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# *SGL Activities with Uplink Communication from Switzerland with the T-AOGS*

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# SGL Activities with Uplink Communication from Switzerland with the T-AOGS

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## ABSTRACT

The Transportable Adaptive Optical Ground Station, which was located at Tenerife (Spain) from 2014 until 2019 was shipped for a refurbishment and several enhancements to Switzerland. Following the refurbishment, a measurement campaign at the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald (Switzerland) was performed, in July/August 2021. The optical counter terminal for the experiments was the TDP1-LCT at the geostationary Alphasat satellite. In the seven weeks of the campaign, measurements for optical uplink communication at a rural site in Europe at an altitude of 900 meters to a GEO spacecraft were gathered. We give an overview of the improvements of the T-AOGS and the actual status after the refurbishment. We present the results of the link activities, e.g. the uplink budget (ground to space) and the dynamic of the atmosphere (scintillations index, number of fades, fade duration).

**Keywords:** optical space to ground communication, atmospheric channel, feeder link, Alphasat

## 1. INTRODUCTION

The improvement of laser communication is driven by different interests. On the one hand, higher bandwidths and capacities for internet applications are needed. On the other hand, a higher amount of data is generated on earth observation satellites and needs to be transmitted to the ground. Optical payloads combine a great number of advantages: the mass, required space and power consumption is less than for RF-payloads due to the narrow beam. Additionally higher data rates are possible due to a higher spectral bandwidth. The main challenge for optical communication is pointing, acquisition and tracking between the two laser terminals, for space to ground links additionally atmospheric turbulences and clouds are challenges [1].

The Technology Demonstration Payload No. 1 (TDP1) is a TESAT payload which combines a Laser Communication Terminal 135 (LCT with 135 mm aperture) with a Ka-Band transmitter for relay of the received optical data via radio frequency to a RF-ground station. The payload, which is located on Europe´s largest telecommunication satellite Alphasat, served originally as demonstration mission of the Space Data Highway EDRS and was launched in 2013. At the beginning of the mission, mainly optical inter-satellite links with Sentinel-1A and Sentinel-2A (Copernicus mission) were performed. The progression of the versatility and improved capabilities have converted TDP1 in a formidable testbed for different applications. For experiments, all LCT telemetries are available with 25 kHz and during operation a real time telemetry can be used. Moreover, the German Space Agency has included in the TDP1 program the use of the Transportable Adaptive Optical Ground Station (T-AOGS) for characterization of the optical channel and improvements of the space and ground segment for potential commercial applications. This ground station is fully operated by TESAT. Currently there is a significant number of partners making use of the complete TDP1 system + T-AOGS in order to validate their new technologies and applications [2].

The T-AOGS was located at the observatory del Teide (Tenerife, Spain) from 2014 until 2019. During the first five years of operation, TESAT performed 59 weeks of link activities along 25 measurement campaigns. As a result, more than 600 optical links with stable tracking and pointing were successfully accomplished. The activities were spread over all times of the day and all seasons for the analysis of the behavior of the optical link under different atmospheric disturbances. The total uplink communication´s duration was in summary 2,486 minutes. This is equivalent to 268 TBit of data transferred [3].

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Figure 1. TDP1 test system (left) and T-AOGS located at Zimmerwald observatory (right).

The transportable capabilities of the T-AOGS makes it the perfect unit for site characterizations. The T-AOGS can be shipped very easy due to its modular design with one single container. The small container that contains the optics is integrated in the operator container, which is the bigger one. For more details see Figure 1 (right). This results in a huge advantage since the same system can be used in different locations, allowing the comparison between them.

Additional advantage of the TDP1 + T-AOGS test bed is that TESAT in cooperation with INM, TECO and GSOC has achieved a very high operational reliability which is exceptional for an experimental system. The operational products and the link planning are performed in cooperation with GSOC, TECO and INM. All procedures have a high level of standardization and the interfaces are fully automated. Currently the T-AOGS is located at the observatory del Teide at 2400 meter altitude. TESAT performed the of the T-AOGS on lower altitude in Zimmerwald, because this is of high interest for potential optical ground station networks.

## 2. T-AOGS TECHNICAL STATUS

After five years of operations, degradation was observered at the ground system. In the receive path a degradation of approx.. 30% could be measured, which was affecting the downlink-communication from satellite to ground station. Therefore, it was discussed and agreed that a refurbishment and enhancement of the ground station was necessary. With this purpose the T-AOGS was transported from Tenerife to Switzerland, where the partner for the envisaged tasks (Synopta) is located.

