The Flying Laptop Mission after more than four years of Operation

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ABSTRACT

The „Flying Laptop“ (FLP) small satellite was developed as a technology demonstration platform which was launched on July 14th 2017 into a 600 km Sun synchronous Low Earth Orbit (LEO). It is currently being operated by the University of Stuttgart's Institute of Space Systems (Germany). Although the designed lifetime of the satellite was two years, more than four years into the mission, it is still fully operational. During the past four years of operation, all systems on-board were used extensively for technology demonstration, earth observation, and education. This Paper describes the major achievements of the mission so far. One of the accomplishments is the successful operation of its optical laser terminal OSIRISv1. The instrument OSIRISv1 was developed by the Institute of Navigation and Communication of DLR in Oberpfaffenhofen. Involving experiments with DLR, ESA, JAXA, KSAT and NICT, this payload is used to test body-fixed optical links from LEO to ground. Apart from experimental links, additional downlinks were performed to characterize optical ground stations for further use within the developing market of optical communication payloads in the near future. This paper describes the operational challenges of optical communication for Direct-to-Earth links from LEO based on the experiences made during the FLP mission. In addition, an overview of the challenges faced for mission planning and on-board attitude control is presented. Flying Laptops second mission goal, earth observation, is also performed on a regular basis. The paper includes a summary of the activities executed with the cameras and the AIS receiver on-board of FLP. Furthermore, as small satellites have become an important tool in education, this paper describes how FLP is integrated in the curriculum of aerospace engineers in Stuttgart. This includes the usage of satellite data and ground infrastructure in the training of students. The paper contains the lessons learned from more than four years of education. Overall, the FLP mission shows that small satellite operations can be performed reliably within the context of a University and with a small core team size.

1 INTRODUCTION

The small satellite *Flying Laptop* (FLP) was developed and built by graduate and undergraduate students at the Institute of Space Systems (IRS) of the University of Stuttgart with support by space industry, most notably "Airbus Defence and Space" and "Tesat Spacecom". The "German Aerospace Center" (DLR) provided valuable knowledge, different instruments and their ground station network. [1]

FLP, was launched in July 2017. The mission goals are technology demonstration, earth observation and serving as an educational satellite. *FLP* has a three-axis stabilized attitude control, a completely redundant bus architecture, and five payloads requiring different pointing maneuvers. With a mass of 110 kg it belongs into the category of micro satellites. The satellite is designed as a single point failure tolerant system with an expected life time of 2 years which it has already exceeded by more than 2.5 years. *FLP* is compatible with the ECSS packet utilization standard (PUS) (Version A) [2].
The payloads consist of:

- The Multi-Spectral Camera System (MICS). It consists of three cameras in the green, red and near-infrared spectrum.
- A Panoramic Camera (PAMCAM) which is used to take colored pictures for public outreach.
- An AIS-Receiver to receive signals from ships in cooperation with DLR Bremen.
- The optical communication Terminal OSIRISv1 from DLR Institute of Communications and Navigation. The instrument is body-fixed and does not include an optical receiver. Hence, the satellite body must be pointed towards the Target.
- A S-Band Transmitter (DDS) for payload data developed at the IRS.
- The Payload Onboard Computer (PLOC) developed at IRS.

All cameras, the DDS and OSIRISv1 are facing in the same direction and are visible in Figure 1. The MICS are mounted in the left upper part and marked in green while the PAMCAM is inside the purple circle on the top right. Both collimators of OSIRISv1 are mounted above the DDS Antenna between the PAMCAM and the MICS inside the red circle. The AIS Antenna is not visible in the Image as it is deployed in Orbit.

