LAUNCH CAMPAGIN AND FLIGHT ANALYSIS OF THE DECAN AQUARIUS STUDENT ROCKET

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Abstract

For more than 27 years students and scientists of the Technische Universität (TU) Berlin are developing experimental sounding rockets within hands-on courses. These practical courses teach the knowledge in (sub-) system design, manufacturing, assembly, integration and testing (AIT) and operation of rockets. The applied processes in development, AIT and operation as well as the quality standards are related to the ones in the aerospace industry. The DECAN/AQUARIUS experimental sounding rocket project team, which is also a DGLR junior research group, works on a two-stage rocket where the upper stage is equipped with a solid fuel rocket (DECAN SHARK) and the lower stage with an environmentally friendly water engine (DECAN AQUARIUS). This paper provides an overview of the final integration, test and launch preparation activities of the DECAN AQUARIUS prior to its single stage launch in April 2022. The rockets main components and its payload will be described. Furthermore, the results of the flight of the DECAN AQUARIUS will be illustrated, including an analysis of the in-flight data of the telemetry system.

Acronyms/Abbreviations

AIT	Assembly, Integration and Test
DECAN	German CanSat Sounding Rocket (Deutsche CanSat-Höhenrakete)
ILR	Department of Aeronautics & Astronautics, TU Berlin (Institut für Luft- und Raumfahrt der TU Berlin)
MGSE	Mechanical Ground Support Equipment
SHARK	Student Hight Altitude Rocket

1. THE DECAN AQUARIUS ROCKET

1.1. Main Properties

The DECAN AQUARIUS is a hot water rocket which can be launched as a single stage system or which can be utilized as the lower stage of the two-stage DECAN student launch vehicle (the papers listed in chapter Bibliography provide additional information concerning the two-stage system). TAB 1 summarizes the characteristics of the single stage version of the DECAN AQUARIUS.
The rocket mainly consists of the hot water propulsion system in the center, two compartments housing the recovery system, the telemetry unit and the payload and a structure connecting the subsystems with one another. Four camera systems were installed in various positions on the launch vehicle for distinct reasons. For example, in-flight camera system IV (number 6 in FIG 1) monitors the release status of the recovery system for later investigation in case of a malfunction. In-flight camera system I (number 9 in FIG 1) on the other hand serves the purpose of flight trajectory monitoring.
Additionally, a launch tower and a hot water rocket release system are needed to perform a launch. FIG 1 shows the DECAN AQUARIUS integrated on the launch tower ready for lift-off.

Parameter	DECAN AQUARIUS
Take-Off Mass	95 kg
Dry Mass	65 kg
Height	2.5 m
Diameter	0.2 m
Propellant Mass	30 kg (water)
Pressure at loaded Conditions	55 bar
Temperature at loaded Conditions	270 °C
Average Thrust (measured)	3,750 N
Thrust Peak (measured)	15,000 N
Engine Runtime (measured)	3.5 s
Total Impulse (measured)	13,000 Ns

TAB 1. Main properties and dimensions of the rocket.

In preparation for the launch of the rocket and for achieving a better knowledge of the hot water rocketry and its engine in particular, the DECAN project group conducted extensive basic research. This was vital since the necessary information to evaluate the engine's characteristics was not available. After the last single stage flight of the DECAN AQUARIUS in 2017, this became additionally obvious since the measured in-flight data did not match the rough performance assessment conducted during the initial design process. This led to a malfunction of the release system causing a premature ejection of the parachutes (for more information see paper [6] from chapter Bibliography).
Thus, a test bench was built and utilized to determine the main motor characteristics. Properties such as mean thrusts, thrust peaks, engine runtimes and total impulses

were investigated for different nozzle geometries. Therefore, the expected loads introduced into the rocket were now known during the design process.
Additionally, an optimized nozzle geometry could be determined and an appropriate nozzle was applied during the launch. The measured performance data for the DECAN AQUARIUS engine and its specific nozzle are summarized in TAB 1.

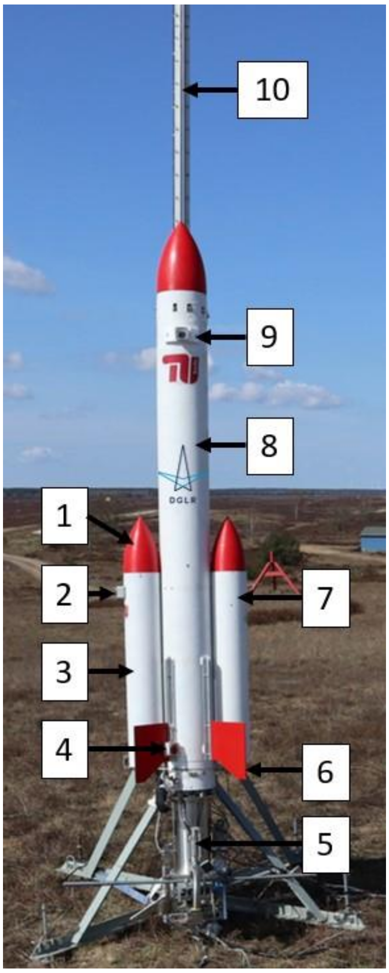

FIG 1. DECAN AQUARIUS Systems and Subsystems.

