EARLY RESULTS AND IN-FLIGHT EXPERIENCE OF THE 6U-MISSION SONATE-2

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ABSTRACT

SONATE-2 is a 6U+ CubeSat for technology demonstration developed at the University of Würzburg. It was launched on SpaceX' Transporter-10 mission into a 527x505 km Sun synchronous orbit on March 4, 2024.

Recent missions have used AI for on-board image analysis only with models trained on ground. The SONATE-2 mission introduces on-board training of the AI models, allowing new applications like anomaly detection, which are only possible by training in space using images captured on-board. This is an important feature for future interplanetary missions, where no sufficient image data is available for pre-training AI models on the ground and supervised training is difficult due to a limited communication link. The primary goal of the SONATE-2 mission is the in-orbit demonstration of a new AI processing platform, which was developed based on COTS hardware. Secondary objectives include several ADCS experiments, tests of a pulsed plasma thruster for attitude control, and the operation of an amateur radio payload.

During the first weeks of its operation in orbit during LEOP and commissioning the SONATE-2 performs as expected. All systems have been checked out and the post-launch calibration of the AI payload and satellite bus has started. The amateur radio payload was activated on several days and was successfully received by radio amateurs worldwide.

1 INTRODUCTION

Artificial Intelligence (AI) has already become a regular part of our everyday lives and is deliberately and actively used by the public with the recent rise of large-language models like ChatGPT. Many terrestrial applications like mobile devices, speech recognition or autonomous vehicles rely on machine learning, particularly deep learning, and therefore specialized processors. But also, for scientific purposes AI is used. For example, deep learning helped to discover new types of galaxies in a recent astronomy survey [1]. So far, successful AI applications were rarely seen in nanosatellite missions. The last few years have seen big advancements in COTS-hardware for AI applications, which makes these systems increasingly feasible for applications in space and even on nanosatellites. Previous missions like ESA's PhiSat missions [2] [3] only use pre-trained model and are limited to model inference by their hardware.

SONATE-2 will expand on this approach and furthermore create the possibility of supervised and unsupervised on-board training. The possibility of on-board training enables a new range of possible applications like anomaly detection or in-flight model optimization. Anomaly detection is particularly interesting with regards to interplanetary exploratory missions, because data for training is not available pre-flight. The limited communication bandwidths on these missions make in-situ training necessary. On-board processing enables the analysis of huge amounts of data while only keeping the interesting parts for the downlink to Earth. Being able to adapt by training during the mission to previously unknown environments or data will further improve the capabilities of those missions.

As a technology demonstrator mission SONATE-2 verifies novel artificial intelligence (AI) hardware and software technologies in Low Earth Orbit. The satellite can analyze the Earth’s surface autonomously with its multiple image sensors in the visible and near infrared spectrum. In addition to the classification of objects already known at the start of the mission from pre-launch training on ground, the payload also has the capability of anomaly detection by on-board training for the detection of previously unknown objects or phenomena.

As one of the secondary objectives, SONATE-2 is also able to detect transient light phenomena such as lightning by using classical image processing algorithms. The mission also includes the verification of a new star sensor, tests of the ADCS’s target-pointing capabilities, tests of a propulsion system and the operation of an amateur radio payload.

2 SPACE SEGMENT

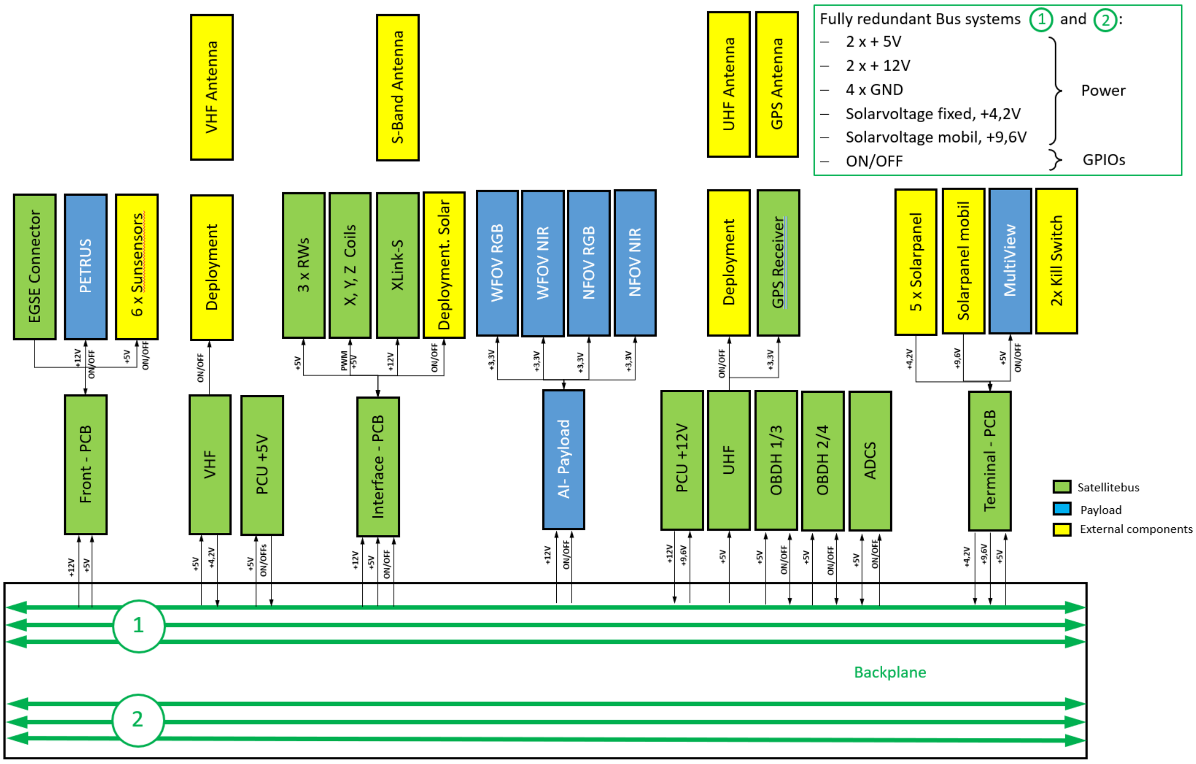

Figure 1. System overview of the SONATE-2 space segment (one redundant half).

This chapter gives a short overview of the satellite’s payload and most important bus subsystems, as summarized in Figure 1. A detailed description can be found in [4].

