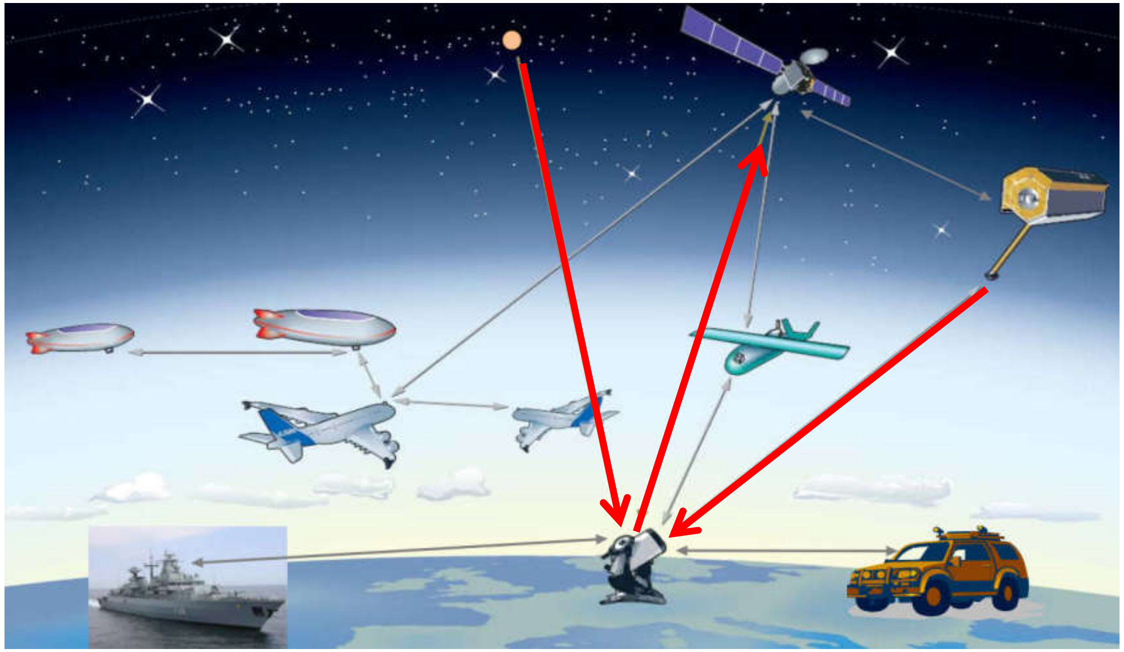
Optical Technologies for very high throughput satellite communications

2019 Oberpfaffenhofen Workshop on High Throughput Coding

Institute of communications and navigation
Ramon Mata Calvo

DLR

Global Connectivity with optical free-space communications



- Data retrieval from LEO satellites
  - Direct-downlinks
- Communications in Emergency situations
  - Aeronautical links
- Global Connectivity with GEO satellites
  - Optical high throughput links
- Exploration
  - Deep-Space communications
- Atmospheric Turbulence
  - Research through theory, simulations and demonstrations
  - Compensation methods: adaptive optics

Global connectivity with GEO satellites

- Motivation: Global Networking

- **Broadband Internet** everywhere
    - User access: internet with 50 Mbit/s and more
    - Data transport: optical infrastructure for space

- Internet availability for **Industry 4.0**
    - Towards a **versatile industry**: *Smart Service World*
    - **Adaptive Logistic**: world-wide networking of mobile sensors
    - Networking for a **cloud-based** business model
    - Requirements on security, availability and quality of service (reliability, data-rate, low latency requires LEO or HAPS constellations)

- Gaps in broadband access: e.g. 28% in European rural areas
    - Global provision of broadband connectivity using satellite communications

Motivation: satellite optical communications

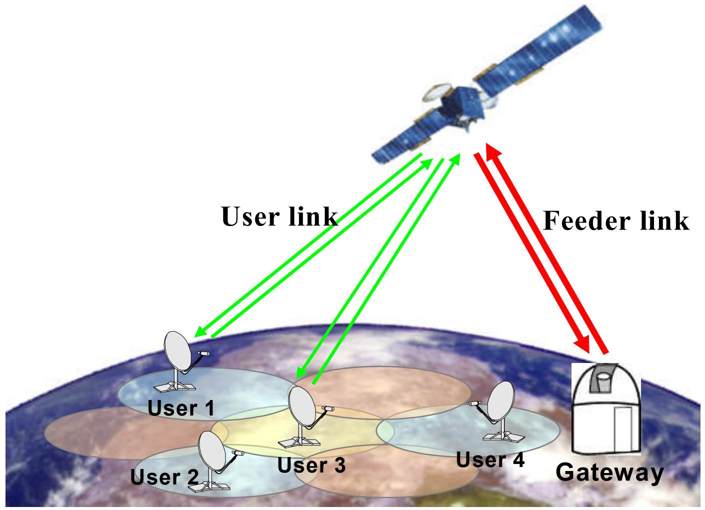
- Few GEO satellites with worldwide coverage

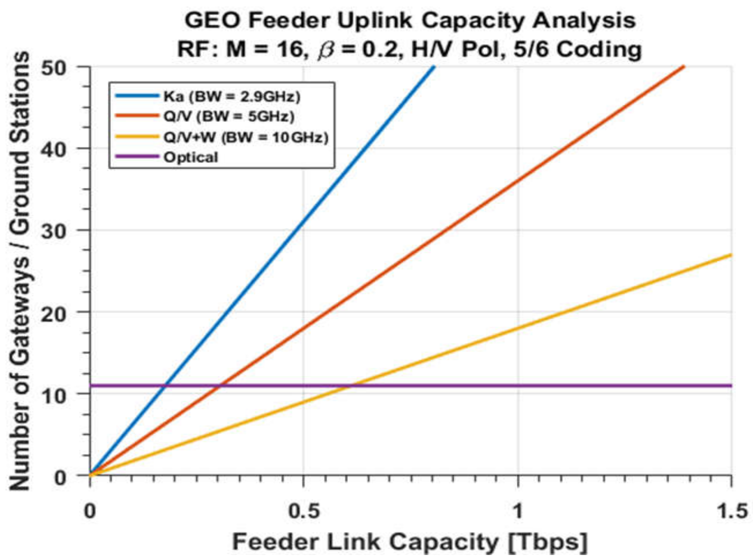
- Currently: Ka-Band (user + feeder)
  - Ka-Sat (70 Gbps), ViaSat-1 (140 Gbps), ViaSat-2 (350 Gbps)

- GEO satellite communications
  - RF user-link with 50Mbit/s
  - Feeder Links with Terabits/s throughput
- Number of required gateways increases linearly with throughput

- **Approach: optical feeder link**
  - every gateway provides full capacity
  - DWDM Technology from fiber communication

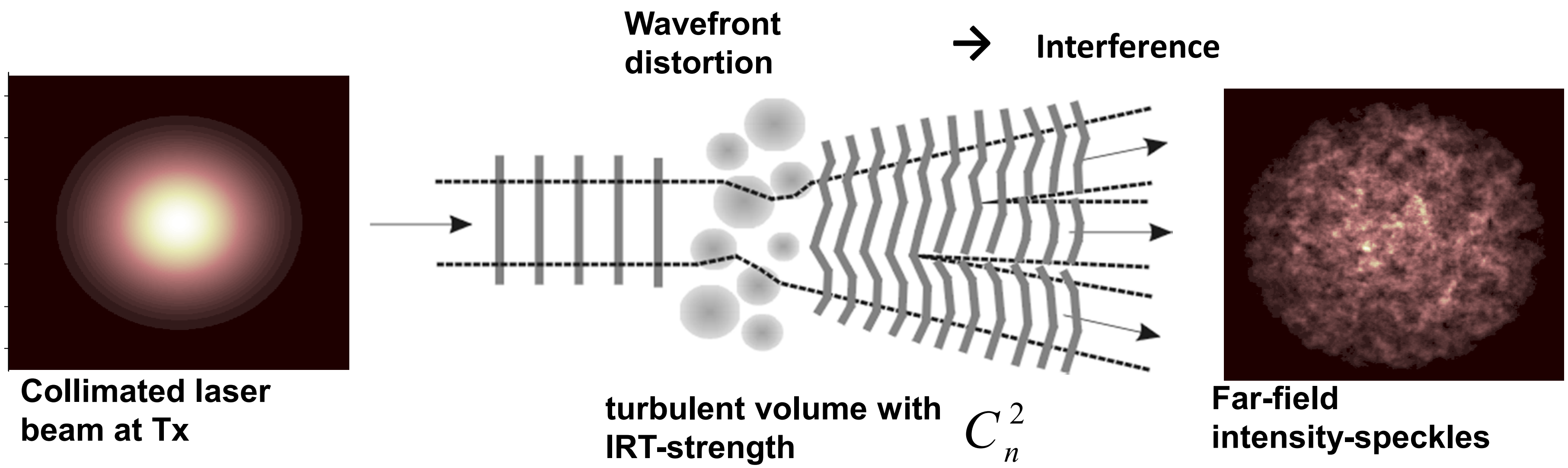
- **Optical frequencies**: several **THz** of bandwidth and **no-regulation**





