

Embedded Tip-Tilt Fine-Pointing System with Turbulence-Matched Validation for Free-Space Quantum Links

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ABSTRACT

We present the design and laboratory validation of a fine-pointing system for our quantum optical ground station equipped with a 1 m Ritchey-Chrétien telescope in Innsbruck, Austria. The system enables tip-tilt stabilization of the received beam for satellite-to-ground quantum key distribution. The embedded control loop combines an InGaAs camera to measure atmospheric tip-tilt with a fast-steering mirror. To validate our design under realistic conditions, we inject synthetic tip-tilt disturbances shaped to match the angle-of-arrival power spectral density measured by star tracking (elevations 20°–79°) with our ground station, reproducing the local alpine turbulence in the laboratory. At a 1 kHz framerate with a measured end-to-end latency of 1.4 ms, the loop achieves a closed-loop bandwidth of ≈ 60 Hz and a root mean square angle-of-arrival jitter reduction by a factor of 6 for the measured profiles and a factor of 8 for a scaled-up worst case. As an optical link figure of merit, we show the recovery of single-mode fiber coupling from a mean value of 0.56 to 0.98 of an undisturbed baseline for the scaled-up scenario. These results show that a compact, camera based feedback system is a practical solution for tip-tilt stabilization in free-space optical links for satellite-based quantum communication.

Keywords: fine-pointing, tip-tilt stabilization, angle-of-arrival, atmospheric turbulence, satellite quantum key distribution, optical ground station, free-space optical communication, embedded control, single-mode fiber coupling

1. INTRODUCTION

Terrestrial fiber quantum key distribution (QKD) links are limited to several hundred kilometers due to exponential scaling losses.^{1,2} To reach globe-spanning networks, free-space satellite links can overcome these distance limitations.^{3–6} These require a quantum optical ground station (OGS) to receive and transmit quantum and classical signals, which can only be done by accurate tracking of the satellite. Coarse tracking by a telescope system alone is not sufficient for efficient optical communication. In addition, atmospheric turbulence continuously displaces the received beam relative to a detector, keeping this pointing error in real time within the coupling tolerance is the task of the OGS *fine-pointing* system. For both ground-to-space and space-to-ground links, this closed-loop pointing correction through the turbulent atmosphere is necessary for optical links.^{7,8}

For any free-space optical link, the atmosphere perturbs a propagating beam due to refractive-index fluctuations described by the Kolmogorov power-law spectrum.⁹ In first order, these manifest as angle-of-arrival (AoA) fluctuations, a time-varying tip-tilt of the wavefront which displaces the focal spot and degrades coupling into a receiver. This is the dominant low-order turbulence term and is correctable with a two-axis fast steering mirror (FSM). Higher-order phase aberrations also reduce coupling, but their compensation requires a full adaptive optics (AO) system, in which a wavefront sensor drives a deformable mirror at kHz rates.^{10,11} AO has been demonstrated in quantum links,¹² but it drastically increases complexity and cost for a quantum optical ground station. This motivates a compact and cost-effective tip-tilt-only correction, which can already substantially improve link performance.^{13,14}

The exact cost of higher orders on link efficiency depends on the detection scheme. A single-mode fiber (SMF) is the most demanding receiver interface; by accepting only a single spatial mode, it requires not only the correct

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focal spot position, but coupled power also depends on the residual wavefront quality. This carries the advantage of the narrow acceptance of the quantum signal for superconducting nanowire single-photon detectors (SNSPDs). Another possibility of photon detection is with free-space avalanche photodiodes (APD), where active areas on the order of several hundred micrometers are less sensitive to atmospheric-induced effects; higher-order aberrations have little influence on the detection efficiency. What matters here is that the focal spot stays on the active area, which requires a more lenient AoA jitter correction. Tip-tilt stabilization is therefore required for both architectures, and we report the SMF coupling case as the more demanding scenario. Since the exact coupling efficiency gain by jitter suppression depends on the exact optical configuration, we report it as a representative measure of a relative improvement rather than stating absolute link budgets.

Tip-tilt fine-pointing is well established both in classical free-space laser communication¹⁵ and in free-space quantum communication.^{4,16–18} Less explored is a fine-pointing loop validated against *measured, site-specific* AoA statistics, with a fiber coupling efficiency as the figure of merit. Existing satellite-QKD emulation studies^{19,20} focus on channel loss profiles but leave the dynamic pointing dimension unaddressed.

We close this gap with a compact, camera-based fine-pointing system and a full pipeline to validate the system against measured AoA jitter in the laboratory. With embedded processing, we keep size, weight, and power low enough for deployment at a remote, unstaffed OGS. It is based on an InGaAs camera sensor and FSM. We validated the performance in the laboratory against AoA power spectra measured at our 1 m ground station with the same camera. We show that the tip-tilt correction stage removes the majority of AoA jitter relevant to detector and fiber coupling and can serve as the first element in a higher-order AO system if required. With the assumption that the atmospheric-induced jitter measured from stars is representative of a low-earth-orbit (LEO) satellites downlink due to the same path-integrated turbulence, we record the stellar AoA time series $\theta_x(t)$, $\theta_y(t)$ (usually referred to *jitter* when fast, and *drift* when slow)¹⁰ from 40 stars in a single night, ranging elevations from 20° to 79°; for 31 usable recordings we compute power spectral density (PSD) $S_\theta(f)$ and by integration of the PSD the total root mean square (RMS) fluctuation σ_θ

$$\sigma_\theta = \sqrt{\int S_\theta(f) df}. \quad (1)$$

We reproduce S_θ in the laboratory with a disturbance mirror in the beam path, matching both the shape of S_θ and the value σ_θ , in absolute μrad measured in the sky. We quantify the closed-loop FSM correction in both time and frequency domains, using single-mode-fiber coupling efficiency as a proxy for link performance. In addition, we demonstrate a scaled-up scenario where we amplify a measured atmospheric condition to probe the limits of the loop. The validated loop directly addresses the satellite-to-ground downlink scenario, where the OGS receives and corrects the incoming beam. Extension to uplink pre-compensation and mitigation of turbulence in a terrestrial horizontal link, where the exact AoA statistics will differ from the ones measured here, but the main methodology stays the same, is left to future work.

