MICRO RETURN CAPSULE 2 – REXUS EXPERIMENT RESULTS

Ehresmann, Manfred(1), Baumann, Jean-Pierre(1), Behnke, Alexander(1), Franz, Julian(1), Friedrich, Lion(1) , Gäßler, Björn(1), Galla, Daniel(1), Grabi, Florian(1), Hießl, Robert(1), Koller, Markus Tobias(1), Kumpf, Philipp(1), Müller, Nicolas(1), Papanikoloau, Athanasios(1), Rieser, Jakob(1), Schäfer, Felix(1), Schöneich, Viktoria(1), Seiler, Helge(1), Siedorf, Martin(1), Starlinger, Valentin(1), Stier, Annika(1), Tabelander, Alexander(1), Wizemann, Sascha(1), Vardar, Firat(1), Pagan, Adam Sean(2), Montag, Christoph(2), Herdrich, Georg(2), Laufer, René(3)(4)

(1) Small Satellite Student Society University of Stuttgart, Pfaffenwaldring 29, 70569 Stuttgart, Germany, kontakt@ksat-stuttgart.de
(2) University of Stuttgart Institute of Space Systems, Space Center Baden-Wuerttemberg, Pfaffenwaldring 29, 70569 Stuttgart, Germany, herdrich@irs.uni-stuttgart.de
(3) University of Cape Town Department of Electrical Engineering, 7701 Rondebosch, Capetown, South Africa, laufer.rene@uct.ac.za
(4) Concept Evolutions UG, Am Glockengarten 6,73733 Esslingen, Germany,

The Micro Return Capsule 2 REXUS is a technology demonstrator for a CubeSat standard compliant return capsule with a maximum diameter of 10 cm. Such a capsule will allow for low cost atmospheric re-entry missions to qualify thermal protection systems and study of occurring high enthalpy flows. To qualify the flight behavior of such a miniaturized capsule, functionality of selected components, the communication ability and the overall design a sub-orbital sounding rocket experiment was performed with the capsule being ejected in the apogee. A specifically designed separation mechanism was used to eject the capsule and qualified for utilization in later missions in orbit. The capsule itself was equipped with several thermocouples, pressure sensors and a thermopile to measure future heatshield performance and parameters of the surrounding environment during descent. An IMU and a GPS receiver were used to determine attitude and position of the capsule and the data was transmitted via the Iridium satellite network to produce an estimated landing location of the capsule. The capsule was successfully recovered. An electrical mirror system of the capsule resided within the sounding rocket to generate additional reference data of the flight.

1 MOTIVATION

MIRKA2-RX is a precursor experiment for the planned CubeSat Atmospheric Probe for Education (CAPE) mission [1], which aims to involve students of the University of Stuttgart and enhance the educational activities of the Institute of Space Systems (IRS). CAPE consists of a CubeSat system that uses a Service and Deorbit Module [2], equipped with a pulsed plasma thruster, to deorbit from an initial orbit comparable to the orbital altitude of the International Space System (see Fig. 1). The low thrust of the electric propulsion system allows for an additional investigations of the lower thermosphere during spiraling down. The second part of the system is the miniaturized atmospheric entry module AEM [3], which is separated at an altitude of 150 km and will then enter Earth's atmosphere on its own. On-board sensors are used to determine the performance of an experimental heat shield to be qualified with this mission. Additionally a radiometer is used to characterize occurring plasma species during the hot phase of the re-entry, opening up the field of atmospheric entry research to CubeSat missions. The capsule itself is designed to comply with the CubeSat standard and therefore has a maximum diameter of 100 mm, making it world's smallest atmospheric entry capsule to date. The shape itself is derived from the Reentry Breakup Recorder [4] with a well-established flight heritage. Although the shape is identical the smaller diameter might lead to unstable flight behavior especially during the transonic regime of the descent. Because the smallest available Iridium satellite communication transmitter was required to fit into the volume constraints of the capsule only a low data transmission rate will be available. As no recovery is planned and no additional deceleration systems are implemented into the capsule, all relevant gathered data needs to be transmitted before impact and after the plasma shroud of the re-entry subsided. This data transmission bottleneck should be quantified before the actual flight to develop data prioritization schemes to maximize the scientific benefit of the mission.

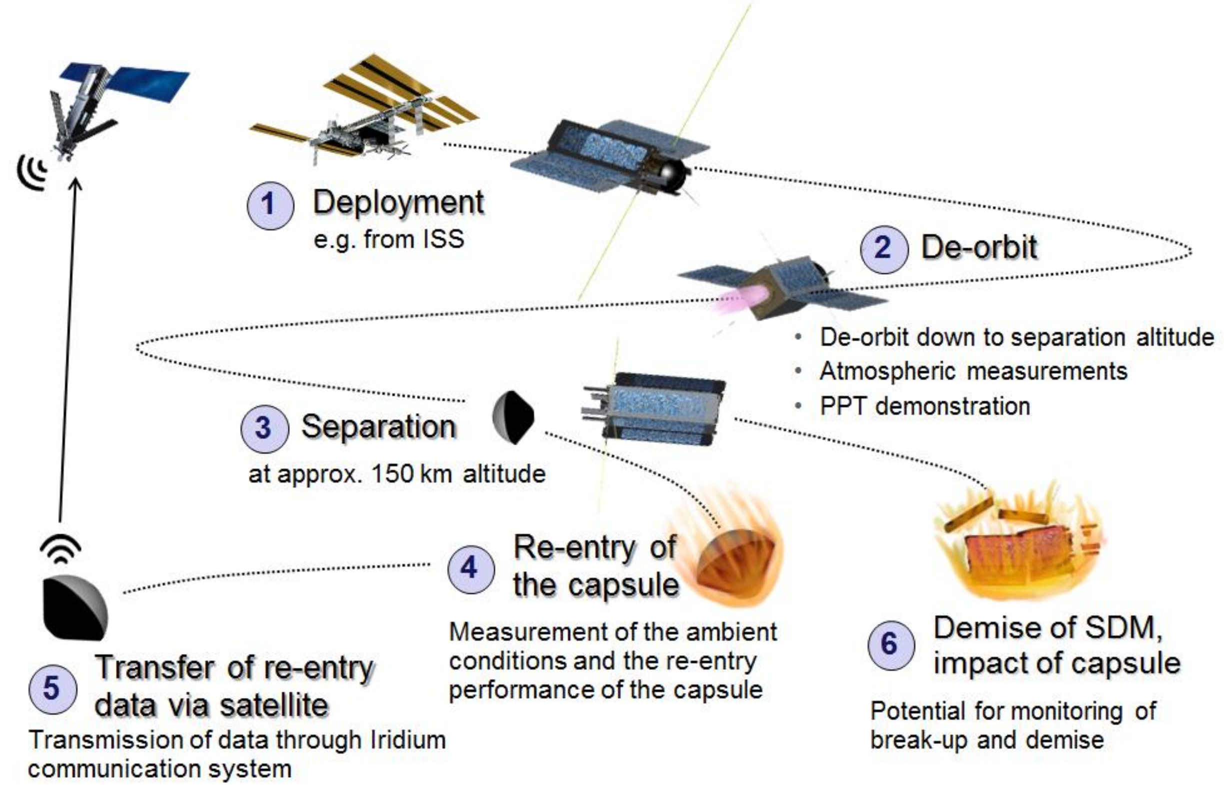

Figure 1. CAPE mission scenario

To resolve these open issues, qualify manufactured hard- and software and increase the technology readiness level of developed components an application for an experiment on a REXUS [5] sounding rocket was made in mid-2014, which succeeded and resulted in a launch on 18th March 2016, with the "Micro return capsule 2 REXUS" (MIRKA2-RX) experiment.

