

Aircraft to Geostationary Satellite Optical Links - First Results from the UltraAir Flight Test Campaign

Thomas Liebig^a, Sjoerd van Kuijk^a, Karen Saucke^b, Thomas Marynowski^b,
Stephanie Straub^c, Erhard Elsaesser^c, Ricardo Barrios^c, Kevin Shortt^c

^aTNO, Stieltjesweg 1, 2628 CK, Delft, The Netherlands; ^bTESAT, Gerberstraße 49, 71522, Backnang, Germany; ^cAirbus Defence and Space, Willy-Messerschmitt-Straße 1, 82024, Taufkirchen, Germany
Author e-mail address: thomas.liebig@tno.nl

Abstract: One of the biggest challenges in free space optical communication is connecting mobile and vibrating platforms over long distances. We developed an airborne laser communication terminal that successfully demonstrated reliable optical link acquisition, tracking and coherent communication between a jet aircraft and geostationary satellite. © 2026 The Author(s)

1. Introduction

Today's optical networks are facing increasing challenges when it comes to resiliency and speed of deployment. With the rapid adoption of AI, optical network architects are rethinking their approach to the future of optical network infrastructure, including the use of free-space optical communication (FSOC) technologies, which expand networks beyond the reach of fiber while providing an additional layer of resiliency. However, FSOC comes with its own challenges, e.g. accurate pointing and tracking between terminals, particularly when those terminals are deployed on moving platforms such as aircraft. The UltraAir project, a partnership between TNO and Airbus Defence & Space GmbH, set out to demonstrate the ability to establish an optical link between an aircraft in flight and Alphasat's TDP-1 terminal, further maturing a capability demonstrated in [1, 2].

For this purpose, the Air-LCT was developed and tested through a series of ground-based tests [3] that culminated in the final airborne tests that took place over the Mediterranean Sea in December, 2025 to the TDP-1 terminal, an established platform for research into satellite-based optical links [4]. Although TDP-1 is based on the CCSDS HDR 1064nm standard [5] (i.e. homodyne BPSK modulation at the modest symbol rate of 2.8125 Gs/s), a flight demonstration to this terminal nevertheless validates the foundational capability that can later be expanded to higher data rates and other optical wavelength. Already, the SDA and ESTOL family of standards [6,7], have laid the groundwork for adopting the terrestrial technologies that can deliver data rates of hundreds of Gbps that can ultimately be applied in this same operational context.

This paper shows an initial analysis of measurements captured during the December 2026 flight campaign from a Dassault Falcon 20 aircraft, during which a total of 31 optical links were conducted over a link range of about 38,000 km to TDP-1. While the analysis provided here is merely a cursory one, it nonetheless confirms the proper functioning of the terminal in flight conditions and validates the measurements taken conform to established atmospheric channel modeling.

2. Setup

The Air-LCT was intended to demonstrate an operational capability and therefore was designed to be installed inside the aircraft cabin (see Fig. 1). The transmit and receive laser signals traversed a custom-made fused silica window that was installed in one of the aircraft's emergency exit doors. The Air-LCT is composed of the optical head and 3 half height 19" racks that mount peripheral electronics, controllers, PC's and the laser interlock system. The system was primarily managed by one operator inside the aircraft while the link execution was performed automatically.

Inside the optical head, the optical bench is mounted to a baseplate, which is suspended on four springs on a stiff frame that is connected to the cabin floor (see Fig. 1), thus reducing vibrations generated by the aircraft. Following a monostatic design where the Tx and Rx signals share the terminal entrance optics, the optical bench is built around a CPA (Coarse Pointing Assembly, TNO custom) that enables a ± 8 deg field of regard in azimuth and elevation and a telescope with an expansion/compression ratio of 10. To correct for atmospheric and aircraft induced pointing errors, a fast steering mirror (Optics In Motion part #OIM5001) is implemented in the common Tx/Rx optical path between the telescope and the other conditioning optics.

