

Closing the Loop with Intensity-Based Estimation for Pre-Compensated Optical Ground-to-Satellite Links : Simulation and First Experimental Results

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ABSTRACT

Adaptive optics (AO) pre-compensation can significantly enhance optical ground-to-satellite links, but its performance is fundamentally limited by point-ahead angular anisoplanatism, which induces residual phase errors and beam wander. Building on our previous intensity-based angular phase estimation framework, we investigate its integration within a pseudo-open-loop control (POLC) architecture for real-time uplink correction. The proposed controller combines conventional phase measurements with downlink intensity information through a minimum mean square error (MMSE) reconstructor, enabling improved estimation of the uplink phase at the point-ahead angle. The approach is evaluated through numerical simulations and experimental implementation on the ONERA PICOLO-LISA adaptive optics testbed under representative satellite communication conditions. Initial simulation results demonstrate stable closed-loop operation and improved performance compared to phase-only control. This work represents the first implementation of an intensity-based angular phase estimation method within an AO control loop and constitutes an important step toward operational uplink pre-compensation for future satellite optical communication systems.

Keywords:

1. INTRODUCTION

Atmospheric turbulence fundamentally limits the performance of high-data-rate optical ground-to-satellite communication links. In particular, optical feeder links to geostationary (GEO) satellites are expected to be a backbone of future satellite optical networks and require the transmission of data at very high rates (at the Terabit per second¹). However, through its propagation, the optical beam is distorted by atmospheric turbulence, which induces wavefront distortions resulting in fluctuations of the irradiance received on board the satellite, leading to deep and long-lasting signal fades and ultimately limiting the achievable communication performance.

Adaptive optics (AO) pre-compensation of the uplink beam has been shown, both numerically^{2–5} and experimentally,^{5–8} to significantly mitigate turbulence-induced attenuation. In state-of-the-art demonstrations, the pre-compensated uplink beam is corrected using the downlink AO correction. However, as the uplink and downlink beams propagate along different paths separated by the point-ahead angle (PAA), the downlink wavefront is suboptimal to correct the turbulence experienced by the uplink beam. This PAA anisoplanatism therefore limits the performance of conventional pre-compensation, with residual errors particularly affecting low-order modes such as tip-tilt and resulting in persistent beam wander and deep signal fades.

In previous work, we proposed an intensity-assisted minimum mean-square error (IMMSE) estimator⁹ to reconstruct the uplink wavefront from a combination of downlink phase and intensity measurements and statistical priors derived from the atmospheric turbulence profile and link geometry. Numerical simulations demonstrated a significant reduction of the residual phase error at the point-ahead angle, with a particularly strong improvement in the estimation of uplink tip-tilt modes.^{9,10} More recently, we experimentally validated the underlying

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principle using phase and intensity measurements obtained from a binary-star observing configuration.¹¹ This experiment showed that intensity measurements provide additional information on off-axis phase fluctuations and can improve the estimation of low-order phase modes.

These results established the potential of intensity-assisted estimation for mitigating PAA anisoplanatism. However, the IMMSE approach has so far only been demonstrated in a static open-loop framework through post-processing. To integrate this correction into an operational AO pre-compensation system, the estimator must be embedded within a real-time control architecture capable of dynamically applying the estimated correction.

In this work, we investigate the integration of the IMMSE estimator into a pseudo-open-loop control (POLC) framework. Pseudo-open-loop control (POLC) was initially developed in astronomy, to enable the use of minimum-variance reconstructors within closed-loop adaptive optics systems.^{12–15} By reconstructing pseudo-open-loop measurements from residual wavefront sensor data and previously applied DM commands, POLC preserves the statistical consistency required by model-based reconstructors while maintaining the robustness of conventional closed-loop control. As the proposed IMMSE estimator relies on the same statistical framework, POLC constitutes a natural candidate for its real-time implementation. We first describe the proposed control architecture, which combines conventional wavefront sensor measurements with intensity-derived information. We then present numerical end-to-end simulations of the controller and discuss the main challenges associated with its experimental implementation. Finally, we present preliminary implementation results obtained on the ONERA PICOLO-LISA adaptive optics testbed.

2. IMMSE PRE-COMPENSATION: PRINCIPLE AND DEMONSTRATION STATUS

2.1 Point-ahead angle anisoplanatism in pre-compensated links

Adaptive-optics pre-compensation relies on the reciprocity between the downlink and uplink propagation paths. In an ideal reciprocal configuration, the phase measured on the downlink can be applied to the uplink beam, allowing atmospheric turbulence to be compensated before transmission. However, in practical ground-to-satellite links, reciprocity is broken by the point-ahead angle (PAA) required to account for the satellite motion during the propagation time of the optical signal. For a GEO satellite, the PAA is typically on the order of $18.5 \mu\text{rad}$ and results in a spatial separation between the uplink and downlink beam paths, as illustrated in Fig. 1a. As a consequence, the turbulence sampled by the downlink differs from that experienced by the uplink beam, leading to angular anisoplanatism. Applying the downlink correction on the uplink therefore results in a residual phase error given by

$$\Phi_{\text{res}}(\mathbf{r}) = \Phi(\mathbf{r}, \alpha_{\text{PAA}}) - \Phi(\mathbf{r}, 0) \quad (1)$$

