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OSIRIS Payload for DLR's BiROS Satellite

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Abstract— **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 for Communication and Navigation is currently developing an experimental communication payload for DLR's BiROS satellite. The OSIRIS payload consists of a tracking sensor for a precise alignment between satellite and groundstation, an optical uplink channel, two different and independent laser sources and an optical bench with the transmission optics.

This paper will give an overview about the BiROS satellite, the OSIRIS payload and the performance of the system, including space-qualification of the hardware and transmission tests.

Keywords—Optical Communication, Satellite Communication, Free-Space Optics, FireBird, BiROS

I. INTRODUCTION & OVERVIEW

A. Optical space-to-ground communication links and OSIRIS

Optical free-space communication links are being used more and more in applications with huge demands of data-transmission capacity. Optical communication experiments are carried out in e.g. aircraft downlink scenarios [1,2], as well as in space applications. Especially for inter-satellite link applications, optical communication systems have reached a very mature level [3] and will be used operationally for LEO-to-GEO links in the framework of the European Data Relay System (EDRS).

A further area under investigation is the field of direct space-to-ground links. The feasibility of these links has been shown by several experiments [4,5] and a number of technology demonstrators are currently under development around the globe [6,7,8,9]. The OSIRIS project (Optical Space Infrared Downlink System) of DLR's Institute of Communications and Navigation has the goal to develop optical communication technology optimized for small satellites. Commercial-of-the-shelf hardware is used to obtain a cost-effective approach and is suitable to fulfill scientific goals like atmospheric measurements, experiments with adaptive optics systems and to proof concepts like optical ground station diversity.

B. The BiROS Satellite

The BiROS satellite (Bispectral Infrared Optical System) has been optimized for fire detection applications and can be seen as a successor of the TET-1- and BIRD-satellites. BIRD was launched in 2001, laying the foundations and demonstrating the fire detection instrument used aboard TET-1 and BiROS [10]. TET-1 was launched in July 2012. BiROS, once available, will form a satellite constellation with the TET-1 satellite. Both will be used within in the so-called Firebird mission [11]. Figure 1 shows a picture of the BiROS satellite. The mounting position of OSIRIS is underneath the hatch marked by the black arrow. Besides the optical data link payload, BiROS carries several further experimental payloads, as e.g. a propulsion system and a pico-satellite launcher. BiROS is foreseen for launch in the first quarter of 2015.

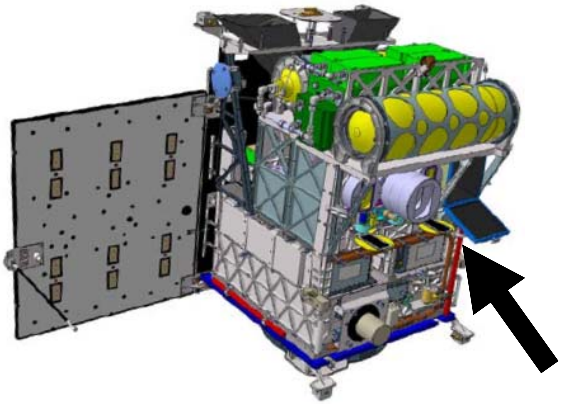


Figure 1: The BiROS Satellite

C. OSIRIS for BiROS

OSIRIS is a concept for optical data transmission from small satellites to optical ground stations on the earth surface. The goal is to demonstrate technologies enabling high-rate data links with up to 10 Gbit/s applicable to small satellites, which are typically restricted to RF-links in S-Bands with only few Mbit/s of available data rate.

OSIRIS for BiROS carries two separate laser sources with IM/DD modulation at 1550 nm and has been designed for a data rate of 1 Gbit/s, which is an increase of a factor 500 compared to the 2 Mbit/s S-Band link available for BiROS. Pointing and tracking is accomplished by steering the full satellite, resulting in a simple and robust system design without mechanics. Therefore, a tracking sensor is installed as well, allowing the usage of a beacon laser to aid the tracking of the satellite.