The experiment had the following primary objectives:

- Qualification of the separation system for a miniaturized capsule in space
- Qualification of the electronic system of the capsule
- Qualification of the Iridium communication link

With the additional secondary objectives:

- Acquire scientific data of aerodynamic behavior of the capsule
- Recovery of the capsule

2 LAUNCHER

Launch site is the Esrange Space Center near Kiruna, Sweden, which offers a designated land impact area of 5200 km². The REXUS program allows for two launches per year, which is conducted by the Swedish National Space Board (SNSB) and the German Aerospace Center (DLR) Non-German teams are supported by ESA. The REXUS sounding rocket [5] is a single stage rocket powered by an Improved Orion motor, which uses solid fuel as propellant. The complete rocket has a mass of about 595 kg, with a total payload mass of about 95 kg. Fins are used to achieve spin stabilization during flight. Up to three student experiment modules with a cylinder height of 300 mm and a diameter of 356 mm can be integrated into the rocket with a possible additional nose cone experiment. A TV channel is available for real time observation of experiments. The motor burns out 26 s after launch, while the rocket will experience a peak acceleration of up to 20 g. The nose cone is ejected after 61 s to expose the nose cone experiment to space. Four seconds later a yo-yo system is used to reduce the spin of the rocket to 0.08 Hz. One second after the rocket motor is separated from the service module and will make a return to Earth without the use of deceleration devices to slow down the descent. After 140 s an apogee of 75 – 100 km is reached, depending on the payload mass. The service module then returns to Earth. A parachute will be deployed to slow the descent in the more denser atmosphere from 150 m/s down to 8 m/s and will usually hit the ground around 800 s after launch. Both the rocket motor and the service module are recovered via helicopter.

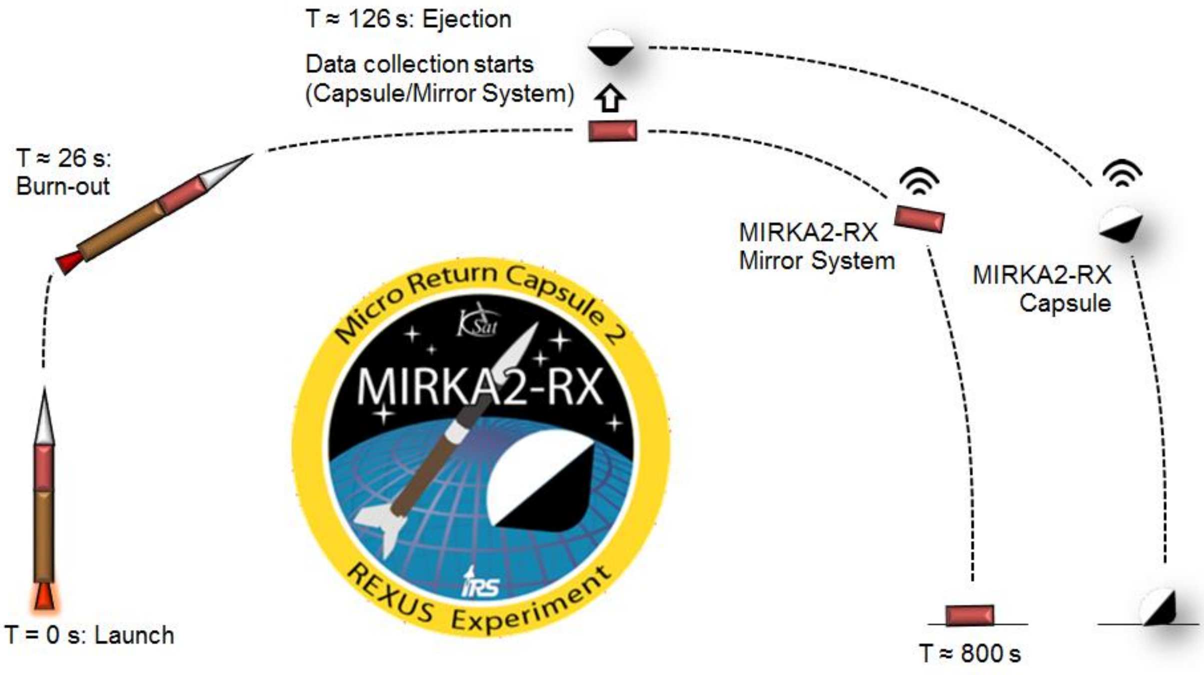

Figure 2. MIRKA2-RX Mission Scenario

3 EXPERIMENTAL SETUP

The experimental setup of MIRKA2-RX is divided into three segments depicted in Fig. 3: The capsule, the ejection mechanism and the on-board electronics, which shall be described here in some aspects, for a more detailed description of the used components see [6] [7].

