SONATE-2 – A TECHNOLOGY DEMONSTRATION MISSION FOR ARTIFICIAL INTELLIGENCE

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ABSTRACT

The increasing amount of data produced by sensors, combined with low download rates, are a challenge for nanosatellites. On-board data processing and classification can be used to reduce the amount of data that needs to be downloaded. This edge computing approach has become more and more present in various terrestrial applications and embedded devices. Recent missions have used artificial intelligence (AI) models, pre-trained on the ground, for on-board image analysis. The SONATE-2 mission expands on this approach by also introducing on-board training capabilities, enabling new applications including on-board model generation and improvement.

This paper presents an overview of the SONATE-2 technology demonstration mission with an emphasis on the AI payload. The primary goal of the mission is the in-orbit demonstration of a new AI processing platform, which is currently developed based on COTS hardware. The platform will use a Nvidia Jetson module with integrated CPU and GPU for high flexibility and high performance. The mission will verify the platform's processing capabilities in space using multiple cameras in the visible and near-infrared spectrum. Images captured by these cameras will be analyzed using conventional image processing and AI models. The experiments consist of a broad range of applications including lightning detection, image segmentation, object detection and anomaly detection. Anomaly detection requires the models to be trained in space using images captured on-board. This demonstration of on-board AI training is important for future interplanetary missions, where there might be limited or no data of the target area available. This will also enable a better detection of transient phenomena. The platform will also include an over-the-air update function for new applications.

Secondary objectives of the SONATE-2 mission include 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. To support the AI platform, the 3U satellite bus of the predecessor mission SONATE is adapted to a new 6U design. The SONATE-2 satellite is planned to be launched in 2024.

1 INTRODUCTION

Artificial Intelligence (AI) has already become a regular part of our everyday lives. Many terrestrial applications like mobile devices, speech recognition or autonomous vehicles rely on Machine Learning (ML), particularly deep learning (DL) and therefore specialized processors. AI is most useful when analyzing massive amounts of data for example telemetry or image data. For example, DL helped to discover new types of galaxies in a recent astronomy survey [1]. So far these very successful AI implementations were rarely seen in nanosatellite missions. The main reasons were a lack of available hardware as well as the missing reliability of the model outputs. The last few years have seen big advancements in COTS-hardware and AI reliability, which makes these systems increasingly feasible for applications in space and even on nanosatellites.

Recent missions like ESA's PhiSat-1 Mission have successfully shown the potential of using ML algorithms in space for on-board data analysis [2]. By autonomously detecting cloud coverage in captured images a prefiltering was now possible which leads to a better bandwidth utilization. There are further AI missions planned like the QlevEr Sat [3] or the PhiSat-2 mission [4]. These missions are using pre-trained models and processors which are optimized for model inference.

SONATE-2 will expand on this approach and furthermore create the possibility of on-board training using the NVIDIA Jetson chips. The possibility of on-board training enables a new range of possible applications like anomaly detection or in-flight model optimization. Anomaly detection often requires data for training, which is not available preflight. One example are interplanetary missions, where no training datasets are available preflight, and the communication bandwidth is limited. Another important target for on-board anomaly detection can be transient events like weather phenomena. On-board processing enables the analysis of huge amounts of data while only saving the interesting parts. Being able to adapt by training during the mission to previously unknown environments or data will further improve the possibilities of small-scale satellite missions.

2 SONATE-2 MISSION

The SONATE-2 mission is a technology demonstrator mission for AI currently prepared at 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 50RU2100). The SONATE-2 mission will verify novel artificial intelligence hardware and software technologies in miniaturized format in a low Earth orbit. By using such AI technologies, the satellite will be able to analyze the environment autonomously with its multiple sensors in the visible and near infrared spectrum. Deep learning plays a central role as a versatile image processing tool. Thus, in addition to the classification of targets already known at the start of the mission, the payload will also have 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 will also be able to detect transient light phenomena such as lightning by using classical image processing algorithms. The mission will also include 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.

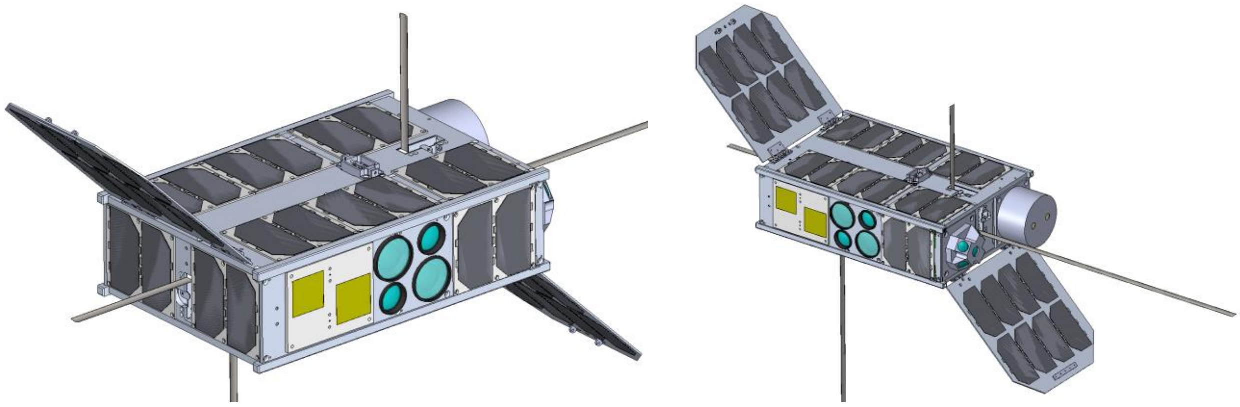

Figure 1. SONATE-2 satellite design

The mission is based on the satellite bus of the SONATE mission, which was successfully launched in 2019 [5]. The space segment of the SONATE-2 mission consists of a 6U CubeSat with a mass of about 12kg. The launch is planned in Q1 2024 into a 550 km Sun-synchronous orbit. The mission is designed to be operated for at least one year. On the ground segment side SONATE-2 will be operated from its mission control room at the University of Würzburg, primarily using the university's ground stations.

