UNIVERSITÀ DEGLI STUDI DI PADOVA

Sviluppo di sistemi di ottica adattiva per satelliti

Lorenzo Borsoi - 39th Cycle

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Co-Supervisors: Dr. Stefano Bonora, Prof. Francesco Vedovato

Admission to the second year - December 11th, 2024

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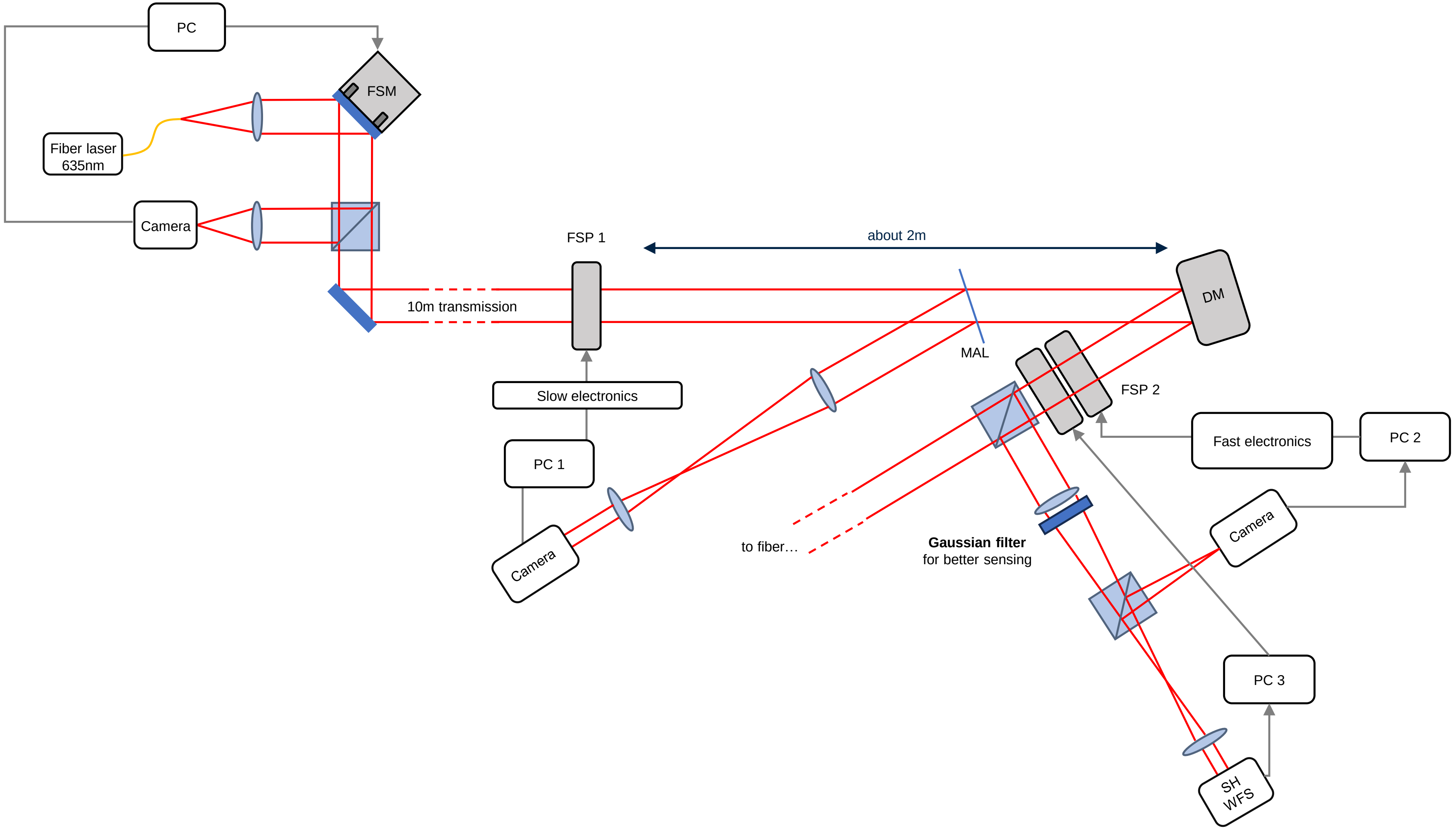
Research Project objectives

QUANTERA

- **Name:** Quantum Dots for Entanglement-based Quantum Key Distribution (**QD-E-QKD**).
- **Consortium:** University "La Sapienza" of Rome (Coordinator), CNR-IFN of Padua and others.
- **Funding:** This project is funded within QuantERA II Programme, a European network of Research Funding Organisations (RFOs) dedicated to advancing Quantum Technologies (QT).
- **Objective:** Develop a novel quantum key distribution (QKD) technology based on semiconductor quantum dots (QDs) to enable entanglement-based QKD networks without trusted nodes.
- **Communication Approaches:** Implements QKD via single-mode fiber and free-space optical channels, integrating time-to-digital conversion, optical clock recovery, and adaptive optics with deformable lenses for stable operation.
- **Benchmarking and Certification:** Provides quantitative benchmarks and theoretical modeling to certify advancements over current entanglement-based QKD systems.
- **Impact:** Offers a scalable, robust technology for future complex QKD networks, addressing limitations of current probabilistic photon-generation methods.
- **Website**: https://quantera.eu/qd-e-qkd/