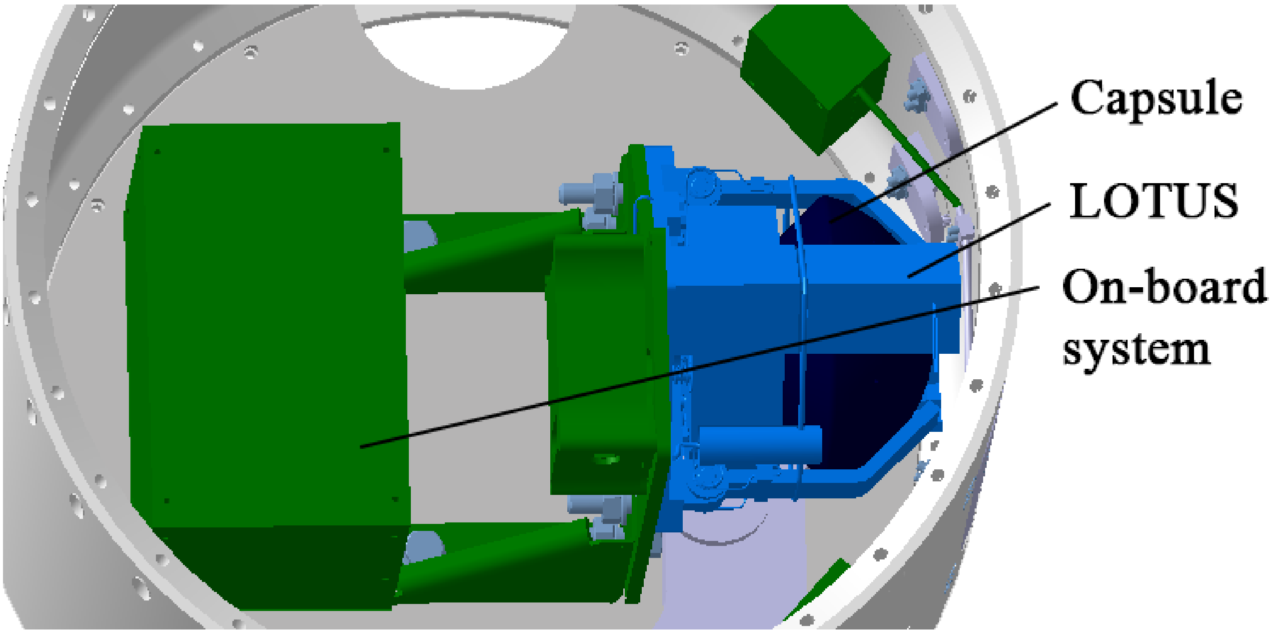

Figure 3. MIRKA2-RX subsystems

3.1 MIRKA2-RX

The total mass of the capsule was measured to be 528 g before the integration into low orbit technical unit separator (LOTUS). It has a maximum diameter of 100 mm and a height of 78.6 mm. A 3D-printed aluminum structure is used to mount components. A tungsten weight with a mass of 102 g was placed near the tip to shift the center of gravity to allow for a stable flight. The capsule is equipped with a dummy heat shield made out of carbon fiber reinforced polymer with an overall thickness of 10 mm. A hole with a diameter of 2 mm is placed at the tip of the capsule, to allow for measurement of stagnation point pressure, the thermopile measurement and to accommodate the deactivation stick. The back of the capsule is covered with WHIPOX (an oxide fiber ceramic) [13] to allow for data transmission.

3.1.1 Diagnostics Setup

Several sensors are used within the capsule to either measure the behavior during the flight of the return capsule or qualify sensors for later use in a re-entry mission. Six thermocouples *SK5100B/TC-GG-KI-30-40* of Type K determine temperatures at specific points. Five thermocouples are placed within the heat shield dummy. Two pairs of thermocouples within differing depths allow for the estimation of heat fluxes with one of these pairs is placed near the stagnation point of the capsule. The other pair is placed in the mid-section of the capsule and the remaining heat shield thermocouple is placed near the shoulder region. The remaining thermocouple is placed at the WHIPOX shell to characterize the thermal behavior of this novel material during the flight.

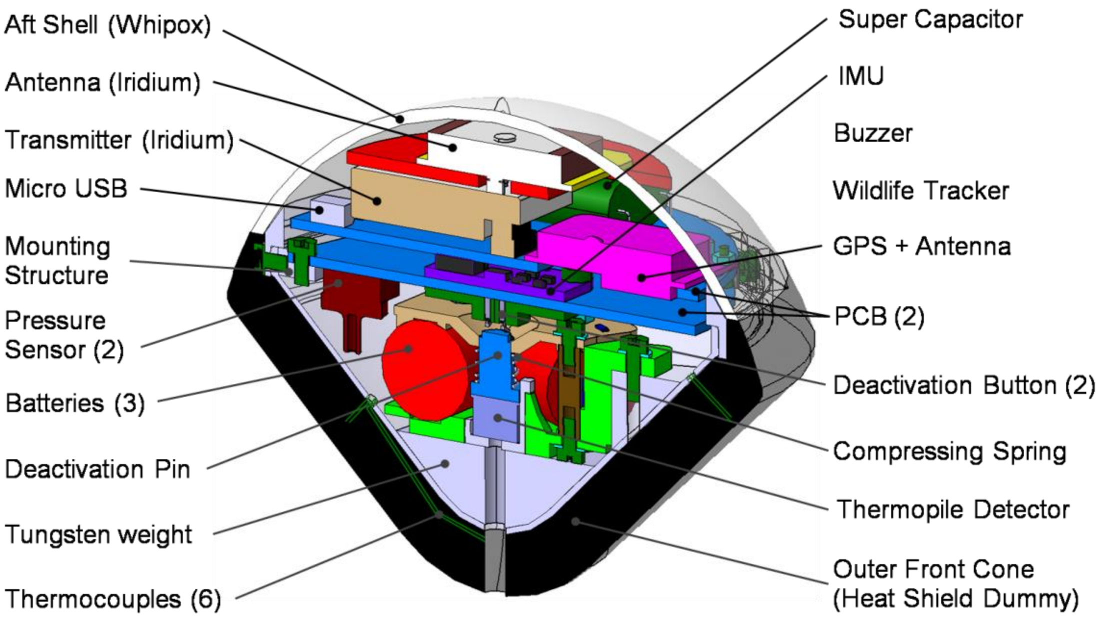

Figure 4. Capsule components

Two different types of pressure sensors are used. The digital pressure sensor *MS5607-02BA03* is used twice once to measure stagnation point pressure at the tip of the capsule and secondly to measure the internal pressure of the capsule. Additionally the analog pressure sensor *MP3H6115A* is also used to monitor the internal pressure. The two different type of sensors are used to provide redundancy and gain handling experience.

Table 1: Pressure sensors

Sensor	**Pressure range [kPa]**	**Output**	**Data type**
MS5607-02BA03	1-120	SPI/I²C	digital
MP3H6115A	15-115	Voltage	analog

To determine the trajectory and attitude during flight an inertial measurement unit (IMU) *BNO055* is used, which features an accelerometer, gyroscope and magnetometer. To supplement the estimated trajectory determined from the IMU and to serve as redundancy the GPS *LS20031* module is used. This module is not unlocked for space applications and is therefore only activated when a timer is expired.

The *Dexter ST60* is the thermopile of choice. In the current return mission only a change in signal amplitude might be used as an indication of attitude as no plasma species will occur at the expected temperatures. Nonetheless this device is flown to qualify it for later use and to validate the setup for a sensor which fits inside a TO-5 package that looks at the stagnation point of the capsule.