3 SPACE SEGMENT SYSTEMS OVERVIEW

Figure2 gives a complete overview of the SONATE-2 satellite components like the payloads and the bus.

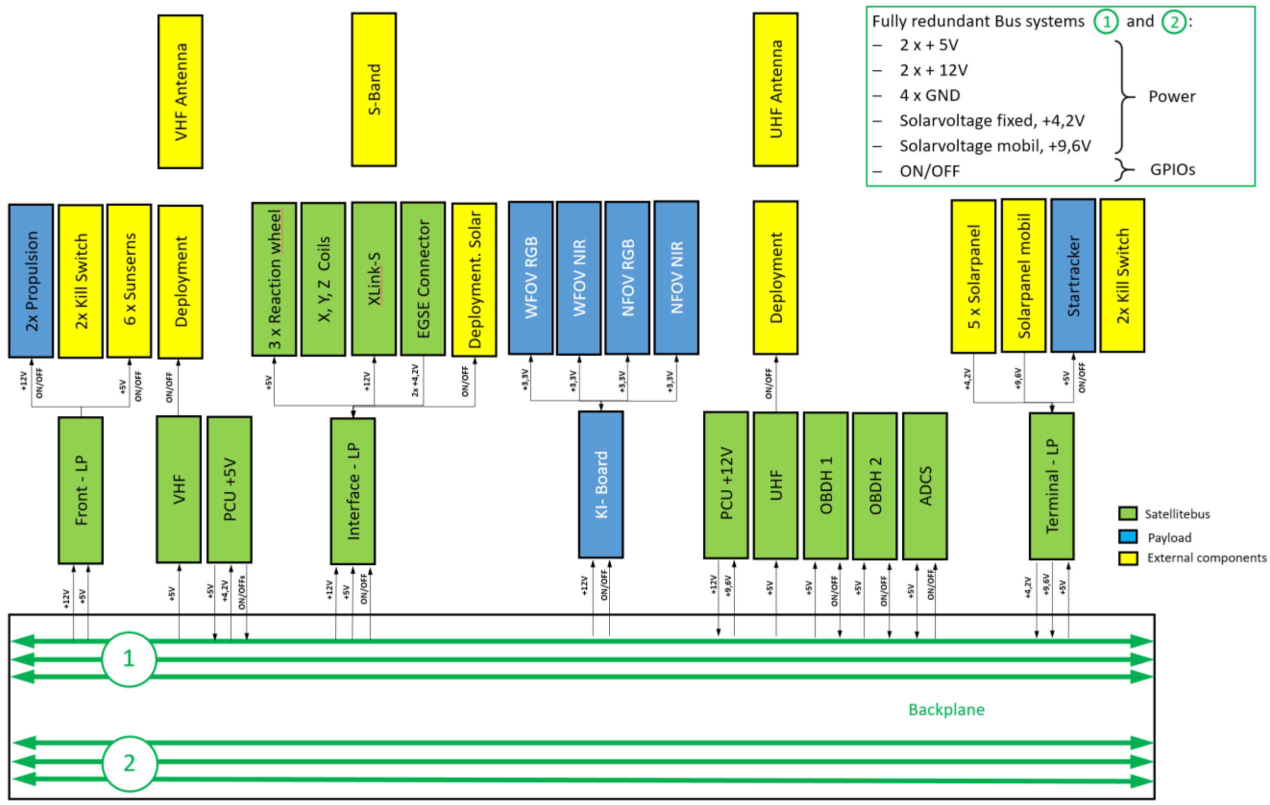

Figure 2. System overview of the SONATE-2 space segment

4 AI PAYLOAD

The AI platform is the primary payload of the SONATE-2 mission and provides a platform for artificial intelligence applications as well as other highly autonomous algorithms. The platform enables a wide range of computationally expensive applications, particularly in the area of deep learning. To provide the computing resources required for this, the **Nvidia Jetson Xavier NX** processor will be used. The platform will also have several optical sensors integrated for image acquisition in the visual and near-infrared spectrum. A unique feature of the platform is its ability to train sophisticated deep learning models in orbit. This will enable use cases such as on-board anomaly detection on the captured image data.

Specialized processors are required for the execution and especially for the training of neural networks. During mission analysis systems based on FPGAs, ASICs and GPUs were considered. 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 even 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 will be used in its 10 W peak power configuration. Another advantage is that development on desktop computers can easily be transferred to the Jetson platform, because of the similar architecture and the Linux operating system.

The Xavier NX will be integrated into the satellite bus 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 a microcontroller which will control power sequencing, redundancy and is used as a watchdog. The AI platform will be integrated fully redundant on two buses into SONATE-2. The Jetson module and carrier board were successfully tested using thermal-vacuum, shock and radiation tests.

