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THE FLYING LAPTOP UNIVERSITY SATELLITE MISSION: GROUND INFRASTRUCTURE AND OPERATIONS AFTER ONE YEAR IN ORBIT

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Abstract

The small satellite *Flying Laptop*, launched in July 2017, was developed and built by PhD, graduate and undergraduate students at the *Institute of Space Systems* (IRS) of the *University of Stuttgart* with assistance by industry and research institutions. The project goals include technology demonstration, earth observation and improving the education of students at the *University of Stuttgart* in the fields of satellite development, integration, test, and operations.

The satellite is operated from the IRS by a team of students applying different professional tools, e. g. ESA's SCOS-2000 for command and control. To execute in-orbit operations from the IRS, infrastructure was set up and taken into operation before the launch of the satellite. Furthermore, an operations team consisting of undergraduate, graduate, and PhD students was trained for in-orbit operations. Beginning with the launch from Baikonur, the team successfully operated the satellite through the first critical days in which the system was taken into operation, followed by the commissioning phase and eventually routine operations.

This paper highlights the ground infrastructure set up for the operations of the *Flying Laptop* mission, operations preparations and execution through the different mission phases, as well as some operational experience and developments during the first year of in-orbit operations.

1. INTRODUCTION

The small satellite *Flying Laptop* was developed and built by PhD, graduate and undergraduate students at the *Institute of Space Systems* (IRS) of the *University of Stuttgart*. The project was supported by industry, most notably *Airbus Defence and Space* and *Tesat Spacecom*, providing knowledge and sponsoring PhD candidates as well as hardware. Furthermore, the *German Aerospace Center* (DLR) also provided knowledge, different satellite instruments as well as their ground station network for satellite operations. The bus of the *Flying Laptop* is commercialised by *Airbus Defence and Space* as the *Flexible LEO Platform* [1].

The satellite was launched on 14th July 2017 on-board a Soyuz Fregat launcher from Baikonur into a sun-synchronous orbit in 600 km altitude.

1.1. Project and Mission Goals

Being the first satellite developed at the IRS, the *Flying Laptop* project goals comprise

- setup of the infrastructure and establishment of the knowledge at the IRS in the fields of satellite development, integration, test, and operations,
- improvement of the education of students in all aspects of a satellite mission through hands-on experience using professional tools and applying industry standards like CCSDS and ECSS.

One main goal of the satellite mission is technology demonstration of a variety of devices built both in-house at the IRS and by cooperation partners. Examples include

- a novel On-Board Computer (OBC) design in cooperation with *Airbus* and other partners [2],
- a Power Control and Distribution Unit (PCDU) serving as the reconfiguration unit for the OBC [3],
- an Optical high Speed Infra-Red Link System (OSIRIS) built by DLR to downlink payload data via a laser link,
- a deployable sail for faster de-orbiting in cooperation with *Tohoku University*,
- a commercial-off-the-shelf (COTS) components based Data Downlink System (DDS) for payload data in S-Band.

Furthermore, there are also scientific mission goals including

- multi-spectral, multi-angular earth observation, among others for vegetation analysis, in cooperation with several partner institutions, with the Multispectral Imaging Camera System (MICS),
- observation of objects in orbit with the Star Tracker (STR) cameras, e.g. space debris to improve orbit determination in cooperation with DLR,
- attitude determination using three GPS receivers on-board the satellite in cooperation with DLR [4],

- reception of Automatic Identification System (AIS) signals from ships using a DLR built receiver.

1.2. Satellite Systems

At a mass of 110 kg, a size of 600 x 700 x 870 mm³ and a power consumption of up to 120 W, the *Flying Laptop* is of considerable size and complexity for a university mission. The satellite bus features redundancy in all devices to achieve a one failure tolerant design. FIGURE 1 shows the satellite with deployed solar panels.

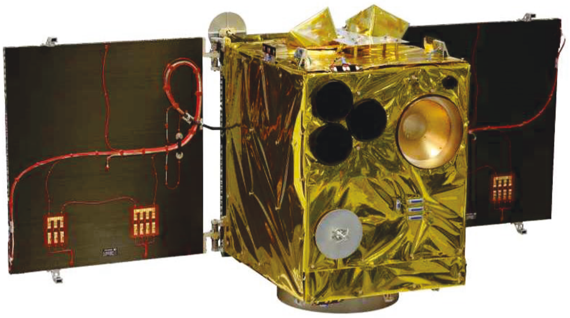

FIGURE 1: *Flying Laptop* satellite, image: J. Keim, IRS

The *Flying Laptop* features a three-axis stabilized Attitude Control System (ACS) with a “safe mode” using only sun sensors and magnetic control to orient the panels to the sun or detumble the satellite when necessary. The higher attitude control modes use Star Trackers, GPS receivers, and Fibre Optical Gyros as additional sensors, and Reaction Wheels as actuators. With these devices, the attitude control allows orienting the solar panels to the sun precisely (“idle mode”), pointing of the cameras in an inertial direction (“inertial pointing”), towards the earth centre (“nadir pointing”), or towards a certain point on earth (“target pointing”) [5]. These are necessary to fulfil the mission goals of multi-angular earth observation, ship tracking, laser data downlink, and others.

The Power Supply System (PSS) consists of three solar panels, two of which are deployable, providing a maximum of 270 W. A COTS Li-Ion cell based 35 Ah battery system [6] is charged by the PCDU, which also provides power to all other devices and acts as the watchdog for the OBC [3].

