Systematic Design of a Parachute Recovery System for the Stratos III Student Built Sounding Rocket

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In the summer of 2016 a group of students from Delft Aerospace Rocket Engineering (DARE) started a project to reclaim the European altitude record for amateur rocketry currently set at 32.3 km by HyEnD. This project was named Stratos III as a follow-up on Stratos II+. To recover the flight data, video footage, payload and valuable hardware, the nose cone would have to be recovered. The Stratos recovery team, consisting of Bachelor and Master students from the TU Delft, was tasked with this job.

During the conceptual phase it was decided to separate the rocket just before it will enter the atmosphere and only recover the nose cone. Removing the mass of the empty tank and engine reduces the difficulty of recovering the flight data, as well as the required mass of the recovery system. Additionally, it would create an aerodynamically unstable nose cone. Upon contact with the atmosphere, the nose cone will enter a flat spin with a frequency of 2 Hz, this bleeds off velocity thus making recovery easier.

At an altitude of 4000 meters a Hemisflo ribbon drogue parachute will be deployed. This type of parachute is designed to handle the high dynamic pressures and supersonic conditions encountered during the flight. To be capable of handling the high temperatures which are experienced in supersonic flight, the drogue parachute is made out of aramids. Due to the spin experienced by the nose cone it is required to eject the drogue such that the suspension lines are stretched within half a revolution of the nose cone. This is achieved using a cold gas deployment device. The drogue parachute ensures that the nose cone is stabilized and slowed down to subsonic velocities which assures the main parachute will be deployed in its operating envelope. The main parachute is a cruciform parachute with its corners attached. The aspect ratio of this parachute is 0.7, which ensures a high drag coefficient combined with sufficient oscillatory stability. To determine whether the entire recovery system was capable of handling all possible flight conditions a grid search simulation was done to find the operational limits of the system. It was seen that the inflation load of the drogue parachute was highly sensitive to changes in the altitude and velocity at apogee. These simulations showed that there are possible cases where the inflation loads of the drogue parachute approached the structural limit of 10 kN, however none of the flight cases crossed the maximum loads. This system gives the team confidence that the flight hardware will be recovered.

Nomenclature

A.R.   aspect ratio
CGDD   Cold Gas Deployment Device
DARE   Delft Aerospace Rocket Engineering
ISA   International Standard Atmosphere
ParSim Parachute Simulation Tool
PLA   Polylactide

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I. Introduction

Delft Aerospace Rocket Engineering (DARE) is a student rocketry society that aims to reach space and get students involved in rocketry. In 2009, DARE set the European amateur altitude record with the Stratos I rocket at 12.5 km.[1] The record was updated with the launch of Stratos II+ in 2015 to an altitude of 21.5 km.[2] When the German team HyEndD set the record at 32.3 km[3] in 2016, DARE started project Stratos III to reclaim the European amateur altitude record.

The Stratos III recovery system aims to safely retrieve the fight data, video footage and payload. The project aims to be completed within one year. These mission statements lead to a set of top level requirements, these can be seen in Table 1.

Table 1: Driving requirements of the recovery system

Rec - 1	The recovery system shall be capable of providing a landing velocity of less than 20 m/s
Rec - 2	The recovery system shall be capable of handling a maximum apogee of 130 km
Rec - 3	The recovery system shall be capable of handling a minimum apogee of 30 km
Rec - 4	The recovery system shall have a maximum mass of 8 kg excluding external hull
Rec - 5	The recovery system shall fit in a cylinder of 400 mm height
Rec - 6	The recovery system shall be capable of recovering a nose cone of 20 kg
Rec - 7	All structural elements in the recovery system shall have a safety factor of 2
Rec - 8	The maximum force of the drogue parachute on the structure shall be less than 10 kN
Rec - 9	The maximum force of the main parachute on the structure shall be less than 4 kN
Rec - 10	The system shall be flight ready within 12 months

A plot showing the apogee ranges mentioned in Rec - 2 and Rec - 3 can be found in figure 1. Furthermore, the general information on the nose cone can be found below.
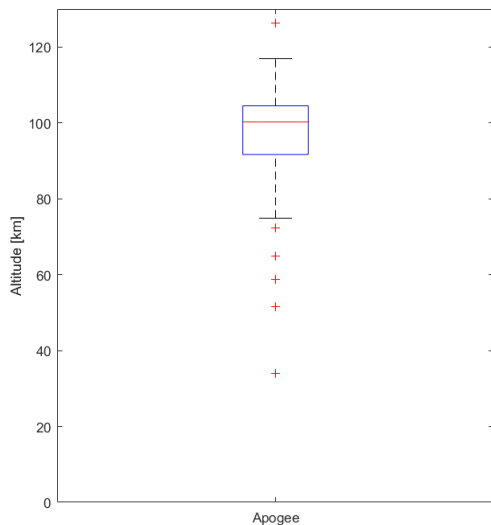
General information on the Stratos nose cone:

- Mass: 20 kg

- Length: 1.4 m

- Maximum structural load (drogue parachute): 10 kN

- Maximum structural load (main parachute): 4 kN

- Velocity at apogee: 330 m/s

- Rocket Diameter: 0.278 m

Figure 1: Preliminary apogee projections for Stratos III

The team performed a conceptual design study to determine the potential recovery systems for the mission. The next step was the preliminary design phase, during which the individual subsystems were broken down into further detail. Small scale testing was performed to validate the assumptions. The preliminary design phase was followed by the detailed design phase where the system and all subsystems were designed. During this phase the large scale testing, such as wind tunnel, tensile and flight tests, were performed. All wind tunnel tests were performed at the TU Delft Open Jet Facility. After the detailed design, a grid search was done to show that all foreseeable trajectories stay within the system envelope.

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II.   Conceptual Design

In order to design the recovery system a ground up approach is used. This means the flight was analyzed in reverse, starting from the landing conditions. It was determined that the rocket would almost certainly come down in water, which lead to a maximum landing velocity of 20 m/s (Rec - 1).

For Stratos II+, the intention was to recover the entire rocket, however due to unexpected events the tank and engine section was lost. As the flight data is located in the nose cone it was decided for Stratos III to only recover this section and allow the tank and engine to splashdown into the ocean. The separation of the nose cone and tank section has the added advantage, that the nose cone is intrinsically aerodynamically unstable. This means that it will enter a spin and therefore bleed off velocity.

In order to reduce the risk of collision between the nose cone and tank, it was desired to separate at low dynamic pressure, hence a separation altitude of 65 km was selected. According to the International Standard Atmosphere (ISA), the air density at this altitude drops to 0.01 % of sea level. Nearly all trajectory simulations performed in the conceptual design phase indicated that the apogee of the rocket would exceed 65 km, as can be seen in Fig. 1. In order to comply with Rec - 3, the system should be able to function at lower altitudes as well.

A render of the nose cone can be found in Fig. 2a. The figure shows the location of the electronics and payload. The bottom section of the nose cone is referred to as the recovery bay, a render of this can be found in Fig. 2b. This bay houses the parachutes, parachute deployment systems, and parachute attachment points.

