Demonstrations of Pre-Distortion Adaptive Optics for Free Space Optical Communications

COAT2019

Andrew Reeves
Institute of Communications and Navigation
German Aerospace Centre

DLR

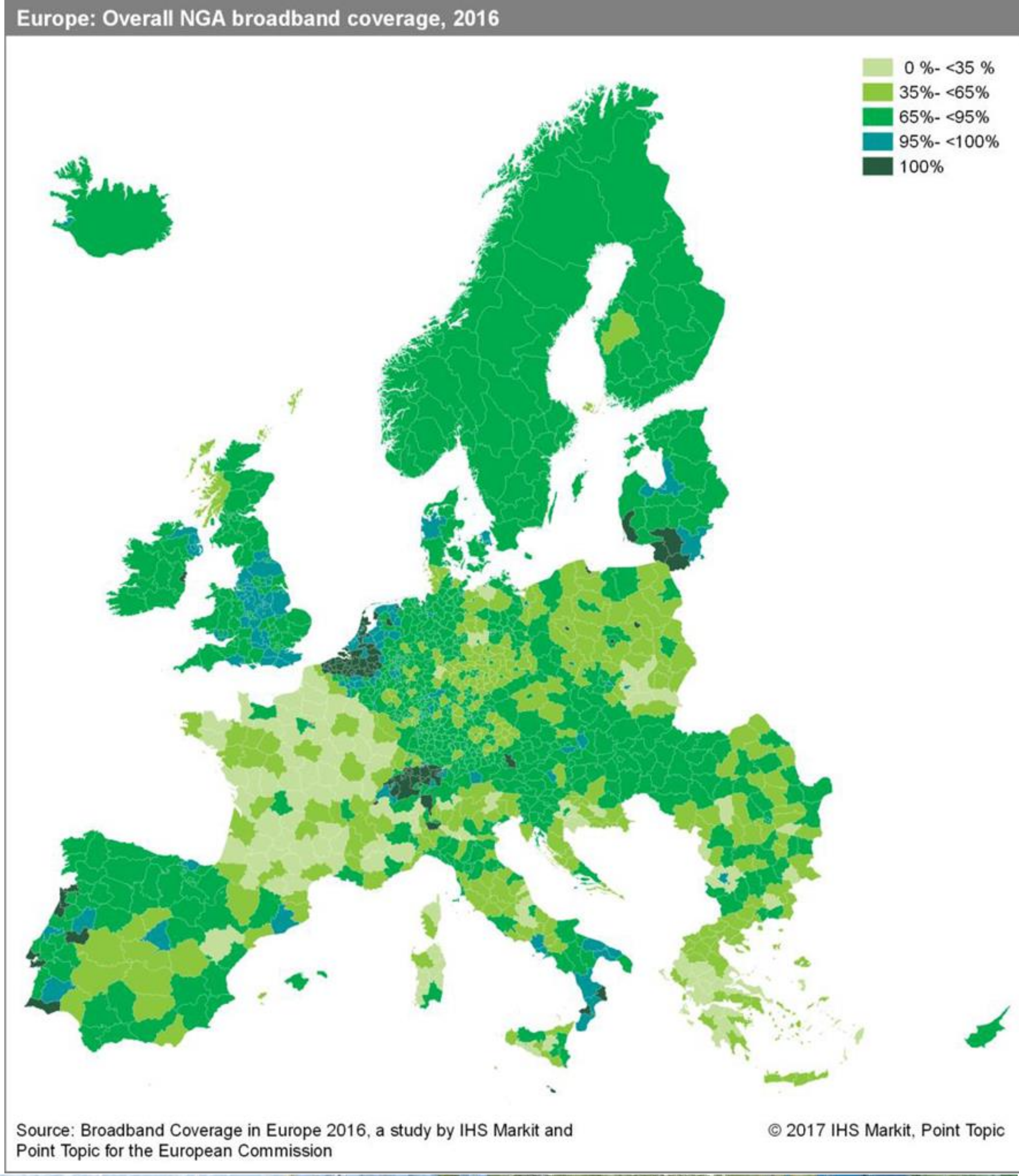
Agenda

- Global Connectivity
- The Atmosphere and Free Space Optical Communications
- Adaptive Optics and the Institute of Communications and Navigation FSOC Demonstrator
- AO improvements and areas of ongoing research

Global Connectivity:
For People and Machines

- Many places around the world, even in highly developed countries do not have access to good quality, high speed internet.
- Laying new terrestrial network to these locations may not be viable or profitable.
- **Global Connectivity** is a mission for the DLR Institute of Communications and Navigation
  - Towards a versatile **Industry 4.0**
  - **Adaptive Logistic**: world-wide networking of mobile sensors
  - Connectivity for the **Internet of Things**
  - Networking for a **cloud-based** business model

- Satellite Communication is a solution to this problem



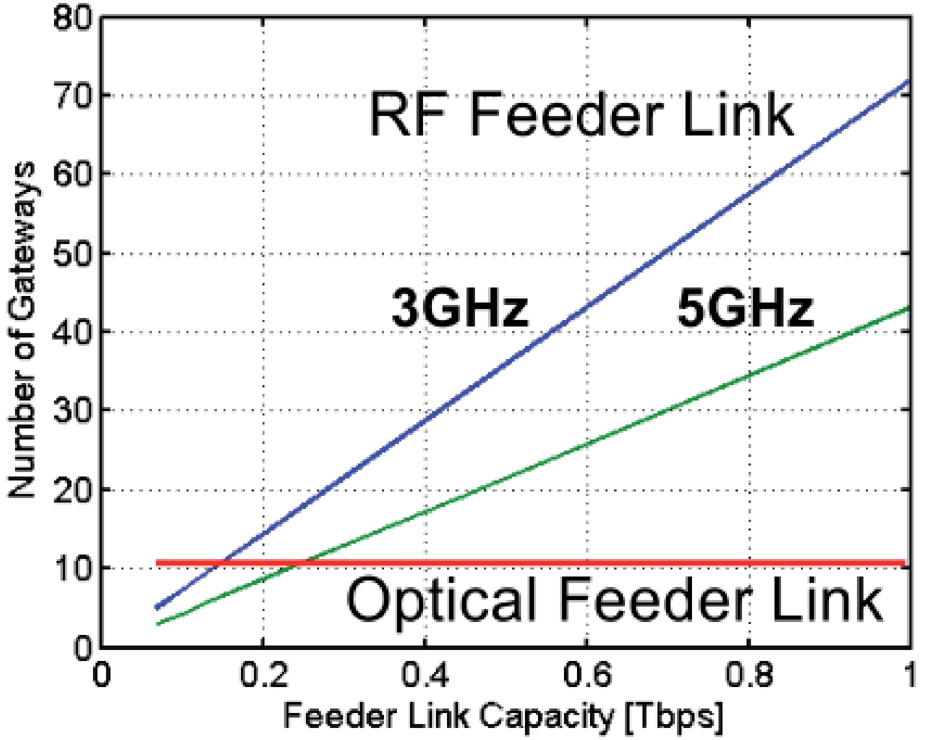
Global Connectivity:
Optical vs RF

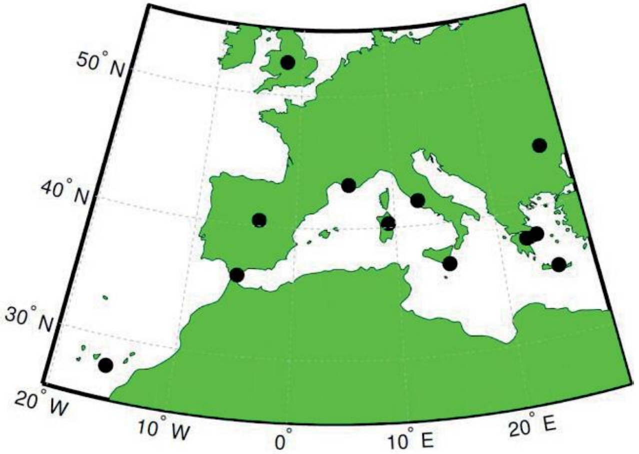
- RF links also proposed to supply global satellite networks

- The optical spectrum supports multiple THz of available bandwidth, without regulatory issues.
    - To support Tbps satellite network, 10s or 100s RF links required.

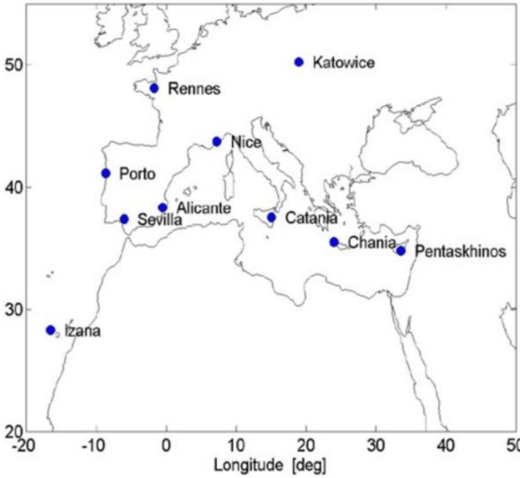
- Multiple Optical Ground Stations must be present to account for outages caused by poor weather, etc…
    - Approximately 11 OGSs around Europe required to provide 99.9% uptime for all foreseen data throughput requirements

- **An Optical Feeder Link allows increased bandwidth of the user-link, maximising the system throughput capabilities**