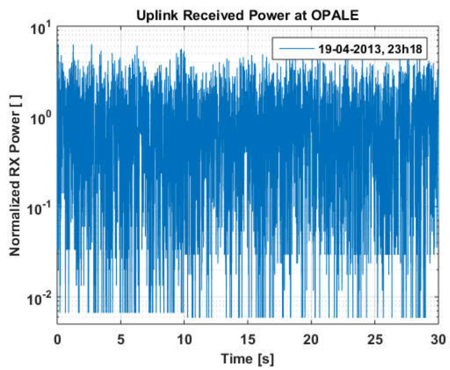
Optical Communications: Atmospheric Channel

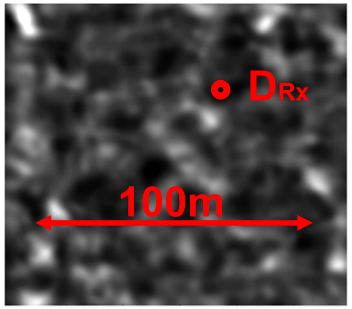
- Received signal fluctuations due to atmospheric turbulence
  - Scintillation: phase-distortions lead to Intensity fluctuations
  - Beam wander: uplink pointing errors
- Fading duration between 1 and 10 ms
  - 1 Gbit is lost each 1 ms of fading when transmitting 1 Terabit/s



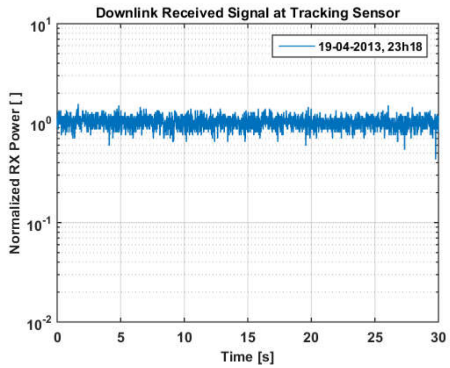
Atmospheric channel

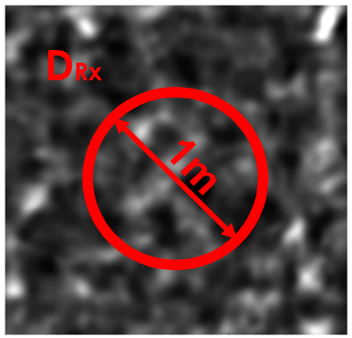
- SAT
  - Strong fluctuation
  - Almost perfect fibre coupling

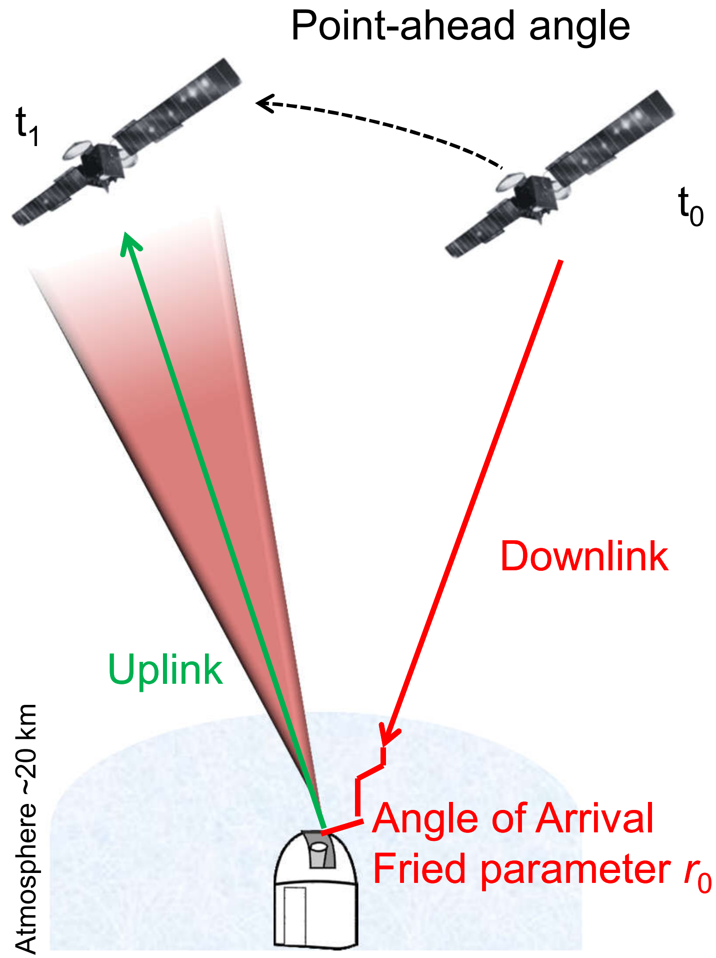




- Ground station
  - Aperture averaging
  - More stable signal







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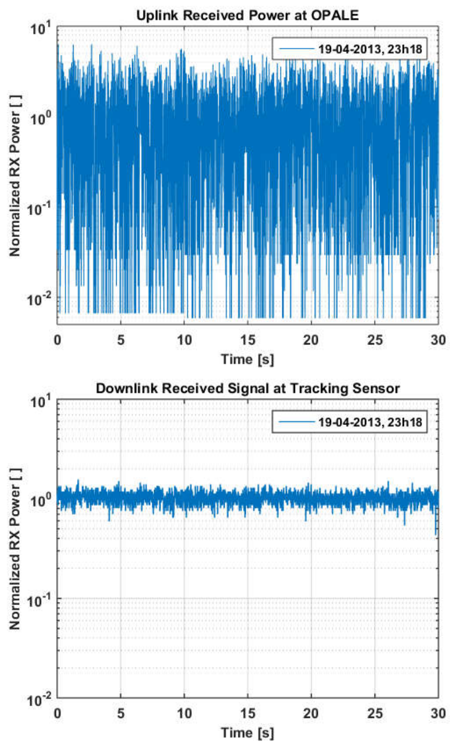
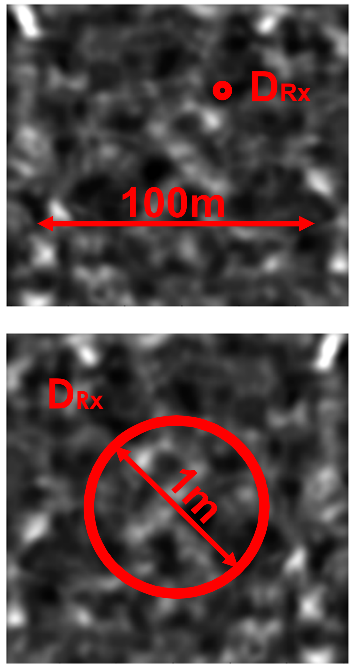
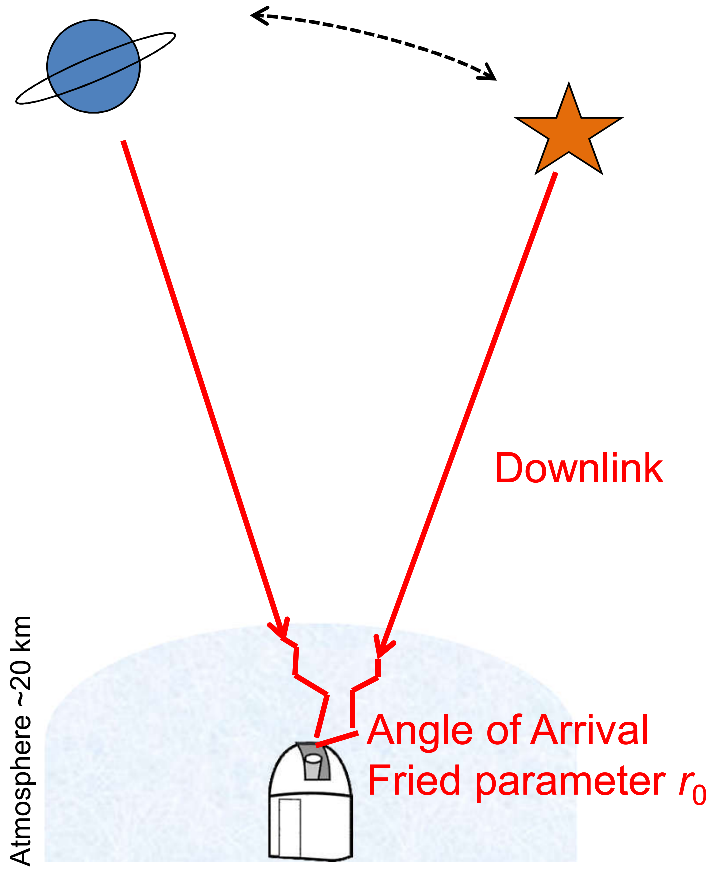




