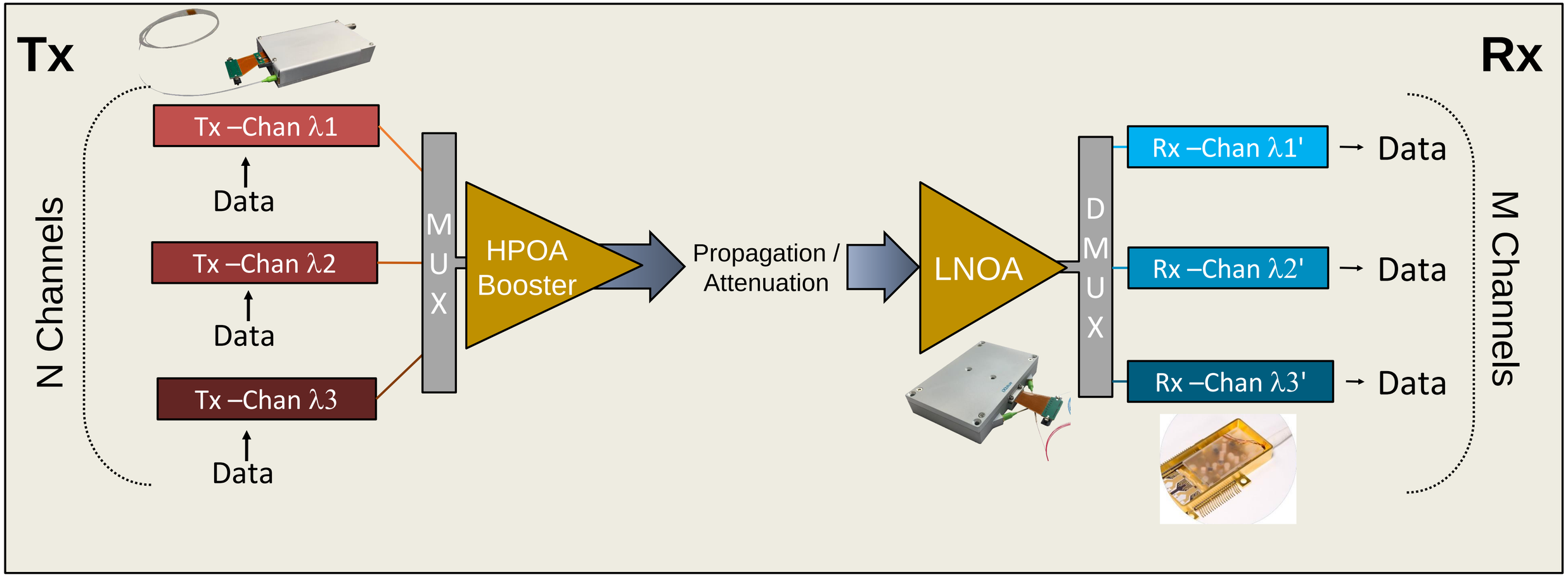
APPENDIX

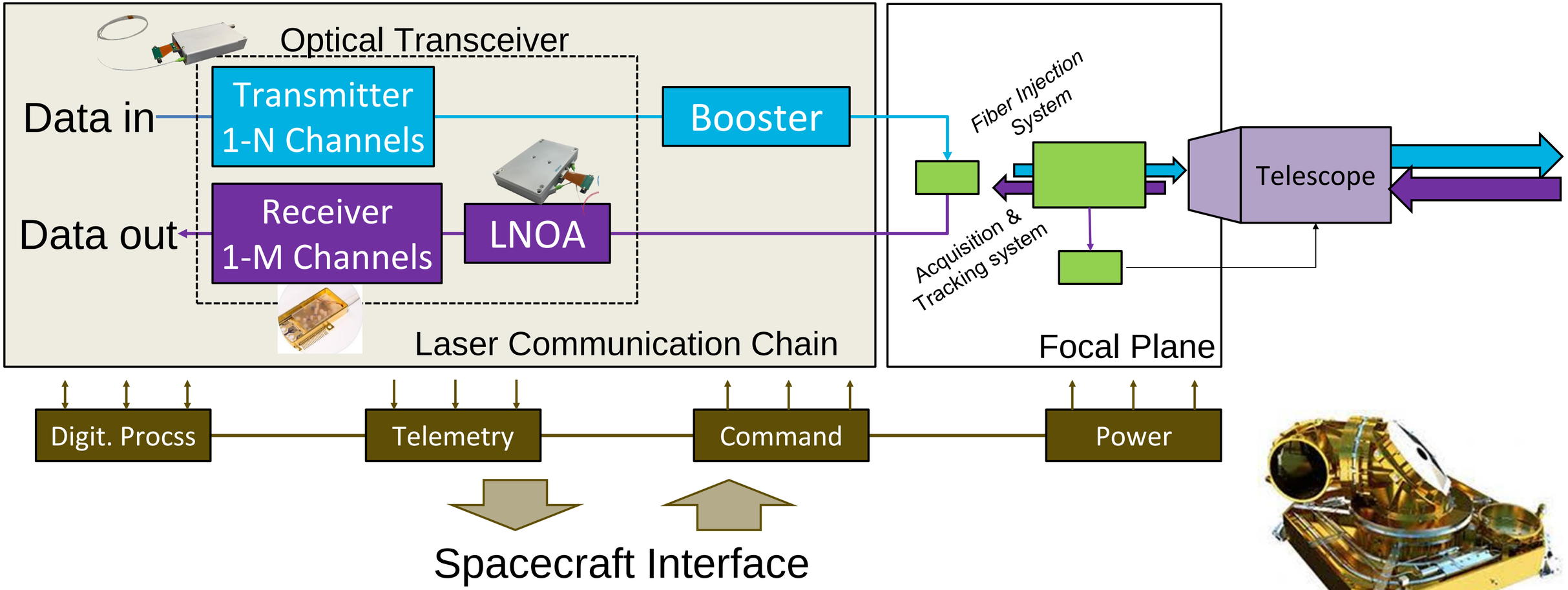
Space laser communication

Architecture WDM Architecture (wavelength multiplexing)



Space laser communication

Typical LCT architecture (Laser Communication Telescope)



TESAT

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Quick overview of the transceiver for TELEO demonstration

- **Dimensions:** 27x28x10 cm^3
- **Mass:** 6.6 kg
- **Power consumption:** ~22W

(1 Tx and 1 Rx simultaneous active channels)