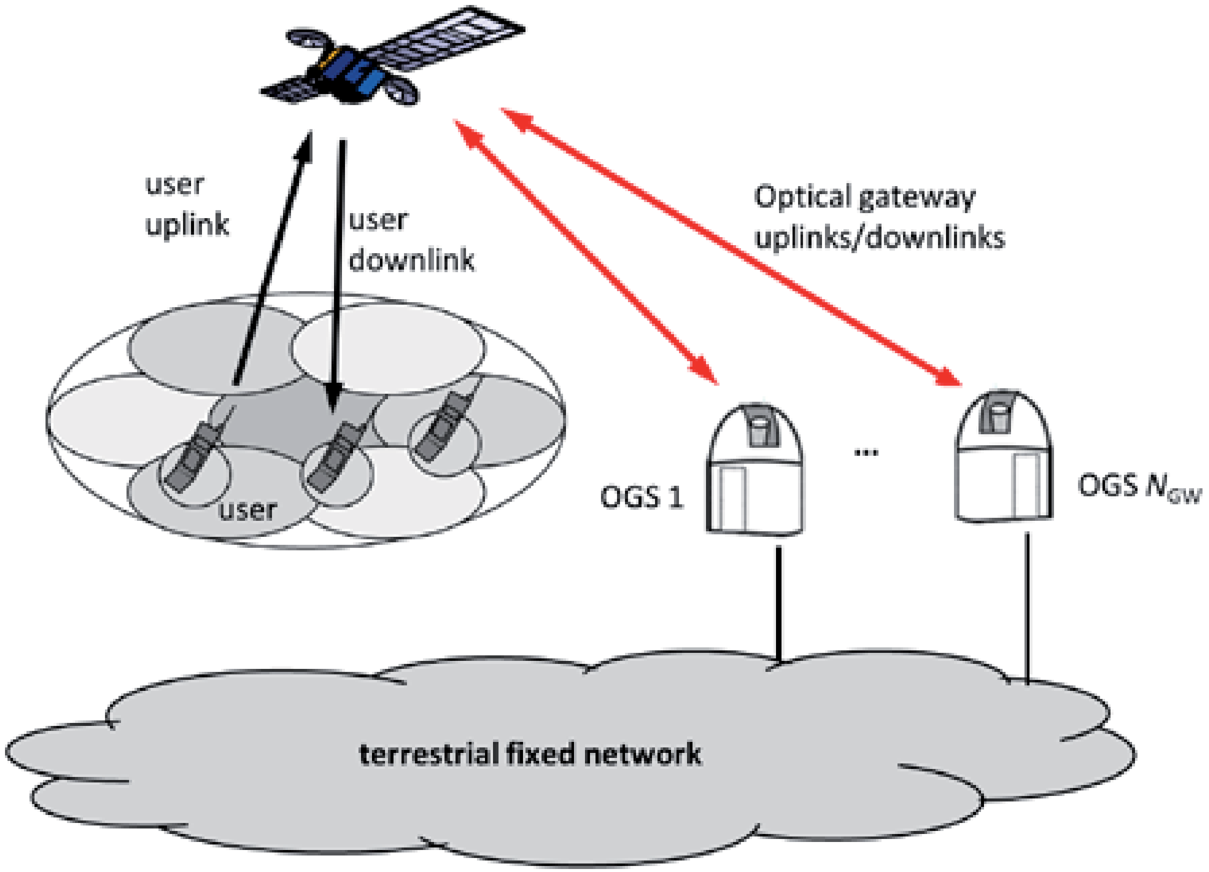
Giggenbach et al, 2015



Poulenard, Sylvain, et al. 2017

Global Connectivity
GEO-Feeder Links

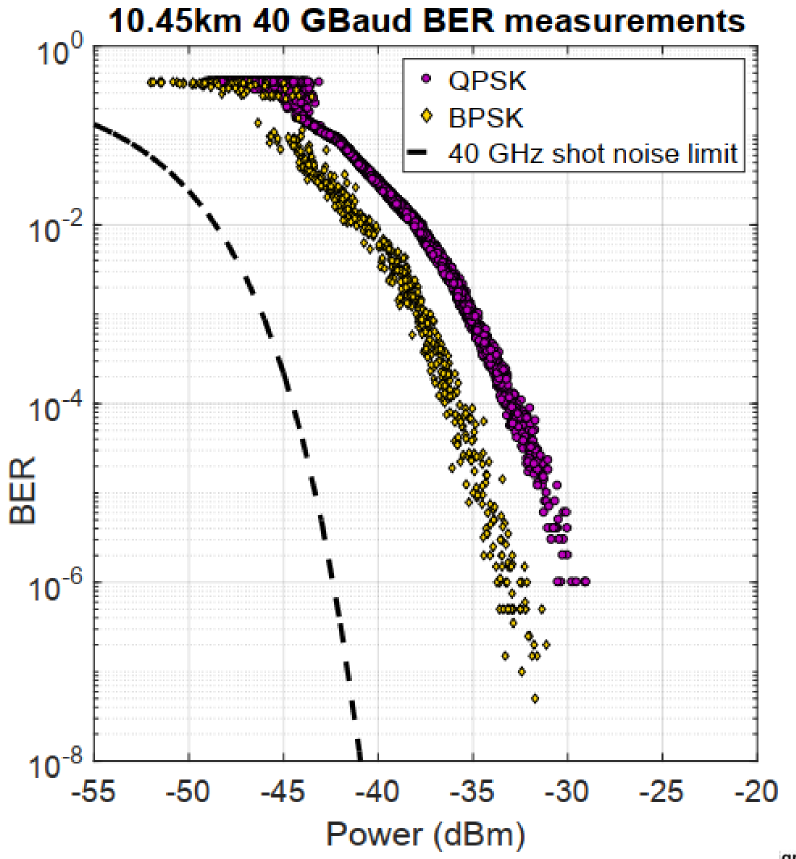
- GEO-feeder links aimed to provide high bandwidth, reliable internet access to regions where fibre connections difficult or unprofitable around Europe and the World.
- High throughput optical link to GEO satellite, connecting it to terrestrial network
  - GEO simplifies acquisition and tracking of satellite
- Clients connect over RF links
  - Guaranteed availability

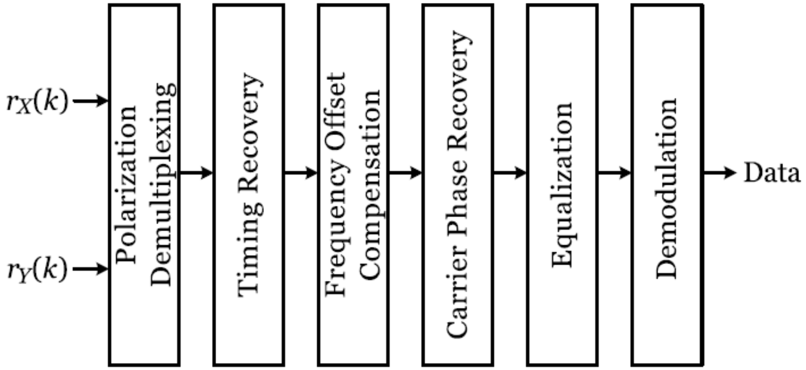


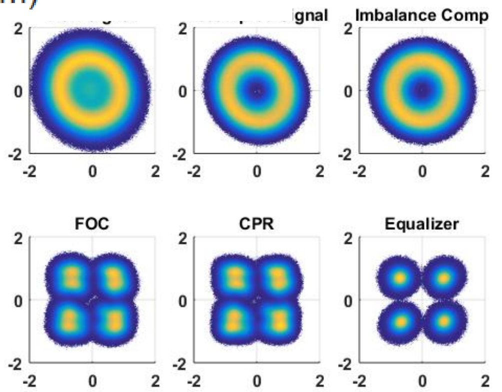
Global Connectivity
Coherent Communications

- Coherent Communications provide high spectral efficiency
- Intradyne (digital homodyne) concept developed in 2016 tested for **30Gbaud BPSK** [1]
- Mid-2017 [2]
  - 40 Gbaud receiver
  - More robust timing recovery (Lee algorithm)
  - Equalization
- Autumn 2017 integration of I/Q Modulator -> **40Gbaud QPSK**
- **13.16 Tbps** with 52 channels of 50 GHz DWDM with 16 QAM in collaboration with ADVA

- **Must efficiently couple light into a single mode optical fibre at OGS terminal for these schemes!**



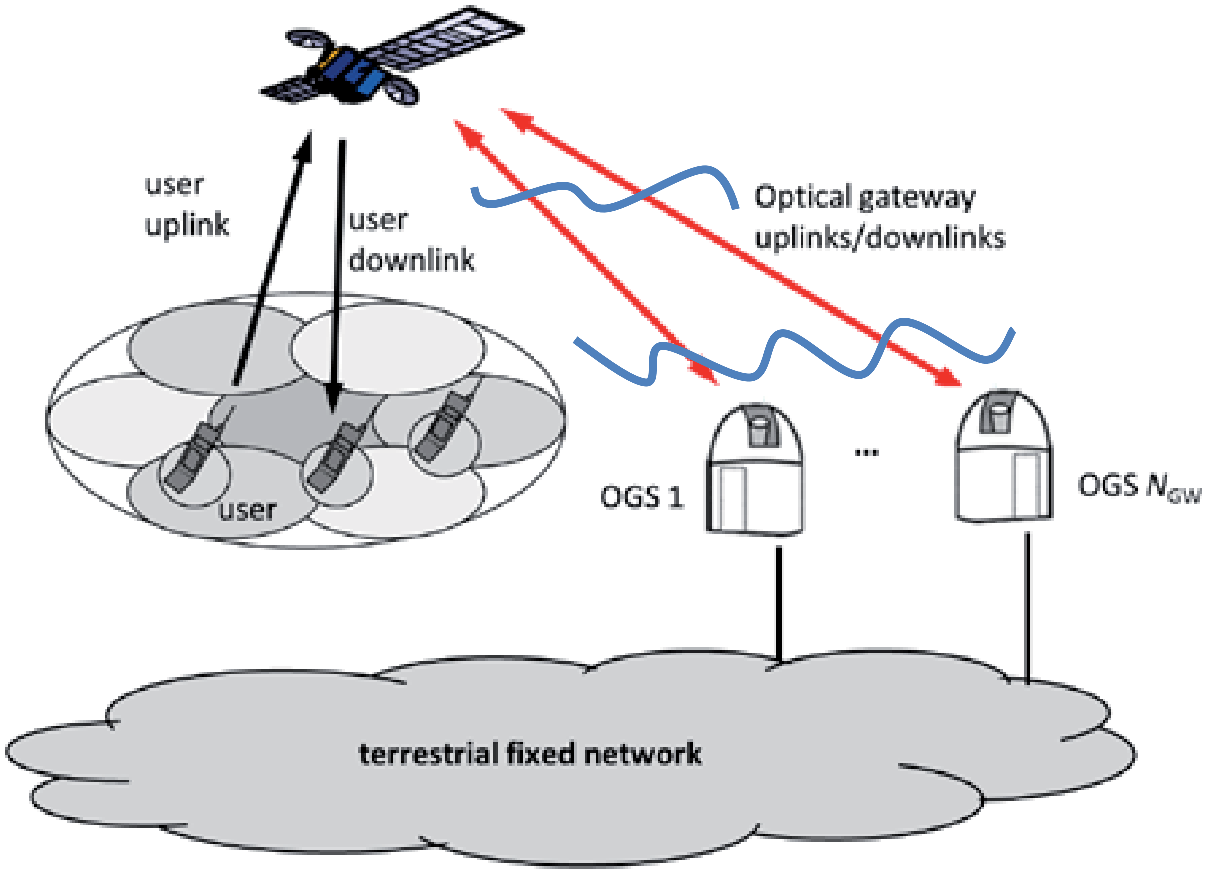




[1] J. Surof, J. Poliak, and R. Mata Calvo, "Demonstration of intradyne BPSK optical free-space transmission in representative atmospheric turbulence conditions for geostationary uplink channel," Opt. Lett. 42, 2173-2176 , 2017
[2] P. Conroy, J. Surof, J., J. Poliak, J. and R. Mata Calvo, "Demonstration of 40GBaud intradyne transmission through worst-case atmospheric turbulence conditions for geostationary satellite uplink," in Appl. Opt., OSA, 2018, *57*, 5095-5101

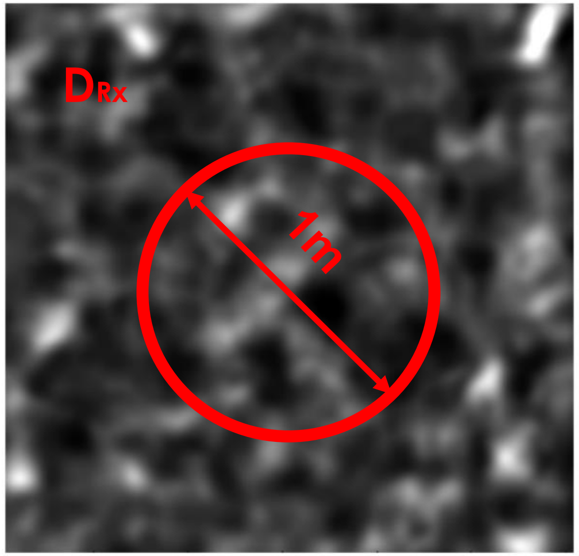
Free Space Optical Communications
Atmospheric Turbulence

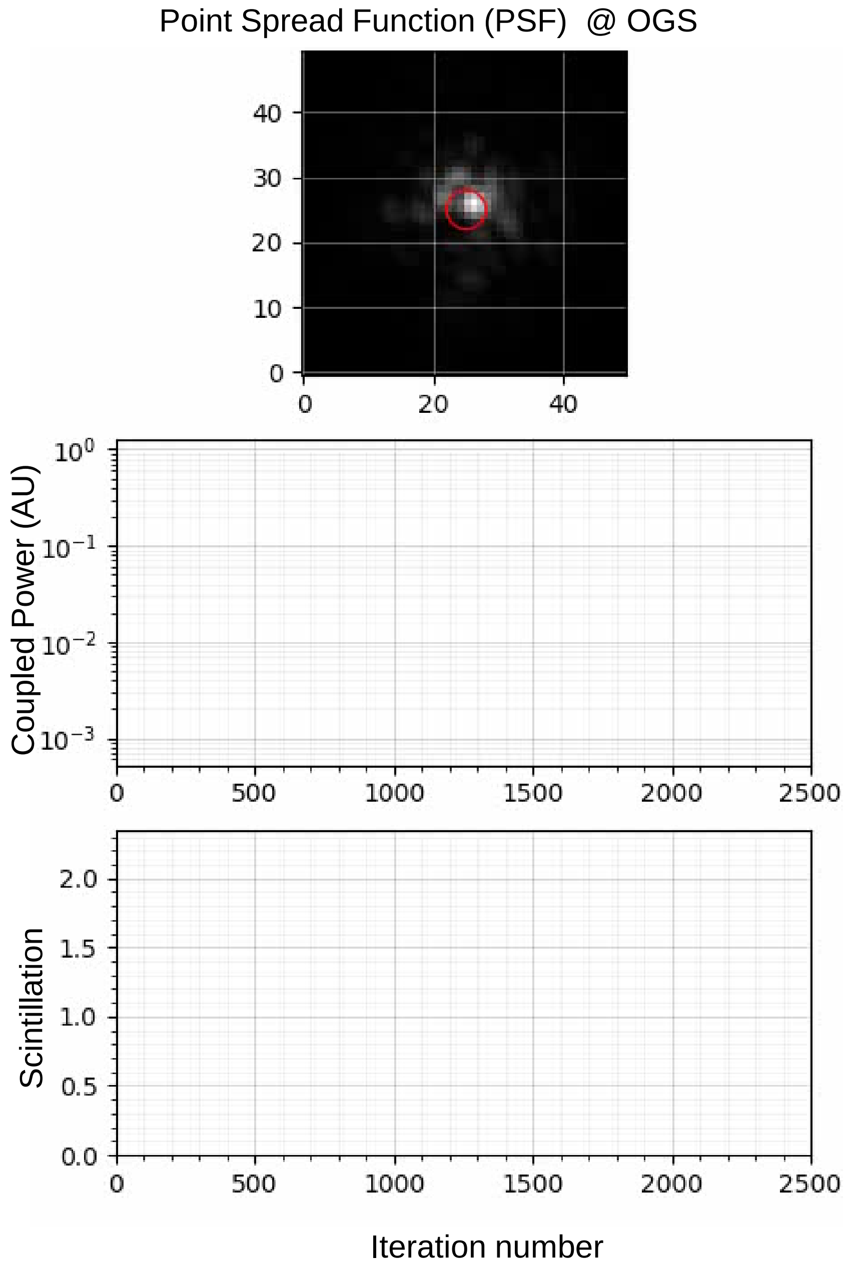
- …but atmospheric turbulence adversely affects the reception and transmission of the signal from the GEO satellite!
- Turbulence strength, speed and vertical profile change depending on location and time
- Turbulence up to ~20 km altitude
- “Ground layer” effects generally strong due to:
  - Turbulence due to telescope structure and local topology
  - Heat sources close to ground
- Must also correct vibrations and pointing errors of OGS



