

UltraAir Airborne-to-GEO Optical Communication Demonstrator: Pointing, Acquisition and Tracking Results

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ABSTRACT

This paper presents flight test campaign results of UltraAir, a demonstrator for optical communication between an airborne laser communication terminal and a geostationary satellite. Specifically, pointing, acquisition and tracking performance is addressed. It provides analysis of the system performance during the link acquisition phase, assessing the initial pointing accuracy and performance of a Pointing Estimator. Furthermore, the tracking performance is analyzed by investigating the achieved closed-loop control error in presence of external disturbances such as atmospheric turbulence and aircraft vibrations. Analysis of the tracking error has been used for feedback controller modifications to improve tracking and thereby link stability during the flight campaign. System identification measurements have been performed to analyze closed-loop system dynamics during an airborne link. The measurement results of the flight test campaign provide valuable insight into the future challenges of developing airborne optical communication systems.

Keywords: airborne optical satellite communication, Pointing Acquisition and Tracking, feedback control, disturbance modeling, line-of-sight control

1. INTRODUCTION

The demand for high bandwidth and secure communication has led to significant developments in Free-space optical communication (FSOC) systems. These systems are designed for various use cases, including ground stations, satellite terminals and airborne platforms. To enable optical communication links over large distances, accurate Pointing, Acquisition and Tracking (PAT) of the laser beam is required. This is particularly challenging for communication from an airborne platform to a geostationary satellite, due to the link distance of approximately 36000 to 41000 km, the presence of external disturbances such as atmospheric turbulence and severe aircraft motion and vibrations. To mitigate these disturbances, accurate pointing knowledge combined with high-bandwidth closed-loop control is required to achieve robust PAT. This imposes challenging requirements on optomechanical design, actuator and sensor performance, system calibration and closed-loop control performance. To address these challenges, TNO, together with Airbus and TESAT, developed an airborne laser communication terminal (Air-LCT) to demonstrate an optical communication link between an aircraft and a geostationary satellite (Alphasat's TDP-1). In Q4 of 2024, a successful ground-to-space test campaign on Tenerife at the ESA Optical Ground Station was performed verifying the functionality and feasibility of the system.¹ In Q4 of 2025 the system was integrated into a Falcon-20 aircraft (See Figure 1 (left)) and a flight demonstration was performed with TDP-1.² Nine test flights were performed with a total of 33 link opportunities. One flight typically consisted of 2 to 5 link opportunities with a link duration varying from 6 to 14 minutes. The flights were operated from the AVdef airbase, with the fly-zone being above the Mediterranean Sea, to the southeast of Marseilles, France (see Figure 1 (right)). This paper presents flight test results related to Pointing, Acquisition and Tracking and is organized as follows. In Section 2 an overview is presented of the Air-LCT system design. Then, in Section 3 the acquisition process and control architecture is described. Finally, Section 4 presents flight test results on PAT.

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Figure 1. Falcon20 Aircraft operated by AVdef that is used in the flight test campaign (left), and a typical flight path trajectory during a test flight (right).

2. SYSTEM DESCRIPTION

The work presented in this contribution considers the flight test results of the window flight demonstrator (WFD) of the Air-LCT. In this WFD configuration, the system is mounted completely inside an aircraft and the optical power is received and transmitted through an optical window integrated into the emergency exit of the aircraft. The design considerations regarding this flight configuration are extensively described in Liebig et al.,¹ as well as the design approach and the details on the optical system design. This section summarizes the optomechatronic architecture.

The core of the Air-LCT system is an optical bench (OB) that carries the sensitive optics, detectors and active mechanisms to perform pointing of the received and transmitted laser. One of the key challenges is to compensate for the aircraft vibrations, which is achieved by a combination of passive vibration isolation, accurate attitude estimation and active Line-Of-Sight (LOS) control. Figure 2 shows the design of the OB with the important sensor- and actuators indicated (left), and the realized hardware (right). In the figure, the Fine Steering Mirror (FSM) and Point Ahead Mirror (PAM) are shown. The FSM performs the short stroke, high bandwidth beam steering and disturbance rejection using feedback control. The FSM is part of both the receiving channel (Rx) as well as the transmitting optical path (Tx). The PAM is a similar tip-tilt mechanism that performs pointing of the Tx beam w.r.t. the received Rx beam. Therefore, it is used to apply the Point Ahead Angle (PAA) and to perform scanning (spiral) patterns (see Section 3.2). Furthermore, the Fine Detector (FD) and Coarse Detector (CD) are depicted. These are a four-quadrant detector and a Xenics XSW640 camera respectively, and perform

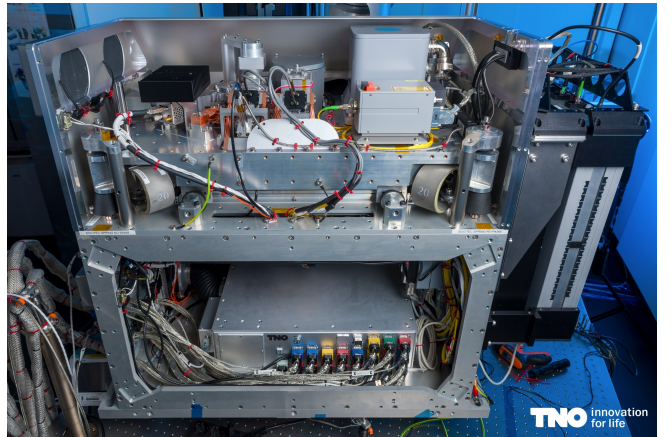
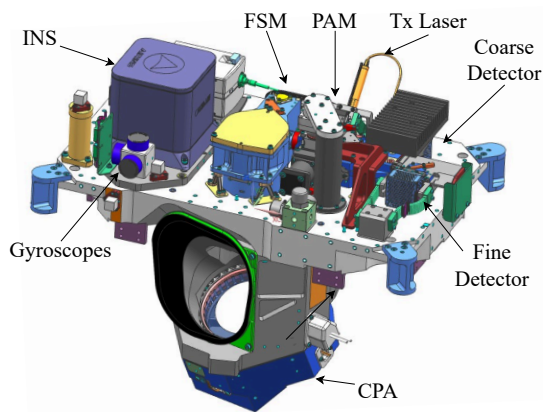


Figure 2. Design of the Air-LCT Optical Bench (OB) (left) and the realized OB suspended on the passive vibration isolation in the fixed frame, with covers removed (right).

the fine-and coarse pointing measurement. The FD has a total on-sky FoV of ± 50 μ rad, while the CD has a range of ± 3.5 mrad. The Inertial Navigation System (INS) and Gyroscope measurements are combined to one attitude estimation to determine the attitude of the OB. Finally, the Coarse Pointing Assembly (CPA) is a large stroke pointing mechanism with a total range of ± 8 degrees on-sky. The CPA is used for the coarse pointing and to offload the stroke of the FSM (see Section 3.2). In Figure 2, the right picture shows that the complete OB is mounted on a fixed frame, supported by passive vibration isolation. This vibration isolation is effective in suppressing a large contribution of the aircraft vibrations towards the OB. The design of the passive vibration isolation is discussed in more detail in Liebig et al.¹

3. POINTING, ACQUISITION AND TRACKING DESIGN

This section provides a brief overview of the acquisition process and state machine design as well as the control architecture. First, an overview is provided of the beaconless acquisition process and its integration into the link state-logic design of the Air-LCT. Then, the control algorithm architecture is presented that clarifies how the different actuators and sensors achieve the desired acquisition and tracking performance using feedback-and feedforward control.

