PREDICTIVE CONTROL SCHEMES FOR ADAPTIVE OPTICS IN FREE SPACE OPTICAL COMMUNICATION

J. S. Torres (1,2), H.-F. Raynaud (2), A. P. Reeves (1), D. Laidlaw (1), C. Kulcsár (2)

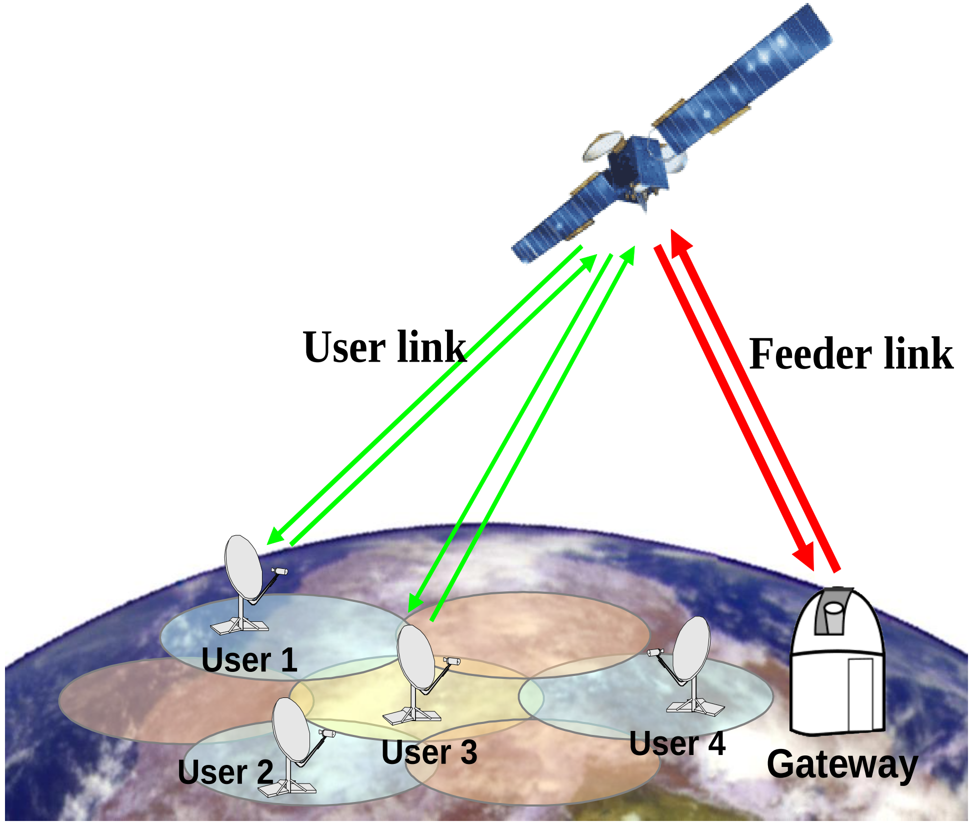
(1) Institute for Communication and Navigation, German Aerospace Center (DLR), 82234 Weßling, Germany

(2) Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127, Palaiseau, France

Introduction

Free Space Optical Communication (FSOC)

- High-speed data transmission in free space using light as an information carrier;
- Significantly advantageous over Radio Frequency (RF):
  - High bandwidth;
  - Unregulated spectrum;
  - Enhanced security.
- <u>Atmospheric Turbulence:</u>
  - Scintillation and fades at the satellite;
  - Reduced and unreliable fibre coupling efficiency at the Optical Ground Station (OGS).