Free Space Optical Communications
Atmospheric Turbulence

- At the **Optical Ground Station**:
- Large aperture averages spatial intensity fluctuations
- But Large aperture also captures wavefront distortions…
- Focussed light breaks up into “speckles”, **limiting the coupling efficiency into the optical fibre**
- Speckle pattern changes quickly, so coupled light into fibre varies greatly
- **Intensity fluctuations observed in light coupled into fibre**





Free Space Optical Communications
Atmospheric Turbulence

- At the **Satellite:**

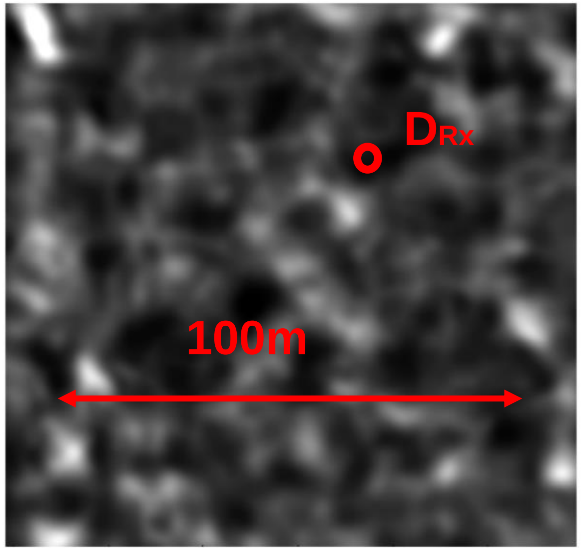
- Wavefront aberrations caused by turbulence on a much larger scale relative to the satellite terminal

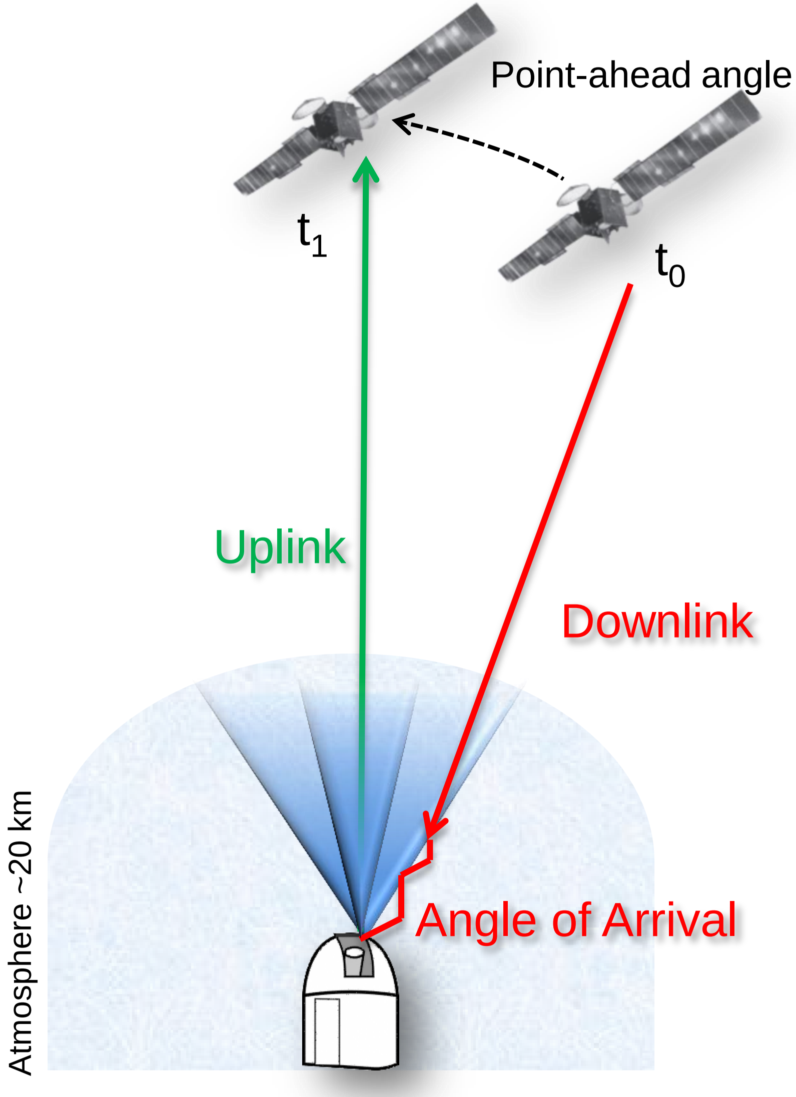
- Light is focussed to a perfect spot

- Pointed errors due to tip/tilt aberrations

- Aperture much smaller than scale of spatial fluctuations

- **Scintillation observed in light coupled into fibre**





Free Space Optical Communications
Adaptive Optics

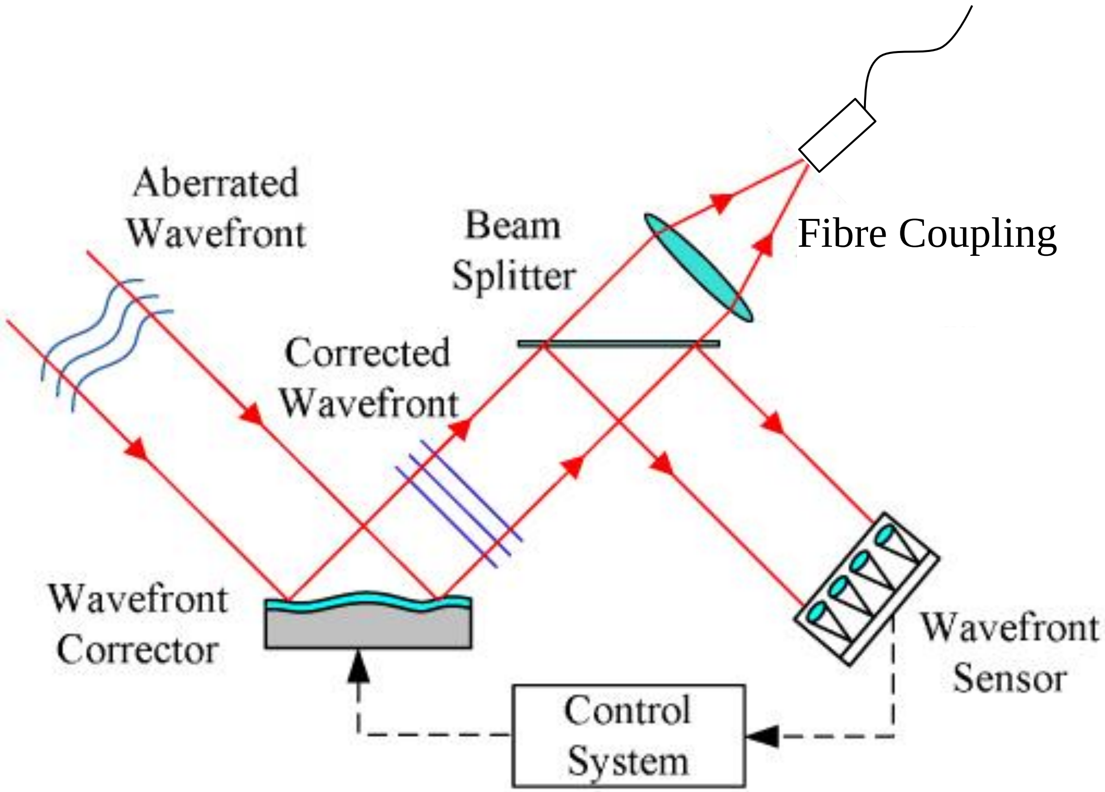
- AO corrects for the effects of atmospheric turbulence
- Light enters the telescope with an aberrated wavefront
- AO Closed Loop:

Deformable Mirror (DM) Corrects phase distortion

Light focussed for imaging and/or fibre coupling

Light picked off by Wavefront Sensor to measure residual wavefront error

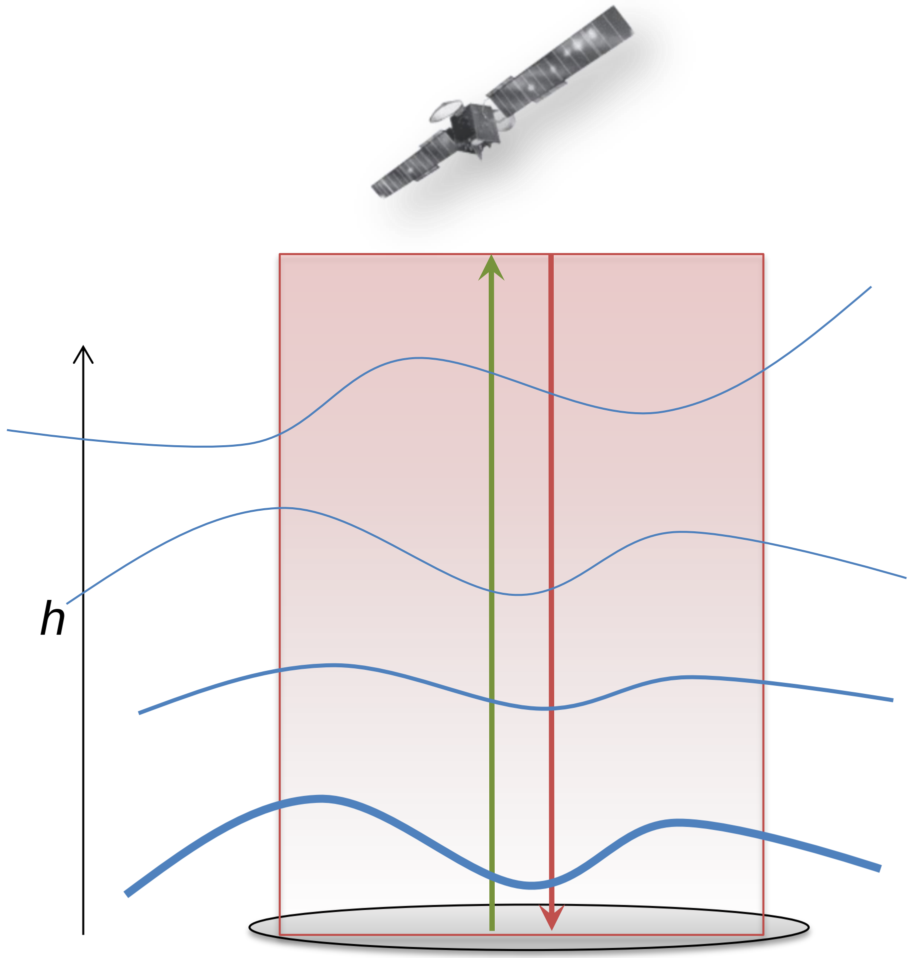
WFS Measurement processed and update of DM shape computed



AO System concept in OGS terminal

Adaptive Optics: **Pre-distortion AO**

- Can simultaneously correct the received and transmitted beam using an AO system installed at OGS.
  - Project both beams off the same DM



