KRAKsat Satellite Mission – Lessons Learned [EN]

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KRAKsat Lessons Learned

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Introduction

Space 4.0 age has come with numerous changes in a way space exploration is being perceived. This area of study evolved from the political and economic ground to academic and commercial fields of interest. Such a rapid spread led to quick growth of the CubeSat market, as more and more units are engaging in small satellites development projects.

KRAKsat nanosatellite project, held on AGH University of Science and Technology in Cracow, stands out as one of the beneficiaries of Space 4.0 transformations. The initiative began in 2016 when a group of students started their research on an innovative idea called Ferrofluid Reaction Wheel. As a reliable orientation and rotation control system, it could, in the future, replace currently used solutions. In January 2018 the cooperation with SatRevolution has been established. Project KRAKsat, consisting of academic experimental payload and commercial platform, has officially started. After one year of development, in January 2019, the satellite was finally integrated and launched on board Cygnus NG-11 with a regular International Space Station delivery. The actual mission has started on the 3rd of July 2019, after successful deployment into LEO orbit.

Satellite Systems

Payload

The payload consists of a PCB and a Ferrofluid Reaction Wheel. The component was built entirely by members of the KRAKsat project.

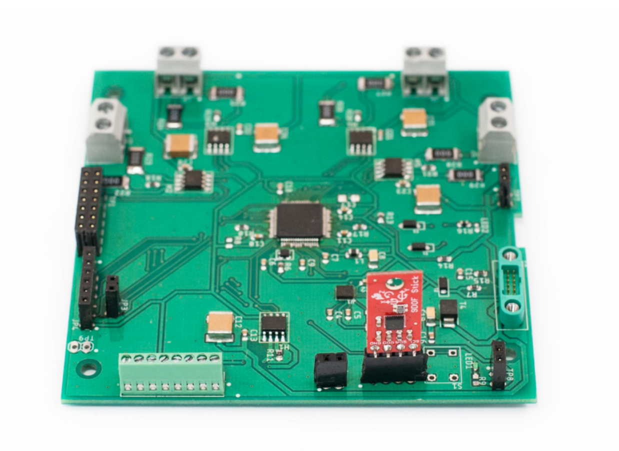

Figure 1: PCB with Ferrofluid Reaction Wheel control system [photo by A. Kubera]

The board shown in Figure 1 contains the STM32L476RCT6 microcontroller, with software supporting the experiment, performing detumbling and analyzing data from the sensors - thermometer LM74 and IMU LSM9DS1. H-bridges (A4950ELJTR-T), located on the board, are electronic elements, which allow the microcontroller to control the current on 12 V electromagnets.

Figure 2: Payload [photo by A. Kubera]

The Ferrofluid Reaction Wheel is a prototype of the solution used for stabilization and control of nanosatellites orientation. It consists of a toroidal tube with ferrofluid inside and 8 'C - shaped' solenoids mounted on the tube.

Platform

Elements of the SR-NANO-BUS platform, used in the KRAKsat project, were provided by SatRevolution.

On-Board Computer + ADCS

The PCB contains two microcontrollers: the OBC microcontroller responsible for proper platform functioning and the ADCS microcontroller that is designed to control 2 ADCS magnetorquers. The ADCS microcontroller back-up detumbling algorithm implementation can be performed on mission control demand. A 8 MB flash memory is also included on the board, used for storage of data both from the platform and the payload.

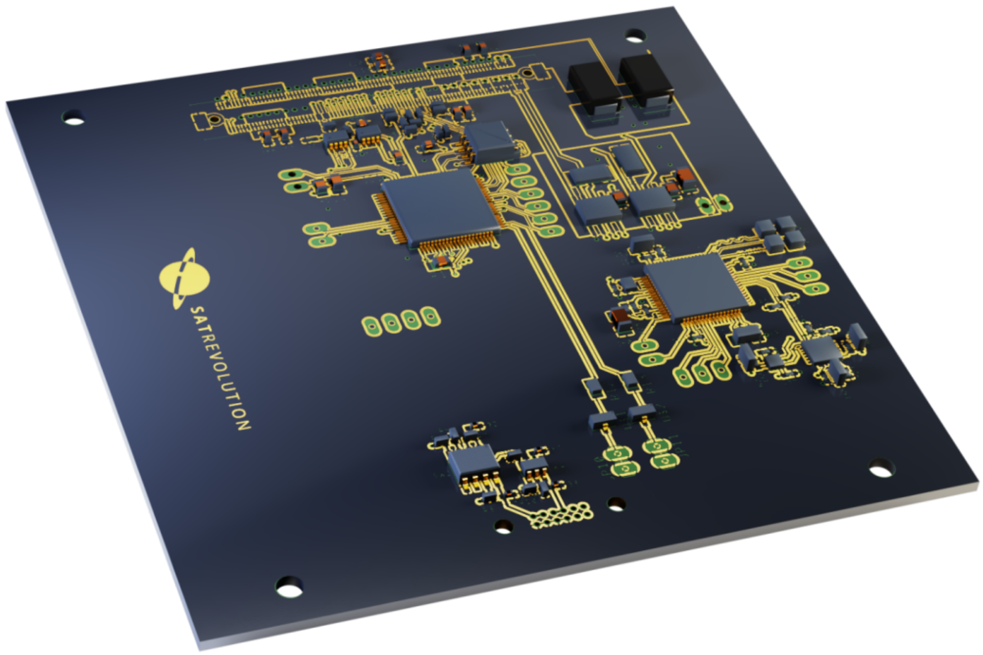

Figure 3: OBC [photo by SatRevolution]

Electronic Power System

The EPS system consists of two PCBs used to manage the electric power in the satellite. The setup is responsible for the solar panels proper functioning, 3200 mAh battery charging and power supply of all satellite's modules with 12 V and 3.3 V voltage.

