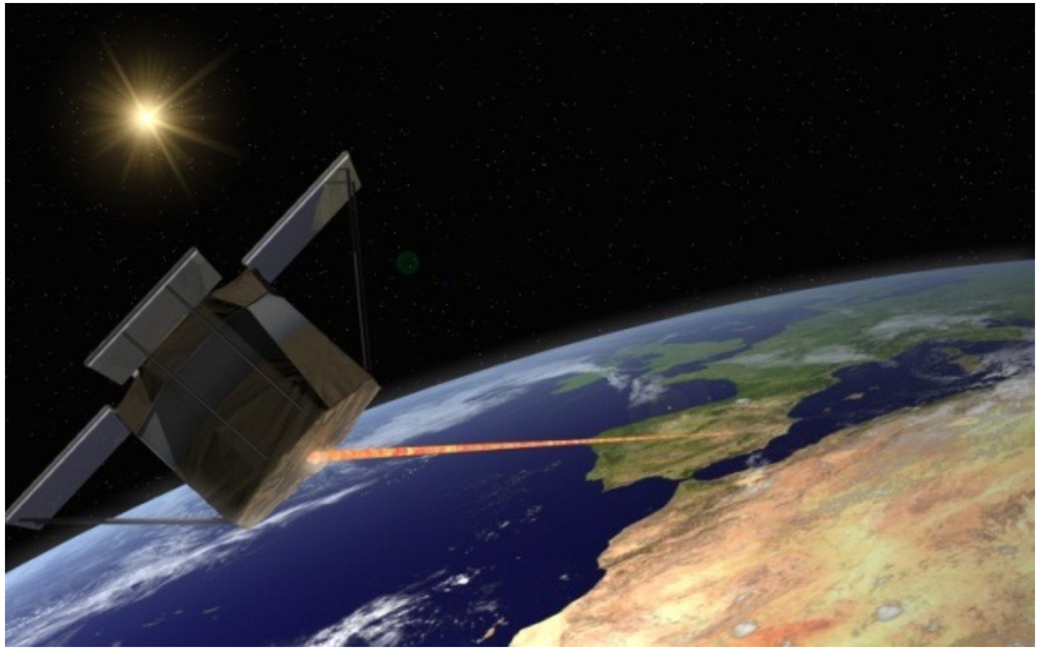
DLR'S SOLUTIONS FOR OPTICAL COMMUNICATIONS ON CUBESATS

Institute of Communications and Navigation
German Aerospace Center (DLR)

Benjamin Rödiger et. al.

Outline

- Optical Satellite Links department
- Selected projects and applications
  - OSIRIS
  - CubeSat developments
  - Optical feeder links
  - Kepler
- Quantum communications
- Optical Ground Station technologies
  - Optical Ground Stations at DLR
  - OGS Networks
- Optical transmission technologies
- Standardization



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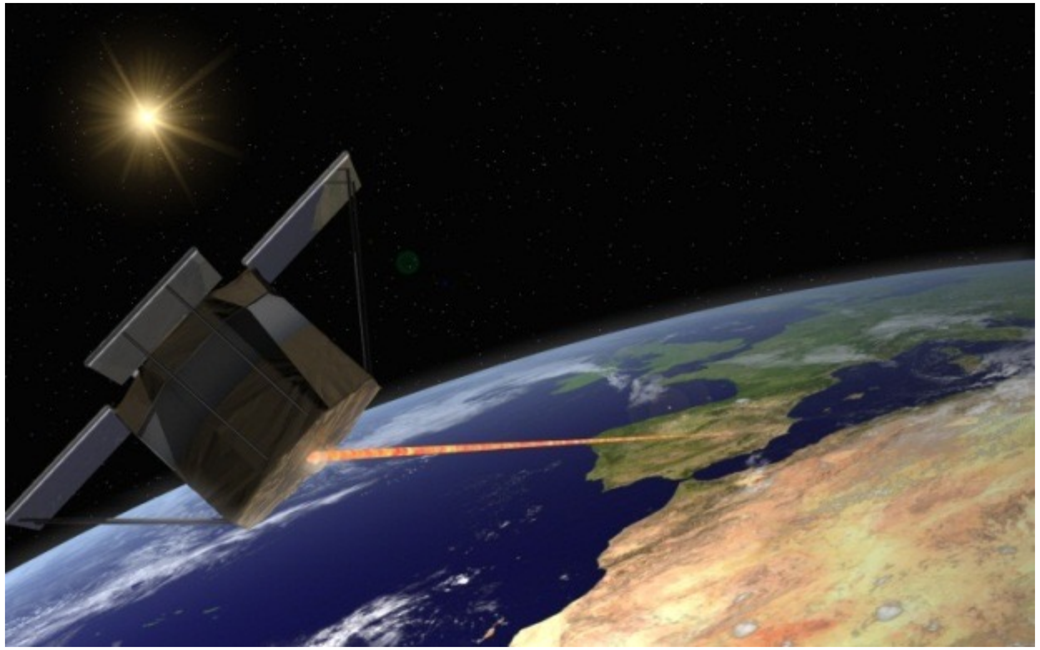


Optical Satellite Links Department in a nutshell

Staff

- 46 Scientists, 6 DLR-DAAD fellows (PhD students)
- 5 Groups
  - Compensation of Atmospheric Turbulence (Andrew Reeves)
  - Optical Technologies for Space Applications (Juraj Poliak)
  - Optical Communication Terminals (Christopher Schmidt)
  - Optical Ground Stations (Christian Fuchs*)
  - Quantum Communication Systems (Florian Moll)

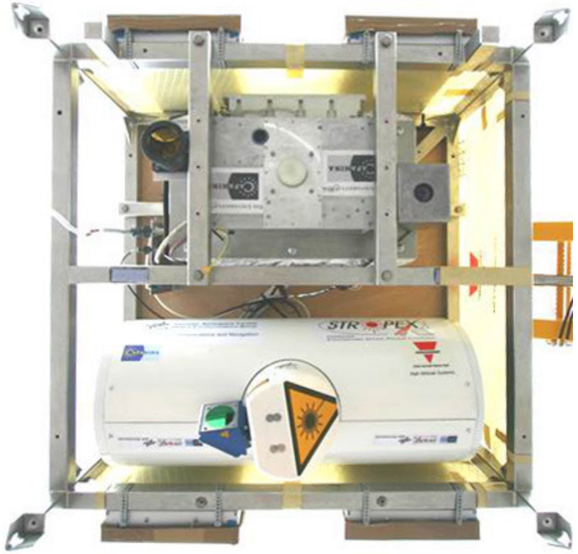
Main Research Topics

- Optical satellite communications and quantum key distribution
- Optical time- and frequency transfer
- Channel modeling and turbulence mitigation techniques

Optical Ground Station Oberpfaffenhofen

OSIRIS terminal for Cubesats

Heritage in Free-Space Optical Communication



2004: First link from a tethered balloon

2005: First link from the stratosphere, 22 km height
1.25 Gbps, 100 mW

2008: First air-to-ground link
1.25 Gbps, d=120 km

2011: First QKD air-to-ground link

2013: First air-to-ground link
Mach 0.7, 1.25 Gbps, d=60 km
jointly with ViaLight (now Mynaric)
contract by Airbus

QKD: Quantum Key Distribution

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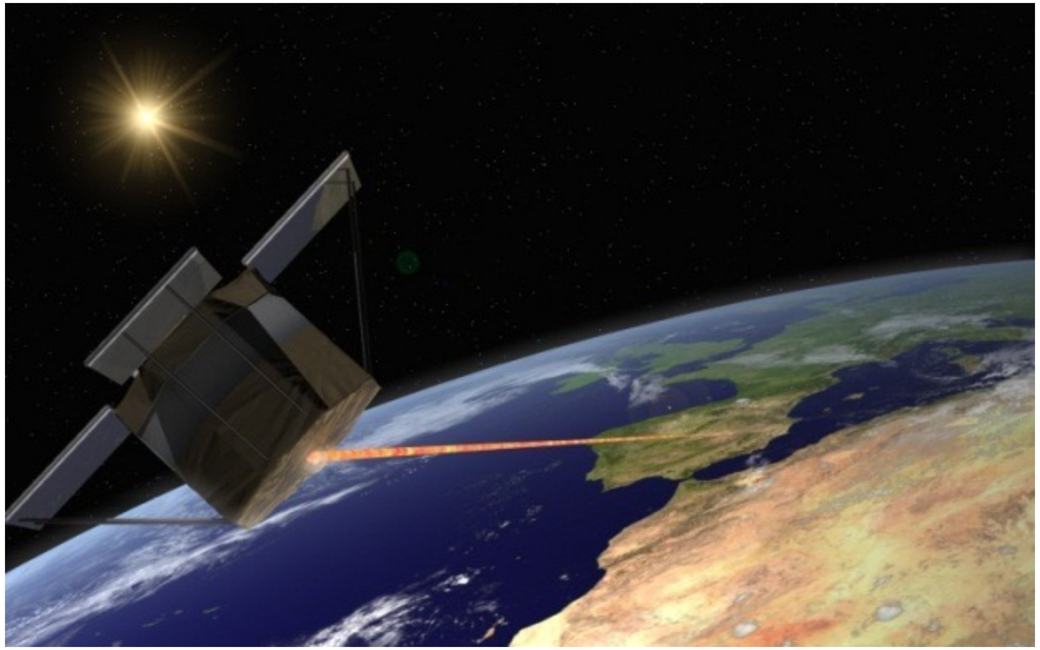


OSIRIS Program

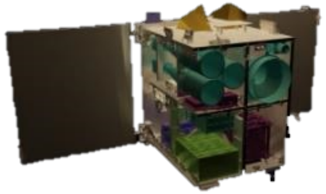
Proof of Concept

Commercialization by TESAT

2017

Jan 2021

2024



OSIRISv1
Open-Loop Body Pointing
Data rate: 200 Mbit/s

OSIRIS4CubeSat
CubeSat Terminal with active beam steering
Data rate: 100 Mbit/s

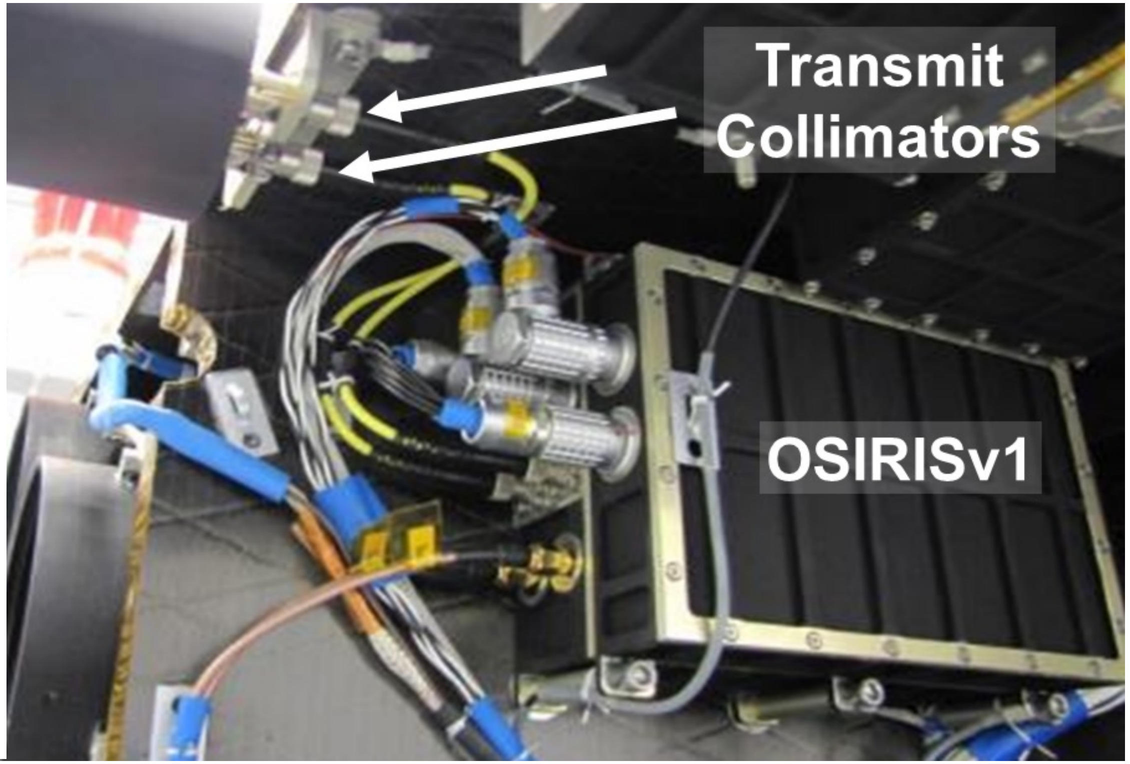
Base for several developments

OSIRISv3
High performance with pointing assembly
Data rate: 10 Gbit/s

OSIRIS: Optical Space Infrared Downlink System

OSIRISv1 – Flying Laptop

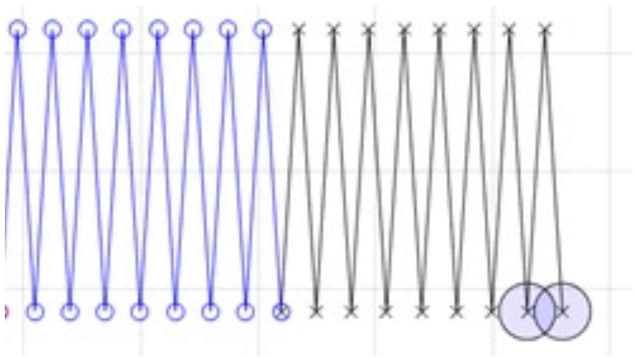
Flying Laptop, Univ. of Stuttgart



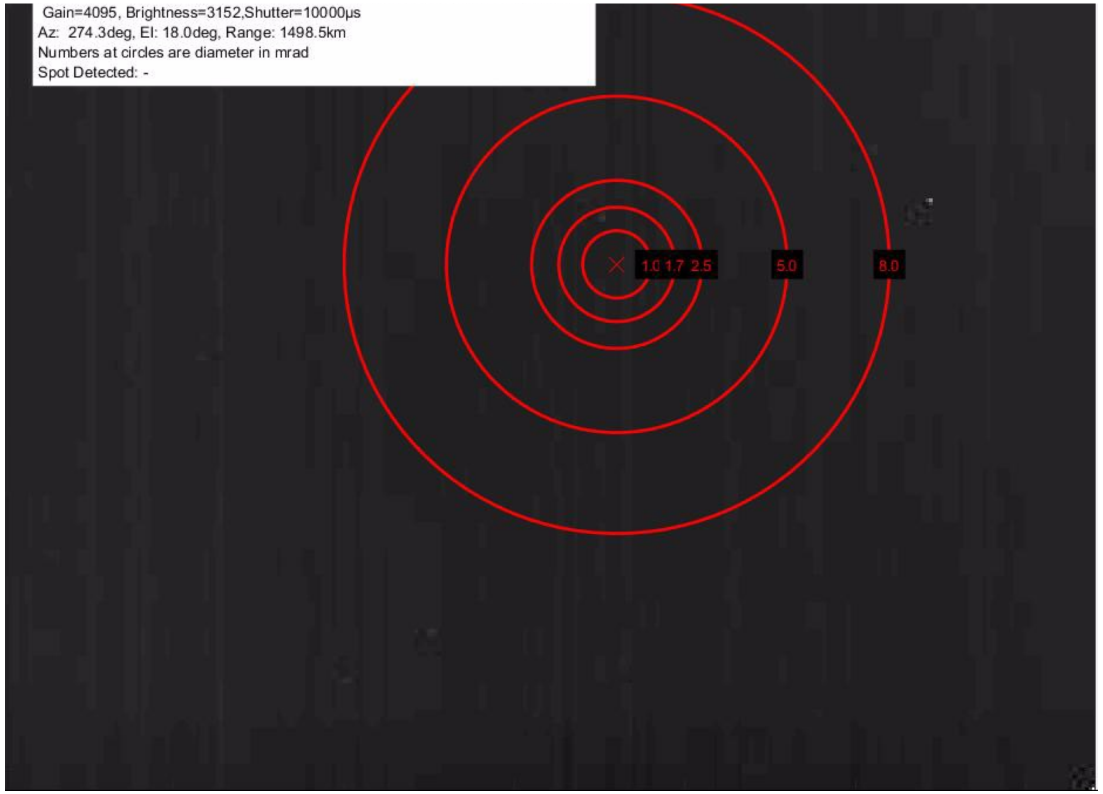
OSIRIS Flight Model integrated in satellite

OSIRISv1 – First „flash“

- Relying on Satellites ADCS
  - Open-Loop body pointing
  - No feedback from ground
- Zig-zag search pattern
- Decreasing pointing error
  - Hexagon pattern
  - Axial swipes
  - Correlation between measured power and ADCS

