TALK TO SATELLITE – GROUND STATION TECHNOLOGY

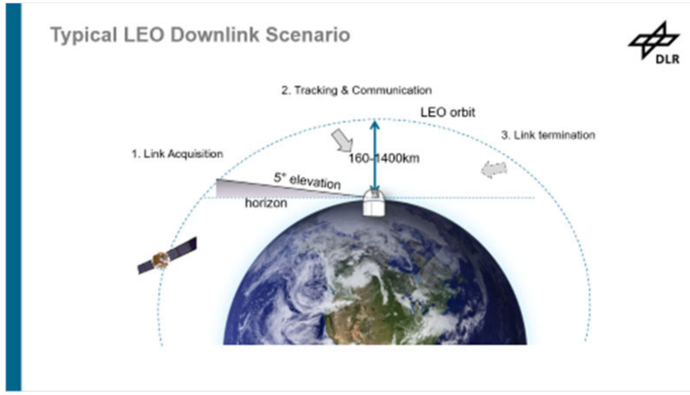
Amita Shrestha
Institute of Communications and Navigation
German Aerospace Center (DLR)

DLR

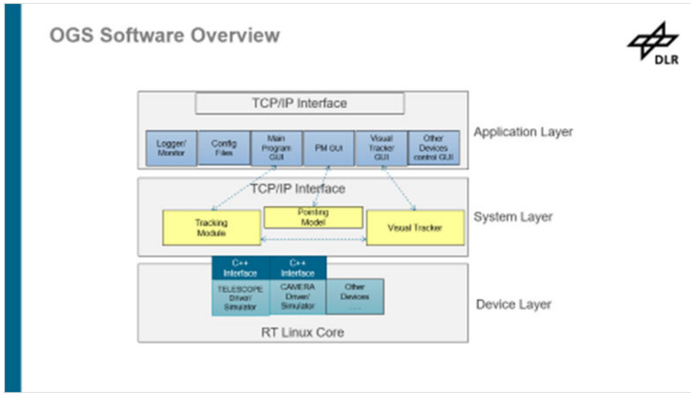
Contents


Institute for Communications and Navigation
DLR
Optical Satellite Links Department


Free Space Optical Communication
DLR

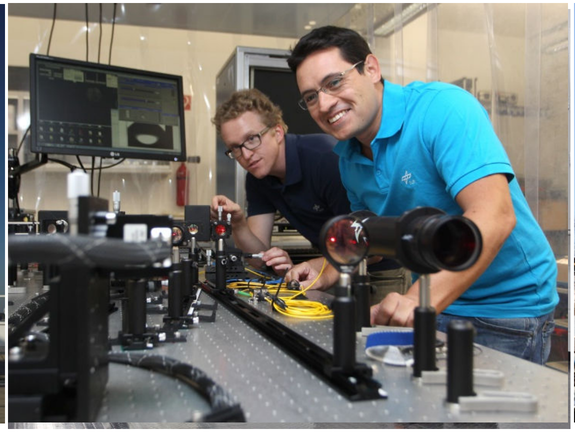

Typical LEO Downlink Scenario
DLR
2. Tracking & Communication
LEO orbit
3. Link termination
1. Link Acquisition
160-1400km
5° elevation
horizon


Optical Ground Stations


OGS Software Overview
DLR
TCP/IP Interface
Application Layer
TCP/IP Interface
Tracking Module
Pointing Model
Visual Tracker
System Layer
Device Layer
RT Linux Core


Satellite Based QKD
Why Satellite?
→ bridge large distances
FSO and QKD enable worldwide fast and secure data communications
Why QKD over FSO? → use of fiber is range limited → QKD using satellite node with QKD relay protocol
Combination of FSO and QKD technology in one device → high synergies → lower costs
QKD schemes: Distrete varibale (BB84) or continuous variable (and various others..)

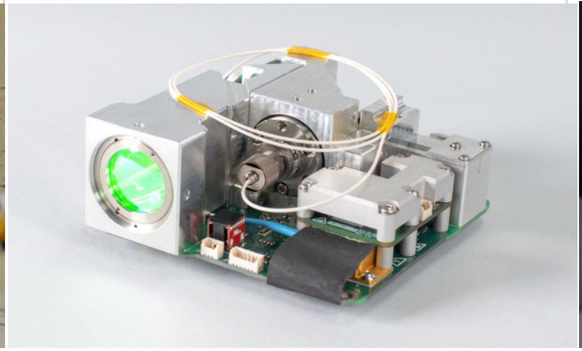
Institute for Communications and Navigation

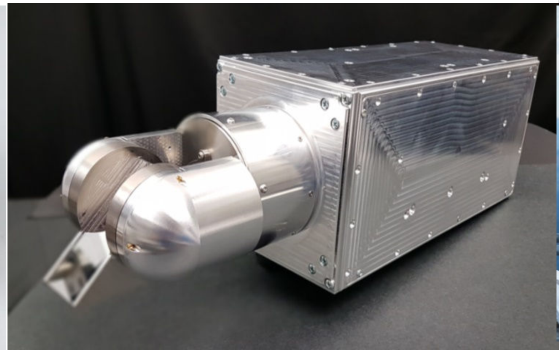


The institute is engaged in the design, analysis and realization of systems for communication and navigation for applications in the fields of space, aviation, transport and security.

The work ranges from the scientific fundamentals to technology demonstration in a real environment and technology transfer in cooperation with industry.

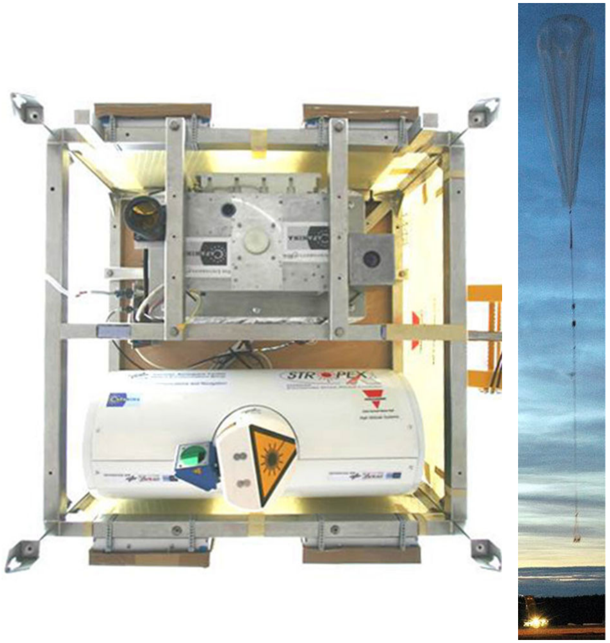
Optical Satellite Links Department





Heritage in Free-Space Optical Transmission

2004: First link from a
tethered balloon



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

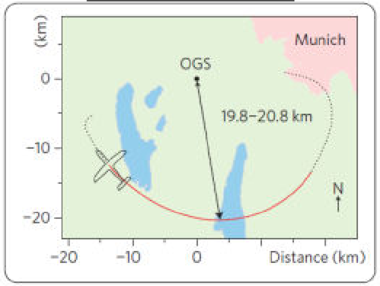
2008: First air-to-ground link
1.25 Gbps, d=120 km

2013: First air-to-ground link
Mach 0.7, 1.25 Gbps, d=60 km
jointly with ViaLight, Contract by Airbus

Quantum Key Distribution (QKD) from aircraft to ground

aircraft: Alice

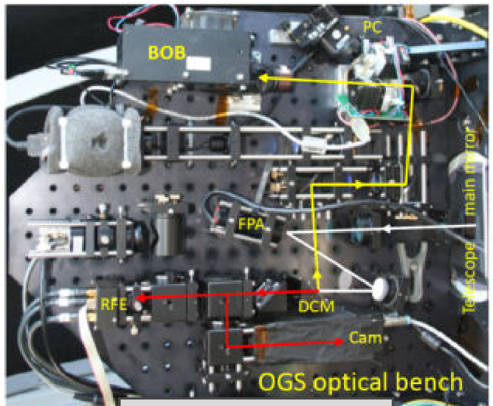
Flight path



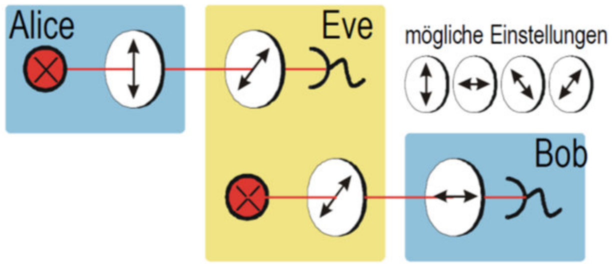
Ground Station: Bob

- Investigation of Quantum Key Distribution (QKD) with BB84 protocol
- **Physically secure communications**
- Polarization states of single photons exploited as quantum effect
- Demonstration of QKD between aircraft and ground segment in 2011

Aircraft Optical bench



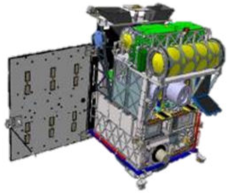
Ground Station Optical bench



Weinfurter 1998

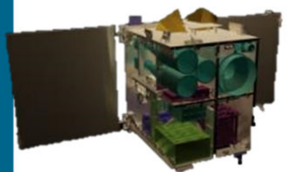
OSIRIS* Program at IKN

<u>OSIRISv2</u>
Closed-Loop Body Pointing
Data rate: 1 Gbit/s



2017

2016



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

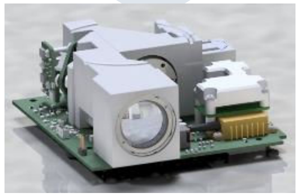
<u>OSIRISv3</u>
Active Beam Steering
with Coarse Pointing Assembly (CPA)
Data rate: 10 Gbit/s

2021

<u>OSIRIS4CubeSat (O4C)</u>
Active Beam Steering
combined with Body Pointing
Data rate: 100 Mbit/s

TESAT

2024

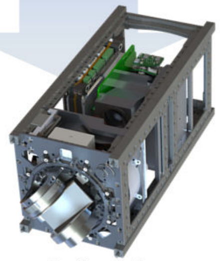


<u>QUBE</u>
O4C Evolution
for QKD-technology
with 1550 nm and 850 nm

2024

<u>CubeISL</u>
O4C Evolution
Inter-Satellite Links: 100 Mbit/s
Downlinks: 1 Gbit/s

2025



<u>Cube1G</u>
CubeISL Evolution
Active Beam Steering with CPA
Downlinks: 1 Gbit/s

DLR

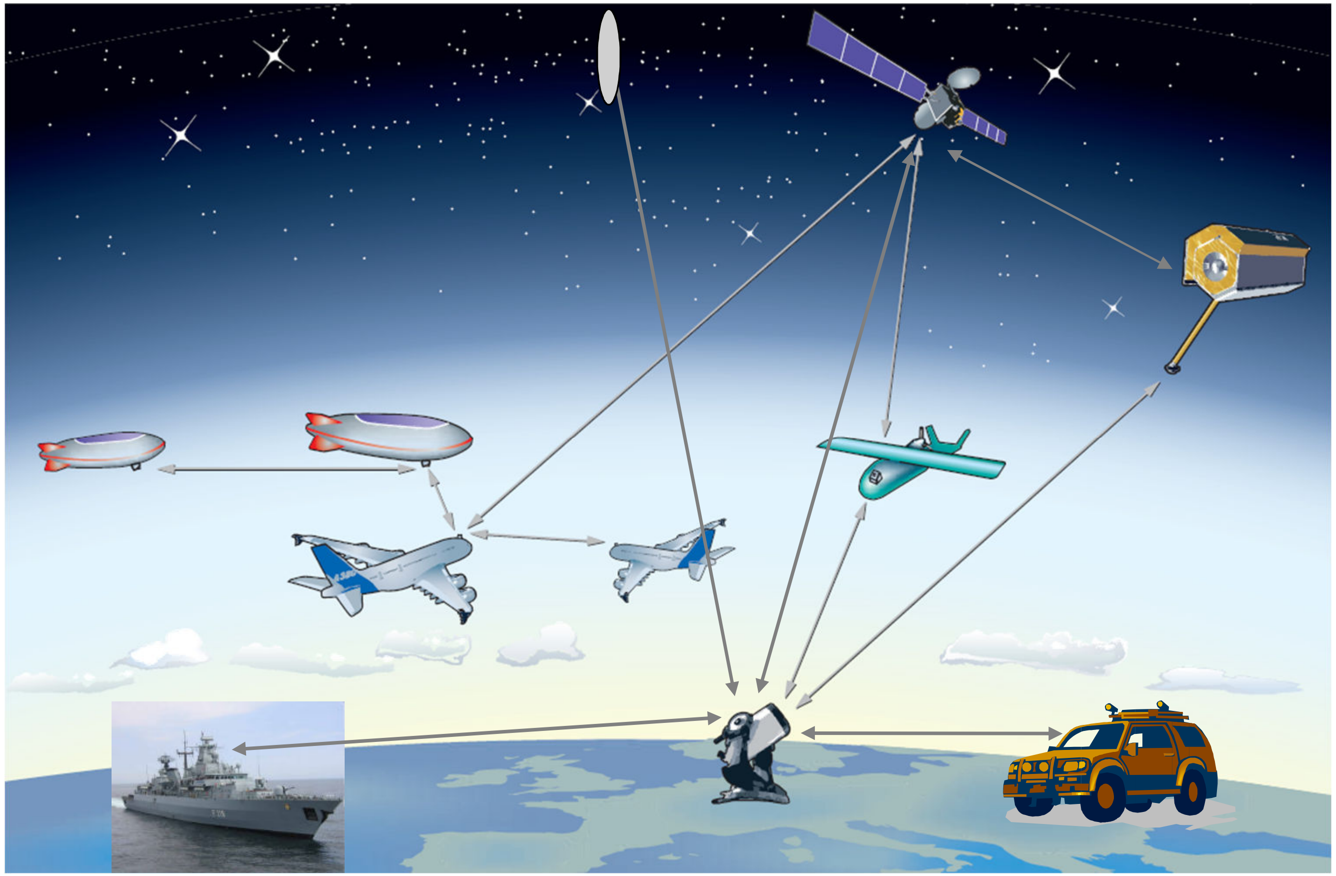
*Optical Space Infrared Downlink System

DLR IKN Optical Ground Stations

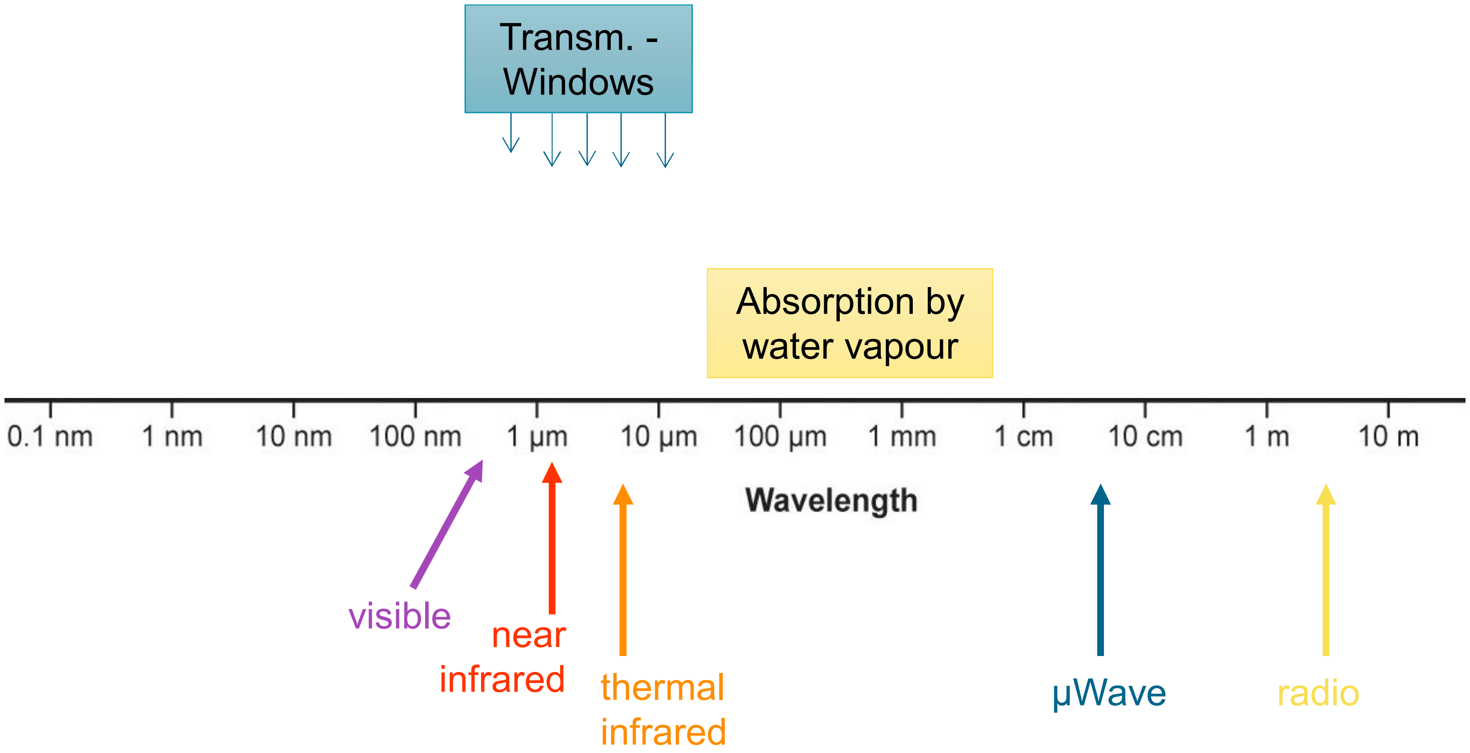
Optical Ground Station Oberpfaffenhon (OGSOP)

