

Impact of Predictive Adaptive Optics Control on SKR in LEO QKD Downlinks

Joana Sul Torres^a, Henri-François Raynaud^b, Andrew Reeves^c, Douglas Laidlaw^a, Stefanie Häusler^a, Davide Orsucci^a, Lisa Bardou^a, and Caroline Kulcsár^b

^aInstitute of Communications and Navigation, German Aerospace Centre (DLR), 82234 Weßling, Germany

^bUniversité Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127, Palaiseau, France

^cSpace Research Centre, Physics Department, Durham University, South Road, Durham, DH1 3LE, UK

ABSTRACT

Quantum key distribution (QKD) is a promising method aiming to generate encryption keys to secure data transmissions against eavesdroppers. The secret key rate (SKR) in QKD is limited by channel loss and quantum bit error rate (QBER). One use case of interest is free-space optical communication (FSOC). Since optical feeder links between spacecraft and Optical Ground Stations (OGS) rely on propagation of light through the atmosphere, these systems have to contend with the effects of turbulence, which distorts the incoming wavefront and hinders the communication channel. Adaptive Optics (AO) systems are often deployed on the ground segment in order to counteract the atmospheric influence and improve the optical communication channel. Current AO systems usually rely on classical integral action control. This control solution is prone to instability when considering harsh atmospheric conditions such as the ones expected during LEO links. Predictive AO control in the form of Linear Quadratic Gaussian (LQG) regulators have been proposed for LEO downlinks, leading to a reduction of 2.30 ± 0.02 dB on mean coupling loss with regards to a tuned integrator in low elevation, strong scintillation conditions. Here, an initial assessment of the impact of such high-performing controllers on the quantum communication channel is shown, with a resulting improvement of 70% on the SKR.

Keywords: Adaptive Optics, Free Space Optical Communication, Predictive Control, Linear Quadratic Gaussian Control, Quantum Key Decryption, Secret Key Rate

1. INTRODUCTION

Free space optical communication (FSOC) is a prolific research field due to its many advantages over traditional radio-frequency links, such as higher expected throughput and channel security with the potential to enable quantum encryption. Several European initiatives seek to harness the advantages of FSOC to create global networks. For instance, HydRON envisions an FSOC network supported by numerous LEO nodes, and including AO on the ground segment for mitigation of the atmospheric influence. Whilst any links through the atmosphere see their performance significantly affected by the influence of the turbulence, LEO links represent an added challenge. The nature of the LEO orbits results in fast tracking winds, with a significant portion of a link to the ground segment taking place at very low elevations, making these especially vulnerable to the effects of scintillation. Scintillation significantly affects single-mode fibre (SMF) coupling due to increased fade events in terms of count, depth and duration. It is often proposed that an increased AO loop rate can help mitigate the challenges brought forth by fast changing turbulence, strong scintillation conditions. However, it has been shown that simply increasing the loop rate is not sufficient to obtain a stable link, whereas predictive AO control in the form of optimal LQG regulators provides a clear advantage, regardless of loop rate.¹ A growing body of

Correspondence:

Joana Sul Torres, Institute of Communications and Navigation, German Aerospace Center (DLR), Weßling, Germany
Email: joana.dosuldamoto@dlr.de

evidence supports the use LQG control over the traditional integrator for FSOC links.²⁻⁴ However these results focus solely on metrics regarding the quality of the traditional communication channel such as SMF coupling efficiency. QKD relies on high signal-to-noise ratio (SNR); however, as information is encoded onto an individual photon via its quantum properties, it is not possible to increase SNR by simply increasing transmitted power.⁵ Thus optimised fibre coupling is vital towards QKD performance. Metrics such as the quantum bit-error rate (QBER) and Secret Key Rate (SKR) can be used to assess the impact of coupling loss on the quantum key exchange.