2 OPERATIONS

The launch and early orbit phase (LEOP) was successfully finished after the first four days of in-orbit operations. Afterwards the commissioning phase was finished after 100 days in orbit. Since then, the mission has been in its routine operations phase. A detailed overview of the early phases was provided at IAC 2018 [1]. As of March 2022 all components are operational. The only exception being the De-Orbit Mechanism from Tohoku University which will be used to increase the drag during the Disposal Phase.
The operations team was reduced to two PhD candidates in 2021 with the support of Students and PhD candidates of other satellite projects at the IRS. Therefore, the shifts were reduced to three uplink passes during the week and a shift for offline Telemetry observation. This is only possible due to a

Figure 1. FLP in deployed configuration. Marked are: MICS in the green circle, PAMCAM inside the purple circle and the collimators of OSIRISv1 in the red circle, image: J. Keim, IRS

high degree of automation in the mission planning. In the current ground segment, this is achieved by a Mission planning suit developed internally. In addition, SCOS-2000 is used as a Mission Control System, although it is only used for commanding as the Telemetry processing is implemented independently from SCOS-2000. However, the whole ground segment is currently being replaced by a new ground data system which was presented on the SpaceOps Conference 2021 [3]. The new system focuses on multi-mission operation which is necessary with the upcoming two satellite Missions EIVE and SOURCE at the IRS.

2.1 Bus Experiments

With the GENIUS experiment by the DLR, the first scientific measurements were executed in the first year of operations [4]. This experiment used three GPS Receivers to successfully calculate the satellite attitude. Three studies were published in the following. The first one focuses on radiation effects in the bus components. This analysis was published in Advances in Space Research [5]. A follow up Paper was presented on the 13th IAA small satellite symposium on small satellites for earth observation in Berlin 2021 [6]. The third study was based on recorded Telemetry of the onboard telecommand receivers [7]. Over the time of three years *FLP* recorded the signal levels received around its center frequency of 2083.5 MHz. Although the receivers where not designed to perform this kind of study, it was found that some regions on Earth have increased their radio noise during this period of time. However, without a specific instrument the resolution of the data is low.

In addition to those Studies *FLP* performed passes with its 2408 MHz DDS for Amateur Radio operators. Also, the Telemetry of *FLP* is available publicly and can be downloaded from the University of Stuttgart [8].

2.2 Bus Component Issues

During the 4.5 years of Operation there were some operational issues with onboard components. The two main challenges were caused by the Power Control and Distribution Unit (PCDU). This component manages the power distribution from the three independent solar panels and batteries to the all onboard components. In the design of *FLP* it is also the main A/D converter and acting as a RIU [9]. On 2019-10-28 the Flight Software reported that one of the MICS has its power switch activated although it should be off. After checking the Telemetry, there was no current flowing. The conclusion was that the switch is actually off. At the same time five other power switches reported a wrong state. Further analysis showed that the location at the time was inside the South Atlantic Anomaly and a radiation event inside the OBC was detected a few seconds before. However, the attribution to radiation can not be confirmed but is highly likely. The issue resolved itself after the PCDU switched to its other CPU due to an unknown issue. As a reaction to this issue a fix for the Flight Software which allows to ignore the switch state returned by the PCDU was developed. The issue has not reoccurred yet.