Number	Sub-/System
1	Payload
2	In-Flight Camera System III
3	Recovery Compartment incl. Parachutes
4	In-Flight Camera System II
5	Nozzle Release MGSE
6	In-Flight Camera System IV
7	Electrical Compartment incl. Telemetry Unit
8	Propulsion System
9	In-Flight Camera System I
10	Launch Tower incl. Guiding Rail

TAB 2. DECAN AQUARIUS systems and subsystems.

1.2. Payload

Since the off-the-shelf telemetry unit is the only source of in-flight data, a payload was developed to collect redundant information about the flight trajectory. Additionally, further details shall be gained, which are not tracked by the telemetry unit.
Therefore, an appropriate off-the-shelf sensor platform was chosen, which provides the payload with a 3-axis accelerometer, a gyroscope and a magnetometer. Using this unit, redundant information regarding acceleration, speed and distances can be tracked. Additionally, the attitude of the rocket and the rotation rate around all three axes can be determined.
For in-flight data processing, a standard microcontroller was selected, since they provide a high number of program libraries and development support opportunities. After the gathered information is processed by the microcontroller the data will be stored on a SD card. The entire system can be powered by a simple block battery since power usage is low and the flight time of the rocket is short. Additionally, a plug for powering the unit through a laboratory power supply is present in case long time non-flight tests need to be performed.
After the flight of the rocket the data can be inspected by using a self-developed and independent data analysis and visualization tool.
This payload can be altered and equipped with further functionalities such as GPS tracking, in-flight data downlink and a high number of sensors such as temperature sensors or pressure sensors for both the engine tank and the atmosphere. FIG 2 shows a basic schematic of the payload.

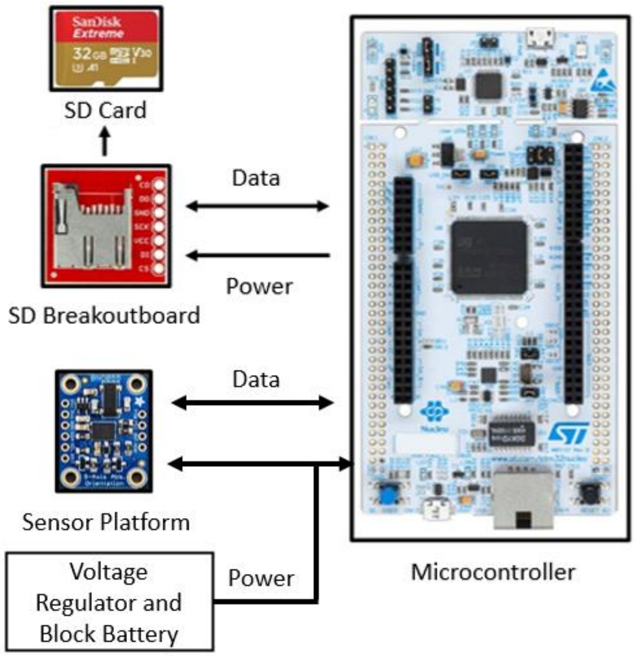

FIG 2. Payload schematic sketch.

After breadboard tests and prove of concept, two demonstration and test devices and one flight unit were built. The demonstration units serve the purpose of testing of various natures such as software tests and for sensor calibration prior to a rocket launch. FIG 3 shows one of the demonstration and test units.

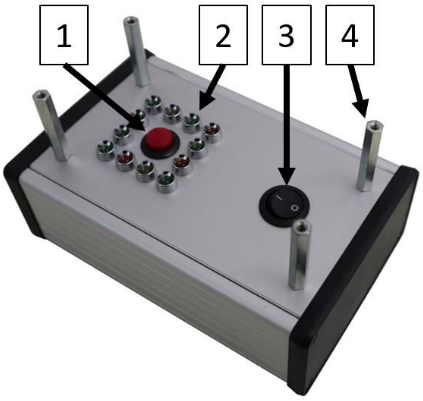

FIG 3. Payload Demonstrator.

