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New Results and Lessons Learned from the MOVE-II and MOVE-IIb CubeSats

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ABSTRACT

This paper covers the operations and lessons learned for the MOVE-II and MOVE-IIb satellites. Both are 1U CubeSats, with their purpose being hands-on education for students of all technical fields related to aerospace. The hardware of the spacecraft consists of a commercial on-board computer and an electrical power system, while all other systems, including the software, were designed by the student team. The MOVE-II CubeSat was successfully launched on December 3rd, 2018 and remains active in orbit to this day with almost daily commanding. The operations were full of surprises that pre-launch simulations did not foresee. With on-orbit data, we were able to correlate thermal, electrical and attitude dynamics simulations, thus uncovering flaws in former assumptions. We present the evolution of key properties of the spacecraft over its lifetime, such as the internal battery resistance, temperature and hardware defects. Compared to the expected 23 °C average temperature, the satellite is quite cold at 3 °C average. Furthermore, it shows a tendency to spin up uncontrollably due to a current loop in the solar cell wiring. To replicate the real behavior with simulations, a thermal model and a solar cell wiring current loop were added to the model. We also corrected the internal resistance of the battery in the model from $0.42\,\Omega$ to $1.26\,\Omega$ and added a temperature dependency to the internal resistance. The tendency to spin up, combined with a tight power budget, has remained a problem since the beginning of on-orbit operations. Although the anomaly shows non-deterministic behavior, regular detumbling maneuvers keep the spacecraft at tumbling rates between $2.5\,^\circ\,\mathrm{s}^{-1}$ and $200\,^\circ\,\mathrm{s}^{-1}$. At low turn rates, we downloaded a significant amount of data from the attitude determination and control system, enabling us to calibrate the magnetometer on ground with data recorded and downlinked over a span of several months. Additionally, we were also able to conduct payload measurements.

The MOVE-IIb CubeSat, which launched on July 5th 2019 from the Vostochny Cosmodrome, is a copy of MOVE-II with minor improvements to correct the flaws of its predecessor. Unfortunately, a signal strength of 15 dB less than MOVE-II hindered any practical operations but it has been confirmed as alive in space. As possible causes we analyzed our initial guesses of a faulty deployment of the solar panels and antennae but also a malfunction of the transmitter. With the lessons learned from the MOVE-II/IIb missions, critical mistakes can be avoided for future CubeSat missions. As part of these lessons learned, the most useful and most hindering features of the spacecraft and its ground infrastructure are discussed. Furthermore, the training routine for the Mission Control team and its changes over time are described. The impact of the COVID-19 pandemic on spacecraft operations is also discussed, including lessons learned for future missions. This paper takes a look at the evolution of this mission since 2018. It discusses new findings, degradation of the spacecraft, lessons-learned and operations of the CubeSats.

Introduction

After more than three years since its launch on December 3rd, 2018,[1] the CubeSat Munich Orbital Verification Experiment II (MOVE-II) continues active operation in space. On July 5th, 2019, a copy of MOVE-II, called MOVE-IIb, was launched into space from Vostochny cosmodrome.[1] Meanwhile, the students under the supervision of the Chair of Astronautics (LRT) at the Technical University of Munich, students of the Scientific Workgroup for Rocketry and Spaceflight (WARR) and the MOVE project are already developing MOVE-III,[2] the next MOVE satellite in line. The goal of this paper is to look back at the achievements and shortcomings of MOVE-II and MOVE-IIb, but also discuss the latest lessons learned, mission operations and improvements during this very educational and unique mission over 3 years of operations. Finally, an outlook on future mission operations and MOVE-III shall be given.

MOVE-II Mission

First, this paper will provide an overview of the MOVE-II satellite, as well as some of the data collected by the satellite during its lifetime. MOVE-II is a 1 Unit (U) CubeSat with a magnetic attitude control system. As a payload it carries multiple four junction solar cells.[3] For more information about the individual subsystems see Rückerl et al.[4] for communication, Messmann et al.[5] and Messmann et al.[6] for ADCS as well a as Rutzinger at al.[7] for the payload. For a general overview see Rückerl et al.[3] Figure 1 has been added for better understanding when referencing different parts of the satellite.

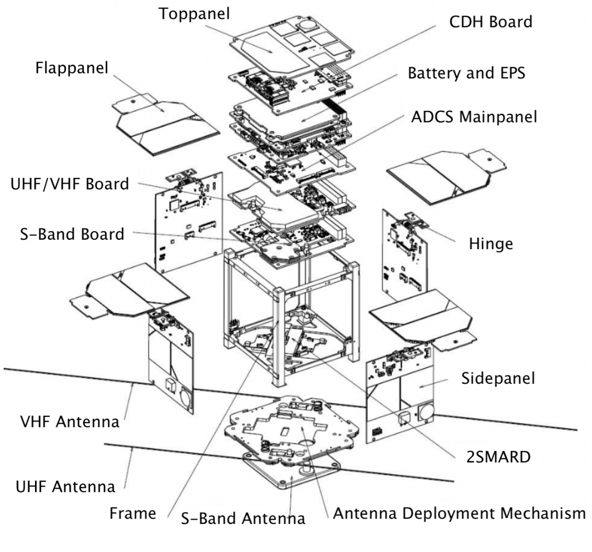


Figure 1: Explosion drawing of MOVE-II[8]

Mission Data

Since its launch, MOVE-II has experienced high spin rates of up to $500\,^{\circ}\,\mathrm{s}^{-1}$.[3] We believe that a dipole moment, generated by current loops in the wiring of the deployable solar panels, called Flappanels (see Figure 1), has caused the satellite's fast spinning motion. After initial Attitude Determination and Control System (ADCS) experiments, a sequence was executed regularly that led to the successful detumbling of MOVE-II in May 2019.[3] Unfortunately, the problem of acceleration to very high spin rates still persists. Hence, we continue to detumble the satellite with the goal of reducing the spin rate to under $20\,^{\circ}\,\mathrm{s}^{-1}$. This is the optimal range for operation of the satellite's ADCS. We have managed to successfully detumble MOVE-II multiple times. Figure 2 depicts the evolution of the satellite's spin rate from January 2021 until April 2022. From April 2021 to June 2021, frequent detumbling led to a gradual decline in the turn rate, reaching $3.96\,^{\circ}\,\mathrm{s}^{-1}$ as measured by the on-board ADCS system, on June 19th. The satellite started to spin up again in the first half of July 2021 because we faced technical issues with the ground segment, which prevented us from performing productive overpasses. But after active trouble shooting, we restarted detumbling the satellite and successfully slowed it down enough to stay below $20.0\,^{\circ}\,\mathrm{s}^{-1}$ throughout most of July, September and November 2021, reaching an all-time low of $2.46\,^{\circ}\,\mathrm{s}^{-1}$ on September 28th. During these low turn-rate phases, we were able to successfully record and download ADCS sensor data. This telemetry data was analyzed to characterize important system parameters of different on-board sensors for a better understanding of subsystems in space and will be discussed in a later subsection.

It has not been possible to frequently initiate actuation schemes since December 2021 due to multiple software and hardware malfunctions as well as ground station issues. As a result, the turn rate evolution of the satellite has been subject to an ascending trend for the first quarter of 2022. The satellite has been spinning at angular velocities higher than $200\,^{\circ}\,\mathrm{s}^{-1}$ since mid-March 2022. This has led us to use the sun-pointing controller with a negated magnetometer signal, as opposed to the B-dot detumbling controller to decelerate the spin. Due to a phase delay, the attitude controllers gets unstable, when a certain angular velocity is exceeded. To counteract this instability, we can negate the magnetometer signal to decelerate the satellite. We denote a negated magnetometer signal as *inverted*. For very high spin rates, the sun-pointing controller acts as a detumbling controller. For more information about this detumbling strategy the reader is referred to Rückerl et al.[3] and Kiesbye et al.[9]

For spin rates in the ranges of $0\,^{\circ}\,\mathrm{s}^{-1}$ to $160\,^{\circ}\,\mathrm{s}^{-1}$

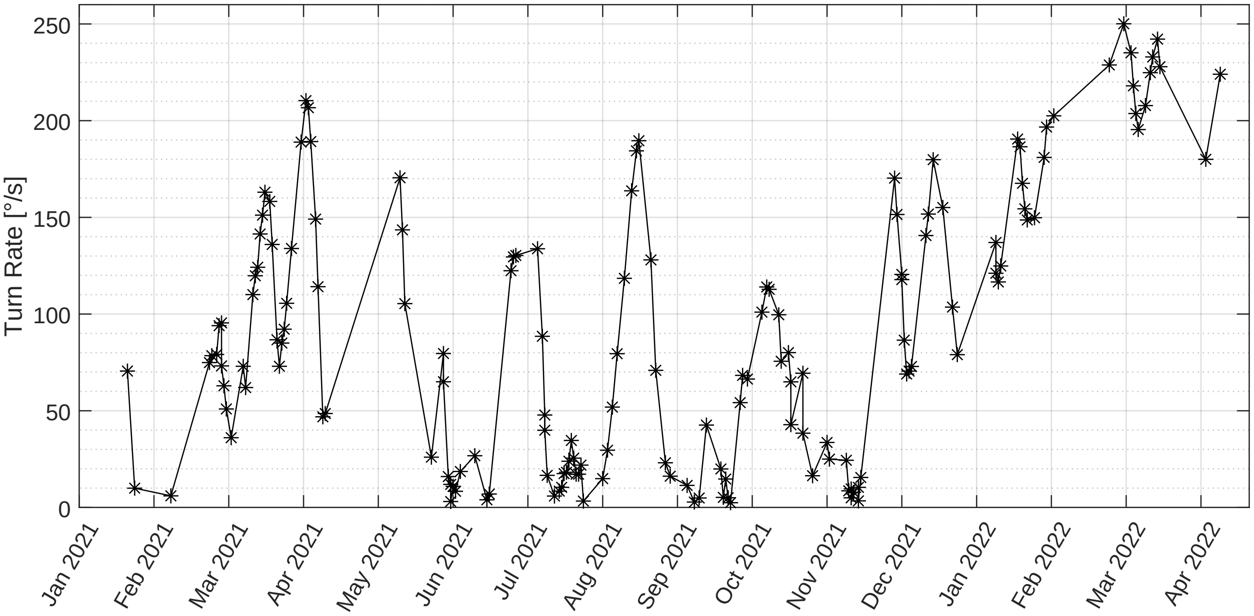


Figure 2: Turn Rate Evolution of MOVE II since January 2021

and 220 $^\circ\,\mathrm{s}^{-1}$ to 412 $^\circ\,\mathrm{s}^{-1}$, the sun-pointing controller has proven to be more effective, as explained in the first paper[3] and in the paper about the Hardware-In-The-Loop setup of MOVE-II.[9] Meanwhile for ranges of 160 $^\circ\,\mathrm{s}^{-1}$ to 230 $^\circ\,\mathrm{s}^{-1}$ and 412 $^\circ\,\mathrm{s}^{-1}$ to 700 $^\circ\,\mathrm{s}^{-1}$, the B-dot detumbling controller is stable and hence, can successfully decelerate the satellite. Table 1 depicts the ideal operating ranges for all ADCS controllers and the according state of the magnetometer necessary. The Mission Control (MC) team continues to work on slowing down the satellite through daily commanding and expects to retrieve more scientific data from MOVE-II in the future.

