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Development and demonstration of an airborne laser communication system

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ABSTRACT

Free-space optical communication (FSOC) offers numerous advantages such as high-speed and secure connectivity that will complement and challenge traditional radio-frequency (RF) communication. It comes with specific challenges such as very precise pointing in the presence of atmospheric turbulence and platform vibrations. Within the UltraAir project these are driven to the extreme with the ambition to develop a demonstrator of an airborne laser communication system compatible with the SpaceDataHighway (EDRS). While the system will be integrated into an aircraft typically travelling at 800km/h at an altitude of 10km, the counter terminal is Alphasat's TDP-1 in geostationary orbit, resulting in link distances of up to 40000km. This paper will report on a number of design challenges as well as on the first demonstration results of the ground to space optical link testing at 2.8Gbps from the ESA Optical Ground Station (ESA OGS) on Tenerife.

Keywords: free-space optical communication, airborne laser communication, Air-LCT, ALCOS, EDRS, Space Data Highway

1. INTRODUCTION

With the ever-growing demand in bandwidth, (free-space) optical communication (FSOC) becomes attractive in many domains and applications complementing or challenging radio-frequency (RF) communication technology. One of the applications that is significantly distant from achieving commercial implementation is connecting mobile platforms. Connecting a jet aircraft to a geostationary satellite is particularly challenging, due to platform vibrations, relative motion and its link distance of about 40000km [1, 2]. While this type of link had been successfully demonstrated with the LOLA program for the French Ministry of Defense in 2006 [3], the technology is not commercially available. Therefore, TNO was subcontracted by Airbus Defence and Space with the project called UltraAir to develop a laser communication terminal that could demonstrate the optical link between an aircraft and the geostationary SpacedataHighway, owned by Airbus. The project is supported by TESAT, who developed the optical counter terminal TDP-1 and operates the optical ground station T-AOGS aiding the ground to space testing.

The aim of this paper is to report on the design and development of this airborne terminal demonstrator referred to as Airborne Laser Communication Terminal (Air-LCT). Specifications of the Air-LCT design and interfaces are described, including vibration isolation, the optical system as well as the laser system. First test results of the ground to space test campaign between TDP-1 and he Air-LCT performed in fall 2024 are shared.

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2. AIR-LCT INTERFACES

The primary user requirement for the Air-LCT is to demonstrate the capability of establishing and maintaining an optical communication link between a geostationary satellite and a jet aircraft in a normal flight scenario (i.e. speed about 800km/h, altitude of about 10km, etc.) with a link distance of about 40000km. In addition, the characteristics of the optical channel will be measured. Therefore, TDP-1 was chosen to be the optical counter terminal as it is an ideal testbed, representative for the geostationary satellite network. To be compatible to this network, the Air-LCT has to comply to the requirements specified by the HDR-1064nm Orange Book [4]. This comprises the requirements for the optical and data interface, as well the procedure for the acquisition of an optical link.

2.1 Geostationary terminal – TDP-1

A precursor to the optical terminals aboard the commercial EDRS satellites is TDP-1, a technology demonstration payload carried by Alphasat (Inmarsat-4A F4), that operates in a geostationary orbit at a longitude of 25 degrees east since 2014. Due to its proven reliability, versatility and availability for research [5, 6], it was selected as counter terminal to the Air-LCT for all optical link experiments within the project. TDP-1 was developed and built by TESAT in compliance to the HDR-1064nm Orange Book [4]. It is an LCT-135 (see Figure 1) with an aperture diameter of 135 mm, comprising a 1064 nm laser source and using homodyne Binary Phase Key Shifting (BPKS) modulation to transfer up to 1.8 Gbps of data. The optical signal received by TDP-1 is measured at 25 kHz and can be transferred, instead of user data, in full data rate to ground via the TDP1-Ka-band system.

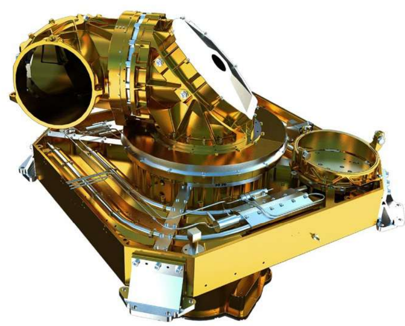

Figure 1. TDP-1 laser communication terminal (LCT) of Alphasat.