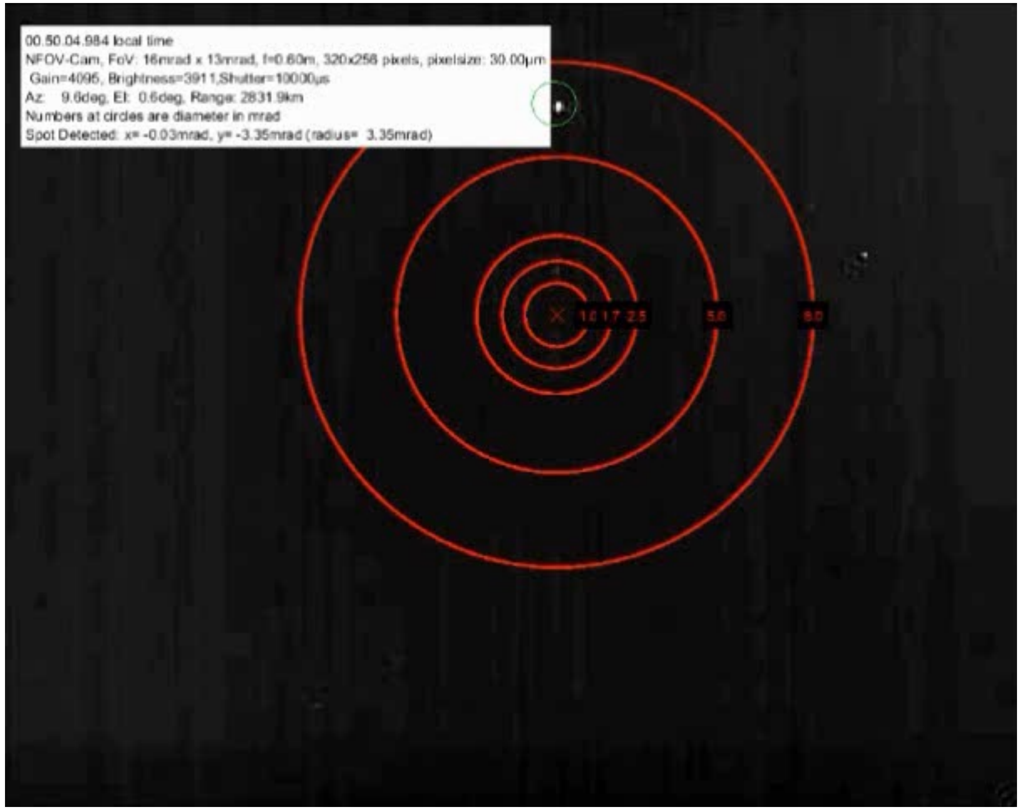


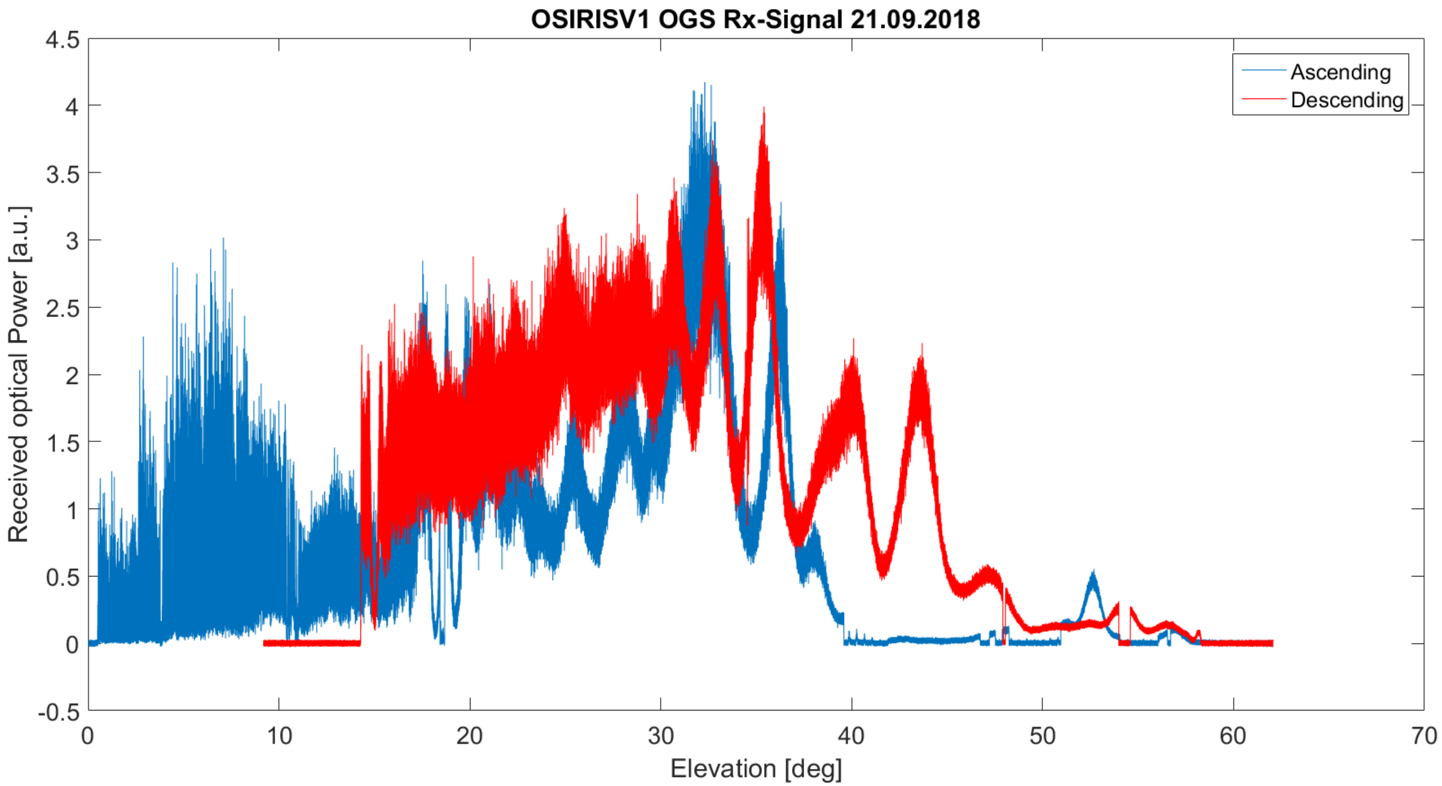
Zig-zag pattern



First flash from OSIRISv1

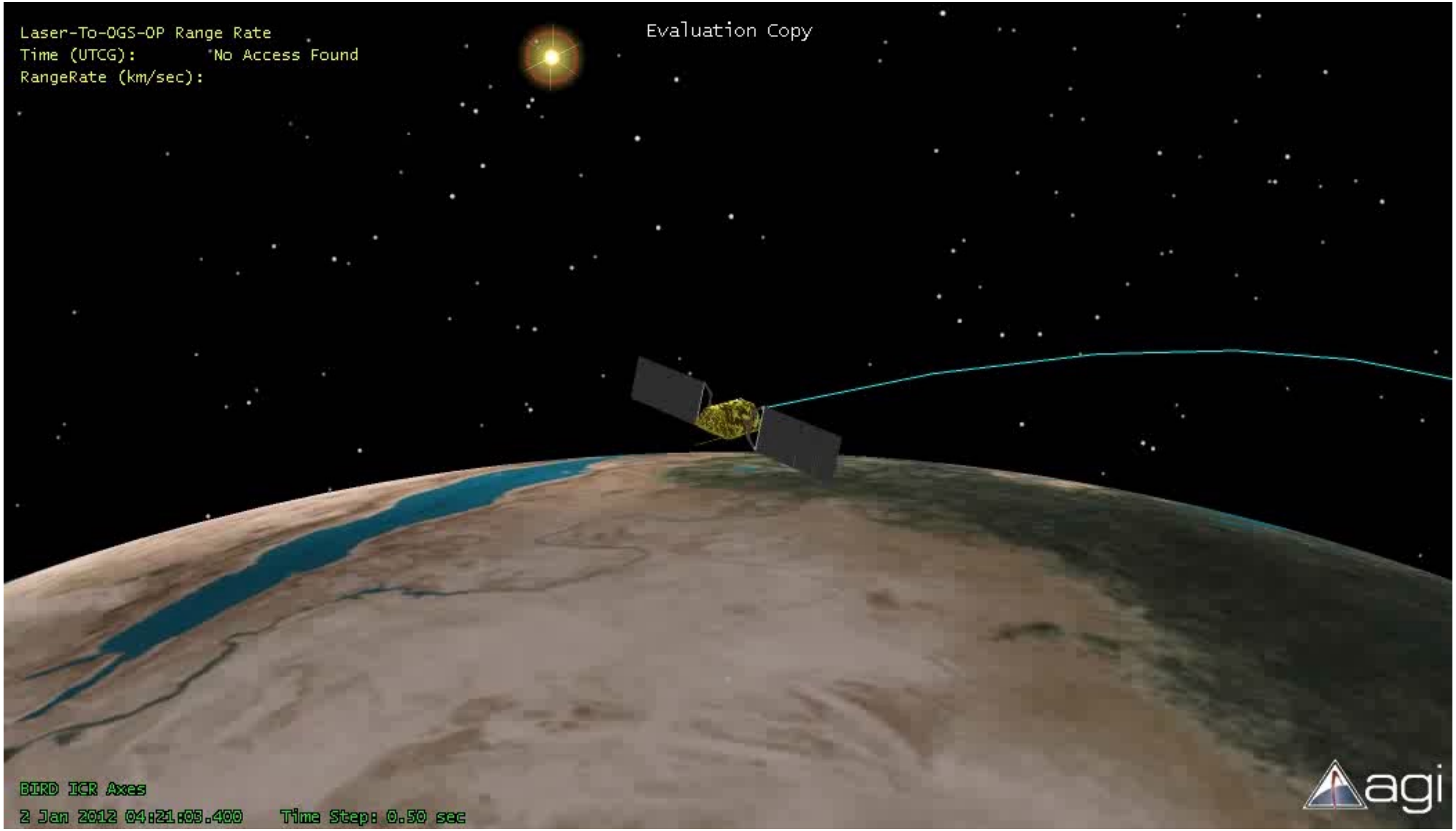
OSIRISv1 – Signal Reception





- 21st September 2018
- Pointing Optimization
- Acquisition at 0.4° elevation
- 10 minutes duration

Point Acquisition and Tracking

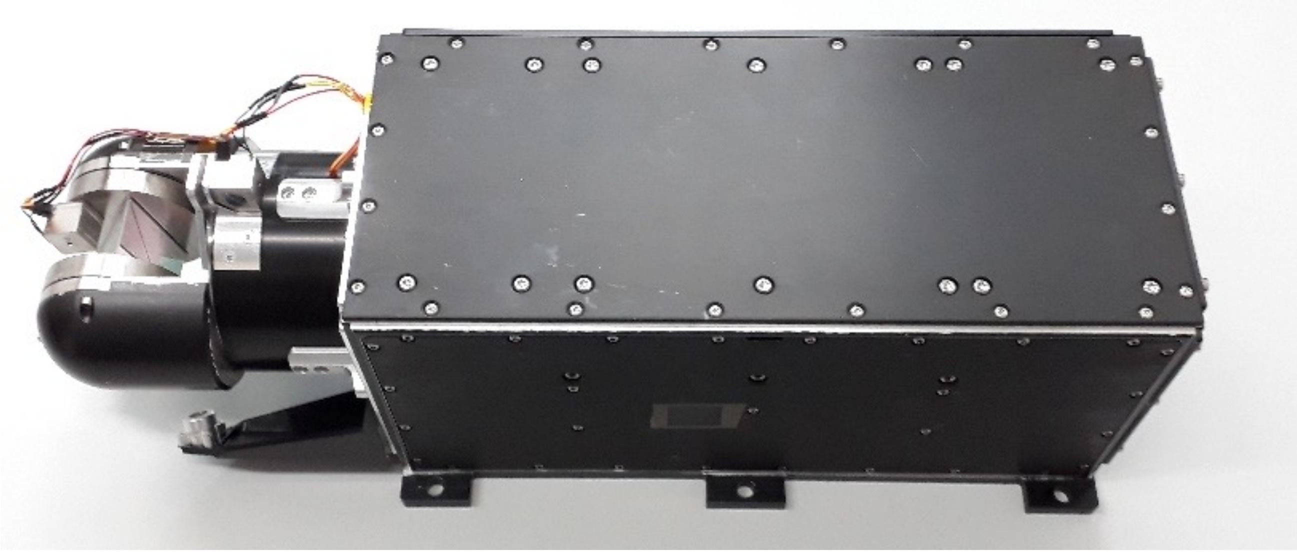


OSIRISv3

Payload Parameters

- Key system parameters:
  - Weight: 9 kg
  - Power consumption:
    - 130 W (operation)
    - 16 W (Stand-By)
  - Downlink data rate: 10 Gbit/s
- Equipped with a Coarse Pointing Assembly (CPA)
- Data handling included in the TOSIRIS terminal
- ARQ system for reliable data transmission (space segment)
- Modular system concept for different missions and applications

- Commercialization partner: TESAT



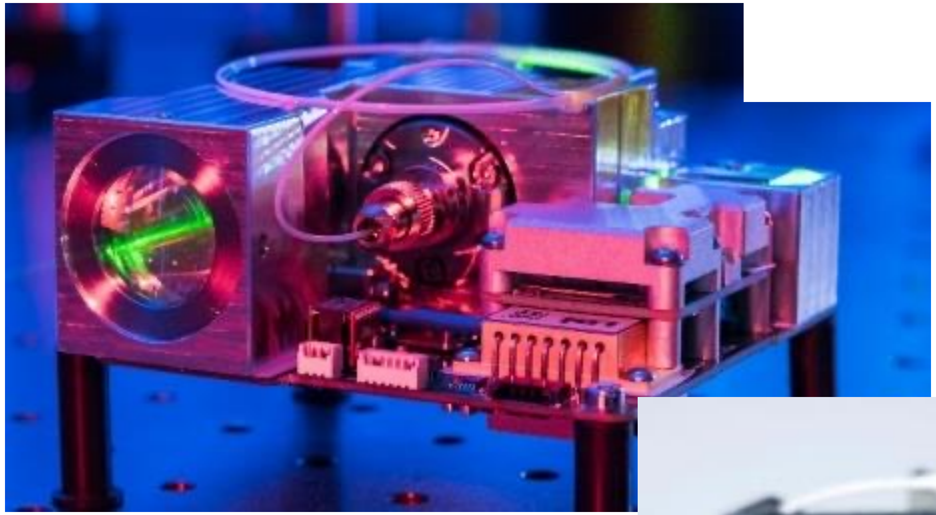
OSIRISv3 EQM

CPA: Coarse Pointing Assembly
ARQ: Automatic Repeat reQuest

OSIRIS4CubeSat

Parameters

- 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 pointing inaccuracy up to ±1°
  - PAT system with L-Band beacon
  - Compatible to CCSDS O3K standard
- Handover to Industry
  - Tesat produces “CubeLCT” as product
- Basic technology for further developments
  - Modular design
  - Standard interfaces

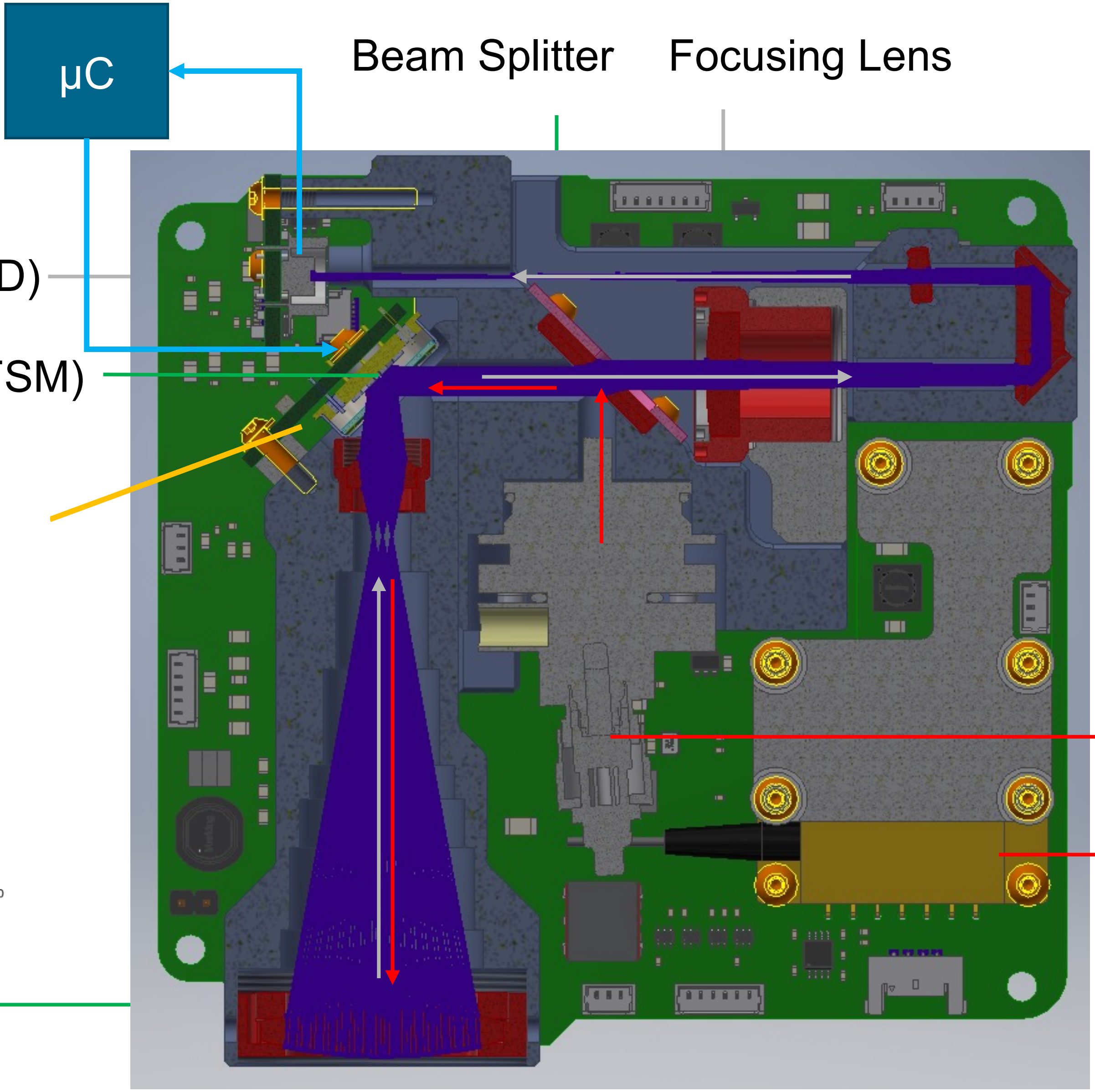


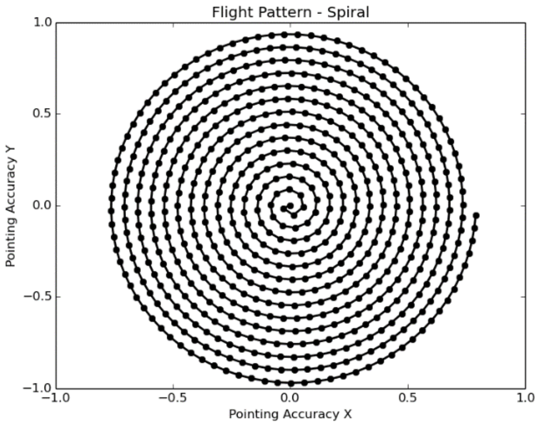
OSIRIS4CubeSat Flight Model

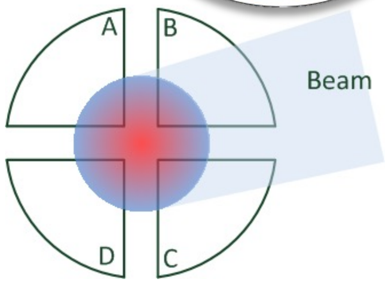
First sold „CubeLCT“

CCSDS: Consultative Committee for Space Data Systems
O3K: Optical On-Off-Keying

OSIRIS4CubeSat – PAT Concept







$$X_{pos} = \frac{(A+B)-(C+D)}{A+B+C+D}$$

$$Y_{pos} = \frac{(B+C)-(A+D)}{A+B+C+D}$$

μC: Microcontroller

OSIRIS4CubeSat – PIXL-1

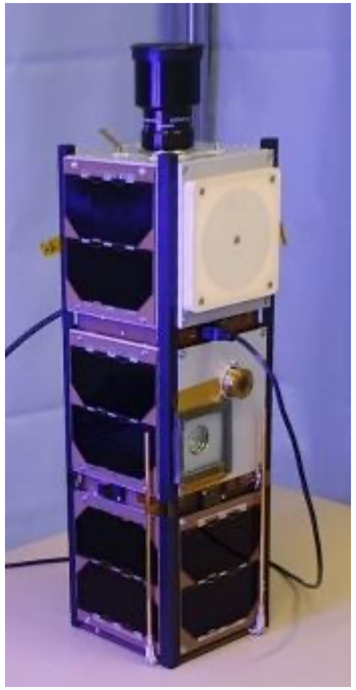
Mission Status

<u>3U CubeSat „CubeL“</u>

- Demonstration of capabilities of OSIRIS4CubeSat / CubeLCT
  - Quasi-operational scenario
  - Transfer of RGB-pictures to Optical Ground Station
- Operation via UHF and S-band by GSOC
  - Integration of a CubeSat into a professional ground segment

<u>Launch</u>

- SpaceX Mission „Transporter 1“
  - Date: 24th of January 2021
  - Launcher: Falcon 9
  - Site: Cape Canaveral

