LAUNCH CAMPAIGN OF THE DECAN UPPER & LOWER STAGE AND DEVELOPMENT OF A 3D-PRINTED EXPERIMENTAL ROCKET AT TU BERLIN.

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Abstract

This document describes the current development status of the DECAN rocket project at the Technische Universität Berlin. Therefore, the hot water lower stage of the rocket, as well as the solid propellant upper stage, are presented. The two-stage sounding rocket serves as practical example for the development team and improves their knowledge in a variety of engineering fields. In October 2015, the engineering qualification model and flight model of the DECAN upper-stage have been launched as single stage rockets from ESRANGE, near Kiruna, in Sweden. The hot water lower stage will be launched in 2016 near Berlin. The launch campaigns of both stages will be described in this document. Moreover, the development of one of DECAN's new features will be introduced, a 3D-printed experimental rocket.

1. INTRODUCTION

The DECAN program (DEutsche CANsat-Höhenrakete) is a student project within the framework of the STERN (STudentische Experimental-RaketeN) project of the DLR Space Administration. Engineering students get the opportunity to work on a real aerospace project under professional supervision. The different phases of the project follow the ECSS guidelines and are frequently reviewed together with the DLR.

This paper will describe the current development of the rocket at the Technische Universität Berlin. The different subsystems will be presented and the status of the project will also be described. As of now, the DECAN team has successfully launched the engineering qualification model and flight model (SHARK I&II - Student High Altitude Rocket in Kiruna) of the DECAN upper-stage. The lower stage will be launched in 2016. A two-staged rocket will be launched in a follow-up project phase. In the last few months, the possibility to design a 3D-printed experimental rocket has been investigated.

2. TWO-STAGE ROCKET ARCHITECTURE

The rocket consists of a two stage rocket with a take-off mass of less than 150 kg. DECAN will be capable of launching a CanSat to an altitude of up to 7 kilometers. The first stage is comprised of a hot water propulsion system developed at TU Berlin. The water will be heated to over 250 °C, producing a pressure of approximately 50 bar inside the vessel. After the release of the rocket, the lower stage will produce an average thrust of 2.2 kN for a brief amount of time. The second stage of the rocket has a solid rocket motor. This stage carries the main payload, which will be a CanSat. Figure 1 shows the current development status of DECAN. Both stages have been configured in such a way as to allow them to be flown independently from each other. The relatively small altitude of the lower stage (less than 1 kilometer) assures the usage of nearby launch pads. Hence, hardware and software components can be tested frequently. The nose cone in the image contains the inter-stage adapter for when a two-stage configuration is desired.

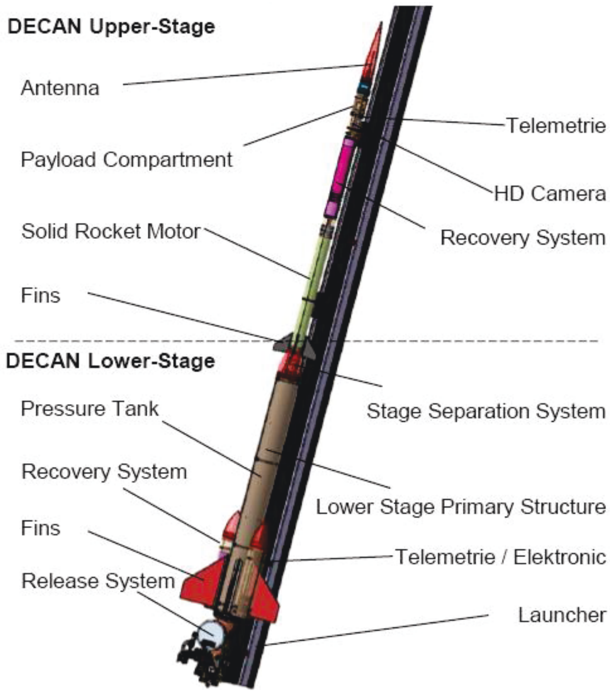

Figure 1 DECAN two-stage rocket and its main components.

Both stages possess recovery systems in order to ensure reusability. The lower stage recovery system is designed to carry both rockets in the case of a malfunction of the stage separation system. Figure 2 shows the mission concept of DECAN two-stage sounding rocket. After release of the rocket, the exhaust (hot water) accelerates the two-stage rocket. At the end of the accelerating phase, the lower stage will be separated (2) and the upper stage solid rocket motor will be ignited (3).

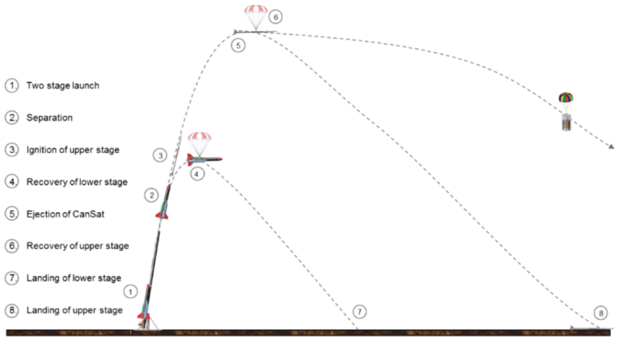

Figure 2 DECAN Mission Concept

The upper stage transports the CanSat payload to a peak altitude of 7 km. At apogee, the payload will be ejected (5). Both stages, as well as the payload, will return with the support of a recovery system (4) (6) safely to the ground (7) (8).

