QUALIFICATION AND CALIBRATION OF DLR'S OPTICAL BIROS PAYLOAD

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INTRODUCTION

Direct optical communication links might offer a solution for the increasing demand of transmission capacity in satellite missions. Although direct space-to-ground links suffer from limited availability due to cloud coverage, the achievable data rates can be higher by orders of magnitude compared to traditional RF communication systems.
DLR's Institute of Communications and Navigation is currently developing an experimental communication payload for DLR's BiROS satellite. The laser terminal consists of 4-Quadrant-Detector as tracking sensor with an uplink channel and two kinds of laser sources: a directly modulated semiconductor laser diode and a fiber amplifier.
The BiROS satellite bus is funded by the German Federal Ministry of Education and Research (FKZ01LK0904A). The payload is funded by the DLR space programmatic. The BiROS satellite will be launched middle of 2015 by the Indian PSLV-C3 [1].
This paper will give an overview about the hardware of the laser terminal with a special focus on the calibration of the optical system and the space-qualification, including a radiation test especially for the optical components. Further, the data reception and storage on ground station site will be discussed.

I. LASER COMMUNICATION

Optical free-space communication links offer a high data rate, low power consumption and thereby a high efficiency as well as the safety from interception. The Institute of Communications and Navigation of the German Aerospace Center developed within the project OSIRIS an optical payload for DLR's BiROS satellite, built at DLR's Institute of Optical Sensor Systems in Berlin-Adlershof.
The OSIRIS payload is an experimental system for direct optical downlinks from a LEO-orbit to an optical ground station. For pointing the laser to the ground station, the attitude control system of the satellite is used. To increase the accuracy to the required level, OSIRIS is equipped with a tracking sensor, receiving the beacon signal from the ground station. Besides the tracking sensor, the optical bench aligns three transmission collimators. Two transmission collimators are directly included in the OSIRIS system and are both connected to a High-Power-Laser-Diode (HPLD) and an Erbium-Doped-Fiber-Amplifier (EDFA) by a X-Coupler. The third transmission collimator is used for an optical link in parallel to the S-Band-RF-Link of the satellite bus. With these sources, OSIRIS provides data rates up to 1 Gbit/s with an IM/DD modulation at 1550 nm. The OSIRIS system is further equipped with an optical uplink channel that uses the 4-Quadrant-Diode (4QD) as receiver.

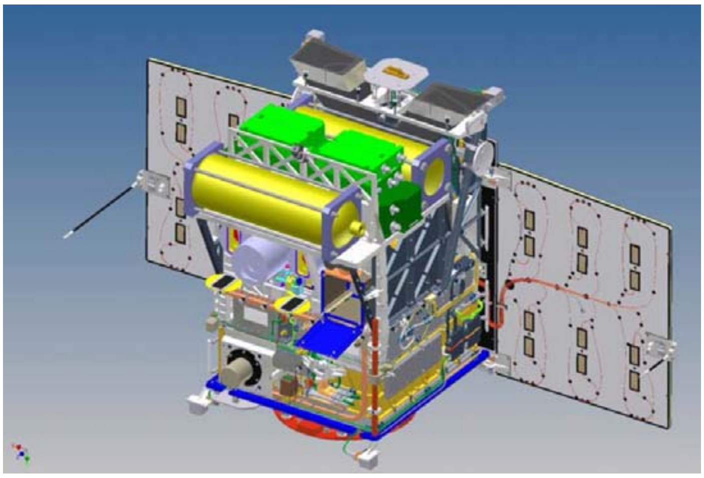

Figure 1: BiROS satellite for constellation flight within FireBIRD Mission [1]

BiROS will be part of the FireBird mission for forest fire detection and will form a constellation flight together with the TET-1 satellite, launched in July 2012. In this constellation the satellites will be able to detect forest fires and to monitor it. BiROS launch is foreseen for 2015.