(a) Cross section of the Stratos III nose cone
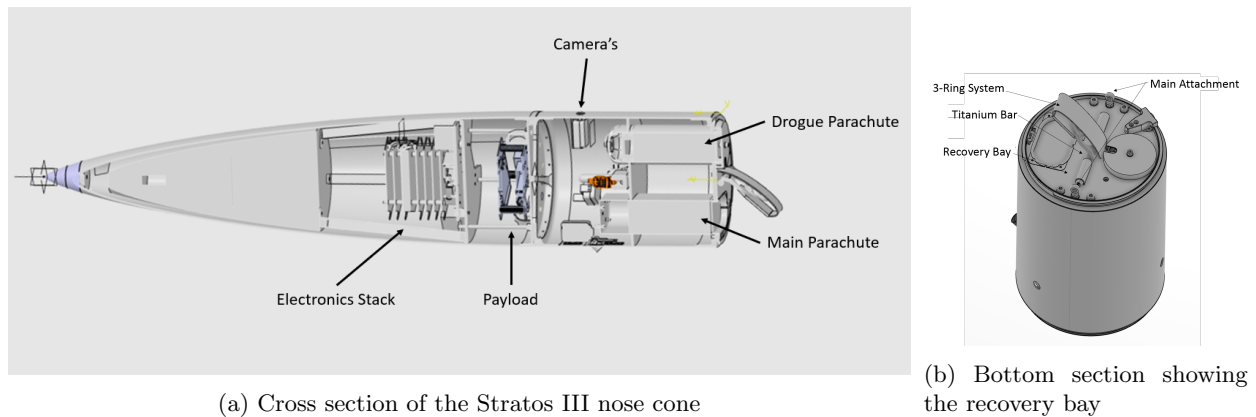
(b) Bottom section showing the recovery bay

Figure 2: Renders of the Stratos nose cone

As there was still significant uncertainty in the apogee altitude and horizontal velocity at apogee, the highest estimates were used in the simulations. Apogees were taken at 80, 100, and 120 km with a horizontal velocity of 330 m/s, as were determined by the Stratos Simulations team. The location of the centre of gravity and centre of pressure of the nose cone are unknown, hence all simulations have been done using an angle of attack of zero as the worst case scenario. The various configurations were run through the DARE Parachute Simulation tool (ParSim), which determined the free fall trajectories of the nose cone. The drag peaks in Fig. 3 are the result of the body drag of the nose cone.

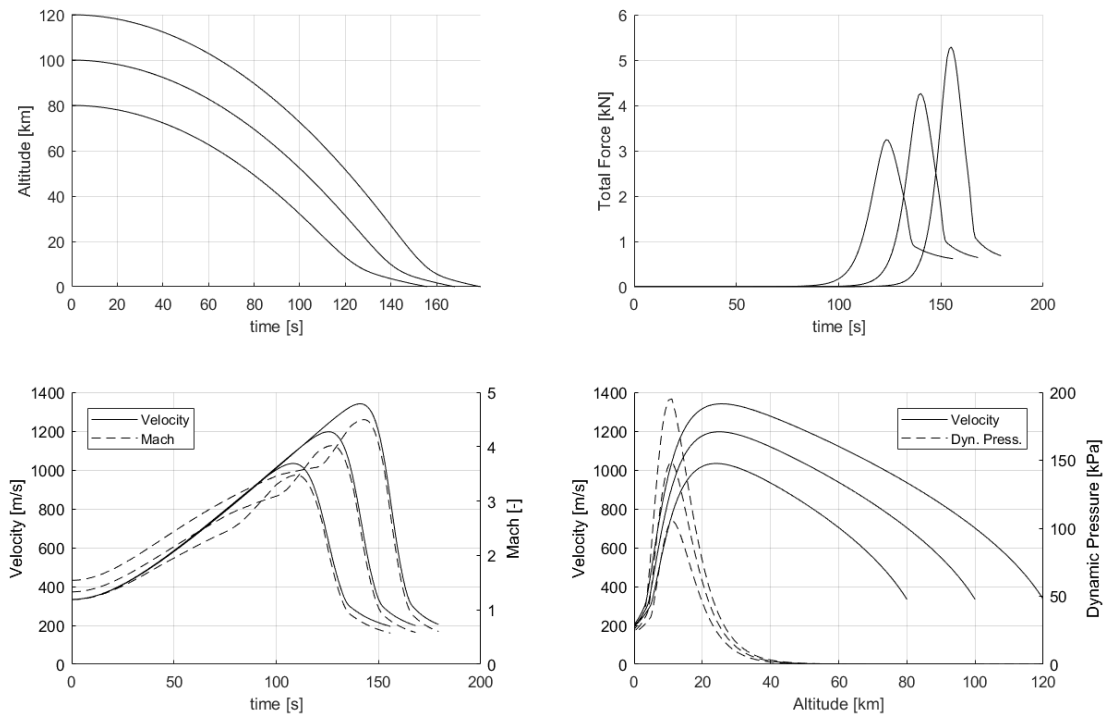American Institute of Aeronautics and Astronautics

Figure 3: Free fall trajectory of the recoverable mass for initial altitudes of 80, 100, and 120 kilometres. The body is assumed to be in a stable, nose down orientation

During the conceptual phase multiple concepts were considered, which can be found in Fig. 4. Clustering parachutes was discarded at the onset of the project because of the added complexity and the lack of significant benefit due to the small size of the system.

For Concept 1 indicated in Fig. 4, the only feasible drogue parachute option is a Ballute. This is due to the high Mach range and low dynamic pressure, as can be seen in Fig. 3. For Concept 2 the most feasible parachute for this project is the Hemisflo ribbon parachute, since it has a relatively high drag coefficient, can function up to Mach 3[4] and has been researched previously within DARE. For all subsonic main parachutes, a cruciform parachute is selected due to ease of manufacturing and flight heritage in DARE.
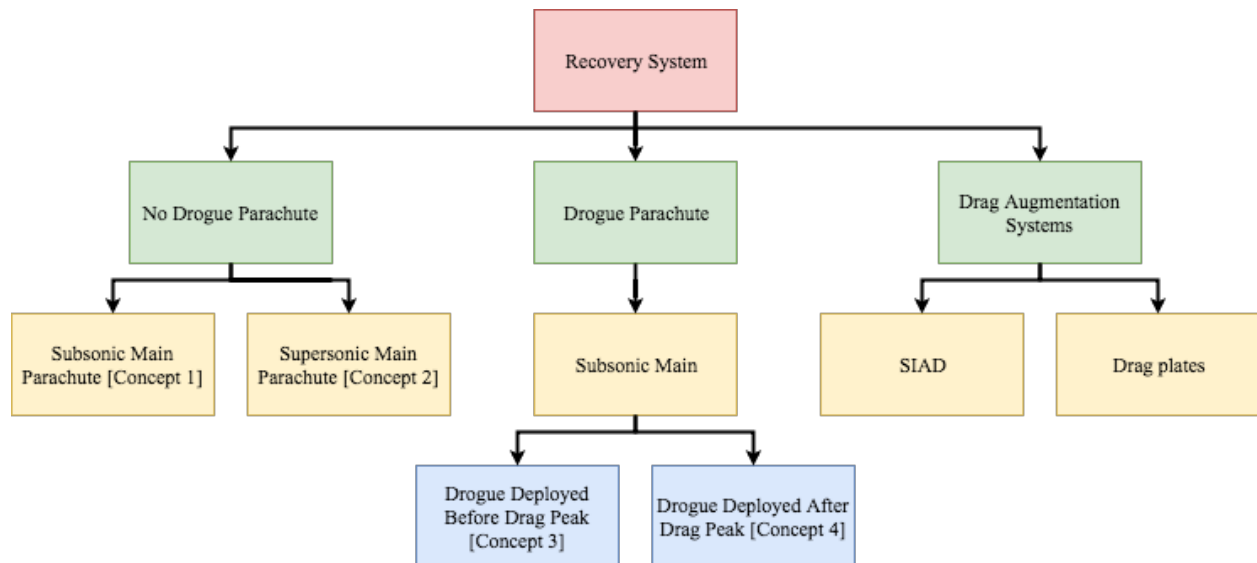

Figure 4: Recovery concept discovery tree

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The drag augmentation systems were discarded due to volume constraints in the recovery bay. This left four feasible concepts. All concepts were judged on four criteria: if it can perform in the Mach range, if the inflation loads lie within the requirements, if there is sufficient literature available on the systems and if there is any design and/or production experience within DARE. The Mach range was taken from the available literature, where as the inflation loads were calculated using the DARE ParSim tool. The results can be seen in Table 2.