Table 1: Detumbling Controller selection depending on angular velocity of the satellite

Spin Rate [$^\circ\,\mathrm{s}^{-1}$]	**Controller Mode**	**Magnetometer**
0 - 160	Sunpointing	Not Inverted
160 - 230	Detumbling	Not Inverted
220 - 412	Inverted Sunpointing	Inverted

Analysis of ADCS data from MOVE-II

As mentioned earlier, due to the successful detumbling of MOVE-II, we were able to record and download telemetry data from the ADCS. ADCS telemetry recorded from July 2019 until April 2021 was collated and evaluated to characterize calibration parameters for different attitude sensors of the satellite. The analysis of all the magnetometer data recorded from the CubeSat was performed with a focus primarily on magnetometer calibration.

Magnetometer Calibration Approach

The magnetometer's raw data is biased by systematic and statistical effects. Only systematic errors can be directly compensated. Without compensation, the magnetometer would not be useful for attitude determination because the calibration parameters and the expected measurement values are of similar size. The effect of hard-iron errors looks similar to a permanent magnet in the satellite.[10] They cause a constant offset in the magnetic field vector. Soft-iron errors look as if there was a highly permeable material without remanence in the satellite.[10] They cause a scaling of the magnetic field vector. Misalignment errors are caused by mounting errors of the Sidepanels (see Figure 1) orientation and sensor axes. In general, a correction of offset, scaling and misalignment is described by

$$r = \mathbf{A}r' + c \tag{1}$$

where $r' \in \mathbb{R}$ is the distorted magnetometer data, $\mathbf{A} \in \mathbb{R}^{3\times3}$ is a calibration matrix with scaling and rotation parameters for soft-iron and misalignment correction; $c \in \mathbb{R}$ is an offset for hard-iron correction and $r \in \mathbb{R}$ gives the corrected magnetometer data. One constraint is required to solve it: The magnetic field vector length at orbital position is the same for all attitudes.

Calibration Results

We use four calibration algorithms to correct the magnetometer reading that we have recorded and downloaded from space and compare the performance. Before applying the calibration, we removed outliers in the magnetometer data that were caused by the active magnetorquers. The algorithms used to correct the measured and smoothed magnetometer signals include two versions of the so-called TwoStep algorithm. The first implementation[11] (mentioned as Bias-TwoStep in this paper) recovers only the bias, while the second one[12] (referred to as Full-TwoStep) determines the scaling and non-orthogonalities as well. In addition, we utilize an Extended Kalman filter approach[12] to estimate bias, scaling and non-orthogonalities, and MATLAB's® `magcal` function.[13] The reference magnetic field is computed using the International Geomagnetic Reference Field (IGRF) model,[14] which requires the known orbit position and time information. We compute the position with a valid Two-Line element (TLE) set and a Simplified General Perturbation 4 (SGP4) orbit propagator.[15]

Figure 3 shows the result of the calibration procedure. The blue dashed curve shows the theoretical magnetic field strength. The smoothed uncalibrated magnetic field strength is depicted in black, whereas the calibrated signal is given in magenta. Each algorithm applies the calibration parameters differently. The misalignment of the magnetometer signal calibrated using `magcal` with the reference indicates that the way calibration parameters (ellipsoidal fitting) are computed in this case is ineffective. This can be attributed to the assumption made by this algorithm that the reference magnetic field is constant, when in reality it varies with time and position. The magnetometer bias along each body-axes of MOVE-II,[16] as estimated by three different calibration methods, is compared in Table2.

Table 2: Estimated bias for different calibration methods in body-axes of MOVE-II[16]

Calibration Method	x [T]	y [T]	z [T]
Bias-TwoStep	-5.9322×10^{-7}	-2.4840×10^{-7}	5.3496×10^{-6}
Full-TwoStep	-4.9862×10^{-7}	-7.2479×10^{-7}	5.3746×10^{-6}
Kalman Filter	-5.3108×10^{-7}	-7.2382×10^{-7}	5.0292×10^{-6}

The calibration parameters, achieved from the `magcal` function are neglected in this comparison since the magnetic field is not constant when the magnetometer data is recorded. All three calibration methods estimate similar values but the Bias-TwoStep shows a higher offset as compared to the Full-TwoStep and Kalman filter. This observation is expected since the basic two step method uses a simpler measurement model and estimates only the bias, neglecting the scaling and misalignment errors.

After careful comparison of the calibration parameters (with focus on the estimated bias) generated by each algorithm, the Full-TwoStep method was observed to perform the best, followed by the Kalman filter algorithm. Although the Full-TwoStep approach yielded more accurate results, a major drawback of this algorithm was its level of computational complexity. In comparison, the Kalman filter algorithm was relatively simple and offered a good level of accuracy, and hence was found to be the most suited approach for calibrating our magnetometers.

Dzhanibekov Flipping

The analysis of the satellite's gyroscope data revealed that the satellite maintains its attitude for a certain time before changing the position of its rotation axis by 180°. Although the angular momentum does not change, the rotation axis moves in the body frame as shown in Figure 4. If gyroscope data recordings were done over long periods of time, a change in the axis of rotation of the satellite would be observable at regular intervals.

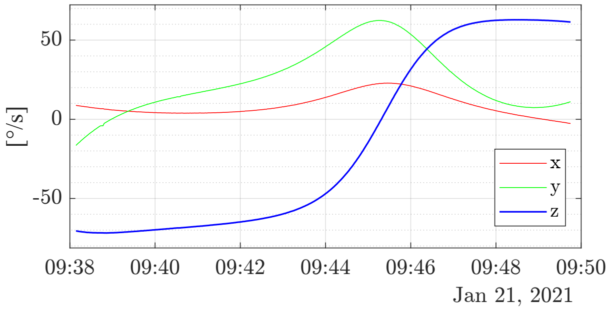


Figure 4: Gyroscope Data showing the Dzhanibekov Effect

This behavior of periodic flipping, whereby the faces perpendicular to this axis effectively swap sides, can be explained by the intermediate axis theorem, popularly known as the Dzhanibekov Effect.[17] The spin of a body is stable in its first and third axes, where its moment of inertia is the smallest and the largest, respectively. However, in its intermediate axis, the rotation of the body is unstable and seems quite peculiar at first glance.[18] In conclusion, the students were able to observe the Dzhanibekov effect affecting MOVE-II's rotation.

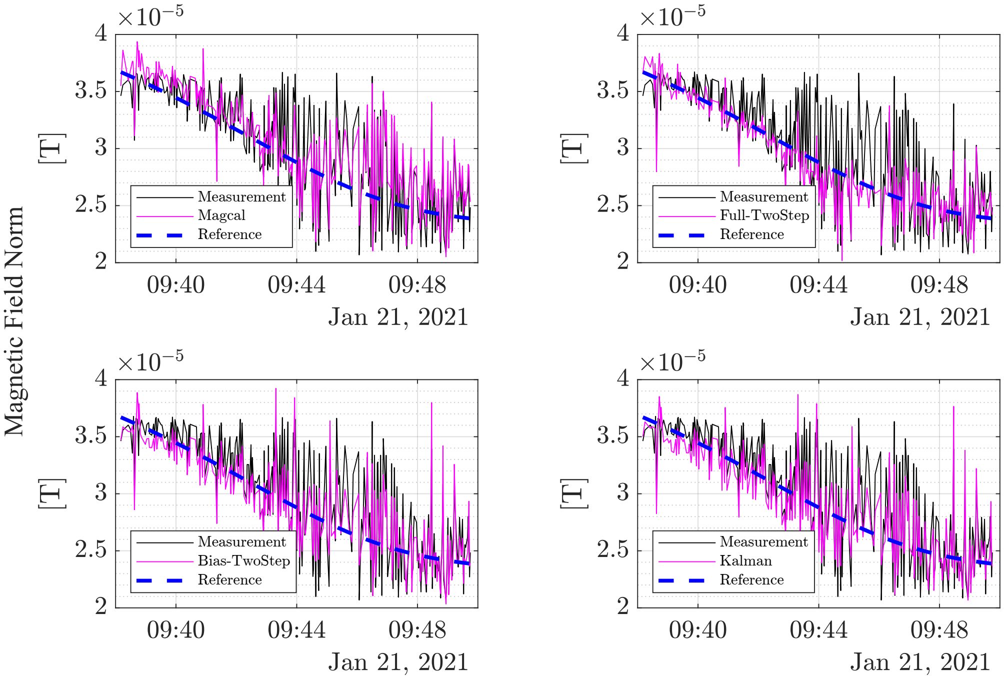


Figure 3: Magnetometer data norm for different calibration algorithms

Problems Faced During Data Gathering and Correlation

Due to issues like an unstable communication link, freezes of the satellite's Command and Data Handling (CDH) system, low State of Charge (SOC) of the battery and ground station malfunctions among others, received ADCS-beacons can be broken or incomplete. For an accurate and useful study of system parameters, it was key to filter out such data packets. Of all the data collected for analysis between July 2019 and April 2021, only 30 ADCS beacons were found to be usable, i.e., complete and uncorrupted. A vital aspect observed during analysis was the importance of accurate orbit position and time information in attitude control and estimation; the calibration models are contingent on these two factors, amplified here incorrect timestamps.

Correlation of Telemetry Data

The following sections will take a closer look at the battery temperature, the battery's internal resistance and the satellite's uptime in an attempt to find a correlation between them.

Battery Temperature

The recorded telemetry data, depicted in Figure 5, reveals the temperature of the battery to be subject to fluctuations throughout the year. The average temperature of the battery in 2021 was measured to be 3.0 °C with 6.4 °C in the winter months (November to February) and −0.6 °C in the summer months (June to August).