II. OSIRIS HARDWARE ON BIROS

A. Optical Bench

The optical bench is the main optical device of OSIRIS. The optical bench hosts the tracking sensor as well as the three transmission collimators. Based on a 4-Quadrant-Detector, the tracking sensor enables the attitude control of the satellite to precisely align to the optical ground station. The tracking sensor is equipped with a lens of 30 mm in diameter and a focal length of 100 mm. Together with the lens, a filter with 8 nm width and a transmission of 95% in the pass band is mounted to suppress background light. Tracking sensor, lens and filter are mounted in a carbon fiber tube to overcome defocussing problems in the tracking sensor which would influence the tracking behavior of the attitude control system.
For transmission, three different collimators are used. The three collimators are adjusted to three divergence angles and data rates:

- Tx1: the collimator is adjusted to a divergence of 1200 µrad. This divergence is adapted to the blind pointing accuracy of the satellite's attitude control based on the star camera. This collimator will be used if the tracking sensor input to the attitude control is not used. Tx1 is connected to the G-Link (1 Gbit/s) and M-Link (100 Mbit/s) with an optical X-coupler inside the laser module.
- Tx2: this collimator is adjusted to a divergence of 200 µrad. The divergence is adapted to the maximum accuracy of the attitude control using the sensor fusion with star camera and OSIRIS tracking sensor. Tx2 is connected to the G-Link (1 Gbit/s) and M-Link (100 Mbit/s) with an optical X-coupler inside the laser module. With Tx2, a data rate of 1 Gbit/s can be achieved at 18° elevation.
- Tx3: the collimator is adjusted to a divergence of 1700 µrad. The collimator is used for an optical link in parallel to the S-Band-RF-Link and provides a corresponding data rate of 2,2 Mbit/s or 137,5 kbit/s.

Figure 2 shows a CAD drawing of the optical bench with the mounted tracking sensor and the three transmission collimators. The challenge for designing the optical bench is to perfectly align four optical axes: the three collimators in reference to the tracking sensor. Based on the minimum divergence of 200 µrad, the 6σ precision of the alignment of the optical bench is 33 µrad. This is the value that has to be measured during calibration and has to be verified after vibration and thermal-vacuum test.

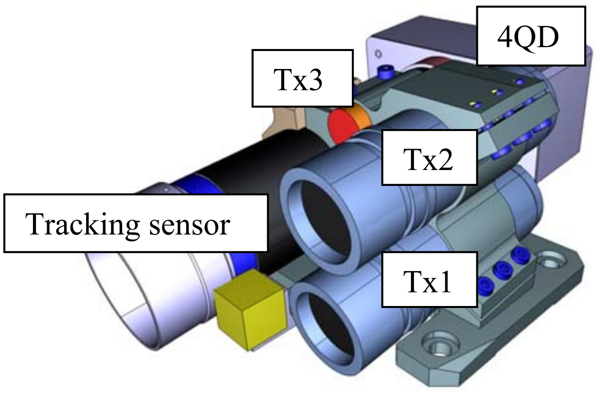

Figure 2: Optical bench of the OSIRIS payload

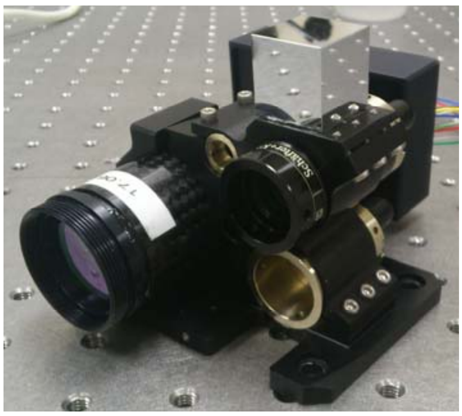

Figure 3: OSIRIS optical bench Qualification Model

The optical bench is further equipped with an alignment cube (yellow cube in Figure 2). The alignment cube gives the reference for the alignment of the optical axis in the lab and the verification measurements after the qualification tests. Furthermore, the alignment cube gives the reference of the optical bench coordinate system to the attitude control coordinate system. Chapter 4, calibration of the optical bench, will explain the process of measuring and aligning the optical axis in more detail.