Table 2: Design option considerations for the Stratos III recovery system

ID	Concept 1	Concept 2	Concept 3	Concept 4
Complies with Mach range?	No	Unsure	Yes	Yes
Inflation loads below 10 kN?	No	Unsure	Yes	Yes
Sufficient literature available?	Yes	Yes	Scarce	Yes
Experience within DARE?	Yes	No	No	Yes

Whilst a single stage subsonic recovery system would reduce the mass and complexity of the overall system, it is discarded due to non compliance with the Mach range. A single supersonic parachute was discarded due to the uncertainty in inflation loads and lack of manufacturing experience in large supersonic parachutes. Therefore, both single stage parachute options are discarded.

To reduce the inflation loads and Mach range of the main parachute, a drogue parachute is required. Concept 3, using a Ballute parachute has the advantage that deployment can be done above the atmosphere and therefore reduce the inflation loads, this however would require an integrated inflation system. Complexity and lack of literature on Ballutes made it unfeasible to design it within a year as stated in Rec - 10. Therefore Concept 4, a combination of a Hemisflo ribbon parachute and a cruciform main parachute, was selected. The system meets all requirements and additionally DARE has substantial experience in the design, production, and operation of such a system.

II.A. Parachute Deployment

During the Stratos II+ flight, it was seen that the nose cone went into a flat spin of about 2 Hz. Literature suggest similar behaviour in other sounding rocket missions.[5] This leads to the conclusion that the Stratos III nose cone will show similar behaviour. Deploying the drogue parachute whilst in a flat spin introduces the risk of entanglement of the parachute wires around the nose cone. This introduced the need for a high speed deployment system that ensures line stretch before entanglement can occur. It was decided to use a Cold Gas Deployment Device (CGDD), as DARE had experience with such a system from previous missions. A pyrotechnic system was excluded due to safety concerns.

From literature, it was seen that a nose cone would find a stable orientation at low subsonic speeds, therefore the main parachute would not have to be ejected at high speed. A spring deployment system was chosen for its simplicity and flight heritage from Stratos II+.

II.B. Actuation Logic

Due to the limited amount of communication between the ground and the rocket, it was decided that the parachute deployment would be initiated using a combination of a static pressure port and a time window. The deployment logic can be found in Fig. 5.
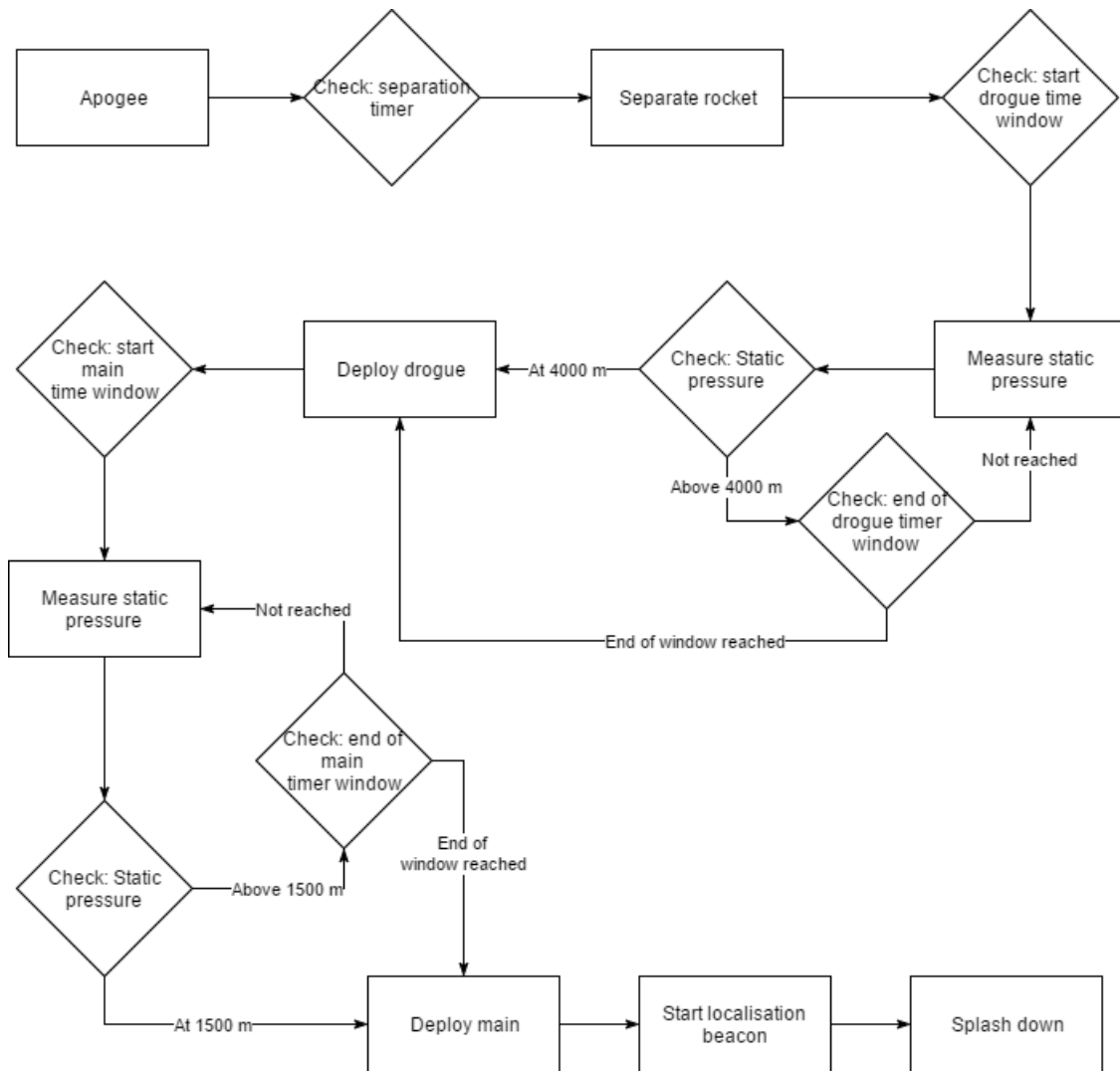
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Figure 5: Recovery logic flow diagram

II.C.   Concept Overview

The flight sequence and the concept trade-off gives a system that requires two parachutes to safely decelerate the Stratos III nose cone to landing velocity. This leads to the following driving requirements on subsystem level, which can be found in Table 3.