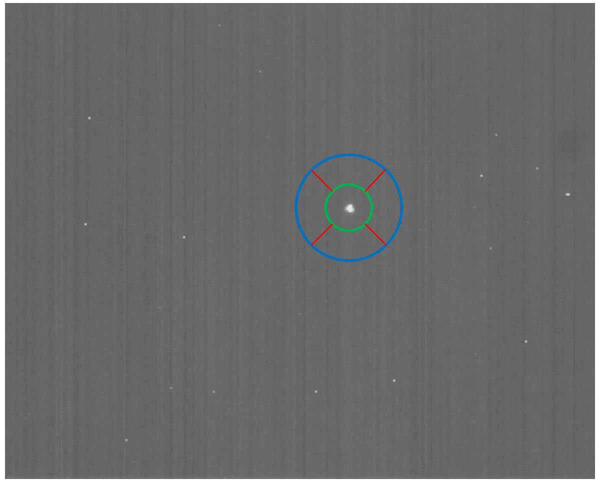

CubeL


Falcon 9 „Transporter 1“ Launch with CubeL

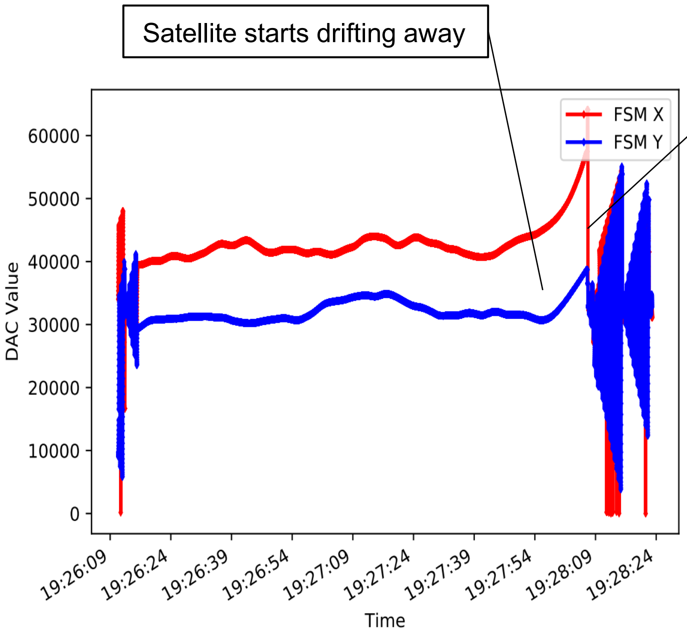
GSOC: German Space Operation Center

OSIRIS4CubeSat – PIXL-1

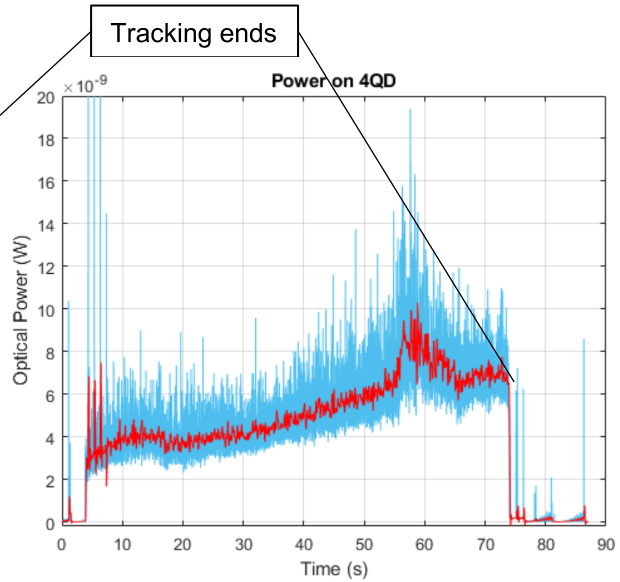
- Pointing of CubeL corrected
- Reproducible link establishment
  - When STR is valid
- Tracking performance verified
  - Immediate re-acquisition after link loss
  - Compensating inaccuracies up to ±1°
- Link Budget verified
  - Signal below 10° elevation
- In orbit verification
  - Payload fully functional
  - No degradation observed
  - In orbit operation > 2½ years


IR-Image at the OGSOP-NG


OGSOP-NG



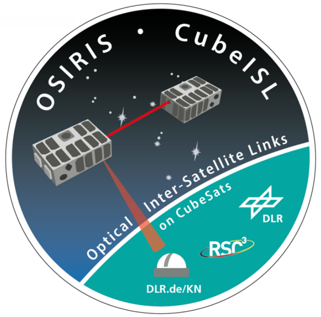
FSM Values



4QD summed power over all four Quadrants

STR: Star Tracker
FSM: Fast Steering Mirror
4QD: Four-quadrant diode

CubeISL

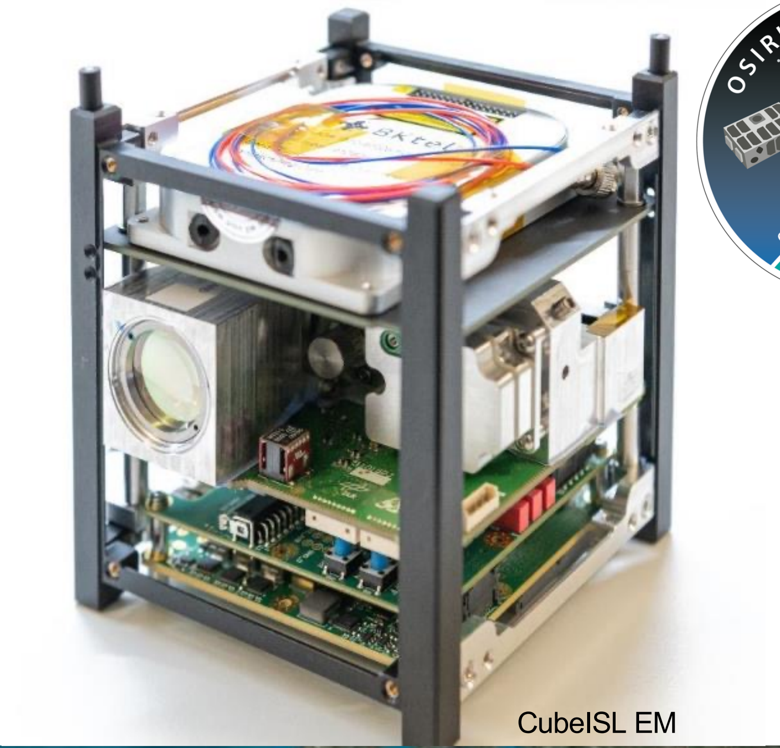


Research Goals

- 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
- Bidirectional Communication via Laser
  - ISL: 100 Mbps up to 1.500 km
  - DTE: 1 Gbps over whole flyover (10° to 10° elevation)

Mission

- LEOP and Operation done by RSC³*
- Two identical 6U CubeSats
- S-Band Communication for TM/TC
- High precision star sensor
- High accuracy ADCS required



CubeISL EM

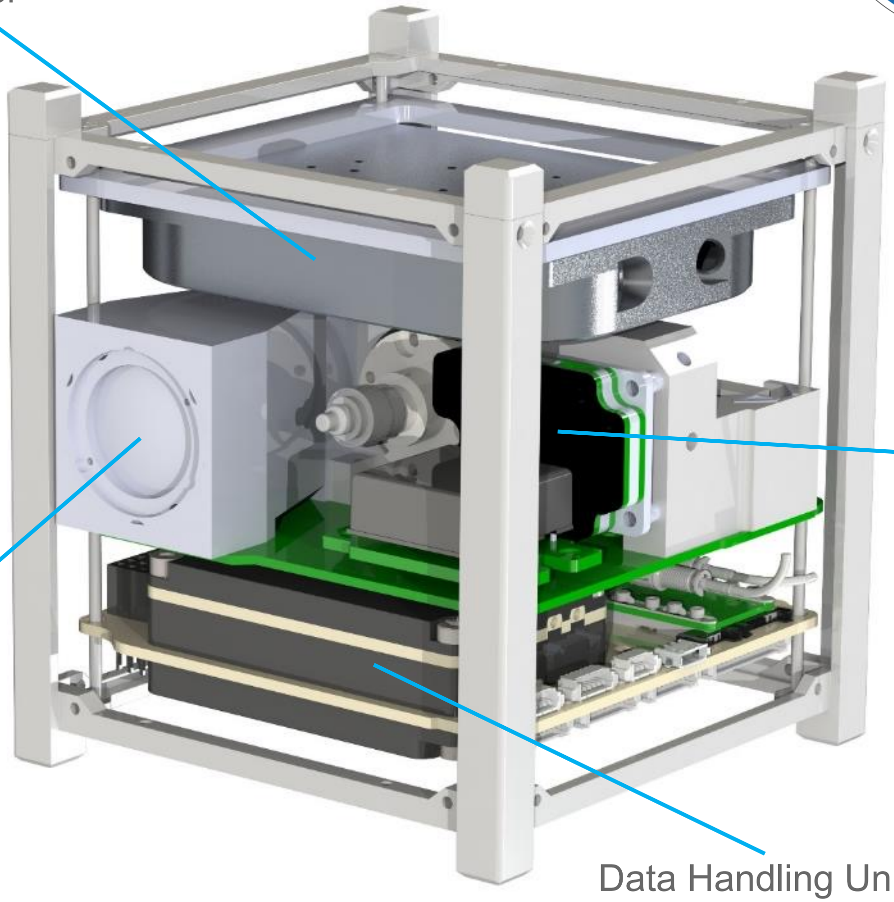
CubeISL Mission concept

RSC³: Responsive Space Cluster Competence Center

CubeISL – Terminal Concept

Payload

- Technology transfer from DTE to ISL
- Basic Technology OSIRIS4CubeSat (O4C)
  - Shorter Development times
  - Subsystem partially already qualified
  - Modular design allows easy adaptions and extensior
  - FPA based on O4C
- Rx- and Tx-Separation by Wavelength
- ISL and DTE possible with the same termi



Parameters

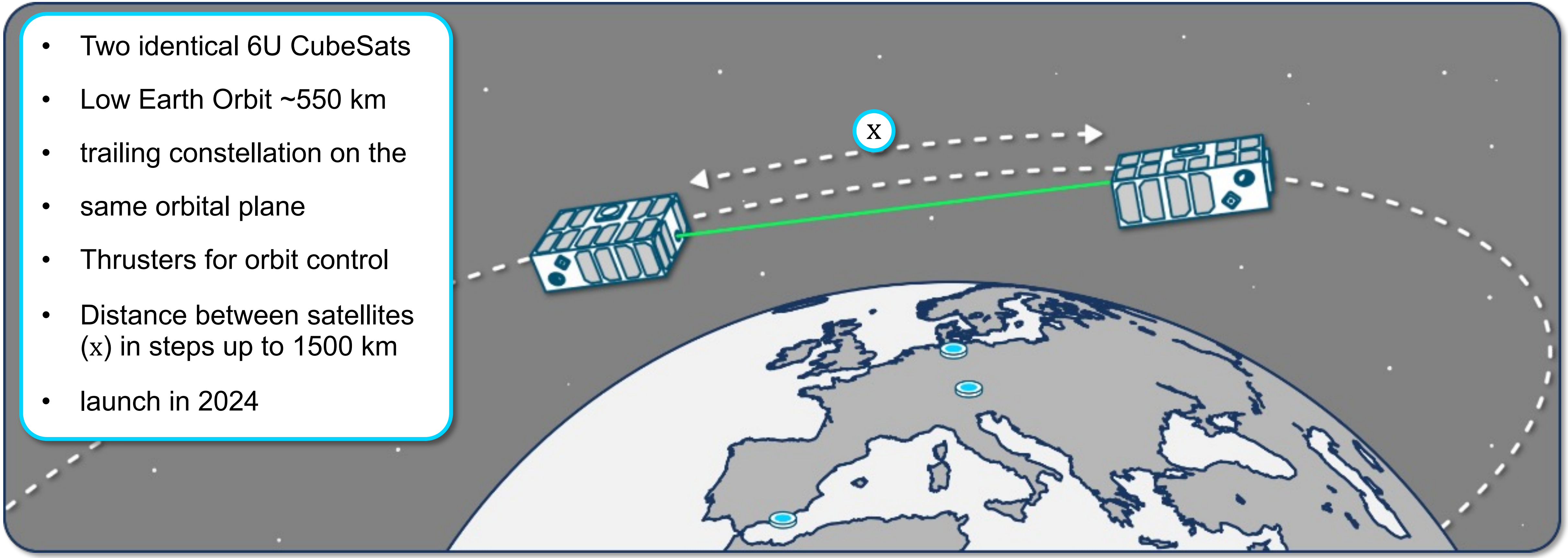
- Data rate ISL: up to 100 Mbps
- Data rate DTE: up to 1 Gbps
- Weight: < 1 kg
- Size: 10 x 10 x 10 cm³ (1 Ur
- Power Consumption: < 30 W

FPA: Dine pointing Assembly

CubeISL – Mission Concept ISL

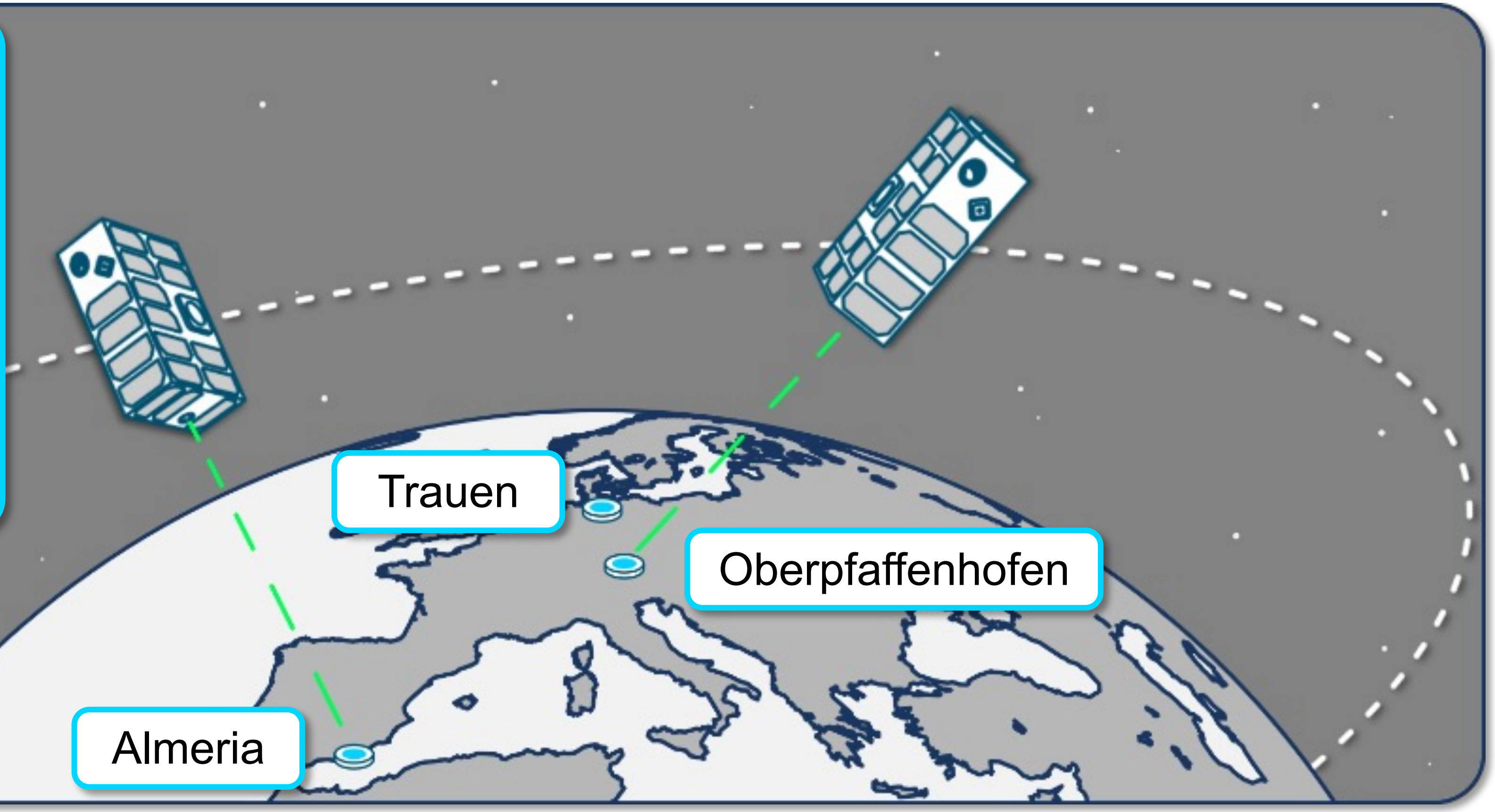
RSC³ DLR
RESPONSIVE SPACE
CLUSTER COMPETENCE CENTER

- Two identical 6U CubeSats
- Low Earth Orbit ~550 km
- trailing constellation on the
- same orbital plane
- Thrusters for orbit control
- Distance between satellites (x) in steps up to 1500 km
- launch in 2024



CubeISL – Mission Concept DTE

- DTE up to 1 Gbps
- second mission phase: demonstrate different use cases for LEO based Lasercomm Networks
- use DLR’s other OGS in Almeria and Trauen

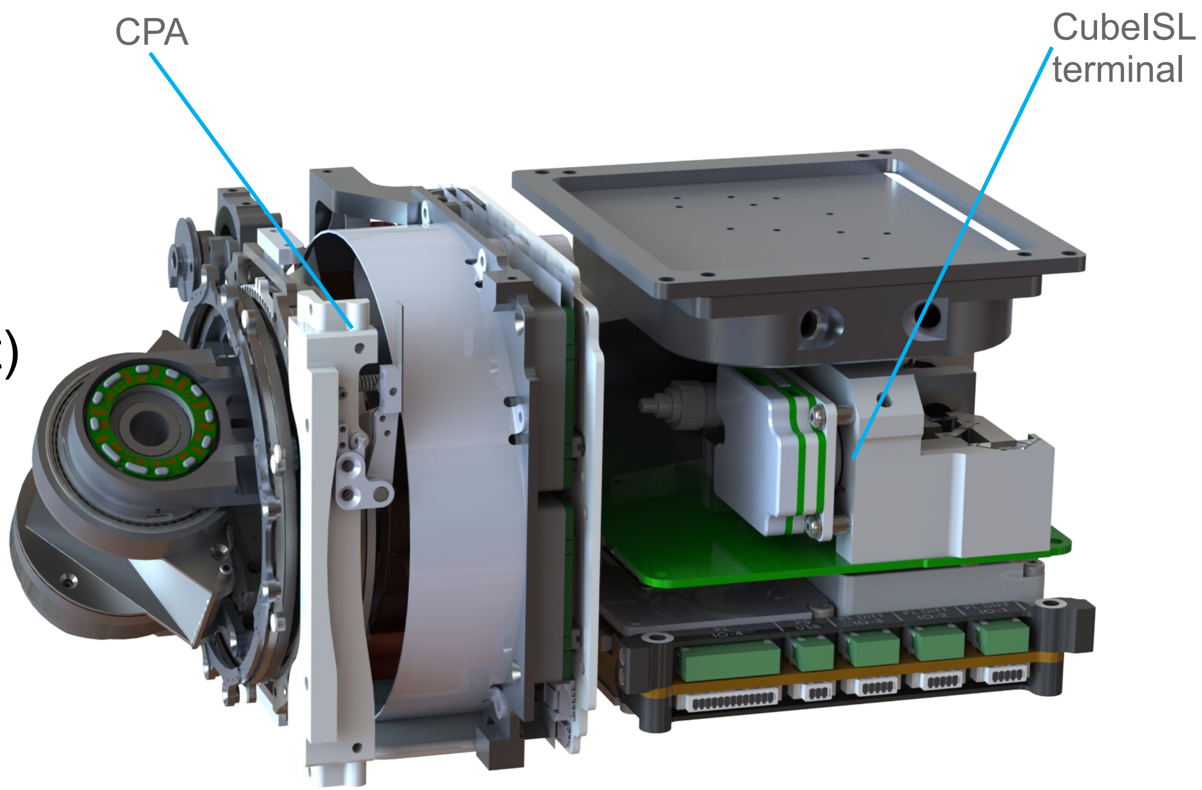


RESPONSIVE SPACE CLUSTER COMPETENCE CENTER

Cube1G

Laser Communication Terminal for high-rated Data Transmission

- Based on CubeISL
- Independancy from Satellite Attitude
- Extended by CPA
  - 20 mm CPA
  - Evolution from Airborne project (DODfast)
  - Suitability for Space
- Improved Data Rate
  - Optical DTE: 1 Gbps