3. LOWER STAGE

As aforementioned, the hot-water powered lower stage is used to increase the overall altitude of the upper stage and therefore its payload to collect more scientific data. At the same time, the apogee of the lower stage is low enough to allow frequent test flights in Germany.
The propulsion system design is based on experience gained from the TU Berlin AQUARIUS project which has been optimizing hot water propulsion systems for over two decades. During the heat-up phase, both pressure and temperature can be monitored for safety reasons. Several safety mechanisms were included in collaboration with the TÜV to provide a safe working environment. Once the release system is triggered, the water jet is ejected and evaporates immediately within the nozzle due to lower external pressure. An average thrust of 2.2 kN is provided for approximately 5 seconds.

3.1 Preparations

The rocket structure is mounted to the vessel with frictionally engaged retaining rings. Hence the vessel is not weakened and the rocket can be assembled and disassembled easily. As seen in Figure 3, four equally spread fins enable a passive aerodynamic stabilization and are connected to the rings. Two compartments provide space for a suitable recovery system, electronic subsystems and optional payload. They are mounted to the rings as well. The recovery system is designed to recover just the lower stage after a tesflight, but it is also dimensioned robust enough to recover both stages in case of a faulty stage separation. The load-bearing parachute rope is wired to the retaining rings and redundantly secured. An Altusmetrum telemetry board measures all relevant flight parameters such as acceleration and height. It also transmits collected data to the ground via downlink. Once the apogee is reached, the board computer triggers the actuator to release the recovery parachute which is inflated by the help of a smaller auxiliary parachute. A pre-stressed spring mechanism helps to release the parachutes. An optional payload may be included in the electronics compartment. Following a design update, a second telemetry unit will be used. It is completely designed and built by students and already successfully tested during the upper stage launch campaign at Kiruna. The electronics determine the rocket orientation, measure temperatures, the altitude, and the rocket's position. All data will be transmitted to ground via 3G network or W-LAN.
Before this summer's test flight, several modifications concerning the lower stage were made. Most of them focused on a more user friendly integration. The casing tube was split and a smaller part mounted via a new set of rings to the end of the vessel. In case of a leak in the nozzle area, the surrounding part of the casing tube can be removed easily and additionally the other components will not be affected as much by hot water vapor.
The tail fins and compartment structures had to be moved into flight direction, changing the aerodynamic behavior. Simulations have shown aerodynamic instability of the current configuration. Therefore, the tail had to be iterated.

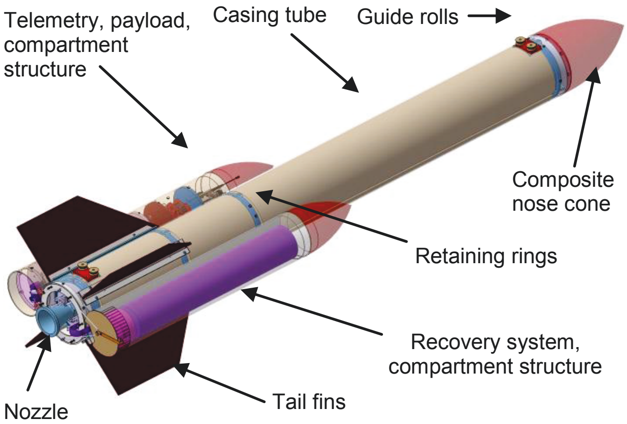

Figure 3 Current development status of TU-Berlin's DECAN's lower stage.

3.2 Trajectory Simulation

The trajectory simulations were done with the open source program OpenRocket. If only the lower stage is launched, calculations of the trajectory predict a peak altitude of 533 m at a take-off weight of 95.5 kg and a launch angle of 80°. The maximum speed will be approximately 89 m/s (0.26 Mach) at a maximum load factor of 1.9 g.

Parameter	Lower Stage
Rocket type	Hot water propulsion
Motor manufacturer	TU Berlin
Propellant	Water (29 liters)
Scientific payload	Telemetry system, positioning and locating system, cameras, heat and altitude measuring
Nominal diameter	ca. 0.2 m
Length	ca. 2.2 m
Liftoff-Mass	95 kg
Average thrust	Ca. 2.2 kN
Burning time	5 s
Maximum acceleration	1.9 g
Apogee altitude	533 m (single-staged)
Minimum stability margin	1.8(@0.26 Mach)

TAB 1. Technical data sheet of the lower stage

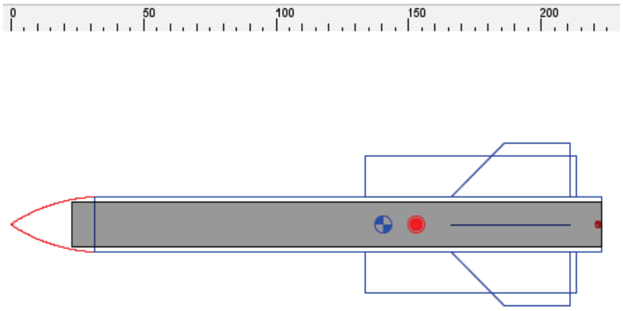

Figure 4 Sketch of DECAN'S lower stage in OpenRocket.

