ASMS 2025

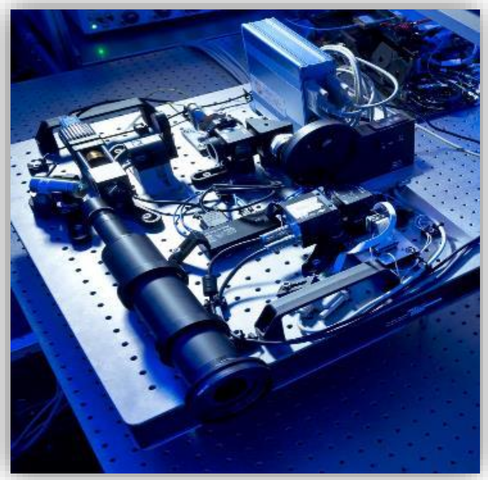
RECENT RESULTS IN OPTICAL SATELLITE LINK RESEARCH AT DLR

Christian Fuchs, Douglas Laidlaw, Florian Moll, Juraj Poliak, Christopher Schmidt, Amita Shrestha

Optical Satellite Links Department
Institute of Communications and Navigation
German Aerospace Center (DLR)

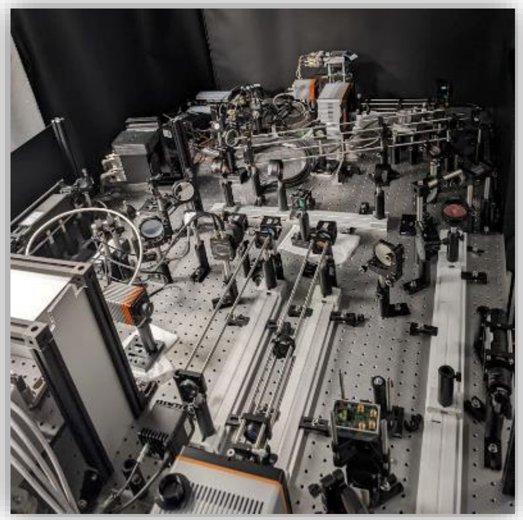
DLR

Optical Satellite Links at DLR in a nutshell



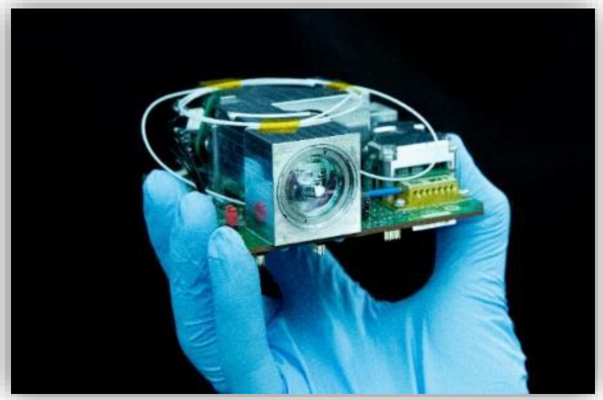
Optical terminals for field demonstrations

Optical Ground Stations

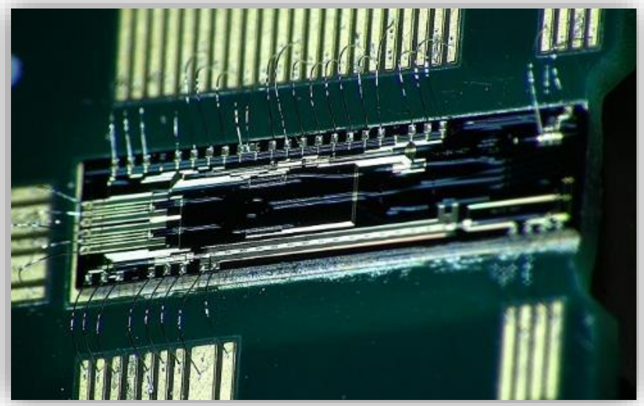


Adaptive Optics

OSIRIS terminals for small satellites and Cubesats



Quantum Key Distribution

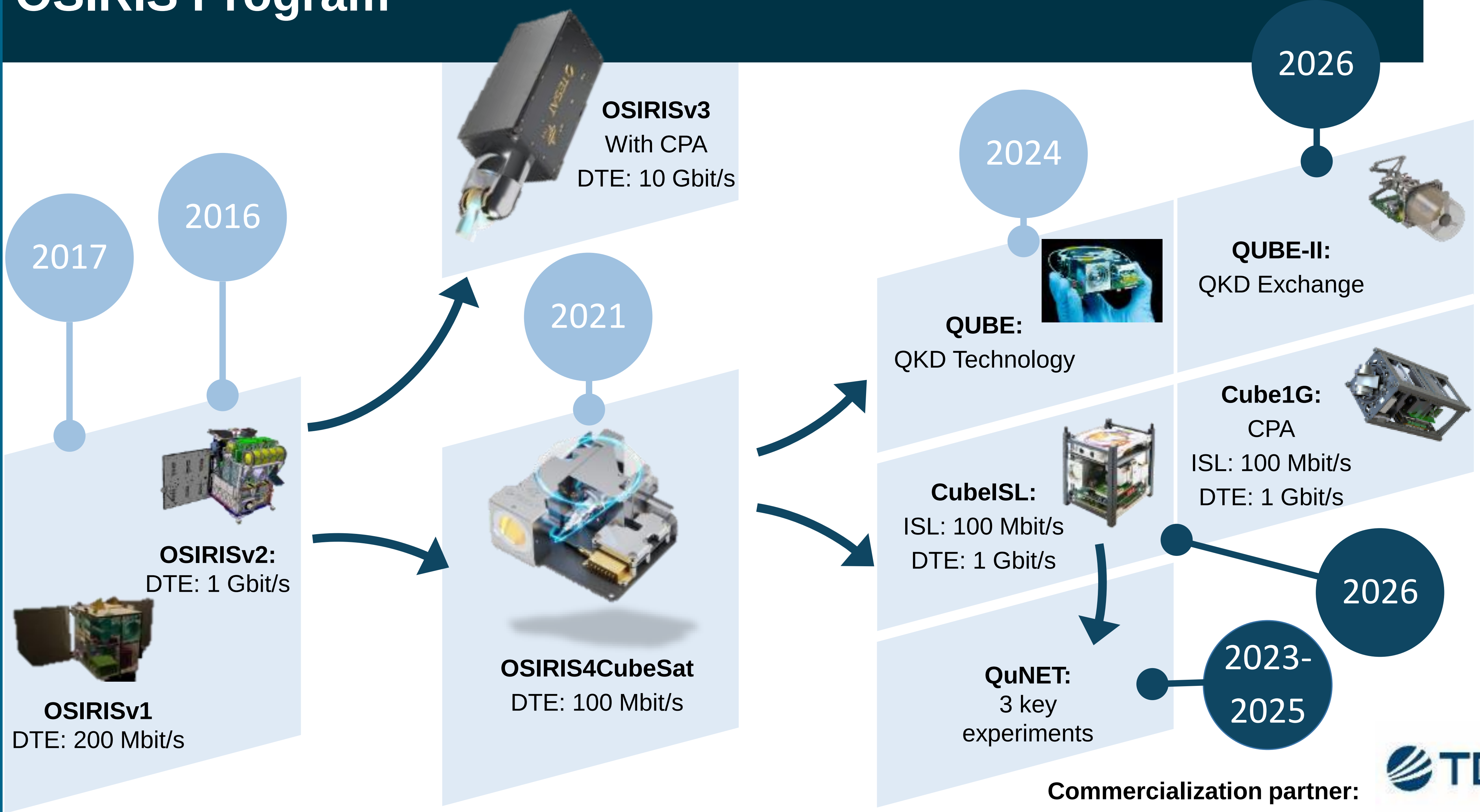


Novell technologies: Opt. time- and frequency transfer, PICs, …

Outline

- Optical Terminals
  - …for classical communications
  - …for QKD
- Optical Technologies for
  - …satellite communications (ISL and space-to-ground)
  - …time-transfer
- Optical Ground Stations
- Summary & Conclusions