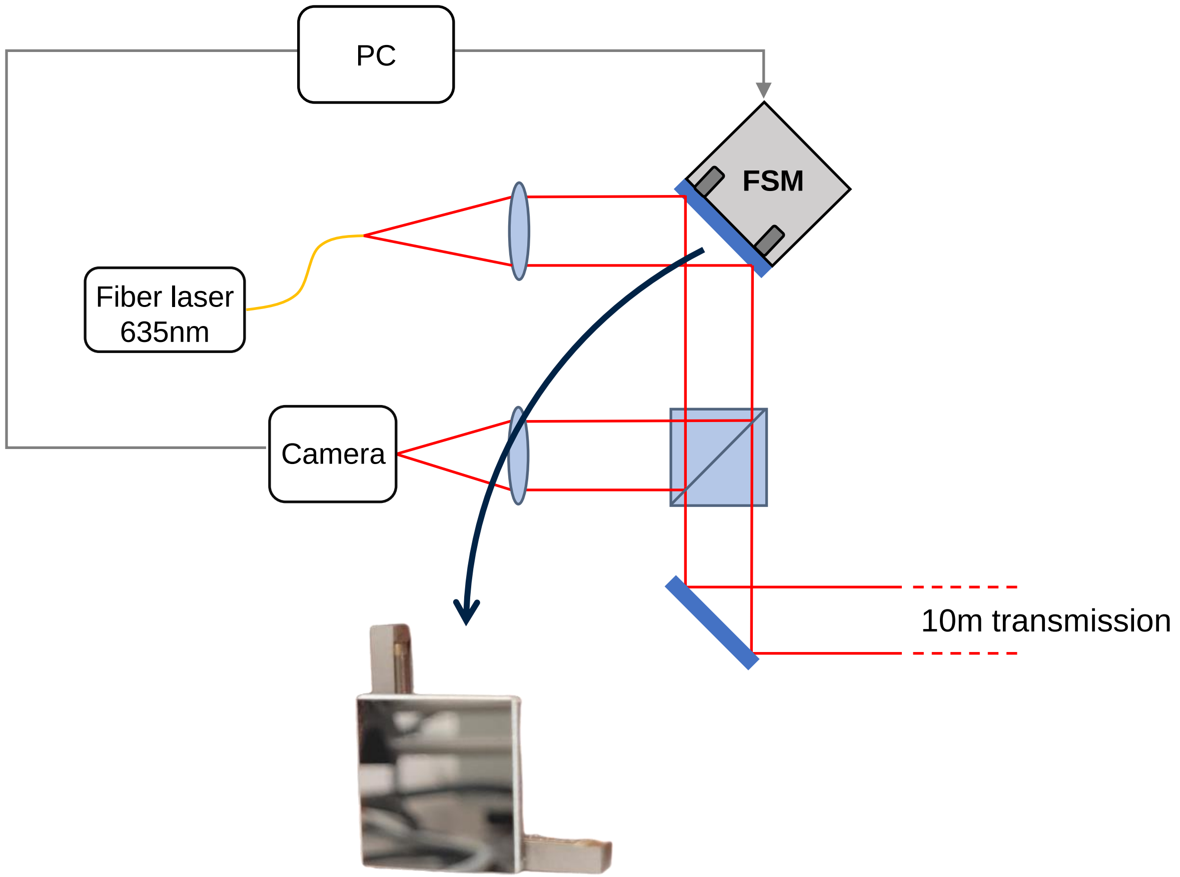
QD-E-QKD: experimental layout



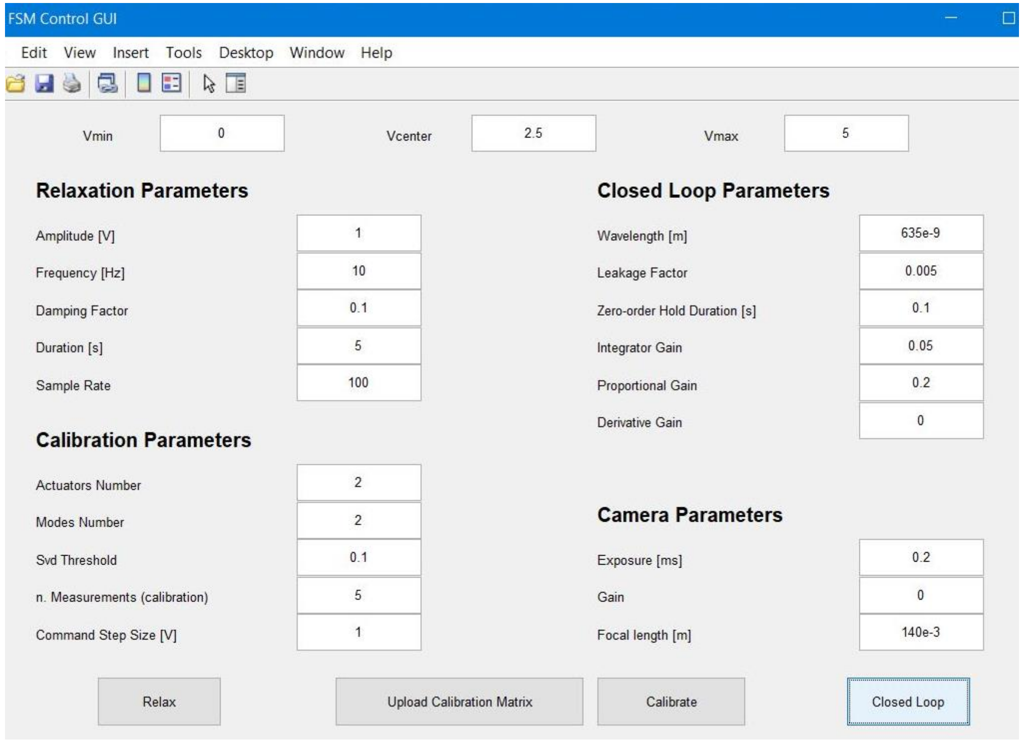
Conceptual layout: Tx (1)