2. SYSTEM ARCHITECTURE

The fine-pointing system will operate as a closed-loop tip-tilt stabilization stage in addition to the telescope’s open-loop coarse pointing.²¹ The design of the system is chosen to be compatible with proposed quantum communication satellite missions such as QEYSSat²² and EAGLE-1²³ (would require a different choice of dichroic beam splitter). In the targeted configuration, light collected by the 1 m, f/7 telescope is collimated by a lens with 75 mm focal length and steered by a two-axis voice-coil FSM (3° angular range, 0.6 μrads angular resolution, 3dB bandwidth of 550 Hz) placed in the collimated beam, after which a 950 nm shortpass dichroic beam splitter directs the 980 nm beacon laser toward the camera, where a 250 mm focal length lens focuses the beam onto the sensor, while transmitting the shorter wavelength quantum signal (here we use a 780 nm laser diode) to a single-mode fiber. Given the camera’s 15 μm pixel pitch, this optical relay sets a plate scale (angular separation related to pixel on the camera) of 0.64 $\mu\text{rad}/\text{px}$ for the planned system. As a tracking sensor we use a fast InGaAs camera (1 kHz full frame, 320 $\times$ 256 px) operated at 1 kHz, whose frames are processed on an embedded computer: the focal-spot centroid is computed for each frame as the binary thresholded center of mass (CoM) and compared against a fixed setpoint (the center of the sensor) to form a two-axis error signal, which a software

proportional–integral–derivative (PID) controller converts into a correction command. The digital command is transmitted via serial peripheral interface (SPI) to a custom mixed-signal board based on a digital-to-analog converter (DAC) (± 10 V), and the resulting analog voltages drive the FSM through a driver stage, closing the loop.

The relay (75 mm collimation lens + 250 mm focusing lens) describes the planned deployment mounted to the telescope as shown in Figure 1. It is not yet present in either of the two setups used to obtain the results in this paper, which instead differ from each other and from the target configuration as described in Table 1. The AoA statistics (S_θ and σ_θ , see Section 1) were gathered with the InGaAs camera mounted directly at the 7 m telescope focus, without the relay: with the camera’s 15 μm pixel pitch, this gives a plate scale of 2.14 $\mu\text{rad}/\text{px}$. The closed-loop validation reported here (Section 5) instead uses a laboratory bench comprising the same FSM, 250 mm focusing lens and camera as the target design, and a disturbance mirror placed in front of the FSM to emulate turbulence. This bench aims to reproduce the target system’s plate scale (0.64 $\mu\text{rad}/\text{px}$). The disturbance mirror is driven to the pixel amplitude that the measured σ_θ would produce at that plate scale, so the open-/closed-loop pixel results (Section 5) map directly onto the planned system’s angular scale rather than the 2.14 $\mu\text{rad}/\text{px}$ scale used for the star-tracking measurement. Implications of these different plate scales are discussed in Section 6.

Table 1: Description of three optical configurations mentioned in this work.

Configuration	Plate scale [$\mu\text{rad}/\text{px}$]	Role in this paper
Target (not yet built)	0.64	intended QKD operation
Star-tracking measurement	2.14	measured AoA statistics (S_θ , σ_θ)
Lab validation bench	0.64	closed-loop results in the laboratory (Section 5)