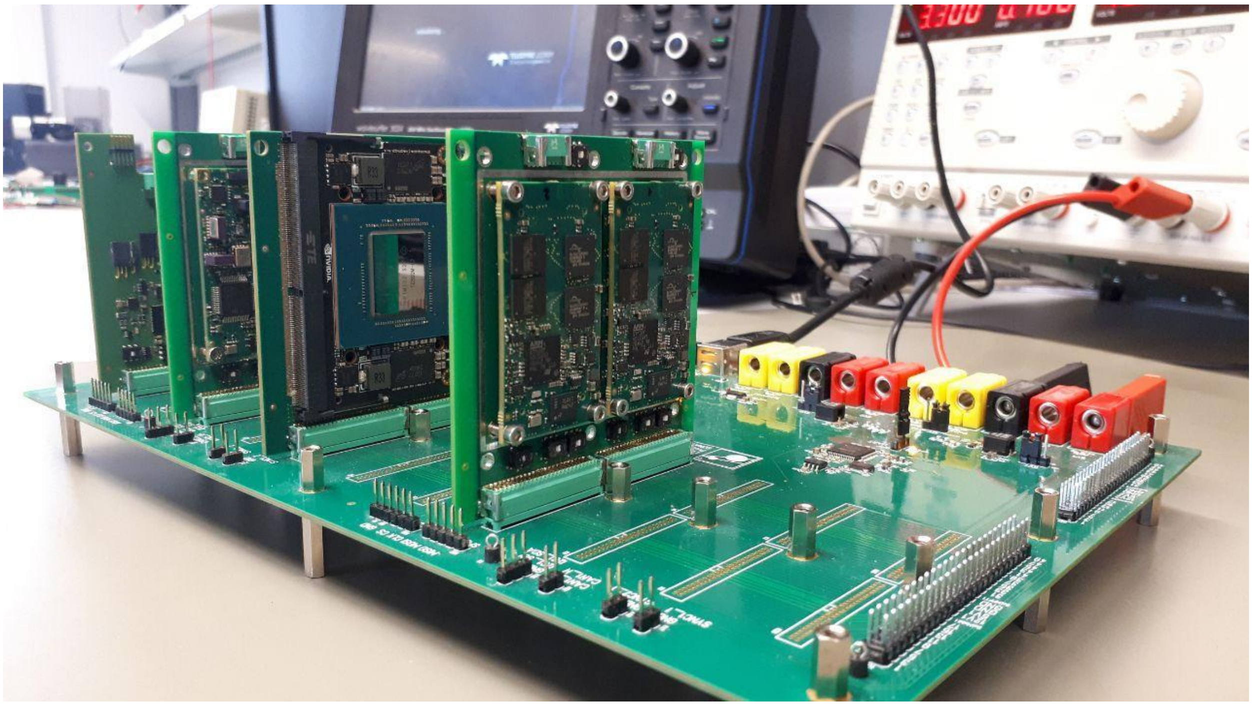

Figure 3. The AI payload with two OBDHs on the FlatSat

The **camera system** uses two fully redundant combinations of sensors and optics capturing the following images:

- Near Infrared (NIR) 820-900nm, Spatial Resolution: 38m, Swath width: 68km
- RGB, Spatial Resolution: 38m, Swath width: 68km
- Near Infrared (NIR) 767-787nm, Spatial Resolution: 379m, Swath width: 683km
- RGB, Spatial Resolution: 379m, Swath width: 683km

SONATE-2 will be able to capture wide field of view as well as close-up images of earth. Each scene is available in multiple spectra including Red, Green, Blue and Near Infrared. The Near Infrared Channel of the wide field of view is used for the detection of lightning and the close-up channel is used for improved vegetation detection. The NIR spectral ranges are selected from the Sential-2 range and the emission line of the atomic oxygen. We will use commercially available filters. To create multispectral images on-board image matching will be performed.

The main consideration beyond resolution and heritage for the sensor was global vs rolling shutter. All sensors were tested in RGB and Monochrome Versions for Color and NIR imagers respectively. We tested two CMOS IMX series sensors, one with full HD resolution and rolling shutter. The contender had a resolution of 1440x1080 and global shutter. Both sensors underwent typical system tests like TDI, color correctness and thermal vacuum exposure. Their performance was mostly equal, however the global shutter technology was considered superior in earth pointing mode.

Additionally, extensive camera lens tests were performed. The main contenders for the tele optics were two commercially available optics from Schneider Kreuznach and Kowa with a focal length of 50mm. Comparisons showed comparable performance and ultimately the winning Kowa optics was chosen due to its ruggedized build. For the wide field optics, the options were two commercially available optics from Cinegon and Kowa, each with 5mm focal length. The choice also fell onto a ruggedized Kowa optics after the testing concluded.

4.1 Software Framework

The basic operating system of the platform is a customized version of Linux. The Jetson Linux Driver Package (L4T) is provided by Nvidia for this purpose. It contains the Linux kernel, the boot loader, Nvidia drivers, flashing libraries and a software system based on Ubuntu 18.04. The use of Linux offers a number of simplifications in development. For example, Linux's own system processes can be used and frameworks such as QT or TensorFlow also speed up the development process. The system behaves in many aspects like a usual Linux desktop computer.

For communication with the on-board computer and as a central control of the AI platform, a dedicated utility app will run on the Jetson. The utility app is implemented using the QT framework, which provides many basic functions and data structures. The applications for the experiments will run as separate processes and will be dynamically started and managed by the utility app. This has the advantage that almost arbitrary programs can also be uploaded and run while in orbit via software update. The main tasks of the utility app are:

- Telecommand and telemetry Handling
- Management of the installed apps and their results in a database
- Starting, stopping and monitoring of apps
- Receiving new applications or AI models via software upload
- Download of the results of the experiments (e.g. images and log files) to the OBDH

Telecommands and Telemetry use the CAN bus, while SPI is used for larger file transfers like software uploads.