OSIRIS Program

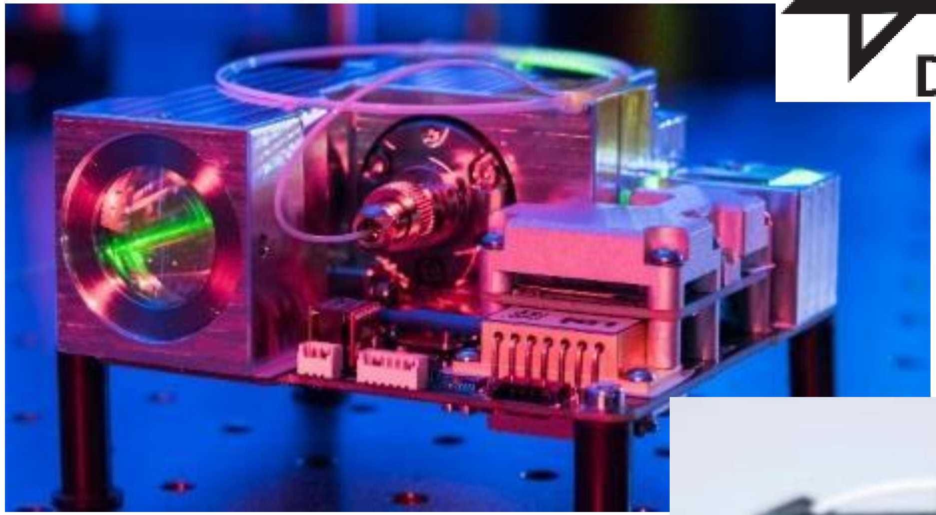


Commercialization partner:

OSIRIS4CubeSat / CubeL on PIXL-1

<u>Payload Parameters</u>

- Highly miniaturized OSIRIS
  - Data Rate: 100 Mbps
  - Size: 90 x 95 x 35 mm³ (0.3 U)
  - Weight: 395 g
  - Power: 8.5 W
- Fine Pointing Assembly (FPA)
  - Compensate satellite inaccuracy up to ±1°
- Handover to Industry
- Basic technology for further developments
  - Modular Design
  - Standard Interfaces

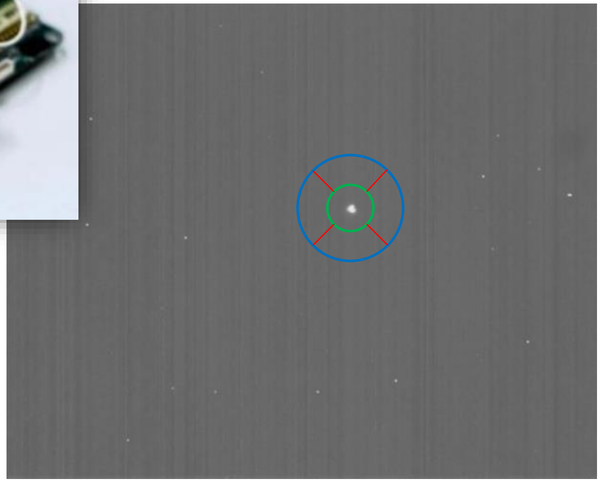


OSIRIS4CubeSat Flight Model

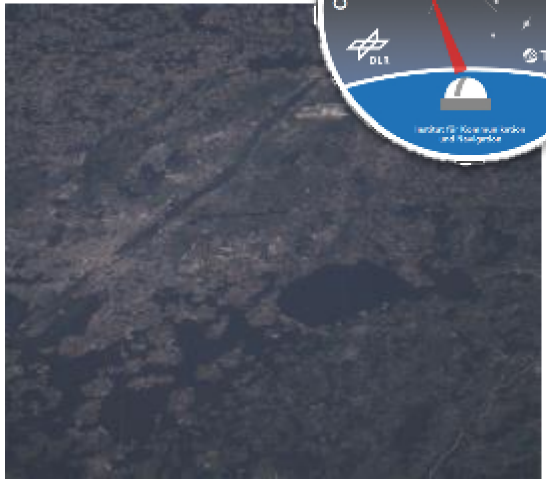
First sold „CubeLCT“

CubeL –
In-Orbit Verification

- Stable signal at Optical Ground Station
- Verification of optical beacon tracking
- Data communication
- Link Budget verified
- **End-to-End system demonstration by transmitting image via optical link**



Trackingcamera at OGS

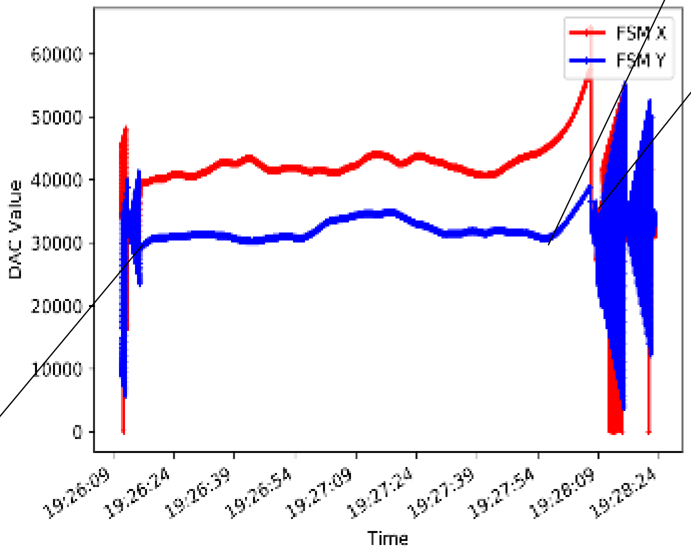


First image transmitted with CubeL

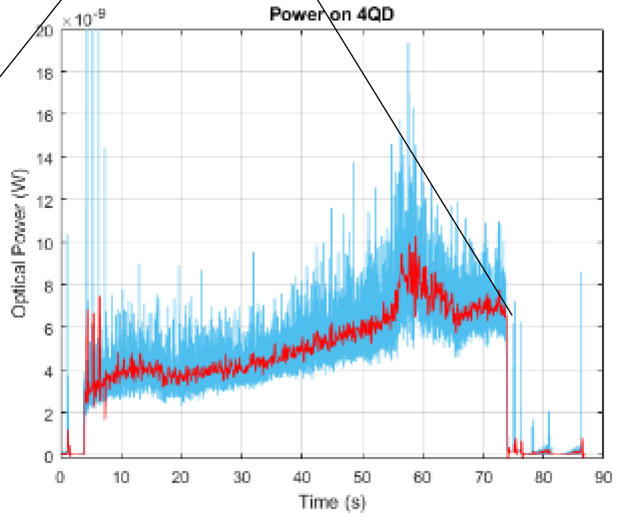
CubeL starts rotating to the edge of +/-1° window

Tracking ends

Acquisition of ground station beacon



Control signals of CubeL tracking mirror



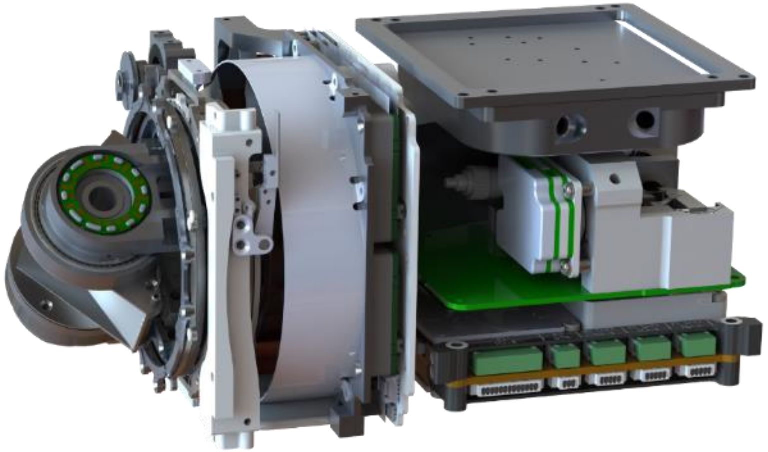
Optical power at tracking sensor

Terminal development for communication applications

CubeISL

- 100 Mbit/s ISL, 1 Gbit/s DL
- 1 U, < 1 kg, < 30 W
- EQM finished, FM in production
- Launch: 2026