### 2.1 Refurbishment

The main goal of the refurbishment, from hardware point of view, was the exchange of all parts which are potentially degraded. That were especially the mirrors of the Coarse Pointing Assemblies and the main telescope mirrors. The optical transmit and receive benches are enclosed as good as possible in order to reduce dust deposition on the optics. Nevertheless, during disassembly some other surfaces were found dusty and have been cleaned. During the refurbishment, the performance of the adaptive optics was checked and the deformable mirror showed constant displacements, which had impact on the performance of the actuators. This mirror was also replaced by the same type. Additionally, the mounting concept of the mirrors for the receive coarse pointing assembly (CPA270) was improved. The previous solution caused a static offset onto the wavefront, which could not be corrected by the deformable mirror and forced to disable the control loop of some subapertures. With the new concept, the correction of all subapertures is possible and the performance of the adaptive optics has improved substantially.

### 2.2 Enhancement

One of the main goals of the refurbishment, from the functional and operational point of view, was the maximization of the experiment time with a high quality of the receive signal on space and ground segment. With this purpose a transmit tracking algorithm was to be implemented at the T-AOGS. For transmission of the laser, the CPA100 as well as the CPA270 can be used. Usually the CPA100 is used for transmission, because the power leaving the ground station is higher.

Until 2019 only the Acquisition camera (AS), within the path of the CPA270, was able to track the spot of the received light from the satellite (see Figure *2*). When using the CPA100 for TX, a slave mode was used, but daily offsets and thermal deformations had to be counteracted by manual alignment during the link itself. Since the refurbishment the Transmit Tracking Controller (TTC) Camera is available at the CPA100 for an independent tracking onto the CPA100 RX light. This ensures faster spatial acquisition, and an automated correction of potential thermal drift [4], and thus a reliable reduction of the pointing error, independently of the manual alignment by the operator.

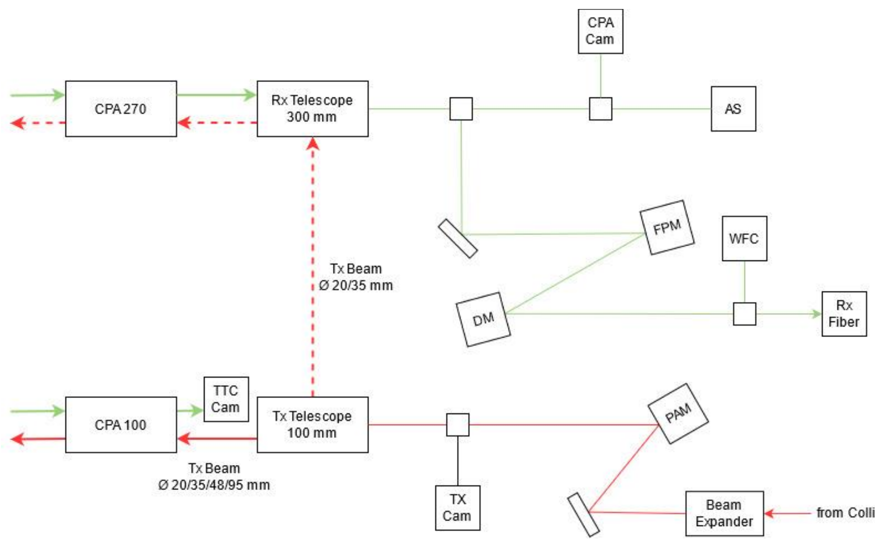


Figure 2. Receive and Transmit path of the T-AOGS.

Furthermore the optical receive bench was prepared for automated fiber coupling. The fiber alignment table was exchanged so that the fiber error can be corrected automatically. In the future an algorithm can be implemented for automatic coupling of the light into the fiber thereby improving the availability of light in the receive fiber, which is currently performed manually by an operator.

Another significant improvement, which also contributes to the increase of link operability time, has been the implementation of a new cooling concept. One of the major operational challenges during the summer season was the high ambient temperature. The optical container needs an internal constant temperature of approx. 23°C, the optimum setting for the alignment. With outside temperatures of above 19°C, the optical container could not be cooled down. The cooling power of the water cooler was not high enough and the over-temperature fuse was activated. During the refurbishment we exchanged the water cooler with one which has a higher cooling power (2.5 kW vs. 11 kW) and decoupled the water cooling of the optical power amplifier from the general cooling system. With this changed setup, we are able to operate the ground station with a tested ambient temperature of 28°C.

# 3. ACTIVITIES IN ZIMMERWALD

## 3.1 Preparation

During the refurbishment and the enhancement in Switzerland, the idea of operating the T-AOGS at an alternative site was discussed intensively. Therefore, a site with existing measures for aviation laser safety was searched. The Zimmerwald observatory (Switzerland) is among others a Satellite Laser Ranging Station to dedicated satellites [8], therefore a laser emergency shutdown concept is available to react on e.g. aircrafts or helicopters. This system was used for the detection of airplanes in the field of view of the T-AOGS as well as the interlock system could be extended with these inputs.