The motor's thrust curve had to be estimated roughly. Therefore, it is an estimation based on experience with similar motors. The basic values of the motors, used for the simulations are:

- Total impulse: 1100 Ns
- Average thrust: 2210 N
- Burning time: 5 s
- Motor take-off mass: 75 kg
- Motor empty mass: 46 kg

The estimated thrust curve, used for the trajectory simulation is shown in figure 5:

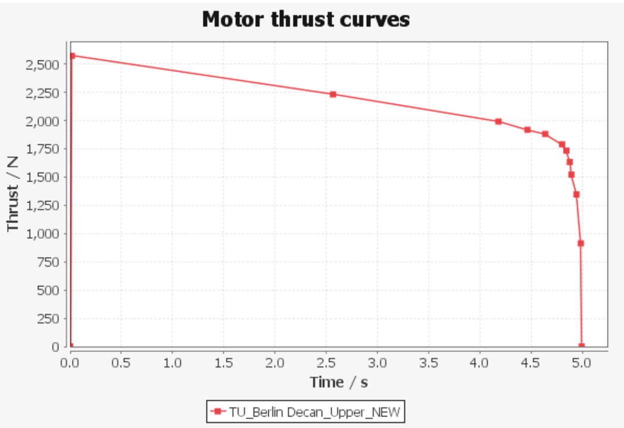

Figure 5 Estimated thrust curve of DECAN'S lower stage

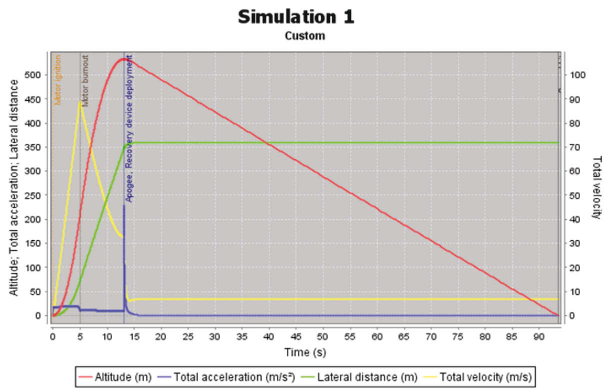

Figure 6 Total acceleration (blue), altitude (red), total velocity (yellow) and lateral distance (green) as a function of time

The output of the trajectory simulation is shown in figure 6.

It can be seen, that the end of burning time goes along with a turning point of the altitude graph. The speed is at the end of the burning time at its maximum (90 m/s). After that, it decreases till reaching the apogee. Due to the release of the parachute in apogee and subsequently its unfoldment, the rocket's acceleration through gravitational force is stopped after a few seconds. The velocity of fall is relatively constant from t=13 s (533 m) till reaching the ground. The landing speed is approximately 6.61 m/s. Therefore, the motor and most of the subsystems should be unharmed. The essential output parameters of this flight are given in table 2:

Parameter	**Lower Stage**
Max. altitude	533 m
Flight time	93.4 s
Max. speed	90 m/s
Max. acceleration	19 m/s^2
Max. Load factor (G-Load)	1,9
Time to apogee	13.1 s
Ground hit velocity	6.61 m/s
Lateral Distance	360 m

TAB 2. Output values of the trajectory simulation

As of today, the center stage is already fully integrated, while the DECAN team is focused on integration of the recovery and telemetry/payload compartment.
Meanwhile several tasks were accomplished to enhance the future success rate, concerning the QMS, tests and protocols. Also special tools were designed to ensure a optimized and standardized integration of the lower stage.

3.3 Electronics Ground Segment

The lower stage is loaded with an FPGA (field programmable gate array) used as an On-board computer appointed with an IMU (inertial measurement unit) to measure all relevant flight parameters such as acceleration, altitude and angular velocity. It also transmits collected data to the ground via downlink. The lower stage also provides visual information by giving the opportunity to mount a handful of cameras onto the tank in which there is no chance of real time videos. Instead, each camera includes an up to 32 GB memory card for storing graphical material which can be evaluated after the landing.
Before take-off, pressure and temperature can be monitored and saved for safety reasons. Thereby one pressure measurement unit and two thermometers are being used to collect the data from the inside of the tank. All supporting electronic devices for the sensors such as power supplies and amplifiers are kept in an external container where all components are protected from water. The plug-and-play design of the box makes it easy for new students to understand and fast to learn, use and assemble, in which colorized wires and plugs are very responsive components for this task. Once assembled, the sensor data will be captured by a data acquisition system to automatically write all collected measurement values to an excel file where pressure and temperature have been plotted in real time. Since there is one continuing file, all graphs from past tests and launches can be compared with the latest results.