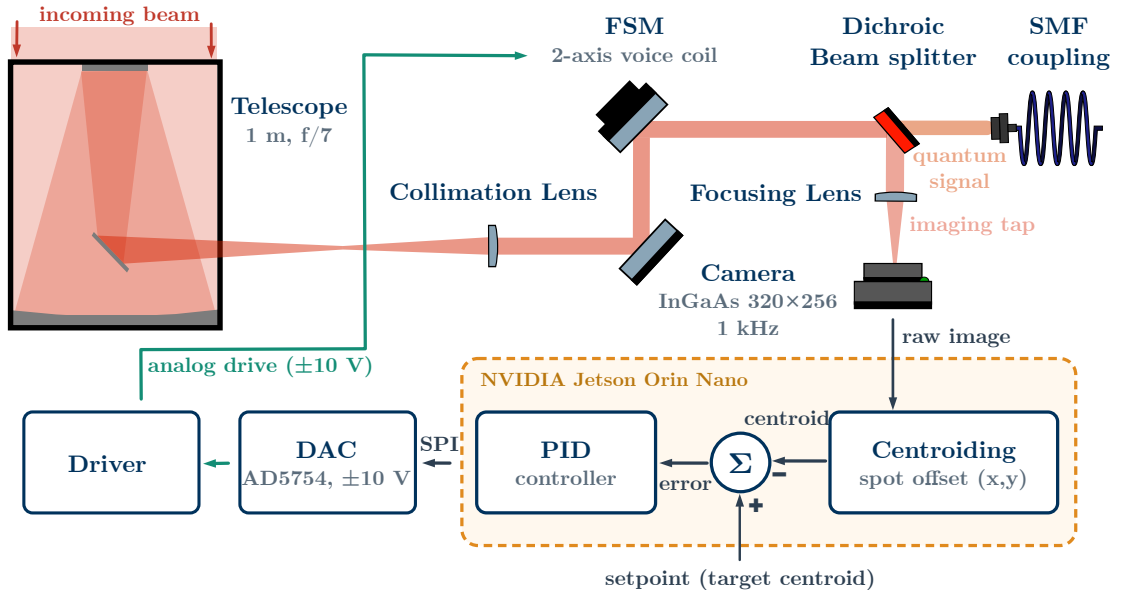


Figure 1: Schematic of the full fine-pointing and telescope control loop. Light collected by the 1 m, f/7 telescope passes the voice-coil fast steering mirror (FSM) and a dichroic beam splitter transmits the quantum signal to the single-mode fiber (SMF) coupling path and reflects the beacon laser at 980 nm to the InGaAs tracking camera (320×256 px, 1 kHz). For each frame, the centroid is calculated and the error signal from the target setpoint processed by a proportional-integral-derivative (PID) controller on the NVIDIA Jetson Orin Nano; the command is sent via serial peripheral interface (SPI) to a digital-to-analog converter (DAC), which sends analog voltages to the driver stage that actuate the FSM. Atmospheric tip-tilt enters as the disturbance of the incoming beam. Line styles denote the optical beam, digital signal, and analog drive paths.

2.1 Latency budget

We measure the end-to-end delay between a command sent to the FSM and the detection of the corresponding correction on the assembled system: with the PID disabled, a sinusoidal command with a frequency of 150 Hz is injected on the FSM x-axis and the delay obtained from the lag of the centroid response.

The measured total delay is 1.43(6) ms at this 150 Hz probe frequency, where the number in parentheses is the standard deviation showing the spread of the timings. This is reported for a 100 s long run with $\approx 97,400$ samples at ≈ 974 Hz effective frame rate (we exclude a short start up period) and a 0.25 ms exposure time. Figure 2 shows the total system latency distribution.

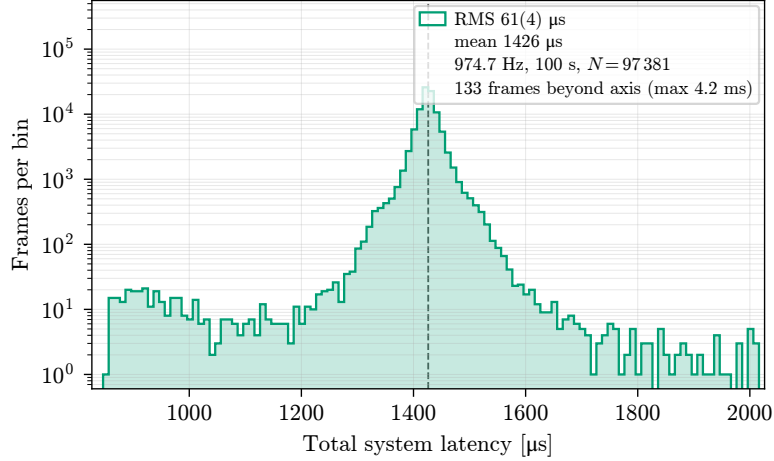


Figure 2: Distribution of the total system latency of the fine-pointing loop (DAC $\rightarrow$ FSM $\rightarrow$ camera $\rightarrow$ centroid) over a 100 s open-loop recording with a 150 Hz sinusoidal command injected on the FSM x-axis. The mean is 1426 μ s (dashed line) with an RMS spread of 61(4) μ s. Of approx. 97,400 frames, 133 fall outside the shown time, the worst at 4.2 ms.

In a separate run, each step in the pipeline is measured and shown in Table 2. About 40 % of the total is software (implemented in C++, OpenCV); the rest is exposure, sensor readout, and USB transfer, which are set by the camera and not addressable in the control loop. Within the software share, the CoM computation over the 200×200 px region of interest dominates at 186 μ s.

Table 2: Contributions to the end-to-end loop latency. Values are means, in parentheses is the standard deviation over $N = 29\,139$ (pipeline stages timing measurement) and $N = 97\,381$ (total delay measurement) frames. The total is measured end-to-end by injecting a 150 Hz sinusoidal signal (amplitude of a few pixels) on the full DAC $\rightarrow$ FSM $\rightarrow$ camera $\rightarrow$ centroid path. The pipeline breakdown (exposure, frame queuing, processing, DAC write) comes from a separate run at the same frame rate and region of interest. The sensor readout, USB transfer, and mirror response time are obtained by difference.

Contribution	Time [μ s]
Half exposure (integration midpoint)	125
Frame queueing (camera callback to loop)	59(27)
Processing (threshold, blur, CoM, conversion)	283(31)
DAC SPI write	221(62)
Software total	563(75)
Sensor readout, USB 3.0 transfer and mirror response (by difference)	≈ 740
Measured total delay at 150 Hz (incl. FSM dynamics)	1426(61)

The loop is not limited by computation, processing one frame takes 283 μ s of the 1025 μ s available between frames, leaving around 740 μ s of headroom, and the camera delivers 976 Hz when 1000 Hz is requested. The spacing between frames is not perfectly regular: it varies by 93(11) μ s. The timing jitter is inherited from the

camera (operated without a trigger) rather than produced by the software. On average, 1.5 frames per second (0.15 %) arrive later than one frame period; the loop then corrects using a slightly outdated frame, which briefly degrades the correction.