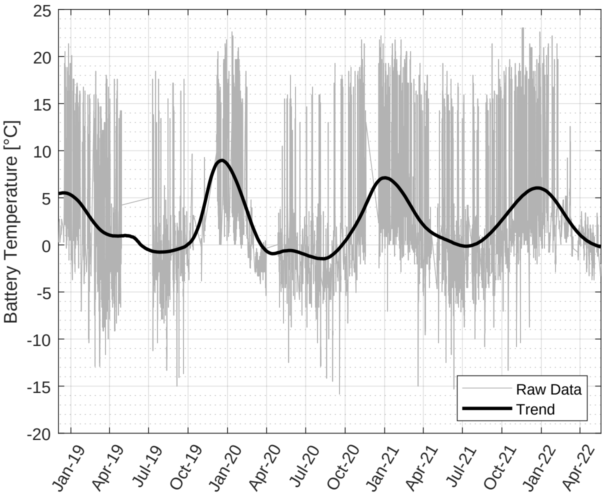


Figure 5: Battery Temperature: Raw and Smoothed Data using a Moving Average Filter

A potential cause for this could be season-dependent eclipse durations. MOVE-II is orbiting Earth on a Sun Synchronous Orbit (SSO) with a slight illumination time variation of 61:58 min on the summer solstice and 62:33 min on the winter solstice per orbit. Combined with the eccentricity of Earth's orbit around the sun with aphelion between July 4th and 5th and perihelion between January 2nd and 5th,[19] this could provide a suitable explanation for the oscillating temperature. According to Datseris and Stevens,[20] a difference in Earth's albedo between its northern and southern hemispheres can be ruled out, since the difference in reflectivity between the two surface compositions is compensated for by more cloud cover on average in the south.

Internal Battery Resistance

The internal resistance of the lithium-ion battery is not measured directly on-board. Instead, it has to be calculated from the voltage and current readings provided in the telemetry data. Due to a lack of data and limited possibilities to determine the remaining energy in the battery during satellite operations, the resistance was averaged over all SOCs. Since we cannot assume that every SOC is reached with equal frequency, inaccuracies in our calculations are unavoidable. Based on the available uptime data, consisting of timestamps since the last boot, and the fact that the power budget was very tight from the beginning on,[3] we have to assume that the battery is in the lower SOC range most of the time. The resulting battery resistance is shown in Figure 6 on a monthly timescale.

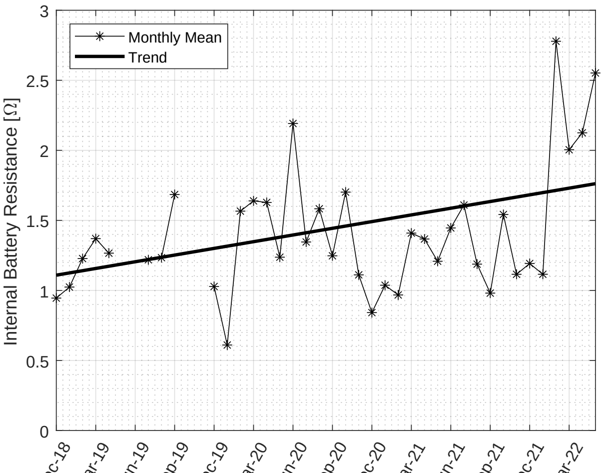


Figure 6: Monthly Average of Calculated Internal Battery Resistance and its Linear Trend

Besides a higher average resistance of 1.26 Ω (in 2021) in orbit than originally measured on ground (0.42 Ω),[3] a slight upwards trend of 191 mΩ per year can also be observed. The main factor for this trend is battery degradation. It is driven by low average temperatures of around 3.0 °C as well as insufficient under-temperature protection, in combination with high fluctuations of the SOC and battery charge currents with peaks of over 1 A.[21]

Uptime

As observed shortly after the launch of MOVE-II, the power budget is, on average, slightly negative, thus leading to an unstable operation of the satellite. This is due to the tumbling mode before reaching a stable pointing mode towards the Sun, which hasn't been reached until now because of the dipole moment created by the solar panel wiring, and subsystems consuming slightly more power than anticipated.[3] The satellite's stability can be quantified by taking a look at its system uptime in Figure 7. As shown, the uptime of the satellite rarely exceeds 100 min. In fact this holds true for 84.6 % of the data-points recorded, which is an indication for regular reboots of the software during the eclipse, as already observed shortly after commissioning.[3] Interestingly, the average uptime per month is higher between the years, around the winter solstice and perihelion. This coincides with the maxima of the temperature measurements discussed previously and is most likely due to the same causes. The global maximum in December 2018, shortly after launch, can most likely be attributed to the fact that the battery was charged to 50 % prior to launch and still in good condition, while its health will have deteriorated significantly in the following years, leading to an increased reboot frequency. It was estimated that the battery would last 5 to 7 days after launch before being completely depleted for the first time.

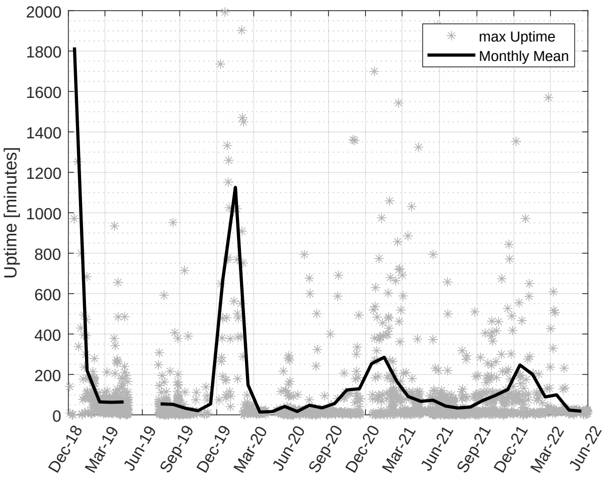


Figure 7: Reported Uptime and Monthly Mean Values

Adaption of the Thermal Simulation Model to Represent Reality

Prior to launch, a thermal simulation, modeled in ESATAN®, consisting of 2597 nodes, was used to estimate MOVE-II's thermal behavior. After launch, a discrepancy of more than 30 °C between this ESATAN-TMS® simulation and the received measurements was observed,[22] leading to a decreased overall performance of the satellite. Therefore, the ESATAN® model was correlated with on-orbit telemetry by Hannemann,[22] resulting in a reduction of the maximum battery temperature offset from 25 °C to below 15 °C. Due to the high number of nodes and a large number of unknown parameters, Hannemann suggested a reduced thermal model as already successfully demonstrated by Rossi and Ivanov on the SwissCube CubeSat.[23] The reduced thermal model of the satellite, simulated in Simulink® as an addition to the ADCS-model for hardware-in-the-loop simulation, created by Kiesbye et al.,[9] consists of only three nodes: An inner sphere, representing the satellites internals, a hollow outer sphere with the properties of the satellites outer shell and four 10x10 cm Flappanel (modeled as one node), located at the external sphere's equator, resembling the solar cells. The Flappanels are only conductively coupled to the exterior ($\dot{Q}_{fp\rightarrow ext,c}$), whereas the inner sphere is coupled thermally to the outer one by conduction ($\dot{Q}_{int\rightarrow ext,c}$) and radiation ($\dot{Q}_{int\rightarrow ext,r}$), as illustrated in Figure 8.

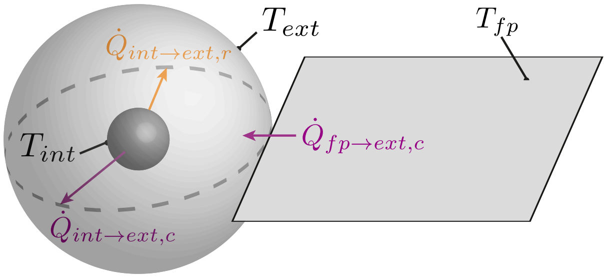


Figure 8: Structure of the Thermal Model and Internal Heat Flow

Only the emissivity (infrared spectrum) and absorptivity (solar radiation spectrum) of the outside of the satellite were varied from an initial estimation to fit the simulated temperature to the measured temperature in a simple manner. Selected data sets with a typical duration of 2 to 10 orbits from January 2019 to April 2022 were used for calibration of the simulation model. For each parameter set, both the deviation of the temperature curve from the telemetry data and its gradient in relation to the latter were calculated. Based on these results, the parameters were adjusted accordingly to obtain better fit values. With this procedure, we were able to reduce the average root mean square error (RMSE) from 7.45 K by a factor of more than three to 2.26 K. This was eventually achieved by increasing the emissivity of the outer shell from 0.70 to 0.79 and decreasing its absorptivity from 0.70 to 0.62. A verifiable change in these parameters could not be observed over the course of the mission.
The successful calibration of the Simulink model is illustrated in Figure 10, where three representative simulation runs per year with adjusted parameters are compared to the uncalibrated model. It can be seen that the temperature curve of the calibrated model follows the telemetry data more closely than the temperature of the uncalibrated model.

As Figure 9 illustrates, an improvement from the original correlated ESATAN® model by Hannemann[22] can clearly be observed. In this case, the RMSE was 1.36 K for the Simulink® and 7.14 K for the ESATAN® model. These results demonstrate that it may be easier to achieve a good temperature fit with very few thermal nodes, rather than with a complex model. Thus, especially for small satellites, depending on the use case, an elaborate thermal model may not be necessary.

