IN-FLIGHT EXPERIENCE AND OPERATIONS OF THE 3U-MISSION SONATE

Tobias Schwarz (1), Oleksii Balagurin (2), Tobias Greiner (3),
Hakan Kayal (4), Andreas Maurer (5)

(1) University of Würzburg, Emil-Fischer-Str. 32, 97074 Würzburg, Germany,
+49-931-31-82010, tobias.schwarz@uni-wuerzburg.de
(2) University of Würzburg, +49-931-31-88637, balagurin@informatik.uni-wuerzburg.de
(3) University of Würzburg, +49-931-31-89582, tobias.greiner@uni-wuerzburg.de
(4) University of Würzburg, +49-931-31-86649, hakan.kayal@uni-wuerzburg.de
(5) University of Würzburg, +49-931-31-83241, andreas.maurer@uni-wuerzburg.de

ABSTRACT

SONATE was a 3U-CubeSat for technology demonstration developed at the University of Würzburg, primarily for the in-orbit verification of the autonomous payloads ASAP-L and ADIA-L, as well as other smaller payloads like star sensors and reaction wheels. On July 5, 2019, it was successfully launched on a Russian Soyuz rocket into a 530 km Sun synchronous orbit. The mission ended after one year of operations. During its operation, SONATE has been commanded and telemetry was received almost daily on two or three passes over the university's ground station.

The autonomous sensor and planning system (ASAP-L) is an optical image sensor, which can autonomously detect events of interest in its observed sensor data like sprite-lightnings or meteors. After detection the autonomous planning system can plan next activities directly on board of the satellite independent of the ground segment. These activities include scheduling of new observations timeslots or automatic contact to ground. The autonomous diagnostic system (ADIA-L) is a model-based diagnostic system for a permanent analysis of the satellite's telemetry. It monitors the whole satellite, can detect root causes of current failures, and predicts possible future failures of the spacecraft. In addition, three reaction wheels and two star sensors are integrated as secondary payloads, as well as a SSTV transmitter as an amateur radio payload.

The primary payloads and all components were successfully commissioned and tested. The experiments performed with ASAP-L, ADIA-L, ADCS, star sensors as well as SSTV also provided positive results. However, the scope of the experiments had to be reduced due to a difficulty with the command uplink and restrictions imposed by the COVID-19 pandemic. This and other difficulties and problems that occurred during launch and early orbit phase, commissioning phase and operational phase are presented, with a focus on communications. Their solution, mitigation or the redundancies that have been used will be presented as well. As a result, the paper summarizes the lessons learned for future missions, especially for the SONATE-2 mission that is currently prepared as a technology demonstration mission for artificial intelligence and is planned to be launched in the beginning of 2024.

1 INTRODUCTION

While today highly autonomous functions accompany us in our everyday life and make our routine daily work much easier, they are, however, a rare case in the space sector, especially in small satellite missions. As one of the main research topics at the Professorship of Space Technologies, the SONATE mission contributes to the development of higher autonomy at the University of Würzburg.

Classical operations of a nanosatellite mission heavily dependent on ground support by expert operations personnel. All activities executed on board of the satellite are planned ahead of time by operators on ground. Using time-tagged telecommands, those planned activities are uploaded to the satellite and executed there. In case of a failure, ground operators have to diagnose the satellite and its failed subsystem during the next ground station passes. The handling of anomalies is usually limited to putting the satellite into a safe mode. Ground-based diagnosis not only takes time but also might put the satellite at risk if certain failures are not dealt with in time. This kind of operations does not allow the observation of unpredictable, transient events like meteors entering Earth's atmosphere, atmospheric light or weather phenomena, or unknown geysers on other celestial bodies in our solar system, because it is impossible to plan this kind of events beforehand.

The SONATE mission was a technology demonstrator mission, prepared and operated at the Department of Computer Science VIII, Professorship of Space Technology, at the University of Würzburg, funded by the German Federal Ministry of Economic Affairs and Energy, represented by the German Space Agency DLR (FKZ 50RM1606) [1-5]. Its prime objective was the in-orbit verification of key elements of two highly autonomous systems developed at the University of Würzburg. Those autonomous systems, the autonomous sensor and planning system (ASAP-L) and the autonomous diagnosis system (ADIA-L) can be used to solve the problems with classical satellite operations described above. As a secondary objective, the SONATE mission is used for the in-orbit demonstration of ADCS components. Since it was a university project, students were included into the mission for educational purposes.

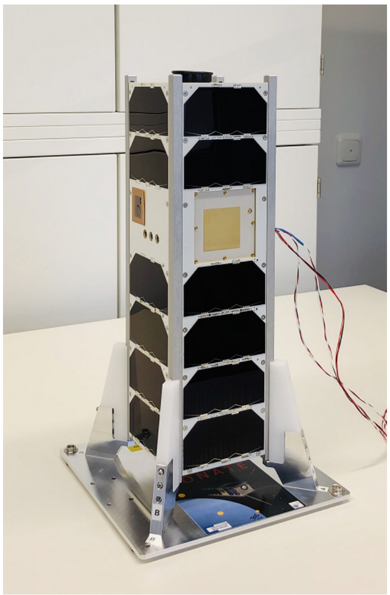

Figure 1. SONATE flight model

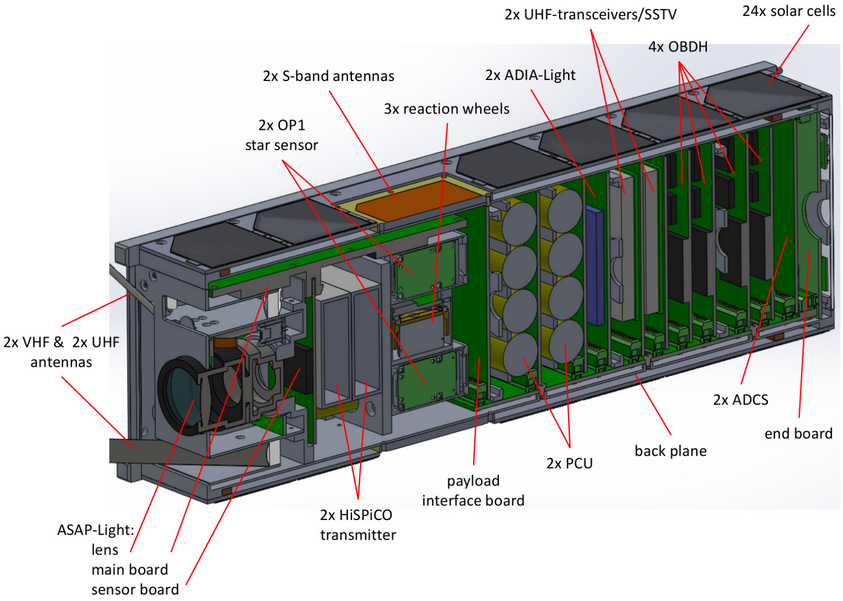

Figure 2. Physical Structure and accommodation of the SONATE space segment

2 SPACE SEGMENT

The space segment of the SONATE mission consisted of a 3U CubeSat with a mass of about 4.2 kg (see Figure 1). This chapter gives an overview of the satellites payloads as well as its newly developed bus. The distribution and interconnection between all subsystems, mainly via PCB cards plugged into a backplane, are shown in Figure 2 and Figure 3.