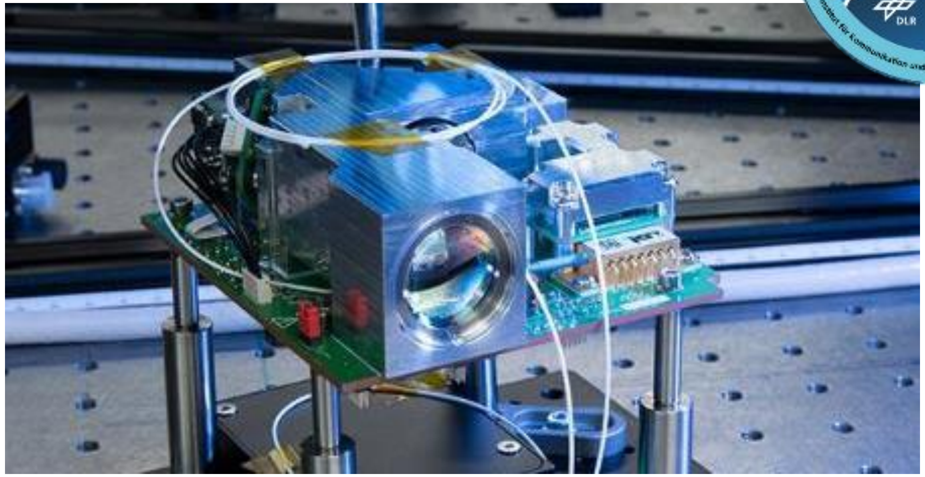
Cube1G



- 1 Gbit/s DL
- ~1.5 U, < 1.5 kg, < 35 W
- Addition of CPA
- SeRANIS mission - Launch: 2026
  (University of the Armed Forces, Munich)

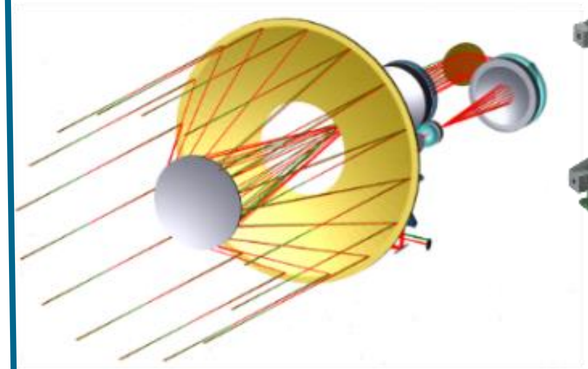
Terminal development for QKD applications

QUBE



- Adaptions for QKD experiments
- Integrated in 3-Unit Cubesat
- Launch: August 2025
- First experiments soon !
  (Project with With LMU, ZfT, FAU, OHB)

QUBE-2



- Extension to 80 mm telescope
- To be integrated in 6U Cubesat
- Launch: 2026
  (Project with With LMU, ZfT, FAU, OHB)

QKD Satellite Missions
EAGLE-1

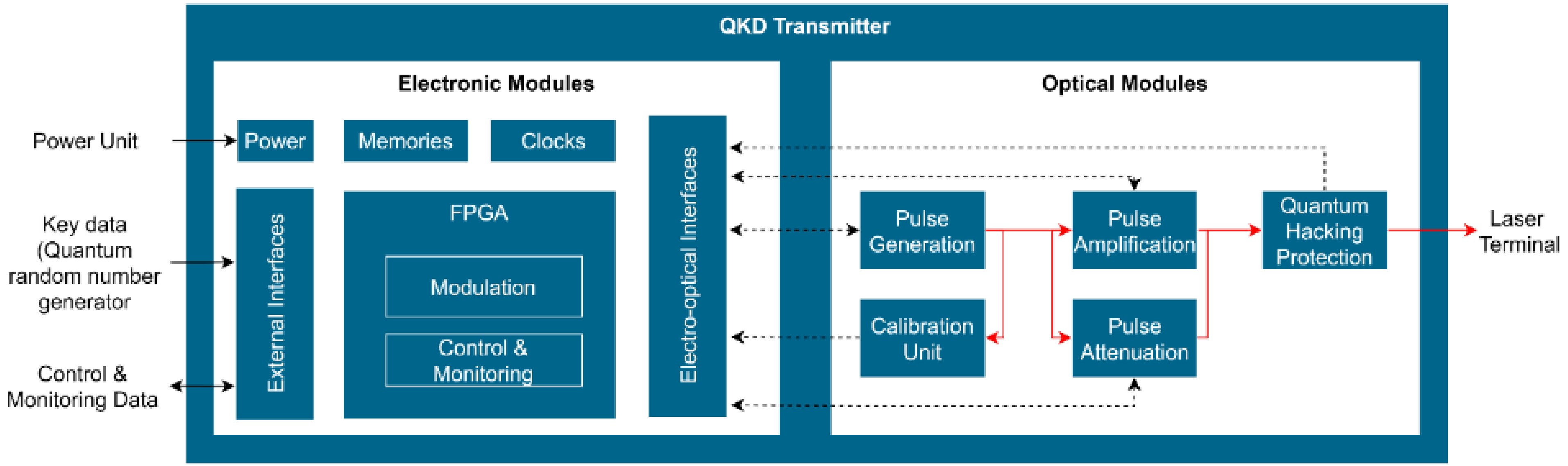
- Funded by ESA Scylight / SAGA
- Partners: SES (Prime), MPL, FAU, LMU, Tesat, AIT, TNO, IDQ, LUXtrust, itrust consulting, Univ. of Palacky, DLR, OHB, …

- Goal: **Develop LEO satellite-based, semi-operational QKD system**

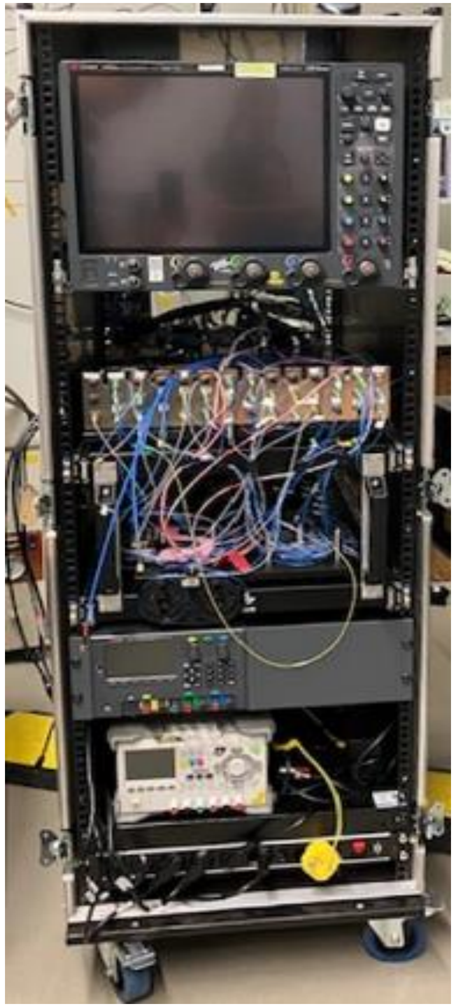
- Phase 1: QUARTZ – End-to-End system level tests with channel simulator in lab
- Phase 2: EAGLE-1 – In orbit demonstration (Launch 2026), LCT by Tesat Spacecom

- <u>Main DLR-KN contributions</u>
  - **QKD transmitter design**
  - **Optical Ground Station for In-Orbit validation**