In this study, a preliminary assessment of the potential impact on the quantum channel of LQG AO control for LEO downlinks is presented. As such, the results reported in Torres et al. (2025)¹ comparing the performance of tuned integrator to that of LQG regulators at different elevations under strong turbulence conditions are summarised. The coupling loss values are translated into QKD metrics such as QBER and SKR, using the methodology reported in Häusler et al. (2023).⁶ These preliminary results are discussed in terms of impact of optimal AO control on QKD.

2. IMPACT OF OPTIMAL AO CONTROL ON FREE-SPACE QKD

AO correction on the optical path improves fibre coupling. Improvements on the classic communication channel are quantified by fibre coupling metrics such as coupling loss and fade statistics. In order to assess the corresponding improvement obtained on the quantum channel, it is necessary to estimate QKD performance metrics such as QBER and SKR considering the resulting total channel loss. The methodology used is described in the Appendix of the publication by Häusler et al. (2023).⁶ Here, a brief summary is presented.

The QBER is the quantum analog of the bit error rate and quantifies the fraction of quantum bits that are received or measured incorrectly. It can be expressed by

$$QBER = \frac{n_{\text{wrong}}}{n_{\text{total}}} = \frac{n_{\text{wrong}}}{n_{\text{correct}} + n_{\text{wrong}}} \quad (1)$$

where n represents the bit count at the receiver. Due to photon losses along the channel, only a small fraction of the sent photons will arrive at the receiver. The QBER is evaluated prior to post-processing and provides an estimate of the potential information available to an eavesdropper. Therefore, a lower QBER translates to better quantum channel performance. The SKR quantifies the rate at which secure and usable key bits are generated. This is accomplished by counting the number of truly secret bits per second that remain after post-processing (i.e. correcting errors, removing bits that could be partially known to a potential eavesdropper). The SKR value depends on channel loss and QBER and a higher SKR signifies faster key rate exchange.

For this study, a decoy-state BB84 protocol is assumed. The BB84 protocol uses rectilinear and diagonal bases to encode and decode quantum states. Through basis sifting, all events in which the basis of transmitter and receiver don't match are discarded. The QBER is calculated from the sifted events, both for the rectilinear and for the diagonal basis. To determine the SKR, detection statistics for the decoy-state BB84 protocol are used. In decoy-state BB84, SKR depends on the probability that an emitted pulse is successfully detected, as well as its associated error rate. The observed detection rate across all optical pulses and QBER determine the information that must be removed during error correction. Thus, reductions in QBER and improvements in the received detection statistics can result in an increased SKR. To estimate the SKR, signals measured in the main rectilinear basis generate the key, and those in diagonal basis estimate eavesdropping parameters. The protocol tallies total detections, sifted bits, and errors. These counts are then used to numerically optimise pulse intensity and transmission probability. The SKR can then be obtained with

$$SKR = \lim_{t_{\text{link}} \rightarrow \infty} \frac{SKL(t_{\text{link}})}{t_{\text{link}}} \quad (2)$$

where SKL is the secret key length obtained from QBER and aforementioned counts, and is a function of the total link time t_{link} .

3. CONSIDERED LEO DOWNLINK CONDITIONS

In this sections the considered downlink conditions are summarised, including both the atmospheric conditions and the AO system architecture. The results presented in this paper are based on the simulation methodology reported in Torres et al. (2025).¹ For a detailed understanding of the simulation and phase screen propagation with inclusion of scintillation, the reader is invited to consult the publication, as only a summary of the conditions and results necessary for the QKD performance metrics are detailed here.

3.1 Atmospheric profile and resulting parameters

The atmospheric conditions were chosen to emulate a fast-moving LEO satellite at low elevation, i.e. 30° in the downlink scenario. The atmosphere was modeled using Hufnagel–Valley 5/7 profile,⁷ considering the parameters reported in La Torre et al. (2024),⁸ and Raffa et al. (2025)⁹ which reflect strong daytime turbulence for link with a LEO satellite at an altitude of 1000 km. The profile is detailed in Table 1.