Number	Sub-/System
1	Reset Button
2	Status LED
3	On/off Switch
4	Feet for Sensor Calibration

TAB 3. DECAN AQUARIUS systems and subsystems.

1.3. Final integration, test and launch preparation activities

Prior to the launch campaign final flight readiness test and integration processes were successfully carried out.
Among others, a hot leakage test took place including the complete set up of the launch tower and the release MGSE. Due to safety reasons, this preparatory test was performed at the launch site under application of the same safety measures as for a flight campaign.
After establishing the mechanical setup, the rocket was fueled and heated up to the launch condition (see TAB 1). The temperature and the pressure within the vessel could successfully be maintained over half an hour proving the tightness of the release MGSE and the propulsion system of the rocket. Additionally, to qualifying the operation readiness of the release MGSE and the flight readiness of the DECAN AQUARIUS propulsion system, this test did also qualify the operations and procedures for setting up the complete launch setup.
Since hot water rockets require relatively high temperatures, the thermal stresses on the hardware are significant. To be able to qualify the bolt connection of the fin assembly to the rocket structure, two possible designs were tested under lifelike conditions during the hot leakage test. This was done by installing them to the rocket in accordance with the integration procedure. Subsequently, the two connection setups were exposed to realistic thermic loads during the hot leakage test. After the test run, the two connection configurations were inspected appropriately and both were able to withstand the thermal stresses. Therefore, as the last integration step prior to the launch a flight configuration for the connection of the fin assembly to the rockets structure was chosen and installed.
The recovery system of the DECAN AQUARIUS mainly consists of a self-developed pyrotechnical actuator, a small and a large parachute, a compartment housing the chutes and a spring-loaded lid for closing the compartment. After the telemetry unit automatically recognizes the apogee of the trajectory, it triggers the pyrotechnical actuator. Thereby, the spring-loaded lid is released and pushed away from the rocket dragging the small chute into the air stream around the vessel. Subsequently, the small chute pulls out the main large one.
To qualify the system for flight and to confirm the ability of the small chute to pull out the main chute, wind tunnel tests were conducted at TU Berlin. FIG 4 shows the test setup during the parachute pull out tests. The wind speeds applied in the wind tunnel were calculated in the frame of a trajectory analysis prior to this investigation using the software ASTOS. After the test setup was finalized, the pyrotechnical actuator was triggered manually. This led to the successful release of the spring-loaded lid, followed by the small parachute being dragged into the wind tunnels air steam. The air stream was always able to completely open the first chute. Thereby, the small parachute always provided enough force to successfully pull out the main one, qualifying the system for flight.

FIG 4. Parachute pull out test at the TU Berlin wind tunnel.

2. DECAN AQUARIUS FLIGHT

The launch campaign of the rocket took place at a military training area of the German Bundeswehr in Brandenburg. At the launch site, the first step was the erection of the launch tower including the installation of the release MGSE followed by the setting up of the measurement and safety electronics. Subsequently, the rocket was installed onto the launch tower and its nozzle was sealed by the release MGSE. The installation of the telemetry unit and the payload finalized the rocket preparation and the DECAN AQUARIUS was ready for fueling. After the propellant was filled into the rocket, the propulsion system was finally sealed and the pressurization process initiated. The heating rods within the tank were powered for approximately one hour before the loaded condition of the rocket was reached (see TAB 1).
To release the nozzle and therefore, to launch the DECAN AQUARIUS, the pyrotechnic actuator of the release

system was triggered manually from a safe distance. The self-developed hot water rocket nozzle release MGSE worked as planned, finally qualifying the design. The DECAN AQUARIUS successfully left the tower after about one second and showed a stable and almost complete straight flight. FIG 5 shows the rocket ascending out of the launch tower.

FIG 5. DECAN AQUARIUS leaving the launch tower.

After approximately 11 s the DECAN AQUARIUS traveled through the apogee of the trajectory in about 650 m height. Since the parachutes of the DECAN AQUARIUS were not ejected, the rocked touched down after a total flight time of 24 s. The malfunction of the recovery system was suspect of an extensive troubleshooting investigation afterwards whose result is presented in chapter 3 of this paper.

Parameter	**Flight 2022**
Maximal Height	650 m
Flight Duration	24 s
Mean Acceleration	3.5 g
Acceleration Time	3.5 s
Maximal Acceleration	15 g

TAB 4. DECAN AQUARIUS flight characteristics.

The downlink of the in-flight data of the telemetry unit was successful over the entire trajectory of the DECAN AQUARIUS. Additionally, the data stored on the telemetry board could also be recovered. TAB 4 summarizes the main information about the DECAN AQUARIUS flight.

