Fiber Optic Sensors Space Applications: The experience of the European Space Agency

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14/09/2023

ESA UNCLASSIFIED – For ESA Official Use Only

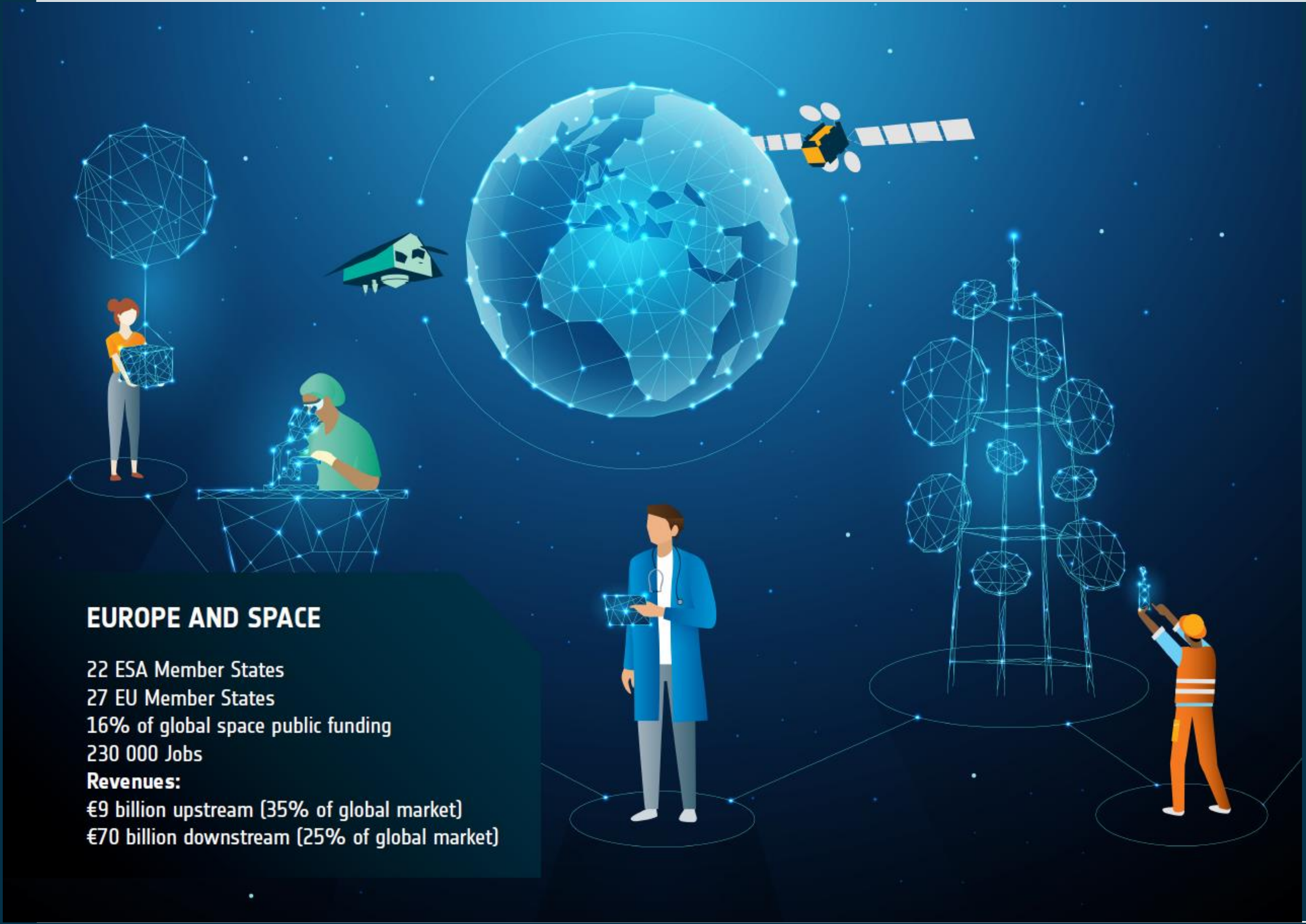
We Are ESA

EUROPE'S GATEWAY TO SPACE

WHAT	22 Member States, 5000 employees
WHY	Exploration and use of space for exclusively peaceful purposes
WHERE	HQ in Paris, 7 sites across Europe and a spaceport in French Guiana
HOW MUCH	€7.08 billion = €13 per European per year

ESA Member States

Space market in Europe by numbers



The value chain in commercial satellite applications

Global Space Market Revenue 2020

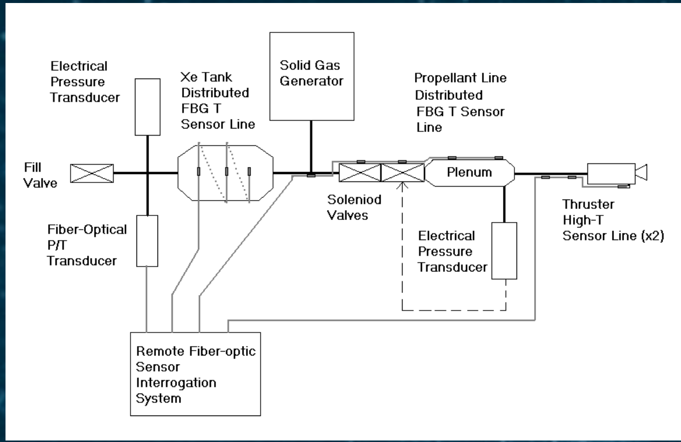
COMSAT business is a multiB$ business

….a small investment in satellite technology can lead to massive downstream revenues from value adding services.

Objectives of Space Technology Development

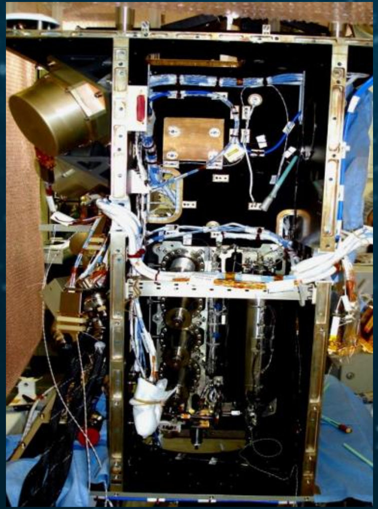
- Future Missions
- Competitiveness of European Industry
- Fostering innovation
- Critical Space Technology Independence
- Technology Transfer: Spin-in & Spin-out

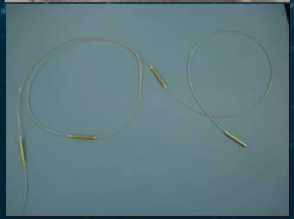
Fibre optic sensors - the right technology for space?



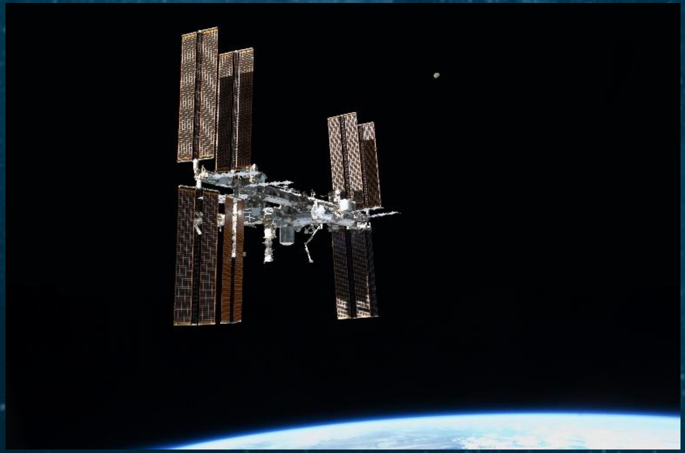
Fibre Optic Gyro – 20 years of flight heritage

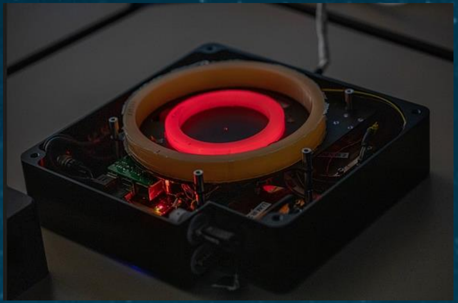
Fibre optic sensors are already in space!





Fiber Sensor Demonstrator integrated on the PROBA 2 satellite – 2009
10 years of flight data.

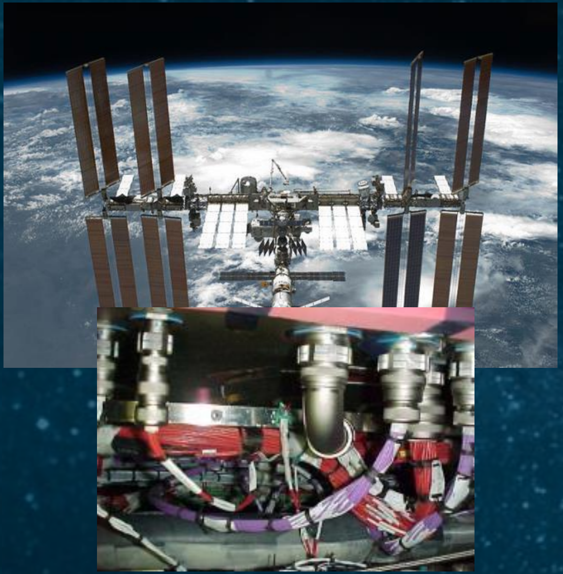




Lumia – Fibre optic radiation dosimeter on the ISS

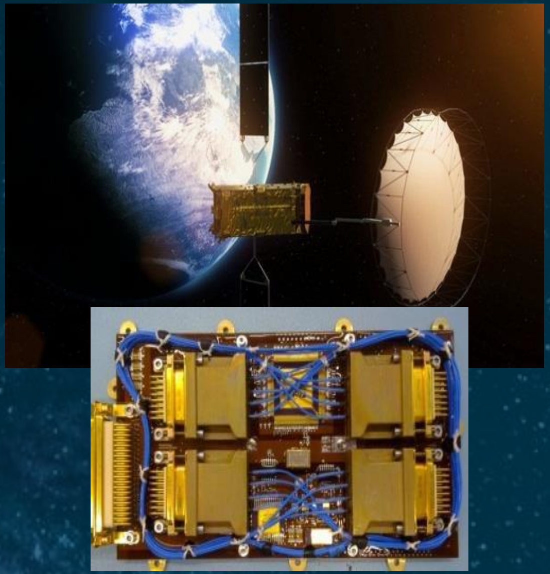
Achievements and highlights – Fibre optics