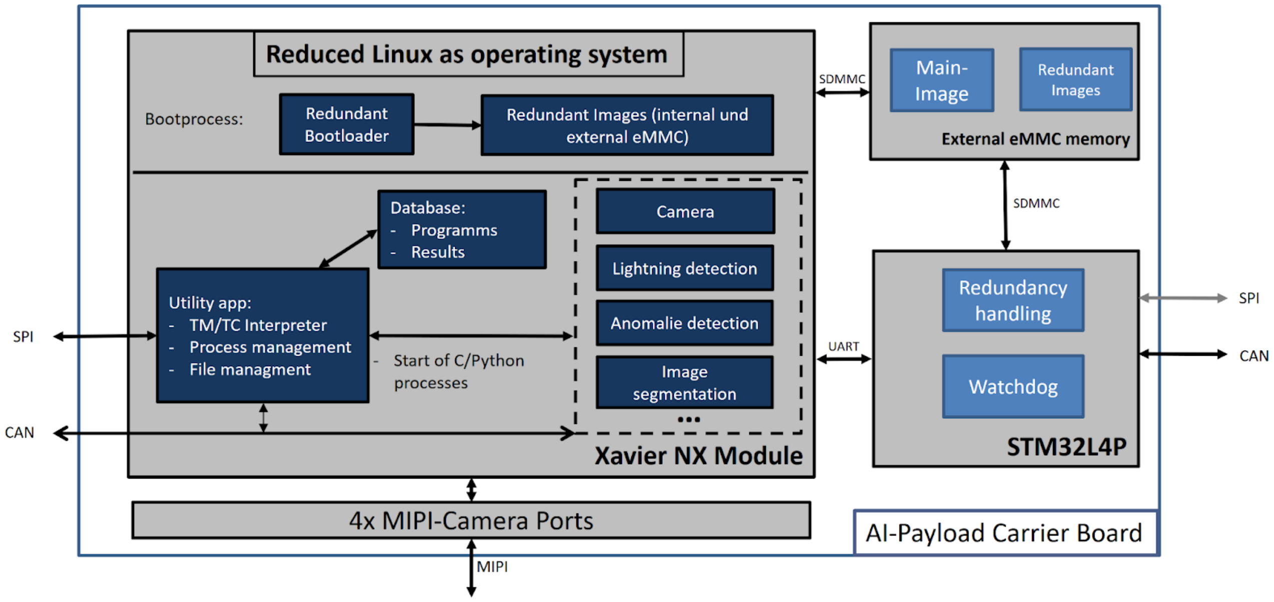

Figure 4. Overview of the AI-payload hardware and software design

The applications for the planned experiment scenarios are developed separately. These are completely independent of the utility app and are started as new Linux processes. They can also use any programming language, provided it is supported by the underlying Linux system. Currently, applications in Python and C++ are planned. Programs can be started and stopped via the utility app. Errors or crashes are detected. If an app produces a result, for example a series of images, the data is given a unique id and is saved on a deterministic path on the flash drive. The id can then be used to download the data or a subset of a result later via a telecommand. Each app has its own telemetry and telecommand handler and functions independently of the utility app. As long as an app runs on the Jetson Linux system it will be able to run on the payload. This makes the AI platform very flexible for arbitrary future use cases.

To compute the neural networks, the TensorFlow Python framework from Google will be used. The framework is widely used and well documented. TensorFlow offers a wide set of features to quickly run and train Deep Learning models. TensorFlow also supports the computation of networks using the GPU and the tensor cores of the Jetson using the CUDA interface, which speeds up the computation enormously. The Python environment will also include other well-known libraries like opencv2, NumPy or SciPy which installed apps are able to use.

4.2 Planned Experiments

To test and qualify the platform, a series of experiment scenarios will be conducted in orbit. These experiments can be divided into three categories: Inference of pre-trained neural networks, on-board training of neural networks, and classical analytical image analysis. These experiments correspond to the most common applications in the field of artificial intelligence in the analysis of image data or in the field of computer vision. Through these experiments, the AI processor is fully tested and utilized.

4.2.1 Image segmentation

The first experiment will be to execute networks pre-trained on the ground which are stored in the payload's memory. Several different network types will be demonstrated to showcase the wide range of possible image analysis models. One of these model types will be image segmentation. This type of network is supposed to recognize a set of pre-trained classes in an image and to localize them with pixel accuracy. This type of network will be used for both close-up and wide-field imagery. In the close-up application the model will be trained using Sentinel-2 and Landsat datasets to distinguish between at least 8 classes. Multiple publicly available datasets like the Slovenia Land Cover Dataset will be used for the training dataset [6]. The NIR channel will also be used to enhance the performance. These classes will include water, forest, agricultural land, grasslands, artificial areas (cities), ice, clouds and bare land. A U-Net model architecture will be used for the deep learning models. The captured images will be split into 256x256px patches, so that smaller neural networks can be used.

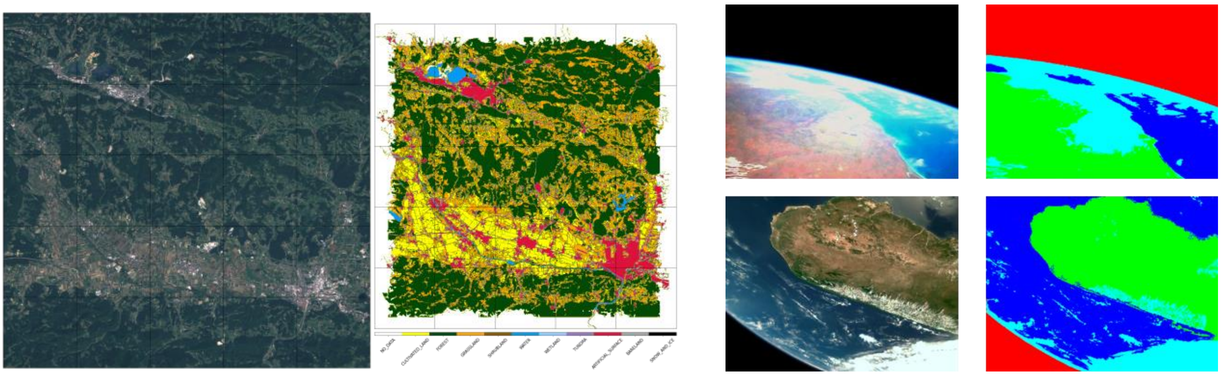

Figure 5. Example of the image segmentation from the Slovenian Land Cover Dataset [6] (Right) Manually segmented images from the EstCube Mission [7]

For wide-angle images in LEO, images from other space missions can be used, for example from CubeSats or the ISS. These images are manually labeled. Here, the classification must be limited to coarser classes since less detail can be resolved on the ground. Also, it is expected that space or the sun could be visible in the image. For this network, the following classes will be used: Land, Water, Clouds, Space and Sun. In preliminary tests a sparse categorical accuracy of 0.79 was achieved.

4.2.2 Object detection

In addition to image segmentation the mission will also use models for object detection and localization. The detected objects are localized with bounding boxes. The network´s first stage proposes a set of regions in the image where interesting objects could be located, a Region Proposal Network (RPN). In the second stage, each of these regions is classified using a classical Convolutional Neural Network (CNN). The outputs are the regions and objects with the highest probability. The network will be trained to detect general geometric shapes like circles, rectangles, lines or triangles. The reason for this kind of network is that geometric shapes on planetary surfaces can indicate interesting geological, chemical or even biological activities. Therefore, the autonomous detection of geometric shapes is of great importance for exploration.

4.2.3 Anomaly detection

To showcase the training capability of the system the mission will also include an anomaly detection application. Several anomaly detection models were examined in several student theses and during mission analysis [8, 9]. The goal is to detect abnormal static objects or transient phenomena. Several target environments were considered during mission analysis for example deserts, the ocean, ice deserts or big forests. One property of these environments, which helps to detect anomalies, are largely homogeneous structures without conspicuously deviating structures.