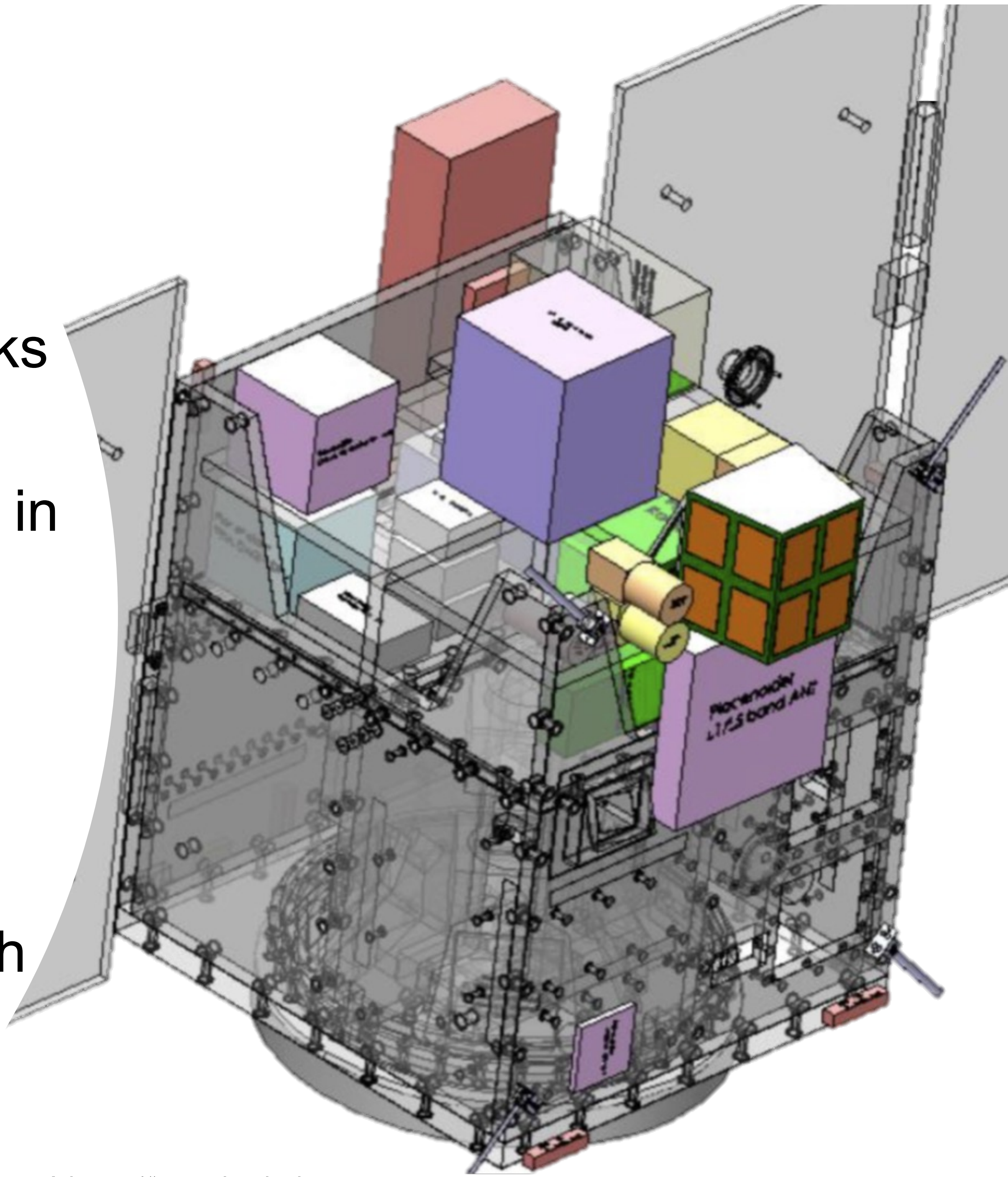


Cube1G terminal design

CPA: Coarse Pointing Assembly
DODfast: Demonstration of Optical Data link fast

Cube1G – SeRANIS

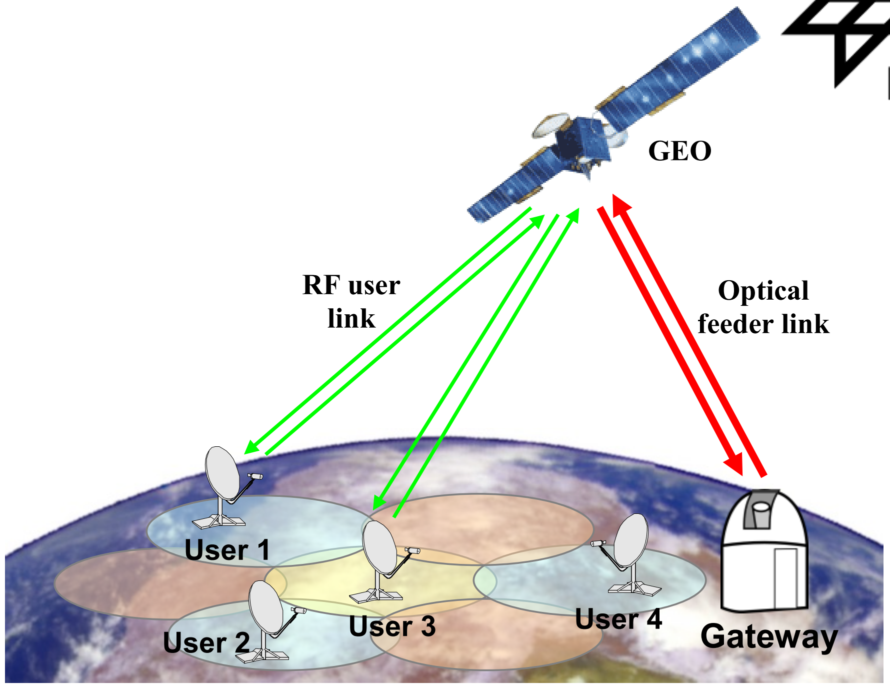
- SeRANIS: Seamless Radio Access Networks for Internet of Space
- Publicly accessible experimental laboratory in orbit
- Worldwide unique on small satellites
- More than 10 innovative experiments
- Funding by German government
- Lead by Universität der Bundeswehr Munich
- SeRANIS – Multifunctional Satellite Laboratory | UniBw M | dtec.bw

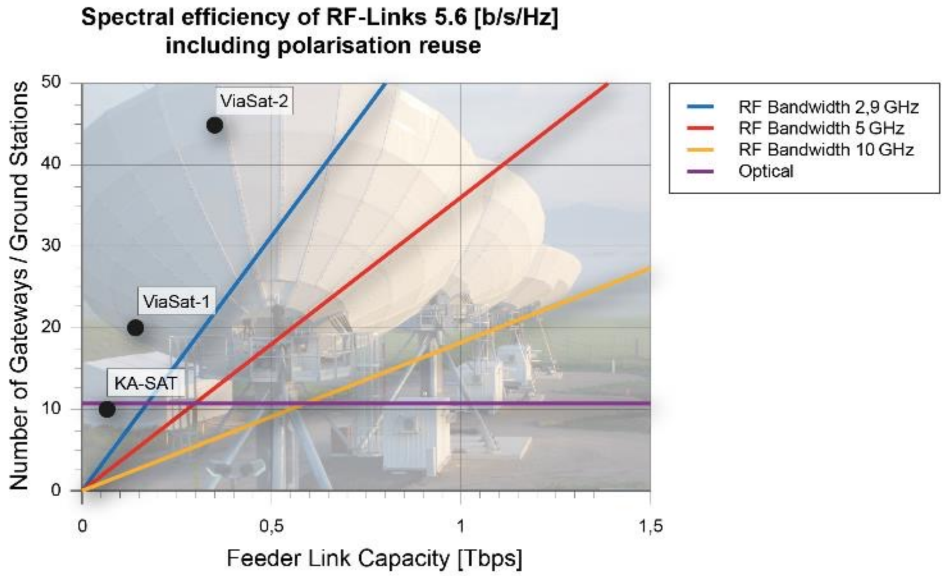


„Athene-1“ satellite design

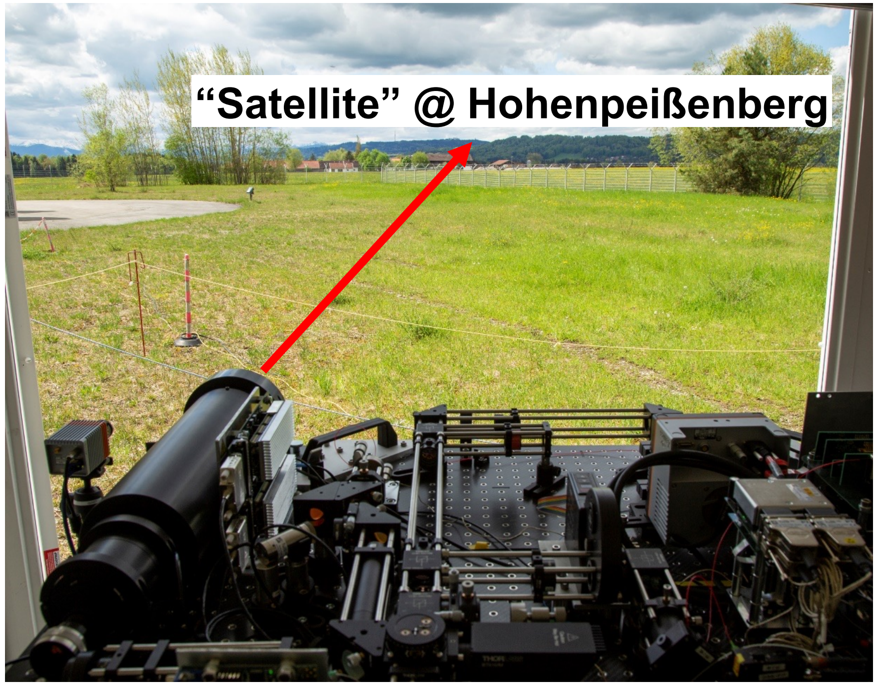
Optical feeder links

- Usage of optical links instead of RF as GEO feeder link, e.g. for television- and/or multimedia satellites
- Single GEO-satellite sufficient to serve Europe
- Multiple ground stations required – both for RF and optical links
  - RF: Frequency re-use to boost capacity
  - Optical: Mitigation of cloud coverage (~11 stations for >99.9 % availability)
- Advantages of optical feeder-links
  - Spectrum freed up for user links
  - High optical bandwidth available
- Extremely high data-rates
  - Terabit per seconds





THRUST – Optical GEO Feeder Links Testbed

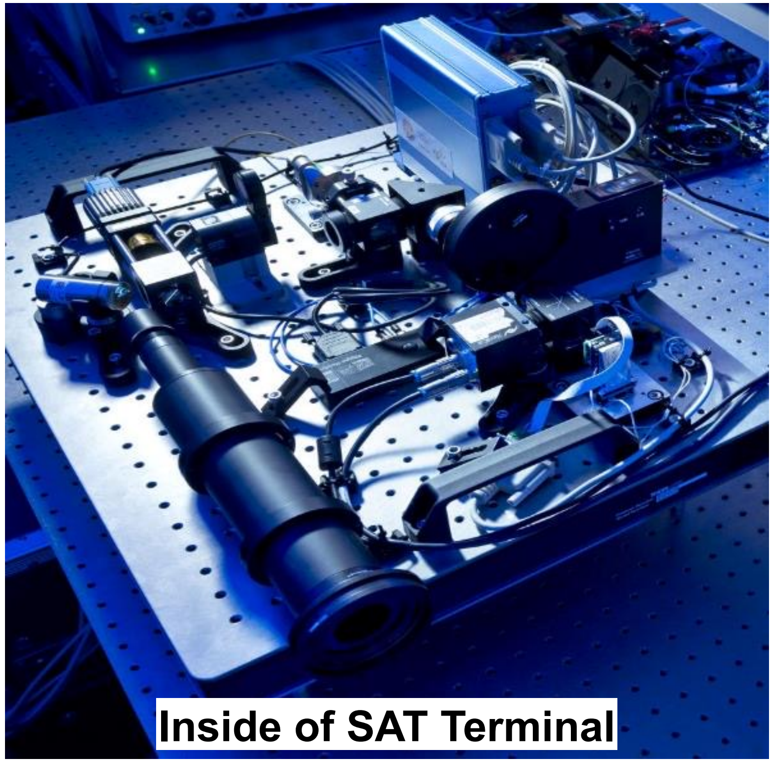


DLR Weilheim - OGS

- Link emulating a GEO Uplink testbed with worst-case turbulence conditions
- Scenario: 337m altitude difference, 10,5km link with 1,9°elevation
- **➔ World Record (2017): 13.2 Tbps**

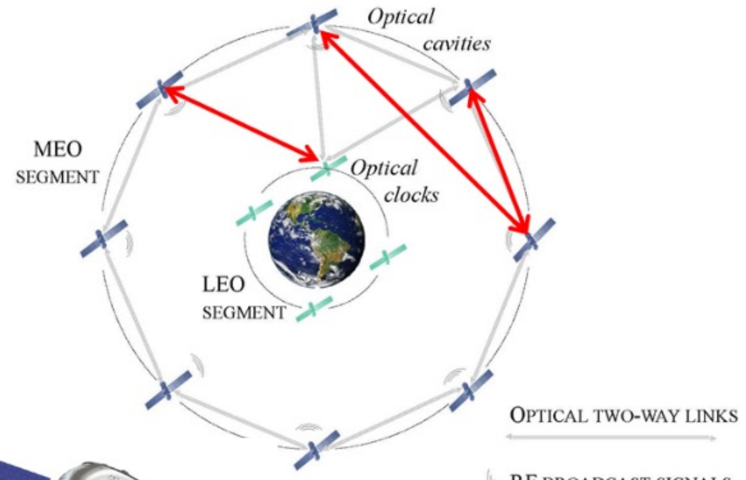
- Single-mode fiber coupling
- Pointing-by-tracking system
- Emulation of point-ahead angle
- Comparison with atmospheric turbulence characterization measurements
- DWDM Technology