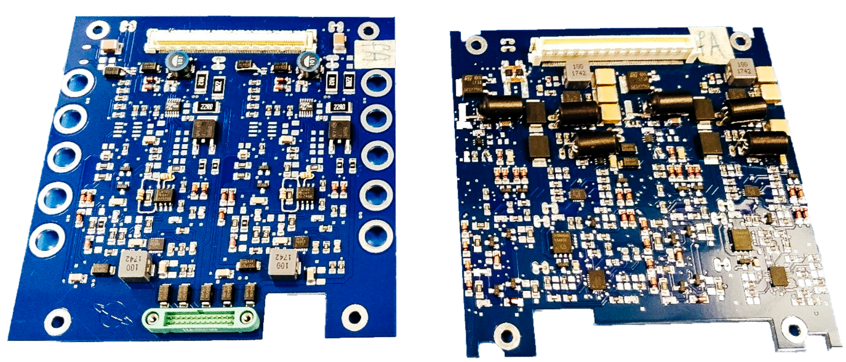

Figure 4: EPS [photo by SatRevolution]

Communication Module

The module responsible for communication between the satellite and Earth has two UHF hardware redundant transceivers. The system provides communication at 435.500 MHz. The modulation used for uplink communication is 2GFSK 9600 bps, while the device data downlink is managed as AFSK 1200 bps.

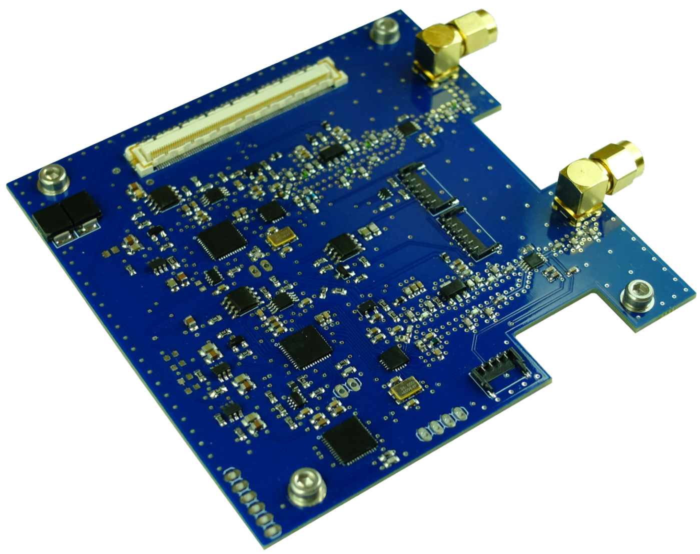

Figure 5: Communication Module [photo by SatRevolution]

Mission Timeline

Mission Phase 1

Phase Description

The KRAKsat satellite was deployed into orbit from the NanoRacks deployer on the 3rd of June 2019, 11:50 UTC. 30 minutes after the event antennas should be released and the detumbling process should start. It is not known if the process was successfully executed, probably not. From the moment the satellite was placed into orbit until the 16th of July 2019, neither was there any downlink received, nor any communication estabilished.

Phase Analysis

It is assumed that the satellite's lack of activity was caused by a power switch malfunction or another temporary mechanical fault, preventing proper operation of the electronic power system. This assumption is based on the fact that on the 16th of July the KRAKsat turned itself on with a full battery and a timestamp suggesting total power cut off since the integration of satellite systems in January.

Mission Phase 2

Phase Description

The first satellite status frame was received on the 16th of July at 12:00 UTC via an amateur radio network, SatNOGS. Since the moment of the devices activation, the battery voltage had been consistently decreasing. From the 16th to the 30th of July, successful two-sided communication was conducted and KRAKsat was fully operative.

Phase Analysis

In the second phase of the mission, the satellite's power supply system had a negative energy budget. On-board devices used more energy than solar panels were able to provide. The attempt to completely turn off the device did not increase the battery voltage, keeping it on a similar or even lower level. Despite stable communication having been achieved, goals of the mission could not be fulfilled. Crucial errors found during the operation of the satellite prevented execution of the Ferrofluid Reaction Wheel experiment.