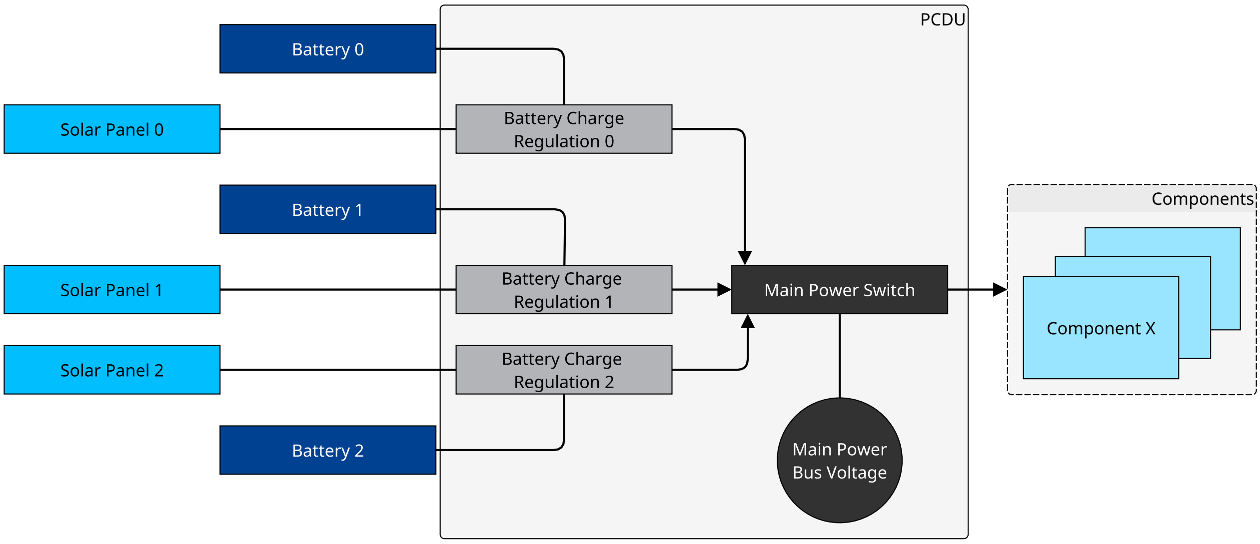

Figure 2. Simplified PCDU schema

The other issue started in the beginning of March 2021, when an increase of Voltage on the Main Power Bus was recorded. The Power Bus Voltage is measured after the combination of all three independent strings of solar panels and their batteries as shown in Figure 2. Its nominal value is in the range of 25.5 V and below. In the end of March 2021 the peaks rose over 26 V which can be seen in Figure 3. As a reaction, the operations team rotated the satellite by $65°$ away from the Sun. This did reduce

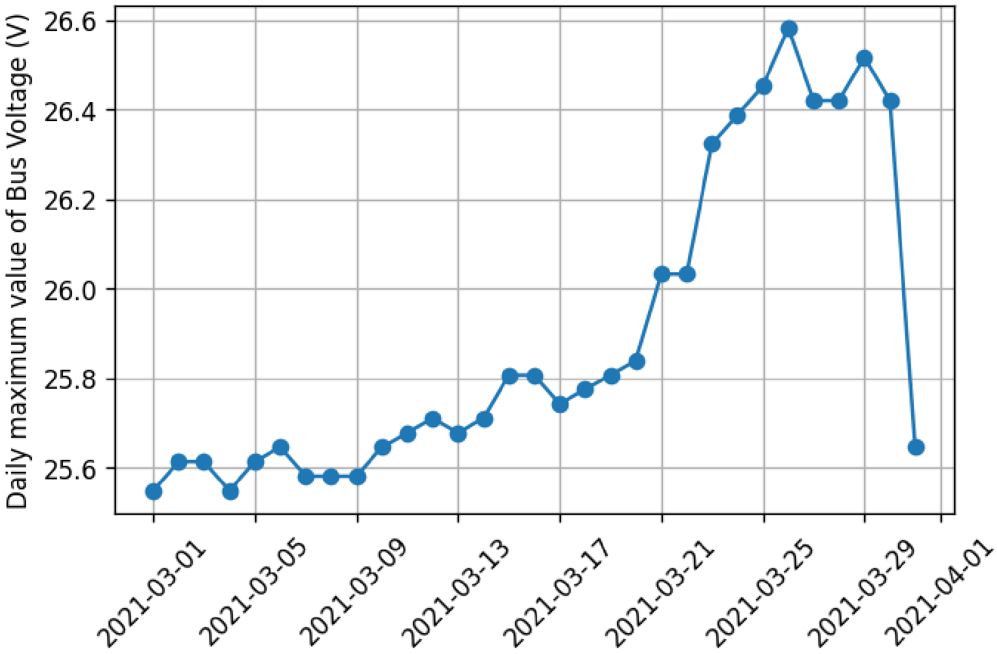

Figure 3. Daily maximum of the Bus Voltage shows the anomaly during March 2021

the peaks and is the reason for the drop of the maximum value in March 2021, as shown in Figure 3. However, the peaks were not resolved completely, so further investigation was required.