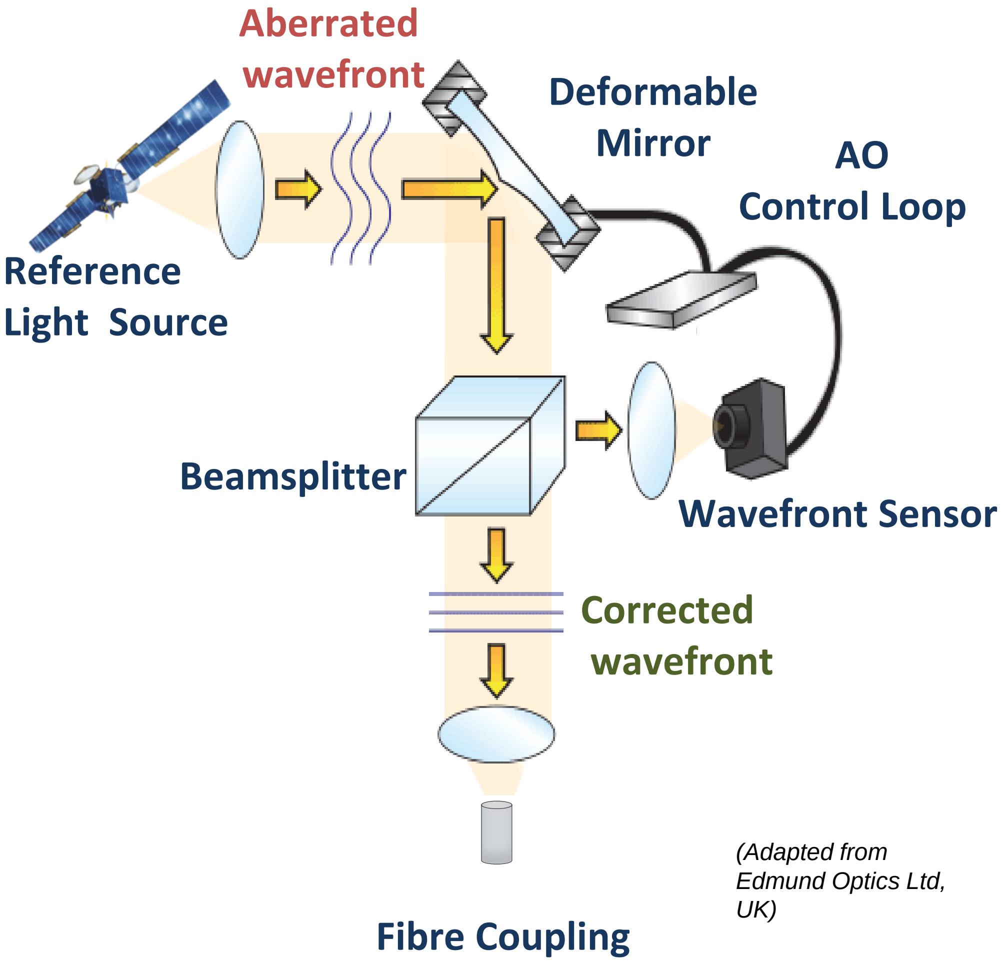
(Adapted from European AO Summer School 2023)

Introduction

Adaptive Optics (AO) for FSOC

- Wavefront distortion and pre-distortion compensation;

- Key differences from Astronomy:
    - − Non-optimal telescope locations;
    - − Stronger and faster changing turbulence;
    - − Lower Fried Parameter (r0);
    - − Required higher operation frequency;
    - ✓ Brighter reference;
    - ✓ Smaller aperture diameters.



(Adapted from Edmund Optics Ltd, UK)

Introduction

Application Specifications

Main Challenges

- Strong, fast changing turbulence;
- Strong scintillation:
  - Elevated number of fades on the wavefront;
  - Missing measurements;

Integral action control prone to instability

Resulting Requirements

- Extract turbulence characteristics to build predictive models;
- Minimise the scintillation and resulting fades;
- Maximise coupling efficiency;

Alternative robust predictive control algorithms

Predictive Control Algorithms

Linear Quadratic Gaussian Regulator

- Build a dynamical stochastic model of the phase:

$$X_{k+1} = AX_k + v$$

$$\phi_k = C_\phi X_k$$

- Predict the phase with a Kalman Filter:

$$\hat{X}_{k+1|k} = (\mathrm{A} - L_\infty C)\hat{X}_{k|k-1} + L_\infty(y_k - M_{int}u_{k-2})$$