Table 3: Driving requirements for different subsystems

Drogue Parachute	Shall be able to function up to Mach 3.0
	Shall keep the inflation load less than 10 kN
	Shall be able to bring the nose cone to below Mach 0.4
	Shall be able to stabilize the nose cone
Main parachute	Shall ensure a landing velocity of less than 20 m/s
	Shall keep the inflation load less than 4 kN
Drogue deployment	Shall ensure an ejection velocity of 20 m/s
	Shall be able to accommodate both the drogue parachute including wiring
Main deployment	Shall be able to deploy without the assistance of the drogue parachute
	Shall be able to accommodate both the main parachute including wiring

III. Detailed Design

III.A. Cold Gas Parachute Deployment Device

The challenge of the drogue parachute deployment is to ensure that the parachute is deployed before the nose cone completes half a rotation to prevent the parachute from entangling with the nose cone. This resulted in a required ejection velocity of 20 m/s.

The system consists of a feed system based upon 16 grams of CO_2 stored at 60 bars. This gas expands to fill the breech volume. Six M4 nylon bolts hold the lid in place, until sufficient pressure is built up to shear the bolts. At that moment the parachute/sabot combination is expelled and the parachute is released from the nose cone. A schematic overview of the CGDD can be seen in Fig. 6.

Figure 6: Render of the CGDD

The system underwent several iterations and test campaigns. The results of one of the earlier, 100 mm diameter version can be seen in Fig. 7. In the plot the pressure build up of inside the breech volume can clearly be seen. At a pressure of just over 4 bars the nylon bolts shear and the drogue parachute is released. From Fig. 7, it can also be seen that the reaction load of the system reached about 2kN.
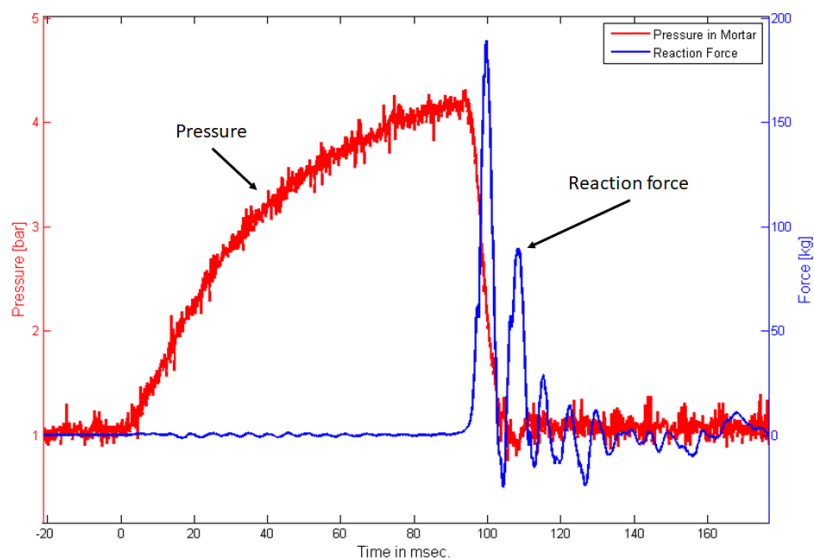
Figure 7: Results of a test fire of an early 100 mm version

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During these tests the system was finalized and updated based upon the findings. To enable better integration with the recovery bay, the diameter was reduced to 80 mm. Furthermore, the material was switched from aluminum to carbon fiber to reduce mass. A detailed overview of the CGDD can be found in Table 8.

III.B. Hemisflo Drogue Parachute

The goal of the drogue parachute is to decelerate the nose cone to less than Mach 0.4 so the main parachute can be deployed. It is a key requirement that the inflation load of the drogue system is lower than 10 kN.

The high operational Mach numbers result in high stagnation temperatures. Twaron® is chosen for the canopy due to its high thermal stability. The thermal stability of Twaron® and nylon in their operational ranges can be seen in Fig.8. These results have been obtained through several tensile test campaigns. In addition to the higher thermal operational range, Twaron® is much stronger than nylon. The riser and suspension lines are made out of Technora®, which has similar thermal properties.

(a) Failure load of Twaron® ribbons

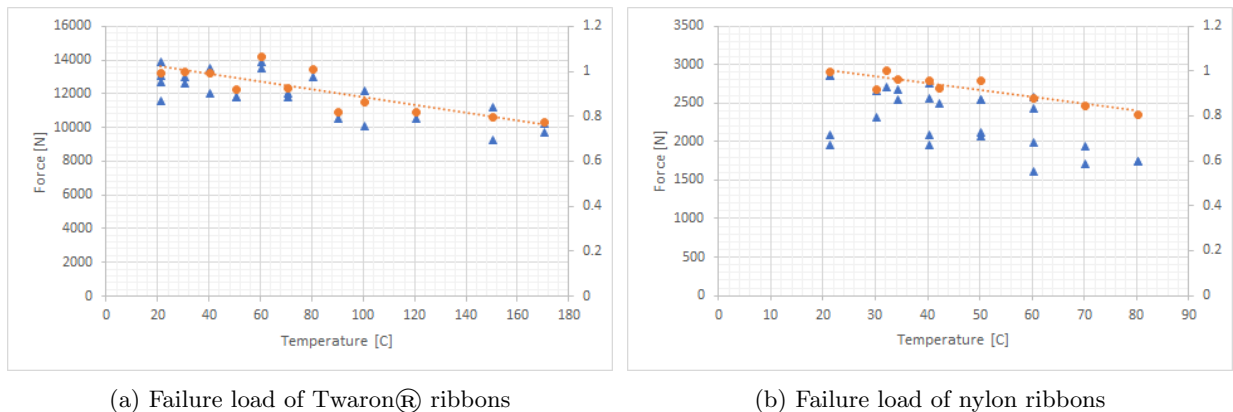(b) Failure load of nylon ribbons

Figure 8: Effect of temperature on the failure load of Twaron® and nylon ribbons. Left axes indicate the failure load in Newtons, shown with (blue) triangles. Right axes indicate relative decrease, shown with (orange) circles and the trend line

The design flow of the Hemisflo drogue parachute for Stratos III is illustrated in Fig. 9. Initially a nylon $0.6m^2$ version of the Hemisflo drogue was designed, made and tested to prove the concept for an earlier technology demonstrator. This model showed some instabilities during tests. The second nylon parachute, as seen in Fig. 10a, proved stable in the wind tunnel. A Twaron® version was made to compare the production process and performance, as seen in Fig. 10b.