Transportable Optical Ground Station (TOGS)

Free Space Optical Communication



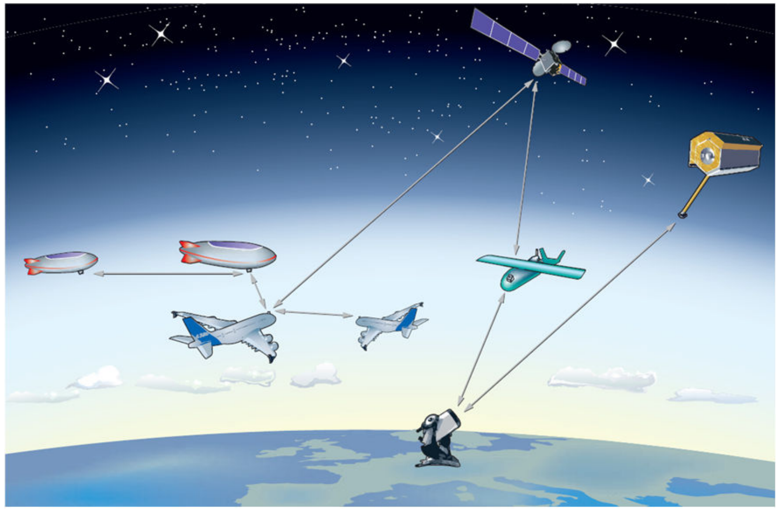
„From RF to Light“ – what wavelengths are used for Space-FSO



Free Space Optical (FSO) Communication

<u>Advantages of FSO</u>:

- ❑ High datarate
- ❑ Low power consumption
- ❑ High security
- ❑ No spectrum regulation
- ❑ Transmission of Single Photons allow application of Quantum techniques



Typical parameters

- Laser-wavelengths in the near infrared (850nm / 1064nm / 1550nm)
- diffraction limited Tx-divergence: below 1/1000 degree → *x* µrad
- datarates from few 100Mbps up to *n* Tbps

FSO Challenges

- Challenges:

❑ Turbulent atmosphere: scintillation, fading

❑ Fog, rain, snow haze: fading, link outages

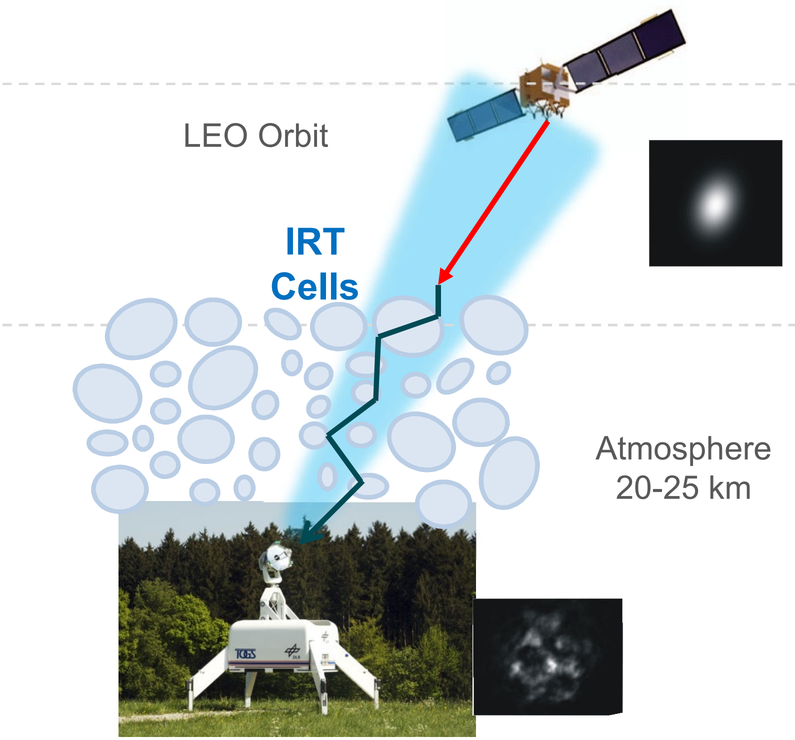
❑ Pointing/tracking error : beam wandering

- Mitigation Techniques:

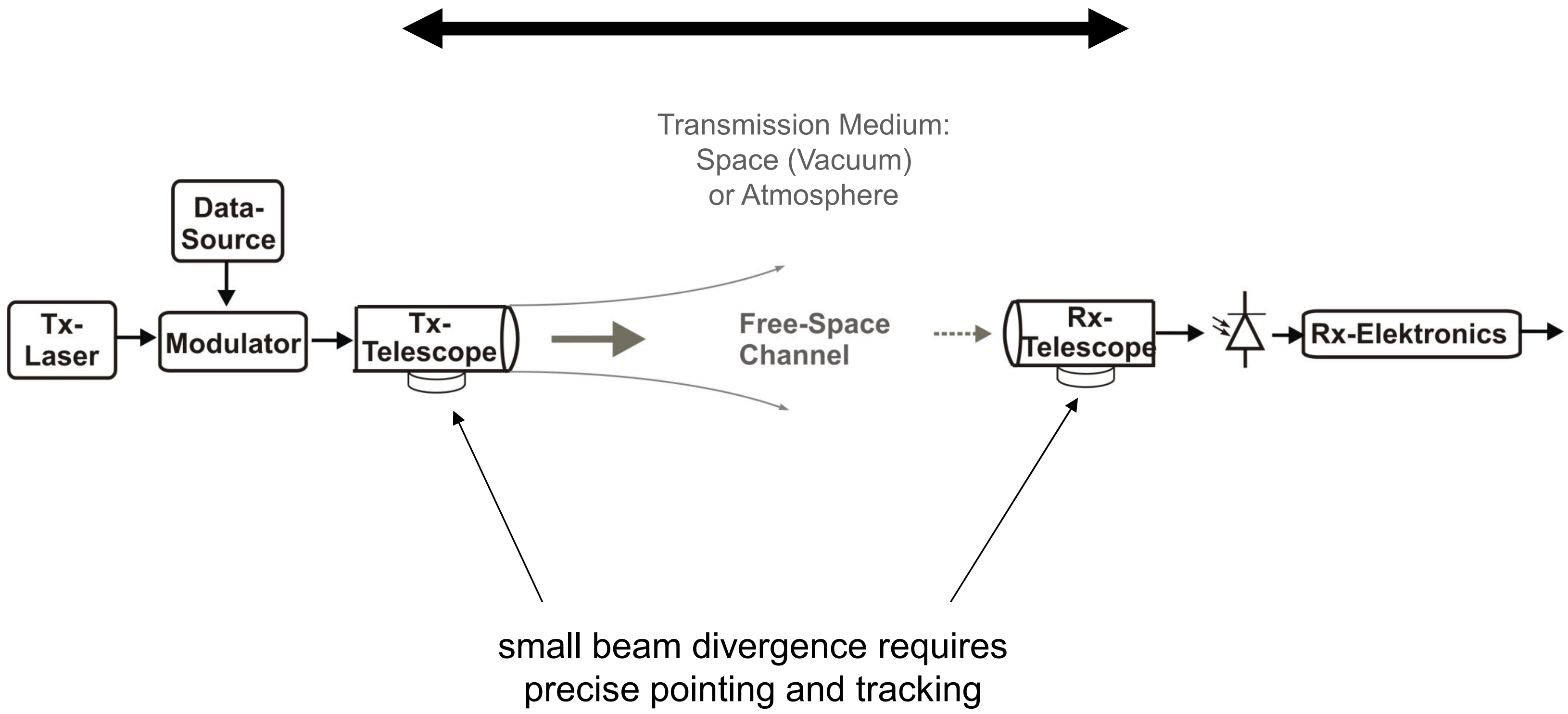
❑ Aperture averaging using bigger telescopes

❑ Complex Adaptive optics

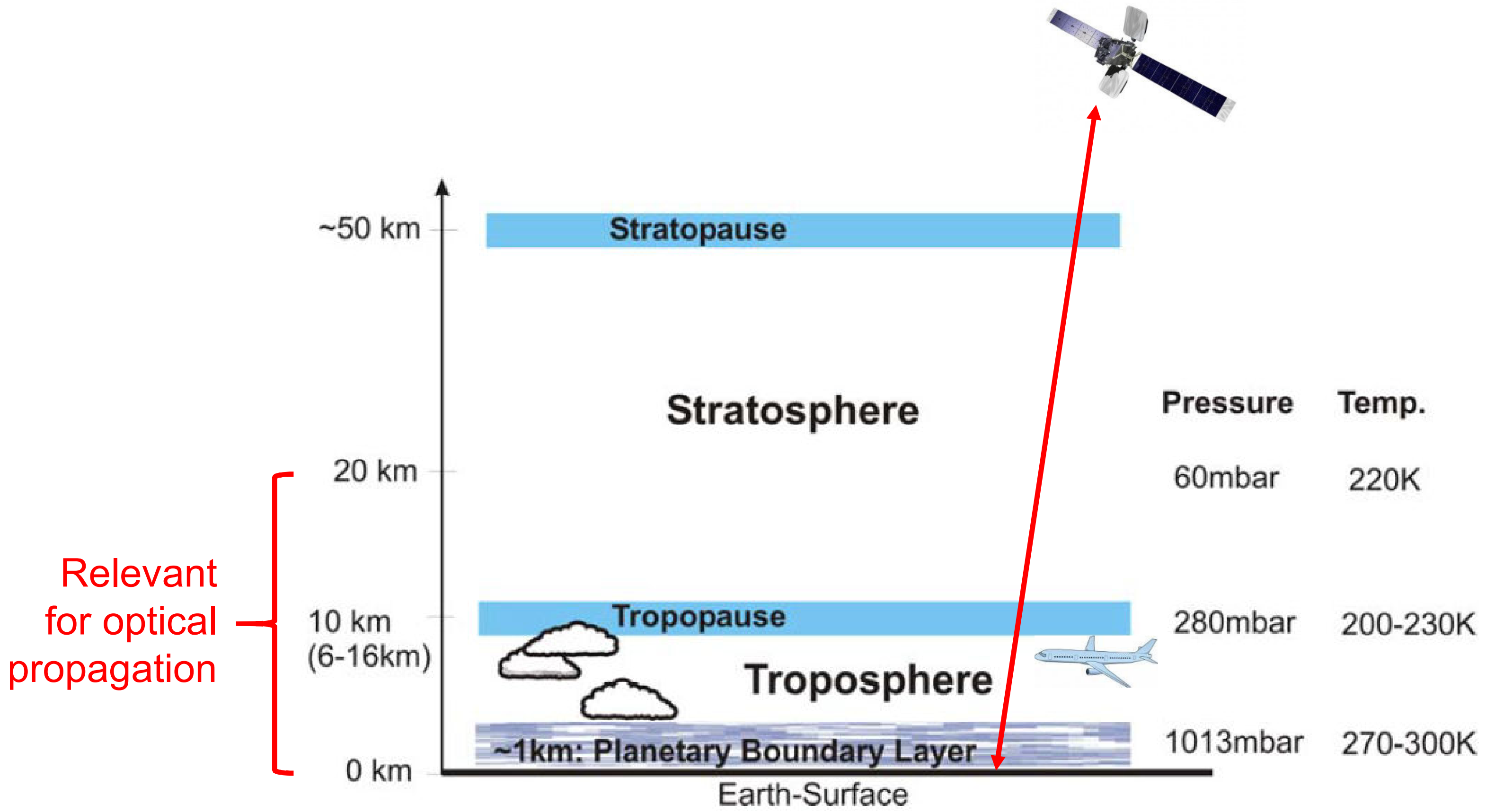
❑ Variable data rate etc.



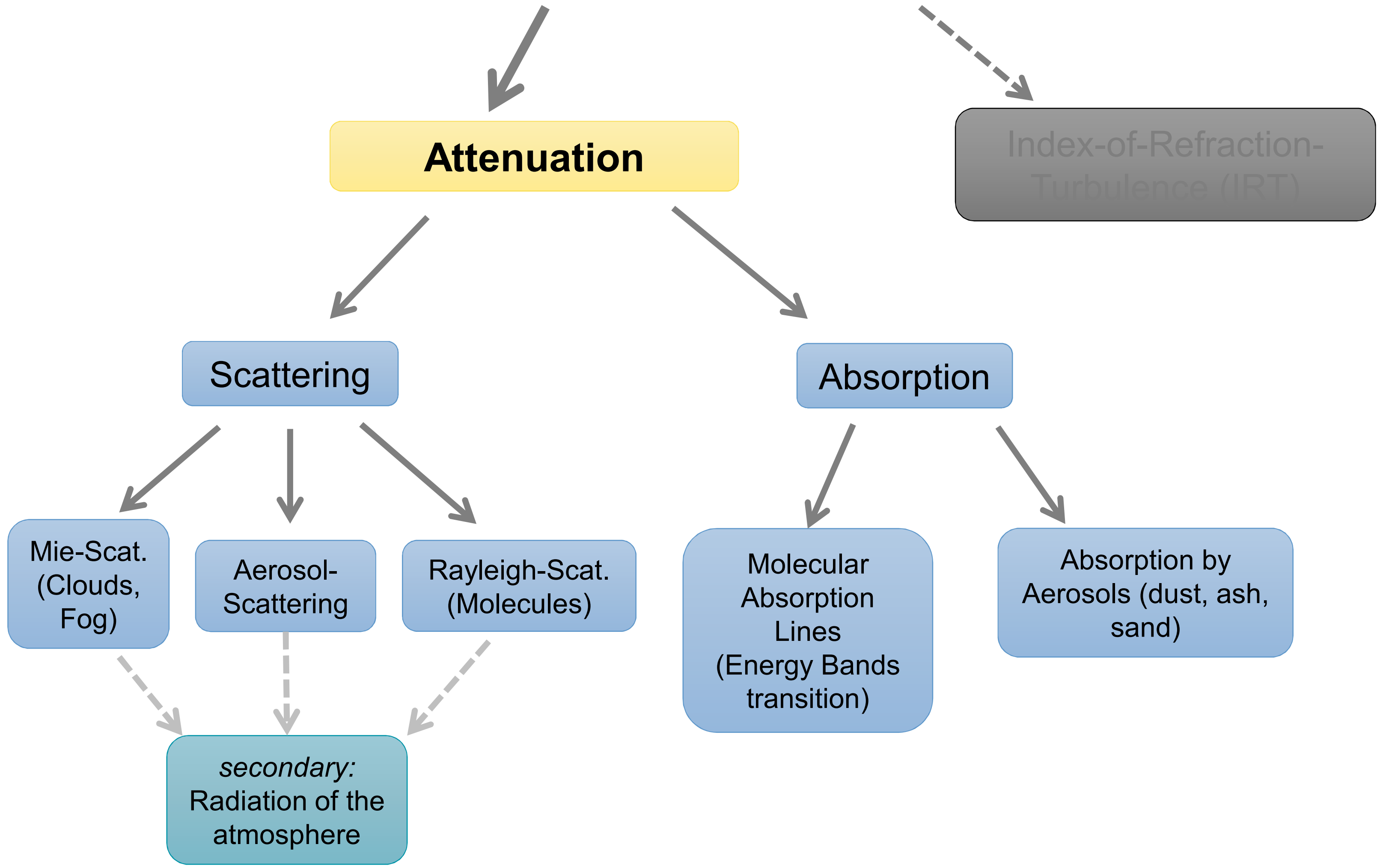
Directed Point-to-Point Links by Modulated Laser Beams → FSOC (Free-Space Optical Communications)



