OVERVIEW OF THE CURRENT WORK ON THE STUDENT ROCKET DECAN-AQUARIUS AT THE TU BERLIN

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Abstract

The Technische Universität (TU) Berlin is developing student experimental sounding rockets within hands-on courses. These practical courses teach the knowledge in (sub-) system design, manufacturing, assembly, integration and testing (AIT) and operations of rockets. The applied processes in development, AIT and operations as well as the quality standards are related to the ones in the aerospace industry.

The DECAN/AQUARIUS experimental sounding rocket project, which is also a DGLR junior research group, works on a two-stage rocket where the upper stage is a solid fuel rocket (DECAN SHARK) and the lower stage is an environmentally friendly water engine (DECAN AQUARIUS). This paper provides an overview of the latest developments of the DECAN AQUARIUS lower stage since the last publication at the DLRK Congress in 2020.

The developments of the electrical components include the breadboard and the breadboard testing of an alternative Telemetry Design B. Amongst other progress, a Pin Puller was developed and tested on the mechanical side. Furthermore, a trajectory analysis using different simulation programs was conducted

Acronyms/Abbreviations

CamRS	Cambridge Rocketry Simulator
CoG	Center of gravity
DECAN	German CanSat Sounding Rocket (Deutsche CanSat-Höhenrakete)
DOF	Degree of freedom
GPS	Global Positioning System
GUI	Graphical User Interface
ILR	Department of Aeronautics and Astronautics, TU Berlin (Institut für Luft- und Raumfahrt der TU Berlin)
MGSE	Mechanical Ground Support Equipment
ODBC	Open Database Connectivity
SHARK	Student High Altitude Rocket

1. THE DECAN ROCKET

1.1. DECAN – a two-stage rocket

The DECAN rocket, which is a two-stage rocket, is being developed by students and scientists at the TU Berlin. The possibilities of participation in this hands-on project are educational courses, Bachelor and Master Thesis, internships as well as a membership in the student/university association “Aquarius”, which is also part of the development team of the rocket and a DGLR junior research group. The two-stage system consists of an upper stage, the DECAN SHARK, and a lower stage, the DECAN AQUARIUS. The total lift off mass of the system will be about 150 kg. The lower stage will lift the whole system to an altitude of approximately one kilometer, where a stage separation system releases the upper stage. Afterwards the DECAN SHARK will climb up to the destination altitude of 7 km in which a small payload – a CanSat – will be ejected.

For a damage free landing of the stages, both stages use a recovery system and beacons will ease the recovery of the rocket. Both stages feature an independent telemetry unit which sends the in-flight data to the ground and stores the information as well. This telemetry board is also responsible for the automatic triggering of the stage separation system and the parachute ejection of the DECAN SHARK and AQUARIUS.

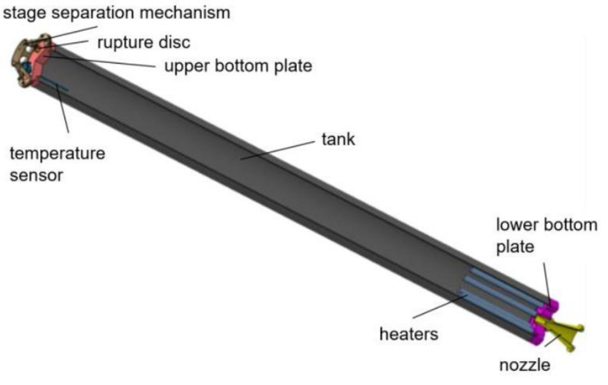


FIG 1. DECAN AQUARIUS Propulsion System.

Single stage test flights were accomplished by both stages. DECAN SHARK, which is propelled by a solid engine, absolved two flights, reaching altitudes of 5.5 km and 5.7 km, from the Esrange Space Center in Kiruna, Sweden in 2015. DECAN AQUARIUS' first flight took place at a facility of the Bundeswehr in 2017. The rocket reached an altitude of 550 m instead of 1200 m (which can be achieved in a single stage flight) because of a recovery system malfunction. Since the whole flight of the AQUARIUS takes place in the visible range, troubleshooting is made easier. Currently the work is concentrating on improving the lower stage of the DECAN rocket, therefore this paper is focusing on the current status of the DECAN AQUARUS.

1.2. DECAN AQUARIUS

The lower stage of the DECAN rocket is equipped with an environmentally friendly hot water engine. The propellant tank, consisting of a lower plate, a tube and an upper plate, is made of a suitable heat resistant stainless steel in which heaters, a temperature sensor and the nozzle are installed (FIG 1).

For launching the AQUARIUS, the nozzle will be sealed with a specially designed launch MGSE which is part of the launch tower. The heaters in the tank are powered electrically to heat the water (which is the propellant) along the boiling curve to approximately 270 °C. Due to the partially evaporation of water a pressure of 55 bar is built up within the tank. A rupture disc installed to the tank and a pressure relief valve which is part of the launch MGSE help to control the process and increase the safety.