B. Laser sources

The basic design of OSIRIS provides a standard housing and electronics that can be used for long range free-space optical communications. The housing is equipped with different FSO technologies: a laser module combined with an Erbium doped fiber amplifier (EDFA) and a high-power semiconductor laser diode (HPLD). An integrated power supply circuit using DC-DC converter technology is used to supply both of the laser sources.

Both technologies have their advantages and disadvantages. The HPLD is small in size and weight compared to the laser module combined with an EDFA, but provides less optical power than the EDFA and lower data rates. Therefore the EDFA can provide higher data rates and a higher output power. At the moment, the size and weight advantage of the HPLD is not used for the final design of OSIRIS since both technologies are integrated inside the same housing and share the same electronics. For future missions, this advantage could be used if power consumption, weight and size become more critical. The HPLD is more robust against cosmic radiation compared to the EDFA due to the doped optical fibers used in the EDFA. This kind of fiber is especially sensitive to radiation and suffers from degradation effects. These effects have been evaluated in a radiation test, explained in detail in chapter 4.

As a laser source for the EDFA, a fiber-coupled laser module commonly used in terrestrial fiber communications is used. These modules can provide data rates up to 2.5 Gbit/s, however in this setup the data rate is limited to 1 Gbit/s by the transmitter capabilities. Gigabit data to be transmitted is connected to the housing by SMA-connectors. The data path uses PECL differential signaling and has redundant cable connections. The active connection can be chosen by an external control signal, which switches between the data sources, using high-frequency-relays. In addition, it is possible to limit the EDFAs output power to an eye safe level for lab operations.

The wavelength of the laser source can be chosen from the ITU C-band DWDM grid at time of integration. The signal modulated by the laser source is fed to the optical amplifier by a single-mode fiber connection. The EDFA is used to amplify the incoming light to a maximum optical power of 30 dBm. The amplified signal is connected to an x-coupler, which splits the power 50:50 into two fibers for the transmission collimators with different divergence angles, as described in chapter 2.

The HPLD is a directly modulated semiconductor laser diode driven by a specialized driver circuit, which converts the data signals into a current, modulating the laser diode. The data connection is redundant and uses LVDS signaling over twisted pair cables due to the lower data rate. It can provide a maximum data rate of 78 Mbit/s and an optical output power of 17 dBm per collimator. A passive cooling system is used for heat dissipation. The optical output of the HPLD is joined to the second input port of the x-coupler and connected to the collimators in a similar way as the EDFA.

III. GROUND SUPPORT EQUIPMENT

For data reception and storage, generation of the beacon signal with uplink data, and control of the OSIRIS modules, a Ground Support Equipment (GSE) was developed. The GSE can be used for laboratory testing and during the mission. Therefore, the interfaces can be tested with either an optical signal or electrical wiring. The coding is compatible to CCSDS.

During testing and qualification of the OSIRIS payload, the GSE is used for supervising and examination of all modules. All interfaces provided by the satellite and used by OSIRIS are also available in the GSE. Therefore, the GSE has to fulfil the following requirements:

Table 1: Requirements for OSIRIS GSE

Independent Operation	Electrical GSE (EGSE - Emulation of satellite bus)
	Optical GSE (OGSE - Emulation of ground station)
Self-Testing	Closed-Loop test of all data interfaces
	Data Source can be either pattern generator or file
Calibration mode	All data channels send constant value (required for optical calibration)
Online statistics	Quality of data transmission
	Quantitative analysis of data transmission
Error generation	GSE can generate logical and physical errors in all laser signals to simulate different transmission scenarios
Data storage	
Displaying of 4QD behavior	
Support of laser safety issues during laboratory testing	

Figure 4 shows the laboratory test configuration of EGSE and OGSE together with OSIRIS. All electrical and optical interfaces are provided and simulated by the GSE. In this configuration the basic system parameters like data transmission with different channel data rates can be tested. After installation of OSIRIS in the satellite, the interfaces for 4QTEL, EDFA and TOL are provided by the satellite bus. Then, the EGSE supports the testing in this configuration with the optical interfaces. In this configuration, also the electrical interfaces to PPU and SBC can be verified by providing optical test signals.