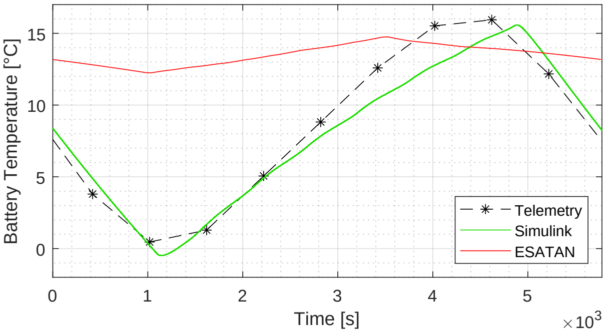


Figure 9: Comparison of Correlated Simulink Model (Simplified) and Correlated ESATAN Model (Complex)

Problems during Mission Operations

We observed multiple limitations on the spacecraft: As already discussed in an earlier section, the satellite suffers from self-induced rotational accelerations. While the turn rates could be contained to a much lower threshold than at the beginning, this is still a major problem in spacecraft operations and consumes much of the operations time of the satellite. Several attempts were made to reach a stable detumbled state. Only in summer 2019 and

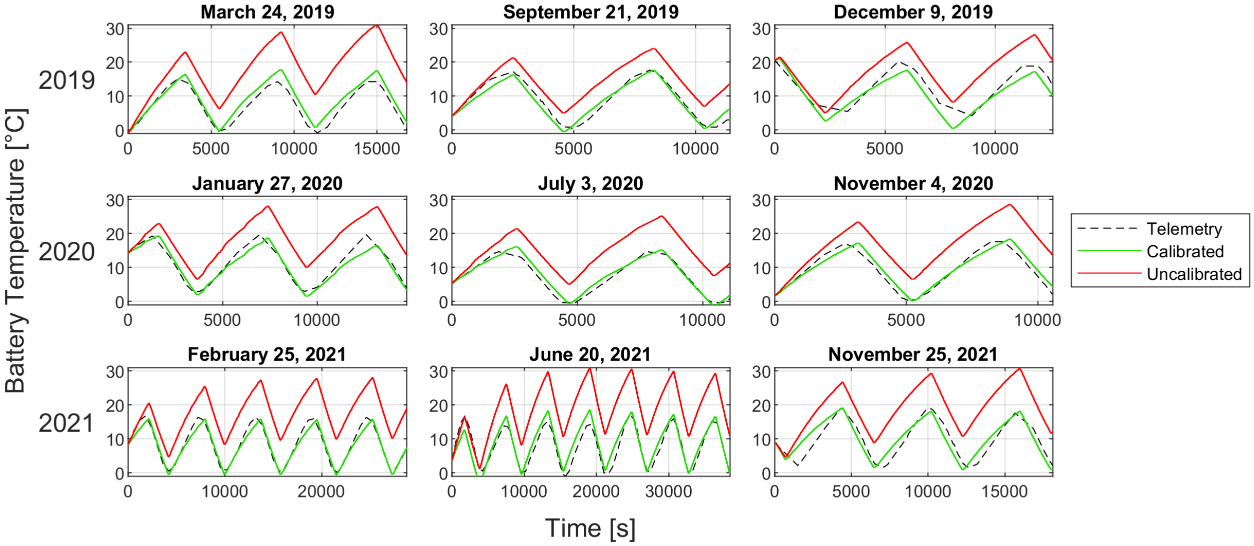


Figure 10: Overview of Simulation Results – Comparing Calibrated and Uncalibrated Simulink Model

spring 2020 were we able to perform active sun-pointing. There are multiple reasons why this is an issue. One of them is that the satellite works with dipole antennae for both the uplink and the downlink. Since the antennae are dipole antennae, their radiation pattern in a plane perpendicular to the antennae axis is omnidirectional. But these antennae also have a local minimum in their radiation pattern along the antenna axis. The radiation pattern forms a torus around the antennae. When the satellite is rotating quickly and uncontrollably, it may happen that one of the minima is pointing towards the ground station, therefore seemingly interrupting the signal. Even though these interruptions might be very short, they can still cause the total or partial loss of packages, resulting in corrupted data. Thus, a data transmission to the ground station can be successful as long as the minimum of the radiation pattern of the satellite antenna does not point towards the ground station. The influence of the rotational velocity on the downlink quality was analyzed by Borrek.[24] The results are shown in Figure 11. It shows a clear correlation between the rotational velocity and the transmittable package size. In addition, the sizes of various standard packets transmitted by the satellite were plotted. A Nanolink package is the biggest package that the satellite sends.[25] It becomes clear that up to a rotational velocity of $56\,^{\circ}\,\mathrm{s}^{-1}$ the rotation does not have an impact on the data transmission of the downlink. The other reason why the rotation is a problem is that the solar cells are not always correctly pointing towards the Sun. As a result, the solar cells produce less power, which contributes to the problem of a negative power budget.

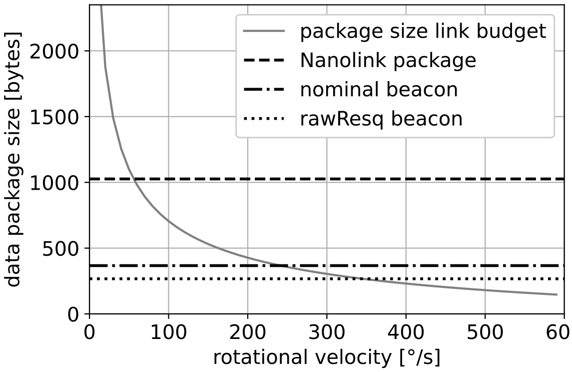


Figure 11: Possible package size that can be transmitted via downlink over rotational velocity[24]

From time to time, the satellite also runs into phases where the CDH system is not responsive and functioning anymore as soon as commands are sent to the satellite. An explanation for why this behavior occurs has not been found yet, but these CDH freeze phases resolve themselves after a few days. Luckily, these unresponsive phases are not too dangerous for the satellite mission since a watchdog in the electrical power system (EPS) will reboot the satellite if it does not receive a signal from CDH for a few minutes.

Furthermore, the memory on board the satellite fills up over time. The commanding system of the satellite relies on a sequentially increasing identification number (ID) to determine which task has been sent to the satellite and which to execute next. If the storage of the satellite is full, CDH can not save the file with the latest ID anymore. In that case, the IDs only increase with every command executed while the satellite is powered on. If it powers off, students in the MC team have to reuse the ID coming after the ID for the last successfully executed command before the storage was full. This state is preserved until storage space on the satellite is freed up again by telecommand. This can complicate operations, but is not dangerous to satellite operations in general. Usually, MC has an overview of how much storage space is left on the satellites memory. Shortly before the on-board storage is full, MC operators execute a command which dumps the data from the Ferroelectric Random Access Memory (FRAM) onto the SD cards, which are also flying on-board the satellite and serve as long term storage space.[3] Usually, the team performs this data dump when the satellite is in a safe state which is defined as follows: The batteries are charged enough (we consider a battery voltage of 7V a good threshold), the satellite is not in a period of reoccurring CDH lock-ups and the spin rate of the satellite is below a certain threshold, i.e. $60\,^\circ\,\mathrm{s}^{-1}$. This did not pose any problems in the past, but from time to time the satellite did not meet these criteria and the team had to make due with no memory space left on the satellite for a while. The storage naturally fills up over time due to housekeeping data being created during the mission. Scientific measurements, such as performed for the ADCS or the payload, are also saved on the Flash memory.

MOVE-IIb Mission

MOVE-IIb is nearly identical to MOVE-II except for a few minor changes, which were implemented due to the first flight results of MOVE-II. The main difference between the two satellites is the orientation of the solar cell wiring under the deployable solar arrays, which was indicated as the main driver of the high rotational rates observed for MOVE-II.[3] The difference in wiring can be seen in Figure 12.

Operations of MOVE-IIb

Just as with the MOVE-II satellite, the first task for MC after the launch of MOVE-IIb was to determine the correct TLE among the different options published for all the satellites launching on the same rocket. Based on the experience from MOVE-II, we used a procedure very similar to the one reported by Rückerl et al.[3] to deal with inaccurate orbit knowledge during the first orbits. We pointed our ground station antenna close to the horizon on which MOVE-IIb was expected to rise and manually followed the predicted path of the preliminary TLE we received from Exolaunch, while observing the received signal strength. Automatic Doppler compensation was turned off and the Doppler shift was manually corrected by the operators from the spectrogram. The baseband signal before this manual correction was recorded and played back with proper Doppler correction once the orbital parameters were verified.

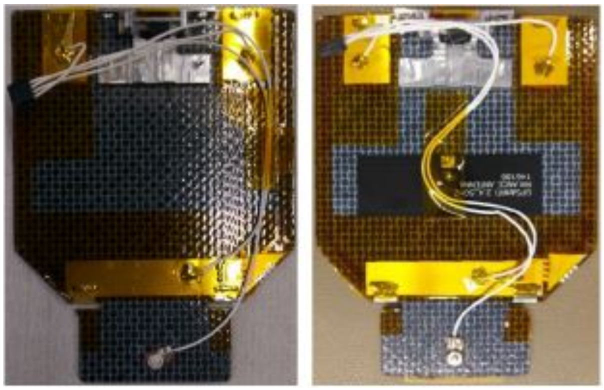


Figure 12: Solar cell wiring under the Flap-panels of MOVE-II (left) and MOVE-IIb (right)[3]

We used the same tool that was already used for the MOVE-II TLE lottery[3] to plot the spectrogram of our baseband recording and overlay it with predicted Doppler shifts from potential TLE orbits. Again, this tool proved very valuable to assess the quality of the preliminary TLEs, as well as to discard potential new TLE sets that were published by NORAD in the days following the launch that were not matching the Doppler shift observed from MOVE-IIb. It was also very valuable to synthetically modify the best matching TLEs to adjust them further to our Doppler observations of MOVE-IIb. In particular, modifications in the mean anomaly and mean motion allowed us to predict acquisition and loss of signal times well before any TLEs were released by NORAD (SatCat #44398).

In contrast to MOVE-II, no sufficient communication to allow operations with MOVE-IIb could be established. Despite that, several data packets could be recorded with the help of different radio amateurs who supported different tests performed with the satellite. Shortly after launch several theories for the existing communication problems were developed, ranging from problems with the ground station to a failure of the satellite's CDH system or a failed deployment of the solar panels, which would also result in a non-deployment of the antennae. With the reception of the first data packets by a ground station in Tartu, Estonia, it was confirmed that the satellite is sending data packets. With the existing data packets, an analysis of the satellite was conducted and several results could be obtained, including updates of the initial theories regarding the satellites problems. As the number of received data packets was very low at the beginning of the analysis, corrupted data packages were taken into consideration in order to obtain more data points. Therefore, new tools had to be developed. The data packages can be converted into text files, containing the data of all different subsystems. Tools were developed to read the values from the text files, convert them if necessary and provide the information in a graphical way.[26] The first theory addressed in the analysis covered the theory of a failed or partial deployment of the solar arrays and the antennae. Due to the design of MOVE-II and -IIb, the deployable solar panels block the antennae from unfolding in the launch configuration. After launcher separation, a cassette (see Figure 1) should be pushed downwards, giving way to the solar panels, which again allow the antennae to unfold.[16] The data point of choice for this analysis were the battery charge regulators (BCRs). These provide information about the incoming power on the solar panels, which are located on the deployable panels, as well as on the Sidepanels as seen in Figure 1. In total, there is data for four BCRs, the BCR-1, -2, -3A and -3B. The BCR locations can be seen in Figure 13.