To lift-off the rocket, the nozzle is being released pyrotechnically from the Launch MGSE. The gaseous phase in the tank pushes the remaining water in the nozzle. Since the water is overheated for an ambient environment, it evaporates in the nozzle leading to a volume expansion and therefore thrust. The DECAN AQUARIUS generates an average thrust of 3,000 Newton over approximately 4 seconds using 30 kg of water.

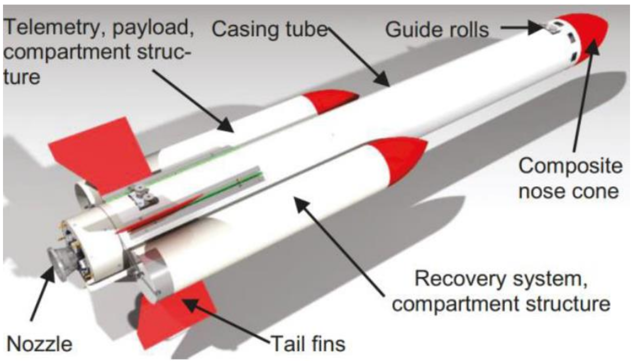


FIG 2. DECAN AQUARIUS rocket

The propulsion system is the main part of the rocket. Dedicated metallic rings are used to connect all other systems to the tank, like the guiding rolls, that are the interface to the launch tower, the two compartments, which are housing the telemetry unit, the recovery system and the tail fins, which enable the AQUARIUS to fly stable.

The telemetry unit is situated in the left-hand compartment of the rocket as can be seen in FIG 2. The main task of the telemetry board is to trigger the parachute ejection, to collect in flight data, to send this data live to the ground, to store this information on the board itself and to track the AQUARIUS via GPS.

An aluminium crash box was designed for the protection of the telemetry board in case of an anomaly in the recovery flight phase of the rocket. This enables the recovery of the recorded flight data making possible a better data analysis, since the data recorded on the board is more detailed than the data which is sent down. An antenna outside the crash box makes possible the downlink of the data in real time.

The recovery system consists of two parachutes, a small and a big main chute. The small one will be ejected in the apogee of the trajectory to pull out the main parachute. Subsequently, the main chute will realize a safe landing of the AQUARIUS. Therefore, the small parachute is connected to the main one, which itself is connected to the rocket using a steel cable and cable clamps.

FIG 2 shows the lower stage and its main subsystems and TAB 1 provides an overview of the main parameters of the rocket.

Parameter	DECAN AQUARIUS
Take off mass	90 kg
Dry mass	60 kg
Propellant mass	30 kg (water)
Height	2.5 m
Diameter	0.2 m
Average thrust	3,000 N
Acceleration time	4 s
Apogee	1200 m
Ascent time	19 s

TAB 1. Technical properties DECAN AQUARIUS

1.2.1. Flight test of DECAN AQUARIUS

The first test flight of the lower stage took place on 31st of March 2017. After the nominal launch tower set up and rocket preparation the release system pyro actuator was triggered and the launch MGSE released the AQUARIUS normally. The assumption for the efficiency of the engine, which was significant for the design process of the lower stage, slightly differed from the reality. This led to unexpected accelerations and velocities during the test flight and thereby to the rupture of the steel cable connecting the parachutes to the AQUARIUS. Also, the elevation, which was set to 79° by the launch tower, was slightly reduced, leading to a higher horizontal distance covered. The key data of this flight can be seen in TAB 2.

The telemetry unit worked partially nominal. The data transmission to the ground as well as the collection and storage of the flight data worked well. After the touchdown of the AQUARIUS the flight computer could be recovered. The crash box was able to protect the board from damage and the stored data could be recovered for further investigation. Unfortunately, the crash box narrowed the view window of the telemetry board, which made it impossible to lock in with enough GPS satellites. Therefore, only limited GPS data was available. Nevertheless, the first flight of the new developed DECAN AQUARIUS was a success since a lot of subsystems could be qualified such as the propulsion system or the main structure.

Parameter	**Test flight data**
Max. altitude	550 m
Flight time	22 s
Max. speed	120 m/s
Time to apogee	10.6 s
Acceleration time	3.3 s
Horizontal distance	1100 m

TAB 2. Measured test flight data DECAN AQUARIUS

1.2.2. Propulsion system test bench

Since 2020 a test bench for the propulsion system is under development. The aim of this test bench is to collect measurement data on the thrust of the propulsion system without test flights. This should provide insights for optimizing the propulsion system, especially the nozzle geometry.

The test bench consist of the propulsion system which is clamped with the nozzle downwards, a framework where all operations at the system are performed and the measurement computer located at a safe distance (FIG 3).