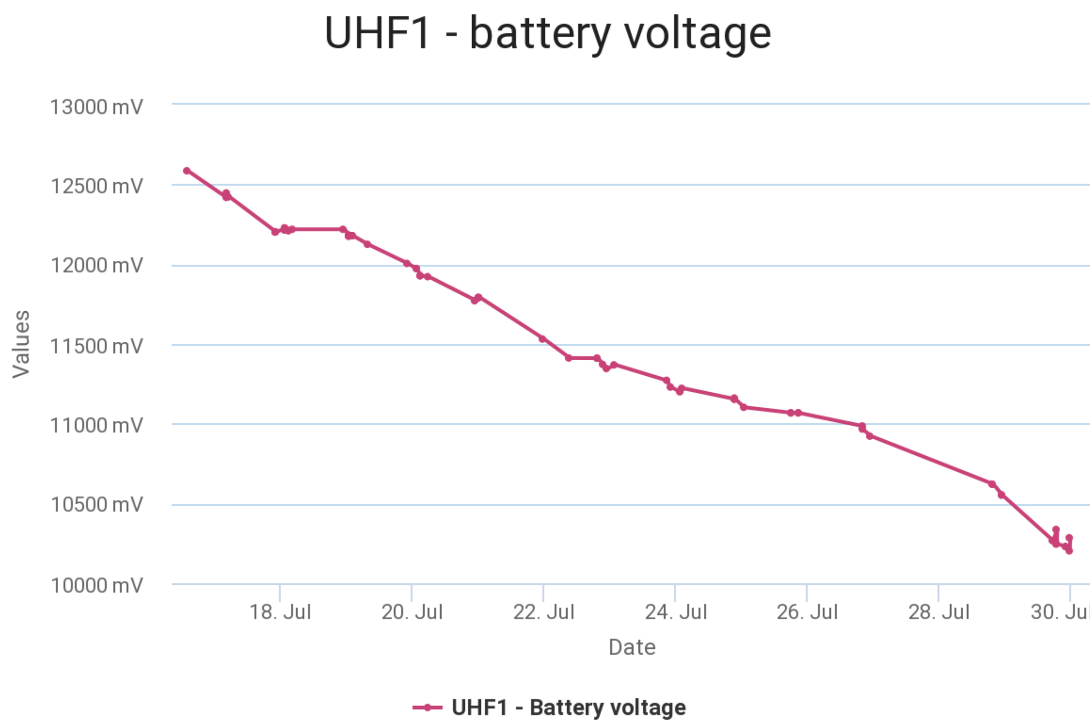

Figure 6: KRAKsat satellite power graph

Mission Phase 3

Phase Description

On the 30th of July 2019, KRAKsat's power dropped to its limit value, causing all systems to shut down. Due to the lack of hysteresis implementation, turning off the device resulted in lifting voltage values, which then led to another restart of the satellite. Each time the KRAKsat is turned on, it should transmit information about radio activation, the reboot number and all status frames in the form of a beacon. Attempting such a transmission overloaded the devices EPS, causing the satellite to turn off, and several seconds later, when the voltage increased slightly, another start-up. The third phase restart loop was characterized by a relatively constant frequency of about 150 reboots on one orbit around the Earth. Between reboots of the UHF1 and the UHF2 radios, a very short time window took place in which it was possible to communicate with the satellite.

Phase Analysis

According to the data collected during the third phase of the mission, the KRAKsat probably only restarted in the sunlight - remaining turned off in the shadow. The restart loop was caused directly by the power droping below the limit value and the lack of implementation of the hysteresis, which should have allowed the battery to charge to the level at which the satellite could work properly. Many time windows gave chances of communication with the satellite of which, few were used. The mission control team was able to shift the frequency of the KRAKsat broadcast by 2kHz to reduce jamming with the Światowid satellite signal (operating in the same range of frequency), as well as receive a frame with information about the power supply from one of the radios. The response to each of the uplink commands discharged device, causing another restart.

Mission Phase 4

Phase Description

On the 19th of August, a temporary failure of the UHF1 radio module has occurred. The satellite still remained in the restart loop, but it had enough energy to attempt to transmit several beacon frames. The fourth mission phase lasted until the 23rd of August.

Phase Analysis

During the fourth mission phase, the mission control team attempted to shut down all satellite subsystems twice to keep it in its lowest possible energy-intensive condition. The maximum achieved time of a manual shutdown lasted about one hour. Despite deactivated payload and radios, the KRAKsat discharged again in shadow and failed to reach full orbit in sleep mode.

Mission Phase 5

Phase Description

On the 23rd of August, the UHF1 radio started to function properly again by itself. The energy consumption of the satellite increased to the state before the radio failure, and remained stable in terms of restart frequency (150 reboots every 90 min). The loop lasted until the 12th of October. From the 12th of October the frequency of restarts began to drop irregularly. Residual data could not determine the exact progressive pattern changes, however, it seemed to be non-deterministic. The lower frequency of restarts has continued until around the 24th of October, which then return to the previous typical values.