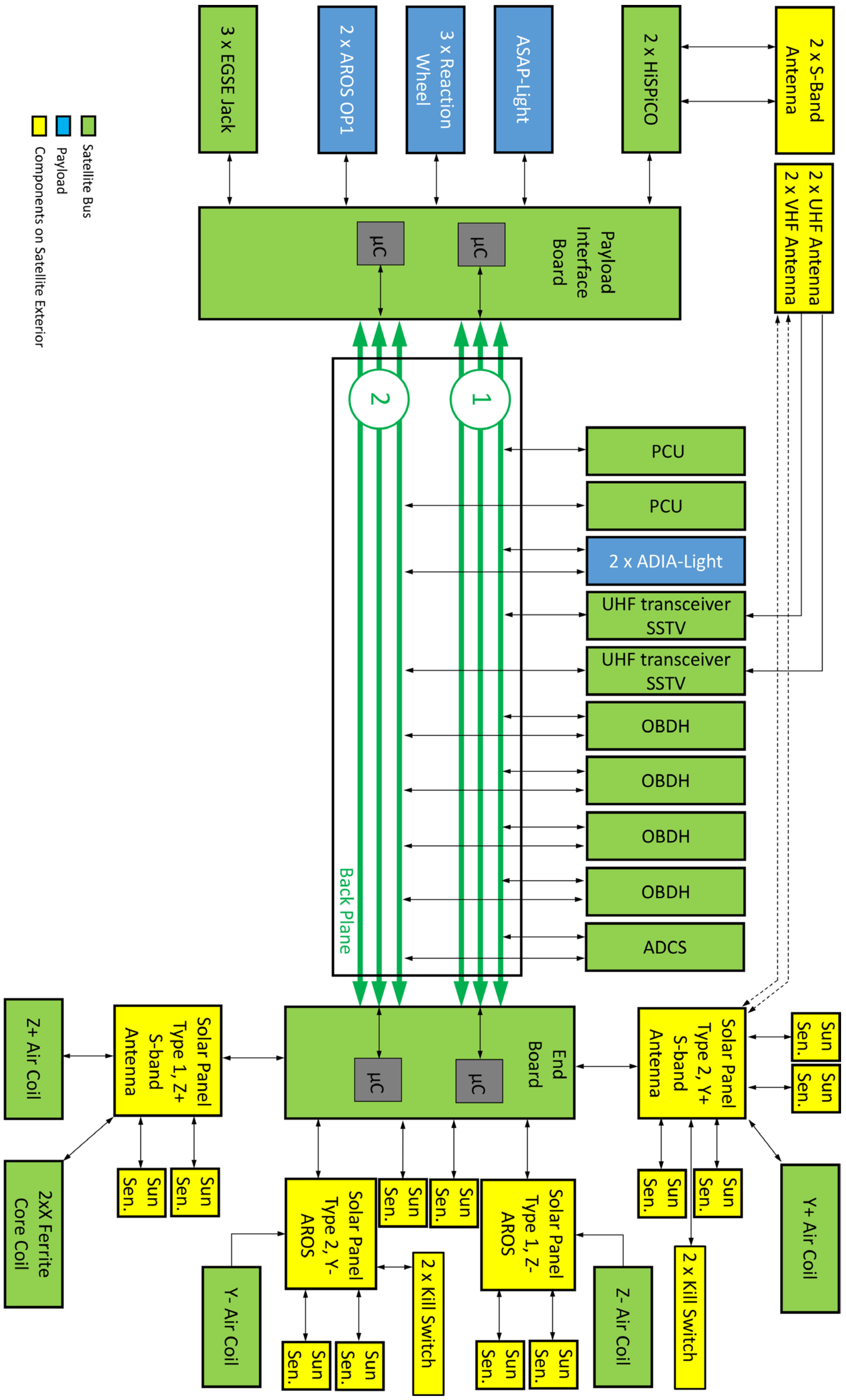

Figure 3. System overview of the SONATE space segment

2.1 Autonomous Sensor and Planning System (ASAP)

The ASAP System is a highly autonomous payload for observations in the optical spectrum [6]. In a project funded by the German Federal Ministry for Economic Affairs / German Space Agency DLR (FKZ 50RM1208), it has already been developed and qualified. It comprises of two main components: the ASAP imager and the ASAP planning system:

The ASAP imager is an optical instrument able to detect transient events like meteor passes, lightnings, sprites and other phenomena in the atmosphere. Detected events are categorized and meta data like the type, duration, and direction are extracted and passed to the ASAP planning system. The ASAP planning system is a highly autonomous system, which can react interactively and intelligently to certain events provided by sensor systems. The planning software can schedule next actions and create new command lists for the satellite [7].

This payload posed several requirements onto the SONATE mission and heavily influenced the overall design: Firstly, the planning system must be able to manipulate the satellite's current command list held by the onboard data handling system (OBDH). Secondly, the OBDH must regularly provide relevant parts of the telemetry for the planning system. Thirdly, ASAP-L collects quite large amounts of payload data in the order of 100 MB per day, which affects the design of the payload data handling system as well as the communication system. Fourthly, the original ASAP system was designed for a 27U platform and hence cannot be accommodated on a 3U-CubeSat. Therefore, a reduced version named ASAP-L, see Figure 4, which features all key elements but a smaller and less powerful imaging system, was developed [8]. However, ASAP-L was still large enough to put several constraints onto the mechanical structure. The same applies to the power subsystem due to ASAP-L's peak power consumption of 12 W, and an average power consumption of 8W.