In the transmit optical chain of the system, a laser beam originates from a fiber coupled seed laser (Coherent Mephisto) that is connected to a custom-built high power optical fiber amplifier from Amonics before entering a polarization beam splitter, some additional conditioning optics, and finally the telescope. The outgoing beam is circularly polarized with a max. avg. power of 20 W and is modulated in amplitude and phase as per [5] with acousto- and electrooptical modulators (custom modbox iXblue). The uplink data is generated by a custom electronic module developed by TESAT that used a continuous 0-bit pattern at the nominal net data rate of 1.8 Gbps and applies the standard forward error correction coding specified in [5].

In the receive direction, after exiting the telescope and traversing the conditioning optics and Tx/Rx polarizing beam splitter, the received signal is split between the acquisition camera (Xenics XSW 640) and tracking sensor (TNO custom quad cell sensor, sensitivity <-60 dBm) respectively. The Air-LCT is a data uplink-only terminal driven by the anticipated use case and the focus on the characterization of the optical channel.

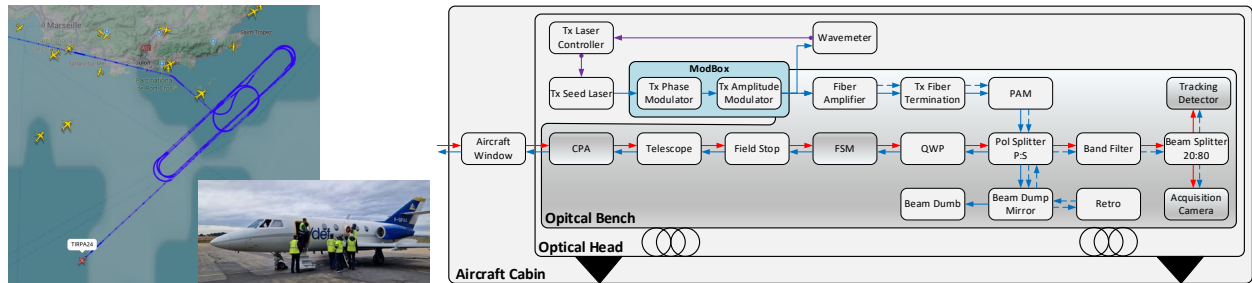


Fig. 1 Left: Falcon 20 aircraft and typical flight pattern during optical link testing; Right: Block diagram of the primary optical components of the Air-LCT

3. Results

Nine test flights were performed between 6 and 16 December 2025 in a flight area above the Mediterranean Sea, south of Cannes (see Fig. 1). From there, Alphasat appears at an elevation angle of about 37 deg at a distance of about 38,000 km. For these flights, 33 link opportunities were planned that resulted in 31 links where the Air-LCT achieved tracking. This resulted in a total of more than 200 minutes of telemetry during tracking. During the two links that were not successful, dense, overhead cloud coverage was observed. Depending on the specific test goal of each link, test parameters like aircraft speed (nominal ground speed 600 km/h), altitude (nominal 10 km), link duration (6 min to 14min), etc. were varied. In addition, the Air-LCT can continuously vary its Tx divergence between 10 μ rad and 40 μ rad during operation to optimize link budget, which was also successfully tested.

For the Air-LCT Tx settings of 12 W avg. power (free space) and 10.1 μ rad divergence (half-angle, e^{-2}), typically about -40 dBm (see Fig. 2) are received by TDP-1 into its entrance aperture. At the same time, the Air-LCT receives about -43 dBm into its entrance pupil at the nominal TDP-1 settings of 2.2 W avg. power and about 7 μ rad divergence. In seven links, the OPLL on TDP-1 was activated to test the homodyne communication. Bit error free communication was achieved several times with a max. continuous duration of about 2 min (limited by deep fades).