4. UPPER STAGE

The upper stage is equipped with a solid propellant rocket motor which is mounted between two structural rings inside the outer aluminum alloy shell tube. Four fins are spread circumferentially at the tail section of the rocket to ensure an aerodynamically stabilized ballistic flight trajectory. A recovery system is responsible for the safe return and recovery as part of the STERN requirements. This system is controlled by the integrated electronic system, which has to comply with the ESRANGE Safety Manual [1] as well. Below, Figure 4 illustrates the cross section of the rocket and depicts its particular sub-systems on a detailed part level.

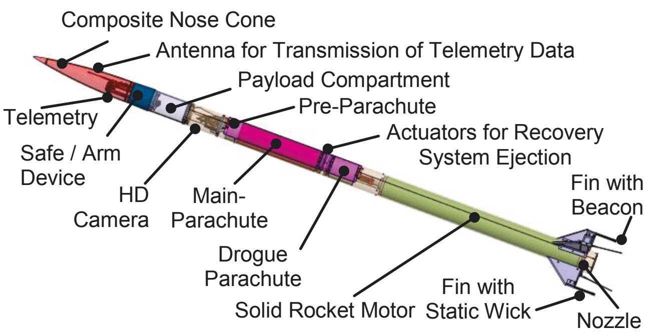

Figure 7 DECAN upper stage rocket and its main components.

The unguided sounding rocket carries a payload to an altitude of up to 6.5 km when launched independently from the lower stage. The payload consists of both a commercial and an in-house developed telemetry system.

Parameter	Upper Stage
Rocket type	Solid propellant
Scientific payload	Telemetry system, video camera
Nominal diameter	ca. 0.1 m
Length	ca. 2.9 m
Dry Mass	17,3 kg
Maximum thrust	3 kN
Burning time	7 sec
Maximum acceleration	14 g
Predicted apogee	6.5 km (@ 90°) 5,9 km (@ 80°)
Minimum stability margin	2.1 cal (@ 2.1 Mach)

TAB 3. Upper stage technical data sheet

Preliminary tests of the DECAN-X rocket have shown high survivability of the attached fins, even in an event of a malfunction within the recovery system. Hence, beacons for ranging have been installed within the Fins.

4.1. Preparation

The high power solid rocket motor has been selected to power the DECAN rocket and has been qualified for integration and flight readiness. Independent tests have been performed at a DLR site in Trauen to verify that the mission and test requirements will be met. The tests depict stable engine combustion with an average thrust time of 7 seconds. The maximum measured thrust is reached after 1.4 seconds.

To ensure the functionality of the telemetry under real time circumstances, a compulsory flight test for verification was necessary. Therefore, the Technische Universität Berlin used a small experimental test rocket of the DECAN rocket family, named DECAN-X. All data have been successfully saved and sent to ground. The pyro events (recovery system) have been triggered according to plan.

The recovery system will be triggered by the rocket's telemetry system. At apogee, the drogue parachute will be ejected in order to provide a controlled descent of the stage to an altitude of 500 m. At this altitude, the main igniter will initiate the pyro-actuator for a deployment of the main parachute. The main recovery system of the rocket consists of a main parachute and an auxiliary parachute. The auxiliary parachute is connected to the cover of the recovery system with a leash. Once the panel flap is unlocked, it opens through a pre-stressed spring mechanism and pulls the auxiliary parachute out of its chamber. The auxiliary parachute pulls the main parachute, which is connected with a leash and a shackle to the upper motor closure. The recovery system has been successfully tested under laboratory conditions. Wind tunnel tests could not be performed.

The air path speed limit for the drogue parachute at an altitude of 6,000 m has been estimated with 356 m/s. The air path speed limit for the auxiliary and the main parachute at an altitude of 500 m has been estimated with 125 m/s and 67 m/s respectively. These speeds must not be exceeded in order to prevent parachute disintegration. The trajectory of the upper stage is plotted in Figure 8. At the time of parachute ejection the air path speed is lower than the calculated limits.