1998: ISS – Optical Comms

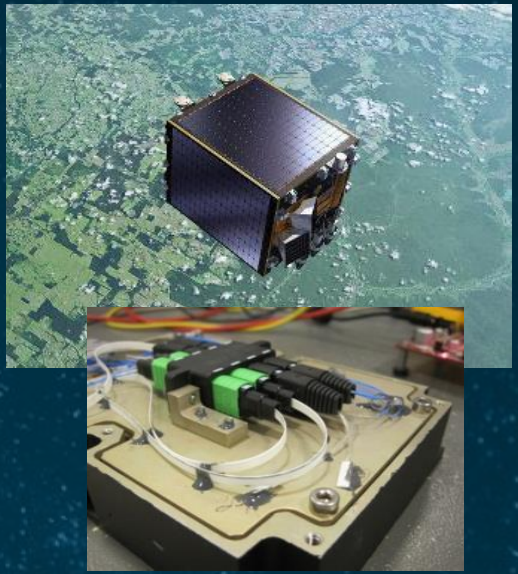


2009: SMOS – Optical Data and Clock Distribution

2013: AlphaSAT – TDP 8



2013: PROBA V- HERMOD



2004: Demeter – Opto-pyrotechnic demonstrator

2009: Planck – Fiber optic gyro (4 axis)

Oct. 2021: SES-17 VHTS Payload

Fibre Optic Sensors at ESA (Cryo – Over 1000 ºC)

Large Telecom Satellites

- Ground
  - TV test
  - Mechanical test
- In-flight
  - Attitude - FOG
  - Temperature (payload and service module)
  - Propulsion system (chemical/electric)
  - Antennas (thermal distortion)

Launchers

- Temperature
- Strain
- Pressure
- Structural monitoring
- Cryo - Propellant management
- Leak detection

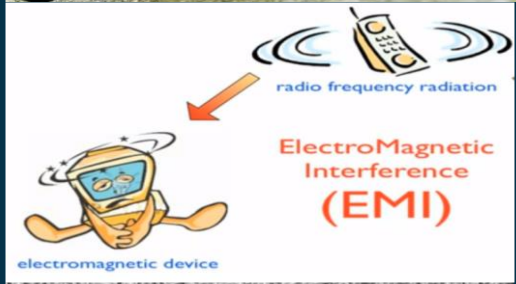
Re-entry Vehicles (Expert, IXV, SHEFEX)

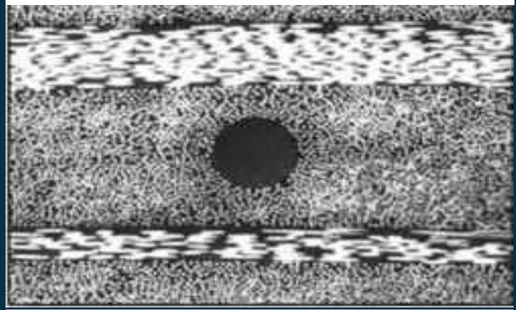
- Thermal mapping (>1000oC)
- Erosion of ablative TPS
- Dynamic pressure
- Strain
- Skin friction

McKenzie Iain, Ibrahim Selwan, Haddad Emile, Abad Silvia, Hurni Andreas, Cheng Lun K.Fiber Optic Sensing in Spacecraft Engineering: An Historical Perspective From the European Space Agency, Frontiers in Physics ,2021. https://www.frontiersin.org/articles/10.3389/fphy.2021.719441

Motivation – why introduce FOS into spacecraft?

- Harness reduction
  - Flexible, small, light weight harness
  - Wavelength multiplexing (sensors, functions)
  - Can be embedded in composites or panels
- Harness immune to EMI with excellent EMC properties
- Low Optical Transmission Loss
- Galvanic isolation
- Low thermal conductivity of optical fibres
- Multi-parameter measurement
- Increasing use of composite materials in spacecraft
- Performance (FOG)
- Cost - mature high quality COTS components from telecom





1 minute Satellite AIT video

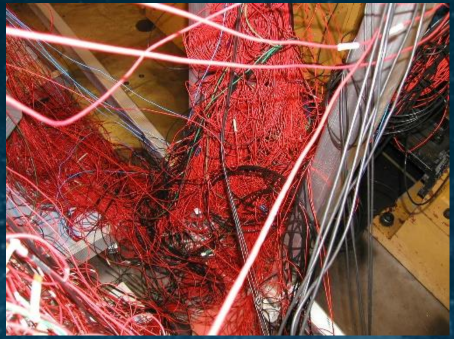
Courtesy of Thales Alenia Space

Ground Testing Large Telecom Satellite

Thermal Testing – 400 thermocouples
Flight sensors 400 thermistors typically

Mechanical testing - 250 accelerometers

Large telecom satellite undergoing mechanical testing
Image courtesy Airbus 2022



Galileo satellite undergoing thermal vacuum testing

>50% mass reduction for flight harness
Significant AIT effort reduction possible
No need for space qualification

Photonically Wired Spacecraft Panels

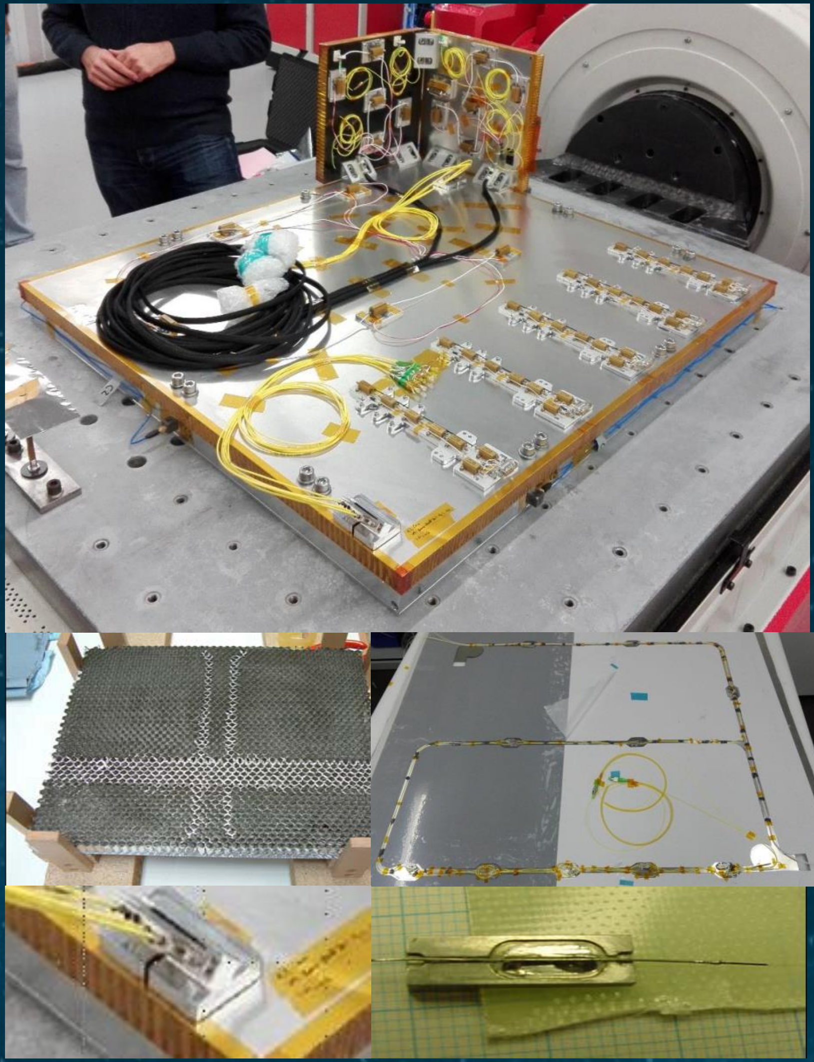
Embedding of optical fibres in the panel walls to provide a lightweight communication and sensor harness inside the walls of the satellite.

Expected advantages

x6 reduction in mass
x2 reduction in AIT effort
Improved EMI and EMC performance
Full thermal mapping of panel using embedded sensors

Disadvantages

Late changes in configuration are less easily accommodated
Position of sensors need to be defined early in the definition, additional sensors will have to be added externally.



Pressure sensor for pVT method

Use of pVT method to monitor fuel quantity in fuel tanks.

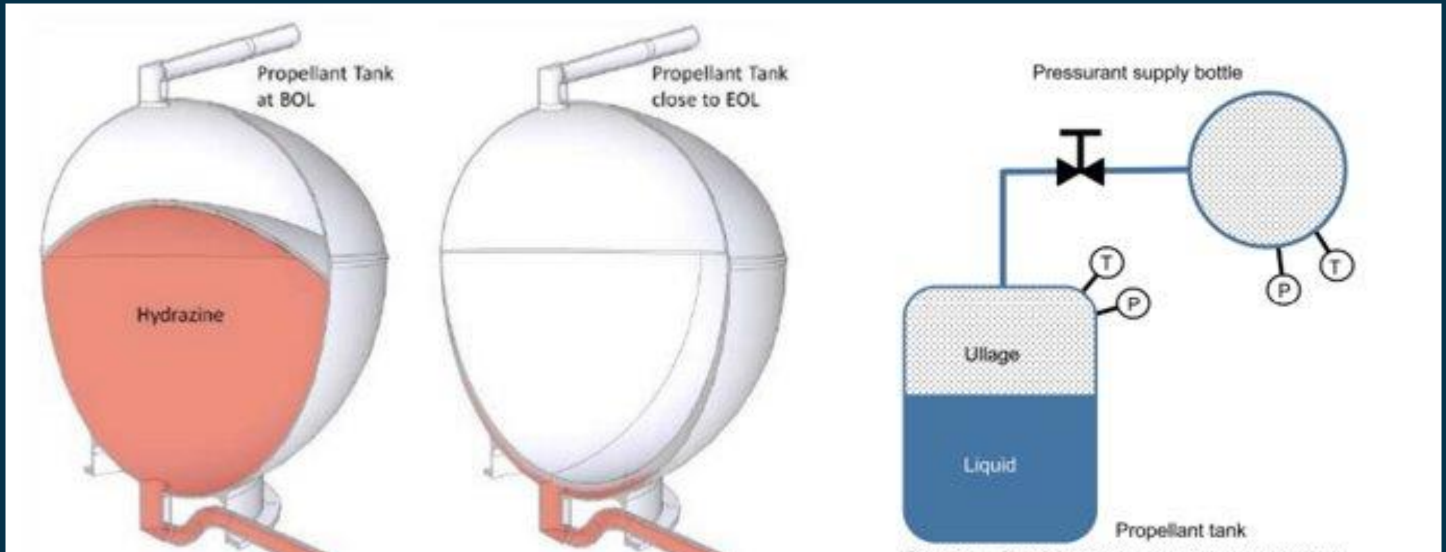


Figure 1.—Simplified pressure-volume-temperature schematic showing locations of pressure, P, and temperature, T, gauges.