The Sahara Desert was chosen as the primary target region, because of its large size, stable weather conditions and easy to detect anomalies like cities, water or agriculture. The anomaly detection will use all four available spectral channels from the close-up image sensors. In order to evaluate and test the algorithms and the deep learning models, test datasets of Sentinel-2 images containing over 50.000 labeled images of the Sahara Desert and the ocean were created.

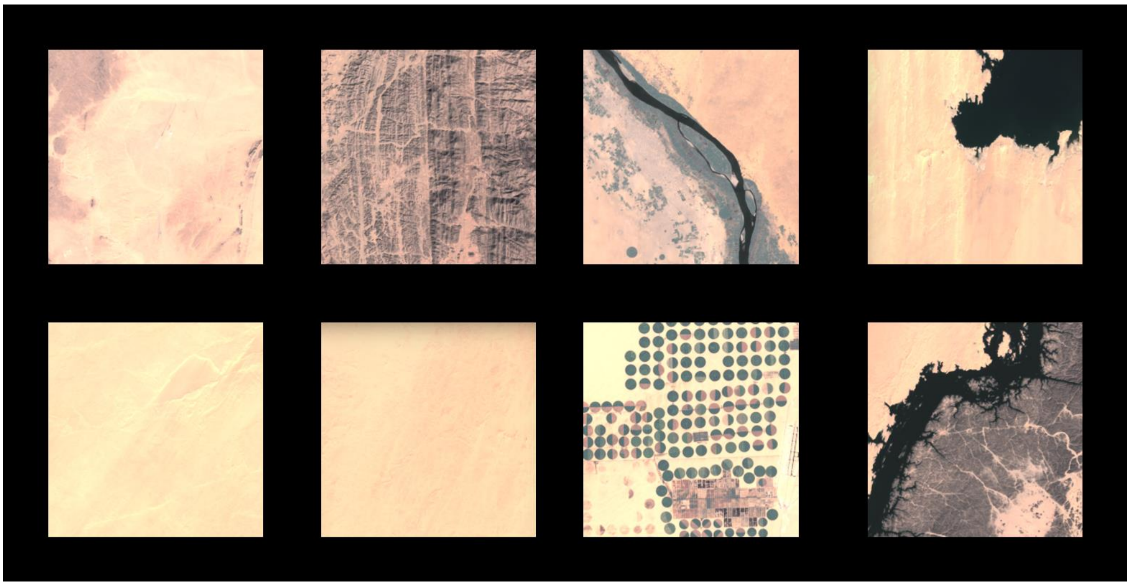

Figure 6. (Left) “Normal” Sentinel-2 images of the Sahara Desert. (Right) Potential anomalous images containing the Nile, a lake and irrigation circles.

Autoencoder (AEs) and Generative Adversarial Networks (GANs) are the model architectures that will be used in this experiment. The main idea of DL anomaly detection is to learn the normal distribution of an environment and to detect anomalies as a deviation from this distribution. AEs and GANs are both well suited for this task, but AE are less risky to train, which is why they will be primarily used. Training and anomaly detection are both based on the reconstruction loss of these networks. The model takes a four channel 64x64px image as an input, decreases the size using multiple convolutional layers to a latent representation and then tries to reconstruct the image. GANs use the BiGAN architecture in order to be used for anomaly detection [10]. This reconstruction works well for normal images, as they were part of the training distribution, but doesn’t work well for anomalous images.

The anomaly detection experiment coarsely follows these steps:

1. Capture multiple images in orbit from the target region

These images will be the training dataset for the on-board training. First experiments have shown that about 200-300 images, resulting in 4000-6000 image patches, are sufficient.

2. (Optional) Download the images in very compressed form

The training works best if only non-anomalous images are used. To filter anomalies from the training dataset all images are downloaded heavily compressed and are assigned an id. Those containing anomalies are discarded. This step can also correct targeting errors of the ADCS. This step is optional, because the same effect might be also achieved using on-board clustering algorithms. These are currently under consideration.

3. (Optional) Upload the ids of pictures with anomalies

Blacklist the images with anomalies to finalize the training dataset. The ids of the anomalous images are uploaded via telecommand.

4. Training on-board models
A model selected preflight is trained using the new training dataset. Training will be split into 30-minute blocks. First experiments show a total necessary training time of 2-3 hours, although this is heavily dependent on the size of the model and whether transfer learning techniques are used.

5. Autonomous anomaly detection during the next fly-over of the target region
The model is now ready for anomaly detection. Anomalies are detected using a custom designed classifier, which uses the reconstructed image, reconstruction losses and other hyperparameters.

4.2.4 Lighting and transient phenomena detection

In addition to the artificial intelligence-related applications mentioned so far, classical image processing methods will also be used on SONATE-2. This serves to demonstrate the versatility of the payload to be able to perform classical methods in addition to modern AI applications. In this course, short-term luminous phenomena on Earth are to be detected with the help of **classical image processing**. The focus on SONATE-2 is the detection of lightning from space. Therefore, a custom application is being developed for the Jetson Xavier NX for autonomous detection of lightning from space. As a detection camera a Sony IMX296 global shutter grayscale camera equipped with a narrow bandpass filter in the near infrared at 777.4 nm and a 5mm optics is used. This wavelength corresponds to the emission line of the atomic oxygen OI(1), stands out very strongly from the background noise and is used for detection mainly for this reason [11].

The application captures images from the lightning detection camera at 30 FPS. These captured frames are then searched for lightning using background subtraction, noise rejection and region labeling algorithms using the GPU and CPU of the Jetson. For each detection, a short image sequence and metadata is saved. The short image sequence does not consist of the full image, but only of a section centered around the detection. Metadata contains for each detected flash the time stamp, the center of gravity of the detection in image coordinates, the number of detected pixels, the averaged brightness over the detected pixels and the maximum brightness of the detection. Additionally, another camera in the visible range of the electromagnetic spectrum is available to check the algorithm. Short image sequences are also stored from this camera when a flash is detected. Figure 7 shows the planned algorithmic flow of the lightning detection algorithm.