It was found that the time of the peaks correlates with the end of the charging of one battery. This correlation is shown in Figure 4. The first part of the charging is caused by the satellite leaving the eclipse phase. Afterwards, the battery will be charged again after 3 min. Every time the string is charged again it causes a new peak until the voltage difference is too low.

Unfortunately, there is no switch to disconnect this string from the main power bus. A temporary solution was found with the manufacturer: the end voltage to force off the battery charging for this string was set to a lower value. The Peaks were resolved for some time but further spikes occurred in the end of October 2021. This time the peaks reached the maximum voltage of the Main Power Switch of 28 V. The Main Bus switched off as to protect the components. The voltage dropped after a few seconds and the satellite rebooted. As a reaction, the voltage, at which the charging is stopped, was further reduced. The reason of the peaks in the bus voltage is currently unknown but it might be caused by the drift of a Voltage reference. Therefore, the expectations are that the voltage to end the charging needs to be lowered even more in the future. Unfortunately, this can only be done as long as the lowest possible value is not reached. The strategy afterwards includes maximizing the power dissipation on the component side.

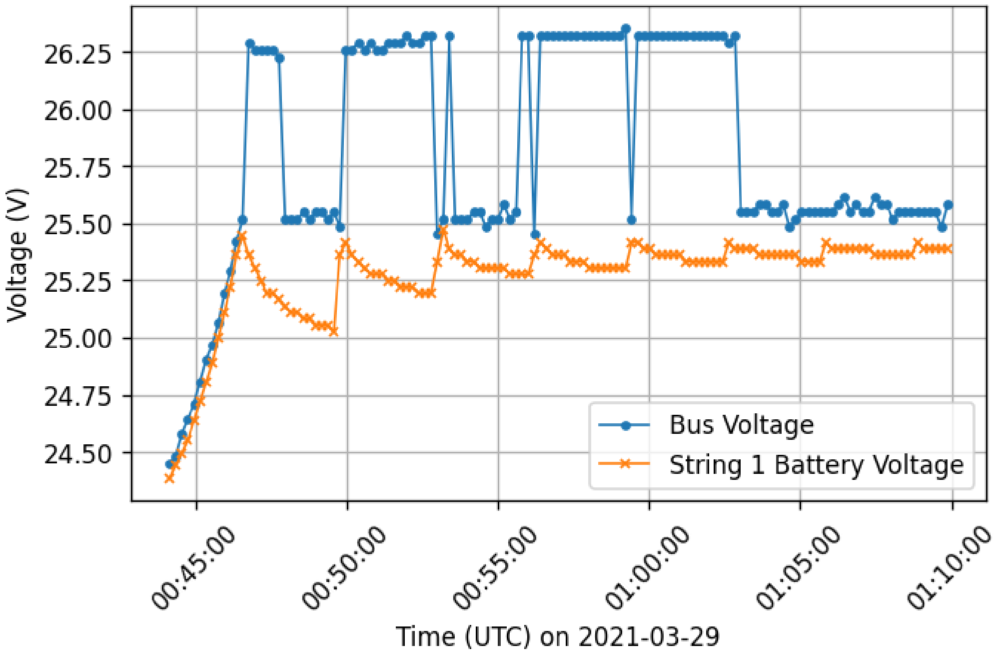

Figure 4. Bus Voltage vs Battery Voltage of String 1 on 2021-03-29

2.3 Payload Experiments

The MICS and PAMCAM are used on a regular basis. While Pictures from the PAMCAM are mostly used for public outreach, pictures of the MICS are used for scientific purposes. Images from the MICS have been used in cooperation with the Universiti Putra Malaysia (UPM) to analyze the vegetation of palm plantations in Malaysia. In Stuttgart, the images have been used in an earth observation lecture by Students. Multiple studies on various topics have been performed with a combination of pictures of Flying Laptop and Copernicus data. One of those studies was used as a baseline for a performance characterization of the Attitude Control System [10]. Other groups of students used the payload data to combine the AIS ships signals with image data, create vegetation index images or observe melting ice surfaces.