3.1.2 Communication

The only available transceiver that fits within the given volume is the *Iridium 9603* transceiver, which offers only a short burst data transmission mode. A link to the Iridium satellite constellation needs to be established first, then a data package of 340 bytes will be transmitted and the link is closed. This process needs to be repeated for each data package. The electronic design allows for a transmission of one message every 5 s hence a maximum data rate of 68 byte/s can be reached, however tests under clear sky and ideal conditions revealed an average data rate of 23 byte/s. If all sensors would be treated equally an overall sampling rate of 1.2 Hz will be achieved. The small size of the capsule makes it mandatory to use a heat shield material, which is able to allow the passing of electromagnetic waves to allow for communication. The **W**ound **Hi**ghly **P**orous **Ox**ide Ceramic Matrix Composite (WHIPOX) material developed by German Aerospace Center (DLR) is a suitable candidate especially for the heat loads of the envisioned re-entry mission. A thin shell with an overall thickness of 2 mm is used.

A tracking beacon emitting a signal pulse every 2 s is specifically implemented for the MIRKA2-RX mission to allow for a near range tracking within approximately 250 m, improving the chances of successful recovery. An autonomous energy system allows for continuous operation of over 7 days. The beacon is triggered by either getting electrically separated from the PCB during impact or when the voltage of the capsule drops below a certain threshold that indicates that the mission is fulfilled.

3.1.3 Electronics

The electronic system consists of two custom made printed circuit boards [8]. Three Atmega 328 P microcontrollers are used to connect to and communicate with all the aforementioned components. The triple system is used to provide the required amount of pins and to add some resilience to the system as two microcontrollers together are able to reset a faulty detected third microcontroller. An elaborate description of the implemented electronic system and its components can be found in [8]. The same microcontroller is used on the Arduino Nano evaluation board, which was used to develop and test subsystems of the capsule electronics.

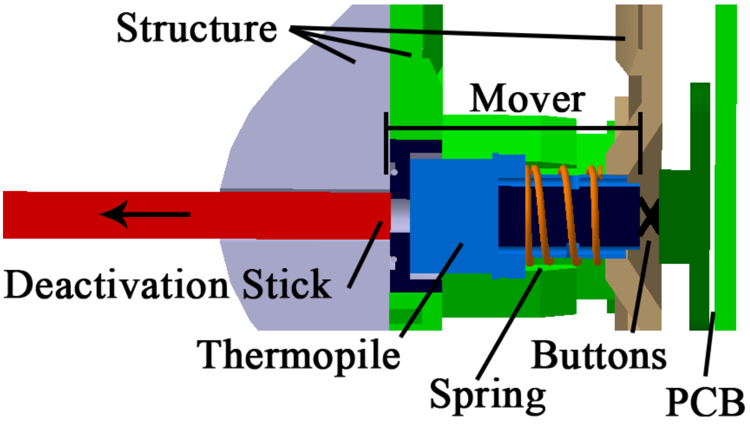

Figure 5. Activation mechanism

The system is powered by three LM17130 lithium-manganese dioxide primary batteries. These are lined up in a serial circuit to reach a nominal voltage of 9 V, with a capacity of 0.5 Ah and allow for a maximum continuous current of 0.3 A. The system is designed to be nominally operative for 26 minutes, depending on the ambient temperature with all components operating at full power. The main consumer is the Iridium transceiver with a consumption of 0.86 W.

3.1.4 Activation mechanism

The deactivation of the capsule before release is required as primary batteries have a strictly limited capacity and radio silence is obliged by the launcher at the launch site. A physical deactivation was chosen due to its simplicity and safety. When the deactivation stick is removed a coil spring will push the deactivation housing in the direction of the tip of the capsule and trigger the deactivation buttons. The mechanism is illustrated in Fig. 5. A deactivation stick is used to press the deactivation housing against the two used deactivation buttons *PHAP3378R*. When one of the buttons is released the electrical circuit is closed and the capsule will initiate its activation procedure. After 12 s, the Iridium transmitter is activated.

3.2 LOTUS

The low orbit technical unit separator (LOTUS) [9] is a simple and reliable CubeSat standard compliant separation device to eject the capsule out of the REXUS rocket with a defined velocity. The capsule is secured within the mechanism by clamps that keep it in position. As illustrated in Fig. 6 a pyrocutter severs the securing wire and the clamps swing open by the force of torsion springs. The carriage with the capsule is then accelerated by the force of four helical springs for a length of 19.5 mm, which will lead to a final ejection velocity of 1.6 m/s. The used guiding rails are lined with Teflon to reduce the friction of the carriage along the rails. For a more detailed characteristics and design description see [9].

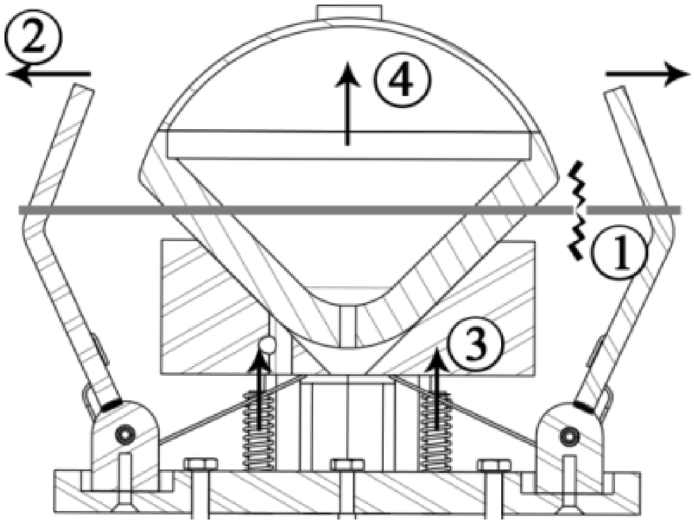

Figure 6. LOTUS schematic [9]

3.3 On-Board electronics

The remaining components of the experiment are part of the on-board system. The on-board computing unit (OCU) handles the triggering of pyrocutters and cameras. The first set of pyrocutters triggers the ejection of the module hatch, while a third pyrocutter triggers the capsule ejection mechanism. Two cameras are used to provide footage of the flight, hatch ejection, separation mechanism and capsule ejection. The cameras are a *GoPro Action Cam Hero CHDHA-301* and a *GoPro Hero 3 Silver Edition* which record high definition videos with 29 frames per second. As a live TV link was provided to the MIRKA2-RX experiment one camera provides live footage during the flight. A mirror system of the capsule electronics was implemented into the payload module to provide a backup qualification opportunity of the electronic components and produce reference data. The Iridium transmitter was replaced by an emulator and the data that should be transmitted was stored to an SD card, which will be recovered with the rocket module. For more details on the design of the on-board system see [6] and [7].

4 EXECUTION

The launch occurred on the 18th of March 2016 at 05:10 UTC with a local temperature of -16 °C under clear sky at the Esrange space center from the Multi-Range Launcher ramp commonly used for REXUS rockets. After 80 s the ejection of the hatch was recorded as well as the despinning of the rocket after 94 s. The capsule was ejected 126 s after the launch. A video is available from two different perspectives [10] [11]. The rocket reached its apogee at 136 s at an altitude of 78.221 km and touched ground after approximately 850 s.