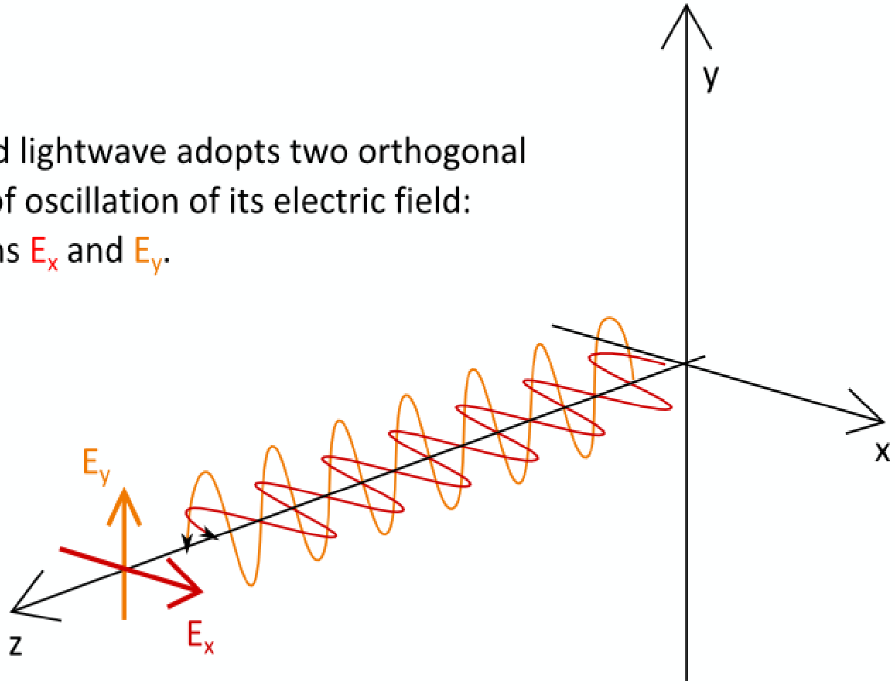
OPTECH

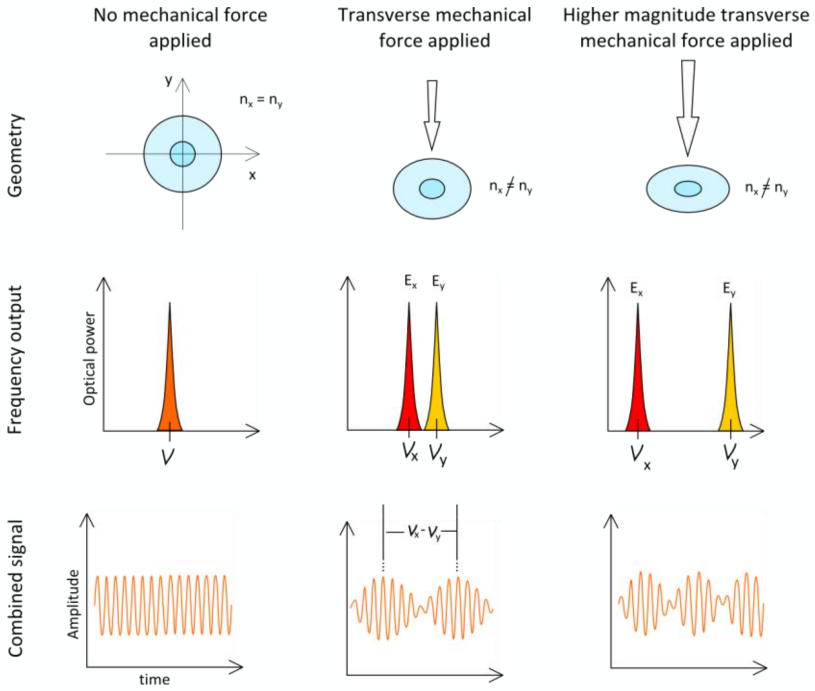
Optech DBR pressure sensor

Measurement technology	Piezoelectric HAPT	FBG (Proba 2)	Optech DBR pressure sensor
Pressure resolution(mBar)	13	2	**0.03**
Pressure resolution (%FS 0-25 Bar)	0.05%	0.01%	**0.00015%**
Temperature (K)	0.5K/300K	0.05	**0.004-0.1**

Measurement principle

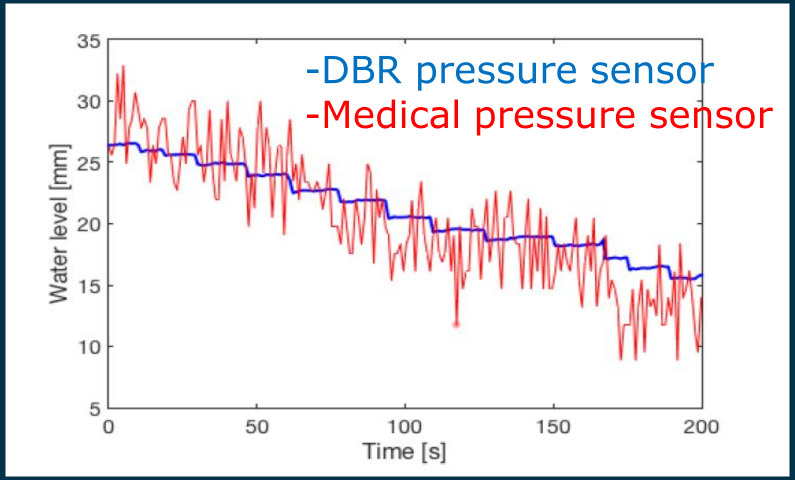
The emitted lightwave adopts two orthogonal directions of oscillation of its electric field: polarisations E_x and E_y.



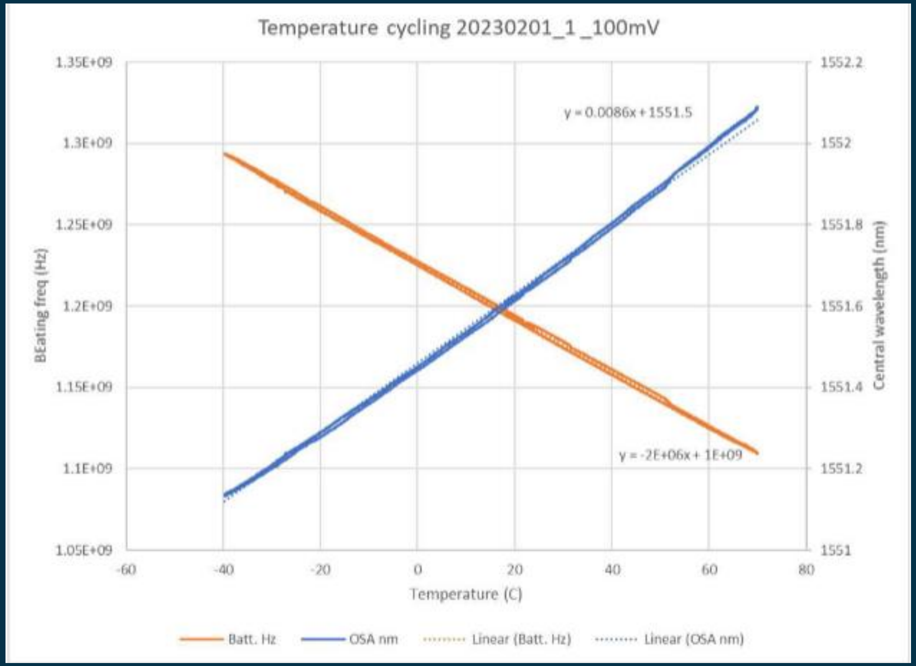


Pressure sensitivity and laser temperature Characterization

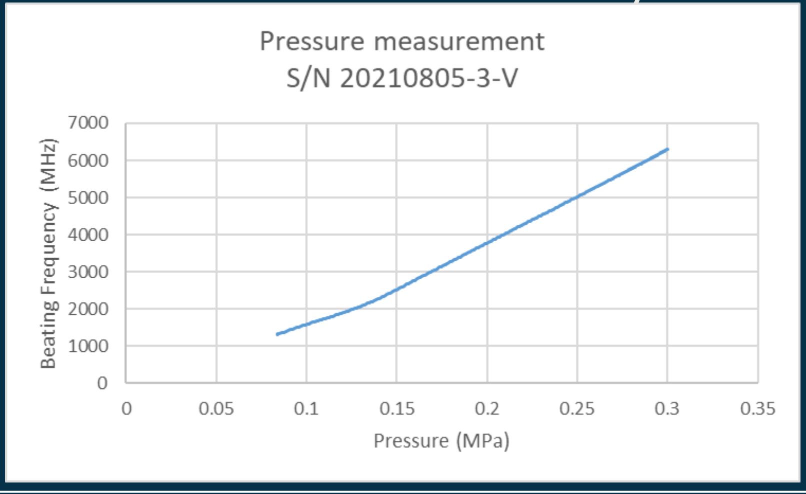
Water level millimeter sensitivity measurement comparison



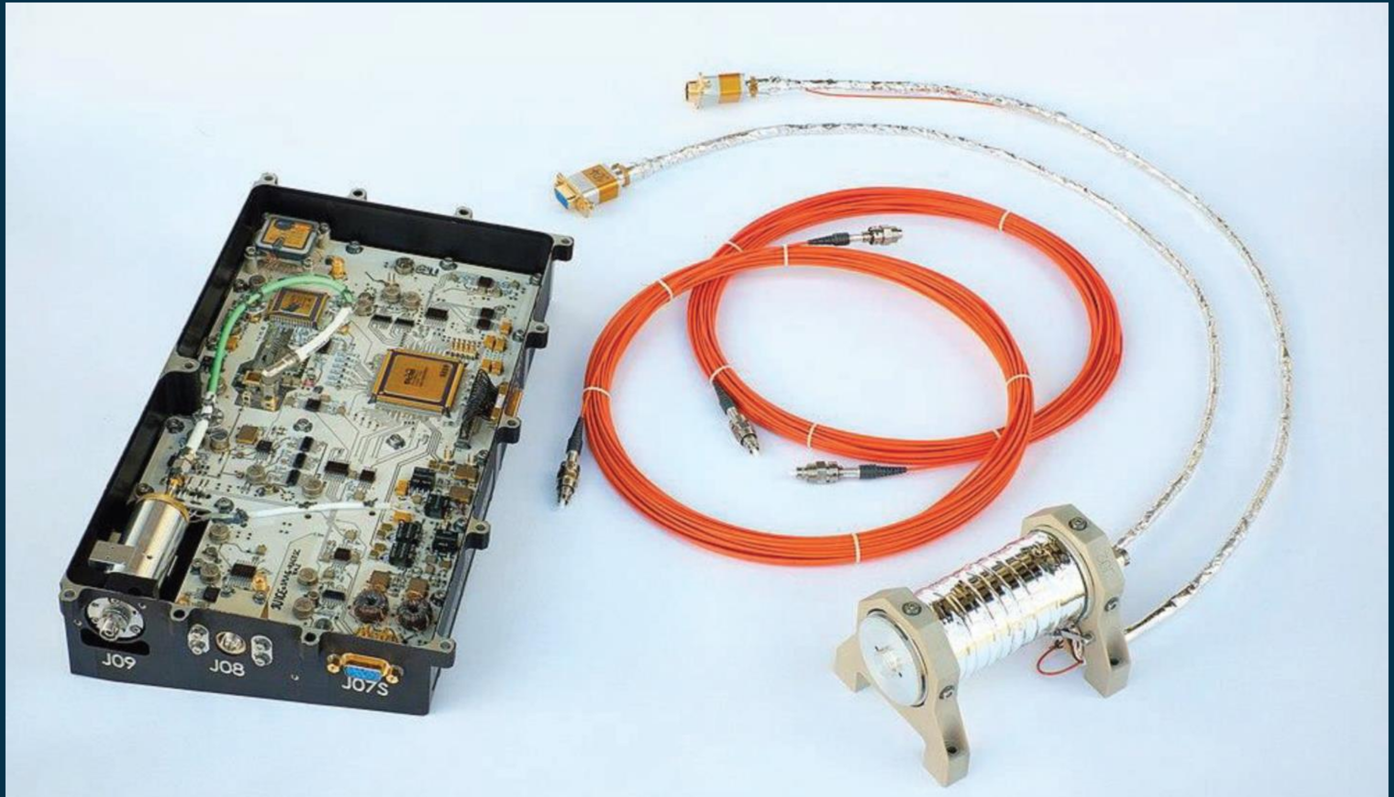
DBR laser temperature dependency
Central Wavelength and Beating Frequency