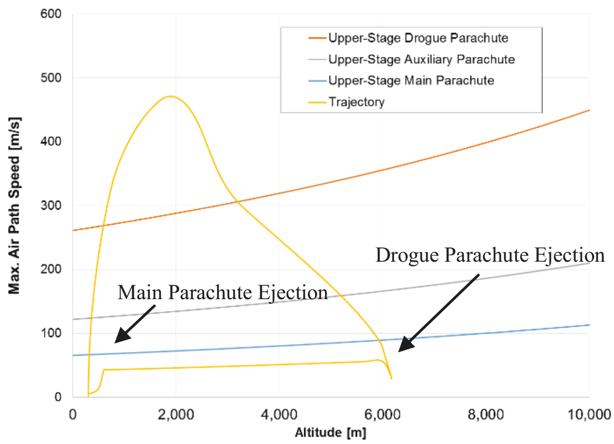

Figure 8 DECAN upper stage rocket and its main components

4.2. ESRANGE Launch

The DECAN upper stage has been launched in a single-staged configuration at the ESRANGE facility near Kiruna (Sweden) in mid-October 2015 within the STERN launch campaign. During the campaign, the EQM and the PFM of the upper stage were launched. Both models are fully identical. The EQM has been build using the EM. The FM was built shortly before launch. This approach ensured that at least one rocked is launched to avoid a failure of the launch campaign if a rocket is damaged during transport. At the ESRANGE facility, the Medium Range Launcher (MRL) was selected. The MRL is stored in a protective house with a removable roof.

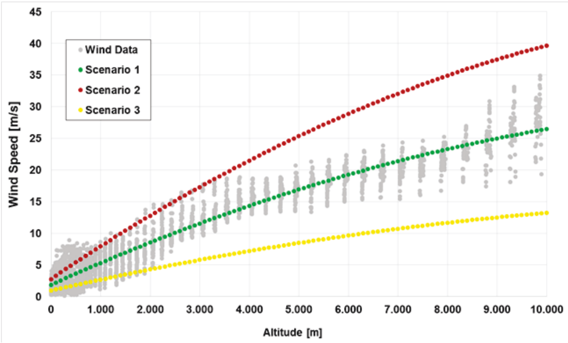

Figure 9 Wind Scenarios 1-3 displayed in wind speed above the altitude

The flight path was simulated using the software ASTOS Release 7.1. The mean wind conditions (Scenario 1) for the launch site Kiruna were provided by the Swedish Meteorological Service (SMHI). To estimate the flight path for lower and high wind conditions, the calculation was also done using 150% (Scenario 2) and 50% (Scenario 3) of the provided wind velocity as shown in Figure 9. The calculation was done for wind directions from 0° to 340° with 20° steps.
TAB 4 displays the critical flight events. According to the flight plan the drogue parachute was intended to be ejected shortly after the apogee is reached to reduce the shock caused by the opening of the parachute. The drogue chute assures a constant sinking rate. 500 meter before impact, the main parachute was set to be ejected. The main parachute reduces the sink velocity to less than 5 m/s to ensure minimum damage during the impact.

Event ID	Flight Time [sec]	Description
01	0.3	Rocket leaves the rail
02	2.8	Mach 1.0
03	5.3	Max. Dynamic Pressure
04	35	Apogee
04	36	Drogue Parachute Ejection
05	150	Main Parachute Ejection
06	180	Landing on Ground

TAB 4. Upper stage critical flight events (calculated)

The main performance data are summarized in the table below.

Parameter	Calc.	SHARK-I	SHARK-II	Unit
Apogee	5880	5550	5700	m
Time to Apogee	35	30	32	sec
Total Flight Time	180	71	80	sec
Max. Mach Number	1,4	1,3	1,3	-
Max. Flight-Path Velocity	440	400	410	m/s
Max. Load factor (G-Load)	13	10,2	10,5	-
Max. Dynamic Pressure	121	100	105	kPa

TAB 5. Upper stage flight performance

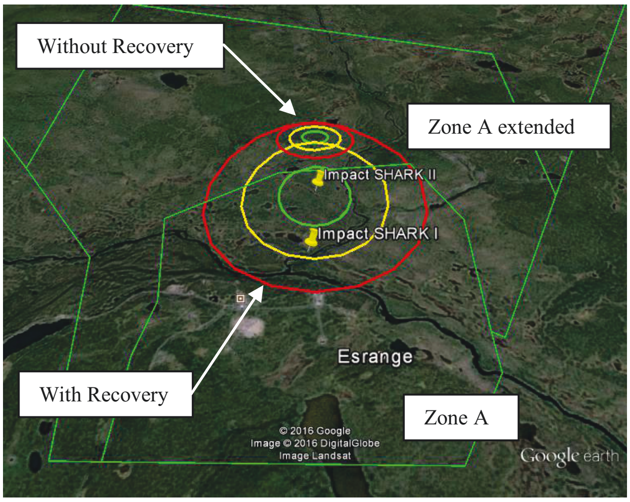

Figure 10 Estimated landing zones of the upper stage

The landing area at the ESRANGE facility is structured in 4 zones. As the zones B and C would have to be evacuated, the DECAN rocket has to land within zone A and zone A extended, shown in Figure 10. The DECAN upper stage will land within zone A or zone A extended considering all defined scenarios. The impact areas are shown for each wind velocity in Figure 10.
Figure 11 displays the calculated flight path (yellow) and the real flight path of the SHART II (green/black). During the calculation, the wind direction was set from south, while during the flight a northern wind was dominating. Therefore the rocket glided back to zone A during the flight.