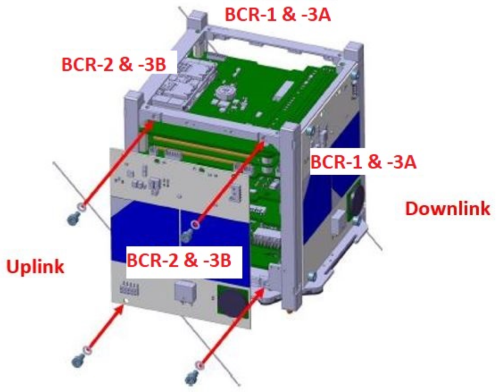


Figure 13: Location of the BCRs and antennae[27]

Each of the BCRs 1 and 2 provides information about the incoming power via two of the deployable solar panels, whereas BCRs 3A and B measure the incoming power generated by the solar panels located at the side panels, with each BCR covering 2 side panels.[28] The maximum power available on the BCRs can be estimated by multiplying the solar constant, the area of the solar cells of the corresponding BCR, the solar cells' efficiency and the cosine of the incoming angle of the sun towards the solar cells. For BCRs 1 and 2, the maximum incoming power can be estimated to 5 W, whereas for BCR-3A and -3B, the maximum power can be estimated to 1.6 W.[26]

For BCR-1, several data points show a value close to the estimated maximum power, which can only be the case when both deployable panels are pointing towards the Sun nearly orthogonally. This indicates that at least the two deployable panels that power BCR-1 must have been deployed. In addition, the difference of nearly 2 W between the incoming power of BCR-1 and -2 for the data points with maximum incoming power on BCR-1 indicates that one of the panels feeding BCR-2 was not deployed successfully. The plot for the power difference of BCR 1 and 2 can be seen in Figure 14. The BCR 1 and 2 power values can be seen in Figure 15.

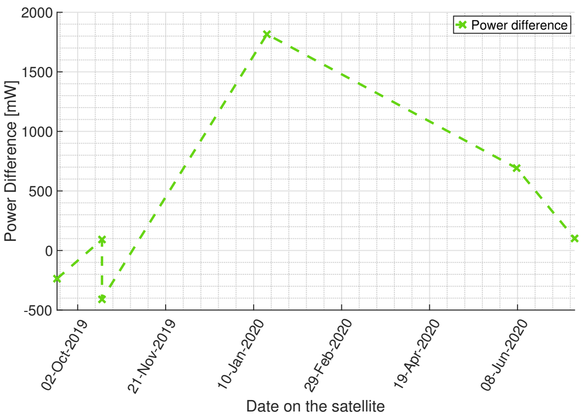


Figure 14: Power difference between BCRs 1 and 2 on MOVE-IIb[26]

Additionally, a comparison with data collected from MOVE-II never shows a difference in the incoming BCR power of more than 1.5 W and especially not for values, where one of them shows approximately 5 W.[26] As a next step, the geometry of MOVE-IIb was considered, which shows that an undeployed panel feeding BCR-2 would cover the solar cells mounted on a Sidepanel feeding BCR-3B. In Figure 16 it can also be seen, that BCR-3B is never close to the theoretical maximum, whereas this is the case for BCR-3A. This also supports the hypothesis of an undeployed panel. Despite all that, it has to be said that all the analysis is based on a small number of data points and therefore still carries some uncertainty.[26]

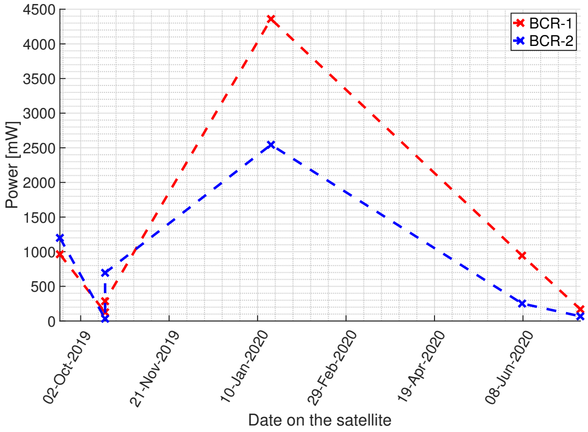


Figure 15: Power of BCR 1 and 2 on MOVE-IIb[26]

In addition to the relative location of the different solar cells feeding the BCRs, the location of the two antennae (uplink and downlink) was considered. This showed that the downlink antenna was blocked by the Flappanel feeding BCR-1 in launch configuration, whereas the BCR-2 feeding panels blocked the uplink antenna. With the previously explained Flappanel configuration and the results following the BCR analysis, we concluded that the downlink antenna could have unrolled. Therefore, it is unlikely that a not fully deployed Flappanel is responsible for the reduced power of the downlink signal received.[26]

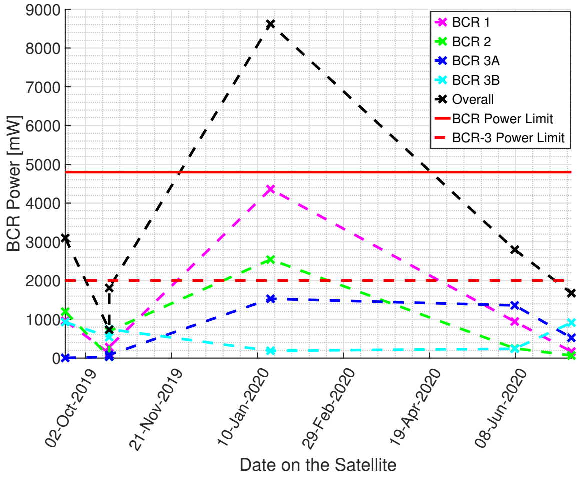


Figure 16: BCR power of MOVE-IIb[26]

As a second hypothesis, a failure in the Telemetry and Telecommand (TM/TC) transceiver was investigated. The data packets provide the used power of the transmitter power amplifier (PA). This device is responsible for increasing the transmission power of the outgoing signals. The available data points mostly show 0 W for this PA power. A possible explanation is the point in time and the method it uses to collect data from the subsystems. As the satellite's PA is only switched on while transmitting, which is only the case when the satellite transmits a beacon once per minute or a defined continuous wave (CW) signal once every 20 seconds,[16] the beacon data might be collected when the satellite's PA is switched off. It was assumed that when the PA power is requested by CDH, neither a beacon nor a CW signal is transmitted. The only time a non-zero value could be recorded was during a test performed together with a radio amateur. During this test, the MOVE MC team tried to command MOVE-IIb, while the radio amateur recorded the satellite. By design, the satellite sends Automated Repeat Requests (ARQs) if it does not receive a valid command. The command sent was intentionally invalid to trigger those ARQs and allow the CDH to record a non-zero value of the transmitter PA power. These types of tests were repeated several times, but only one attempt was successful. In this test, we could observe, that the PA power recorded was 87 mW. Again, a comparison with MOVE-II was performed for a time frame of four months and significantly higher PA powers could be observed. A distribution of all non-zero PA power values of MOVE-II can be seen in Table 3. This comparison shows that the recorded value of MOVE-IIb is in a range, where only 2.2 % of the recorded MOVE-II PA powers are located. This could be a hint that the problem with the weak communication is in the satellite's communication system, but as only one data point is available this can not be seen as proof and requires more testing and investigation.

Table 3: Distribution of non-zero PA power values in MOVE-II beacons

Power [mW]	Absolute Number	Relative Number
less than 100	4	2.2 %
100 - 200	6	3.2 %
200 - 300	41	22.0 %
300 - 400	71	38.2 %
more than 400	64	34.4 %
Total	**186**	**100 %**

Ground Segment

Throughout MOVE-II's mission lifetime, the ground segment underwent a few changes while other parts remained the same. This chapter shall give an overview of the issues and their solutions that were encountered during the mission. The main antennae are mounted on a commercial of the shelf (COTS) 2-axis rotor, which are connected to a COTS low noise amplifier (LNA) on the RX chain and a high power amplifier on the TX chain. Both chains are connected to a dedicated software defined radio. A ground station server is responsible for coordinating overpasses and the radio signal data processing necessary.

Issues with the Ground Segment

The ground segment experienced repeated issues with the PA of the antenna. Unreliable connectors and unfavorable weather conditions for the PA were the most common reasons for the system to fail. Additionally, over time the antenna became misaligned and had to be recalibrated on several occasions. A calibrated position of the antenna is important so that the automatic satellite tracker on the rotors can point in the correct direction to track the satellite as it passes over the ground station. These situations were worsened by the fact that there was no permanent dedicated ground station team since satellite operations is done by students and the number of students responsible for mission operations varies. Maintenance was only done sporadically. Therefore, quick repairs on different components on the ground station, i.e. the rotors, could take longer than expected since the team was relying on outside help. This is something that shall change with the next satellite mission as a permanent ground station team is organized. The team learned a valuable lesson about the importance of the ground station. A severe limitation of the satellite operations is the fact that bidirectional contact is not possible with the spacecraft. If the uplink of the ground station is turned on, strong interference in the downlink signal can be observed. It is impossible to receive any data from the satellite when the uplink is turned on. Due to the lack of a ground station team, no attempts were ever made to solve this problem, even though it might have greatly improved operations. To receive data from the satellite, operators have to turn off the uplink. Beacon data from the satellite gets sent down once a minute,[29] therefore operators have to toggle the uplink at least once a minute.