- Collaboration with ADVA

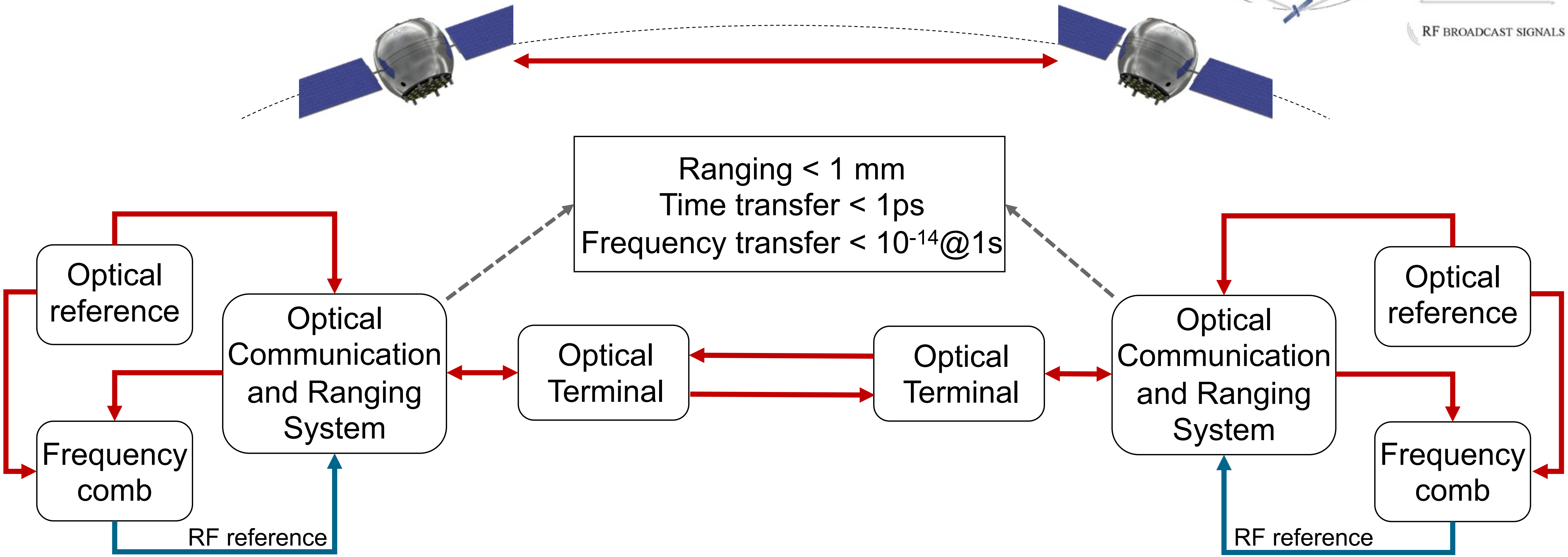


DWDM: Dense Wavelength Division Multiplexing
OGS: Optical Ground Station

Kepler



- Terminals for optical time and frequency transfer



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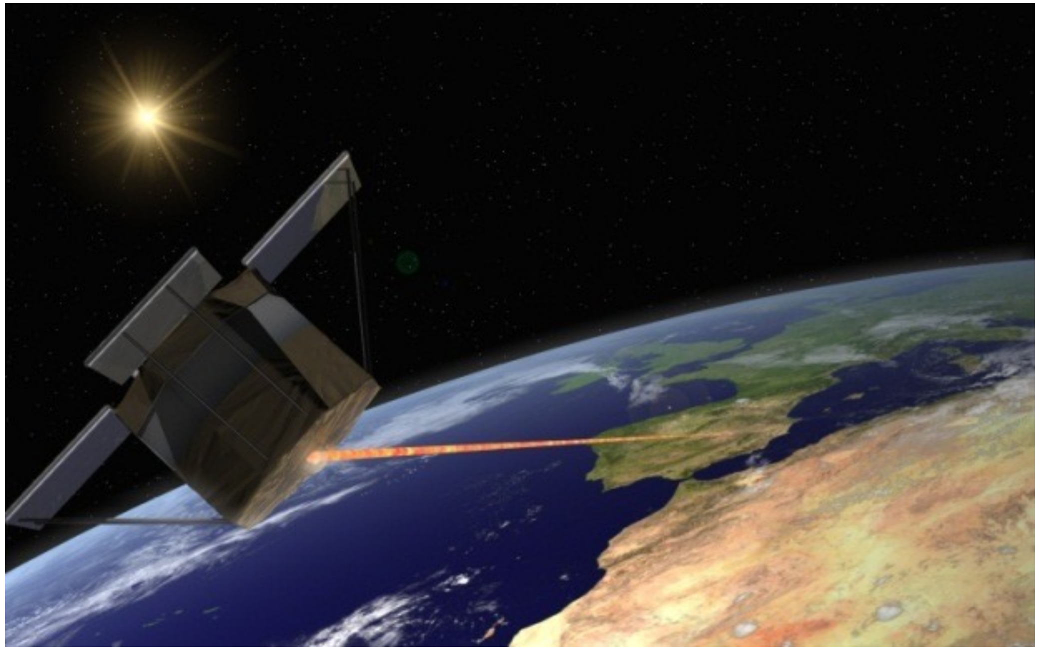
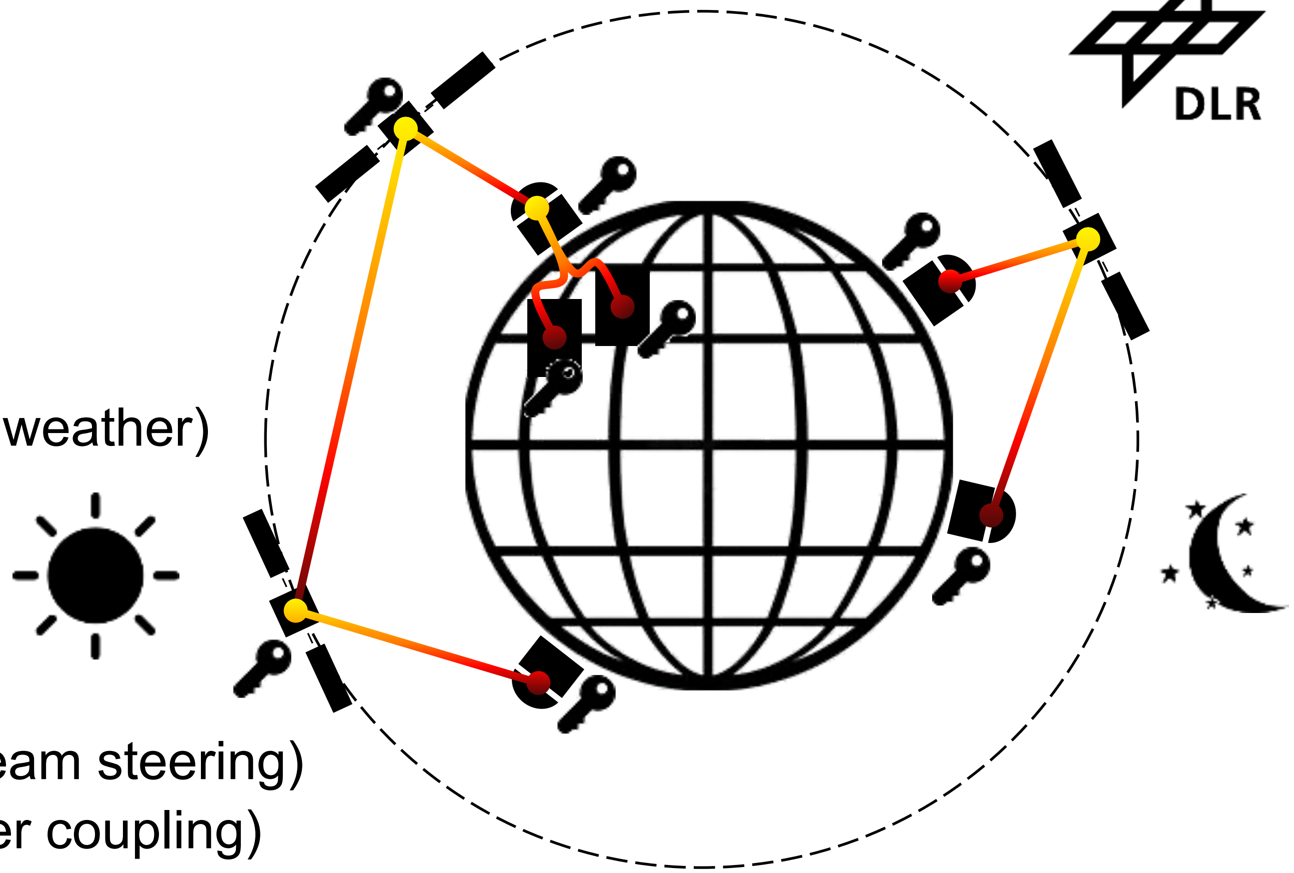


Satellite Based QKD

- Challenges
  - Large Distance
  - Channel (background light, turbulence, weather)



- Research Topics
  - Space qualified QKD transmitter
  - Laser terminals (high gain antennas, beam steering)
  - Ground interface (system concepts, fiber coupling)
  - Filter concepts for night and day operation
  - Channel models (background light, turbulence, clouds, QBER, extinction)
  - QKD with single satellites or constellations
  - Concepts with trusted nodes (BB84) and entanglement distribution
  - and other…

QKD: Quantum Key Distribution
QBER: Quantum Bit Error Rate

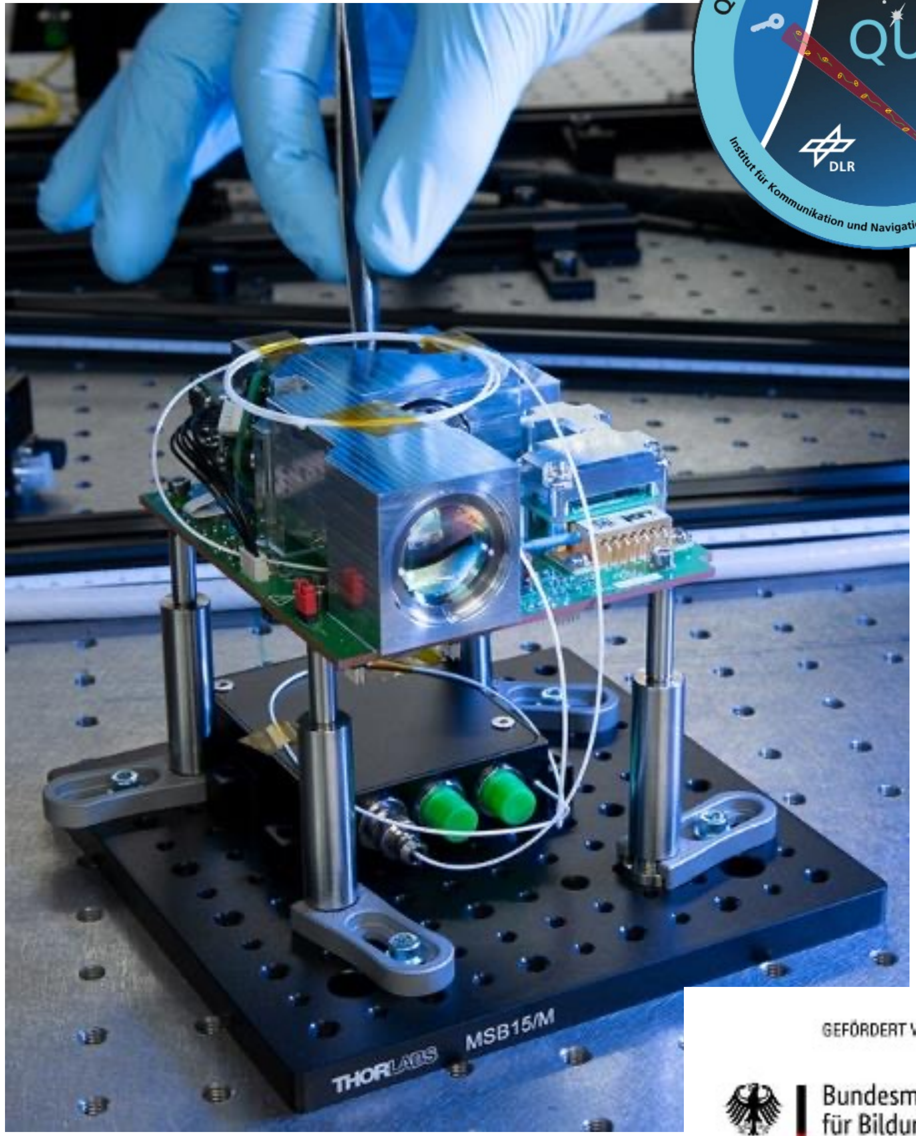
QUBE

<u>Project</u>

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

<u>Main goals for DLR</u>

- Transfer technology of OSIRIS4CubeSat to QKD capabilities
- Adapt mechanical design to satellite bus of ZfT
- Couple signals of different wavelengths into OSIRIS
- Adapt optical system for different wavelengths



OSIRIS4QUBE EQM

Quantenexperimente auf CubeSat
QUBE
DLR
Institut für Kommunikation und Navigation

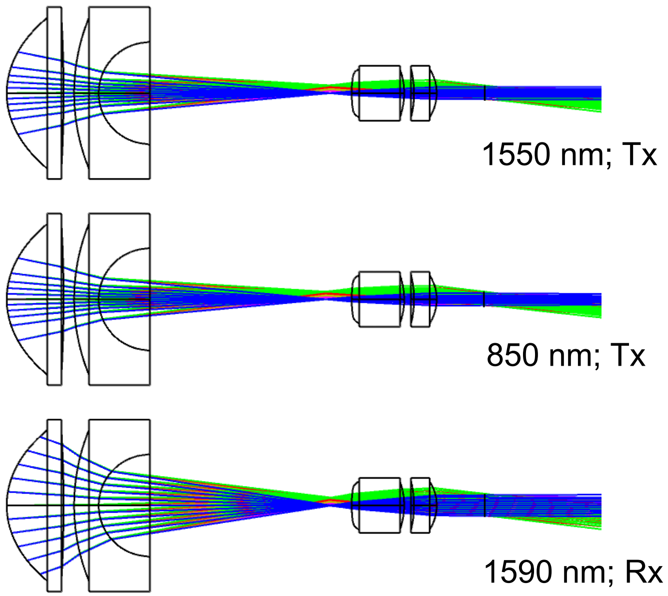
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

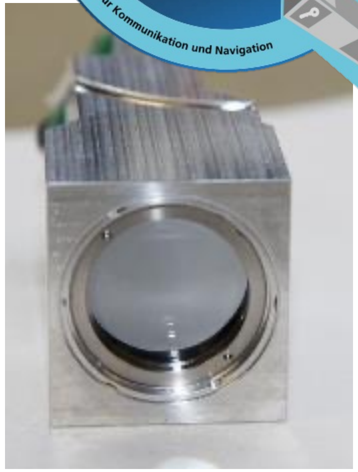
LMU: Ludwig-Maximilan University
MPL: Max Planck Institute for Scinece of Light
ZfT: Center for Telematics
BMBF: Federal Ministry of Education and Research

QUBE – Optical System

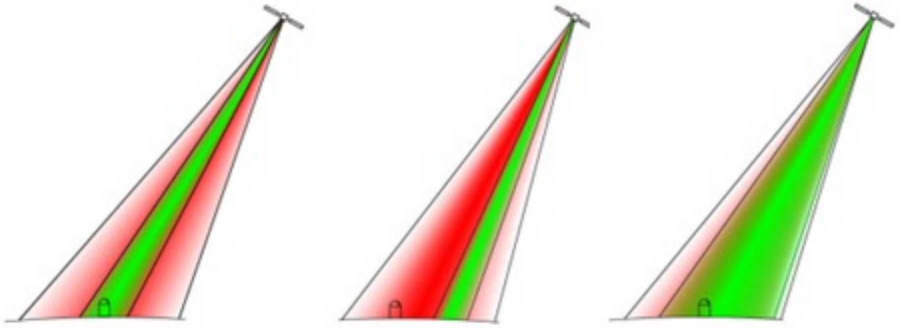
<u>Adaptations compared to OSIRIS4CubeSat</u>

- Additional wavelength at 850nm
- Longer telescope required
  - Telescope separated from rest of optomechanics
- Fiber coupling of the three different signals
  - Triplexer design





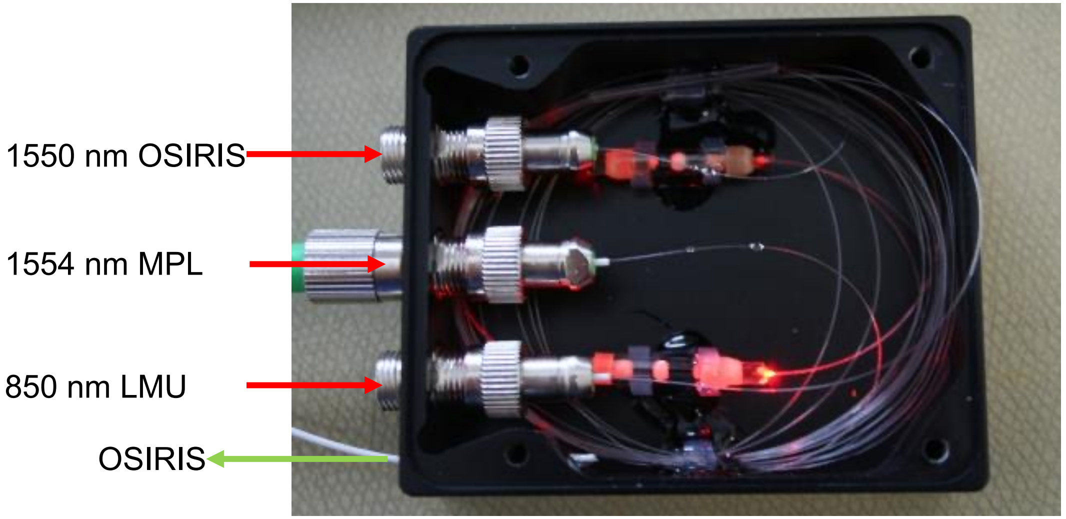
Adapted telescope



Ideal System

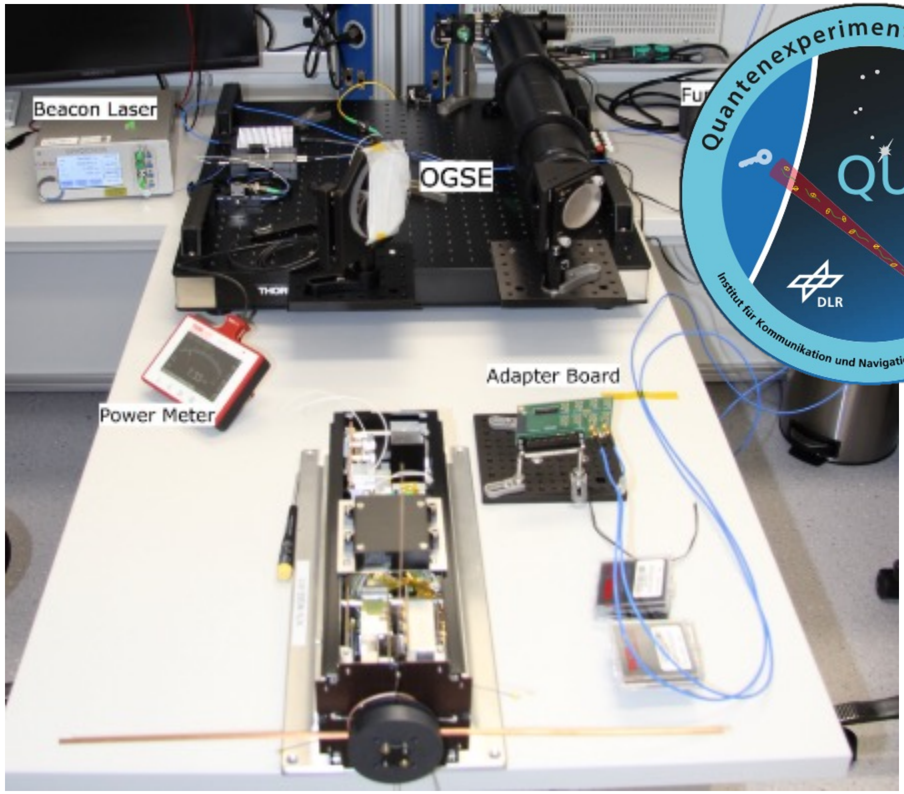
Lowest divergence (realistic)

Compromise (realistic)



Triplexer

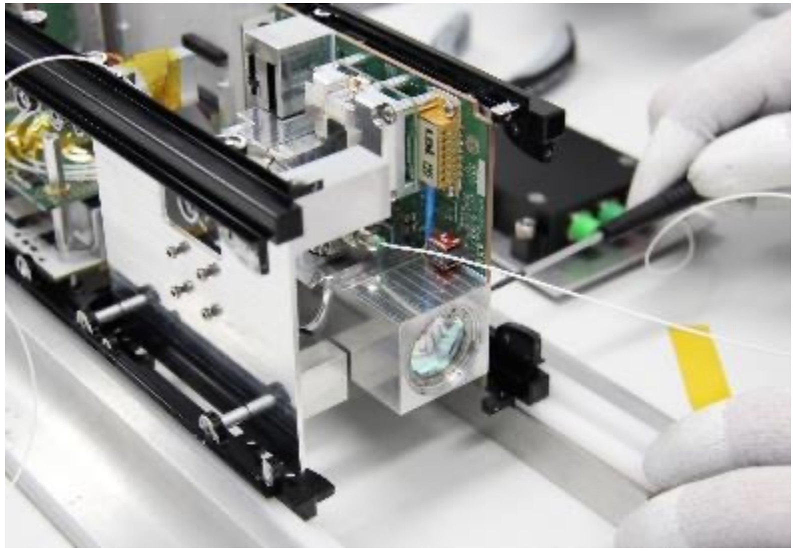
QUBE – Satellite Integration



Optical Test Setup

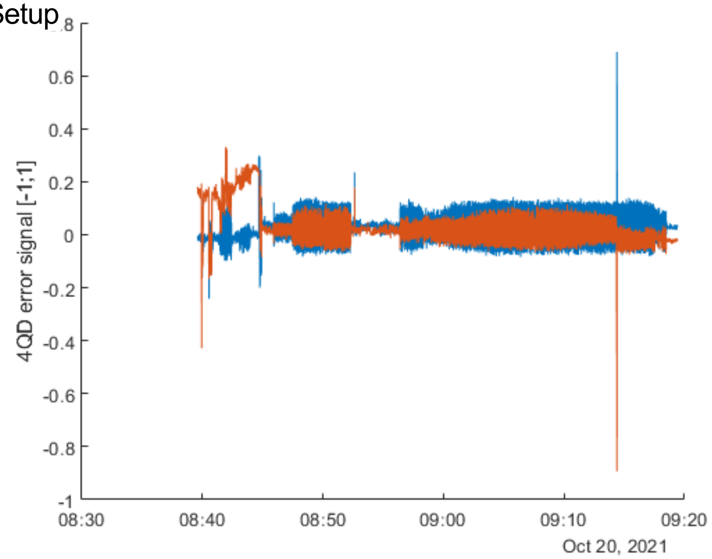
<u>Test at ZfT with transportable OGSE</u>

- Payload integrated in final satellite
- Verification of all interfaces
- Tracking tests successful