The Thermal Control System (TCS) is designed as a passive, cold-biased system using thermistors as sensors and electrical heaters as actuators. Multi-layer insulation, second surface mirror radiators and black paint on all structure elements are used for passive temperature control [7].

A commercial transceiver is used as the Telemetry/ Telecommand (TMTC) system in commercial S-Band with a 128 kbit/s telemetry (TM) downlink and a 4 kbit/s telecommand (TC) uplink.

The Command and Data Handling (CDH) subsystem consists mainly of the OBC [2], which runs an object oriented On-Board Software (OBSW) developed at the IRS. The OBSW features a hierarchical model of the satellite hardware and sophisticated Failure detection, Isolation, and Recovery (FDIR) functionalities [8], [9].

Finally, the payload set of the *Flying Laptop* comprises [10]:

- the monochromatic MICS camera system with three separate spectral channels with a ground resolution of 20 m per pixel,
- the Panorama Camera to take colour images at a ground resolution of 200 m per pixel,
- the AIS ship signal receiver built by DLR,
- the OSIRIS laser communication terminal built by DLR,
- the DDS payload data downlink system operating in ham radio S-Band at 10 Mbit/s,
- a dedicated Payload On-Board Computer controlling all other payload devices and providing payload data handling functionalities.

2. GROUND INFRASTRUCTURE

An overview of the ground infrastructure implemented for *Flying Laptop* operations at the IRS before the launch of the satellite is shown on FIGURE 2. The system has already been described in previous publications [11], [12], so it is only briefly described here, including some more recent developments. According to the project goals, the ground infrastructure makes use of professional software tools and equipment where possible and useful. Furthermore, it follows a modular approach allowing the exchange of certain components by providing open, standard interfaces.

2.1. Ground Station Network

The ground station networks used during the first few days of the mission differs from that used for routine operations afterwards. Both networks are introduced here briefly.

2.1.1. LEOP Network

The ground station network used for the *Flying Laptop* mission during the Launch and Early Orbit Phase (LEOP) consists of three professional DLR stations. The use of these stations is enabled by adhering to CCSDS standards for the communication links in commercial S-Band. The DLR stations used are the *German Space Operations Center’s* (GSOC) Weilheim (WHM) station in Bavaria, Germany, as well as the *German Remote Sensing Data Center*’s O’Higgins (OHG) station on the Antarctic Peninsula and Inuvik (INU) station in northern Canada. All DLR stations support live TM and TC links to the satellite through a Space Link Extension (SLE) based connection via a Virtual Private Network (VPN). A SLE Switchboard system provided by DLR is used to establish the network connection [11], [13].

Set-up and testing of the necessary infrastructure, as well as ground station usage during the first four days of the mission were provided by DLR free of charge. This ground station network provided global coverage with frequent ground contact opportunities with professional stations during LEOP, minimising the risk of mission loss in this critical mission phase.

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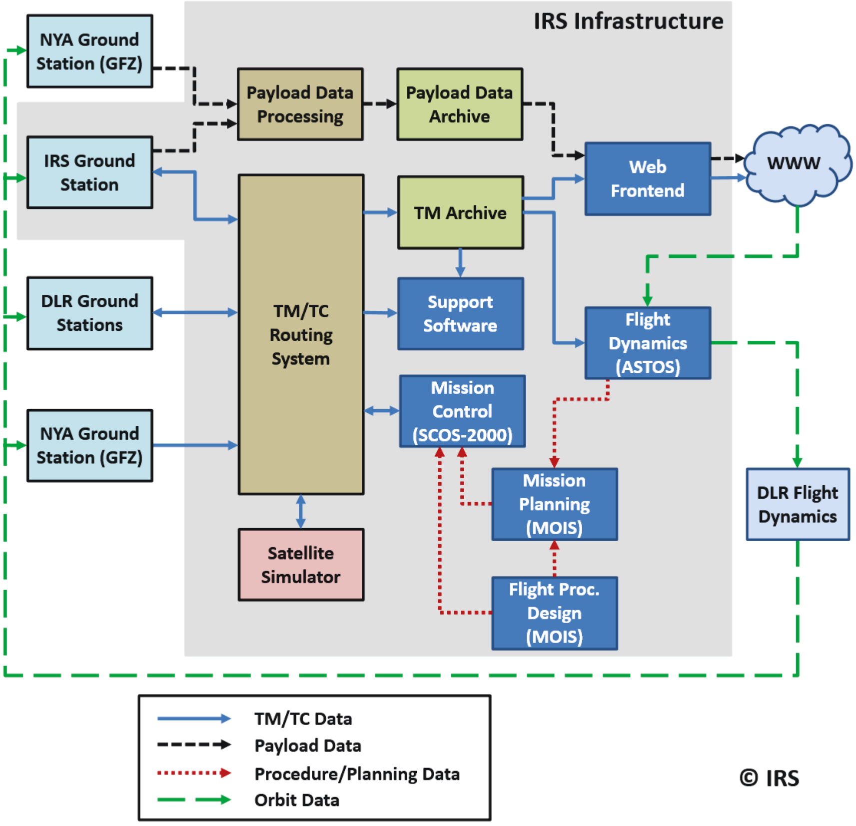

FIGURE 2: Ground segment overview

2.1.2. Routine Operations Phase Network

After the LEOP, the main ground station used for TM, TC, and DDS links was the IRS ground station at the *University of Stuttgart*. It features a 2.5 m parabolic dish with a custom designed feed to cover both the commercial and ham radio S-Band [14]. A *Cortex-CRT* unit manufactured by *ZODIAC Aerospace* is used as the baseband unit together with other COTS equipment for radio signal processing. A custom developed *Java* software is used to control the IRS ground station.