3.1 Spatial Acquisition and State Machine Design

The spatial acquisition strategy of the Air-LCT with TDP-1 follows a similar approach as described in the CCSDS Orange Book Optical high data rate (HDR) communication - 1064 nm.³ At the start of the acquisition process, both terminals are misaligned due to limited position and pointing knowledge of the Air-LCT and the Geostationary Laser Communication Terminal (Geo-LCT). Thereby, the required pointing vector from each terminal is initially uncertain and to spatially align the two platforms the acquisition process is followed. Figure 3 depicts schematically the steps involved. In this flight demonstration the Geo-LCT is the Lead (L) and the Air-LCT is the Follower (F). At T_0 , the acquisition process starts with **Coarse Acquisition Phase 1** (CA1). The Geo-LCT starts spiraling with an uncertainty cone that covers its initial pointing uncertainty. The Air-LCT is pointing towards the satellite and uses its CD to measure the incoming laser power that passes through its aperture. The received optical power intensity over time is a short pulse of a few hundred microseconds, referred to as a *blip*. These measured blips are used to perform a pointing correction of the Air-LCT, and reduces its pointing uncertainty. In the following **Coarse Acquisition Phase 2** (CA2), the Air-LCT starts spiraling with a reduced uncertainty cone, resulting in received *blips* at the Geo-LCT. In the Air-LCT, these spirals are performed by the PAM. The spirals are carefully designed such that with proper feedback- and feedforward control (see section 3.2) the uncertainty cone is covered and the spiral tracking error does not deteriorate the probability to *hit* the counter-terminal. The Geo-LCT performs a pointing correction using the received blips.

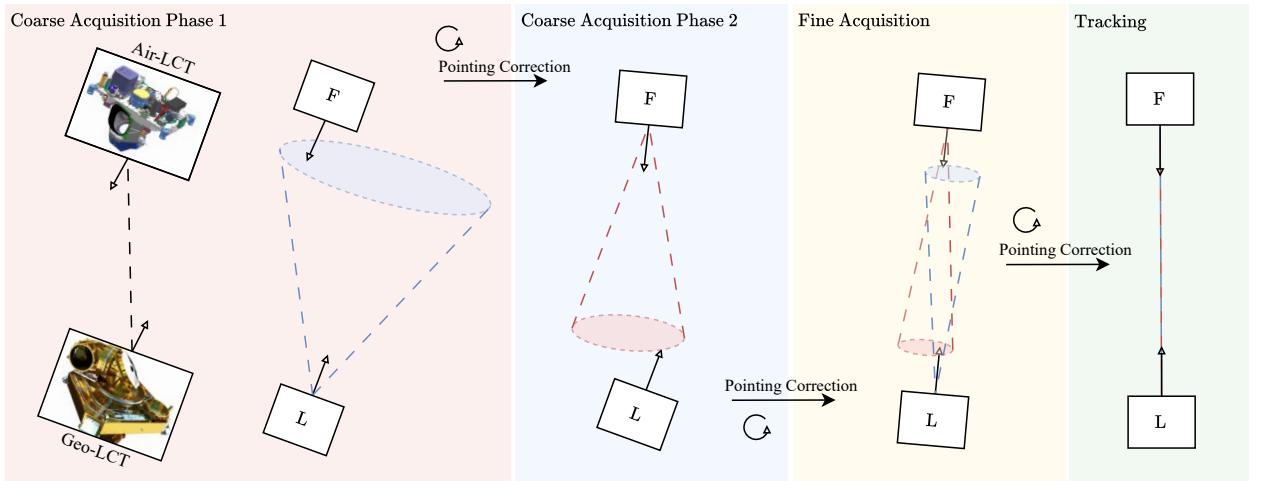


Figure 3. Acquisition process that is used to set up an optical communication link between the Air-LCT and Geo-LCT.

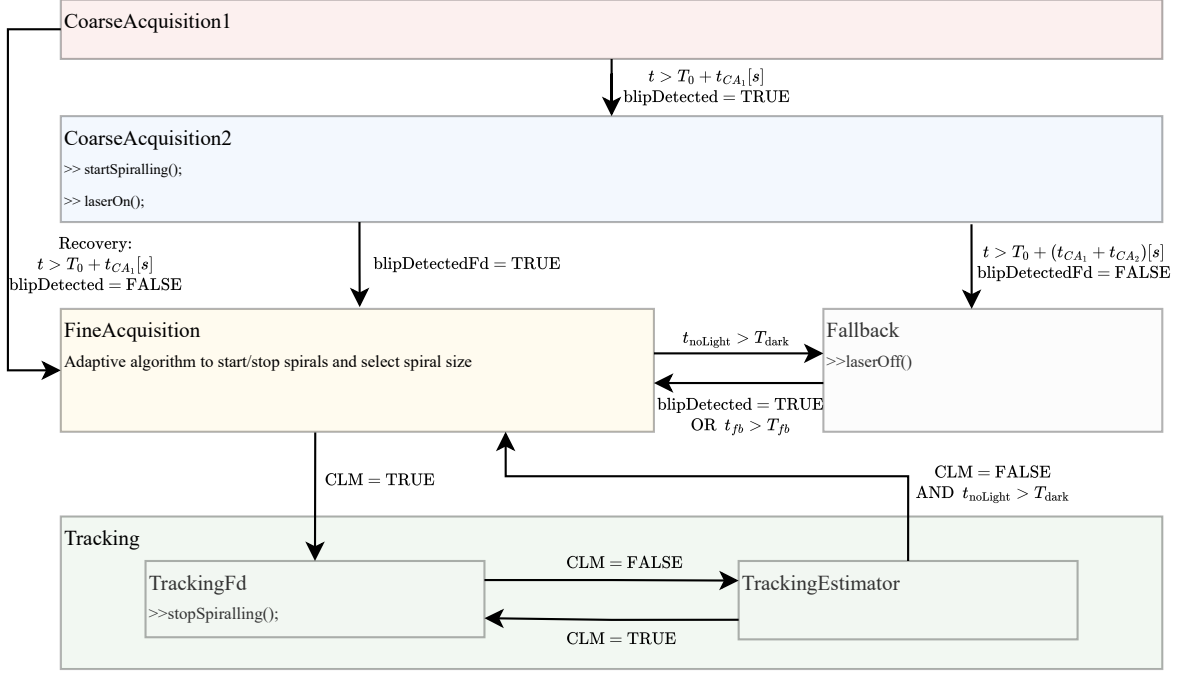


Figure 4. Simplified Air-LCT Acquisition logic state-machine to implement the acquisition process.