- LCE/Transceiver is a standalone unit composed of three **6U-extended boards**

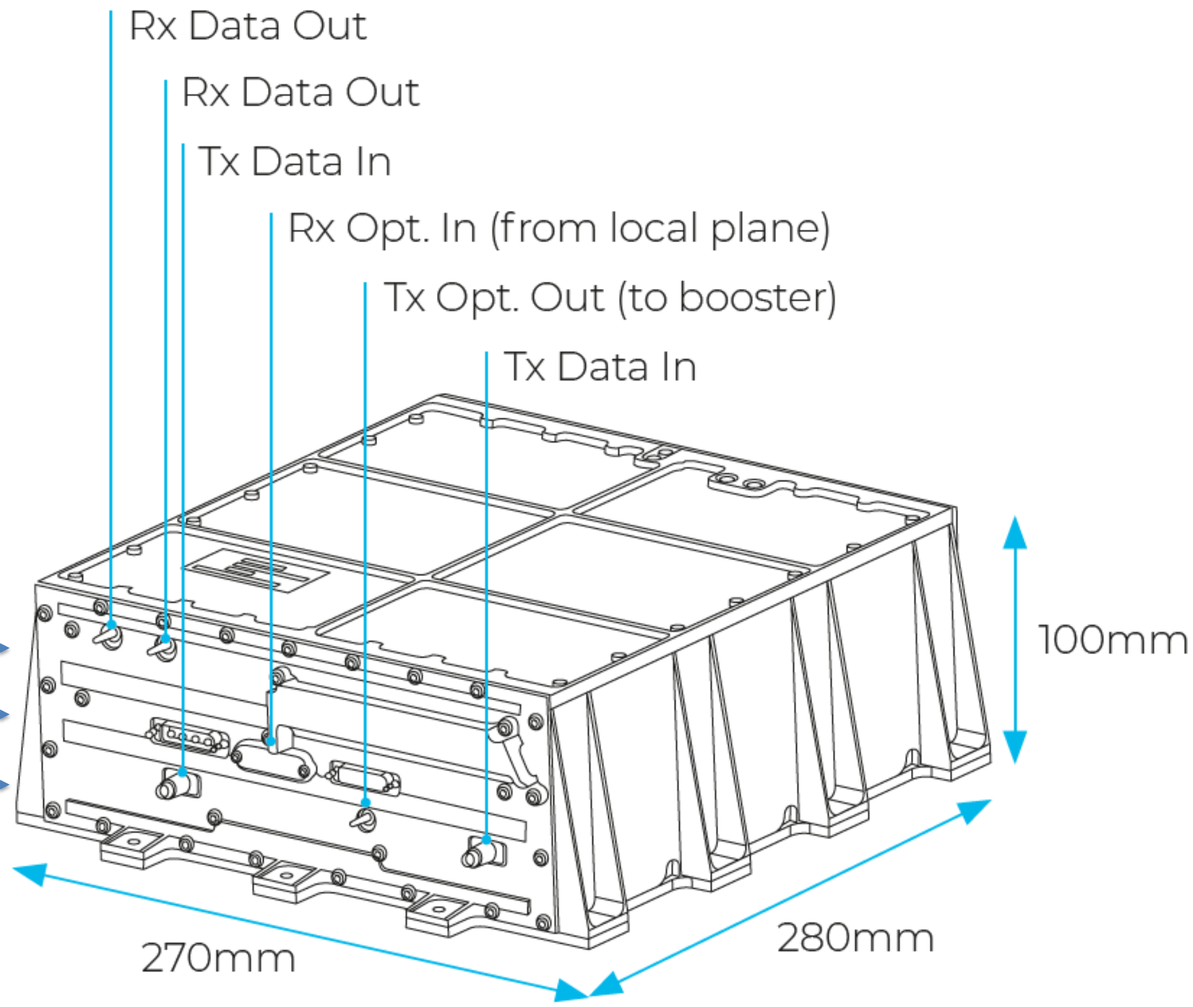
Receiver stage

CV stage

DC/DC converter – 100V power supply