2.2 Airborne platform

The airborne platform was chosen to be a Dassault Falcon 20 (see Figure 2), as it complies with the intended operational flight parameters (speed, altitude, etc.), is spacious enough to host the demonstrator and as importantly, is available for these kind of test activities by the aircraft operator “Aviation Défense Service” (AVdef) based in Nimes (France).

Figure 2. Falcon 20 A/C operated by Avdef (left); OH mass model installed inside A/C cabin for vibration test flight (right).

3. AIR-LCT DESIGN

Together with the selection of the aircraft platform, an important architectural decision had to be made on the mounting position of the Air-LCT. A hemispherical coverage of the Air-LCT would be most desirable for the potential use case as well as to not limit the flight patterns for the final verification flight testing. This would require for some portion of the Optical Head (OH) of the Air-LCT to protrude the airframe. The OH is that part of the system that contains the optics, sensors and actuators as well as the laser emitter. To read-out, drive and control the Optical Head components, electric and electronic modules are required that are mounted in separated electronic rack(s) (see Figure 3). While it is rather obvious that the electronics rack will be mounted within the airframe/cabin it is thus less desirable for portions of the optical head. However, at the beginning of the development of the Air-LCT, its mass, volume and the design of the vibration controlling system were rather uncertain. Together with the very limited availability of large electro-optical pods (diameter about 600mm) that can achieve pointing errors of a few microrad and the impact of most likely having to modify an aircraft to integrate such an electro-optical pod for the flight verification testing, it was concluded that a protruding optical head solution would pose too large of a risk to the project mainly in terms of cost and schedule. Therefore, an alternative concept was devised, that keeps all the Air-LCT components within the airframe of the aircraft. This means that both the received and transmitted laser light would need to pass through a window of the aircraft, hence the designation “window flight demonstrator” (WFD) of the Air-LCT. While this system configuration allows for a more straightforward integration of the Air-LCT, it requires a custom A/C window that on the one hand is approved for safe operation of the aircraft and on the other hand is of sufficient optical quality, having low wave front error (WFE) and optical coatings applied that reduce the transmission losses for the Rx and Tx beam while rejecting a large portion of the solar background. Also, with this configuration, the pointing range of the system is reduced to about ±8deg in azimuth and elevation relative to the nominal pointing direction of the Air-LCT. The latter is chosen such, that optical links can be achieved from the site selected for ground to space testing (ESA OGS Tenerife) as well as when performing verification flight tests over the Mediterranean Sea.

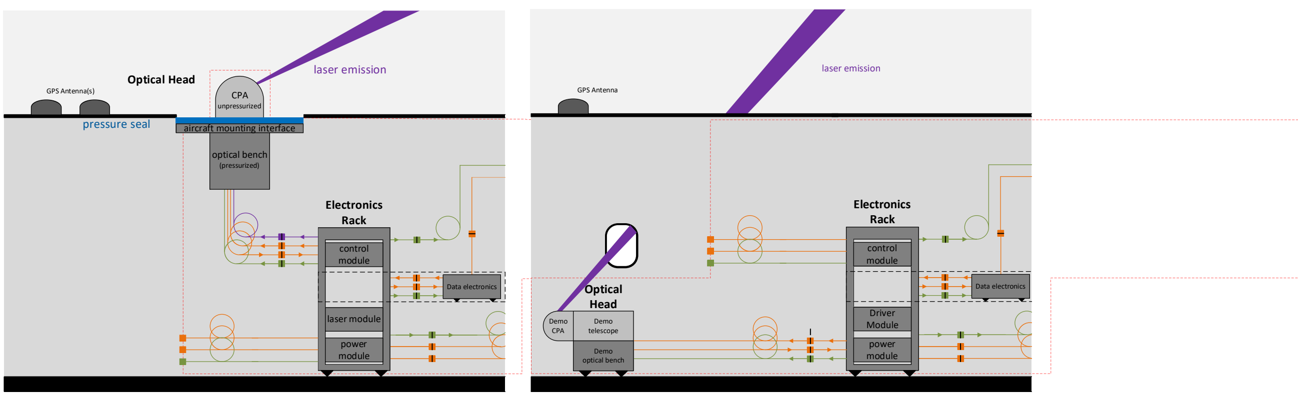

Figure 3. Air-LCT architecture for ideal use case (left); Air-LCT Window Flight Demonstrator (WFD) architecture for technology demonstration (right).

