

QKD Downlink Study: From OPS-SAT VOLT to the C3PO Optical Ground Station at ESOC

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ABSTRACT

Quantum key distribution (QKD) via space-to-ground optical links is a key enabling technology for secure global communications. The OPS-SAT Versatile Optical Laboratory for Telecommunications (VOLT)* aims to demonstrate a QKD downlink from a low-Earth orbit (LEO) CubeSat to ground, providing an important in-orbit validation of quantum optical communication using a compact satellite platform. Such links are inherently demanding due to their highly dynamic link geometry, stringent pointing, acquisition, and tracking (PAT) performance requirements, atmospheric turbulence, and operation at the single-photon level in the quantum channel. Addressing these aspects in a consistent and quantitative manner is essential to ensure reliable photon reception and to fully exploit the mission's capabilities.

This paper presents an end-to-end link budget assessment for the QKD downlink between OPS-SAT VOLT and Commercial Direct-to-Earth Prototype Optical Ground Station (C3PO)[†]. The analysis focuses jointly on PAT performance and QKD downlink communication, explicitly addressing their coupled impact on end-to-end link performance. In this context, a detailed and coherent link budget framework has been developed to support mission preparation, system verification, and operational readiness. The analysis includes transmitter and receiver optical parameters, pointing errors, atmospheric transmission losses, turbulence effects, receiver coupling efficiency, background noise, detector performance, and PAT-related losses, as these directly affect received quantum signal levels and achievable key generation rates.

A key contribution of this work is the explicit coupling of spacecraft attitude knowledge, control errors, and fine-pointing jitter to the photon detection probability at the ground station. This enables early identification of critical sensitivity drivers and operational constraints for both the space and ground segments, as well as consistency checks between predicted pointing behaviour and expected link performance. In parallel, the link budget analysis is used to support the preparation of C3PO to enable the OPS-SAT VOLT mission before launch and throughout its operational phase. This includes defining optical alignment requirements, filter and detector configurations, acquisition strategies, and expected performance envelopes under varying atmospheric and geometric conditions representative of an urban ground station environment. The resulting predictions provide a baseline against which on-orbit measurements can be compared, enabling systematic cross-verification of pre-flight models with flight data.

By establishing a consistent and traceable analysis methodology ahead of launch, this work lays the foundation for robust in-orbit validation of space-based QKD links. The presented approach not only supports the OPS-SAT

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*OPS-SAT VOLT is a satellite mission led by Craft Prospect Ltd. (CPL) in partnership with European Space Agency (ESA) and UK Space Agency (UKSA).

[†]C3PO is an upcoming optical ground station led by Officina Stellare developed under the ESA general support technology programme (GSTP) and planned for deployment at the European Space Operations Centre (ESOC) in Darmstadt, Germany.

VOLT demonstration but also could contribute more broadly to future QKD missions by providing validated tools and lessons learned for PAT-driven link budget analysis.

Keywords: OPS-SAT VOLT, C3PO, QKD, Quantum Communication, Bennett-Brassard 1984 quantum key distribution protocol (BB84), Optical Link Budget, Free-space optical communication (FSOC)

1. INTRODUCTION

The increasing maturity of quantum computing has raised concerns regarding the long-term security of classical cryptographic systems based on computational complexity assumptions. QKD offers an alternative approach in which security is derived from the fundamental laws of quantum mechanics rather than from the assumed difficulty of mathematical problems, thereby providing information-theoretic security against adversaries equipped with arbitrarily large computational resources.^{1–3} Among the various prepare-and-measure QKD protocols, BB84 and its decoy-state variants remain the most widely adopted due to their conceptual simplicity, proven security, and compatibility with practical weak coherent pulse sources.^{1,4} While early demonstrations were primarily limited to laboratory environments and metropolitan-scale fiber networks, the exponential attenuation of optical signals in terrestrial channels fundamentally restricts the achievable communication distance.^{1,5} Satellite-based QKD has therefore emerged as the most promising solution for extending quantum-secured communications to continental and global scales, as demonstrated by satellite-to-ground and intercontinental quantum communication experiments.^{6–8} Consequently, satellite platforms are now regarded as a key enabling technology for future global quantum communication infrastructures and quantum networking architectures.^{9,10} In other words, since quantum states must ultimately be exchanged between satellite and terrestrial users, optical satellite-ground links constitute an indispensable component of any satellite QKD system.

Recent advances in miniaturized photonic payloads, compact optical terminals, and low-cost access to space have stimulated growing interest in microsatellite- and CubeSat-based QKD systems.^{11–13} However, the severe photon budget constraints imposed by diffraction losses, atmospheric attenuation, pointing and tracking errors, and limited satellite visibility windows require highly efficient key-generation protocols.^{1,5,14} Practical satellite implementations therefore predominantly employ decoy-state BB84 protocols, which mitigate photon-number-splitting attacks while maintaining compatibility with weak coherent pulse sources and existing space-qualified optical hardware.^{1,4,14} Beyond conventional symmetric implementations, where the two BB84 bases are selected with equal probability, efficient asymmetric decoy-state protocols intentionally bias the basis-selection probabilities to reduce basis-sifting losses and improve secret-key generation efficiency.^{4,15} Such improvements are particularly attractive for CubeSat missions, where communication opportunities are short and available resources are inherently limited.^{5,11,14} Consequently, decoy-state BB84 implementations, including asymmetric variants, have emerged as promising protocol candidates for next-generation resource-constrained satellite quantum communication systems.^{4,5,14}

The realization of optical and quantum space-ground links critically depends on the performance of the PAT subsystem.¹⁶ Owing to the narrow divergence of optical beams, PAT architectures are typically organized into hierarchical control loops comprising coarse spacecraft body pointing provided by the attitude determination and control system (ADCS) and fine-pointing stages implemented using fast steering mirror (FSM) and optical tracking sensors.^{17–22} Early LEO optical communication missions, such as the Optical Payload for Lasercomm Science (OPALS), relied primarily on gimballed pointing mechanisms with pointing requirements on the order of several hundred microradians (μrad).²³ More recent CubeSat-class systems have pursued highly integrated architectures with reduced mechanical complexity. For example, the CubeSat Laser Infrared Crosslink (CLICK) mission employs a two-stage pointing architecture in which spacecraft body pointing is used for acquisition with a 1.3 mrad beam, followed by FSM-based fine tracking of a 70 μrad communication beam.^{17,24,25} Similarly, the TeraByte Infrared Delivery (TBIRD) payload incorporated a closed-loop pointing feedback system capable of estimating line-of-sight pointing errors with an accuracy better than 10 μrad , enabling the precise beam alignment required for optical downlinks at data rates of up to 200 Gbps.^{18,22} More recently, OSIRIS4CubeSat demonstrated autonomous acquisition and closed-loop tracking in orbit, achieving a mean tracking error of 71 μrad while supporting optical downlinks of up to 100 Mbps.¹⁹ Collectively, these developments illustrate a clear trend toward highly integrated, low-size, weight, and power (SWaP) PAT architectures that increasingly

exploit precise spacecraft body pointing while minimizing reliance on bulky mechanical steering mechanisms, making them particularly attractive for CubeSat-scale optical and quantum communication payloads.^{17–22, 24, 25}

Building upon recent advances in CubeSat optical communication, pointing and tracking technologies, and space-based quantum communication, the OPS-SAT VOLT mission represents the next generation of integrated optical and quantum communication platforms, for more information please visit the OPS-SAT webpage. Developed through a collaboration between the ESA and CPL within ESA’s Secure and Laser Communication Technology (ScyLight) programme, VOLT is conceived as a 16U CubeSat technology demonstrator scheduled for launch mid 2027. Unlike previous missions that focused on individual capabilities such as optical downlinks, inter-satellite laser communication, or quantum payload demonstrations, VOLT combines multiple enabling technologies within a single orbital laboratory. The spacecraft payload incorporates quantum-state generation for QKD, bi-directional optical communication terminals, fine PAT subsystems, hyperspectral Earth-observation instruments, artificial intelligence (AI)-enabled context imaging, and high-performance onboard processing units. Such an integrated architecture provides an opportunity to investigate not only the performance of individual subsystems but also the interactions between optical communication, quantum security, autonomous operations, and advanced data-processing technologies within a resource-constrained CubeSat platform.

A key objective of OPS-SAT VOLT is the demonstration of operational services enabled by this integrated optical and quantum communications infrastructure. The mission is designed to be compatible with existing and emerging optical ground terminals while supporting the development of portable optical ground stations, ground-based quantum receivers, and optical communication back-end systems. This infrastructure will enable the demonstration of the augmented QKD service (AQKD), which aims to provide secure cryptographic key generation through QKD and subsequent key delivery to end-user nodes; the resilience constellation satellite system (RCSS), which is focused on automated hyperspectral Earth-observation data products and advanced onboard processing; and the OPS-SAT Experimenter (OSE) service, an in-orbit laboratory supporting third-party experiments in optical communications, quantum technologies, artificial intelligence, and Earth observation. By combining advanced PAT capabilities, optical communication links, and quantum payloads within a common CubeSat platform, VOLT provides a unique opportunity to evaluate the practical challenges associated with future operational quantum communication networks and secure space-to-ground optical services.

As one of the ground counterparts to OPS-SAT VOLT, the C3PO optical ground station is being developed under ESA’s GSTP through a collaboration between ESA and Officina Stellare, with deployment planned at ESOC in Darmstadt, Germany, in early 2027. The station provides the optical reception, single-photon detection, and PAT capabilities required to support space-to-ground quantum communication experiments under representative operational conditions. Together, the VOLT-C3PO architecture constitutes an end-to-end testbed for investigating key challenges associated with photon-starved optical links, atmospheric propagation, and precision pointing, thereby providing valuable insight into the implementation of future operational quantum communication systems. The remainder of this paper is organized as follows. Section 2 presents the system architecture, including the space terminal, the free-space optical channel, and the ground terminal. Section 3 introduces the QKD framework and performance analysis. Section 4 presents the results and their discussion. Finally, Section 7 concludes the paper.