The capsule transmitted no data during the flight. After 630 s the first data package of the capsule was transmitted, part of the first data package was the GPS location of the landing site at *68°13'04.2"N; 20°51'44.2"E* with an approximate distance of 32 km to the launch site. The capsule kept transmitting data for 29 m and 23 s, when the last data package was received. With the GPS lock the recovery helicopter was launched and the crew recovered the capsule from a snowfield in approximate depth of 0.4 m.

Table 2: MIRKA2-RX events

Event	**t [s]**
Launch	0
Engine Burnout	26
Hatch Eject	80
Despin	94
Motor separation	95
Capsule Eject	126
Rocket Apogee	136
First capsule data	630
Rocket touchdown	850
Last capsule data	2393

5 ANALYSIS

After the delivery of the recovered capsule and experiment module an initial analysis for damages was done by disassembly of the components. No visible damages were detected on the components of the (payload) service module. Some superficial damage on the WHIPOX shell of the capsule occurred, probably from the impact of a shovel used during recovery, while the capsule was dug out of the snow. All other components appear seem intact.

5.1 Activation mechanism

The deactivation mechanism failed when the deactivation stick was withdrawn, but fortunately the mechanism triggered by inertia forces when the capsule hit the ground. Two reasons for the initial jamming were detected. First an edge connector of the PCB perforated a thermopile wire. Although this did not hinder the electrical operation of the capsule the added friction of the cable probably was beyond the force of the coil spring and thus jammed the mechanism. As this error was most probably introduced during integration, minor design changes will allow to avoid this fault in future.

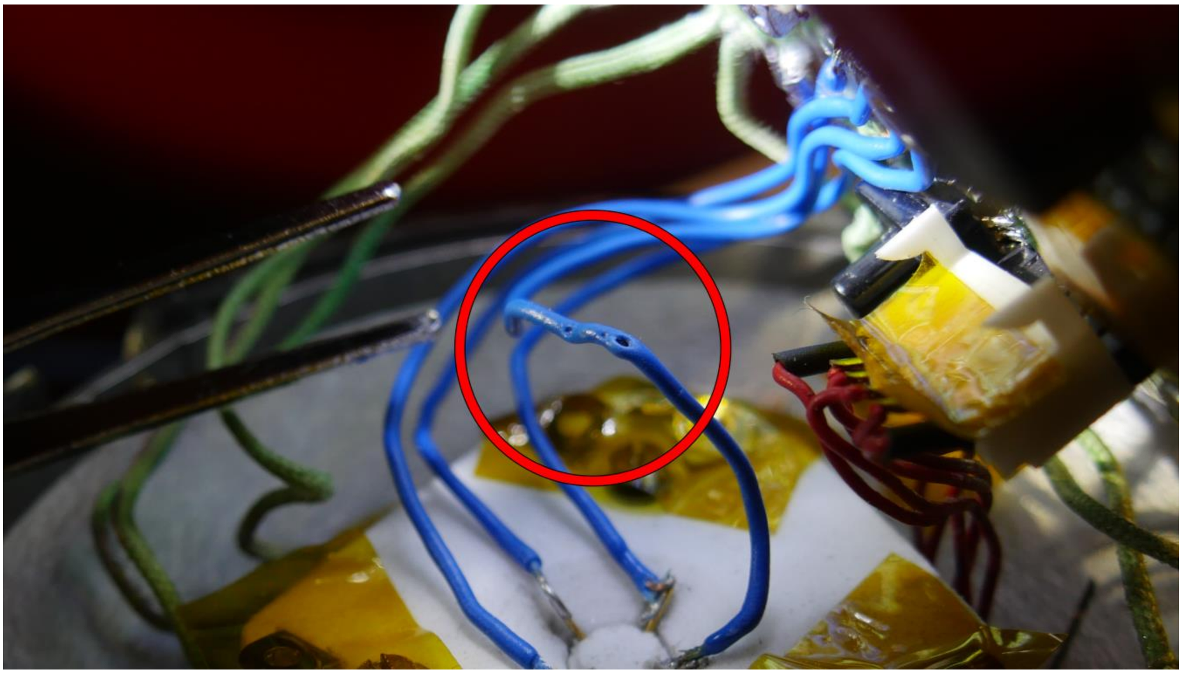

Figure 7. Punctured wire

Second most of the components of the mechanism where manufactured from 3D printed laser-sintered polyamide. The rough surfaces of these components do increase friction and might have contributed to the jamming problem. Properly milled polyamide components may reduce the likelihood of jamming of the mechanism.

5.2 Capsule Electronic System

The electronic system of the capsule performed according to specifications. The expired timer triggered properly the GPS module, which calculated a correct position although the capsule was covered by snow. Inter-component communication functioned without any detected faults. From the time stamps of the transmitted data packages, it can be inferred that the capsule was in full operation for at least 30 minutes before battery voltage was too low to transmit further. This value is 15 % more than the expected nominal operational lifetime. By considering that the transmitted internal temperature of the capsule of – 16 °C and the fact that the capsule was encompassed by snow a cold case was certainly given, which reduced the usable energy of the primary batteries. The primary battery voltage progression is given in Figure 8. It can be seen that the gaps between messages events are not dependent on the voltage level of the batteries. Furthermore a remarkable resilience of the electronic system is proven, as it was able to operate over 6 minutes successfully with about 2.5 V. Even when voltage levels became erratic, the capsule continued to transmit data. Therefore the electronic system and power supply exceeded its design parameters and is considered qualified.