During **Fine Acquisition** (FA), both communication terminals have their lasers on and perform spiral scans. When receiving blips, the pointing knowledge improves and the spiral size is reduced. This results in more frequent received blips and thereby a more frequent pointing correction. It should be noted that in this phase, the Air-LCT can no longer use its CD, since the camera is blinded by its own emitted Tx laser light. Therefore, after CA1 the system relies on the FD with a limited FoV of only ± 50 μ rad. When the pointing uncertainty is small enough and covered by the divergence, the Air-LCT stops spiraling. If both terminals receive sufficient optical power above their detector thresholds, **Tracking** is achieved. An overview of the resulting acquisition state-machine design for the Air-LCT to perform this acquisition process is depicted in Figure 4. The different acquisition phases can be recognized, and a concise version of the decision logic is shown that implements this acquisition process. In the figure, T_0 is the link start time and $t_{CA,1}$ and $t_{CA,2}$ are the configured durations of the two first acquisition phases. CLM is a boolean that defines if the system is in Continuous Light Mode, receiving uninterrupted optical power. Furthermore, timings can be recognized related to the fallback duration (t_{fb}) and the duration that no light is received ($t_{noLight}$). Next to the nominal design of the acquisition process from CA1 to Tracking, a Fallback state is included in the state machine. This state is used when unexpectedly no blips are detected or no optical power is received for an extended duration on the FD. The system deliberately turns of its own Tx laser in order to be able to use the CD to re-acquire blips. Using these blips on the CD, a pointing correction can be performed to reduce the pointing uncertainty to be smaller than the FD FoV allowing to proceed with FA. In FA, an adaptive algorithm is employed to determine the required spiral size to cover the estimated uncertainty cone. In the Tracking state, there is a mechanism to temporarily switch to the Pointing Estimator for feedback control during fades of the received optical power.

3.2 Control Architecture

To achieve pointing, acquisition and tracking of the counter terminal it is required to actively reject disturbances that affect the system pointing performance. Critical disturbances in airborne optical communication platforms are aircraft vibrations, atmospheric turbulence and detector noise. Feedback control enables to actively control the FSM and CPA, based on the measurements performed by the FD and CD and other metrology in the Air-LCT. The PAM is used to perform spiraling of the Tx beam w.r.t. the received Rx beam and to apply the PAA.

Feedforward control of the PAM is effective in improving closed-loop setpoint tracking performance for known trajectories (such as acquisition spirals).

The control architecture of the Air-LCT is presented in Figure 5. In this figure the system is depicted in grey, and contains many in- and outputs. The most crucial pointing performance of the Air-LCT system is determined by the high-bandwidth FSM control of performance variable θ_P . This performance variable is the result of a pointing estimator that uses all available sensor inputs to estimate the true pointing. The estimator uses the calibrated position of the mechanisms θ_{FSM} and ϕ_{CPA} , as well as the on-sky angle measured by the Coarse- and Fine Detectors θ_{CD}, θ_{FD} and the attitude estimation of the Optical Bench Ω_{OB} . This attitude estimation is based on the gyro- and INS measurements $\omega_{gyro}, \Omega_{INS}$. The FD is a low-noise high-bandwidth four quadrant detector. The FD FPGA output for feedback control is 20 kHz and designed for low latency.⁴ The CD has a frame rate of 100 Hz and is complemented by a Centre of Gravity (CoG) algorithm implemented on the FPGA of the control system. The controller C_{FSM} computes controller output u_{FSM} based on feedback of θ_P . Furthermore, the calibrated mechanical angle of the CPA, ϕ_{CPA} is used in feedback for controller C_{CPA} . Similar structure is observed for the calibrated output angle of the PAM, θ_{PAM} that is in feedback using controller C_{PAM} . Since the FSM is a fine pointing mechanism with a high bandwidth, but with a limited mechanical stroke (see Section 2), a control structure is employed to offload the FSM stroke towards the CPA. This is realized through the design of controller C_{OFF} that computes a setpoint towards the CPA (u_{OFF}) based on the current control effort of the FSM (u_{FSM}). Finally, it can be seen that some more complex algorithms are required such as an online PAA calculator, an attitude estimator and robust detection logic and processing algorithms. The satellite track prediction X_{SAT} is the output of careful link planning and is fed from the Link Scheduler to the Pointing Estimator.

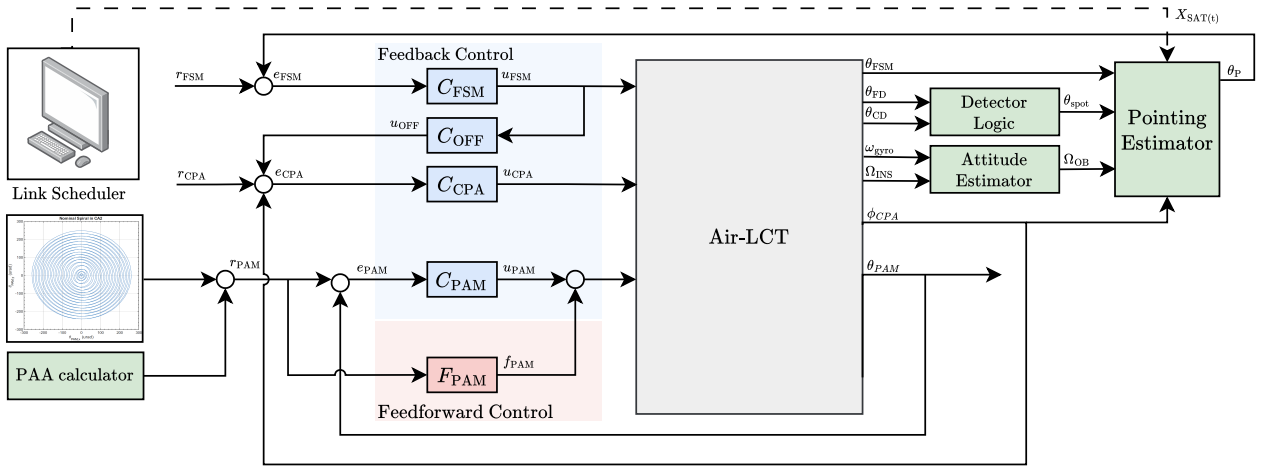


Figure 5. The control architecture of the Air-LCT. The architecture contains feedback- and feedforward controllers together with algorithms to perform attitude- and pointing estimation and detector processing.

4. FLIGHT TEST PAT RESULTS

This section presents results of the flight test campaign, specifically regarding PAT of the Air-LCT system. Results of the flight tests with respect to link characterization are presented in detail in Barrios et al.⁵ First in Section 4.1, a short overview is given on the selected links to analyze PAT performance. Next in Section 4.2, the Acquisition performance is analyzed in more detail, addressing successful implementation of the spatial acquisition procedure and state machine design as well as initial system pointing and performance of the pointing estimator. Finally, in Section 4.3, closed-loop tracking results are presented. It is shown that FSM feedback controller updates enabled stable tracking. Results of in-flight system identification are shown and the FD tracking error is analyzed for different flight conditions.