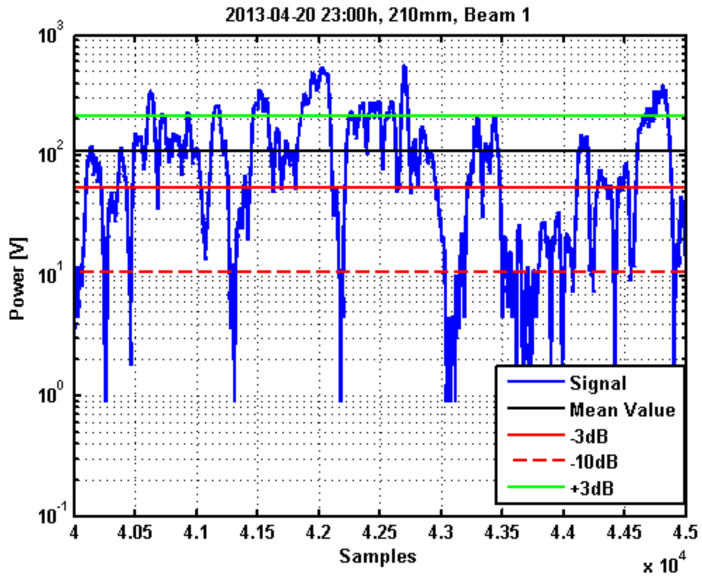


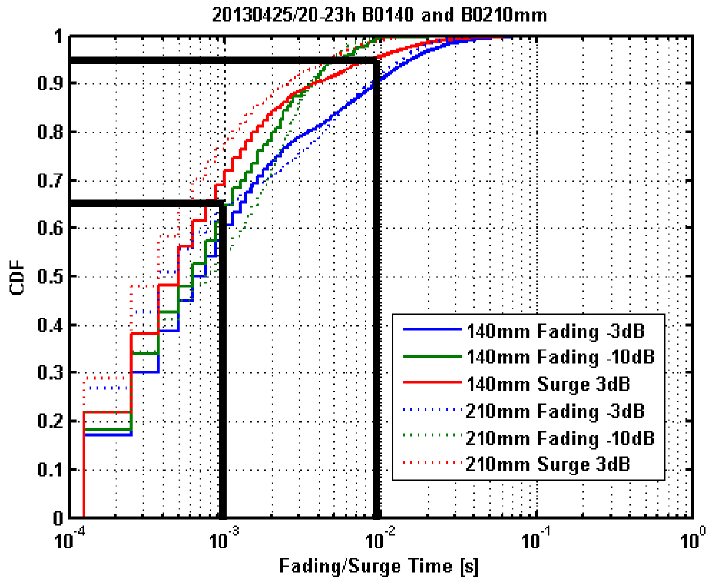
- Ground station
  - Aperture averaging
  - More stable signal

Uplink channel

- # Fades increase with small divergences
- TX Diversity decreases deep fades
    - More fades at -3dB but shorter
    - More surges at +3dB

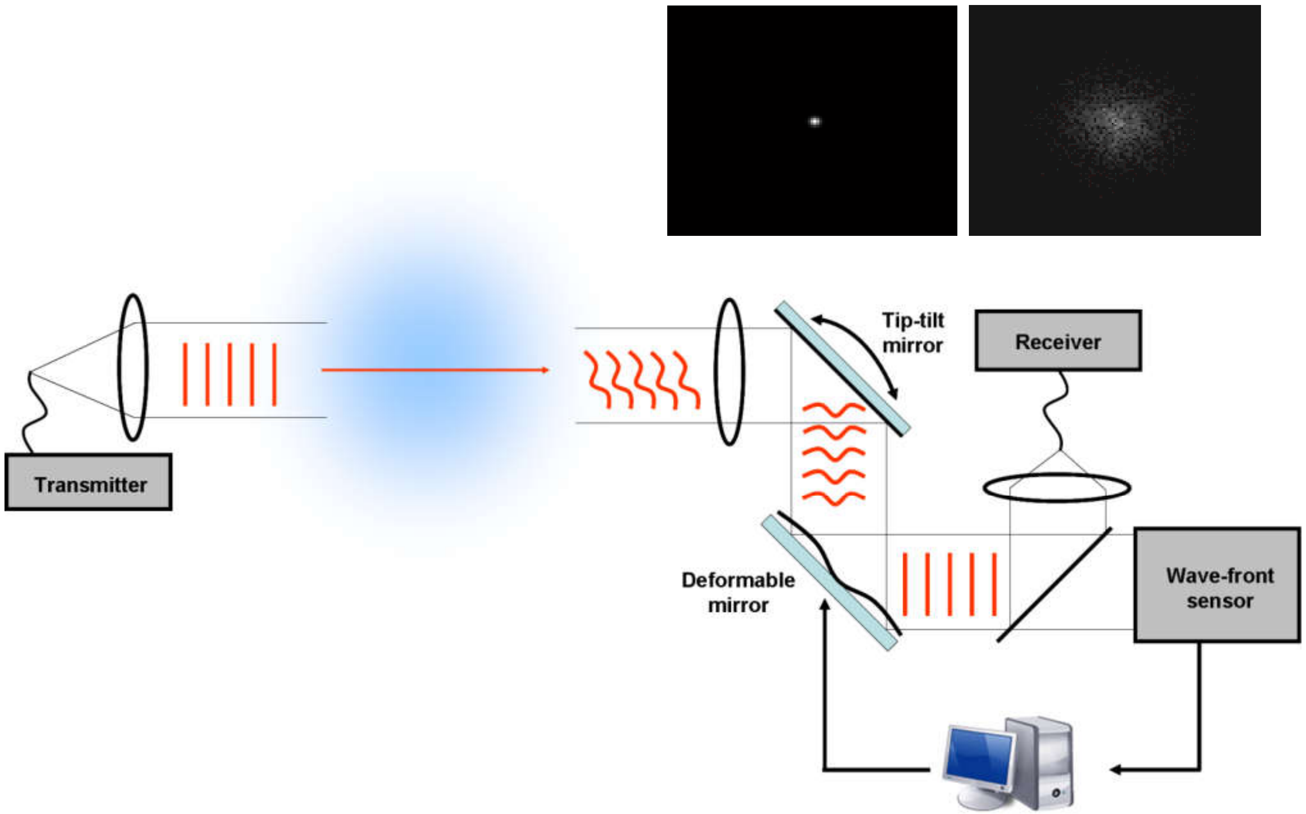
	210 mm	140 mm
Fade/Surge Time	20 April-23h B0210-1	25 April-23h B0140-1
Mean -3dB	10.3 ms	10.6 ms
#Fades -3dB/s	45	29
Mean -10dB	2.9 ms	3.9 ms
#Fades -10dB/s	46	10
Mean +3dB	7.2 ms	7.2 ms
#Surges +3dB	22	15.5





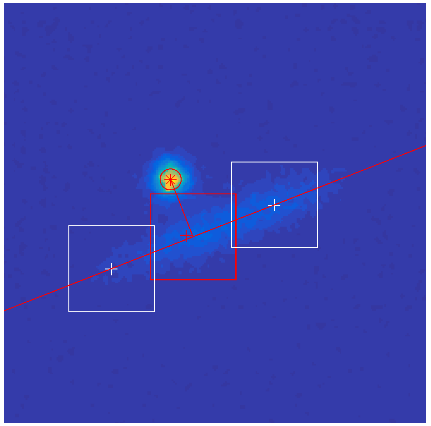
Adaptive optics for phase-correction

- Technology from astronomy
- Phase distortions
  - Coupling losses
- Stronger turbulence conditions
  - Communications scenario
- Wave-front estimation
- Control-loop approaches
- Pre-distortion for uplink