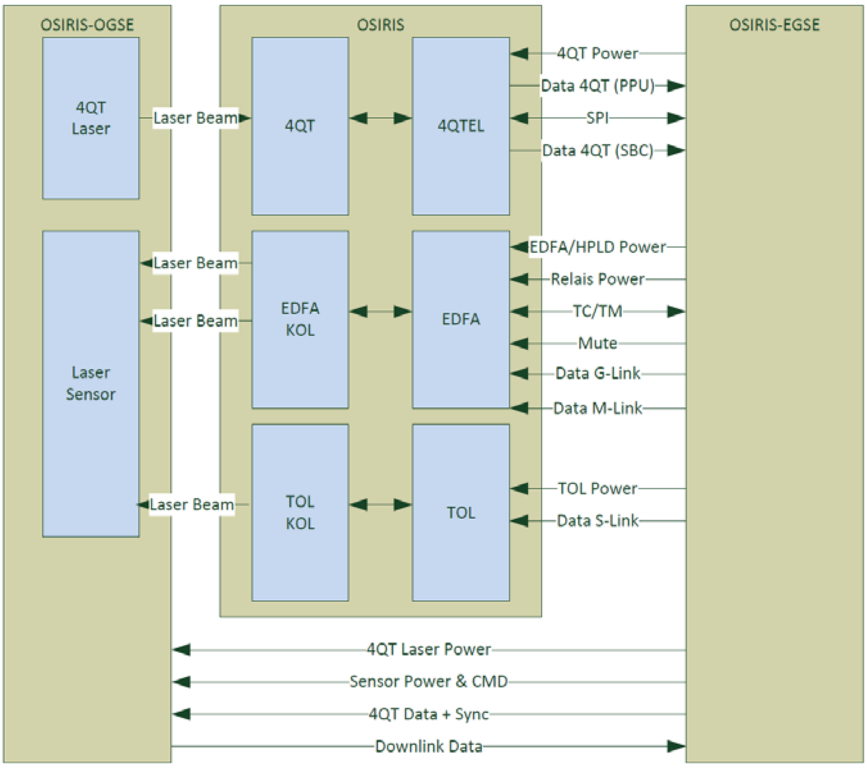

Figure 4: GSE configuration for testing with OSIRIS integrated in the satellite

The EGSE also provides a self-testing mode. Compared to Figure 4, the four data interfaces Data 4QT, Data G-Link, Data M-Link and Data S-Link are short-circuited to have a closed-loop between data generation and data reception.

Figure 5 describes the GSE configuration for mission use with the BiROS satellite in orbit. The OSIRIS payload is fully integrated and connected. Instead of the OGSE, an optical ground station at the Institute of Communications and Navigation is used. The EGSE is connected to the ground station for downlink data storage and uplink signal generation.

