ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

OPTEL-μ LEO to ground laser communications terminal: flight design and status of the EQM development project

G. Baister

R. Greger

M. Bacher

M. Stumpf

et al.

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105622U · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296075

OPTEL-μ® LEO TO GROUND LASER COMMUNICATIONS TERMINAL: FLIGHT DESIGN AND STATUS OF THE EQM DEVELOPMENT PROJECT

G. Baister[1], R. Greger[1], M. Bacher[2], Dr. M. Stumpf[1], Dr. L. Francou[1], K. Buchheim[1]
[1]OEI Opto AG, Switzerland. [2]RUAG Space, RUAG Schweiz AG, Switzerland

I. INTRODUCTION:

The OPTEL-μ® terminal is designed to transmit data generated on-board LEO satellites to an optical ground station at a data rate of 2 Gbps. This would allow operators of LEO satellites to downlink the large amounts of data being generated by their payload to ground. To make this technology attractive to LEO satellite user community the design of the OPTEL-μ® has minimal impact to the spacecraft resources. For a 2 Gbps OPTEL-μ® laser terminal the form factor is 8 kg mass, 8 litres volume and 45 W power consumption.

The flight design and EQM development for the OPTEL-μ® terminal is being supported under the co-funded ESA ARTES-3-4 programme through the TESLA-C project. The scope of this project is to develop the OPTEL-μ® terminal flight design to meet near term market opportunities and the production of an EQM terminal in order to verify the design.

The OPTEL-μ® terminal comprises three units:

1. Optical Head which is mounted on the outside of the spacecraft and performs the beam steering, acquisition and tracking functions for the laser terminal,
2. Electronics Unit which includes the power conditioning electronics, terminal processor electronics to operate the laser terminal and the data electronics that includes the mass memory for storage of the data before transmission to ground.
3. Laser Unit which modulates the optical carrier with the LEO payload data to be transmitted to ground (implemented in the Pulsed Laser Transmitter) and an optical amplifier stage that boosts the power of the modulated carrier to the required level to meet the link budget.

This paper reports on the flight design for the OPTEL-μ® terminal including results from the supporting engineering model development of key subsystems, as well as results of the EQM development and qualification tests. The EQM qualification programme comprises full functional performance tests and environmental qualification of the Optical Head, Laser Unit and Electronics Unit. In addition, end-to-end tests of the OPTEL-μ® terminal are to be carried out to verify the performance of the communications and pointing, acquisition and tracking (PAT) subsystems.

II. SYSTEM DESCRIPTION:

The OPTEL-μ system implements a bi-directional, asymmetric laser communications link from Low Earth Orbit to a fixed optical ground station network as depicted below in **Error! Reference source not found.**. Key elements within the system are the OPTEL-μ are the Space Terminal (ST) and the Optical Ground Stations (OGS) that are to be deployed at 4 to 10 different site locations in a global network for sufficient clear sky availability . The key system aspects have been described in detail in [1] and [2]. This paper will present an overview of the OPTEL-μ® ST flight design and summary of the current status.

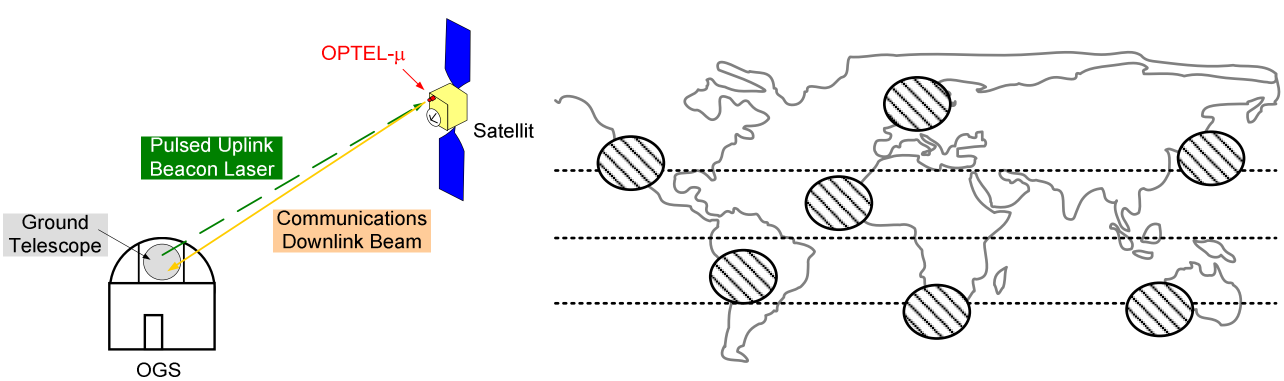

Fig. 1: Optical Downlink Scenario from LEO with Key Elements of the OPTEL-μ System