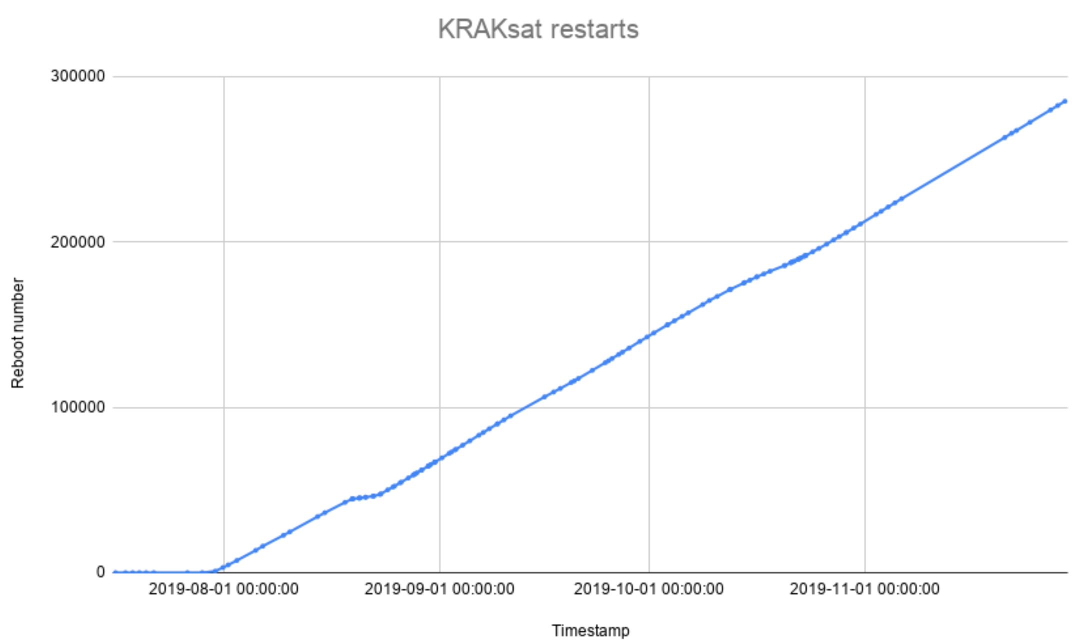

Figure 7: KRAKsat satellite reboots graph

Errors Analysis

Errors affecting the KRAKsat mission have been classified into three categories. Crucial errors are defined as those which in the second phase of the mission prevented from achieving the mission's main goals and led to the third phase, in which the satellite became inoperative. Crucial errors are big-impact malfunctions that directly affected the failure of the project, and these should be addressed first in the context of future satellite missions. The important error category included problems that indirectly led to the device malfunctioning or temporarily blocking the missions performance. Avoiding important errors would not change the final state of the satellite, but combined with resolving some crucial errors, would have a huge impact on the mission status. The third group, minor errors, did not directly affect the success of the mission, but their elimination could help meet its objectives faster. This category also includes defects that did not apply to the KRAKsat satellite itself but were identified as potential problems in satellite missions with similar specifications. In the last category, entitled 'Issues to consider', restrictions that are not classified as errors were included, ones related to issues important to address during setting mission goals.

1. Crucial Errors

1.1. Energy budget calculated imprecisely.

Error description

In CubeSat satellites properly calculated energy budget is a key element of the mission. Due to the small size of the satellite, there is limited space for solar panels, which may prove inefficient in the event of even a small malfunction. In the KRAKsat project, the energy budget was calculated with an insufficient safety margin. No tests had been carried out which would have taken into account the rotation of the satellite and could eliminate possible problems with the discharge of the device.

Mission impact

Since the launch of the satellite on the 16th of July, the voltage level on the batteries has been constantly dropping. Due to the insufficient data received from KRAKsat, the mission control team was unable to determine the root cause of the problem. Precisely calculated energy budget and pre-flight tests of integrated systems in the simulated orbital environment could prevent discharge or locate the possible cause to eliminate it in advance.

Proposed solution

When designing a satellite, the largest possible safety reserve should be included in the energy budget. Such an approach would guarantee a positive energy balance on the orbit. Accurate tests must be carried out on the integrated device to check probable battery consumption by individual components in different lighting conditions.

1.2. Lack of hysteresis implementation in the EPS.

Error description

A well-designed EPS should have a hysteresis loop implemented. The voltage level switching on the satellite should be significantly higher than the level switching it off. The missing hysteresis implementation caused an endless loop of satellite restarts when its voltage dropped below 9.5 V.

Mission impact

This critical error caused an irreversible blockage of the satellite in the restart loop. It became the key reason for the inoperability of the satellite after entering the third phase of the mission.

Proposed solution

There should be a hysteresis system implemented in the EPS. Voltage levels should be selected in a way that the switch-off level would protect the battery against damage, and the switch-on level would allow the satellite to function at least until the next communication session.

1.3. Problem with clearing the flash memory.

Error description

The command to clear the memory sector did not work correctly in the situation in which the buffor dedicated to logs had been filled. The cleared data appeared in the memory as bits set to the value 1, while the process of writing data was done using logical AND of saved data and flash memory. As a result, incorrect data was stored in the flash memory.

Mission impact

The error was identified during the mission and it took several days of communication sessions to find the solution. Correct data storage has been proved to be possible through the usage of other commands that allow more advanced flash memory handling. A lot of time had been wasted by this mistake, which, combined with the falling voltage, meant that the satellite operators failed to obtain any valid data from the experiment.

Proposed solution

Tests have to be carried out taking into account both correct communication, as well as atypical situations. In order to properly simulate the mission and data collection, multi-day tests should be performed. It is recommended to have additional, redundant commands that execute similar tasks in a various ways. All commands must be well documented in advance.

1.4. Impossibility to download data from the flash memory by radio UHF2.

Error description

Two hardware redundant radios UHF1 and UHF2 were placed in the KRAKsat satellite platform - to be able to perform two-way communication with the satellite in case one of them fails. However, the radios had different software implementation and UHF2 has not been adapted for correct flash memory data transmission, i.e. the key for mission's ferrofluid flywheel experiment.

Mission impact

The UHF2 radio signal strength was proved to be better than that of the UHF1. Because of this, the mission control team decided to use only the UHF2 for transmission and temporarily turn off UHF1 to save energy, while having no awareness of the mentioned error. As a result of the decision, problems connected to data transmission from memory appeared that seriously delayed the mission.

In the fourth phase of the mission the error proved itself to be the key reason why data from payload was not successfully downloaded. The temporary failure of the UHF1 radio caused a small surplus of the satellite's power, because of which a small chance of restoring the device to its operative state appeared. However, even if the stable status could be achieved, it would not be possible to gather information about the actual course of experiment using only radio UHF2.

Proposed solution

The redundancy of satellite components should occur on both hardware and software level. The UHF1 and UHF2 radios should operate in exactly the same way in order to be able to complete the mission using only one radio in case of failure of the other.