3.1 Design approach

The design of the Air-LCT was guided by two primary technical budgets. One is the link budget, that essentially sums up all optical gains and losses along the optical link path and thereby identifies the link feasibility and robustness in terms of link margin. The other is the pointing budget. It aims to capture all contributors of detecting the systems pointing error with respect to the incoming beam as well as those of the beam transmitted towards the counter terminal. Both budgets are highly intertwined since any Tx pointing error, based on the Rx pointing error in open or closed loop and including atmospherically effects, results in a loss of received optical power at the counter terminal. This however, requires a certain amount of optical power entering its aperture to be able to detect and thus acquire and track the optical link itself. This optical power can be scaled by increasing the emitted power of the Tx beam by increasing its laser output power, reducing the transmission loss of its optical system, the wavefront error, etc. Finally, decreasing the Tx beam divergence will result in an increased peak irradiance that will only translate into a higher power received by the counter terminal when the Tx pointing errors can be reduced accordingly. Thus, finding the correct balance between these budgets and all their derived sub-budgets is rather complex, especially when different use cases (i.e. flight demonstration vs. ground to space test) and atmospherical conditions are considered.

On the other hand, being a demonstrator development there was less pressure on aspects like size power and weight of the system. While these also had to be managed carefully to meet all interface requirements especially that of the aircraft, including for example load limits and EMC/EMI requirements, optimizing them is considered to be addressed during industrialization in the prototype phase.

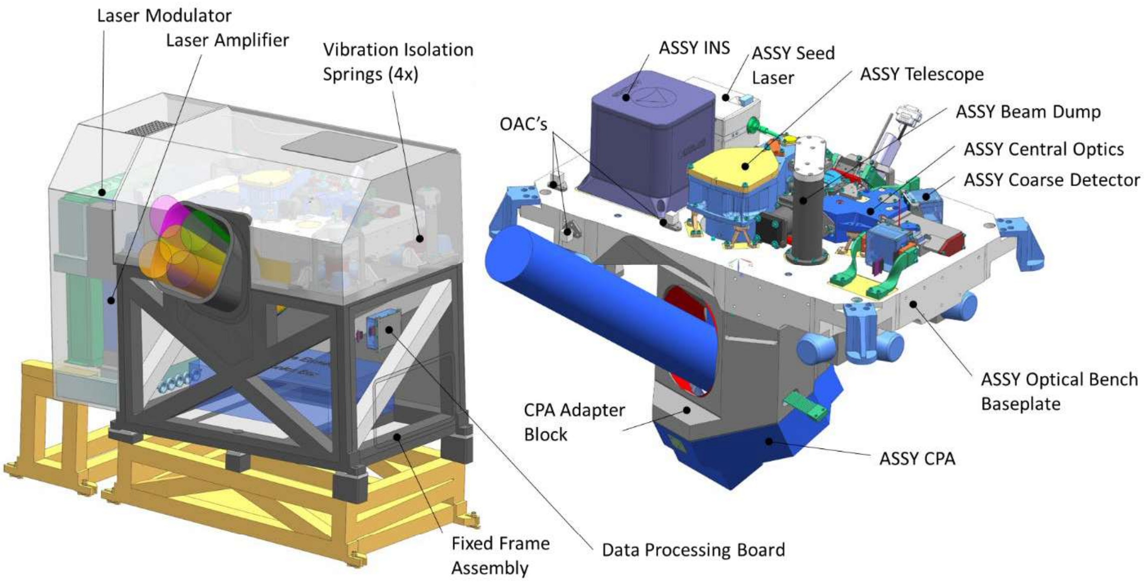

Figure 4. CAD model of the Air-LCT Optical Head (left); CAD model of the Optical Bench suspended inside the OH (right).

3.2 Vibration isolation

Achieving a stable line of sight with sufficiently low pointing errors towards the counter terminal is one of the key tasks common to all laser communication terminals. The main difference of airborne terminals, compared to other LCTs, is the presence of high frequency linear and rotational vibrations (turbulence and motor induced) as well as large stroke, low frequency rotations (several deg/s) due to predominantly roll of the aircraft. Their compensation is critical for the system pointing performance considering the rather small pointing budget of only a few microrad of the Air-LCT.