Due to the hart landing of the rocket, the payload and its data storage unit got damaged and no data could be recovered.

3. FLIGHT DATA AND MALFUNCTION ANALYSIS

After the touchdown of the DECAN AQUARIUS, the possible faults of the recovery system malfunction were investigated. FIG 6 provides an overview of the potential defects including their likelihood.

3.1. Possible hardware errors

One possibility for the malfunction may be a mechanical error in the operation of the recovery system release mechanism. But after the recovery of the rocket, it turned out that the pyrotechnical ignition subsystem for the pyro actuator was still intact and never triggered during the flight. Additionally, the footage of the in-flight camera monitoring the corresponding pyro proved that no ignition was triggered. Therefore, a mechanical error of the release mechanism is impossible since the release sequence was never initiated.
Naturally, the next hardware related malfunction investigation focused on the ignition subsystem and whether it was faulty. In the run-up to the launch, the ignition process of the pyros was extensively tested. Both, manual ignition by ignition device and ignition by means of the telemetry unit were tested, always successfully. Thus, the telemetry unit is generally able to ignite the utilized pyros. Additionally, since the pyro could be recovered after the flight, an inspection of the actual flown flight hardware could be carried out. A first visual and electrical inspection showed no anomalies. Subsequently, the team was able to manually trigger the corresponding firing pellet using the manual ignition device. Therefore, it is very unlikely that a faulty ignition subsystem was the reason for the malfunction of the recovery system.
A further possible reason for the malfunction of the recovery system could be that the pyro ignition subsystem never received an ignition signal during the flight. This could have been for example due to a loose contact between the pyro and the corresponding channel of the telemetry unit. But this cause is very unlikely since the telemetry unit checks and tracks whether a closed circuit is connected to its channels or not. This includes information regarding the voltage present at the channels. Both, the downlink data and the information stored on the board during the flight show that the connection between the ignition subsystem and the board was error-free the entirety of the flight. Additionally, this data also proves, that there was always enough voltage present to be able to ignite the pyro if a trigger signal would have been initiated.
Lastly, the team checked if the physical installation of the telemetry unit was carried out correctly. The telemetry unit offers different modes in which it can operate. Only when the board successfully enters "pad mode” it can fulfil its task of triggering the release system and sending of telemetry data. According to launch day documentation and photographs, the board was properly integrated into the electronics compartment. The documentation also indicates that the telemetry unit successfully switched to "pad mode” at the launch site, which can also be confirmed by the successful reception of telemetry.