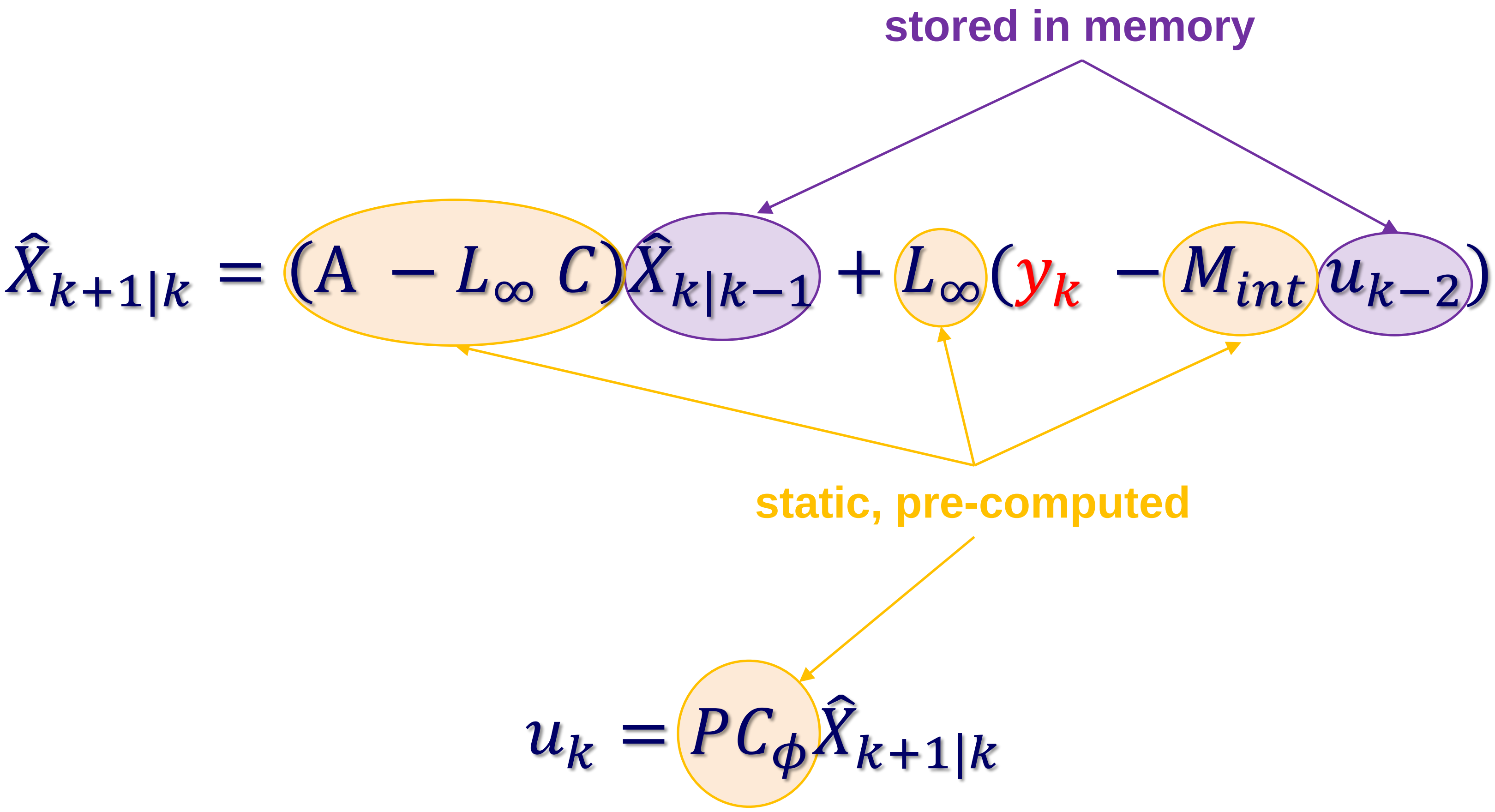
- Project the predicted phase onto the actuator space:

$$u_k = P\hat{\phi}_{k+1|k} = PC_\phi\hat{X}_{k+1|k}$$

X	State vector
A	State matrix
v	Process noise
ϕ	Phase disturbance
C_ϕ	State to phase
L_∞	Kalman gain
y	Vector of measurements
M_{int}	Actuator to measurement
u	Vector of control commands
P	Phase to actuators

Predictive Control Algorithms

Linear Quadratic Gaussian Regulator



stored in memory

$$\hat{X}_{k+1|k} = (A - L_\infty C)\hat{X}_{k|k-1} + L_\infty(y_k - M_{int} u_{k-2})$$

static, pre-computed

$$u_k = P C_\phi \hat{X}_{k+1|k}$$

X	State vector
A	State matrix
v	Process noise
ϕ	Phase disturbance
C_ϕ	State to phase
L_∞	Kalman gain
y	Vector of measurements
M_{int}	Actuator to measurement
u	Vector of control commands
P	Phase to actuators