Furthermore, a ground station in Ny-Ålesund (NYA) on Svalbard, Norway, operated by the *German Research Centre for Geosciences* (GFZ), is used for additional TM and payload data downlink twice a day during routine operations. Received data are transferred to the IRS network after each pass though file exchange servers.

2.2. Control Centre Infrastructure

The control centre infrastructure set-up at the IRS consists of a mixture of commercial/professional, off-the-shelf, and custom developed software tools [12].

2.2.1. Mission Control System

The *European Space Agency*'s (ESA) SCOS-2000 Mission Control System (MCS) was chosen early in the project as the main control software. It is a generic MCS software with extensive manual and automatic commanding as well as TM packet and parameter display functionalities [15]. It requires the application of the ECSS Packet Utilization Standard (PUS) for TM and TC definitions.

2.2.2. Ground Data Systems

The core software for the TM/TC data handling is the TM/TC Routing System (TMTCRS), an in-house developed *Java* software that can route TM and TC packets and frames. It provides interfaces for different systems based on standard internet protocols, including

- the Network Command and Telemetry Routing System (NCTRS) used by SCOS-2000,
- the *Cortex* protocol to interface with the baseband unit in the IRS ground station,
- generic packet and frame socket interfaces,
- Command & Control (C&C) interfaces used by ground support equipment.

The interfaces of the TMTCRS can be configured in a flexible way, allowing different set-ups for test and operations [12]. Offline TM frame data from the NYA ground station can be piped into socket interfaces of the TMTCRS.

The TMCTRS also forwards TM data to the TM Archive, which maintains a MySQL database of all received TM packets and the calibrated TM parameter data in engineering units. The TM Archive is also a *Java* application developed at the IRS to allow a more flexible access to TM data than possible with SCOS-2000 alone.

It needs to perform the same processing as SCOS-2000 to retrieve calibrated TM parameter data from the packets, but this redundancy was accepted in order to be able to replace the legacy SCOS-2000 with another tool for future missions [12]. Other support applications for additional TM display and processing, e.g. to check TM dumps for completeness, also interface to both the TMTCRS and TM Archive.

A browser based web frontend was developed at the IRS to make use of modern web technologies for platform independent, flexible TM display based on the TM Archive database. Further applications of the web frontend include a display for upcoming passes, monitoring of the TMTCRS and TM Archive applications, and payload data display. It is used both within in the operational network, but can also be reached through VPN via the internet so that operators can check TM data from home.

2.2.3. Procedure Handling

The Manufacturing and Operations Information System (MOIS) toolchain developed by *Rhea* is used to define both test and Flight Operations Procedures (FOP) based on the same database SCOS-2000 uses for TM and TC definitions which is referred to as the Mission Information Base (MIB). Procedures can be executed automatically by MOIS, which was applied for automated hardware checks and software regression testing [11], [17]. The MOIS toolchain was supplied free of charge by *Rhea*.

FOPs are exported as command sequences into the MIB as well, allowing to load them onto command stacks in SCOS-2000. The validated FOPs are used to execute flight operations both live during passes with uplink and offline with time-tagged commands.

2.2.4. Flight Dynamics System

The Flight Dynamics System (FDS) is an in-house developed Python software which can process Two Line Elements (TLE) and GPS data measured on-board from the TM Archive to propagate the orbit. For orbit propagation, the commercial Analysis, Simulation and Trajectory Optimization Software (ASTOS) tool is used, whose execution is automated by the *Python* software [12], [16]. The FDS generates information on ground station passes and earth observation target visibility as well as eclipse times, which it writes to a MySQL database. This flight dynamics database is further used for pass and earth observation planning. Furthermore, the FDS generates a file containing a CCSDS standardised set of orbit parameters from the filtered on-board GPS measurements. This file is forwarded to DLR flight dynamics at GSOC, where it is converted to a TLE file. This TLE file is of higher accuracy than those provided online by NORAD and is used for antenna control at all ground stations.

2.2.5. Mission Planning System

For mission planning, the MOIS Scheduler tool is used [18], which takes information on orbital events from the FDS as well as predefined FOPs as input. A human operator can plan the execution of offline FOPs based on the orbital events and check the resulting plan for conflicts based on configurable rules. From the plan, a command stack file for import into SCOS-2000 can then be exported.

2.2.6. Payload Data Processing

Separately from the TM/TC processing, a payload data processing chain was implemented with custom developed *Java* software. The reception software extracts payload data from the data stream, determines its source (camera system, AIS receiver), and handles incomplete or duplicate data by generating complete images from multiple downlinks of the same image. It then performs additional image processing and saves the data to a *MongoDB* database. It can then be viewed by an operator using the web frontend.

2.2.7. Operations Documentation

The open source issue tracking system *redmine* is used to document operations. Ground station passes, anomalies, recommendations on what operations to perform, orbit data, and other operational products are tracked as issues within *redmine*.