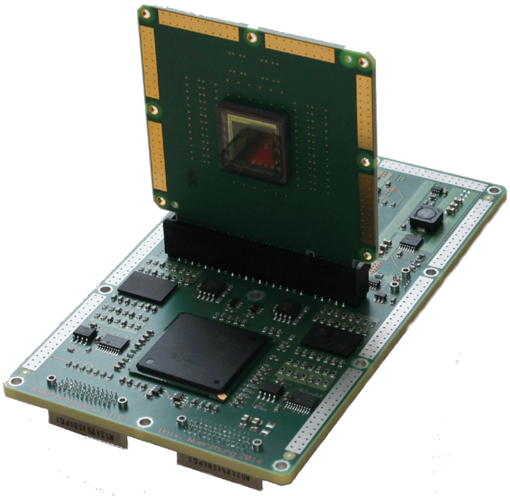

Figure 4. ASAP-L

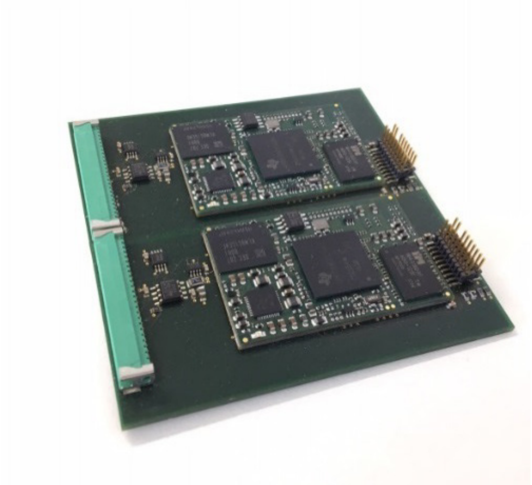

Figure 5. ADIA-L

2.2 Autonomous Diagnostic System (ADIA)

ADIA is an autonomous, model-based diagnostic system for nanosatellites. In the context of the ADIA++ project, funded by the German Federal Ministry for Economic Affairs / German Space Agency DLR (FKZ 50RM1524), a diagnostic engine in form of a desktop software has been developed [9]. The diagnostic engine takes measured sensor, commands, and housekeeping data as an input to simulate a model of the satellite and thereby computes the expected state of the system. This simulated state is compared to the observed system state. Every threshold breach of a measured value and every discrepancy between a simulated and a measured value generates a symptom. The model is described by port-wise connected components with arbitrary many input and output ports with a quantitative description of their nominal behavior. Since the classical model-based approach limits the diagnostic capabilities to only being able to detect faults on component level, heuristic knowledge is used to enhance the quality of the computable diagnoses. Trend knowledge is also used to compute possible future threshold breaches and therefore to detect future errors [10].

A version adapted to the available resources of the SONATE mission, ADIA-L, was developed in the context of the ADIA-L project, funded by the German Federal Ministry for Economic Affairs / German Space Agency DLR (FKZ 50RM1723) [11]. For this ADIA was ported to run on the TI-RTOS operating system running on a BeagleCore, an industrial embedded computing module derived from the popular Beagle-Bone Black platform, see Figure 5. For redundancy, two BeagleCore modules were integrated into SONATE, running in cold redundancy mode.

The ADIA-L payload posed several requirements onto the SONATE satellite bus. For one, ADIA-L requires the knowledge of all the satellite's housekeeping parameters, which must be provided to the bus. Since a failure of a SONATE subsystem was not desirable, the OBDH was able to fake the housekeeping data provided to the ADIA-L payload.

2.3 Secondary Payloads

There are three secondary payloads on the SONATE satellite: two star sensors, three reaction wheel and a redundant amateur radio payload.

Attitude control is an important part of most satellite busses. For control, sufficiently accurate knowledge of the current state is required, determined by a sensor. Among the existing attitude determination sensors, star sensors are usually the most exact, but also not the smallest and energy-saving ones. Therefore, ways to optimize star sensors are an active field of research at the University of Würzburg. In the AROS research project, funded by the German Federal Ministry of Economic Affairs and Energy, represented by the German Space Agency DLR (FKZ 50RM1522), a software tool was developed to optimize the design process of star sensors for pico- and nanosatellites [12,13]. As a result of the optimization algorithm and to verify the output two sensors were built. One of those sensors, OP 1, is optimized for the use on pico satellites. The space available in the SONATE satellite allowed the integration of two OP1 sensors.

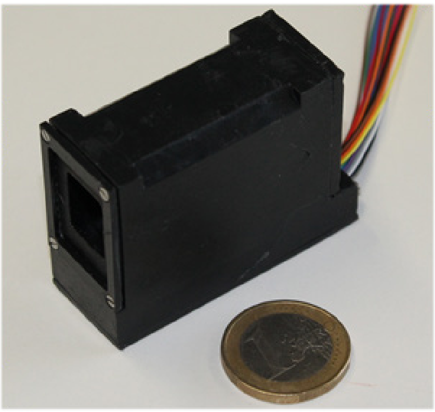

Figure 6. OP1 star sensor

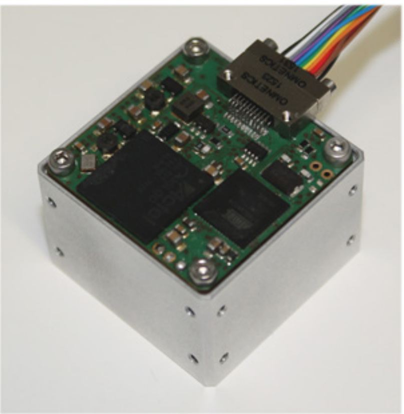

Figure 7. reaction wheel

For fast and precise attitude control, usually reaction wheels are used. In the context of student theses [14] a reaction wheel has been developed at the University of Würzburg and was adapted to the SONATE satellite. The SONATE structure was able to accommodate three of these reaction wheels, one per each major axis.

The last secondary payload, the amateur radio payload, was also developed with contributions from student theses [15], It consisted of a VHF transceiver which served the SONATE mission as an SSTV transmitter. Using the images taken by the image sensors of the ASAP-L or star sensor payloads, this payload allowed the transmission of low-resolution images from space to radio amateurs world-wide.

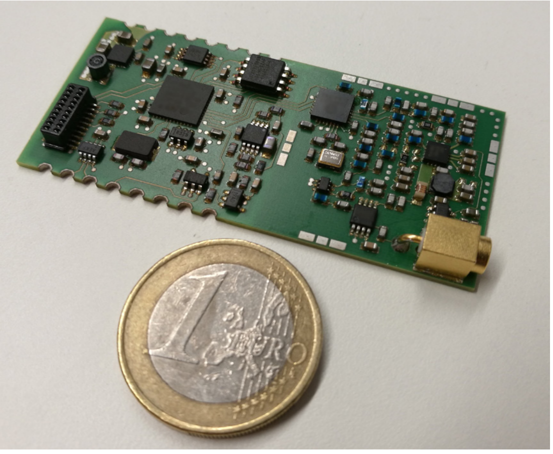

Figure 8. Photo of the SSTV transceiver board (without HF shielding)

2.4 OBDH

SONATE deployed special OBDH software and hardware, to ensure safe handling of the autonomous experiments with ASAP-L and ADIA-L without jeopardizing the success of the mission, parallel to typical tasks such as time management and orbit propagation, telemetry collection and resource monitoring. This was achieved by using three different telecommand lists. One of these lists is autonomously created by ASAP and can be activated during its experiment time [17].