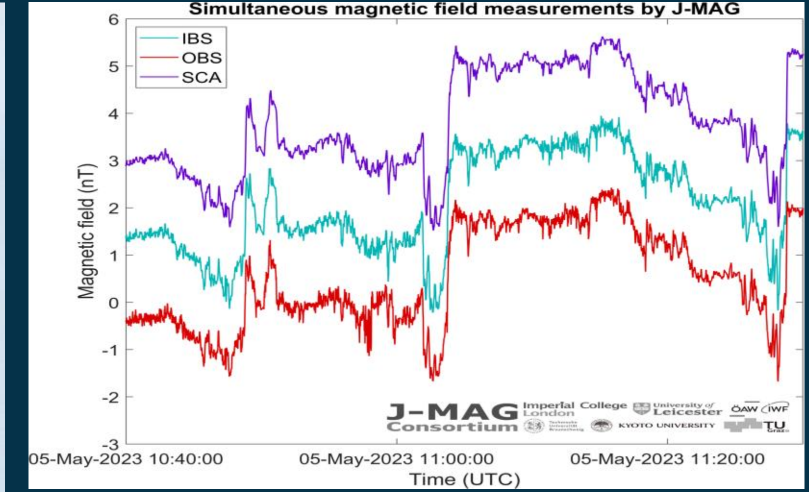
Pressure sensitivity



Juice Satellite - MAGSCA



Credit: Andreas Pollinger/IWF/OEAW, MAGSCA flight model, CC BY 4.0)



AIRBUS

esa European Space Agency

ÖAW IWF

TU Graz

Schäfter+Kirchhoff OPTICS, METROLOGY, AND PHOTONICS

Linden Photonics Inc. Optical packaging

Fraunhofer INT

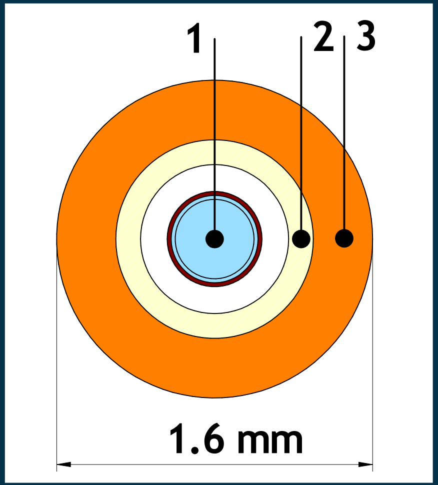
ALTER TECHNOLOGY

The challenge design a fiber optic cable suitable:

Temperature Range: -170 to +120 degrees C

Radiation TID: 20Mrad

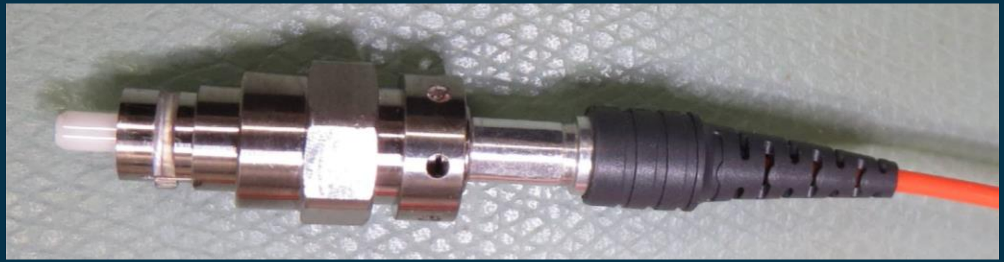
JUICE - FIBER, FIBER JACKET AND FIBER CONNECTOR



Fiber selection: Total Ionising Dose (TID) radiation tests at cryogenic temperatures (40 K, 100 K) and different dose rates (150, 3.4, 0.3 rad/s)

Fiber jacket: manufactured by Linden Photonics, USA

- Optical Fiber: 400 µm/440 µm/480 µm (core/cladding/coating)
- Sheath / Strain Relief: Liquid Crystal Polymer (LCP)
- Fluorinated Ethylene Propylene (FEP)

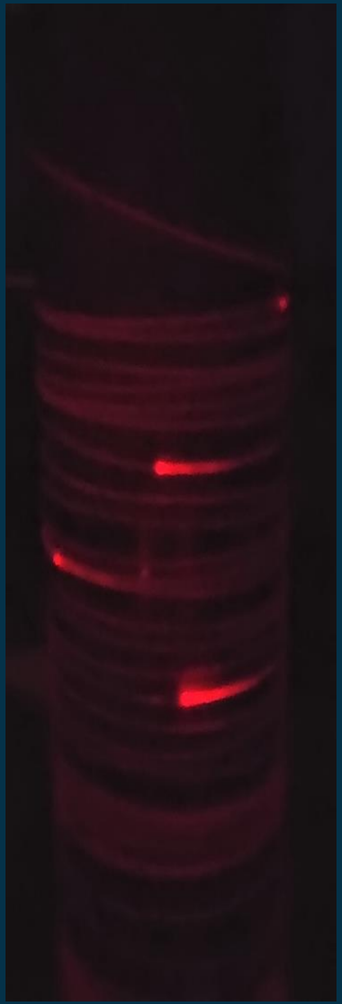


Schäfter+Kirchhoff GmbH
OPTICS, METROLOGY, AND PHOTONICS

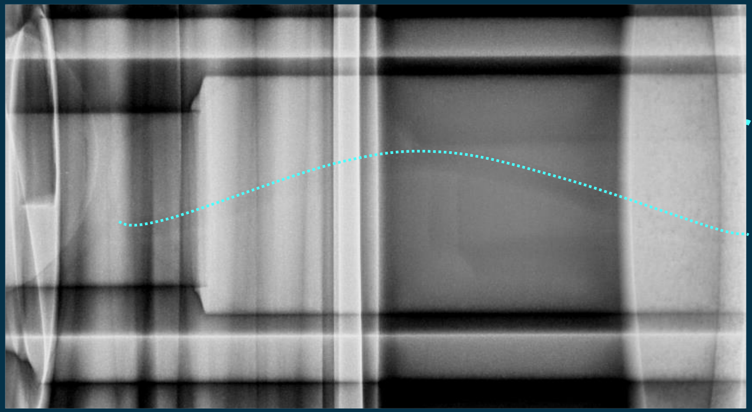
Fiber connector: manufactured by Schaefter+Kirchhoff, Germany