Table 1. Summary of the simulated turbulence conditions by atmospheric layer, with detailed wind profile at an elevation of 30° . The turbulence profile is presented at zenith, but integrated to the correct elevation within the simulation. The apparent wind is considered to be a dominant effect, and thus all layers are assumed to have the same direction.

Altitude (m)	$C_n^2 dh$ ($\text{m}^{-1/3}$)	Wind speed at 30° (m/s)
242	1.03e-11	7.99
6036	5.20e-14	55.21
9093	6.96e-14	83.17
12325	5.67e-14	114.77
15709	2.10e-14	147.16
19168	4.63e-15	175.13
22664	7.25e-16	196.25

The resulting atmospheric parameters are summarised in Table 2 for an elevation of 30° at the considered seeing wavelength of 1550nm. These parameters suggest a strong, fast-changing turbulent atmosphere, with resulting strong scintillation as is reflected in the Rytov Variance σ_R^2 . These values were shown to be consistent with those obtained on-sky, reported in Beesley et al. (2025).¹⁰

Table 2. Summary of the resulting atmospheric parameters at wavelengths of 500 nm and 1550 nm.

Satellite Elevation	τ_0 (ms)		θ_0 (μrad)		r_0 (cm)		σ_R^2	
Wavelength (nm)	500	1550	500	1550	500	1550	500	1550
30°	0.3	1.2	1.91	7.42	1.08	4.19	2.22	0.59

3.2 AO architecture

The chosen AO parameters correspond to those of the updated AO system in the DLR optical ground station in Oberpfaffenhofen (OGS-OP) due to its relevance as in-orbit testing OGS for EAGLE-1 (EAGLE-1 IoT OGS), built to demonstrate satellite-to-ground QKD using optical links.¹¹ The AO system includes a Shack-Hartmann wavefront sensor (SH-WFS) of 29 by 29 subapertures, and a deformable mirror (DM) of 32 by 32 actuators. A two-frame delay is considered, and the loop rate is simulated at 2 kHz. The parameters are summarised in Table 3.

Table 3. Summary of the AO system parameters.

Parameter	Value
Telescope aperture	0.8
Central obscuration	0.3
DM	32×32 grid (812 valid actuators)
SH-WFS	29×29 subapertures (1088 total measurements)
Rx wavelength	1550 nm
AO loop rate $F_s = \frac{1}{T_s}$	2 kHz
Delay	2 frames

3.3 End-to-end simulation

The coupling loss results in this study were obtained with an end-to-end Monte Carlo Python-based simulation developed in-house at DLR (German Aerospace Centre) with the purpose of modelling light propagation and AO compensation for FSO. This simulator has been tested against theoretical results and was shown to be in good agreement with modeled FSO links.¹² A summary of the simulated downlink pipeline is described in Figure 1.