The OBDH hardware was based on a Cortex-M4 microprocessor from ST Microelectronics. SONATE used four identical OBDH-PCBs, each running one of four possible roles determined dynamically by software: OBC or PDH as a master or slave. The PDH role handled all payload telemetry of SONATE including images and video sequences of ASAP-Light and prepared the collected data for sending them to the ground. The software design was based on the real time operating system RODOS [16].

2.5 Power-Subsystem

SONATE's EPS had to provide a relatively high output power of 20 W for simultaneous operation of the autonomous payloads and the communication components. The required electrical energy was generated by four electrically identical solar panels with six GaAs solar cells each. The conditioning of the solar voltage took place on the backside of the solar panels, so have a regulated constant voltage for further distribution. Two solar panels each were interconnected and operated on one of two redundant solar bus systems. The energy was stored in two redundant battery packs, consisting of four industrial Li-Ion cells each with a total capacity of 12.8 Ah. A CV charge controller was responsible for safe charging of the batteries. All redundant satellite components are connected via one of two separate +5V power busses.

2.6 Communication

The communication between space segment and ground segment was established using amateur radio frequencies in the UHF band for the transmission of housekeeping telemetry to and telecommands from mission control with a data rate of 9600 bps. Therefore, the satellite bus includes two redundant AstroDev Lithium transceivers operating in hot redundancy, i.e. both transceivers are always receiving while only one transmits when required. A frequency of 437.025 MHz was coordinated by the IARU for SONATE's UHF up- and downlink. The SSTV payload operated in the VHF amateur radio band on 145.840 MHz. For each of both bands, two monopole antennas had to be deployed at one end of the satellite. These antennas were made of steel tape which was rolled up inside the satellite during launch. After release from the launch vehicles upper stage a motor had to set the tape free to allow it to unroll outside of the satellite.

Because the optical sensor of the ASAP-L payload can generate large amounts of data, a high-speed payload data downlink was required, too. Hence, two redundant HiSPiCO S-band transmitters were integrated into SONATE together with one patch antenna mounted on the satellite's side panels each. This allowed up to 1.65 Mbps downlink in the non-amateur, space operation/space research service in S-band between at 2268,7 MHz.

2.7 ADCS

The ASAP-L payload required that its camera to be pointed towards the Earth's horizon. At the same time, the S-band downlink for payload data required to point the satellite's antenna to the ground station with at least nadir pointing.

As actuators, SONATE was equipped with 6 magnetic coils, two in each axis for redundancy purposes. For the Y- and Z-axes (axes perpendicular to the satellites larger sides) air coils were used directly under the solar panels, whereas in the X-axis (along the longest axis of the satellite) ferrite core coils were used, to use the limited space inside the 3U CubeSat as efficiently as possible.

For attitude determination, several different sensors were used. A set of redundant MEMS gyros were available for measuring the satellite's rotational rate around each axis. Both flux gate and magneto-resistive magnetometers were used to measure the local magnetic field vector. In order to meet pointing requirements, two redundant sun sensors on each side of SONATE completed the nominal sensor set. These sun sensors were being developed in-house with regard to meeting accuracy and size requirements of the SONATE mission [18]. To allow a high degree of redundancy in case of sensor failures, SONATE was equipped with at least two redundant instances of each sensor on each axis.

3 GROUND SEGMENT

All operations of the SONATE mission were primarily controlled and supervised from the SONATE mission control room at the University of Würzburg, shown in Figure 9. To receive housekeeping telemetry from and to transmit telecommands to the space segment, the university has its own amateur radio station that is compatible to the satellite's UHF and VHF transceivers. It consists of two X-quad antennas for the VHF and UHF amateur radio band mounted with an azimuth-elevation rotor on the rooftop (see Figure 10), rotor controller, transceiver, modem and a control computer. To receive the payload data via S-band the university has a 2 m parabolic dish ground station. It is mounted on a car trailer for flexible operation site selection. It was equipped with a HiSPiCO receiver compatible to the transmitter onboard of the satellite. All three components, the two ground stations and the mission control room are connected via the university's intranet.

Due to the COVID-19 pandemic, starting March 2019 until the end of the mission, all operations were conducted remotely from the homes of the operator, which resulted in some drawbacks, described in the next chapter.

Figure 9. SONATE mission control room

Figure 10. VHF/UHF ground station antennas

4 MISSION OPERATIONS

4.1 LEOP and Commissioning

SONATE was launched on July 05, 2019, 05:41 UTC from the Vostochny Cosmodrome with on a Soyuz/Fregat rocket into a SSO with an altitude of 550 km. About 3.5 hours later the first contact with our ground station was expected. Unfortunately, the pre-launch TLEs were a bit off (about 15 km lower on the semi major axis), so the first contact that could successfully be established was on the next day. The received housekeeping telemetry showed that all critical system were running nominally, all antennas were fully deployed, and the EPS was charging the batteries as planned.

On the Second day after launch, we received the post-launch TLE from NORAD, but in the first weeks the commanding of SONATE was still very unstable, because the small satellite cluster it was launched with was still too close to each other for an unambiguous identification. SONATE was operated in 2 shifts for the day and the night passes. On average only a handful of commands per pass were correctly received by the satellite via the secondary communication link on VHF. The primary link on UHF was still unsuccessful.

Only after about three weeks it was possible to identify SONATE as object 2019-038Q, or so we thought, as we would see later. This increased the quality of the UHF downlink and much more telemetry frames per pass were correctly received, but commanding the satellite was still not very successful. Between 5-10% of the transmitted telecommands were received via VHF uplink, the primary UHF uplink was still much worse. It was assumed that this was mainly due to interferences in the amateur radio band, primarily from terrestrial sources. Increasing the transmitter power did not significantly improve the performance.

Under these conditions the LEOP could not be concluded until the end of August, almost two months after the launch. In the following commissioning phase one subsystem after another was successfully turned on for the first time and checked. Only the temperatures were a bit lower than expected. This required to change all critical temperature limits for some temperature sensors, as they were constantly causing the satellite to go into safe mode. Changing the limits significantly increased the stability of the OBDH. Commissioning was concluded four months after the launch.