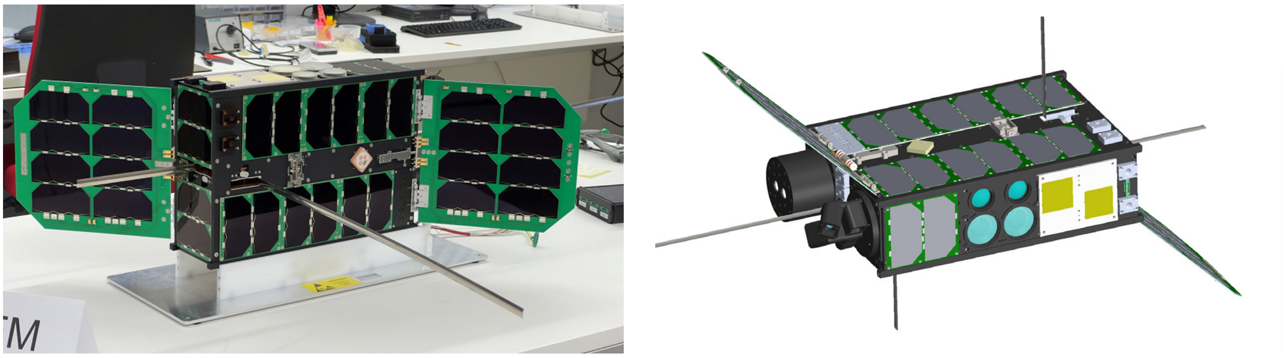

Figure 2. SONATE-2 flight model (left), CAD model (right)

The SONATE-2 satellite is designed as a 6U+ CubeSat with two deployable solar panels, using the two “tuna cans” as shown in Figure 2. The satellite is fully redundant both in the satellite bus and the payload. It is based on the bus of the previous mission SONATE [5], which was successfully launched in 2019 and operated for one year. Upscaled from 3U to 6U+, SONATE-2 has a mass of about 11.2 kg.

2.1 Primary Payload: AI Platform

To provide the computing resources required for in-orbit training of AI models, the **Nvidia Jetson Xavier NX** processor is used as the main component. The platform also has several image sensors integrated for acquisitions in the visual and near-infrared spectrum that can be matched on-board, each with a wide and a narrow field of view:

- Near Infrared (NIR) 820-900nm, ground resolution: 38m, field of view: 5.7°x4.3°
- RGB, ground resolution: 38m, field of view: 5.7°x4.3°
- Near Infrared (NIR) 767-787nm, ground resolution: 379m, field of view: 52.8°x40.9°
- RGB, ground resolution: 379m, field of view: 52.8°x40.9°

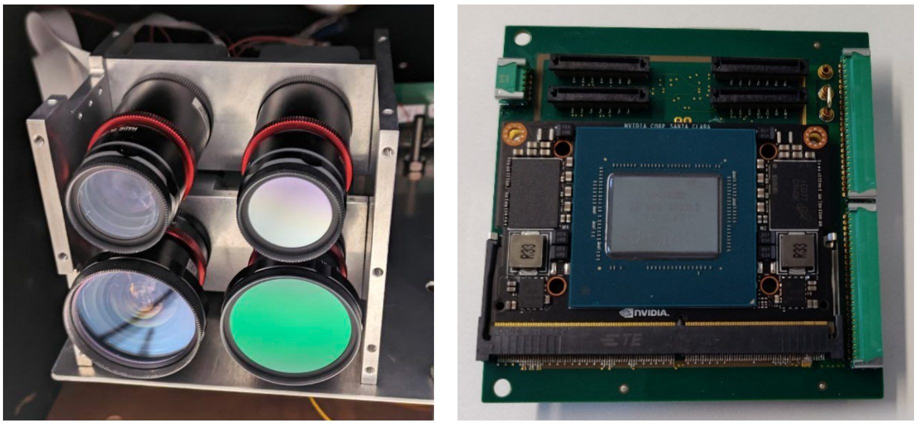

Figure 3. AI payload: optical system incl. lenses, filter, image sensors (left), Xavier NX on carrier board (right)

Specialized processors are required for the execution and especially for the training of neural networks. Due to the great flexibility, graphics processors (GPUs) were chosen for this mission. The Xavier NX is a combined CPU and GPU system and has a high efficiency and peak performance. This makes it possible to quickly calculate and train even complex AI models. The 8GB of RAM are sufficient for training state-of-the-art neural networks and the 48 Tensor Cores provide acceleration for network inference. The Xavier NX is used in its 10 W peak power configuration, operating with a customized version of Ubuntu Linux 18.04.

The Xavier NX was qualified in thermal-vacuum, mechanical and radiation tests [6] for SONATE-2 and integrated into the satellite using a custom designed carrier board. The carrier board includes four MIPI ports to connect the image sensors, two eMMC flash memory chips which store redundant images and an ARM Cortex M4 microcontroller which controls power sequencing, redundancy and is used as a watchdog for the Xavier NX. The AI platform and its cameras are integrated fully redundant on the two isolated buses of SONATE-2.

2.2 Secondary Payloads

The secondary payloads mainly include experiments for ADCS subsystems: a new star sensor called MultiView and a pulsed plasma electric thruster for attitude control maneuvers. Both are installed in the satellite's tuna cans as shown in Figure 4.

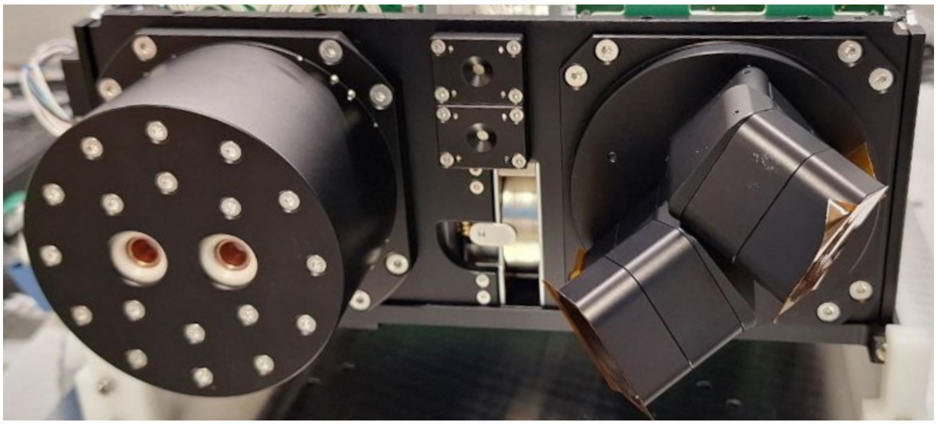

Figure 4. Pulsed plasma thruster (left tuna can) and MultiView star sensor (right tuna can)

The combination of multiple star sensors can increase the availability of attitude information when used in the right configuration. In the best case there is always at least one sensor which is not blinded by the Sun or the Earth albedo. The limited volume in a CubeSat is one of the challenges when implementing this. Using the space in a tuna can be a solution to this problem [7]. For SONATE-2 a combination of four star sensors into one tuna can was considered optimal. As a secondary payload the performance of the MultiView star sensor will be tested in orbit, before it can be integrated into the ADCS control loop later in the mission.

