REXUS 24 FAILURE INVESTIGATION

Stefan Völk[1], Mikael Viertotak[3], Stefan Krämer[4], Simon Mawn[5], and Katharina Schüttauf[2]

[1]*German Aerospace Center (DLR), Space Operations and Astronaut Training, Mobile Rocket Base (MORABA), Oberpfaffenhofen, 82234 Weßling, Germany, Stefan.Voelk@dlr.de, Tel. +49-8153-28-3382*
[2]*German Aerospace Center (DLR), Space Operations and Astronaut Training, Mobile Rocket Base (MORABA), Oberpfaffenhofen, 82234 Weßling, Germany, Katharina.Schuettauf@dlr.de, Tel. +49-8153-28-2617*
[3]*Swedish Space Corporation (SSC), Science Services division, Esrange Space Center, P.O. Box 802, SE-981 28 Kiruna, Sweden, Mikael.Viertotak@sscspace.com, Tel. +46-980-72063*
[4]*Swedish Space Corporation (SSC), Science Services division, P.O. Box 4207, SE-171 04 Solna, Sweden, Stefan.Kramer@sscspace.com, Tel. +46-8-627-62-44*
[5]*Center of Applied Space Technology and Microgravity (ZARM), Universität Bremen, Am Fallturm 2, 28359 Bremen, Germany, Simon.Mawn@zarm.uni-bremen.de, Tel. +49-421-218-57758*

ABSTRACT

On Monday, March 12 at 14:30 UTC, 2018, the sounding rocket REXUS 24 was launched from Esrange Space Center. After T+$8.9\,\mathrm{s}$, the payload separated unintentionally from the motor. The payload impacted $2\,\mathrm{km}$ north east of the launcher. The thrusting motor continued to fly down range. All objects were contained within safe areas, causing no damage on human beings or property.

The methodical approach of the conducted failure investigation is introduced and the most probable failure cause is identified. A summary of performed studies is given and it is described how the most probable failure cause was deduced. Finally, recommendations and restrictions referring technical and procedural aspects are covered which are planned to be applied in future campaigns.

Key words: failure investigation; sounding rocket; REXUS.

Figure 1: REXUS 24 vehicle configuration. From [2].

1. INTRODUCTION

After the launch of REXUS 24, it was unclear if the failure was caused by a non-nominal performance of the used standard systems or by one of the experiments. Therefore, and until the root cause was found, the failure entailed a grounding of further REXUS rockets such as REXUS 23 which should have launched within the same campaign. The failure investigation followed an approach which is known as root cause analysis and which is widely used in many science and engineering disciplines [1]. Unlike treating symptoms, an effective problem solving process focuses on uncovering and removing the failure's root cause. If it is not properly corrected, the same problem may reappear or even spread to other areas. From an organizational point of view, an open failure culture is desirable, so that failures can be discussed openly and generate knowledge.

2. REXUS 24 VEHICLE

The vehicle configuration for the REXUS 24 mission is shown in Fig. 1. For the REXUS program, the unguided solid propellant single stage Improved Orion motor from military surplus is used. Technically, the motor assembly comprises the actual Improved Orion rocket motor, the tail can, three fins, the launch lug and the motor adapter including the yo-yo despin system and the manacle ring. Forward of the motor assembly, there are attached the payload support systems, namely the Recovery Module and the Service Module (SM). Above these systems, there were arranged the modules of the experiments MORE, ROACH and WOLF. The two experiments PIOneERS and BlackBox were directly located under the nosecone.

3. METHODICAL APPROACH

Immediately after the failed launch of REXUS 24, Esrange Space Center and DLR MORABA established a Failure Investigation Board (FIB) with members from SSC, MORABA and ZARM. The main objectives of the FIB were:

- Leading the failure analysis process
- Reporting to agencies
- Reporting to third parties
- Interface to experts
- Management of resources
- Preparing failure report
- Deducing of lessons learned and recommendations

The failure investigation was structured into several *topics* and *task forces*. *Topics* group vehicle systems or properties whereas *task forces* are working groups for specific methods and tasks of the investigation. The participants of the working groups involved FIB members and experts from SSC, ZARM and DLR. For each topic and task force, one representative was assigned. This structure provided a clear baseline and clear responsibilities throughout the investigation which ultimately conveyed its successful outcome.