The tool allows a customisation of forms and workflows for the issues as well as a manipulation of issues through an open programming interface. This allows for automation, e.g. issues for ground station passes are generated from the information in the flight dynamics database (see section 2.2.4).

2.2.8. Control Room

A control room was set-up at the IRS to perform in-orbit operations as well as operational simulations for operator training and educational purposes. Two large screens show the main SCOS-2000 windows for commanding, the orbit ground track as well as a live video feed of the IRS ground station antenna (see FIGURE 3).

It features a total of nine standard desktop computer consoles, one for each operator position (see section 3.1). Most of these consoles feature a modern *Linux* installation with a virtual machine for the older SCOS-2000 version in use. At the command console, two physical machines run two SCOS-2000 servers for redundancy, whereas all other consoles have SCOS-2000 client installations, which can connect to either server as needed.

2.2.9. Network Infrastructure

The operational infrastructure is mainly deployed within an operational network that has very limited interfaces to other networks, including the public internet, for security reasons. The only interfaces allowing data in- and output are the SLE connection to the DLR ground station, which has its own dedicated firewall, and a file exchange network drive that can also be reached from the IRS office network. Other interfaces only allow data to be transferred from the operational to the office network, e.g. to send notification emails and duplicate the databases to allow access via the web frontend from outside.

FIGURE 3: IRS control room

2.2.10. Simulation and Test Infrastructure

A spacecraft simulator was set-up early in the project to allow tests of the OBSW, especially the ACS algorithms, and to perform operational simulations. It features an engineering model of the OBC as hardware-in-the-loop with a software simulating the orbital environment as well as the communications with all devices on-board the satellite. While the physical simulation of the environment is based on software provided by *Airbus Defence and Space*, the equipment models were developed at the IRS [19]. The interface to the TMTCRS is provided by a TM/TC frontend manufactured by *Celestia STS*, which uses the C&C protocol. Dedicated SCOS-2000 and MOIS installations allow a simulation of the complete TM/TC chain and to execute software tests automatically.

Testing of the actual satellite hardware, from “flatsat” tests to the verification of the integrated flight model of the satellite, was executed with a similar infrastructure. A complete check-out system also manufactured by *Celestia STS* was in use, which featured additional communication capabilities on radio frequency level. Thus the control system for the simulator, flight hardware testing, and in-orbit operations is the same, which allows an early validation of operational products.

3. SATELLITE OPERATIONS

After the introduction of the ground infrastructure in the previous section, this section describes the operations team, operations preparations, and practices applied over the first year of in orbit operations.

3.1. Operations Team

An operations team with a total of 26 members was assembled before launch for *Flying Laptop* operations. Half the people are PhD candidates employed full time at the university and the other half are undergraduate and graduate students working part time assistant jobs. The PhD candidates were involved to different degrees with satellite design, integration, and test before the launch, so they provided invaluable system knowledge to the operations team.

In order to closely supervise all subsystems involved in operations, nine operator positions were defined similar to those used at GSOC [13], allowing the execution of operations in the control room in a professional manner:

- a *Flight Director* (FD) planning and overseeing operations, guiding the operations team during passes,
- a *Command Controller* (CC) preparing command stacks and uplinking TCs during passes,
- four *Spacecraft Controllers* (SC) monitoring and planning operations for the satellite subsystems (ACS, PSS/TCS, CDH/TMTC, Payload),
- a *Ground Controller* (GC) monitoring and controlling ground software and data flows,
- an *Antenna Controller* (AC) monitoring and controlling the IRS ground station and communicating with DLR operators for DLR station passes,
- a *Mission Planner* (MP) executing flight dynamics and mission planning operations.

3.2. Operations Preparations

Operations Preparations include the definition and validation of operational products like the MIB and FOPs, a multitude of system and interface tests, as well as training for the operations team. Some aspects of these activities are described in this section.

3.2.1. Definition and Validation of Operational Products

The MIB was gradually built along with the OBSW development. As the effort for full formal MIB tests was deemed too high, only basic dedicated MIB tests were performed. The majority of validation was achieved through OBSW and system tests using the MIB in SCOS-2000 as the main testing tool. Thus through high levels of usage, the MIB was “validated” as a side effect of system tests.

A total of over 200 FOPs were defined based on the MIB covering system mode changes, check-out and maintenance activities, payload data takes, as well as contingency operations. Each FOP was executed both on the simulator as well as on the satellite flight model before launch for validation. A majority of FOPs was also used in system tests.

3.2.2. Operational Tests

Some operations related tests were executed before the launch both with the satellite flight model and the simulator.

One class of tests are compatibility tests between spacecraft and ground station. For the IRS station, this was possible by feeding a coaxial cable out of the integration room to a wide-band test antenna on the roof of the building, which then transmitted the signals between the satellite and the ground station antenna on the roof of the neighbouring building via the air interface. As no transportable model of the TMTC was available, the whole spacecraft was transported to the WHM ground station for compatibility tests via cable. Due to the similarity of the DLR stations and the remote locations of the other stations, no compatibility tests were performed for the near polar DLR stations (see also section 2.1.1). For the NYA ground station, a test opportunity was seized when its *Cortex* receiver was in Germany for maintenance and could be brought to the IRS for a compatibility test in the integration room. However, at the time only the TM link could be tested.