Predictive Control Algorithms

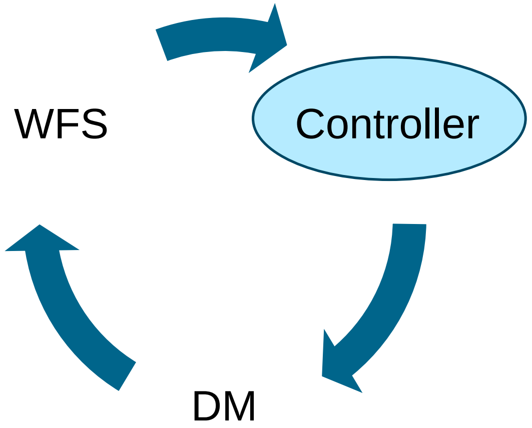
Linear Quadratic Gaussian Regulator

Optimization: Parallel Computing

$$\hat{X}_{k+1|k} = M_1 \hat{X}_{k|k-1} + M_2 y_k - M_3 u_{k-2}$$

$$u_k = M_4 \hat{X}_{k+1|k}$$

Main Loop Process



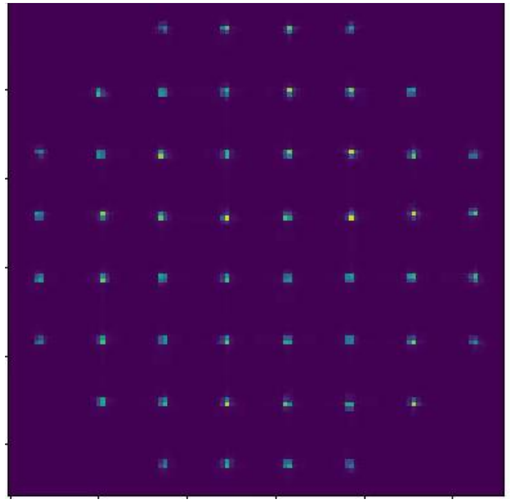
$$u_k = n_{k-1} + M y_k$$

Parallel Calculations

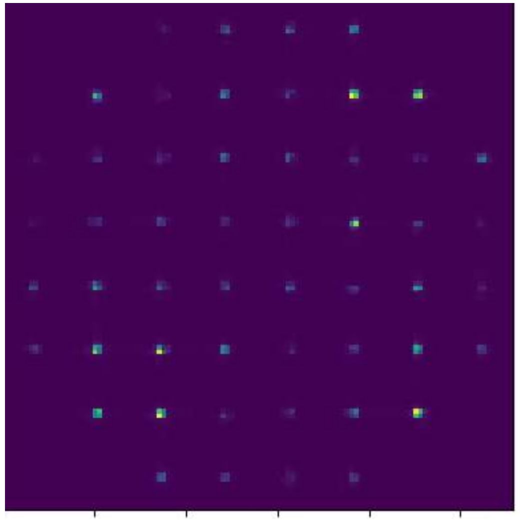
- intermediate variables
- recurrences

Predictive Control Algorithms
Addressing Scintillation

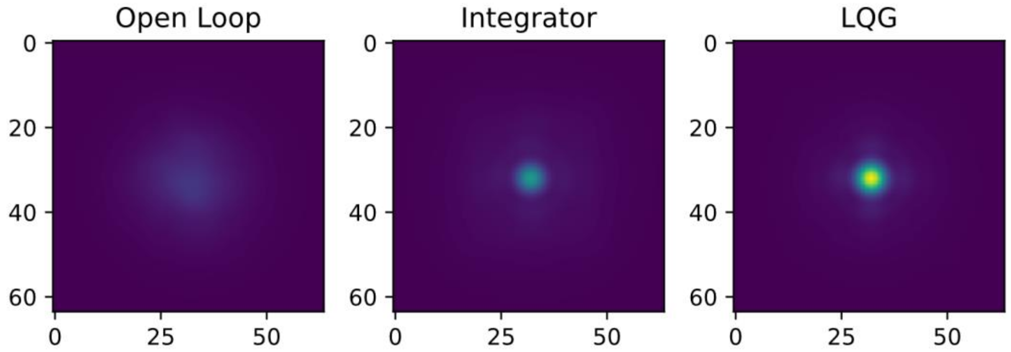
without scintillation

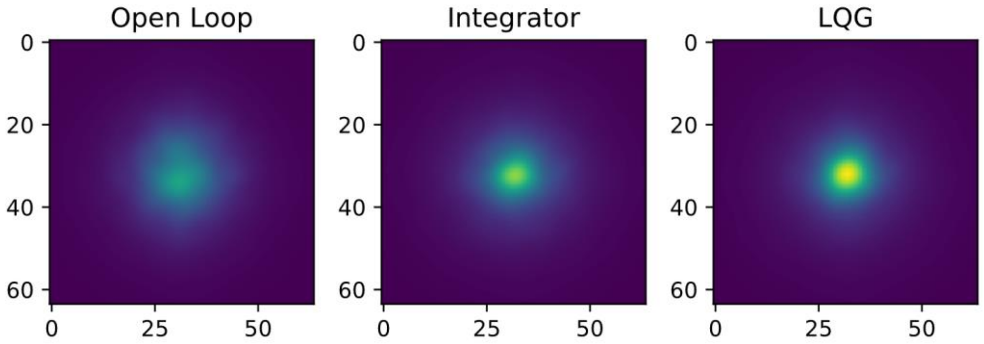


with scintillation



Animations slowed down:
- r0 = 2 cm @ 550nm
- 2000 frames (at 2 kHz)
- 1second →1 minute