Optical Ground Station Telescope

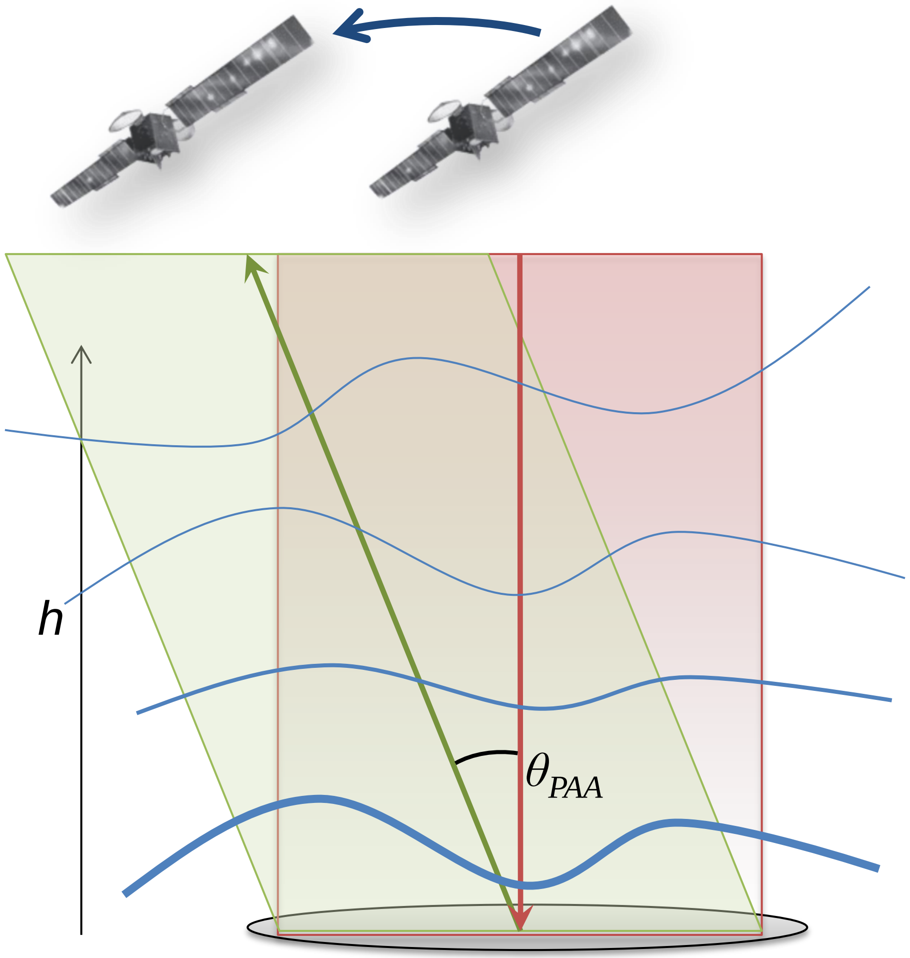
Adaptive Optics: **Pre-distortion AO**

- Can simultaneously correct the received and transmitted beam using an AO system installed at OGS.
  - Project both beams off the same DM

- However, transmitted beam launched in a different direction from the received beam. This difference referred to as the "Point Ahead Angle" (PAA) angle.

- The turbulence encountered by the transmitted beam is different to that encountered by the received path, so the measurement may not be valid.

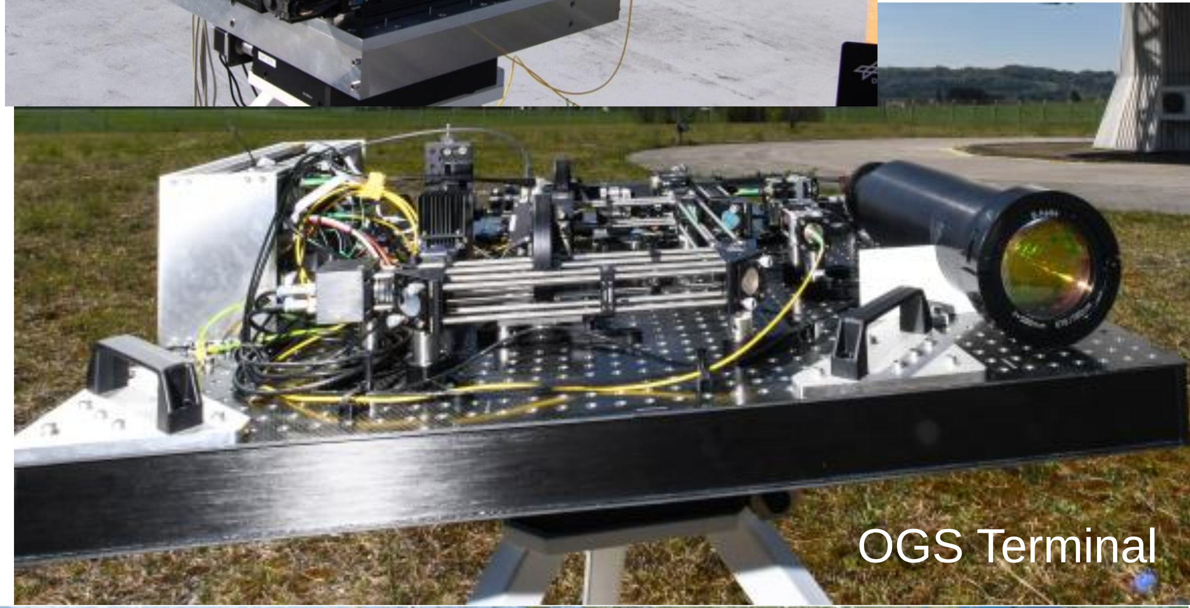
- The extent to which it is invalid is dependent upon the "isoplanatic angle".



Optical Ground Station Telescope

Free Space Optical Communications AO Demonstrator

- A flexible system to demonstrate advanced technologies in FSOC
    - Coherent Communication Technologies
    - Adaptive Optics with Pre-distortion
    - Alternative methods for fibre coupling, in collaboration with CAILabs
    - …
- Bidirectional optical communications link between terminals
- Set record for free space optical communications throughput as part of THRUST project
    - **2016: 1.72 Tbps with OOK**
    - **2017: 13.16 Tbps** with 16 QAM in collaboration with ADVA

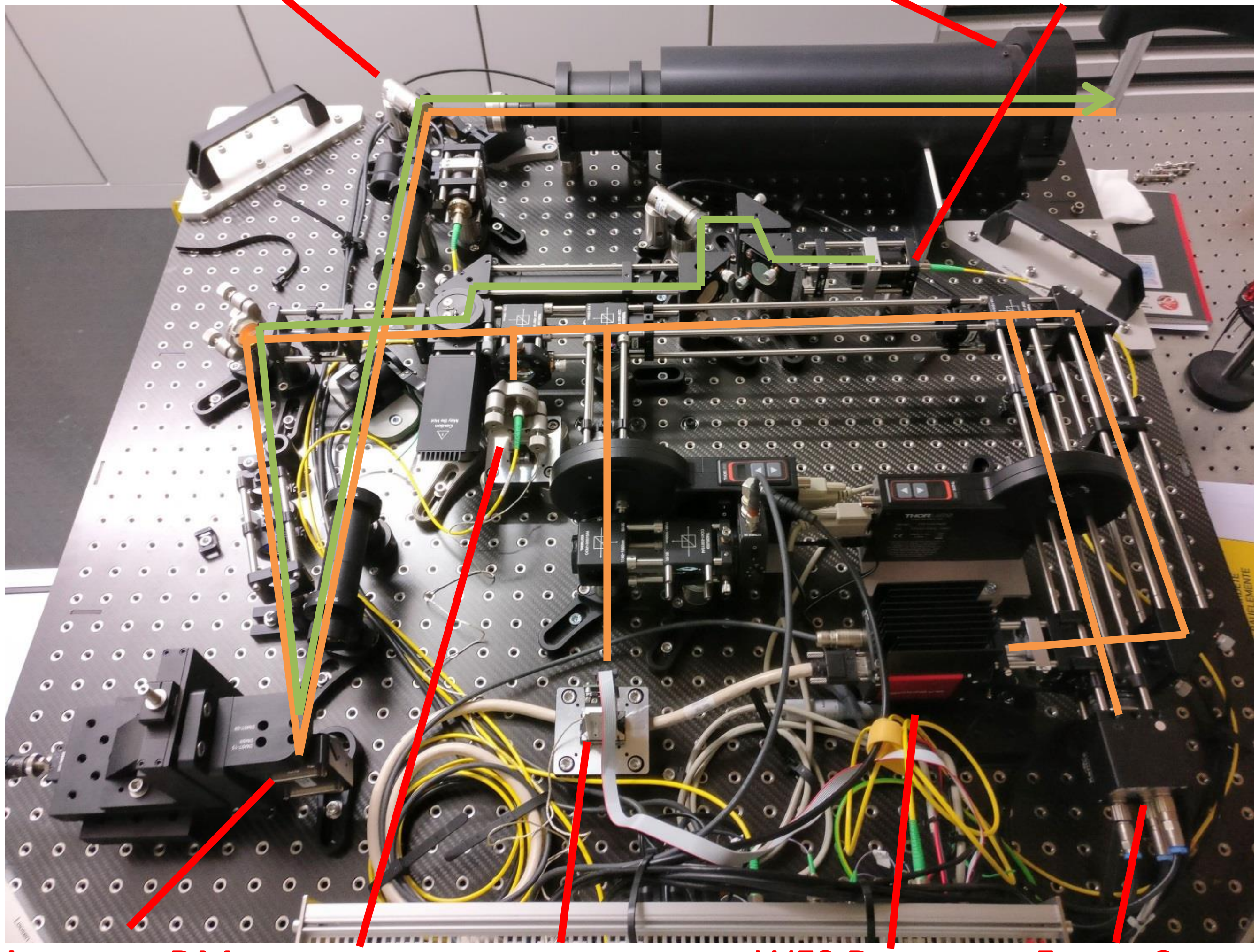


FSOC AO Demonstrator: **Sat**

- **Emulate the optical terminal in a satellite**
- ~1-5cm aperture (smaller than light coherence length)
- Fast Pointing loop
- Can receive/transmit through main aperture
- Can offset aperture and "beacon" source to emulate PAA effect

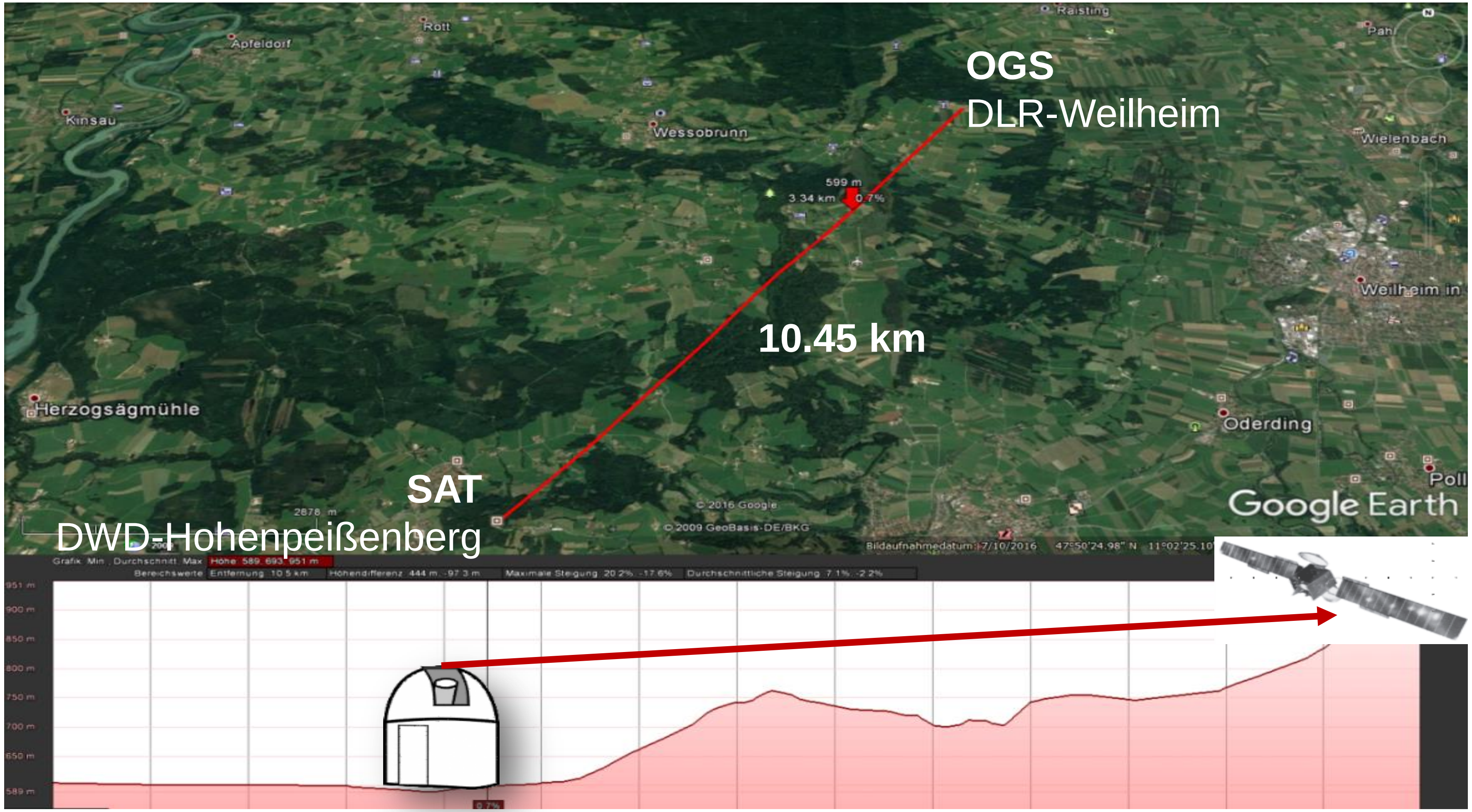
FSOC AO Demonstrator: **OGS Terminal**

- **10cm main aperture**
- **Fast Steering Mirror**
- **97 Actuator ALPAO DM**, transmitted and received beam projected from same DM, so pre-distortion AO can be demonstrated.
- **Fibre coupling** into single mode optical fibre
- **Total Power** measured by free space photodiode
- **SH-WFS** with 8x8 sub-apertures. InGaAs, Short Wave Infra-Red WFS detector, running between 500 – 6000Hz
- **Focus Camera** observes corrected spot for diagnostics
- **TX light coupled with RX path. Both projected from same DM**
- TX light can be steered by “Point Ahead” mirror