- Non-magnetic FC/APC fiber connector,
- anti-twist, longitudinal stress relief

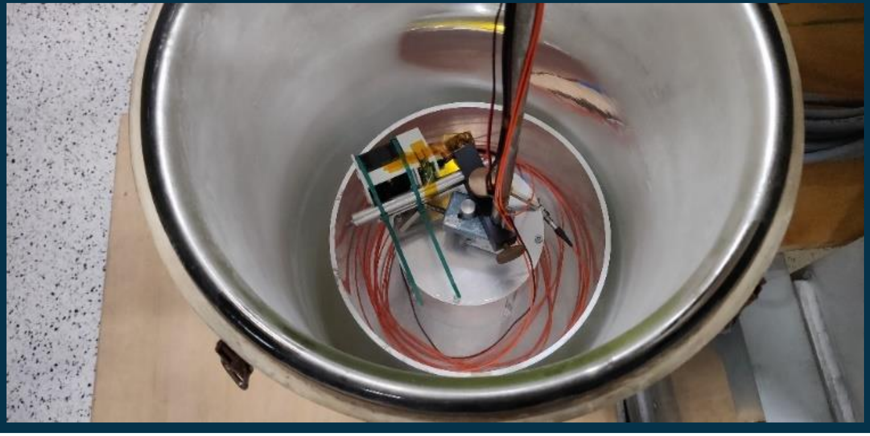
Light Scattering Test

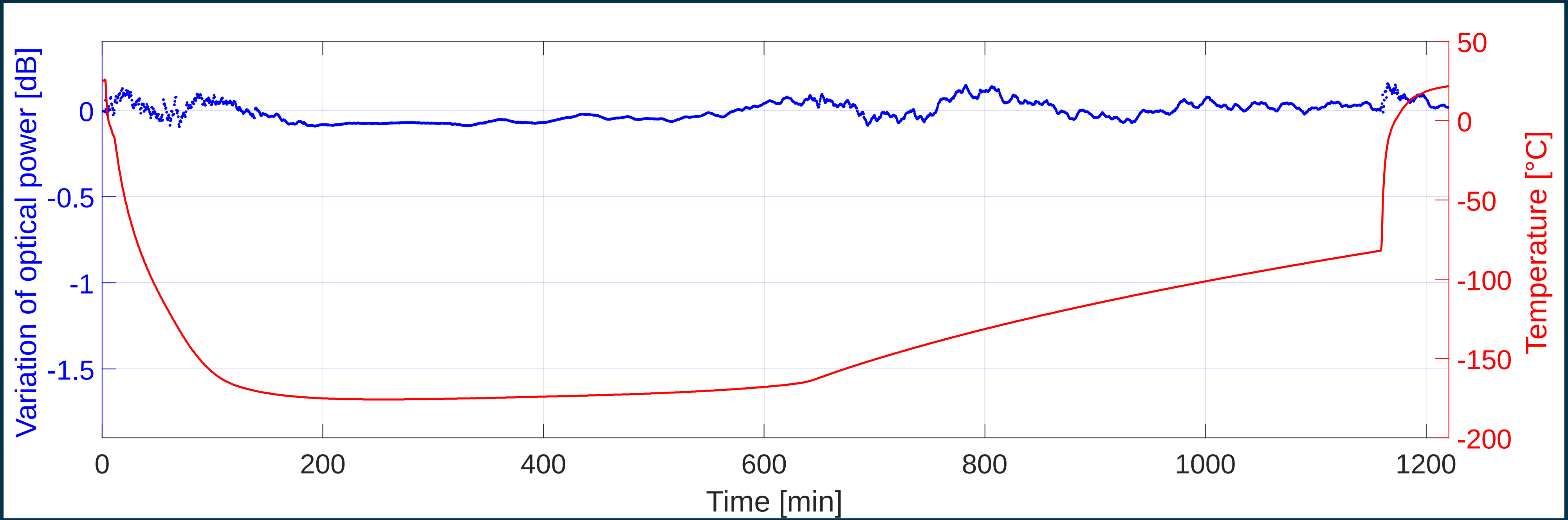


X-Ray Inspection



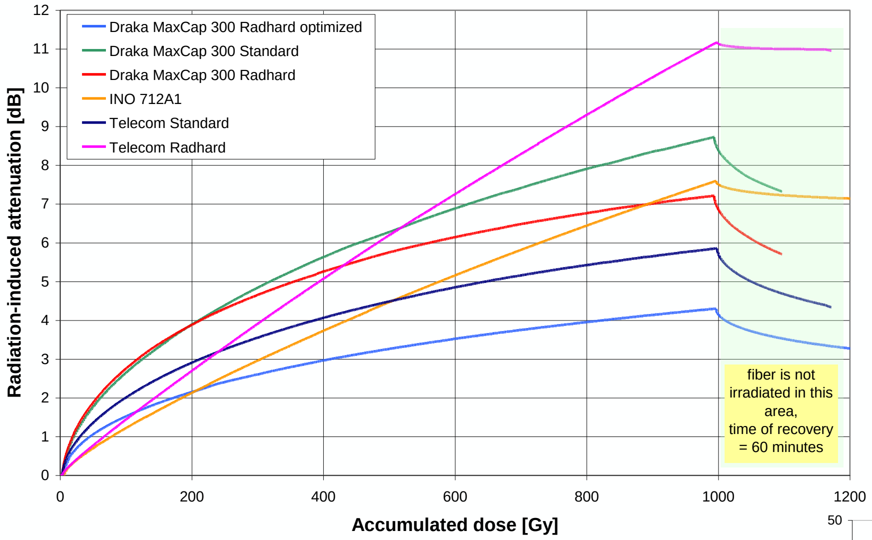
LOW TEMPERATURE TESTS



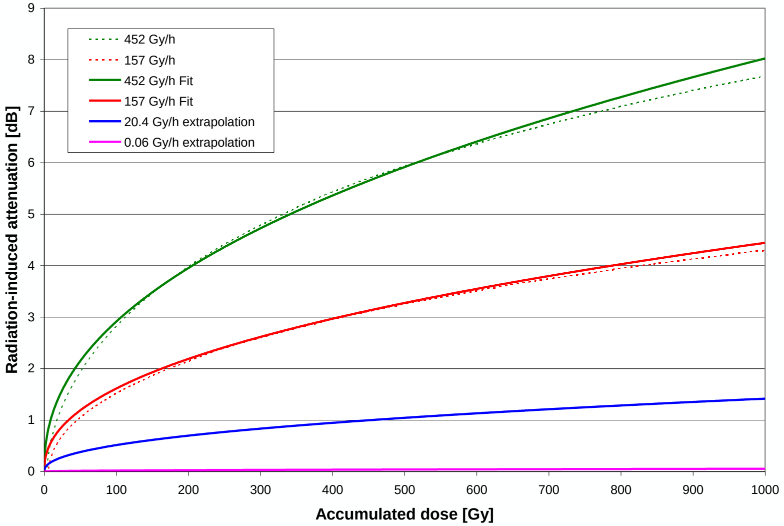


Radiation Darkening in Optical Fibres

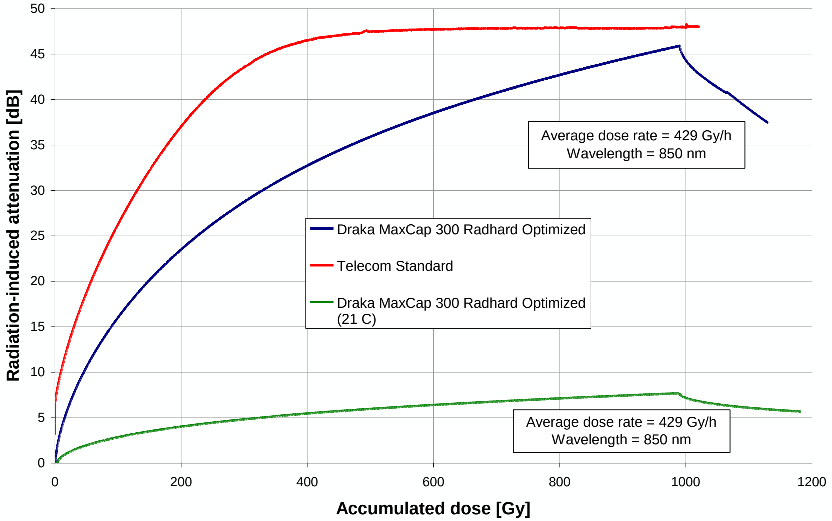
Radiation-induced attenuation in some COTS fiber samples (100 metres)
Average dose rate = 157 Gy/h, Total dose = 1000 Gy



Radiation-induced attenuation fits and extrapolations at 850 nm
of the Draka MaxCap 300 Radhard Optimized fiber
exposed to gamma radiations



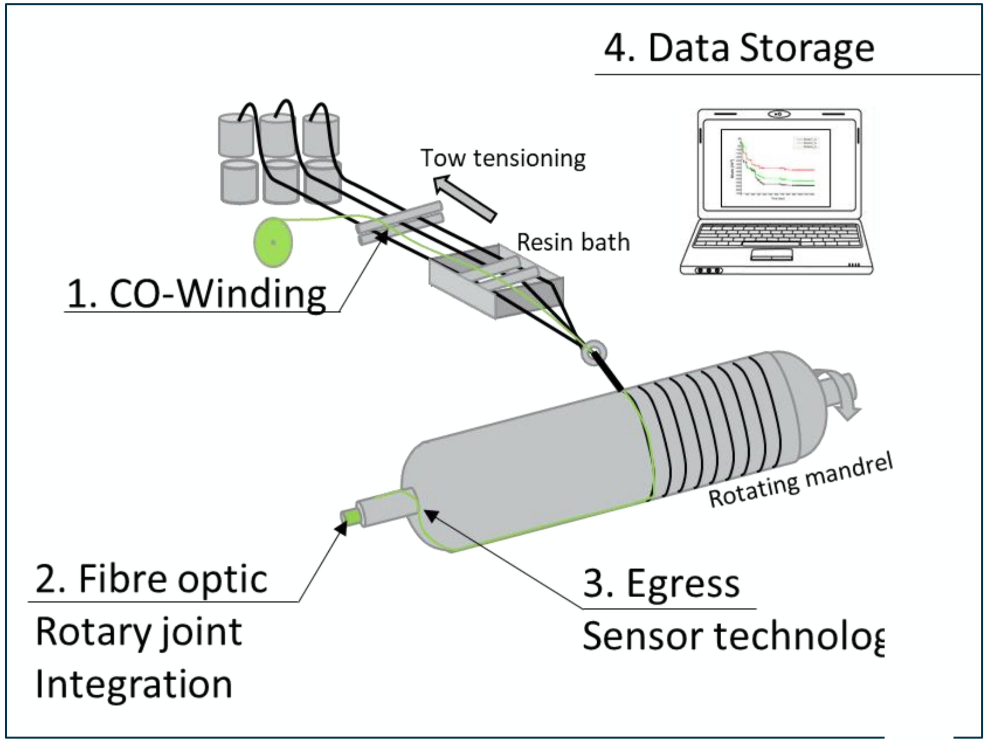
Radiation-induced attenuation at 850 nm
performed at an average temperature of -17 °C

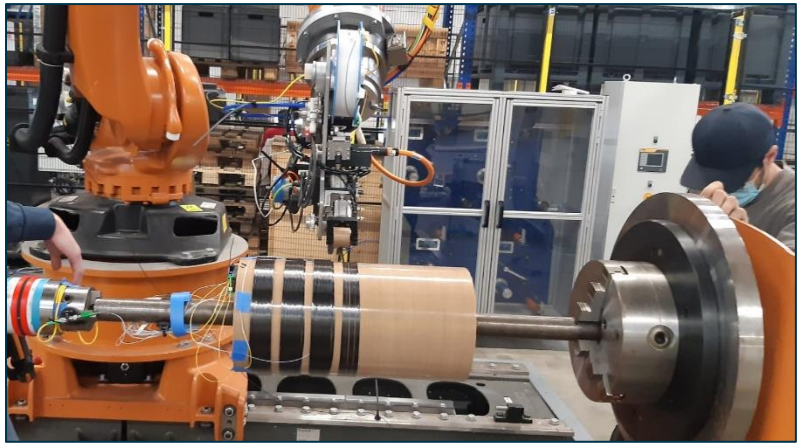


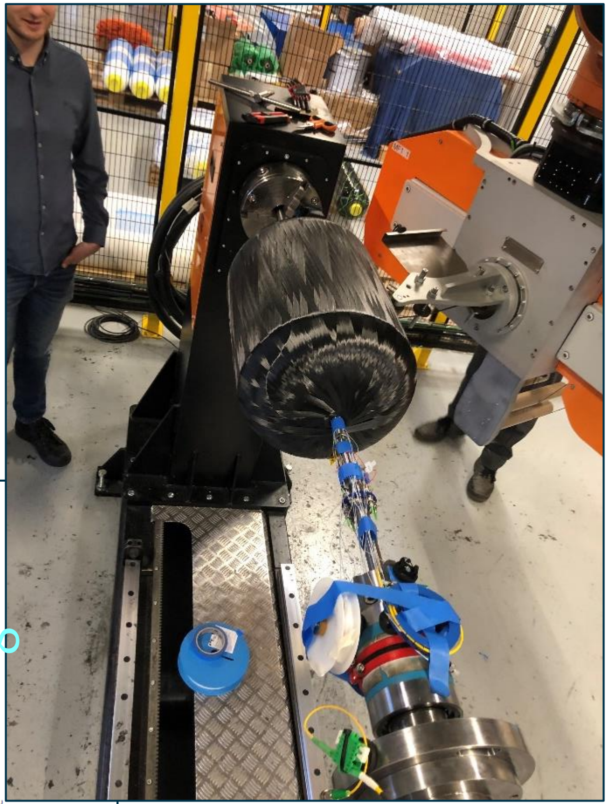
Courtesy of INO and the SpaceFibre Project