On the map (Figure 3) the relative position of Alphasat at the equator, 25 East, and the two sites of the T-AOGS are marked. The Zimmerwald observatory is located more in the north than the Tenerife observatory, but its position along longitude is closer to the Alphasat position. This means that the distance between the OGS and the satellite is approximately the same from both sites and the elevation angle is only 0.7 different. Only the altitude of the Zimmerwald observatory is roughly 1500 meters lower.

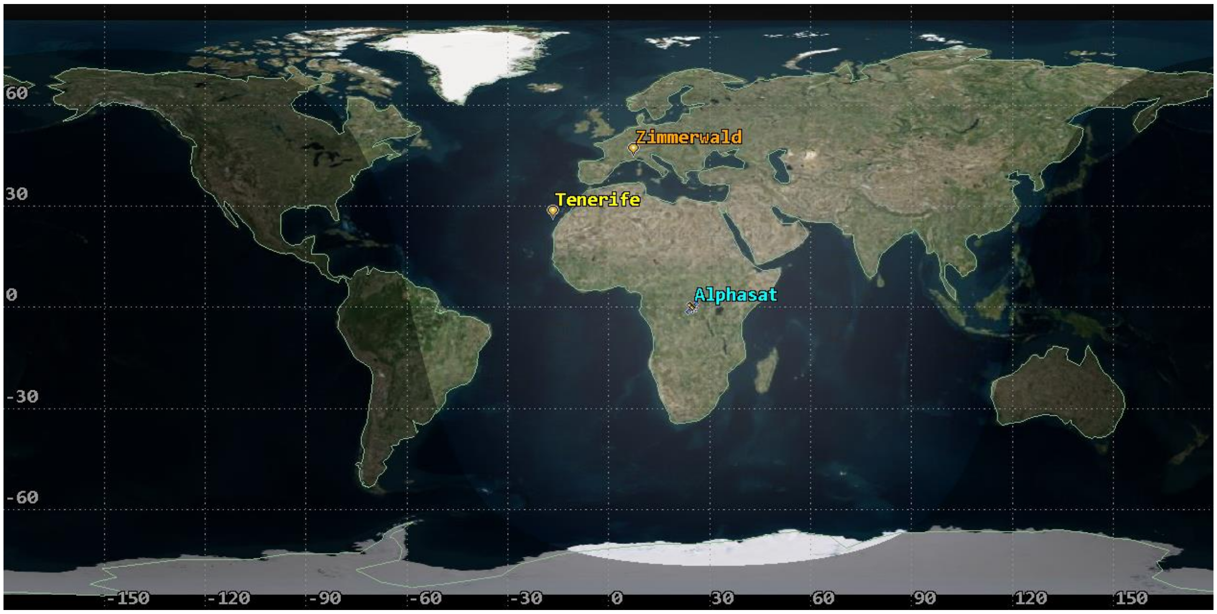


Figure 3. Alphasat position in orbit with T-AOGS positions @ Tenerife and @ Zimmerwald.

The relocation of the T-AOGS from one location to another one, is a well described process and can be performed in a few days. The full preparation of the transport (e.g. fixing moving parts, packing of equipment) is done in one day with two persons. After preparation of the containers, a crane is moving the optical container inside the loading bay of the 20 feet operator container (see Figure *4*, left), which is afterwards loaded onto the truck. The unload process works vice versa at the destination. After transport the setup of the station takes one day, an additional day is needed for calibration checks and measurements and one clear night is a requirement for automatic star calibration to determine the position of the ground station as precise as possible (see Figure *4*, right). After completion of these steps, the first optical link can be performed.

Figure 4. Movement of the optical-container into loading bay of operator-container (left) and calibration procedure of the automatic star calibration (right)

### 3.2 Operation

The setup of the T-AOGS was performed at the beginning of July 2021. The operation was planned as two blocks of three weeks. For all planned links an operational statistic summarizes which links were performed and includes the category of the corresponding issue, if present. The category weather issue states that at least one parameter (humidity, precipitation, clouds, wind or dust) is preventing the operation and the link could not be executed. The category operational issue states that the telecommands were not sent to the spacecraft for a planned link. In case of a technical error, the corresponding system does not behave as expected and the link cannot be performed. This can happen at the space and the ground segment. In the category priority all links are included which were planned but cannot be executed due to a change in priorities on ground (e.g. compliance with german working regulations on working hours, non-expected/planned maintenance, …).