4.1 Link Test Description

The flight test campaign resulted in a data set of 31 successful links with varying flight and link conditions. In this paper, a subset of link results that are especially relevant for PAT are presented in more detail. The links presented in this section are performed over multiple days in the test campaign, in varying conditions and times of the day. An overview of the considered link measurements in this section is presented in Table 1. In this table, the date and link start time T_0 for each link are denoted together with a short comment on the analysis for which they are used in this contribution. Initial pointing performance is analyzed by looking at the coarse acquisitions of all links. Furthermore, multiple links are selected to analyze the Tracking performance for varying link conditions. In-flight experiments were performed to evaluate the effects of varying aircraft vibration such as in Link MeasNr 136. This was achieved by performing an aircraft glide; significantly reducing throttle power of the aircraft. This resulted in decreasing altitude of the airplane and reduced engine induced vibrations. Finally, in Link MeasNr 150, experiments were performed where the link acquisition timing parameters were altered intentionally to perform measurements of the Pointing Estimator performance.

Table 1. Link measurement numbers (MeasNr) for the analyzed results in this contribution. The table shows the date and start time T_0 , as well as a short remark related to PAT.

MeasNr	Date	T_0 (UTC)	C_{FSM}	PAT remarks
All	N/A	N/A	A-C	Initial Pointing performance validation
123	10-12-2025	08:00:00	A	Initial FSM feedback controller design
136	12-12-2025	13:20:00	B	Aircraft performed glide-mode part of the link
142	13-12-2025	14:25:00	B	Updated FSM feedback controller design
143	13-12-2025	15:01:30	C	Tracking performance validation
150	16-12-2025	18:10:00	C	Pointing Estimator validation
151	16-12-2025	18:30:00	C	Tracking performance validation

4.2 Acquisition Performance

An overview of a typical successful link acquisition is provided in Figure 6 (left). The top sub-figure indicates the system state as a function of Link Time. Here, the Link Time is defined as the time in seconds from the link start time T_0 . In the middle and bottom sub-figure, the spot location on the CD and the received optical power on the FD are depicted respectively. Until $t_{CA,1} = 60$ s, the Air-LCT receives blips from the Geo-LCT and the system state is CA1. In the figure it can be observed that the subsequent blips are received near the center of the CD and approximately 10-15 nW blips are received on the FD. After CA1, within approximately 6-7 seconds the transitions from CA2 to FA into tracking is achieved. In the middle sub-plot of Figure 6 (left), the initial received blip on the CD is omitted for readability, since the initial blip spot location typically has a larger offset due to the initial pointing performance of the system. The system acquisition performance is addressed by three different analysis. First in Section 4.2.1, the initial pointing accuracy of the Air-LCT system is analyzed with all first CD blips locations. Second, in Section 4.2.2 the performance of the pointing estimator is analyzed. Finally in Section 4.2.3 the transition from acquisition into tracking is shown.

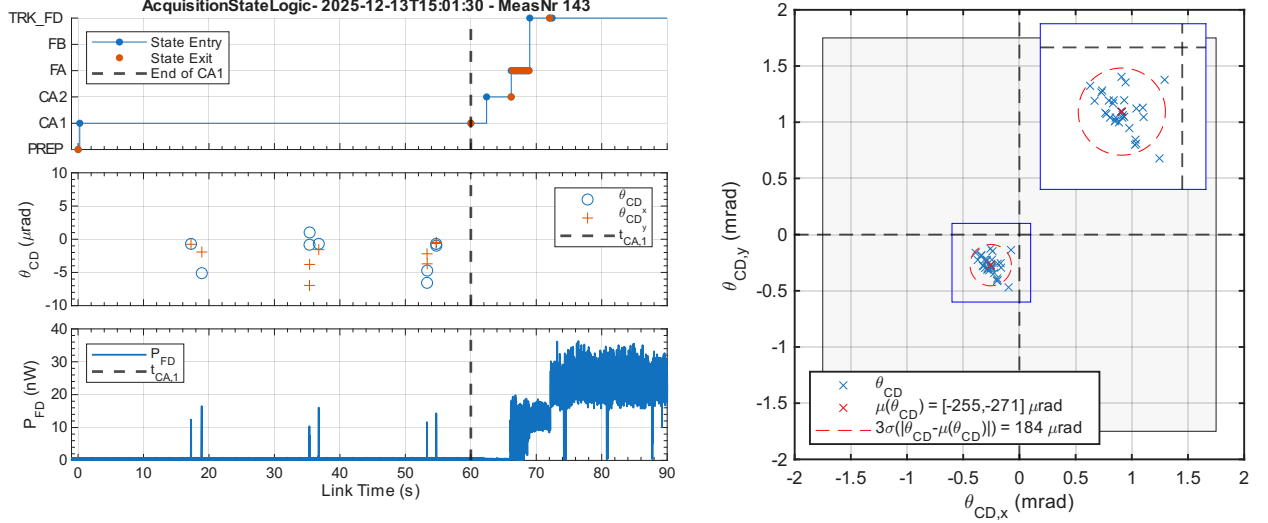


Figure 6. Acquisition overview of link MeasNr 143, with the state logic and the spot location on the CD and received optical power on the FD respectively (left). First CD blip locations (x) and their mean (x) and the 3σ value of the distance to the mean (-) for 31 flight test links (right).

4.2.1 Initial pointing accuracy

At link start time T_0 , the Geo-LCT starts to perform a spatial acquisition spiral with an initial uncertainty cone covering its own pointing uncertainty. If the Air-LCT is able to point with sufficient accuracy toward the Geo-LCT such that the received optical power is within the CD Field of View (FoV), it will receive blips, enabling pointing corrections for the Air-LCT. The full CD FoV is approximately ± 3.5 mrad on-sky angle. It is desired to reduce the initial pointing uncertainty even further down to ± 1.75 mrad, since large input angles into the systems telescope can lead to spot deformations that result in deteriorated CD performance. In Figure 6 (right), the initial pointing accuracy of the Air-LCT system is analyzed by comparing the first CD blip of all different links. Each blue cross represents the first received blip of a separate link. The red cross indicates the mean blip location and the red circle has a radius equal to the 3σ value of the distance to the mean for each blip. In the right top, a zoomed plot is shown of the blue indicated area. Note that the displayed range of ± 2 mrad does not cover the full CD FoV. In gray the target requirement of ± 1.75 mrad is shown. In the figure it can be seen that a small bias in initial pointing of the system is observed, where the initial spot locations have a mean $\mu(\theta_{CD}) = [-255, -271] \mu\text{rad}$. The distance to the mean $d_i = |\theta_{CD,i} - \mu(\theta_{CD})|_2$ has been computed for each initial spot location $\theta_{CD,i}$, where $3\sigma(d) = 184 \mu\text{rad}$. It is expected that the performance is limited by residual system calibration errors and orientation accuracy of the INS. The achieved initial pointing performance is below 0.5 mrad for each axis, well within the CD FoV of ± 3.5 mrad and target requirement of ± 1.75 mrad.