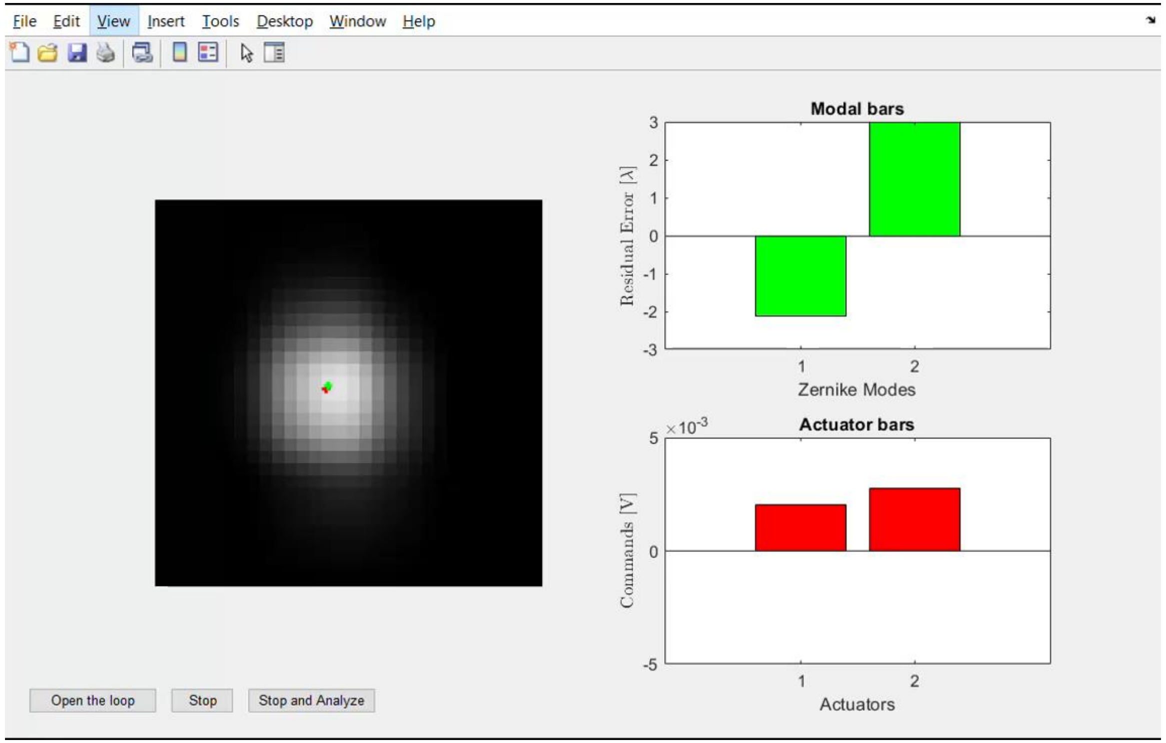
Transmitter

- 635nm Gaussian beam
- Fast Steering Mirror (FSM) at the transmitter with feedback from camera for slow drift correction and beam wandering generation (open loop)
- Propagation distance is 10m inside laboratory with multiple reflections
- Beam Wandering is generated to resemble the one registered in Rome’s 270m free-space optical link.



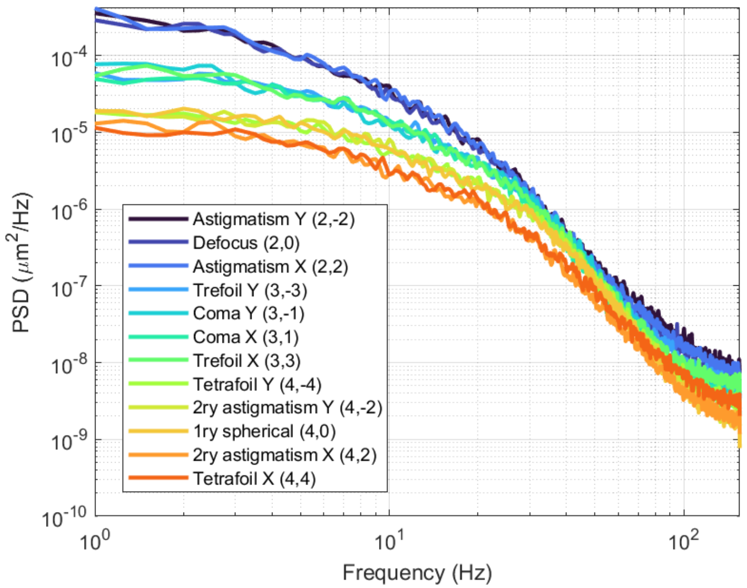
FSM: PID controller





Conceptual layout: Tx (2)

- The atmospheric turbulence time series was recorded in Rome, using a real physical system.
- The Power Spectral Density (PSD) is shown in the adjacent image.