From simulations, it was identified that a $0.2m^2$ parachute would reduce the inflation loads to below 10 kN, whilst still being able to slow down the nose cone to less than Mach 0.4. A nylon engineering model of a $0.2m^2$ drogue parachute was made to determine its manufacturability. The manufacturability of the drogue is constrained by the availability of ribbons in 25 mm and 12.5 mm sizes. A $0.2m^2$ Twaron® drogue parachute for the final flight version is shown in Fig. 10c. All drogue parachutes were designed with a geometric porosity of about 25 % for sufficient airflow to prevent canopy choking.[4] Lower porosity may lead to violent oscillations.[6]
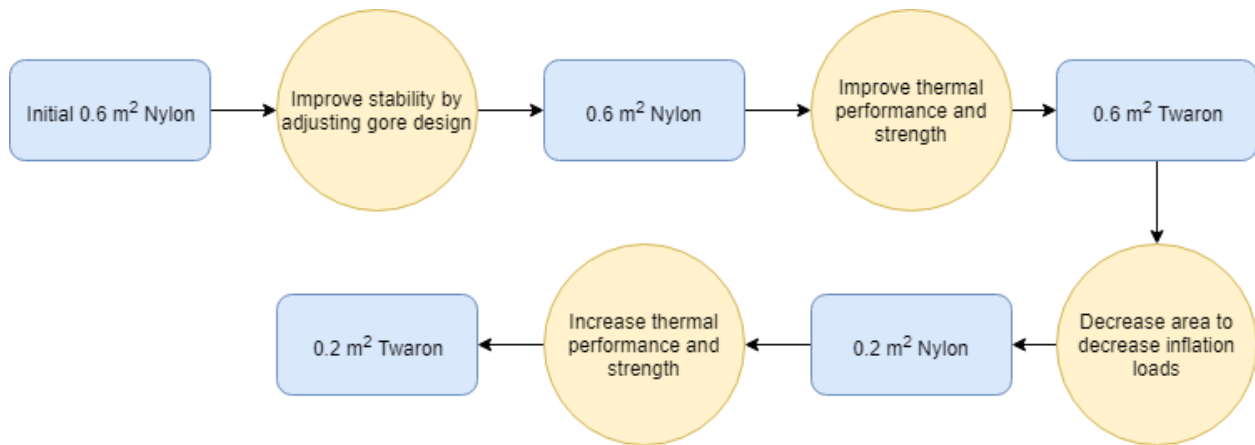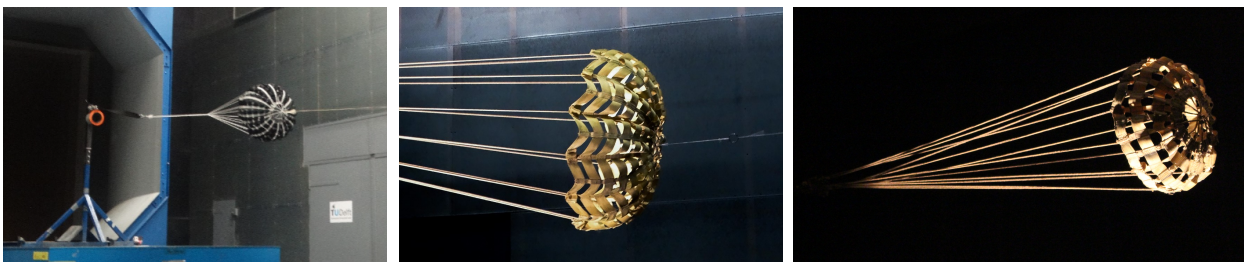
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Figure 9: Design flow of the Stratos III drogue parachute

(a) The Nylon 0.6 m^2 drogue parachute

(b) The Twaron® 0.6 m^2 drogue parachute

(c) The Twaron® 0.2 m^2 drogue parachute

Figure 10: Three different drogue parachutes being tested

Production of a Twaron® drogue is more complicated than the production of a nylon drogue. This is mainly due to Twaron's® high stiffness and cut-resistance. These difficulties were overcome by using industrial sewing machines and by laser cutting the ribbons. Additionally, the Twaron® ribbons are prone to fraying. This was mitigated by careful handling of the ribbons during production.

During wind tunnel tests, the team observed the stability and measured the drag coefficient of the drogue parachutes, as can be found in Table 4. It is observed that the C_D of the nylon drogue is slightly lower than the C_D of the Twaron® drogues. Difference between the C_D of nylon and aramid Hemisflo parachutes have been observed in literature, however no concrete reasoning could be established.[11] The C_D of both aramid drogues are within 1% of each other.

Stability can be divided into lateral and rotational stability. Lateral stability is a measure of the oscillatory motion of the parachute, whereas the rotational stability can be measured by the revolutions of the parachute in the wind-tunnel. The wind tunnel tests showed that the drogues were laterally and rotationally stable. The drogue parachutes displayed no visible oscillation in the wind-tunnel, which is a critical requirement for supersonic parachutes. This is because stability at subsonic speeds is an essential indicator of stability at supersonic speeds for ribbon parachutes.[6]

Table 4: Wind tunnel test results for the drogue parachutes

Drogue	Drag Coefficient	Lateral Stability	Rotational Stability
Nylon 0.6 m^2 drogue	0.2317	Completely stable	Completely stable
Twaron® 0.6 m^2 drogue	0.2919	Completely stable	Completely stable
Twaron® 0.2 m^2 drogue	0.2948	Completely stable	Completely stable

In Table 5 the failure loads for the various materials can be seen. A suspension length of $2D_0$ is recommended for supersonic parachutes, where D_0 equals 0.5 m.[6] The maximum design criteria for riser length to minimize wake effects is $10D_B$, where D_B is the body diameter of 0.278 m.[6]

The sizing of the drogue parachute wiring is done based upon the maximum drogue parachute load of 10 kN and safety factor of 2 (Rec - 7 and Rec - 8). The load requirement of the radial and vertical ribbons is $0.51L_s$, where L_s is the suspension line strength.[7] The load requirement of the horizontal ribbon is $0.55L_s$.[7] The Failure loads mentioned in Table 5 include the strength reductions due to knots and stitching. The values have been obtained through tensile testing.

Table 5: Characteristics of the flight drogue

Type	Amount	Material	Required load	Failure load	Length	Mass
Horizontal ribbons	4	Twaron®	$\geq$ 0.94 kN	$\geq$ 1.85 kN	-	
Vertical ribbons	12	Twaron®	$\geq$ 0.87 kN	$\geq$ 3.5 kN	-	0.1925 kg
Radial ribbons	12	Twaron®	$\geq$ 0.87 kN	$\geq$ 3.5 kN	-	
Suspension lines	12	Technora®	$\geq$ 1.7 kN	$\geq$ 1.8 kN	1 m	
Riser	1	Technora®	$\geq$ 20 kN	$\geq$ 20 kN	$\geq$ 2.78 m	0.24 kg

In order to ensure line stretch before canopy inflation, the drogue parachute has a parachute bag, which reduces snatch forces. This parachute bag is attached to the lid of the CGDD. The momentum of the lid ensures that the drogue parachute is released from the parachute bag. A detailed overview of the Hemisflo drogue parachute can be found in Table 9.

III.C.   Main Parachute Deployment System

Once the vehicle has slowed down to subsonic velocities and is in a stable zero angle of attack orientation, the main parachute can be deployed to further slow the vehicle down to landing velocity. Before the main parachute can be deployed, the drogue parachute must be cut away to eliminate the risk of entanglement. This is achieved using a modified three ring system. This system was chosen because it does not require the load bearing part of the riser to be cut. Three ring systems are used widely in skydiving and therefore have a great deal of flight heritage. The system will be actuated using CYPRES™ pyrotechnic wire cutters, which are also used extensively in commercial parachute systems. One wire cutter needs to actuate for the release of the parachute, however, a second wire cutter is included for redundancy. A diagram of the system is shown in Fig. 11a indicating the configuration and location of the wire cutters. Additionally, an image of the assembled three ring system is shown in Fig. 11b. The system was able to successfully release the drogue parachute in wind tunnel tests.