OSIRIS integrated in QUBE satellite

QUBE satellite



Tracking results – Sensor Feedback

OGSE: Optical Ground Support Equipment

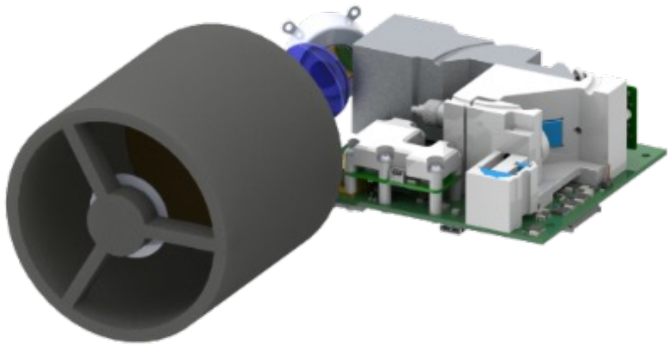
QUBE-II

GEFÖRDERT VOM

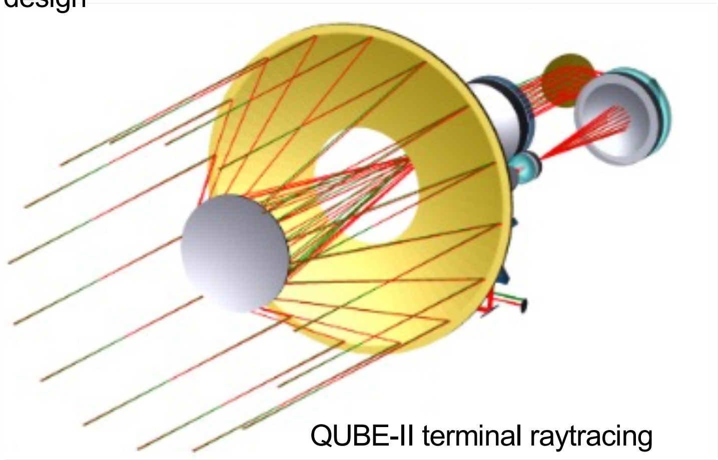
Bundesministerium für Bildung und Forschung

<u>Project</u>

- Cooperation between DLR, LMU, MPL, ZfT and OHB
- Goal: Demonstrate full Quantum-Key-Distribution (QKD) implementation between a CubeSat and a ground station



QUBE-II terminal design



QUBE-II terminal raytracing

<u>Main goals for DLR</u>

- Further development of the QUBE terminal to an aperture of 85 mm (external telescope)
  - Adapt optical system for operation with two wavelengths
  - Couple signals of different wavelengths into OSIRIS
- Implement receiving path to allow bi-directional classical communication
- Upgrade Optical Ground Station (OGS) to enable QKD

QUARTZ / EAGLE-1
Satellite Mission with full QKD Implementation

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

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

- Phase 1: QUARTZ – End-to-End system level tests with channel simulator in lab
- Phase 2: EAGLE-1 – In orbit demonstration (Launch 2024), LCT by Tesat Spacecom

- Main DLR-KN contributions
  - QKD transmitter design, manufacturing, qualification, …
  - Optical Ground Station for In-Orbit validation
  - System testbed in DLR lab

- **Key elements of QUARTZ / EAGLE-1 are designed in Germany (QKD protocol, QKD Tx & Rx, …)**

AIT: Australian Institute of Technology
IDQ: ID Quantique
LCT: Laser Communication Terminal

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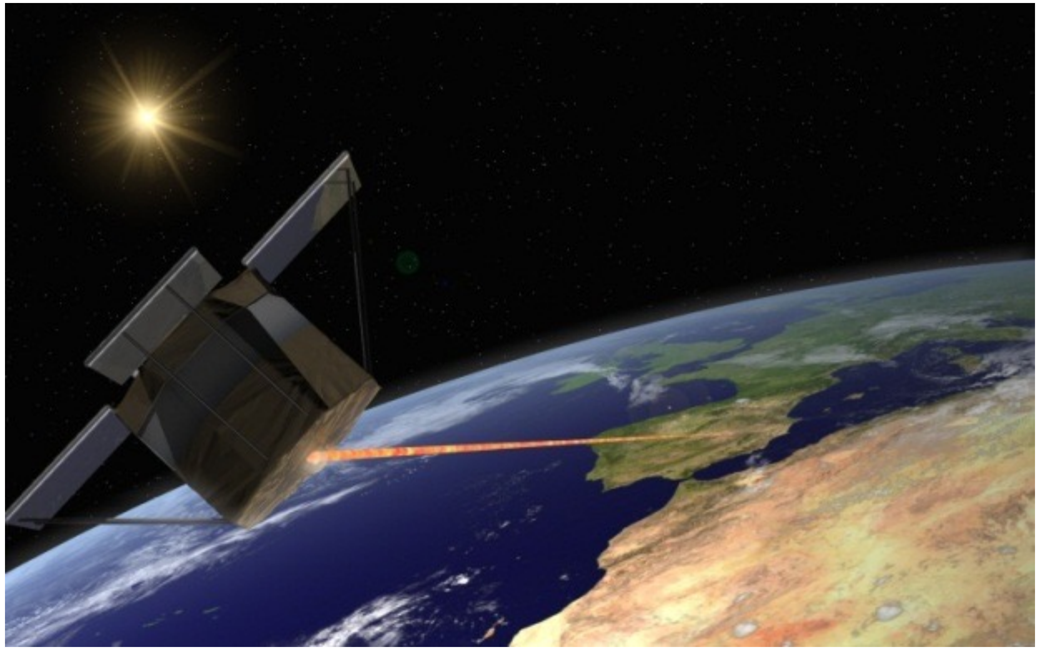
  - OGS Networks
- Optical transmission technologies
- Standardization



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

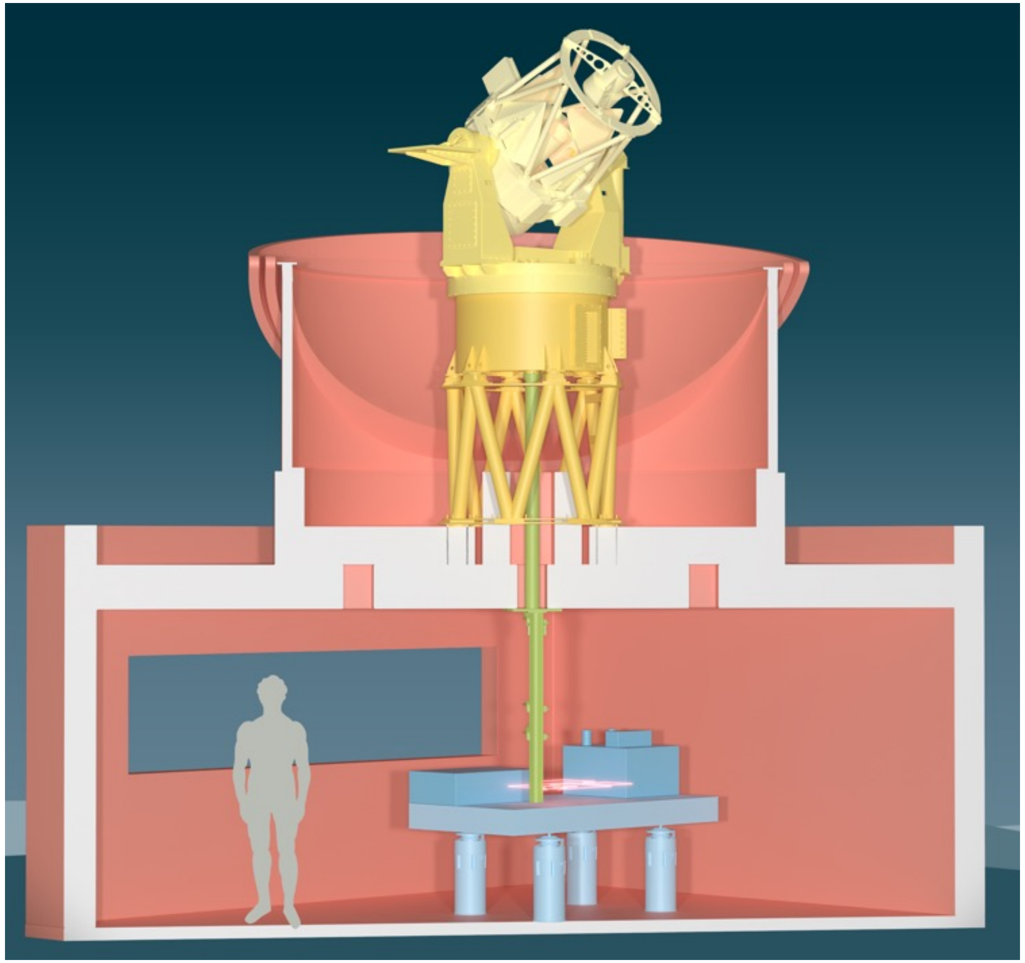
Characterization of the atmosphere

- Measurement instruments for recording of key atmospheric parameters


OGSOP-NG

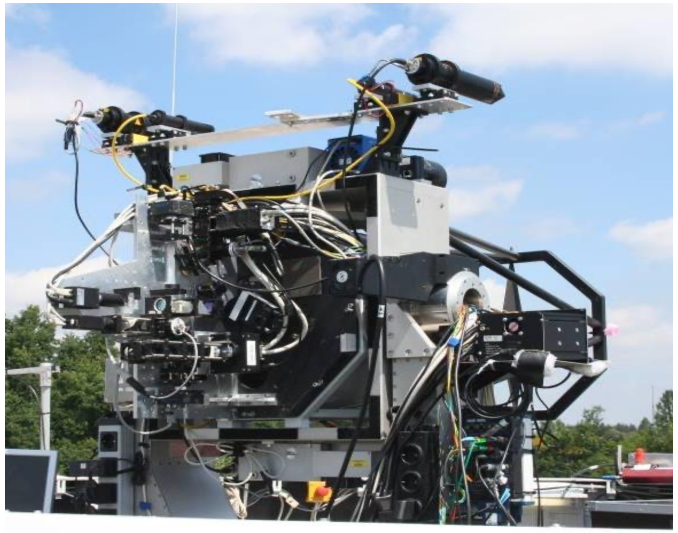
OGSOP-NG: Optical Ground Station – “Next Generation”

OGSOP-NG – Coudé setup


OGSOP-NG including Coudé setup


OGSOP-NG with Nasmyth ports

Three Nasmyth Ports

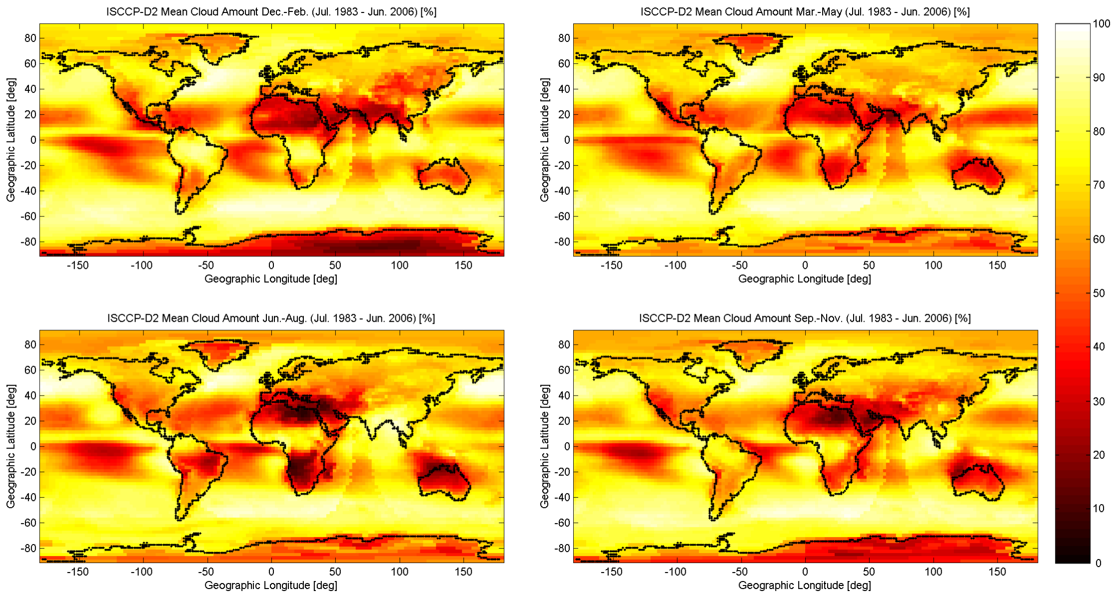

Old 40cm OGS

Transportable Optical Ground Station

- 60 cm Ritchey-Chrétien telescope
- Aluminum mirrors
- Carbon fiber fork mount, foldable
- 500kg
- Operations room in truck
- Worldwide use within a couple of hours

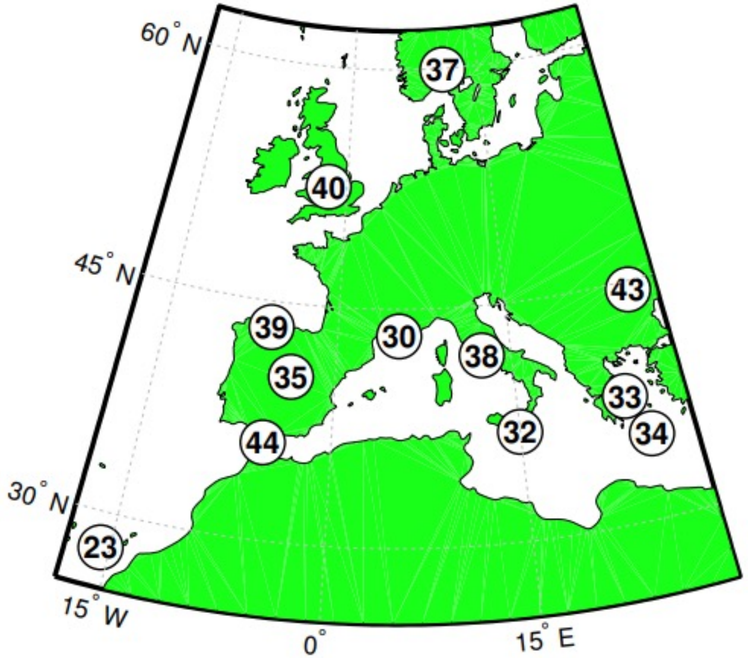
What about the clouds?

Applications from space-to-ground require **OGS-diversity**: Multiple OGS at suitable locations



brighter: higher cloud probability

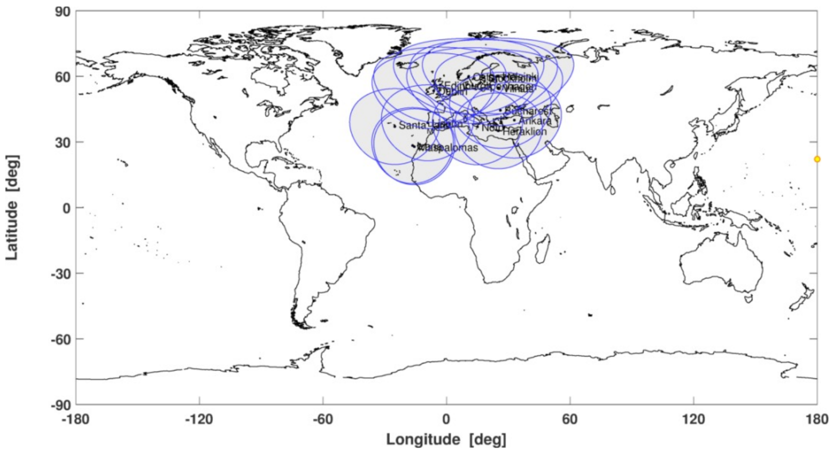
Worldwide cloud cover (annual mean)



Example of European wide OGS-network for LEO-Downlinks
(taken from ESA-project ONUBLA; DLR, HHI, LOA, ABDS)

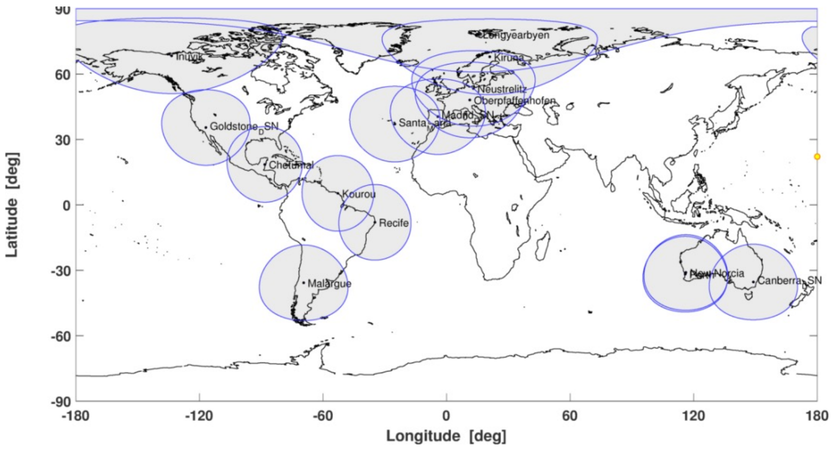
Investigated scenarios

- Several OGS network topologies:
  - Europe only (LEO 1)
  - Europe + Africa (LEO 2)
  - Europe + polar sites (LEO 3)
  - Worldwide Sites (LEO 4)
  - Space Agency Sites (LEO 5)



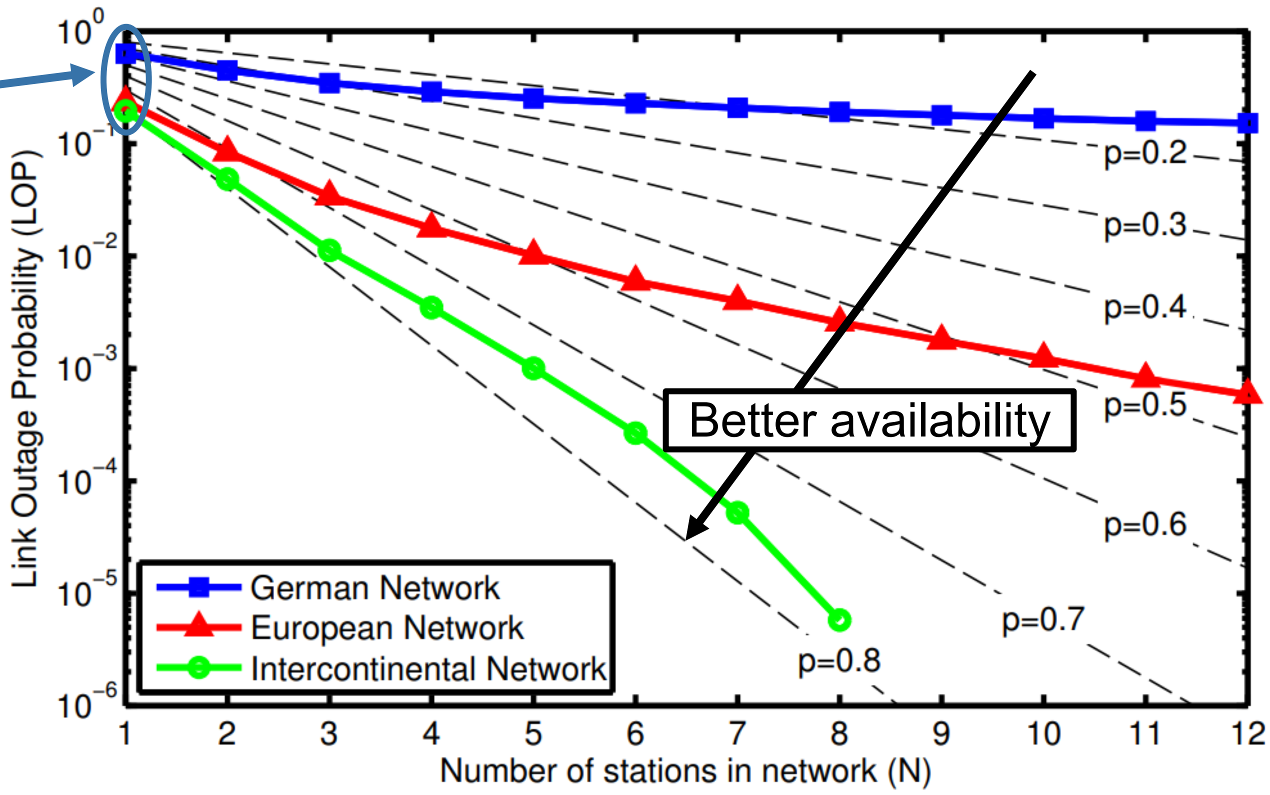
- Optimized OGS locations based on large pool of selected sites