After setting up the test hardware, the propulsion system is sealed and filled with water. As described above, the water is now heated up to 270 °C by inputting electrical energy with heaters. After reaching the temperature the sealing is removed pyrotechnically and the propulsion system delivers the thrust. During the test the thrust profile and the pressure at the system are measured and recorded by the computer.

FIG 3. Propulsion system test bench

The first thrust test was carried out at the May 2020 since then various nozzles with different geometries was tested.

1.2.3. Challenges to tackle concerning the AQUARIUS rocket hardware

After analyzing the test data and the rocket itself, two main issues regarding the flight hardware were identified:

1) To maximize the achievable apogee, it is necessary to optimize the geometry of the thrust nozzle. Therefor the different measured thrust profiles from the propulsion tests are used to perform trajectory analyses. Based on the analysis results, the nozzles are evaluated to determine an optimized nozzle geometry for the hot water rocket. The decisive factor here is the apogee height achieved in the simulation. Since it is initially unknown which simulation software is most suitable for hot water rockets, the simulation is performed in different programs and the results are then evaluated.
2) In addition to the existing telemetry, a redundant system is currently under development. This extends the currently used system with additional features for data acquisition and storage. That will also increase the reliability of the system even if one telemetry component fails.

All other systems shall be altered as little as possible since they have worked nominally during the first test flight and therefore have flight heritage.

2. TRAJECTORY ANALYSIS

2.1. RASAero II

The RASAero II simulation tool is provided free of charge by developers Charles E. Rogers and David Cooper for aerodynamic analysis and simulation of hobby and model rockets [1]. Subsequently, different models of the DECAN AQUARIUS are simulated and the results are discussed. A final conclusion for the use of this software for AQUARIUS is drawn at the end.

2.1.1. Implementation of AQUARIUS

The trajectory analysis in RASAero is done by modelling the rocket in the implemented user interface. The nose cone, the body tube, the fin canister and the boattail were designed in accordance with the DECAN AQUARIUS dimensions. The result can be seen in FIG 4.

Due to the high complexity of the DECAN AQUARIUS Rocket, it is not possible to integrate the specific features of the fins in the software. Therefore, the first simplification was made at this point. The second simplification needed to be done in the area of the tail of the rocket, because the used nozzles cannot be represented. The diameter of the nozzle was used as tail diameter of the fuselage. Furthermore, the compartments cannot be added. There is a "Booster" area in the user interface, but it is there to possibly add a second stage.

In order to test whether it is possible to apply the software in such a way that meaningful analysis data can be obtained, various configuration options were considered. In the following section these configurations with the respective analysis results are shown.

1) First, the acceleration, velocity and altitude plots as a function of time were created for the rocket without compartment alternatives (FIG 4) to have a basis for comparison.

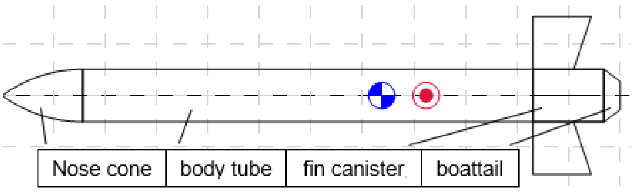


FIG 4. DECAN AQUARIUS in RASAero II with CoG (blue) and pressure point (red)

2) One way to represent the DECAN AQUARIUS rocket in RASAero II was to thicken the fuselage (FIG 5) according to the area at the position of the compartments.

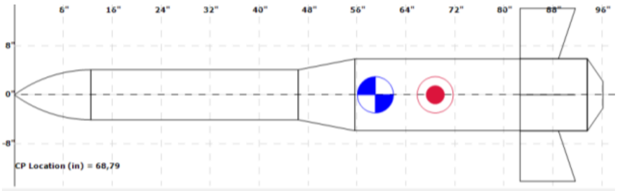


FIG 5. Rocket with thickened hull

3) Another alternative to the compartments is the thickened Rocket model (FIG 5) with activated Base Drag Protuberance and Inclined Flat Plate Protuberances option. At this point, however, no realistic simulation results are provided because with the implementation of Protuberances the program says that the configuration is supposedly unstable in flight. Actually, however, the relationship between the CoG and the pressure point in this configuration is similar to FIG 4. Even after manipulating the CoG into the nose tip, no meaningful results are provided with the same reasoning.

2.1.2. Simulation of the trajectory

TAB 3 summarizes the simulation results of all variants once again. It can be clearly seen that the drag coefficient C_D is too small for the first two configurations. An alternative to the compartments is the configuration with the protuberances (TAB 3). However, this model is also not a realistic representation, since it is only possible to a limited extent to vary the pressure and CoG in order to generate realistic simulations for the application case of a hot water rocket. In addition to the assumptions of the software described above, the correct handling of the data export of the software could not be implemented in the scope of the project. This only allows a visual comparison between simulation data, making further processing and analysis with other programs difficult. In conclusion, it can be said that the program offers sufficient functionality and good usability for hobby and model rockets, but is only partly suitable for a complex rocket such as the DECAN AQUARIUS.