3.1. Topics

For the REXUS 24 investigation, following topics have been identified:

- *Scientific Payload*: This topic included the recovery and investigation of the REXUS 24 payload. Moreover, interviews with the experiment teams have been prepared and conducted.
- *Motor*: A focus of this topic was the search for the rocket motor which separated from the payload during flight and could not localized. Regardless of being able to examine the physical hardware, possible failure scenarios of the rocket motor were studied and qualitatively assessed using existing flight data.
- *Rocket Systems*: This topic comprised the investigation of the Service Module, the Recovery System and the Separation System.
- *Vehicle Dynamics*: This topic focused on analyses of the dynamic behavior of the rocket vehicle.

3.2. Task forces

In the beginning of the investigation, securing of available data was most relevant. For REXUS 24, two task forces have been established reflecting the importance of this effort:

- *Data*: This involved the maintenance and security of the data repository of the failure investigation across the participating organizations.
- *Media*: Plenty of image, video and audio footage was recorded both, from inside the scientific payload and from outside during launch. Furthermore, the rocket launch was visually observed by many participants of the REXUS program. Main tasks were the collection, the ordering and the synchronization of the manifold and diverse sources.

Timeline A common method of root cause analyses is the composition of a timeline including both, nominal and non-nominal events. A major work related to the timeline became the synchronization of the various data sources. This was necessary since it was critical to determine the correct sequence of events recorded by different systems. In particular around $T+3.6\,\mathrm{s}$, several events relevant for this investigation occurred within a short time interval. In order to be able to determine which event occurred before the other, an accuracy of around $20\,\mathrm{ms}$ was required. For this investigation, a *Corrected Timeline (CTL)* was introduced which defined $T+0\,\mathrm{s}$ as the moment of the first detected motion of the vehicle (lift-off) and which achieved the required accuracy across the different data sources.

Failure Tree A failure tree was used as a method for deductive top-down failure analysis. Beginning with the top-event (premature payload impact), various failure branches and nodes are determined. For each node, the likelihood of occurrence is qualitatively assessed. Typically, an increasing number of branches are developed towards the bottom of the failure tree. Finally, nodes are determined which cannot be further broken down. This leads to the (multiple) root cause(s).

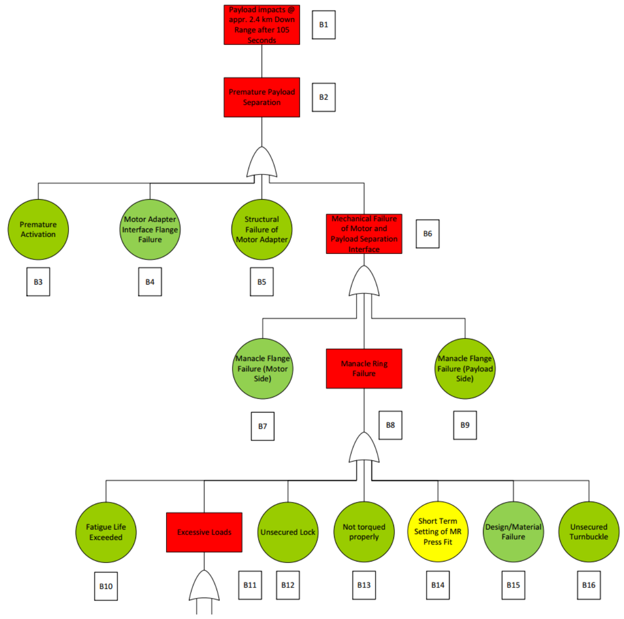

Figure 2: Upper part of the developed failure tree for REXUS 24. Circles denote nodes which cannot broken down any further. Rectangles denote nodes with sub-branches which are linked to the parent element with a logical *OR*. The colors have following meanings:

Green: Did NOT occur

Red: Occurred

Yellow: Cannot be excluded

4. FINDINGS

Out from the defined topics and task forces, several findings have been identified which have been considered as most relevant for this investigation. In the following, these findings are presented and discussed.

4.1. Media

The media footage taken from inside the rocket payload as well as from outside during launch have been analyzed. The two video cameras of experiment ROACH detected a noticeable "bang" sound and a visible mechanical shock around T+3.56 s (CTL). From this time onwards, the sound changed to a whistling noise and repeating light reflections were visible in the compartment as shown in Fig. 3. At T+6.20 s, a second small "bang" and mechanical shock was detected by these cameras and from T+6.741 s onwards, a repeating red light reflection was seen in the compartment. Around T+8.8 s, a large shock and "bang" occurred. Subsequently, the amount of light flooding the module increased significantly, debris and damages were visible in the ROACH compartment.