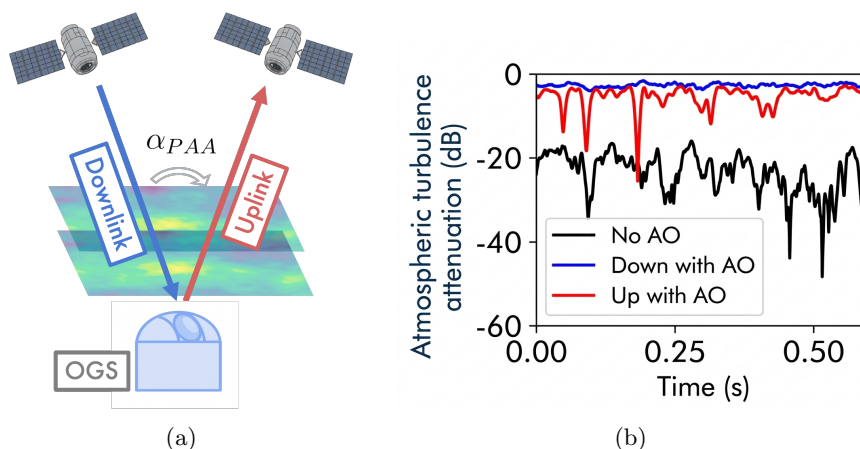


Figure 1: (a) Geometry of a GEO optical feeder link showing the separation between the uplink and downlink propagation paths induced by the point-ahead angle. (b) Simulated coupling efficiency time series illustrating the deep signal fades compared with the uncorrected and downlink AO corrected cases.

where Φ_0 and $\Phi_{\alpha\text{PAA}}$ denote the atmospheric phase in the downlink and uplink directions, respectively. The anisoplanatic phase error is particularly large on low-order modes such as tip and tilt. These residual wavefront errors, in particular the residual tip-tilt, induce beam wander and distorts the irradiance pattern in the satellite plane and therefore strongly affect the amount of optical power coupled into the detector. An example of signal fades induced by point-ahead anisoplanatism is illustrated in Fig. 1b in red, compared with the atmospheric induced signal losses in i) a no correction scenario in black and the ii) a downlink scenario in blue not impacted by anisoplanatism. These residual fades ultimately limit the achievable link availability and motivate the need for a dedicated estimation of the uplink phase at the point-ahead angle.

2.2 Intensity based phase estimation at the point-ahead angle

In previous work,⁹ we proposed an intensity-assisted minimum mean-square error ($MMSE_{\Phi\chi}$) estimator to reconstruct the phase in the uplink direction from downlink measurements. The estimator combines conventional phase measurements with downlink intensity information and statistical priors derived from the atmospheric turbulence profile and the link geometry. These intensities spatial structures inform on the phase disturbances along the line of sight, in particular on the upper turbulence disturbances, whose layer are at the origin of the anisoplanatic phase error. The estimated phase in the point-ahead direction can be expressed as

$$\hat{\Phi}_{\text{PAA}} = \mathbf{R}_{\text{IMMSE}} \mathbf{y}_m, \quad (2)$$

where $\mathbf{R}_{\text{IMMSE}}$ denotes the MMSE reconstructor and $\mathbf{y}_m$ the measurement vector composed of the open-loop downlink phase and intensity measurements. The reconstructor is obtained from analytical covariances expressed in the Zernike basis between the atmospheric phase and log-amplitude fluctuations and therefore depends on the turbulence profile, the propagation geometry, and the point-ahead angle. The full derivation can be found in.⁹

An important feature of the approach is that it is entirely model-based, as there isn't any measurements available of the phase at the PAA to construct a data-based reconstructor. It therefore requires a measurement of the atmospheric turbulence profile and the knowledge of the link geometry to compute the analytical $MMSE_{\Phi\chi}$ reconstructor.

Numerical validations demonstrated a significant reduction of the residual phase error at the point-ahead angle, with the largest gains observed on tip and tilt modes.^{9,10} More recently, the underlying principle was validated experimentally using a binary-star observing configuration, providing the first experimental demonstration of intensity-based angular phase estimation.¹¹ Although these results demonstrated the validity of the IMMSE estimator in an open-loop framework, its integration into a real-time AO pre-compensation architecture remains to be demonstrated. This requires not only the real-time computation of the estimator, but also its integration within a suitable control law capable of dynamically applying the estimated correction.

2.3 From open-loop estimation to real-time pre-compensation

We summarize the different building blocks required to deploy $MMSE_{\Phi\chi}$ -based pre-compensation within an operational optical feeder link. Beyond the estimator itself, several elements must be demonstrated before real-time implementation can be achieved:

- Accurate estimation of the atmospheric turbulence profile to compute the IMMSE reconstructor;
- Wavefront sensing performance compatible with communication flux levels;
- Real-time computation of the IMMSE phase estimate;
- Design of a control law capable of dynamically applying the estimated correction;
- Implementation of a dedicated correction stage in the adaptive optics system.