Laser guide stars for communications

- Laser at 589 nm creates an „artificial star“
    - Sodium layer of the atmosphere at ~90 km
- Technique used in astronomy for adaptive optics
    - Imaging of astronomical objects
- Reference for the uplink direction
    - Use of adaptive optics in pre-correction
- „Tilt“ cannot be directly measured
    - Off-axis telescope
    - Challenge also for astronomy
- Collaboration with ESO, Durham University, INAF



Link budget comparison

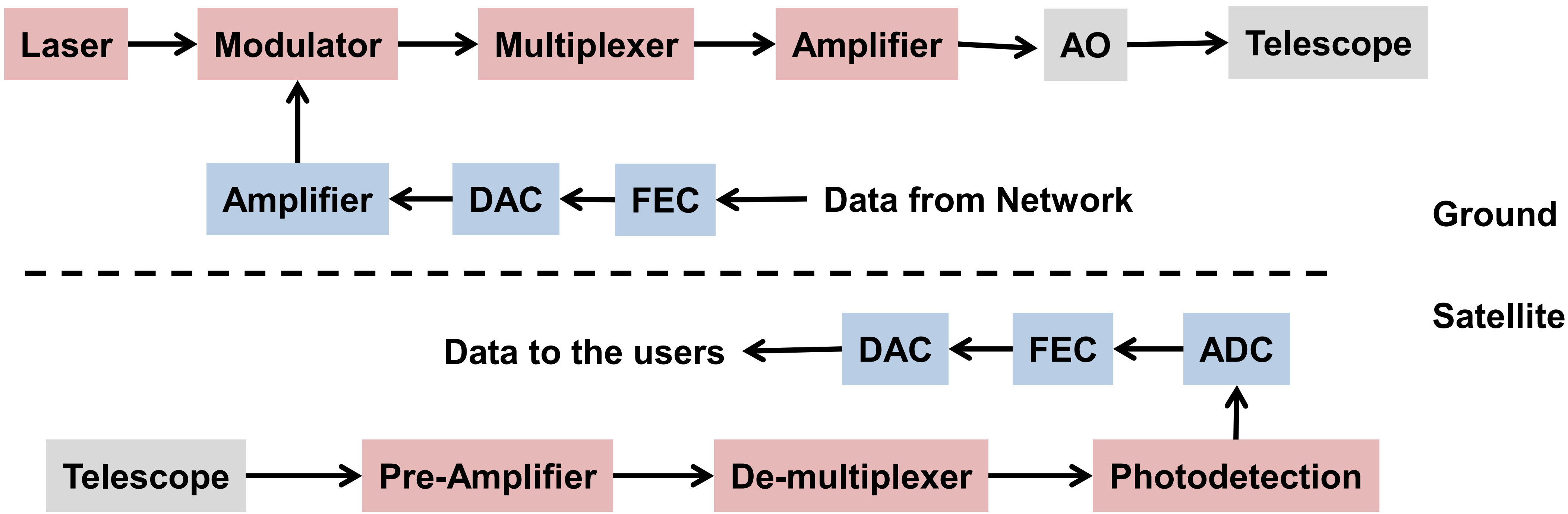
- Advantage in distance is lost due to pointing stability
- ~2 dB margin gain for LEO compared to GEO

- It is assumed
  - Bigger telescopes for MEO and GEO
  - TX divergence is optimized for the transmitted power

Link budget	LEO	MEO	GEO
Pointing strategy	Open-loop	Open-loop / DL-tracking	DL-Tracking
Spacecraft altitude [km]	1000.0	20000.0	36000.0
Elevation [º]	30.0	30.0	30.0
Transmitted divergence (e-2-radius) [µrad]	30.1	30.1 / 14.0	6.0
Beam wander or pointing jitter [µrad]	11.2	11.2 / 4.9	1.7
Ground Antenna Gain [dB]	99.5	99.5 / 106.1	113.4
Free-space loss [dB]	-262.8	-285.3	-290.0
Margin w.r.t. GEO [dB]	*+27.2*	*+4.7*	*0*
Mean pointing-loss [dB]	-4.8	-4.8 / -4.3	-2.8
Scintillation margin for 99.99% availability	-6.6	-6.6 / -5.6	-3.7
Atmospheric attenuation + Cloud Margin	-2.0	-2.0	-2.0
Satellite Rx Antenna [cm]	15	30	30
Satellite Rx Antenna Gain [dB]	109.7	115.7	115.7
Margin w.r.t. GEO [dB]	*-6.0*	*0*	*0*
Tx and Rx efficiency	-4.0	-4.0	-4.0
Additional Margin (ancillary losses)	-2.0	-2.0	-2.0
Total Link loss [dB]	-73.1	-89.5 / -81.3	-75.3
Margin w.r.t. GEO [dB]	*+2.3*	*-14.2 / -6.0*	*0*

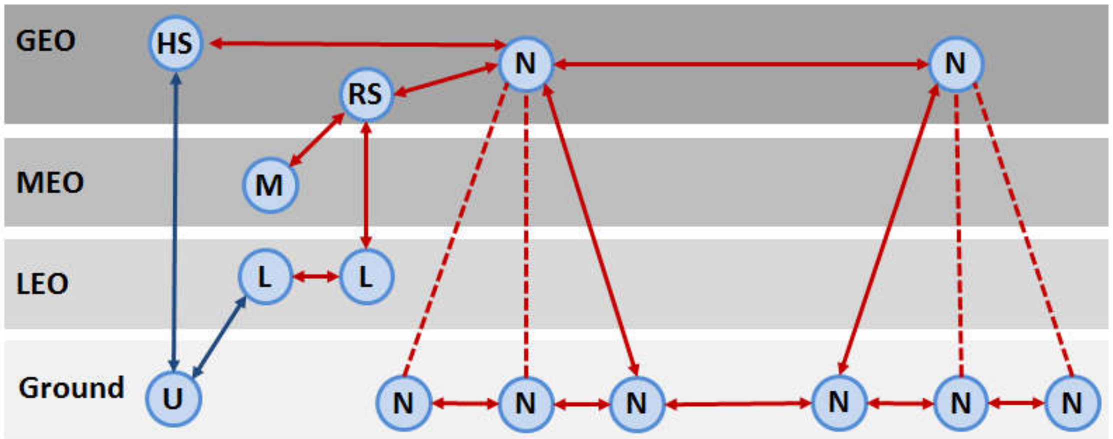
Uplink communications architecture

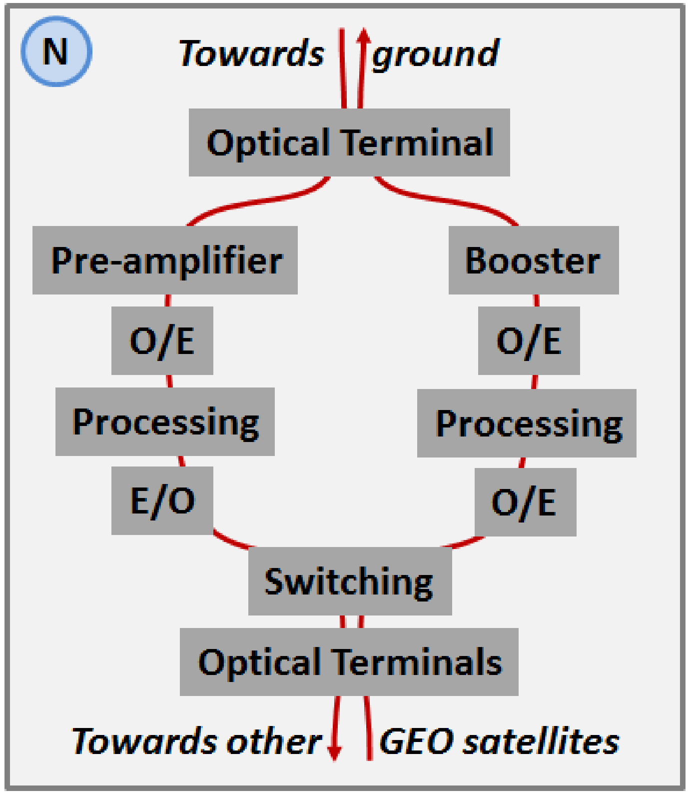
- Satellite has a limited resources in power, mass and heat dissipation.
  - e.g. Alphabus offers 12-14kW payload power



Very high throughput satellite communications

- Optical Satellite Network, considering node connections between GEO and ground
- Dedicated platforms vs. application oriented
  - Higher number of platforms, smaller
- GEO as monitoring for the other orbits: higher visibility for traffic management.