TeleMetry / TeleControl

Transmitter stage

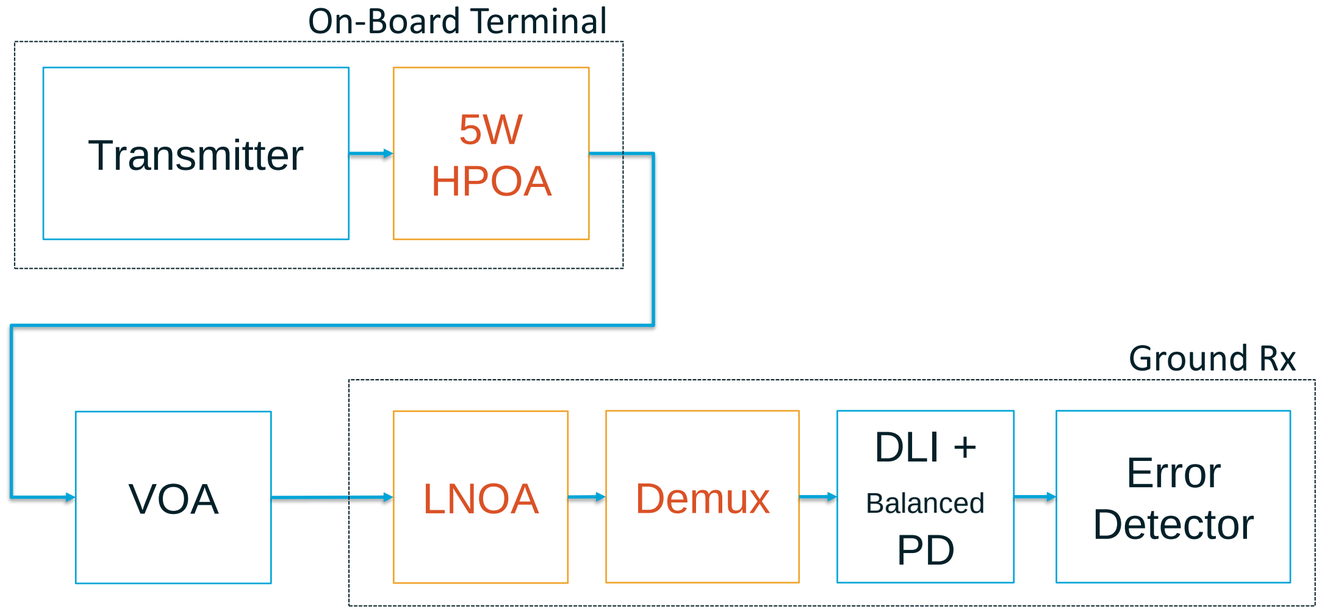


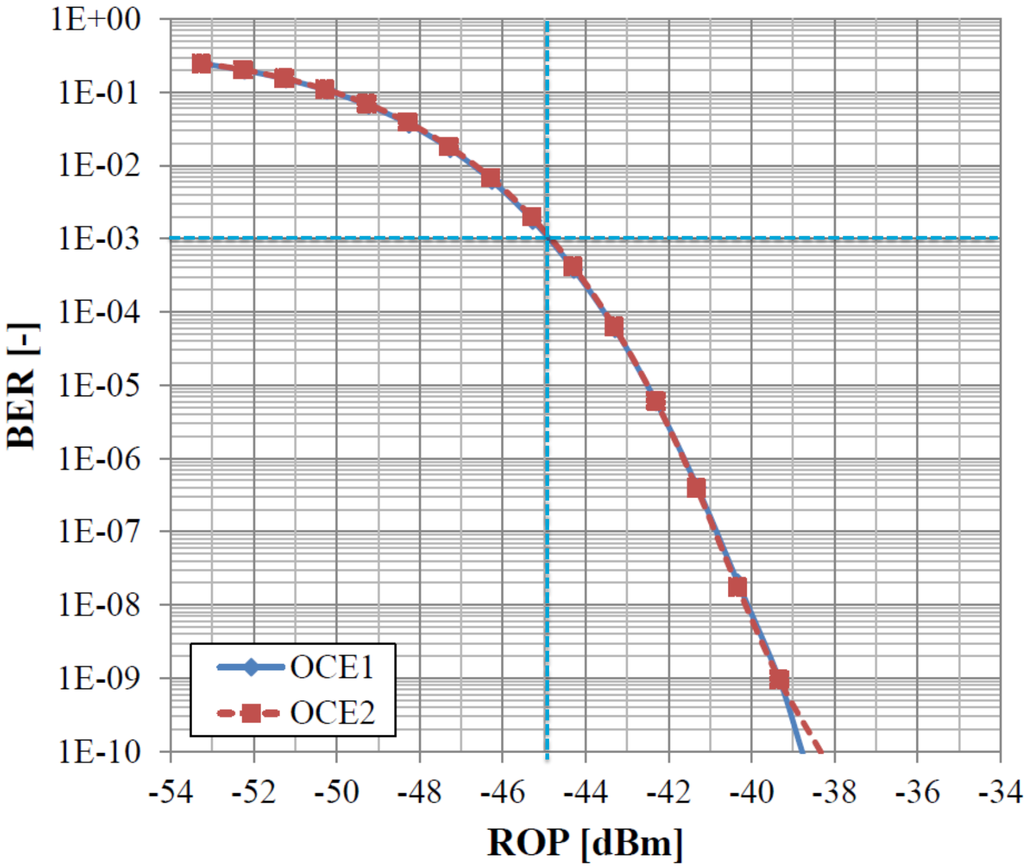
Transmitter stage

Nominal OCE Bit Error Rate (DPSK)

Full chain performance (room temperature)