Several of these elements have already been addressed. We've shown in a previous study that reconstructing few turbulence-profile layers was sufficient to provide an accurate estimate,¹⁶ with 4 layers being sufficient in a GEO configuration. This is compatible with current profiling techniques based on external profilers such as the

SHIMM¹⁷ or on AO system telemetry.¹⁸ In addition, the IMMSE principle has been validated experimentally through an on-sky binary-star demonstration, confirming the ability of intensity measurements to improve off-axis phase estimation. The current status of the different developments can be summarized as follows:

- ✓ Definition of the turbulence-profile resolution requirements;
- ✓ Numerical validation of the IMMSE estimator;
- ✓ Experimental on-sky open-loop validation using binary stars;
- ✓ Derivation of a model-based IMMSE reconstructor;
- Design and validation of a closed-loop control law;
- Experimental demonstration of dynamic PAA correction;
- Real-time update of the new command matrix.

In the present work, we focus on the design and validation of the control-law component by integrating the IMMSE estimator within a pseudo-open-loop control (POLC) architecture. Parallel developments are performed at ONERA in the work of Kyliann Robert.¹⁹ This piece of work has been developed in collaboration with ONERA with the aim to test it on ONERA PICOLO-LISA AO Bench with turbulence emulation.^{20,21}

3. PSEUDO OPEN-LOOP CONTROL FRAMEWORK

The implementation of the proposed $MMSE_{\Phi\chi}$ reconstructor requires an estimate of the open-loop wavefront while operating in closed loop. To achieve this, we choose to implement Pseudo Open-Loop Control (POLC) scheme. A detailed description of the framework can be found in Refs.^{12,13,22}

3.1 Classical POLC

In the modal implementation considered here, the residual phase estimate is updated recursively according to²² as:

$$\hat{\phi}_{n+1} = f \hat{\phi}_n + \gamma \hat{\phi}_{n-1} + g \mathbf{e}_n, \quad (3)$$

where $\hat{\phi}_n$ denotes the estimated modal phase at time step n , $\mathbf{e}_n$ is the reconstruction error, and f , γ , and g are controller gains. In this work, an AR1 controller is considered, yielding the simplified update law:

$$\hat{\phi}_{n+1} = f \hat{\phi}_n + g \mathbf{e}_n. \quad (4)$$

The reconstruction error is defined as the difference between the phase estimated from the current measurements and the previous modal estimate,

$$\mathbf{e}_n = \hat{\phi}_n^{\text{MMSE}} - \hat{\phi}_{n-1}, \quad (5)$$

with

$$\mathbf{e}_n = \mathbf{R}_{\text{MMSE}}^{WFS \rightarrow Z} \mathbf{y}_{POL} - \hat{\phi}_{n-1}, \quad (6)$$

where $\mathbf{R}_{\text{MMSE}}^{WFS \rightarrow Z}$ denotes the MMSE reconstructor expressed in the Zernike basis. For a conventional phase-only controller, the pseudo open-loop measurement vector is obtained from the residual Shack-Hartmann slopes and the previous deformable mirror command,

$$\mathbf{y}_{POL} = \mathbf{s}_n + \mathbf{M}_{int} \mathbf{u}_{n-1}, \quad (7)$$

where $\mathbf{s}_n$ is the residual slope measurement vector, $\mathbf{u}_{n-1}$ is the command applied during the previous iteration, and $\mathbf{M}_{int}$ is the interaction matrix relating deformable mirror commands to wavefront sensor slopes. The MMSE reconstructor used in this work is derived from atmospheric spatio-angular covariance matrices and provides the minimum mean-square error estimate of the modal phase from the available measurements. The following subsection describes how this classical formulation can be extended to incorporate intensity measurements and implement the proposed $MMSE_{\Phi\chi}$ estimator.

3.2 Extension to intensity measurements

The implementation of the $MMSE_{\Phi\chi}$ estimator within the POLC framework requires two main modifications. First, the POL measurement vector must be augmented to include intensity fluctuations measured by the SH-WFS. Second, the reconstruction matrix must be extended to transform both slope and intensity measurements into modal coefficients. The resulting reconstruction can be written as

$$\mathbf{R}_{MMSE}^{WFS \rightarrow Z} y_{POL} = \mathbf{R}_{MMSE} \begin{bmatrix} \mathbf{D}^\dagger & 0 \\ 0 & \mathbf{E}^\dagger \end{bmatrix} \begin{bmatrix} sl_{POL} \\ \chi_{subap} \end{bmatrix} \quad (8)$$

where $\mathbf{R}_{MMSE}$ is the MMSE reconstructor expressed in the Zernike basis, $\mathbf{D}$ is the matrix relating Zernike coefficients to SH-WFS slopes, and $\mathbf{E}$ is the matrix relating Zernike log-amplitude coefficients to subaperture-averaged log-amplitude measurements. In this work, we calculate these matrices numerically using a SHWFS numerical model. An example of the new reconstructor is given in Fig. 2. The log-amplitude measurement associated with subaperture k is estimated from the integrated subaperture intensity. Assuming weak scintillation, the intensity measured in subaperture k can be written as:

$$i_k = \int_{\Omega_k} I(\mathbf{r}) d\mathbf{r} = \bar{i}_k \int_{\Omega_k} e^{2\chi(\mathbf{r})} d\mathbf{r}, \quad (9)$$

where $\bar{i}_k$ is the mean intensity in the absence of turbulence and Ω_k denotes the subaperture area. Decomposing the log-amplitude as

$$\chi(\mathbf{r}) = \langle \chi \rangle_{subap} + \delta\chi(\mathbf{r}), \quad (10)$$

with $\langle \delta\chi \rangle_{subap} = 0$, yields

$$i_k = \bar{i}_k e^{2\langle \chi \rangle_{subap}} \int_{\Omega_k} e^{2\delta\chi(\mathbf{r})} d\mathbf{r}. \quad (11)$$

Provided that the log-amplitude fluctuations within a subaperture remain small, the term involving $\delta\chi$ can be neglected to first order, leading to

$$i_k \simeq \bar{i}_k e^{2\langle \chi \rangle_{subap}}. \quad (12)$$

Taking the logarithm and linearising under the weak-perturbation assumption gives

$$\langle \chi \rangle_{subap} = \frac{1}{2} \ln \left(\frac{i_k}{\bar{i}_k} \right) \approx \frac{i_k - \bar{i}_k}{2\bar{i}_k}. \quad (13)$$

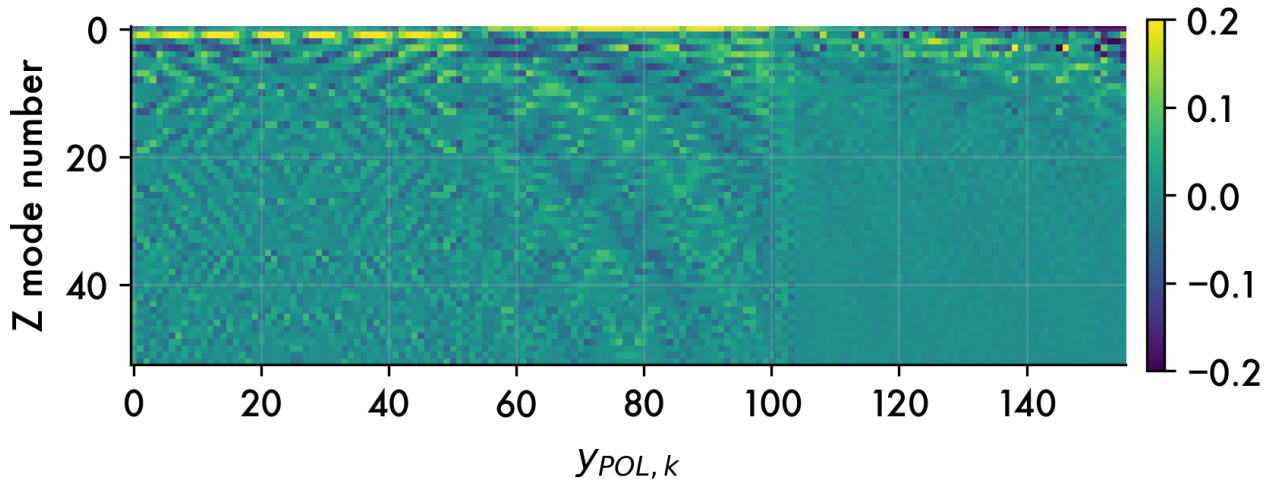


Figure 2: Example of the augmented reconstruction matrix implementing the $MMSE_{\Phi\chi}$ estimator, showing the mapping from Shack-Hartmann slope and intensity measurements to Zernike modal coefficients.

The subaperture log-amplitude measurement is therefore defined as

$$\chi_{subap} = \frac{i_k - \bar{i}_k}{2\bar{i}_k}. \quad (14)$$

This approximation lies on the assumption that scintillation structures smaller than the sub-aperture size can be neglected and on the weak scintillation regime assumption.

The integration of intensity measurements into the POL framework has several practical consequences for the control loop. First, the measurement vector is augmented with one additional measurement per SH-WFS subaperture, increasing the size of the telemetry stream and of the associated reconstruction matrices. However, this increase is not expected to represent a significant computational burden in the context of free space optical communication, as the number of subapertures is typically modest compared to astronomical AO systems. The resulting increase in complexity therefore remains small with respect to the overall reconstruction cost. Second, the intensity measurements must be normalised by their reference values $\bar{i}_k$ before being injected into the reconstructor. This normalisation is required to convert the measured flux fluctuations into log-amplitude fluctuations estimates and to maintain robustness against slow variations of source brightness, transmission, or detector gain.