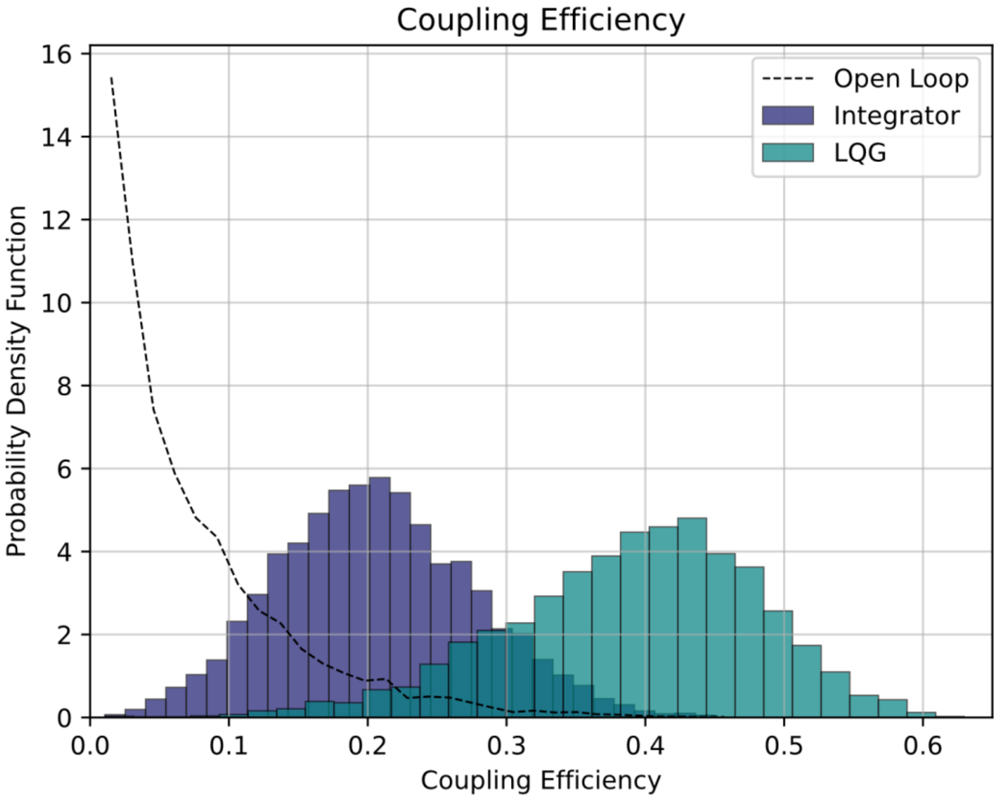




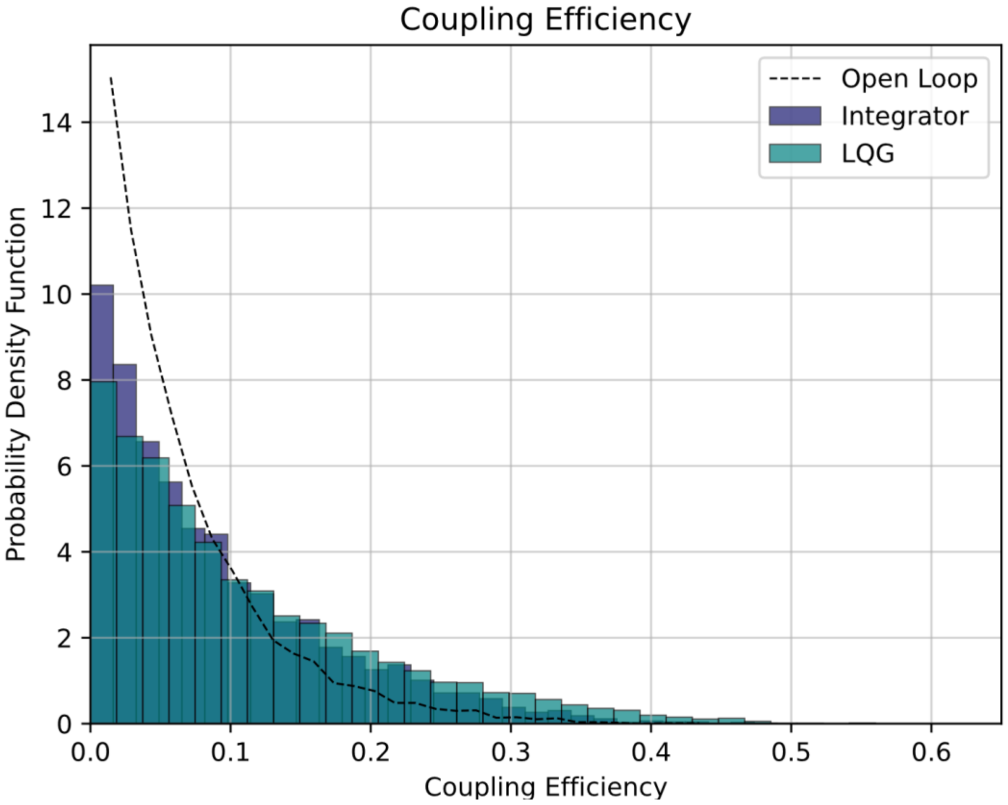
J. S. Torres, A. P. Reeves, C. Kulcsár, H. -. Raynaud, R. M. Calvo, and H. F. Kelemu, "Turbulence Characterization of a Free Space Optical Communication Link for High Performance Adaptive Optics Control," in Imaging and Applied Optics Congress 2022.