3. ANGLE-OF-ARRIVAL MEASUREMENT

The reference disturbance used throughout this paper is derived from AoA jitter recorded with our own ground station. This section describes the station, the measurement campaign, and the resulting AoA statistics that the laboratory disturbance synthesis of Section 4 aims to reproduce. The “Marietta Blau” quantum optical ground station is located at Hafelekar, close to Innsbruck, Austria (47°18′45.7″ N, 11°23′01.4″ E, 2283 m altitude). It is intended as a node in a future satellite-based quantum network. The 2283 m Alpine site sets the turbulence conditions sampled here. The station features a 1 m Ritchey–Chrétien telescope (7 m focal length), on an alt-az mount whose open-loop tracking provides the coarse pointing in addition to which the fine-pointing stage will operate. To fully capture the atmospheric jitter, the telescope was slewed to each target star and set to open-loop to track the star for the duration of the recording.

The measurement configuration and parameters are summarized in Table 3. The tracking camera was mounted directly at the telescope’s 7 m focus, without the collimating/focusing relay of the planned design (see Section 2). The light intensity is low compared to a guiding beacon, for this reason, the camera was operated over its broad short-wave-infrared (SWIR) response rather than a narrow beacon band. The wavelength difference to the planned QKD operation is discussed in Section 6. We used an exposure time of 0.1 ms, short enough to avoid centroid blur.

Table 3: AoA star-tracking measurements (night of 25–26 May 2026).

Parameter	Value
Telescope	1 m Ritchey–Chrétien, f/7 (7 m focal length)
Camera	SWIR InGaAs, 320x256 px, no filter
Spectral band	~0.9–1.7 μm
Plate scale	2.14 $\mu\text{rad}/\text{px}$ (15 μm px / 7 m)
Exposure time	0.1 ms per frame
Frame rate	974 fps effective , Nyquist $\approx$ 487 Hz
Recording length	100 s (median), $\approx$ 97,300 frames per star
Stars recorded	40 (31 usable after quality cuts)
Magnitude range	−0.04 to 2.79
Elevation range	20°–79°
Elevation segments	low 20°–34° ($n=11$), mid 35°–48° ($n=10$), high 52°–79° ($n=10$)
Centroid algorithm	2-D Gaussian fit

Over one night, 40 stars were recorded across elevations from 20° to 79°, spanning a range of airmass values while remaining bright enough for reliable centroiding (magnitudes −0.04 to 2.79). Of those, 31 of the recordings pass data-quality cuts (framerate drops, recordings stopped preemptively, signal-to-noise ratio SNR) and enter the spectral analysis. Each recording is 100 s long ($\approx$ 97,300 frames at 974 fps effective) with a $\approx$ 487 Hz Nyquist frequency. Wind speed and temperature during the measurements were logged at an average wind speed of 4(3) km/h and an average temperature of 9.7(3) °C.

All frames were saved with a 200x200 px region of interest (ROI), and in post-processing, the centroid was computed by a 2D Gaussian fit to get an accurate centroid position of the stellar image. It is converted to angular units through the 2.14 $\mu\text{rad}/\text{px}$ plate scale, which gives a per-axis AoA time series $\theta_x(t)$, $\theta_y(t)$. This centroiding is different from the binary-thresholded CoM used in the control loop (Section 2). In real-time control, algorithmic speed is crucial, and therefore the faster centroiding method is used, while for the post-processing we favor accuracy.

For each recording, we estimate PSDs for each axis with Welch’s method,²⁴ average them over the two axes, and smooth them with a Savitzky-Golay filter to remove noise. In addition, we interpolate the measurements to a common logarithmic frequency grid (0.1 Hz–487 Hz), to account for frame jitter (see Section 2.1). We group

the recordings into three elevation tertiles spanning 20° – 79° (Table 3), and average them. This results in one target PSD $S_\theta(f)$ per elevation group, in px^2/Hz , converted to angular units via the $2.14 \text{ } \mu\text{rad}/\text{px}$ plate scale of the star-tracking setup (Section 2).

Figure 3 summarizes the measurements. The averaged PSDs follow the expected Kolmogorov atmospheric power law across the low-frequency, turbulence-dominated band and roll into an instrumental white-noise floor at high frequency. Both the integrated jitter σ_θ and the noise floor rise toward low elevation, reflecting the larger airmass and typically lower SNR of the fainter, lower-elevation targets. A fixed narrow spectral line near 5.7 Hz appears in most recordings independent of elevation and atmospheric condition; we attribute it to a mechanical resonance of the mount or wind-induced vibrations, and its prominence over the turbulence trend grows with elevation (buried at low, clearly visible at high).

Because the disturbance is used as a representative realization for closed-loop validation, a single night’s campaign is used for the present purpose. Our synthesis matches both the measured spectral shape and the σ_θ in absolute μrad (see Section 4). The sampled stars span a range of elevations and azimuths, probing different atmospheric path lengths and directions.