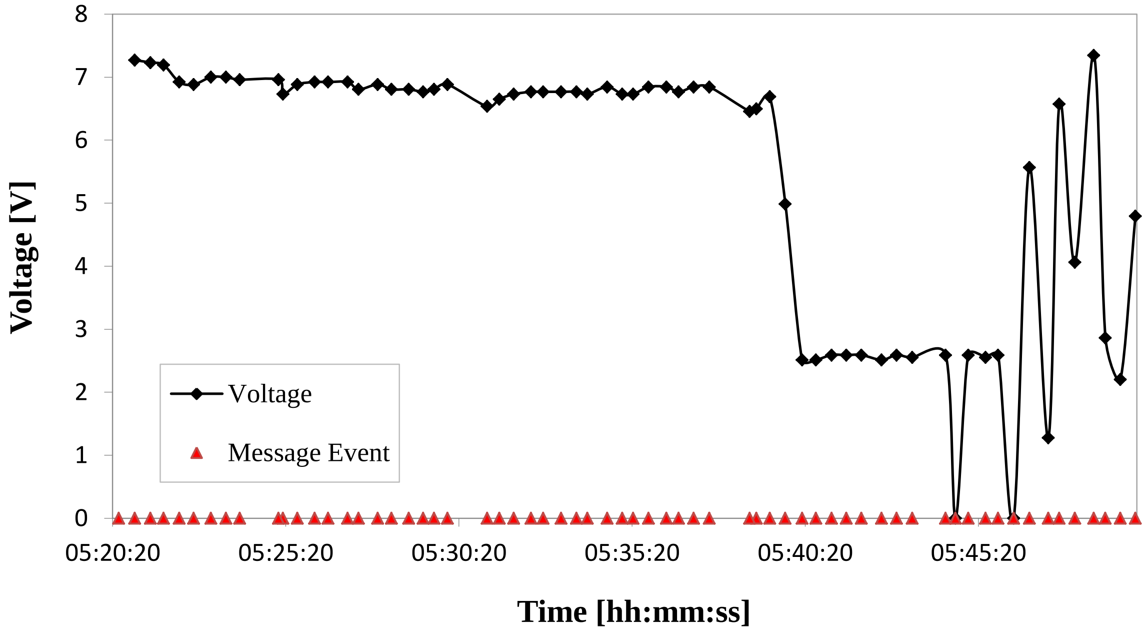

Figure 8. MIRKA2-RX Battery voltage over time - Date: 18.12.2016 - Time: UTC

5.3 Capsule Communication

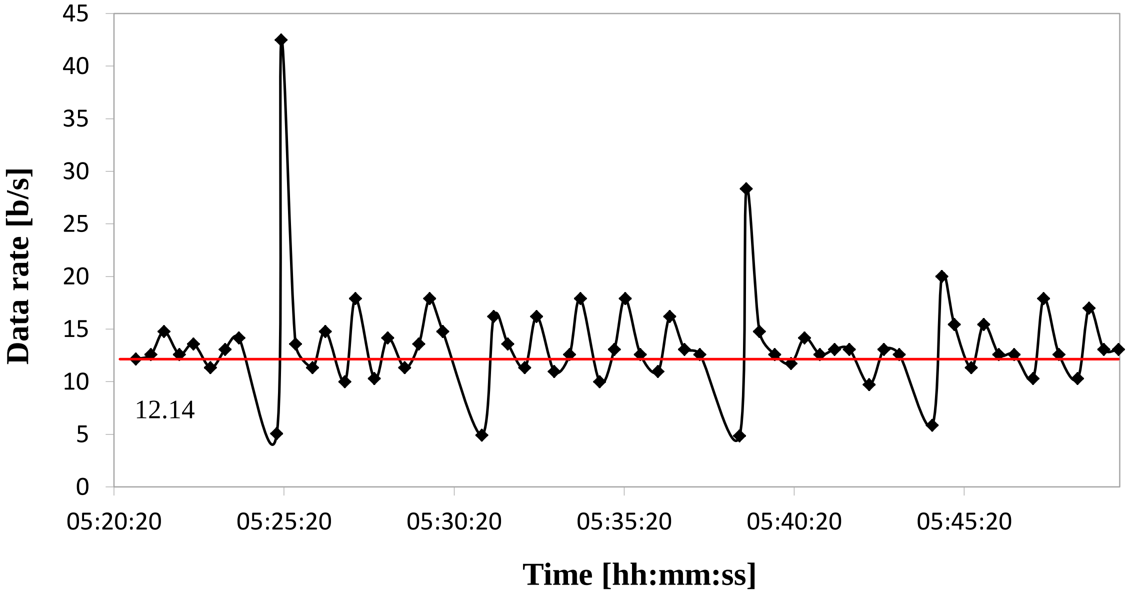

Figure 9. Iridium 9603 burst mode data rate - Date: 18.12.2016 - Time: UTC.
Red line indicates average data rate.

The Iridium communication with the Iridium 9603 was able to transmit 63 messages of 340 bytes each over the course of 29 minutes and 53 seconds. Four packages were lost during the process, thus the reliability rate of the link is 94%. As the lost packages occur during relatively regular spaced intervals the satellite visibility might be the decisive factor. Because the failed packages do not occur in exactly regular intervals a software error seems unlikely. The data rate is calculated by dividing the time between two successful messages by the amount of bytes the package. Thus the average achieved data rate is 12.1 byte/s, due to the short burst mode the data rate has a range of maximally 42.5 byte/s and minimally 4.8 byte/s. The variation of the data rate is shown in Fig. 9. The four obvious drops in data rate are caused by lost packages.

Additionally the time between successive messages are given in Fig. 10. The average time between two messages is 28 seconds, with a minimum of 8 seconds and a maximum of 68 seconds due to lost data packages. The data rate of 12.1 byte/s lacks behind the expectation of 23 byte/s and might be caused by the signal dampening of the covering snow layer leading to longer duration of link establishment for each short burst message. This data rate is a strong indicator for the creation of prioritization tables for later missions, where only the most relevant data can be transmitted. Nonetheless it was shown that the capsule is able to transmit data via Iridium link after sustaining launch loads, descent and impact.

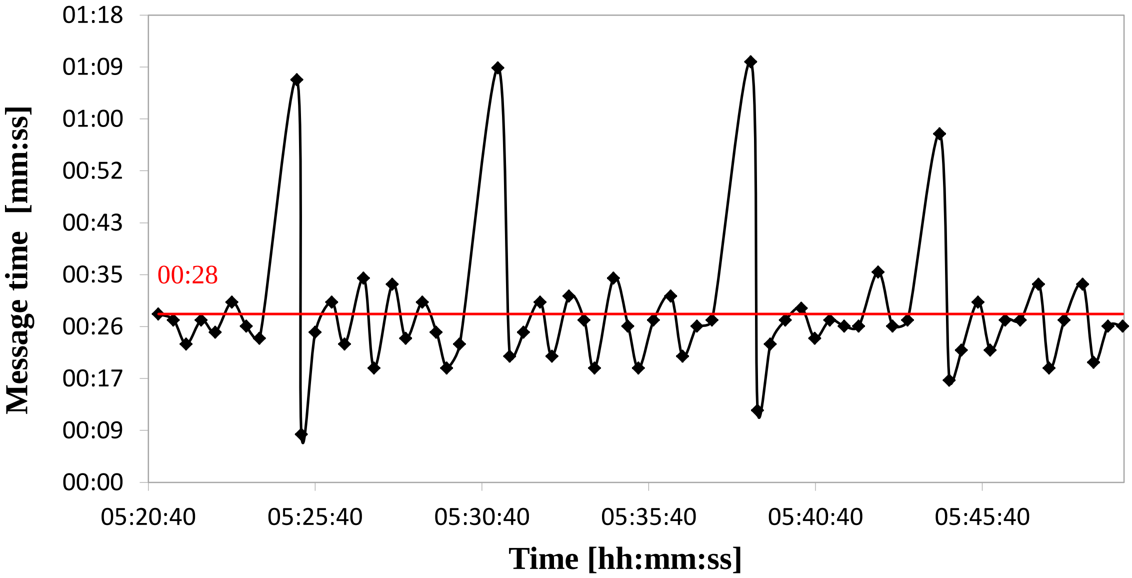

Figure 10. *Iridium 9603 time between messages - Date: 18.12.2016 - Time: UTC. Red line indicates average data rate.*

5.4 Capsule Trajectory

From the taken video footage trough the hatch a spin rate of the rocket module of 0.0674 Hz was calculated by taking the time interval between two successive sun glare events. Ground station tracking data showed the eject took place at Longitude 20.9821°; Latitude 68.0928° and an altitude of 77.744 km and a velocity of 219.8 m/s (198.34 m/s horizontally and 94.74 m/s vertically. Other initial conditions like the ejection vector require further studies of the available data as the integration of spin rates is error-prone and thus not produce reliable values. A spin rate of 48 °/s around the pitch axis of the capsule was detected from analyzing available videos [10] [11] indicating a stable first flight phase.