1.5. No emergency option to shutdown satellite subsystems permanently.

Error description

In the KRAKsat satellite there was no implementation of a emergency option to permanently disable components, so that they do not restart after a reboot.

Mission impact

In the third phase of the mission, when the satellite got into the restart loop, all of the systems (including payload and ADCS) were activated during each reboot. As a result, the energy surplus was consumed immediately and there was no possibility for KRAKsat to leave the loop.

Proposed solution

It should be possible to forcibly turn off selected subsystems permanently in the satellite. The solution could completely change the fate of the satellite mission, especially in the event of problems with the energy budget or a restart loop.

1.6. The lack of an own ground station.

Error description

The lack of an own ground station resulted in the need to rent a station from an external entity. Hiring a station generates costs for each session performed, which in the case of limited missions resources caused a reduction in the number of communication sessions with the satellite as well as the mission potential.

Mission impact

Due to the limited number of sessions, not all available satellite flights were used. There is a good chance that the usage of other possible communication sessions would allow faster diagnosis of flash memory error, enabling correct experiment data generation and downlink.

Proposed solution

To fully exploit the missions potential, it would be necessary to build an own ground station and, after obtaining the appropriate permits to use it, manage the communication sessions by ourselves.

1.7. Repeated performance of the experiment after satellite startup.

Error description

The state machine of the KRAKsat experimental system has been designed to automatically launch cycles consisting of diagnostics, detumbling and experiment modes.

Mission impact

Each time the satellite was rebooted, the experimental module was turned on as well as the state machine cycle. In case of detection of available space in the flash memory, the experiment ran until filling up the buffer. After the first launch of the KRAKsat cycle it has been performed for a total of several hours, which could seriously affect subsequent operation of the device.

The idea of the automatic cycle start resulted in unnecessary energy consumption, after a normal restart. This error was partially solved by planning multiple shutdowns of the experimental module after each planned reboot.

Proposed solution

After each reboot, only the modules necessary for basic satellite operation should be started.

1.8. Inaccurate analysis of the missions requirements.

Error description

The satellite mission requires proper preparation which in the case of KRAKsat satellite was not properly accomplished. The requirement analysis and project goals were inaccurate and the team did not prepare adequately for the mission.

Mission impact

Too superficial analysis resulted in uncertainty and inability to make quick decisions during communication with the satellite. Under the pressure of time and between the sessions it was not possible to conduct all necessary analyses.

Proposed solution

To avoid problems related to the proper functioning of the satellite, at the stage of selecting the mission objective a detailed analysis of the requirements for the platform and performed experiment should be carried out. This analysis should be developed as more mission details appear. Such a study should include:

- analysis of the amount of data needing to be collected and the possibility of downloading it,
- functionality of the delivered platform analysis, including a list of functionalities that should be adapted,
- power budget analysis taking into account various scenarios,
- data analysis in terms of their usefulness and logging frequency,
- collection and analysis of examples of implemented solutions from previous satellites,
- analysis of the parameters of orbit on which the satellite will be located,
- simulation of the satellite lighting during each part of the mission,
- availability of communication sessions for given ground stations,
- statistical data on flights within the range of ground stations affiliated to the SatNOGS platform.

2. Important errors

2.1. No proper timestamp logging in the flash memory.

Error description

Each line of logs saved to the memory consisted of two to six bytes per key, two bytes per value and two bytes per relative timestamp, containing not arbitrary real time but only the information about the time passed from the last payload restart, with the accuracy of 0.2 s.

Mission impact

Possible flash memory damage or communication problem between payload<- >flash or flash<- >OBC, that occurred during the mission combined with a limited relative timestamp information resulted in the lack of knowledge about the arbitrary moment data downloaded from the satellite was generated. The fact that the quantity of information obtained from the device's flash may be negligible was also disregarded - in that case recognizing their timestamp may become impossible. In the period of the proper satellite operation only 4 kB of data could be received, so it was not possible to determine when it was logged.

Proposed solution

Despite the restrictions resulting from the baudrate of the radio communication protocol and available memory, the timestamp should be logged in full Unix format.

2.2. No file system in the flash memory.

Error description

Data in the flash memory was stored directly in two buffers, one normal and the other, special. The normal buffer, containing less important information from an idle mode, could be overwritten. While the special buffer, with detumbling and experimental data, was implemented as persistent. There was no file system used to store logs and, to be able to download a data packet, mission control operators had to refer directly to the specific address in memory by placing the pointer on it.

Mission impact

Address conversion and the manual pointer setting could have been inaccurate and took a lot of time, delaying the satellite mission. Implementing a simple file system could help to separate data derived from different modes and, perhaps, it could prevent problems with the flash memory that occurred later during the mission.

Proposed solution

There should be a layer of abstraction implemented in the flash memory possibly in the form of the file system (e.g. YAFFS, used in another Polish satellite PW-Sat2). The solution would significantly simplify controlling the memory and avoid potential data management issues.

2.3. Downloading data from the flash memory.

Error description

Downloading the payload data the from flash memory was done through transactions. Raw data saved directly to the memory was divided into one kB packages, encoded by OBC to Base91 and transmitted in the form of so-called chunks, with a total length about 35-38 lines. In case of incompleteness, an absence of any single fragment, the data packet would become non-decodable and retransmition of specific lines had to have been performed. To properly handle transactions it was required to define several commands in a row. Ending every process with proper SUCCESS or FAIL status was also needed to correctly manage pointer position in the memory, i.e. move it forward or keep it on its current position to repeat transmission.