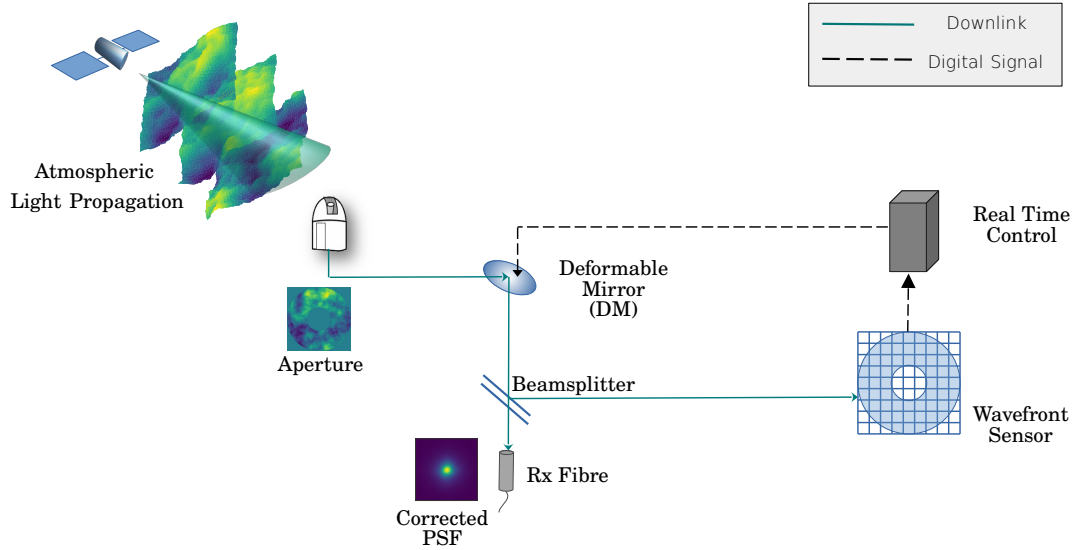


Figure 1. Visualisation of the simulation configuration. Light is assumed to enter the atmosphere as a plane wave. It is propagated between atmospheric layers using angular spectrum propagation. An aperture function is applied to the electric field distribution at the ground, and the result corrected by a simulated DM. The residual electric field is observed by a simulated SH-WFS, using a full diffractive model and therefore including scintillation effects on subapertures.¹

4. SIMULATED AO CONTROLLERS

In this section, the integrator together with the state-space representation for the considered LQG regulators are shown. The relevant simulation coupling loss results are summarised. A more detailed understanding of the regulator synthesis and expanded results in coupling loss and fade events is reported in Torres et al. (2025).¹

4.1 AO integrator

The most commonly deployed AO regulator is the integrator. This is therefore used here as benchmark of the performance improvement obtained with predictive AO control. The command vector u_k to be applied at time kT_s , where T_s is the sampling period, is computed as

$$u_k = u_{k-1} + gM_{\text{com}}y_k, \quad (3)$$

where g is the integrator gain and y is the measurement vector. The command matrix M_{com} is obtained by calculating the pseudo-inverse of the interaction matrix M_{int} . This matrix maps DM commands to SH-WFS measurements and is easily obtained during AO calibration.

4.2 LQG regulator synthesis

The optimal LQG control working principle for AO minimises of the residual phase variance $\phi^{\text{res}} = \phi - \phi^{\text{cor}}$.^{13–15} For the case of a two-frame servo-loop delay, in which the DM response time is considered to be negligible relative to the AO sampling period, the optimal control vector u_k is obtained by projecting a prediction of the incoming phase $\hat{\phi}_{k+1|k}$ onto actuator space

$$u_k = (N^T N)^{-1} N^T \hat{\phi}_{k+1|k}, \quad (4)$$

where N is the DM influence-function matrix and the conditional expectation $\hat{\phi}_{k+1|k} = E(\phi_{k+1} | \mathfrak{J}_k)$ is the minimum-variance one-step-ahead prediction of ϕ_k knowing the set $\mathfrak{J}_k$ of all past information up to time k . The prediction is obtained using a Kalman filter applied to a linear state-space model in the form

$$\begin{aligned} X_{k+1} &= AX_k + \Gamma v_k, \\ \phi_k &= C_1 X_k, \\ y_k &= CX_k + w_k + M_{\text{int}} u_{k-2}, \end{aligned} \quad (5)$$

where X_k represents the atmospheric disturbance state, A , Γ , and C_1 define the chosen disturbance model, and C describes the WFS measurement model. The measurement y_k is modeled as a linear function of the disturbance, and noises, v_k and w_k , assumed to be independent Gaussian and white. The interaction matrix is given by $M_{\text{int}} = DN$, with D denoting the WFS measurement matrix.