This is achieved by carefully designing a passive vibration isolation system inside the OH, that dampens the high frequency vibrations (frequency > 250 Hz) by a factor of about 20, in conjunction with an active pointing control that reduces the remaining low frequency component. The passive isolation system is comprised of a solid aluminum optical bench (about 100kg) that is suspended with 4 springs of low Q-factor (high damping) in a fixed frame connected to the A/C floor. The active pointing control system is comprised of an Inertial Navigation System (INS), that measures low frequency absolute pointing (and position) and is complemented by 3 fiber optic gyroscopes for a faster and more accurate pointing readout. Further it is comprised of a Fast Scanning Mirror (FSM) that can stabilize the optical path with a bandwidth of up to 250Hz. With an effective range of ±0.2deg on sky, its range is too small to compensate all the rotational vibrations in flight. Therefore, the FSM is offloaded with a custom Coarse Pointing Assembly (CPA) developed by TNO that also enables the pointing range of the Air-LCT of ±8deg. Once the Rx beam is received by the Air-LCT, the FSM will be controlled by the optical feedback of the Coarse Detector, during the acquisition phase, and the Fine Detector, rather than by the INS and gyros.

In order to achieve the very low pointing errors, the vibration isolation was modelled and verified by test in several steps along the development. Starting with a 1D model, it became apparent that resonances in the fixed frame suspending the

Optical Bench inside the OH will have critical impact on the pointing performance. Next to that, it is unclear on how to extrapolate from 1D to 3D in order to assess actual system performance for example on the effects of cross-coupling between linear and rotational vibrations. In consequence TNO developed the Dynamic Optical Performance Evaluation (DOPE) model to simulate the dynamic behavior of the Optical Head in 3D. With this model and the experience with topology optimized high dampening spring assemblies [7], it was possible to derive the desired specifications for Q-factor and eigen frequencies of the springs suspending the optical bench in the fixed frame to achieve a cut-off frequency of about 10Hz for rotational frequencies. With these spring parameters identified, commercially available springs were selected. Since their properties were not accurately specified, a small batch was ordered and qualified during a dedicated vibration test. Later a "vibration test flight" was performed in 2021 to verify the vibration isolation performance and quantify the vibrations experienced by the Optical Head of the Air-LCT. Then, a mass representative, but simplified model of the Optical Head of the Air-LCT was integrated in the Falcon 20 aircraft (see Figure 4->4?) to record vibrations on the floor as well as on the suspended Optical Bench (mass model). The measured vibrations on the OB were combined with a DOPE model of the opto-mechanical system mounted on it to quantify the system pointing performance. The results confirmed the performance of the designed passive vibration isolation model and thus created confidence in the pointing budget and allowed the development to continue.

3.3 Optical system

At the beginning of an optical link the terminals are pointing "open loop" towards each other based on a prescribed trajectory of the counter terminal and the knowledge of the terminals own position and orientation. In the case of the Air-LCT, the attitude knowledge is obtained by the INS complemented by the optical gyros. Its output is used to control the Fine Scanning Mirror (FSM). While it has a high control bandwidth of about 250Hz its total stroke is limited. To achieve the required optical pointing range of the Air-LCT and to compensate the large stroke vibration inside the A/C, the FSM is continuously offloading its stroke to the Coarse Pointing Assembly (CPA) shown in Figure 5 with a bandwidth of about 10Hz. The CPA has an on-sky optical pointing range of about ±8deg in azimuth and elevation.