While such compatibility tests prove the functioning of the interface between spacecraft and ground station, further tests are necessary for the rest of the TM/TC chain between control centre and ground station. For the IRS ground station, these could be combined with the compatibility tests. For the DLR stations, a series of tests was conducted to check the SLE connection to all three stations, operational procedures for establishing the connection, and offline data delivery after the pass. The TC uplink was tested by sending commands from the control centre and checking their reception at the station, while the TM link was checked by replaying a TM file recorded previously during the compatibility tests at the station and checking TM reception in the control centre.

Besides such interface tests, two operational scenarios were simulated on both the flight model (FM) and the simulator: the LEOP and a week of typical routine operations (“week-in-the-life”). The main goal of these tests was to simulate operational scenarios in a realistic way with ground station pass times, dumping of TM saved between the passes, usage of FOPs and time-tagged commanding, etc.

For both tests, a number of passes of realistic lengths was defined, which were simulated by enabling/disabling the transmitters on the FM and the data forwarding in the TM/TC frontend on the simulator. Operations were planned around the passes and simulated sunlight/eclipse phases. While most operations are executed during live passes for the LEOP test, intensive use of the mission planning tool was made for the week-in-the-life test to generate stacks of time-tagged commands. Besides revealing several bugs in the OBSW, these tests also produced valuable input for operations execution and planning.

3.2.3. Team Training

While the PhD candidates in the operations team had various degrees of knowledge of the satellite system and its operations before training began, the students did not. Furthermore, no team member had any previous practical experience with satellite operations. Thus all team members needed a certain amount of training.

For team training, a new spacecraft operations course was established at the *University of Stuttgart* before the launch. The course covered some basics of satellite systems, communication, and operations, and provided in-depth knowledge of the *Flying Laptop* satellite system and its operation, including the ground segment infrastructure. Establishing this course as a lecture for aerospace engineering students allowed the graduate students to receive credits towards their degree for taking part, while the PhD candidates could still participate.

The course consisted of normal lectures and hands-on exercises in the control room to teach the basics of commanding and the behaviour of all subsystems. The participants needed to pass a final exam with a written and a practical part to be allowed to work as an operator. The course was offered the second time one year later to provide satellite operations knowledge to the next generation of students and recruit new operators. It is planned to keep this course up at least for as long as the vital subsystems of the satellite remain operational.

After the course, which was not specialised for any subsystem, the participants who wanted to work in actual operations chose operator positions and were trained by more experienced PhD candidates in these positions in a few informal lecture sessions.

Starting three months before the launch, operational simulations were performed in the control room using the simulator on a roughly weekly basis, focusing on LEOP and commissioning operations. While during the first simulations nominal operations were trained, failures were injected in the simulator software later on to simulate devices malfunctioning and other contingency scenarios. This way, the operators gained some hands-on experience in their future roles and trained communication in the control room, documentation, etc. The simulations ended with a 48 hour LEOP simulation shortly before the launch including night shifts. Besides the actual training, results from the simulations included the introduction of some automation in stack generation and optimisation of operational processes.

3.3. Operations Execution throughout the Mission

Following the operations preparations, this section details the operations of the different mission phases during the first year of in-orbit operations.

3.3.1. LEOP

During LEOP, i.e. the first four days after launch, operations were performed 20 hours a day in two shifts with all consoles manned. The two teams for the day and night shifts were balanced in experience and system knowledge, so both teams were authorised to perform all kinds of operations. Shift handover meetings were conducted once a day in the evening to keep the other team informed through a personal conversation. Console logs detailing operations and problems for each operator position were used for shift handover in the morning.

A total of 60 passes were planned using the DLR ground stations, the vast majority of which could be executed successfully. Unsuccessful passes were caused by some interface problems in the beginning as well as a few minor ground station issues, including too strong winds at OHG.

Operations executed during the LEOP included the first contact approximately 3 hours after launch over the WHM ground station, solar panel deployment, and check-out of several functions, mainly the higher ACS devices and modes, as well as certain redundancies. In general, all devices, modes, and subsystems performed as expected so that the planned operations could be executed ahead of schedule at the end of the LEOP. The ACS reached pointing accuracies of below 1°, which still needed some optimisation especially for OSIRIS pointing operations.

One minor issue postponed panel deployment, as the performance of the ACS could not be judged very well before panel deployment when the battery was fully charged. This was caused by the panels being used as additional sun sensors before deployment, as some actual sun sensors can be shadowed by the undeployed panels. When the battery was close to fully charged, the panels could not be used as sun sensors due to PCDU control activities. Furthermore, due to the low power consumption of the system and the large battery, the battery was basically always close to fully charged. Thus the operations team took some actions to consume more power during eclipse to provoke lower battery charge states so that the correct functioning of the ACS could be verified before panel deployment.

Further unexpected issues included a bug in the OBSW which prevented both STR camera heads from being used at the same time. Thus before the first OBSW update, the STR had only a cold redundancy available. However, this did not lead to any significant problems.

Once during LEOP a safe mode fallback was triggered, as the OBSW detected a high rotation. It turned out that the limit for this breach was set too low and the “high” rate seen represented a rotation reached regularly during nominal pointing operations. This could easily be resolved with a parameter update.

The team was very satisfied with the spacecraft’s performance during the LEOP. The battery state of charge remained above 95% throughout the LEOP, temperatures were generally between 5°C and 20°C, stable communication links were achieved, the OBC did not reboot, and all attitude control modes worked as expected with their precision still to be optimised. A total of 4750 TCs were sent during the LEOP with a success rate of 99.8%.