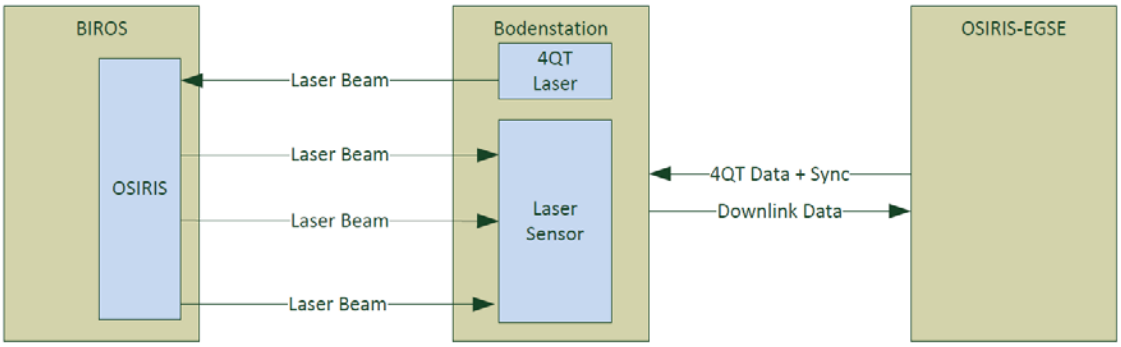

Figure 5: GSE configuration for mission use

The GSE is realized as a PC-Raid-System (Xeon) with 4TB harddrives and a PCIE FPGA card (Xilinx Hitech Global Kintex™ 7, HTGK 700) with an Add-on board. The add-on board is used for interface adaptation and is equipped with a parallel-serial-converter for the G-Link (HDMP 1032A and HDMP 1034A) as well as a bit synchronizer (ADN 2817) for the M-Link. The SPI-interface is realized by a SPI-USB-Adapter and a miniRFE-1G (ViaLight Communications GmbH) is used for data reception.

IV. CALIBRATION AND SPACE QUALIFICATION

A. Calibration of optical bench

During calibration of the optical bench, the four optical axes of the tracking sensor and transmission collimators need to be aligned. In chapter II the required accuracy of 33 µrad was given, that will be verified during the calibration process.
For the calibration of the optical bench, the "Kameramessplatz" (KMPL) in the optics lab clean room of DLR's Institute of Optical Sensor Systems was used. The laboratory is equipped with a measurement collimator as source and a manipulator for positioning the Device Under Test (DUT). The manipulator is able to align payloads with a maximum mass up to 100 kg with a precision of 8 µrad. The precision of the manipulator is higher by a factor of 4 compared to the required accuracy for evolved calibration.
For the calibration of the OSIRIS optical bench, a calibration process has been developed. Figure 6 shows the calibration setup. The optical bench is mounted on the manipulator to enable a precise alignment. In the next step, the measurement collimator is used as light source, illuminating the tracking sensor of OSIRIS. Therefore, the measurement collimator is equipped with the OGSE beacon signal behind a 100 µm pinhole that is interferometrically positioned. Subsequently, the optical bench is tipped and tilted to the center of the tracking sensor. This position is the basis for all further measurements.

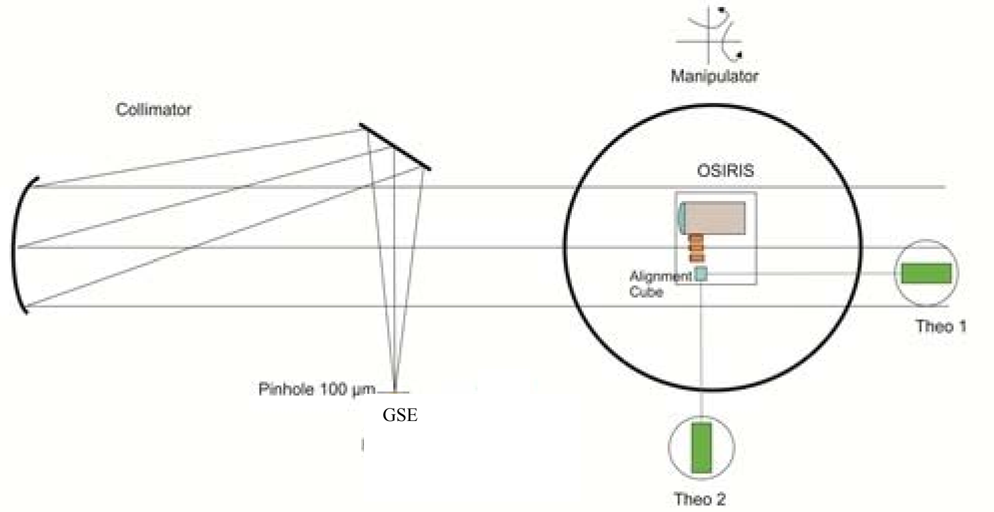

Figure 6: The collimator works as transmitter and illuminates the tracking sensor