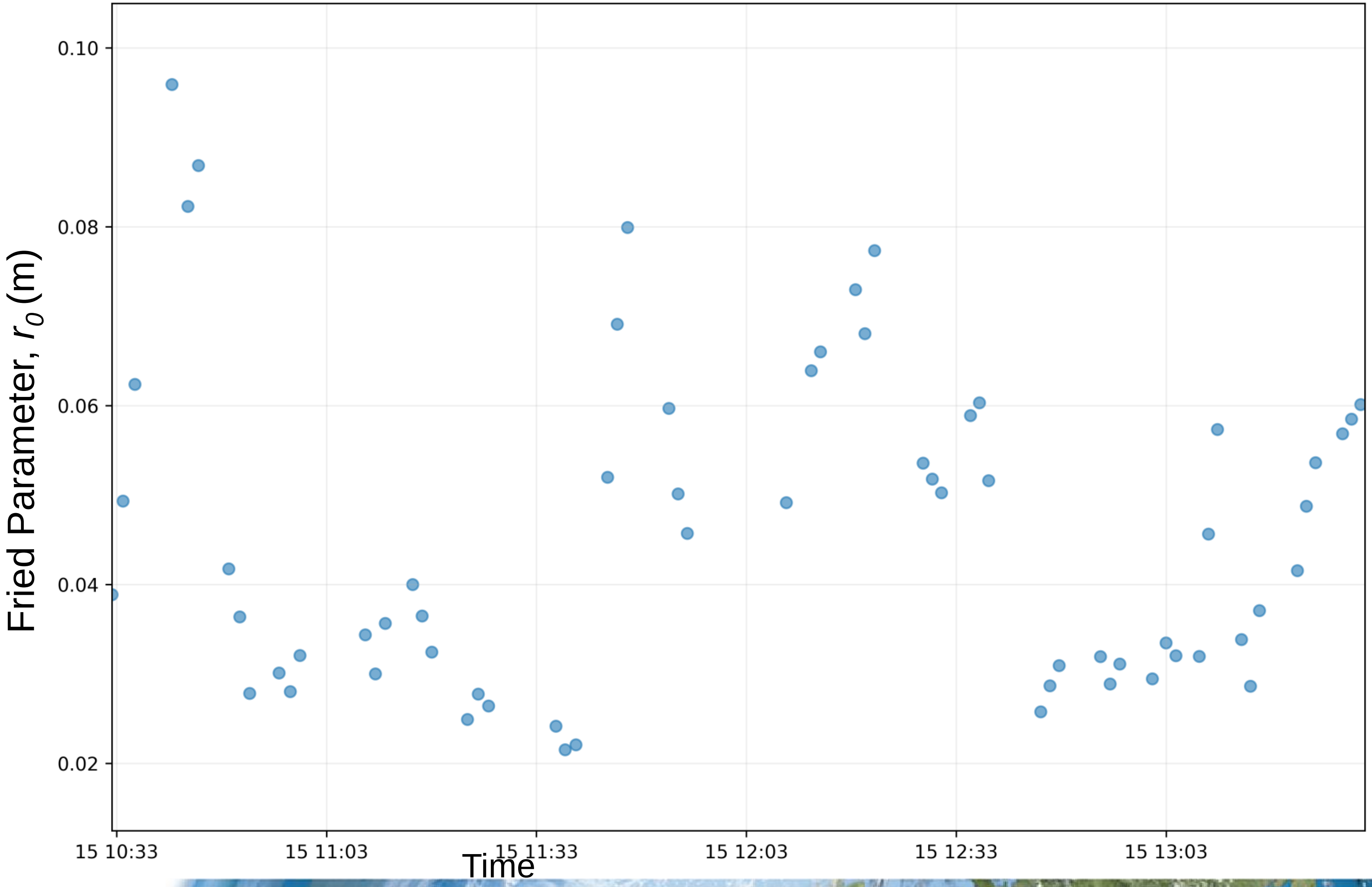
FSOC AO Demonstrator: **Optical Channel**

- Link Distance:
    - 10.45 km
- OGS situated at DLR Ground station in town of Weilheim
    - ~600m altitude
- SAT located at DWD weather tower on Hohenpeisenberg hill
    - ~950m altitude
- Link elevation of ~2º
- **Strong Turbulence**



FSOC AO Demonstrator: **Optical Channel**

- Turbulence strength in channel varies over day
- Fried Parameter typically between 1 – 10cm @ 1550nm
- D/r_0 between 10 - 1
- Measured Rytov variance between 0.05 - 2



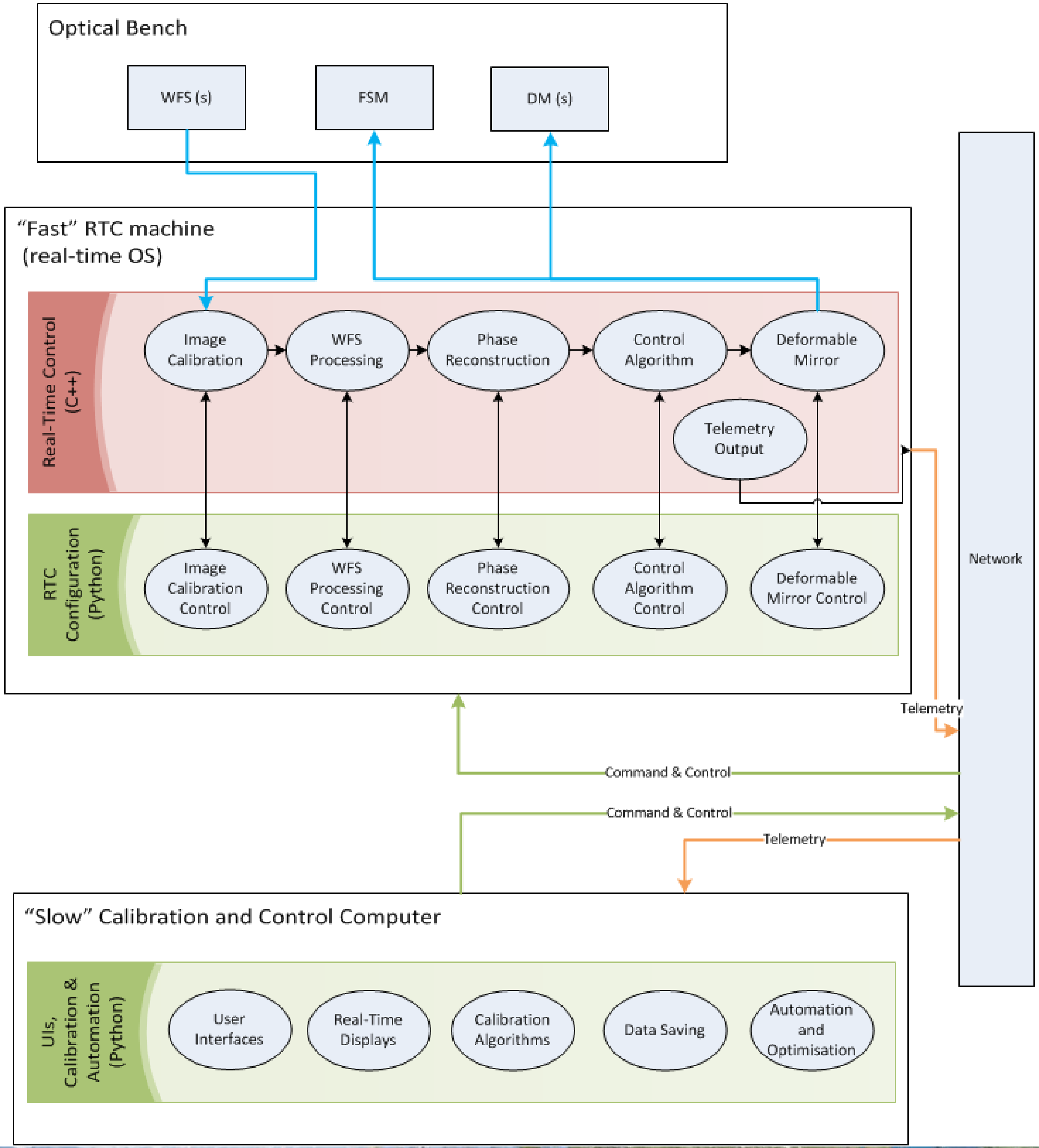
FSOC AO Demonstrator: **AO Control**

- AO Real-Time Control System developed
  - CPU based control system
  - “Fast” core in C/C++ running on dedicated high performance workstation
  - “Slow” supervisor tasks in Python, running on separate workstation

- Flexible architecture allows fast integration of new algorithms and hardware

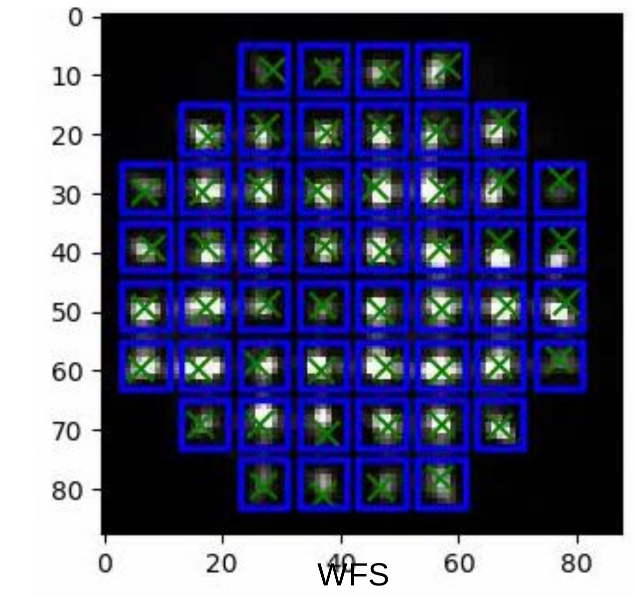
- High performance:
  - Capable of low latency, high frame rates
  - **<50µs** latency
  - Loop iteration rate typically between **2 – 5 kHz**