4. CLOSED LOOP RESULTS

4.1 PICOLO LISA system and turbulence scenario

The proposed control law is experimentally evaluated on the PICOLO-LISA testbed at ONERA, providing a first demonstration under controlled laboratory conditions. Originally developed to emulate atmospheric turbulence and adaptive optics correction for LEO downlinks,^{21,23,24} the bench was recently upgraded to a GEO configuration. In addition to the on-axis downlink beam, a second off-axis beam is introduced with an angular separation of $18.5 \mu\text{rad}$, corresponding to the point-ahead angle and therefore representing a reciprocal uplink path. The two beams operate at different wavelengths (1550 nm and 1600 nm), allowing the reciprocal uplink beam to be filtered out on the wavefront sensor path. This configuration provides a realistic platform for testing uplink-oriented control laws under dynamically evolving turbulence conditions. A detailed description of the PICOLO-LISA bench can be found in.^{20,21}

In the GEO configuration, the turbulence emulator incorporates three phase screens, enabling the reproduction of a range of atmospheric conditions. In this study, a two-screen configuration is selected to generate significant anisoplanatic effects while remaining within the weak-fluctuation regime. The screen characteristics and corresponding integrated atmospheric parameters are summarized in Table 1.

The LISA AO system emulates a 40 cm aperture telescope equipped with an 8×8 Shack-Hartmann wavefront sensor and a 9×9 actuator deformable mirror. The experimental AO loop operates at 1175 Hz. To implement

	CONFIG PICOLO
PAA	$18.5 \mu\text{rad}$
D	0.4 m
$N_{modes,OA}$	54-77
$f_{AO,loop}$	2kHz (sim) / 1.1 kHz (Expe)
N_{subap}	8×8 - 52 valid
d_{subap}	5 cm
Heights	$[0.08, 10] \text{ km}$
Cn2dh	$[2.563\text{e-}11, 1.015\text{e-}12] \text{ m}^{1/3}$
Wind	$[5, 10] \text{ m/s}$
r_0	4.35 cm @ 1550 nm
θ_0	$9.69 \mu\text{rad}$ 1550 nm
σ_χ^2	0.09

Table 1: Table of the system PICOLO LISA parameters.

the POLC correction, a single deformable mirror is optimized in the off-axis direction while the on-axis beam is sensed by the wavefront sensor. Consequently, the simulations presented in this work also assume a single-DM architecture. Future work will investigate the use of a secondary low-order deformable mirror to simultaneously compensate the beams on the downlink and uplink propagation paths.

4.2 Numerical simulation results

To assess the proposed controller under statistically representative conditions, end-to-end numerical simulations were performed using the open-source adaptive optics simulator *SOAPY*. A reciprocal uplink configuration matching the PICOLO-LISA experimental setup was implemented. For each controller configuration, five independent turbulence realizations were generated, each with a duration of 1.5 s and sampled at 2 kHz. The simulated adaptive optics system reproduces the main characteristics of the experimental bench, including the Shack-Hartmann wavefront sensor and the modal correction architecture. For simplicity, the deformable mirror is represented by an ideal modal phase corrector rather than a physical actuator-based model. Consequently,