Any of this categories can trigger an issue to be documented in the operational statistics, while multiple categories are possible, which means that the sum of all parameters is higher than 100%. If no issue is present, the corresponding link is “without issue” and is performed by ground and space segment.

Table 1. Operational statistic Tenerife (2014-2019) versus Zimmerwald (2021).

| **Year/ Site** | **Number execution weeks/ days** | **Links planned** | **Weather Issue** | **Operational Issue** | **Technical Issue Space Segment** | **Technical Issue Ground Segment** | **Priority Issue** | **Without Issue** |
|---|---|---|---|---|---|---|---|---|
| Tenerife 2014-2019 | 59/ 260 | 1541 | 31% | 4% | 8% | 10% | 8% | 41% |
| Zimmerwald Jul/ Aug 2021 | 7/ 40 | 338 | 78% | 3% | 5% | 7% | 34% | 17% |

Table 1 shows a comparison of the operational statistic for Tenerife (2014-2019) [3] and for Zimmerwald (Jul/ Aug 2021). At Tenerife a higher number of weeks were planned covering almost all seasons. This implies a significant amount of inputs from the Tenerife location. At Zimmerwald only seven weeks of operation during one summer are used for the statistic. It can be seen that the weather issue corresponds to 78% of the planned links, which is much higher than at Tenerife. During operation, the humidity level was exceeded many times and a lot of clouds were present. The operation times were also reduced at the Zimmerwald observatory compared to other years. The statistics shown here are only representative for the year 2021. The documented weather issues are not representative for all seasons and for all years. One important factor for similar experiments in future would be to schedule enough time for resilient results.

The operational issues and technical issues are as expected and are comparable with Tenerife. For the operation on other sites, the system does not change and the same amount of operational and technical issues are expected. Since the T-AOGS was refurbished, most of the links not performed were related to the remaining issues. The priority issues are 34% and much higher than before. During operation at Zimmerwald we planned a high number of links which couldn´t be executed by the team on site. The idea was to check the weather one day in advance and plan the corresponding shifts using this information. This leads to a high number of links which were planned, but not executed on purpose. In the end, 17% of the planned links could be executed.

During the campaign, several tests and experiments were performed. One of the main goals of the activities was the partial commissioning of the T-AOGS. The transmit path was already fully refurbished and the new transmit tracking algorithm needed to be tested with different settings. The adaptive optics and the fiber coupling were not finished due to missing parts. This work was finished after the Zimmerwald campaign before going to Tenerife. Therefore the chacterization of the site was performed as much as possible with the capabilities of the T-AOGS at this point.

In addition to the site characterization, the communication performance was analyzed. The focus during the measurements was on the uplink communication (from ground to space), which was performed on 2021-08-11 at 19:30 for example (see Figure *5*). After the spatial acquisition, a stable signal on the tracking sensor of the LCT in orbit was possible. After the lock of the optical phase lock loop, an increase in the tracking signal is visible and the Coded BER at TDP1-LCT decreases. Because an airplane was flying in the area of the beam, the transmit power of the ground station was switched off. Afterwards the tracking and the communication were established again for over 10 minutes. The complete reacquisition (from OPA switched on at ground segment until uplink communication was established) took 25 seconds. In sum, the communication duration of this link was 15 minutes and 33 seconds which corresponds to 1679.4 Gbit transferred data at 1.8 Gbps user data rate.