The optical signal is transmitted by two collimators with different divergence angles. This redundant approach enables an open loop pointing just based on the satellite's attitude sensors, and a closed loop pointing using the attitude sensors together with the OSIRIS tracking sensor. Wherever possible, all electronics have been designed one-error-tolerant. Figure 2 shows the link budget versus elevation for the erbium doped fiber amplifier (EDFA), which is one of the two laser sources of the system.

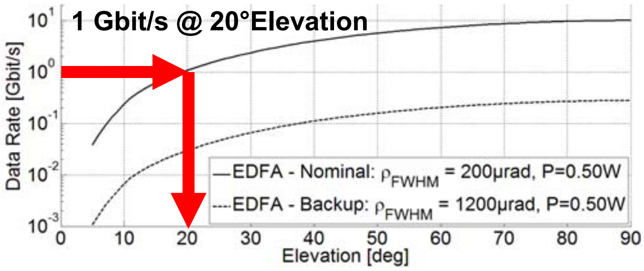


Figure 2: Link Budget (60 cm OGS @ DLR Oberpfaffenhofen, Atmospheric visibility: 22 km; Losses for atmospheric fading, the optical systems, tracking, etc. are included in the budget)

With the current setup and a 60 cm Optical Ground Station, a data rate of 1 Gbit/s can be reached at an elevation angle of 20°. The two divergence angles (200 µrad and 1200 µrad, both values FWHM) are still relatively large for this experiment and can be further reduced in future developments. This gain will allow for higher data rates or simply an improved link margin.

D. Ground Segment

Two optical ground stations will be available for experiments with OSIRIS: Optical Ground Station Oberpfaffenhofen (OGS-OP), as well as the Transportable Optical Ground Station (TOGS). Both are visible in Figure 3 and 4. The optical-bench setup of OGS-OP will focus on an installation of measurement devices for characterizing the atmospheric downlink channel, while TOGS will focus on data reception and BER measurements.

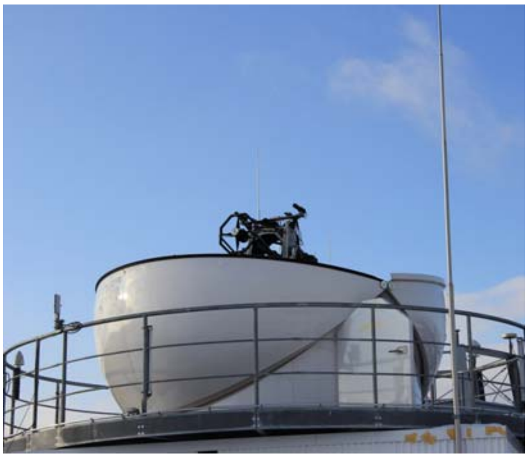


Figure 3: Optical Ground Station Oberpfaffenhofen (OGS-OP)

Figure 4: Transportable Optical Ground Station (TOGS)

E. OGS Diversity and Achievable Data Throughput

Optical satellite downlinks suffer from limited availability due to cloud coverage. To mitigate these effects, a network of optical ground stations must be used to make operational use of optical data links for direct downlinks. The optimization of suitable OGS networks is a current research topic, and standardization efforts are pursued by the consultative committee for space data systems (CCSDS) to ensure interoperability of free-space optical communication systems around the globe.

For the present experiments with BiROS, a simple estimation based on the BiROS orbit and single-site cloud-availability statistics has been done to obtain a rough throughput figure. The result is of course depending on the minimum link elevation and is compared to the data throughput achieved with the 2 Mbit/s S-Band link. Oberpfaffenhofen, Neustrelitz, Adelaide and Izaña/Tenerife have been considered as ground station sites. Each ground station contact above the corresponding minimum elevation is considered for data transmission. Effects due to scattered clouds (resulting in links that are only partly available) or restrictions due to limited satellite memory have not been considered. The results are visible in Figure 5.