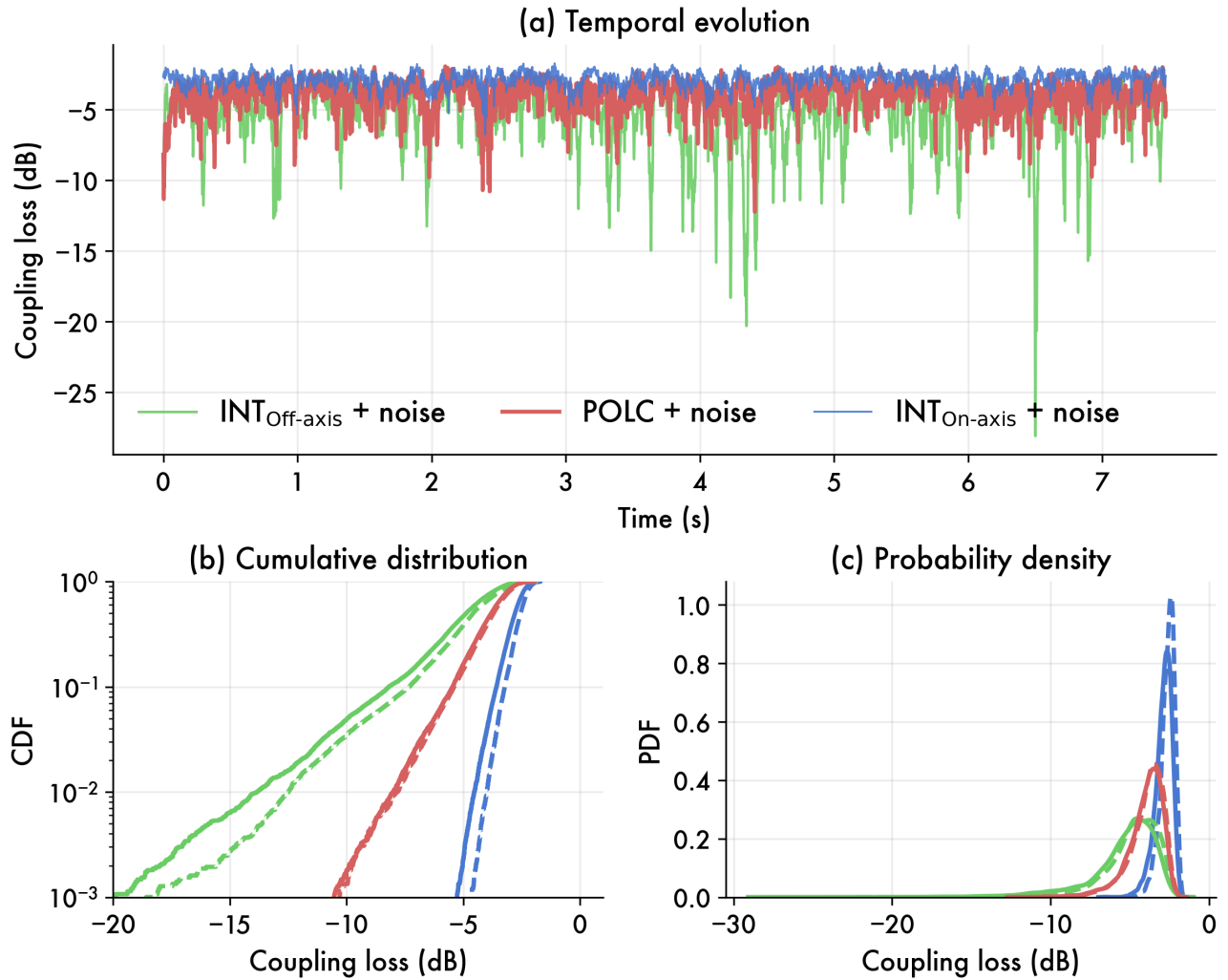


Figure 3: Simulation results obtained in the reciprocal uplink configuration with integrator gains of 0.3 and for the POLC $f=1$ and $g=0.5$. (a) Temporal evolution of the coupling loss for the off-axis integrator controller ($\text{INT}_{\text{Off-axis}}$), the proposed POLC controller, and the ideal on-axis integrator reference ($\text{INT}_{\text{On-axis}}$). (b) Corresponding cumulative distribution functions and (c) probability density functions of the coupling loss. Solid lines correspond to noise-free measurements, while dashed lines include measurement noise.

the simulations are performed entirely in the phase domain, with a numerical propagation chain consisting of phase generation, wavefront sensing, phase reconstruction, and correction. This approach enables the evaluation of the proposed control strategy while avoiding hardware-specific effects associated with the deformable mirror dynamics and influence functions.

Figure 3 compares the uplink coupling-loss statistics obtained with the conventional off-axis integrator controller ($\text{INT}_{\text{Off-axis}}$), the proposed POLC controller, and the ideal on-axis integrator reference ($\text{INT}_{\text{On-axis}}$). The temporal evolution shown in Fig. 3(a) highlights the strong coupling-loss fluctuations induced by anisoplanatism when the correction is optimized using only off-axis measurements. Deep fading events reaching values below -15 dB are frequently observed with the off-axis integrator. In contrast, the POLC controller substantially mitigates these events, resulting in a more stable link and temporal performance closer to the on-axis reference. The improvement is more clearly visible in the statistical distributions shown in Figs. 3(b)-(c). The cumulative distribution function demonstrates a significant reduction of the low-probability, high-loss events when using POLC. While the coupling-loss distribution remains broader than the ideal on-axis case, the left tail is markedly reduced compared to the off-axis integrator. This indicates that the proposed controller efficiently