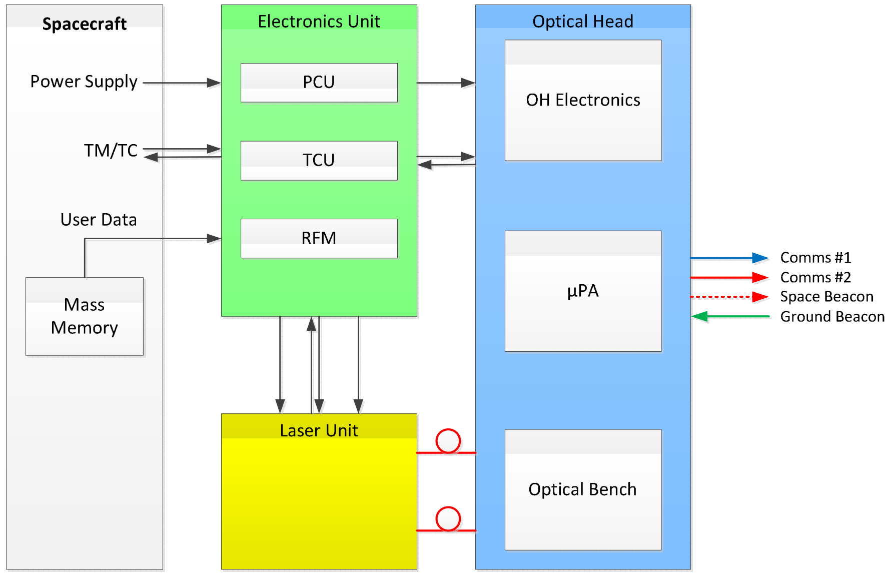

Fig. 2: Block Diagram for the OPTEL-µ ST

The design of the OPTEL-µ Space Terminal follows a modular approach as shown in Fig. 2. The ST comprises three functional units, these being:

- Optical Head Unit (OH) attached mounted to the outside of the spacecraft on the nadir panel. Two options are considered for the mounting of the OH on the spacecraft – these being with the OH mounted through a cut-out of the panel such that the centre of mass for the OH is close to the mounting plane, or with the OH mounted directly to the spacecraft panel (using a support frame).
- Laser Unit (LU) located inside the spacecraft,
- Electronics Unit (EU) located inside the spacecraft.

The OH, LU and EU are connected to one another by a harness comprising both electrical and optical fibre.

A. Space Terminal – Optical Head

The Optical Head constitutes an integral part of the pointing, acquisition and tracking (PAT) subsystem that ensures that the optical communications link between ST and OGS can be established and maintained during the satellite pass over of each OGS. To achieve this the OH performs the following:

- Pointing of the OPTEL-µ communication laser beams and space beacon towards the OGS using a pointing mechanism,
- Acquisition of the beacon laser from the OGS,
- Tracking of the ground based beacon by providing pointing functionality and spot detection and closed loop tracking between the PAT sensors and the ST pointing mechanism.

During closed loop tracking of the ground beacon the OPTEL-µ is then able to transmit the date from the LEO satellite payload to the OGS. In addition, the OPTEL-µ system foresees a low rate communications link from the OGS to the ST which acts as a service channel to transfer data to optimize the optical link.

The flight design for the Optical Head (OH) is shown in Fig. 3 for the configuration where the OH is mounted through a cut out in the spacecraft panel. To achieve the above functionality the OH comprises the following three assemblies:

1) Micro-Pointing Assembly (µPA) which is required to:

- Receive angular pointing commands from PAT controller (in the Electronics Unit),
- Receive and point the optical axis towards the ground station based on feedback from PAT controller,
- Provide as-is pointing information to the PAT controller.