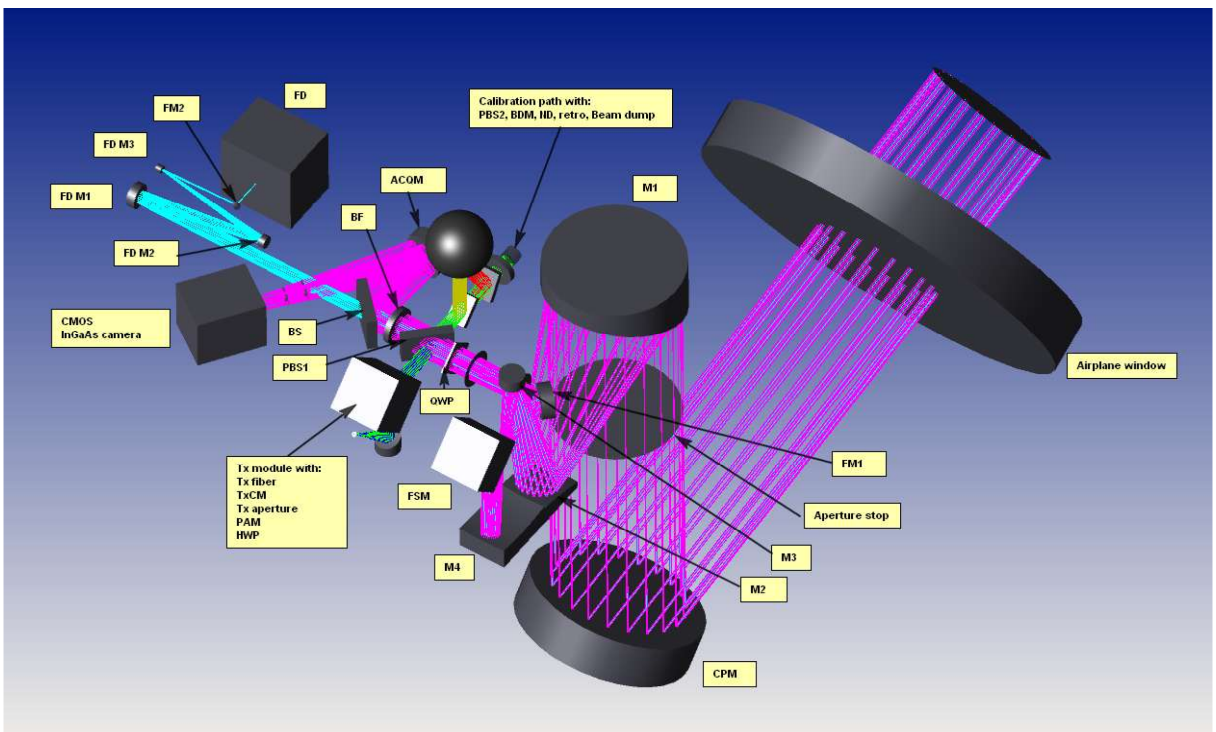

Figure 5. Optical system of the Air-LCT.

By carefully designing the spiral parameters, this initial “open loop” pointing is accurate enough for the Air-LCT to receive “blips” from TDP-1 during acquisition enabling a beaconless acquisition. They are generated, when the Tx beam of TDP-1 crosses the Air-LCT aperture on its spiral path. The CPA having a clear aperture of 160mm directs the incident laser beam towards the telescope having an entrance pupil of 100mm and consisting of four AR coated aluminum mirrors (M1 to M4) that were diamond turned, MRF polished and AR coated by TNO to achieve the demanding specifications derived from the WFE (< 110nm RMSi) and transmission budget (>75% for Tx and >65% for Rx). For tolerance control and simplified alignment, M2 and M4 were manufactured on a common substrate. The telescope demagnifies the incoming Rx beam to 10mm diameter at the FSM. Behind the FSM a quarter wave plate (QWP) transforms the incoming circular polarized light into linear polarized light. Since Rx and Tx are defined to have respectively right and left handed circular polarization, they transform into s and p linear polarization at the polarization splitter (PBS1) behind the QWP. PBS1 separates the Air-LCT Tx and Rx light. While the Rx light is transmitted through it, the Tx light is reflected off by 90deg into the PAM assembly. It holds the high power fiber, the Point Ahead Mirror (PAM) and a Half Wave Plate (HWP) to match the linear polarization of the Tx beam with the polarization beam splitter PBS1. The high power polarization maintaining fiber deliverers the single-mode 20W laser beam from the laser amplifier. It is mounted on a leaf spring assembly that enables continuous adjustment of the Tx beam divergence from 10µrad to 40µrad (e^{-2} half-angle) on-sky by changing the distance between the fiber facet towards the collimating mirror TxCM with minimal lateral displacement. To calibrate any residual displacement, as well as the absolute pointing of the PAM, thereby the coalignment between Rx and Tx beam, the Air-LCT provides an optical path for an internal calibration that reflects the portion of the Tx beam that is transmitted at PBS1 back into the Rx channel via a retroreflector. Behind PBS1 the light is directed towards the beam splitter BS that splits the received light towards the Coarse Detector in reflection and in transmission towards the Fine Detector (FD) with a ratio of 20:80. For both detectors an imager creates a spot image of the irradiance pattern entering the Air-LCT entrance pupil. The FD imager is more complex, consisting of 4 mirrors similarly produced to those of the telescope, and has a focal length of 1m to produce a spot diameter of about 70µm on the FDs four quadrant diode. While the diode is an off-the shelve product, its analog readout circuit and digital processing have been developed by TNO to achieve the desired SNR and suppress straylight and background radiation. The FD has an on-sky Field of View (FoV) of 50µrad with a linear range of about 8µrad and an error of determining the pointing of the incident beam of about 3.7µrad (3σ) for the static error sources and about 2.7µrad (1σ) for the dynamic contributors when in tracking. The FD provides the optical (pointing error) feedback for the FSM to achieve closed loop optical tracking of the light received from TDP-1. With its very limited angular range though, the FD can practically not acquire an optical link, since the initial “open loop” pointing error can exceed 1mrad. This, on the other hand can be achieved by the Coarse Detector that is based on a Xenics XSW640 camera and has an on-sky FoV of 0.2deg in combination with its imager and of course the telescope.