For the alignment of the transmission collimators, the OGSE source is replaced by an InGaAs-Photodiode detector behind the pinhole. One after the other, the OSIRIS collimators are connected to the OSIRIS laser sources. In the basic position of the manipulator, the adjustable transmission collimators are aligned to the tracking sensor. Due to mechanically limitations, the resulting mispointing is compensated by the manipulator. The angle between the basic position of the manipulator (equal to the optical axis of the tracking sensor) and the compensated position for every transmission collimator is saved and is the basis of the verification of the alignment before and after the vibration test.
The optical bench is further equipped with an alignment cube. After the compensation of the resulting mispointing with the manipulator, the angular error to the alignment cube is measured with two theodolites so that all four optical axes can be represented as an angular offset to the alignment cube. Due to that fact, the alignment cube is chosen as the basis of the OSIRIS coordinate system that will be referenced to the coordinate system of the satellite's attitude control and will be used as reference for the verification measurements after the space qualification tests.

B. Vibration- and Thermal-Vacuum-Test

The vibration test is mostly connected with the launching phase of the satellite. Here the expected accelerations in x, y and z axis are simulated. Afterwards the payload is inspected for potential failures and the optical alignment is verified on the KMPL. In order to verify the integrity of the payload, the resonance frequencies of the DUT can be used. The test includes a sinusoidal-sweep and a random vibration test for every axis. The sinusoidal-sweep stimulation gives generally an indication about the behavior in single frequency systems. Here instead, the passing through a wide frequency range covers potential resonant frequencies inside the payload.

The random vibration is used to represent the expected environment [2] during launch. Even though, a random vibration test gives more realistic results, both methods are foreseen in the applied ECSS standard [3]. After each run, the resonance frequencies are cross checked with an initial reference measurement. Figure 7 shows exemplarily the measured frequency response of the optical bench in z-axis before and after the vibration test. It is visible, that the resonance frequencies remained stable. The qualification model of the OSIRIS payload passed the test within all tolerances.

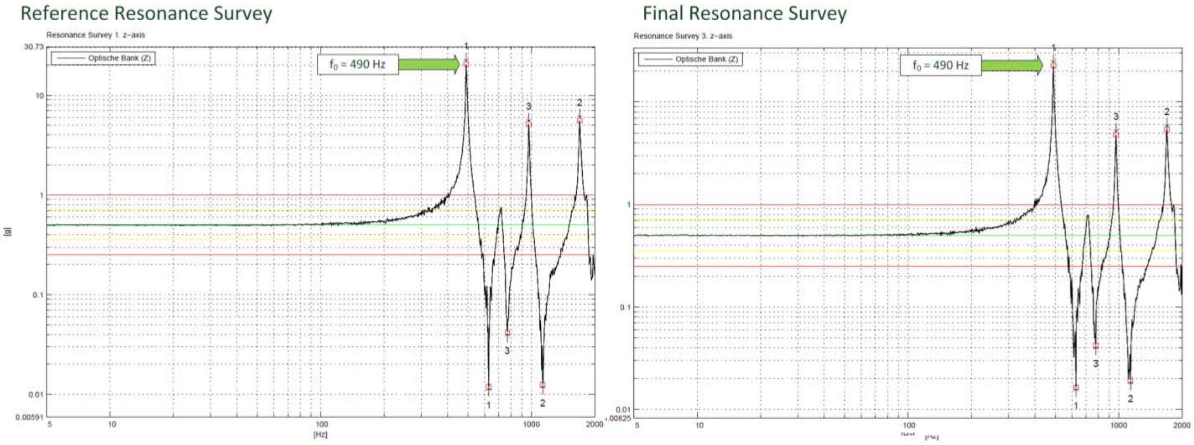

Figure 7: Resonance survey of the optical Bench in z-axis

Testing the payload under operating conditions includes the pressure and thermal environment. For this, a thermal-vacuum-test was carried out. Only the combination of both physical values allows conclusions for the actual operation on the satellite.
Two major effects have to be considered during the test. On the one hand the payload is heating up due to its power dissipation. On the other hand it is possible that the payload is heated by an external source like the sun or the satellite bus. Both possibilities are considered in the test. The test-temperature range reaches from -20°C to +60°C. This temperature is introduced by the test adapter where OSIRIS is mounted on in order to optimize the heat transfer. The pressure is reduced to $5 \cdot 10^{-6}$ mbar. The payload has to pass eight temperature cycles for the qualification test. During each cycle OSIRIS is turned into operational state two times (at -20°C and +60°C, steady state). Like this the payload is tested at its defined operating boundaries and internal as well as external heating effects are considered.