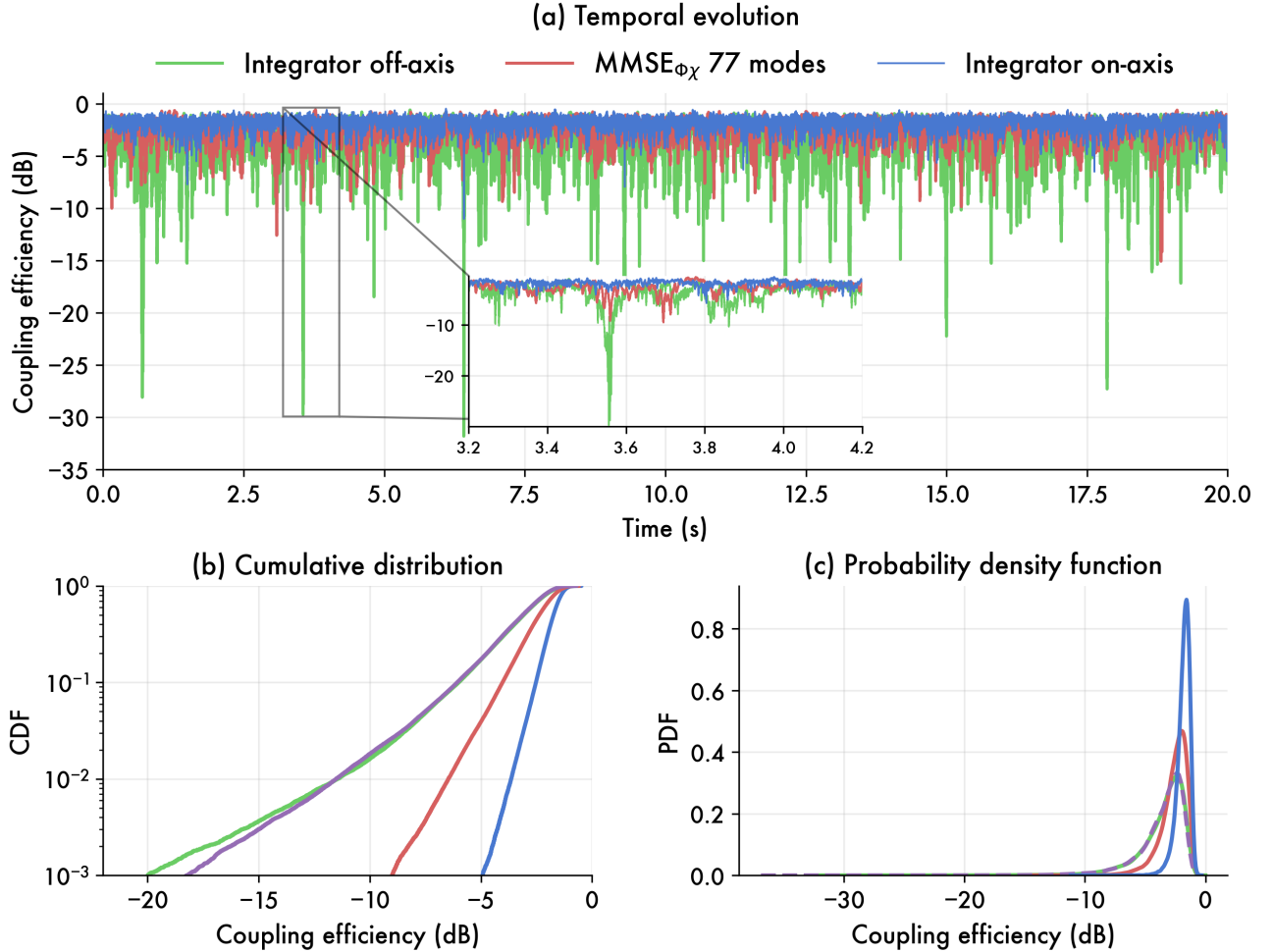


Figure 4: Experimental results obtained on the PICOLO bench on the two screens configuration. At the top (a), we plot 22 s time-series of the reciprocal uplink coupling efficiency using (i) an on-axis integrator in blue (ii) the off-axis integrator in green, (iii) the POLC MMSE_{Φ_χ} in red and (iv) the POLC MMSE_{Φ} in purple. The bottom curves depict in (b) the cumulative density function of the coupling efficiency and (c) the probability density function of the coupling efficiency.

compensates for a large fraction of the anisoplanatic error responsible for severe fading events. The probability density functions further confirm this behaviour. The POLC distribution is shifted toward lower losses and exhibits a narrower spread than the off-axis integrator, showing that the controller not only improves the average performance but also reduces the variability of the received signal. Although a performance gap remains with respect to the on-axis reference, the POLC controller recovers a significant fraction of the anisoplanatism-induced penalty using only information available from the downlink measurements.

4.3 Experimental results

Finally, Fig. 4 depicts the experimental results obtained on the bench. Between 20 s and 40 s of data were acquired for each configuration: the on-axis integrator, corresponding to the optimal correction case; the off-axis integrator, representative of a classical pre-compensation architecture where the correction computed from the downlink is directly applied to the uplink; the POLC $MMSE_{\Phi\chi}$ controller; and the POLC $MMSE_{\Phi}$ controller, used as a benchmark to quantify the contribution of the intensity measurements.

The temporal evolution shown in Fig. 4(a) highlights the strong impact of anisoplanatism on the classical off-axis integrator. While its average coupling efficiency remains comparable to the other controllers, it exhibits frequent deep fading events, with losses occasionally exceeding 20 dB. Both POLC implementations significantly reduce the occurrence and severity of these fades, producing a more stable coupling efficiency over time and bringing the uplink performance closer to the on-axis reference. This behaviour is further confirmed by the cumulative distributions displayed in Fig. 4(b). The POLC controllers substantially shift the low-probability tail toward higher coupling efficiencies compared to the off-axis integrator, indicating a strong reduction of outage-like events. The improvement is particularly visible for losses larger than approximately 8-10 dB, where anisoplanatism dominates the residual error budget. A comparison between the two POLC variants demonstrates the benefit of including intensity information in the estimation process. While the phase-only controller ($MMSE_{\Phi}$) provides little gain over the off-axis integrator, the intensity-assisted controller ($MMSE_{\Phi\chi}$) significantly reduces the probability of deep fades and yields coupling-loss statistics that are consistently closer to the on-axis reference. This trend is also visible in the probability density functions shown in Fig. 4(c), where the $MMSE_{\Phi\chi}$ distribution is shifted toward higher coupling efficiencies and exhibits a narrower spread than the phase-only solution. Overall, these experimental results validate the ability of the proposed POLC approach to exploit both phase and intensity measurements to compensate anisoplanatic effects in reciprocal uplink configurations, leading to a significant reduction in coupling-efficiency fluctuations and improved link robustness.