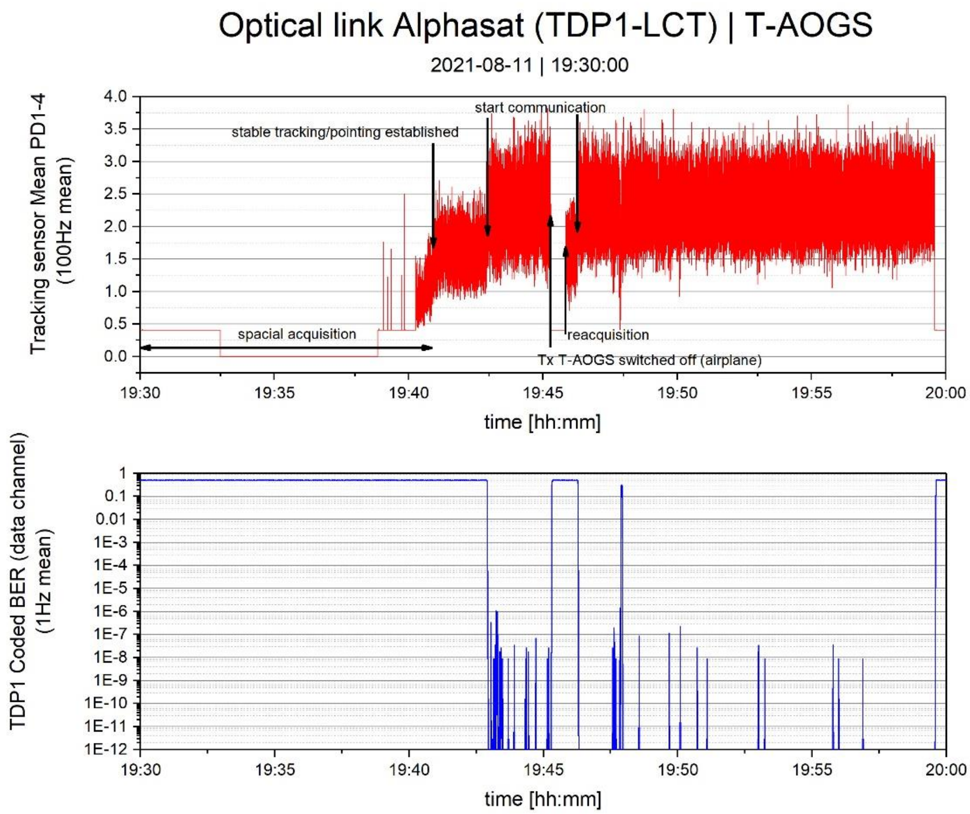


Figure 5. Optical communication link between T-AOGS and TDP1-LCT on 2021-08-11 19:30

# 4. EVALUATION

For optical communication from a site the uplink and downlink channel characteristics are of interest. During the activities at Zimmerwald the refurbishment of the adaptive optics was not finished and the downlink was not working properly. Therefore, only the uplink characteristics are analyzed. On the one hand, the absolute link budget for the location Zimmerwald is compared to a link at Tenerife. In the analysis the mean receive power at the space segment is shown.

On the other hand some effects, e.g. atmosphere fades and tracking/ pointing accuracy, results in a higher fluctuation of the signal. Especially the minimum power, which is important for the optical phase lock loop and communication, are not analyzed in the link budget. Therefore, the dynamic of the uplink channel is analyzed separately with a few manual selected links. The transmit power of the T-AOGS was reduced for the analyzed links. Therefore, only the meaningful results are shown.

## 4.1 Ground to Space Link Budget Verification

The theoretical ground to space link budget of the two sites can be analyzed and the received power at the LCT in orbit can be compared. Since the TDP1-LCT telemetry includes the voltage of the tracking sensor diodes, a calibration function is used to calculate the corresponding optical receive power in Watt at the space segment with a minimum power of -54 dBm and with an uncertainty of 10% [5]. As input for the conversion, the mean values of the tracking sensor voltages are used.

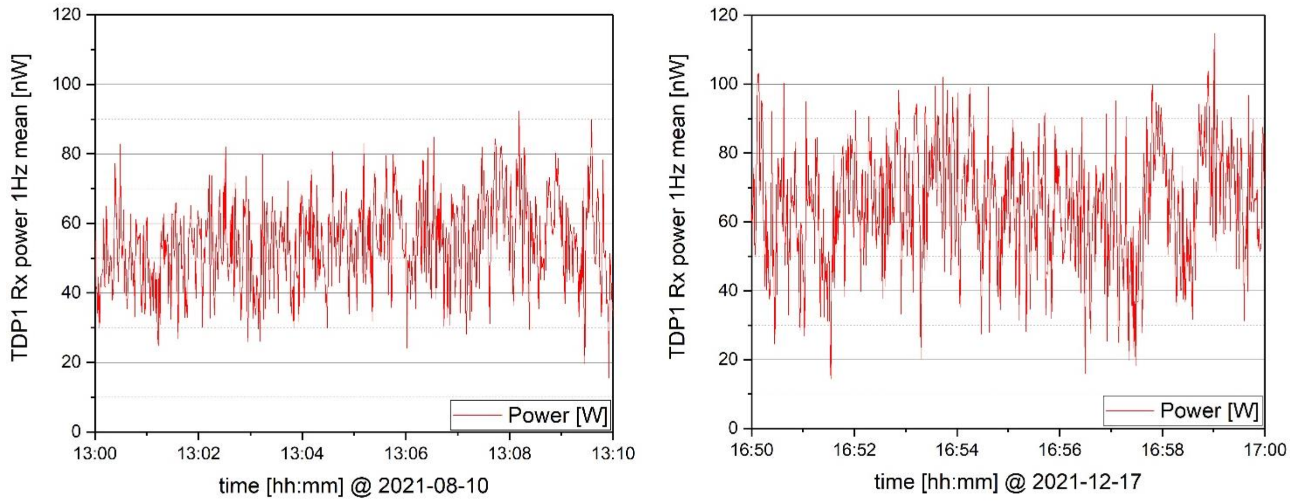


Figure 6. Receive power performance (1 Hz calibrated mean) for Zimmerwald (2021-08-10) and Tenerife (2021-12-17).