Configuration	max. altitude	C_D
Without compartments	1,189.3 m	0.24
With hull thickening	1,172.6 m	0.14
With protuberances	1,126.2 m	0.44

TAB 3. Comparison of the configurations

2.2. Cambridge Rocketry

The Cambridge Rocketry Simulator (CamRS) was developed by Simon Box and Willem Eerland from 2008 to 2011 [2]. It is a simulator for the ascent of unguided sounding rockets in 6-DOF. The program is divided into three elements. The first element is a GUI adopted from OpenRocket and is therefore implemented in Java. The second element is the simulation core, which simulates the forces acting on the rocket and calculates the trajectory. This is written in C++. A Monte-Carlo wrapper is implemented to account for uncertainties in the rocket dynamics and in the atmosphere. This method changes the initial conditions of the simulation slightly for each run, so that instabilities become visible, also the results tend to be more realistic. This uncertainty consideration is a strength of the program over others. A visualization of the flight path is done with Python.

2.2.1. Implementation of AQUARIUS

To analyse the performance of the DECAN-AQUARIUS, the rocket had to be implemented in CamRS. For this task the program offers the OpenRocket GUI that enables the user to model the rocket, define the motor and set the simulation conditions. For modelling the rocket shapes like cones, tubes and fins can be connected. The internal geometry can also be defined. As the program is geared towards the simulation of rockets with solid propellant motors, the internal geometry of DECAN-AQUARIUS is not reproducible. Therefore, it was decided to model the surface only and define derivative properties like mass and CoG manually. For the DECAN-AQUARIUS three different nozzles are available so far which produce different thrust profiles. The thrust curves measured for each in performance test were entered into CamRS. The flight was simulated for all three nozzles. The simulation conditions were selected to introduce no external influences like e.g. wind. A difficulty in the modelling process was that it is not possible to define side compartments in CamRS. As the DECAN-AQUARIUS uses such a design to house the electronics and recovery system it was necessary to find a method to incorporate them. The solutions found were to increase the diameter of the rocket in the length of the side compartments (FIG 6). To determine the diameter necessary to produce the aerodynamic properties of the side compartments, the Barrowman equations were used. Another option was to add thick fins to create the additional drag and aerodynamic forces (FIG 7). The dimensions for the fins were derived from the side compartments.

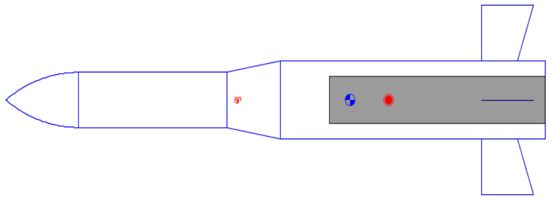


FIG 6. AQUARIUS in CamRS with increased diameter

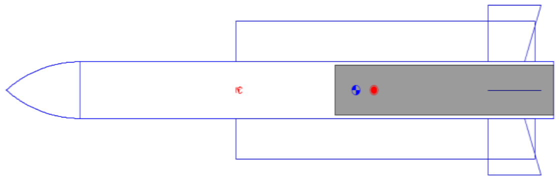


FIG 7. AQUARIUS in CamRS with thick fins

Also the nozzle of the motor and the geometry of the tail could not be modelled. As they are leeward of the core tube the nozzle was ignored in the simulation. The flight of the rocket was then simulated with the developed configuration as well as a version with only the core body in multiple Monte-Carlo runs.

2.2.2. Simulation of the trajectory

The software provides the simulation data of the time, the eastern and northern distance to the starting point, the height, the flight phase and the ID of each Monte Carlo run. The following (TAB 4) is a summary of the significant results of the configuration with no compartments.

Nozzle	max. altitude in (m)	max. velocity in (m/s)	max. acceleration in (m/s²)
1	1,800	175	50
2	1,580	160	45
3	1,380	152	45

TAB 4. Simulation results for the configuration without compartments

The results show a realistic correlation between height, velocity, acceleration and thrust for the different nozzles, since the nozzle 1 provides the largest thrust and therefore achieves the largest altitude, as well as the largest velocity and acceleration. Overall, the Cambridge Rocketry Simulator offers several advantages, such as a simple user interface and a Monte-Carlo wrapper to account for uncertainties in the simulation. However not every geometry can be created. The compartments of the DECAN Aquarius and the nozzle could not be modelled. The tail geometry had to be simplified as well. Another significant weakness of the program is the missing output of drag coefficients and the position of CoG and center of pressure. Furthermore, the missing output of velocity and acceleration has to be considered. To verify the simulated trajectories a direct output of these values would be helpful. Due to these weaknesses the further use of the Cambridge Rocketry Simulator for DECAN Aquarius is not recommended.