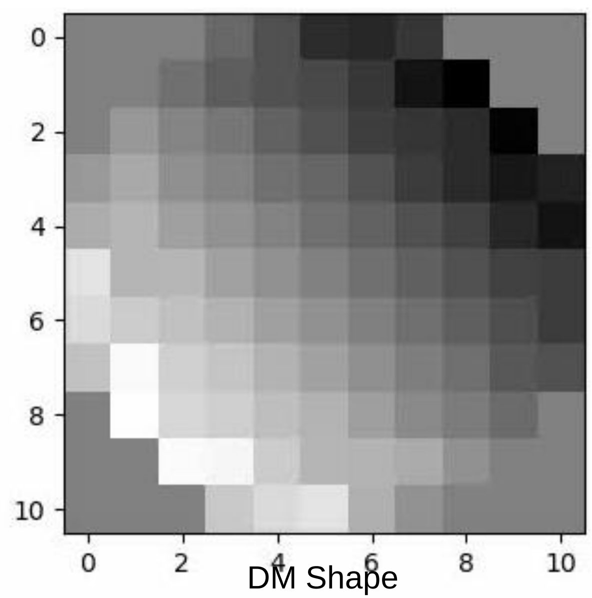
- Classical AO Integrator Control

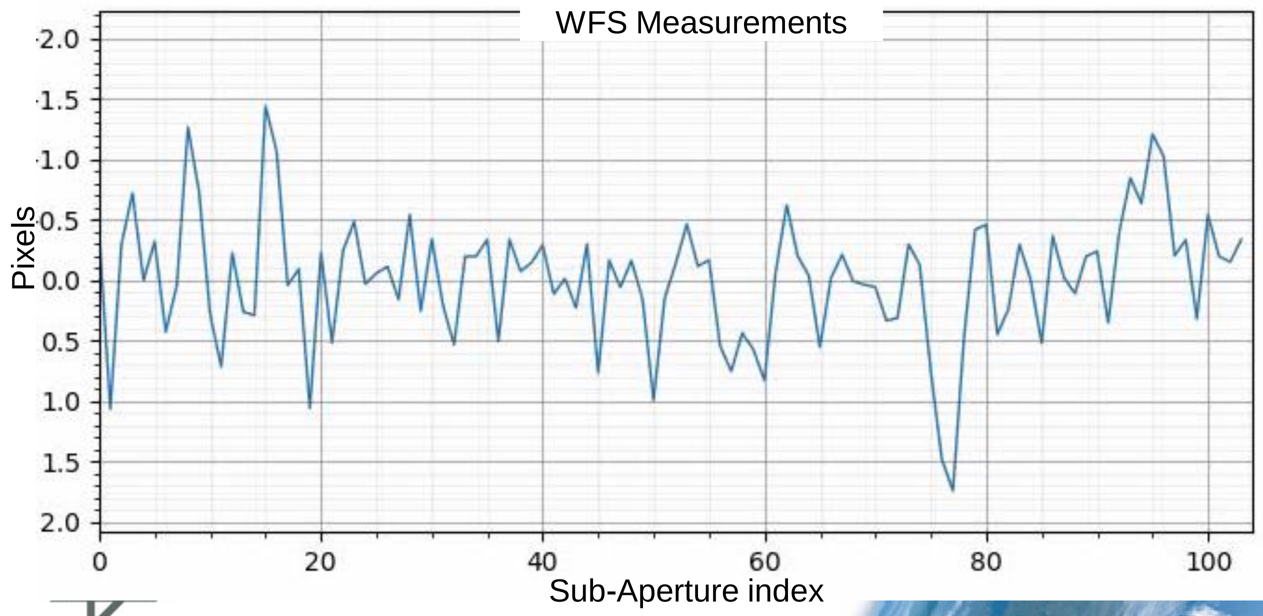


DLR

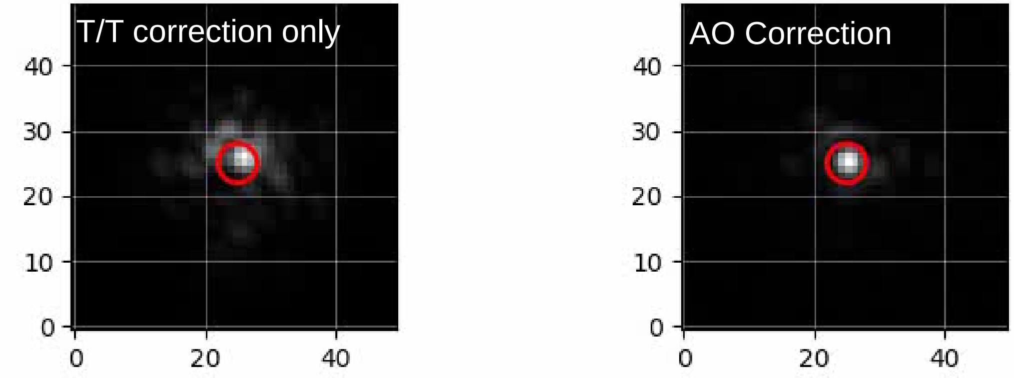
FSOC AO Demonstrator: **AO Operation**

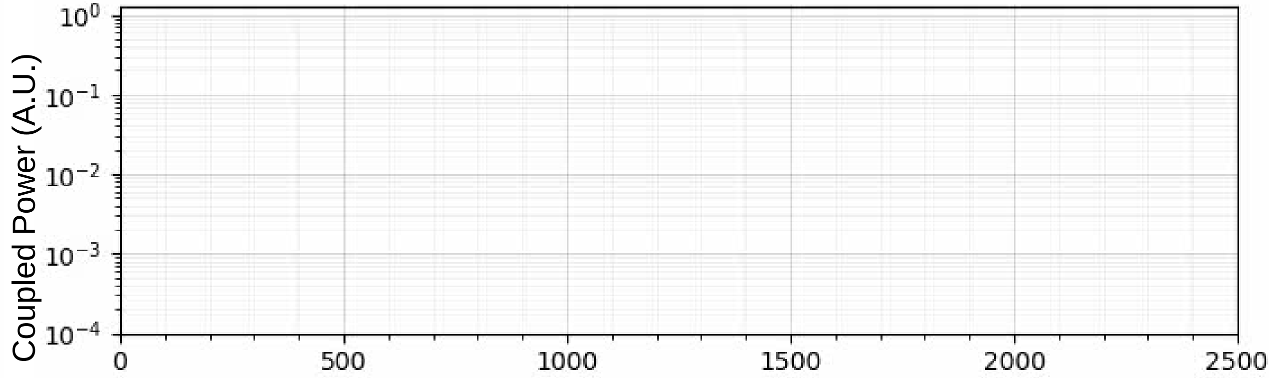


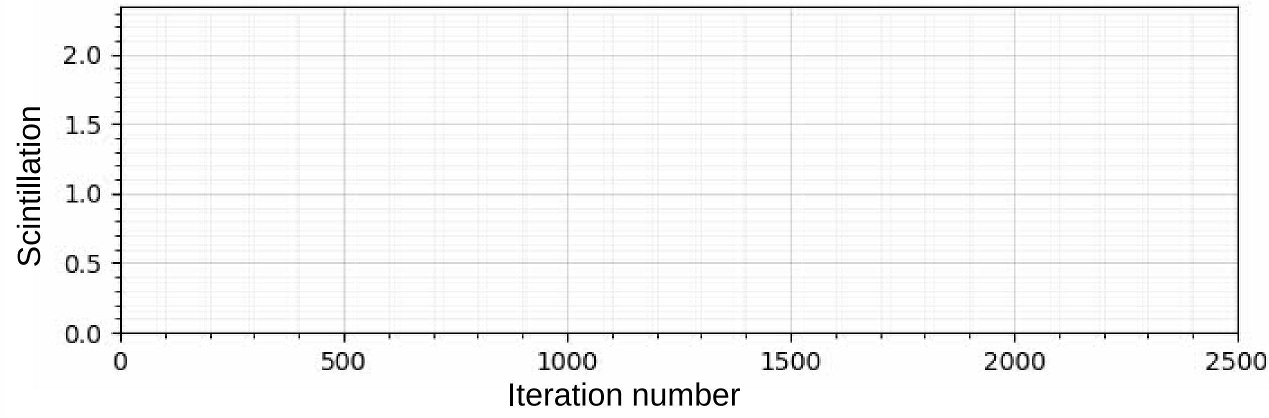




Point Spread Function (PSF) @ OGS

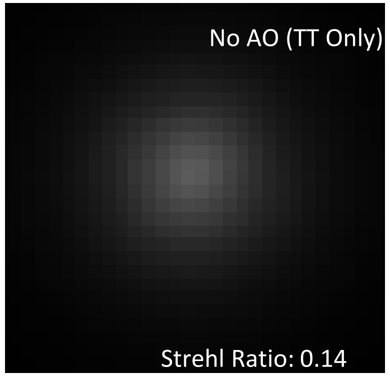


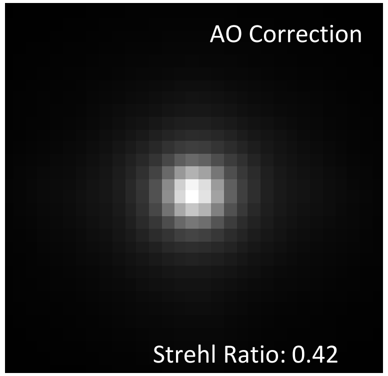




FSOC AO Demonstrator:
OGS Performance

r_0: 3cm @ 1550nm



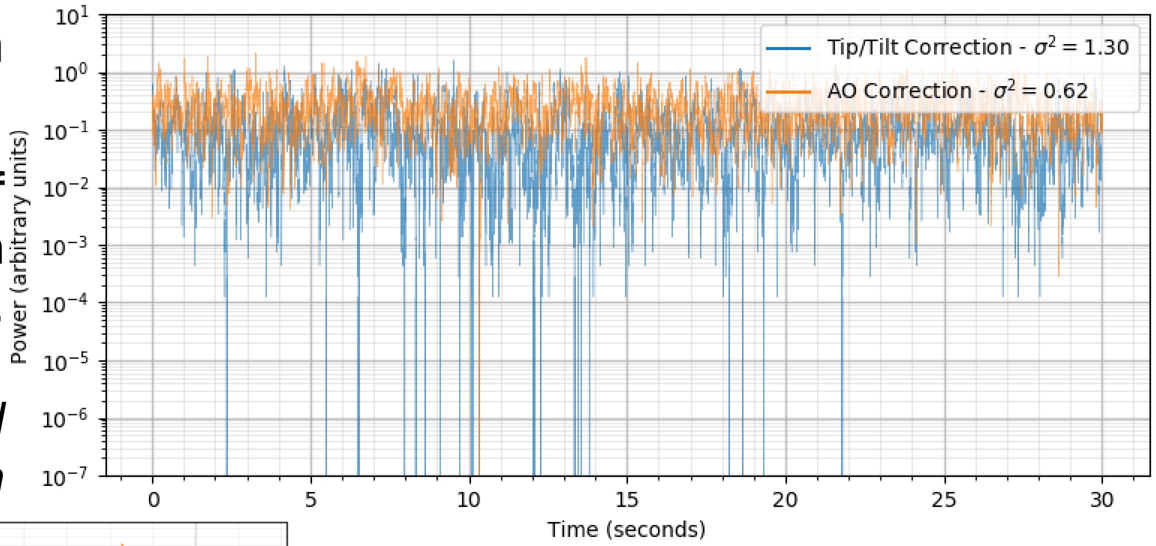


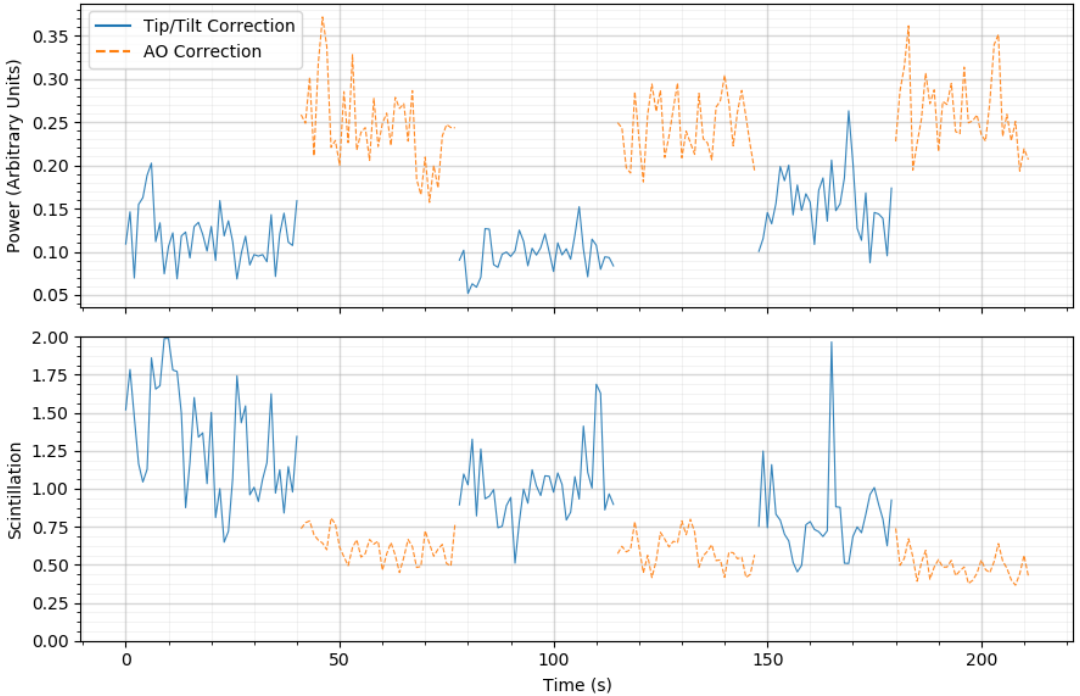
Long Exposure PSFs observed by *OGS* focus camera.

AO reduces size of the PSF and concentrates power.

High time resolution comparison of received power at *OGS* terminal when AO on or off for single link.

AO results in fewer fades and reduced scintillation





Power and Scintillation received at *OGS*, alternating between AO on and off.