The one-step-ahead phase prediction is then calculated as

$$\hat{\phi}_{k+1|k} = C_1 \hat{X}_{k+1|k}, \quad (6)$$

where the state $\hat{X}_{k+1|k}$ is recursively estimated using the steady-state Kalman filter

$$\hat{X}_{k+1|k} = (A - L_{\infty} C) \hat{X}_{k|k-1} + L_{\infty} (y_k - M_{\text{int}} u_{k-2}). \quad (7)$$

The corresponding Kalman gain L_{∞} is obtained from the solution of the discrete algebraic Riccati equation. A noise-scaling factor γ is used to tune the measurement noise and account for model discrepancies. A detailed implementation can be consulted in Torres et al. (2025).¹

In this study, LQG regulators were synthesised using a zonal representation of the phase, with a disturbance model based on auto-regressive models of the second order, built from phase covariance matrices theoretically generated with von Kármán phase structure function.² The zonal representation is based on the oversampling of the prediction grid² with regards to the estimated phase points in so-called Fried Geometry, and is mapped with the WFS measurement matrix D . This oversampling methodology, together with the disturbance models are also detailed in Torres et al. (2025).¹ The regulator labelled **LQG1** utilises a phase sampling grid corresponding to an actuator grid in a Fried configuration; **LQG2** oversamples phase points by a factor of 2 in each direction; **LQG22** takes the configuration from LQG2 and extends phase points to an extra ring of subapertures outside the pupil. The different configurations are summarised in Figure 2.

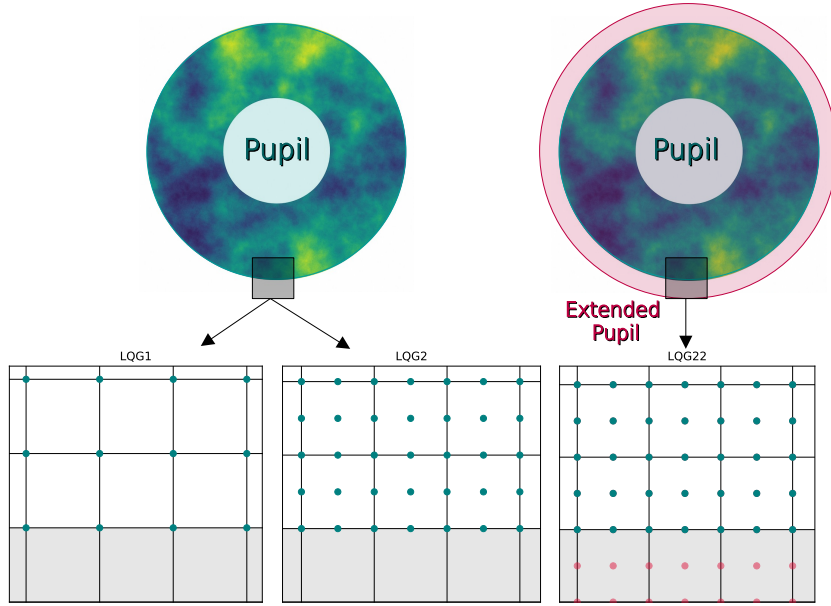


Figure 2. Zoom in of the phase sampling grid for each regulator superimposed to the WFS grid. White squares represent active SH-WFS subapertures, whilst gray ones are outside the pupil and thus are not illuminated.¹

5. QBER AND SKR ESTIMATION FROM COUPLING LOSS RESULTS

The different AO regulators described in section 4 were used in the LEO downlink simulation described in section 3.3, considering the atmospheric turbulence conditions described in 3.1. All regulators were tuned for best fibre coupling. An in-depth analysis of these results can be consulted in Torres et al. (2025).¹ Here only the results obtained in terms of mean coupling loss are presented. Following the methodologies described in 2, the impact of the coupling loss on QBER and SKR was estimated. These results are presented in Table 4.

Table 4. Performance summary for LEO satellite-to-ground link at an elevation angle of 30° across all simulated adaptive optics regulators, showing mean coupling loss, quantum bit error rate (QBER), and secret key rate (SKR).