When going beyond LEO in the absence of an external magnetic field alternative actuators are necessary for attitude control. Electric thrusters can be such an alternative. The Institute of Space Systems at the University of Stuttgart has previously developed a pulsed plasma thruster for the GREENCUBE satellite [8]. For SONATE-2 the thruster was further improved. It will be used for experiments to desaturate a spinned-up reaction wheel on one of the three axes.

Another secondary payload is the amateur radio payload. It will operate on the VHF transceivers described in 2.4 and regularly provide two amateur radio services:

1. SSTV: SONATE-2 will transmit images taken by the AI payload's cameras in a low-resolution encoding to the ground, which can be received by radio amateurs worldwide with a relatively simple setup.
2. Digipeater: This is a digital repeater on-board of SONATE-2: Messages in form of AX.25 frames transmitted by a radio amateur on ground can be received by the satellite and retransmitted back to Earth, where another radio amateur can receive the message.

2.3 OBDH

SONATE-2 integrates four on-board data handling computers (OBDH). The OBDHs are designed to ensure that at least two of them are always switched on and the other two serve as a cold redundant reserve. Each of the OBDH has access to three external NOR flash devices and uses an Arm Cortex M4 as a sole processor. Two OBDH boards are mounted on a common carrier board, as shown in Figure 5. SONATE-2's OBDH use a modified version of the real-time operating system RODOS [9].

Its main tasks are the processing of telecommands and housekeeping telemetry, the time management, the management of redundant components, the allocation of interfaces to all subsystems onboard SONATE-2, and the monitoring of the state of the whole satellite.

Figure 5. SONATE-2 on-board computer.

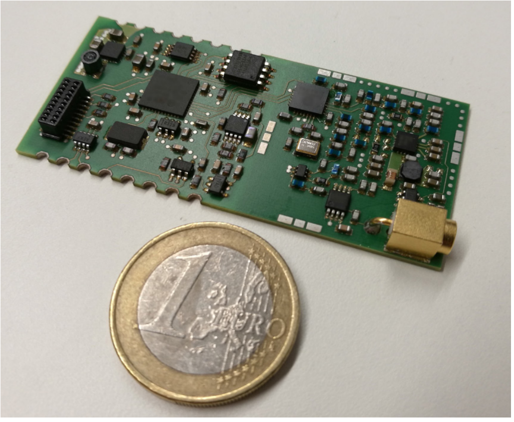

Figure 6. SONATE-2 VHF/UHF transceiver

2.4 Communication

The communication between space segment and ground segment is 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 UHF transceivers 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-2's UHF up- and downlink.

The amateur radio payload operates in the VHF amateur radio band on 145.880 MHz (SSTV) and 145.825 MHz (digipeater). At the same time the VHF band is used as a backup for the uplink of telecommands. Likewise, the satellite bus includes two redundant VHF transceivers in hot redundancy.

For each of both bands the same transceiver is used (see Figure 6), just in different configurations. Each transceiver is connected to its own monopole antennas that had to be deployed directly after separation from the launch container. These antennas are made of steel tape which was rolled up inside the satellite during launch.

Because the AI payload has higher requirements for the communication link in terms of both up- and downlink, two redundant XLink-S transceivers are integrated into SONATE-2 together with a dual-band patch antenna mounted on the satellite's side panels each (see Figure 2). This allows up to 2 Mbps downlink and 56 kbps uplink in the space operation/space research service in S-band.

2.5 Power Subsystem (EPS)

For the generation, storage, and distribution of electrical power of up to 20W peak to the AI payload and the S-band transceivers as the biggest consumers, the EPS has both a +5V power bus from the SONATE satellite and a newly added +12V power bus. To supply the +12V bus, two deployable solar panels with 8 cells each are used in addition to the body mounted solar cells. For both voltages there are two separate power busses and power control units for redundancy. Each power bus uses four commercially available 18650 Li-Ion batteries with a capacity of 40Wh for storage (see Figure 7). The used switching boost converters can provide peak power of up to 20W and continuous power of 10W per bus.

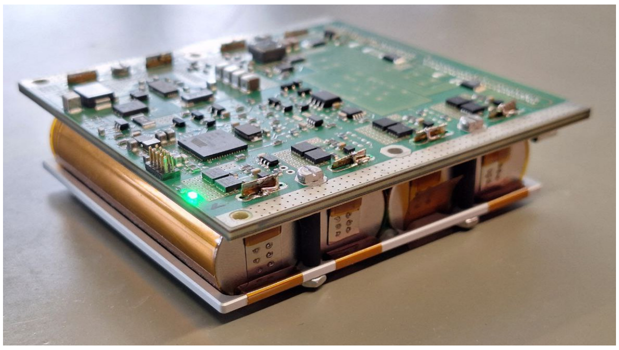

Figure 7. One of four of SONATE-2's battery pack.

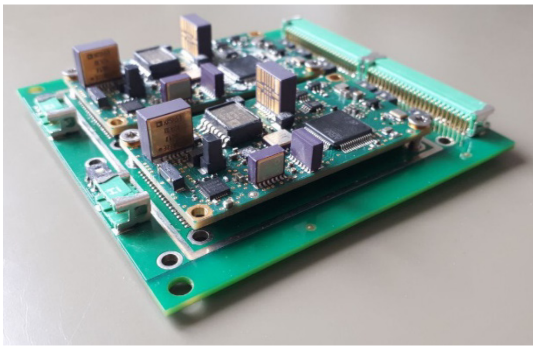

Figure 8. SONATE-2 ADCS main board

2.6 ADCS

To determine the attitude of SONATE-2, sun sensors, magnetometers and gyroscopes are used. While in the sun both the magnetic field and the sun vector are combined using QUEST or TRIAD. On the night side, the previous attitude is integrated with the gyroscopes. After its verification experiments, attitude determination can be extended by including the MultiView measurements into the attitude calculation. To control the satellite's attitude, reaction wheels along each principal axis are used in combination with magnetorquers. The magnetorquers can be used to desaturate the reaction wheels or detumble the CubeSat if necessary.

To get more accurate position information and support the identification of SONATE-2 after launch, the satellite is equipped with two Navspark Orion B16 GNSS receivers, each with an antenna mounted on the largest sides of the satellite pointing in opposite directions for better coverage.