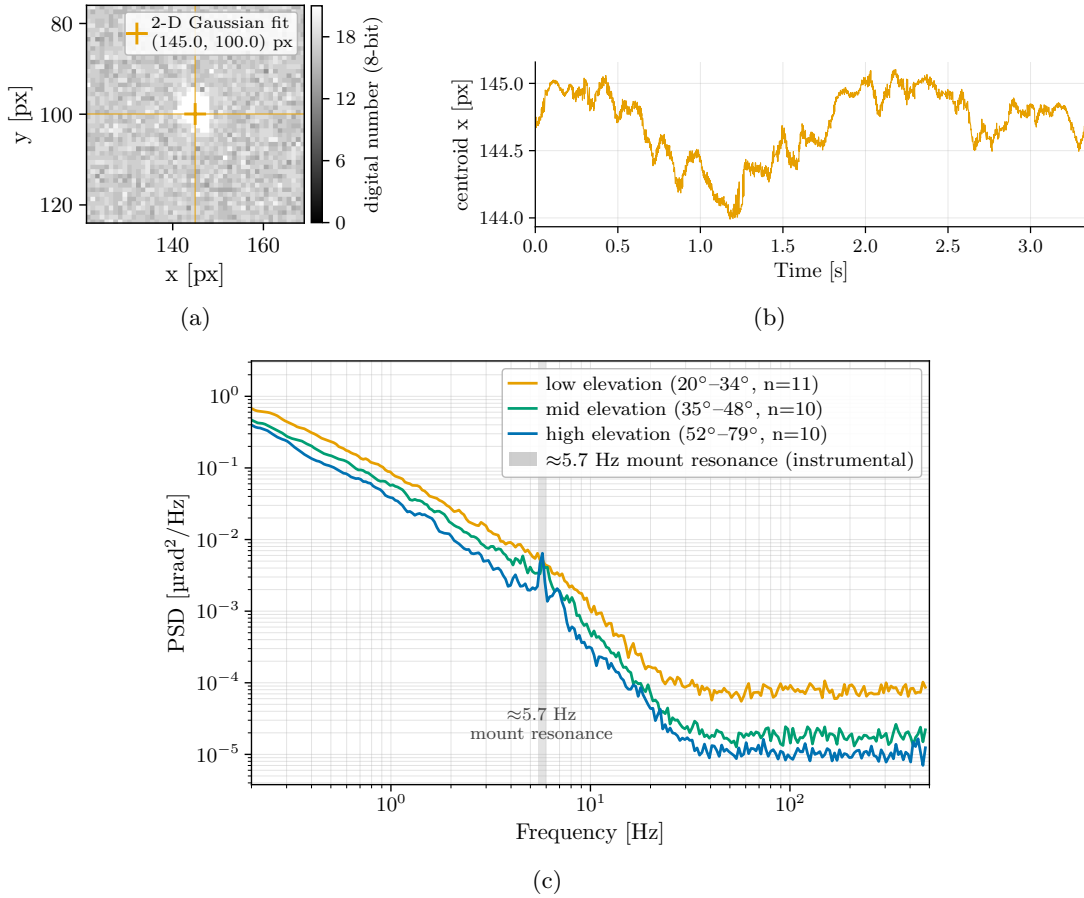


Figure 3: Measured angle-of-arrival (AoA) statistics gathered by tracking 31 stars with our optical ground station. (a) single-frame of a representative star (Mirfak, $m = 1.79$, elevation 20.2°) with the 2-D Gaussian-fit centroid marked; (b) 3 s sample of the x -centroid time series for the same star (c) the averaged power spectral densities (PSD) $S_\theta(f)$ for three elevation segments (Table 3), shown over the full band to the $\approx 487 \text{ Hz}$ Nyquist limit and including the high-frequency white-noise floor. The shaded band marks a fixed $\approx 5.7 \text{ Hz}$ mount or wind-induced resonance.

4. TURBULENCE-MATCHED DISTURBANCE SYNTHESIS

For the generation of disturbance in the laboratory matched to the measured turbulence statistics we use the averaged PSDs derived in Section 3. We remove the narrow mount- or wind-induced resonance near 5.7 Hz by interpolation around the resonance.

To reproduce the target PSD in the laboratory, a random-phase time series is synthesized following the spectral-representation method,²⁵ assigning each frequency bin the target amplitude X_k and a phase ϕ_k from a uniform random distribution $\mathcal{U}$:

$$X_k = \sqrt{S_\theta(f_k)} e^{i\phi_k}, \quad \phi_k \sim \mathcal{U}[0, 2\pi), \quad (2)$$

Following that, we apply an inverse Fourier transform and rescale the entire signal to a peak amplitude determined experimentally. This preserves the measured spectral shape and allows it to be replayed at different disturbance levels, e.g. matched to the measured RMS σ_θ , or amplified for the scaled-up disturbance in Section 5. The resulting time series drives the disturbance mirror described in Section 2 in one axis (x-axis), reproducing the shape and the amplitude of the measured turbulence in the lab.

5. RESULTS

To characterize the control loop, we inject disturbances with an additional tiltable mirror in the beam path (see Section 2) before the fine-pointing system; a 980 nm laser beam with a corresponding tip-tilt disturbance then enters the system.

We first measure the closed-loop sensitivity function $|S(f)|$ (Fig. 4), giving the transfer from an injected disturbance to the residual pointing error. It is obtained both from injecting a broadband white-noise reference and several sinusoidal frequencies (in two different runs). The loop rejects disturbances up to a bandwidth of 60(1) Hz (where $|S|$ crosses 0 dB), the sensitivity then peaks at +5.2(1) dB at a frequency of 132 Hz, the “waterbed” noise-amplification region.