The µPA design is based around a two degree of freedom gimbal to allow pointing of the optical axis in azimuth (alpha axis) and elevation (beta axis) direction with respect to the mounting plane. The beta axis stage features a differential indirect drive e.g. its motion is transferred from the motor placed on the alpha axis via a conical gear and the angle of rotation is obtained as difference of the rotations of the alpha axis and of the compensation gear. In order to simplify the construction and control a 1:1 gear ratio is adopted.

This configuration allows to have all electrically powered element only connected to the baseplate in order to avoid the need for flexible harness, cable-drum or slip ring to transfer the power on the moving stages as would be required in a typical gimbal design with the beta axis stage on top of the alpha one. Another advantage of this configuration is to be able to use the same components (e.g. motors and position sensors) for both the axes and to have a similar mounting which makes the procurement of the parts and the integration easier.

2) Optical Bench (OB) which is required to:

- Receive ground beacon and relay it onto the acquisition and tracking sensors and to ensure co-alignment with the transmit laser signals,
- Receive the communications laser signals (from the Laser Unit), collimate the beams and send them to the µPA,
- Receive the space beacon laser (from the Laser Unit), collimate the beam, ensure co- alignment with the communications laser signals and relay it to the µPA.

The optical bench uses a monolithic aluminium baseplate that interfaces to the underside of the µPA using three bipod struts. The optical paths within the baseplate comprises the transmit path for the communications signals and the space beacon, a receive path to the acquisition sensor and a receive path to the tracking sensor. Connecting these optical paths is the common path within which is implemented a beam expander and collimating optics to generate a 15mm diameter collimated optical beam.

3) Optical Head Electronics (OHE) which is required to:

- Readout all sensors of the Optical Head Unit,
- Drive all actuators and motors components of the µPA according to the commands from the PAT controller,
- Provide pulse-timing information to the communications electronics (Service Channel) and to communicate with the PAT controller.
- Provide sensor readout and OH status data to the Electronics Unit and to receive commands including closed loop feedback for the control of the µPA.

The OHE consists of three electronic boards – a control board which is a flex-print PCB using an RTAX2000 FPGA to implement the firmware needed for the above together with the associated interface electronics, an acquisition sensor board and a tracking sensor board. These two boards each contain one four-quadrant detector and the close-proximity electronics for read-out and operation of the sensor. The sensor boards are attached to the Optical Bench and a flex-cable used to connect with the control board.

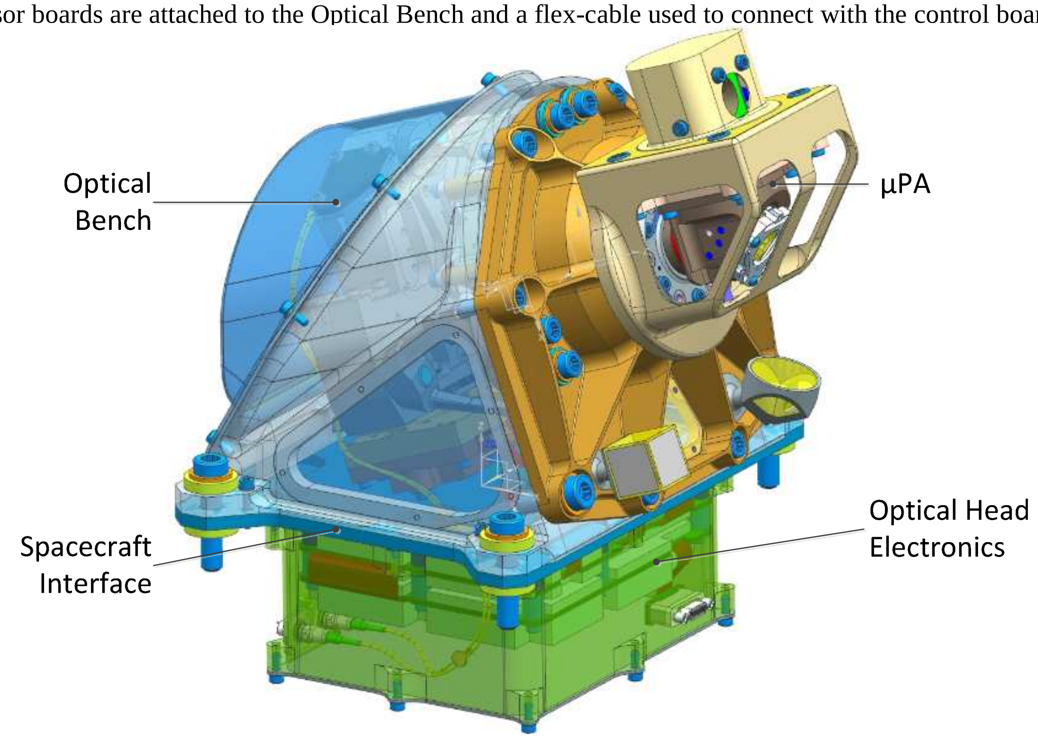

Fig. 3: Optical Head Design Showing the Main Assemblies (without MLI Blanket)