EAGLE-1 QKD Transmitter Breadboard



Mobile breadboard of QKD transmitter



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- Optical Terminals
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  - …time-transfer
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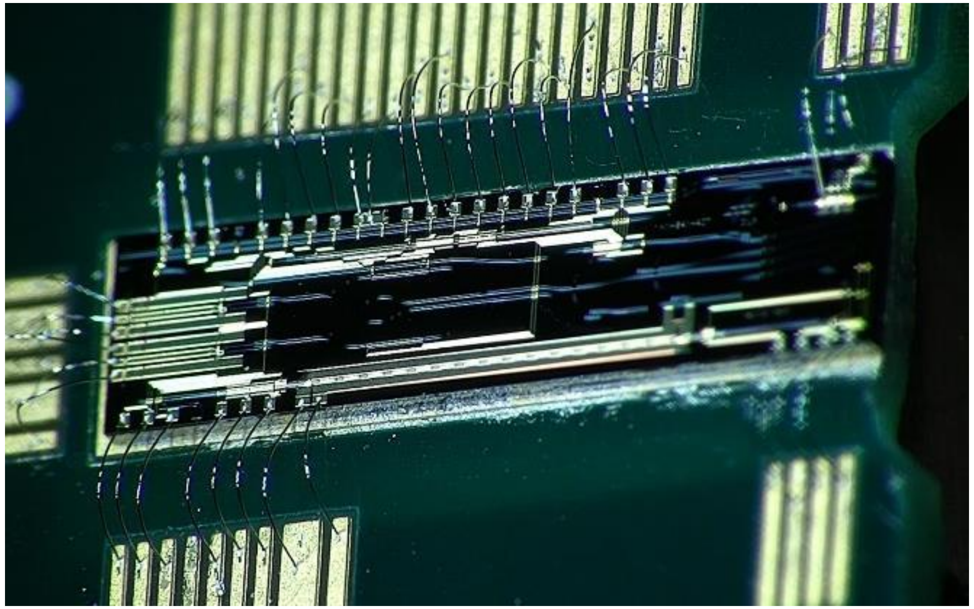
Optical coherent transceivers for satellite communication applications

Coherent Communication Systems

- Rise of satellite constellations (Starlink, Eutelsat OneWeb, IRIS2…) requires dedicated optical technologies such as optical transceivers
- COTS components under-perform in SatCom environment
  - radiation
  - Doppler effect and rate
  - fading channel (erasures)
- Coherent optical waveform for
  - sensitivity (longer link range) and
  - scalability (higher order modulation formats)

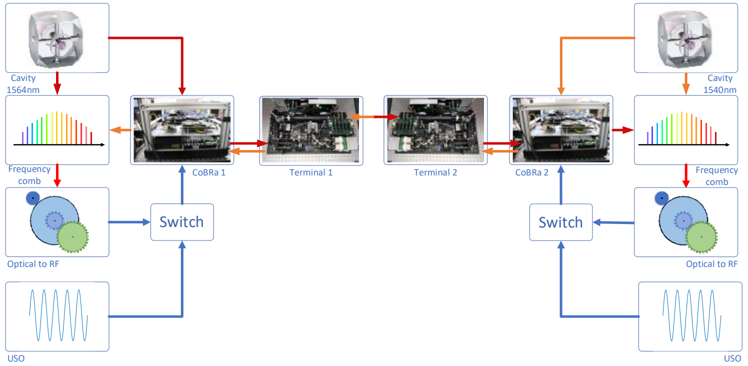
➔ Photonic Integrated Circuits (PICs)

- Coherent optical transceiver optimized for **communications & time-transfer**
- Enables miniaturized and robust systems
- 2nd gen design available / to be tested soon
- 1st gen of DLR PIC after wire-bonding:



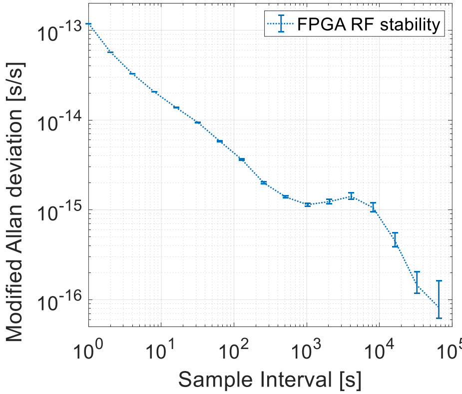
Optical transceiver developments for TT&R

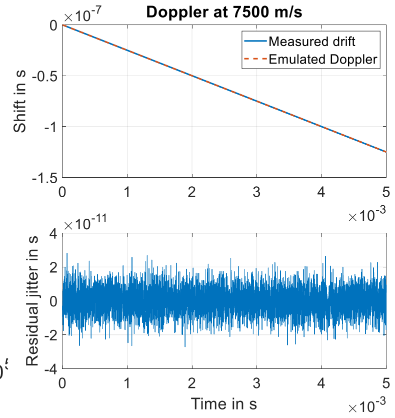
- OISL in GNSS enables ps-level TT and mm-level ranging
  - Based on DLR´s *Kepler** concept for future GNSS
  - Currently developed towards IOD in *COMPASSO*- and *OpSTAR*-projects



- COMPASSO (DLR-internal)
  - Demonstration of optical core technologies, such as optical clocks and optical time- and frequency-transfer to ground
  - To be demonstrated on ISS in 2027

- OpStar (ESA)
  - Demonstration of optical time-transfer and ranging between two satellites and to ground
  - Contract signed on 10th of February
  - To be demonstrated in 2028





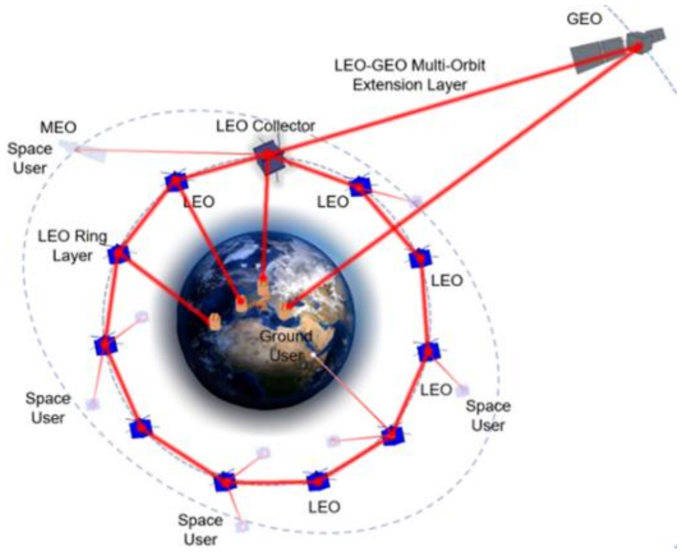
* C. Günther, *Kepler – Satellite Navigation System Description and Validation, Navitec 2018 Signal Workshop*.