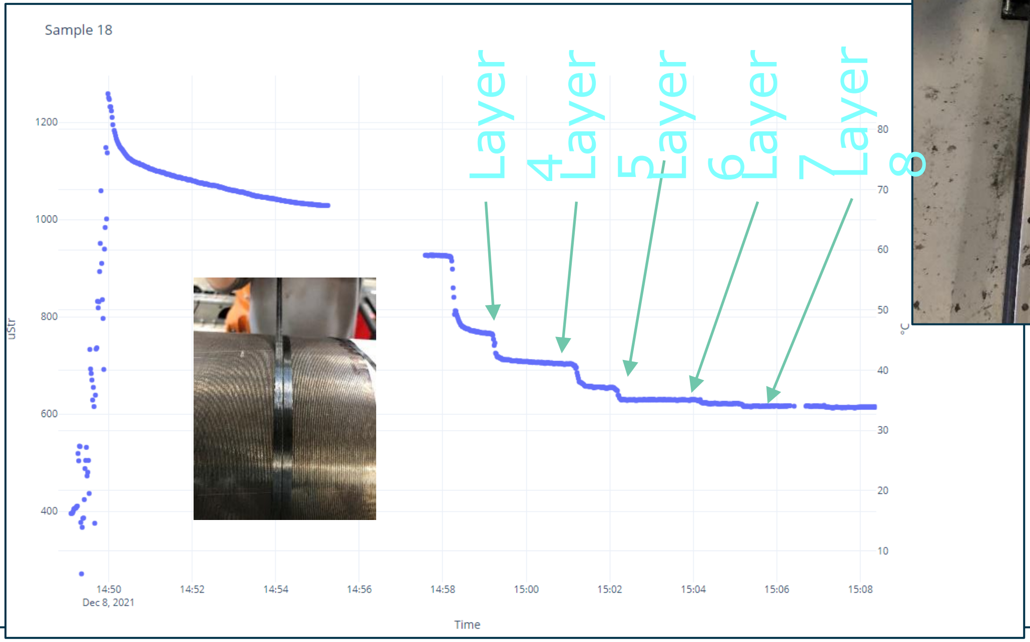
Monitoring of Composite Overwrap Pressure Vessels (COPV)

Filament winding







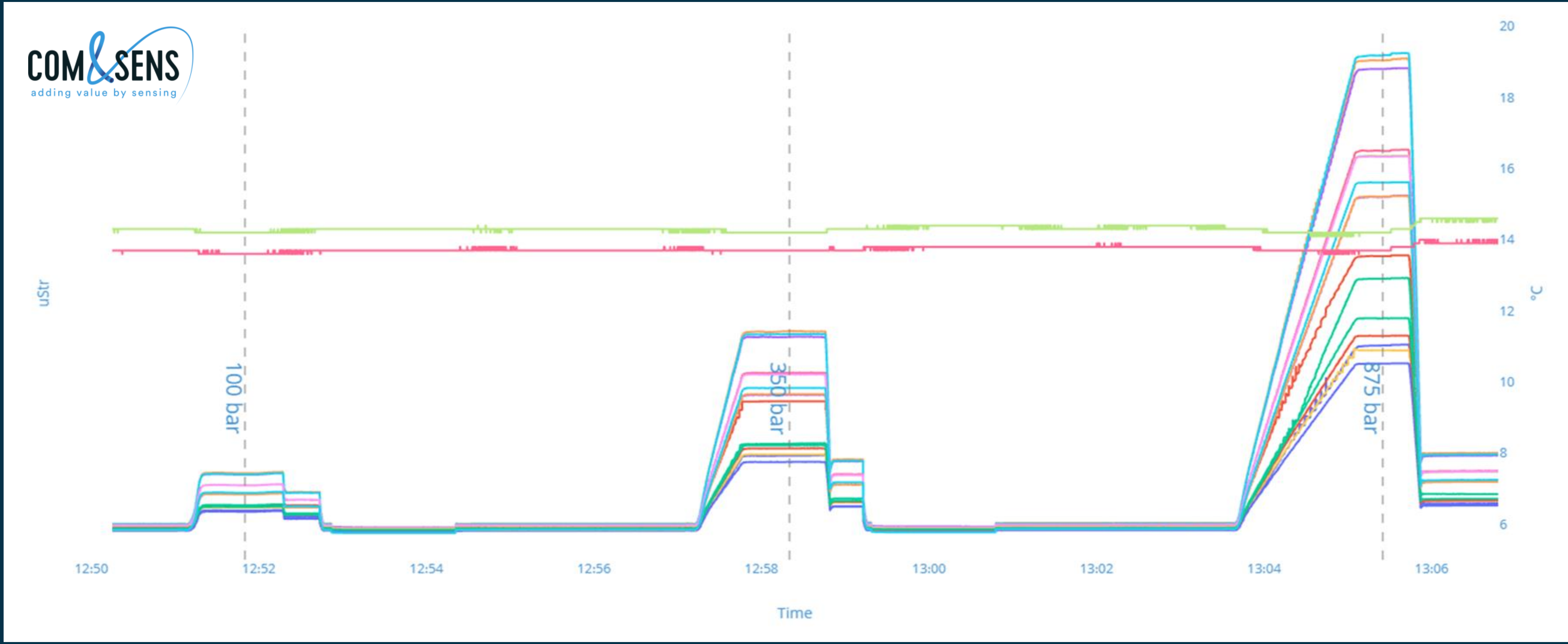


COM&SENS adding value by sensing

DAWN AEROSPACE

COPV Process Monitoring

Expansion testing of a COVP



Life Cycle Monitoring of Composite Structures

PRODUCTION MONITORING - MAIT

STORAGE – TRANSPORT - HANDLING

IN SERVICE MONITORING

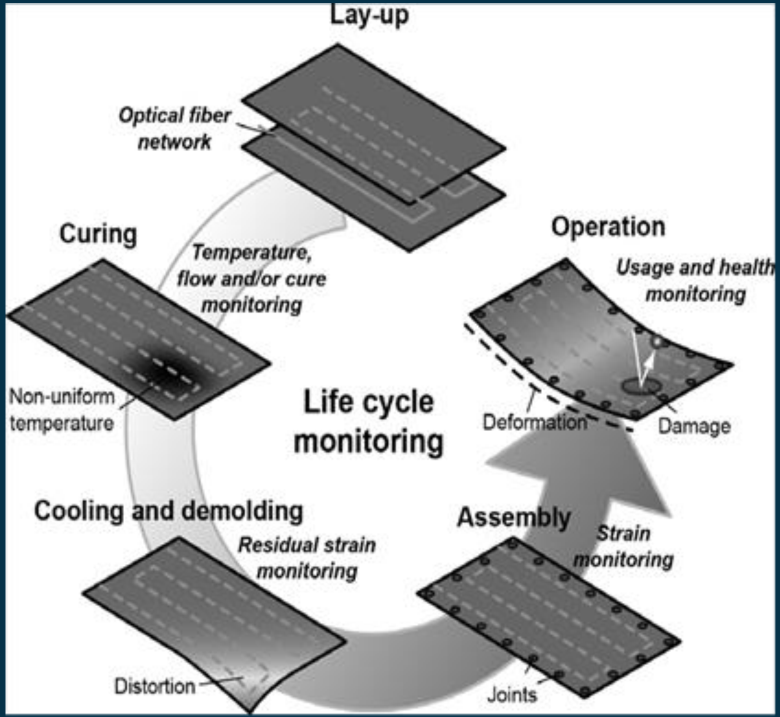
COM&SENS adding value by sensing

ENGIE Laborelec

S.A.B.C.A.