Mission impact

In conjunction with (2.2. No file system in the flash memory), error caused a delay in satellite data transmissions, impeding both communication sessions plan and management of received data packets. Every disruption, causing a problem in receiving even one data line, forced station operators to perform a retransmission that required proper termination of the previous transaction and start a new one with appropriate parameters. In practice, this meant a series of commands, unnecessarily complicated and too time-consuming for a short communication session.

Proposed solution

Experimental data should be stored in the memory with usage of the file system and its transmission flow should be significantly simplified. The process of the downlink must be rethought and a great emphasis should be put on designing a way to select a fragment of memory for downloading and minimizing the time needed for the entire operation.

2.4. Current state machine mode logged too rarely.

Error description

The satellite payload modes duration time and the amount of data logged during their execution have not been properly described. In a single packet of data (1 kB) there is no information about the current mode, because this register is saved to the flash memory with too low frequency (only once per minute).

Mission impact

Due to the error there were huge difficulties in determining the current satellite state for the downloaded data frame. Consequently, it became impossible to define whether the data from a specific storage location is relevant for the course of the mission.

Proposed solution

Knowledge of the current state machine mode gives a lot of information about the proper functioning of the payload and it should be logged in often enough to appear in every downlink data packet.

2.5. Frames transmission in ASCII format.

Error description

Data transmission from the KRAKsat satellite, including both beacons and data from the experiment, was carried out using the APRS protocol AX.25 and the information was formatted as ASCII. Broadcasting data in this format requires much more time and consumes the valuable power energy.

Mission impact

Transferring data in a binary form rather than ASCII could significantly improve the effects of communication sessions and help to stabilize the unstable energy budget. The impact would be particularly noticeable when transmitting big chunks of information from the experiment.

Proposed solution

The solution to the problem would be to adapt the communication module to allow binary data transmission, especially regarding the Ferrofluid Flywheel experiment data.

2.6. No possibility to download data from satellite platform sensors.

Error description

Each transmission line sent by KRAKsat was formatted as an ASCII string terminated with '\0'. Downlink communication used the APRS protocol, calculating the data length with the strlen() function. The error prevented transmission of valid data from platform sensors, which were saved by subsystems in the binary form.

Mission impact

Due to the inability to download information from platform sensors (including the ADCS system), diagnostics of the satellite's malfunction has become very difficult. In the case of potential problems with sensors in the payload, redundant use of subsystems located in the platform would be impossible.

Proposed solution

A partial solution to the problem could be to encode the data from the platform sensors, just like the other information from the device, to the ASCII format. However, the most reasonable option would be to carry out transmissions with a correctly implemented communication module including proper direct binary data broadcast.

2.7. Lack of information about the solar panels efficiency.

Error description

The possibility to download information about the power supply from the EPS and solar panels was not implemented in the satellite platform.

Mission impact

The lack of information about the operation of the solar panels resulted in the inability to identify the problem of the satellite battery being discharged. Data about power efficiency could help resolve the issue of decreasing voltage and verify if it is caused by panel defects, uncontrolled rotation of the device or excessive power consumption by the subsystems.

Proposed solution

There should be a feature in the power control module implementation designed for downloading solar panel efficiency data. As this information is crucial for small satellites it should be additionally transmitted in every beacon.

2.8. No implementation of the satellite status frame.

Error description

The first line of cyclic beacon frames (M1; STS) were not implemented. KRAKsat transmitted eight frames containing data every 15 minutes, including a 32-bit component status frame that did not show the actual satellite status.

Mission impact

The lack of frame implementation resulted primarily in the absence of the information about the current status of individual platform components. In addition, the frame that was sent unnecessarily consumed energy, which, taking into consideration the unstable energy budget of the satellite, should be maximally saved. It is worth mentioning that the unimplemented frame was also the first one emitted, sometimes the signal of the first frame can be strong enough to be decoded even in the restart loop, so their order became particularly important.

Proposed solution

Before the satellite integration all systems should be thoroughly tested and both payload and platform data transmission analyzed for its usability. Non-implemented or test frames should be removed so that they do not unnecessarily occupy valuable time for transmission. The order of sent data is also extremely important. To be prepared for emergency situations, it should be considered a good practice to arrange frames in the correct order, from the most important to the least important.

2.9. Hard-coded minimum voltage required to run the experiment.

Error description

The payload software blocked the start of the experiment if the voltage dropped below a certain pre-determined value, which was hard-coded.

Mission impact

During the mission, after resolving errors which blocked data collection, the power level became too low to successfully run the experiment.

Proposed solution

The minimum required voltage level should be implemented just like other configuration parameters, i.e. saved in a dedicated memory area. It should be possible to change its value using the appropriate command. This is especially important in possible emergency situations.

2.10. No mission planning for emergencies.

Error description

The KRAKsat satellite mission was not planned correctly. Communication flow and satellite data management had been analyzed after the satellite integration, shortly before placing it in orbit. The team has only prepared action scenarios assuming the proper functioning of CubeSat, without developing flow charts required in the event of an emergency.

Mission impact

The lack of planned strategies that could be applied in the event of an emergency caused a delayed response to every problem that occurred during the mission.

Proposed solution

Thorough mission analysis, planning and functional tests are required prior to satellite integration. As many possible problems and emergency situations as possible should be identified and proper preparation of operating schemes that can be used quickly, is needed.

2.11. Restrictions in communication flow as a result from sharing infrastructure with the Światowid satellite.

Error description

KRAKsat and Światowid were placed in orbit simultaneously and at first had an almost identical trajectory. Communication with both satellites was carried on frequency of 435,500 MHz and both mission control teams used the same ground station infrastructure.