ESA‘s HyDRON programme

- <u>Element #1:</u> 10 LEOs
  - Lead by Kepler Communications

- <u>Element #2:</u> LEO extension layer w/ GEO option
  - Lead by TAS-I

- DLR-KN contributions
  - (Atmospheric) channel modeling
  - Contributions to overall architecture design
  - Fixed optical ground station design & demonstration
  - Code Design for Element #2



Pictures: ESA

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Optical Ground Station Oberpfaffenhofen „Next generation“ – OGSOP-NG

Improved performance and sensitivity

- 80 cm aperture
- Measurements with better spatial resolution
- Supports links in GEO-, deep space- and quantum key distribution-applications

Multiple foci, including Coudé

- High flexibility to change between setups, enabling multi-mission support
- Adaptive Optics on Coudé-Bench (2.4x1.2m)

Past Experiments & Commissioning

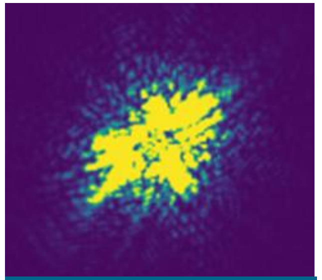
- FSOC links to GEO – an Adaptive Optics (AO) system was developed for downlink correction and uplink pre-compensation

Installed in 2021, commissioned in 2022

Moon Crater

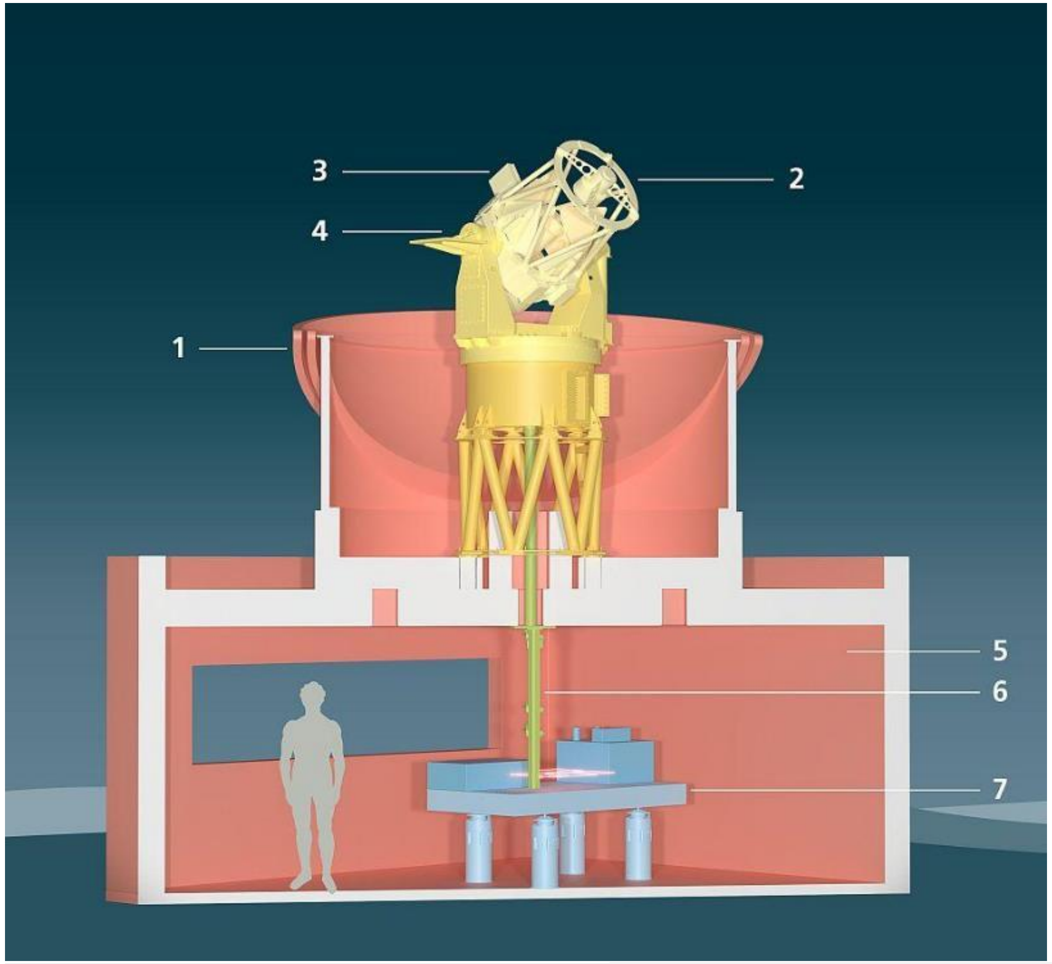
ISS

FLP

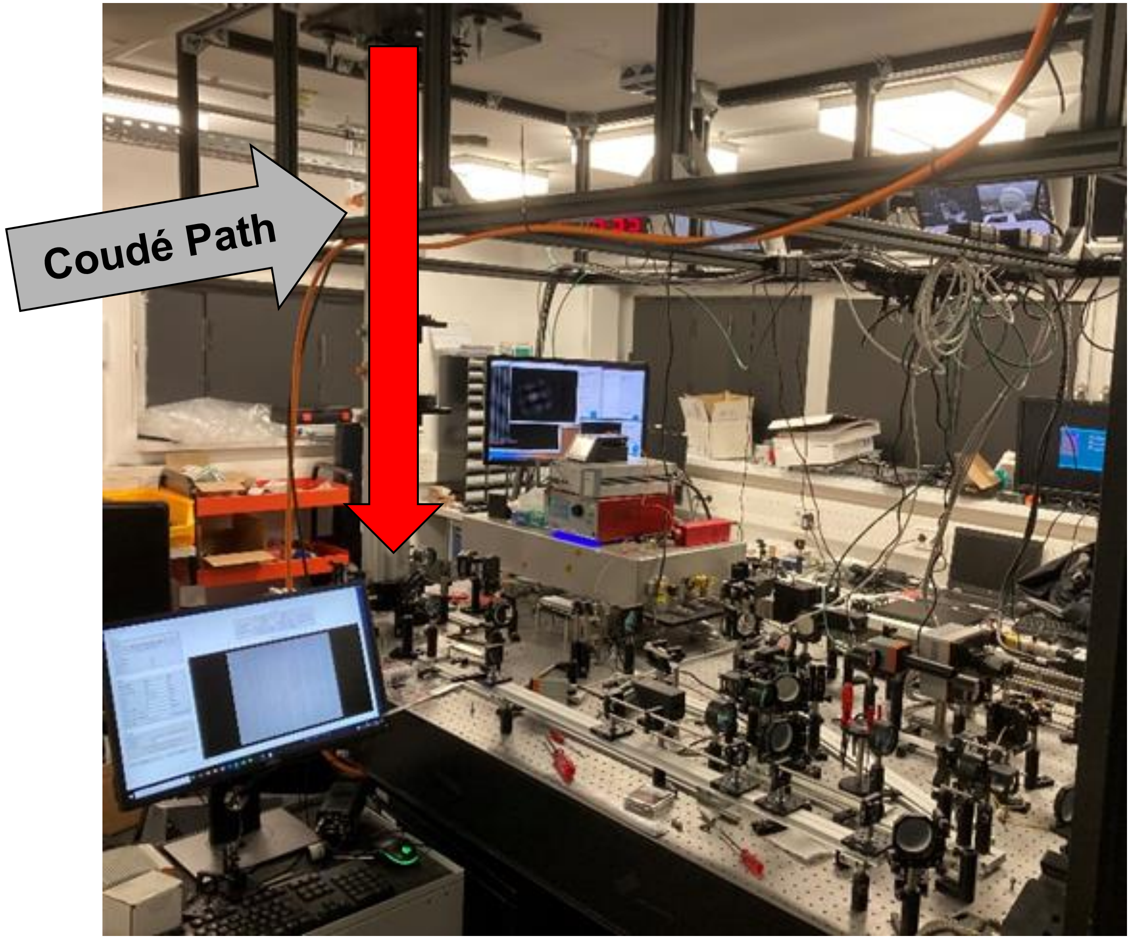


Alphasat

OGS-OP NG – Coudé lab with adaptive optics and single-mode fiber coupling



1. Dome
2. Telescope
3. Optical Bench st Sharkfin Port
4. Optical bench at Nasmyth Port
5. Coudé Laboratory
6. Coudé path from telescope to the laboratory
7. Optical Bench with AO