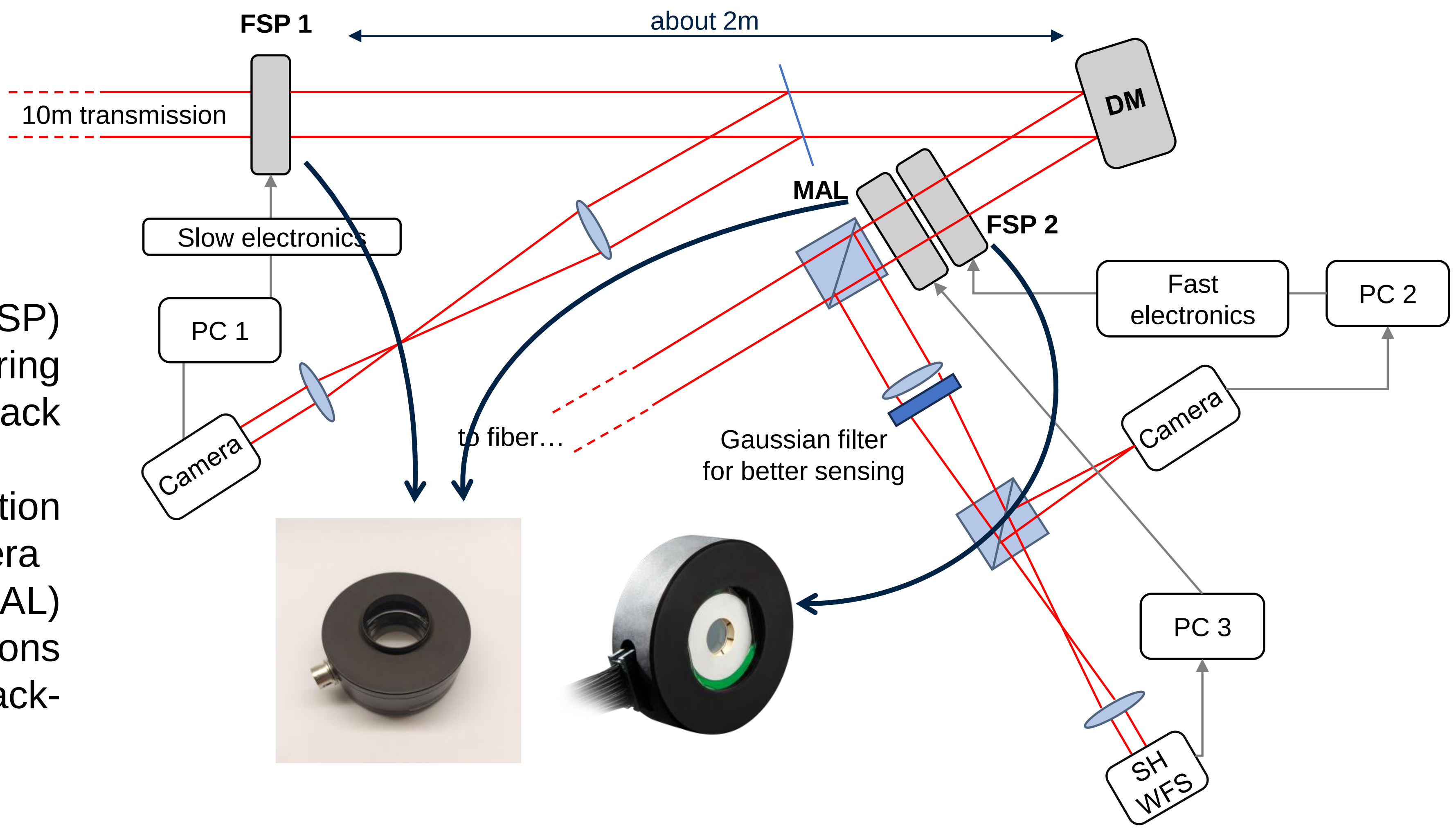


- The time series was input into a 64-actuator Deformable Mirror (DM) to generate high-order Zernike modes.