2. SYSTEM ARCHITECTURE

In the following, we introduce the end-to-end QKD downlink considered in this work.

2.1 Space Terminal: OPS-SAT VOLT

OPS-SAT VOLT is equipped with uplink and downlink beacon subsystems, uplink and downlink FSOC subsystems, and a downlink QKD system as summarized in figure 1. The optical payload includes an 80 mm aperture telescope with a field of view of 0.25° , together with a high-performance PAT subsystem. The PAT system combines coarse body pointing provided by the spacecraft ADCS with a dedicated fine-pointing subsystem integrated into the optical payload. The system is designed to achieve a coarse-pointing accuracy better than 0.2° (3σ) and a fine-tracking accuracy better than $5\mu\text{rad}$ (3σ). Furthermore, it incorporates dynamic point-ahead compensation to account for the relative motion between the spacecraft and the ground terminal during link acquisition and maintenance.

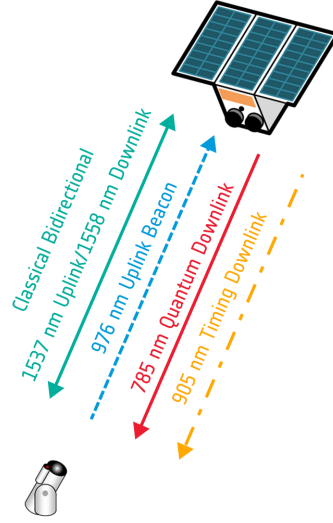


Figure 1. OPS-SAT VOLT optical communication links.

The nominal PAT sequence of the mission is summarized as follows. At the beginning of a communication pass, the optical ground station transmits a high-divergence 976 nm uplink beacon (ULB) toward the predicted spacecraft position. Simultaneously, the spacecraft slews its telescope toward the known location of the ground station using ADCS-generated attitude commands. The onboard fine-tracking subsystem then searches within the telescope field of view for the incoming ULB signal. Once detected, the ULB is aligned with the internal optical axis of the payload, thereby steering the downlink beacon (DLB) signal toward the ground station. The ground segment subsequently acquires the 905 nm DLB and closes its own tracking loop. Following successful establishment of the bidirectional beacon links, QKD operations are initiated. During active operation, a dynamic point-ahead correction is continuously applied to compensate for the relative motion between the spacecraft and the ground station. Note that in the event of beacon loss, communications are suspended and the terminal enters reacquisition mode until tracking is restored.

In addition to supporting fine optical tracking, the 905 nm spacecraft beacon provides timing recovery and synchronization for the received quantum states and serves as a polarization reference for the QKD channel. By comparing the polarization states of the quantum signal and beacon, the quantum receiver (QRx) can monitor and compensate for polarization distortions introduced by the optical link.

The quantum transmitter (QTx) implements a polarization-encoded BB84 protocol with two decoy states using weak coherent pulses at 785 nm and a repetition rate of 100 MHz. Thermal stabilization ensures wavelength and polarization stability, while an integrated quantum random number generator (QRNG) enables secure state preparation. The mean photon number can be adjusted through in-flight calibration, and both symmetric and asymmetric protocol configurations are supported to optimize performance under varying link conditions. Generated keys are managed through a dedicated framework aligned with applicable ETSI recommendations. In addition to the QKD payload, VOLT incorporates a bidirectional FSO subsystem that shares the terminal's optical and tracking infrastructure, operating at 1558 nm in the downlink and 1537 nm in the uplink.

2.2 Ground Terminal: C3PO

For the mission configuration considered in this work, C3PO provides a dedicated secondary Nasmyth interface designed to host a custom-furnished PAT and QRx bench. This interface enables the integration of the complete VOLT optical tracking and quantum reception chain. At the Nasmyth port, the PAT subsystem performs fine optical tracking using the 905 nm spacecraft beacon, thereby stabilizing the incoming beam on the receiver (Rx) optical axis and maximizing photon-coupling efficiency. The QRx recovers qubits in line with the BB84 protocol, dynamically corrects polarization offsets during an overpass, and recovers timing information from the DLB for

aligning detections with the satellite. Following synchronization and polarization correction, the quantum states are directed to the photodetection chain, where detection events are recorded by high-resolution time-tagging electronics for subsequent QKD post-processing. The Nasmyth interface is located at a nominal mechanical back focal length (MBFL) of 140 mm behind the focal plane of the 70 cm aperture telescope and provides an optical beam with an F-number of approximately F/7. Under operational conditions, the telescope maintains focal-plane positioning within ± 1 mm and wavefront quality better than 70 nm RMS after focusing. These parameters define the optical boundary conditions for the QRx and influence the achievable Rx coupling efficiency.

2.3 Free Space Channel

The free-space optical channel establishes the propagation path between the QTx and the QRx. The QTx employs weak coherent pulses characterized by a mean photon number per transmitted pulse, μ_{Tx} . Since a coherent state exhibits Poissonian photon-number statistics, the probability of transmitting n photons per pulse is given by

$$P_{\text{Tx}}(n) = \frac{\mu_{\text{Tx}}^n e^{-\mu_{\text{Tx}}}}{n!}. \quad (1)$$

A fundamental property of coherent states is that propagation through a lossy channel preserves their Poissonian statistics through the thinning property, whereby losses reduce only the mean photon number while leaving the distribution unchanged. Consequently, the photon number at the Rx remains Poisson distributed with mean

$$\mu_{\text{Rx}} = \mu_{\text{Tx}} \eta_{\text{tot}}, \quad (2)$$

where η_{tot} denotes the overall end-to-end optical transmission efficiency of the link. The photon-number distribution per transmitted pulse is therefore

$$P_{\text{Rx}}(n) = \frac{\mu_{\text{Rx}}^n e^{-\mu_{\text{Rx}}}}{n!}. \quad (3)$$

Assuming the beam size at the Rx is much larger than the Rx aperture, the total average end-to-end link efficiency can be expressed as

$$\eta_{\text{tot}} = \underbrace{\eta_{\text{Tx}} \eta_{\text{Rx}} G_{\text{Tx}} G_{\text{Rx}}}_{\text{Tx, Rx}} \underbrace{\tau_{\text{FS}} \tau_{\text{ATM}}}_{\text{Channel}} \underbrace{\tau_{\text{PAT}}}_{\text{PAT}}, \quad (4)$$

where the factors can be grouped into three physically distinct contributions.

Terminal efficiencies: The first group of terms in (4) accounts for gains and losses associated with the optical terminals themselves. These factors characterize the ability of the transmitter (Tx) to launch optical power into the channel and the ability of the Rx to collect and detect the incoming signal. The corresponding contribution is determined by the Tx and Rx coupling efficiencies, denoted by η_{Tx} and η_{Rx} , respectively, together with the telescope gains G_{Tx} and G_{Rx} . The transmit telescope gain is determined from the effective far-field divergence of the transmitted Gaussian beam and is given by

$$G_{\text{Tx}} = \frac{8}{\theta^2}, \quad (5)$$

where θ denotes the effective far-field half-angle beam divergence corresponding to the $1/e^2$ beam intensity peak. As evident from (5), a smaller beam divergence yields a larger transmit gain, reflecting the increased concentration of optical power in the desired propagation direction. The receive telescope gain depends on the Rx aperture size and is expressed as

$$G_{\text{Rx}} = \left(\frac{\pi D_{\text{Rx}}}{\lambda} \right)^2, \quad (6)$$

where D_{Rx} is the Rx telescope aperture diameter and λ is the optical wavelength. Equation (6) shows that larger Rx apertures provide greater optical gain by collecting a larger fraction of the incident optical field.

Propagation channel losses: After leaving the Tx, the optical beam experiences losses during propagation through the free-space channel. These losses are primarily caused by beam spreading due to diffraction and by absorption and scattering processes within the atmosphere. The overall propagation loss is therefore represented

by the combined effect of the free-space transmission factor τ_{FS} and the atmospheric transmission factor τ_{ATM} . The free-space path-loss factor describes the attenuation resulting from the geometric expansion of the optical beam as it propagates over long distances. As the beam footprint increases, the optical power density at the Rx decreases, reducing the fraction of transmitted power intercepted by the receiver aperture. The corresponding free-space transmission factor is given by

$$\tau_{\text{FS}} = \left(\frac{\lambda}{4\pi Z} \right)^2, \quad (7)$$

where L denotes the instantaneous slant range between the satellite and the ground station. Assuming a spherical Earth,

$$Z = \sqrt{(R_E + h)^2 - R_E^2 \cos^2(\theta_{\text{elev}})} - R_E \sin(\theta_{\text{elev}}), \quad (8)$$

where R_E is the Earth's radius, h is the satellite altitude, and θ_{elev} is the elevation angle of the satellite as observed from the ground station.