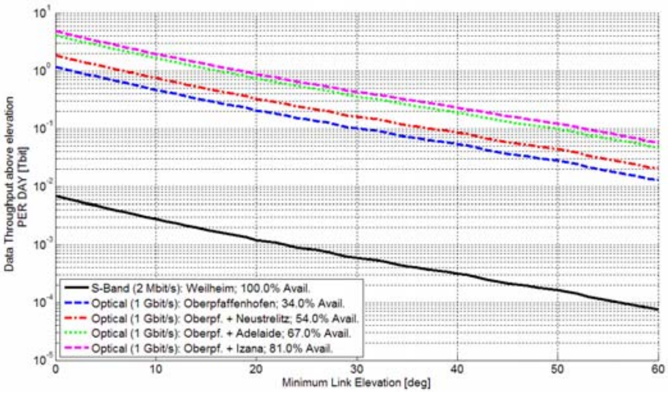


Figure 5: Mean daily data throughput for BiROS with different data links (RF, optical) and OGS setups versus minimum link elevation

With a minimum link elevation of 5° and an availability of 100%, and making use of each contact with DLR's RF ground station in Weilheim near Oberpfaffenhofen, the S-Band RF-Link enables the transmission of roughly 4 Gbit per day.

Even despite the poor cloud availability of Oberpfaffenhofen and the comparably high minimum link elevation of 20°, the optical link enables the transmission of roughly 200 Gbit per day with only Oberpfaffenhofen as ground station. By using both OGS-OP and TOGS for diversity, the theoretical mean daily throughput is further increased and reaches values of roughly 1 Tbit per day.

II. OSIRIS HARDWARE

A. OSIRIS Setup

The OSIRIS payload for DLR's BiROS satellite consists of three main parts as shown in Figure 6: The tracking sensor with its electronics, that receives and processes the beacon signal from the ground station and provides the tracking signal for the satellite payload computer and the attitude control. The tracking sensor is mounted on the same optical bench together with the transmitter collimators. The collimators are connected with the laser sources, providing two different laser signals.

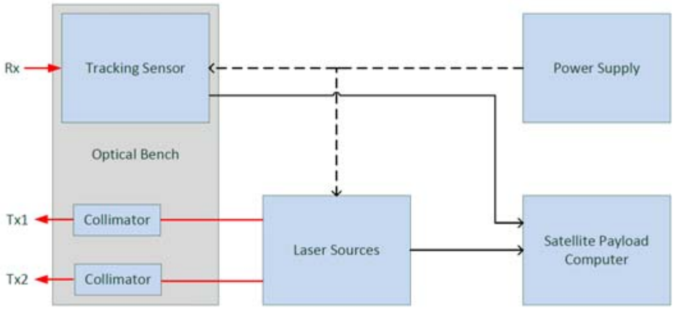


Figure 6: OSIRIS Hardware overview

The following chapters will discuss the parts of the OSIRIS system in more detail.

B. Tracking Sensor

The OSIRIS tracking sensor mainly consists of a quadrant type InGaAs PIN diode with an active area diameter of d=1mm. This detector is an integral part of the sensor and is mounted within a telescope parallel to the sending laser collimators on the optical bench. During operation, the ground station beacon laser illuminates the satellite and with this the detector. This beacon signal is modulated with tracking and data signals. The resulting spot on the sensor is defocused to a diameter of ~d/2 in order to achieve a large Field-of-Regard. Consequently every quadrant causes a current proportional to the incoming optical power. Since optical power in the range of a few 100 pW is expected and with this also a small current, the analog signal processing is challenging.

Critical parts of the analog circuit are placed close to the PIN diode to reduce EMI and parasitic effects. The large area of the PIN diode allows on the one hand a high resolution with acceptable mechanical tolerances. On the other hand it causes the main problem of this sensor topology: a high junction capacitance. Indeed a reversal voltage on the diode reduces this effect, but anyway we have to deal with a capacitance of ~20 pF per quadrant. This capacitance combined with the needed high amplification reduces the bandwidth of the sensor extremely. High data rates and rectangular signal wave forms suffer from this restriction. The capacitance also causes circuit instability, which is not discussed in detail in this paper. Furthermore, circuit noise is problematic due to the small input signal power. The passband, component values but also dimensions of the circuit have to be chosen wisely to achieve optimal results.