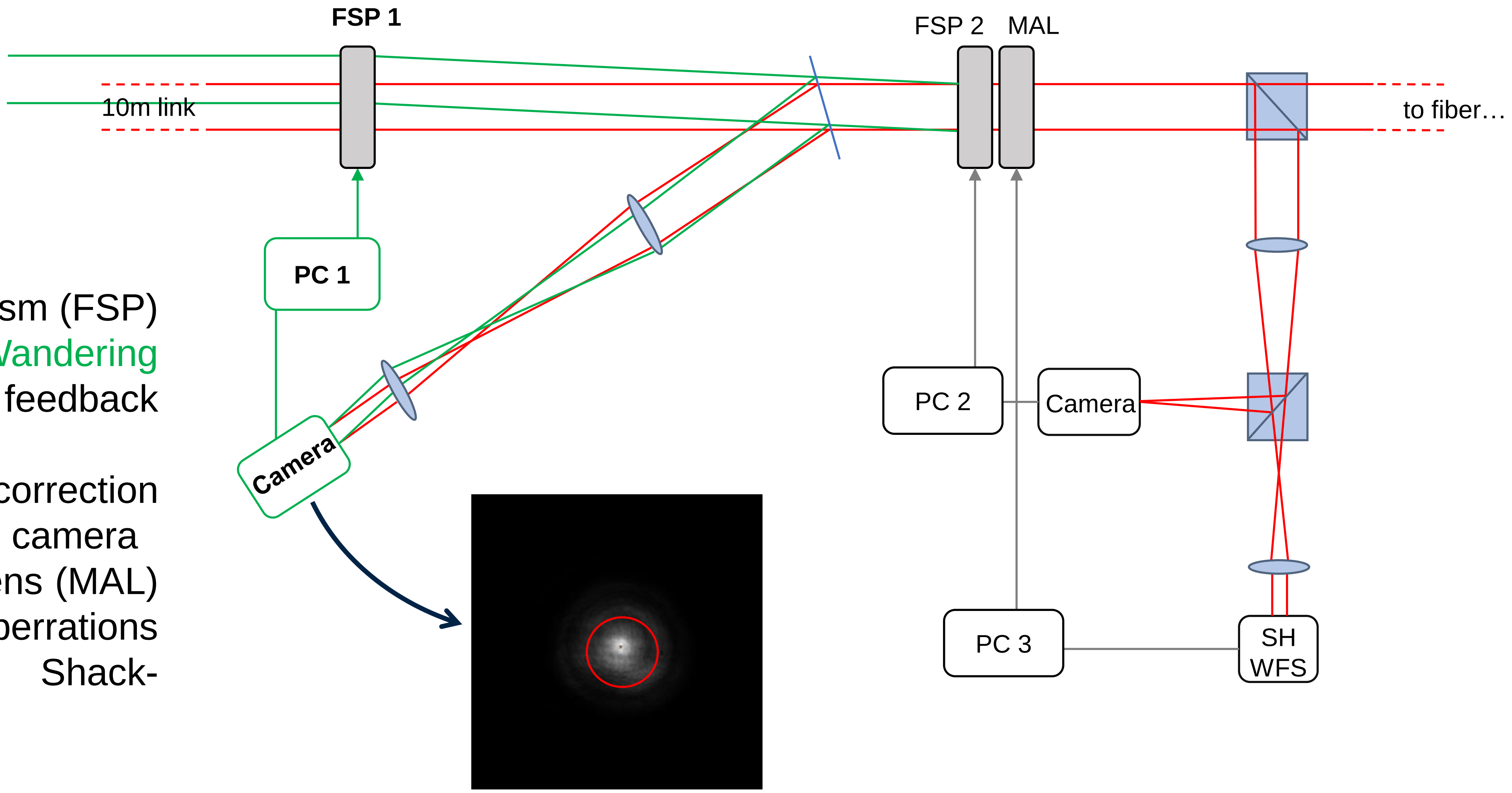
Conceptual layout: Rx (1)

Receiver

- 1 Fast Steering Prism (FSP) for Beam Wandering correction with feedback from camera
- 1 FSP for tip tilt correction with feedback from camera
- 1 Multi Actuator Lens (MAL) for high order aberrations correction with Shack-Hartmann WFS



Conceptual layout: Rx (2)