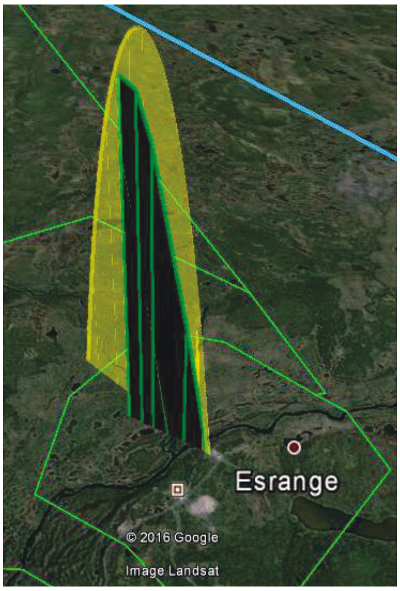

Figure 11 Upper flight path displayed in Google Earth for a low wind velocity from the south

Figure 12 to Figure 14 show the measured data of the actual flights. Due to a complex design of the parachute ejection mechanism, the main parachute of SHARK I and

II as well as the drogue parachute of SHARK I did not open during flight. Hence the data is compared to a nominal trajectory without recovery system. Considering the high impact velocity of the SHARK I rocket, it was not possible to find and secure the EQM. Due to the opened drogue parachute of the SHARK II, the rocket could be secured. The upper part was highly damaged; hence only transmitted flight data could be used.

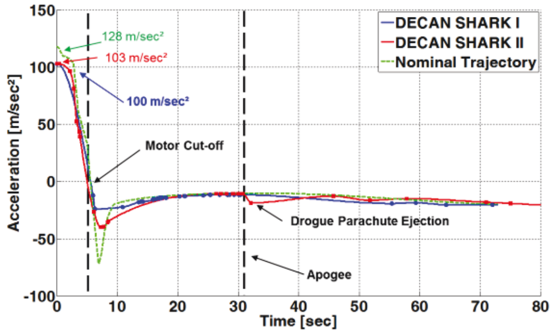

Figure 12 Acceleration of test rockets

The figure above displays the actual as well as the nominal acceleration. The high start acceleration driven by the solid fuel motor drops rapidly after the fuel is burned. After less than 8 seconds the speed shown in Figure 13 has reached its maximum. The acceleration then stabilizes after 20 seconds and stays constant negative till the impact.

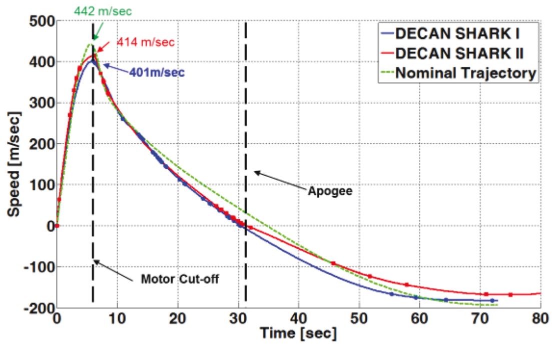

Figure 13 Speed of test rockets

30 Seconds after launch, the SHARK I & II rockets reached the apogee. With an altitude of 5703 m, a new record for German student rockets has been set.

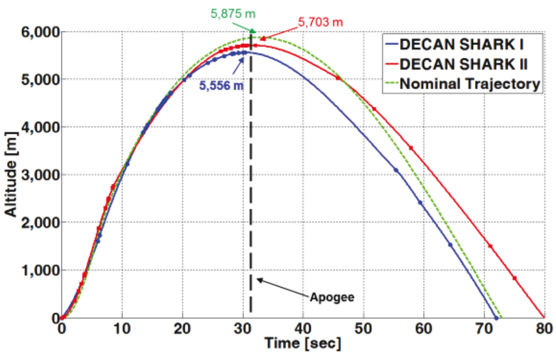

Figure 14 Altitude over ground of test rockets

Due to a difficult telemetry connection from the ground station to the rockets, the recording of measured points was not fully continuous. Still it confirms the calculations done pre flight and the overall design of the DECAN Rockets. The minimal disparities result from the natural wind conditions which could not be fully resolved in the calculations.

5. 3D-PRINTED ROCKET

In order to assure an ongoing development of solid propellant rockets and frequent launch campaigns the project costs have to be optimized. Hence, the rocket design and campaign costs have been identified to bear the highest potential of cost reduction.

5.1. Rocket design

The SHARK rockets have been designed for traditional manufacturing processes. Therefore, hundreds of small parts had to be assembled to lager components. These small parts have been manufactured by milling machines causing high personal effort. The selective laser sintering allows to 3D-print whole rocket segments as one part. Instead of manufacturing and assembling hundreds of parts, five rocket segments will be printed and easily assembled. The new rocket design will be inspired by the SHARK rockets containing slight changes regarding aerodynamics and lightweight construction. The main differences to the original design are the increasing diameter of the main tube from 110 mm to 114 mm and a decreased lift-off mass of 4 kg in total. The rocket will be able to carry three different motor sizes to ensure maximal flexibility.