The AIS Receiver records data on a daily basis. Recent campaigns include the observation of the Mexican coast, the Indian Ocean between Australia and India, and the North Pacific.

3 OSIRIS

During the 4.5 years of operations, the optical downlink system on *FLP* was used for various campaigns. An overview of the most important one is presented in the next section.

The instrument OSIRISv1 consists of two 1550 nm light sources which are connected to two different collimators. One collimator is connected to an erbium-doped fiber amplifier (EDFA) which has an output power of 30 dB_{mW}. The other source is a high power laser diode with a mean output power of $20\,\text{dB}_{\text{mW}}$. However, all experiments described in this paper were performed with the EDFA laser. The instrument is capable of $200\,\text{Mbit}\,\text{s}^{-1}$ with its internal bit sequence generator but the data rate for payload images is limited to $80\,\text{Mbit}\,\text{s}^{-1}$ by the Payload Onboard Computer of FLP. Both collimators are set to a half power beam width of $1.2\,\text{mrad}$ and are mounted to the body frame.

3.1 Campaigns

The campaigns with OSIRISv1 on *FLP* started in July of 2018. During this campaign, with the optical Ground Station of DLR in Oberpfaffenhofen, the target was to spot the laser beam. Without an optical uplink the beam must be found with search patterns. After a few tests the first flash was observed in August of 2018. This allowed to calibrate the direction of the instrument. Afterwards, the beam was spotted on a regular basis but the performance was not consistent over the passage [11]. During those campaigns the descending part of the pass showed a consistently better signal intensity than the ascending part.

In December 2018 a campaign in cooperation with CNES was performed. The optical G/S in Grasse was used to successfully detect the signal of *FLP* [12]. The signal was recorded in every pass but the signal intensity fluctuated, which could be attributed to the satellite.

During further campaigns in Oberpfaffenhofen it was found that the Star Camera Head Units (CHU) on *FLP* were slightly above the ideal temperature. A procedure to cool down the star cameras was developed and further tests showed that the signal was more stable. In combination with this procedure, the calibration of the pointing direction of the laser collimator was improved in a Campaign in September 2020. This resulted in the first successful transmission of a *FLP* payload image with OSIRISv1 in the beginning of October 2020.

In February of 2021 experiments with the National Institute of Information and Communications Technology (NICT) in Japan were performed [13]. The ground station in Japan received the signal from *Flying Laptop* with its $1\,\text{m}$ aperture telescope. The aim of this experiment is to measure atmospheric turbulence for future optical communication systems.

As *FLP* is one of only few satellites with a working optical downlink system it is used to provide a target for new optical ground stations. The first tests were performed with Kongsberg Satellite Services (KSAT) in May of 2020. A still from the video feed from the telescope, receiving the laser signal, can be seen in Figure 5. In addition, in March 2022 a portable G/S from Astrolight was used to successfully detect *FLP* during night passes over Vilnius.

3.2 Challenges

An optical link without an uplink has some unique challenges. At launch, the pointing accuracy of *FLP* did not fulfill the requirement of $150''$ Absolute Performance Error during the target overflight. Improvements in filtering and fusion of attitude data from the star cameras and rates from the fibre-optic gyroscope allowed a more stable pointing. The pointing requirement can be fulfilled during parts

Figure 5. Still from Video from OSIRISv1 on FLP received by KSAT G/S [14]

of a pass, which was shown with MICS pictures [10]. However, the pointing of the optical terminal was still not stable enough.