3.3.2. Commissioning

During commissioning, operations were still performed in two daily shifts, only using passes over ground stations in Germany. This reduced the length of the shifts considerably. Furthermore, during night and weekend shifts reduced team sizes were introduced with only FD, CC, one SC, and AC on console. The day shift team size was also reduced gradually, e.g. as GC were not needed anymore shortly after the end of the LEOP due to the ground system’s stability.

On the other hand, the CC, AC, and MP had significant amounts of manual work to do, so activities were started to reduce this work through automation and optimisation of processes. This included higher complexity in the automatic generation of command stacks and the automatic execution of flight dynamics tools generating pass and orbit data. More details on these activities can be found in [20].

During the first week of commissioning, the WHM ground station was still being used while the IRS ground station was actively taken into operation. This included passive tests at first with the IRS station in reception mode during passes over the nearby WHM station, and later also activating the uplink at lower elevation passes during which the WHM station was not used. After this week, the IRS station was fully operational and has been in use as the main station for up- and downlink since then. The NYA ground station was also included as an operational station during commissioning with two downlink only passes each day. As only the TMTC link could be tested during the compatibility tests with NYA (see section 3.2.2), some effort was necessary to achieve a workable configuration for the DDS link.

During commissioning, further redundant bus equipment was checked out. Furthermore, all payload devices were taken into operation. The payload devices worked fine from the start, resulting in the first image taken by the PAMCAM camera received on ground five days after launch (see FIGURE 4). The DDS payload data downlink on the ham radio S-Band frequencies is negatively influenced by Wi-Fi signal interference, which is mitigated mainly by resending the data several times and “repairing” them on ground (see section 2.2.6). The antenna of the AIS receiver was deployed successfully during commissioning, which resulted in the first AIS messages being received.

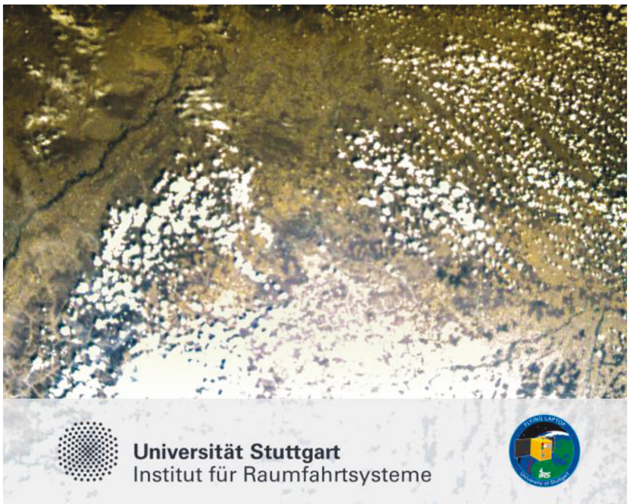

FIGURE 4: First image taken by the PAMCAM camera of south-west Germany with Stuttgart in the centre

Due to the reduced number of ground station passes, a fixed scheme for TM data dump and deletion was introduced during commissioning. This became necessary as dump and deletion of arbitrary data from the TM stores required some scrolling time through the memory with the OBSW version in use at launch.

The commissioning phase was executed successfully as all payloads could be operated and returned data as expected. The satellite bus continued to work fine throughout the commissioning phase and all passes were executed in target pointing mode, resulting in very stable TM/TC links over the IRS ground station.

3.3.3. Routine Operations

There was a smooth transition from the final commissioning activities to routine operations some 5 weeks after launch, during which TM data generation rates were reduced to facilitate TM data downlink, and operational effort was reduced further by eliminating night shifts altogether. Weekend shifts were still conducted up to late 2017 when the full automation of the IRS ground station was implemented, which allowed downlink only passes without human supervision. As an operator must be present for legal reasons when the ground antenna's uplink is enabled, complete lights out operations are not possible. Day shifts are now executed by an FD and a CC only.

This is enabled by further automation of operations including a complete automation of all flight dynamics activities and automated stack generation for all payload data takes and dumps based on *redmine* issues [20]. Furthermore, a tool executed each hour analyses the TM received over the past days to check when passes happened and how long they were, if all critical TM parameters are within their allowed limits, and if critical events occurred. The tool displays the information on a web page in the web frontend, allowing an operator to get an immediate view of the system's state and current issues.

Operations continued using mainly the IRS and NYA ground stations, with monthly proficiency passes with the DLR stations to keep the network connection ready for use in case of contingencies.

The satellite kept performing well during the first year in orbit and payload and technology demonstration data could be gathered nominally. As an example, FIGURE 5 shows a red dot for each AIS message received by the *Flying Laptop* AIS receiver in a 24h data take period. Furthermore, the GPS based attitude determination on ground was executed successfully by DLR as published in [21].

The OBC redundancy was not checked out during the LEOP and commissioning phases, because the check-out procedure requires an OBC reboot. Before the first OBSW update was uplinked in December 2017, this redundancy was eventually checked out successfully. Afterwards the first OBSW update was installed, which introduced several bug fixes and simplified TM dump and deletion operations (see section 3.3.2).