After drogue release, the main parachute is deployed. The parachute sits in an elongated circle shaped canister to optimally utilize the space in the recovery bay. The canister is made from glass fiber to realize this shape and have a lightweight design. As the nose cone will not be spinning, the risk of entanglement is lower, therefore there is no ejection velocity requirement. To ensure that the parachute enters the airflow, a spring is used to push it out of the canister. The system is secured in the canister using a 3D-printed lid, held down by an Twaron® wire. At main parachute deployment, the Twaron® wire is cut by two CYPRES™ wire cutters, one on each side of the canister for redundancy. A 3D-printed cart is placed on top of the spring to prevent entanglement with the main parachute. An overview of the system can be seen in Fig. 12 and Table 7.
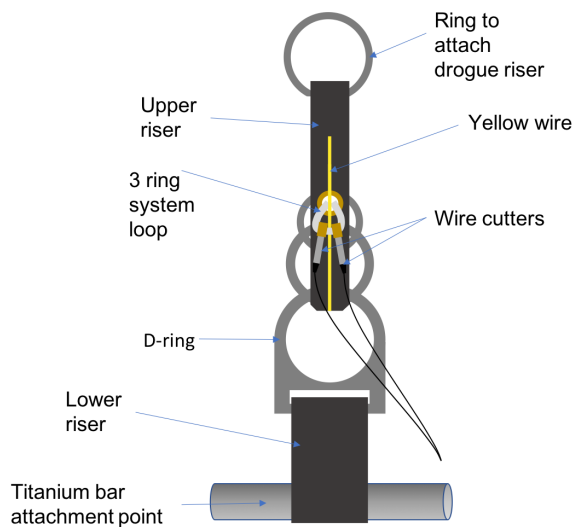
(a) Drogue release system schematic

(b) Close up photo of the 3 ring system

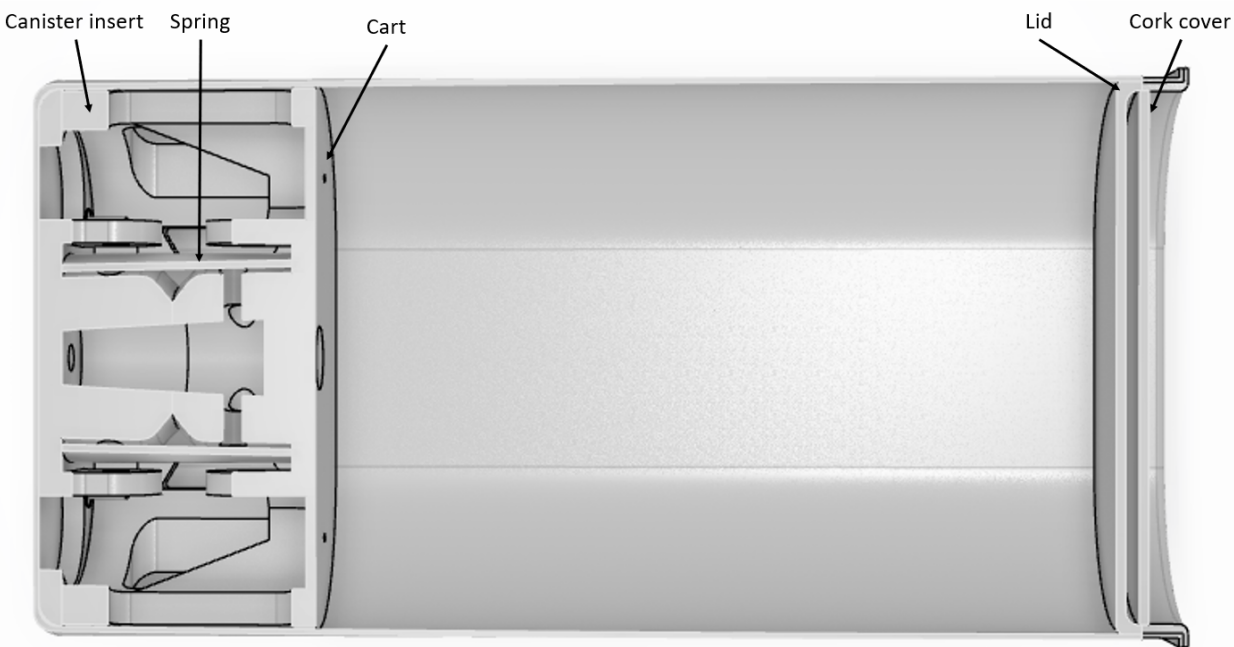Figure 11: Drogue release system

Figure 12: Render of the main canister

III.D. Cruciform Main Parachute

The primary requirement for the main parachute is to decelerate the nose cone to the required landing velocity of less than 20 m/s. This is done using a cruciform main parachutes with the corners attached and an aspect ratio (A.R.) of 0.7. The aspect ratio in this case is defined by Eq. (1). Where the dimensions A and B are given in Fig. 13.
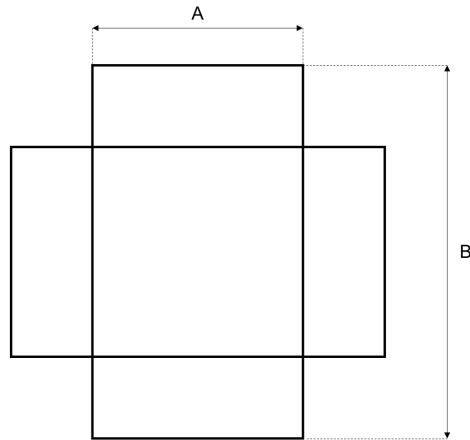
$$A.R. = \frac{A}{B} \tag{1}$$

Figure 13: Indication of aspect ratio dimensions

The canopy is made out of low-porosity ripstop nylon fabric and the suspension lines are made out of Spectra®, rated to 825 lbs. The edges of the parachute are reinforced with nylon tape.

Previous DARE missions used a standard cruciform parachute, A.R.=0.33, as it has a relatively high C_D of about 0.6 and is easy to produce. However, during wind tunnel tests it proved to be unstable. These instabilities introduce the risk of a high drift during the flight, which would make predicting the landing zone more difficult.

To increase the stability of the parachute, the corners of the standard cruciform were attached to each other for approximately 1/4 of the edge size, leaving a vent hole for the remaining 3/4 of the edge. This solution was inspired by the T-11 personnel parachute.[8] Multiple test parachutes were produced and tested in the Open Jet Facility, which confirmed this stability, however also showed that the drag coefficient dropped to about 0.4.

This was undesirable, a solution was to increase the aspect ratio of the canopy. With an A.R. of 0.7 the C_D increased to 0.68. In the wind tunnel the parachute was still unstable, however during test flights on medium sized sounding rockets, it proved to be stable.