A small circular impact crater in the snow field indicated a stable late flight phase. This hypotheses is further supported by the upright position of the capsule in the snow as seen in Fig. 11.

Further indication is given by the IMU data of the capsule, from the available quaternion a small misalignment to a vertical axis of 2.8 ° was calculated. Therefore it can be concluded that the shape and COG of the capsule allow for stable flight for at least the initial and later parts of the trajectory, while the middle part of the trajectory remains unknown.

Figure 11. Capsule recovery: crater (left), dug out (right)

5.5 LOTUS performance

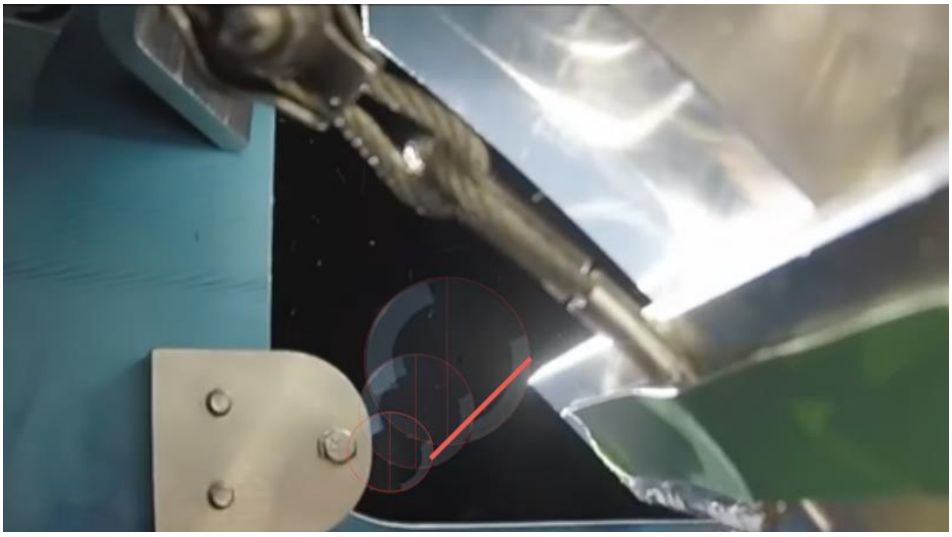

Figure 12. Capsule ejection super imposed image [10]

The Low Orbit Technical Unit Separator did function properly and ejected the capsule with a defined velocity. An analysis of the available videos [10][11] and Fig. 12 leads to the conclusion that an ejection velocity of 0.775 m/s was reached - lower than the expected ejection velocity of 1.6

m/s [9]. Nonetheless LOTUS is qualified to serve as a simple and reliable CubeSat separation device.

5.6 Electronic Mirror System

The electronic mirror system functioned properly within the design parameters and the emulated Iridium messages were properly written to an SD card. The trajectory data of the mirror system is used to extract initial conditions for the trajectory of the capsule. In Figure 13 the recorded roll rates of the IMU of the electronic mirror system are shown in red and compared to the roll rates given by the on-board gyrometer of REXUS19. It is shown that the IMU functions properly. The lower sampling frequency might lead to some aliasing effects, which might explain some discrepancies.

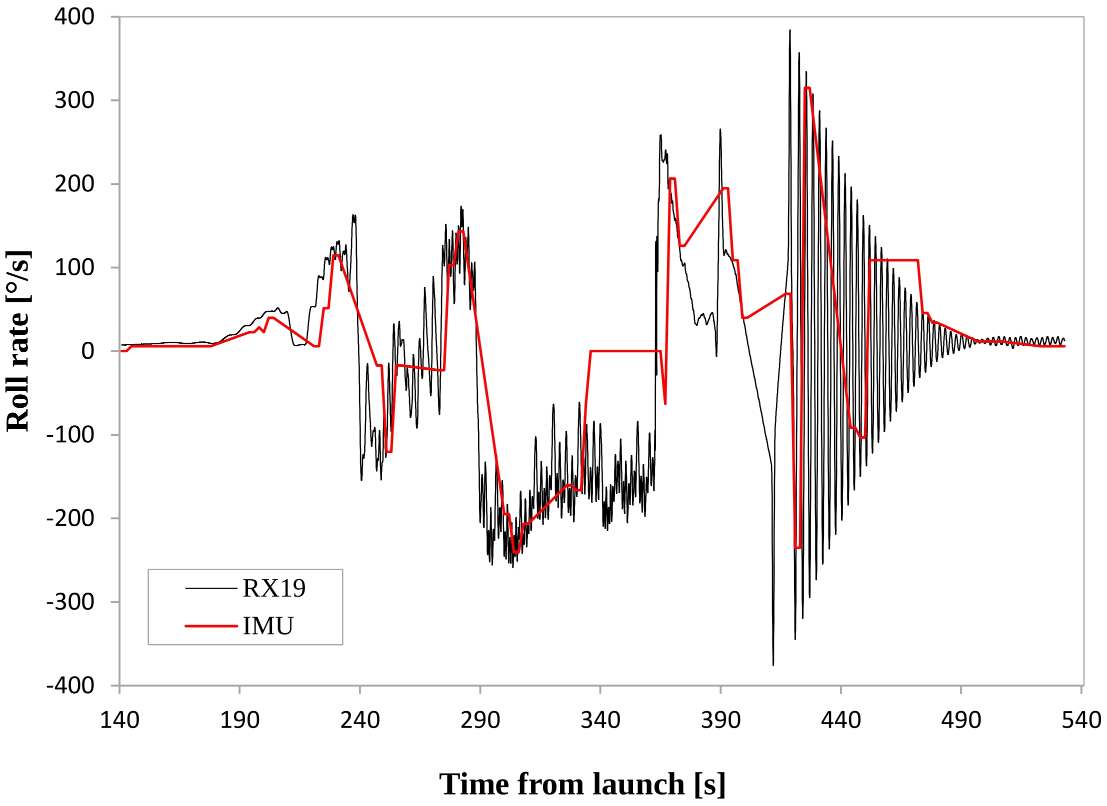

Figure 13. MIRKA2-RX mirror system IMU rollrate comparion with REXUS19

5.7 OCU Performance

The on-board computing unit functioned properly. The data fluxes of the cameras were properly saved to SD cards. The pyrocutters were triggered on time to eject hatch and capsule. The mirror electronic system was properly managed.