An analysis of a video taken from the Radar hill – approximately at a distance of 2.4 km from the launch site

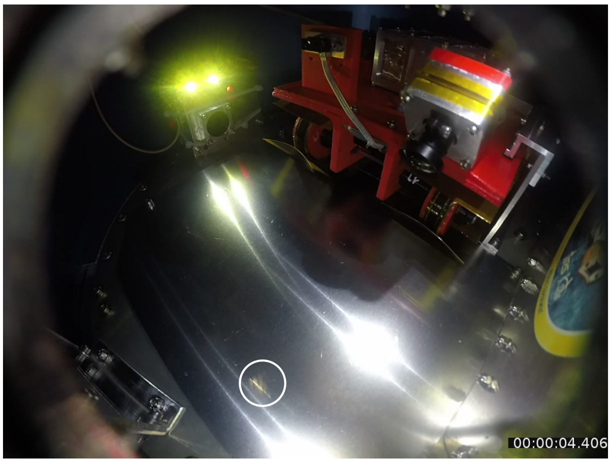

Figure 3: ROACH payload video. T+4.406 s. Frame showing bright light reflection pattern indicated by the white circle.

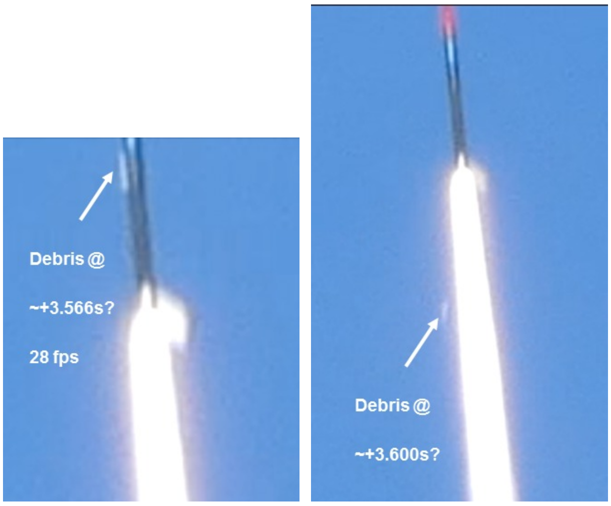

Figure 4: Magnified video frames taken from Radar hill (Team ROACH). Arrows indicate observed debris. The accuracy of the given times is limited by the video frame rate (30 FPS).

– revealed an object falling next to the rocket vehicle around T+3.6 s (see Fig. 4). This event occurred at that time when the first "bang" and mechanical shock in the experiment module ROACH were recorded.

4.2. Scientific Payload

Several findings associated with the FFU retention / ejection mechanism of experiment WOLF have been observed. For a further study, it is important to understand the design of the ejection mechanism. As shown in Fig. 5, two Free Falling Units (FFUs) were planned to be ejected in radial directions. In order to benefit most from the available space, the two FFUs are accommodated on top of each other. The ejection system relies on both, the centrifugal forces of the spinning rocket vehicle and

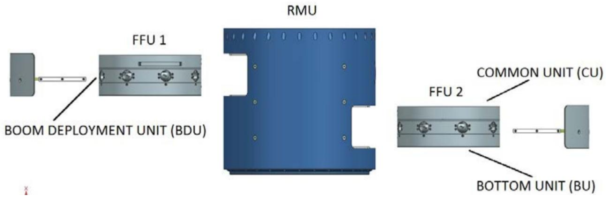

Figure 5: Side view of WOLF module with FFUs and hatches. From [3].

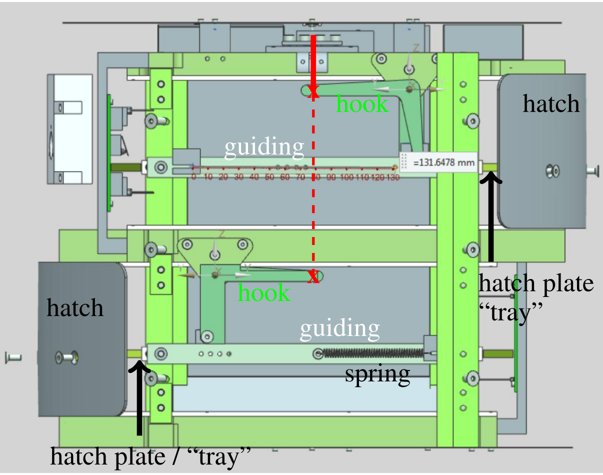

Figure 6: WOLF ejection system. The cable of the upper ejection mechanism is indicated by a red thick line, whereas the cable of the lower ejection mechanism is indicated by a dashed red line. The mounting positions of the tensioning cables at the hooks are marked with **x**. Adapted from [3].

the spring-energized pusher plates which are tensioned during assembly and released at the pre-programmed time. The module openings are covered with hatches which are designed to be flush with the outer structure.