3 GROUND SEGMENT

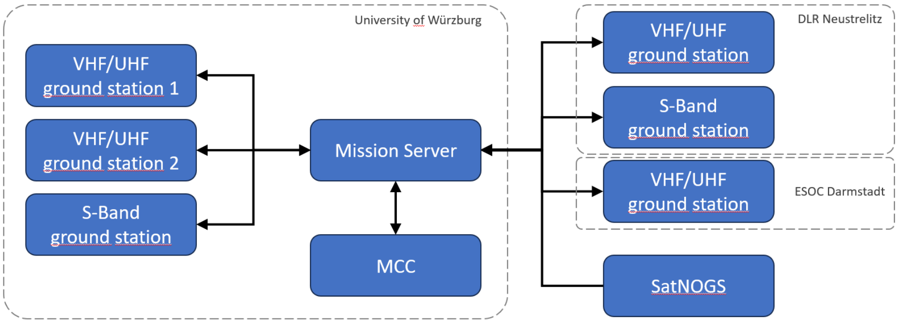

Figure 9. Overview of the SONATE-2 ground segment structure.

The SONATE-2 ground segment consists of a network of ground stations at the University of

Würzburg and external ground stations. The data flow to and from all ground stations is combined in a central mission server, to which the operators in the mission control room connect to to operate the satellite. The elements of the ground segment shown in Figure 9 are described in the following chapter.

All operations of the SONATE-2 mission are controlled and supervised from the SONATE-2 mission control room at the University of Würzburg, shown in Figure 10.

Figure 10. SONATE-2 mission control room.

This mission control room and most operational software were built and developed for the previous SONATE mission, where they demonstrated good performance. They were adjusted and refined to be reused for SONATE-2.

3.1 Ground Stations at University of Würzburg

To receive housekeeping telemetry from and to transmit telecommands to the space segment, the university has two amateur radio stations that are compatible to the satellite's UHF and VHF transceivers. They consist of X-quad antennas for the VHF and UHF amateur radio band mounted with an azimuth-elevation rotor on the rooftop, rotor controller, transceiver, modem, and a control computer. The older ground station of the two was already used during SONATE operations. For SONATE-2 a new, similar ground station was built to further improve the communication link. Its antennas are stacked, and they are mounted operated on top of a 8m mast, as shown in Figure 11.

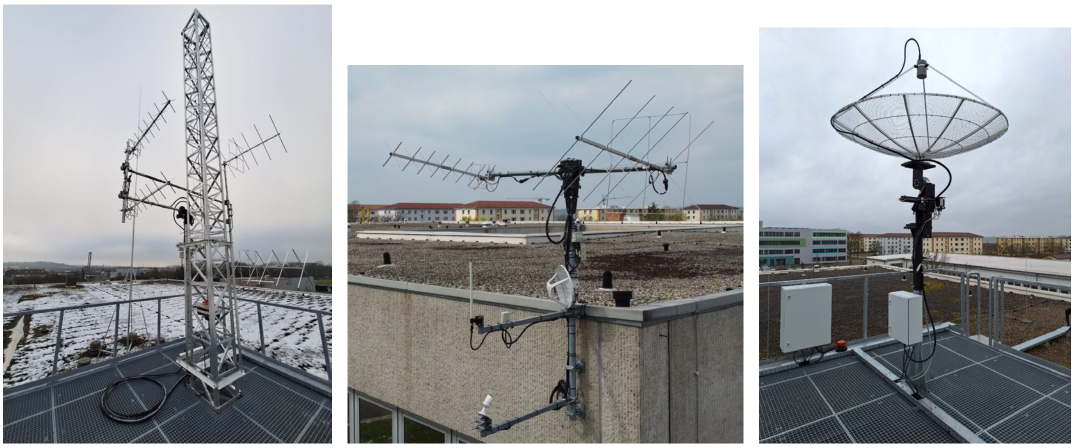

Figure 11. Ground station antennas at the University of Würzburg: new VHF/UHF ground station (left), old VHF/UHF ground station (center), S-band ground station (right)

For S-band operations another new ground station was added. It consists of a 1.9m mesh dish antenna mounted with a bi-directional helical feed on an XY rotor for faster tracking.

3.2 External Ground Stations

To achieve redundancy and to improve the communication link, the SONATE-2 mission uses a set of different external ground stations. For S-band the ground stations operated by the German Aerospace Center (DLR) in Neustrelitz are prepared for SONATE-2. These ground stations with diameters of 7 or 11 meters are not only a backup but much more powerful than our own ground station in Würzburg. As backup in the VHF/UHF bands there is one ground station available at the same location, operated by the local DLR School Lab. Another one is operated by the European Space Operations Center (ESOC) in Darmstadt.

In addition to these specific ground stations, the SatNOGS ground station network, a community-based »Open Source global network of satellite ground-stations« [10], is used for telemetry downlink. The University of Würzburg operates two ground stations within the SatNOGS network. SatNOGS can be used to schedule passes of SONATE-2 for ground stations world-wide, but for SONATE-2 it is mainly used over Europe to extend and improve the downlink during passes over our own ground stations in Würzburg.

4 LEOP

4.1 Launch and First Days

SONATE-2 was launched with a Falcon 9 rocket on March 4, 2024, 22:05 UTC from Vandenberg Space Force Base on SpaceX' Transporter Mission 10 into a 527x505 km Sun synchronous orbit. It was deployed from the launch container 55 minutes later, as shown in Figure 12.

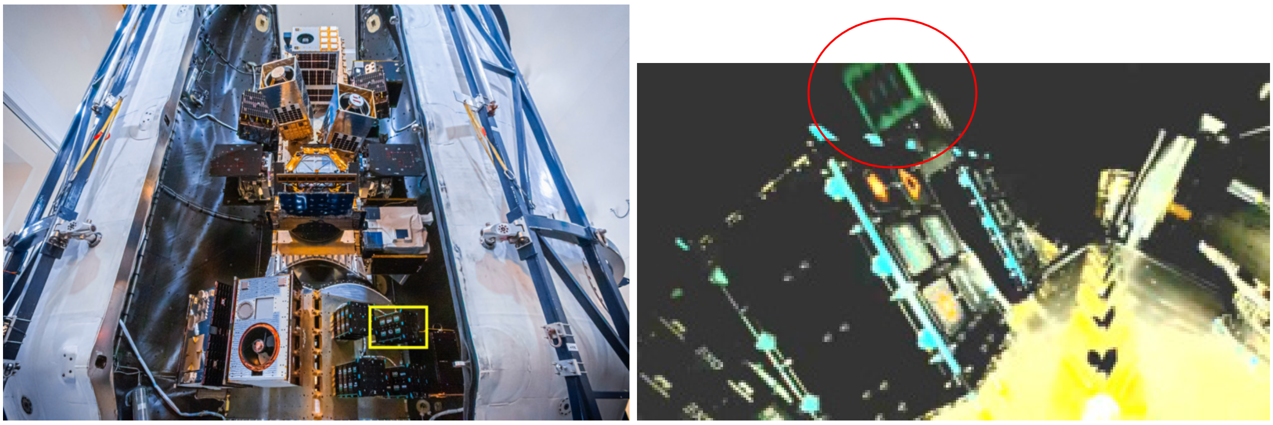

Figure 12. SONATE-2 in the launch container mounted to the Falcon 9 upper stage before launch (left, yellow box). Deployment of SONATE-2 from the launch container (right, red circle). Image source: SpaceX