Predictive Control Algorithms
Addressing Scintillation

without scintillation



with scintillation



J. S. Torres, A. P. Reeves, C. Kulcsár, H. -. Raynaud, R. M. Calvo, and H. F. Kelemu, "Turbulence Characterization of a Free Space Optical Communication Link for High Performance Adaptive Optics Control," in Imaging and Applied Optics Congress 2022.

Predictive Control Algorithms

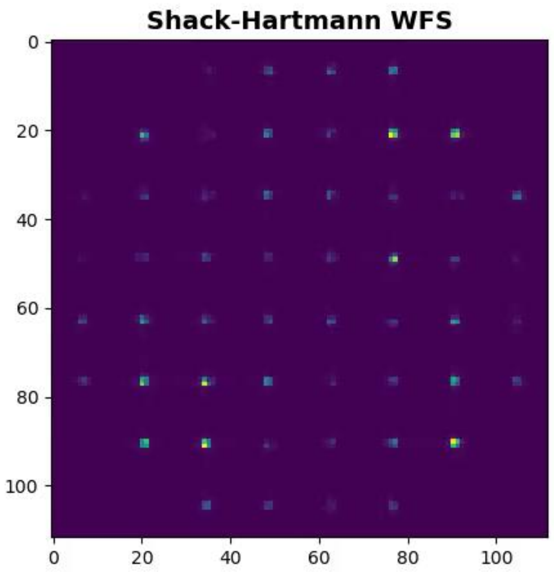
Addressing Scintillation

Degraded Measurement Replacement Strategy

[L. Marquis, SPIE 2022]

- Scintillation causes degraded wfs measurements;
- Measurements have set flux threshold:
  - if below threshold, then it is set to 0.
- Replace invalidated measurements by Kalman filter predictions computed from:

$$\hat{y}_{k|k-1} = C\hat{X}_{k|k-1} - M_{int}u_{k-2}$$



X	State vector
C	State to Measurements
y	Vector of measurements
M_{int}	Actuators to measurements