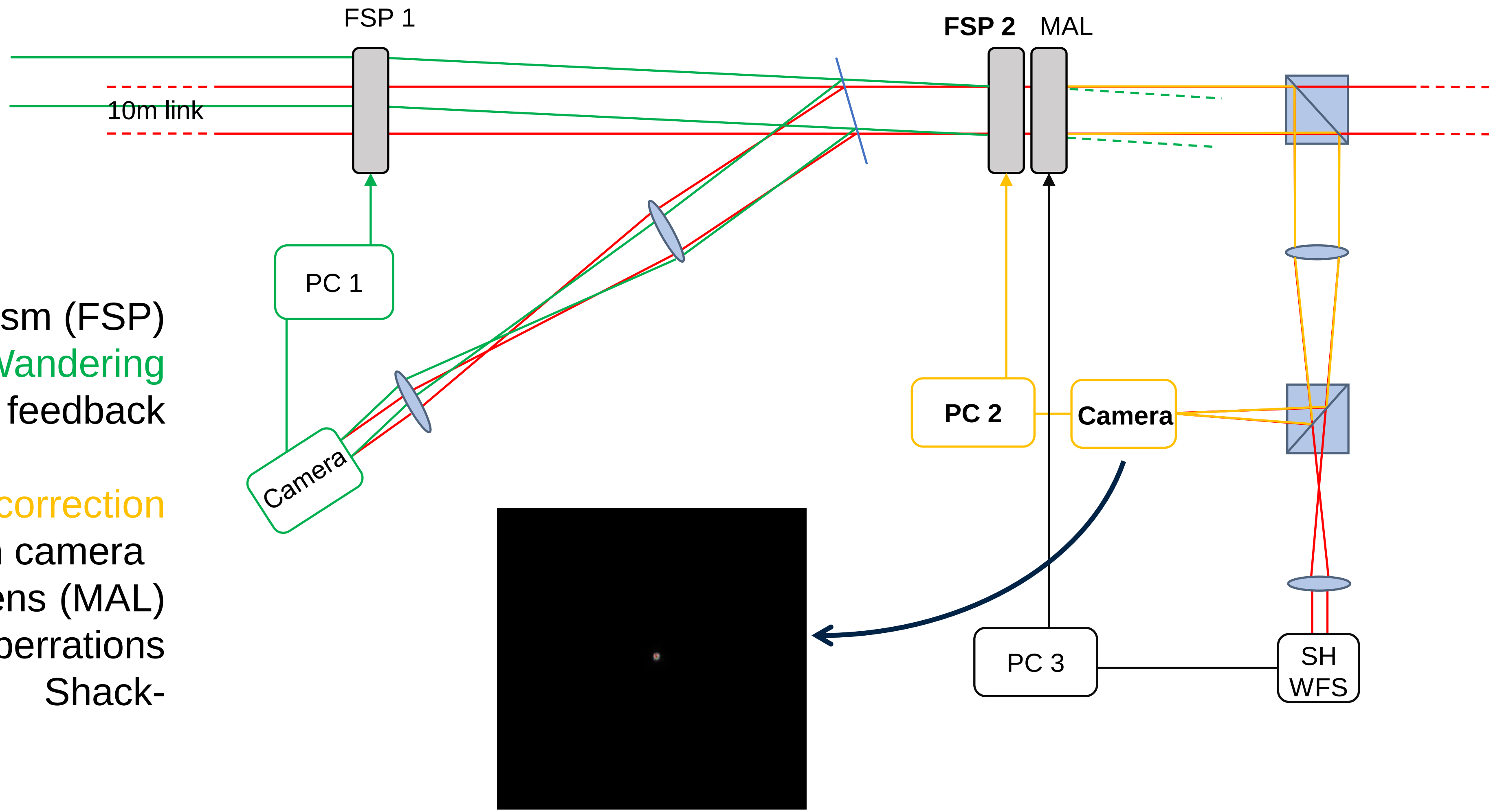
Receiver

- 1 Fast Steering Prism (FSP) for Beam Wandering correction with feedback from camera
- 1 FSP for tip tilt correction with feedback from camera
- 1 Multi Actuator Lens (MAL) for high order aberrations correction with Shack-Hartmann WFS

Conceptual layout: Rx (3)

Receiver

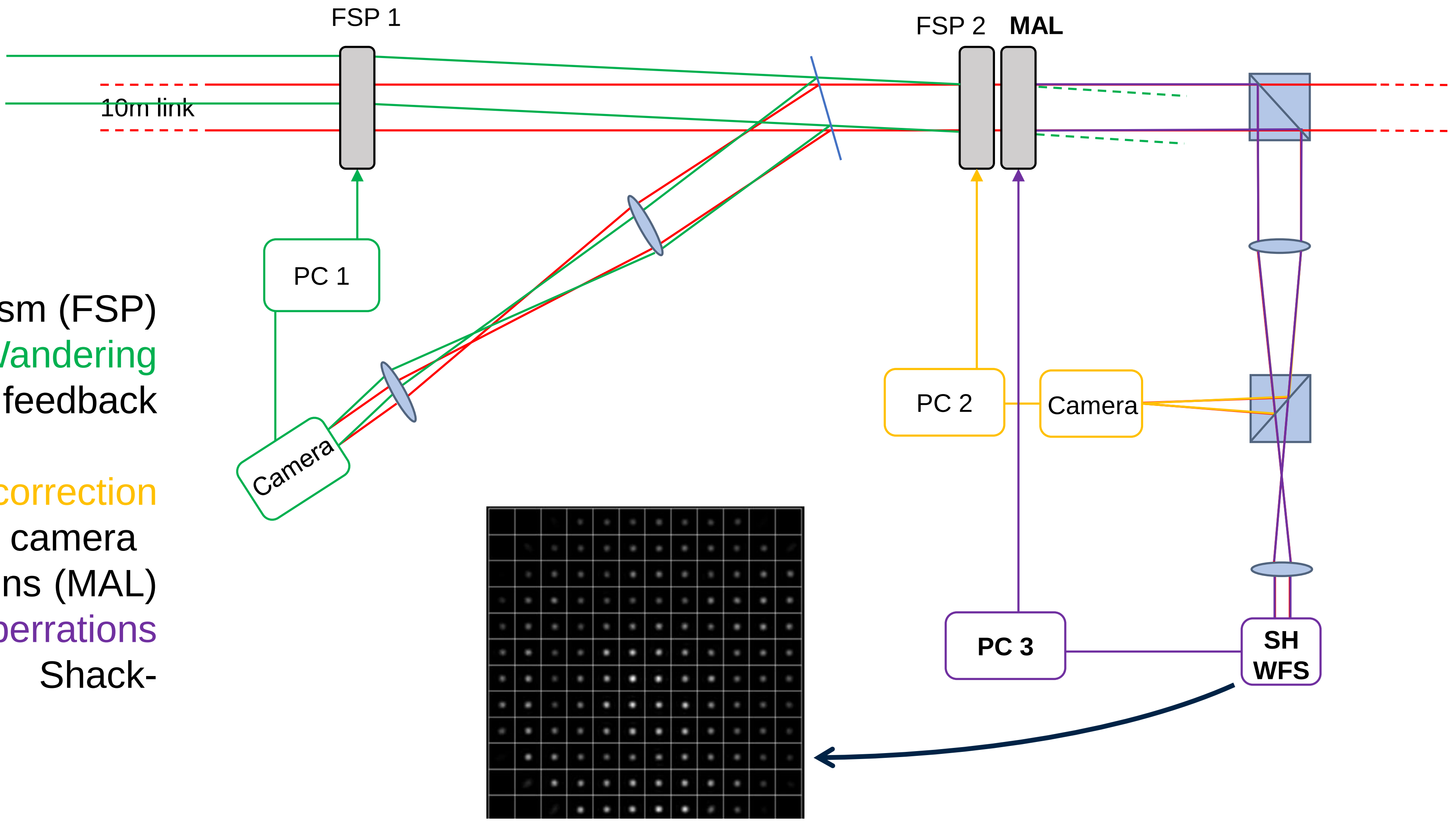
- 1 Fast Steering Prism (FSP) for Beam Wandering correction with feedback from camera
- 1 FSP for tip-tilt correction with feedback from camera
- 1 Multi Actuator Lens (MAL) for high order aberrations correction with Shack-Hartmann WFS