Structure of Earth‘ Atmosphere



Atmospheric Effects on Optical Signals



Atmospheric transmission: Beer‘s law

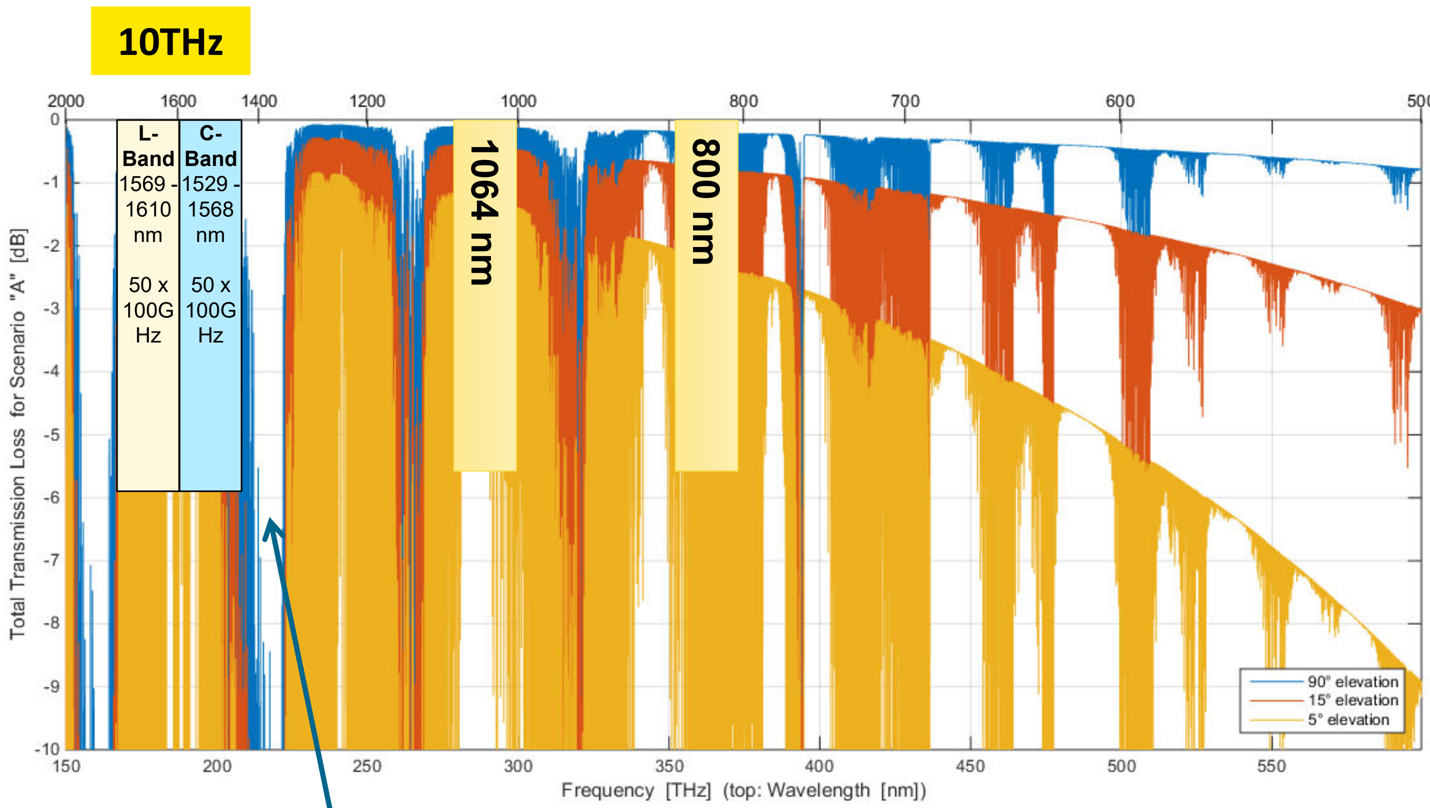
- Calculation of transmission with extinction coefficient (1/km)
- Extinction = Scattering + Absorption
- Accumulated effects considered with one equation → Beer‘s law
  - Rayleigh scattering
  - Aerosol scattering and absorption
  - Molecular absorption lines

$$I_{out} = I_{in} \cdot \exp(-\int_0^L \alpha_{ext}(z,\lambda)dz)$$

$$\alpha_{ext}(z,\lambda) = \sum_i \alpha_i(z,\lambda)$$

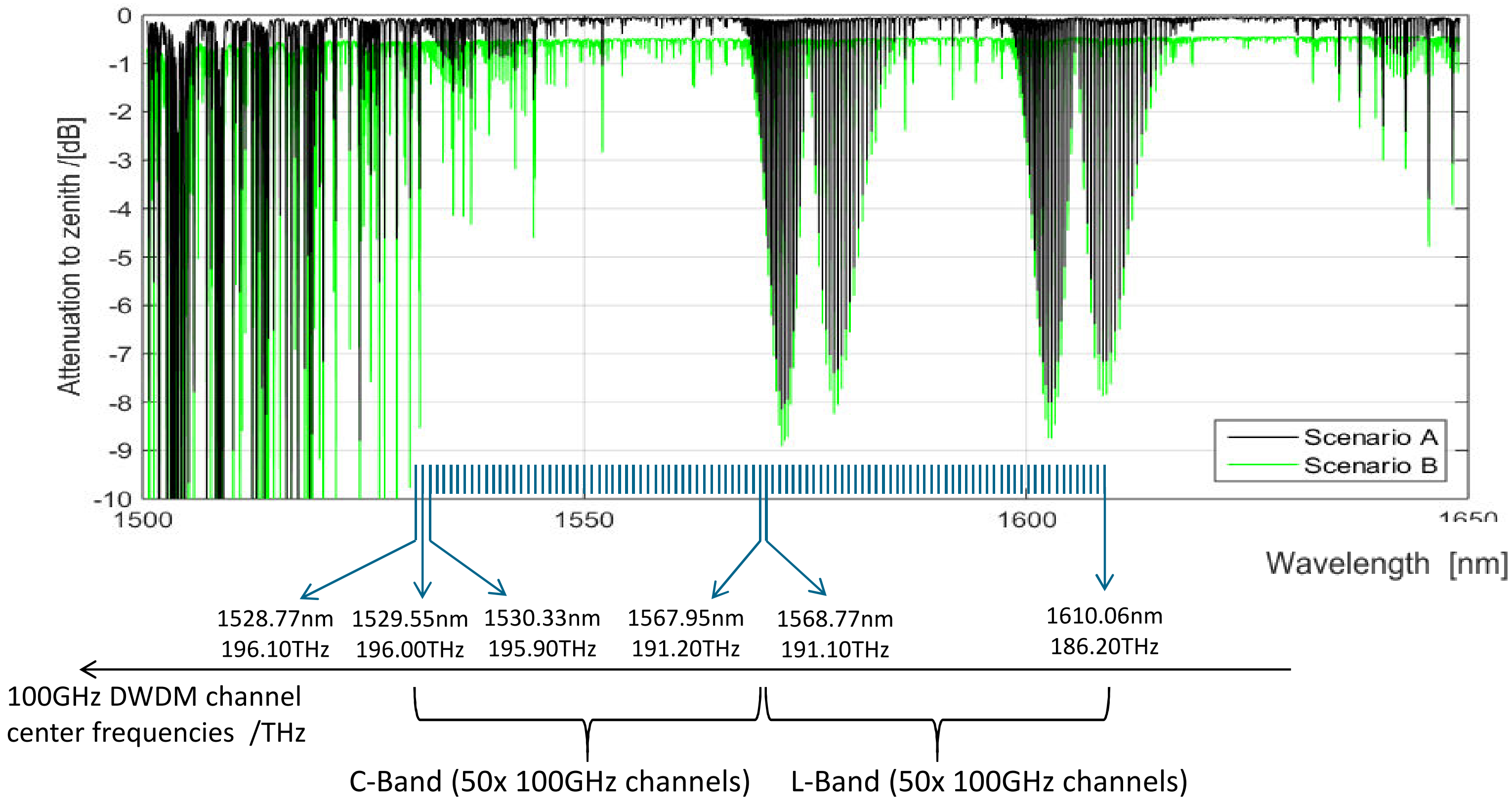
α_{ext}	complete extinction coefficient [km^{-1}]
α_i	various scat./abs. coefficients [km^{-1}]
I	output intensity [W/m^2]
I_0	input intensity [W/m^2]
λ	Wavelength [µm]
L	path length [m]
z	path variable [m]

Available Optical Spectrum between Molecular Absorption Lines



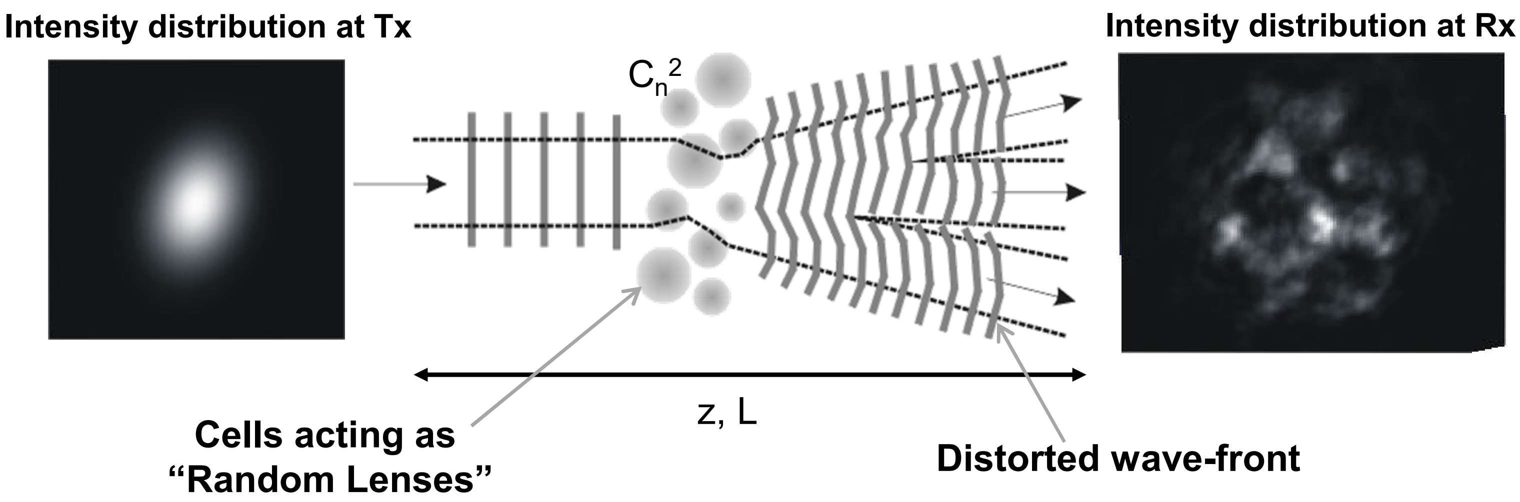
near-IR: absorption mostly by H_2O, in thermal infrared also CO_2

The C- and L-Band DWDM Channels and their transmission (1520nm – 1620nm)



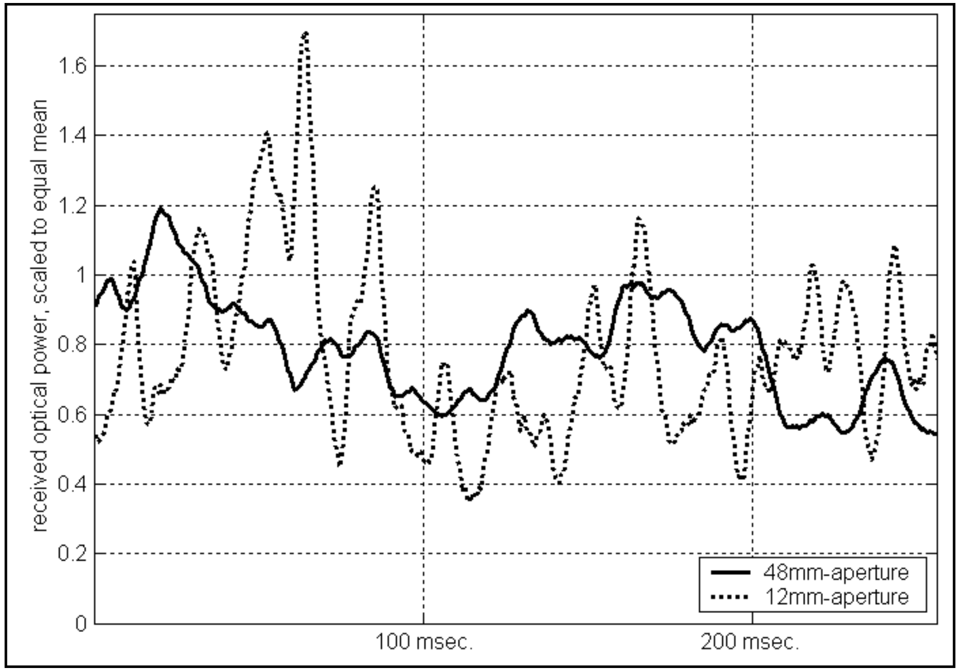
IRT-Scintillation through self-interference

- Beam propagating through optical turbulence → wave-front distortions → several effects
- Severity of the cumulated turbulence and fluctuation regime (weak/moderate/strong)



Aperture Averaging with IRT-Scintillation

depends on ratio intensity-structure vs aperture-diameter

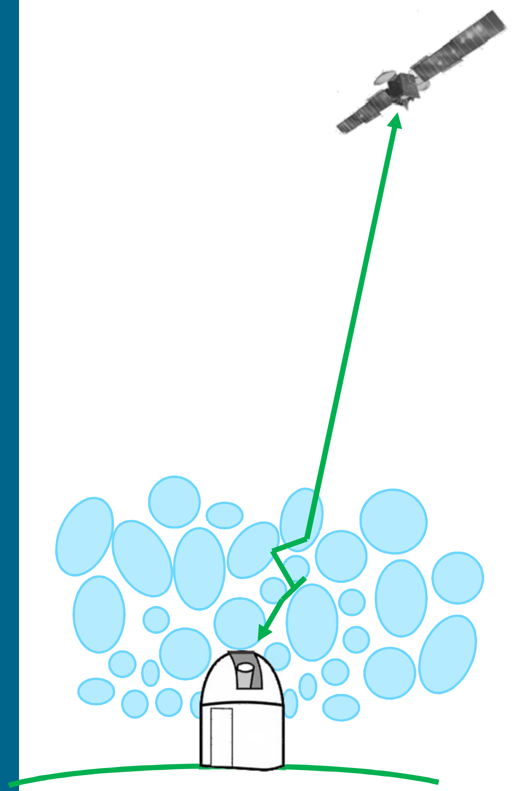


same IRT, two apertures

$$A_f\left(D\right) = \frac{\sigma_P^2\left(D\right)}{\sigma_I^2}$$

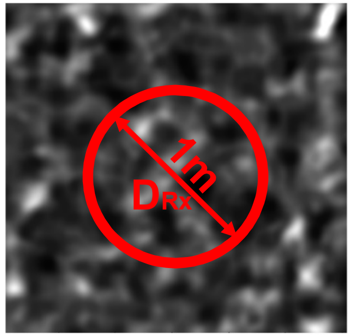
Aperture Averaging with different intensity-cell sizes

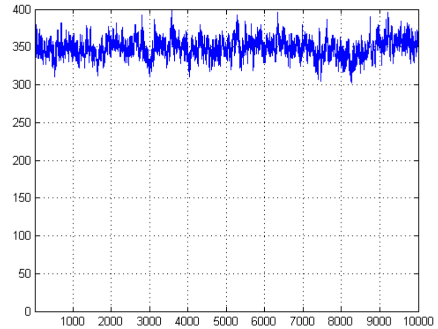
Asymmetry in Satellite Uplink vs. Downlink Channel

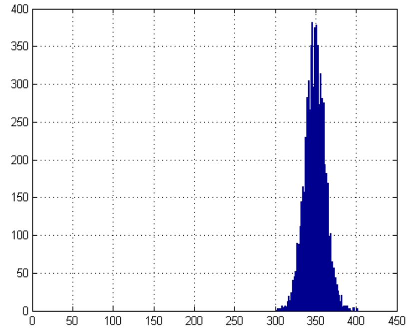


Downlink into OGS:

With 1 m aperture averaging



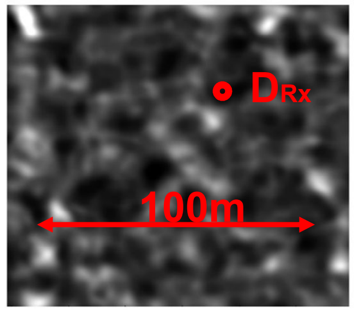


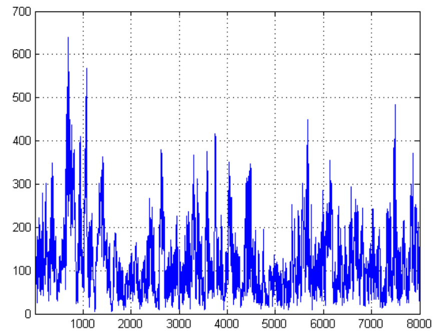


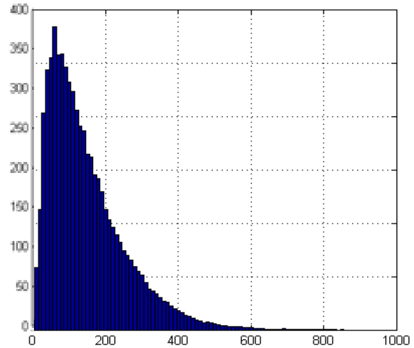
Intensity | **1s Rx-Signal** | ***Histogram***

Uplink at Satellite:

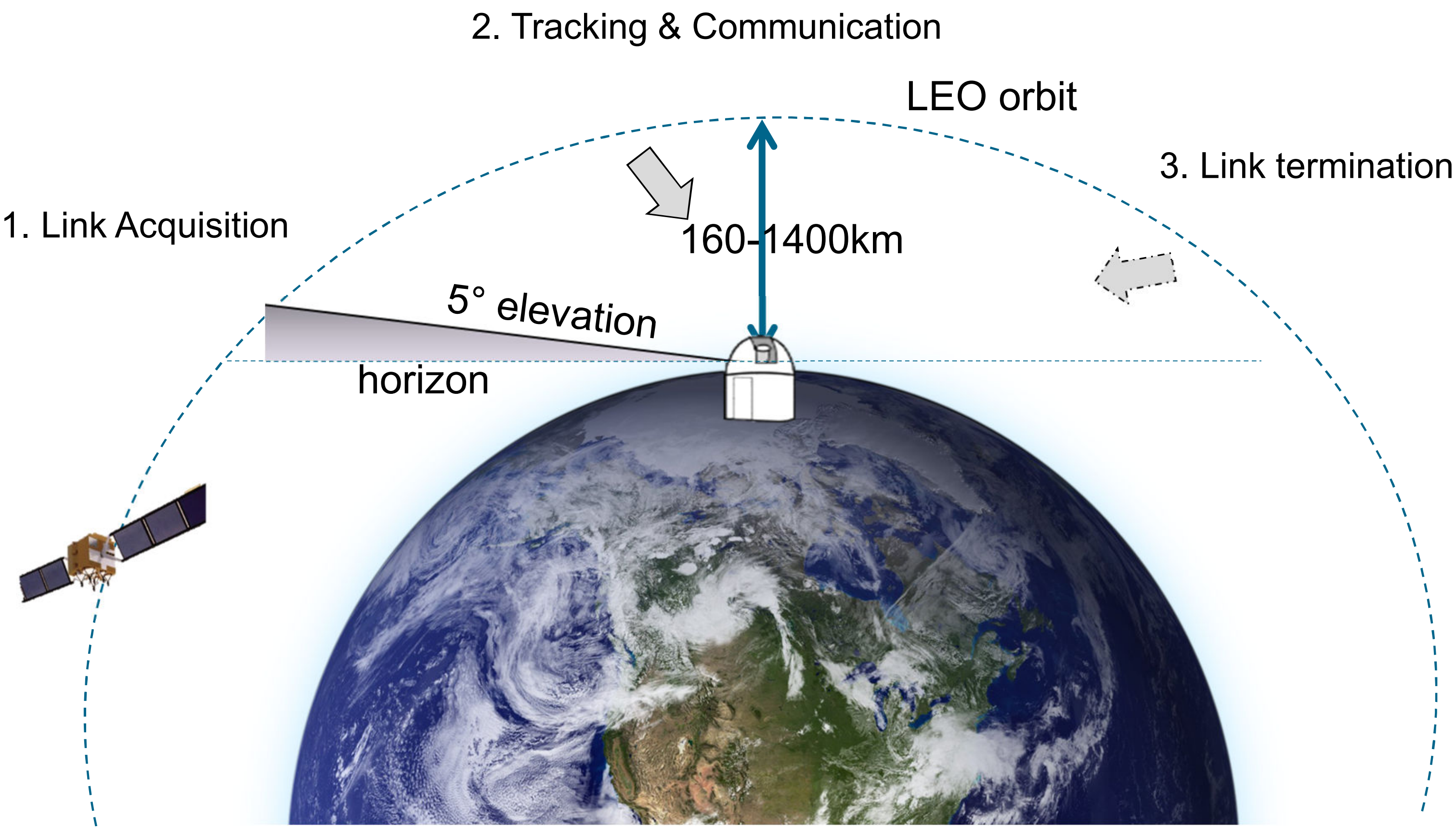
No aperture averaging possible





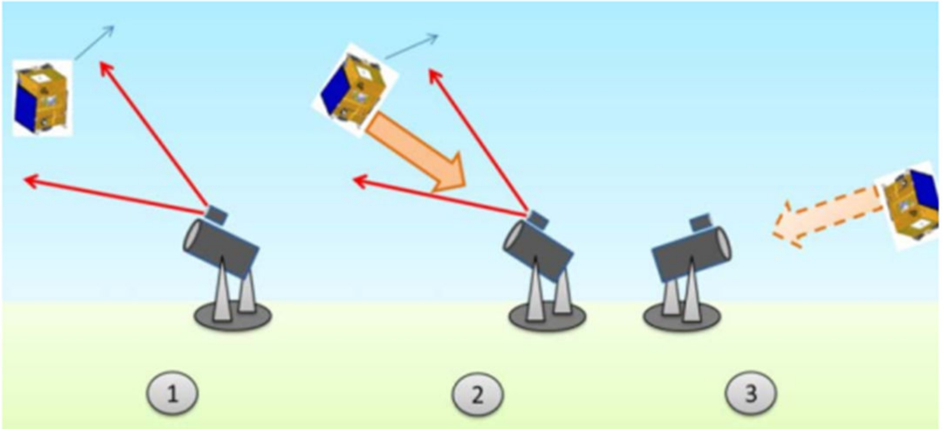


Typical LEO Downlink Scenario

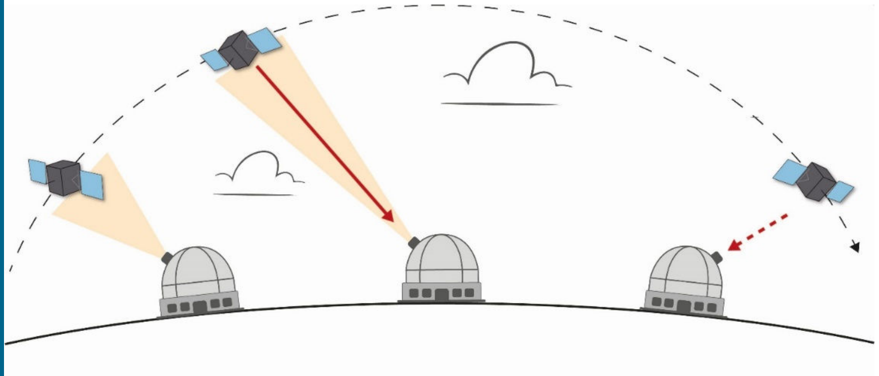


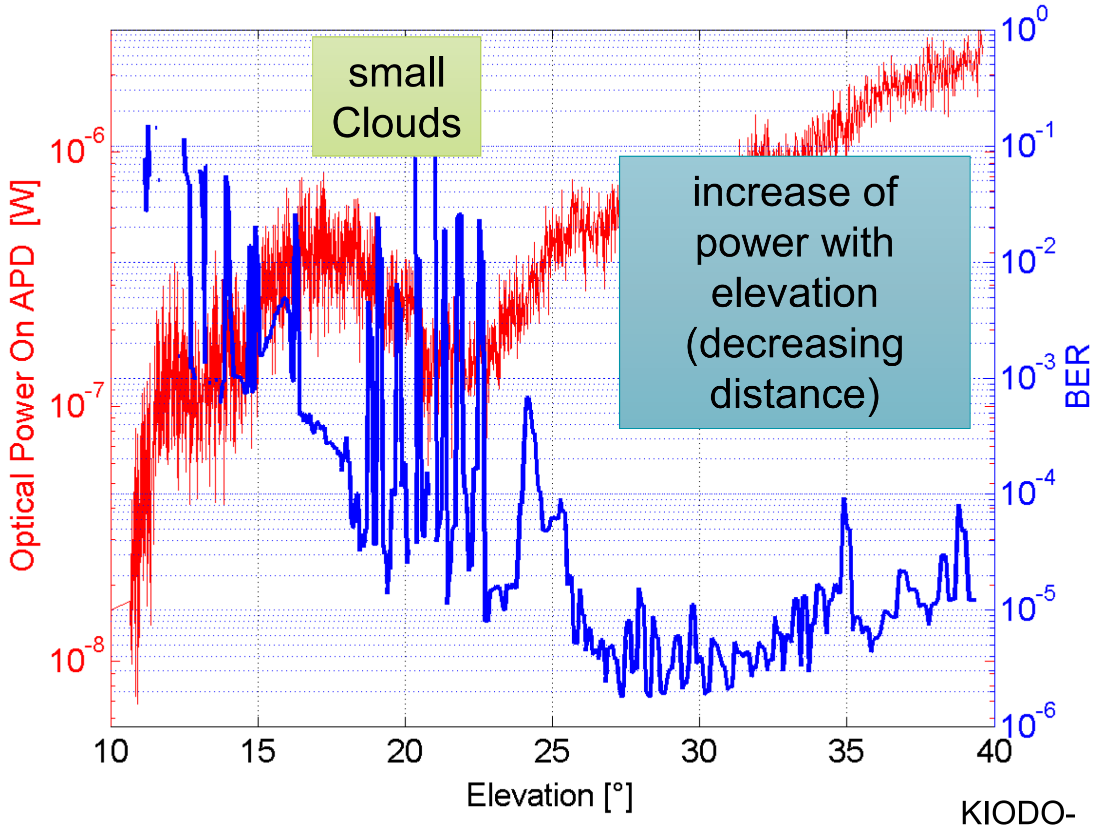
Pointing, Aquisition and Tracking (PAT)

- Pointing
  - Both satellite and GS points towards each other using GPS coordinates, orbit data etc.
- Acquisition
  - Terminals acquires the signal from each other in their acquisition sensor
- Tracking
  - Continous tracking of the acquired signal with coarse pointing or fine pointing assembly



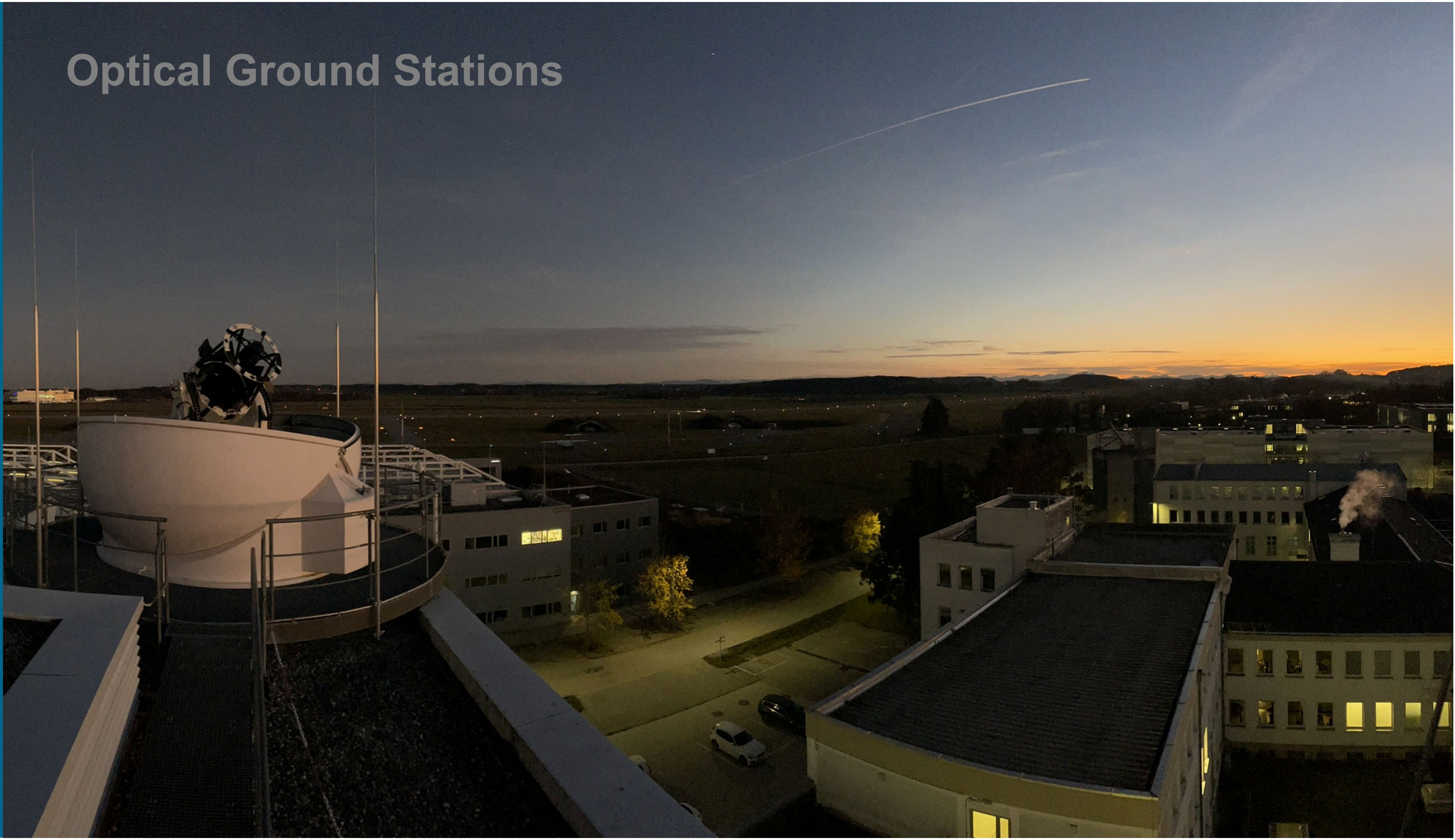
Optical LEO – Direct-to-Earth: Measured Received Power and Bit Error Rate over Elevation