Finally, we investigate the impact of the POLC $MMSE_{\Phi\chi}$ controller on the fading statistics. Figure 5 reports the fade frequency, mean fade duration, and maximum fade duration as a function of the coupling-efficiency threshold. A fade event is defined as an interval during which the coupling efficiency remains below a

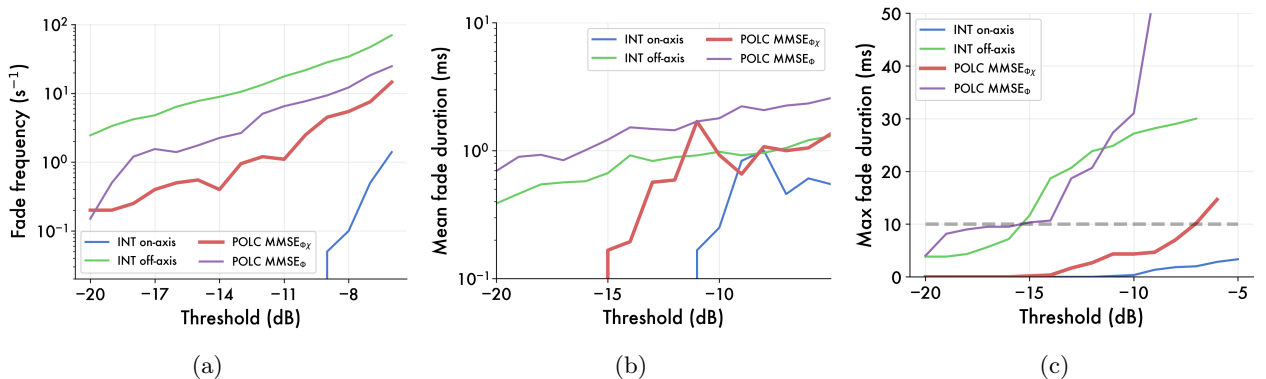


Figure 5: Experimental fading statistics measured on the PICOLO-LISA bench for the different control schemes as a function of the coupling-efficiency threshold. (a) Fade frequency, defined as the number of fade events per second. (b) Mean fade duration. (c) Maximum fade duration observed in the acquired time series. Results are shown for the on-axis integrator (blue), off-axis integrator (green), POLC $MMSE_{\Phi\chi}$ controller (red), and POLC $MMSE_{\Phi}$ controller (purple). The dashed line in (c) indicates a fade duration of 10 ms.

given threshold. The results confirm that anisoplanatism strongly degrades the performance of the conventional off-axis integrator. For all considered thresholds, the off-axis integrator exhibits the highest fade frequency, indicating frequent drops in coupling efficiency. The proposed POLC $MMSE_{\Phi\chi}$ controller significantly reduces the occurrence of these events, yielding statistics much closer to the on-axis reference. The reduction is particularly pronounced for severe fades, corresponding to thresholds below approximately -10 dB. Beyond reducing fade occurrence, POLC also decreases fade duration. While the mean fade duration remains of the order of a few milliseconds for all controllers, the maximum fade duration is substantially reduced when using POLC. For example, the off-axis integrator produces fade events lasting several tens of milliseconds, whereas the POLC $MMSE_{\Phi\chi}$ controller keeps the longest fades below approximately 15 ms over the investigated threshold range. This reduction is especially relevant for communication links, where long-lasting fades generally have a larger impact on outage probability and data availability than isolated short events.

Interestingly, the phase-only controller $MMSE_{\Phi}$ provides limited improvement with respect to the off-axis integrator and can even generate longer fade events for some thresholds. In contrast, the intensity-assisted controller $MMSE_{\Phi\chi}$ consistently reduces both the frequency and duration of fades, demonstrating that scintillation measurements contain valuable information for mitigating anisoplanatic effects and improving uplink link stability.

5. CONCLUSION

In this work, we investigated, in close collaboration with ONERA, the integration of an intensity-assisted $MMSE_{\Phi\chi}$ estimator within a pseudo open-loop control framework for adaptive optics pre-compensation of optical ground-to-satellite links. Numerical simulations performed under the PICOLO-LISA configuration demonstrated stable closed-loop operation and confirmed the feasibility of combining phase and intensity information within a POLC architecture. Experimental results obtained on the PICOLO-LISA bench constitute, to the best of our knowledge, the first demonstration of an intensity-assisted POLC scheme in a GEO-relevant optical communication scenario. The results show that the incorporation of intensity measurements can improve the estimation of the uplink phase and enhance the resulting communication performance compared with conventional phase-only approaches. In parallel to this work, the proposed estimator has also been integrated within an LQG control framework by Robert et al.,¹⁹ where stable closed-loop operation has likewise been demonstrated.

Future efforts will focus on a detailed comparison of the different control strategies, the extension of the approach to LEO communication scenarios, and the investigation of dedicated secondary deformable-mirror correction stages for uplink optimisation. Ultimately, an on-sky demonstration will be pursued to validate the concept under real atmospheric propagation conditions. To deploy this technique in an operational on-sky system, the requirements on atmospheric-profile retrieval will need to be further investigated. In particular, the need for an external turbulence profiler and the update rate required for the reconstruction and command matrices will need to be assessed.

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