Mission impact

Plan of communication sessions had to be carefully coordinated between mission control teams. Sessions could not take place at the same time due to the use of the same station and signal interference on the same frequency.

Proposed solution

In the case of two satellites with similar trajectories in orbit being placed at the same time, it is worth to consider using separate ground stations. Communication should be planned on frequencies that will not interfere with each other. The solution allows full use of each of the available communication sessions and excludes the risk of signal interference between devices.

2.12. No consultation with experts.

Error description

When conducting missions in such a different environment as Earth's orbit, many of the solutions used on Earth become impossible to apply. Correct implementations of solutions are often non-intuitive and difficult to verify in terrestrial conditions. A lot of information about the structure of satellites can be read in the professional studies, but many practical tips can only be obtained directly from people with experience in the space sector.

Mission impact

Many critical and important errors could be avoided if the experts' knowledge and their experience with satellite issues was reused when designing new satellites and planning their missions. A large subset of problems turns out to be repetitive in various space missions, which is why learning from the mistakes of predecessors becomes so important.

Proposed solution

During satellite missions it becomes very important to establish contact with people experienced in the space industry. Verification of the proposed solutions and advice related to the behavior of satellites in space can help a lot in achieving every mission goal.

2.13. No possibility to remote software update.

Error description

The KRAKsat satellite had no support for software updates during the mission. A limited number of commands allowed interaction only with the selected components, giving no possibility to change the values of many important parameters.

Mission impact

The implementation of a remote software update would allow attempts to disable less needed subsystems and stop the progressive decrease of the power. The possibility to update could also give the mission control team a chance to eliminate flash errors, while providing flexibility in the case of the other issues.

Proposed solution

It is worth to consider implementing a software update system in order to be able to correct errors and add missing functionalities during the satellite mission. This applies especially to projects where the time to build a satellite is limited. Software can be polished after the subsystems integration and uploaded as the new version during the first communication sessions.

2.14. Incomplete tests after payload and platform integration.

Error description

Very little time has been allocated for functionality testing after satellite platform and payload integration. Appropriate test scenarios had not been prepared and the final activities of integrated components had not been checked before flight.

Mission impact

Accurate post-integration tests could help detect many errors, including serious problems with the energy budget that had critically affected the course of the mission.

Proposed solution

Before the final satellite integration, detailed test scenarios for use after assembling should be prepared. It is important to perform the integration early enough to have time to test all subsystems functionalities, analyze the test results and possibly make the necessary software corrections.

3. Minor errors

3.1. Low frequency of beacon frames.

Error description

Due to the imprecisely calculated energy budget with a risk of running short of energy, it was decided to implement the transmission of beacon frames once every 15 minutes. Compared to other CubeSat missions it is relatively infrequent. Taking into account KRAKsat's orbit parameters and the fact that the average communication session lasted for a maximum of 10 minutes, there was a high probability not to receive any set of information during this time.

Mission impact

During eight to eleven minutes, which is how long most communication sessions and recordings from the SatNOGS platform lasted, it was possible not to receive any beacon, despite the fact that the satellite was working properly. For this reason, the detection of irregularities in the operation of KRAKsat was difficult. In addition, the error could have been a demotivating factor for radio amateurs, who are able to provide great support during satellite missions.

Proposed solution

To ensure the optimal amount of information about the state of the satellite, the transmission of beacons should be scheduled for every five to seven minutes. Thanks to this frequency the messages can be received in every LEO orbit communication session. The frame transmission time can also be implemented as re-programmable and adaptable to current needs depending on the mission status.

3.2. Invalid mode value in payload status.

Error description

The payload state machine parameters, transmitted in the beacon, were updated every minute. The current state machine mode and the one to which payload will go next, are encoded in payload status frame (PL; STATUS) and described by three bits. Because the number of states is nine, one of them could not be saved. This made it impossible to distinguish between MODE_IDLE and MODE_IDLE_FOR_TIME.

Mission impact

If the mission were carried out correctly, the error would affect the interpretation of data from the satellite.

Proposed solution

It is important to carry out tests for code validation. The size of the memory for all variables needs to be appropriate for their possible values, also taking into account the expected duration of the mission.

3.3. Improper order of frames in beacon.

Error description

The frames in the beacon were arranged in order:

Frame name	Description
CMD_STATUS_G	Platform status
CMD_LOG_G	Mission status
UHF1_LOG_G	Radio 1 status - first part
UHF1_MODEM_STAT_G	Radio 1 status - second part
UHF2_LOG_G	Radio 2 status - first part
UHF2_MODEM_STAT_G	Radio 2 status - second part
ADCS_LOGS_ASCII_GET	ADCS module status
Payload_Status	Payload status

The platform status has not been implemented (2.8. No implementation of the satellite status frame), which led to the lack of usability of the first beacon frames. Frames with relevant information for the mission were sent subsequently.

Mission impact

In the third phase of the mission, when the satellite was in the restart loop, the signal of the first frame sent was sometimes strong enough to be decoded. If a different arrangement of the frames in the beacon was implemented, it might have been possible to collect data that would allow diagnosing the cause of the satellite failure.

Proposed solution

It is an important decision to properly choose which messages are most important and organize their order in beacon according to priority.

3.4. Same frequency for uplink and downlink communication.

Error description

The uplink and downlink communication with the satellite was conducted at the same frequency - 435.500 MHz.