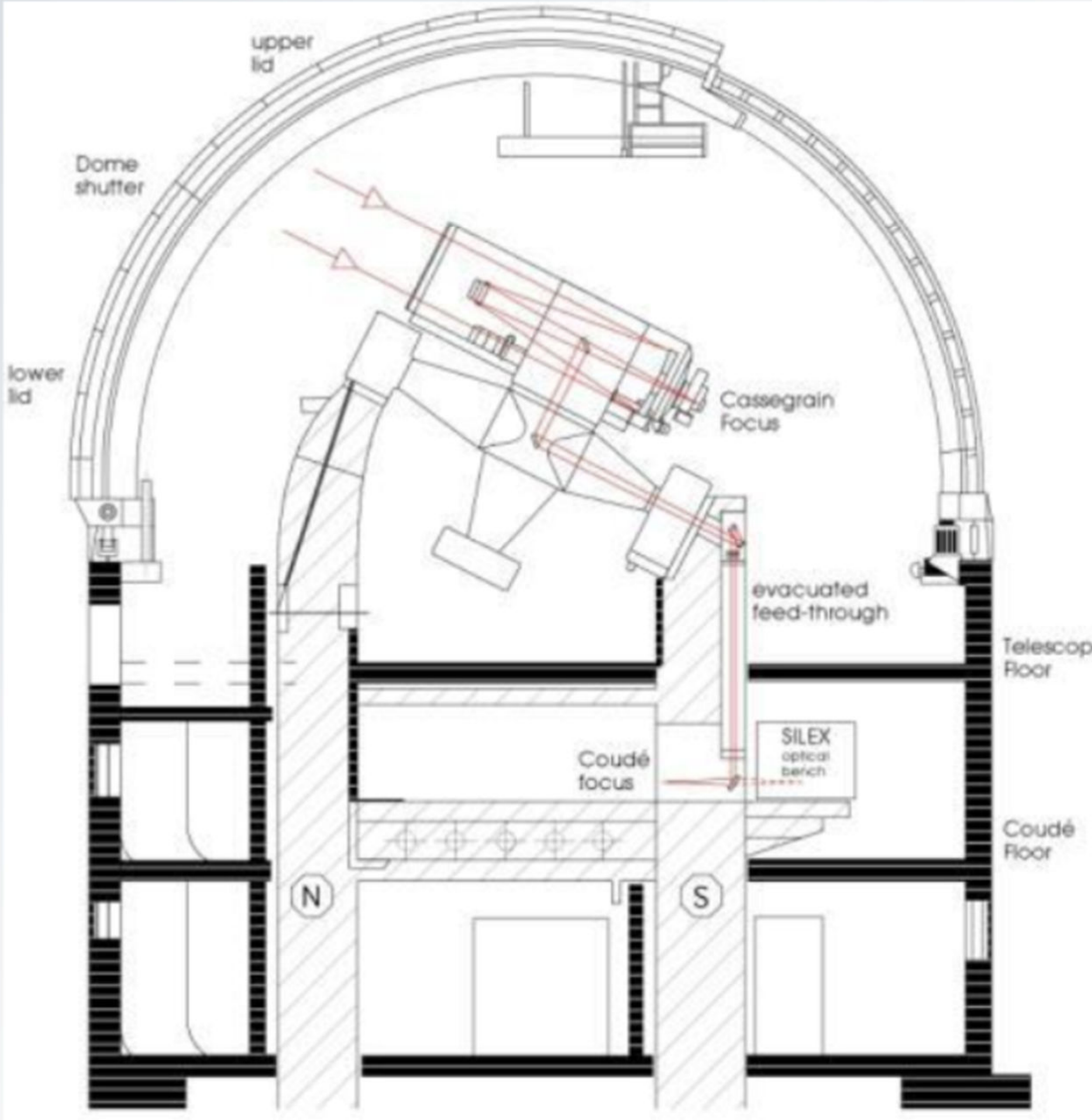


KIODO-downlinks

Optical Ground Stations



ESA-OGS (Teneriffa), 1 m



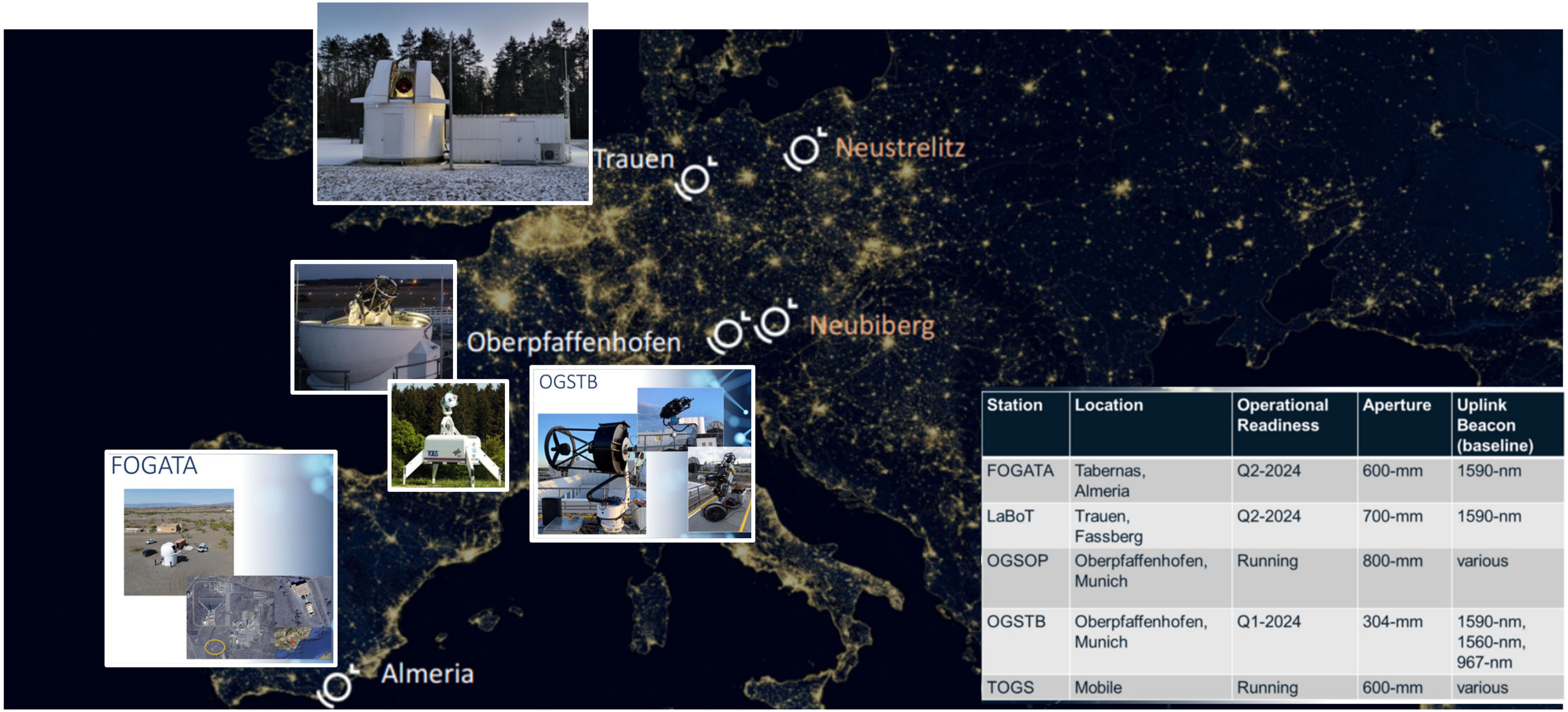
Bilder: ESA

Some more Ground Stations

- OGS des NICT
- Standort: Tokyo
- 1,5 m

- OGS von NASA-JPL
- Standort: Table Mountain, Kalifornien
- 1 m

DLR Ground Stations



Station	Location	Operational Readiness	Aperture	Uplink Beacon (baseline)
FOGATA	Tabernas, Almeria	Q2-2024	600-mm	1590-nm
LaBoT	Trauen, Fassberg	Q2-2024	700-mm	1590-nm
OGSOP	Oberpfaffenhofen, Munich	Running	800-mm	various
OGSTB	Oberpfaffenhofen, Munich	Q1-2024	304-mm	1590-nm, 1560-nm, 967-nm
TOGS	Mobile	Running	600-mm	various

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

Improved performance and sensitivity

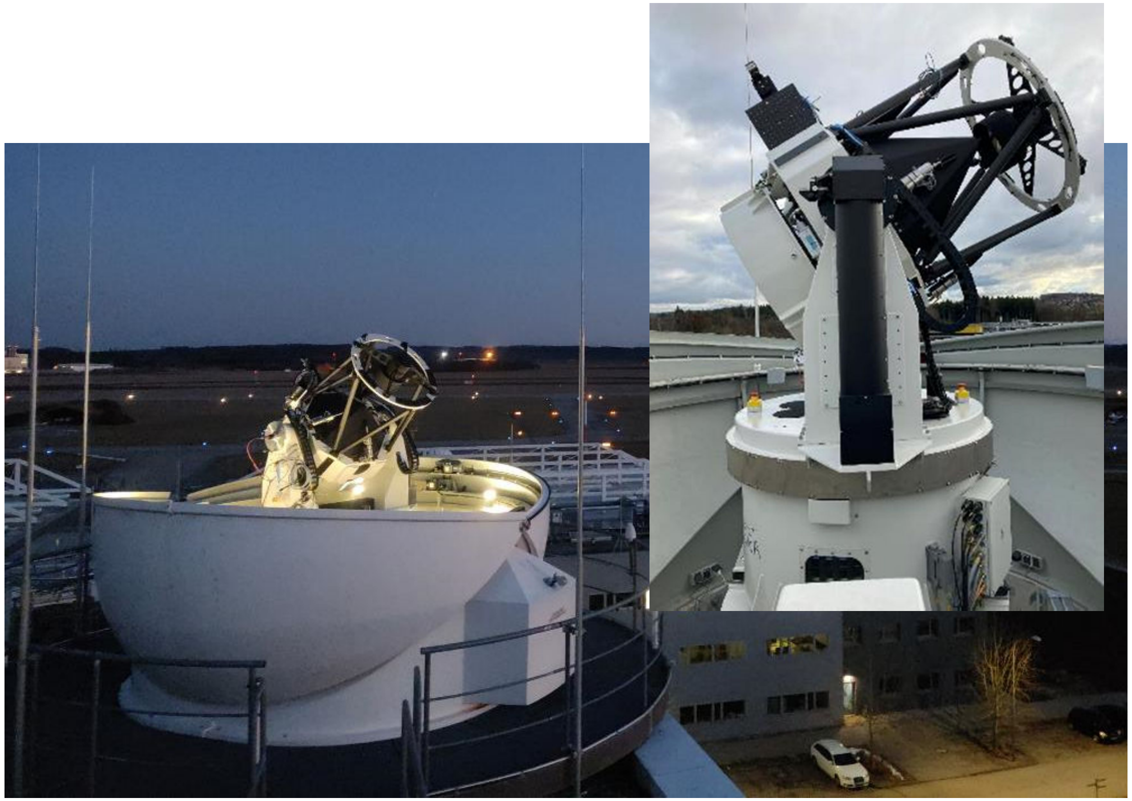
- 80 cm aperture
- Measurements with better spatial resolution
- Supports links in GEO-, deep space- and quantum key distribution-applications

Multiple foci, including Coudé

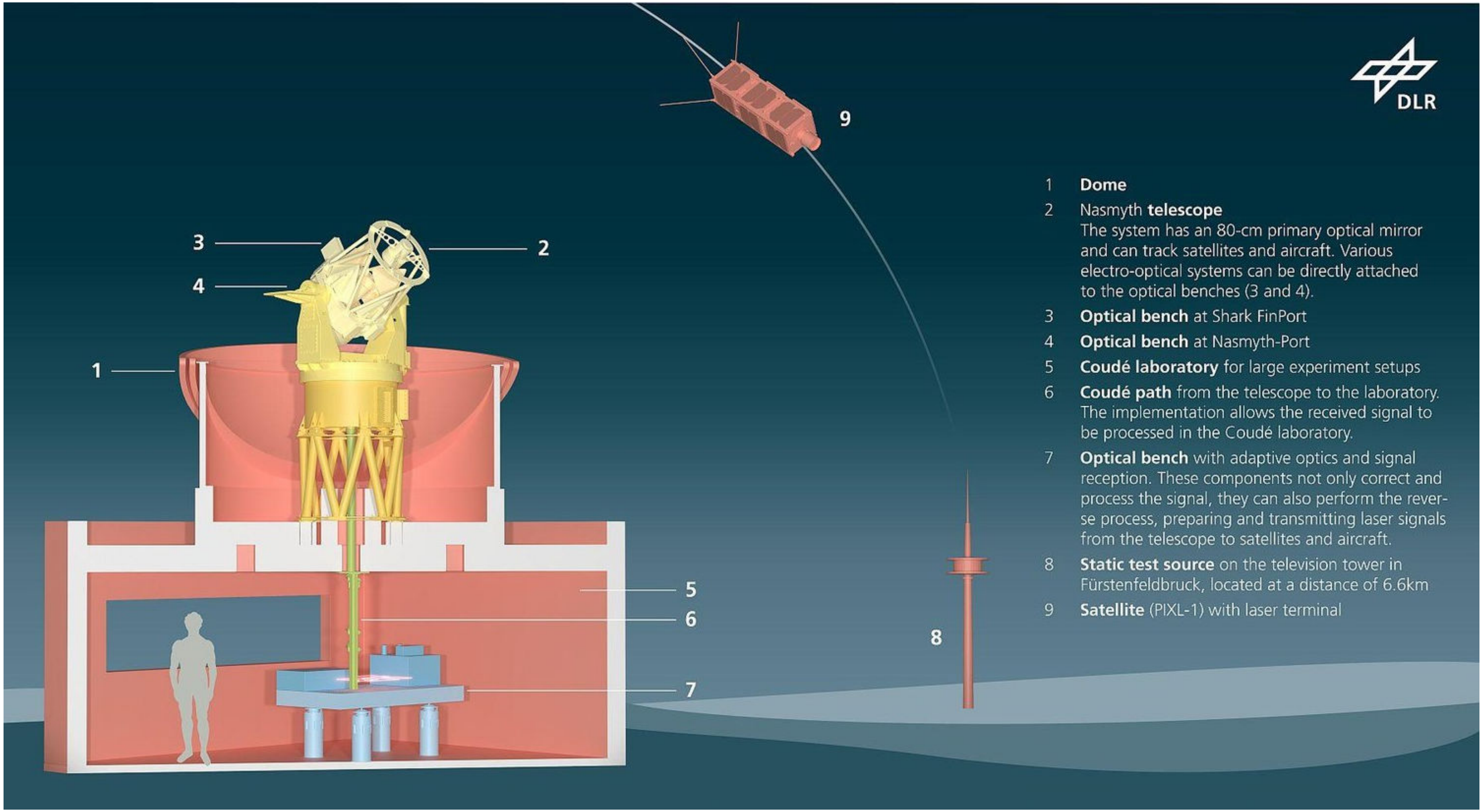
- High flexibility to change between setups, enabling multi-mission support
- Adaptive Optics on Coudé-Bench