3.4 Laser system

From the link budget the need for a transmit beam with a single mode beam shape (BPP<1.05) and laser power of 20W was derived. In addition, a very narrow laser linewidth of about 1kHz at 1064nm is required for communication with phase modulation according to [4] to enable homodyne amplification. The combination of these requirements showed impossible to be met by commercially available laser systems. Therefore, the Air-LCT laser system is composed of a seed-laser, modbox (comprising the modulators for amplitude modulation at about 1MHz and 1.76MHz and phase modulation at about 2.8GHz of the transmitted beam) and a custom developed laser amplifier. It is capable of delivering up to 20W (continuous wave) at the narrow laser line width, single mode and linear polarization provided by the SEED laser. While the SEED laser is mounted on the vibration isolated Optical Bench to reduce the introduction of optical phase noise into the Tx beam, the amplifier is mounted onto the fixed frame. Therefore, it was qualified for compliance to the vibrations expected when mounted inside the aircraft.

Ultimately, the laser power is limited by Stimulated-Brillouin Scattering (SBS), a non-linear optical effect that highly amplifies counter propagating signals inside the optical fiber potentially leading to its destruction. To reduce the fraction of laser light reflected back into the fiber at the optical interface between the fiber and free space an end cap was used that also reduced the intensity at the interface and thus providing sufficient margin with respect to the Laser Induced Damage Threshold (LIDT).

4. GROUND TO SPACE TEST CAMPAIGN

The target of the project is to demonstrate and characterize the optical link between the Air-LCT when integrated into the A/C and its counterpart TDP-1 in geostationary orbit. However, as one of the risk mitigation activities, two ground to space test campaigns each of about three weeks were planned, the 1st in September and the 2nd in October 2024. For these, the Air-LCT was installed at the ESA OGS on Tenerife (see Figure 6). The Air-LCT successfully demonstrated its capability to transmit and receive the laser bundles at the budgeted power levels and according to their performance specs (e.g. wavelength, polarization, divergence, etc.) in a previous laboratory verification campaign with the Ground Support Equipment (GSE) developed in parallel. With the ground to space test campaign the link and pointing budgets are be verified for the first time by establishing and characterizing optical links with the counter terminal TDP-1, even though in a static configuration. This also requires the correct implementation of all pointing calculations, as well as the acquisition logic and all control algorithms.

4.1 Air-LCT installation at ESA OGS

For the ground to space test campaign the ESA OGS on Tenerife was selected. Not only does it provide a good site for astronomical observation with a lot of heritage in linking with optical satellite terminals, but is the T-AOGS [8] ground station located right next to it. The T-AOGS is operated by TESAT and does routinely establish optical links with TDP-1. This proved to be very valuable with the first links planned between the Air-LCT and TDP-1 as it enabled a gradual transition of the Air-LCT into being able to acquire, maintain and recover optical links on its own. Having experienced operators of the T-AOGS on site including real-time telemetry of the T-AOGS and TDP-1 very much benefitted an efficient test execution. During the campaign, the Air-LCT was installed inside dome room of the ESA OGS next to and independent of its 1m primary telescope. To provide a controlled environment with respect to temperature and humidity, limit access and simplify the measures to achieve laser safety, the Air-LCT was placed inside a tent. Emitting a class 4 laser of 20W with a Nominal Ocular Hazard Distance (NOHD) of 50km a Notice To AirMen (NOTAM) had to be issued to ensure a laser-safe operation of the Air-LCT also with respect to air traffic at the island.

Figure 6. View of the Esa OGS (left); Air-LCT installed in a tent on the floor of the OGS dome room (right).