All four deployable antennas (2m and 70cm amateur radio bands) were successfully deployed 200 seconds after separation from the deployment container. Unfortunately, the automatic deployment of the deployable solar panels 60 seconds later failed. As the separation and solar panel deployment as well as the first contact occurred on the night side of Earth, the temperature of the deployment mechanism was already lower than expected. Therefore, the solar panels were successfully deployed manually by telecommand later in LEOP during a pass in the Sun. This was no problem for the LEOP operations as power budget und communications were designed to be sufficient in case the solar panel deployment would fail.

From the first successful contact 1 hour after launch SONATE-2 was operated on all passes over the ground stations in Würzburg. Except the deployment of the solar panels the satellite was in nominal state as expected. After five days, only the weekday passes between 12:00 and 16:00 UTC were used to command the satellite, while the night and weekend passes were solely for automated telemetry downlink. During the first days, all subsystems have been turned on at least once on both redundant busses to see that everything survived the launch as expected.

Active detumbling of the satellite during LEOP was not necessary. After separation the remaining rotation was around 5 deg/sec around the primary axis of the satellite (see Figure 13), slowing down by 1 deg/sec/day. The remaining rotation of less than 1 deg/sec is preferred for thermal reasons compared to a total detumbling by active control. Therefore, further detumbling is only performed when required for payload operations.

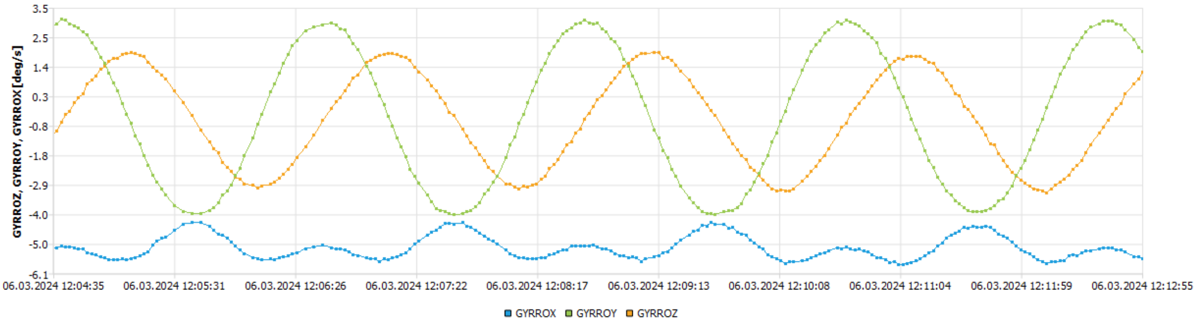

Figure 13. First gyro data of SONATE-2 showing a 5 deg/sec rotation around the satellite's x-axis and an oscillating rotation around the minor axes.

4.2 Identification

In contrast to SONATE, where post-separation identification of the correct TLE/NORAD object was complicated and never completely answered [11], the identification of SONATE-2 was very easy and straightforward. This had several reasons:

The pre-launch TLEs of the SONATE launch in 2019 provided by the launch provider where a bit off, thus the first contact 3.5 hours after the launch were unsuccessful because the antenna tracking and doppler shift correction were wrong. It took almost a day to establish the first contact. For SONATE-2 on the other hand, the pre-launch orbital parameters were very accurate and only off by a few seconds. Therefore, the first contact was established on the first pass about 1 hour after the launch. The following days the pre-launch TLE was propagated from the Doppler curves during the passes using *strf* [12]. The differences again were minimal, only a few seconds per day.

Ten days after launch of SONATE-2 the first TLE for objects with a final satellite catalog number (NORAD-ID) were published. We were able to immediately identify SONATE-2 as object 2024-043Q (59112) by matching its TLE to the Doppler observations made over a ground station using *ikhnos* [13]. The results shown in Figure 14 for object Q and its nearest neighbors P and R at that time show a very good match for object Q. During LEOP of the SONATE mission, this was not possible because the objects were still too close.

Another beneficial factor during SONATE-2 LEOP was the fact, that there were only very few satellites operating on amateur radio frequencies. Hence it was possible to schedule many observations on the SatNOGS ground station network that accelerated the identification of SONATE-2. For SONATE this was not possible since there were many satellites operating on amateur radio frequencies on the same launch, some satellites even used the same frequencies.

Lastly, SONATE-2's identification could be verified using the satellites' GNSS receiver.