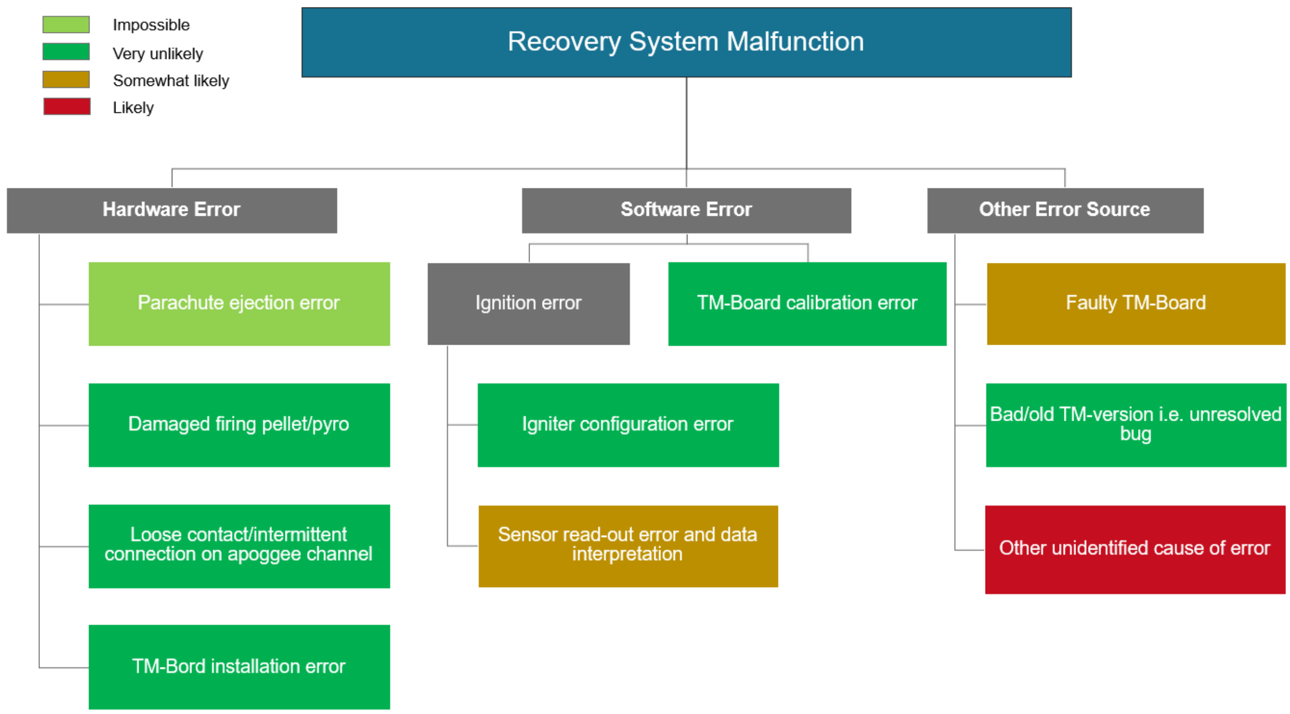

FIG 6. Possible recovery system malfunctions.

In addition, the recorded on-board data is plausible. Thus, an error in the integration and activation of the TM board is very unlikely as the cause of the malfunction.
Summarized, an error of the hardware components is very unlikely, since the telemetry unit was operated in the correct mode, the pyro and the corresponding ignition pellet were error free and voltage was available.

3.2. Possible software errors

Firstly, the investigation focused on the software configuration of the telemetry unit. The corresponding paperwork, namely the telemetry unit preparation procedure was checked for faulty settings of the board. Ignition critical configurations such as the deploy mode and the deployment delay time were inspected with special attention. All settings were done appropriately and should have led to the release system being triggered while travel through the apogee. A faulty software setup of the board is therefore very unlikely to have caused the recovery system malfunction.
Furthermore, the measurements of the telemetry unit sensors were checked. After analyzing the flight data, it can be considered that the measurements do not show any critical errors and the gathered information is plausible. Therefore, the apogee should have been identified correctly. The telemetry unit utilizes information of various sensors to determine the apogee. This includes an unknown filtering algorithm. Therefore, the possibility of errors during the sensor read-out and data interpretation cannot be excluded and are somewhat likely.
Lastly, it was analyzed if the telemetry unit was calibrated correctly at the launch site. According to the corresponding procedure, the calibration had proceeded nominally. Also, the board itself did not detect any anomalies which indicate a faulty calibration. An additional indication of successful calibration is the fact that the board has sent telemetry. This can only happen when the board is in pad mode and the pad mode is only activated if the calibration is error-free. Based on these two facts, the possibility that the failure of the recovery system occurred due to a faulty calibration is very unlikely.
Summarized, a malfunction of the software is somewhat likely since the sensor read-out and data interpretation may have been executed incorrectly. This seems further likely since the setup and calibration of the telemetry unit have been carried out error-free.

3.3. Other possible errors

During the investigations other potential causes of error were identified in addition to hardware and software-related errors.
During the design of the DECAN AQUARIUS all the crucial functions of the telemetry unit were always successfully tested. Nevertheless, it cannot be excluded altogether that a partially defective telemetry board was utilized during the launch campaign.
Another potential cause of failure of the recovery system is an error in the code of the used software version. The telemetry boards manufacturer works permanently on the corresponding applications, updates the program continuously and bug fixes and updates are published. Our investigation showed that no software bugs could be found that indicate a false trigger for the software version utilized during the launch. Occurrence of an undocumented software error cannot be excluded completely. However, since only the basic functions of the telemetry board were used and no unusual settings were made, a programming error in the flown software version is rather unlikely as the cause of the error.
Although this investigation was carried out with a high amount of conscientiousness and diligence and under review and supervision of external reviewers and experienced professionals, it is not unlikely that the actual error that caused the malfunction is still not found. This

seems further likely since a lot of possible errors could be evaluated as unlikely. Therefore, the investigation will be carried on in the next semester.

4. FLIGHT SUMMARY AND OUTLOOK

Even with the damage of the rocket, the 2022 flight of the DECAN AQUARIUS can be seen as another important milestone within the development of hot water rocketry at the TU Berlin.
The achievements obtained are the qualification of the newly developed and innovative release MGSE, the qualification of the telemetry downlink (telemetry concept A), the qualification of the plastic crashbox and the partial qualification of the recovery system (no premature ejection of the chutes).
Additionally, the flight confirmed the mean thrust and thrust peak values measured on the test bench and therefore, verified the basic research efforts of the team.
Besides the ongoing investigation regarding the malfunction of the recovery system, the team is currently planning the repair of the rocket.

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