In order to size the main parachute deployment system, the size of the main parachute had to be frozen relatively early. This lead to the size calculations to be done using a C_D of 0.4. This gave a worst case estimate on the required parachute area of 2 m^2. As the parachute with A.R. 0.7 proved to be stable in test flights, it was decided to opt for this design. The final design can be seen in Fig. 14.
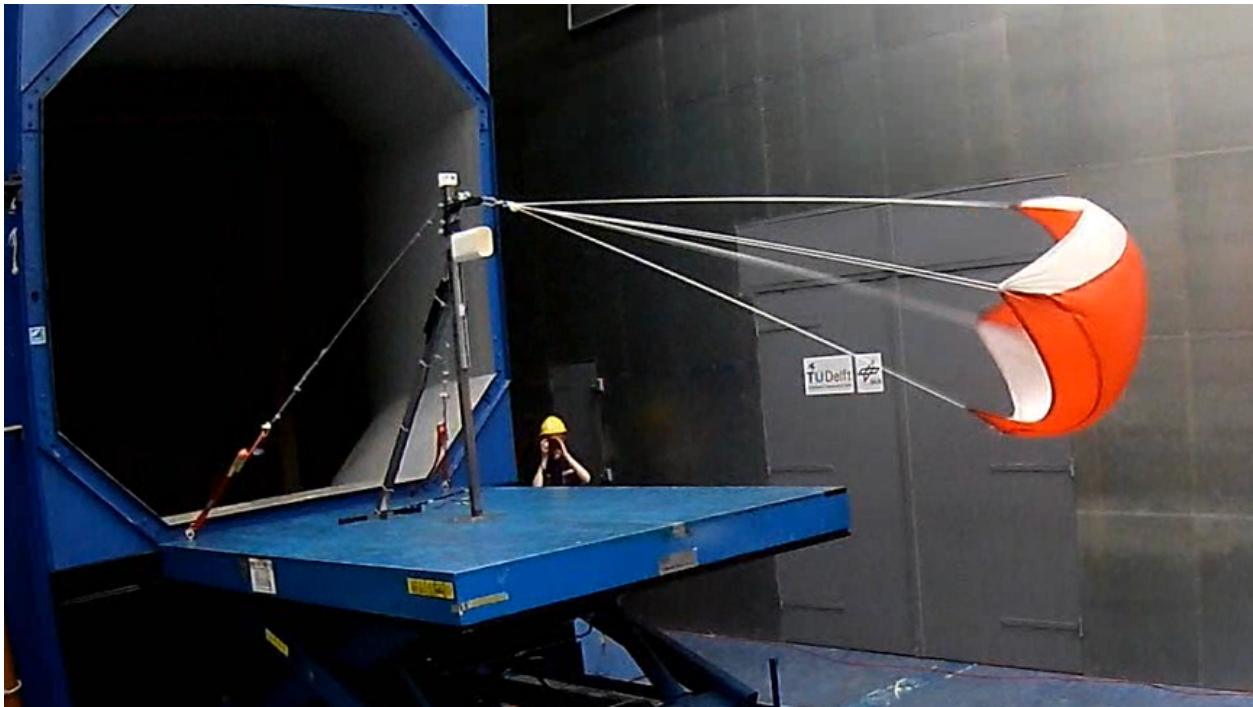
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Figure 14: Stratos III main parachute in the wind tunnel

The Spectra® suspension lines are looped through the canopy to ensure a good force transition from the canopy to the lines. This led to 8 suspension lines from four corners of the canopy to the swivel. A suspension line length between D_0 and $2D_0$ is desired,[4] where D_0 is the nominal diameter of the parachute. Shorter lines have a smaller chance of entanglement, but can restrict full inflation of the canopy and therefore decrease performance. Varying the number of suspension lines, the attachment points and/or length can increase performance and reliability of the parachute.[9] However, while testing different cruciform parachutes with an area between 0.5 and 3.0 m^2, it was observed that the influence of suspension line variations was negligible. The line length was set to $1.35D_0 = 2.16m$. They are spliced at the ends and attached to a swivel using two soft links. A riser of 1m nylon webbing connects the swivel to the bridle, consisting of two 0.5m Spectra® lines.

As with the drogue parachute, it is preferred to have line stretch before canopy inflation. In order to achieve this, a parachute bag is used. A 0.33 m^2 pilot chute is used to remove the parachute bag. The design has been successfully tested in the wind tunnel, showing controlled and reliable inflation. A detailed overview of the main parachute can be found in Table 10.

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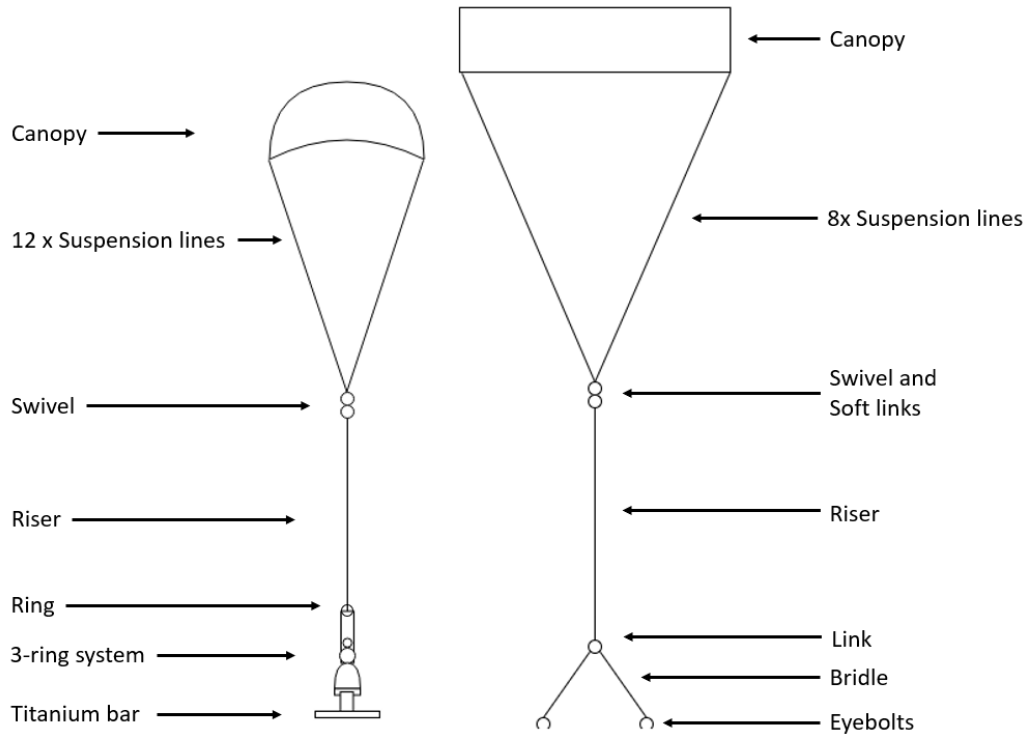
III.E. Design Overview

Figure 15: Schematics of the Stratos III recovery system (Drogue parachute on the left, main parachute on the right)

A flight envelope is made to visualize the system limits of the recovery system. The envelope is limited by three parameters. These are the maximum and minimum Mach numbers the system can operate at,[4] the maximum and minimum dynamic pressure the system can operate at, and the maximum loads that can be introduced into the structure. By using the equations for the speed of sound, dynamic pressure, and the ideal gas law the following equation is derived.[10]

$$M = \sqrt{\frac{2q}{\gamma P}} \tag{2}$$

Where, P is the atmospheric pressure as a function of altitude in Pa, γ is the heat capacity ratio for air which is 1.4,[10] q is the dynamic pressure in Pa and M is the Mach number. To compute the envelope limit loads, the corresponding dynamic pressure is substituted into Eq. 2.