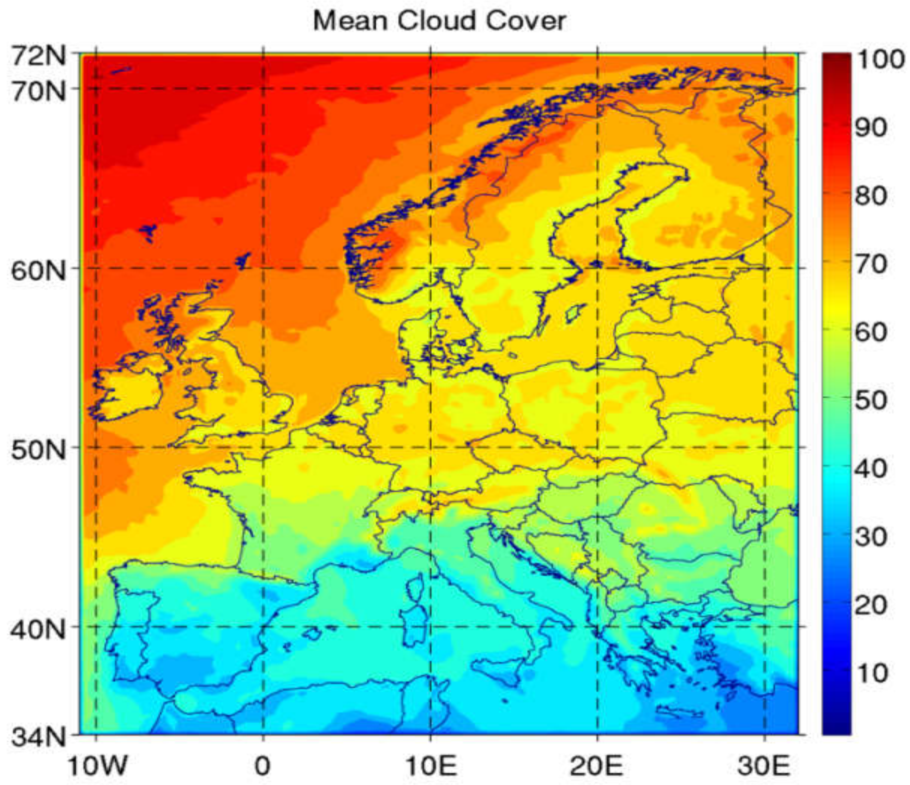
Technology Challenges

- Space-qualification for satellite usage
  - DWDM technology, amplifiers, receivers

- Satellite on-board processing
  - **Communications architecture**
  - Terabit/s throughput on-board processing

- Multiple Terabit/s switching between gateways
  - Network of gateways: ~10 in Europe for 99,9% availability to avoid cloud coverage

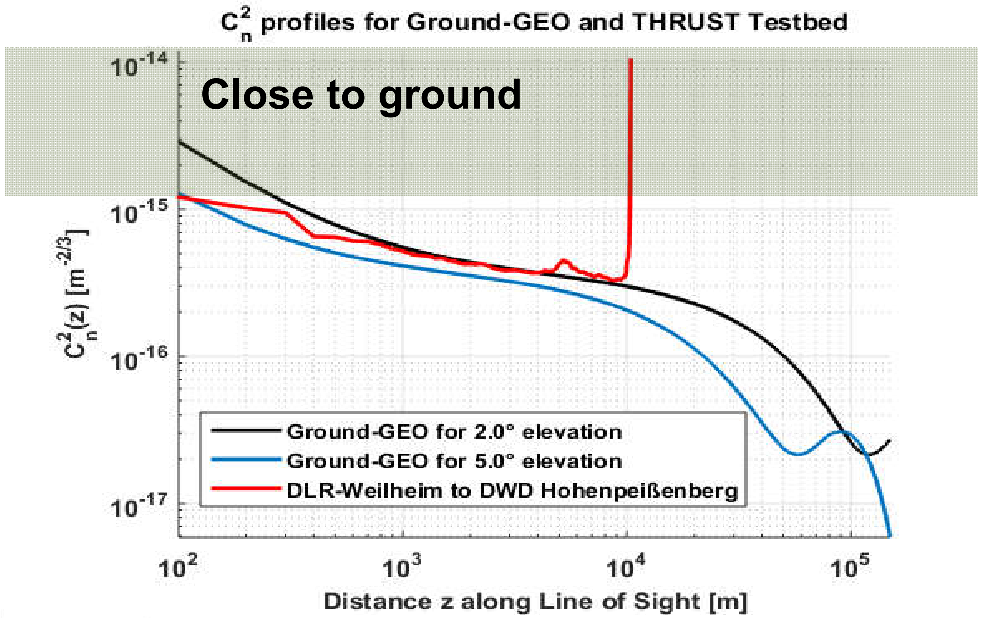
- Atmospheric turbulence
  - **Mitigation of channel impairments**
  - **Optimization of the feeder-link**

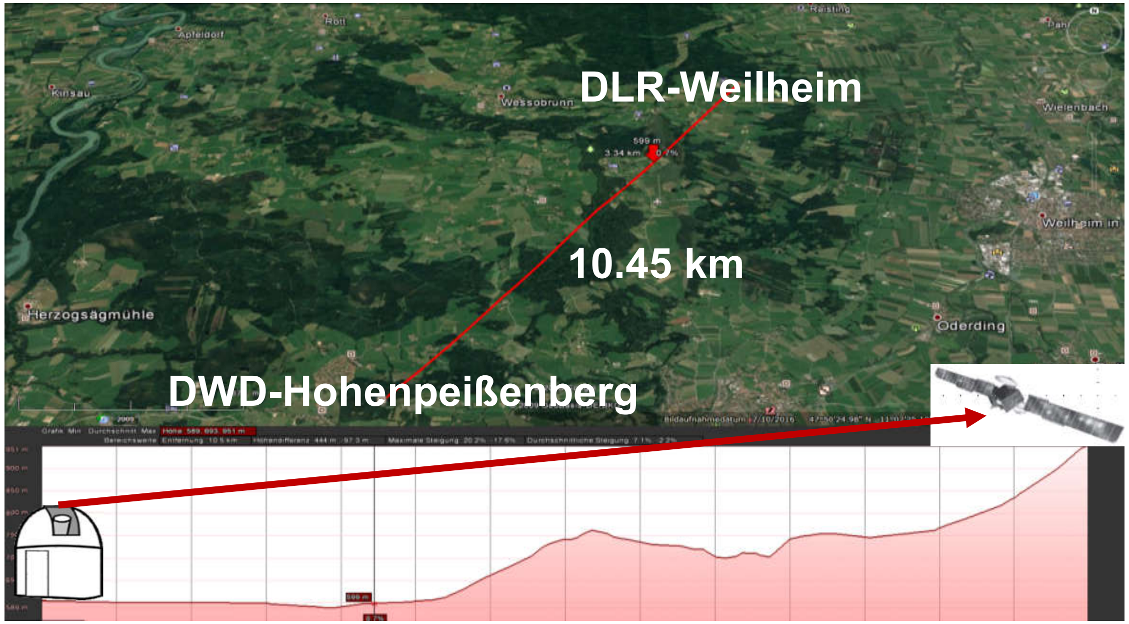


First step: Demonstrate DWDM Technology in relevant environment

Free-space technology demonstration

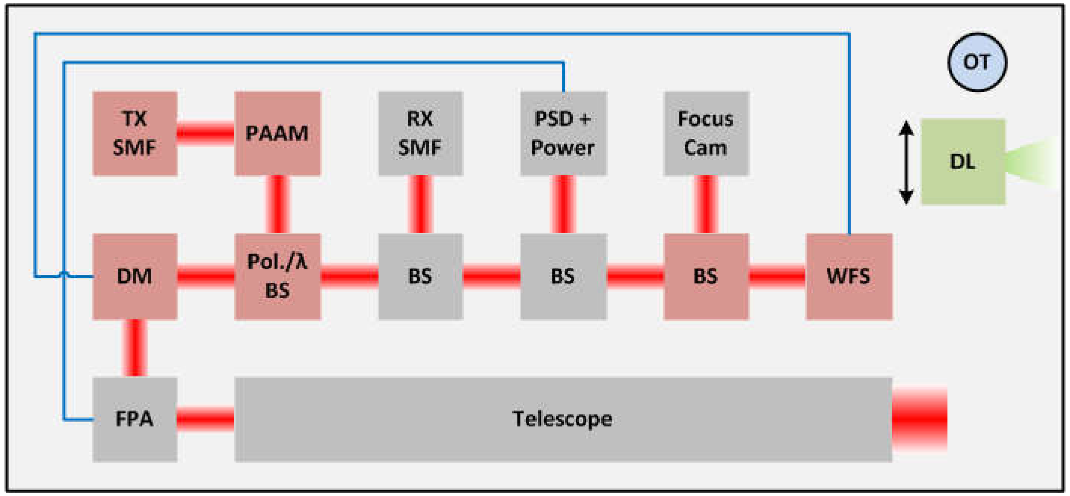
- Ground link emulating the GEO feeder link
- Measurement of the communications performance with strong fluctuations
- Development of two terminals representing a satellite and a ground station
  - Single-mode fiber coupling