The atmospheric attenuation factor, denoted by τ_{ATM} , accounts for optical power losses caused by absorption and scattering during propagation through the atmosphere. Unlike free-space path loss, which results from geometric beam divergence and scales as Z^{-2} , atmospheric attenuation follows the exponential Beer–Lambert law and is governed by the optical depth of the propagation path. In this work, the zenith atmospheric transmittance τ_0 is obtained from the MODTRAN-based Atmospheric Transmission Calculator, which provides wavelength-dependent transmission estimates for specified atmospheric conditions, aerosol models, and seasonal profiles.²⁶ The atmospheric transmittance at an arbitrary elevation angle θ_{elev} is then derived using the Pickering air-mass model, which accounts for the increased propagation distance through the atmosphere at lower elevations. The corresponding air mass is calculated as²⁷

$$m(\theta_{\text{elev}}) = \frac{1}{\sin\left(\theta_{\text{elev}} + \frac{244}{165 + 47\theta_{\text{elev}}^{1.1}}\right)}, \quad (9)$$

where θ_{elev} is expressed in degrees. The transmittance at elevation angle θ_{elev} is subsequently obtained from the zenith transmittance according to

$$\tau_{\text{ATM}} = \tau_0^{m(\theta_{\text{elev}})}, \quad (10)$$

which assumes a homogeneous atmosphere and scales the zenith optical depth by the corresponding air-mass factor.²⁷ This approach provides an efficient means of estimating atmospheric attenuation for arbitrary link elevations while retaining the wavelength dependence predicted by the MODTRAN model.

PAT efficiency: The received optical power is also affected by residual misalignment between the Tx and Rx line of sight, denoted by $\tau_{\text{PAT}}^{\text{inst}}$. For a diffraction-limited Gaussian beam with a beam footprint on the Rx plane much larger than the Rx telescope aperture, the instantaneous pointing efficiency is given by

$$\tau_{\text{PAT}}^{\text{inst}} = \exp\left(-\frac{2}{\theta^2}[(\alpha_x - \delta_x)^2 + (\alpha_y - \delta_y)^2]\right) = \exp\left(-\frac{2}{\theta^2}\|\boldsymbol{\alpha} - \boldsymbol{\delta}\|^2\right), \quad (11)$$

where θ denotes the $1/e^2$ beam-divergence angle, $\boldsymbol{\alpha} = (\alpha_x, \alpha_y)^T$ is the random angular displacement of the beam centroid relative to the receiver boresight, and $\boldsymbol{\delta} = (\delta_x, \delta_y)^T$ is a deterministic boresight offset. By definition, perfect alignment is achieved when $\boldsymbol{\alpha} = \boldsymbol{\delta}$, in which case the instantaneous pointing efficiency is normalized to unity, i.e., $\tau_{\text{PAT}}^{\text{inst}} = 1$.

Unlike the previously introduced terms, the PAT efficiency is inherently stochastic because the residual tracking error $\boldsymbol{\alpha}$, arising from tracking inaccuracies, mechanical vibrations, platform jitter, and other dynamic disturbances, is a random variable. Essentially, the residual tracking error causes a displacement of the received beam relative to the center of the Rx aperture, reducing the end-to-end channel efficiency. The residual tracking-error components along two orthogonal axes are commonly modeled as Gaussian random variables.²⁶ This assumption is justified by the Central Limit Theorem, as the overall tracking error results from the aggregation of many independent random contributions, such as platform jitter, sensor and actuator noise, atmospheric effects, and centroiding errors associated with the tracking sensor's spot-position estimation algorithm.

In the following, we provide closed-form expressions for the average PAT efficiency and the corresponding outage probability under a general correlated Gaussian model for the angular pointing jitter with non-zero mean values. The commonly adopted isotropic and uncorrelated jitter model is recovered as a special case.

Remark 1. (Average Pointing Efficiency): Let vector $\boldsymbol{\alpha} = (\alpha_x, \alpha_y)^\top \sim \mathcal{N}(\boldsymbol{\delta}, \boldsymbol{\Sigma}_\alpha)$ be the angular pointing-error vector modelled by a bivariate Gaussian random variable with the mean vector $\boldsymbol{\delta} = (\delta_x, \delta_y)$ and the covariance matrix

$$\boldsymbol{\Sigma}_\alpha = \begin{bmatrix} \sigma_x^2 & \rho\sigma_x\sigma_y \\ \rho\sigma_x\sigma_y & \sigma_y^2 \end{bmatrix}, \quad -1 < \rho < 1, \quad (12)$$

where ρ denotes the correlation coefficient and σ_x^2 and σ_y^2 are the variances of the tracking-jitter components along the two orthogonal angular axes. The average pointing efficiency under the above correlated Gaussian angular jitter is given by

$$\tau_{\text{PAT}} \triangleq \mathbb{E}[\tau_{\text{PAT}}^{\text{inst}}] = \frac{1}{\sqrt{D}} \exp \left[-\frac{2}{\theta^2 D} \left(\left(1 + \frac{4\sigma_y^2}{\theta^2} \right) \delta_x^2 - \frac{8\rho\sigma_x\sigma_y}{\theta^2} \delta_x\delta_y + \left(1 + \frac{4\sigma_x^2}{\theta^2} \right) \delta_y^2 \right) \right], \quad (13)$$

where $\mathbb{E}[\cdot]$ is the statistical expectation, and D is given by

$$D = \left(1 + \frac{4\sigma_x^2}{\theta^2} \right) \left(1 + \frac{4\sigma_y^2}{\theta^2} \right) - \frac{16\rho^2\sigma_x^2\sigma_y^2}{\theta^4}. \quad (14)$$

For the special case of zero boresight bias, i.e., $\boldsymbol{\delta} = \mathbf{0}$, the average pointing efficiency simplifies to

$$\tau_{\text{PAT}} = \frac{1}{\sqrt{D}} \quad (15)$$

Furthermore, if the angular jitter is isotropic, i.e., $\sigma_x = \sigma_y = \sigma$, and uncorrelated and fully correlated jitters, i.e., $\rho = 0$ and $\rho = \pm 1$, the expression (15) reduces to

$$\tau_{\text{PAT}} = \frac{\theta^2}{\theta^2 + 4\sigma^2}, \quad (16)$$

and

$$\tau_{\text{PAT}} = \sqrt{\frac{\theta^2}{\theta^2 + 8\sigma^2}}, \quad (17)$$

respectively. Note that the cases $\rho = +1$ and $\rho = -1$ yield the same result because (13) is an even function of ρ .

Proof. Please refer to Appendix A. $\square$

Remark 2 (Pointing-Outage Probability): Let the angular pointing-error vector satisfy the assumptions of remark 1 with zero mean[‡], i.e., $\boldsymbol{\alpha} = (\alpha_x, \alpha_y)^\top \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\Sigma}_\alpha)$, and for a predefined pointing-efficiency threshold τ_{th} , the pointing-outage probability, i.e., the probability that the instantaneous pointing efficiency falls below the minimum acceptable value τ_{th} , is given by

$$P_{\text{out}} \triangleq \Pr(\tau_{\text{PAT}}^{\text{inst}} \leq \tau_{\text{th}}) = Q_1 \left(\sqrt{\frac{1-q^2}{2q^2\Omega}} \gamma, \sqrt{\frac{1+q^2}{2q^2\Omega}} \gamma \right), \quad (18)$$

where $Q_1(\cdot, \cdot)$ denotes the first-order Marcum Q -function, and

$$q = \sqrt{\frac{\lambda_2}{\lambda_1}}, \quad \Omega = \lambda_1 + \lambda_2, \quad \gamma = -\frac{\theta^2}{2} \ln(\tau_{\text{th}}). \quad (19)$$

[‡]The zero-mean case is considered here because the corresponding outage expression admits a tractable closed-form representation, whereas the general non-zero-mean case results in considerably more involved expressions that offer limited additional insight.

Here, λ_1 and λ_2 ($\lambda_1 > \lambda_2$) are the eigenvalues of the covariance matrix Σ_α in (12). For the special case of $\sigma_x = \sigma_y = \sigma$ and uncorrelated and fully correlated jitters, i.e., $\rho = 0$ and $\rho = \pm 1$, the expression (18) reduces to

$$P_{\text{out}} = \tau_{\text{th}}^{\frac{\theta^2}{8\sigma^2}}. \quad (20)$$

and

$$P_{\text{out}} = \text{erfc}\left(\frac{\theta}{\sqrt{8}\sigma} \sqrt{\ln(\tau_{\text{th}}^{-1})}\right), \quad (21)$$

respectively, where $\text{erfc}(\cdot)$ is the complementary error function. Note that similar to remark 1, the cases $\rho = +1$ and $\rho = -1$ yield the same result. This follows from the fact that, for $\sigma_x = \sigma_y$, the eigenvalues of Σ_α are $\lambda_1 = \sigma^2(1 + |\rho|)$ and $\lambda_2 = \sigma^2(1 - |\rho|)$ after ordering, so that the parameters q and Ω in (18) depend only on $|\rho|$. Hence, $P_{\text{out}}(\rho) = P_{\text{out}}(-\rho)$.

Proof. Please refer to Appendix B. $\square$

Remarks 1 and 2 provide complementary metrics for assessing the impact of residual pointing errors on the performance of optical communication links. Specifically, remark 1 quantifies the average pointing efficiency, which captures the mean power coupling loss due to tracking jitter and a static bias, while remark 2 characterizes the probability of severe performance degradation through the pointing-outage probability. An interesting observation is that the effect of correlation between the residual pointing-error components, α_x and α_y , is fundamentally different for these two metrics. As shown in remark 2, increasing the correlation increases the likelihood of large joint pointing deviations, thereby increasing the probability that the instantaneous pointing efficiency falls below a prescribed threshold. Consequently, the pointing-outage probability becomes larger as the residual errors become more strongly correlated. In contrast, remark 1 reveals that a higher correlation does not necessarily imply a reduction in the average pointing efficiency. In fact, for a given pointing-jitter variance, the average pointing efficiency increases with the correlation coefficient. This seemingly counterintuitive result arises because stronger correlation constrains the randomness of the two-dimensional pointing-error process to a narrower subspace, reducing the effective spread of the beam displacement and thereby improving the mean collected optical power. Therefore, correlation introduces a trade-off: it improves the average pointing efficiency while simultaneously increasing the probability of extreme pointing events and, hence, the outage probability.