The beacon laser signal is modulated with a high frequency data signal up to 1 Mbit/s. The data signal is mixed with a 10 kHz rectangular signal as it can be seen in Figure 7. This allows a combination of high data rates and sensitive tracking. The basic circuit topology is presented in Figure 8. The four anode connections are used to sense the tracking signal. The small diode current is amplified with four transimpedance amplifier circuits (TIA). In order to remove background light, the signal is then high-pass filtered and a mean value is composed with the use of a rectifier circuit. This value, which is proportional to the incoming light intensity on every single quadrant, is now sampled with 12 bit resolution. Consequently the alignment of the OSIRIS sensor can be calculated by the satellite bus. These four signal paths are optimized to be noiseless and sensitive, which means that the bandwidth is highly limited and only the 10 kHz tracking signal can be seen. These paths are not suitable for high data rates.

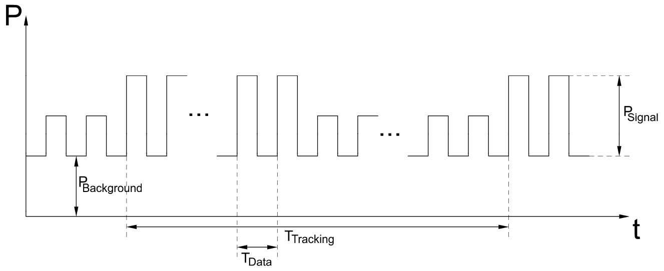


Figure 7: Optical Uplink Signal Waveform

In order to receive data, another TIA structure is placed on the common cathode connection. This circuit has a higher bandwidth and it is optimized for data reception. Here the total current of all quadrants is sensed, so that we can expect a higher signal current, though the seen junction capacity is also bigger. After an active filter/buffer, a comparator provides a bit decision. For this, the 10 kHz tracking signal needs to be suppressed with a sharp edge high-pass filter. In order to reduce random switching events, the comparator is implemented with a hysteresis. For this a positive resistive feedback is established. With appropriate resistances, the hysteresis can be set slightly above the noise level. Like this, the circuit noise doesn't increase for the case of low input power or for tracking without data transmission.

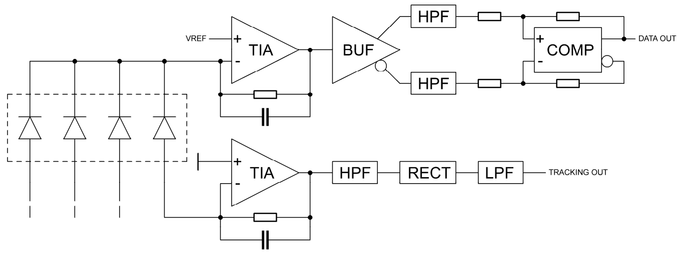


Figure 8: Basic Sensor Circuit

Figure 9 shows the measured output signal of one tracking path. The limited bandwidth leads to the typical RC charging waveform. It has to be mentioned, that this RC is correlated with the junction capacitance. Higher reversal voltages allow better values, but also limit the operational range of the system due to the limited output voltage swing of the TIA. Nevertheless, tracking is possible with 70 pW optical input power per quadrant. As it can be seen, the signal to noise ratio is the greater 3dB. Furthermore it can be seen, that high frequencies, which are caused by the transmitted data are suppressed efficiently.

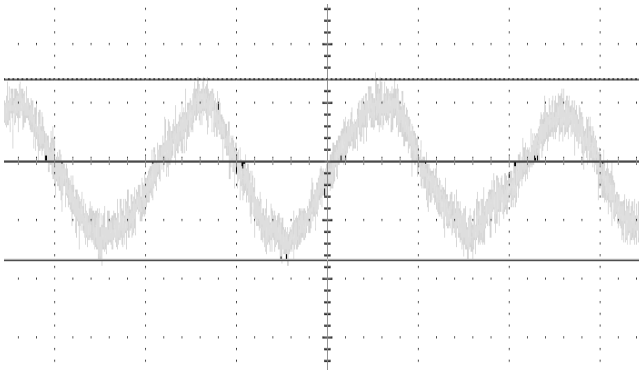


Figure 9: Analog tracking output with 70pW input power

In Figure 10, the received analog data signal is presented in an eye diagram. It can be seen, that the system is able to handle frequencies up to 1 Mbit/s. Figure 11 shows the analog data signal and the digital signal after the bit decision. Here an uplink frequency of 250 kbit/s is used. The 3dB attenuation can be observed. Furthermore it can be seen, that the data transmission is not disturbed by the tracking signal.