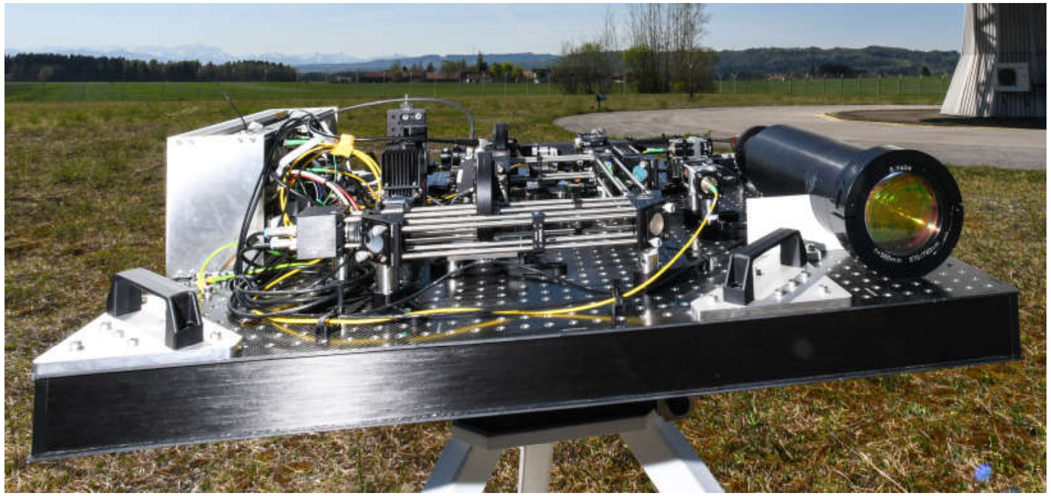




The optical terminals

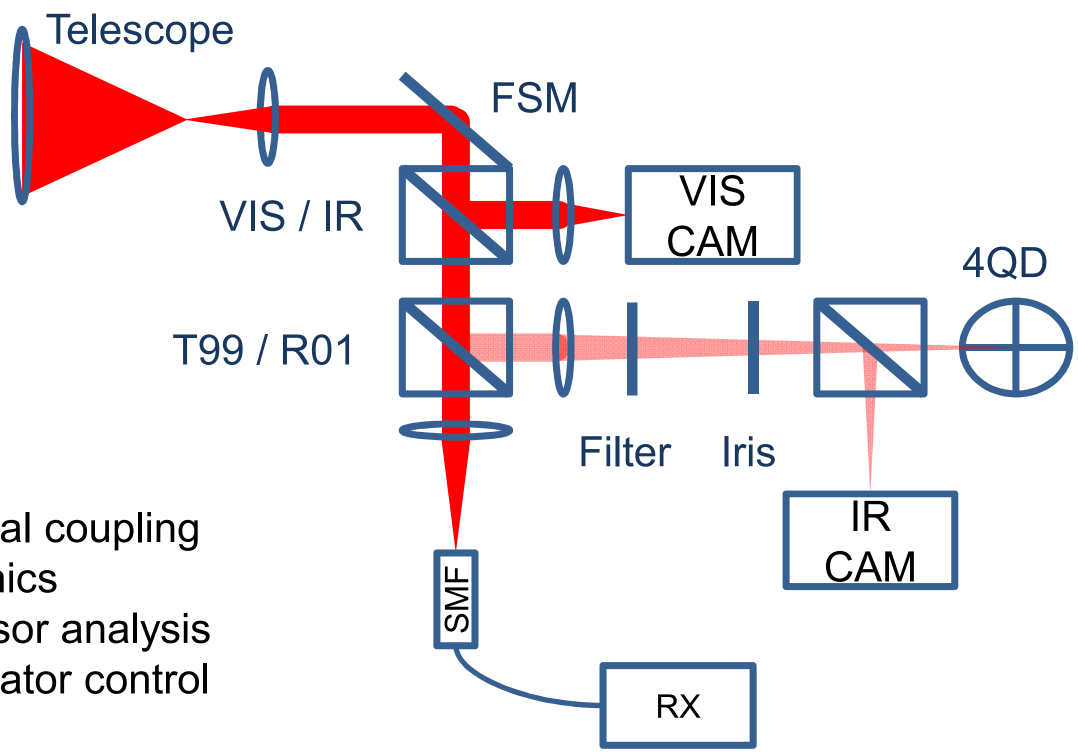
- Ground station terminal with fiber coupling and adaptive optics
- Point-ahead emulation
    - lateral shift of downlink beacon in the satellite terminal
    - Point-ahead mirror in the ground station
- Atmospheric turbulence monitoring instruments





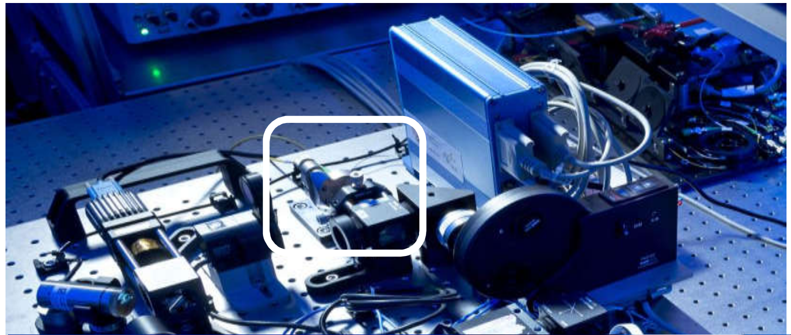
Hardware setup for fiber coupling

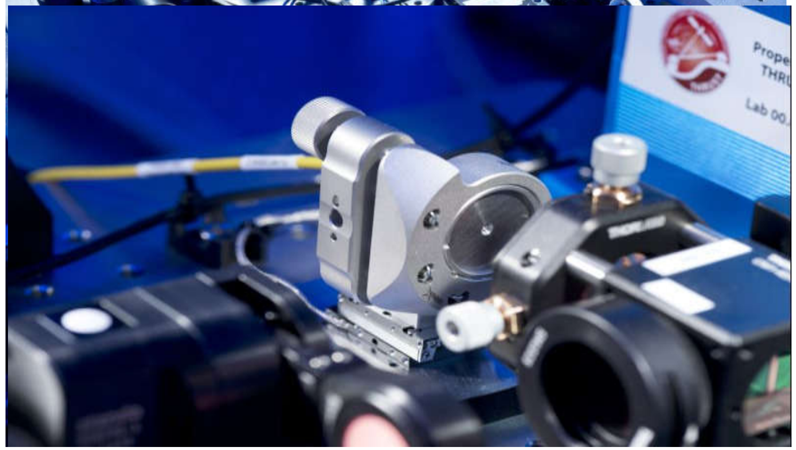
- Satellite terminal with single-mode fiber coupling