2.3. Open Rocket

OpenRocket is an open source Java application that can be used to simulate ascent trajectories of model rockets. The program has its origin as part of a master thesis in Helsinki in 2009 [3]. Over the years it has been continuously developed and improved, so that the current version is 15.03. Various parameters can be used to customize the simulations and the rocket design. In addition, thrust curves can be imported. For the flight simulations, OpenRocket uses the 6-DOF Runge-Kutta calculation method and an extended Barrowman calculation method, which will be briefly discussed in the next section.

2.3.1. Assumptions

The software OpenRocket makes a few simplifications for the calculation. The most important ones are presented here. They are taken from the technical documentation of the program. The standard atmosphere is considered for the atmosphere model. It is internationally established and often used for calculations in aviation, so the assumptions are not considered significant. When calculating the aerodynamic properties, it is important that they are calculated in the subsonic and supersonic regions. The transonic range is interpolated from this. However, the inaccuracies that occur are not relevant, since the DECAN Aquarius only moves in the subsonic range.

To compute the normal force, the pitching moment and pressure point position, the Barrowman method is used, which makes the following assumptions [3]:

- The angle of attack is close to zero
- The flow around the body is rigid and does not rotate
- The rocket is a rigid body
- The nose is a sharp point
- The fins are flat plates
- The body is axially symmetrical

A correction factor was added by the OpenRocket creator, which also allows a force calculation of higher angles of attack and thicker fins. For the position of the pressure point, all components of the rocket are considered individually, and the location is then summed from the individual pressure points to make the effects of individual components more understandable. In addition, when calculating the fins, it was found that serrated fins lead to a high degree of error and should not be regarded. The diameter of the body is assumed to be continuous. This can lead to warnings in the simulation, so the effects on the results must be tested. In this project it did not lead to relevant errors in the test results. For the consideration of the drag (especially the shear stress) a continuous turbulent boundary layer is assumed. During tests in the development, errors of the height of the apogee up to 5% (compared with calculation with laminar and turbulent boundary layer) occur. The interference drag and vortices around the fin tips are neglected in the calculation because they are very small compared to the other drag forces. The drag forces are calculated for an angle of attack close to zero. For higher angles of attack, this is scaled via a second-degree polynomial. Overall, it can be said that most assumptions are common calculation procedures or have no relevance to the DECAN Aquarius ascent trajectory. The software was validated by subsequent tests. The accuracy depended on the selected rocket and engine. For a very small rocket model, errors of 7 % to 16 % (in the height of the apogee) were calculated; for a slightly larger rocket with a hybrid motor, the apogee is about 12 % to 16 % smaller than in the test [3].

Comparisons with data from the wind tunnel showed that the calculation of the position of the pressure point is reliable up to a Mach Number of 1.5, but the normal force coefficient turns out to be too small, which leads to the fact that the rocket corrects its orientation a bit slower than in the realistic case [3].

2.3.2. Implementation of AQUARIUS

The implementation of the DECAN-Aquarius in OpenRocket is conducted in two parts. First, the available data, i.e., parameters of the parachute, three different thrust curves of the hot water engine, the mass and the CoG of the rocket, is transferred to OpenRocket. Second, the rocket's aerodynamic properties are calculated, e.g., its center of pressure and its drag coefficient. For this calculation, the DECAN-AQUARIUS has to be designed with tools provided by the software. However, only the main body can be modelled in OpenRocket. This includes the composite nose cone, the casing tube, the tail fins and a simplified nozzle which are depicted in FIG 8. A parachute is also added to the main body, but it is not possible to add the compartment structures to the design. To compensate this the main body is altered before the trajectory analysis starts. Instead of three casing tubes next to each other, consecutive tubes with different diameters are used. The diameter is calculated at each point under the assumption that the model and the DECAN-Aquarius are aerodynamically similar when their cross-sectional areas are equal. Thus, the diameter of the model gradually increases at the position where the compartment structures would start and abruptly decreases where the structures would end (FIG 8).

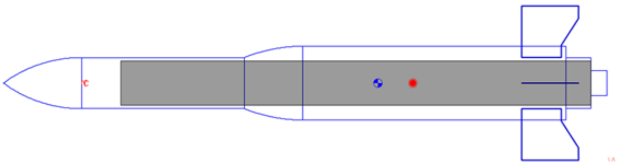


FIG 8. AQUARIUS model in OpenRocket

2.3.3. Simulation of the trajectory

After the design process of the DECAN-AQUARIUS in OpenRocket was finished, the preparations for the simulation of the trajectory can be performed. This includes the adjustment of some launch conditions like the wind, the coordinates of the launch site and the launch ramp. Since it was a project wide decision to neglect the influences of the wind in the first step, the velocity here is set to zero. The most important setting at this point is the configuration of the launch ramp. The angle and the length of this essential equipment have meaningful influence on the simulated trajectory. With all those settings configured, the simulations can be conducted. As described before, there are three thrust curves which correspond to three different nozzle configurations. The generated data can now be plotted within OpenRocket (FIG 9).