In Table 2 the link budget comparison is shown for two explicit links, for items which have the same values the cells are merged. The basic idea is to calculate the theoretical link budget without atmospheric influence. Afterwards the difference to the measured power at the LCT in orbit is calculated and the difference should be the atmospheric influence.

Table 2. Link budget (mean) comparison Zimmerwald/ Tenerife).

| **Description** | **ZIM \| 2021-08-10 \| 12:50** | **TNF \| 2021-12-17 \| 16:40** |
|---|---|---|
| Telescope Diameter (TX) | 100 mm | |
| Beam Diameter at aperture | 48 mm | |
| Opening angle 1/e² radius with truncation | 19 µrad | |
| Elevation from OGS | 34.4° | 33.7° |
| Altitude OGS | 948 m | 2452 m |
| Distance OGS - LCT | 38226 km | 38284 km |
| CPA100 mode | CPA100 Transmit Tracking mode | |
| Scintillation Index LCT | 0.306 ± 0.095 | 0.233 ± 0.175 |
| OPA signal Power | 47.06 dBm (50.7 W) ± 0.41 dB | |
| Tx Transmission (near field) | - 2.00 dB | |
| Tx Effective Antenna Gain | 99.05 dB ± 0.70 dB | |
| Tx Pointing Error static (5 µrad ± 2 µrad) + Tx Pointing Jitter mean (3 µrad ± 2 µrad) | - 1.50 dB + 1.1/-1.9 dB | |
| Range Loss | - 293.09 dB | - 293.11 dB |
| Rx Ideal Antenna Gain | 112.01 dB ± 0.30 dB | |
| Rx Input Power (ex CPA) | - 38.48 dBm +2.5/-3.3 dB | - 38.49 dBm +2.5/-3.3 dB |
| Measured Mean Power @ TDP1 | - 42.17 dBm ± 0.41 dB | - 41.55 dBm ±0.41 dB |
| | 0.424 nW/cm² | 0.489 nW/cm² |
| Difference (budget - measured) | 3.69 dB | 3.06 dB |

The links are manually preselected for having similar transmit properties of the ground station. The timeline of the receive signal for both links can be seen partially in Figure 6. For both links the beam diameter 48 mm was used which results in an opening angle of 19 µrad while the CPA100 was utilized for the transmission. The pointing was performed with the CPA100 transmit tracking algorithm, which ensures that the static Tx/Rx-misalignment is stable during the link. The elevation angle at the OGS was 34.4° at Zimmerwald and 33.7° at Tenerife (degrees relative from the ground). The height difference of the two sites is approximately 1.5 km, which results in a higher percentage of atmosphere at the Zimmerwald observatory.

In the following, the link budget is described in detail. The measured power at the output of the optical power amplifier of the T-AOGS as of December 2019 is used as input power. By design, the transmit optics have a loss of 2dB. The Tx effective antenna gain consists of the ideal antenna gain, M² (far field), polarization losses (begin of life), Degnan Klein (near and far field) and wave front error (begin of life). Due to the refurbishment of the T-AOGS the realistic values should be close to the begin of life assumptions. For the Tx Pointing, a distinction is made between the static error and the jitter. The static pointing error is the inaccuracy of the transmit tracking algorithm which is corrected manually by the operator on ground. The pointing jitter mainly has influence on the minimum and maximum values. The static error is assumed to be 5 µrad and the pointing jitter to be 3 µrad. The difference of the distance to the satellite between the two sites is 58 km and in the order of the accuracy and the potential effect on the link budget is with 0.02 dB negligible. The ideal antenna gain is given by the design with 112.01 dB. This results in the Rx input power at the telescope of the TDP1-LCT (ex CPA). The difference of the theoretical optimal link budget between both sites is only 0.01 dB.

The difference of the calculated power and the measured power corresponds to the atmospheric influence. Since we are analyzing the mean power budget, the influence of the atmosphere is mainly attenuation and turbulence induced beam spread. The corresponding values are for Zimmerwald 3.69 dB and for Tenerife 3.06 dB with an uncertainty of +2.5/-3.3 dB. The difference between both sites is 0.63 dB, the uncertainty for the comparison of the two sites is due to the usage of the same system only the static Tx-mispointing with ± 0.6 dB.