3. QKD DOWNLINK STUDY

The performance of the proposed satellite-to-ground QKD system is evaluated in terms of the quantum bit error rate (QBER) and the achievable secret-key rate (SKR). To this end, a decoy-state BB84 framework is adopted. The resulting model establishes a direct connection between the physical-layer characteristics of the optical link and the corresponding performance metrics. In particular, transmission losses, background radiation, detector noise, and residual pointing errors jointly determine the photon-detection statistics, from which the QBER and the finite-key SKR are obtained. The following subsections present the protocol assumptions, detection and QBER model, and finite-key SKR formulation employed throughout the performance evaluation. The finite-key SKR formulation is based on the finite-key decoy-state analysis presented in.²⁸

3.1 Protocol Overview

The QTx employs a polarization-encoded decoy-state BB84 protocol based on weak coherent pulses. Both symmetric and asymmetric basis-selection schemes are considered. Let p_X and p_Z denote the probabilities that Alice (QTx) and Bob (QRx) independently select the X and Z bases, respectively, such that²⁸

$$p_X + p_Z = 1. \quad (22)$$

The probability that Alice and Bob select the same basis and therefore retain a detection event after basis sifting is

$$q = P(\text{same basis}) = p_Z^2 + p_X^2. \quad (23)$$

For the symmetric protocol, $p_X = p_Z = 0.5$, which yields the well-known sifting factor $q = 0.5$. In the asymmetric implementation, the basis-selection probabilities are deliberately biased, typically with $p_Z > p_X$, to reduce basis-sifting losses and increase the fraction of detection events contributing to secret-key generation.

During a satellite pass, Alice prepares polarization-encoded signal and decoy states and transmits them to Bob through the QKD downlink channel. Bob performs polarization measurements using randomly selected bases and records all valid detection events. Following the quantum transmission phase, Alice and Bob execute the standard BB84 post-processing procedure consisting of detection announcement, basis sifting, parameter estimation, authenticated error correction, error verification, and privacy amplification. The resulting finite-size detection statistics are subsequently used to estimate the achievable secret key length (SKL) and SKR.²⁸

3.2 Detection Statistics and QBER Analysis

The received quantum signal is characterized by a finite number of photons and is therefore inherently subject to quantum fluctuations. In photon-counting Rxs, the detection process is commonly modeled using Poisson statistics, allowing the probability of signal and noise detection events to be quantified and subsequently related to the resulting QBER. Based on (3), the probability of detecting at least one signal photon is given by

$$P_{\text{sig}} = 1 - \exp(-\eta_{\text{det}}\mu_{\text{Rx}}), \quad (24)$$

where μ_{Rx} denotes the mean number of received photons per pulse and η_{det} is the detector quantum efficiency. In addition to signal detections, detector clicks may also originate from background radiation and dark counts. Assuming both contributions follow Poisson statistics, the probability of at least one noise-induced detection event within a detection gate of duration T_g is

$$P_{\text{n}} = 1 - \exp[-(R_{\text{bg}} + R_{\text{dc}})T_g], \quad (25)$$

where R_{bg} and R_{dc} denote the background-count rate and aggregate dark-count rate of the Rx, respectively. Assuming statistically independent signal and noise processes, the overall probability of obtaining a detector click can be expressed as

$$P_{\text{det}} = 1 - \exp[-(\eta_{\text{det}}\mu_{\text{Rx}} + (R_{\text{bg}} + R_{\text{dc}})T_g)]. \quad (26)$$

The QBER is defined as the ratio of erroneous detections to the total number of detections. In practice, erroneous detections arise from both polarization imperfections and noise-induced detector clicks. Polarization-related errors may originate from imperfect state preparation, residual polarization misalignment, depolarization effects introduced by the optical channel, finite extinction ratios of optical components, and imperfect polarization compensation at the receiver. These effects are collectively represented by a polarization-error probability e_{d} . Since noise-induced clicks are equally likely to produce a correct or incorrect bit value, half of the noise detections contribute to the error count. The overall error-detection probability is therefore

$$P_{\text{err}} = e_{\text{d}}P_{\text{sig}} + \frac{1}{2}P_{\text{n}}. \quad (27)$$

The resulting QBER can be approximated as

$$\text{QBER} = \frac{P_{\text{err}}}{P_{\text{det}}}. \quad (28)$$

Equation (28) highlights the dependence of the system performance on both polarization fidelity and the balance between signal and noise detections. As the received photon number decreases due to propagation losses or pointing impairments, the relative contribution of noise events increases, resulting in a higher QBER. Likewise, depolarization and polarization-tracking errors increase e_{d} and therefore directly degrade the achievable QBER.

3.3 Finite-Key Secret-Key Rate

The finite-key analysis follows the composable-security framework in.²⁸ For a satellite pass of duration T and pulse repetition frequency f , the total number of transmitted optical pulses is

$$N_{\text{pulse}} = fT. \quad (29)$$

In the BB84 protocol, only those events for which Alice and Bob select compatible bases contribute to the sifted key. Using the basis-sifting probability q introduced in the previous subsection and the overall detection probability P_{det} , the expected sifted-key size can be written as

$$N_{\text{sift}} = N_{\text{pulse}} q P_{\text{det}}. \quad (30)$$

Following basis reconciliation and parameter estimation, the information disclosed during error correction is upper bounded by

$$\lambda_{\text{EC}} = f_{\text{EC}} H_2(\text{QBER}) N_{\text{sift}}, \quad (31)$$

where f_{EC} denotes the error-correction inefficiency and

$$H_2(x) = -x \log_2(x) - (1-x) \log_2(1-x) \quad (32)$$

is the binary entropy function. In the decoy-state BB84 protocol, the observed signal and decoy detection statistics are processed using a finite-key parameter-estimation procedure to determine the security-relevant quantities. Specifically, lower bounds on the numbers of sifted detection events originating from vacuum and single-photon pulses are obtained, denoted by s_0 and s_1 , respectively, together with an upper bound on the single-photon phase-error rate, e_1^{ph} . In this work, these quantities are determined using the finite-key decoy-state analysis implemented in SatQuMA <https://github.com/cnqo-qcomms/SatQuMA>,²⁸ which employs Chernoff-bound statistical estimation to account for finite-size fluctuations. The resulting bounds are subsequently used to evaluate the composable secure secret-key length

$$\ell = s_0 + s_1 \left[1 - H_2(e_1^{\text{ph}}) \right] - \lambda_{\text{EC}} - 6 \log_2 \left(\frac{21}{\epsilon_s} \right) - \log_2 \left(\frac{2}{\epsilon_c} \right), \quad (33)$$

where ϵ_s and ϵ_c denote the secrecy and correctness parameters, respectively. For a satellite pass of duration T , the corresponding secret-key rate is

$$R_{\text{SKR}} = \frac{\ell}{T}. \quad (34)$$

The above formulation establishes a direct link between the optical-channel performance and the achievable cryptographic performance of the QKD downlink. Atmospheric attenuation, geometric spreading losses, detector noise, and residual PAT errors determine the overall channel transmission and consequently the received signal level at the QRx. These factors directly influence the detection probability, gain, and QBER, which are then used as inputs to the finite-key decoy-state analysis. The resulting estimates of s_0 , s_1 , and e_1^{ph} ultimately determine the achievable SKL and SKR.

4. RESULTS

4.1 System Parameters

The results presented in this section are obtained for VOLT at an altitude of 500 km. The optical ground station (OGS) is assumed to be the C3PO, located at an elevation of 176 m above sea level. These parameters define the geometric link conditions and are used throughout the performance analysis. Atmospheric transmission was evaluated using MODTRAN for four representative seasonal scenarios corresponding to Darmstadt, Germany. Owing to the availability of only two standard mid-latitude atmospheric profiles in MODTRAN, the Mid-Latitude Winter atmosphere was used to represent both winter and spring conditions, whereas the Mid-Latitude Summer atmosphere was used to represent both summer and autumn conditions. Ground temperatures of 275 °K, 285 °K, 295 °K, and 285 °K were assumed for winter, spring, summer, and autumn, respectively. For all

scenarios, an urban aerosol model and a visibility of 23 km were assumed. Since atmospheric absorption and scattering occur predominantly below approximately 100 km altitude, the Tx was placed at the maximum available MODTRAN sensor altitude of 99 km, thereby approximating a space-to-ground propagation path through the full atmosphere http://modtran.spectral.com/modtran_home. The resulting clear-sky zenith atmospheric transmission coefficients τ_0 , accounting for both molecular and aerosol absorption and scattering, are summarized in Table 1. The corresponding atmospheric transmission coefficient at an arbitrary elevation angle, τ_{ATM} , is subsequently obtained from (10). Table 2 summarizes the principal system parameters adopted in the end-to-end VOLT-C3PO QKD downlink model. In particular, the Tx efficiency (η_{Tx}) is set to unity because the emitted mean photon number is referenced to the telescope exit aperture. Internal losses within the transmitter are assumed to be accurately characterized and compensated during system calibration by appropriately adjusting the weak coherent pulse source brightness. As a result, transmitter losses are not treated as a separate term in the link-budget analysis. On the Rx side, the overall Rx efficiency (η_{Rx}) accounts for the combined impact of the telescope obscuration, the Rx-telescope optical throughput, and the internal optical losses of the QRx. Accordingly,

$$\eta_{\text{Rx}} = (1 - \epsilon_{\text{Rx}}^2) \eta_{\text{Tel,Rx}} \eta_{\text{QRx}}, \quad (35)$$

where ϵ_{Rx} denotes the telescope obscuration ratio, $\eta_{\text{Tel,Rx}}$ is the Rx-telescope optical efficiency, and η_{QRx} is the efficiency of the QRx. To this end, unless otherwise stated, these parameter values are used as the nominal baseline configuration for all simulations presented in the following subsections.