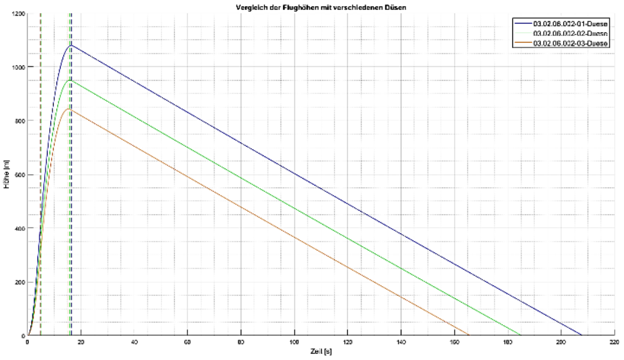


FIG 9. Simulated flight trajectory for the different nozzles

The program calculates a total of 54 datasets. The flight events like the apogee are also included in the file. For the further data evaluation, the program MATLAB is used. This enables the direct comparison between the different simulations, something that is not possible in OpenRocket. The data analysis is especially focused on the altitude, velocity, and acceleration time. The results showed that the rocket would reach its highest apogee with nozzle 1, which has the widest diameter. It reached 1,079 m, compared to nozzle 2 with 950 m and nozzle 3 with 843 m. As expected, the rocket configuration with the highest apogee also takes the longest time to get there. The maximum speed occurs at roughly 4 seconds into flight, one second before the burnout of the motor. The course of the acceleration is during the burn time directly proportional to the thrust curve of the motor. Afterwards, it drops below zero which means that the rocket is decelerating. Until the rocket gets to the apogee, the simulated deceleration is quite constant. Then, the deployment of the parachute causes a peak, but after a couple seconds, the acceleration drops to zero because the speed of the sinking rocket with the parachute is constant. Finally, the total flight duration and also the lateral distance which the rocket travelled are also corresponding to the other results. This shows clearly that the size of the nozzle has a meaningful impact on the performance of the rocket. The following table shows some of the most important results of the simulations for nozzle 1 (TAB 5).

Parameter	Simulation results
Max. altitude	1,079 m
Max. velocity	130.5 m/s
Flight time	208 s
Acceleration time	4.9 s
Drag coefficient	0.29 (Mach 0.3)

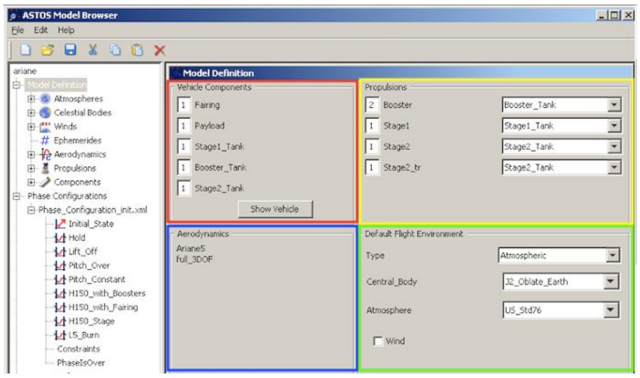
TAB 5. Simulation results for nozzle 1

2.4. ASTOS

The calculations of the DECAN sounding rocket ascent trajectories are performed with a simplified version of the ASTOS software: ASTOS Amateur Rockets 7.3.2, which was initially released in 2006 [4] and still meets the complexity and accuracy of the calculations to a high degree. The focus of this software is exclusively on the simulation of suborbital trajectories. ASTOS contains an extensive library of differential equations to describe the motion of rockets in all three spatial directions, both translationally and rotationally. In addition, the software has a clearly arranged user interface with which it is possible to create simulations just by entering or importing the required data, without the need for any programming knowledge.

2.4.1. Implementation of AQUARIUS

One of the most important tools in ASTOS is the Model Browser (FIG 10). The Model Browser reads and writes XML files that the user can indirectly influence by entering parameters and importing data. The Initialize sign can be used to start the simulation and the Viewer can be used to visualise the simulation results.