5.8 Preliminary Analysis Conclusion

This initial analysis and the executed mission can be summarized to as a great success. The primary goals were achieved as the electronic system of the capsule, the Iridium communication link establishment and separation mechanisms were qualified. Furthermore the secondary goal of capsule recovery was achieved and several unknown parameters were successfully quantified. The in-flight stability and communication link of the capsule will be subject of further investigation.

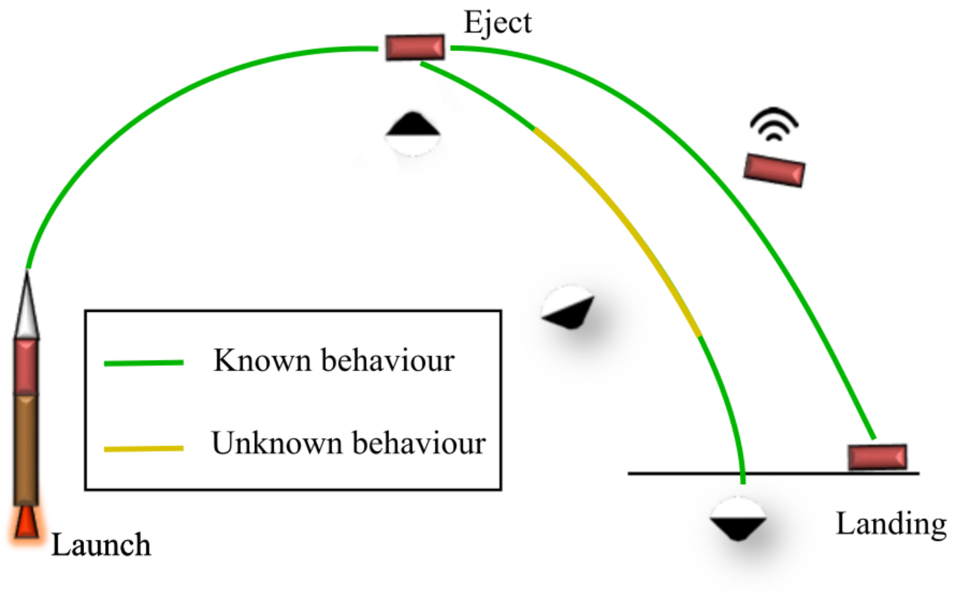

Figure 14. Behavior Knowledge overview

6 OUTLOOK

In the near future two project tasks are planned. First the analysis and recalculation of the trajectory of the capsule using the Institute of Space Systems in-house 6DOF re-entry code REENT [12]. Secondly for the CAPE mission a hot case experiment is required. A mockup capsule will be tested at IRS plasma wind tunnel facilities to estimate the bearable heat loads and heat fluxes that will render the capsule electronics operative. To investigate the in-flight behavior and qualify the communication link during flight, another experiment on a smaller sounding rocket or a balloon is envisioned, with a simplified capsule being dropped. In mid-term, the current design will be reiterated to increase the usability and increase the performance of certain subsystems. On the long term, the CubeSat mission CAPE is planned to be performed, where the results of this mission will be utilized.

7 ACKNOWLEDGMENTS

This experiment was made possible by the Swedish National Space Board and the German Aerospace Center (DLR) within the scope of the REXUS program. The development and design process as well as the qualification was strongly supported by the personnel of the Institute of Space Systems (IRS) of the University Stuttgart and Thales Alenia Germany. Several key components were made available by the following supporters: DLR Cologne – WHIPOX cap, DLR Stuttgart – heat shield dummy, NamTrack – Tracking beacon, Multiband Antennas – Iridium Components, Laser Components – Thermopile. Additional testing and qualification of the capsule design was made possible by Institute of Fluid Mechanics and Hydraulic Machinery (IHS) of the University of Stuttgart and Albert Wager Bauunternehmung GmbH & Co. The printed circuit board layout design was made possible by Eagle licenses provided by CadSoft.

8 REFERENCES

[1] Pagan A. S., et al. *CubeSat Atmospheric Probe for Education (CAPE)*, 10th IAA Symposium on Small Satellitees for Earth Obervation, Berlin, 2015

[2] Schöneich V., et al. *Service and Deorbit Module for CubeSat Applications*, 10th IAA Symposium on Small Satellitees for Earth Obervation, Berlin, 2015

[3] Ehresmann M., et al. *CubeSat-sized Re-entry Capsule MIRKA2*, 10th IAA Symposium on Small Satellitees for Earth Obervation, Berlin, 2015

[4] Feistel A. S., et al. *Comparison of Reentry Breakup Measurements for Three Atmospheric Reentries*, 6th IAASS Conference: Safety is Not an Option, Montreal, 2013

[5] Mawn S., Schmidt A., *REXUS User Manual*, ZARM, University of Bremen, Bremen, 2014

[6] Wizemann, S., et al. *Micro-Reentry-Capsule-2 REXUS*, 1st Symposium on Space Educational Activities, Padua, 2015– Setup detailed infos

[7] Galla D., et al. *Student Experiment Documentation MIRKA2-RX*, Institute of Space Systems University of Stuttgart, Stuttgart, 2016

[8] Koller M. T., *DEVELOPMENT OF THE ELECTRONIC SYSTEM FOR THE MRIKA2 MICRO RETURN CAPSULE*, bachelor thesis IRS-15-S077, Institute of Space Systems University of Stuttgart, Stuttgart, 2015

[9] Siedorf M., DESIGN, CONSTRUCTION AND TEST OF THE LOW ORBIT TECHNICAL UNIT SEPRARATOR LOTUS, bachelor thesis IRS-14-S014, Institute of Space Systems University of Stuttgart, Stuttgart, 2016

[10] KSat e.V., MIRKA2-RX Capsule Ejection 1. Video, 2016, Link: https://www.youtube.com/watch?v=V7-P_HCwBiw

[11] KSat e.V., MIRKA2-RX Capsule Ejection 2. Video, 2016, Link: https://www.youtube.com/watch?v=idRL7uG6_LU

[12] Burkhardt J. REENT 6D – a Simulation and Optimization Tool for Re-entry Missions, Internal Report, IRS 00-IB07, Institute of Space Systems University of Stuttgart, Stuttgart, 2006

[13] Göring J., Hackemann S., Kanka B., *WHIPOX®: Ein faserverstärkter oxidkeramischer Werkstoff für Hochtemperatur-Langzeitanwendunge*n, Mat.-wiss. u. Werkstofftechnick 28 , 2007, doi:10.1002/mawe.200700191