Further investigation pointed out that the star cameras do not provide the required accuracy. This is attributed to the temperature of the Camera Head Units (CHU). As *FLP* has two CHUs, the comparison between the solutions allows monitoring the accuracy. The quantity is called Inter-Boresight-Angle and the temperature dependency of this is shown in Figure 6. Although this allows the detection of an issue with one of the cameras, the attribution to one of them is not possible. During an overflight over an G/S the satellite needs both CHU as one will be blinded in the beginning and one in the end of the pass. Additional errors might occur if the Moon or the Sun enters the field of view of one of the camera heads. Due to the higher brightness the risk of blinding from the Sun is higher than from the Moon. Hence, night passes will usually provide a greater accuracy as the Sun will be behind Earth.

Another challenge is the degrading performance over higher rotation rates in the middle of the passage. This relation between the rotation rate and the Inter-Boresight-Angle of the star cameras is shown in Figure 7. The maximum error is reached after the peak rotation rate.

As most G/S can not provide a measurement of the received intensity but only a relative brightness it is difficult to calibrate the collimator direction. Challenges are due to different Data Formats and the lack of comparability between G/S. In the case of *FLP*, the calibration of the collimator direction allows a continuous signal for Oberpfaffenhofen but shows fluctuations over other G/S. The reason for this is currently unknown but might be caused by a static error in the onboard Navigation which is equalized by a constant off-pointing. This issue needs to be investigated with data from other ground stations.

Furthermore, a specific type of fluctuations is caused by the onboard Reaction Wheel management.

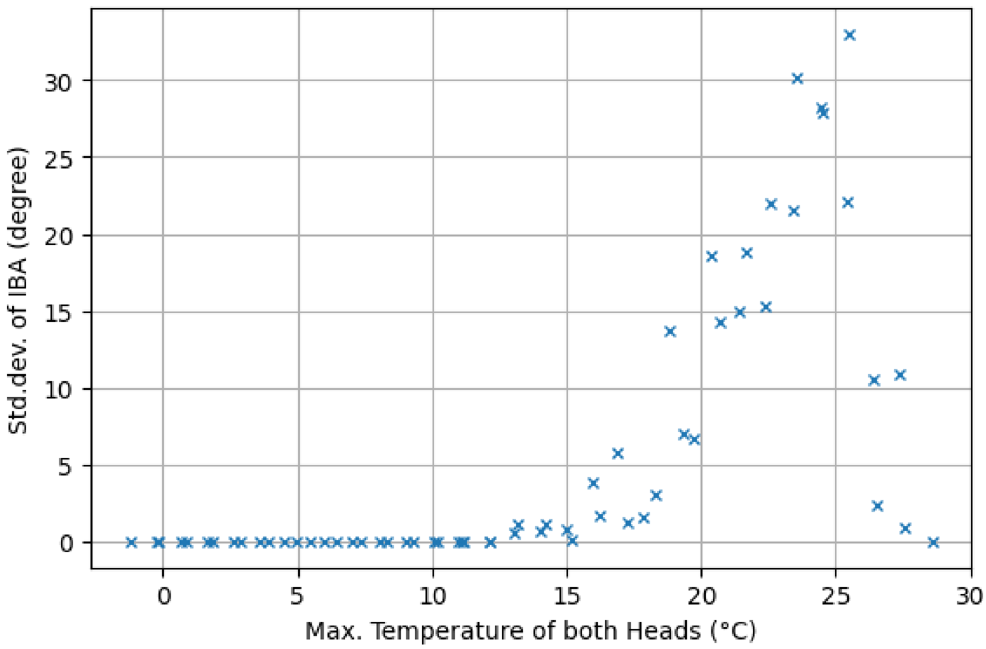

Figure 6. Standard Deviation of Inter-Boresight-Error between CHUs over the maximum Temperature of the heads

The vibrations in the rotation rates shown in Figure 7 is caused by ACS controller. If a Reaction Wheel changes its rotation direction during the pass it is commanded to provide a constant torque to avoid the wheel to get stuck. Even though the controller uses a hysteresis, this mechanism still causes the controller to oscillate. A fix for this behavior was implemented but has not been deployed on the Satellite yet.