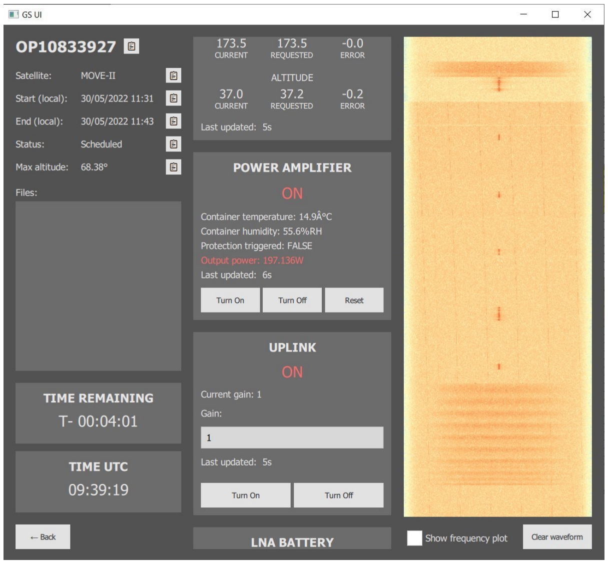
Improvements and Lessons Learned for the Ground Segment

The most important lessons learned regarding the ground station is the fact that the ground segment is a mission-critical element that requires an appropriate amount of attention during development. If not given the necessary development time, this will strongly impact satellite operations as it represents the communication link with the satellite. This might seem like an obvious observation, but it is an easy oversight if everybody on the team is focused on building a spacecraft. While building something is part of the educational program for students at MOVE, it should cover all aspects. To address these lessons learned two steps are necessary: First, the development and therefore also the testing of the ground segment has to start much earlier than it did for the MOVE-II missions. For this reason, the ground station team of the next satellite mission is already being introduced to the MOVE-II ground station. While commercial ground station services are available, in an educational program like MOVE, students will gain a lot more know-how when building infrastructure like this themselves. Secondly, there needs to be a permanent team responsible for the ground segment. Ideally, this would be a student team whose only task it is to maintain and improve the ground segment. In case no ground segment team is available, this could also be done by MC. But this is only feasible if there has been an appropriate transfer of knowledge and access to the ground segment team beforehand.

Software Improvements of the Ground Segment

Several small improvements to the GNURadio flowgraph for the decoding of the downlink have been made since the beginning of the mission. The loop parameters of the phase and timing synchronization blocks have been tweaked with baseband recordings of MOVE-II from space rather than samples from the engineering model (EM) on the ground, which had been used before. We also implemented a new frame synchronization algorithm based on a method proposed by J. Massey,[30] rather than a straightforward correlation of the synchronization word. Unfortunately, these changes did not improve the amount of data that was received. The ongoing rotation of MOVE-II is still the main limiting factor for stable communication with the satellite. A key improvement for future satellite missions would be to use feed-forward burst synchronization rather than continuous tracking loops, at least during the launch and early operations (LEOP) phase, to be able to quickly reacquire the signal once the antenna of the satellite turns back towards the ground station during tumbling. In general, there should be a dedicated communication plan for the tumbling satellite, with higher link margins and shorter packet lengths so that the link can be reacquired, synchronized and a complete packet transferred before the satellite antenna turns away again from the ground station.

The overall data flow for the MOVE-II ground station has remained mostly unchanged with respect to what is described in the last publication.[3] Nevertheless, several improvements have been implemented on the software side, reworking the previous system to implement software engineering best practices and to automate a number of actions that previously had to be performed manually by the mission controllers (e.g. deactivating the charging of the LNA battery just before the overpass and restarting it just after). The most significant change in the software stack has been to implement an Infrastructure as Code (IaC) approach. Historically, the MOVE ground station server has been managed completely manually by many different system administrators. This led to a situation in which precisely knowing the entire network of dependencies between the various programs running on the ground station was impossible. This has been solved by replacing the manually installed software (GNURadio, the custom uplink software, etc.) with Docker images generated automatically from a script as part of a continuous integration pipeline. In this way, all the dependencies between different software have to be clearly specified in a programmatic way. This approach resulted in a significantly lower operational burden for system administrators. A custom scheduler written in Python keeps track of when a satellite overpass is occurring (as computed from the satellite's TLE) and starts the appropriate Docker container to perform the overpass for that satellite. This scheduler is generic enough to be easily portable to other ground stations, keeps track of all the executed overpasses in a database for easy inspection, and offers additional services to the Docker containers (e.g. automatic Doppler correction factor computation). The other significant improvement in the MOVE-II ground station was the user interface offered to mission controllers. The previous implementation relied on a command-line interface which worked unreliably and was particularly unfriendly for users with limited computer science background. Moreover, a separate user interface was used to display the spectrogram of the signal received by the antenna, but the software solution used for this introduced massive latencies, resulting in an end-to-end delay of 30+ seconds which made the spectrogram effectively useless for operators. A completely new graphical user interface has been developed to solve these problems and to integrate in a single place all the ground station-related information that is needed by mission controllers to perform their duties. The spectrogram was also integrated into this new user interface, completely removing the delay present in the previous solution. Operators can also use this new interface to start and stop the uplink with a single mouse click. The new graphical user interface interacts with the scheduler running on the ground station server through a standard Representational State Transfer Application Programming Interface (REST API), potentially enabling future different applications to interact with the ground station server in the same way.



OP10833927

Satellite: MOVE-II
Start (local): 30/05/2022 11:31
End (local): 30/05/2022 11:43
Status: Scheduled
Max altitude: 68.38°
Files:

T- 00:04:01

09:39:19

173.5 CURRENT
173.5 REQUESTED
-0.0 ERROR

37.0 CURRENT
37.2 REQUESTED
-0.2 ERROR
Last updated: 5s

ON
Container temperature: 14.9Â°C
Container humidity: 55.6%RH
Protection triggered: FALSE
Output power: 197.136W
Last updated: 6s

ON
Current gain: 1
Gain: 1
Last updated: 5s

Figure 17: Picture of the newly created GS-UI that greatly improved MC Operations

Operations Interface

The operations interface, described by Rückerl et al.,[3] which was supposed to receive data from the ground station server and to display it to mission controllers, turned out to be less effective than expected. This was mostly due to the delay that was present between the reception of a data packet from the ground station and its appearance in the user interface, which is of several seconds, if not minutes. Moreover, the operations interface discards all data with an incorrect checksum and does not offer sufficient facilities to examine partially corrupted packets, which were particularly common in the beginning due to the communication issues that MOVE-II experienced. In day-to-day use, the operations interface has de-facto been replaced by custom Python scripts written by operators. This results in two lessons that should be taken into account when developing future operation interfaces: End-to-end latency matters a lot during the tight time window of an overpass, and the system is bound to receive partially corrupted packets, which must therefore be easily inspected.

Operation Methodology

The operation methodology includes all organizational things regarding MC, such as the evolution of the overpass procedures over the mission time, for example.

Overpass Procedure Changes during the Mission

At the very beginning of mission operations for MOVE-II the plan was to have multiple operators present during an overpass. Several roles were created to use the time during an overpass as effectively as possible. These roles were flight director, whose purpose it was to lead the other operators during the overpass. Data analyst, who was tasked with analyzing the state of the satellite, based on the data coming in. Command controller, responsible for sending commands to the satellite and file transfer controller who oversaw the file transfer from the satellite to ground and vice-versa. Finally, a mission controller was tasked with documenting the events during the overpass. When operations consolidated after most of the issues during launch and early operations (LEOP) were solved,[3] the operator team shrunk to only two operators necessary during an overpass. The remaining roles were commanding controller and ground station operator. We decided to lower this number due to the limited number of members, the limited time available in a student team and to man at least one overpass per day. During the COVID-19 pandemic beginning in 2020, this evolved further to only one operator being necessary per overpass. The reasons for the downsizing were an increased proficiency of the team in handling and commanding both the ground station and the satellite, as well as the need to socially distance during the pandemic.

Description of current Overpass Procedures

An overpass is characterized by three different phases: Preparation, execution and post-processing. For a regular overpass the operators commanding the satellite will meet ten minutes earlier to prepare everything for the overpass according to our well-established protocols. This includes verifying what has to be sent to the satellite and that all necessary tools are working. During the execution phase of an overpass the operators usually wait for aquisition of signal (AOS) of the satellite. The satellite might need high elevations to successfully transmit a complete beacon. This can cost valuable commanding time during an overpass. Furthermore, in extreme cases, only corrupted data packages can be received, so-called "broken beacons". While not optimal, this can give insight into the state of the satellite and allow for targeted recovery efforts. The ability to view broken beacons can be very useful to assess the state of the satellite. Broken beacons can still contain correct values for some subsystems. Experienced operators are able to differentiate between correct and faulty values in the beacons. Especially during phases of high spin rates, as described earlier, this feature is very useful. The commands sent during this phase heavily depend on the state of the satellite and what the short-term goals are. Frequent commands sent to the satellite include commands to detumble the satellite to counteract the acceleration caused by the dipole moment increasing its angular velocity but also commands to set the correct time on the satellite since it tends to turn off during eclipse phases due to its slightly negative power budget. Since the ground station is not able to establish bidirectional contact with the satellite, the operator responsible for the ground station has to toggle the uplink when a data signal from the satellite is expected in order to receive it successfully. Usually, operators try to confirm that the commands they sent to the satellite were successfully executed. This can be achieved by checking the radio signals sent by the satellite or changes in the beacon data. Beacons are data packages regularly sent by the satellite containing telemetry information about the state of the satellite.

The execution phase usually ends with the operators turning off the uplink signal. This marks the beginning of the post-processing phase. Operators will retain critical information about the events during the overpass, the satellites state and behavior as well as tasks for the next overpass in a template document. If anything off-nominal occurred during the overpass, for example with the ground station, the responsible people are informed. Additionally, if any scientific data has been downlinked from the satellite it is passed on to the people responsible for processing and analyzing this data. Finally, the operators make sure that the Mission Control Center (MCC) is left in working condition for the next overpass. A picture of the MCC can be seen in Figure 18.

Figure 18: The Mission Control Center shortly before an overpass

Keeping Knowledge in the Team

The most difficult task is to prevent brain drain and maintain knowledge and experience in the MC team, even if students are joining and leaving regularly. To this day, this is a problem that the team is facing. Due to these satellite missions being student projects, it is difficult to maintain a consistent team for long periods of time. Educational programs, such as MOVE, and their success are highly dependent on the student's commitment. Except for a few individuals, students will naturally leave the project after two semesters, typically. Often, students are discovering other interests they want to pursue or are finishing their studies and preparing to pursue a career in the industry or academia. The resulting loss in knowledge poses a risk to the mission and limits the scope of operations but also impacts any future projects that could benefit from it. To counter this problem, the team implemented different solutions. Among other things, the team focuses on improving existing documentation. Not only documentation about the operations of the satellite but also its development. Some documentation went through multiple iteration steps or is still being improved at the moment. As the mission evolves the needs of the operators may change. Such an example is the so-called logbook. In this document, operators note down relevant information about past overpasses and the satellite for other operators. Team members are encouraged to propose, adapt and change documentation wherever they deem necessary. Furthermore, operators that are leaving the project are encouraged to hand over their work to other operators and train them in their respective specialties. Work was put into centralizing all documentation in one place. The thought was that centralized documentation creates an incentive to expand existing documentation due to it being easy to find and to use. Another major loss of knowledge occurred right after the launch of the satellite when the rest of the team started to work on the following satellite mission, while the MC team was left alone with a system they only partly understood.