Part of the ejection mechanism displayed in Fig. 6 are the pairs of hooks which prevent the hatches to move. The hooks are restrained by 1 mm thick steel cables that are cut for ejection by a pyrotechnical cable cutter triggered by the REXUS SM. The cables are fed through small holes at the lever arms of the hooks (marked by red crosses in Fig. 6). The cable ends at the hooks are prepared as loops around a nut in order to provide a stop in case of slipping. The loops are crimped according to a procedure [3, 4]. Moreover, the cable ends are attached to the hooks with zip ties through the nuts as depicted in Fig. 8. The cables are bent 90 deg between the hook and the crimp. The other ends of the cables are fed through the cable cutter and are clamped on a plate in the upper part of the module.

Upon recovery of the payload, the two hatches and FFUs of the WOLF module were seen to be missing. Marks, scratches and damages around the openings and inside the module suggested a non-nominal ejection with

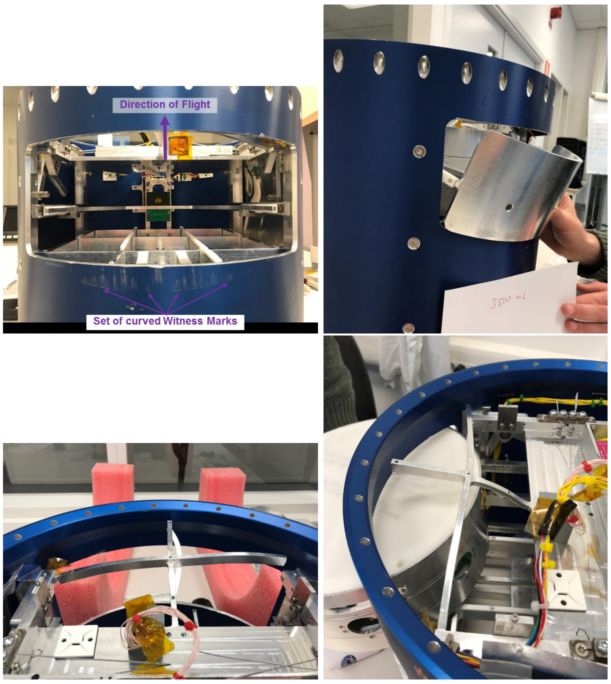

Figure 7: Post-flight investigation of WOLF experiment module. Witness marks and reconstructed positions of hatch and FFU.

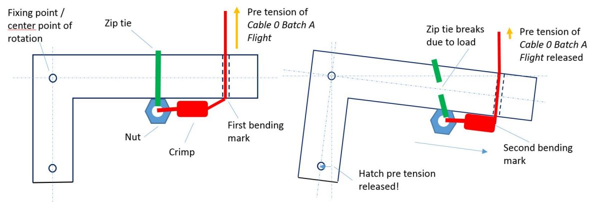

Figure 8: Sketch of possible slipping scenario of crimp on hook.

an external force pressing the upper hatch against the lower rim of the FFU bay. The possible positions of the hatch and of the FFU before their detachments could be reproduced with the recovered module and spare hardware of hatch and FFU as shown in Fig. 7.

A drop in WOLF power consumption indicates that the power umbilical of at least one FFU unit was disconnected around T+3.7 s. The assumption of a non-nominal and premature opening of a hatch is also supported by the repeating light reflections and audio changes recorded in module ROACH – the module mounted directly below WOLF – and by the video recordings from ground as shown in Fig. 4.

The failure investigation found that one of the cable crimps of the upper hatch was missing. It was determined that this probably led to the release of the hatch tray assembly. It was also demonstrated that a slipping of the cable end compromises the pre-tension of the hook as depicted in Fig. 8. After the payload was recovered, one zip tie (lower hatch), which was intended to hold the cable end in place, was found broken in the module.