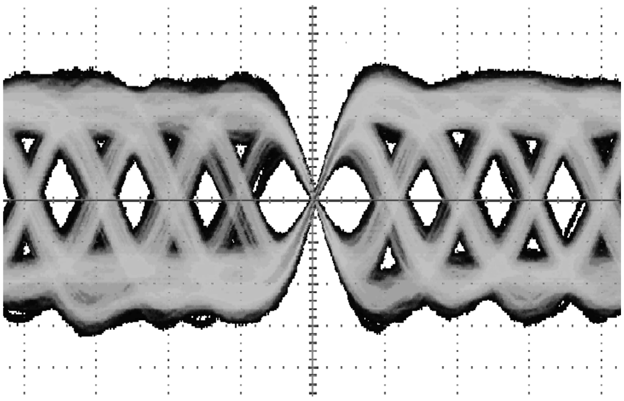


Figure 10: Data signal eye diagram (1µs/div)

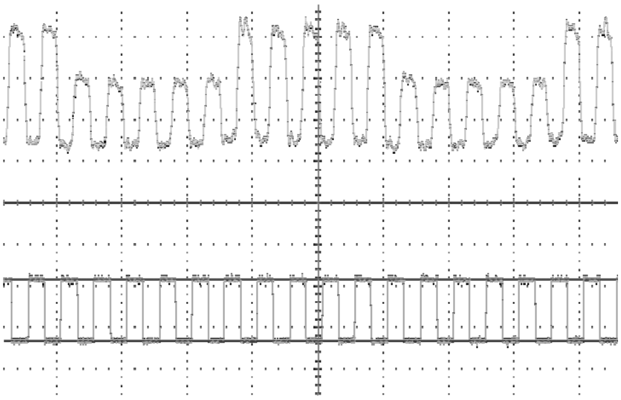


Figure 11: Data signal overlaid by tracking signal

C. *Optical Bench*

The optical bench is the mount for all optical components of the OSIRIS system. The optical bench consists of the tracking sensor as a receiver for the beacon signal from the groundstation and the uplink data channel as well as of two adjustable transmission collimators. To reduce the weight of the optical bench, an aluminium- carbon-fibre-construction has been chosen.

The challenge in designing the optical bench is the precise alignment of the three optical axes of the tracking sensor and the two collimators. For the data downlink, two overlapping collimators are used: one collimator with a divergence of 1200 µrad for pointing to the groundstation using the attitude sensors of the satellite and a second collimator with 200 µrad for pointing with the OSIRIS tracking sensor. The requirement for the precision of the alignment of the optical axes of the optical bench depends on the smallest divergence used. The boundary value for the alignment error should be +/-3σ, which leads to a maximum misalignment of 30µrad for the optical axes of tracking sensor and collimators.

Standard collimators suffer from a misalignment between the mechanical axis of the housing and the optical axis of the lens system. To reach the goal of a maximum misalignment of 30 µrad, the optical bench is equipped with adjustable collimators that provide the possibility to align the mechanical and the optical axes.

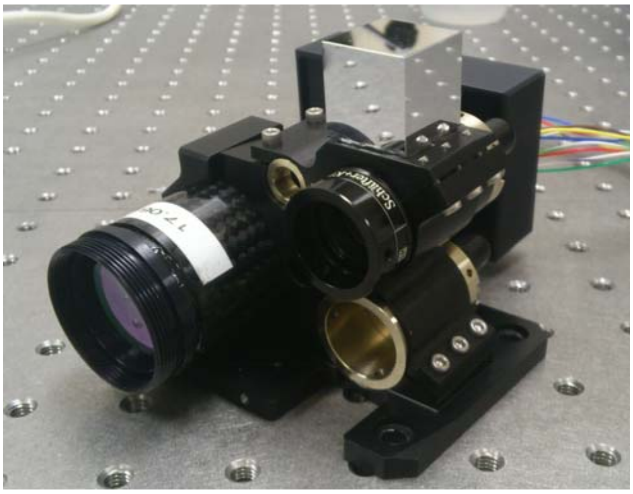


Figure 12: Optical bench with tracking sensor mounted on carbin-fibre-tube (left) and two adjustable transmitter collimators (right)