AO for FSOC Simulations
System Characteristics

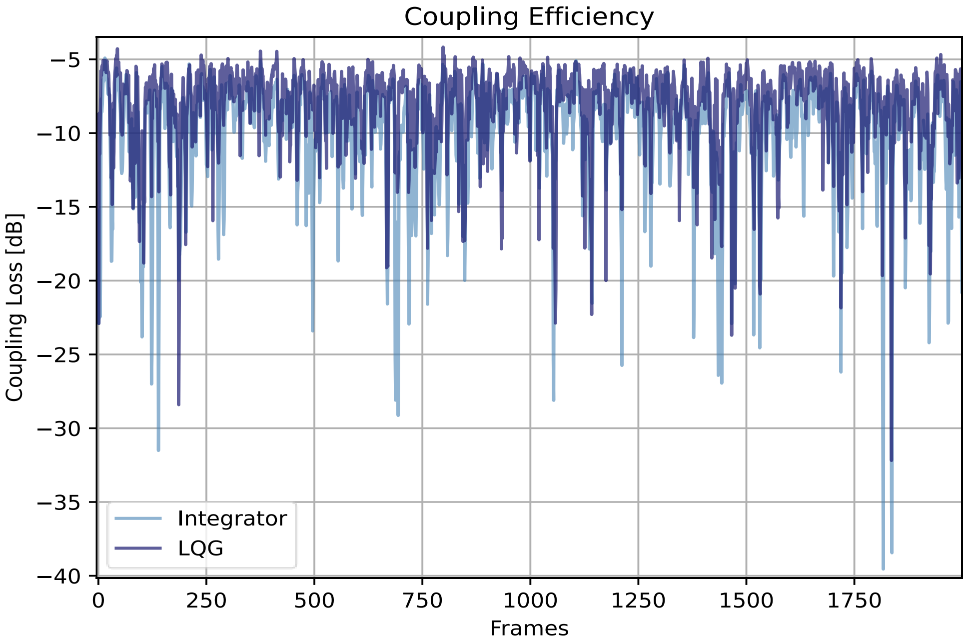
DLR OGS

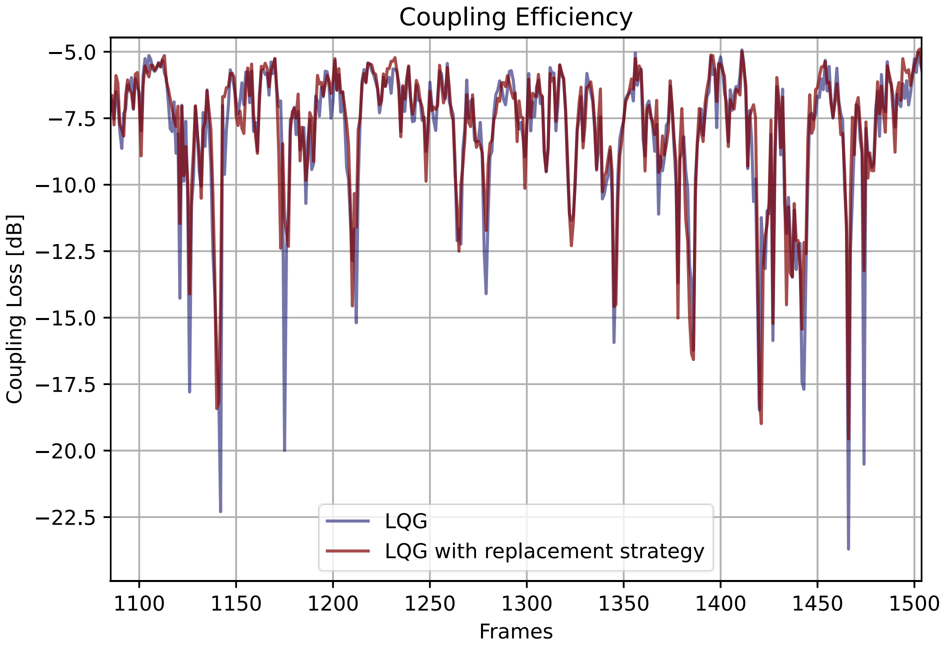
- Telescope
  - diameter 80 cm
  - obscuration 30 cm
- AO system
  - DM192 (16 x 16 actuators)
  - SH-WFS (13 x 13 subapertures)

AO for FSOC Simulations

Simulation Results for LEO scenario

Angular Spectrum Propagation	Mean Coupling Efficiency (%)	Mean Strehl Ratio (%)
Integrator	12.9	20.6
LQG	18.0	28.9
LQG w/ Replacement	18.4	29.6