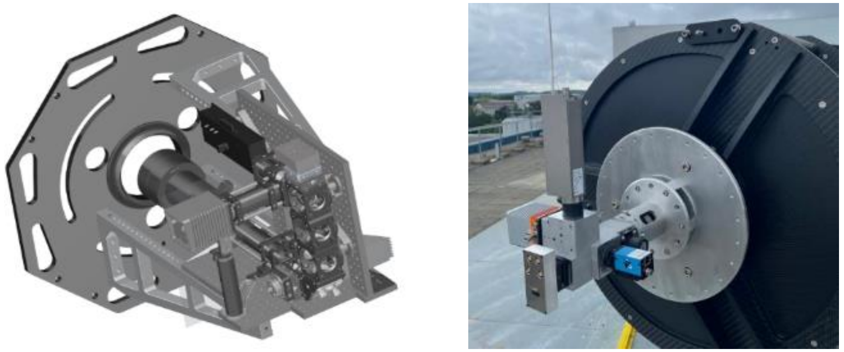


Coudé Laboratory

Small OGS Focal Assembly and tests in New Zealand

- Dedicated optical bench for easy integration with Off-The-Shelf telescopes
- Integrates key-components for optical ground stations (tracking camera, receiver front-end, beacon lasers)
- Industrialization planned

- First tests in collaboration with Univ. of Auckland, New Zealand
- First light from OSIRISv1 received on 14th of February, 2025



Small OGS Focal Assembly (SOFA)

Teams during first satellite experiments

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Summary and Conclusions

- The Optical Satellite Links department within DLR‘s Institute of Communications and Navigation performs research and conducts demonstrations missions for several application scenarios of optical links

- This includes the development of
  - …optical terminals for communications, quantum key distribution as well as optical time-transfer and ranging
  - …technologies for satellite links, such as photonic integrated circuits, forward error correction coding, etc.
  - …Optical Ground Stations and atmospheric mitigation techniques

- Several satellite missions with DLR‘s optical terminals are already ongoing, further missions are planned in the near future

THANK YOU VERY MUCH FOR YOUR ATTENTION

ASMS 2025

RECENT RESULTS IN OPTICAL SATELLITE LINK RESEARCH AT DLR

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Impressum

Topic: Recent Results in Optical Satellite Links at DLR

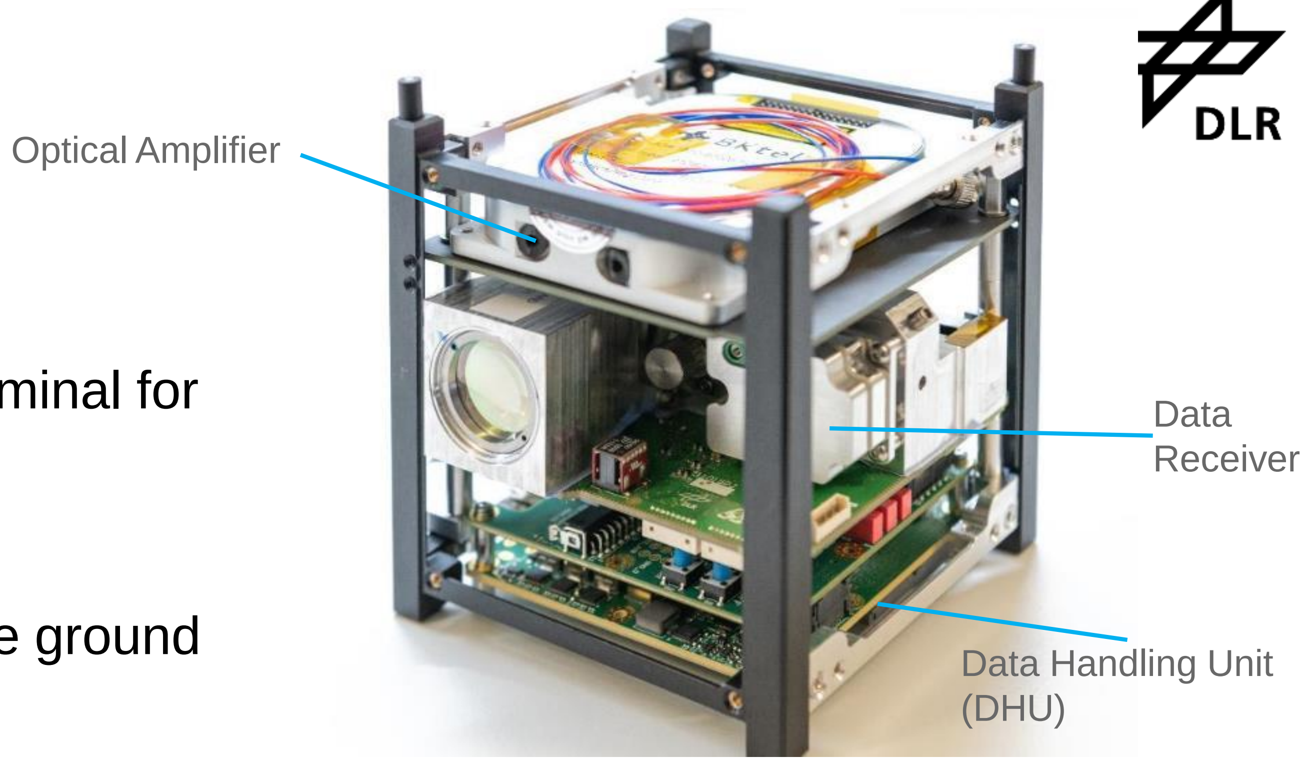
Date: 28th of January, 2025

Author: Christian Fuchs et. al

Institute: DLR Institute of Communications and Navigation

Pictures: DLR

CubeISL



Research Goals

- Development of a laser communication terminal for Optical Intersatellite Links on CubeSats
- Demonstrator Mission in Space
- Increasing data rate from the satellite to the ground
- Launch: 2026

Parameters

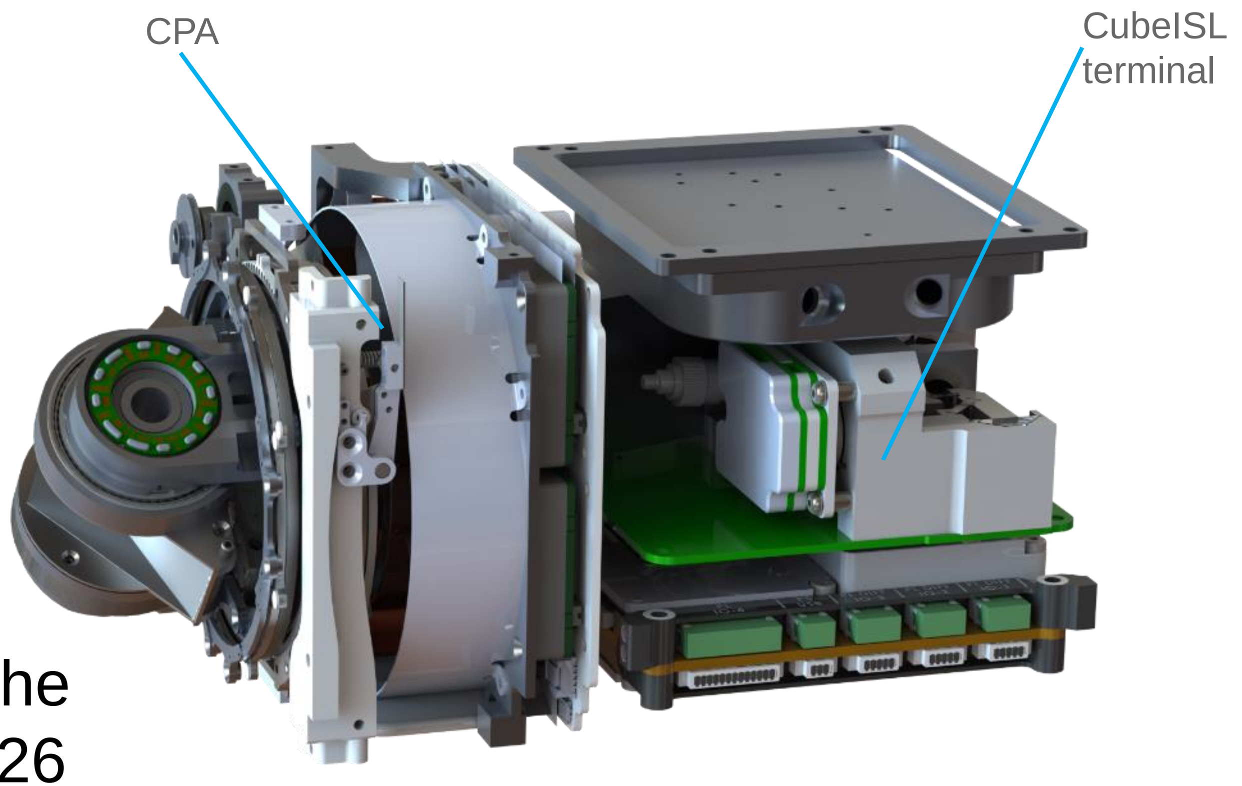
▪ Data rate ISL:	up to 100 Mbps
▪ Data rate DTE:	up to 1 Gbps
▪ Weight:	< 1 kg
▪ Size:	10 x 10 x 10 cm^3 (1 Unit)
▪ Power Consumption:	< 30 W