Table 1. Clear-sky Zenith Atmospheric Transmission Coefficient τ_0 .

λ (nm)	Spring/Winter	Summer/Autumn
785	0.80	0.78
905	0.77	0.66
976	0.74	0.60

4.2 Performance Evaluation of the QKD Link

The first step in the performance evaluation is the calculation of the overall link efficiency according to (4), which determines the mean number of photons arriving at the Rx and forms the basis for all subsequent QKD performance calculations.

Figure 2 illustrates the impact of the correlation coefficient ρ on both the average pointing loss and the pointing-outage probability at zenith ($\theta_{\text{elev}} = 90^\circ$) and zero bias ($\delta = \mathbf{0}$) for anisotropic pointing jitter with $(\sigma_x, \sigma_y) = (5, 3) \mu\text{rad}$. The outage probability is evaluated for a pointing-efficiency threshold of $\tau_{\text{th}} = 0.01$ using Monte Carlo simulations based on the Gaussian pointing-error model, thereby avoiding the numerical evaluation of the Marcum- Q function appearing in the Hoyt-distribution formulation. As shown in Fig. 2(a), the average pointing loss decreases monotonically with increasing correlation, dropping from approximately 4.18 dB for uncorrelated jitter ($\rho = 0$) to about 3.25 dB for fully correlated jitter ($\rho = 1$), corresponding to an improvement of nearly 0.93 dB. This behavior can be explained by the increasing statistical dependence between the horizontal and vertical pointing-error components. For uncorrelated jitter, the pointing-error vector occupies a broader two-dimensional region, whereas increasing correlation progressively concentrates the error realizations along a preferred direction. In the limiting case of fully correlated jitter, the pointing-error distribution collapses onto a one-dimensional subspace, reducing the effective spread of the angular displacement. Since the pointing efficiency of a Gaussian beam decreases exponentially with the squared radial pointing error, this concentration effect increases the average collected power and consequently reduces the average pointing loss. In contrast, Fig. 2(b) shows that the pointing-outage probability increases monotonically with ρ , rising from approximately 7.9% at $\rho = 0$ to about 10.4% at $\rho = 1$. Although stronger correlation improves the average pointing efficiency, it simultaneously increases the likelihood of large joint angular excursions along the dominant error direction. As

[§]The QTx efficiency is assumed to be unity because the pulse intensity is adjusted such that the desired optical intensity is achieved at the satellite output aperture.

Table 2. Key Parameters of the VOLT-C3PO QKD Downlink.

Parameter	Value
Orbit altitude	500 km
C3PO height above sea level	176 m
QTx repetition rate	100 MHz
QTx effective far-field divergence half angle	$6.25 \mu\text{rad}$
QTx efficiency (η_{Tx})	$1^{\S}$
Signal mean photon number	0.5 photons/pulse
Decoy mean photon number	0.2 photons/pulse
Vacuum mean photon number	0 photons/pulse
Rx diameter (D_{Rx})	70 cm
Rx obscuration ratio (ϵ_{Rx})	0.39
Rx telescope efficiency ($\eta_{\text{Tel,Rx}}$)	0.288
QRx efficiency (η_{QRx})	0.26
Detector efficiency (η_{det})	0.64
Detector dark count rate per detector (R_{dc})	100 counts/s
Background count rate (R_{bg})	500 counts/s
Correctness parameter (ϵ_c)	10^{-15}
Secrecy parameter (ϵ_s)	10^{-9}
Intrinsic QBER (e_d)	0.02
Error correction factor (f_{EC})	1.16
Detector gate width (T_g)	2 ns

a result, extreme pointing-error events become more probable, increasing the probability that the instantaneous pointing efficiency falls below the prescribed threshold. These results highlight an important distinction between average performance and link availability. While stronger correlation improves the mean pointing efficiency and reduces the associated average loss, it also increases the probability of severe pointing degradations and hence the outage probability. Therefore, correlation between the orthogonal pointing-error components has a non-trivial impact on optical-link performance and should be accurately accounted for through the full pointing-error covariance matrix when assessing system availability. Since Fig. 2(a) shows that the maximum average pointing loss occurs for uncorrelated jitter, the remainder of this work adopts the conservative assumption of $\rho = 0$.

Figure 3 presents the impact of the residual tracking-jitter standard deviation on both the total link loss and the resulting QBER as functions of the satellite elevation angle. As shown in Fig. 3(a), the link efficiency improves with increasing elevation angle for all jitter levels due to the reduction in both propagation distance and atmospheric air mass. Increasing the residual tracking jitter introduces additional pointing loss, shifting the link-loss curves upward. The impact of tracking accuracy is significant, with a difference exceeding 6 dB between the cases of $\sigma = 4 \mu\text{rad}$ and $\sigma = 10 \mu\text{rad}$. The corresponding QBER results are shown in Fig. 3(b). For all jitter levels, the QBER decreases with increasing elevation angle, primarily as a consequence of the reduced channel loss and the resulting improvement in the signal-to-noise ratio. Larger residual tracking jitter leads to higher QBER values because the associated pointing losses reduce the received signal-photon rate while leaving the noise contribution essentially unchanged. This effect is particularly pronounced at low elevation angles, where the link is already strongly affected by propagation losses. At high elevation angles, the QBER approaches a floor that is mainly determined by the intrinsic system error rate and detector noise. For the results presented in Fig. 3(b), a background-count rate of $R_{\text{bg}} = 500$ counts/s was assumed, corresponding to favorable dark-sky

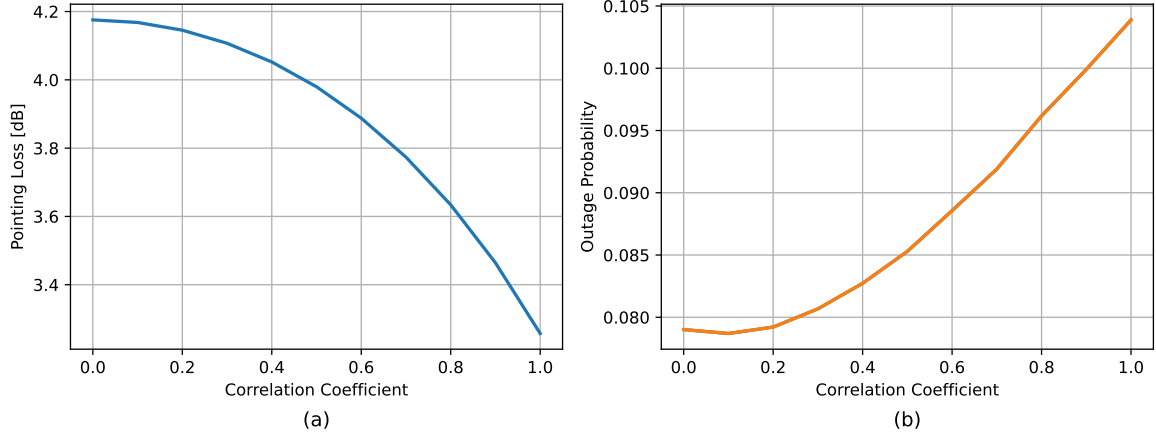


Figure 2. (a) Average pointing efficiency loss and (b) pointing-outage probability as functions of the correlation coefficient ρ at zenith ($\theta_{\text{elev}} = 90^\circ$) for anisotropic pointing jitter with $(\sigma_x, \sigma_y) = (5, 3) \mu\text{rad}$. The outage probability is evaluated for a pointing-efficiency threshold of $\tau_{\text{th}} = 0.01$.

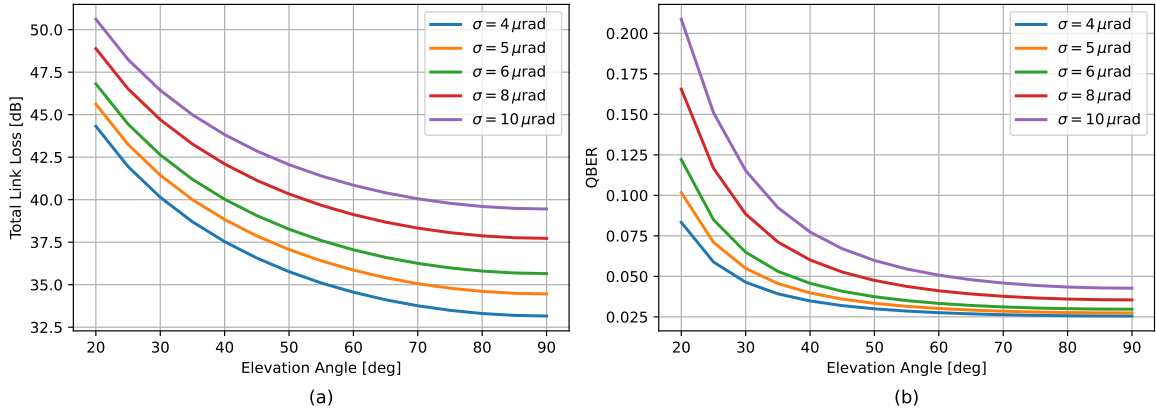


Figure 3. (a) Total link loss and (b) QBER as functions of elevation angle for different values of the pointing-jitter standard deviation σ .

conditions, as listed in Table 2. Together with a dark-count rate of $R_{\text{dc}} = 100$ counts/s per detector and four active single-photon detectors, this yields a total noise-click probability of approximately $P_n = 1.8 \times 10^{-6}$ for a detection gate duration of $T_g = 2$ ns.