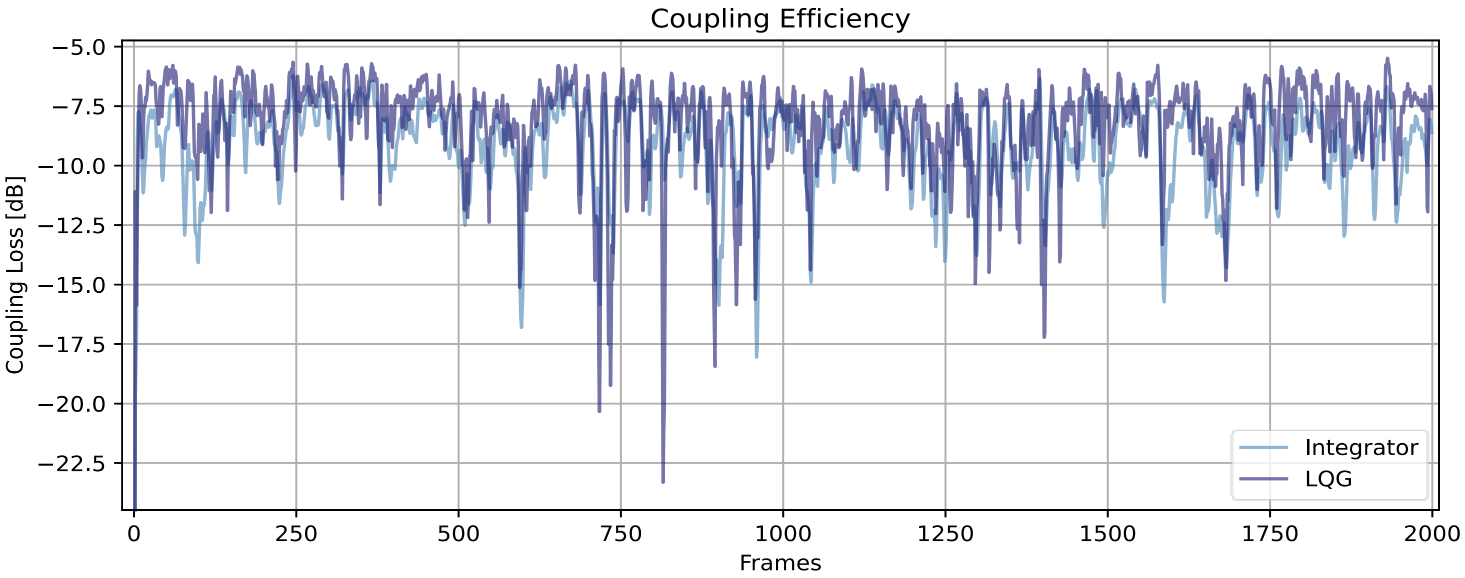
AO for FSOC Simulations

Simulation Results for GEO scenario

Conditions simulated:

- HV 5/7, strong ground layer turbulence
- Bufton wind profile
- Low elevation angle

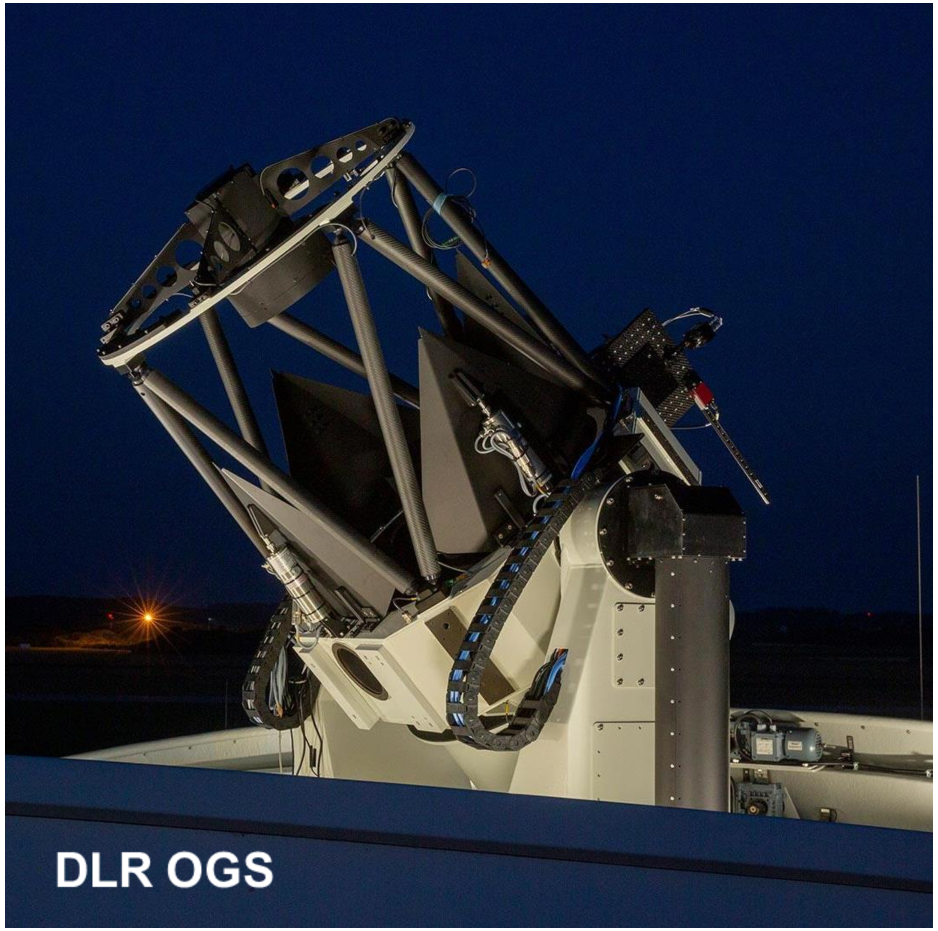
Angular Spectrum Propagation	Mean Coupling Efficiency (%)	Mean Strehl Ratio (%)
Integrator	13.2	21.2
LQG	15.9	25.5
LQG w/ Replacement	16.2	25.8



Conclusion

Summary

- FSOC has several advantages over RF but links are hindered by **atmospheric turbulence;**
- Tight requirements in FSOC AO can be addressed by predictive control algorithms;
- RTC main loop process computations can be optimised with parallel computing techniques;
- Simulation results show improvements in fibre coupling, added stability and reduced fade depth, further improvements underway;
- On-sky testing in 2024.



THANK YOU!

Joana Torres

joana.dosuldamotatorres@dlr.de

DAAD

université PARIS-SACLAY

LABORATOIRE CHARLES FABRY

INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech

cnrs dépasser les frontières

DLR