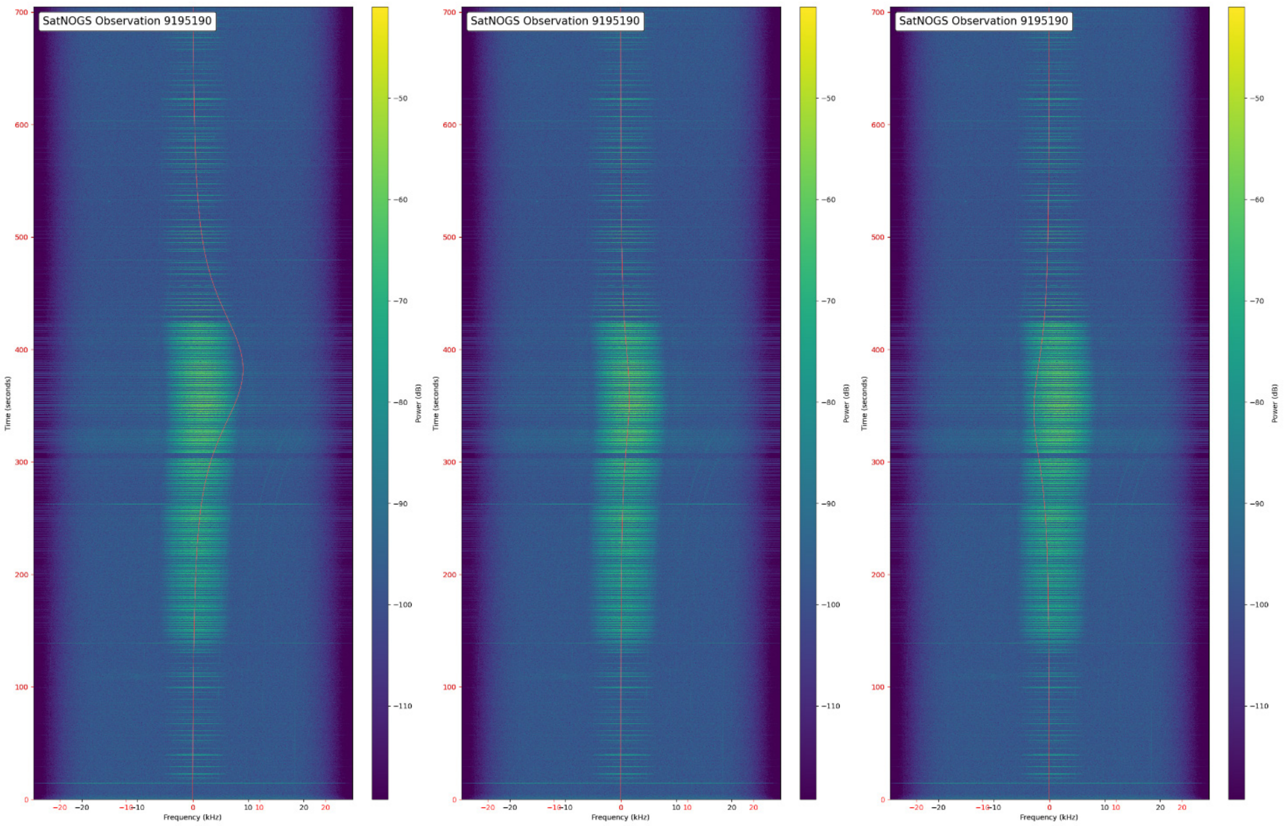

Figure 14. Doppler shift matching of SatNOGS Observation 9195190 to OBJECT Q (SONATE-2, center) of the launch to the nearest objects P (left) and R (right) directly after publication of the first TLEs on Celestrak 10 days after launch.

5 COMMISSIONING

5.1 ADCS Calibration and Modes Testing

To prepare the ADCS for the operational phase, the determination and control of the attitude has to be verified in all ADCS modes. At the beginning, the calibration of the magnetometers was performed using Particle Swarm Optimization [14]. To verify the sun sensor calibration, telemetry over one orbit was recorded and checked, whether the sun vector a) matches to the telemetry of the solar arrays and b) that the transitions between the different sun sensors are without jumps in the sun vector. After that the attitude could be determined from the magnetic field and the sun vector. To improve attitude integration in the Earth's shadow, the gyroscopes where recalibrated by comparing the calculated attitude from magnetic field and sun vector to an integration of the rotational rates of the gyroscopes.

To verify the determined attitude, images taken by the AI payload were manually georeferenced onto the Earth's surface, see Figure 15. The resulting attitude was compared to the attitude determined by the ADCS.

With a calibrated attitude determination, the directions of the actuators were verified by activating them one by one. After that, the tests of control modes began. So far detumbling, Sun pointing and first Nadir pointing tests were successfully performed.

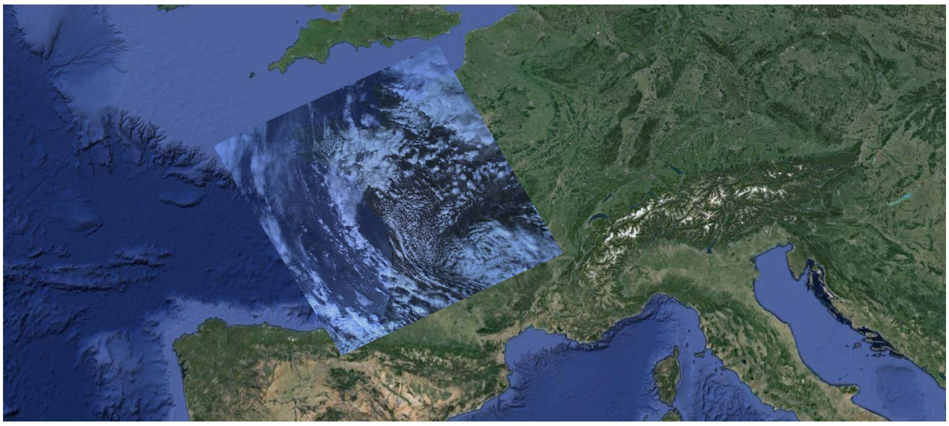

Figure 15. Image taken with the AI payload georeferenced on the Earths' surface.

5.2 Payload Calibration

Although the cameras have been calibrated in terms of exposure time, white balancing, and image matching, it is necessary to do a recalibration before starting with the AI experiments, since the conditions on ground differ from those in space.

Cloud cover and the atmosphere reduce the amount of light reaching the ground. This is reinforced by the fact that during integration and calibration of the satellite in the fall of 2023, there were no sunny days in Würzburg. Hence, a recalibration of the exposure time in space is necessary. This can be done by using the auto-exposure or by a binary search with a series of images taken at different exposure times. A fixed exposure time is necessary for the AI models to keep the light conditions constant. For the calibration of the white balancing the procedure is similar. It is necessary since the blue light is scattered stronger by the atmosphere. This is shown very noticeable in 6.1.

The first NIR and RGB images cannot be matched sufficiently with the image matching matrices determined pre-launch. This is expected due to the mechanical loads during the launch. Therefore, new matching matrices will be determined during commissioning.

5.3 OBC Calibration

The OBC required some calibration as well. First, the sensor limits of the battery temperature sensors had to be adjusted, as the measured temperatures in orbit were a few degrees colder than expected, and therefore at least one time triggering the safe mode. To avoid unnecessary activation of the safe mode, the limit was reduced.

Additionally, a drift of approx. 800 ms per day was observed on the satellites' UTC clock managed by the OBC. The real-time clock's calibration was adjusted for drift compensation. For more details, see [15].

6 FIRST RESULTS

6.1 AI payload

Since the launch of SONATE-2 was delayed by approx. two months, the commissioning of the AI payload has been successful so far but is still ongoing at the time of writing this paper. Therefore, only a few preliminary results from the commissioning of the AI payload can be presented. Initial tests of all subsystems and software modules were successful. The NVIDIA Jetson NX system running a modified Linux operating system is thermally stable and fully functional.