### 4.2 Dynamic of Optical Channel at Zimmerwald

One of the most impacting parameter in optical space to ground links is the scintillation. The scintillation can be described with the scintillation index (see [6]), in the following the scintillation seen at the GEO-LCT are shown [7]. The scintillation index calculated with the calibrated receive power at the TDP1-LCT for the link 2021-08-02 at 16:20 is shown in Figure 7. The alignment of the Tx-pointing of the T-AOGS is done manually. During the final manual Tx/Rx-Alignment starting from 16:25, the scintillation index varies around the mean value of 0.3. After the initial alignment is completed at 16:29, the mean of the index is 0.2. During the link the alignment needs to be corrected permanently manual, which can be seen in the changes of the scintillation index.

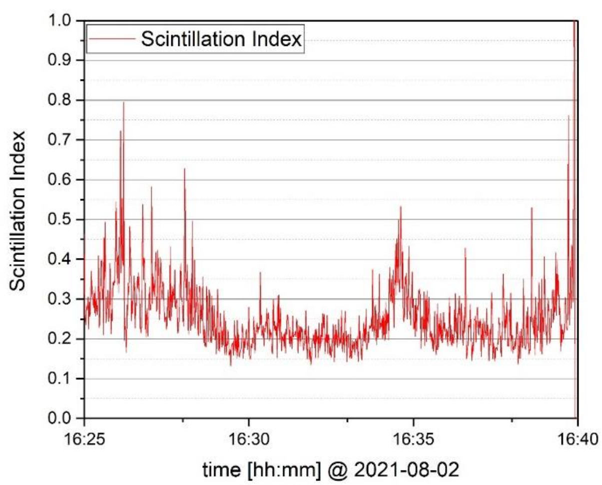


Figure 7. Scintillation Index of a link from the T-AOGS at Zimmerwald to TDP1-LCT at 2021-08-02 16:20.

After five years of operation at the Teide observatory, an automated tool for optical channel characterization with the TDP1-LCT was developed [5]. The tool, called ATLANTIS, is able to split a link in several chunks and analyzes each chunk individually regarding receive power and fade statistics. For this analysis the 25kHz telemetry of the TDP1-LCT and the 5kHz telemetry of the T-AOGS are used. After processing, different configurable filters (e.g. beam diameter, transmit CPA, …) can be applied for the evaluation of the specific question. The existing tool was used for the analysis of the Zimmerwald data.

For the activities in Zimmerwald only three links are suitable for the evaluation. For the comparison of the statistics the settings of the ground station should be the same. The comparable settings are only available for links with reduced transmit power of the T-AOGS, which means that the fades with -3 dB and -6 dB are resilient. The mean power of the links corresponds to 24 nW at the TDP1-LCT. Fades with a depth of -10 dB are not evaluated because these fades are lower than the minimum calibrated receive power at the LCT.

In Table 3, the uplink fade statistics of links with 48 mm transmit beam diameter from Zimmerwald and Tenerife are shown. For the Zimmerwald evaluation, 601 seconds from two links are used while for the Tenerife analysis 73 minutes of data over five years and different seasons are available. The dataset from Zimmerwald contains values from 16:30 until 18:30 UTC.

Table 3. Uplink fade statistics from Zimmerwald and Tenerife for 48 mm beam diameter

| | **48mm Zimmerwald** | | **48mm Tenerife [5]** | |
|---|---|---|---|---|
| **Fade Threshold** | **Mean Fade Duration** | **Number of Fades/s** | **Mean Fade Duration** | **Number of Fades/s** |
| -3 dB | 5.7 ms | 24.7 | 6.1 ms | 27.1 |
| -6 dB | 4.0 ms | 6.2 | 4.6 ms | 9.1 |

When comparing the uplink fade statistics of Zimmerwald with the average of several years at Tenerife, it can be seen that the mean fade duration and the number of fades per second are in the same order for -3 dB and -6 dB fades. The mean fade duration of the Zimmerwald data, which is recorded at very good atmospheric conditions, is reduced by 30% (-3 dB fades) and 25% (-6 dB fades) compared to the Tenerife data being an average of all times. The cumulated density function of the number of fades relative to the fade duration at the space segment is shown in Figure *8*. At Zimmerwald 50% of the fades are shorter than 3.1 ms, where at Tenerife 50 % of the fades are shorter than 2.2 ms.