- Key system parameters under investigation
  - Data rates
  - Satellite orbit
  - Buffer sizes
  - Sensor acquisition rates
  - Link planning lead time
  - …



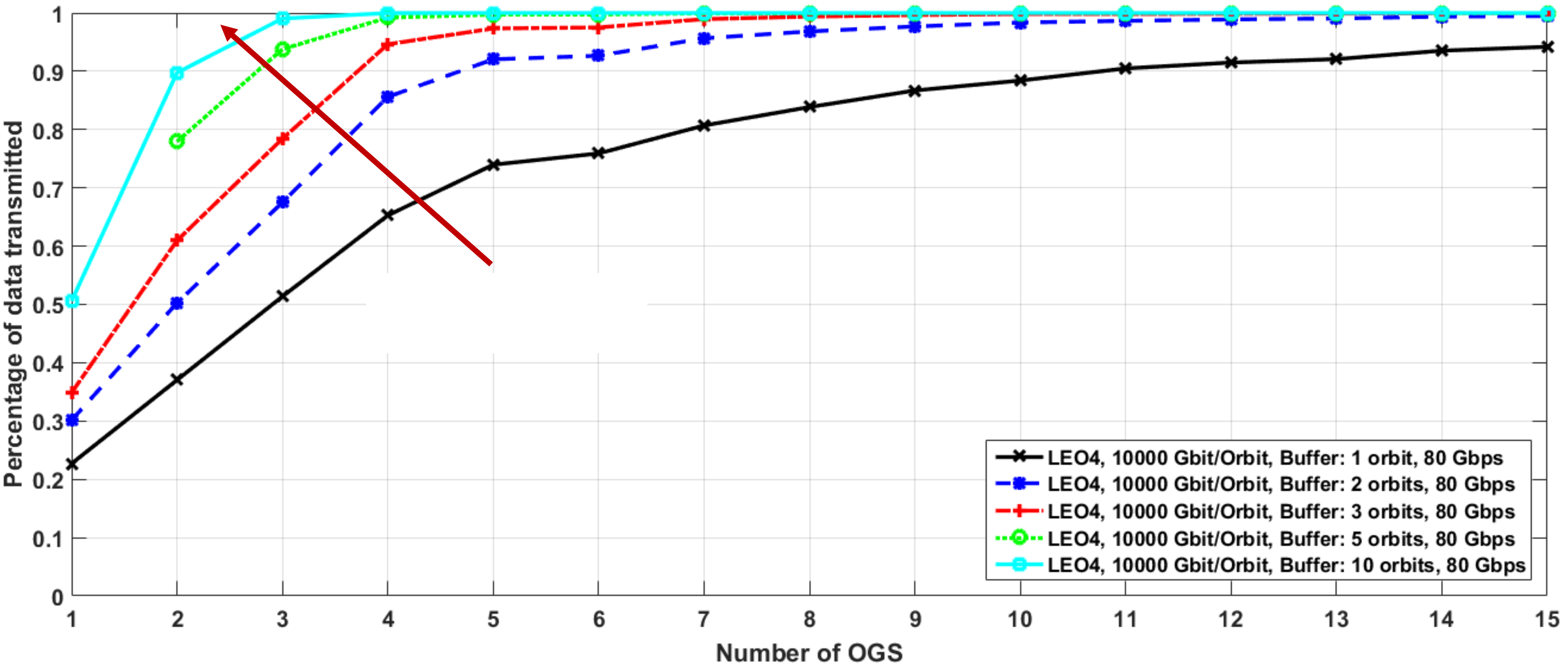
Combined network availability for selected optimized OGS networks

Single-site availability



Fuchs and Moll, „Ground Station Network Optimization for Space-to-Ground Optical Communication Links", J. Opt. Comm. Netw., Vol. 7, No. 12, December 2015

Influence of buffer size – Scenario LEO 4 (Worldwide Sites)



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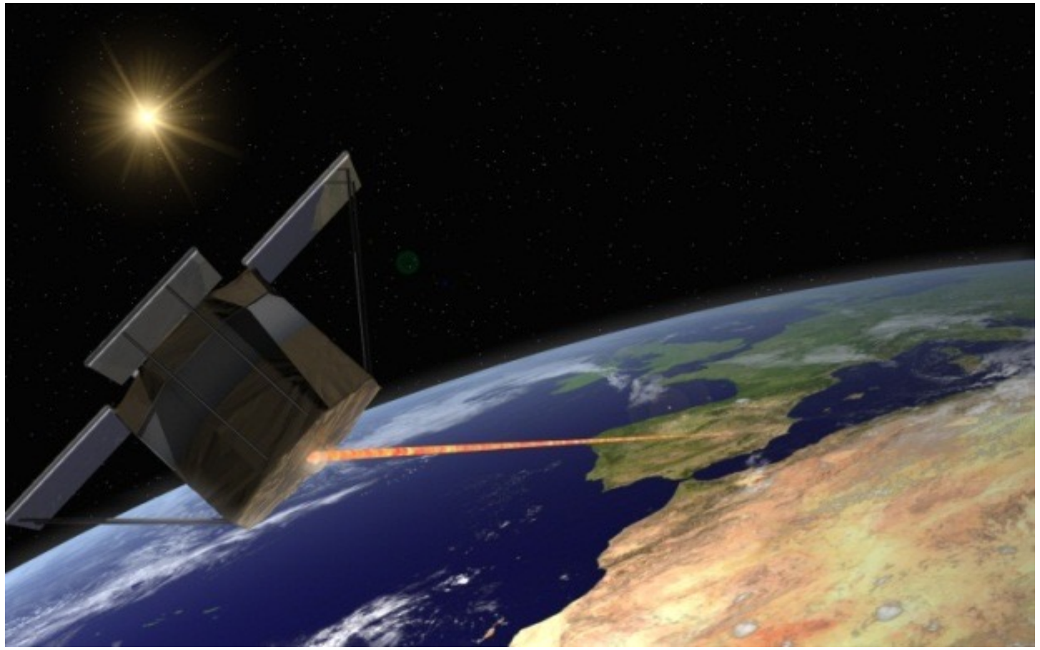
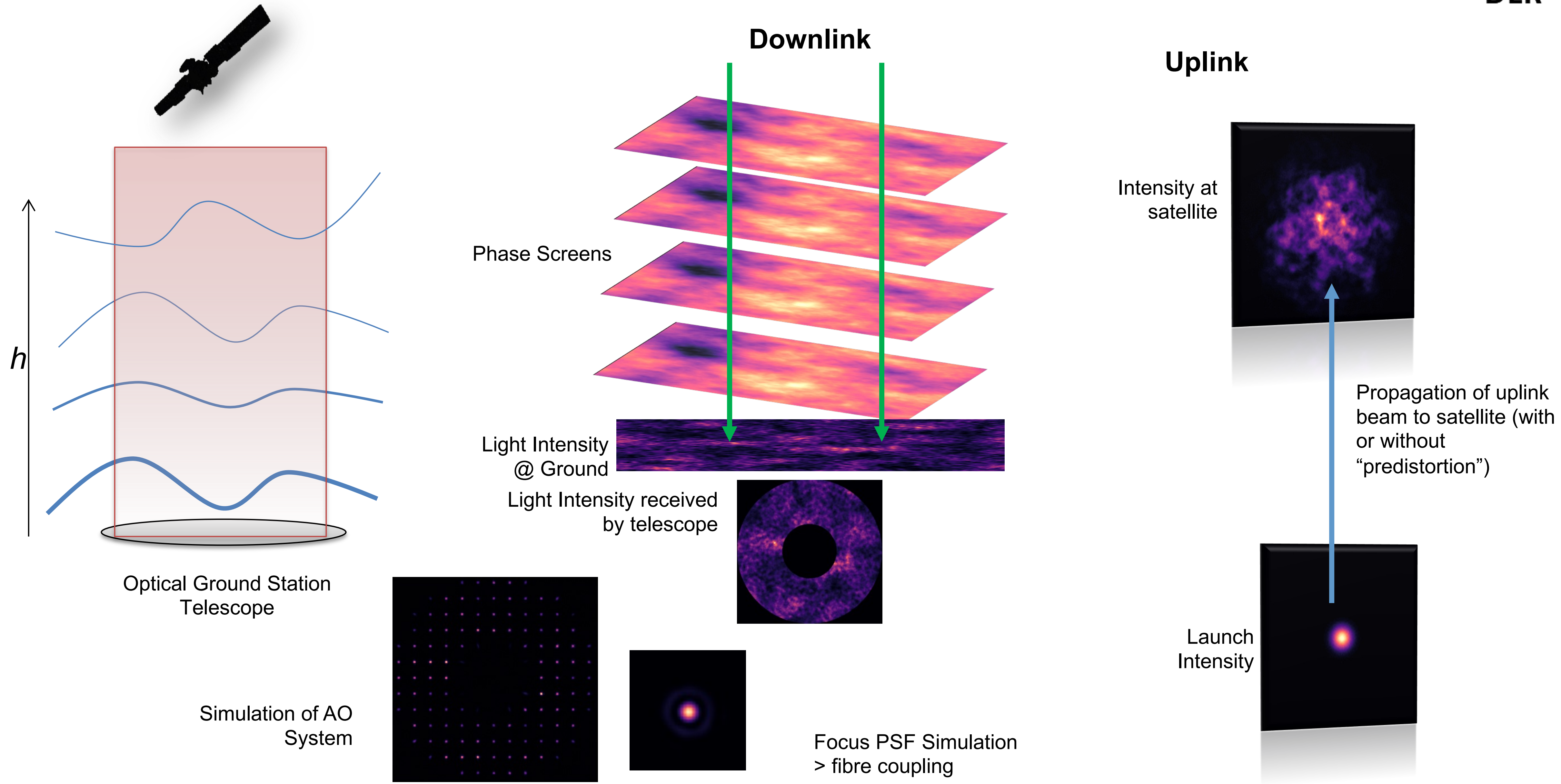
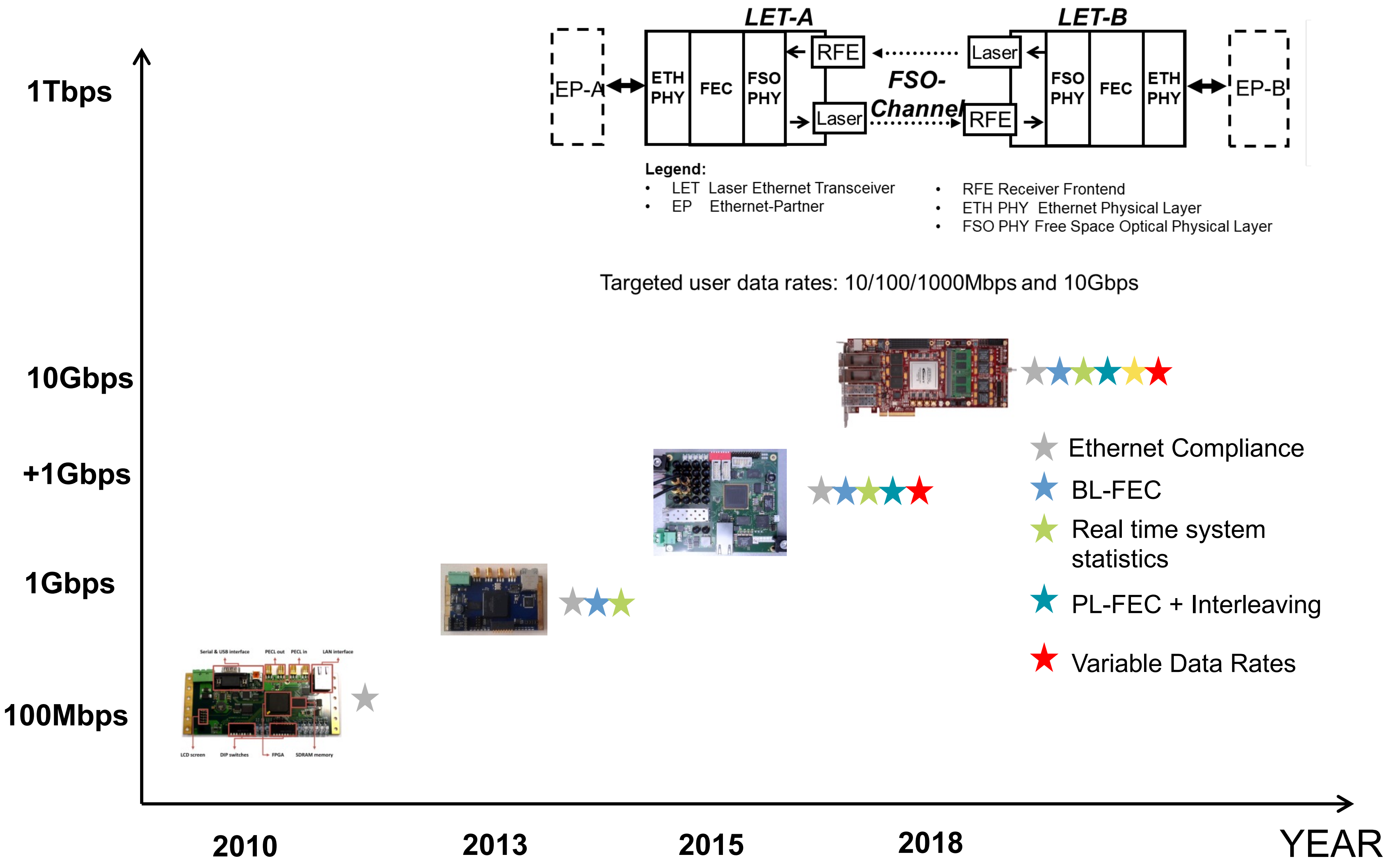
- **Optical transmission technologies**
- Standardization



Atmospheric Effects



FSO Modems

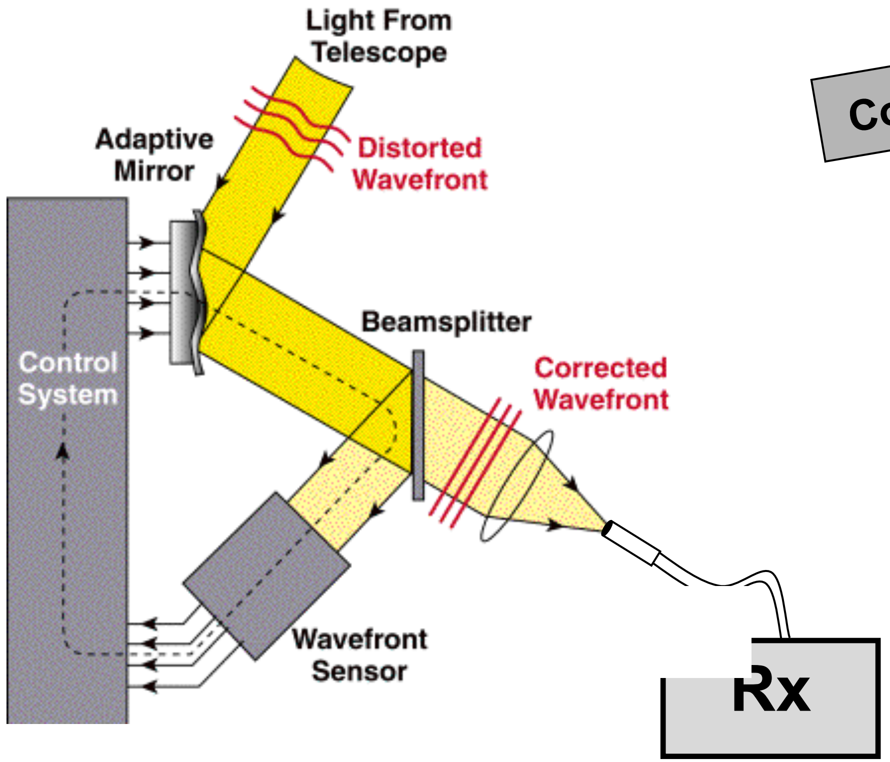


LETs

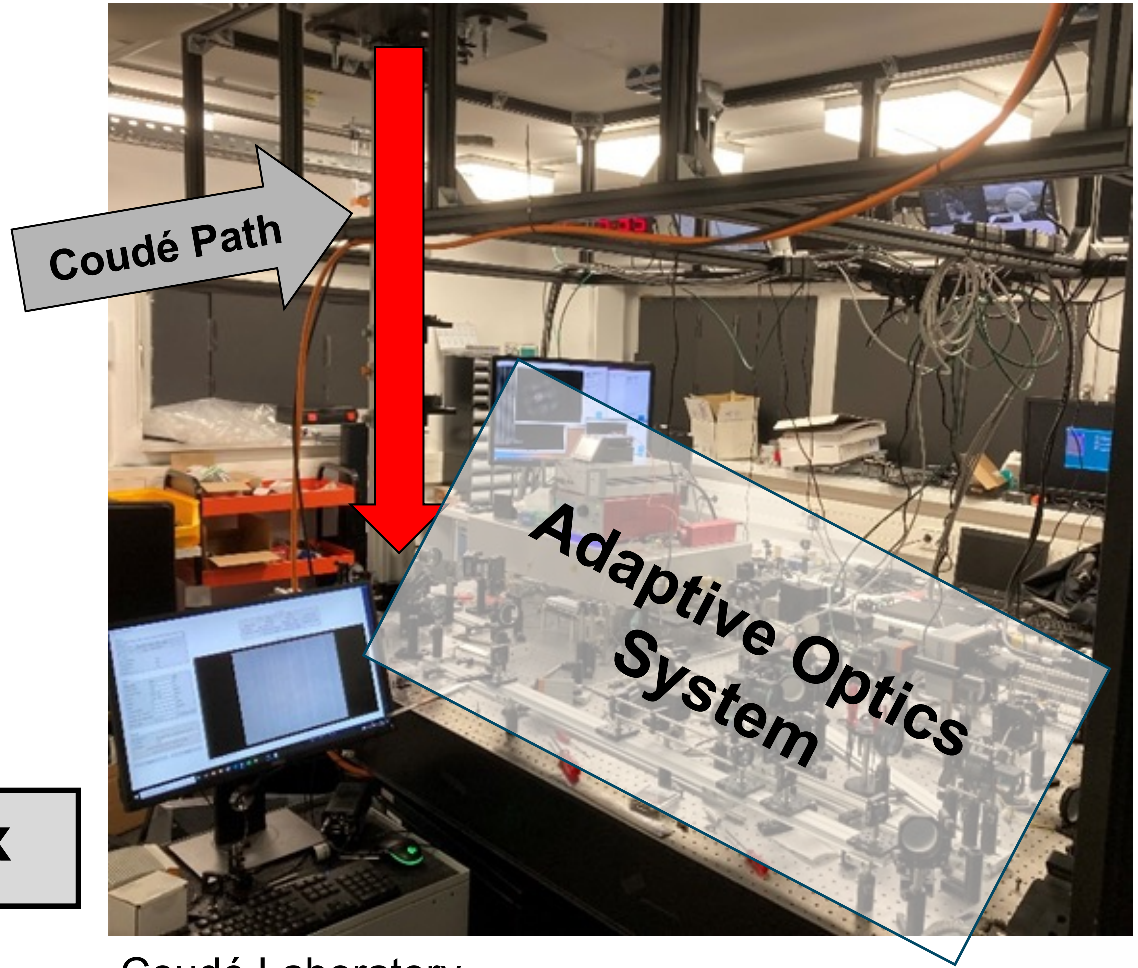
- Demonstrated in ground to ground scenarios (e.g. Hi-CLASS, HIPERON-T)
- Demonstrated in ground to air scenarios (e.g. VABENE++) including hybrid FSO/RF
- Enabled the study of ARQ schemes and higher level FEC (LDPC and Raptor Codes)
- Legacy development for OSIRISv3 Modems and influenced O3K CCSDS Standardization
- Several DLR Patents