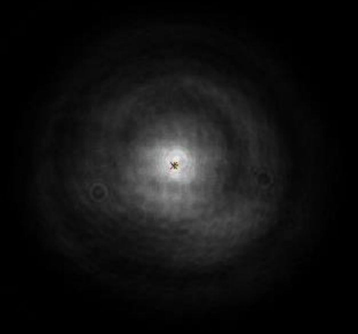
Conceptual layout: Rx (4)

Receiver

- 1 Fast Steering Prism (FSP) for Beam Wandering correction with feedback from camera
- 1 FSP for tip tilt correction with feedback from camera
- 1 Multi Actuator Lens (MAL) for high order aberrations correction with Shack-Hartmann WFS

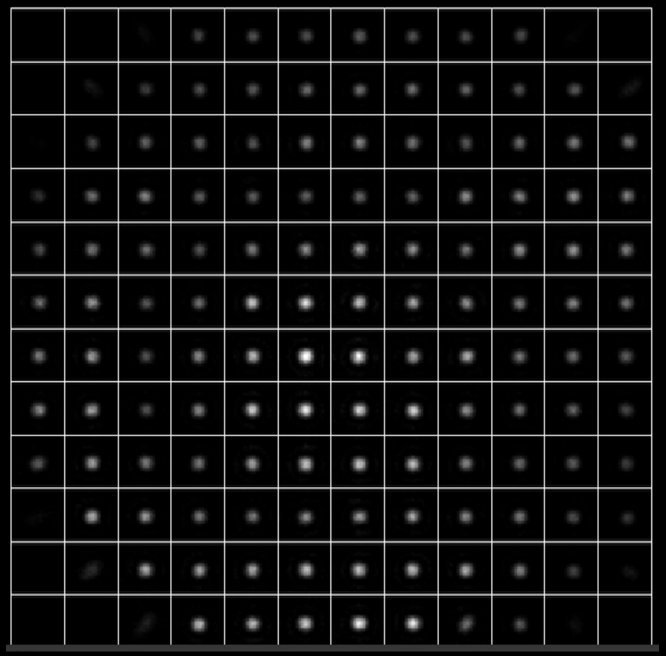


CAMERA 1 (FSP 1)



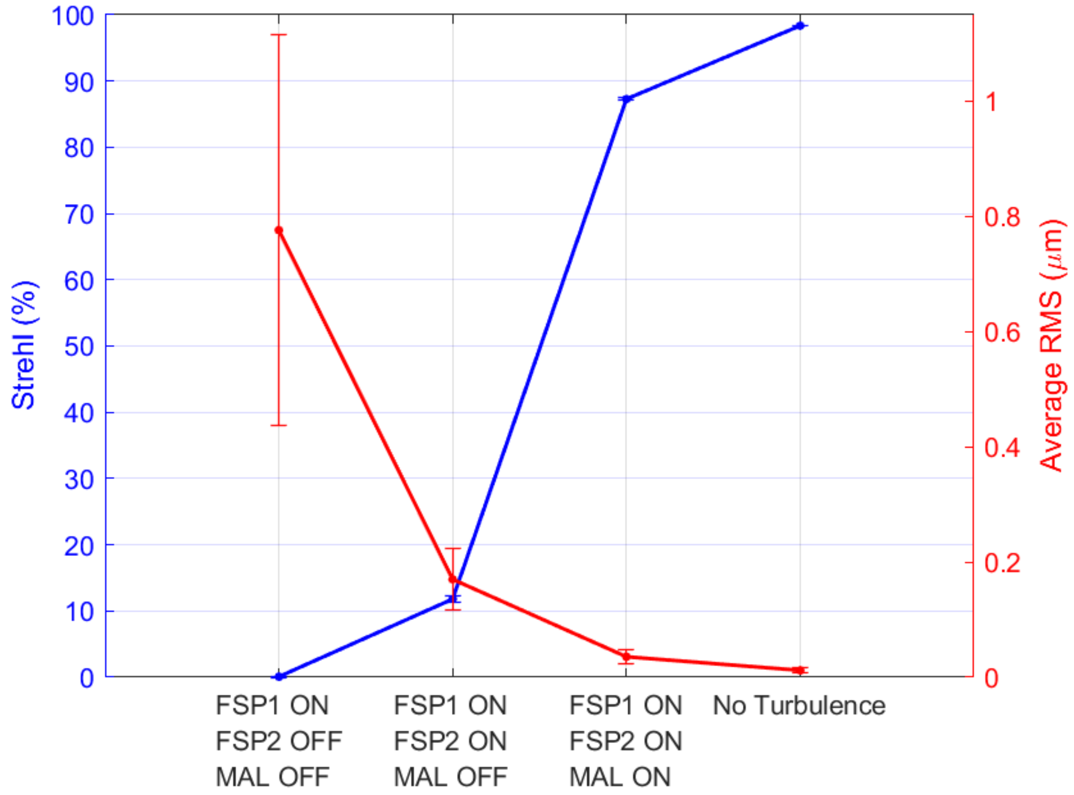
CAMERA 2 (FSP 2)

SH-WFS (MAL)