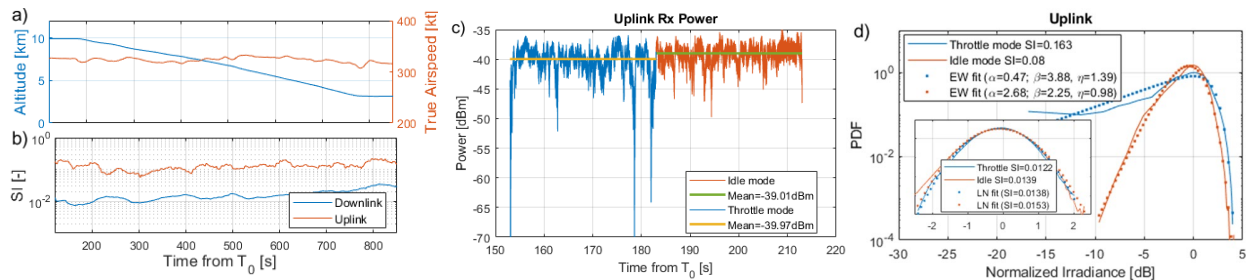


Fig. 2 (a) Aircraft altitude and true airspeed. (b) Downlink and uplink scintillation index. (c) Uplink Rx power for 120 s around the time where the aircraft engines transition from throttle to idle mode. (d) PDF of uplink and downlink Rx optical power.

Fig. 2 shows a preliminary analysis of the data set collected on 2025-12-13 with T_0 at 15:38:00 UTC. This link was selected as its duration is ca. 14 min and covers a wide range of aircraft altitude conditions. Initially, the aircraft flew at a 10 km altitude with nominal speed and throttle, then the throttle was reduced to about 70 % approximately

180 s after T_0 . With the aircraft engines in idle, the aircraft descended to about 3 km altitude, when engines were turned back to nominal throttle. Fig. 2(a) shows the altitude and true airspeed (TAS) during the whole link duration.

In Fig. 2(b), it is readily seen that the scintillation index (SI), averaged over 30 s, in the downlink increases as the aircraft descends, indicating a larger portion of atmosphere being traversed by the optical wavefront reaching the Air-LCT. Nevertheless, the SI lays inside the range between 0.056 and 0.219 in the uplink with no clear trend that correlated with the aircraft altitude. This scenario suggests the measured uplink SI is dominated by the turbulence conditions created around the aircraft skin - namely the aero-optics effects - and the platform induced pointing errors. These are particularly visible in Fig. 2(c), where a trace of the uplink received optical power is shown, for 30 s before and after the engines transition from nominal throttle to idle. Moreover, it is apparent that the uplink received optical power varies between +5 and -7 dB around its mean value, for both nominal throttle and idle speeds, with the distinction that in the nominal throttle mode there are additional deeper fades, which could be associated with a stronger micro-vibration regime.

In addition, an initial assessment of the received power probability density function (PDF) has been performed, both for downlink and uplink as presented in Fig. 2(d). The PDF from experimental data is shown with solid lines, while the best fit for two theoretical models are shown with dots. Most noticeably, a distinct skewness is observed with the left tail of the PDF having a shallower slope than the right tail of the distribution. This stems from the detrimental impact of deeper fade events, which could be attributed to atmospheric beam wander and mechanical pointing jitter. Particularly, Fig. 2(d) highlights the weight the extremely deep fades during nominal throttle speed have over the left tail of the PDF. In such scenarios, the asymmetries of the received power data PDF cannot be captured by a single parameter model like the LN PDF, and here a best fit for the exponentiated Weibull (EW) PDF [8] is shown. As evidenced by the plots, the EW PDF is able to produce the shape of the experimentally measured optical power PDF in the uplink. Finally, as shown in the inset of Fig. 2(d), the downlink analysis has revealed a very stable scenario, where statistics can be very well described by a lognormal process.

4. Conclusion and Next Steps

The flight tests have demonstrated that the Air-LCT can establish and maintain optical links with Alphasat in mid-flight. While specifics of the implementation are a result of the choice of heritage hardware, more than 200 min of optical tracking provides valuable insights into the design and operation of an airborne terminal. Measurements of the optical channel can be used to validate atmospheric models and predict the real-world performance of FSOC implementations for this application. The key takeaway here is that the data indicates there is a minor influence in the uplink coming from the aircraft flying altitude, and the channel characteristics are dominated by the platform's microvibrations and turbulent boundary layer around the aircraft skin. Thus, an uplink to a GEO satellite does not require additional measures to support different flying altitudes. In the context of non-terrestrial optical networks, these results provide key insights that will inform the ongoing development of fade mitigation strategies at the physical layer and network control plane concepts. Following a more detailed analysis of the telemetry, miniaturization of the terminal, adaption to SDA/ESTOL standards and links with terminals in Low Earth Orbit are envisioned.

Acknowledgments

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