4.2.2 Pointing estimator performance

When the Air-LCT is not in Tracking, its pointing and acquisition performance is dependent on the Pointing Estimator. To assess the performance of the Pointing Estimator of the Air-LCT, measurements are performed where the initial acquisition phase CA1 is extended from 60s to 300s. Figure 7 shows the result of such a measurement (MeasNr 150). During the extended CA1, the Air-LCT receives blips with an interval of approximately 39 seconds, which is determined by the spiral size of the Geo-LCT. The figure shows the received optical power on the FD P_{FD} , together with the FD spot locations θ_{FD} and measured optical bench attitude Ω_{OB} . It should be noted that around the Link Time of 118 seconds, a set of blips is missed on the FD. This is caused by a false CD blip detection. Quick correction on a new blip on the CD, resulted that the following blips were within the FD range. It can be observed that for the full duration of CA1, the Pointing Estimator enables to keep the received blips within the position sensitive range of the FD (approximately 10 μrad) in presence of significant aircraft motions and vibrations up to almost a degree RMS.

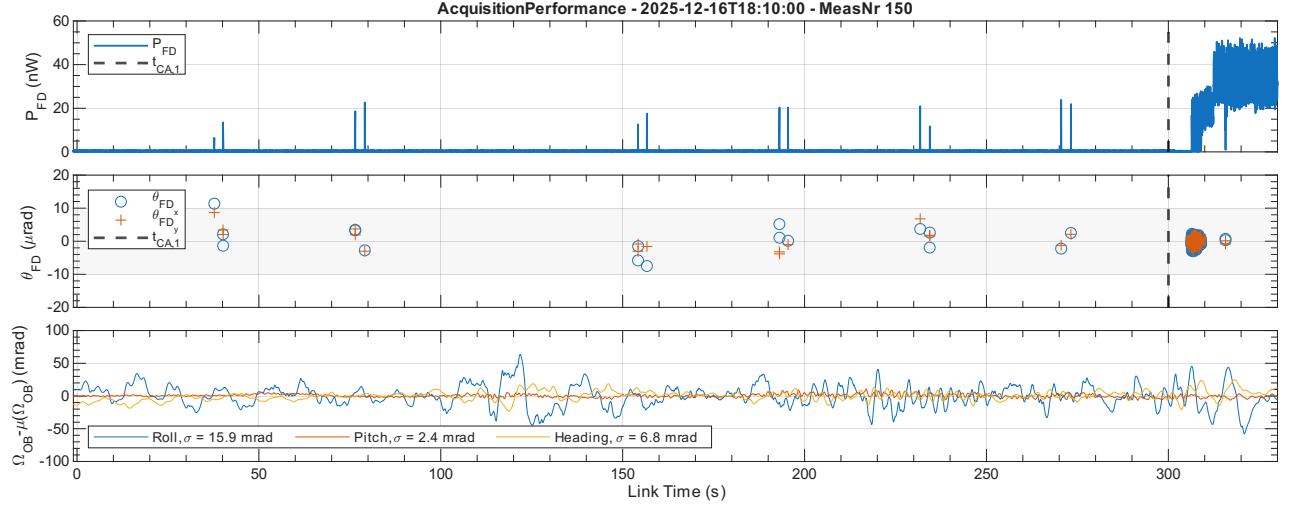


Figure 7. Blips received within $\pm 10 \mu$ rad on FD during CA1 while tracking on Pointing Estimator in presence of significant aircraft motion and vibration up to almost a degree RMS.

4.2.3 Coarse acquisition to tracking

After successful initial pointing and receiving blips on the CD, in CA2 the Air-LCT starts to perform spirals and through FA it reaches Tracking. Figure 8 shows a typical convergence from CA2 to Tracking. On the left, the system state and the angle of the PAM θ_{PAM} is shown together with the received optical power on the FD. On the right, the spatial result of the spiral highlighted in blue in the second sub-plot is depicted. It is observed that after receiving optical power on the FD, the algorithm decreases the spiral radius and that after approximately 2.9 s after leaving CA2, Tracking is achieved. The track width and velocity of the spiral scan are matched to the link design and system parameters such as optical divergence. Note that in the center of the spiral, the tracking performance is limiting the coverage of this spiral. A combination of tuning maximum spiral setpoint accelerations and PAM feedforward design can improve this result.

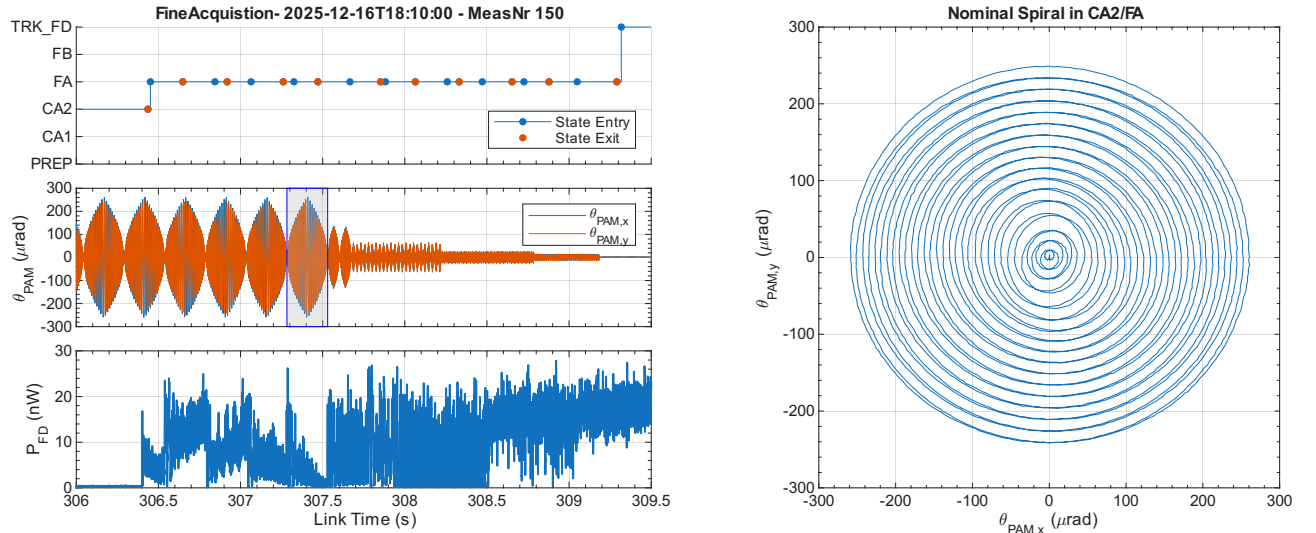


Figure 8. Fine Acquisition into tracking (left) and a nominal spiral performed in CA2/FA (right).

4.3 Tracking Performance

This section presents the tracking performance results. The first flight links showed instability effects during tracking that were (partly) observed during the Tenerife ground-to-space test campaign. By careful analysis and minor controller updates, these link instabilities could be completely removed as described in Section 4.3.1. System identification experiments were performed to validate system performance and stability of which results are shown in 4.3.2. Finally, in 4.3.3 the tracking performance is analyzed. Measured aircraft vibrations and a model for atmospheric turbulence effects are used to explain the achieved tracking error.