4.3. Motor

Valuable information had been expected from an inspection of the rocket motor. Therefore, several approaches have been pursued to localize the motor hardware. These involved impact analyses based on flight data available until payload separation, $14\,\mathrm{h}$ of helicopter search within the impact area, airborne surveys by the Swedish Coast Guard, requests to facilities operating surveillance radars and a search campaign with the satellites TerraSAR-X and TanDEM-X which are instrumented with phased array Synthetic Aperture Radar (SAR). Furthermore, the tracking data and video footage of both telemetry stations being operational during the REXUS 24 launch have been analyzed and a reconstruction of the motor trajectory after payload separation have been performed. Unfortunately, none of these efforts resulted in the localization of the rocket motor.

Despite not being able to examine the motor hardware, the video footage of the telemetry station operated by MORABA provided relevant indications of the nominal functioning of the Improved Orion motor. By analyzing the evolution of the exhaust plume and comparing it to previous REXUS launches, a time range of the motor burnout was determined. Both, the minimum and maximum time boundaries are within the nominal performance range. Therefore, a burn through of the rocket motor could be excluded.

4.4. Vehicle dynamics

The most noticeable anomalies seen in the flight data were a discontinuity and steep increase of the roll rate at T+$3.6\,\mathrm{s}$ as shown in Fig. 9. At the same time, pronounced spikes in the lateral rates have been detected. The time resolution of the SM data is limited to $50\,\mathrm{ms}$.

Supporting Computational Fluid Dynamics (CFD) Euler analyses have been carried out by the DLR Institute of Aerodynamics and Flow Technology. Three different vehicle configurations and various inclination angles have been studied: clean (nominal) configuration, configuration with removed hatch and configuration with partially opened hatch. Subsequently, the computed forces and torques have been compared. However, none of the studied configurations could explain the observed discontinuities around T+$3.6\,\mathrm{s}$.

The investigation showed that a significant change in aerodynamic properties of the vehicle can be the cause

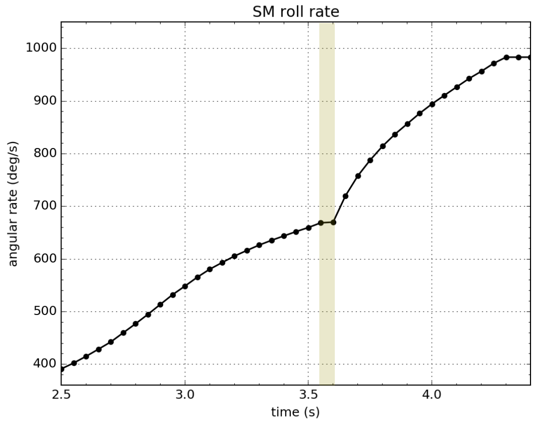

Figure 9: Roll rate measured by SM. Within the highlighted time interval (T+$3.55\,\mathrm{s}$ - T+$3.60\,\mathrm{s}$) which cannot further resolved by SM data, the slope of the roll rate changes significantly.

of the steep increase in the roll rate (Fig. 9) and the changes in the lateral rates. The measured roll rate could be reproduced in a simulation by assuming that the net fin incidence angle of all fins is increased by $0.1\,\mathrm{deg}$ from T+$3.6\,\mathrm{s}$ onwards. A mechanism was reproduced that appears to be able to cause such change: the impact of a hatch on one of the Improved Orion fins.

In the framework of the failure investigation, impact tests were performed together with the DLR Institute of Structures and Design. Improved Orion fin structures were used as target and reconstructed hatch assemblies from the WOLF experiment setup were used as impactors. The overall aim of the test series was to evaluate potential effects of such impact. Although these tests did not provide a conclusive proof for an impact, it can be showed that such impacts cause serious (local) damages which lead to geometry changes of the fin. A detailed review of the test results is presented in [5].

The WOLF experiment carried its own Inertial Measurement Unit (IMU) recording acceleration and angular rates [6]. Apart from the measured roll rate and partly due to the mounting of this sensor, the IMU data cannot compared quantitatively to the corresponding SM data. However, since the time resolution of this data is much higher ($1\,\mathrm{ms}$) than for SM data, this makes it highly attractive for qualitative assessments for possible events below the $50\,\mathrm{ms}$ limit. Within the two data points recorded by the SM at T+$3.55\,\mathrm{s}$ and T+$3.60\,\mathrm{s}$, the WOLF IMU measured two impulses with an oscillating pattern which is observed in the acceleration along roll axis plotted in Fig. 10 and also in the lateral angular rates.