BER Experimental setup (Airbus D&S)





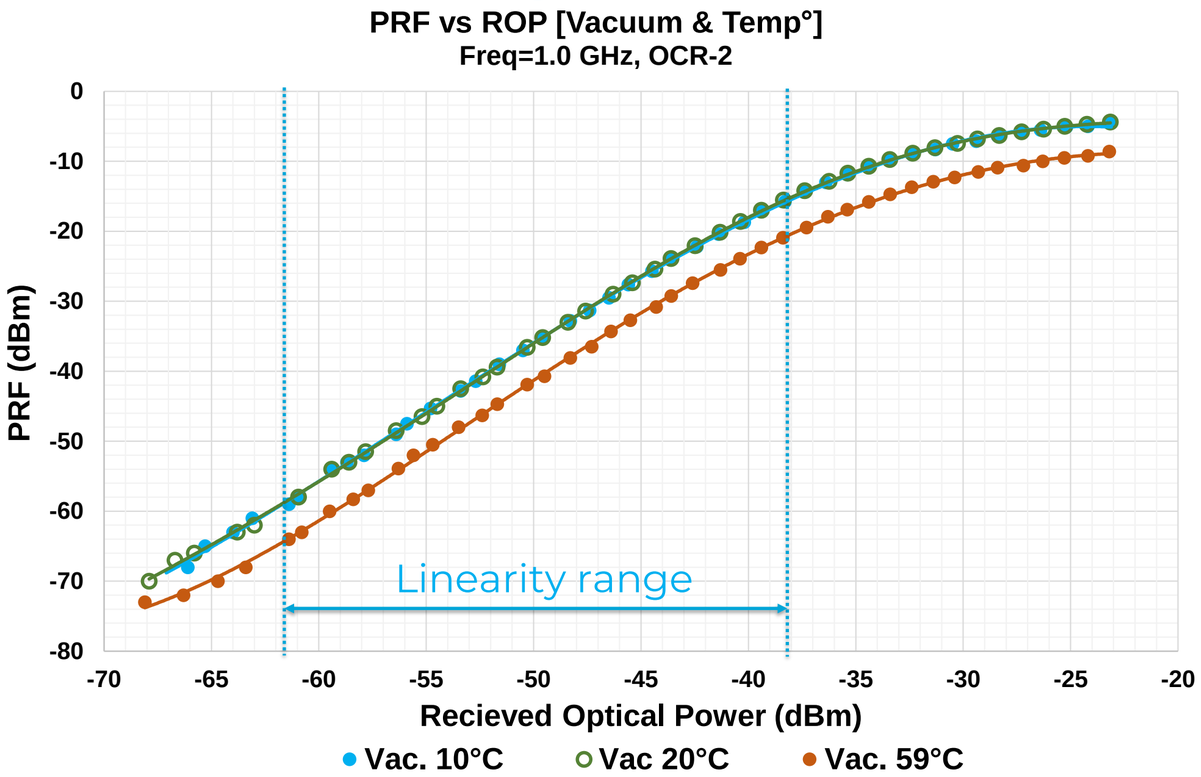
Result: uncoded **10^{-3} BER** obtained for ROP **-45 dBm** with PRBS 2^{63}-1 RF input signal.