Parameter	Upper Stage
Rocket type	Solid propellant
Scientific payload	Telemetry system, video camera, CanSat
Nominal diameter	ca. 0.11 m
Length	ca. 2.9 m
Dry mass	13 kg
Primary structure mass	4,5 kg
Maximum thrust	4 kN
Burning time	7 sec
Maximum acceleration	17 g
Minimum stability margin	1,7

TAB 6. 3D-Printed rocket technical data sheet; design criteria

5.2. Material tests

The selective laser sintering technology is still relatively new. There is still a lack of knowledge regarding standards and databases. Hence, the quality of manufactured parts depends on the used printer and settings. Therefore, material tests have been performed at Fraunhofer Applications Centre for Large Structures in Production Technology AGP according to DIN EN ISO 527-2. The samples were kindly sponsored by Fabb-It. During motor tests, the heat build-up outside of the motor case stayed under 20 K and of the nozzle under 70 K. Hence, synthetic materials can be used for the primary rocket structure. To ensure a low-cost production, only adequate materials under 1,5 €/cm³ production cost were picked. Four print directions where investigated. Tree directions have been printed in the xy-plane to investigate the homogeneity of the material. The fourth direction is upright to investigate the merge of the layers. The empirical variance of the samples has been under 5 %, demonstrating high quality and reproducibility of the samples.

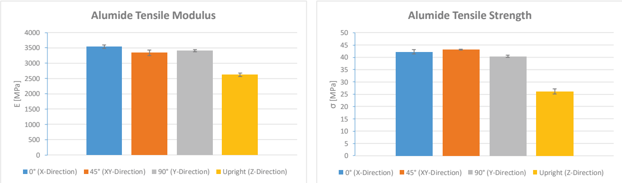

Figure 15 Tensile Modulus and Tensile Strength of Alumide depending on print direction

The influence of the print direction can be seen in Figure 15. While all samples within the xy-plane have roughly the same value, the upright direction differs from the others. The tensile modulus louses 24 % and the tensile strength 38 % if printed upright. Figure 15 illustrates that the alumide layers do not merge perfectly. This effect is constant with a low empirical variance and can therefore be considered for structural design measures.

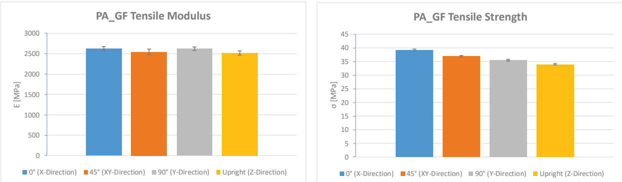

Figure 16 Tensile Modulus and Tensile Strength of PA-GF depending on print direction

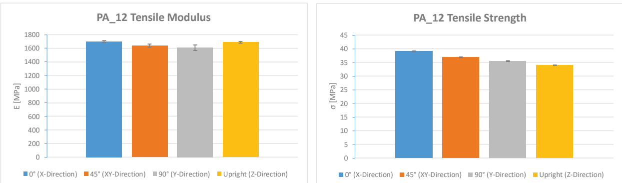

Figure 17 Tensile Modulus and Tensile Strength of PA-12 depending on print direction

The Tensile Modulus and Tensile Strength of PA-12 and PA-GF do not depend significant on the print direction, as can be seen in Figure 16 and Figure 17. A strong shrinking of PA-GF due to the cooling process after manufacturing, leading to furrows, could be witnessed.

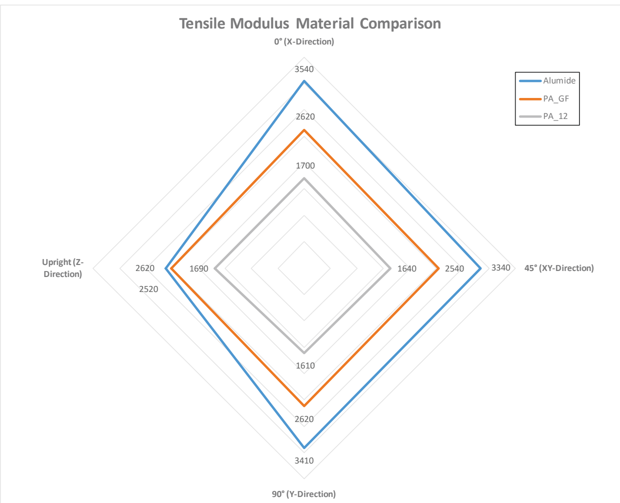

Figure 18 Tensile Modulus material comparison depending on print direction

Alumide offers the best tensile modulus, even though it's nearly identical with PA-GF if printed upright.