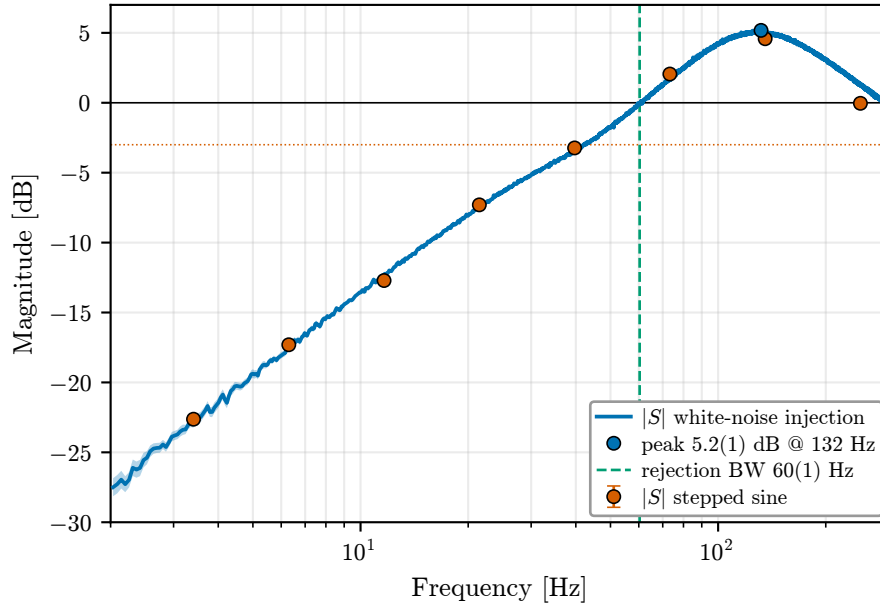


Figure 4: Measured closed-loop sensitivity function $|S(f)|$ for the x axis, obtained with two different methods: by injecting a broadband white-noise reference into the loop, and by a stepped sine measurement. $|S| < 0$ dB indicates disturbance rejection, the loop rejects disturbances up to a bandwidth of 60(1) Hz (dashed vertical line), above which $|S|$ rises to a +5.2(1) dB “waterbed” peak at 132 Hz. The dashed horizontal line denotes the -3 dB threshold.

Open- and closed-loop performance is evaluated under four disturbance conditions: three turbulence-matched regimes from the low-, mid-, and high-elevation tertiles of the star-tracking dataset (see Section 4), and one stronger scaled-up disturbance (an amplitude-scaled version of the low-elevation atmospheric condition) used to probe the limits of the loop. Figure 5 compares the open- and closed-loop AoA PSD for all four conditions. The disturbance is suppressed by up to 40 dB at low frequencies. Below 10 Hz, the loop suppresses the disturbance by more than 10 dB, consistent with the integrated RMS reduction shown in Table 4. At ≈ 50 Hz the closed-loop begins to exceed the open-loop level, consistent with the closed-loop bandwidth (60 Hz) derived from the sensitivity function measurement shown in Figure 4.

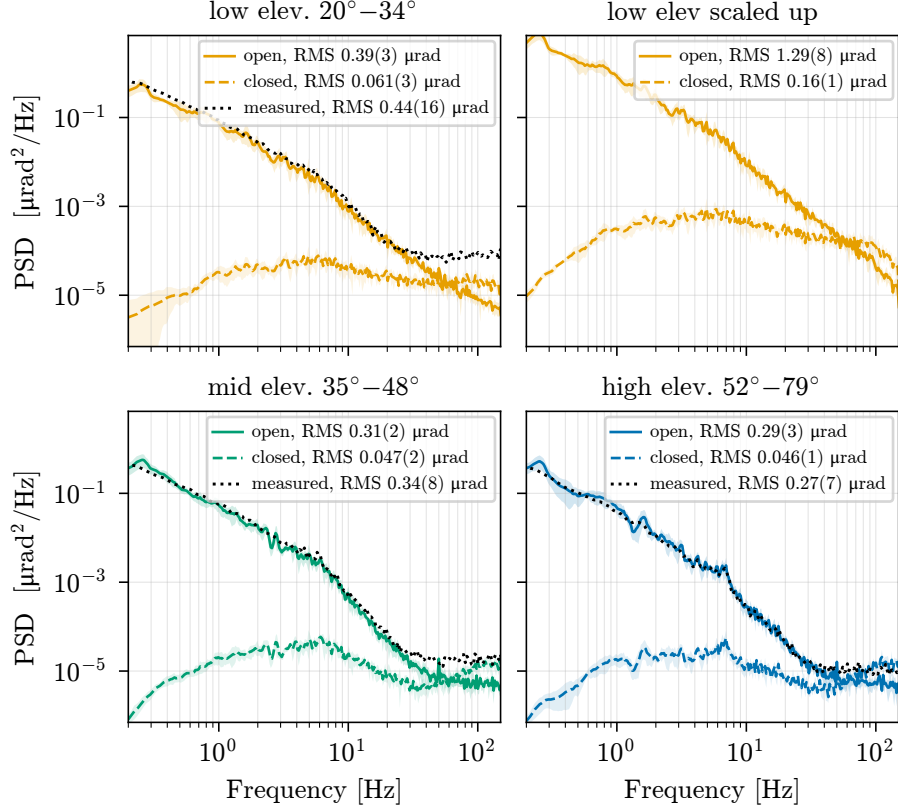


Figure 5: Open- and closed-loop angle-of-arrival power spectral densities (PSD) under four disturbance conditions: low-, mid-, and high-elevation turbulence-matched regimes and the amplitude-scaled stress test (top right). Solid curves are open-loop, dashed closed-loop, and dotted show the measured star PSDs (which we set as our target). Shaded bands span $\pm 1\sigma$ over 10 repetitions. With the loop closed, the disturbance PSD is suppressed by up to ~ 40 dB at the lowest frequencies, the rejection decreasing with frequency until the closed-loop residual approaches the open-loop amplitude. Integrated RMS values are listed in Table 4.