To assess the impact of elevated ambient illumination on system performance, additional background-count rates of up to $R_{\text{bg}}^{\text{max}} = 5000$ counts/s are considered, i.e., corresponding to $P_n = 1.8 \times 10^{-5}$ for the set of considered parameters. Such conditions may arise during bright-moon operation or in the presence of increased sky radiance and light pollution. Throughout this analysis, the residual tracking-jitter standard deviation is fixed at $\sigma = 8 \mu\text{rad}$, which exceeds the OPS-SAT VOLT tracking-performance requirement, thereby providing a conservative assessment of the combined effects of pointing imperfections and background noise. Figure 4 shows the resulting variation of the QBER as a function of the background-count rate. Higher background illumination produces more noise-induced detector clicks, thereby increasing the error probability. In contrast, the QBER decreases with increasing elevation angle due to the improved channel transmission and higher received signal power. As a result, the influence of background noise is most pronounced at low elevations, where propagation losses are highest, while its impact becomes less severe at high elevations.

For completeness, the following subsections present the link-budget analyses for both the ULB and DLB. The total link loss is decomposed into its constituent components, including free-space propagation losses, atmospheric losses, pointing losses, and terminal losses, thereby highlighting the relative contribution of each impairment to the overall system performance.

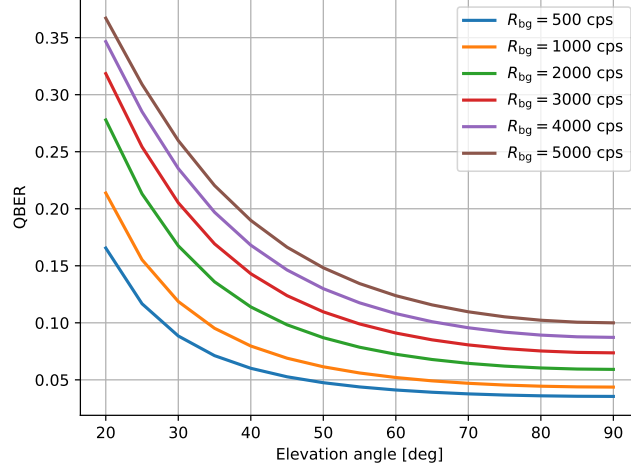


Figure 4. QBER vs. elevation angle for different background-illumination count rate R_{bg} .

5. UPLINK BEACON LINK BUDGET

The uplink beacon link budget is evaluated using the same framework introduced for the QKD downlink in Section 2.3 equation (4). Consequently, the received optical power is obtained from the transmitter and receiver terminal efficiencies, free-space propagation loss, atmospheric attenuation, and pointing losses. Since the corresponding expressions for the telescope gains, free-space transmission factor, and atmospheric transmission factor have already been introduced in Section 2.3, they are not repeated here. Unlike the QKD downlink, however, the uplink beacon propagates through the strongest turbulence layers immediately after leaving the optical ground station causing turbulence-induced distortions to accumulate over the entire propagation path and therefore results in a more pronounced degradation of beam quality. Consequently, additional turbulence-induced effects must be considered in the uplink budget, namely beam wander, wavefront degradation, and scintillation fading.^{16, 29}

Pointing efficiency: Using equation (13) for isotropic and uncorrelated angular fluctuations, the average uplink pointing efficiency is obtained by^{16, 29}

$$\eta_{PAT,UL} = \frac{\theta^2}{\theta^2 + 4\sigma_{ul}^2} \exp\left(-\frac{2\delta^2}{\theta^2 + 4\sigma_{ul}^2}\right), \quad (36)$$

where θ denotes the uplink beacon divergence, δ is the static pointing bias, and

$$\sigma_{ul}^2 = \sigma_{jt}^2 + \sigma_{bw}^2 \quad (37)$$

is the total angular variance arising from transmitter jitter and atmospheric beam wander. The turbulence-induced beam-wander variance is given by^{16, 29}

$$\sigma_{bw}^2 = 0.54(H - h_{OGS})^2 \csc^2(\theta_{elev}) \left(\frac{2w_0}{r_0}\right)^{5/3}, \quad (38)$$

where r_0 is the Fried coherence parameter, w_0 is the transmitter beam radius, H is the orbital altitude, h_{OGS} is the ground-station altitude, and θ_{elev} is the satellite elevation angle. Equation (36) highlights the fundamental difference between acquisition and tracking. In the downlink QKD analysis, the PAT loop is assumed to be locked such that the residual pointing error is a zero-mean random process. During uplink acquisition, however, the uncompensated ADCS uncertainty introduces a non-zero mean pointing error represented by the bias term δ , which leads to the exponential penalty in (36).

Wavefront degradation: Besides beam wander, atmospheric turbulence induces random phase aberrations across the transmitted wavefront, causing a redistribution of optical energy in the far field and a reduction of

the on-axis irradiance. This effect results in an additional loss mechanism in the uplink beacon link budget and is commonly characterized by the Strehl ratio S , defined as the ratio of the peak far-field irradiance of the turbulence-distorted beam to that of an ideal diffraction-limited beam. Under the weak-turbulence approximation, the Strehl ratio can be expressed as¹⁶

$$S = \left[1 + \left(\frac{w_0}{r_0} \right)^{5/3} \right]^{-6/5}, \quad (39)$$

where r_0 is the Fried parameter. The Strehl ratio may therefore be interpreted as the transmission efficiency associated with turbulence-induced wavefront distortion and is included as a multiplicative factor in the uplink link budget. The physical meaning of (39) can be understood by considering two limiting cases. When $w_0 \ll r_0$, the turbulence strength is weak across the transmitter aperture and the wavefront remains nearly planar, resulting in $S \approx 1$ and negligible wavefront-degradation loss. Conversely, when $w_0 \gg r_0$, the aperture spans many independent turbulence cells, leading to significant phase distortions across the wavefront and consequently $S \ll 1$. In this regime, a substantial fraction of the optical power is redistributed away from the diffraction-limited central lobe, reducing the received beacon irradiance and degrading tracking performance. Since r_0 depends on the integrated turbulence strength along the propagation path, the Strehl ratio is inherently elevation dependent; lower elevation angles correspond to longer atmospheric paths, stronger wavefront distortions, and consequently reduced Strehl efficiency.

Scintillation fade margin: Let factor τ_{turb} account for atmospheric turbulence-induced irradiance fluctuations resulting from refractive-index inhomogeneities along the propagation path. These fluctuations, commonly referred to as scintillation,¹⁶ produce random variations in the received optical intensity and consequently reduce the power available for detection. In this paper, turbulence is characterized using an altitude-dependent refractive-index structure parameter profile $C_n^2(h)$ along the ground-to-satellite slant path, modelled using the hufnagel-valley (HV) profile as

$$C_n^2(h) = 0.00594 \left(\frac{v}{27} \right)^2 \left(\frac{h}{10^5} \right)^{10} e^{-h/1000} + 2.7 \times 10^{-16} e^{-h/1500} + A e^{-h/100}, \quad (40)$$

where v is the RMS high-altitude wind speed, h is the height of satellite above the OGS, and A is the near-ground turbulence strength. Irradiance fluctuations are modelled using a log-normal (LN) distribution for weak-to-moderate turbulence conditions and a gamma-gamma (GG) distribution for moderate-to-strong turbulence conditions. For a specified fade probability P_{fade} , the turbulence transmission factor, τ_{turb} , is obtained from the inverse cumulative distribution function (CDF) of the corresponding irradiance distribution,

$$\tau_{\text{turb}} = F_I^{-1}(P_{\text{fade}}), \quad (41)$$

where $F_I(\cdot)$ denotes the CDF of the normalized received irradiance, modelled using either an LN or GG distribution depending on the turbulence regime. In other words, τ_{turb} represents the minimum normalized received irradiance exceeded with probability $1 - P_{\text{fade}}$. This factor is incorporated into the link budget as a turbulence-induced fading term and quantifies the additional optical power margin required to maintain the desired link availability under atmospheric turbulence conditions. While the inverse CDF can be evaluated analytically for the LN model, this is generally not the case for the GG distribution, whose CDF is expressed in terms of special functions and does not admit a simple closed-form inverse. Therefore, for GG fading, $\tau_{\text{turb}} = F_I^{-1}(P_{\text{fade}})$ is more conveniently obtained via Monte Carlo simulation, where the desired transmission factor is estimated directly as the quantile associated with the target fade probability. The complete uplink beacon transmission factor can therefore be written as

$$\tau_{\text{ULB}} = \eta_{\text{Tx}} \eta_{\text{Rx}} G_{\text{Tx}} G_{\text{Rx}} \tau_{\text{FS}} \tau_{\text{ATM}} \eta_{\text{PAT,UL}} S \tau_{\text{turb}}, \quad (42)$$

where the first six terms are identical to those introduced in (4), while the PAT term is replaced by the acquisition-phase pointing efficiency $\eta_{\text{PAT,UL}}$ and augmented by the additional turbulence factors S and τ_{turb} .

The parameters used for the numerical evaluation are listed in Tables 3 and 4. The resulting link budget is reported in Table 5. During acquisition, the ADCS pointing uncertainty is modelled as a static bias of $\delta = 0.2^\circ$

and is therefore included in the PAT loss calculation through (36). The budget is referenced to a transmit power of 1 W (0 dBW); results for higher beacon powers can be obtained by adding the corresponding transmit-power increment in decibels. As shown in Table 5, the dominant losses arise from geometric spreading, atmospheric attenuation, and acquisition-pointing uncertainty. Owing to the relatively large beacon divergence of 4.44 mrad, aperture averaging significantly mitigates scintillation, resulting in a fading penalty below 0.25 dB even at low elevation angles.

Table 3. Atmospheric turbulence parameters.