4.3.1 FSM feedback controller improvements

In preparation of the Air-LCT flight verification tests, system identification and feedback controller design based on laboratory and ground-to-space experiments¹ lead to a nominal design of the Air-LCT feedback controllers. Important in achieving the stringent tracking requirements is the design of C_{FSM} , which is the high-bandwidth FSM feedback controller. After performing the first successful links during the flight campaign, preliminary data processing indicated that the link stability could be optimized. A combination of atmospheric effects and system parameters induced short instabilities in the tracking loop of the system. It was concluded by analysis of the traced system data and in-flight system identification experiments that minor updates to the design of C_{FSM} could improve tracking stability. Figure 9 shows an overview and zoomed in plot of the recorded trace data of θ_{FD} during three different links (MeasNr 123, 142 and 143). The top sub-figure shows the achieved tracking performance with Controller A, the nominal FSM feedback controller. Here it is observed that oscillations lead to deteriorated pointing performance. An update to FSM Controller B was implemented, based on data analysis and system identification. In the second sub-figure, tracking results of Controller B are shown. Although the comparison shown is for different links and thereby different link conditions, Controller B shows clear improvements. The observed instabilities are reduced from multiple seconds to tenths of seconds. Implementation of Controller B confirmed the right design updates, but did not mitigate the effect completely. A final update to Controller C was performed to completely remove the induced instabilities. This resulted in superior tracking performance, mitigating the observed link instabilities as can be seen in the bottom sub-figure. In the zoomed in plot a single instantaneous pointing error is still present which is expected to be unrelated to the analyzed effects. It is seen that the system quickly recovers while staying in tracking.

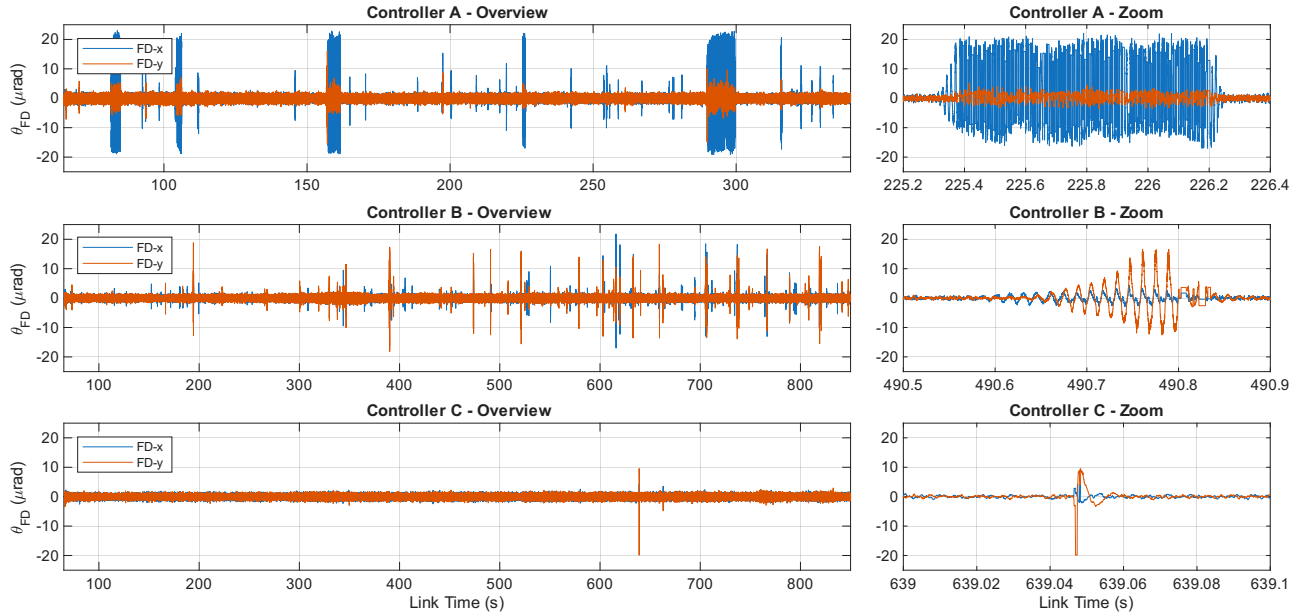


Figure 9. Time trace of FD tracking error for controller A (MeasNr 123), B (MeasNr 142) and C (MeasNr 143). It is observed that FSM feedback controller adaptations show significant improvements in tracking performance.

4.3.2 In-flight system identification

System identification experiments were performed to assess the real system behavior in closed-loop during a link. More specifically, Frequency Response Functions (FRFs) were measured. In FRF measurements the system is perturbed by a known exogenous signal and specific output signals of the system are measured to identify the response of the dynamical system. It should be noted that to identify closed-loop dynamics for the tracking feedback loop on the FD, the system requires a stable optical input beam. In the flight test campaign, FRF measurements were performed while airborne and in tracking on the Geo-LCT, providing insightful data that was used for system characterization and controller updates. Considering the small detector range of the FD, the identification experiment should be performed when the system is in closed-loop on the FD. Conditioning the injected disturbance amplitude and selecting best quality FRF data is important to improve the estimation quality of the FRF.

Figure 10 (left) shows the result of a closed-loop FRF measurement. Here the magnitude plot of the Multiple-Input-Multiple-Output (MIMO) FRF of the MIMO Sensitivity $\tilde{S}_{\text{FSM}}$ describing $d_{\text{FSM}} \rightarrow u_{\text{FSM}}$ is shown. Here, d_{FSM} is the injected disturbance at the input of the FSM (i.e. added to u_{FSM}). This transfer $\tilde{S}_{\text{FSM}}$, is described as

$$\tilde{S}_{\text{FSM}} = (\mathbf{I} + \underbrace{C_{\text{FSM}} \tilde{H}_{\text{FSM}}}_{\tilde{L}_{\text{FSM}}})^{-1}, \quad (1)$$

where $\tilde{H}_{\text{FSM}}$ is the equivalent transfer from $u_{\text{FSM}} \rightarrow \theta_{\text{FD}}$, while the CPA and offloading are in closed-loop. It is observed that for frequencies < 100 Hz suppression of the disturbances is achieved. This is important since significant contribution of the aircraft vibrations are present in this frequency range. It can also be seen however, that beyond 100 Hz no rejection and even slight amplification of disturbances holds due to the waterbed effect. Note that < 30 Hz, the estimation quality of the FRF is poor, especially on the y-axis. This is due to the closed-loop nature of the identification resulting in poor coherence below the bandwidth. Furthermore, external disturbances that are not injected such as aircraft vibrations also interfere with the FRF estimation quality. In Figure 10 on the right, the Characteristic Loci of the loop gain $\tilde{L}_{\text{FSM}}$ are shown. The result shows that the MIMO closed-loop system is stable according to the Generalized Nyquist Theorem.⁶