4.2 First light and test results

The first light from TDP-1 was received on the 1st day (Link 10-09-24 UTC14:10) of the test campaign when receiving blips on the Coarse Detector (see Figure 7). Soon thereafter the optical control loops could be closed to acquire and track the optical links on the Fine Detector (Link 11-09-24 UTC14:50).

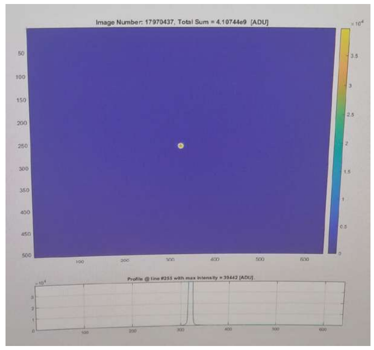

Figure 7. First light received from TDP-1 in the form of a blip on the Coarse Detector.

One of the first tests performed was the verification of the Point Ahead Angle (PAA). It is computed based on the motion of the terminals and relies on an accurate co-alignment of the Air-LCTs Rx and Tx beam that is achieved by the internal calibration mentioned above. When both are correct, the power received by TDP-1 has a maximum at their nominal settings when adding an offset to the PAM. With a rather constant PAA for the ground to space links, the offset was manually applied and observed in real time while performing a hill climbing optimization at the beginning of the closed loop tracking and repeated towards the end. There it was confirmed that there is no unexpected large PAA offset or drift present. With this confirmation a more detailed test ran for about 15min during Link 16-10-24 UTC08:00, where a star shaped PAA scan was performed with radial offsets of 1, 2.5, 5 and 7.5µrad at the nominal Tx beam divergence of 12.5µrad. The PAA variation started in the center at the precomputed nominal PAA and returned to this position after each offset step in order to compensate for Rx power variations during the test. Each PAA step was held for a dwell time of 15s. The results obtained in post-processing of the telemetries of TDP-1 and the Air-LCT are shown in Figure 8. First the Rx signal received by TDP-1, available at a 1kHz sample rate, was filtered using a moving average filter of 1s length (blue signal in Figure 8, top left). From this, the mean Rx power at this PAA setting for the dwell time of 15s was determined (yellow signal). Then the signal at every non-nominal PAA angle was power corrected relative to the actual power at the previous nominal PAA step compared to the power at the start of the test for this PAA.

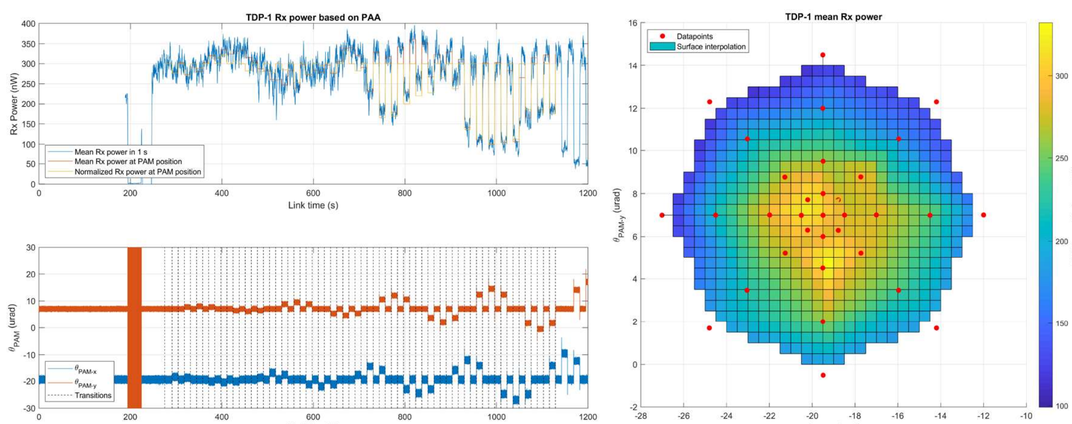

Figure 8. Rx power received by TDP-1 (top left), corresponding PAM angle settings (bottom left), heat map of the received Rx power over PAM angle (right).