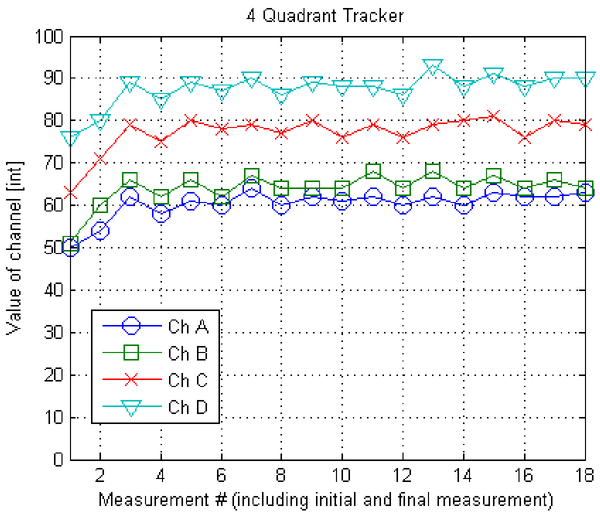

Figure 8: Channel measurement of 4 quadrant tracker during thermal vacuum test

The results of the thermal-vacuum-test show, that the EDFA works according to its specifications. The HPLD suffers from its temperature dependency. The measurements which are performed in the high temperature phases result in a lower output power. This behavior is explainable by the characteristic of the laser diode itself and can be accepted due to the thermally stabilized satellite bus. Also the 4QD is tested and the measurements, which are presented in Figure 8, indicate that it is working stable in the operating environment. Further it can be verified, that there is no change in the relative position due to thermal effects. The OSIRIS payload passed the vibration- as well as the thermal-vacuum-test within the specifications.

C. Radiation Test of laser sources

To complete the space qualification tests, a Total Ionizing Dose (TID) test with a Cobalt-60 source was performed at the Hahn-Meitner-Institute in Berlin.
The critical components to be identified are the electronic equipment, which could get degraded or even destroyed under radiation influence, and the optical fibers and components used in the EDFA and HPLD laser sources. Optical fibers - especially Erbium doped fibers - are known to degrade under gamma radiation and suffer from increased attenuation. This effect is intensified by additional dopants like aluminum and germanium, which are used for gain flattening and to increase the index of refraction.
The purpose of this test was to determine the amount of fiber degradation and the reliability of the electronic components in a radiation environment. The test was performed with the radiation parameters in the following table:

Table 2: TID test parameters

Total Ionization Dose (TID)	20 krad
Dose rate	4 krad/h
Test duration	5 hours (equals 5 years in space)
Measurement interval	1 krad (equals 15 minutes in test or 3 months in space)

The components were operated during the test in the following way:
Both Laser sources (HPLD and EDFA) were subject to the radiation test. The EDFA was operated in Automatic Current Control (ACC) mode to be able to monitor the degradation process. During the test the EDFA was switched on continuously at a low pump current. Each 15 minutes, the EDFA was switched to a higher pump current for 1 minute. Afterwards, the EDFA is completely switched off for 1 minute while the HPLD is powered. The optical output power was measured with the internal monitor diode of the EDFA module and an external optical power meter at the fiber output port.