Parameter	Value
Fade probability, P_{fade}	10^{-2}
Satellite speed	7500 m/s
Near-ground turbulence strength (HV 5/7)	$1.7 \times 10^{-14} \text{ m}^{-2/3}$
RMS high-altitude wind (HV 5/7)	21 m/s

Table 4. ULB System Parameters

ULB System Parameters	Value
Orbit altitude	500 km
C3PO height above sea level	176 m
ULB divergence angle (θ)	4.44 mrad
ULB transmit power (P_t)	1 W
ULB Tx aperture diameter (D_{Tx})	47 mm
ULB wavelength (λ)	976 nm
ULB central obscuration ratio	0
Rx diameter (D_{Tx})	80 mm
Rx central obscuration ratio (ϵ_{tx})	0.41
ADCS half-cone uncertainty (δ)	3.5 mrad

Table 5. ULB Link Budget for 0 dBW Transmit Power and 0.2° Pointing Bias

Elevation Angle [deg]	10	20	40	90
Tx gain [dB]	56.069	56.069	56.069	56.069
Free-space pathloss [dB]	271.38	265.49	260.01	256.17
Atmospheric loss [dB]	7.53	3.82	2.03	1.30
Scintillation fading margine [dB]	2.28×10^{-1}	6.59×10^{-2}	2.07×10^{-2}	9.22×10^{-3}
Strehl ratio [dB]	2.05	1.14	0.64	0.42
Rx gain [dB]	107.42	107.42	107.42	107.42
Pointing loss [dB]	5.35	5.35	5.35	5.35
ULB Link Budget [dBW]	-123.050	-112.385	-104.568	-99.772
Irradiance at the satellite [dBm/m ²]	-69.264	-58.598	-50.781	-45.986

6. DOWNLINK BEACON LINK BUDGET

The DLB link budget is evaluated using the same propagation model introduced for the QKD downlink in Section 2.3. The system parameters adopted for the downlink beacon are summarized in Table 6 and the resulting downlink beacon budget is reported in Table 7. The narrow beacon divergence provides substantial transmit gain, while the large ground-station aperture results in a receiver gain of approximately 127 dB.

The results demonstrate that the downlink beacon provides a substantial received-power margin throughout the pass. Furthermore, the contribution of scintillation and pointing losses is small compared with the deterministic propagation losses, indicating that system performance is predominantly driven by link geometry rather than atmospheric turbulence effects.

Table 6. DLB System Parameters

DLB System Parameters	Value
DLB divergence angle (θ)	73 μ rad
DLB transmit power (P_t)	28 mW
DLB wavelength (λ)	905 nm
DLB obscuration (ϵ_{Tx})	0.41
Rx diameter (D_{Tx})	70 cm
Rx obscuration (ϵ_{rx})	0.39
Static pointing error (δ_{static})	10 μ rad
Jitter pointing error (σ_{dyn})	5 μ rad

Table 7. DLB Link Budget

Elevation Angle [deg]	10	20	40	90
Tx gain [dB]	91.76	91.76	91.76	91.76
Free-space pathloss [dB]	272.03	266.15	260.67	256.83
Atmospheric loss [dB]	6.30	3.30	1.76	1.13
Scintillation fade margin [dB]	0.25	0.07	0.02	0.01
Rx gain [dB]	127	127	127	127
Pointing loss [dB]	0.24	0.24	0.24	0.24
DLB Link Budget [dBm]	-45.83	-36.54	-29.46	-24.98
Irradiance at the OGS [dBm/m ²]	-40.96	-31.68	-24.60	-20.12

7. CONCLUSIONS

This paper presented an end-to-end performance assessment of the QKD downlink between the OPS-SAT VOLT CubeSat and the C3PO optical ground station. A comprehensive link-budget framework was developed that consistently combines transmitter and receiver characteristics, free-space and atmospheric propagation losses, detector and background-noise effects, and residual pointing-acquisition-and-tracking (PAT) errors into a unified QKD performance model. The resulting methodology provides a quantitative basis for mission preparation, system verification, and operational performance prediction for the forthcoming VOLT mission.

A key contribution of this work is the explicit treatment of PAT-induced losses and their impact on quantum-link performance. Closed-form expressions were derived for both the average pointing efficiency and the pointing-outage probability under a general correlated Gaussian jitter model. The analysis accommodates unequal jitter

variances and arbitrary correlation between orthogonal tracking axes, while commonly used isotropic and uncorrelated models emerge as special cases. The results show that correlation between pointing-error components can significantly increase the probability of outage even when the marginal jitter statistics remain unchanged, highlighting the importance of characterizing the full pointing-error covariance rather than relying solely on RMS jitter values.

The developed analytical framework was subsequently integrated into a decoy-state BB84 QKD model linking physical-layer channel impairments to detection statistics, QBER, and finite-key secret-key generation performance. This establishes a direct connection between spacecraft attitude-control performance, optical tracking accuracy, atmospheric propagation conditions, and the achievable cryptographic performance of the downlink. Such a coupled analysis is particularly important for CubeSat-based QKD systems, where limited link durations and stringent photon budgets leave little margin for pointing and tracking imperfections.

Beyond supporting the design and operational preparation of the VOLT-C3PO demonstration, the presented methodology provides a general tool for evaluating future satellite QKD missions and optical space-ground links. Following launch, the predicted performance envelopes can be compared with on-orbit measurements to validate the proposed models and refine future system designs. More broadly, the results demonstrate the critical role of PAT performance in determining the viability of photon-starved quantum communication links and contribute to the development of robust engineering methodologies for future operational space-based quantum communication networks.

8. ACKNOWLEDGMENT

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APPENDIX A. PROOF OF REMARK 1.

Let α_x and α_y denote the angular residual tracking-error components along two orthogonal axes in the Rx plane. These components are modeled as jointly Gaussian random variables with mean vector and covariance matrix given by Eq. (12). Assuming a diffraction-limited Gaussian beam, the received optical power depends on the angular offset between the beam centroid and the receiver boresight. Consequently, the instantaneous pointing efficiency is given by

$$\tau_{\text{PAT}}^{\text{inst}} = \exp\left(-\frac{2}{\theta^2} (\alpha_x^2 + \alpha_y^2)\right) = \exp\left(-\frac{2}{\theta^2} \|\boldsymbol{\alpha}\|^2\right), \quad (43)$$

where θ denotes the $1/e^2$ beam divergence angle. The average pointing efficiency is therefore

$$\tau_{\text{PAT}} = \mathbb{E}[\tau_{\text{PAT}}^{\text{inst}}] = \mathbb{E}\left[\exp\left(-\frac{2}{\theta^2} \boldsymbol{\alpha}^\top \boldsymbol{\alpha}\right)\right]. \quad (44)$$

Substituting the probability density function of the bivariate Gaussian random vector yields

$$\begin{aligned} \tau_{\text{PAT}} &= \frac{1}{2\pi\sqrt{\det(\boldsymbol{\Sigma}_\alpha)}} \int_{\mathbb{R}^2} \exp\left[-\frac{1}{2}(\boldsymbol{\alpha} - \boldsymbol{\delta})^\top \boldsymbol{\Sigma}_\alpha^{-1}(\boldsymbol{\alpha} - \boldsymbol{\delta}) - \frac{2}{\theta^2} \boldsymbol{\alpha}^\top \boldsymbol{\alpha}\right] d\boldsymbol{\alpha} \\ &= \frac{\exp(-\frac{1}{2}\boldsymbol{\delta}^\top \boldsymbol{\Sigma}_\alpha^{-1}\boldsymbol{\delta})}{2\pi\sqrt{\det(\boldsymbol{\Sigma}_\alpha)}} \int_{\mathbb{R}^2} \exp\left[-\frac{1}{2} \boldsymbol{\alpha}^\top \mathbf{A} \boldsymbol{\alpha} + \mathbf{b}^\top \boldsymbol{\alpha}\right] d\boldsymbol{\alpha}, \end{aligned} \quad (45)$$

where

$$\mathbf{A} = \boldsymbol{\Sigma}_\alpha^{-1} + \frac{4}{\theta^2} \mathbf{I}, \quad \mathbf{b} = \boldsymbol{\Sigma}_\alpha^{-1} \boldsymbol{\delta}. \quad (46)$$

Applying the Gaussian integral identity

$$\int_{\mathbb{R}^2} \exp\left(-\frac{1}{2} \mathbf{x}^\top \mathbf{A} \mathbf{x} + \mathbf{b}^\top \mathbf{x}\right) d\mathbf{x} = \frac{2\pi}{\sqrt{\det(\mathbf{A})}} \exp\left(\frac{1}{2} \mathbf{b}^\top \mathbf{A}^{-1} \mathbf{b}\right), \quad (47)$$

gives

$$\tau_{\text{PAT}} = \frac{\exp\left[-\frac{1}{2}\boldsymbol{\delta}^\top (\boldsymbol{\Sigma}_\alpha^{-1} - \boldsymbol{\Sigma}_\alpha^{-1}\mathbf{A}^{-1}\boldsymbol{\Sigma}_\alpha^{-1})\boldsymbol{\delta}\right]}{\sqrt{\det(\boldsymbol{\Sigma}_\alpha)\det(\mathbf{A})}}. \quad (48)$$

Using the matrix identities

$$\det(\boldsymbol{\Sigma}_\alpha)\det(\mathbf{A}) = \det\left(\mathbf{I} + \frac{4}{\theta^2}\boldsymbol{\Sigma}_\alpha\right) \quad (49)$$

and

$$\boldsymbol{\Sigma}_\alpha^{-1} - \boldsymbol{\Sigma}_\alpha^{-1}\mathbf{A}^{-1}\boldsymbol{\Sigma}_\alpha^{-1} = \frac{4}{\theta^2}\left(\mathbf{I} + \frac{4}{\theta^2}\boldsymbol{\Sigma}_\alpha\right)^{-1}, \quad (50)$$

the average pointing efficiency becomes

$$\tau_{\text{PAT}} = \frac{\exp\left[-\frac{2}{\theta^2}\boldsymbol{\delta}^\top \left(\mathbf{I} + \frac{4}{\theta^2}\boldsymbol{\Sigma}_\alpha\right)^{-1}\boldsymbol{\delta}\right]}{\sqrt{\det\left(\mathbf{I} + \frac{4}{\theta^2}\boldsymbol{\Sigma}_\alpha\right)}}. \quad (51)$$