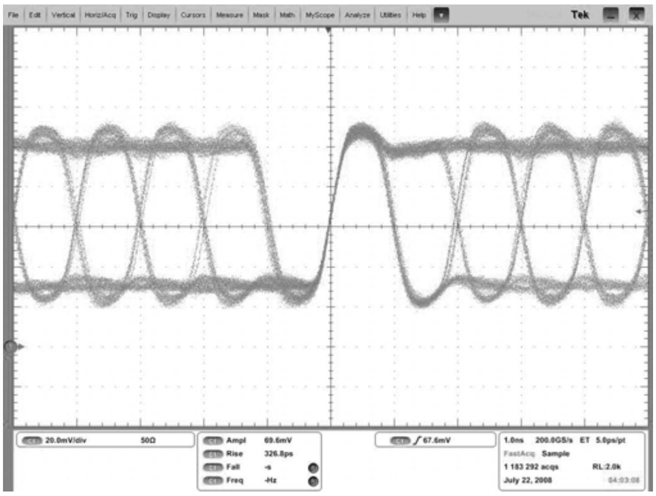
Furthermore the optical bench provides an alignment cube. During calibration measurements, the axes of the tracking sensor and the collimators are measured in respect to the alignment cube. The satellite's attitude control system and star camera is also referenced with an alignment cube that gives an absolute correlation between the satellites coordinate system and the OSIRIS coordinate system for pointing OSIRIS dependent on the satellites attitude control.

D. Laser Sources

The basic design of the OSIRIS laser sources 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 Laser Diode (HPLD). A power supply circuit based on 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 cannot deliver highest 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 design of OSIRIS, since both technologies are integrated inside the same housing and share the same electronics. But for future missions this advantage can be used if power consumption, weight and size are critical. The HPLD is more robust against cosmic radiation compared to the EDFA, which contains doped optical fibers that are sensitive to radiation and might degrade after a few years in space [12,13].

As a data source for the EDFA, a fiber-coupled laser module commonly used in terrestrial fiber communications is employed. 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. The wavelength can be chosen from the ITU C-band DWDM grid at time of integration. The signal modulated by the laser module is fed to the optical amplifier by a singlemode fiber connection. The EDFA is able to amplify the incoming light to a maximum optical power of 1W. The output signal of the EDFA is shown as an eye diagram with 1 Gbit/s in Figure 13. The amplified signal then is sent to a cross-coupler, which splits the power 50:50 into two fibers for the Tx-collimators.



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C1 20.0mV/div    50Ω     C1 Ampl   69.6mV     C1 ∫ 67.6mV    1.0ns   200.0GS/s  ET  5.0ps/pt
                         C1 Rise   326.8ps                   FastAcq  Sample
                         C1 Fall   -s                        1 183 292 acqs        RL:2.0k
                         C1 Freq   -Hz                       July 22, 2008         04:03:08
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Figure 13: Eye diagram of an 1 Gbit/s PRBS7 signal at EDFA output

The HPLD is a directly modulated semiconductor laser diode driven by a specialized driver circuit, which provides a current in order to modulate the laser diode. The HPLD has a maximum data rate of 78 Mbit/s and a mean optical output power of 50 mW in the current development stage. It is expected, that 100 Mbit/s at 100 mW output power can be reached in future. 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. SPACE QUALIFICATION

For the space qualification, OSIRIS had to pass several tests: thermal-stress test for the optical bench, vibration test with verification of spatial calibration and a thermal-vacuum-test. The tests and the results will be discussed in this chapter.

A. Thermal-Stress-Test

The optical bench has to keep the alignment between the optical axes of the tracking sensor and collimators with a precision of 30 µrad. Due to its position in the satellite, the optical bench has to work within the specification over a temperature range from -20°C to +60°C. To ensure the required precision within the full thermal range, a thermal-stress-test has been performed.