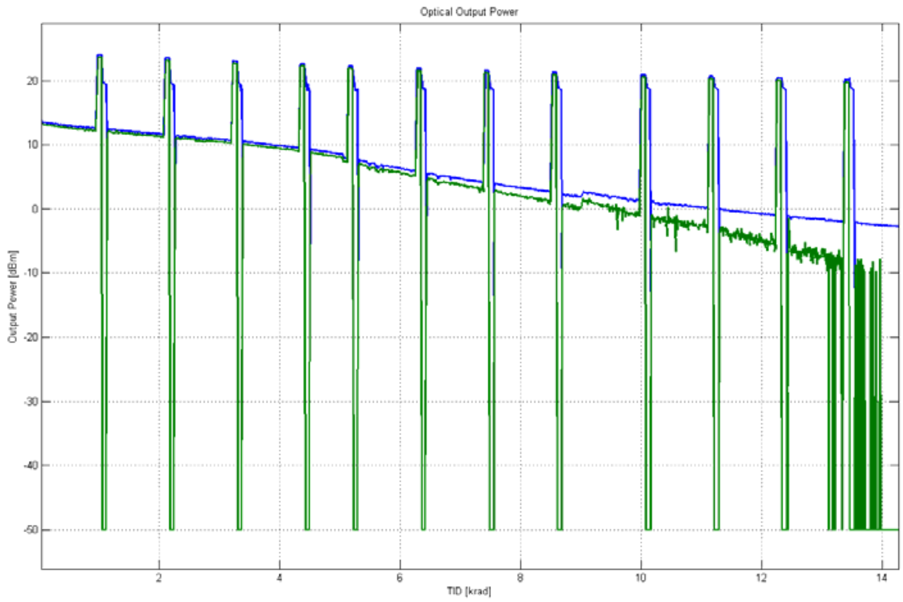

Figure 9: Optical Output Power over TID

Figure 9 shows the output power of O4B-EDFA. The blue line depicts the measured power at the output fiber whereas green is the EDFA output power measured by the internal monitor diode. It can be seen, that the measurement within the EDFA is correct and gives the same values as the external measurement device at the fiber output port. Figure 9 also shows the test procedure: first, the EDFA is running with low output power in standby for 15 minutes (1 krad). After 15 minutes, the EDFA is switched to a higher output power level for 1 minute (first half of the first peak). After 1 minute, the EDFA is switched off completely and the HPLD is

switched on with maximum power (second half of the first peak). After 1 minute, the HPLD is switched off and the EDFA goes to standby power level.
It can be seen, that the EDFA output power decreases from 24 dBm to 23 dBm within the first year. Over 5 years, the EDFA loses 5 dB of output power. In addition, a drift between internal measurement and external measurement for low power (standby mode) can be seen. The internal monitor diode is not able to detect power levels lower than a threshold of approximately -10 dBm – this is not relevant for a use in space because the EDFA will be used at higher power levels.
Furthermore, the EDFA will be operated in Automatic Power Control (APC) mode, which will automatically compensate for the increased attenuation. At some level, though, the internal gain of the EDFA will be too small to reach the desired output power, but this is to be expected after the satellites' end of life.
The output of the HPLD didn't show a significant decrease of output power. This leads to the conclusion that only Erbium-doped fibers, which are mainly used in EDFAs suffer from increased attenuation caused by gamma radiation.
The electronic devices used in O4B-EDFA didn't show any degradation or failure during the test. The DC/DC converters providing the supply voltage for the EDFA showed an increase of the output voltage by 3% after a TID of 10 krad, which is within the specification of the EDFA and can be tolerated.

V. SUMMARY AND OUTLOOK

The optical communication payload OSIRIS for DLR's BiROS satellite consists of an optical bench with tracking sensor and transmission collimators as well as two laser sources. The payload was calibrated and underwent a vibration-test as well as thermal-vacuum- and radiation-test. The OSIRIS payload passed all verification measurements and space qualification tests within the specification.
For laboratory testing and data storage during the mission, a GSE was developed that is able to provide all required optical and electrical interfaces to OSIRIS.

Figure 10: Optical Ground Station Oberpfaffenhofen (OGS-OP)

Figure 11: Transportable optical ground Station (TOGS)

After the launch of the BiROS satellite in 2015, the downlink experiments will be carried out with DLR's Optical Ground Station Oberpfaffenhofen (OGS-OP, Figure 10) and the Transportable Optical Ground Station (TOGS, Figure 11). Furthermore, an international downlink campaign involving ESA, NICT and NASA JPL is foreseen to continue the cooperation started in the OPALS experiment.

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