4.2 Normal Operations

The normal operations occurred on weekdays during 3 passes between 11:00 and 16:00 UTC, each for around 10 minutes, using our mission control room and ground stations. In total, 96000 House-keeping Frames and about 4 MB extended telemetry from the payloads was received via UHF and successfully decoded. Unfortunately, the limitations with the uplink remained, meaning 20-30 telecommands on an average pass. This largely limited the procedures and experiments with the payloads that could be performed during the mission

Several things were investigated and attempted to improve the quality of the uplink. One point that was considered is the possibility of interference with MOVE-IIb, which apparently was coordinated the same VHF frequency as SONATE. This has the potential to interfere the VHF uplink but since MOVE-IIb never had contact with their own ground station [19] and we did not see any of their signal on our ground station, it does not seem very likely. Nevertheless, this gave us cause for looking again into the assigned NORAD object of SONATE. Objects 2019-038Q and 2019-038K were always very close and never more than a few minutes apart with fluctuating distance of no more than a few minutes. Therefore, in April 2020 we did a another doppler analysis of the UHF downlink signal (see Figure 11 and Figure 12), which showed that apparently SONATE has to be, in fact, object 2019-038K as there remains a curve in Object Q around the closest point of contact that does not exist for Object K.

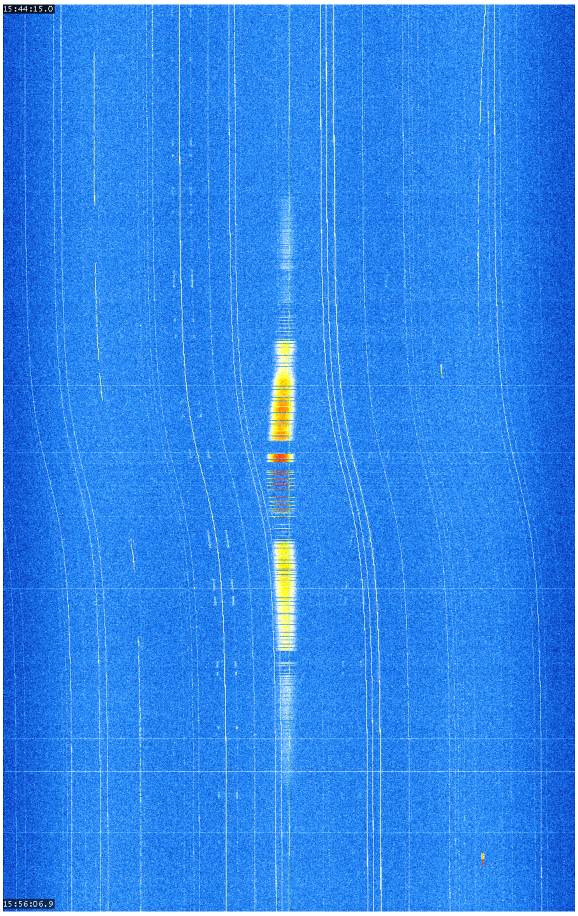

Figure 11. Object 2019-038Q

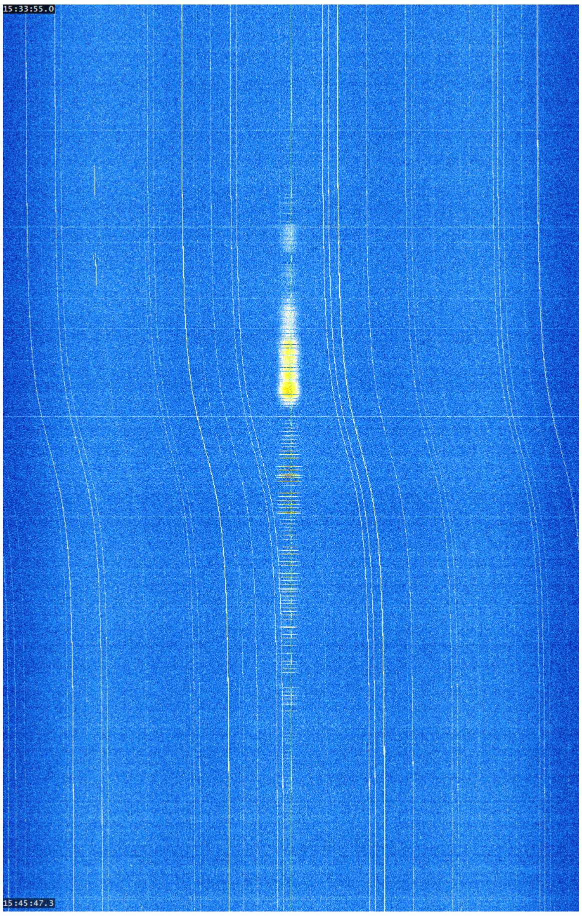

Figure 12. Object 2019-038K

A change to Object 2019-038K for the ground station tracking, however, did not significantly improve the communication with SONATE.

Figure 13 shows the success rate for the uplink of telecommands. It clearly shows measures taken to improve the quality of the uplink by operational means, other configurations of the satellite or potentially even other external influences like the first wave of the COVID-19 pandemic, during which for a few weeks, almost doubled the telecommand success rate. Apparently, people staying at home might have caused less noise in the affected bands for some reason. On the other hand, our analysis did not show a significant difference between weekdays and the weekend. The most improvement that could be achieved, however, was due to a software update. A detailed and lengthy code analysis of SONATE's OBDH showed a problem with the telecommand decoder of the VHF uplink. After the software update, the success rate increased drastically to sometimes almost 50%. Nevertheless, the UHF uplink remained mostly unusable.