To prevent this from happening, MC should be part of the development of the system form the very beginning. During the mission, we learned that it would greatly improve operations if MC members would begin to learn sooner about the system that is being developed and actively participate during activities such as testing or the development of control schemata. This knowledge could be used to write the first mission operations procedures. The goal for the next mission is to develop procedures earlier than it was the case for MOVE-II. All in all, the implementation of these lessons would lead to MC being better prepared for the satellite's will launch into orbit and the inevitable anomalies during the mission. Another very important way to prevent loss of knowledge is the training, which will be addressed in the next section.

Training

What Problems are Student Groups Facing in Training?

The training must be designed in such a way that every student, independent of their field of study, can understand follow the training as the team consists of different engineering, computer science and physics students, who all have different knowledge sets. The next challenge is that the training should not be too long and exhausting because the team experiences a high fluctuation of members. The students must also be motivated and encouraged as they spend their free time on the project. The complexity of the satellite itself is the final challenge since many former students who were responsible for the different subsystems already left university. Understanding the subsystems must at least cover the basics to ensure that in the case of an anomaly the Mission Controller can understand where the issues came from. Therefore, the goal is to design the training to cover a basic understanding of the subsystems of the satellite and the commanding infrastructure while making it accessible to all students.

Innovative Mission Control Training Approach

The team had several approaches to the training over the past years, which evolved with the development of the satellite and the mission. In this section, the new training method developed by Holl[31] will be discussed.

Original Approach

Formerly, the approach was to divide the training into several theoretical lessons and some further practical ones with no test needed at the end. An overview of the original training approach is given in Figure 19. The problem was that not all of the important topics were covered and due to the issues encountered during the early days of operations as described by Rückerl,[3] new topics of interest arose. The practical training was also very limited and the Operations interface, as described by Rückerl et al.,[3] that should be used to command the satellite in orbit, changed. Therefore, a new concept was needed.

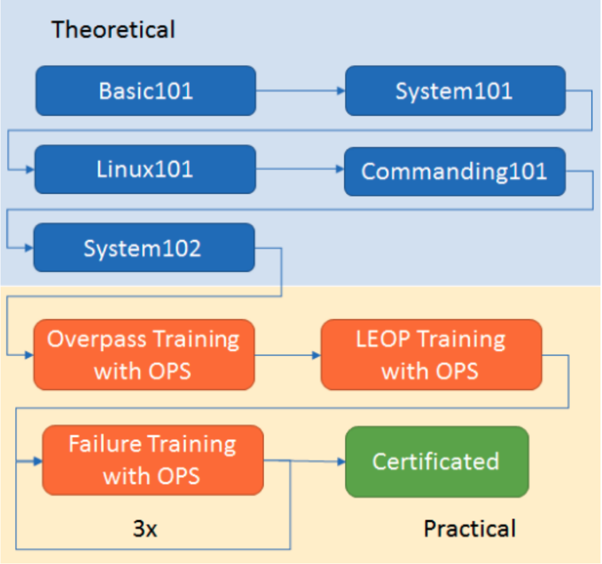


Figure 19: Flowgraph of the original training approach

First Training Iteration

The main goal for the reworked training was to better reflect real operations and the behavior of the satellite in space. The basic training structure was kept the same but several improvements were made. The old topics (as listed in Figure 19 have been reworked and the training is still separated into a theoretical and a practical part but now with a short test in between. An overview for the new training structure is given in Figure 20. Furthermore, the trainees now also receive a handout for every training session in order to have all the information condensed in one place.

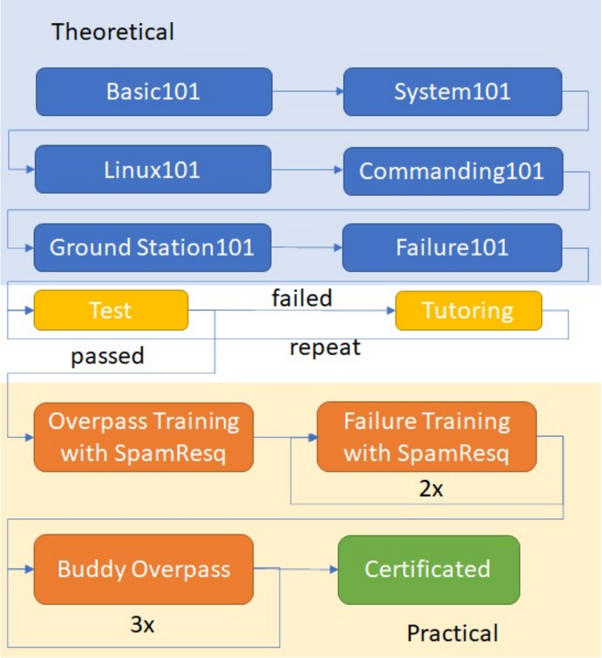


Figure 20: Flowgraph of the first iteration of the training approach

The first training session is designed to get a basic understanding of space and satellites. The goal is to bring all students to the same level of knowledge. Afterwards, MOVE-II itself is introduced with an explanation of all subsystems, their tasks and functionality. A Linux training is required because the software of the satellite is based on the Linux computer and therefore the commanding includes the standard Linux commands. Satellite commanding itself, as well as the functionality of the Operations interfaces are covered afterwards. During an overpass, the ground station is commanded by the MC team too, therefore, the team needs to know radio amateur rules and the electrical functionality of the ground station itself. Finally, failure cases that occurred during the early operations and re-occurred later are discussed. With this training, it is ensured that a fast recovery can be achieved. After all theory lessons are completed, a short test needs to be passed. This is an oral exam with questions about the theoretical topics presented to the trainees. A trained operator leads the test and the trainee passes the test when the operator has the impression that the student understood all questions. There is no fixed number of questions that need to be asked and correctly answered. Instead, the exam should be similar to a conversation about the theoretical topics and flow naturally. The purpose of the exam is to get an idea of the level of understanding of the trainee. In the case that knowledge is missing, personal tutoring will be provided, in which the failed topics get discussed again and open questions get answered. Then the test will be redone with a focus on the old, failed topics. The last step is the practical training. First, a nominal overpass is simulated to show the normal work with the satellite and obtain first hands-on experiences with the system itself. Two failure trainings follow afterwards. In this training, the EM[8] of the satellite is used, in combination with a simulator. This simulator can simulate the space environment and the resulting inputs for the satellite itself. Scenarios for the training are based on real failures that occurred and situations that have a high probability of occurring. The last step is to do normal overpasses with one of the trained operators utilizing the real satellite in space. The trained operator will be passive during the overpass and only step in if the trainee needs help. If all this is completed the trainee becomes a fully certificated operator and is allowed to handle overpasses on their own.

Second Training Iteration and Simulator Improvements

After the first iteration of the training, some minor changes and additions to the training were made. The main structure proved itself effective and four new operators passed. Another prominent topic involved software issues during the failure training which were also improved. The section about the ground station was also modified. Furthermore, a battery simulator was added to the training simulation. Created in MATLAB® Simulink, this simulator was implemented in the already existing HIL setup for the EM of MOVE-II originally published by Kiesbye et al.[9] The simulator made it possible to include the temperature dependency of the battery charge via the battery resistance since the former was shown to fluctuate heavily on MOVE-II and cited as one of the reasons for the negative power budget. It should be noted though, that the dependency was only modeled as approximately linear. Additionally, an undervoltage protection (UVP) was added to the simulator. In training with the EM, a more realistic mission scenario can be simulated now.

Results

With the new training concept, the deficits of the old training could be resolved and the operators were better prepared for their task in the MC team as the tests in the theoretical training yielded good results and all scenarios in the practical training could be solved. After each training feedback was gathered from the 5 to 7 participants present, with the scale ranging from 1 to 6, the former being the best grade and the latter the worst grade. Overall, the whole training received the grade 2, the theoretical training specifically received the same grade. The preparation of the trainees for real overpasses received the grade 1.5. The complexity and length of the training achieved an acceptable level. Here, feedback wasn't graded with numbers but rather judged with a range from "far too less" to "far too much". During both iterations of the training when asked about the amount of information the participant mostly answered "perfect". When asked about the mental challenge of the trainings, the results were more varied with answers across all ranges but with a slight tendency towards the lower spectrum. The new training concept was trialed with trainees. Four of those attended all training sessions and finished as certified Mission Controllers. With the usage of the simulator, the real situation is now better represented and can also be used for trained operators to refresh their knowledge or test different scenarios. Feedback indicated that the trainees wished for more hands-on training time. The training concept was used to train several new team members over the past one and a half years.

Future Outlook on Training

The training of the students to become MC Operators will also need to be adjusted in the future as new problems occur. To have a theoretical and a practical part in the training is important to give hands-on experience to the trainee. Also, the digital twin and the test scenarios can always be improved to get a more realistic scenario.

Impact of COVID-19 on Operations

As mentioned before, the MOVE operations team was fortunate enough to not be impacted too much by the beginning of the pandemic. This is partly because we were able to streamline operations and the number of operators necessary down to two people per overpass, later down to one person per overpass. Furthermore, the proficiency of the operators and familiarity with the system added to an easier handling of the situation. In contrast, the team struggled with other things during the pandemic. The team around the operations struggled with the recruitment of new team members due to university going online with virtually all courses. In contrast to software development for example, operations are very hard to do from home. Communication inside the team was also impaired since the team members could not see each other as often. This was quickly corrected though since chat tools were already in use and therefore the team members quickly adapted. Regular checkups on the status of the team, spacecraft operations and the team members' well-being, became routine and were made possible via online services such as Zoom, enabling the team to socially distance and yet maintain a close working relationship. The smooth continued operations of the two satellites during the whole pandemic show the robustness of currently existing procedures, but also the commitment of the team to the mission. Also confirming the usefulness of existing and implemented procedures was the successful acquisition of more payload data from the satellite.