Therefore, a telescope has been equipped with an infrared-camera and has been mounted on an optical table. On the other end of the table, the optical bench is mounted together with thermal sensors and a heating unit. During the measurement, the x- and y-position of the collimator on the camera and the thermal sensors are monitored by software. This measurement is repeated for every single optical axis.

The optical bench was cooled down to -20°C at the beginning of the measurement. During the measurement, the optical bench was heated up to a maximum of +60°C. Figure 14 shows the results taken by the software: thermal range and x- and y-position during a 4-hours thermal cycle with a thermal rate of change of approximately 15°C/h. The measurement setup is calibrated in a way, that one sub-pixle correlates to 10 µrad angular change. Applied to the measurement result in Figure 14, the optical axis of the collimator stays within an angular range of 22 µrad in one thermal cycle, which is well below the specified threshold of 30 µrad.

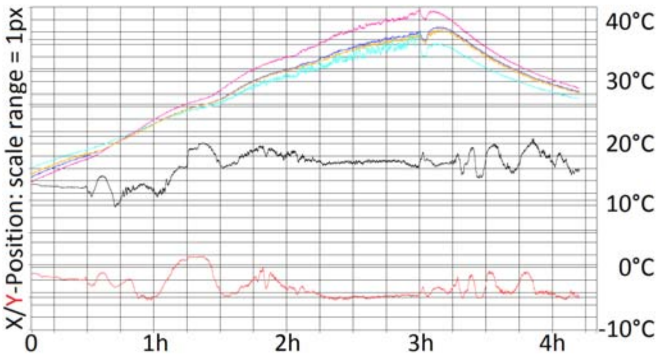

Figure 14: Measurement of one collimator over thermal range (position in x and y (red and black) full diagram range 100 µrad, temperature curves at different measurement points of optical bench (yellow, blue, magenta, cyan))

B. *Calibration and Vibration*

For aligning the optical axes it is necessary to align the mechanical and optical axes of the collimators to the optical axis of the tracking sensor. Thereby, also inaccuracy during manufacturing of the optical bench itself can be compensated. During calibration process, the spot diameter of the tracking sensor, which influences the tracking and attitude control dynamics, as well as the angles between the axes and the alignment cube are measured and aligned.

For a highly-precise calibration of the setup, DLR's optical calibration lab in the Institute of Optical Sensor Systems in Berlin was used. The cleanroom is equipped with an interferometrically aligned collimator and a tip-tilt-unit for a 100 kg-payload with a positioning accuracy better than 10 µrad. Figure 15 shows the tip-tilt-unit with the OSIRIS optical bench installed. Besides the bench, two theodolites are mounted to measure the angular reference between the optical axes and the alignment cube.

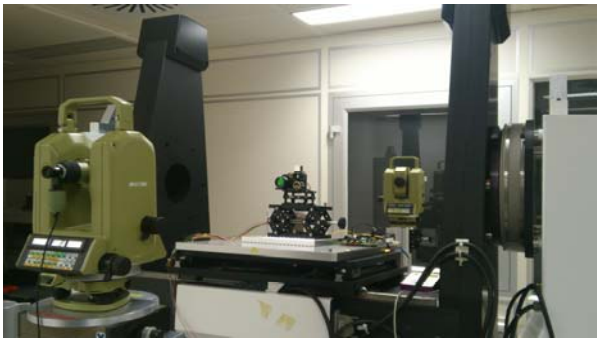

Figure 15: OSIRIS Optical bench mounted on tip-tilt-unit

Due to the high requirements regarding the calibration and alignment of the OSIRIS optical system, the vibration test is necessary both for the verification of the optical bench and the vibration acceptance test for the electronics. Therefore, a vibration test according to MIL-STD-810F with a sine sweep and a random vibration was performed.

Figure 16 shows the test setup on the shaker. The OSIRIS components optical bench, tracker electronics and laser sources are mounted on a test adapter and equipped with acceleration sensors.