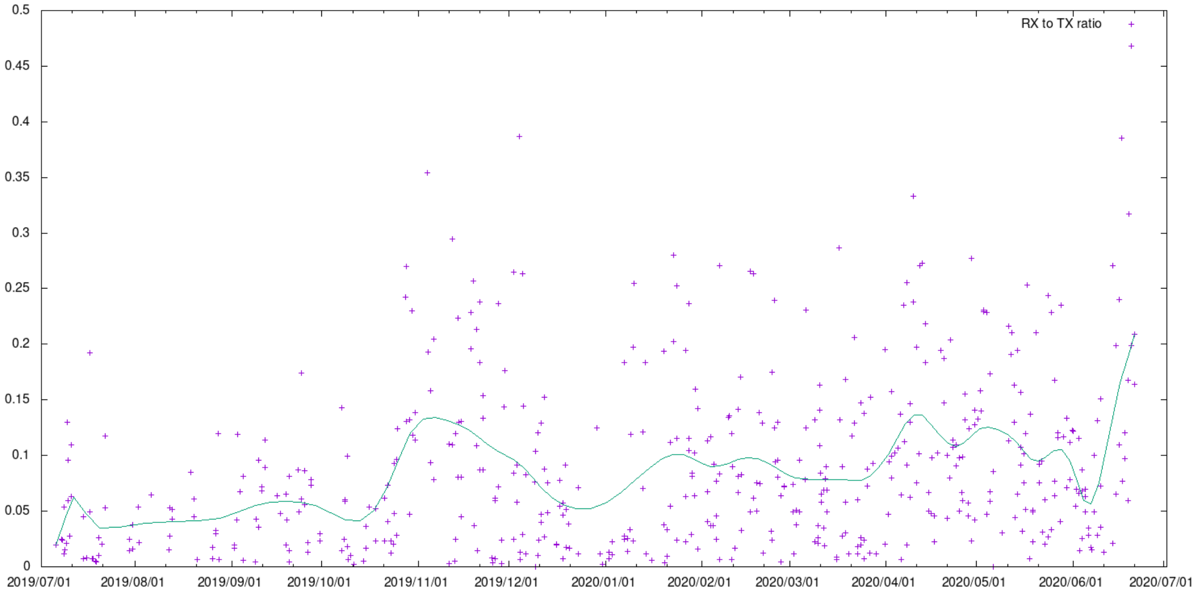

Figure 13. Ratio between telecommands transmitted by the ground station to the number of telecommands successfully received and decoded by SONATE's on-board computer

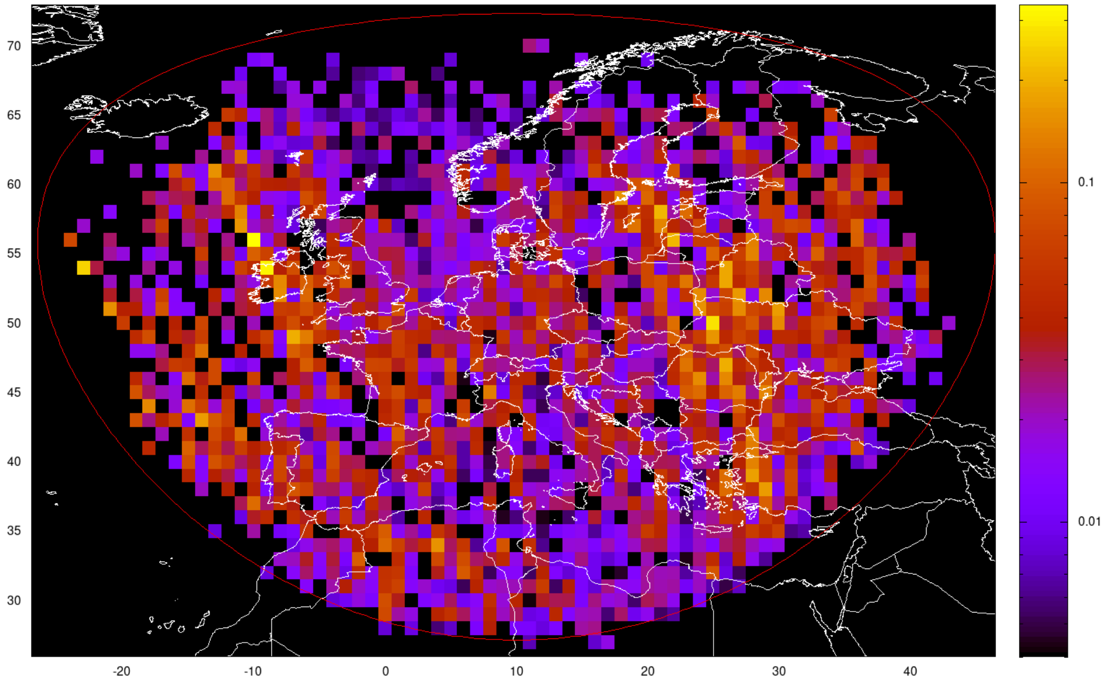

Figure 14. Average success rate by position of the satellite during a pass over our ground station in Würzburg

With the beginning of the COVID-19 pandemic, all operations were conducted remotely from the homes of the operators. For normal communications via VHF/UHF this made no noticeable difference. However, for the operation of the S-band ground station it is required to be there on-site. Due to restrictions this was not possible therefore it was decided to push pack the S-band downlink for a few weeks.

During the passes that usually were from south to north, the successful reception rate for telecommands was always the worst in the last minutes of a pass, while telemetry reception was still fine, sometimes even up to a few degrees below the horizon. This is shown in Figure 14, where you can clearly see that it is worst at the northern boundaries. The reason for this could not be explicitly determined, but it should not be due to the topographic surroundings of the ground station, as it is almost the same in all directions.

4.3 End of Mission

After the improvement of the VHF uplink due to the software update it was planned to catch up on the payload experiments that were limited before due to the interfered telecommand uplink. Unfortunately, a shortly after that, contact with the satellite abruptly ended. At this time at the end of June 2020, SONATE has been operated for about one year, which is its designed mission lifetime. In the following months there were numerous unsuccessful attempts to re-establish contact and an extensive failure analysis was performed, which did not identify a clear reason for the loss of contact.

5 RESULTS

Due to the limited uplink capabilities and the sudden end of mission, it was not possible to perform all planned payload experiments. This renders the mission only a partial success. Nevertheless, a lot of experiments were executed. The results of some of those are presented here.

While the ASAP-L payload according to the housekeeping telemetry performed as expected, it was not possible to download high resolution images via S-band due above-mentioned operational restrictions. Unfortunately, after that the contact with the satellite ended. The only images received from ASAP-L are in the form of low-resolution SSTV images, as shown in Figure 15. On the other hand, the images received via SSTV verified the SSTV transceiver that was developed for SONATE with some student participation.

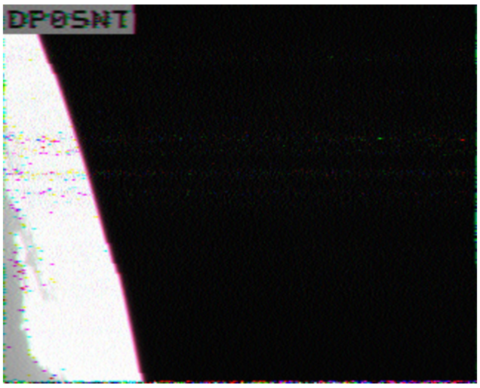

Figure 15. Image of the Earth's horizon taken by the ASAP-L payload and transmitted to the ground as an SSTV signal

Figure 16 shows a typical result of one of the reaction wheels' experiments, proving, that the reaction wheel, developed partially in the context of a student thesis, is working as expected, as it causes the expected rotation of the whole SONATE satellite. Originally it was planned to integrate the reaction wheels into the control loop of the ADCS as soon as they were verified to operate in space as planned. Again, due to the sudden end of the mission, it was not possible anymore to test this.