LEO Downlink 30°	Mean Coupling Loss (dB)	QBER (%)	SKR (kbit/s)
Integrator	-6.65	0.793	24.84
LQG1	-5.75	0.787	30.59
LQG2	-4.37	0.779	42.07
LQG22	-4.35	0.779	42.26

All LQG regulators ensure better performance when compared with a tuned integrator. The oversampled LQG regulator (LQG2) brings a mean improvement of 1.38 ± 0.02 dB over the non-oversampled LQG1. The regulator implementing both the oversampling and edge extension (LQG22), shows a marginal improvement over the LQG2 in mean coupling loss.

When it comes to QBER, the impact is very modest, with only a slight decrease (0.014%) in the rate of erroneous detections. However this translated into a significantly higher SKR with the LQG regulators compared to the integrator. This can be mainly attributed to the increase in signal transmission, with a small role played by the decrease in QBER. In fact, in this QBER regime the increase in SKR is almost exactly linear in the total channel transmission. Therefore, the large improvement in channel transmission results in more signals

reaching the detector and a corresponding increase of the SKR by 23% with LQG1 compared to the integrator with the key rate jumping from 24.84 kbit/s to 30.59 kbit/s. Figure 3 adds a visual summary of the best performing predictive regulator against the benchmark AO control (i.e. the integrator).

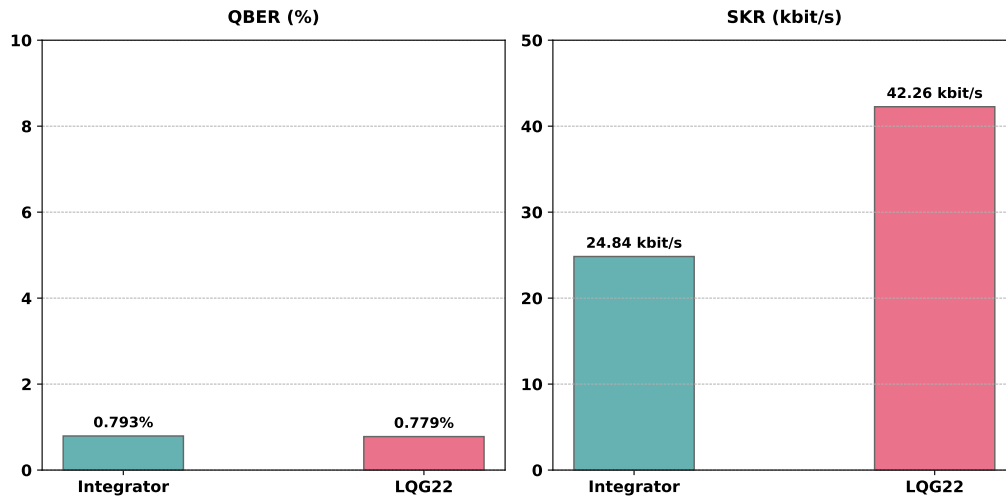


Figure 3. Comparison of a well-tuned classical AO regulator (i.e. integrator) with the best performing predictive regulator (LQG22) in terms of QBER and SKR.

The best regulator LQG22 increases the key rate to 42.26 kbit/s corresponding to 70% improvement with regards to the tuned integrator. Both QBER and SKR values are in range with expected results from comparison with those reported in Häusler et al. (2023).⁶ These findings showcase a substantial performance improvement for QKD and provide a compelling justification for adopting LQG control over conventional integral control in FSOC-AO systems. Furthermore, because signal power cannot simply be increased to improve the SNR in QKD, LQG AO regulators provide effective optimisation that can be deployed alongside mitigation strategies to address background light.⁵

ACKNOWLEDGMENTS

This work was partially funded by DLR-DAAD research fellowship (57540125). The atmospheric profiles are adapted from Project HyDRON-DS Phase A/B1, ESA Contract No. 4000136544/21/NL/CLP. The results presented in this paper make use of Python and libraries such as NumPy, Matplotlib, Pandas and AOTools.

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