While the OSIRIS laser terminal hardware works nominally, the actual laser link could to a ground station could not be established during the first year of satellite operations, likely because the attitude control is not precise enough (a pointing accuracy below 100'' is necessary) and there is no independent pointing control of the OSIRIS laser and no closed-loop feedback function.

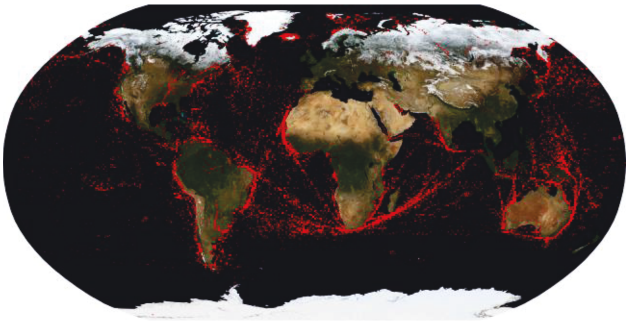

FIGURE 5: AIS messages received during a 24h data take

3.3.4. Activities Planned in the Future

In the near future, the FD shifts will transition to offline preparations and documentation only, leaving the CC to execute routine passes alone using prepared stacks. Thus nominal passes of this complex satellite system will be performed by a single operator, the lowest legally possible number. Additional automation functionalities are planned to reduce the remaining workload further without reducing the amount of payload operations.

The most recent OBSW update introduces additional filtering capabilities for the attitude control algorithms which are expected to result in an increase in pointing accuracy to the range necessary for OSIRIS laser downlink operations. After optimising of the algorithm's gain settings, further experiments are planned to achieve a working laser downlink in cooperation with DLR.

3.4. Operations Experience and Lessons Learned

This section contains some operational experience and lessons learned regarding the operations team, the ground station network, functionalities of the spacecraft, and ground operations.

3.4.1. Operations Team

As already mentioned before, the effort put into operations in terms of operator hours could be reduced significantly over the first year of operations, mainly due to the introduction of automation features. FIGURE 6 shows the working hours per day of the FD (blue), SC (red), and the complete operations team (yellow) as well as the shifts per day performed by the complete team (blue). Significant drops can be seen after the first week, i.e. after the LEOP, as well as after the night shifts were not performed anymore around week 5. Around Christmas (week 24), a drop represents reduced operations executed over the holidays. After the holidays, the weekend shifts were abolished, leading to another decrease in operational effort.

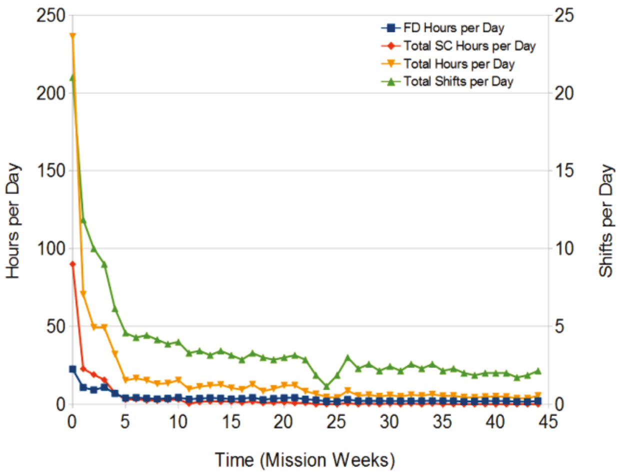

FIGURE 6: Number of hours and shifts worked by the operations team over the mission since launch

During the LEOP, two equally qualified teams covered the day and the night shifts. The idea was to proceed with the complex check out procedures through the nights to make maximum use of the large, professional ground station network available during this phase. Check out activities were therefore planned equally over all passes available, not considering the time of day. However, fewer passes were planned during the nights to reduce the night shift's workload and thus their stress.

Unfortunately, unforeseen developments led to some problems. As the single STR camera in operation was often blinded during the night passes, certain check out procedures could not be executed nominally. Also, the first pass of the night shift was generally shortly after the shift handover meeting, so sophisticated planning was not possible for this pass. Thus there were only a few passes remaining for complex check out operations during the night, which led to the day shift executing most of the more "interesting" operations. Together with longer pauses between passes, which were meant well but added to the inconveniences of the night shift, this led to some dissatisfaction among the night shift team. In such a situation with two equal teams, it is probably helpful to make sure that both shifts are able to execute a similar amount of operations as far as possible.

3.4.2. Ground Station Network

Compatibility tests between ground station and satellite are obviously useful to avoid any interface problems especially during the critical LEOP. As mentioned, such tests were not performed for the OHG and INU stations (see section 3.2.2). This led to some problems during the first OHG and INU passes. A wrong sweep rate was configured at INU, which was stated incorrectly in a document, but used correctly by WHM due to the compatibility tests. Furthermore, establishing a working configuration for the untested DDS link at NYA proved to be tedious, as settings from the IRS ground station could not be directly translated due to the different types of the *Cortex* receivers in use. Finding the correct settings for the QPSK modulation scheme required a lot of tests and analyses of raw data.

Thus even with stations using very similar equipment, compatibility tests should be performed whenever possible. If not, a thorough comparison of settings to a station with which a compatibility test was executed may be helpful, but may also be impeded by differences in the used equipment. Furthermore, regular proficiency passes for rarely used external stations are helpful not only to test the network connection, but also to keep the operations teams trained.