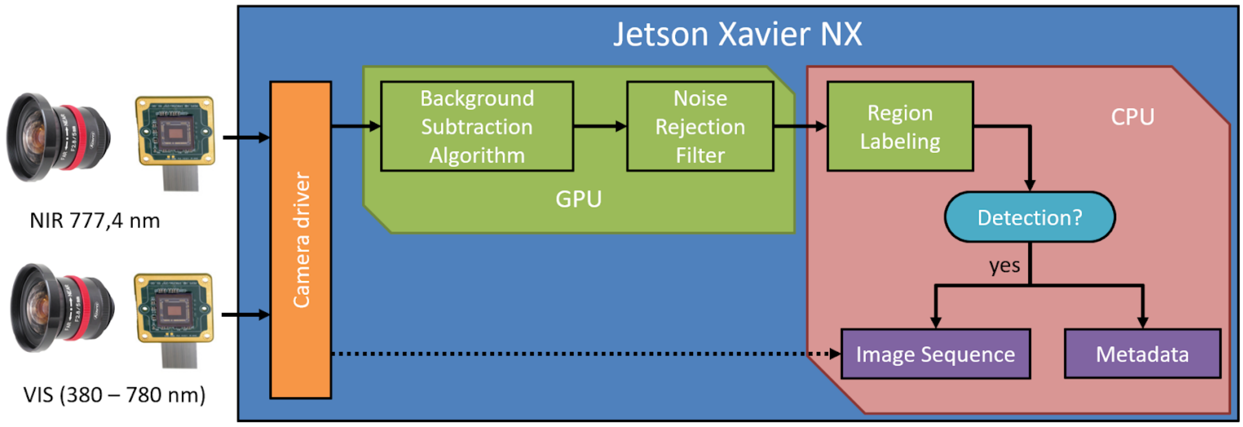

Figure 7. Schematic flow of the lightning detection algorithm

5 SATELLITE BUS

5.1 OBDH

The OBDH represents the central data processing and handling unit, which main tasks are the processing of telecommands and housekeeping, the time management, the management of redundant components, the allocation of interfaces to all subsystems onboard SONATE-2 and finally, the monitoring of the state of the whole satellite with an autonomous response in case of failures or critical values, e.g. a low charge state of the batteries.

All these tasks are performed on a dedicated processing hardware. Its design is based on the lessons-learned during the operation of the predecessor mission SONATE. On SONATE-2, four dedicated hardware components are used as ODBHs. These have four different roles and can perform tasks as both OBC and PDH, depending on the role. The advantage of this configuration is the theoretical fourfold redundancy since any hardware can assume any of the four roles. The role decision is determined purely in software terms by implemented state machines and not by booting different software images in different address ranges. This guarantees that a component is immediately ready for role exchange and does not have to be restarted in orbit.

Just like the predecessor mission SONATE, the STM32F407 microcontroller running the Realtime Onboard Dependable Operation System (RODOS [12]) is used as the sole processing computer. Additionally, each OBDH has access to three 64 MiB large NOR-Flash memories and two 4 MiB large SRAMs. The non-volatile NOR-Flash memories are used to store the offline housekeeping, telecommand lists and extended housekeeping data from each of the payloads. The SRAM is mainly used as a buffer for transfers to and from the AI payload. Other implemented hardware features include the possibility to reset and switch off defect OBDHs. Figure 3 also shows the current OBDH hardware.

Two OBDH boards are mounted on a common carrier board, which serves for the connection of the OBDH to the bus of SONATE-2 and thus provides for its mechanical and electrical integration. One OBDH is thereby supplied by bus 1 and the other by bus 2 with power. In case of a power failure on one of the two power buses two OBDHs are still operational. Each OBDH has access to both CAN-Buses but can only control the GPIOs and SPI lines on one satellite bus.
The two CAN-Buses are used by the OBDH to command and request the housekeeping data from all subsystems and payloads.

Supporting the primary mission goal of SONATE-2 the OBDH features a SPI connection with the AI payload. Through that connection experiment results are transferred to the OBDH. These results are saved in the OBDHs on board flash for a later download via S-band. Also, the upload of new applications or configurations to the AI payload is possible via that interface. For redundancy reasons a small amount of data can also be transferred via the satellite's CAN-Buses. The CAN-Bus is also used to transfer data from and to the secondary payloads of SONATE-2, e.g. writing new images into the SSTV transmitter.

5.2 ADCS

SONATE-2 is equipped with an Attitude Determination and Control System (ADCS) for a variety of tasks. The solar panels need to be oriented towards the sun to maximize the solar current, and the payload cameras need to be pointed towards the Earth. The S-Band antenna also needs to be pointed towards ground stations. Especially for the close-up cameras, it is desired to be able to take images of specific targets on the ground. This requires a pointing accuracy of at least 1°. To achieve this accuracy and the required dynamics, the ADCS uses 2 reaction wheels and 2 magnetorquers on each axis. The reaction wheels serve as the main actuators for pointing. The magnetorquers are tasked with the detumbling of the spacecraft and the desaturation of the wheels. All the magnetorquers are ferrite core coils and can desaturate the reaction wheels while those keep the spacecraft in a desired attitude. The actuators are developed in-house.

For attitude determination, SONATE-2 is equipped with two sun sensors on each side, four sets of MEMS gyroscopes and four 3-axis magnetometers. The sun sensors are also developed by the team. The magnetometers and gyroscopes are distributed between two independent ADCS units. Each ADCS unit is connected to one of the two power busses and data busses. The ADCS units are like those used on the previous SONATE mission.

Aside from providing pointing capabilities for SONATE-2, ADCS-specific experiments are planned. Their focus lies in the testing of new components for future missions into deep space. The first ADCS experiments in orbit will be the validation of the new MultiView star sensor, which is described in chapter 5.3. After its successful in-orbit validation, MultiView will be used for the attitude determination loop during normal operations. In addition, it is planned to include and test an electric propulsion system.