MOVE-III Mission

With the development of MOVE-III[2] by the students of the WARR, operations will have to be adapted to accommodate simultaneous commanding of up to three active satellites, since it is unknown when the MOVE-II missions will end. This has to be achieved without compromising the commanding of MOVE-II and MOVE-IIb, as well as safety. In fact, more safety features, such as audiovisual cues to signify an active overpass in the area, have been implemented throughout the project, which is a trend that should continue into the future. This also means introducing more automation into the day-to-day operations of the satellites and MC. Automation would enable operators to increasingly focus on creative problem-solving, instead of spending valuable time on routine tasks. Since the design of the communications system of MOVE-III is not completed yet (e.g. which frequencies are used, which protocol, etc.), it is also possible that the whole ground segment needs to be updated to make sure it can handle both the MOVE-II missions and the MOVE-III mission, if the former are still operational. To achieve this goal, the project structure must be adapted in a way that a communications team is established, whose mission it is to maintain the ground station, and by extension, communications with the satellite. This is already beginning to happen since the current MOVE-III communications team is slowly being introduced to the current MOVE-II and MOVE-IIb ground station. Decreasing reliance on individual project members not only accelerates the process of solving any issues but also creates more incentive to pass knowledge down to other members. This is critical for ensuring commanding without major disruptions due to hardware failures and therefore consistent data streams from the satellites going forward. If it is not possible to build up a ground station team due to student fluctuations and the know-how required to maintain a ground station is at risk, this is also a task that could be taken over by the MC team. But this will only work if knowledge gets passed on and the team members get trained accordingly on the necessary systems. Yet another part to consider for the next mission is the compatibility of the ground segment with different ground stations. While data from the MOVE-II and MOVE-IIb satellite can be received by other ground stations such as the SatNogs network,[32] it is not possible to send commands from any other ground station. Meaning, that if the MOVE-II ground station breaks down, there is no way of commanding the satellite until it is repaired.

Conclusion

Looking back at over 3.5 years of operations, it is time to review the mission's goals with its achievements. From a technical perspective, the development of a magnetorquer-based attitude determination and control system can be seen as a success. The system and the simulation environment with which it was developed on ground saved the mission when the spontaneous spin-ups were detected. The same level of achievement can be seen for the development of the CDH Software, which even after 3 years in space still works as designed. For the communications with the satellite, it has to be stated that even after 3.5 years we did not achieve the designed full-duplex communication. This is due to the combination of high spin rates of the satellite and cross-talk on the communication lines in the ground station. Due to the lacking pointing stability, the S-Band Transceiver was never tested, as this would have required several passes in a row with stable ADCS operations and corresponding planning. While the goal to daily acquire measurements on the four junction solar cell payload was not reached, the few measurements that were conducted over the 3.5 years can be seen as a significant input. This also brings us to a final technical achievement of the mission: Considering the designed lifetime of six months, the spacecraft is now operated more than 6 times longer than originally planned for.

From a programmatic perspective, the mission can be considered a full success. The main mission goal was to further the hands-on education of students in spacecraft technology. Seven years after the start of development countless students were involved in the development, testing, integration and finally operations of the spacecraft. Parts of the team founded their own company in 2019, which now counts over 70 employees, and which goes to show that the funding of such a simple student CubeSat development is well worth the investment. Students had and have the possibility to learn how actual space missions are conducted, experience the challenges of a large-scale embedded development first-hand and get first-hand experience in struggles such as knowledge transfer, organization with constrained resources and of course the daily operations of an aging satellite.

From a scientific perspective, the aging processes of the spacecraft are interesting, as is the hardware-in-the-loop simulation that allowed predicting the control law stability regions in space way outside the designed functionality. Also, the concept of dealing with a negative power budget by ensuring a sufficient state of charge is reached before the spacecraft is switched back on might be interesting for missions that - like us - discover late in the development that the power budget is tighter than expected.

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References

[1] G. D. Krebs, "MOVE 2, 2b." `https://space.skyrocket.de/doc_sdat/move-2.htm`, 2022. Accessed: 2022-05-26.

[2] X. Oikonomidou, V. Braun, R. Pail, T. Gruber, F. Schummer, D. Messmann, A. Hacker, J. Heapy, L. Martin, and F. Strasser, "MOVE-III: AN IN-SITU DETECTOR TO SUPPORT SPACE DEBRIS MODEL VALIDATION," in *8th European Conference on Space Debris*, 2021.

[3] S. Rückerl, D. Messmann, N. Appel, J. Kiesbye, F. Schummer, M. Faehling, L. Krempel, T. Kale, A. Lill, G. J. Reina Kiperman, P. Schnierle, S. Würl, M. Langer, and M. Lülf, "First Flight Results of the MOVE-II Satellite," 08 2019. Accessed: 2022-04-31.

[4] S. Rückerl, N. Appel, R. Klein, and M. Langer, "Software-Defined Communication on the Nanosatellite MOVE-II," in *Proceedings of the 69th International Astronautical Congress*, 2018.

[5] D. Messmann, T. Gruebler, F. Coelho, T. Ohlenforst, J. van Bruegge, F. Mauracher, M. Doetterl, S. Plamauer, P. Schnierle, T. Kale, *et al.*, "Advances in the Development of the Attitude Determination and Control System of the CubeSat MOVE-II," in *Proceedings of the 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, Italy*, pp. 3–6, 2017.

[6] D. Messmann, F. Coelho, P. Niermeyer, M. Langer, H. Huang, and U. Walter, "Magnetic attitude control for the MOVE-II mission," in *Proceedings of the 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, Italy*, pp. 3–6, 2017.

[7] M. Rutzinger, L. Krempel, M. Salzberger, M. Buchner, A. Höhn, M. Kellner, K. Janzer, C. G. Zimmermann, and M. Langer, "On-orbit verification of space solar cells on the CubeSat MOVE-II," in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, pp. 2605–2609, IEEE, 2016.

[8] M. Langer, F. Schummer, N. Appel, T. Gruebler, K. Janzer, J. Kiesbye, L. Krempel, A. Lill, D. Messmann, S. Rueckerl, *et al.*, "MOVE-II - THE MUNICH ORBITAL VERIFICATION EXPERIMENT II," in *Proceedings of the 4th IAA Conference on University Satellite Missions & CubeSat Workshop, Rome, Italy*, pp. 4–7, 2017.

[9] J. Kiesbye, D. Messmann, M. Preisinger, G. Reina, D. Nagy, F. Schummer, M. Mostad, T. Kale, and M. Langer, "Hardware-in-the-loop and software-in-the-loop testing of the move-ii cubesat," *Aerospace*, vol. 6, no. 12, 2019.

[10] H. E. Soken and S.-I. Sakai, "Magnetometer Calibration for Advanced Small Satellite Missions," in *30th International Symposium on Space Technology and Science*, pp. 10–12, 2015.

[11] R. Alonso and M. D. Shuster, "Twostep: A fast robust algorithm for attitude-independent magnetometer-bias determination," *The Journal of the Astronautical Sciences*, vol. 50, no. 4, pp. 433–451, 2002.

[12] L. Markley and J. Crassidis, *Fundamentals of Spacecraft Attitude Determination and Control*. Springer, 2014.

[13] Mathworks, "magcal - Magnetometer calibration coefficient." `https://de.mathworks.com/help/nav/ref/magcal.html`, 2022. Accessed: 2022-06-09.

[14] Alken, Patrick, "International Geomagnetic Reference Field." `https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html`, 2022. Accessed: 2022-06-09.

[15] D. Vallado and P. Crawford, "Sgp4 orbit determination," in *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, p. 6770, 2008.

[16] M. Langer, F. Schummer, S. Rückerl, D. Vogel, A. Lill, R. Amann, T. Kale, K. Janzer, L. Krempel, J. Kiesbye, and P. Lux, "System Documentation MOVE-II," tech. rep., Technical University of Munich Chair of Astronautics, 2019.

[17] G. Dorrington and P. Trivailo, "Utilising the 'Chaotic' Tumbling of CubeSats," in *18th Australian International Aerospace Congress 27th International Symposium on Space Flight Dynamics*, 02 2019.

[18] A. Petrov and S. Volodin, "Janibekov's Effect and the Laws of Mechanics," in *Doklady Physics*, 08 2013.

[19] F. Espenak, "Earth at Perihelion and Aphelion: 2001 to 2100." `http://www.astropixels.com/ephemeris/perap2001.html`, 2021. Accessed: 2022-15-18.

[20] G. Datseris and B. Stevens, "Earth's Albedo and Its Symmetry," *AGU Advances*, vol. 2, no. 3, p. e2021AV000440, 2021.

[21] M. Fleischhammer, T. Waldmann, G. Bisle, B.-I. Hogg, and M. Wohlfahrt-Mehrens, "Interaction of cyclic ageing at high-rate and low temperatures and safety in lithium-ion batteries," *Journal of Power Sources*, vol. 274, pp. 432–439, 2015.

[22] L. Hannemann, "Analysis and Correlation of the Thermal Model for the MOVE-II CubeSat," 2019. Bachelors Thesis.

[23] S. Rossi and A. Ivanov, "Thermal Model for CubeSat: A Simple and Easy Model from the SwissCube's Thermal Flight Data," 09 2013.

[24] R. Borrek, "Downlink Quality of the CubeSat MOVE-II in Dependence of the Satellite's Status," 2021. Bachelor's thesis, Technical University of Munich Chair of Astronautics.

[25] N. Appel, S. Rückerl, and M. Langer, "NANOLINK: A ROBUST AND EFFICIENT PROTOCOL FOR SMALL SATELLITE RADIO LINKS," in *Proceedings of the Small Satellites Systems and Services–The 4S Symposium*, 2016.

[26] S. Gruber, "Status Analysis and Investigations of a semi-functional Satellite in Space," 2020. Semester thesis, Technical University of Munich Chair of Astronautics.

[27] P. Lux, J. Pletsch, and M. Weisgerber, "MOVE-II Integrationsprozedur," tech. rep., Technical University of Munich Chair of Astronautics, 2020.

[28] N. Faatz, "Untersuchung der Anwendbarkeit eines Artefktemodells in SysML anhand des CubeSats MOVE-II," Master's thesis, Technical University of Munich, 2019. Accessed: 2020-08-12.

[29] WARR e.V., "How to track MOVE-II." `https://www.move2space.de/MOVE-II/satellite/radio-amateurs/`, 2022. Accessed: 2022-05-30.

[30] J. Massey, "Optimum Frame Synchronization," *IEEE Transactions on Communications*, vol. 20, no. 2, pp. 115–119, 1972.

[31] L. Holl, "Improving Operator Training for Cubesat Missions by Incorporating Hardware-in-the-Loop Simulations," Master's thesis, Technical University of Munich Chair of Astronautics, 2020.

[32] SatNogs, "SatNogs MOVE-IIb Observations." `https://network.satnogs.org/observations/?norad=44398`, 2022. Accessed: 2022-06-07.