The use of an external ground station network with professional stations is an important asset for LEOP operations allowing troubleshooting of severe problems with relatively short intervals between subsequent passes. However, some interface or operational problems may always occur, which cannot be resolved internally. With an internal ground station located close to the control centre on the other hand, troubleshooting can be performed internally, but the operational effort increases.

3.4.3. Spacecraft Functionalities

Inflexible on-board memory management functions caused some operational effort during *Flying Laptop* operations. In the TM memory, dumping data not from the earliest data recorded in the memory, but from somewhere in the middle, required the OBSW to "scroll" through the memory until it found the position to start dumping. This took considerable time which is wasted not dumping at the beginning of a pass when commanding live. Furthermore, data deletion also took a lot of time, in the same range as scrolling through or dumping data. Together, these two characteristics of the OBSW led to considerable operational effort, especially when passes could not be used for whatever reasons and gaps in the TM received needed to be dumped again. These complications could be resolved with the first OBSW update, allowing near immediate dump and deletion through TM store indexing.

The payload data is saved on a mass memory unit with no sophisticated memory management. Memory regions for data takes need to be assigned by an operator using a manually maintained memory usage map. This process not only hinders a full automation of payload operations, but is also error prone. This issue is planned to be mitigated by introducing a ground software tool allowing for some automation of the memory management. In general, operations friendly memory management functionalities should be considered early in spacecraft design. Realistic operational simulations can help to test the approach planned during operations for its ease of use.

Some problems were also encountered due to bugs in the OBSW related to full stores, both the TM stores and the on-board TC store for time-tagged TCs. These bugs were not caught during system testing, because not all edge cases were considered, especially after supposedly small bug fixes were introduced. Thorough testing of such cases is obviously a good idea, as OBSW bugs add to the stress of the contingency situation of a full on-board store. Also not surprisingly, providing more than sufficient memory regions for these critical stores would reduce the risk of running into such problems.

3.4.4. Ground Operations

The spacecraft simulator with a full functional model of the spacecraft proved to be essential for many operations related areas, including e.g. the validation of procedures and operator training. However, it is also vital to use the simulator before commanding new procedures or command stacks, even if they are only slight deviations from validated procedures or deemed uncritical.

It also needs to be considered that hardware devices simulated in software will not behave in exactly the same way as the actual hardware. This may cause issues on the actual spacecraft, especially if certain operations cannot be tested with the actual flight hardware. For example the timing of both STR cameras generating a valid solution could not be verified with the flight hardware, because only one optical ground support device was available to simulate a star field. Consequently, both STR cameras generating a valid solution at the same time triggered a bug in the OBSW, which was not seen on the simulator, because the timing of the STR hardware was different from that of the software simulator.

Another example of operations that caused problems was the OBSW update. The TC stack used contains a lot of large TCs, whose data is written to an interface board in the OBC. While this worked fine on the simulator, it was not tested with parallel TM dumps on the actual hardware. Executing both at the same time on the satellite led to some issues with memory access in the OBC hardware. Therefore, such operations should be tested under operational conditions with the actual hardware.

On top of the default PUS functionality for regular housekeeping TM generation, the *Flying Laptop* OBSW allows resetting the generation rate of each packet defined. This allows flexible handling of data generation rates, e.g. to increase them for limited time periods to generate data at a higher resolution for deeper analysis. However, this has caused problems e.g. with CCs not knowing the exact definition of the generation interval (per minute vs. per second) or FDIR functionalities disabling the on-board schedule. In both cases, too large amounts of data were generated (frequency too high, duration too long) which led to full stores and problems dumping the generated data (see also section 3.4.3). Thus these settings should be tracked thoroughly and operators should be taught in the usage and criticality of this functionality.

Another aspect of this problem is the deactivation of the on-board schedule execution for time-tagged TCs. While this may be necessary and useful e.g. to prevent executing payload operations in contingencies, like when the battery is low, this functionality has caused unnecessary interruptions of operations. Disabling the schedule generally resulted in the loss of fully automated downlink only passes. Furthermore, TCs reverting previous changes were not executed, resulting in problems like the full TM stores described above. To prevent this, if there is no on-board sub-schedule functionality implemented, the number of cases in which the on-board time-tagged TC execution is disabled should be limited to those cases where it is necessary to prevent severe problems.

Operating a satellite with an OBSW modelling the satellite system hardware in a hierarchical structure has shown some benefits. This way, the OBSW hides some complexity of the system while still providing all necessary information to the operator. This easy way of controlling the system was also an important factor in reducing the team size over time. More details on this topic are published in [22].

4. CONCLUSION

For *Flying Laptop* operations, a ground segment was developed and implemented based on professional tools and standards. Featuring all subsystems of a professional ground segment necessary to operate a complex scientific mission with six different payloads, the ground segment was realised at manageable costs for a university project. After thorough operations preparations including the assembly and training of an operations team with over 20 members, *Flying Laptop* operations were successfully executed from the LEOP through to routine operations. Despite some minor bugs mentioned in this paper, the spacecraft and especially the in-house developed OBSW performed very well over the first year in orbit.

While the ground segment enabled successful operations of the *Flying Laptop*, it also formed the basis for valuable, hands-on education of the complete team in satellite operations applying professional tools, standards, and operational practices. Further educational outreach is achieved through a new lecture on satellite operations and a seminar on earth observation using satellite imagery.

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