The key physical parameters of the OH are:

- Total mass of the OH is 4.4 kg
- External envelope for the OH (L x W x H) is 204mm x 238mm x 226mm

B. Space Terminal – Electronics Unit

The Electronics Unit (EU) is required to establish full electrical functionality and performance to operate and control the OPTEL-μ ST. The design of the EU is shown in Fig. 4 and has the following interfaces with other spacecraft and terminal subsystems:

- Electrical interfaces with the Spacecraft to exchange TM/TC, to receive the user data to be transmitted via optical downlink to the GT, and to connect to the primary power bus.
- Electrical interfaces with the Laser Unit to provide the downlink signal as serial RF data streams, to monitor and control the LU functionality, and to power the LU by providing the required supply voltages
- Electrical interfaces with the Optical Head Unit to receive the uplink signal as digital serial data stream, to monitor and control the OH functionality, and to power the OH by providing the required supply voltages
- Mechanical and thermal interfaces with the mounting interface plate inside the spacecraft, on which the Electronics Unit will be mounted.

The Electronics Unit (EU) is comprised of the three sub-units:

- Terminal Controller and Communications Electronics Unit (TCU) : The main functions of this block are the control of the OPTEL-μ space terminal through the on-board software implemented on a CPU, telemetry / telecommand (TM/TC) interface as well as the user data interface and a communications controller. The user data from the satellite payload that is to be transmitted to ground via the OPTEL-μ is first stored in a Buffer Memory (BFM) located within the TCU. The BFM used in the TCU has a memory capacity of 100GBytes. When required for a downlink the data is read out from the buffer memory in two channels, each with 10 bit parallel data of 125MHz.
- RF Module (RFM) : The RFM serializes the parallel data stream of each channel coming from the TCU into a serial data stream with data rate of 1.25 Gbps and amplifies the corresponding RF signal. The amplified RF signal is then used to modulate the optical carrier (implemented in the Pulsed Laser Transmitter (PLT) which is part of the Laser Unit (LU)).
- Power Conditioning Unit (PCU) : The PCU derives from a primary unregulated power bus with 24V to 36V the supply voltages needed within the remainder of the EU as well as the electrical equipments of the Optical Head and the Laser Unit. The PCU provides the required supply voltages that allow the OPTEL-μ ST to be operated in a low-power mode (where not all functionality is required) and the ‘downlink’ mode.

The key physical parameters of the EU are:

- Total mass of the EU is 1.8 kg (excluding harness)
- Dimensions of the EU (L x W x H) is 207mm x 227mm x 65mm

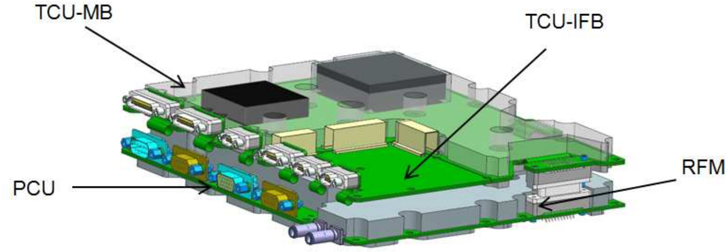

Fig. 4: Electronics Unit Design Showing the Electronic Board Configuration inside the EU Box

C. Space Terminal – Laser Unit

The Laser Unit (LU) of the OPTEL-μ ST comprises two separate modules that are connected to one another using optical fibre – these are the Pulsed Laser Transmitter (PLT) and Optical Fibre Amplifier (OFA) and are shown in Fig. 5. The key features of the PLT and the OFA are:

- Pulsed Laser Transmitter (PLT) : The PLT provides two individually modulated optical channels each at a data rate of 1.25 Gbps in the 1550nm optical C-band. The PLT comprises two optical channels generated using laser diodes operating at 1544nm and 1565nm which are operated in CW mode. A Mach-Zehnder modulator (MZM) is used to modulate the CW laser signal which after being modulated is routed using optical fibre to the PLT output. The PLT also includes the control electronics for operating the laser diodes and MZM.
- Optical Fibre Amplifier (OFA) : The OFA incorporates two individual optical fibre amplifiers that are optically pumped at 980nm to achieve the required amplification. Three output signal are generated by the OFA – these being the two communications signals and the space beacon signal. For each optical channel the output power required from the OFA is 100 mW at end of life. To operate and control the OFA there is also the control and pump laser drive electronics contained within the OFA.

The key physical parameters of the LU are:

- Mass of the LU is 1.6 kg made up from 0.9 kg (PLT) and 0.7 kg (OFA)
- Dimensions of the two modules are 218mm x 115mm x 61mm for the PLT and 158mm x 165mm x 24mm for the OFA.

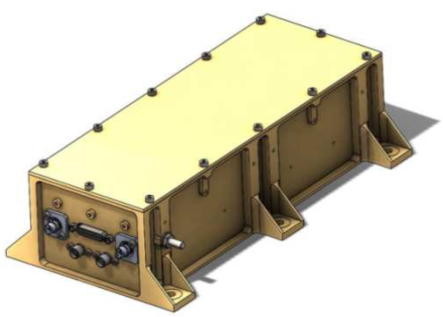

Fig. 5: OPTEL-μ Laser Unit – Pulsed Laser Transmitter (left) and Optical Fibre Amplifier (right)

D. Development Approach

The OPTEL-μ space terminal is developed along the development approach illustrated in Fig. 6. Results of the Preliminary Design phase have been presented in [3] and[4]. Within the design phase culminating in CDR which was held in Dec. 2015 there was also developed a number of critical subsystems to mitigate risk and confirm suitability of the design. These critical subsystems included the μPA, optical bench, sensor electronics, optical head electronics and electronics unit.

Fig. 6: OPTEL-μ Development Flow

III. EQM DEVELOPMENT

A. Development Status

Following the CDR held at end of 2015 the MAIT phase for the OPTEL-µ EQM has been released. The current status is that all hardware items have been released to manufacture and procurement of the EQM parts and the assembly and integration of the key assemblies. The current on-going activities are:

- Optical Head: Assembly and integration of the µPA, qualification testing of the Optical Bench and production of the Optical Head electronics (inc. sensor electronics)
- Electronics Unit: Manufacture of two electronic boards (TCU and RFM) and testing for the PCU is on-going. Software development is progressing with software testing being performed using an Electonics Unit EM+ developed during the design phase.
- Laser Unit: Assembly and integration of the Pulsed Laser Transmitter and Optical Fibre Amplifer. Qualification testing of both assemblies is then to be completed at assembly level.

For the Optical Head and the Electronics Unit once we have received the EQM parts and assemblies the assembly, integration and unit verification (qualification tests) are to be performed for the remainder of 2016. Details of the unit verification are summarized below.

B. Unit Verification

Qualification testing of the OPTEL-µ is planned to be performed at unit level. For each unit (OH, EU and LU) the following tests are to be performed:

- Functional and Performance Tests
- Mechanical Tests (random vibration and shock)
- Thermal-Vacuum Tests (non-operational and operational)

Before and after each environmental test it is foreseen to perform a reduced functional and performance test to check the health status of the unit before proceeding to the next step.

IV. OUTLOOK

A. System level Testing on ground

Following the unit level verification and qualification testing there will the system level testing comprising the assembled OPTEL-µ ST being under-going performance tests in the OEI system test-bed together with the Instrument Box. The Instrument Box comprises the ground based sensors, communications receivers, actuators and beacon lasers to later be installed in the first Optical Ground Station.

The functional and performance tests for the ST comprise the following:

- Commissioning of the EU + LU
- Commissioning of the EU + LU + OH
- Pointing, acquisition and tracking tests for the OPTEL-µ
- Communications tests (ST to ground)

Following the system end-to-end performance tests the OPTEL-µ will undergo EMC testing.