Optics
- Signal coupling

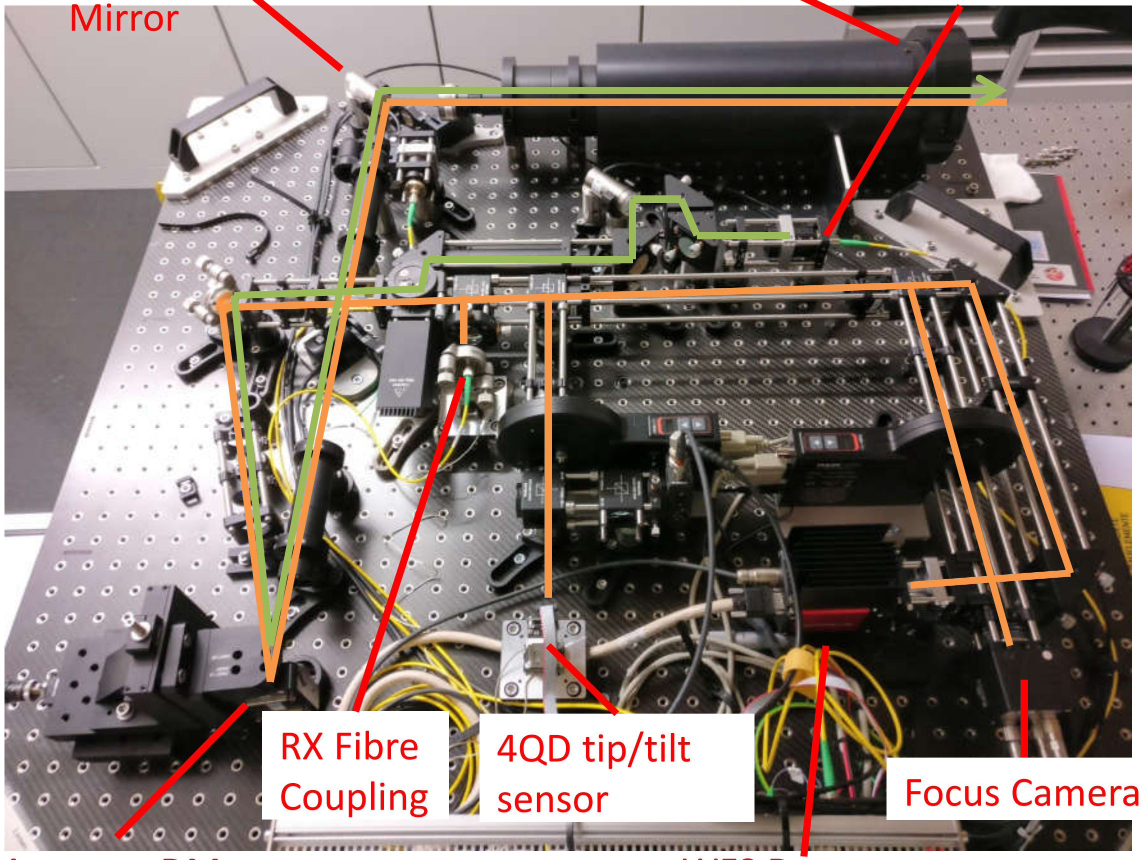
Electronics
- Sensor analysis
- Actuator control





Free Space Optical Communications AO Demonstrator

- AO System installed at OGS terminal
  - SH-WFS with 8x8 sub-apertures
  - InGaAs, Short Wave Infra-Red WFS detector, running between 500 – 3000Hz
  - 97 Actuator ALPAO DM
  - Transmitted and received beam projected from same DM, so pre-distortion AO can be demonstrated.
  - Focus Camera observes corrected spot
- Multiple measurement campaigns completed in 2018



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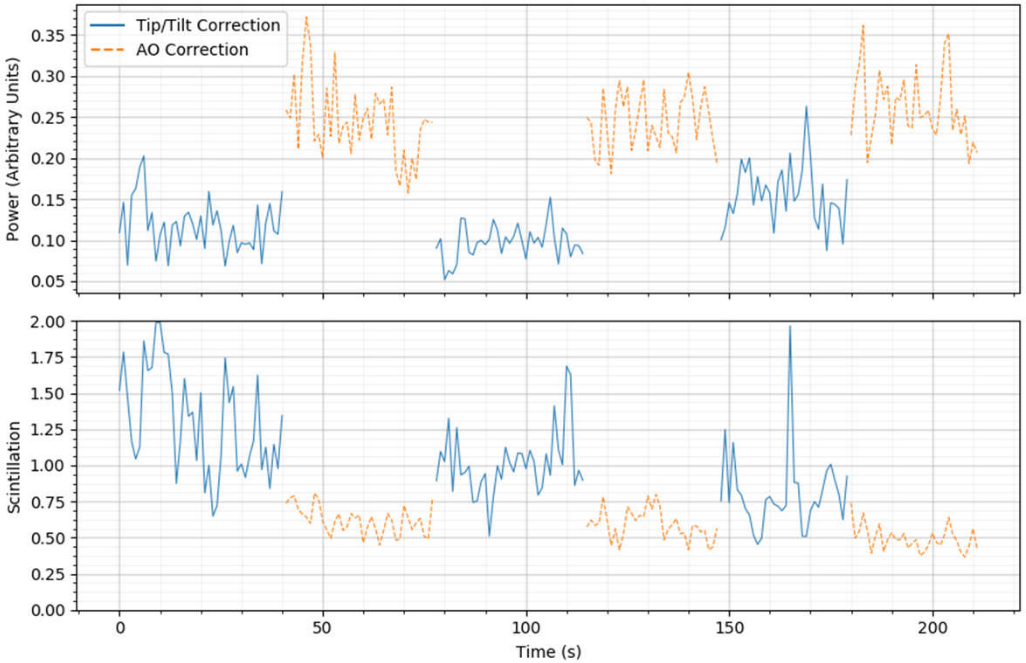
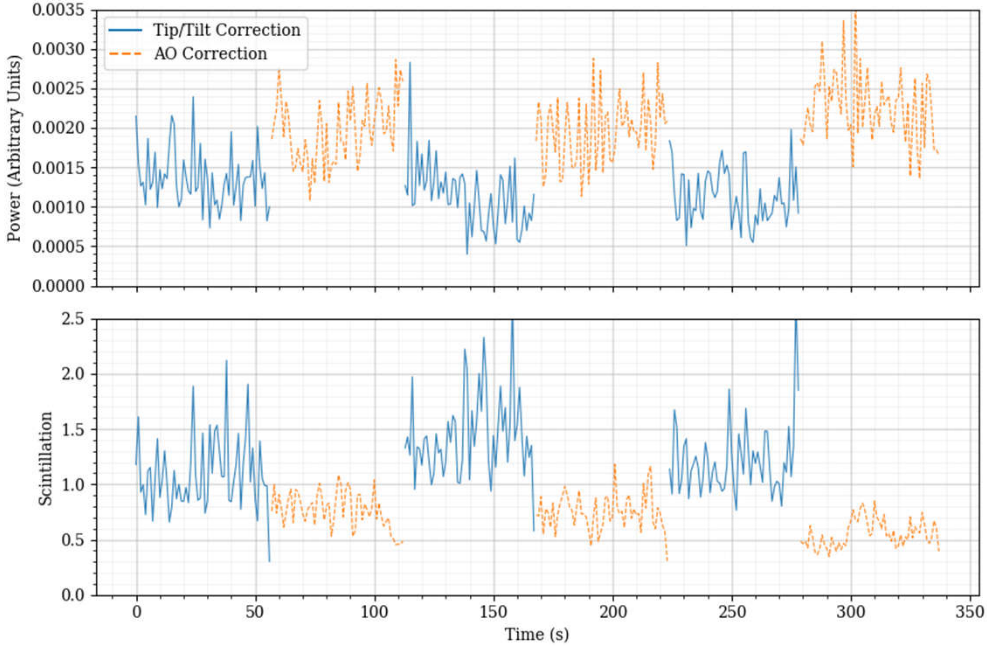
AO Performance for fibre coupling and pre-distortion



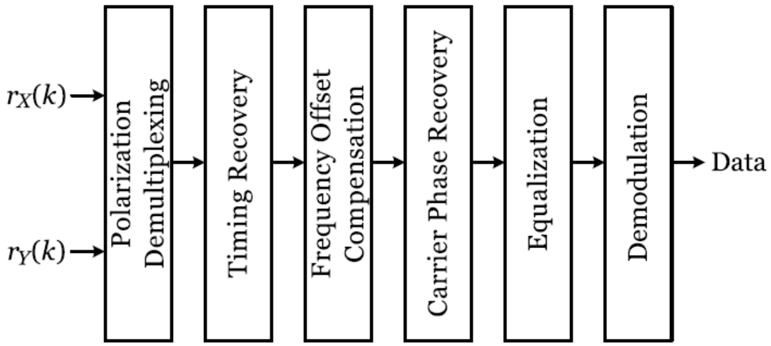
Power and Scintillation received at *OGS*, alternating between AO on and off.
Consistently higher power (+3.1dB) and lower scintillation (50% less) with AO