While the overall pattern is rather centered, two maxima for the PAA offset can be seen in the heatmap (Figure 8, right); one at about (-1, -1)µrad and one at about (-2.5, 0)µrad relative the nominal PAA, resulting in an increase in TDP-1 received power by about 15%. While the observed loss at the nominal PAA is not considered significant with respect to the Tx power margins observed during the first ground to space links, it will be further investigated to avoid a potential risk for the flight verification tests. One likely explanation could be the non-ideal beam shape of the Air-LCT Tx beam. Also, during the laboratory tests a qualitatively similar beam pattern was observed with a beam profiler.

While the theoretically derived link budgets for the ground to space test campaign were marginal for the Air-LCT uplink, uplink communication was achieved with significant link margins. This led to a test to determine the Bit Error Rate (BER) vs. the Air-LCT Tx power (Link 14-10-24 UTC18:40) shown in Figure 9. There, the TDP-1 Rx power is sampled again at 1s (blue signal, top) and the mean signal (green signal, top) computed for the central 30s of each link segment of 60s length of constant Air-LCT Tx power that is shown in the bottom part of the figure. Starting from the initial setting of 12W in tracking (after about 230s into the link), it is decreased in steps of 1W down to 1W (at about 1050s into the link). At around 500s into the link, it was lost for a moment since it was a cloudy period of the day, but the link was reacquired and the test continued. The BER measured by TDP-1 is represented by the orange signal in the top part of the figure. It was 0 for all Air-LCT Tx powers equal or greater than 2W and increased up to a maximum of about 125 at 1W.

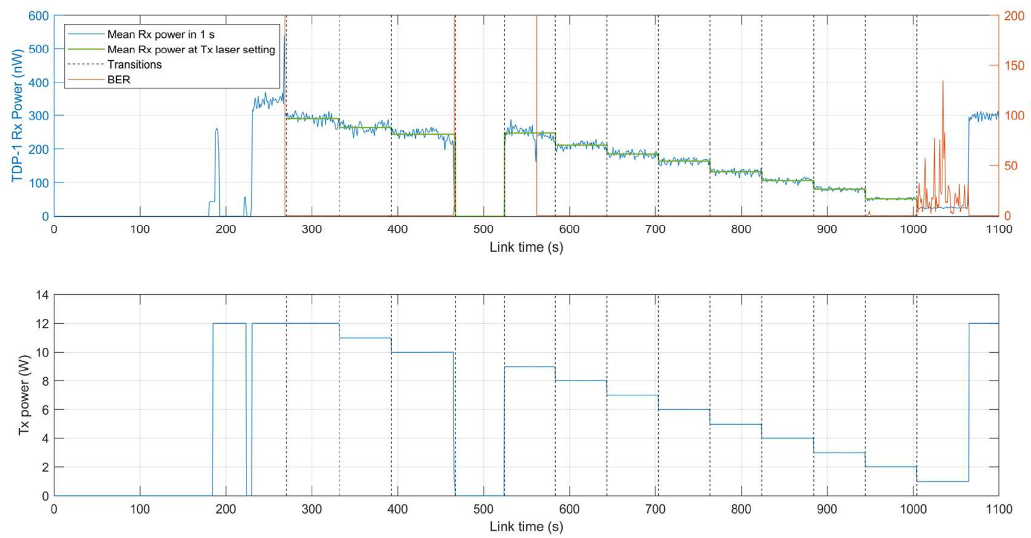

Figure 9. TDP-1 received power and BER vs. time (top) and corresponding Air-LCT Tx power (bottom).

5. CONCLUSION

This paper discussed the development of the Air-LCT and its design; a demonstrator of an airborne laser communication terminal compatible to the SpaceDataHighway (EDRS). It also presented the first results of the ground to space test campaign, linking the Air-LCT with the geostationary TDP-1 terminal from the site of the ESA OGS on Tenerife. This test campaign contributed to the design validation and is an important risk mitigation activity towards the flight verification testing. The findings showed that the Air-LCT system performs significantly better than expected from the link budgets. Closing the optical link between the two terminals on their respective tracking sensors can regularly be achieved with nominal operation parameters of the satellite and starting at 1W of Air-LCT Tx laser power at a divergence of 12.5µrad. Also uplink communication was achieved with significant Tx power margin. With good weather conditions it was practically error free for Tx laser powers of 2W and above. While the ground to space test campaign is still ongoing (i.e. October 2024), the next steps will be a detailed analysis of the obtained data and to update the dynamic control and logic parameters to improve link performance and robustness. Then, the project focus will shift towards preparing for the flight test campaign that is expected to be performed at the beginning of 2025.

ACKNOWLEDGEMENTS

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