Mission impact

The implementation of the uplink and downlink on the same frequency resulted in inefficient usage of communication sessions. It was impossible to send and receive data frames at the same time. Occasionally, commands sent from Earth overlapped with information sent by satellite, preventing correct demodulation and, in consequence, making both frames useless.

Proposed solution

In order to fully exploit the communication session's potential, the frequency of the uplink and downlink should differ to prevent overlapping and increase communication efficiency.

3.5. No direct information about errors in payload modes.

Error description

The KRAKsat satellite state machine only allowed the execution of selected modes (e.g. diagnostic or experimental) after certain conditions were met, e.g. minimum power level or temperature range. Forced exit from the current mode resulted in the information about the event, which was logged only to hard-to-reach flash memory.

Mission impact

The last attempt to perform the experiment was a failure, probably due to low voltage. The absence of direct transmission of information about the error in the chosen mode meant that the mission control team unnecessarily waited for the experiment to be completed. It is uncertain whether it actually did not occur or other previously unknown problems related to flash memory appeared.

Proposed solution

The satellite should return information about the status of the command execution both in the payload and platform software immediately as a direct response to the command.

3.6. Single ground station.

Error description

Communication with a satellite via a single station may result in the inability to operate it due to the weather conditions or unexpected technical problems. In a critical situation, this can directly cause the failure of the mission.

Mission impact

In consolidation with errors 1.6 and 2.11, the usage of a single ground station resulted in a significant reduction in the number of sessions performed, and thus, a reduction in the amount of data received from the satellite.

Additionally, during the fifth phase of the mission, the satellite had been restarting only in the sun, so the ground station located in Poland didn't receive any transmissions for several days. The situation could be avoided by having access to a second station e.g. in Australia or America.

Proposed solution

The greater the number of stations that the ground control team can use for communication with the satellite, the bigger are the chances of the mission's success. Multiple ground stations located in various geolocations provide high availability and robust solution for an operating satellite. Apart from investing in your own ground station, it is important to look for solutions, both non-commercial and commercial, enabling the usage of many stations.

3.7. Low baudrate.

Error description

Communication with the KRAKsat satellite was performed at 435.500 MHz using AFSK (Audio Frequency-Shift Keying) modulation with a baudrate of 1200 bits/second. This is a relatively simple type of modulation, the use of which facilitates decoding transmitted information, however, the chosen baudrate proved inefficient to transfer large amounts of data.

Mission impact

During the execution of detumbling and experimental modes, KRAKsat generated very big amounts of data. Taking under consideration the short time of the communication sessions, low baudrate and other errors mentioned in this article, downloading logs from the satellite turned out to be a very difficult and time-consuming process.

Proposed solution

To ensure efficient transmission of big amounts of data from a satellite, another type of higher-baudrate modulation should be used.

3.8. Limited configuration of logger functionality.

Error description

The payload software specifies the frequency and type of logged parameters. There is a functionality that allows extending the list of logged data, but it is not possible to limit those that were hard-coded as default.

Mission impact

The memory was unnecessarily occupied by the base parameters not needed in any given mission state. Due to the low communication throughput and the big amount of data, it was difficult to obtain parameters relevant for the diagnosis and analysis of the mission.

Proposed solution

The proposed approach for proper logger functionality is to implement several logging levels (debug, info, warn, error). The amount of aggregated data could be controlled by choosing a suitable level for a specific situation. Besides, the functionality should be enriched with the possibility to configure periodical logging for chosen parameters.

3.9. Inaccurate time measurement in satellite modules.

Error description

The time measurement functionality inside the KRAKsat satellite was inaccurate. The timestamp sent by the satellite had a so-called drift, unevenly progressing compared to real time.

Mission impact

The error did not have a significant impact on the mission, but it had to be taken into account when planning the commands.

Mission impact

To prevent incorrect time measurements an external quartz oscillator should be used instead of an RC oscillator and any delay in sending a timestamp between subsystems should be minimized.

3.10. Incorrect implementation of UHF1 radio beacon frames - addressing to SP6ZWR.

Error description

Radio UHF1 transmitted data encoded in accordance with the APRS message format, but radio UHF2 used APRS telemetry format. In connection with the above, frames sent by UHF1 radio were addressed to the recipient with the callsign SP6ZWR.

Mission impact

The error did not have a significant impact on the mission, but caused confusion among radio amateurs.

Proposed solution

Thorough communication tests should be performed before satellite integration. Data transmission formats should be carefully analyzed and selected appropriately for their application.

4. Issues to consider

4.1. Uplink encryption.

Error description

It is a recommended to encrypt uplink commands in order to prevent unauthorized individuals from gaining control over the device. The commands in KRAKsat satellite were secured only using XOR, which does not significantly strengthen its security.

Mission impact

It is unclear whether the error affected the mission. Taking control over the satellite would have been impossible to notice.

Proposed solution

The security issue should be addressed. Analysis of encryption algorithms and implementation of the selected one is required in order to minimise the possibility of taking control of the device by an unauthorized person.

Glossary

ADCS Attitude Determination and Control System

Beacon Periodical data transfer from the satellite with basic status information

CM Communication Module

CubeSat Satellite manufactured according to precise CubeSat design specification

Downlink Data transfer from the satellite

EPS Electrical Power System

FRW Ferrofluid Reaction Wheel

IMU Inertial Measurement Unit

OBC On-Board Computer

PCB Printed Circuit Board

UHF Ultra High Frequency

Downlink Data transfer to the satellite.