source: Starwin Industries

source: MFTech

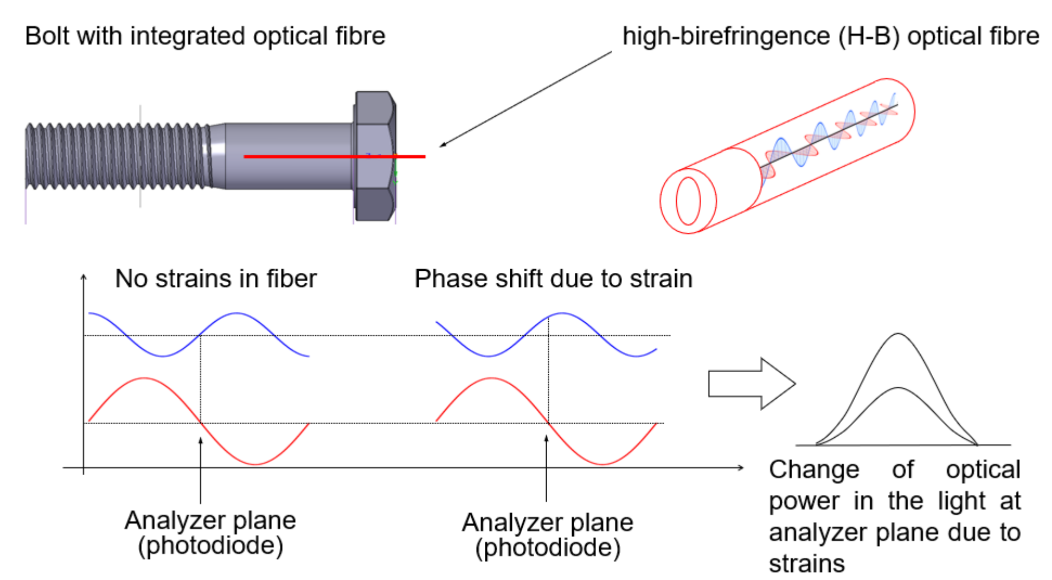


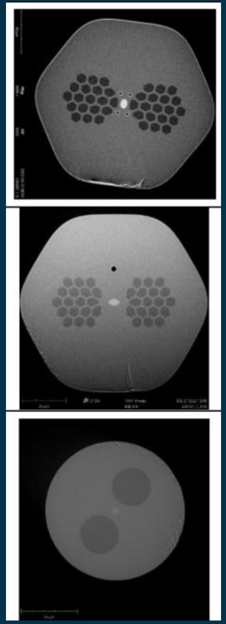
source: Minakuchi, Comp. Part A, 2011

source: ESA FLLP preparing for Europe's next –generation launchers

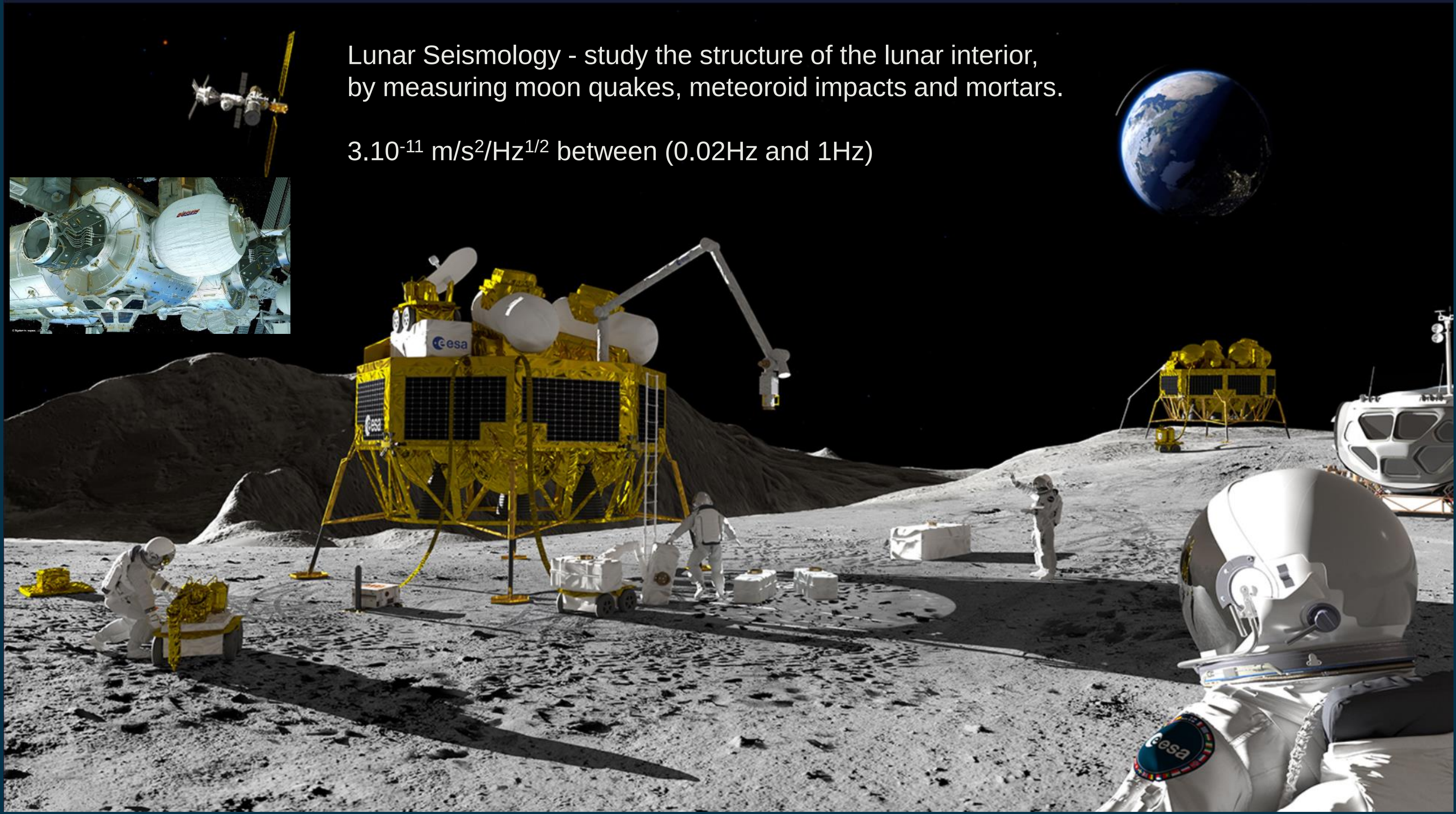
Instrumented Bolt to Measure Pre-load in Critical Bolted Joints

XPANSE UMCS SYDERAL POLSKA

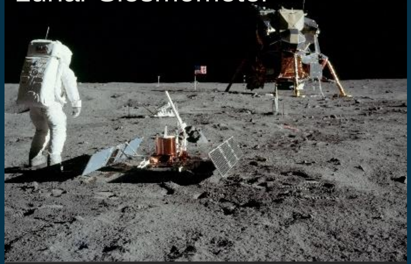


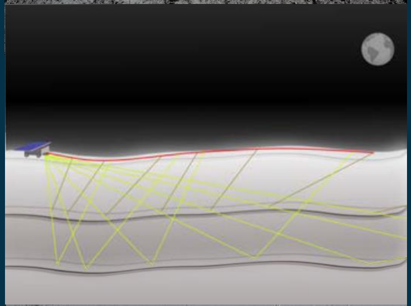


TERRAE NOVAE: Discover new worlds



Apollo 11
Buzz Aldrin installing 1st Lunar Siesmometer

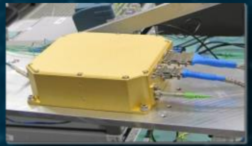




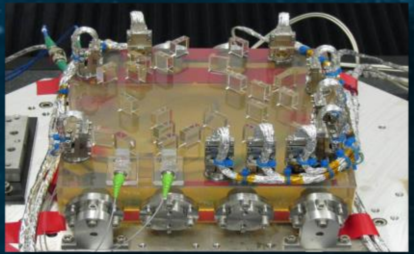
C. Schmelzbach et al. 2020. Lunar Geophysical Explorer Team Report

Micro Kelvin Fiber Optic Sensors for LISA Mission

Metrology laser system developments for LISA pathfinder, LISA and NGGM (GOCE follow on)

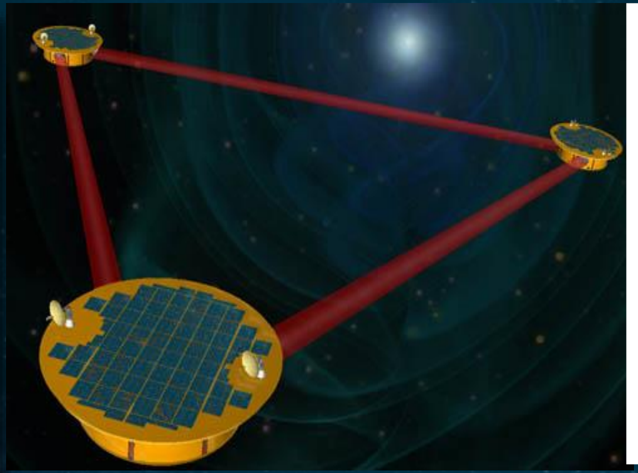

Reference Laser Unit (FM)

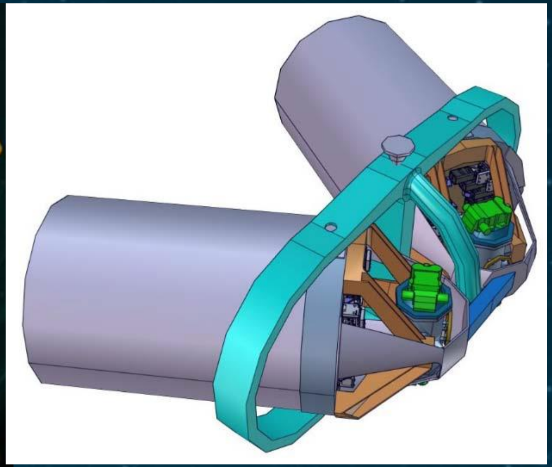

Laser Modulator (FM)

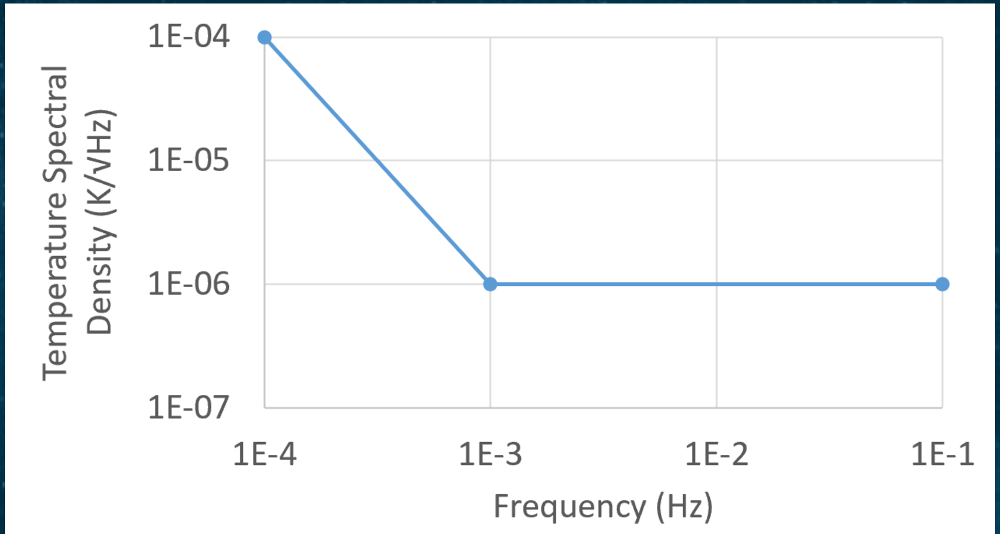

Optical Bench Interferometer (FM)


Phasemeter (FM)


Data Management Unit (FM)







Hollow Core Fibers (HCFs)

Benefits of Hollow Core Fiber over solid core fiber for frequency transfer.

Loss (dB/km)	**Thermal sensitivity (ps/km/K)**	**Non-linear effects**	**Back scattering**	**Thermal sensitivity of chromatic dispersion**	**Latency**
0.17dB/km Theory predicts loss can be lower than solid core fibers, resulting in longer unamplified sections fiber resulting in simplified stabilisation schemes.	20x lower Simpler compensation approaches required.	1000x lower. Higher power injection possible before four wave mixing, SBS and SRS become a problem resulting in longer unamplified sections of fiber.	1000x lower. This has an impact in the purity of the phase noise of the transferred signal.	>10x lower Particularly interesting when propagating broad combs. Stabilisation works over broad wavelength range.	Light travels faster in air. Interesting for other terrestrial communication applications, e.g. finance.

Applications:

Improved Time and Frequency Transfer over Hollow Core Fibers (HCFs)

New resonant fiber optic gyro configurations

Compact gas cells – laser frequency references

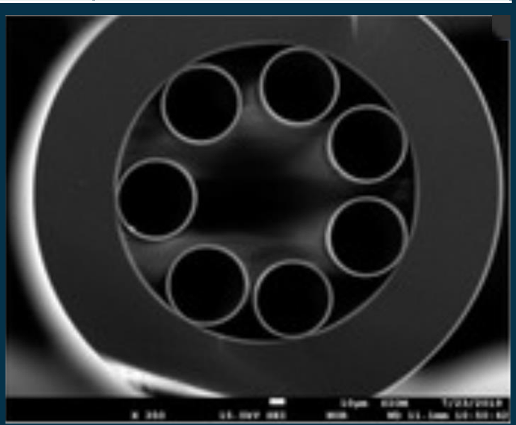


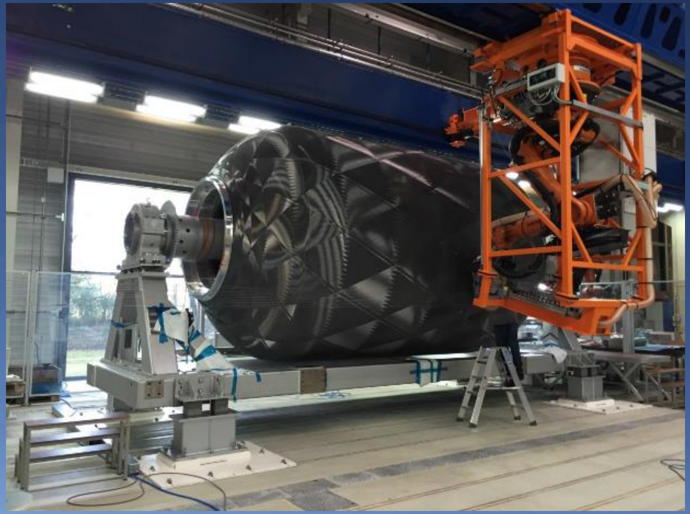
Image of a anti-resonant hollow core fiber