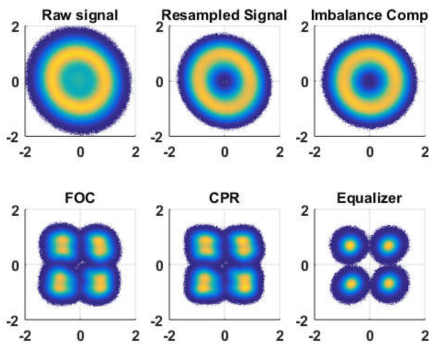


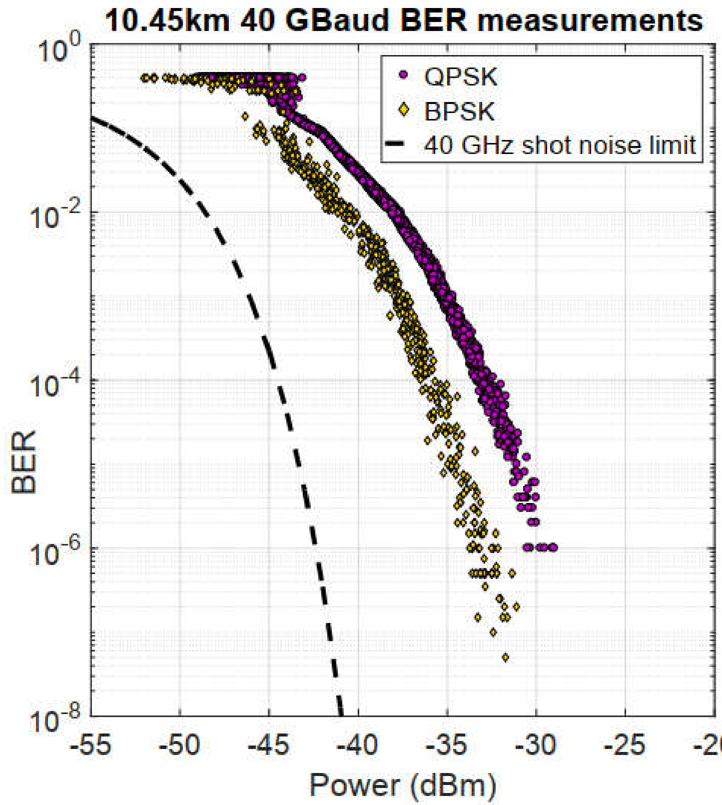
Power and Scintillation received at *SAT* alternating between AO on and off.
Consistently higher power (+3.1dB) and lower scintillation (50% less)

Coherent Communications system

- Intradyne (digital homodyne) concept developed in 2016 tested for **30G BPSK** [1]
  - Minimum lock-time after fading
  - SW complexity vs. HW complexity compared to OPLL
- Mid-2017 [2]
  - 40G receiver
  - More robust timing recovery (Lee algorithm)
  - Equalization
- Fall 2017 integration of I/Q Modulator -> **40G QPSK**







[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

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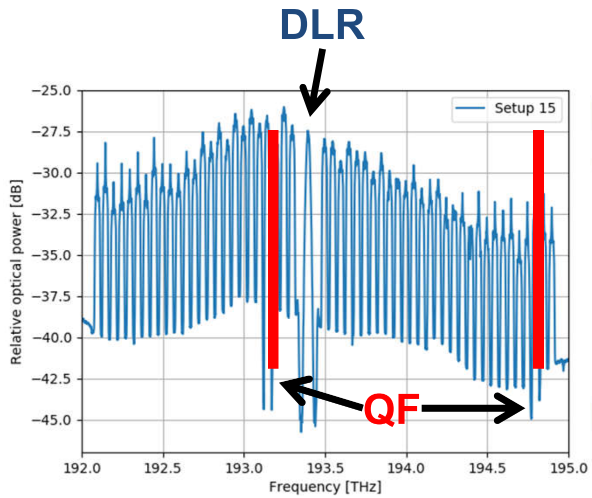
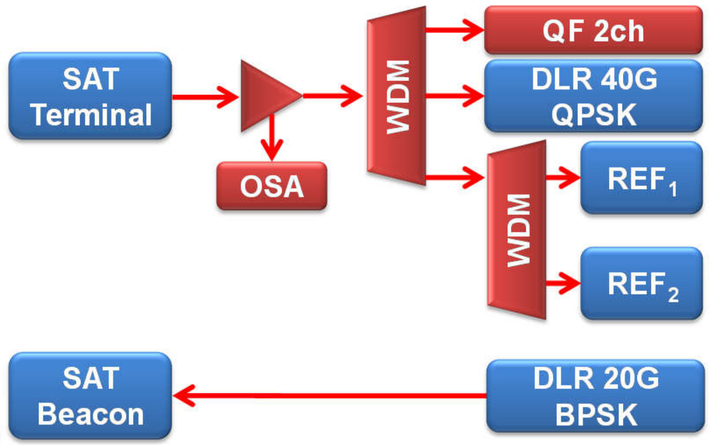
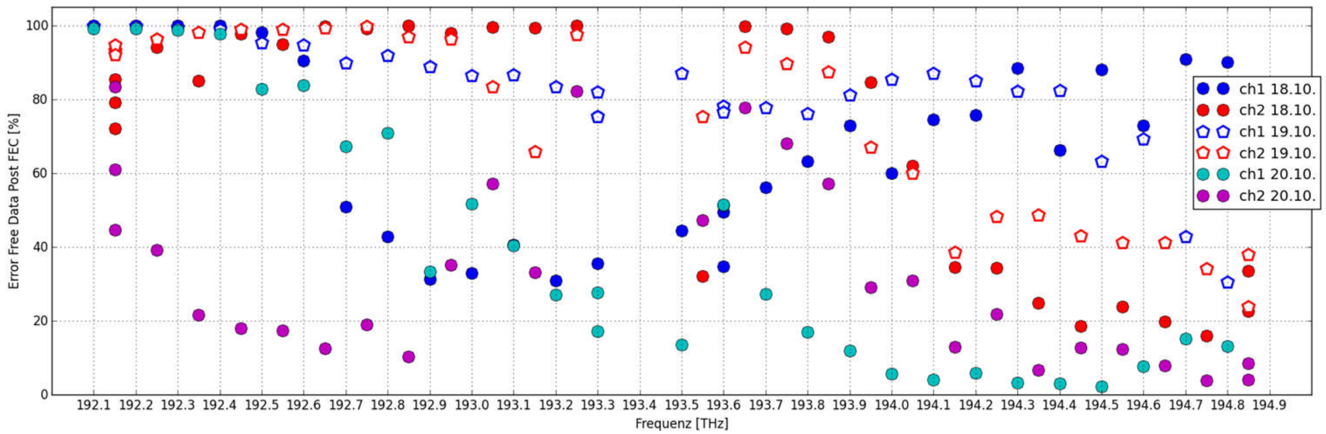
13,16 Tbit/s demonstration in 2017

- Collaboration with ADVA
- FSP 3000 Cloudconnect QuadFlexTM
  - DP-16QAM, DP-8QAM, DP-QPSK
- Channels swept with QF
- Power measurement
  - Full spectrum
  - At fixed channel





- DLR: Duplex operation
  - 80Gbps uplink / 20Gbps downlink
- BER evaluation (QF)
  - Post-FEC / Pre-FEC
  - Strong dependence on atmosphere
    - 3-days with various conditions



Summary

- GEO satellites can provide global coverage
    - Modeling the uplink channel in collaboration with Tesat
- WDM technology
    - Demonstrations under strong turbulence conditions
        - In 2016 1.72 Tbit/s with OOK
        - In 2017 13.16 Tbit/s with 16QAM, in collaboration with ADVA
- Coherent communications
    - Technology already space-proven
    - Digital homodyne have been demonstrated through strong turbulence conditions
- Adaptive Optics
    - For single-mode fiber coupling
    - Pre-distortion has been demonstrated
- Laser guide stars
    - Currently under test on the Canary Islands, in collaboration with the European Southern Observatory (ESO), European Space Agency (ESA), Durham University and Istituto Nazionale di AstroFisica – Osservatorio Astronomico di Roma (INAF-OAR)

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