Characterization of the atmosphere

- Measurement instruments for recording of key atmospheric parameters



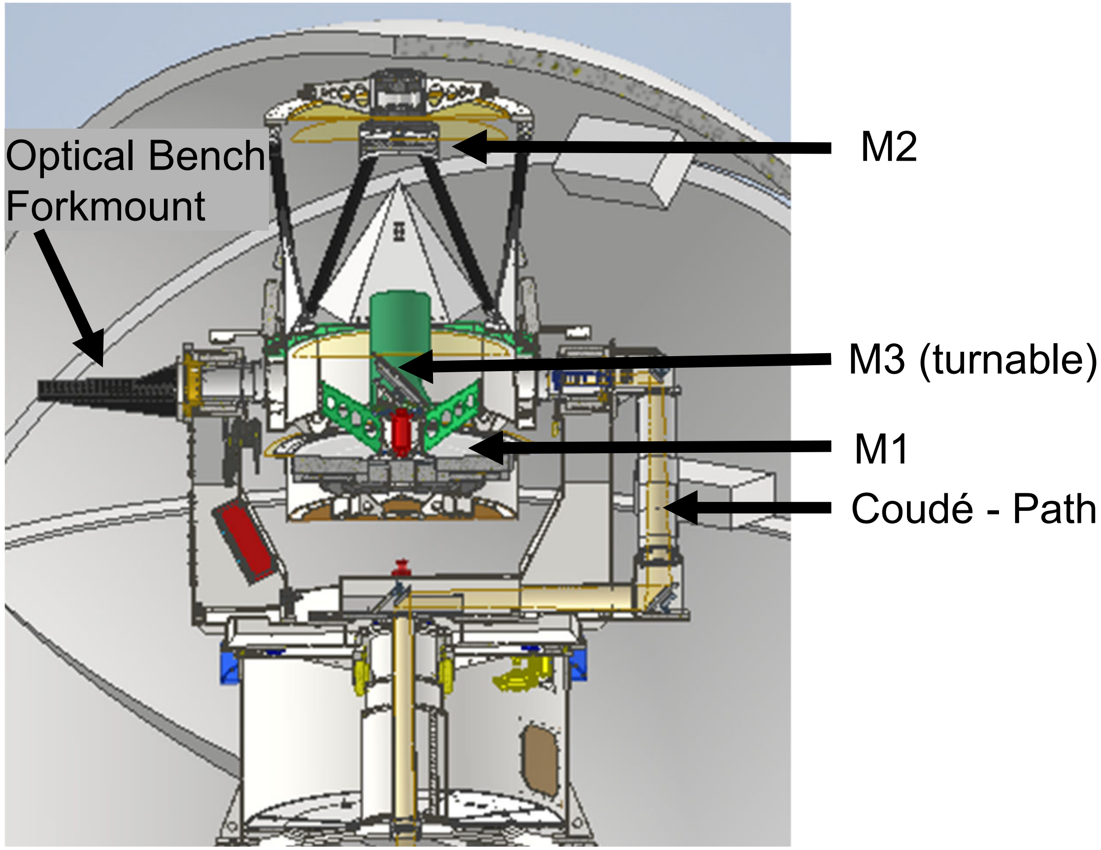
Development OGSOP-NG

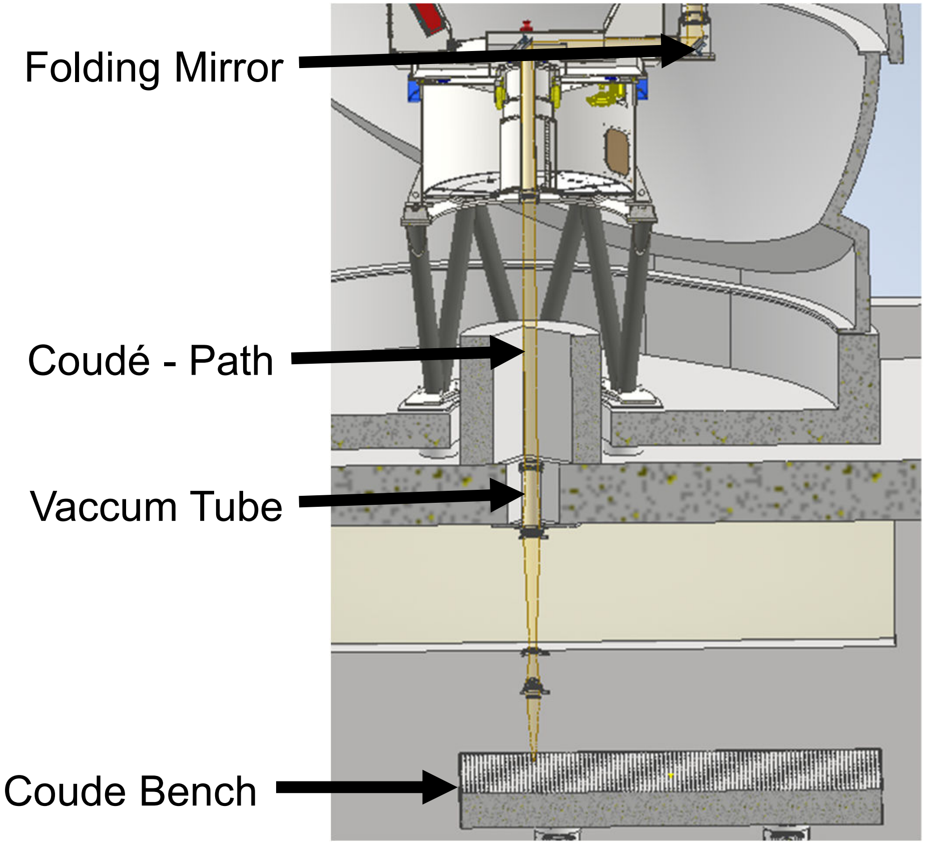


DLR

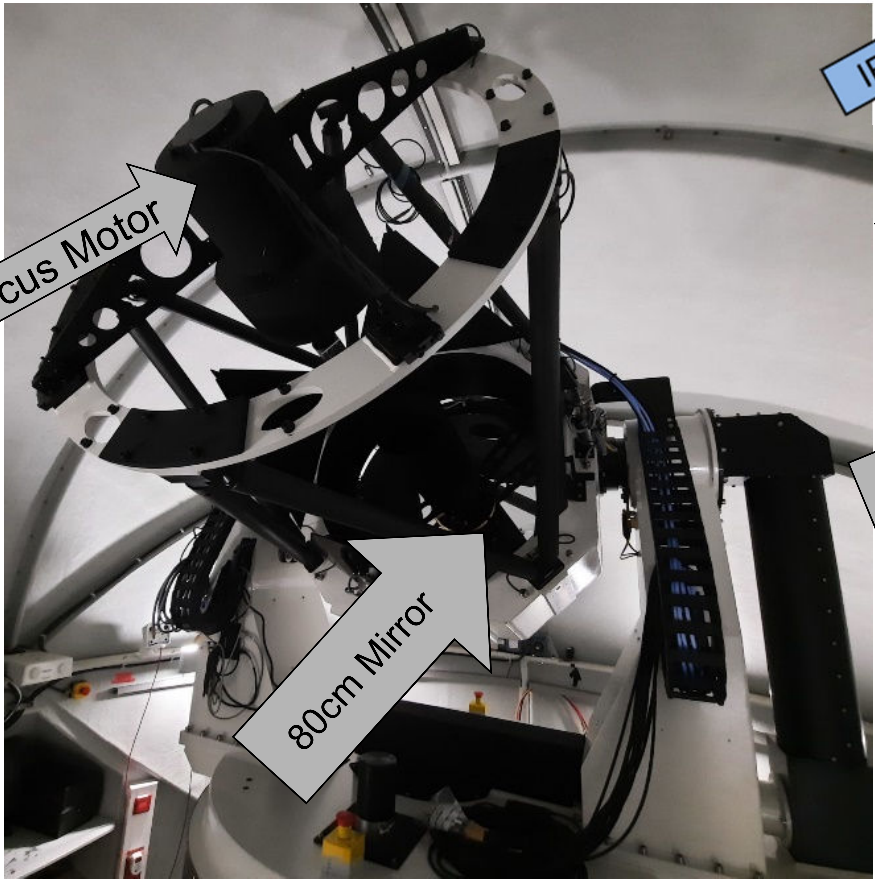
Optical Ground Station OP
OGSOP

Development OGSOP-NG

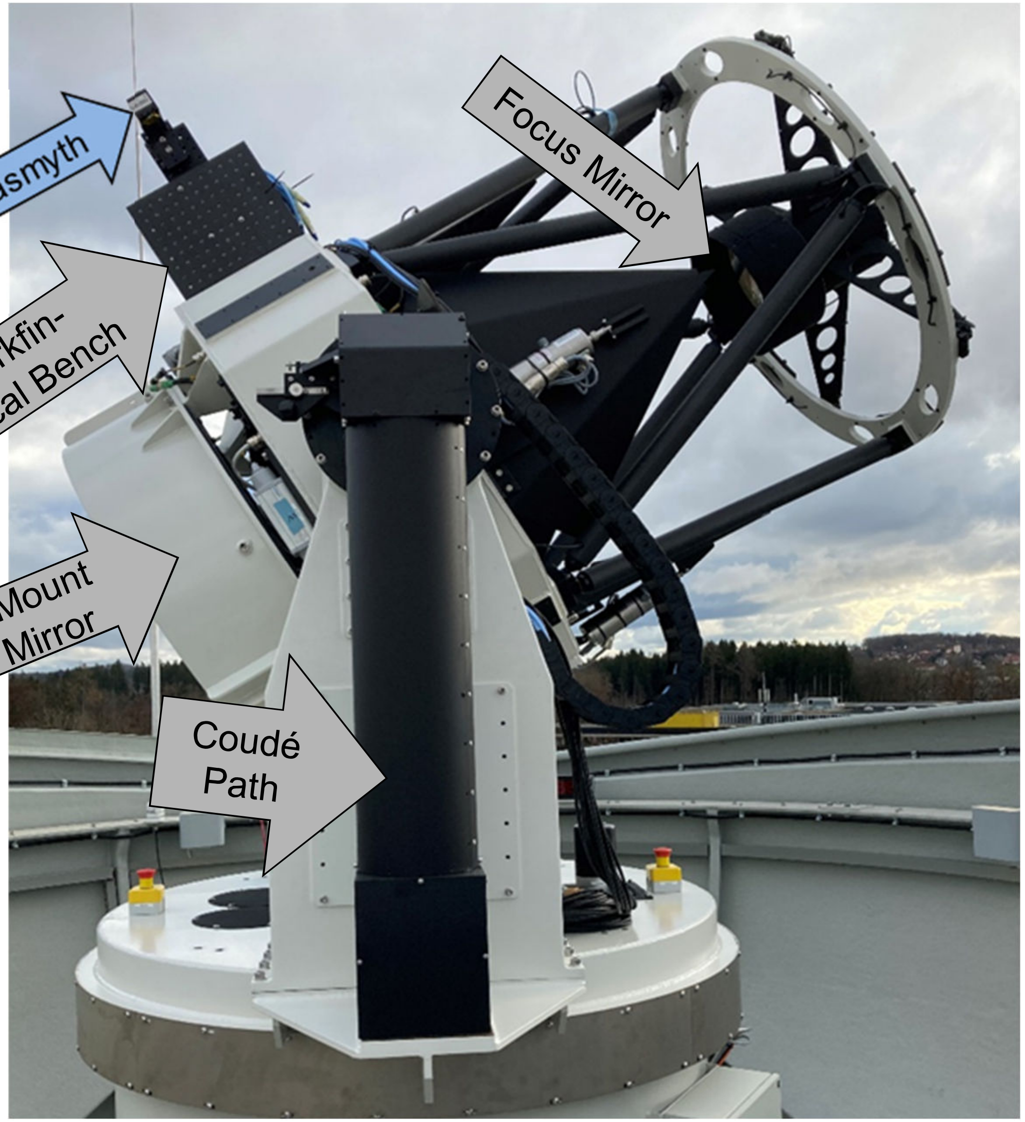




OGSOP-NG

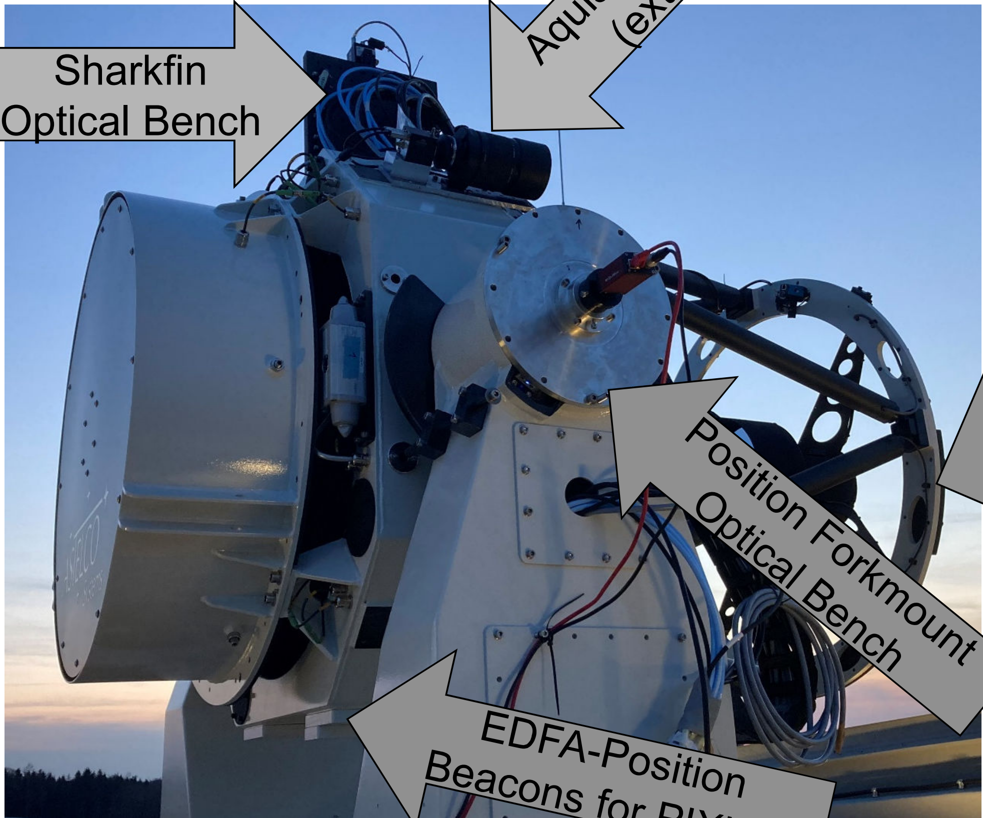


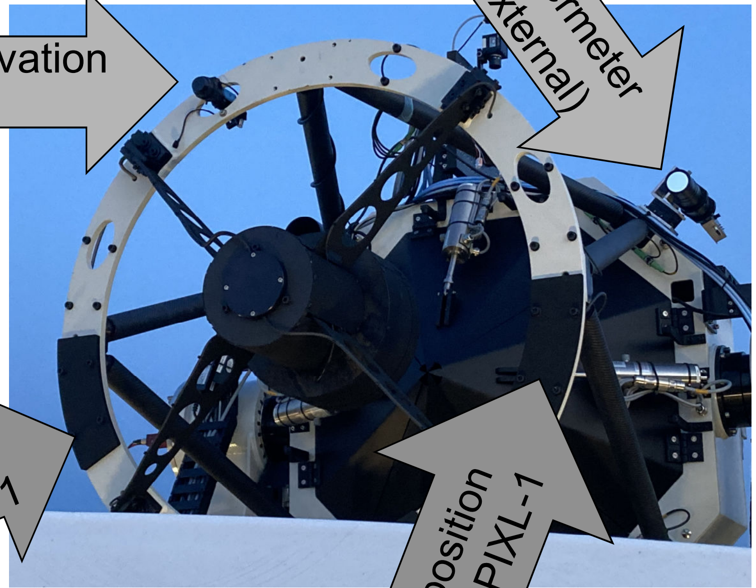
Focus Motor
80cm Mirror



IR-Cam Nasmyth
Sharkfin-
Optical Bench
Mirror Mount
Main Mirror
Coudé
Path
Focus Mirror

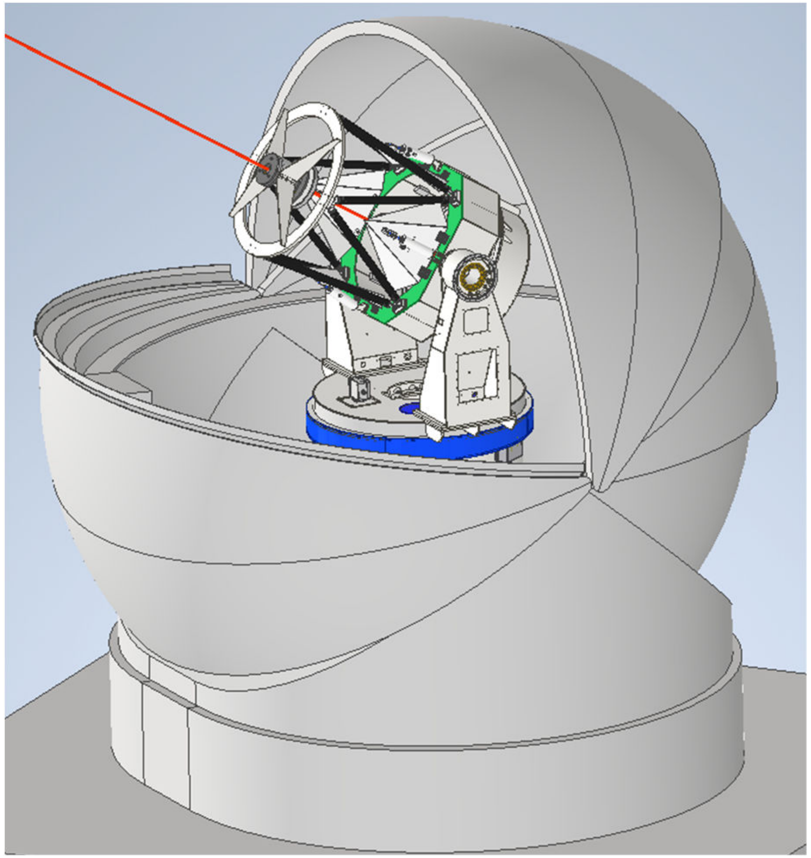
OGSOP-NG

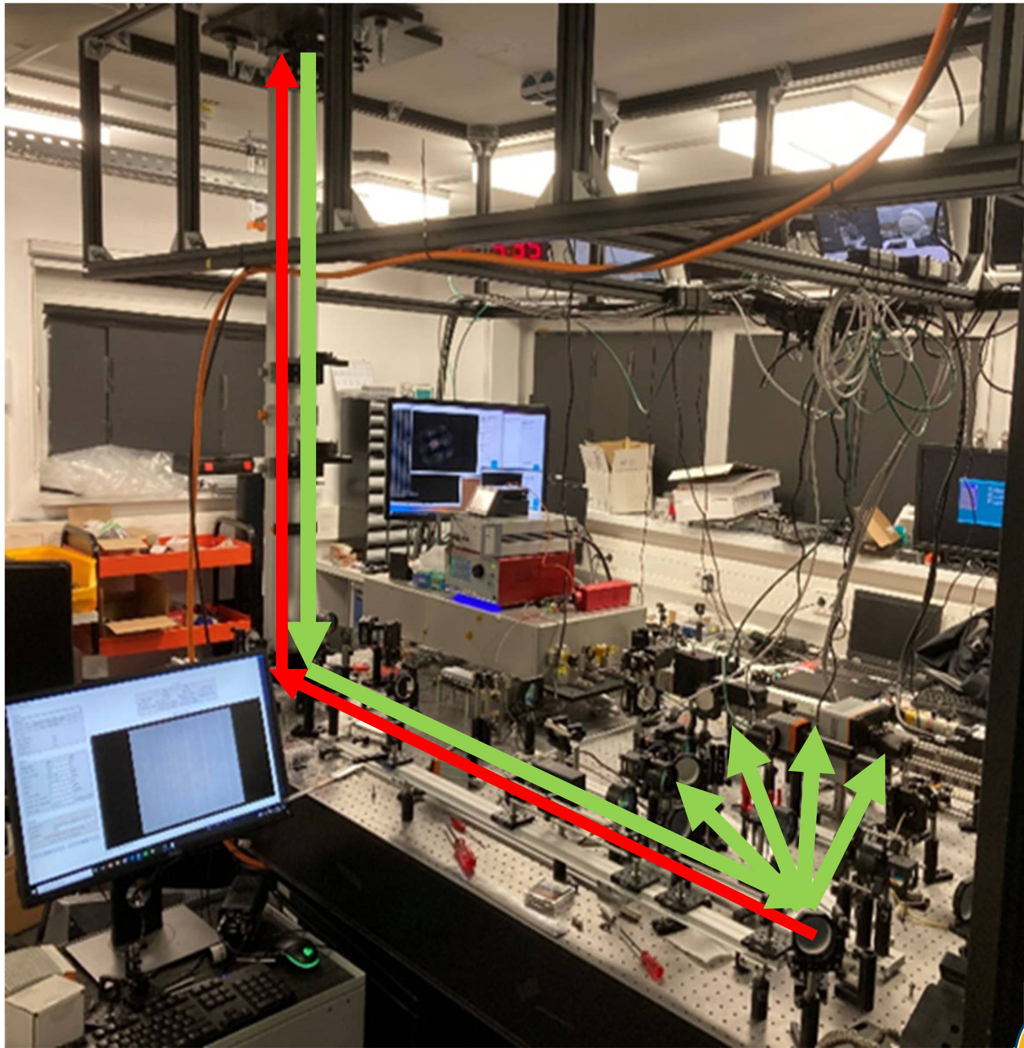




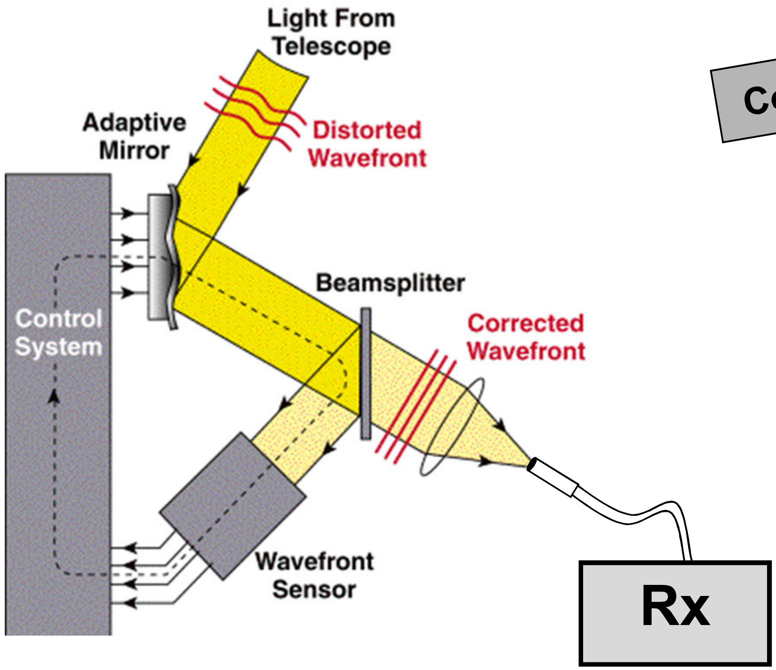
- **Sharkfin** optical Bench
  300mm X 300mm
- **Forkmount** Optical Bench
  500mm X 500mm
- Several smaller **Sideinstallation spaces**
  Parallel to telescope axis