Consistently higher power (+3.1dB) and lower scintillation (x0.55) with AO

DLR

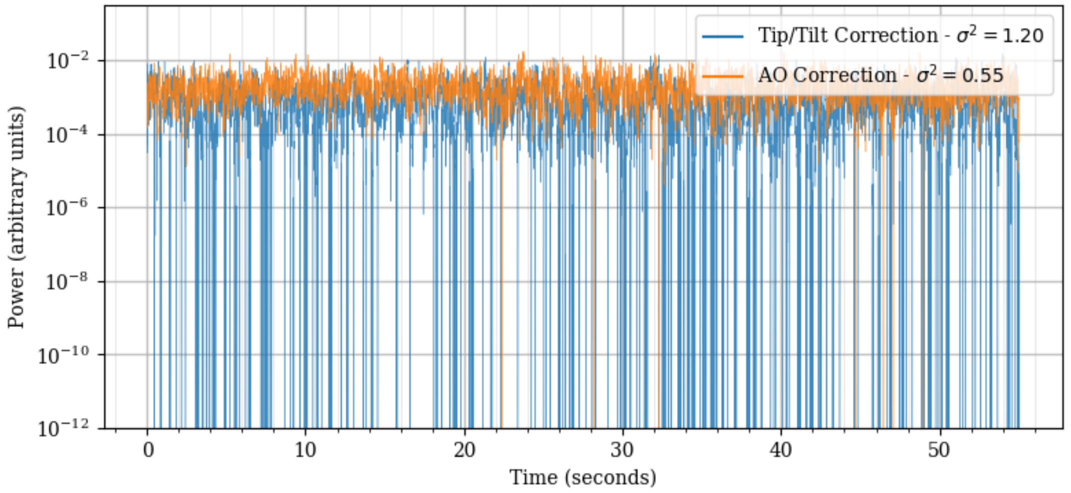
FSOC AO Demonstrator: **SAT Performance**

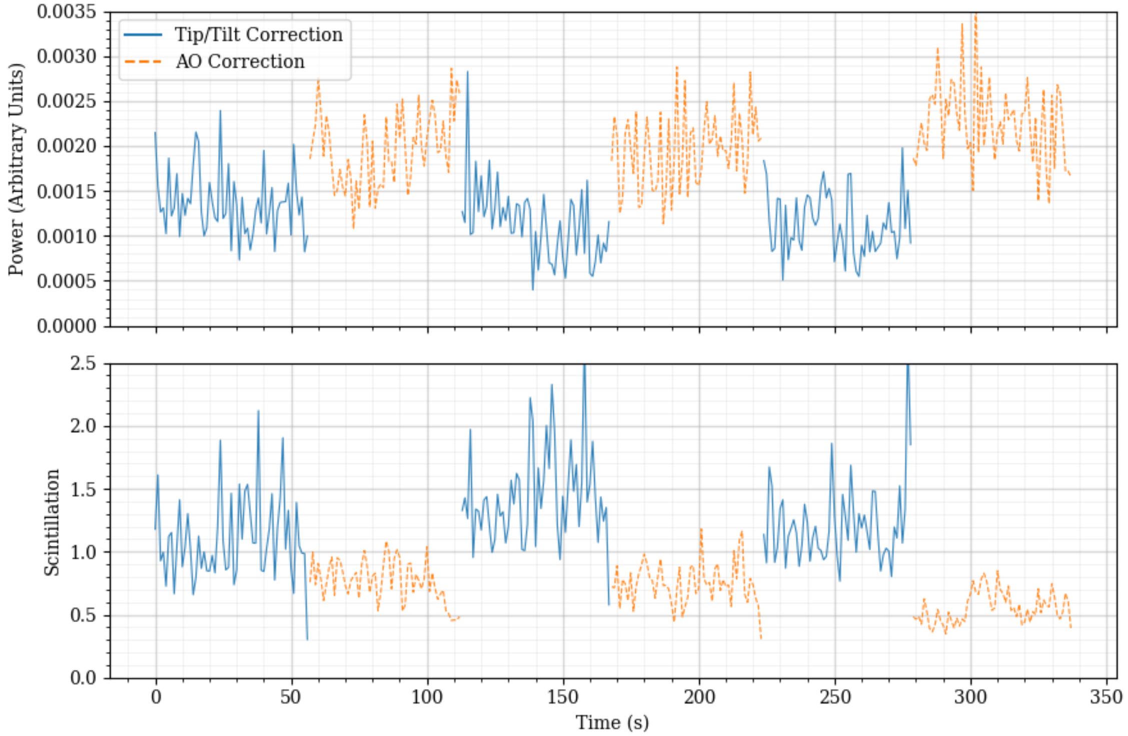
- **First demonstration of pre-distortion AO through turbulence conditions representative of the Geostationary case**

- PAA angle of 0 - Received and transmitted beam along same path

High time resolution comparison of received power at *SAT* terminal when AO on or off for single link.

AO results in fewer fades and reduced scintillation





Power and Scintillation received at *SAT*, alternating between AO on and off.

Consistently higher power (+2.4dB) and lower scintillation (x0.55) with AO

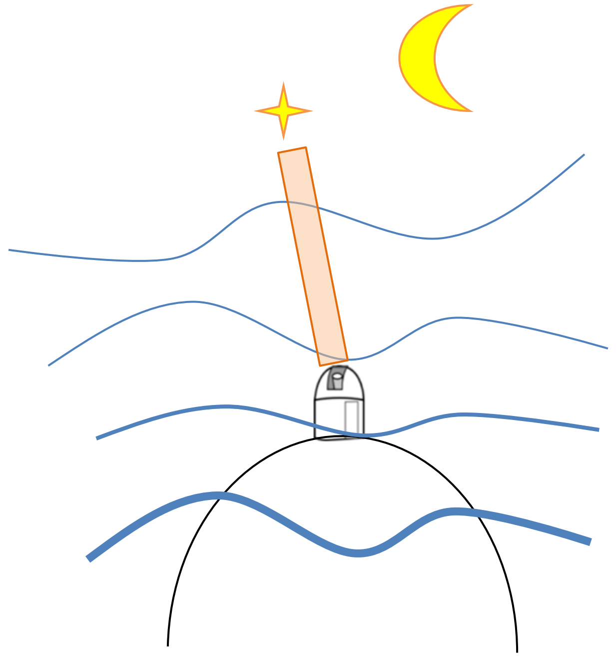
FSOC AO Demonstrator: **AO Performance Summary**

- Adaptive Optics system developed and integrated into OGS terminal on THRUST demonstrator
- Fibre Coupling efficiency and Scintillation statistics at OGS improved with AO
- **First demonstration of pre-distortion AO through turbulence representative of the GEO case**

	OGS			SAT		
Parameter	**Tip/Tilt Correction Only**	**AO Correction**	**Change**	**Tip/Tilt Correction Only**	**AO Correction**	**Change**
Mean Power (Normalized Arbitrary Units)	0.12	0.25	**x2.03 (+3.1 dB)**	0.0012	0.0021	**x1.75 (+2.43 dB)**
Mean Scintillation	1.04	0.57	**x0.55**	1.25	0.69	**x0.55**

- But more work to do to make system robust to all turbulence conditions

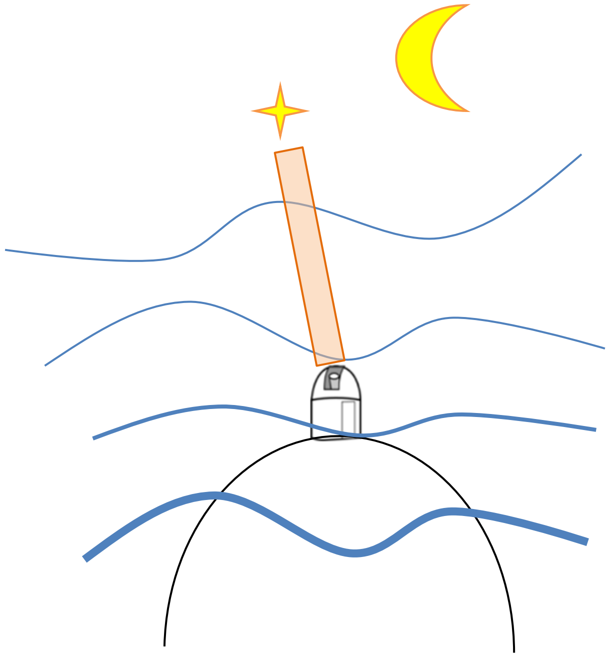
Current Activities:
Wavefront Sensing in Strong Turbulence



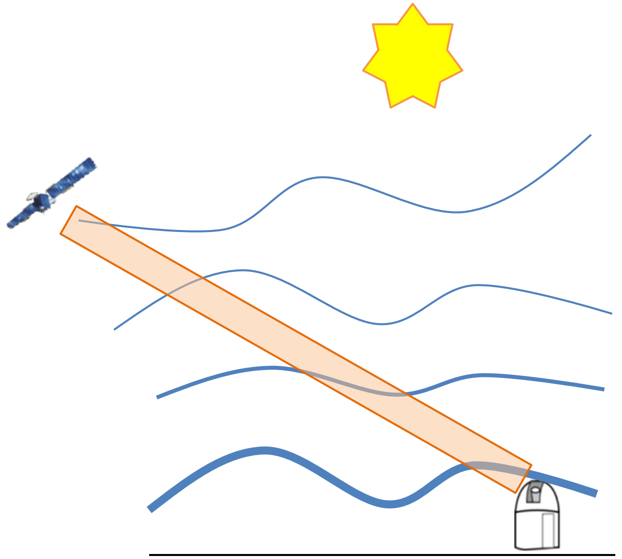
- **Previous AO research focussed on correcting "weak" turbulence**
  - Astronomical quality sites, high above the majority of turbulence
  - Only operate at night, when the atmosphere is cool and hence turbulence weak.
  - Observe closer to Zenith, so minimal path length through the turbulence
  - $r_0 \approx$ 10-20cm

Current Activities:
Wavefront Sensing in Strong Turbulence

- **Previous AO research focussed on correcting "weak" turbulence**
  - Astronomical quality sites, high above the majority of turbulence
  - Only operate at night, when the atmosphere is cool and hence turbulence weak.
  - Observe close to Zenith, so minimal path length through the turbulence
  - $r_0 \approx$ 10-20cm



- **FSOC AO must cope with significantly stronger turbulence**
  - Variety of sites, which may not be at high altitude, or with good "seeing"
  - Must operate at night and daytime
  - Observe at low altitudes, with long path length
  - $r_0 \approx$ 1-5cm

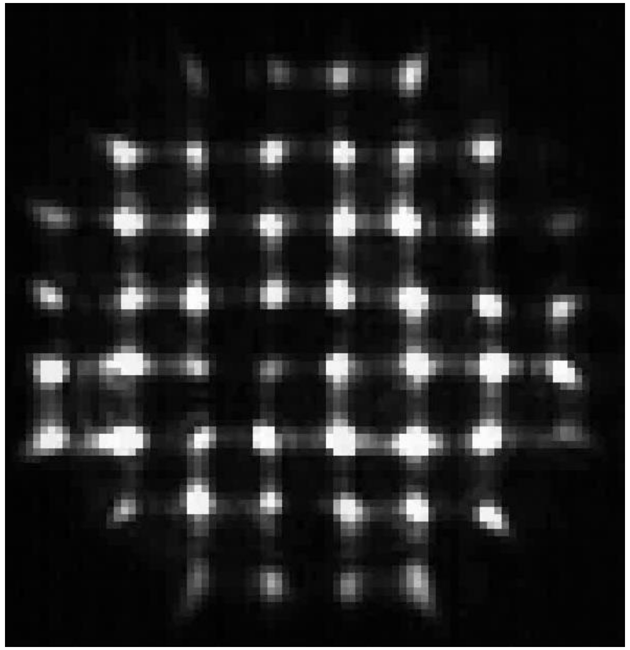


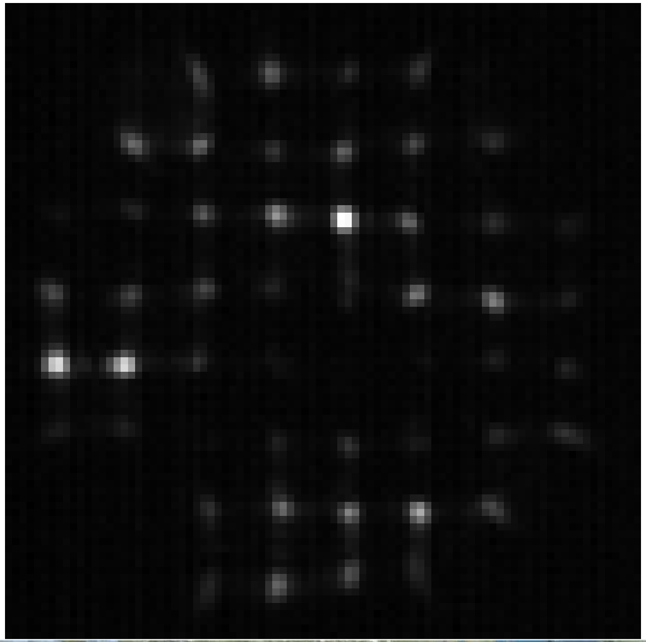
Current Activities:
Wavefront Sensing in Strong Turbulence

- Strong Turbulence makes wavefront sensing more difficult…
    - Phase distortions are strong enough to evolve into amplitude distortions across the telescope aperture. If a SH sub-aperture has no light it can not sense the wavefront at that point
    - “Branch Points” predicted – phase singularities which affect the wavefront but cannot be sensed by a gradient based WFS