The assumption of an impact is supported by the two impulses recorded by the WOLF IMU. The first impulse around T+$3.55\,\mathrm{s}$ is possibly associated to the detachment

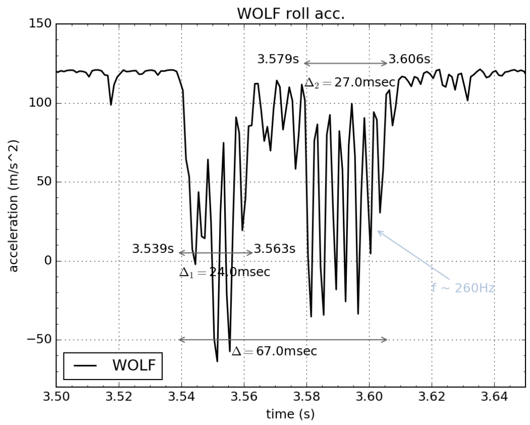

Figure 10: Acceleration along roll axis measured by WOLF IMU.

of one of the hatches whereas the second impulse at T+3.59 s is possibly caused by an impact of the hatch on one of the fins. The derived event times are in line with the evaluated times of the video analysis presented in Fig. 4. Furthermore, a graphical analysis of the roll rate slopes before T+3.55 s and after T+3.60 s independently led to an event time which coincides with the second impulse measured by the WOLF IMU and which is interpreted as the impact of the hatch on one of the fins. Furthermore, these times are in agreement with the computed duration for a hatch transit between payload compartment and fin leading edge.

Furthermore, two discrete reductions of acceleration along roll axis (longitudinal direction) have been recorded by the SM at T+5.5 s and T+6.2 s which are possibly linked to an incremental overhanging of one of the FFUs. This is supported by changes recorded in the video footage of experiment ROACH at the latter time, the found damage pattern within the WOLF compartment and further pictures taken from outside which show an overhanging object next to the payload at times $\geq T + 6.5$ s. Therefore, it is believed that the assumed impact is associated to the hatch and not to the FFU.

5. MOST PROBABLE FAILURE CAUSE

The failure investigation determined that the most probable failure cause was linked to the premature ejection of at least one FFU and the impact of its hatch on one of the fins. Ultimately, the premature ejection of the FFU was linked to a failure of the retention mechanism under flight loads. The premature opening and detachment of the hatch is supported by video footage recorded both, inside the payload and from outside. The observed changes in the vehicle dynamics were most likely caused by an impact of the hatch on one of the fins. This in turn led to an aerodynamically instable flight configuration. Finally, excessive angles of attack led to excessive loads on the manacle ring interface between the payload and the motor resulting in a premature separation.

6. RECOMMENDATIONS

Since the failure was most probably caused by an experiment module specific for REXUS 24 and no non-nominal performance of any of the standard systems could be determined, the failure does not require changes in the general design or setup of systems in the REXUS program. However, it is recommended to pay close attention on the complexity level of the experiments. The requirements must be adapted to the resources available in the program.

In case of future experiment modules with in flight-actuated hatches or FFUs, further guidelines have been elaborated. These guidelines involve technical recommendations and restrictions applied to the design of hatches and frames, the retention system including retention cables and cable ends, pyrotechnics as well as the verification process. In addition, management aspects and procedures have been revised in order to regulate late design changes and flight preparation. The updated guidelines can be found in the latest version of the REXUS User Manual [7].

7. CONCLUSION

Using well established methods of the root cause analysis such as timeline and failure tree analysis, the FIB identified the most probable failure cause of REXUS 24 which is linked to the premature ejection of at least one FFU. The failure investigation was organized in various topics and task forces, and the findings were assessed in a structured way. Beyond determining the root cause, recommendations for future experiments are outlined. The described failure investigation process together with the given recommendations might have the potential to further improve and strengthen the overall successful REXUS program.

ACKNOWLEDGMENTS

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ABBREVIATIONS

CFD	Computational Fluid Dynamics
DLR	German Aerospace Center
Esrange	European Space and Sounding Rocket Range
FFU	Free Falling Unit
FIB	Failure Investigation Board
IMU	Inertial Measurement Unit
MORABA	Mobile Rocket Base
MORE	Measuring Optoelectronics in a Rocket Experiment
PIOneERS	To measure Plasma Impedance due to n_e using an Ejectable System
REXUS	Rocket Experiments for University Students
ROACH	Robotic in-Orbit Analysis of Cover Hulls
SAR	Synthetic Aperture Radar
SM	Service Module
SSC	Swedish Space Corporation
WOLF	WObbling controL system for Free falling unit
ZARM	Center of Applied Space Technology and Microgravity

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