Coudé-Bench

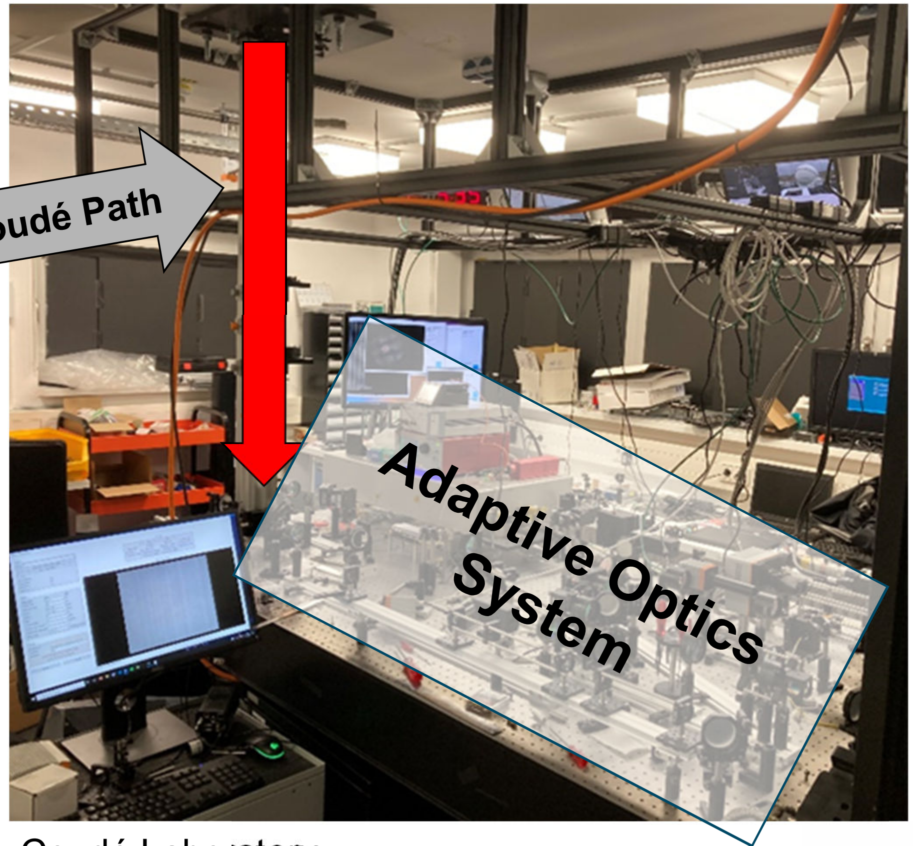




OGSOP – Coudé room with adaptive optics



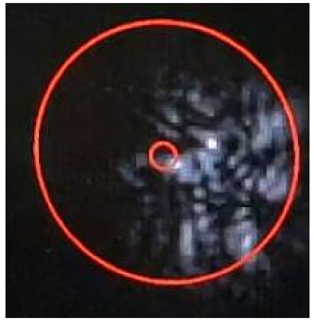
AO System Concept



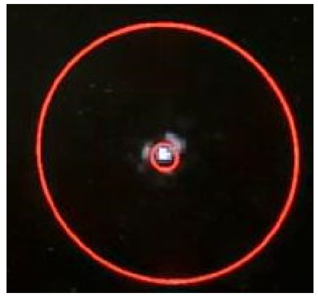
Coudé Laboratory

Meas. with Alphasat-LCT

Without AO

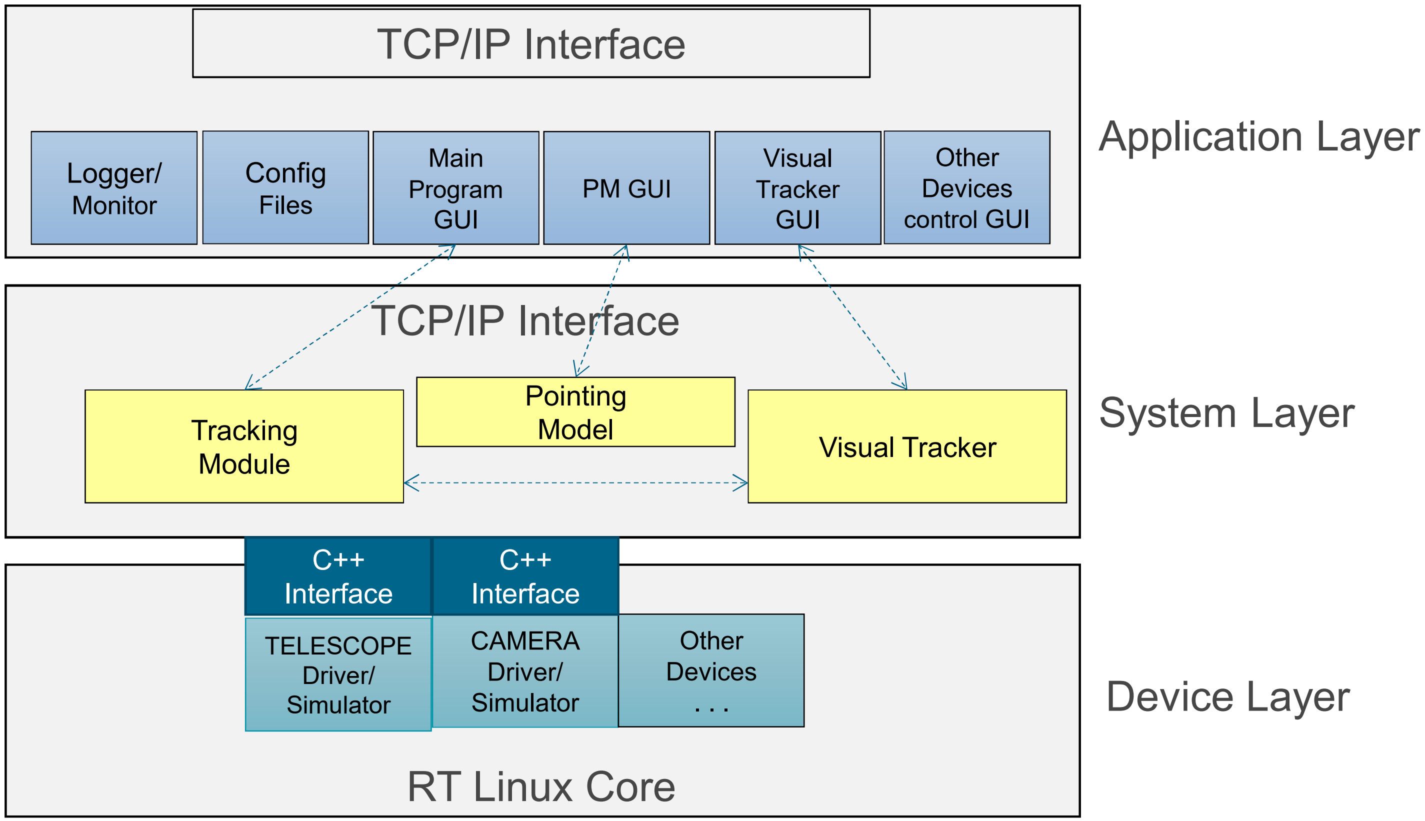


With AO

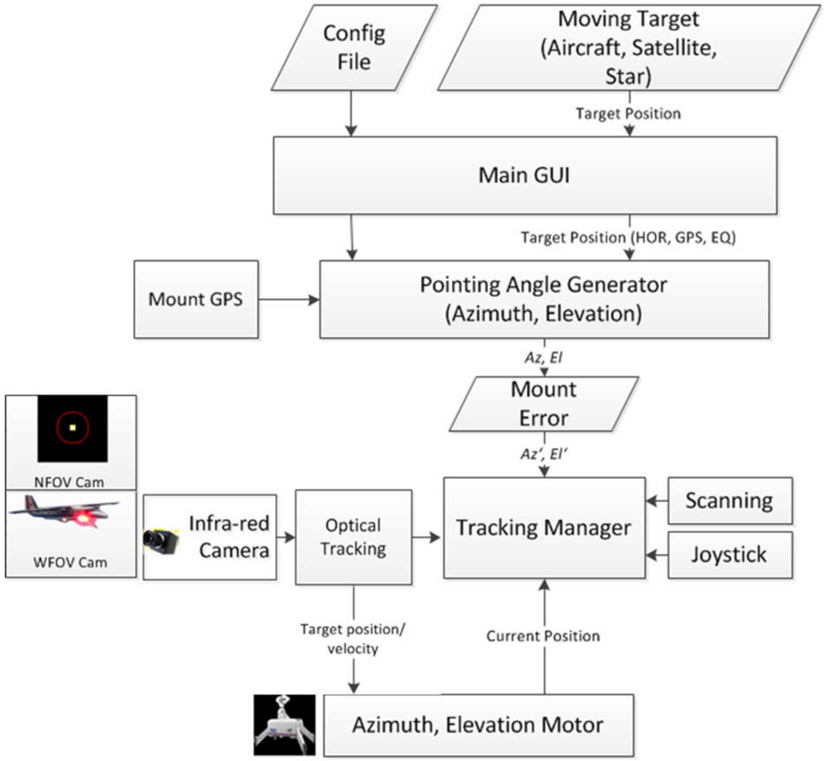


Gefördert durch
Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie

OGS Software Overview



Software Main Features



GPS Tracking

- GPS target (Dynamic or static)
- GPS extrapolation

Satellite Tracking

- Two line elements (TLE)
- Consolidated Prediction Format (CPF)
- Orbit Ephemeris Message (OEM)

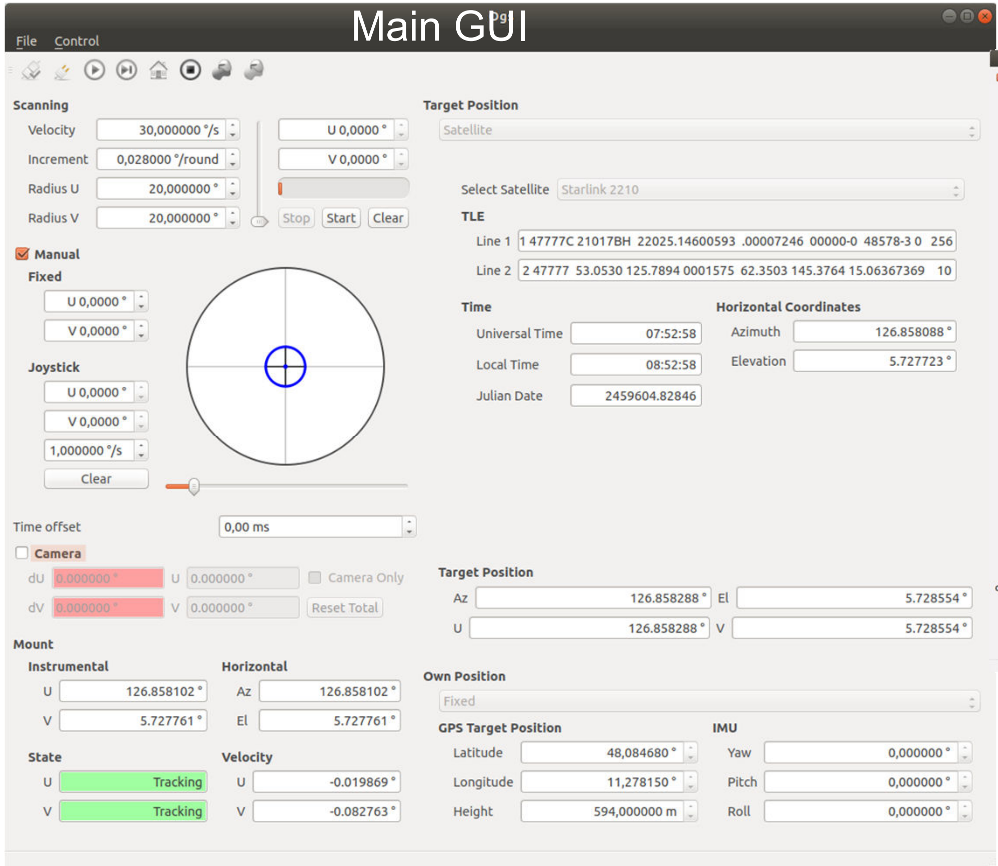
Star Tracking

- Star catalogue
- Right accension (RA), Declination (DEC)