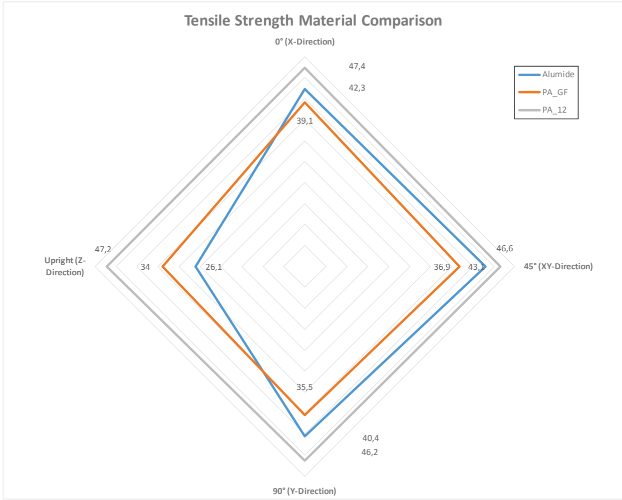

Figure 19 Tensile Strength material comparison depending on print direction

PA-12 offers the best tensile strength in all directions with approximately 47 MPa. The downside of alumides upright print direction can be seen in Figure 20.

5.3. Flight performance

Simulations with three different motors have been performed. Due to good experience during tests in the DLR facility at Trauen and the successful launches of SHARK I & II, only similar motors were investigated.

Parameter	Motor A	Motor B	Motor C	Unit
Propellant mass	7,7	5,3	4	kg
Apogee (@ 80°)	6,2	4,8	3,9	km
Time to Apogee	31	30	26	sec
Total Flight Time	400	370	360	sec
Max. Mach Number	1,7	1	1,2	-
Max. Flight-Path Velocity	540	330	370	m/s
Max. Dynamic Pressure	180	70	85	kPa
Max. Load factor (G-Load)	14,5	6,9	9,7	-
Landing Speed	3,5	3,4	3,3	m/s
Lateral distance	2,0	2,0	1,3	km

TAB 7. 3D-Printet rocket flight performance

The motor choice affects not only the maximal altitude, but also the maximal dynamic pressure and the maximal acceleration, leading to different structural loads. These loads will be calculated in chapter 5.4. The ability to choose the apogee and lateral distance offers a more flexible choice of launch sides

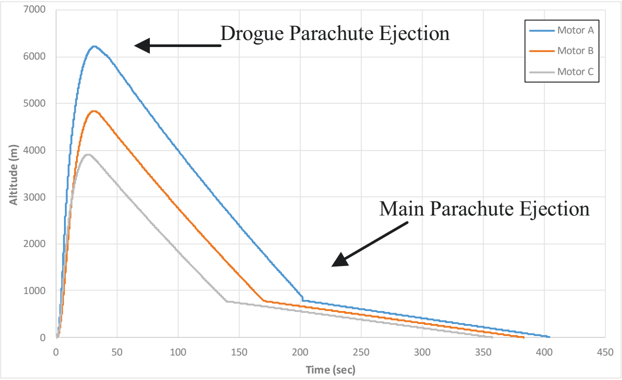

Figure 20 Simulated flight of 3D-Printed rockets with three different motors

5.4. Structural calculation

The knowledge gained from material tests and aerodynamic calculations can be used to perform first structure analyses. TAB 8 shows the safety factors of the primary rocket structure with a wall thickness of 3 mm.

Parameter	Motor A	Motor B	Motor C	Unit
Maximal load	7,7	3,3	3,9	kN
Alumide:				
Safety factor up to yield point	5,6	12,9	10,9	-
Safety factor against buckling	2,1	4,8	4,0	-
PA-GF:				
Safety factor up to yield point	4,8	11	9,3	-
Safety factor against buckling	1,6	3,6	3,0	-
PA-12:				
Safety factor up to yield point	6,5	15,2	12,7	-
Safety factor against buckling	1	2,4	2	-

TAB 8. Safety factors of 3D-Printet rocket structure; 3 mm thick pipe

It can be seen, that the critical property is the safety against buckling. Luckily, the 3D-printing offers easy possibilities to stiffen the rocket using a honeycomb sandwich structure. The design will be finalized in the near future.
Based on these considerations, and taking into account the low production cost, 3D printing offers a great potential for future rocket projects.

5.5. Possible Launch Sides

To assure an ongoing development of solid propellant rockets with affordable launch campaigns, the project costs have to be optimized. Hence, possible launch sides within Germany have been investigated.
The main priority for every launch is safety. The only possible area for a rocket launch in a quite populated country as Germany are restricted areas. The required area would have to satisfy three main criteria: A possible flight allowance up to the apogee, enough lateral space to ensure a safe landing and a sufficient infrastructure to ensure the safety of the launch team.
Together with the air traffic control and the German armed forces five possible launch sides have been identified. We will publish the final launch side as soon as the negotiations have reached the final state.

6. CONCLUSIONS

This work describes the current development of the DECAN rocket at the Technische Universität Berlin. The different components of the rocket were explained in detail. Features such as the newly developed 3D-printed rocket were shown. Future work shall be focused on further qualification of components such as the recovery System. Test flights of the lower stage are scheduled for the next months.

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