The noise floor of the measurements differs by elevation, around 10^{-4} $\mu\text{rad}^2/\text{Hz}$ for low elevation, 10^{-5} $\mu\text{rad}^2/\text{Hz}$ for mid and high elevation. In the lab, this was lower and did not match the star measurements. The noise level was around 10^{-6} $\mu\text{rad}^2/\text{Hz}$, due to more consistent centroid brightness and less environmental noise, leading to a better SNR. We therefore only focus on the frequencies that carry amplitude above the noise floor for the analysis of the closed-loop performance. The integrated RMS values in Table 4 are calculated over the frequency range of 0.5 Hz to 200 Hz.

We then translate the achieved pointing correction into a QKD-relevant figure of merit: single-mode fiber coupling efficiency, as shown in Figure 6. This is highly dependent on the exact optical configuration and serves as a proxy for the possible relative improvement in link performance considering tip-tilt disturbance only. We use a collimator with a 20 mm focal length to couple into 780-HP single-mode optical fiber with a 780(10) nm laser

Table 4: Integrated AoA jitter, open vs. closed loop in the laboratory emulation for all tested scenarios.

Condition	Open loop [μrad]	Closed loop [μrad]	Reduction
Low elevation	0.39(3)	0.061(3)	$6.4\times$ (16 dB)
Mid elevation	0.31(2)	0.047(2)	$6.6\times$ (16 dB)
High elevation	0.29(3)	0.046(1)	$6.3\times$ (16 dB)
Scaled-up	1.29(9)	0.16(7)	$8\times$ (18 dB)

diode. Here we report the mean coupling normalized to the undisturbed baseline power (where 1.0 is the baseline) as well as the 5th percentile value of the data to show the worst values in a given measurement. With the loop closed, mean coupling recovers to within a few percent of the baseline across all tested conditions: closed-loop means are 1.01(1), 1.00(0), and 1.00(0) of the baseline for the low, mid, and high disturbances, compared with open-loop 0.92(1), 0.94(1), and 0.93(3). The effect is most pronounced for the strongest (scaled-up) disturbance, where open-loop coupling collapses to a mean of 0.56(4) with a 5th-percentile value of 0.02, i.e. a communication link would shortly fade out entirely, while closed-loop operation restores the mean to 0.98(0) and holds the 5th-percentile coupling at 0.95 of the baseline. Across all conditions, the closed-loop 5th-percentile (worst-case) coupling stays above 0.94 (1.00, 0.99, 0.99, and 0.95 for the low, mid, high, and scaled-up conditions), compared with open-loop worst cases of 0.66, 0.76, 0.68, and 0.02. This shows that fine-pointing correction is essential for the mean link budget as well as to avoid complete breakdowns of an optical link.

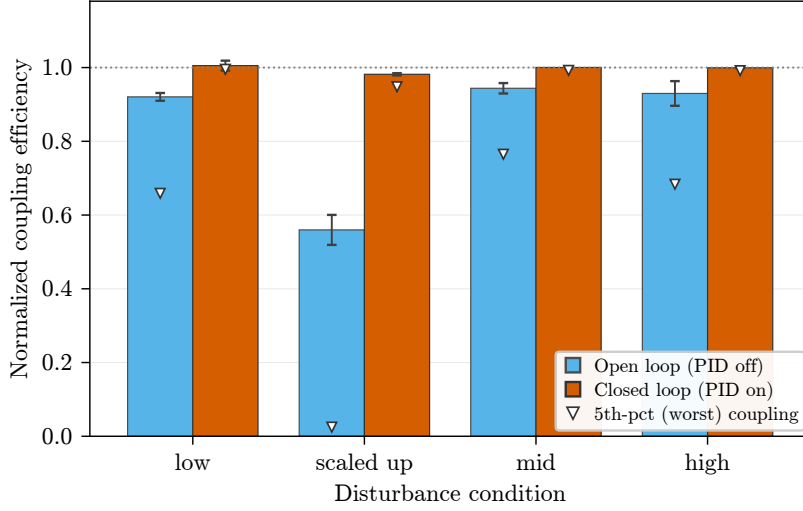


Figure 6: Fiber coupling efficiency (normalized to the undisturbed baseline) with the loop open vs. closed, for different disturbance conditions. Mean closed-loop coupling is 1.01(1), 0.98(0), 1.00(0), and 1.00(0) of the baseline for the low, scaled-up, mid, and high disturbances, compared with open-loop 0.92(1), 0.56(4), 0.94(1), and 0.93(3)

6. DISCUSSION AND LIMITATIONS

Here we demonstrate that our camera-based embedded fine-pointing system with FSM actuation can mitigate atmospheric tip-tilt distortions for our use case, a practical solution for stabilizing free-space optical links in satellite-based quantum communication. The laboratory validation using measured, site-specific AoA statistics shows that the closed-loop system can achieve a significant reduction in AoA jitter and a corresponding improvement in single-mode fiber coupling efficiency.