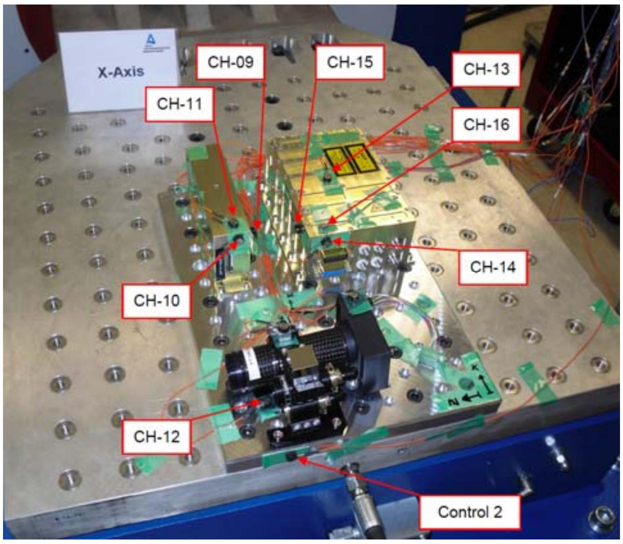

Figure 16: OSIRIS components mounted with test adapter and vibration sensor channels on shaker for vibration test

After each space qualification step, the alignment measurements were repeated, so that the angular stability of the optical axes can be verified. OSIRIS passed the vibration test without any mechanical or electrical damage and without any changes of the alignment within the measuring accuracy.

C. Thermal-Vacuum-Test

The OSIRIS payload is qualified according to the standard ECSS-E-ST-10-03C, thermal vacuum test. For this the payload is tested in an evacuated atmosphere with a specified pressure below 10^{-5} hPa. Since the OSIRIS payload is mounted on a temperature controlled satellite bus, eight thermal cycles between -20°C to +60°C were accomplished. During the test, the OSIRIS payload was mounted on a thermal ground plate which introduces the test temperature into the system. Functional tests at the extreme temperatures were done after a steady state was reached. In Figure 17 one thermal cycle of the test between -20°C and +60°C is presented. The time is measured in minutes. It can be seen, that the thermal connection between the ground plate, the laser sources (HPLD, EDFA) and the tracker electronics is optimal. Since the transmitter collimators are passive elements, a thermal connection to the satellite bus is less important. The effect of the carbon telescope can be seen on the temperature profile of the tracking sensor. The sensor is isolated from the satellite bus, but the power loss in the tracking sensor is unproblematic and causes no problem at this point. The OSIRIS payload passed the thermal vacuum qualification and it worked within the specification.

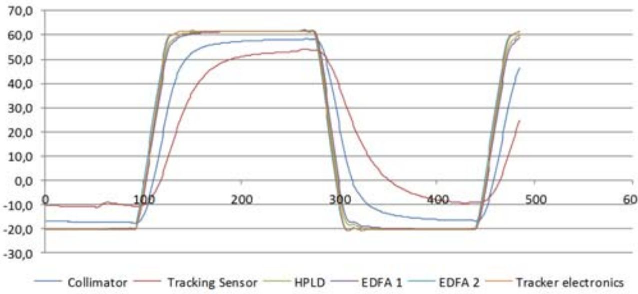

Figure 17: One temperature cycle during thermal vacuum test

IV. SUMMARY

The OSIRIS hardware developed at DLR enables high data rate downlinks from small LEO satellites. The laser terminal is equipped with two downlink laser systems with up to 1 Gbit/s and an optical uplink channel with up to 1 Mbit/s, which is orders of magnitudes higher than currently used RF-links. The OSIRIS Qualification Model passed the space qualification tests successfully. The Flight Model is now to be integrated and ready for launch of the BiROS satellite, scheduled for beginning of 2015. The first measurement campaigns to the optical ground stations of DLR will take place in 2015.

V. ACKNOWLEDGMENT

The authors express their gratitude to the entire OSIRIS team at the Institute of Communication and Navigation in Oberpfaffenhofen and the Institute of Optical Sensor Systems in Berlin with the colleagues Ilse Sebastian, Axel Lauterbach and Friedrich Schrandt for their dedication, support and hard work.

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