The first part of the commissioning of the AI payload is the checkout and calibration of all image sensors. Therefore, a series of images was taken with every sensor. As they were taken before the S-band downlink was available, the images were only downloaded in a lower resolution. Until now, images from all eight camera systems have been captured and downloaded. The optics are intact, and the images are sharp. While some sensors required calibration of the exposure time, all RGB images require a recalibration of the ground-based white balancing calibration, since the blue signal part is weaker on ground. This is clearly visible in an example image shown in Figure 16.

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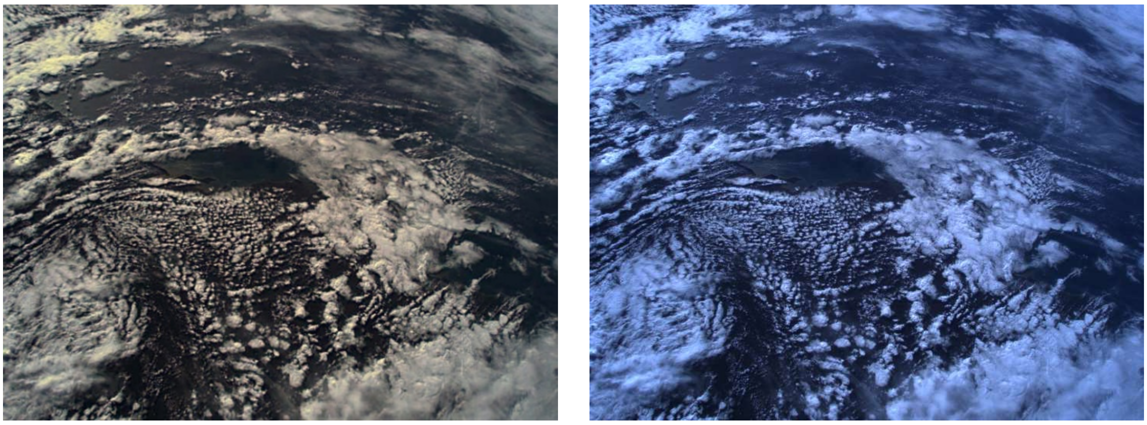

Figure 16. One of the first images taken over La Rochelle, France. The left image shows the image after preliminary white balancing, while the right image shows the raw image.

The white balancing in the shown image is calibrated as follows:

$$Red_{space} = 1.241 \cdot Red_{ground} \tag{1}$$

$$Green_{space} = 1.000 \cdot Green_{ground} \tag{2}$$

$$Blue_{space} = 0.688 \cdot Blue_{ground} \tag{3}$$

On April 2, the first Deep Leaning training was achieved, one of the first ever in this complexity and satellite class. During the training, 1500 Sentinel-2 images, pre-loaded into the payload before launch, were used in a test dataset and the training of an autoencoder model for anomaly detection was successfully executed over 10 epochs.

6.2 Amateur Radio Operations

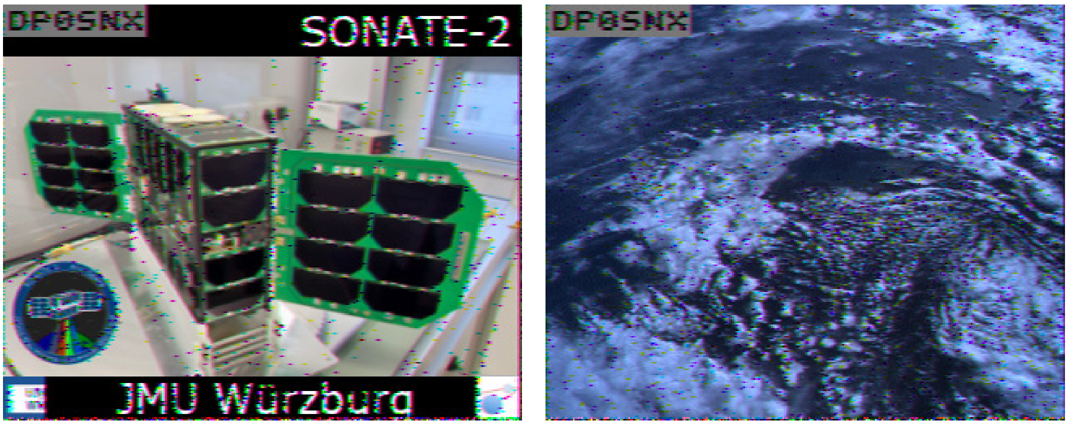

Figure 17. First two images transmitted via SSTV: pre-launch image (left), one of the first images taken by AI payload (right)

The SONATE-2 mission has received a lot of feedback from the amateur radio community worldwide. Already a few minutes after first contact with our own ground station in Würzburg we received the first reception reports via email.

The SSTV payload was activated the first time four days after launch with an image prepared on ground before the launch. Over the four-day long Easter weekend, SSTV was activated transmitting one of the first images taken by the AI payload cameras. At the time of writing this paper the SSTV transmitters have transmitted around 120 times, distributed all around the world. We received a lot of reception reports via e-mail and Twitter/X following these SSTV events. SSTV receptions by our own ground station in Würzburg of both images are shown in Figure 17.

6.3 Communications Performance

Compared to SONATE, the performance of communication links after 6 weeks of operations so far was improved significantly, especially the uplink in the amateur radio bands with already more than 3000 telecommands successfully send to SONATE-2. While on average, the failure rate of the telecommand uplink was between 90 and 95% during one year of SONATE operations [11], the success rate on the SONATE-2 uplink has reached 60 to 70%, as shown in Figure 18. This includes both UHF and VHF uplink in all elevations, whereas the success rate usually correlates with the elevation.