The measured PSDs show that most of the atmospheric tip-tilt disturbance amplitude is concentrated in the low-frequency band. The control loop achieves a closed-loop bandwidth of approximately 60 Hz, providing 16 dB of integrated RMS jitter suppression. This indicates that the low-frequency FSM correction is sufficient to substantially remove the tip-tilt part of the atmospheric disturbance. That bandwidth is set by the sampling

rate of the camera and the 1.4 ms end-to-end loop delay (Section 2.1), of which about 40 % is software, while the remaining time is spent on exposure, sensor readout, and transfer. Raising the bandwidth would therefore require a faster sensor as well as a more optimized control circuit (e.g. with a field-programmable gate array).

To show the practical impact of the fine-pointing correction, we measured the single-mode fiber coupling efficiency under various disturbance conditions for a specific optical setup in the laboratory. The results demonstrate that the closed-loop can recover coupling efficiency to within a few percent of the undisturbed baseline for all tested conditions. The most significant improvement was observed for the strongest scaled-up disturbance scenario where open-loop coupling collapses to a 0.56 mean with a 5th-percentile of 0.02, and the loop restores it to 0.98 while holding the worst-case at 0.95.

The main limitation of the presented work is that it is a laboratory validation of the fine-pointing loop, rather than a demonstration of closed-loop tracking with a telescope. The laboratory setup reproduces the measured on-sky angle-of-arrival statistics in both spectral shape and integrated RMS, but it does not capture all real-world effects such as atmospheric scintillation, wind-induced vibrations, or other environmental factors that can affect the performance of the system in actual operation. Future work will focus on closing the loop on-sky to validate the performance under actual atmospheric conditions. This can also lead to additional problems, depending on whether the telescope is operated in open-loop or closed-loop; the mount residual can push disturbance to higher frequencies – demanding a higher bandwidth for the fine-pointing system.²⁶ This remains to be tested to compare both open and closed-loop operation with our full hardware. Not only with stellar jitter, but actual LEO objects – depending on which turbulence layer dominates, the jitter may also be different.

In addition, both the measurement and the emulation are limited to AoA jitter, and do not capture higher-order phase aberrations that also affect coupling efficiency. Higher-order disturbances could also influence the accuracy of camera centroiding in ways not studied in this work. The number of orders that need to be corrected depends on the required fiber coupling efficiency and is usually a tradeoff between performance and complexity.¹⁴ Should tip-tilt correction alone not suffice for the required link budgets, this system will be used as the first stage of a higher-order correction system. This limitation may also be overcome by the use of APD detection (as discussed in Section 1).

The different effective focal lengths in the measurement and the final deployed configuration set different plate scales (2.14 $\mu\text{rad}/\text{px}$ vs 0.64 $\mu\text{rad}/\text{px}$), which lead to different noise floors in the PSDs, as well as a different angular accuracy. The high-frequency noise is not dominating the jitter, but it is a limitation of the measurement and emulation.

A satellite link will use a narrowband beacon for tracking, as did our lab emulation, while the stellar measurements used a broadband SWIR response to maximize SNR. Angle-of-arrival jitter is, however, achromatic to first order.²⁷ We therefore expect the wavelength mismatch to have negligible effect on the measured and emulated tip-tilt statistics, with only a small influence from secondary wavelength dependencies.

The 1 kHz frame rate of the star-tracking measurement sets an effective 487 Hz Nyquist limit. Since the most of the atmospheric AoA jitter amplitude, the closed-loop bandwidth (60 Hz), and the waterbed peak (136 Hz) all lie well within this band, the frame rate adequately captures the frequencies relevant to the correction. Only the low-energy high-frequency tail above 500 Hz is unresolved. The more significant limitation is statistical: the disturbances are drawn from a single night of data and therefore do not sample different nights or seasonal variability. Characterizing the site-specific turbulence over multiple nights is needed to span the full range of operational conditions and strengthen the validation.

Where possible, the limitations will be addressed by the planned closed-loop operation of the system in combination with the telescope, where the present laboratory validation establishes the expected performance.

7. CONCLUSIONS

We designed and lab-validated an embedded tip-tilt fine-pointing system for the OGS in Innsbruck. We showed the method of measuring turbulence AoA statistics from stars with our OGS, emulating those in the laboratory, and testing the closed-loop correction of the feedback loop. The 1 kHz feedback loop with a measured end-to-end latency of 1.4 ms achieves a 60 Hz closed-loop bandwidth, with a $6\times$ RMS jitter reduction for the measured

profiles, with up to $8\times$ on a scaled-up scenario, and single-mode fiber coupling in a laboratory test setup is held at ≥ 0.95 (of an undisturbed baseline) worst-case, where the open loop faded to 0.02. The validation against measured, site-specific turbulence with fiber coupling as a QKD-relevant figure of merit shows that the compact, camera-based controller is a practical solution for OGS fine-pointing applied to satellite QKD. Next steps include an on-sky closed-loop demonstration in various turbulence regimes, with an extension to uplink pre-compensation and horizontal links as well as a SKR analysis instead of fiber-coupling efficiency.

ACKNOWLEDGMENTS

This project was funded by the Austrian Research Promotion Agency (FFG) with the Quantum Austria project InnQOGniTo and by the European Union with the CEQCI project (Project No.: 101249538, Call: CEF-DIG-2024-EUROQCI), funded by the European Union’s Connecting Europe Facility (CEF) with national co-funding from the FFG. The authors thank Andreas Sinn for the fruitful discussions and help regarding the hardware for the fine-pointing system. Claude Opus 4.8 (Anthropic) and GPT-5 (OpenAI) were used for language refinement, Claude Code was used for coding assistance. The AI tools served in an assistive capacity, all output was reviewed by the authors, who take full responsibility for the entire work.

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