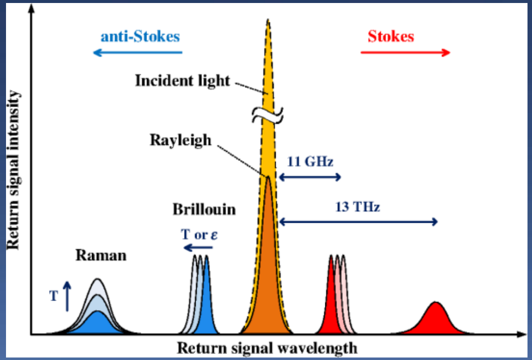
Guarantee European Access to Space – Re-usable Launcher

Structural health monitoring of Europe’s future reusable launchers: Ariane-Next

Increasing use of lightweight composites
Understanding of flight dynamics

Challenges:
Operate in harsh vibration environment (50g rms random)
Shock (several 1000g)
Thermal (hot re-entry to cryo environments)

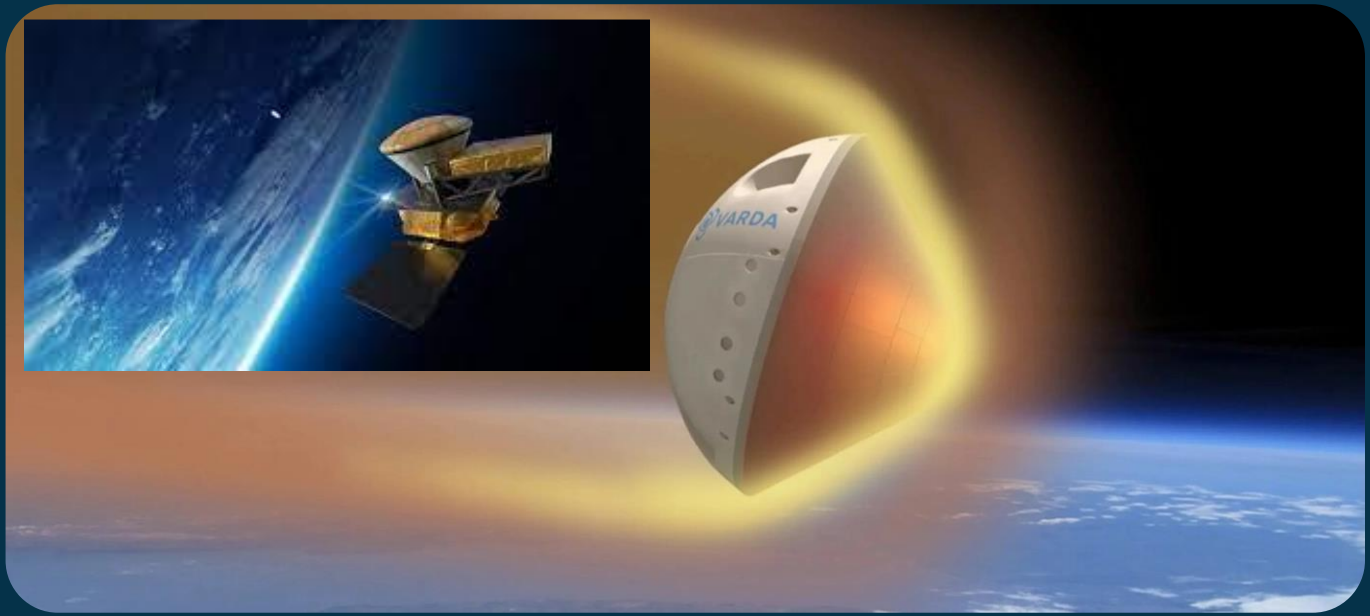




Distributed Fibre Optic Sensing:
High spatial resolution (cm or better)
Strain 10s microstrain (kHz bandwidth)

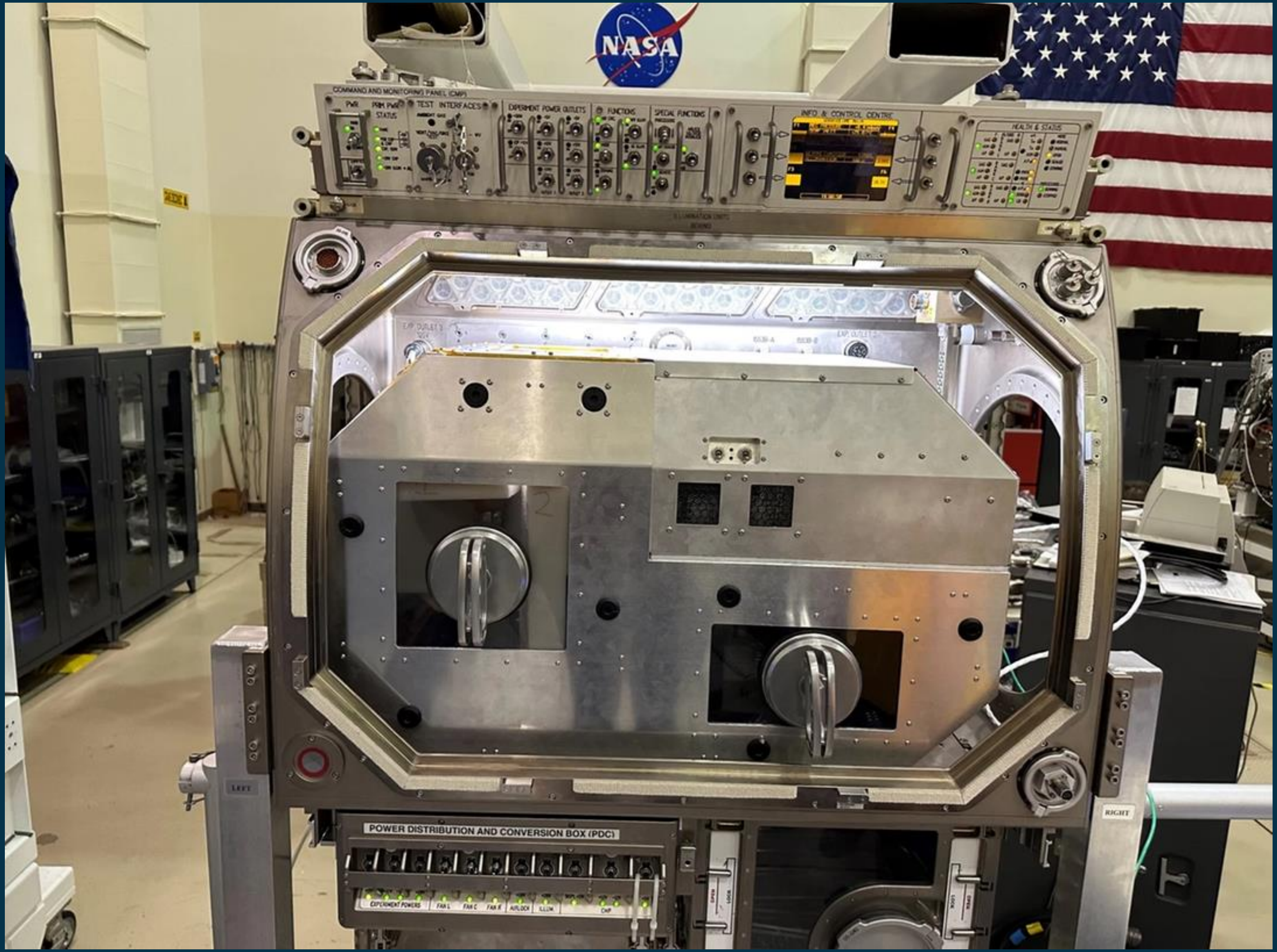
Factories in Space

Image: Rocket Labs



June 12th 2023 Space-X Successfully Launched the first space factory for Varda Space Industries.
Main application drug discovery, additive manufacturing, material processing.

Drawing ZBLAN Fibers in Space



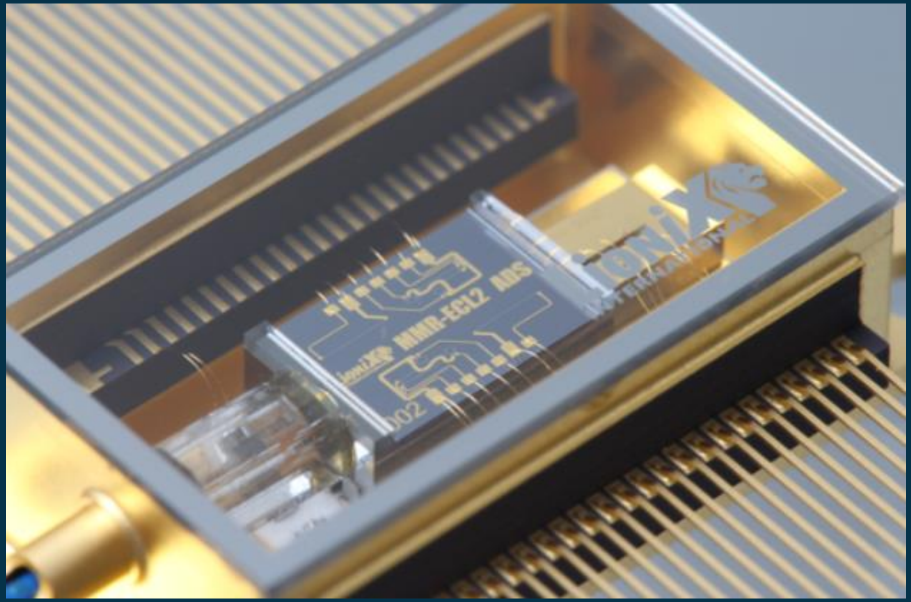
LUXEMBOURG SPACE AGENCY

FLAWLESS PHOTONICS

Microgravity reduces crystalisation in ZBLAN glass during the drawing process. Target market - improved optical fiber for lasers and amplifiers in the MIR

Conclusions

- Space enters a new exciting era.
- Photonics is set to play an increasingly important role in communication and sensing.
- Europe needs to keep up its investment in cutting edge photonic technology development
  - Mature existing technology
  - Take advantage of future flight opportunities.
- Photonic integration to play a key role in enabling complex photonic payloads
- Custom/specialty optical fibers designed to optimize measurement key to improving sensitivity to measurand.
- Re-usable launch vehicles represent an interesting new application for fibre optic senors.



Picture courtesy of Lionix BV

Let’s work together – ESA is open for business

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ESA’s Commercialisation Gateway

https://commercialisation.esa.int/

ESA Open for Business

https://www.esa.int/About_Us/Business_with_ESA/esa-star_open_for_business

Open Space Innovation Platform

https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/The_Open_Space_Innovation_Platform

Secure and Laser communication technology Program (Scylight)

https://artes.esa.int/scylight

General Support Technology Program (GSTP) – Develop, Make, Fly

https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/About_the_General_Support_Technology_Programme_GSTP

Technology Harmonisation at ESA

https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Technology_Harmonisation

Join us at the Industry Space Days – ESTEC Sept (TBD) 2024

https://isd.esa.int/

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Time to get excited about space!

https://www.youtube.com/watch?v=bG3aWXgpcZQ&list=PLbyvawxScNbviLGxC-ahF8Ml4xO8eGgtq&index=19