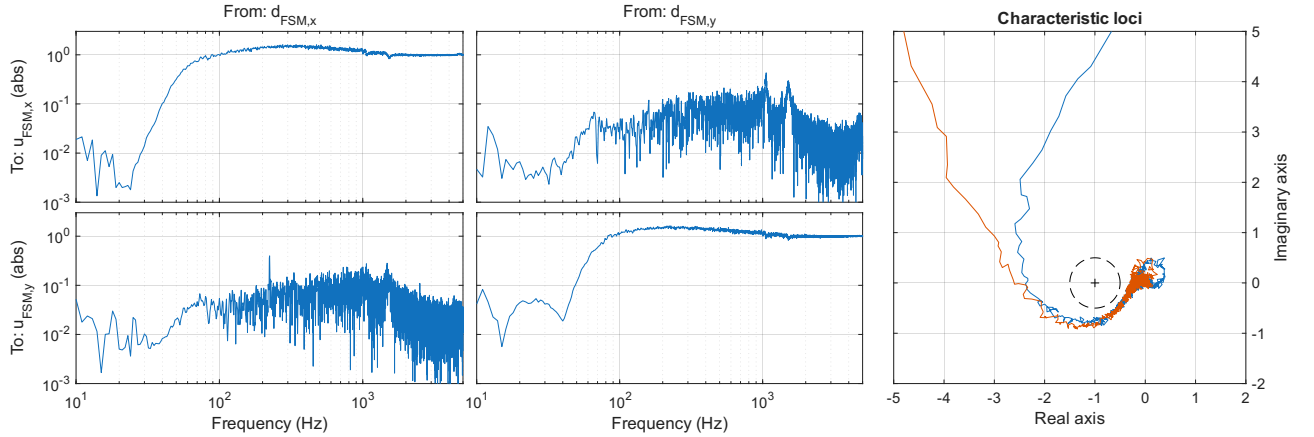


Figure 10. System identification results of the FSM control loop, showing the closed-loop MIMO sensitivity $\tilde{S}_{\text{FSM}}(j\omega)$ (left) and characteristic loci of the loop gain $\tilde{L}_{\text{FSM}}(j\omega)$ (right).

4.3.3 Tracking error

The tracking performance of the Air-LCT system is evaluated by analyzing the measured closed-loop tracking error at the FD. Based on integrated opto-mechatronic dynamic modeling during the design phase of the Air-LCT system (the details of this modeling approach are currently in preparation for a separate journal article, Kramer et al.), it is expected that aircraft vibrations, sensor noise, and atmospheric turbulence effects are main contributors towards observed tracking error on the FD. This was partly already confirmed in laboratory experiments, vibration test flights and ground-to-space tests.¹ Although a complete validation of the performance predictions using the presented flight-test results is beyond the scope of this paper, an initial comparison between the predicted and measured performance is provided.

Due to variations in atmospheric turbulence conditions, aircraft vibrations and controller settings, the observed tracking error is different for each test-flight and optical link. The tracking error has been analyzed for most of the links, but only three representative and interesting links are compared in detail. The specific links were selected based on the measured aircraft vibrations (using the gyroscopes and accelerometers on the OB), while excluding the links where significant instabilities were still present with controller A and B:

1. **Aircraft glide mode:** Link MeasNr 136 was measured while the aircraft performed a glide maneuver by reducing the throttle power of the aircraft. This resulted in low aircraft vibrations and also prevented the induced tracking error instabilities when using FSM controller B.
2. **Low aircraft vibrations:** Link MeasNr 143 was measured during very stable conditions of both the aircraft vibrations and atmospheric turbulence. With FSM controller C, this resulted in the lowest observed tracking error during the complete test campaign.
3. **Moderate aircraft vibrations:** Link MeasNr 151 was measured during moderate aircraft vibrations with FSM controller C, while significant turbulence was observed in the optical link.

Link MeasNr 150 contained **high aircraft vibrations**, but as this link was used for performance validation of the pointing estimator (see Section 4.2.2), it did not include representative tracking error data during high aircraft vibrations. This link is therefore included in the comparison of aircraft vibrations, but excluded from the FD tracking error comparison.

A comparison of measured aircraft vibrations during the different flight links is shown in Figure 11. The aircraft vibrations excite the OB in six degrees-of-freedom, but only the rotational vibrations are shown for clarity. The measured vibrations by the gyroscopes are converted to a Power Spectral Density (PSD), where each line is the average result of a single minute of measurement data and the different colors represent the different links (i.e. for each link six minutes of measurement data is shown). The data clearly shows variation in OB vibration levels at frequencies below 50 Hz, ranging from low (MeasNr 136 and 143), to moderate (MeasNr 151), and high aircraft vibrations (MeasNr 150). At frequencies above 50 Hz, no clear difference is observed, as the PSD is also dominated by gyro sensor noise and aircraft engine resonance peaks.

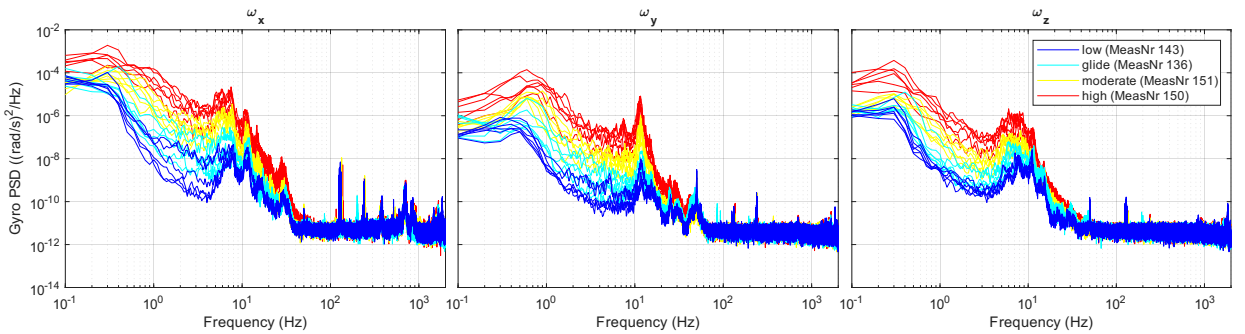


Figure 11. PSD of rotational OB vibrations measured with the three gyroscopes during different flight conditions. The vibrations levels are shown for low vibrations (MeasNr 143), aircraft glide mode (MeasNr 136), moderate vibrations (MeasNr 151) and high vibrations (MeasNr 150).

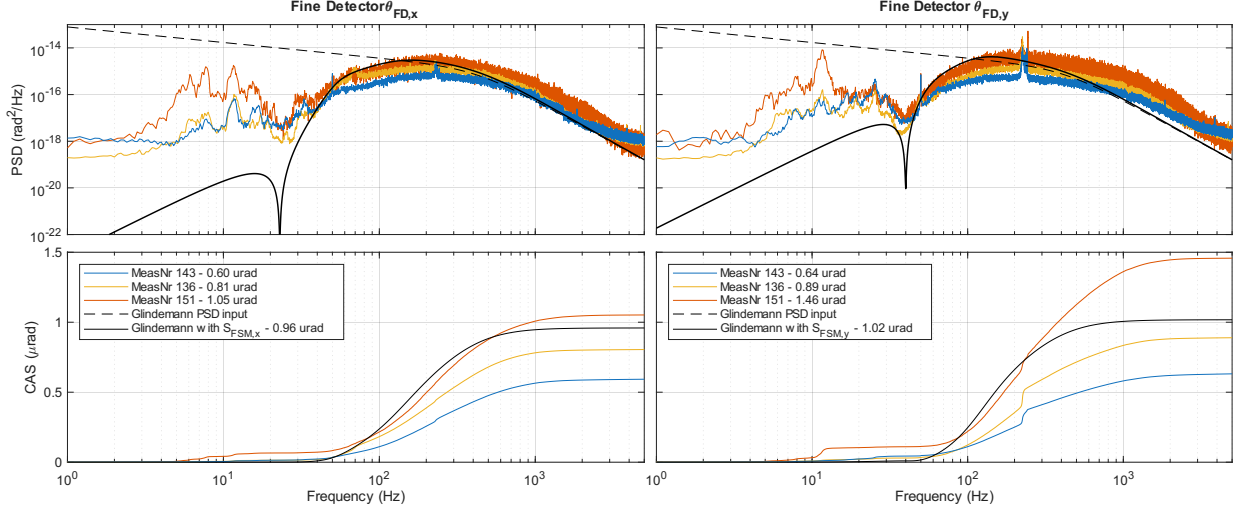


Figure 12. PSD of FD tracking error during low aircraft vibrations (MeasNr 143, controller C), aircraft glide-mode (MeasNr 136, controller B) and moderate aircraft vibrations (MeasNr 151, controller C) compared with the PSD of the Glindemann model.