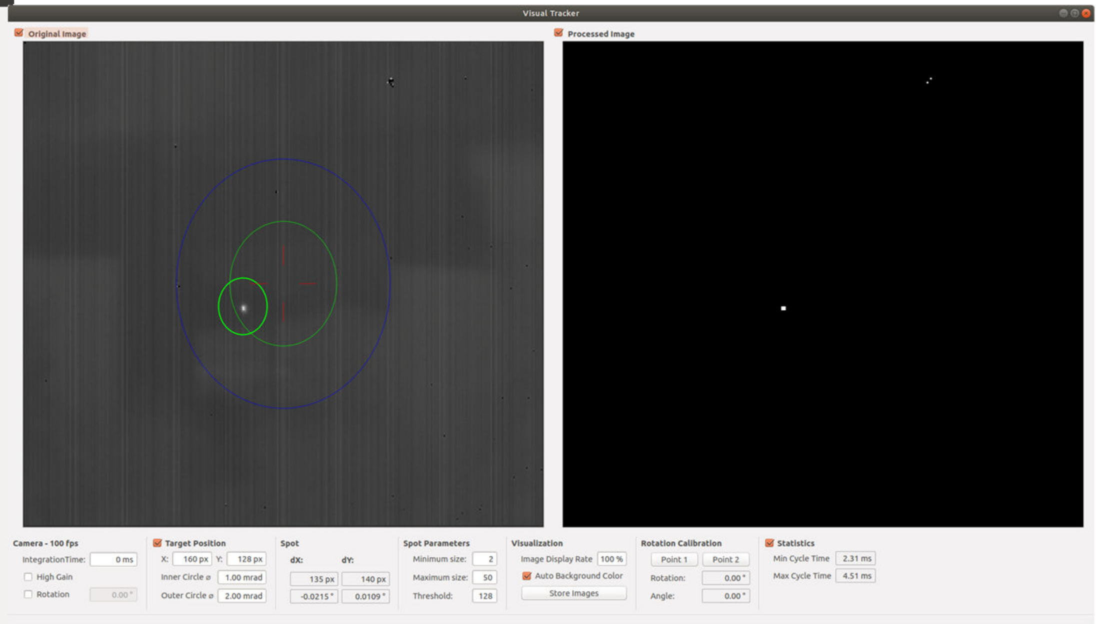
Open Loop Tracking

Optical Tracking

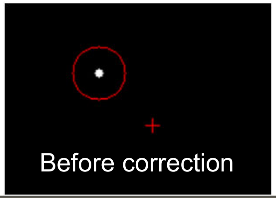
Software User Interface

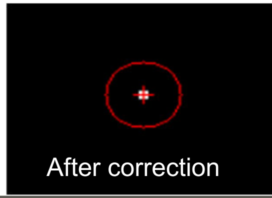


Visual Tracker



Calibration



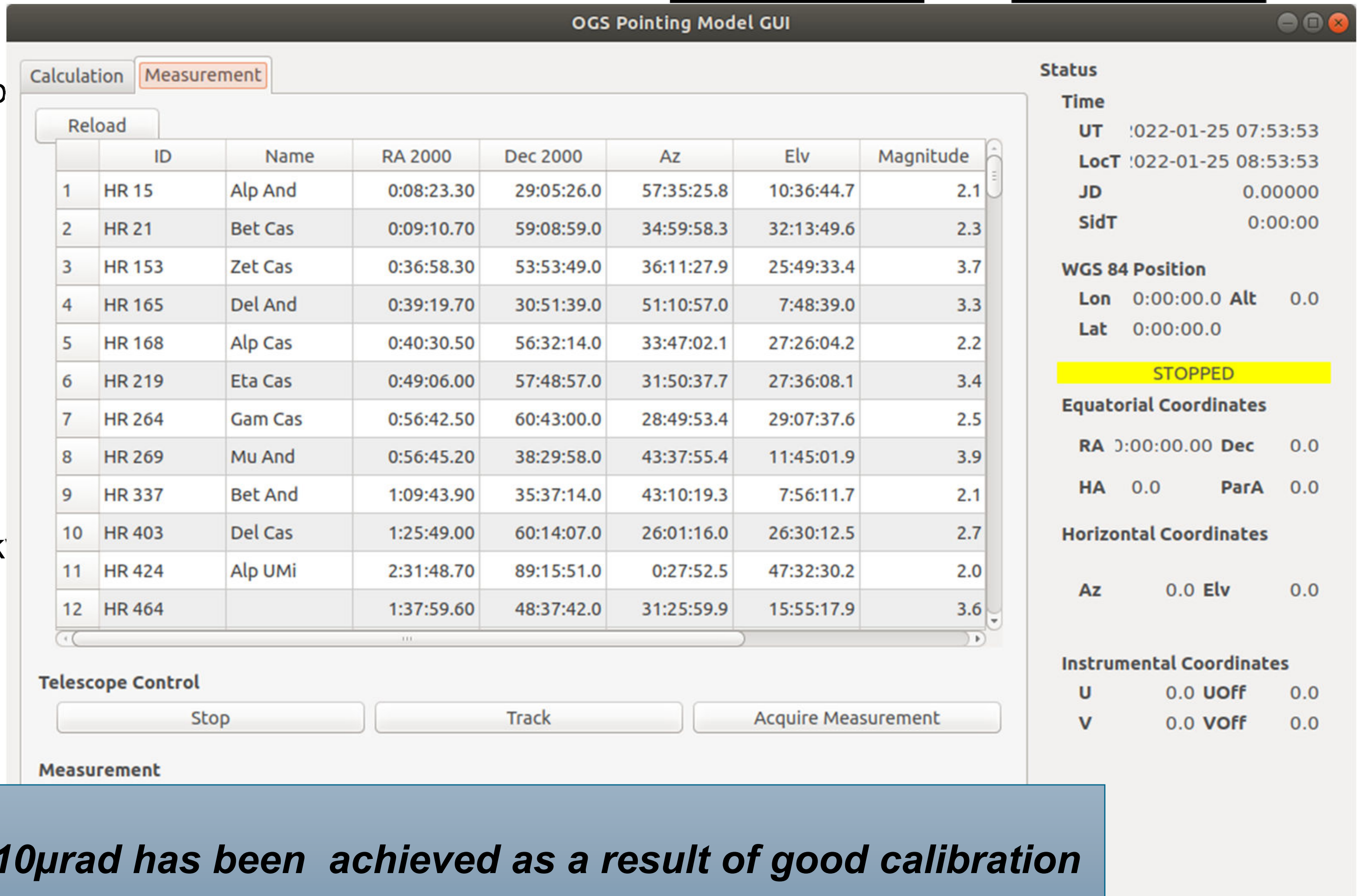


Pointing model is calculated with the help

- Simple Pointing Model
- Classic Pointing Model
- Extended Pointing Model

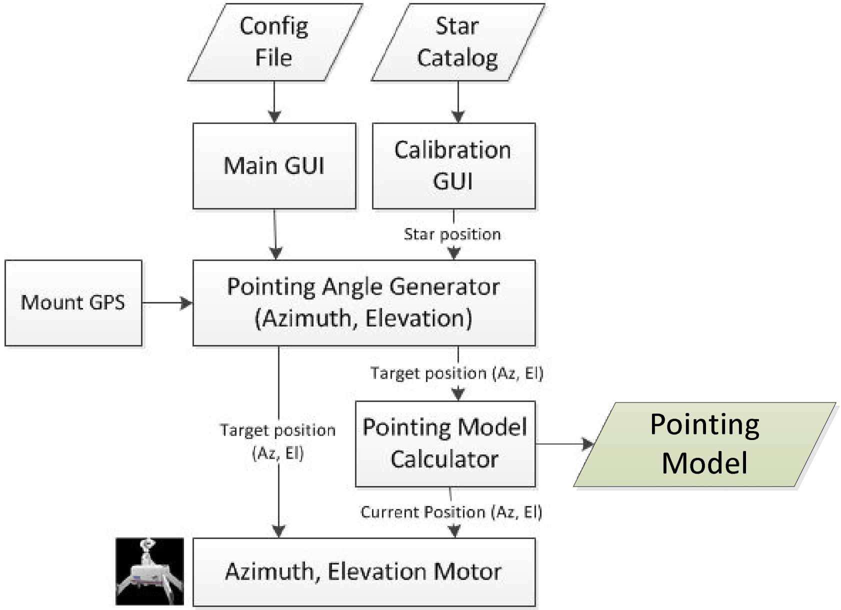
Requirement for good calibration:

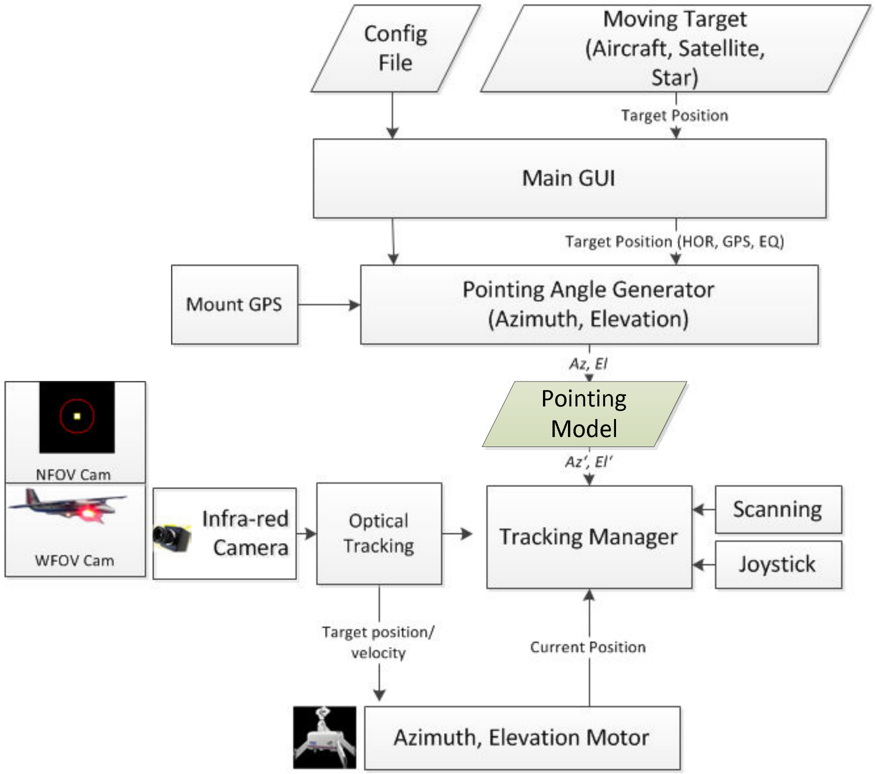
- Enough star measurements
- Uniform distribution of targets in the sk
- Accurate timing of the system



Tracking accuracy up to 10μrad has been achieved as a result of good calibration

Pointing Model



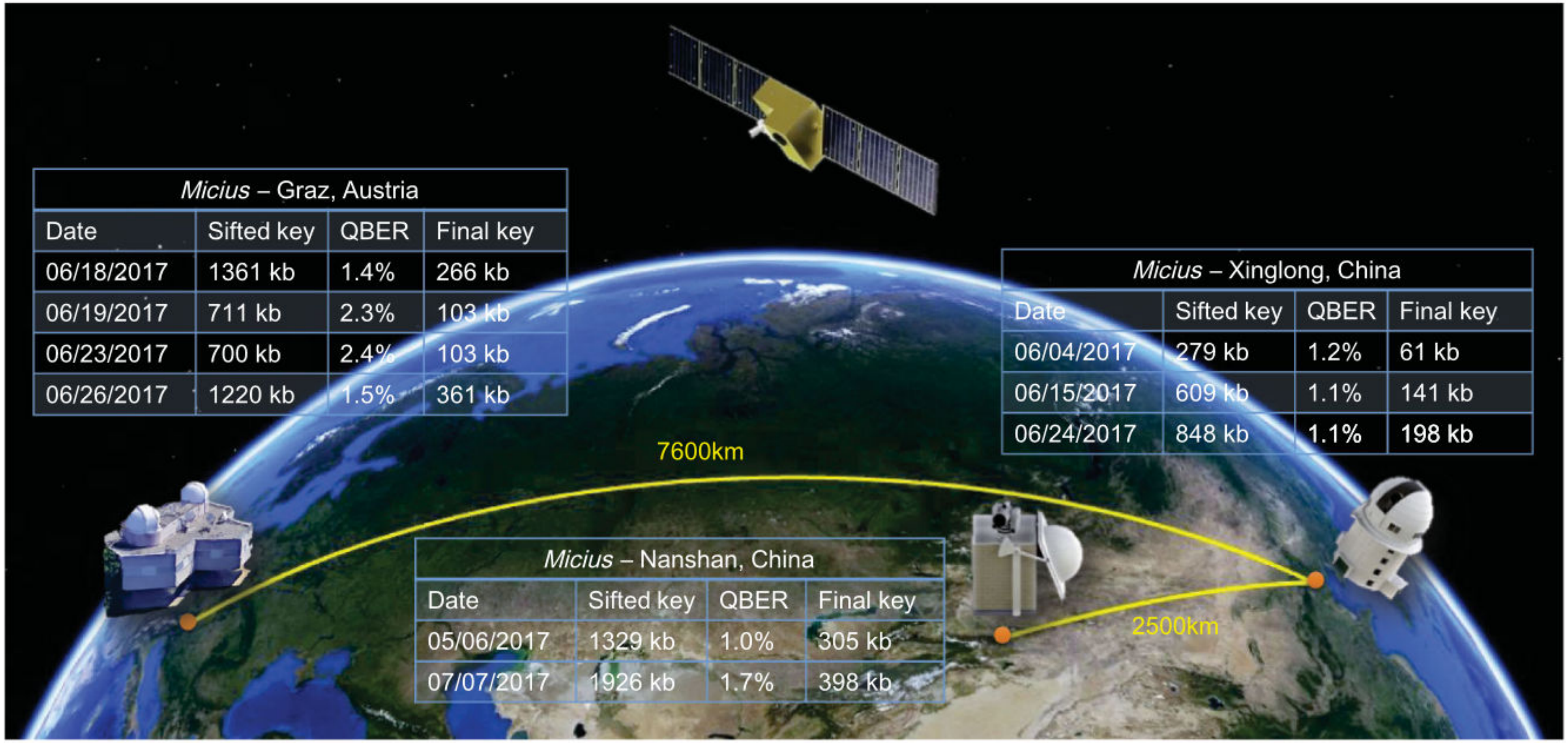


Satellite Based QKD

Why Satellite?
→ bridge large distances

- **FSO** and **QKD** enable worldwide **fast** and **secure** data communications
- Why **QKD over FSO**? → use of fiber is range limited → QKD using satellite node with QKD relay protocol
- Combination of FSO and QKD technology in one device → high synergies → lower costs
- QKD schemes: Distrete varibale (BB84) or continuous variable (and various others..)

BB84 Story
Satellite Experiment with Micius (since 2016)



Micius – Graz, Austria			
Date	Sifted key	QBER	Final key
06/18/2017	1361 kb	1.4%	266 kb
06/19/2017	711 kb	2.3%	103 kb
06/23/2017	700 kb	2.4%	103 kb
06/26/2017	1220 kb	1.5%	361 kb

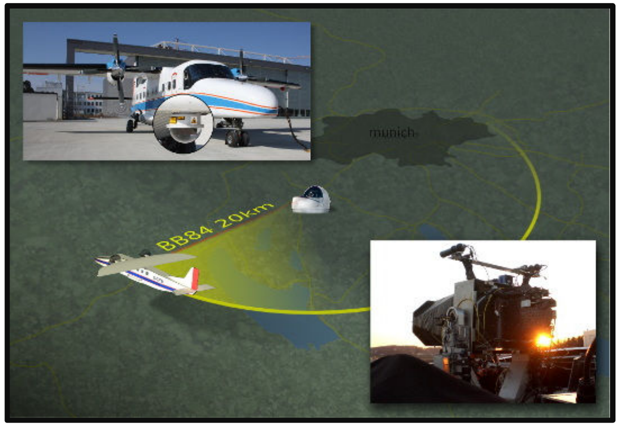
Micius – Xinglong, China			
Date	Sifted key	QBER	Final key
06/04/2017	279 kb	1.2%	61 kb
06/15/2017	609 kb	1.1%	141 kb
06/24/2017	848 kb	1.1%	198 kb

Micius – Nanshan, China			
Date	Sifted key	QBER	Final key
05/06/2017	1329 kb	1.0%	305 kb
07/07/2017	1926 kb	1.7%	398 kb

Liao et al. Satellite-Relayed Intercontinental Quantum Network Phys. Rev. Lett., American Physical Society, 2018, 120, 030501

QKD Projects

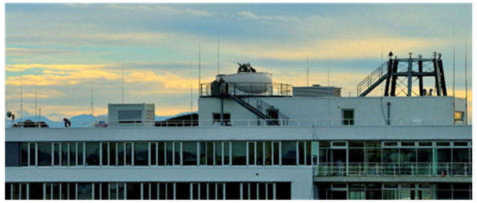
Aircraft QKD



QuKommIn

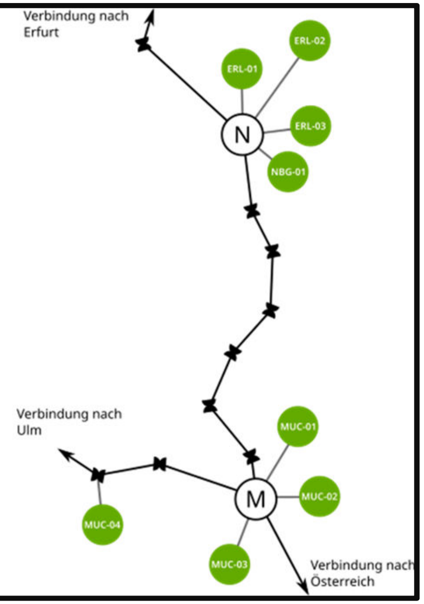
Funkturm FFB

IKN roof with OGS

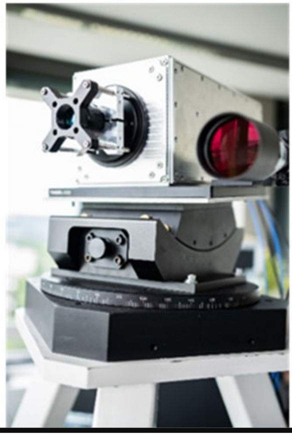


Quantenlabor

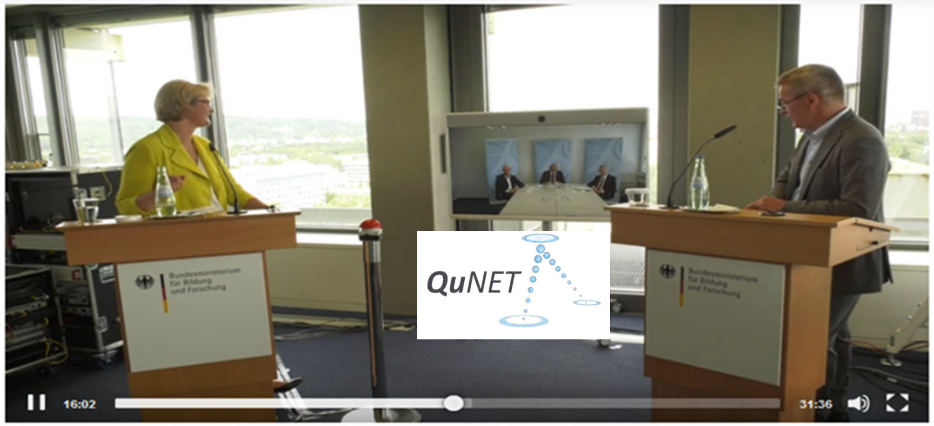
Optiklabor



Tx/Rx pair for satellite QKD Demo



Quantum secure video conference BMBF/BSI



Further Reading and Lectures:

- S.G. Lambert, W.L. Casey, "Laser Communications in Space", Artech House, 1995
- B.J. Klein, J.J. Degnan, „Optical Antenna Gain. 1: Transmitting Antennas“, Applied Optics Vol. 13(9), 1974
- W.K. Pratt, “Laser Communication Systems“, Wiley publishing, 1969
- L.C. Andrews, R.L. Phillips, ”Laser beam propagation through random media”, SPIE-Press 2005
- D. Giggenbach, F. Moll, C. Fuchs, C. Schmidt, A. Shrestha, “*Optical on–off keying data links for low Earth orbit downlink applications“,* Chapter in ‘Satellite Communications in the 5G Era’, Editors S. K. Sharma, S. Chatzinotas, P-D Arapoglou, IET TELECOMMUNICATIONS SERIES, 2018
- D. Giggenbach, F. Moll, *„Scintillation Loss in Optical Low Earth Orbit Data Downlinks with Avalanche Photodiode Receivers“,* IEEE-Xplore, Int. Conf. on Space Optical Systems 2017 (ICSOS), 2017
- D. Giggenbach, A. Shrestha, “Atmospheric Absorption and Scattering Impact on Optical Satellite-Ground Links" Int. Jnl. of Satellite Communications And Networking, 2021

- *S. Scalise, T. de Cola, „Satellite Communications“, yearly lecture at TUM, Winter Semester*
- *M. T. Knopp, „Optical Communications“, yearly lecture at UniBW-Munich*
- *D. Giggenbach, N. Hanik, C. Fuchs, R. Mata-Calvo, “Optische Kommunikation für Satelliten und Flugzeuge“, yearly course at Carl-Cranz-Gesellschaft CCG, Wessling*

Impressum

Topic:	**Optical Satellite Links at DLR** Overview about the Optical Satellite Links department at DLR‘s Institute of Communications and Navigation
Date:	10.09.2024
Authors:	Amita Shrestha (amita.shrestha@dlr.de) et. Al.
Institute:	Institute of Communications and Navigation
Pic.-credits:	DLR

DLR