*Responsive Space Cluster Competence Center

Cube1G

- Based on CubeISL
- Coarse pointing assembly (Independent from satellite attitude)
- Improved Data Rate
  - Optical DTE: 1 Gbps
- Applications also on High-Altitude Pseudo Satellites (HAPS)

- ➔ SeRANIS mission / University of the Armed Forces, Munich – Launch: 2026

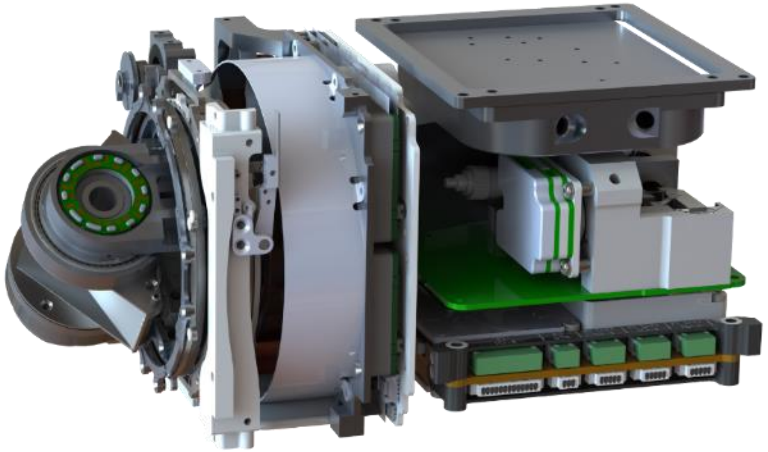


Further highlights: terminal development

CubeISL

- 100 Mbit/s ISL, 1 Gbit/s DL
- 1 U, < 1 kg, < 30 W
- EQM finished, FM in production
- Launch: 2026

Cube1G



- 1 Gbit/s DL
- ~1.5 U, < 1.5 kg, < 35 W
- Addition of CPA
- SeRANIS mission - Launch: 2026
  (University of the Armed Forces, Munich)

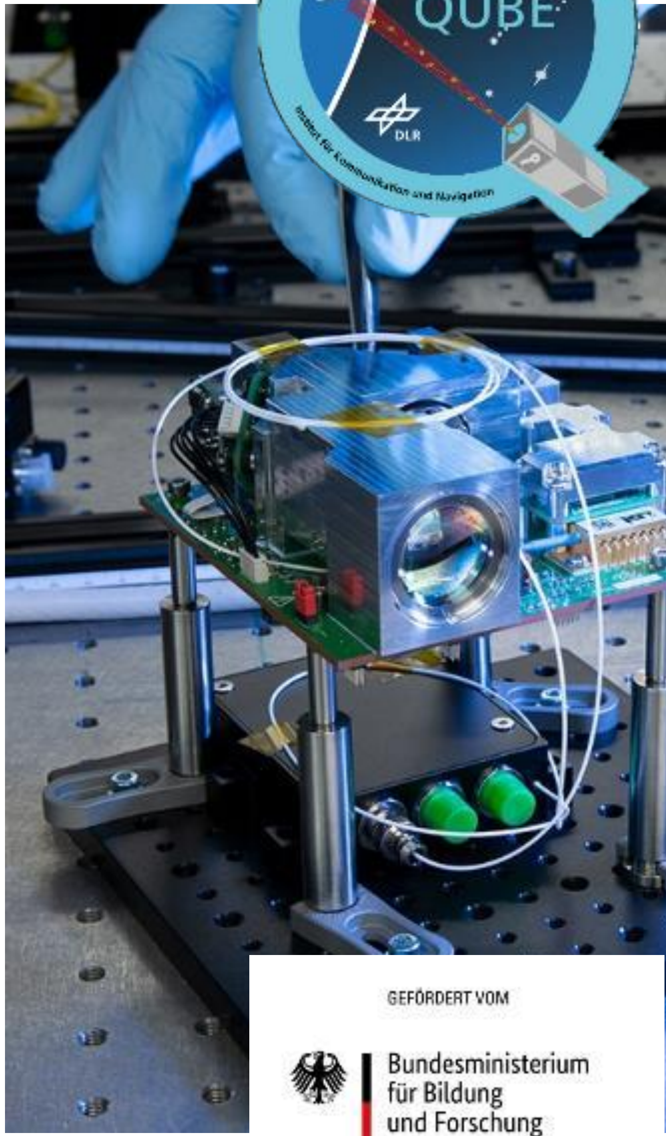
QKD Satellite Missions
QUBE

Quantenexperimente auf CubeSat
QUBE
DLR
Institut für Kommunikation und Navigation

<ins>Project</ins>

- Cooperation between DLR, LMU, MPL, ZfT and OHB
- Goal: Develop and Demonstrate Technologies in Preparation for Quantum-Key-Distribution (QKD) from CubeSats
- Funded by German *BMBF*

- **Launch: Summer 2024**
  → First optical link experiments soon

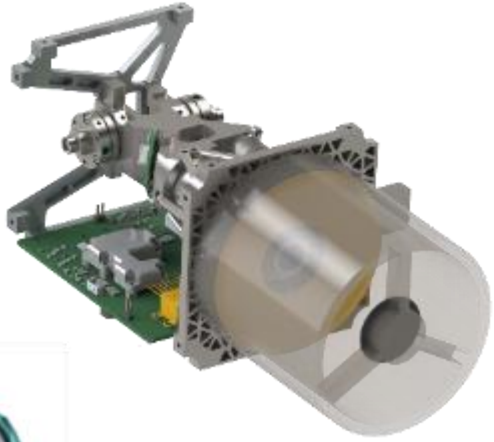


OSIRIS4QUBE EQM

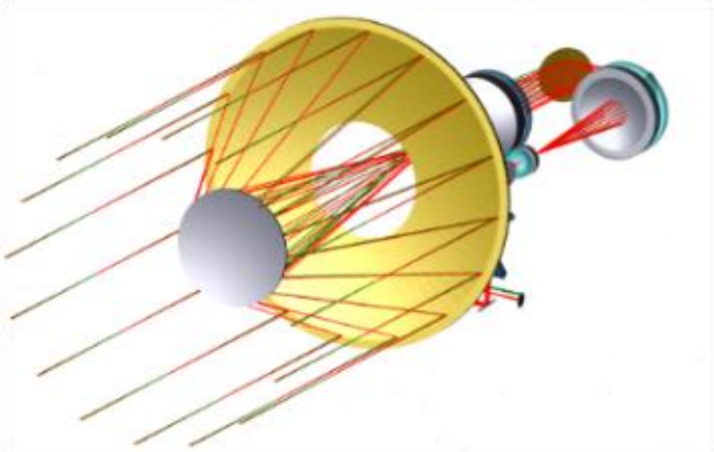
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

QKD Satellite Missions
QUBE-II

- Experimental demonstration of full QKD system on a CubeSat
- Further development of QUBE by extending it with a 85mm telescope
- Dual-wavelength optical design
- EQM currently in production
- Launch in 2026