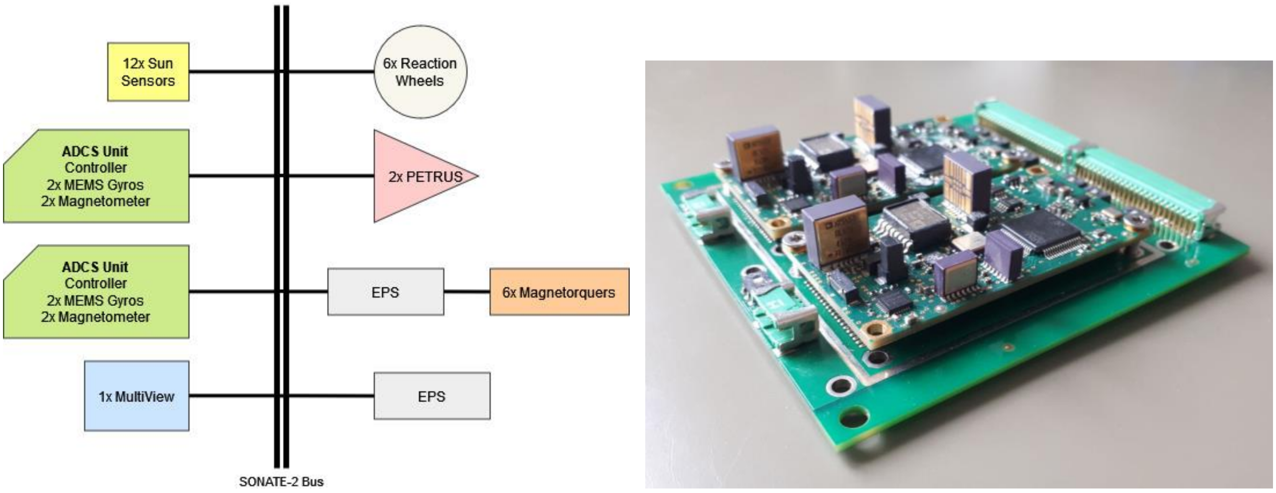

Figure 8. (Left) ADCS components overview. (Right) ADCS system

For deep space missions, magnetorquers are no suitable option for attitude control or for desaturation. Instead, a propulsion system can be used, and it may already be required for performing maneuvers. A suitable candidate for the planned propulsion system is the PETRUS pulsed plasma thruster developed at the University of Stuttgart [13]. Two redundant thrusters could be integrated into a tuna can on the side of SONATE-2. The propulsion system shall be used to attempt the desaturation of one reaction wheel in z-direction without using the magnetorquers, and to lower the spacecraft's orbit at the end of the mission.

5.3 MULTIVIEW Star Tracker

For accurate determination of the satellite's angular orientation, the ADCS is aided by the MultiView Star Tracker. This sensor, built to be placed in a TunaCan slot, features high availability of attitude data and multiple functional redundancies. Those are implemented by placing several image sensors including the optics in a way that they cover several different proportions of the celestial sky. Being able to switch to other internal image sensor units when the currently active one i.e. gets blinded by the sun is the effect of such a configuration. However, this also attains functional redundancy, which is useful should one sensor unit have a defect or is otherwise not usable anymore. The whole MultiView stack can be accessed by CAN-Bus and is capable of internal reconfiguration, star catalog update, software updates, and automatic calibration as fine-tuning of optical parameters during operation. The capturing of images can be timed precisely by utilizing a dedicated synchronization pulse signal. Attitude data can be read out via the CAN-Bus, which lies in the ECI (Earth-Centered Inertial) frame and represents the direction of the MultiView stack within a planned accuracy of 0.05°, independently of which sensor unit captured and identified the stars.

As the ADCS is served by both satellite buses, the MultiView Star Tracker supports the same functionality. For this reason, half of the internal sensor units get their power supplied by one bus, while the rest from the other. A central unit is also needed to coordinate all sensor units regarding their activation, collection of the attitude data, and to serve as a wrapper for the communication with the satellite buses. The central unit has two identical sides, serving each bus. This additionally eliminates a single point of failure.

5.4 Power Subsystem

For the generation, storage and distribution of electrical power, SONATE-2 extends SONATE's electrical power subsystem. To provide a sufficient power of 20W to the AI payload and the S-band transceivers the EPS was further extended by a +12V power bus, in addition to the +5V power bus of SONATE. 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 and redundant buses for redundancy. Each bus uses four commercially available Li-Ion batteries with a capacity of 40Wh for storage. The used switching boost converters can provide peak power of up to 20W and continuous power of 8W per bus.

5.5 Communication

For the communication between space and ground segment, in terms of housekeeping telemetry and telecommand SONATE-2 utilizes the same hardware as the previous SONATE mission [1]: two hot redundant COTS AstroDev Lithium transceivers in the UHF amateur band and two VHF transceivers that were developed for the SONATE mission as a backup and to operate the amateur radio payload. The amateur radio payload consists of a SSTV transmitter, that broadcasts low-resolution images captured by the AI payload, as well as a relays transceiver that allows radio amateurs to extend their range by communicating via satellite. Each of these four transceivers uses its own, monopole antenna, as shown in Figure X. These antennas are made of tape which is rolled up inside the satellite during launch. After deployment a motor will set the tape free and allow it to unroll outside of the satellite.

To deal with the large amount of data, the AI payload requires it to be operated via a high-speed communication link. Hence, two redundant XLink-S transceivers are integrated into SONATE-2 together with one dual band patch antenna mounted on the satellite's side panels each. This allows a 1 Mbps downlink and 56 kbps uplink in the space operation/space research service in S-band.