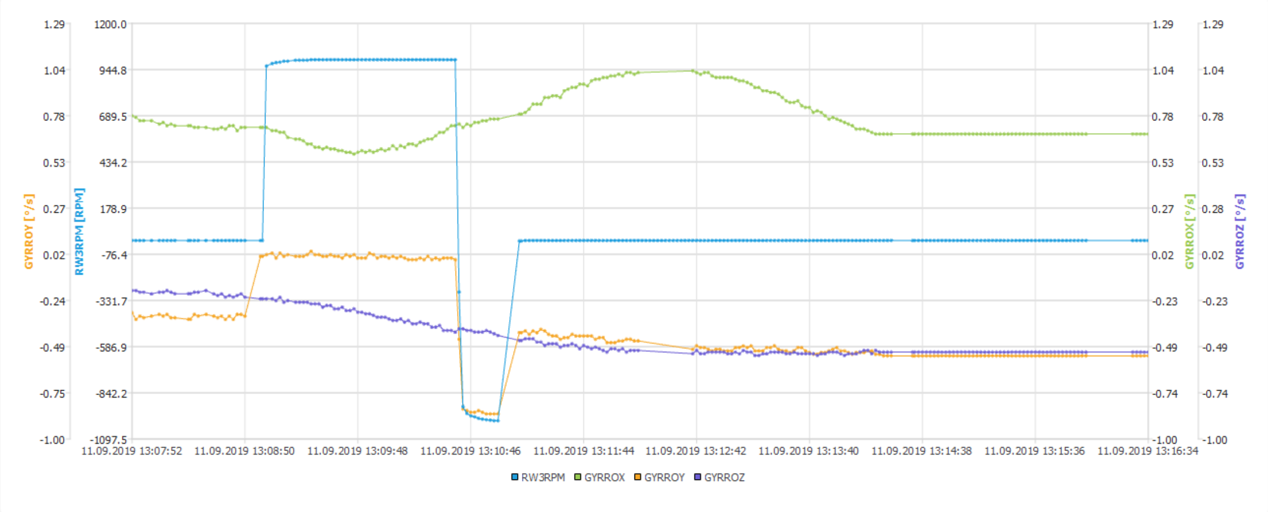

Figure 16. Plot of the housekeeping telemetriy of one of the reaction wheel experiments. The reaction wheel's rotational rate is depicted in light blue, the other three graphs show the resulting rotation rate of the satellite around its three major axes, measured by the ADCS' gyroscopes.

The first step of the experiments with the OP1 star sensors was the determination of the limiting magnitude and noise threshold in space, compared to field tests on ground that are influenced by the Earth's atmosphere. Therefore, an image was taken with the star sensor, as shown in Figure 17. Due to the satellites residual rotational rate of about 0.6 °/s, the integration time of the image of 100 ms causes the star in the image to be in an elongated form. From this image the noise threshold was determined.

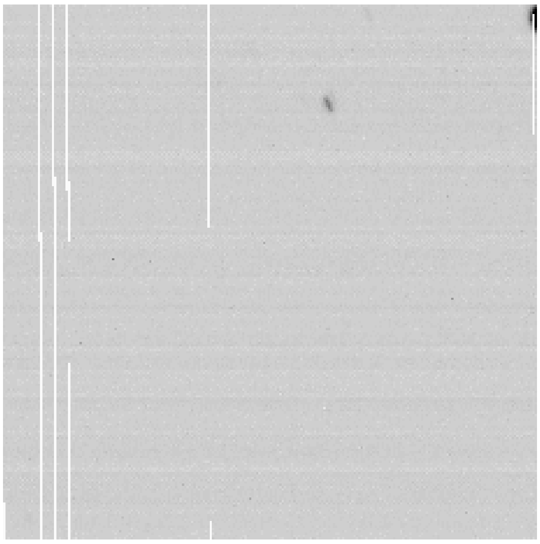

Figure 17. Part of a raw image of a star captured by the OP1 star sensor (inverted). The white lines are due to lost packages during downlink that were not requested again [13]

With this threshold, the star recognition was executed, and the recognized stars were compared to a simulated night sky of the same field of view as shown in Figure 18 and Figure 19. From that the limiting magnitude of the star sensor was set to 5,75^{m}.

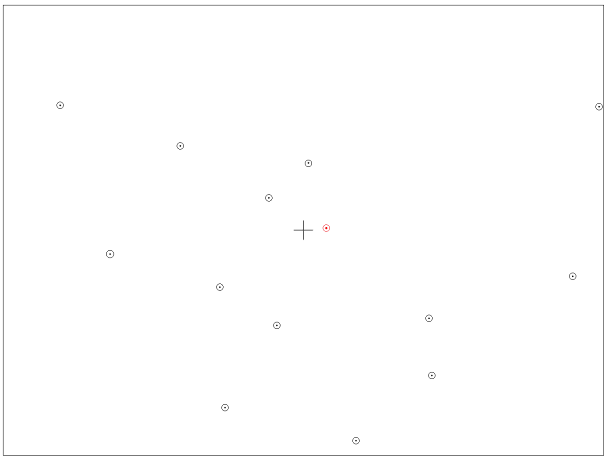

Figure 18. Stars recognized in one image, generated by the stars' coordinates from the telemetry data [13]

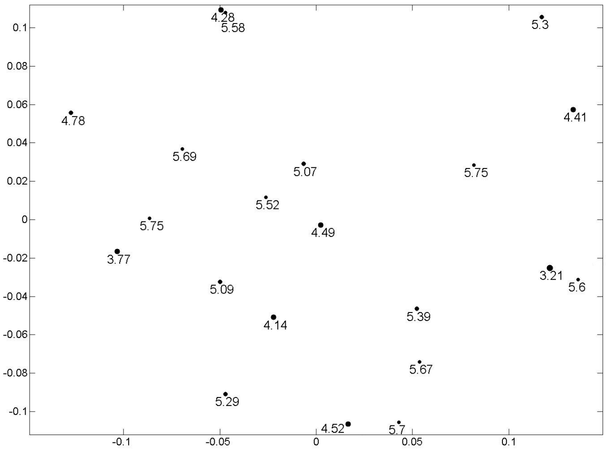

Figure 19. Expected image for stars up to 5,75^{m} from simulation with their respective magnitude [13]

After that, the parameters of the optical system were calibrated for the star sensor to deliver a valid attitude output. The data showed that the limit for the residual rotational rate of the satellite is at around 0.65 °/s. Above that value, the stars get too faint, and a reliable identification is not possible anymore. If the mission would have lasted longer, the calibration of the star sensors would have been continued to achieve more accurate results.