In conclusion of the performance, the signal intensity fluctuates over the passe but the downlinks are repeatable without issues. Every G/S was able to track the satellite.

3.3 Operations

An optical link needs some special considerations for the operation of a satellite. First, in comparison with a S-Band downlink the weather over the G/S has a large impact. Therefore, the links need to be planned very flexible as weather reports are inaccurate for more than a few days. Hence, optical links can only be planned a few days in the future. Second, the required pointing performance for a body-fixed collimator usually needs some preparation. With only one Star Camera a satellite needs to perform a blinding avoidance which introduces an additional rotation. This has a negative impact on the accuracy of the star camera so there is a trade-off to be made. Even with two camera heads the unavailability due to blindings might require a simulation and precautions to be made.

In the case of *FLP*'s issue with high Star Camera temperatures, there is a special procedure needed to cool the heads. During this procedure the satellite will be commanded into its Safe Mode in which

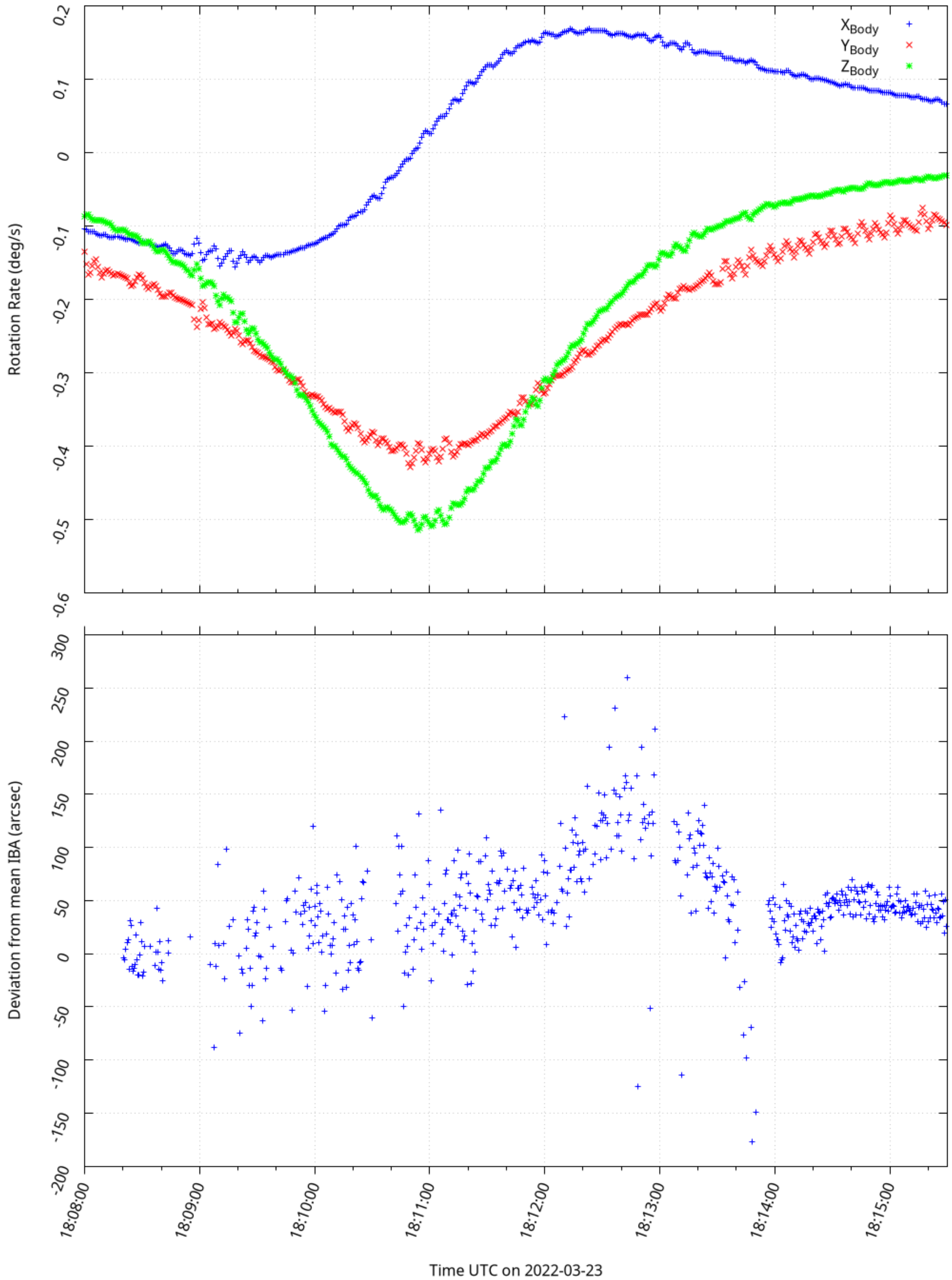

Figure 7. Rotation rate and Deviation of median Inter-Boresight-Angle (IBA) of the two STR Camera Head Units during a G/S Pointing

the heads are deactivated. As the heads are thermally decoupled from the Bus and have their own radiator this is the only practical solution. Another procedure was tested in which the satellite was rotated slightly to hide the outer skin of the MLI on the heads behind the solar panels. This resulted in slightly lower CHU temperatures but pointed the Bus Radiator towards the sun, which caused the other modules to heat up very quickly. Although, the angle was only $25°$, this caused the bus components to reach critical temperatures. Therefore, this could not be used as permanent solution.
During the cool down of the Star Cameras the satellite has to remain in its Safe Mode. Hence, the mission planning needs to reject all other payload campaigns during that time. This requires a dynamic mission planning system with the possibility for flexible updates.

4 EDUCATION

Flying Laptop is integrated in the curriculum of aerospace engineers in Stuttgart with two main lectures. First, the operations lecture which provides an overview of the tasks necessary during spacecraft operations. Second, the earth observation project in which students will work on images from satellites to study the practical usage of such data.