Vehicle Components
1 Fairing
1 Payload
1 Stage1_Tank
1 Booster_Tank
1 Stage2_Tank

Propulsions
2 Booster: Booster_Tank
1 Stage1: Stage1_Tank
1 Stage2: Stage2_Tank
1 Stage2_tr: Stage2_Tank

Aerodynamics
Ariane5
full_3DOF

Default Flight Environment
Type: Atmospheric
Central_Body: J2_Oblate_Earth
Atmosphere: US_Std76
☐ Wind

FIG 10. ASTOS model browser

The DECAN-AQUARIUS is implemented via the Model Browser. To complete the modelling for the simulation of the rocket the components, aerodynamics, propulsions have to be defined.
Since the lower stage is only one component, it is also only this component that has to be defined. Here the structural and propellant mass have to be implemented. A more complex issue is the definition of the aerodynamics of the vehicle. ASTOS separates between a Full 3-DOF models, which only considers the translational motion and Full 6-DOF models, where the rotational motion of the vehicle is considered, as well. For each phase of the flight an aerodynamic model needs to be defined by several aerodynamic coefficients. For a Full 6-DOF model aerodynamic force and moment coefficients needs to be integrated to calculate the motion of the vehicle. The coefficients were calculated by an extern tool called Missile DATCOM. The Full 3-DOF model only needs the force coefficients and is only used for the flight after the chute has deployed. The drag coefficient for the chute is approximated to 1 and the cross-sectional-area of the chute is also implemented as a profile. Another essential part of implementing the AQUARIUS is to define the propulsion of the rocket. For this the nozzle exit-area and mass flow, for each nozzle configuration needs to be input as a value. The thrust profile of various nozzle geometries was determined in various tests as described under chapter 1.2.2. For each of these tests, the thrust profile related to vacuum conditions was imported via ODBC. Furthermore, the distance of the COG to the exit of the nozzle is used to calculate the jet damping effect.

2.4.2. Simulation of the trajectory

In order to start the simulation, the individual flight phases must be defined, whereby the individual aerodynamic models and the propulsion system are selected. In addition, boundary conditions are created, which determine, for example, that the parachute is released at apogee. The numerical solution of the differential equations is carried out using a Runge-Kutta method. The error barrier, which is also necessary to check the step size when integrating, is 10^{-8} by default and is a very good compromise between accuracy and calculation time. The simulation is performed with the U.S. Standard Atmosphere 1976, which represents the Earth's atmosphere very well up to an altitude of 1,000 km. The celestial body Earth is defined in its form as a sphere and the gravitational potential is specified by the geopotential coefficients J2 to J6, which are given in ASTOS.

The results of the flight path simulations for the lower stage with different nozzle configurations and thrust profiles are shown in TAB 6.

Nozzle	**Date of thrust test**	**Simulated apogee height in (m)**	**Max. Mach number**	**Max. Velocity in (m/s)**
1	*10/01/20*	1,044.5	0.365	123.3
	09/01/20	1,075.9	0.371	125.4
2	*10/22/20*	935.0	0.339	114.7
	11/02/20	949.4	0.341	115.6
	03/07/21	934.6	0.338	144.5
3	*02/23/21*	801.8	0.305	103.1
	04/08/21	790.8	0.302	102.1

TAB 6. Simulation results for different nozzles and thrust profiles

Due to the different thrust plateaus and burning times of the nozzles there are also different results of the flight simulations. Due to a lower burning time but a higher thrust level AQUARIUS can reach an apogee altitude of more than 1,000 m with nozzle 1. With the thrust profiles from the nozzle 2 and nozzle 3, which have a lower thrust level but longer burning time, the apogee height decreases significantly.

2.5. Comparison between the analyses

It turns out that the simulation software RASAero II, CamRS and OpenRocket offers only few possibilities for the modelling of the rocket, for example it is not possible to model the compartments or the nozzle correctly. Therefore, the fuselage was aerodynamically equivalently thickened.

In RASAero II the results with thickening and without thickening differs only slightly. In addition, the displacement of the CoG during the emptying of the tank is too small. The usability of the simulation results is therefore questionable. CamRS and OpenRocket offers a better possibility of modelling, because both use the same Modeller. But also in these programs the compartments cannot be modelled. In CamRS the results of the simulation vary strongly. In addition, the achieved apogees of CamRS differ strongly from the results of the other simulation programs. The most plausible simulation results are provided by the ASTOS software. In this software, the rocket is directly represented by the input parameters such as the mass properties (structural and propellant mass, moment of inertia, CoG) and the aerodynamic properties (pressure point, drag and lift coefficient). In addition, it is possible to represent the influence of the wind during the flight, but it was shown that this has only a small influence on the achieved apogee. It can be seen that the highest apogee is achieved with the geometry of nozzle 1. At all simulations an apogee of above 1,000 m can be achieved (TAB 7). Nozzle profiles with shorter exhaust times and thus higher thrust levels cause an increase in terms of apogee height. If nozzle 1 is compared with nozzles 2 and 3, it is evident that an increase in the cross-sections at the nozzle throat and outlet are more efficient, since they significantly increase the impulse thrust.