While not all experiments could be conducted as planned, all payloads have been turned on at different times during the mission, which already fulfills some of the mission's goals to verify the hardware in space.

6 LESSONS LEARNED

From an operational point of view, the problems that occurred already started in LEOP. Due to lower-than-expected temperatures, instead of completing the LEOP command list after the deployment, the OBDH set the satellite into safe mode. This disabled the telemetry beacon that would have automatically started over the ground station of Würzburg. Therefore, it was required for the first contact, to activate the housekeeping downlink via telecommand, which, unfortunately did not work that well due to the limitations of the uplink at the beginning of the missions as well as the unreliable TLE data. This is especially bad, because SONATE was deployed into a swarm of 29 different CubeSats. Hence, it is suggested for future missions to make sure to have a continuous beacon highlighting the satellite and avoid early safe mode. To be independent of TLEs provided from an external source, a GPS receiver should be added which provides position data for orbit determination as early in the mission as possible.

As for the communication problems in the uplink, those seem to be rather common, especially in the UHF amateur radio band as they are not only used by radio amateurs but share the bands for instance with terrestrial ISM band. Unfortunately, the answer of most CubeSat operators seems to be to increase the uplink transmit power to the legal limits of the amateur radio licenses, as the apparently heavily increased order numbers of a German manufacturer of power amplifiers for amateur radio band suggest. If S-band frequencies are not possible for a future mission, non-amateur Sub-1GHz band reserved for space operations might have to be considered.

Last but not least, more testing is required, which is not always easy in short projects like SONATE. Therefore, the testing must be made as easy for the developer as possible by providing all the tools, hardware and software, necessary to do full in-the-loop test as early in the development as possible. It is also important to test the backup systems as extensively as the primary ones, as this was the main reason for the limit performance of the VHF uplink in the first place.

7 OUTLOOK

The SONATE mission has fulfilled its objective as a technology demonstrator and steppingstone to more complex and demanding nanosatellite missions that make use of artificial intelligence. After a successful operation for one year in LEO, the payloads are verified for use in space. The complete concept of SONATE's bus system and ground segment can be reused with minimal adjustments and are a profound basis for following missions as it reduces the risks of failure and base costs drastically.

Perspectively, this will allow not only new autonomous Earth observation missions but also to use this kind of autonomy on nanosatellites that perform interplanetary missions. The SONATE-2 mission, which is currently prepared to be launched in the beginning of 2024, will take this one step further as a technology demonstration mission, utilizing methods of artificial intelligence for on-board image data processing and anomaly detection, including the on-board training of the used neural networks.

8 REFERENCES

[1] Kayal H., et al. *SONATE – A Nano Satellite for the In-Orbit Verification of Autonomous Detection, Planning and Diagnosis Technologies,* AIAA Space and Astronautics Forum and Exposition, Long Beach, California, 2016.

[2] Balagurin O., et al. *A Novel Nano Satellite Mission to Demonstrate Autonomous System Technologies,* Small Satellites Systems & Services (4S) Symposium 2016, Valetta, Malta, 2016.

[3] Schwarz T., et al. *SONATE Nanosatelliten-Mission zur Erprobung von hochautonomen Nutzlasten,* Deutscher Luft- und Raumfahrtkongress, Braunschweig, Germany, 2016.

[4] Schwarz T., et al. *SONATE – 3U Nano Satellite Mission for Highly Autonomous Payloads,* Small Satellites Systems & Services (4S) Symposium 2018, Sorento, Italy, 2018.

[5] Balagurin O., et al. *3U satellite bus SONATE for technology demonstration of autonomous payloads,* 12th IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, 2019.

[6] Wojtkowiak H., et al. *Autonomous Onboard mission planning,* Proceedings of the 65th International Astronautical Congress, Toronto, Canada, 2014.

[7] Wojtkowiak H. Planungssystem zur Steigerung der Autonomie von Kleinstsatelliten, Dissertation, University of Würzburg, Würzburg, Germany, 2018.

[8] Wojtkowiak H., et al. *Autonomous Mission Operations Onboard Satellite SONATE,* Proceedings of the 68th International Astronautical Congress, Adelaide, Australia, 2017.

[9] Fellinger G., et al. *ADIA++: An Autonomous Onboard Diagnostic System for Nanosatellites*, AIAA Space and Astronautics Forum and Exposition, Long Beach, California, 2016.

[10] Djebko K. *Quantitative modellbasierte Diagnose am Beispiel der Energieversorgung des SONATE-Nanosatelliten mit automatisch kalibrierten Modellkomponenten*, Dissertation, University of Würzburg, Würzburg, Germany, 2020.

[11] Fellinger G., et al. *ADIA-L: Implementation and Integration of a Model-Based Autonomous Diagnostic System as Payload for the Nanosatellite Mission SONATE*, Proceedings of the 68th International Astronautical Congress, Adelaide, Australia, 2017.

[12] Balagurin O., et al. *An Optimized Development Process for Small Star Sensor Systems*, Small Satellites Systems & Services (4S) Symposium 2016, Valetta, Malta, 2016.

[13] Balgurin O. *Designoptimierung von Sternsensoren für Pico- und Nanosatelliten*, Dissertation, University of Würzburg, Würzburg, Germany, 2022

[14] Greiner T. *Untersuchung der FPGA-Basierten Ansteuerungsalgorithmen für bürstenlose DC Motoren*, Bachelor Thesis, University of Würzburg, Würzburg, Germany, 2016.

[15] Haller M. *Konzeption und Test eines SSTV-Übertragungsmoduls für die Satellitenmission SONATE*, Bachelor Thesis, University of Würzburg, Würzburg, Germany, 2017.

[16] Montenegro S., et al. *RODOS – real time kernel design for dependability*, Proceedings of DASIA 2009 – Data Systems in Aerospace, Istanbul, Turkey, 2009

[17] Rapp T., et al. *Preparing SONATE for Autonomous Control Through ASAP*, Proceedings of the 69th International Astronautical Congress, Bremen, Germany, 2018.

[18] Baumann T., et al. *CMOS Based High Accuracy Miniaturized Digital Sun Sensor with Optimized Error Compensation on SONATE*, Proceedings of the 70th International Astronautical Congress, Washington D.C., USA, 2019.

[19] MOVE. Mission Control Status Update, https://www.move2space.de/blog/mission-control-status-update/ , July 25, 2020.