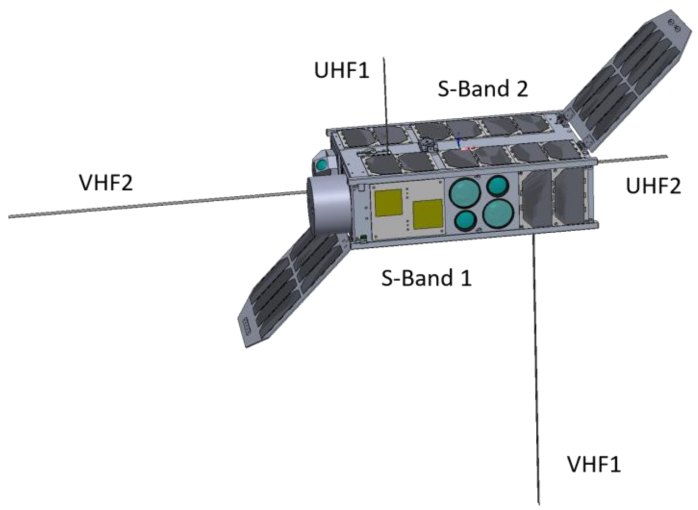

Figure 9. UHF and VHF antennas in deployed state and one of the two S-band patch antennas. The second S-band antenna is on the opposite site of the satellite.

6 GROUND SEGMENT

All operations of the SONATE-2 mission will primarily be controlled and supervised from the SONATE-2 mission control room at the University of Würzburg, shown in Figure 10. 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. The ground station, the mission control room and most operational software were built and developed for the previous SONATE mission, where they demonstrated good performance, and will be reused for SONATE-2 with only little adjustments of the interfaces.

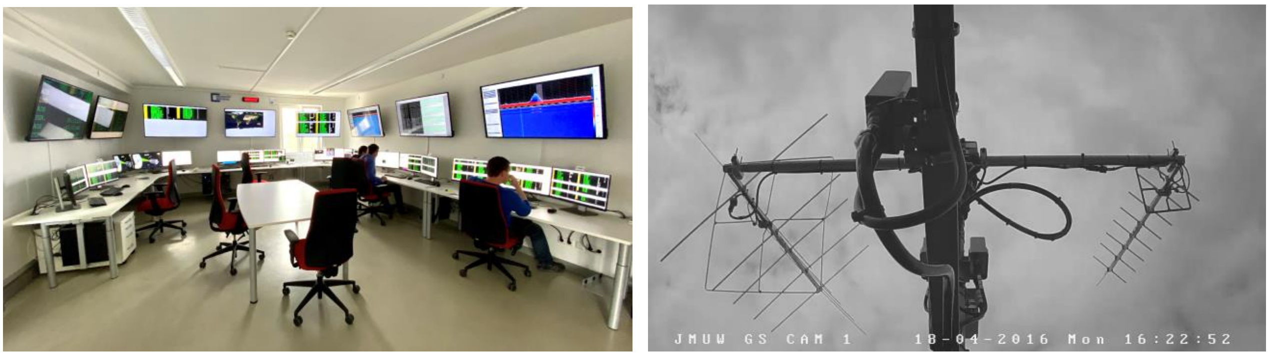

Figure 10. (Left) SONATE-2 mission control room. (Right) VHF/UHF ground station antennas

For the S-band operations the university's 2 m parabolic dish ground station will be modified to be compatible with the space segment. It is mounted on a car trailer for flexible operation site selection. It is currently equipped with SONATE's HiSPiCO receiver. For SONATE-2 a CCSDS modem is integrated, and the feed will be modified for bi-directional operations. All three components, the two ground stations and the mission control room are connected via the university's intranet. To achieve redundancy and to improve the communication link, a cooperation with external ground stations operated by the German Aerospace Center (DLR) in Neustrelitz is currently in preparation.

7 MISSION OUTLOOK

The SONATE-2 project started in the beginning of 2021 and is currently in Phase C, with its planned launch in Q1 2024. After a successful operation for at least one year in LEO, the payload will be verified for space. In the future this will allow not only new autonomous AI-based Earth observation missions but also to use this kind of autonomy on nanosatellites that perform interplanetary missions.

8 REFERENCES

[1] Kojima T. et al. *Extremely Metal-poor Representatives Explored by the Subaru Survey (EMPRESS). I. A Successful Machine-learning Selection of Metal-poor Galaxies and the Discovery of a Galaxy with M * < 10 6 M ⨀ and 0.016 Z*, The Astrophysical Journal 898(2), 2020

[2] Esposito et al. *"Highly integration of hyperspectral, thermal and artificial intelligence for the*

ESA PhiSat-1 mission," Proceedings of the 70th IAC (International Astronautical Congress), Washington DC, USA, 21-25 October 2019

[3] Centre Spatial Universitaire de Grenoble https://www.csug.fr/menu-principal/projets/qlever-sat/ Last checked April 11, 2022

[4] The European Space Agency (ESA) *Next artificial intelligence mission selected:* https://www.esa.int/Applications/Observing_the_Earth/Ph-sat/Next_artificial_intelligence_mission_selected, September 04, 2020

[5] Schwarz T. et al. *SONATE – 3U NANO SATELLITE MISSION FOR HIGHLY AUTONOMOUS PAYLOADS,* 4S Symposium Sorrento, Italy 2018

[6] EO-learn, How To: Land-Use-Land-Cover Prediction for Slovenia : https://eo-learn.readthedocs.io/en/latest/examples/land-cover-map/SI_LULC_pipeline.html, Last checked April 10, 2022

[7] Slavinskis A. et al. *ESTCube-1 In-Orbit Experience and Lessons Learned*, IEEE Aerospace and Electronic Systems Magazine 30(8):12-22, 2015

[8] Greiner T. *Untersuchung zur Anomalie Detektion in Bilddaten mittels Deep Learning in der Raumfahrttechnik,* University Würzburg, Master Thesis, 2020

[9] Bös C. *Evaluation of AI learning techniques for anomaly detection on various geographic scenarios for the SONATE-2 mission,* University Würzburg, Bachelor Thesis, 2022

[10] Donahue J. et al. *Adversarial Feature Learning,* ICLR 2017

[11] Orville et al. *"Absolute Spectral Irradiance Measurements of Lightning from 375 to 880 nm,"* Journal of the Atmospheric Sciences, 1984.

[12] Montenegro S. et al. *RODOS - real time kernel design for dependability*, DASIA 2009 - Data Systems in Aerospace, 2009

[13] Montag C. et al. *Development of a new Pulsed Plasma Thruster and a brief Introduction of a planned Test Facility*, IAC-16-C4.4.13.x35105, 67th International Astronautical Congress, Guadalajara, Mexico.