- Investigating Optimisation of Shack-Hartmann WFS
    - Better wavefront reconstruction
    - Integration of noise statistics into control scheme

- Also investigating other WFS methods:
    - Iterative optimisation of the DM
    - Interferometric WFS





Current Activities:
Control System

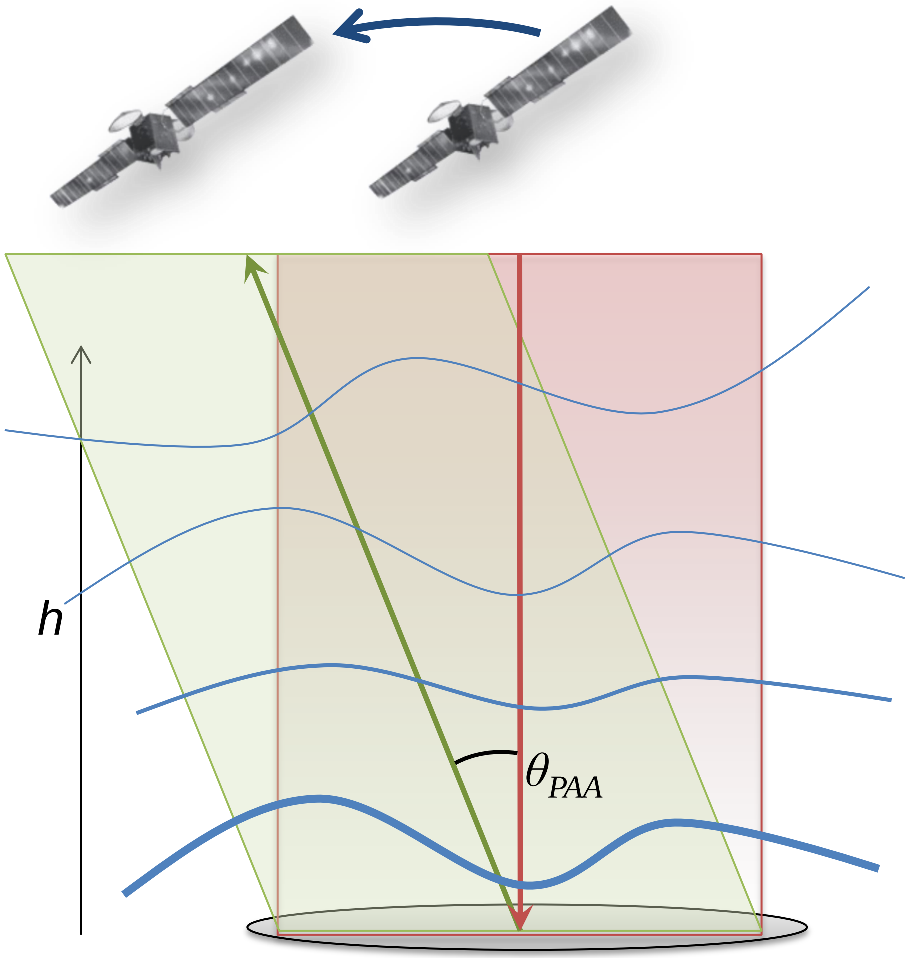
- **Temporal Error dominant in FSOC**
  - Fast, strong turbulence
  - Relatively small receiver aperture
- **Real-Time Control** must be fast, with low-latency and jitter
  - Frame rates of ~ 5kHz and more
  - Low latency and jitter
- Continuing to developing CPU based control systems
  - Fast development time compared to dedicated hardware solutions
  - Flexible software architecture possible
  - Compatible upgraded hardware under constant development

- **Advanced Control algorithms** may provide significant performance gains
  - More robust to WFS errors
  - Turbulence “prediction” to minimise temporal errors

Current Activities:
PAA investigation and mitigation

- PAA problem must be further investigated
  - **FSOC demonstrator can emulate PAA with a separate moveable beacon.**
  - Will further investigate in future measurement campaigns

"Point Ahead" Beacon between 0 and ~50 µRad

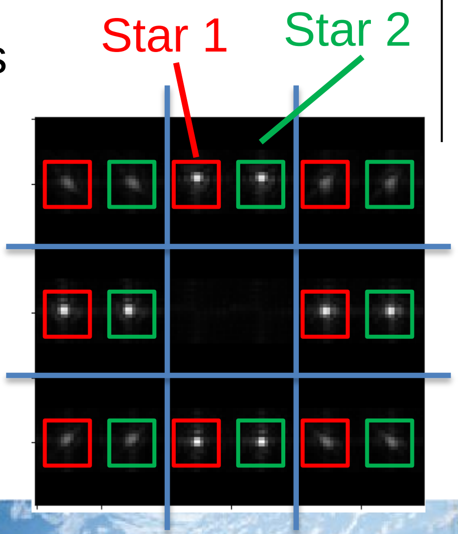


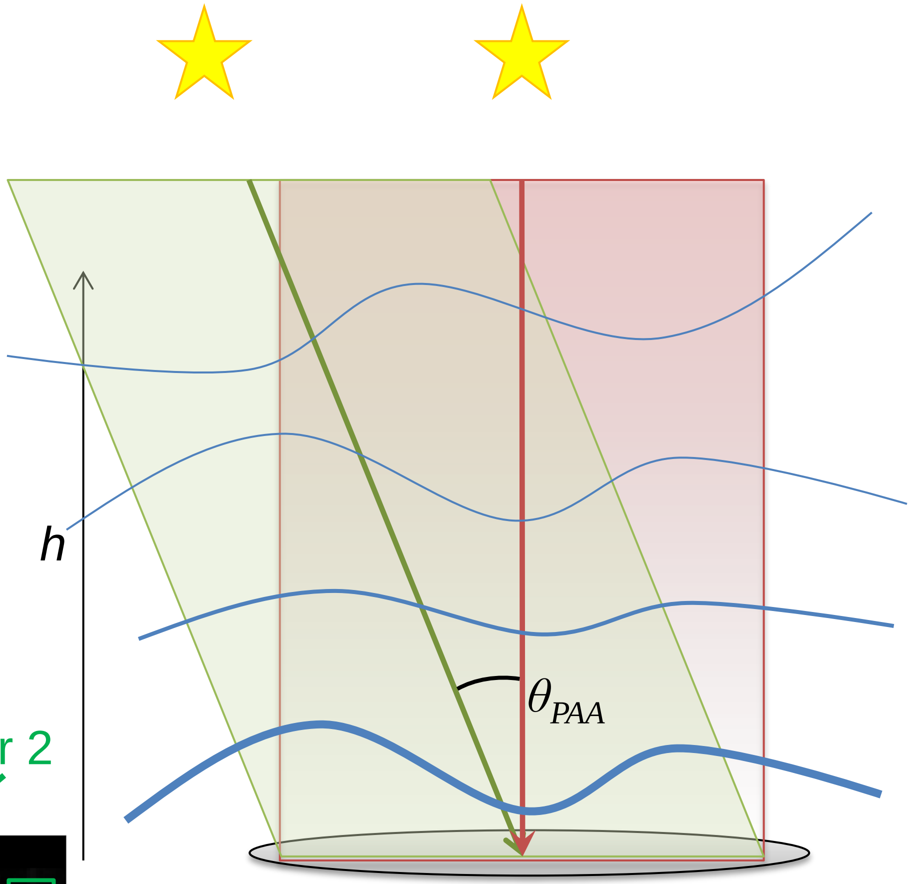
Optical Ground Station Telescope

Current Activities:
PAA investigation and mitigation

- PAA problem must be further investigated
  - **FSOC demonstrator can emulate PAA with a separate moveable beacon.**
  - Will further investigate in future measurement campaigns

- "**Alcor**" project to measure the size of the "isoplanatic" and "isokinetic" patch
  - Observes pairs of natural double stars
  - Measures correlation of low order spatial modes between lines of sight
  - Operate in a variety of conditions





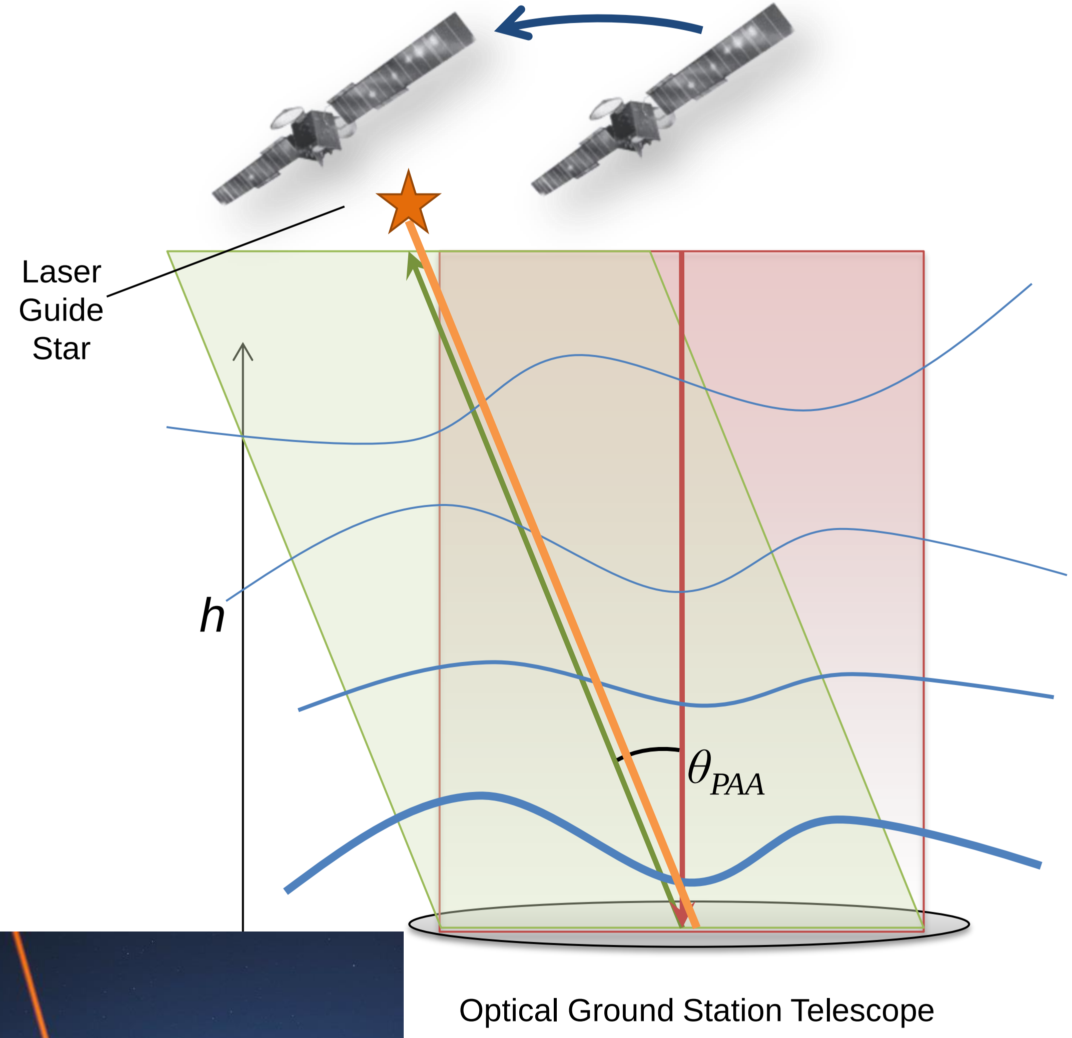
Optical Ground Station Telescope

Current Activities:
PAA investigation and mitigation

- PAA problem must be further investigated
  - **FSOC demonstrator can emulate PAA with a separate moveable beacon.**
  - Will further investigate in future measurement campaigns

- "**Alcor**" project to measure the size of the "isoplanatic" and "isokinetic" patch
  - Observes pairs of natural double stars
  - Measures correlation of low order spatial modes between lines of sight
  - Operate in a variety of conditions

- "**Laser Guide Stars**" can create wavefront reference in desired direction CoI
  - Collaboration with ESO, Durham University and INAF-OAR



Summary

- **Adaptive Optics** has the potential to improve the performance of Free Space Optical Communications by correcting for the adverse effects of atmospheric turbulence

- AO can improve potentially optical communications in downlink and uplink with **pre-distortion**

- **AO demonstrator** has been integrated and operated successfully
  - Improvements observed in **downlink and uplink**
  - Demonstration of pre-distortion AO through GEO-like turbulence case

- Current investigations into optimising AO for FSOC
  - Wavefront sensing in strong turbulence
  - Improving control system and algorithms
  - Quantifying and mitigation of PAA isoplanatism problem

DLR

Demonstrations of Pre-Distortion Adaptive Optics for Free Space Optical Communications

COAT2019

Andrew Reeves
Institute of Communications and Navigation
German Aerospace Centre

DLR