Adaptive Optics for LEO-to-Ground Optical Communication Links

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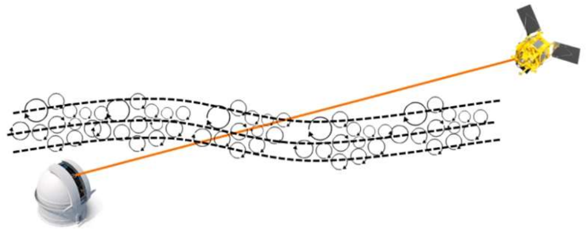
CONTEXT

OPTICAL LEO-TO-GROUND LINKS

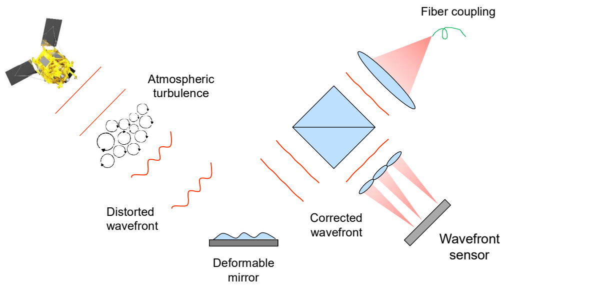
- Optical communications: higher data rates + avoid RF saturation + difficult to intercept + mass/volume/power savings
- Low-Earth-Orbit (LEO) to ground links: direct to Earth links for downloading high volume of payload data

THE NEED FOR ADAPTIVE OPTICS

- Adaptive Optics (AO) corrects phase distortions on optical signal due to atmospheric turbulence
- AO allows coupling into single mode fiber: optical signal amplification, use of available optical fiber communication technologies



ADAPTIVE OPTICS SYSTEM



CHALLENGES

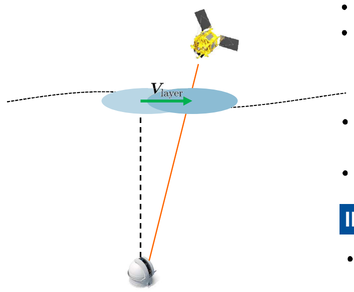
- LEO satellites move across the sky:
  - Need for tracking
  - Observation at different elevations, including low elevations down to 10º:
    - Changing turbulence conditions
    - Strong turbulence at low elevations
  - Relative movement of the satellite results in strong apparent wind:
    - Increase in the turbulence dynamics
    - Increase in AO temporal error

PREDICTIVE CONTROLLER

TEMPORAL ERROR

Error in correction due to delay between phase measurement and correction. Bigger with faster turbulence evolution.

Predictive controller accounts for evolution during delay. In LEO-to-ground case, information of apparent wind speed **known from orbit**.



MODELLING

- Modal description of turbulence using Zernike polynomials
- Vector AutoRegressive (VAR) process for turbulence evolution

$$\phi_{k+1}^{\text{tur}} = \boldsymbol{A}_1 \phi_k^{\text{tur}} + \boldsymbol{A}_2 \phi_{k-1}^{\text{tur}} + \boldsymbol{\nu}_k$$

- Solution to VAR using temporal covariances, equivalent to spatial covariances (analytical formulas available)
- Result: model represents frozen flow with known wind

IDENTIFICATION

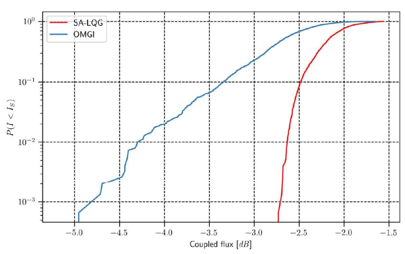
- Analytical expressions for spatial correlation between Zernike polynomials available
- C_n^2 profile: needs to be estimated (altitudes and strength)
- Wind profile: dominated by apparent wind, thus known from orbit

RESULTS

SIMULATION OF THE LISA AO BENCH AT ONERA

Parameter	Value	Parameter	Value	Parameter	Value
D_{RX}	0.4 m	Elevation	30°	Radial orders	12 (91 modes)
Wavelength	1.55 µm	D/r_0	11.38	Loop frequency	2 kHz
Slew rate	3.6 mrad/s	L_0	10 m	Loop delay	2 frames

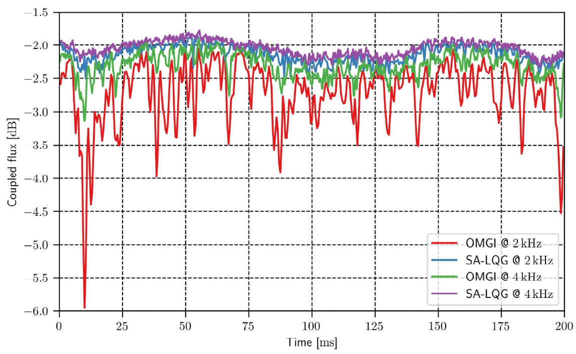
NORMALIZED COUPLED FLUX CDF



Predictive controller (SA-LQG) vs. classical integrator (OMGI).

- Gain of several dB thanks to reduction of fadings and better average coupling.

NORMALIZED COUPLED FLUX TIME SERIES



Predictive controller (SA-LQG) vs. classical integrator (OMGI). Use of two different loop frequencies.

- Reducing temporal error brings gains in fading reduction (even with fitting error)
- Fadings come mostly from low-order modes: not in fitting, but in temporal error
- Can relax system design to a lower frequency with same performance

PERSPECTIVES

- Impact of Shack-Hartmann WFS: aliasing, number of modes to be estimated?
- Identification of the turbulence profile
- Towards sky → test on laboratory:
  - PICOLO (turbulence emulation bench) + LISA (AO system)

PUBLICATIONS

P. Robles, C. Petit, J.-M. Conan, B. Benammar, and B. Neichel, "Predictive adaptive optics for satellite tracking applications: optical communications and satellite observation," in *Adaptive Optics Systems VIII*, 2022, doi: 10.1117/12.2630217