S. Poulenard et al., “10 Gbauds digital optical link and analog link from/to geostationary satellite”, ICSO 2022.

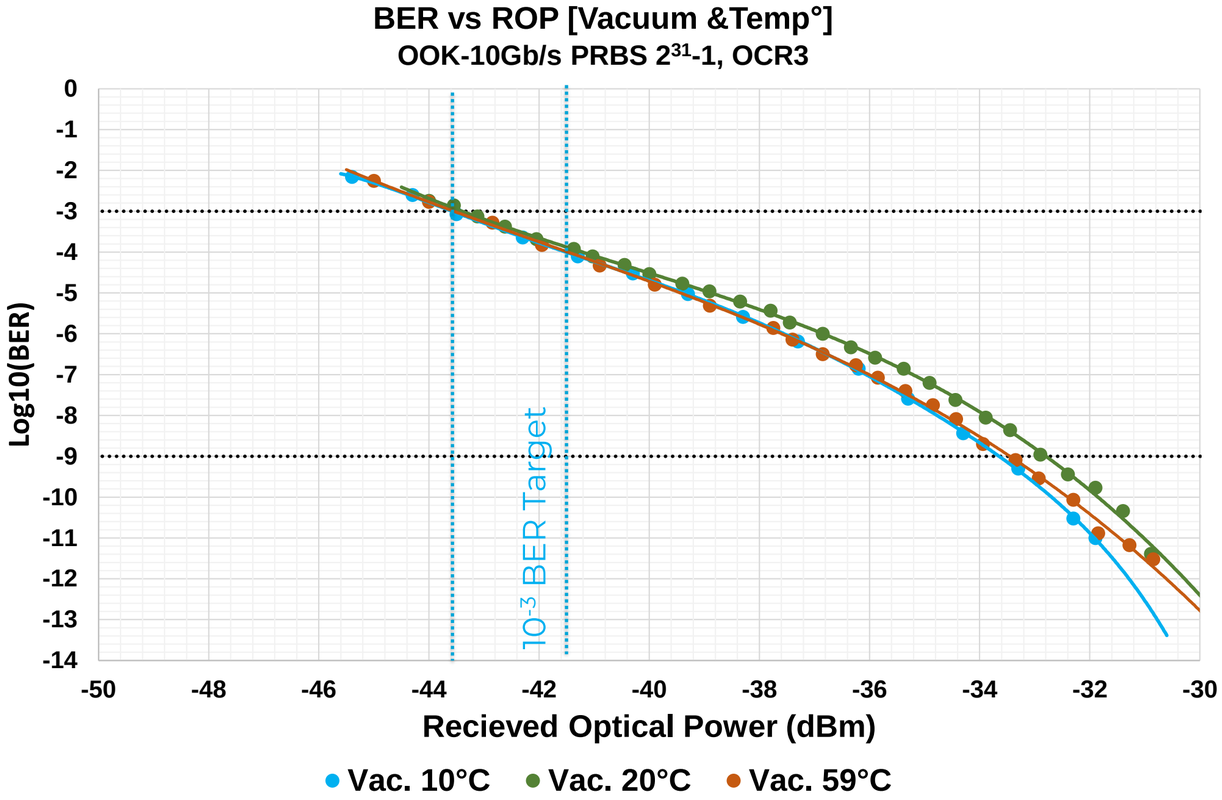
Receiver board

Analog and ditigal performances

Analog channels



Digital channel



Result: whatever the temperature, similar linearity range (ROP -62 / -38 dBm) in analog configuration, and same ROP to reach 10^{-3} BER

iXblue