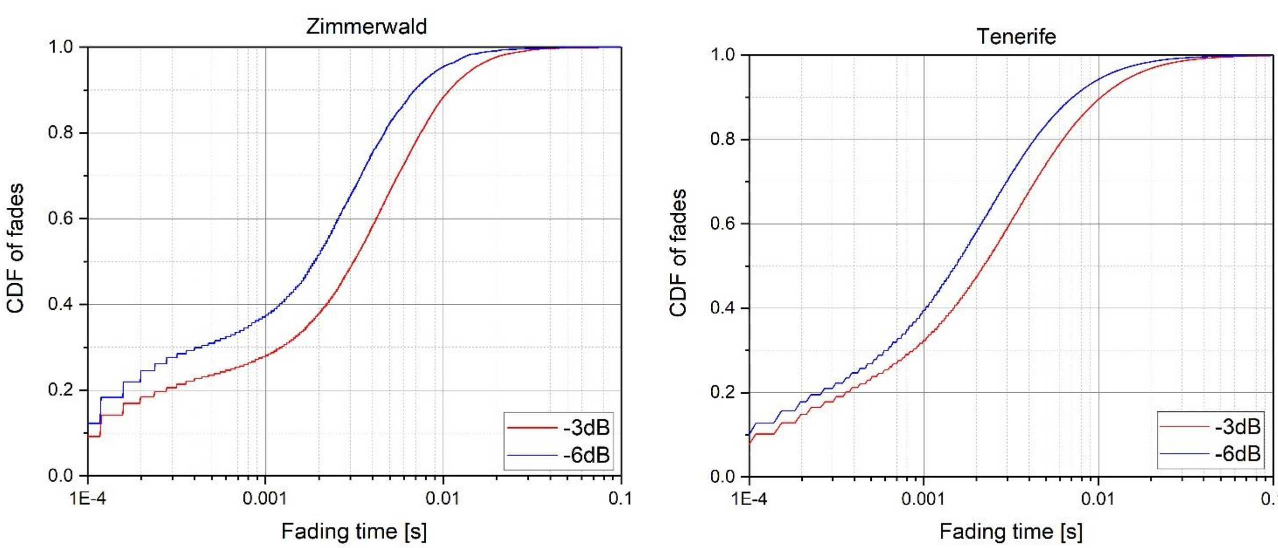


Figure 8. The cumulated density function of the number of fades relative to the fade duration at the GEO LCT for Zimmerwald (left) and Tenerife [5] (right)

## 5. CONCLUSION AND OUTLOOK

A full refurbishment of the T-AOGS was performed in 2020 after five years of operation. The main goal was the exchange of the degraded components. During the refurbishment, some enhancements in comparison with the initial design were implemented. These modifications have led to a reduction of the acquisition time because the Tx-CPA now has its own tracking system and to a maximization of the total experiment time capabilities. Additionally, new cooling concept has been implemented, enabling the T-AOGS to operate under a higher ambient temperature than before.

The increase in performance was validated during a measurement campaign at the Zimmerwald observatory (Switzerland). During the different transport operations, it has been proved that the T-AOGS can be relocated easily. In Zimmerwald, several data sets were recorded for the site characterization to a GEO satellite. One of the major conclusions drawn from the analysis of the uplink power budget is that the influence of the atmosphere can be systematically quantified. At Zimmerwald the atmospheric attenuation is 0.63 dB higher than at Tenerife. For the analysis of the atmospheric characterization, TESAT has performed a manual preselection of the data. The data was compared to the Tenerife´s big data analysis, showing that the mean fade durations and the numbers of fades per second for -3 db and -6 db fades are lower than the mean values of Tenerife. These measurements provide us a very good first indicator of the site characteristics, but further measurements over a larger time span are needed in order to increase the significance of the results.

Since December 2021, the T-AOGS is located back on Tenerife for a continuation of the experiments for the German Space Agency´s projects and external third parties.

The refurbishment has been successfully accomplished and has even improved the downlink performances in comparison with the T-AOGS BoL.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] H. Kaushal and G. Kaddoum, “Optical communication in space: Challenges and mitigation techniques”, IEEE Communications Surveys Tutorials, 19(1):57-96, Firstquarter 2017.
[2] T. Marynowski et al., "6 Jahre erfolgreicher Tests und Experimente des TESAT Laser Communication Terminals TDP1 auf Alphasat", DLRK 2020.
[3] R. Mahn et al., “Durchführung von optischen Satellit-zu-Boden Links: Linkstatistik und Wetterauswertung aus fünf Jahren betrieb der T-AOGS“, DLRK 2020.
[4] K. Saucke et al., “The TESAT Transportable Adaptive Optical Ground Station and the operational experience”, ICSO 2016.
[5] K. Saucke et al., “Characterization of the optical channel GEO to ground: using five years of data from Alphasat TDP1 and T-AOGS for investigation of different conditions”, ICSO 2020.
[6] H. Hemmati, “Deep Space optical communications”, 2006.
[7] K. Saucke et al., “3 Years of Optical Satellite to Ground Links with the T-AOGS: Data Transmission and Characterization of Atmospheric Conditions”, ICSO 2018.
[8] Zimmerwald Observatory, https://www.aiub.unibe.ch/research/zimmerwald_observatory/index_eng.html