The FD tracking error of the three different links are compared by computing the PSD and Cumulative Amplitude Spectrum (CAS) of the recorded time traces and are depicted in Figure 12. The left- and right column in this figure depicts the x - and y -axis of θ_{FD} respectively. The observed tracking error for the individual axis ranges from 0.6 to 1.5 μrad RMS and can be roughly divided into two frequency ranges. The low frequency range (<40 Hz) is dominated by aircraft vibrations, which are suppressed by the high feedback gain of the FSM control loop. The vibration peaks around 10 Hz and the variation in vibration level can be clearly linked to the aircraft vibrations as shown in Figure 11. The high frequency content of the FD PSD (>40 Hz) is dominated by atmospheric turbulence in the optical link, with the exception of a CPA mechanical resonance peak at 225 Hz.

During the system design phase, the turbulence induced tip-tilt effects on pointing performance were estimated using two different models, one being the parametric model as proposed by Glindemann et al.⁷ This parametric model describes a PSD of the expected tip-tilt effects due to turbulence as a function of system and link parameters. The PSD of the atmospheric turbulence Φ_T as function of frequency f is approximated for low and high frequencies with

$$\Phi_{T,\text{low}}(f) = 0.096 \left(\frac{r_0}{v} \right)^{\frac{1}{3}} \left(\frac{\lambda}{r_0} \right)^2 f^{-\frac{2}{3}}, \quad (2)$$

$$\Phi_{T,\text{high}}(f) = 0.0013 \left(\frac{D}{v} \right)^{-\frac{8}{3}} \left(\frac{\lambda}{r_0} \right)^2 \left(\frac{D}{r_0} \right)^{-\frac{1}{3}} f^{-\frac{11}{3}}. \quad (3)$$

The parameters and assumed values are summarized in Table 2. The optical aperture D and wavelength λ are system parameters and the Fried parameter r_0 was derived from atmospheric modeling performed during the design phase. While the system design included a conservative estimate of the dominant turbulence-layer velocity, the velocity parameter v was chosen equal to the aircraft velocity for the comparison with the measurements presented here. Consequently, any additional wind-driven motion of the dominant turbulence layers is not represented by the model. The resulting Glindemann PSD disturbance model is included with a black dashed line in Figure 12. Due to feedback control, the contribution of atmospheric turbulence on FD tracking error is modified with the FSM sensitivity $\tilde{S}_{\text{FSM}}(s)$ as presented in Section 4.3.2. The resulting predicted contribution of atmospheric turbulence to tracking error is shown in black in Figure 12. The atmospheric disturbance is reduced at frequencies below the FSM control bandwidth, while at frequencies above the control bandwidth a slight amplification occurs due to the waterbed effect. Comparing the measured tracking error with the

error contribution predicted by the Glindemann model indicates that the tracking error above 40 Hz can be largely attributed to atmospheric turbulence. Although detailed measurements of the turbulence profile were not available during the measurement campaign, the variation in measured FD tracking error across the different links exhibits a consistent trend. In particular, $\theta_{FD,y}$ shows an elevated spectral amplitude in the range of 0.5-5 kHz. This excess power suggests that the relative velocity between the optical beam and the turbulent layers is larger than represented by the model. Consequently, the turbulence-induced tip-tilt spectrum is shifted toward higher frequencies than predicted when using v equal to the aircraft velocity.

Table 2. Parameters used for the turbulence disturbance model based on Glindemann et al.⁷

symbol	parameter	value
D	Optical aperture	100 mm
λ	Wavelength	1064 nm
r_0	Fried parameter	0.43 m
v	Velocity	175 m/s

The analyzed FD tracking error of the different links demonstrates robust tracking performance across varying link conditions. Stable tracking enabled uninterrupted communication in multiple links at a data rate of 1.8 Gbit/s. Aircraft-induced vibrations at low frequencies are effectively suppressed to below 0.1 μ rad by the high feedback gain of the FSM control loop, while high-frequency vibrations are mitigated through passive vibration isolation and the optimized mechanical design of the Air-LCT demonstrator. Consequently, the residual tracking error is dominated by atmospheric turbulence, which varies with flight and atmospheric conditions. The measured turbulence-induced disturbances exhibit characteristics similar to those predicted by the Glindemann model, although further analysis is required to establish a more representative turbulence model for airborne laser communication links. In addition, a detailed investigation of the received power fluctuations at the counter terminal is required to determine the FSM control bandwidth that optimally balances disturbance rejection and turbulence-induced pointing errors, thereby maximizing end-to-end pointing performance for optical communication.

5. CONCLUSIONS

In this paper the flight test results are presented of an airborne-to-GEO optical communication demonstrator. In the flight test campaign, a total of 33 link opportunities in 9 test flights were planned and acquisition and tracking was achieved in 31 links. This resulted in valuable link data for analysis and input for future design of airborne LCTs. This paper presents results on the pointing, acquisition and tracking performance of the Air-LCT. It was shown that the effective implementation of a PAT state-machine and control architecture design led to robust and reliable link acquisition. The measured initial pointing accuracy of the system, which includes the complete system calibration and active LOS compensation, is within 0.5 mrad for both axes, which is well within the total Coarse Detector FoV of ± 3.5 mrad. Furthermore, analysis of the Pointing Estimator performance shows that while receiving blips with 39 seconds interval, the received blips remain within ± 10 μ rad in presence of significant aircraft rotation and vibration of almost a degree RMS, enabling accurate link acquisition and robustness for fades. During flight tests, initially tracking instabilities were observed. It is shown that minor controller updates could completely remove these instabilities. Results of in-flight system identification experiments are shown that investigated closed-loop system dynamics and stability. Finally, the achieved Tracking Error was analyzed. Motivated by in-flight measured vibrations, it is shown that effective rejection of the aircraft disturbances is achieved. Comparison of the residual tracking error with a parametric atmospheric turbulence model indicates that the tracking error is dominated by atmospheric turbulence. The observed tracking error per axis was 0.6 to 1.5 μ rad RMS in the analyzed links, demonstrating robust tracking performance across varying link conditions. This enabled uninterrupted communication in multiple links at a data rate of 1.8 Gbit/s.

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