Adaptive Optics

DLR



AO System Concept

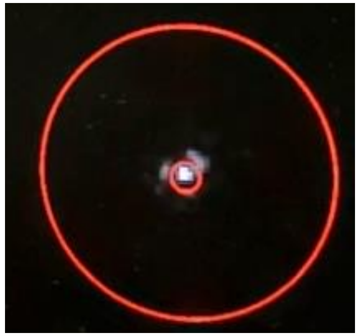


Coudé Laboratory

Meas. with Alphasat-LCT

Without AO

With AO

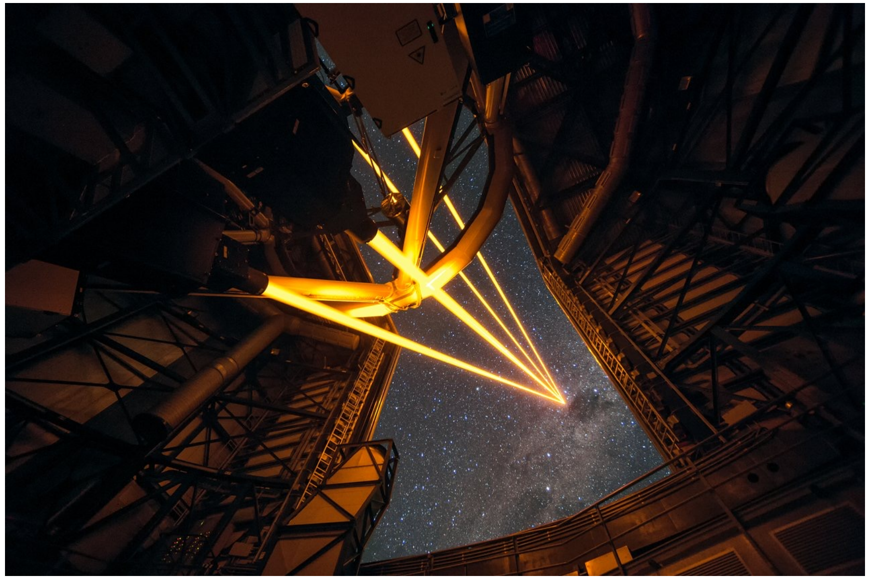


Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

AO: Adaptive Optics
LCT: Laser Communication Terminal

Laser Guide Stars

- Laser Guide Stars are a tool to provide an artificial Adaptive Optics reference
- Useful when „pre-distorting“ the transmitted beam path, where the Rx light cannot be used
- DLR Activities
  - Tests of advanced Laser Guide Star launch schemes to stabilise beam
  - Development of Laser Guide Star Adaptive Optics demonstrator for ESA OGS



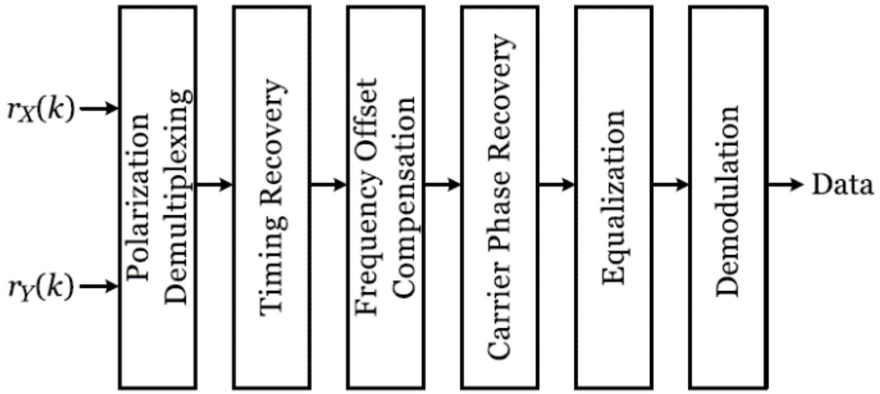
Sodium Laser Guide Stars [ESO]

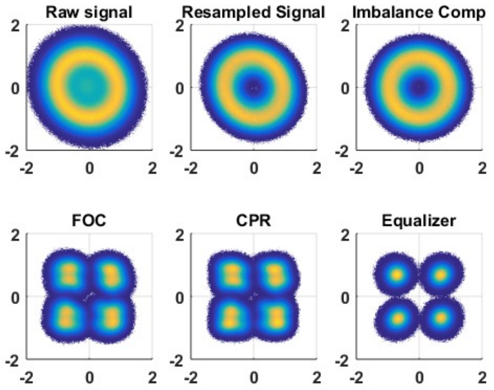
ESA Optical Ground Station [ESA]

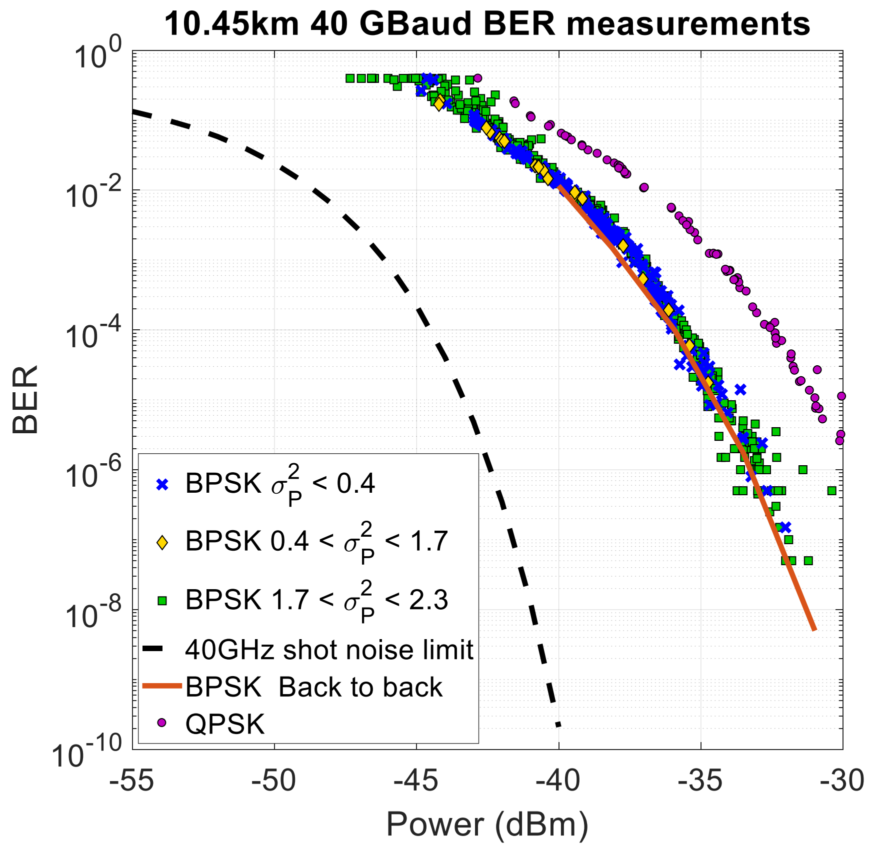
ESO: European Southern Observatory

Coherent technologies for communications

- Intradyne (digital homodyne) concept developed and tested for **30G BPSK** [1]
  - Robustness against fading
  - Less HW complexity compared to OPLL (advantageous in DWDM)
- Later [2]
  - **40G QPSK** receiver
  - More **robust timing recovery** (Lee algorithm) + **equalization**
- Now: online DSP based on FPGA







[1] J. Surof, J. Poliak, and R. Mata Calvo, "Demonstration of intradyne BPSK optical free-space transmission in representative atmospheric turbulence conditions for geostationary uplink channel," Opt. Lett. 42, 2173-2176 , 2017

[2] P. Conroy, J. Surof, J., J. Poliak, J. and R. Mata Calvo, "Demonstration of 40GBaud intradyne transmission through worst-case atmospheric turbulence conditions for geostationary satellite uplink," in Appl. Opt., OSA, 2018, *57*, 5095-5101

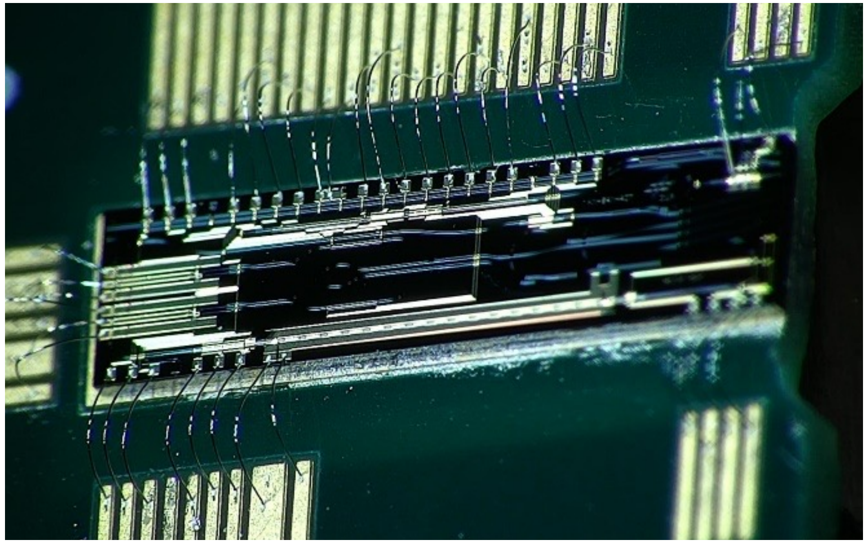
BPSK: Binary Phase-Shift Keying
OPLL: Optical Phase-Locked Loops
DWDM: Dense Wavelength Division Multiplexing

Photonics Integration Circuit (PIC)

- Coherent optical transceiver optimized for time-transfer

- 1st generation completed
  - Design & Testing at DLR
  - Manufacturing at external foundry

- 2nd generation design finished and submitted to foundry for manufacturing
  - Improved optical interface
  - Laser re-design for continuous tunability and higher efficiency
  - Improved testability



1st gen DLR PIC after wire-bonding

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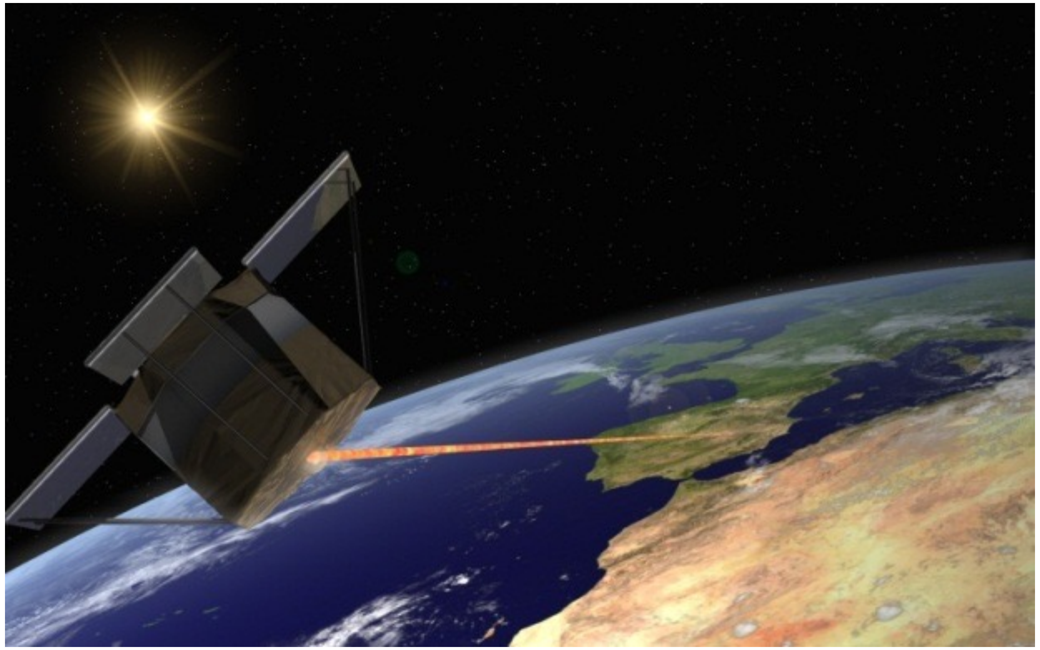


What is CCSDS?

Consultative Committee for Space Data Systems

- The Consultative Committee for Space Data Systems (CCSDS) is a multi-national forum for the development of communications & data systems standards for spaceflight.
- Leading space communications experts from 28 nations collaborate in developing the most well-engineered space communications & data handling standards in the world.
- The goal to enhance governmental & commercial interoperability & cross-support, while also reducing risk, development time & project costs.
- More than 1000 space missions have chosen to fly with CCSDS-developed standards.

BLUE BOOKS
Recommended Standards

Normative and sufficiently detailed (and pre-tested) so they can be used to directly and independently implement interoperable systems (given that options are specified).

MAGENTA BOOKS
Recommended Practices

Normative, but at a level that is not directly implementable for interoperability. These are Reference Architectures, APIs, operational practices, etc.

GREEN BOOKS
Informative Documents

Not normative. These may be foundational for Blue/Magenta books, describing their applicability, overall archtecture, ops concept, etc.

RED BOOKS
Draft Standards/Practices

Drafts of future Blue/Magenta books that are in agency review. Use caution with these… they can change before release.

ORANGE BOOKS
Experimental

Normative, but may be very new technology that does not **yet** have consensus of enough agencies to standardize.

YELLOW BOOKS
Administrative

CCSDS Procedures, Proceedings, Test reports, etc.

SILVER BOOKS
Historical

Deprecated and retired documents that are kept available to support existing or legacy implementations. Implication is that other agencies may not cross-support.

PINK BOOKS/SHEETS
Draft Revisions For Review

Draft Revisions to Blue or Magenta books that are circulated for agency review. Pink Books are reissues of the full book, Pink Sheets are change pages only.

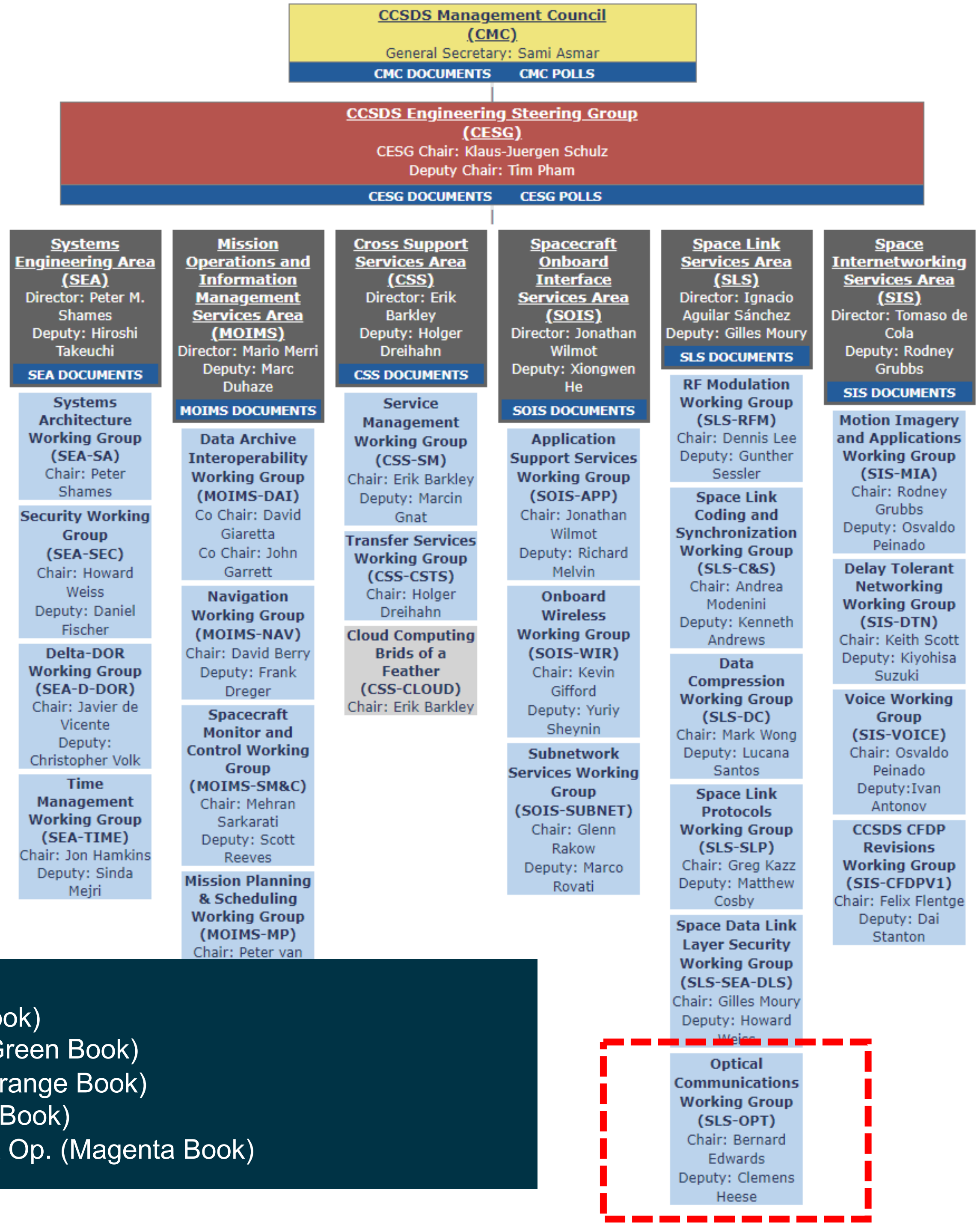
CCSDS SLS-OPT

O3K

(Low Complexity LEO-GND)

Books

- Physical layer
- **Coding and Synchronization layer**
- Supporting green books
- Verification Yellow books
- O3K C&S orange book - JAXA



1) CCSDS 141.0-B-1, Optical Communications Physical Layer (Blue Book)
2) CCSDS 142.0-B-1, Optical Communications Coding and Synchronization (Blue Book)
3) CCSDS 140.1-G-1, Real-Time Weather and Atmospheric Characterization Data (Green Book)
4) CCSDS 141.11-O-1, Optical High Data Rate (HDR) Communication – 1064 nm (Orange Book)
5) CCSDS 141.10-O-1, Optical High Data Rate Communications – 1550nm (Orange Book)
6) CCSDS 141.1-M-1, Atmospheric Characterization and Forecasting for Optical Link Op. (Magenta Book)

Contact

Name: Benjamin Rödiger
Affiliation: German Aerospace Center (DLR) – Optical Satellite Links
E-Mail: Benjamin.Roediger@dlr.de
Phone: +49 8153 28 -2944

„… we really want to make things fly.“

Impressum

DLR

Title:	**DLR's Solutions for Optical Communications on CubeSats**
Date:	13.09.2023
Author:	Benjamin Rödiger et. al
Institute:	Institute of Communications and Navigation
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