QUBE-II terminal design



QUBE-II terminal raytracing

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With partners from:

Optical coherent transceivers development

- Rise of satellite constellations (Starlink, OneWeb, IRIS2…) requires dedicated optical technologies such as optical transceivers
  - COTS components under-perform in SatCom environment
    - radiation
    - Doppler effect and rate
    - fading channel (erasures)
  - Coherent optical waveform for
    - sensitivity (longer link range) and
    - scalability (higher.order modulation formats)
- It is essential to model the **system** [1]
- Channel modelling [2] of atmospheric channel to obtain time-dependent **fading vectors** for system validation (HW-in-loop)

→ Participation at *CCSDS* coherent blue book and *ESTOL* definition

- Fades need to be compensated → time-diversity (interleaving and/or erasure codes)
- Re-synchronisation delay with each fade occurence causes artificial lengthening of erasure
- Contribution to the developments of EC [3] and interleaving [4] to future high-speed optical SatCom networks
- Implementation of efficient physical layer **algorithms** to minimise re-synchronisation times [5]

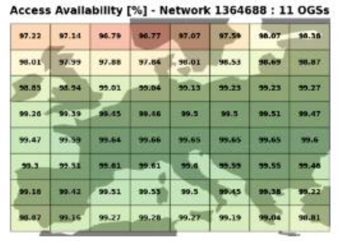
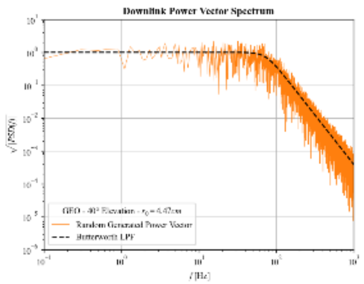
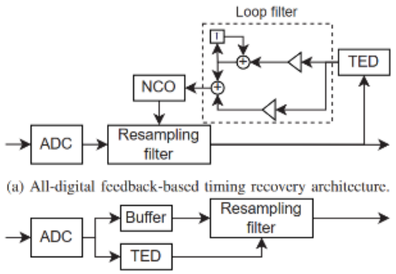


Fig. 14: Access availability for the optimal network of 11 OGSs for Constellation A.





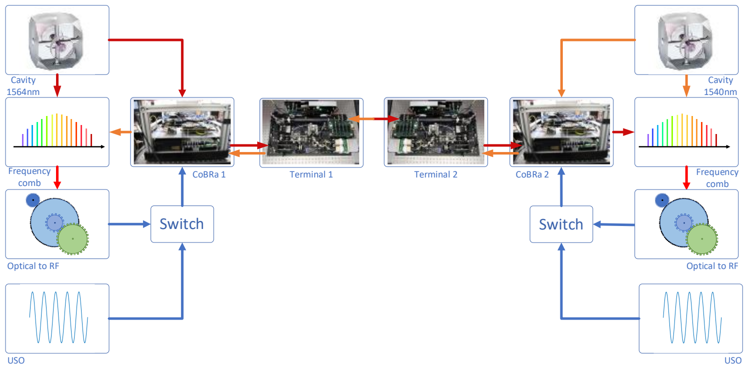
(a) All-digital feedback-based timing recovery architecture.

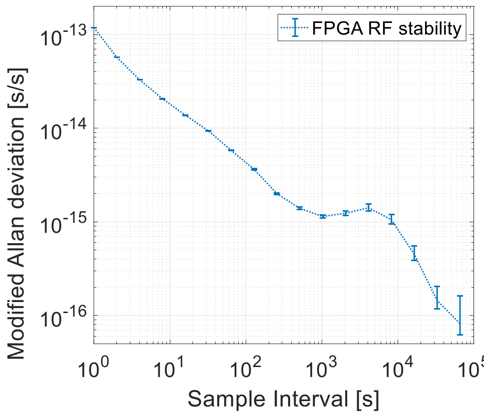
(b) Feedforward-based timing recovery.

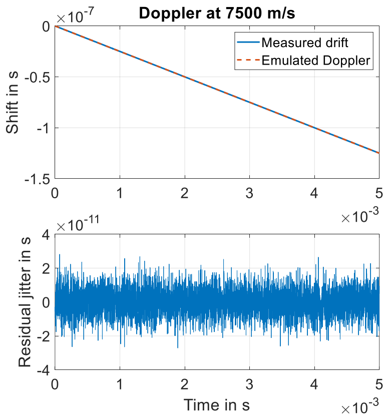
[1] S. Raffa, L. Pizzuto, and J. Poliak, *End-to-End Availability Analysis for an Optical-RF Large Constellation Concept*, *Proceedings of the 75th International Astronautical Congress (IAC)*.
[2] G.L. Torre, S. Raffa, and J. Poliak, *A spectral shaping approach to generate power vectors for optical ground-tospace links*, *SPIE Conference Proceedings: Atmospheric Effects on Light Propagation and Adaptive Systems*, DOI: 10.1117/12.3033903.
[3] J. Poliak, H. Bischl, B. Matuz, and J.C.R. Molina, *Erasure correcting codes for high-throughput optical groundto-satellite links*, *Free-Space Laser Communications XXXIV, SPIE Proceedings*, DOI: 10.1117/12.3001403.
[4] O. Griebel, A. Sauter, U. Wasenmüller, L. Steiner, J. Poliak, B. Matuz, and N. Wehn, *Physical layer error correction for free-space optical links*, *SPIE Conference Proceedings: Free-Space Laser Communications*, DOI: 10.1117/12.3001394.
[5] C. Valjus and R. Wolf, *Comparison of Timing Recovery Algorithms for Optical Feeder Links*, *Photonic Networks; 24th ITG-Symposium*.

Optical transceiver developments for TT&R

- OISL in GNSS enables ps-level TT and mm-level ranging
  - Based on DLR´s Kepler concept [6,7] for future E-GNSS
  - Further developed towards IOD in COMPASSO [8] and OpSTAR
- Waveform adaptation needed to include PRN sequence
  - Transmitted PRN is correlated with a locally generated one (on LO)
  - Breadboarding towards integration as flight model by industrial partner (TESAT)
  - Validation in laboratory [9] and outdoor in 10.5km link [10] shows highly promising results
  - Highly robust against Doppler effect and rate
  - Qualification of essential components, e.g. precise DLL [11]
  - Further developments aim at integration in future SatCom to enable ps-level synchronisation even in presence of Doppler [12]







[6] C. Günther, *Kepler – Satellite Navigation System Description and Validation*, Navitec 2018 Signal Workshop.
[7] T. Schmidt et al., *Optical Technologies for Future Global Navigation Satellite Systems*, *2023 IEEE/ION Position, Location and Navigation Symposium*.
[8] T.D. Schmidt et al., *COMPASSO: In-Orbit Verification of Key Optical Technologies for Future GNSS*, *Precise Time and Time Interval Systems and Applications Meeting (PTTI) 2024*.
[9] J. Surof, R. Wolf, L. Macrì, M. Mehlbeer, and J. Poliak, *COMPASSO: Time and Frequency Transfer In-Orbit Validation for Future GNSS*, *55th Annual Precise Time and Time Interval Systems and Applications Meeting (PTTI)*.
[10] J. Surof, J. Poliak, R. Wolf, L. Macri, R.M. Calvo, L. Blümel, P. Dominguez, G. Giorgi, L. Agazzi, J. Furthner, and others, *Validation of Kepler Time and Frequency Transfer on a Terrestrial range of 10.45 km*, *Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*, pp. 3662–3670.
[11] L. Macrì, S. Raffa, J. Surof, and J. Poliak, *TID Radiation Characterization of a Commercial High-Speed Delay Line*, *2024 RADECS Data Workshop*.
[12] J. Surof and J. Poliak, *Precise Time Transfer for High Throughput Satellite Communications Links in Precise Time and Time Interval Systems and Applications Meeting*, *Precise Time and Time Interval Systems and Applications Meeting (PTTI) 2025*