SH-WFS analysis

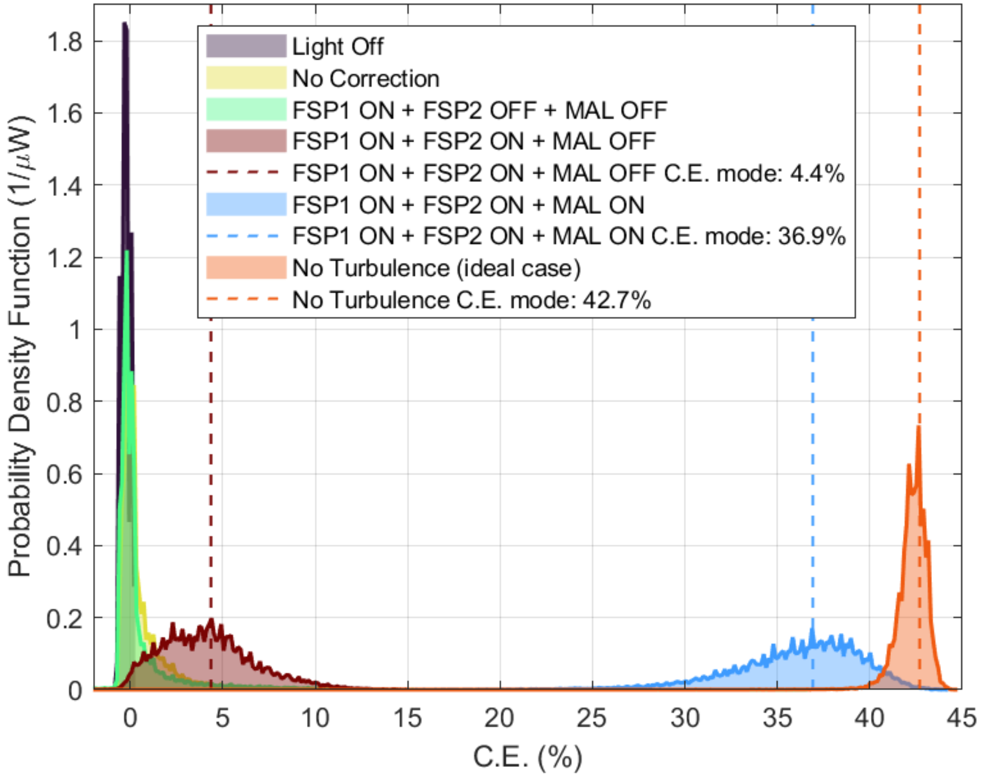
1. **FSP1 ON + FSP2 OFF + MAL OFF:** Nearly zero Strehl ratio, high RMS.
2. **FSP1 ON + FSP2 ON + MAL OFF** : Slight recovery in Strehl ratio and a drop in RMS, showing moderate correction of beam wandering and residual tip-tilt.
3. **FSP1 ON + FSP2 ON + MAL ON** : Significant improvement in Strehl and minimal RMS, due to correction of both beam wandering and turbulence.
4. **No Turbulence**: Highest Strehl and nearly zero RMS, representing the ideal condition.

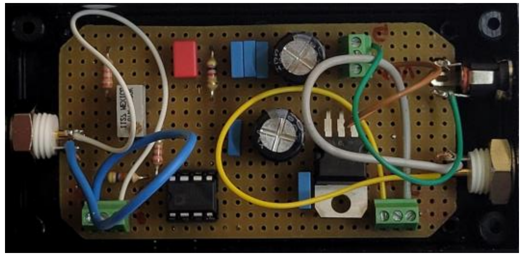


Fiber coupling efficiency

- **No turbulence (ideal case):**
  The coupling efficiency follows a normal distribution around 42.7%.
- **Light off or turbulence uncorrected:**
  The coupling efficiency drops to 0%.
- **FSP1 only activated:**
  Beam wandering is corrected, but the residual tip-tilt remains uncorrected (FSP2 inactive), so the coupling efficiency stays at 0%.
- **FSP1 and FSP2 activated:**
  The residual tip-tilt is compensated, resulting in a coupling efficiency distributed around 4.4%.
- **FSP1, FSP2 and MAL activated (beam wandering and high-order turbulence correction):**
  The coupling efficiency follows a distribution around 36.9%.

- A "handcrafted" linear operational amplifier boost the photodiode's signal to facilitate its reading by the DAQ.





Conclusions and Future works

Conclusions

- The results demonstrate the significant impact of correcting both beam wandering and turbulence on optical performance, with noticeable improvements in Strehl ratio (up to 87% on average) and coupling efficiency (up to 37% on average). This is crucial for improving the reliability and stability of optical communication links without diverging the transmitted beam, which would result in power loss.
- **Field tests** are scheduled for mid-February on a 270-meter optical link in Rome.
- The **paper** is being written, with submission planned for early 2025.

Future works

The use of Digital Micromirror Devices (DMD) for high-speed turbulence correction (>20 kHz) through binary holograms is currently under investigation, with optical bench tests set to begin in January 2025.

Gantt chart

GANTT CHART

PHD STUDENT	Lorenzo Borsoi	DATE	11/12/2024
PHD THESIS	Sviluppo di sistemi di ottica adattiva per satelliti	ADMISSION TO	Second Year

WBS NUMBER	TASK TITLE	% OF TASK COMPLETE
1	System study and definition	
1.1	Scientific literature review	100%
1.2	System definition	100%
1.3	Requirement specification	100%
2	Opto-mechanical design and simulations	
2.1	Optical design	100%
2.2	Mechanical design	50%
2.3	Channel performance simulation	50%
3	Prototyping and testing	
3.1	Experimental setup realization	50%
3.2	System prototyping	0%
3.3	Breadboard testing	0%
4	System improvements	
4.1	Integration and qualification in relevant environment	0%
5	PhD thesis and reports	
5.1	Writing reports	30%
5.2	Writing PhD thesis	0%

FIRST YEAR / SECOND YEAR / THIRD YEAR — T1 T2 T3 T4 — J F M A M J J A S O N D

Thanks for the attention

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