During the operations lecture students learn how to plan the operations, executed procedures and how to interpret satellite telemetry. It includes hands-on experience with the system simulator of *FLP*, which is used to simulate a full LEOP over the semester. During that time, every student has the possibility to work on all control room positions.
The Earth Observation project allows students to analyze data from *FLP* and other satellites over the time of a semester regarding a special topic. This topic is defined by the students together with their supervisor. This can range from calibration of satellite imagery to ice monitoring on Earth or cloud detection in images. The goal of this lecture is a better understanding of earth observation using satellites and to gain hands on experience working with satellite data.
Furthermore, during the *Flying Laptop* Operations more than 15 Bachelor and Master Theses were completed.

5 SUMMARY and OUTLOOK

Flying Laptop has been operational since 4.5 years. The satellite performed various experiments successfully and is used for Earth Observation on a regular basis. This is possible, because every process, that can be automatized, was integrated into a suite of mission planning tools.
One experiment is the optical data downlink OSIRISv1. The possibility of a body-fixed pointing of such an instrument was shown during campaigns with multiple partners. Although, there are still some challenges to be overcome it is shown that it is possible to perform such links. Furthermore, recommendations for future operations of optical links were provided.

FLP is also integrated in the educational aspects of the Institute. Many future aerospace engineers were trained for satellite operations and Earth Observations and the satellite will be used to train operators for future satellite projects.
Further investigation of the Attitude Control is required for the stabilization of the optical links on other G/S as Oberpfaffenhofen. However, future projects might benefit from more standardization on the side of G/S Feedback for optical links.
Overall *Flying Laptop* is a stable platform for technology demonstration, Earth Observation, and education.

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