Substituting the definition of the covariance matrix as in Eq. (12) and defining a new variable D as follows

$$D = \left(1 + \frac{4\sigma_x^2}{\theta^2}\right)\left(1 + \frac{4\sigma_y^2}{\theta^2}\right) - \frac{16\rho^2\sigma_x^2\sigma_y^2}{\theta^4} \quad (52)$$

and after straightforward algebra, we obtain the average pointing efficiency as follows

$$\tau_{\text{PAT}} = \frac{1}{\sqrt{D}} \exp\left[-\frac{2}{\theta^2 D} \left(\left(1 + \frac{4\sigma_y^2}{\theta^2}\right)\delta_x^2 - \frac{8\rho\sigma_x\sigma_y}{\theta^2}\delta_x\delta_y + \left(1 + \frac{4\sigma_x^2}{\theta^2}\right)\delta_y^2 \right)\right], \quad (53)$$

which proves Eq. (13). For the isotropic uncorrelated case $\sigma_x = \sigma_y = \sigma$ and $\rho = 0$, one obtains

$$\tau_{\text{PAT}} = \frac{1}{1 + 4\sigma^2/\theta^2} \exp\left(-\frac{2(\delta_x^2 + \delta_y^2)}{\theta^2 + 4\sigma^2}\right). \quad (54)$$

For $\delta_x = \delta_y = 0$, this reduces to

$$\tau_{\text{PAT}} = \frac{\theta^2}{\theta^2 + 4\sigma^2}, \quad (55)$$

Substituting the probability density function of the bivariate Gaussian random vector yields

$$\begin{aligned} \tau_{\text{PAT}} &= \frac{1}{2\pi\sqrt{\det(\boldsymbol{\Sigma}_\alpha)}} \int_{\mathbb{R}^2} \exp\left[-\frac{1}{2}\boldsymbol{\alpha}^\top \boldsymbol{\Sigma}_\alpha^{-1}\boldsymbol{\alpha} - \frac{2}{\theta^2}\boldsymbol{\alpha}^\top \boldsymbol{\alpha}\right] d\boldsymbol{\alpha} \\ &= \frac{1}{2\pi\sqrt{\det(\boldsymbol{\Sigma}_\alpha)}} \int_{\mathbb{R}^2} \exp\left[-\frac{1}{2}\boldsymbol{\alpha}^\top \left(\boldsymbol{\Sigma}_\alpha^{-1} + \frac{4}{\theta^2}\mathbf{I}\right)\boldsymbol{\alpha}\right] d\boldsymbol{\alpha}. \end{aligned} \quad (56)$$

Using the standard Gaussian integral

$$\int_{\mathbb{R}^2} \exp\left(-\frac{1}{2}\mathbf{x}^\top \mathbf{A}\mathbf{x}\right) d\mathbf{x} = \frac{2\pi}{\sqrt{\det(\mathbf{A})}}, \quad (57)$$

one obtains

$$\begin{aligned} \tau_{\text{PAT}} &= \frac{1}{\sqrt{\det(\boldsymbol{\Sigma}_\alpha)\det(\boldsymbol{\Sigma}_\alpha^{-1} + \frac{4}{\theta^2}\mathbf{I})}} \\ &= \frac{1}{\sqrt{\det(\mathbf{I} + \frac{4}{\theta^2}\boldsymbol{\Sigma}_\alpha)}}. \end{aligned} \quad (58)$$

Substituting Eq. (12) and evaluating the determinant gives

$$\tau_{\text{PAT}} = \left[\left(1 + \frac{4\sigma_x^2}{\theta^2} \right) \left(1 + \frac{4\sigma_y^2}{\theta^2} \right) - \frac{16\rho^2\sigma_x^2\sigma_y^2}{\theta^4} \right]^{-1/2}, \quad (59)$$

which proves Eq. (13). For the spacial case $\sigma_x = \sigma_y = \sigma$, for two extreme cases of ρ , i.e., $\rho = 0$ and $\rho = \pm 1$, the above expression reduces to

$$\tau_{\text{PAT}} = \left(1 + \frac{4\sigma^2}{\theta^2} \right)^{-1} = \frac{\theta^2}{\theta^2 + 4\sigma^2}, \quad \tau_{\text{PAT}} = \left(1 + \frac{8\sigma^2}{\theta^2} \right)^{-1/2} = \sqrt{\frac{\theta^2}{\theta^2 + 8\sigma^2}}, \quad (60)$$

respectively, thereby proving Eq. (16) and Eq. (17). ■

APPENDIX B. PROOF OF REMARK 2

For a prescribed pointing-efficiency threshold τ_{th} , the pointing-outage probability is defined as the probability that the instantaneous pointing efficiency falls below the minimum acceptable threshold, i.e.,

$$P_{\text{out}} = \Pr(\tau_{\text{PAT}}^{\text{inst}} \leq \tau_{\text{th}}), \quad (61)$$

where $\tau_{\text{PAT}}^{\text{inst}}$ is given in (??). Substituting (??) into (61), the outage probability can be rewritten as

$$P_{\text{out}} = \Pr(\alpha_x^2 + \alpha_y^2 \geq \gamma) = \Pr(\|\boldsymbol{\alpha}\|^2 \geq \gamma), \quad (62)$$

with $\gamma = -\frac{\theta^2}{2} \ln(\tau_{\text{th}})$. To evaluate the probability in (62), the probability distribution of $\|\boldsymbol{\alpha}\|$ must be determined. Since $\boldsymbol{\alpha}$ is a correlated Gaussian random vector, the distribution of $\|\boldsymbol{\alpha}\|$ cannot be obtained directly. To remove the correlation, we diagonalize the covariance matrix $\boldsymbol{\Sigma}_{\alpha}$ by its eigenvalue decomposition as follows. In particular, let $\mathbf{z}$ denote a new random vector obtained by rotating the pointing-error vector into the principal-axis coordinate system of the covariance matrix, i.e.,

$$\mathbf{z} = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \mathbf{U}^T \boldsymbol{\alpha}, \quad (63)$$

where $\mathbf{U}$ is the orthogonal eigenvector matrix obtained from the eigenvalue decomposition of the covariance matrix $\boldsymbol{\Sigma}_{\alpha}$ as

$$\boldsymbol{\Sigma}_{\alpha} = \mathbf{U} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \mathbf{U}^T. \quad (64)$$

Since $\mathbf{U}$ is orthogonal, the Euclidean norm is preserved and

$$\|\mathbf{z}\|^2 = \|\boldsymbol{\alpha}\|^2. \quad (65)$$

The transformed vector $\mathbf{z}$ therefore consists of two independent zero-mean Gaussian random variables with unequal variances λ_1 and λ_2 . Consequently, the random variable

$$\|\mathbf{z}\| = \sqrt{z_1^2 + z_2^2} \quad (66)$$

follows a Hoyt (Nakagami- q) distribution, which describes the magnitude of a two-dimensional Gaussian random vector with unequal variance components. Since $\|\mathbf{z}\| = \|\boldsymbol{\alpha}\|$, the outage probability in (62) can be expressed as

$$P_{\text{out}} = \Pr(\|\mathbf{z}\| \geq \sqrt{\gamma}) = 1 - F_{\text{H}}(\sqrt{\gamma}), \quad (67)$$

where $F_{\text{H}}(\cdot)$ denotes the CDF of the Hoyt (Nakagami- q) distribution.^{30,31} Using the Hoyt CDF, the outage probability can be written as in (18). Below, we consider two special cases:

For the spacial case of $\sigma_x = \sigma_y = \sigma$ and $\rho = 0$, we obtain $\lambda_1 = \lambda_2 = \sigma^2$, which implies $q = 1$ and $\Omega = 2\sigma^2$. Therefore, (18) reduces to

$$P_{\text{out}} = Q_1\left(0, \sqrt{\frac{\gamma}{2\sigma^2}}\right) = \exp\left(-\frac{\gamma}{4\sigma^2}\right). \quad (68)$$

Substituting $\gamma = -\frac{\theta^2}{2} \ln(\tau_{\text{th}})$ into (68) yields

$$\begin{aligned} P_{\text{out}} &= \exp \left[-\frac{1}{4\sigma^2} \left(-\frac{\theta^2}{2} \ln(\tau_{\text{th}}) \right) \right] \\ &= \exp \left[\frac{\theta^2}{8\sigma^2} \ln(\tau_{\text{th}}) \right] \\ &= \tau_{\text{th}}^{\frac{\theta^2}{8\sigma^2}}, \end{aligned} \quad (69)$$

which establishes (20).

For the spacial case of $\sigma_x = \sigma_y = \sigma$ and $\rho = 1$, we obtain $\lambda_1 = 2\sigma^2$ and $\lambda_2 = 0$. Thereby, $\mathbf{z} = [z_1, z_2]^\text{T} = [z_1, 0]^\text{T}$ with z_1 is a zero-mean Gaussian variable with variance $\lambda_1 = 2\sigma^2$. Hence, the outage probability becomes:

$$P_{\text{out}} = \Pr(|z_1| \geq \sqrt{\gamma}) = \text{erfc} \left(\frac{\sqrt{\gamma}}{\sqrt{2\lambda_1}} \right) = \text{erfc} \left(\frac{\theta \sqrt{\ln(\tau_{\text{th}}^{-1})}}{\sqrt{8}\sigma} \right), \quad (70)$$

where $\text{erfc}(\cdot)$ is the complementary error function. This completes the proof.

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