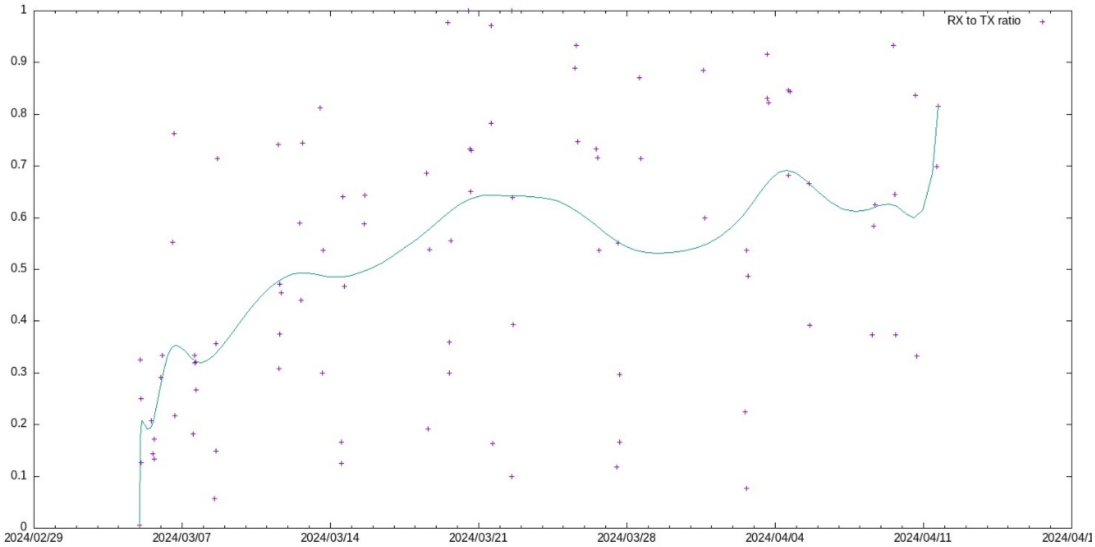

Figure 18. Ratio between telecommands transmitted by the ground stations to the number of telecommands successfully received and decoded by SONATE-2.

During the SONATE mission, the UHF uplink was basically unusable and only the (backup) VHF uplink was used. Although this was attributed to high power radar pulses in the 420-450 MHz band in Europe [16], we do not observe the same for SONATE-2. The UHF uplink in elevations over 20° is now comparable to the VHF uplink. While the improvement in the VHF uplink can be explained in parts by improved software, this is not the case for the UHF uplink. We attribute this to the use of a completely different transceiver than during the SONATE mission, as the local noise in orbit on the UHF uplink frequency, especially over Eastern Europe (and East Asia, see Figure 19), remains around 10 dB higher while not noting a significant difference in uplink performance.

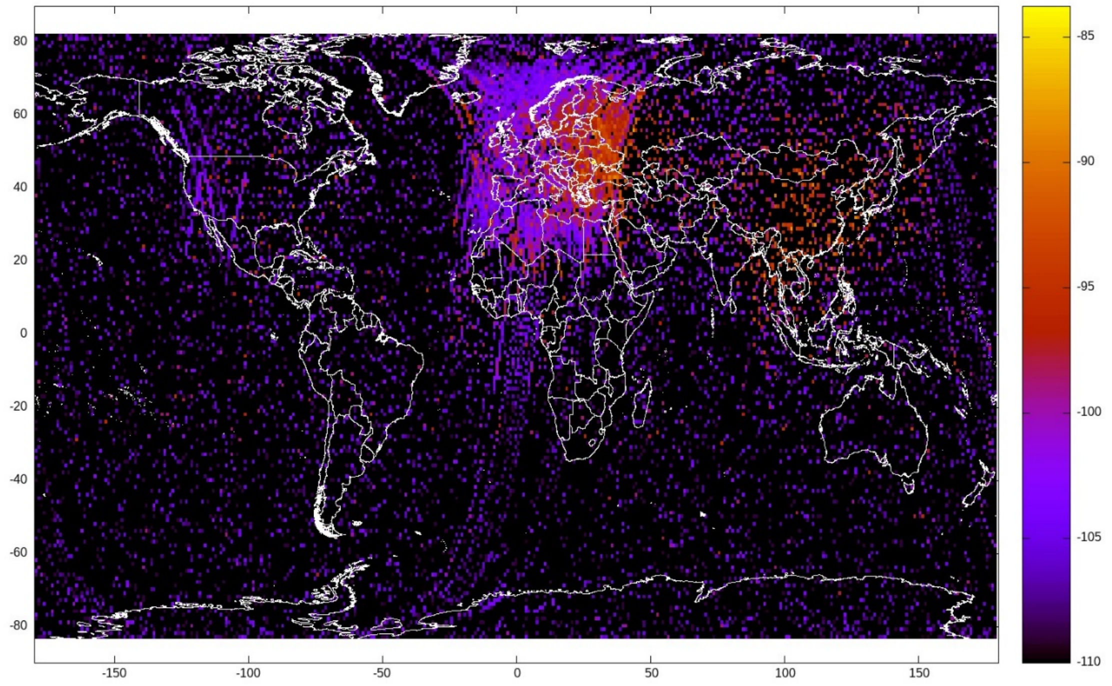

Figure 19. Noise level received by SONATE-2 UHF transceiver on 437.025 MHz.

The downlink performance is comparable to SONATE, but due to the improved uplink and an optimized packet structure, the SONATE-2 database already contains more than 172,000 unique telemetry frames received since launch.

At the time of writing this paper, the S-band link has not been tested enough to make a valid statement about its performance.

6.4 GNSS Performance

As the identification of SONATE-2 did not necessarily require the use of the GNSS receivers as shown in 4.2, they have not been activated on a regular basis yet but only for a few tests. Therefore, so far, the following statements can be made:

The receivers' antennas are mounted on the satellites' outer wall below the deployable solar panels, hence their free view into space is covered by the solar panels before they are deployed. Nevertheless, the GNSS receiver' were able to receive a fix for a short time. A much bigger effect on the quality of the signal comes from the rotation of the satellite. At rates around 3 deg/sec around the satellite's major axis, only occasional fixes are possible for a short period of time. On the other hand, at rates below 0.5 deg/sec a stable, continuous fix can be achieved.

To validate the position of SONATE-2 in orbit, the position from the GNSS receivers was compared to the expected position from propagating the TLE valid at that time. A difference of <100 m vertically and < 3 km horizontally was determined at a first test.

7 OUTLOOK

To complete all planned experiments with the AI payload and the secondary payloads, the SONATE-2 mission is planned to operate for one year. In this time, several AI inference experiments for image segmentation, object detection and anomaly detection will be performed.

The training of the autoencoder will be repeated with images taken during the mission in orbit to detect anomalies in the target area in a subsequent pass. To test classical image analysis algorithms on the AI hardware, a lightning detection experiment using a background subtraction algorithm will also be performed. For more details on the planned experiments, please refer to [4].

Effects from the space environment like extreme temperature changes and the exposure to radiation may change the behavior of the ADCS' sensors over time. Therefore, regular experiments to recalibrate the sensors are scheduled to maintain a good pointing accuracy. To further validate the performance of the GNSS receivers, we want to activate the receivers regularly during the operational phase. Minor bugs in the ADCS software have been identified during commissioning, a software upload in the next weeks is prepared.

It is planned to consolidate the operation of the amateur radio payload to a regular schedule. For interested radio amateurs we will announce every activation on our Twitter/X account @JMUSpace.

After one year of planned operation the update capabilities of SONATE-2 [15] will allow the upload of new experiments as long as the satellite survives, for example to allow students to run their own AI experiments. The deorbiting by natural orbital decay is expected around 2036.

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