Nozzle	Rocket Model	RASAERO II	CamRS	OpenRocket	ASTOS
1	without compartments	1,189.3	1,800	1,143	1,060.2
	increased diameter	1,126.2	400-1,700	1,090	
2	without compartments	-	1,580	1,001	939.7
	increased diameter		320-1,570	961	
3	without compartments	-	1,380	885	796.3
	increased diameter		250 – 1,380	854	

TAB 7. Comparison of the achieved flight altitudes

3. IMPROVEMENTS OF THE FLIGHT HARDWARE OF THE DECAN AQUARIUS

3.1. Improvements of the electrical subsystems

The telemetry of AQUARIUS consists of two redundant parts:

- The primary TeleMetrum board (FIG 11)
- The secondary flight recorder (FIG 12)

FIG 11. TeleMetrum board from Altus Metrum [5]

The TeleMetrum-board is tasked with the deployment of the parachute. It tracks the flight path of the rocket via a 3-axis acceleration sensor, a barometric sensor and a GPS receiver. This data is stored by the Altus Metrum telemetry. On the basis of this recorded data the TeleMetrum-board recognizes the apogee of the flight path. A part of the recorded data is also send to the ground station via radio downlink.

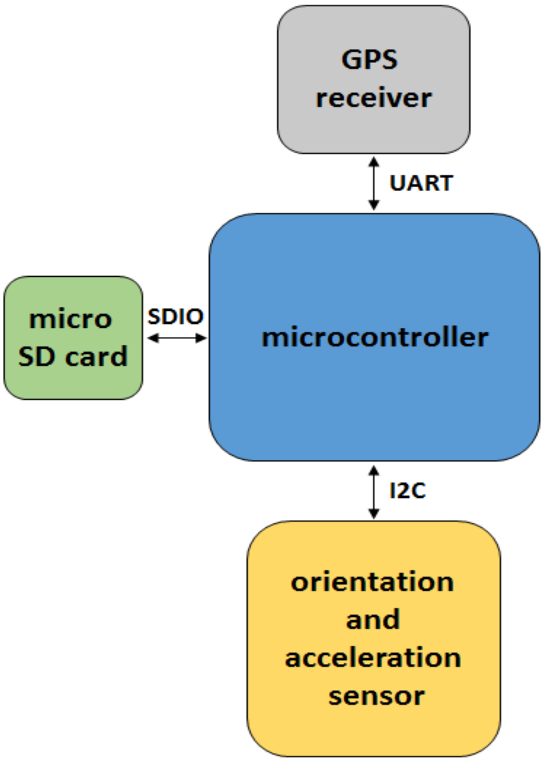


FIG 12. Components of the secondary flight recorder

The redundant flight recorder is currently in development. It is based on a STM microcontroller. The idea is to store redundant GPS data on a micro SD-card. Since the TeleMetrum-board is not able to measure the orientation of the rocket, an orientation sensor is also added to the recorder. FIG 12 shows the parts of the flight recorder. The chosen absolute orientation sensor consists actually of multiple sensors: An accelerometer, a gyroscope and a magnetometer. Therefore, the sensor is able to measure orientation and acceleration data from multiple sources. All of this information is processed on board of the orientation sensor. This data includes the absolute orientation of the sensor, represented as quaternions and the linear acceleration vector (acceleration without the influence of gravity) in inertial coordinates. This data is updated with a 100 Hz rate. The absolute orientation sensor is equipped with an I2C interface. Through this interface the mentioned data is send to the microcontroller. For obtaining redundant GPS data a GPS chipset breakout board is implemented. This module communicates with the microcontroller via UART interface. For the data storage a micro SD-card is used.

In summary the flight recorder should record the:

- Orientation of the rocket in inertial coordinates
- Linear acceleration vector of the rocket in inertial coordinates
- GPS coordinates of the rocket

With the collected data the full rigid body movement of the rocket including flight path and orientation can be displayed. So it should be possible to investigate the in-flight behaviour of the rocket through all phases of the flight.

4. SUMMARY AND CONCLUSION

The first test flight of the AQUARIUS helped to understand which subsystems of the rocket needed improvements. The redundant telemetry system is currently still under development. In the event of a failure, the secondary system will be able to take over the tasks of the primary system, such as determining the position via GPS. In addition, it will be possible to extend the telemetry, which was difficult with the previous telemetry board. Thus, the integration of further sensors is planned, e.g. to measure the orientation of the rocket. In order to further increase reliability, the measured data will be stored on a micro SD-card in addition to the radio data transmission. However, this will be tested extensively before being used in the flight hardware.

During the performance of the trajectory analysis, it became evident that the program ASTOS provided the most reliable results. With this simulation program, an apogee height of more than 1,000 m was predicted with nozzle 1. The analysis of the simulation results and the thrust measurement data used for this purpose will be used for further optimization of the nozzle in order to further optimize the achievable apogee height.

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