B. In-Orbit Demonstration

The objective of the In-Orbit Demonstration is to verify the system and space terminal performance on-board a satellite in Low Earth Orbit. It is foresee to fly the OPTEL-µ EQM developed under the Phase C contract to save cost and reduce the time to implement the IOD.

A flight opportunity for OPTEL-µ ST has been secured and the accommodation of the space terminal on-board of the satellite is on-going.

The OPTEL-µ ST shall fly in its final flight configuration however having specific adaptation to meet mission and platform requirements. Those adaptation are in-line with general product adaptions required for any platform adaptations on future missions. For larger adaptions, it is planned to provide utility hardware to ensure that OPTEL-µ ST is flying in its flight configuration. An example is given in Fig. 7, e.g. a bracket to mount the Optical Head Unit.

A preliminary accommodation of the unit on the IOD satellite looks as follows:

Fig. 7: OPTEL-µ ST Accommodation

The proposed flight opportunity will use the OPTEL-µ space terminal (OPTEL-µ ST) in a "passenger" configuration, meaning the unit will be used and operated independently of the main mission. However possibilities to downlink payload data are foreseen.

For the ground segment, it is foreseen to establish an experimental ground station based on an already developed ground terminal prototype [Ref to paper on Mountain-Top-test] at the University of Applied Science in Winterthur, Switzerland (ZHAW). The ground terminal is located on top of a university building and a joint project between ZHAW and OEI is on-going to prepare the ground station for the IOD.

The duration of the IOD is planned for 12 month, with the phasing summarised in Table 1.

Table 1: IOT Phases

Phases	Tasks	Planed Duration	Results expected
Phase 0	• check-out of ST • check-out of GS • commissioning of OPTEL-µ System (ST and GS) • perform first test links (1-2 week)	3 month	Check Out Report ST Link test results
Phase 1	• perform regular downlinks • measure system performance • confirm main product characteristics (data rate, power requirements) • assess weather impact	3 month	Link test results Selected Terminal Telemetry data
Phase 2	• extended operations with ground station network • measure system performance • confirm main product characteristics (data rate, power requirements) at alternate locations • measure downlinked data volume • assess weather impact • observe ST health and pot. performance degradations in dependence of orbit / operations time	3 month	Link test results Selected Terminal Telemetry data
Phase 3	• additional downlink tests with payload data • downlink experiments with other OGS • regular downlinks with reduced cadence to confirm operation of unit • observe ST health and pot. performance degradations over life-time / orbit	3 month	Link test results Selected Terminal Telemetry data

The IOD shall result in reaching TRL 9 for the space terminal and allow OEI Opto AG to provide the unit for many different missions around the world.

V. ACKNOWLEDGEMENTS
The development of the OPTEL-μ® optical terminal is being funded jointly by ESA and OEI Opto AG under the ARTES programme. The authors would like to acknowledge the work and efforts of the project team at OEI Opto AG. In addition, we gratefully acknowledge the contributions and support from our partners and subcontractors involved in the OPTEL-μ® development – these being Deimos (UK), Gooch & Housego (UK), LusoSpace (Portugal), RUAG Space (Finland), SES Techcom (Luxembourg), SSC (Sweden), TNO and Nedinsco (The Netherlands) and Meopta (Czech Republic). The authors would also like to express our gratitude to Paul van Loock and Dr. Zoran Sodnik at ESTEC, together with the Swiss Space Office and national delegations of all subcontractors for their continued support in the execution of this work.

REFERENCES

[1] Björn Thieme, Thomas Dreischer and Klaus Buchheim , "Space terminal for an optical downlink system on small satellites," *The 4S Symposium 2012*, June 2012.
[2] Thomas Dreischer, Björn Thieme, Michael Bacher, Klaus Buchheim, Petrus Hyvönen, "OPTEL-μ: A Compact System for Optical Downlinks from LEO Satellites", *SpaceOps 2012 Paper-ID 1274781*, June 2012.
[3] Martin Mosberger, Thomas Dreischer, Michael Bacher, "Mountain-top-to-valley optical link demonstration as part of a miniature terminal development" in *Proc. SPIE 8610, Free-Space Laser Communication and Atmospheric Propagation XXV, 86100*, 19 March 2013
[4] Thomas Dreischer, Björn Thieme, Klaus Buchheim, "Functional System Verification of the OPTEL-μ Laser Downlink System for Small Satellites in LEO" *Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2014, S6-4*, May 2014