In Fig. 16, the performance envelope of the drogue (solid line) and main parachute (dashed line) can be seen. The area where the envelopes intersect, is the area where the main parachute can be successfully deployed.
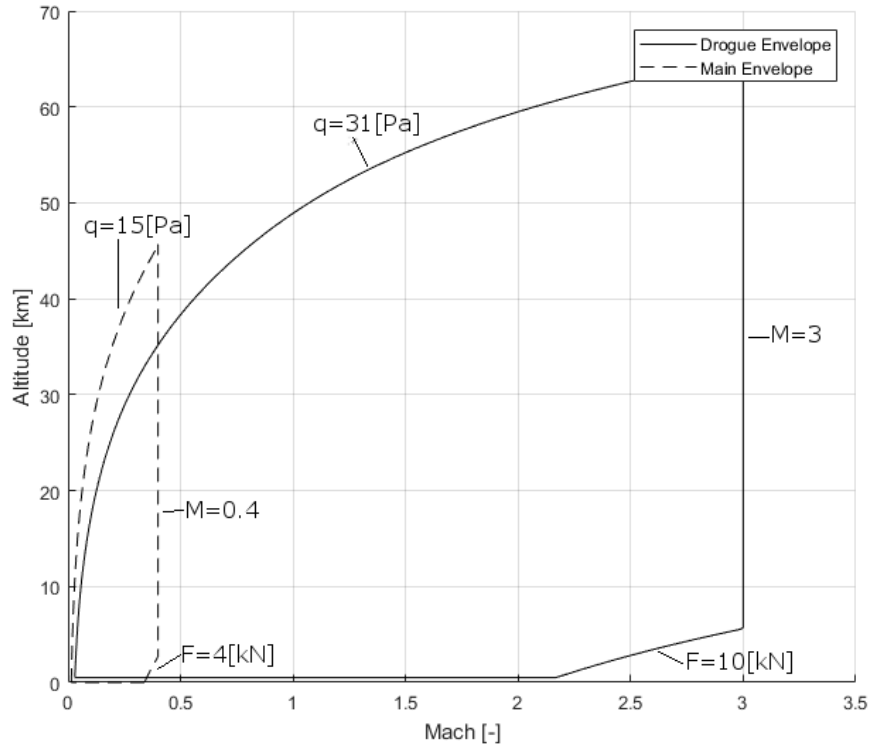
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Figure 16: Envelope of the Stratos III recovery system

IV.   Flight Simulations

IV.A.   Flight Sequence

In order to perform simulations on the recovery phase of the flight, a standard set of parameters needs to be determined, these can be seen in Table 6.

Table 6: Nominal trajectory

Altitude [m]	Phase	Events
30000-120000	Apogee	
30000-65000	Separation	
4000 ± 2000	Drogue parachute	Detect altitude, Open Solenoid, build up pressure, shear off nylon bolts, drogue/body separation, line stretch, parachute bag removal, canopy inflation.
1000 ± 500	Main deployment	Detect altitude, fire wire cutters to release drogue, cut wire of lid, pilot chute in the free air flow, pilot chute inflation, main/body separation, line stretch, parachute bag removal, canopy inflation.
0	Landing	

IV.B.   Flight Envelope

In order to validate that the flight of the nose cone and the subsequent parachute phases fall within the system limits, a grid search is performed. First, a simulation is run with a constant initial altitude of 100km and varying deployment altitudes of the parachutes between the values given in Table 6, as can be seen in Fig.17. As given in Fig. 1, the altitude has a highest probability to be between 80 and 120km. Therefore, a second simulation is run, varying initial altitude between 80-120km and varying drogue deployment altitude between 2-6km. The main parachute is deployed at an altitude of 1000m, as can be seen in Fig. 18.
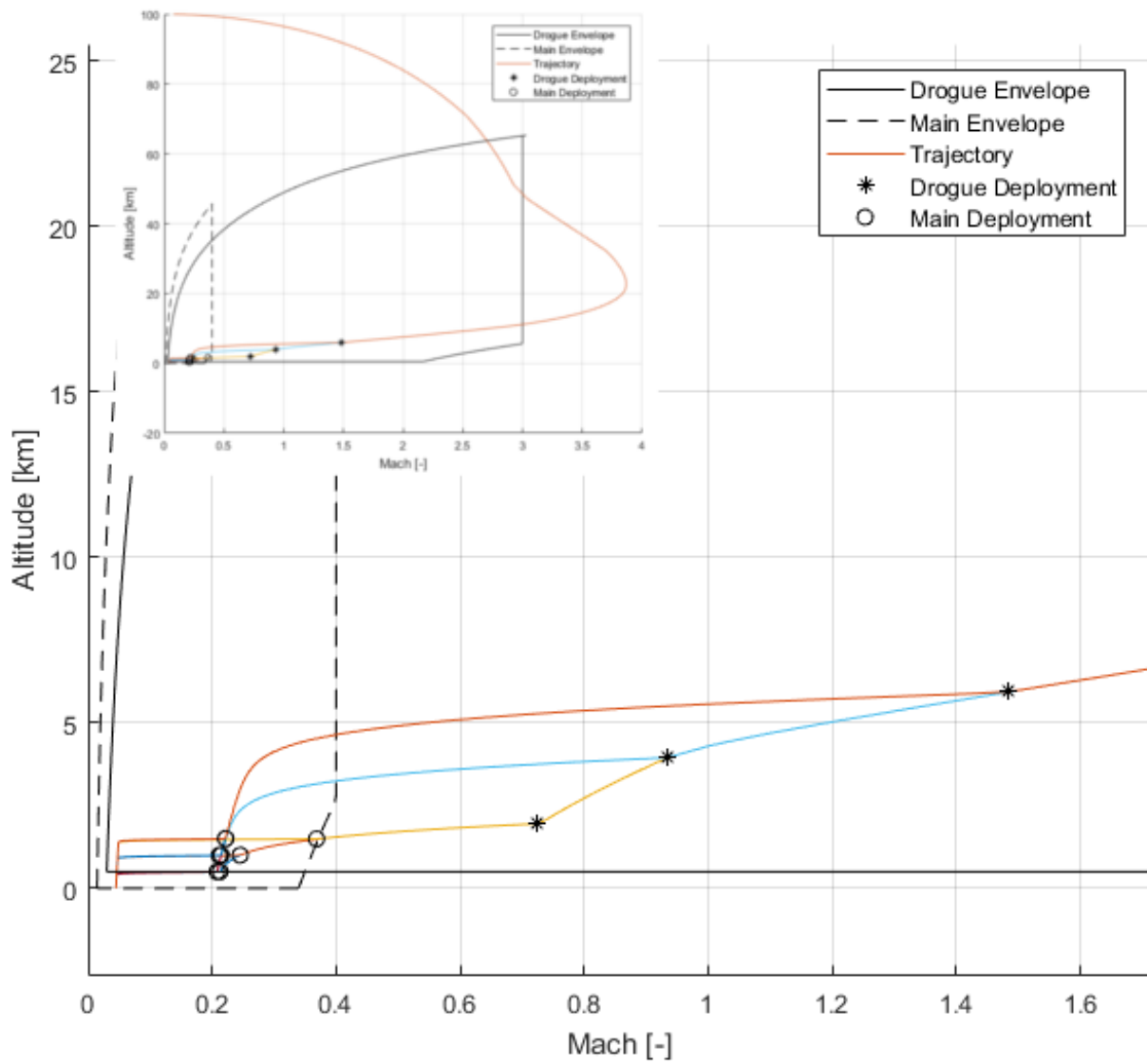
Figure 17: Grid search results with a variation in the deployment altitudes

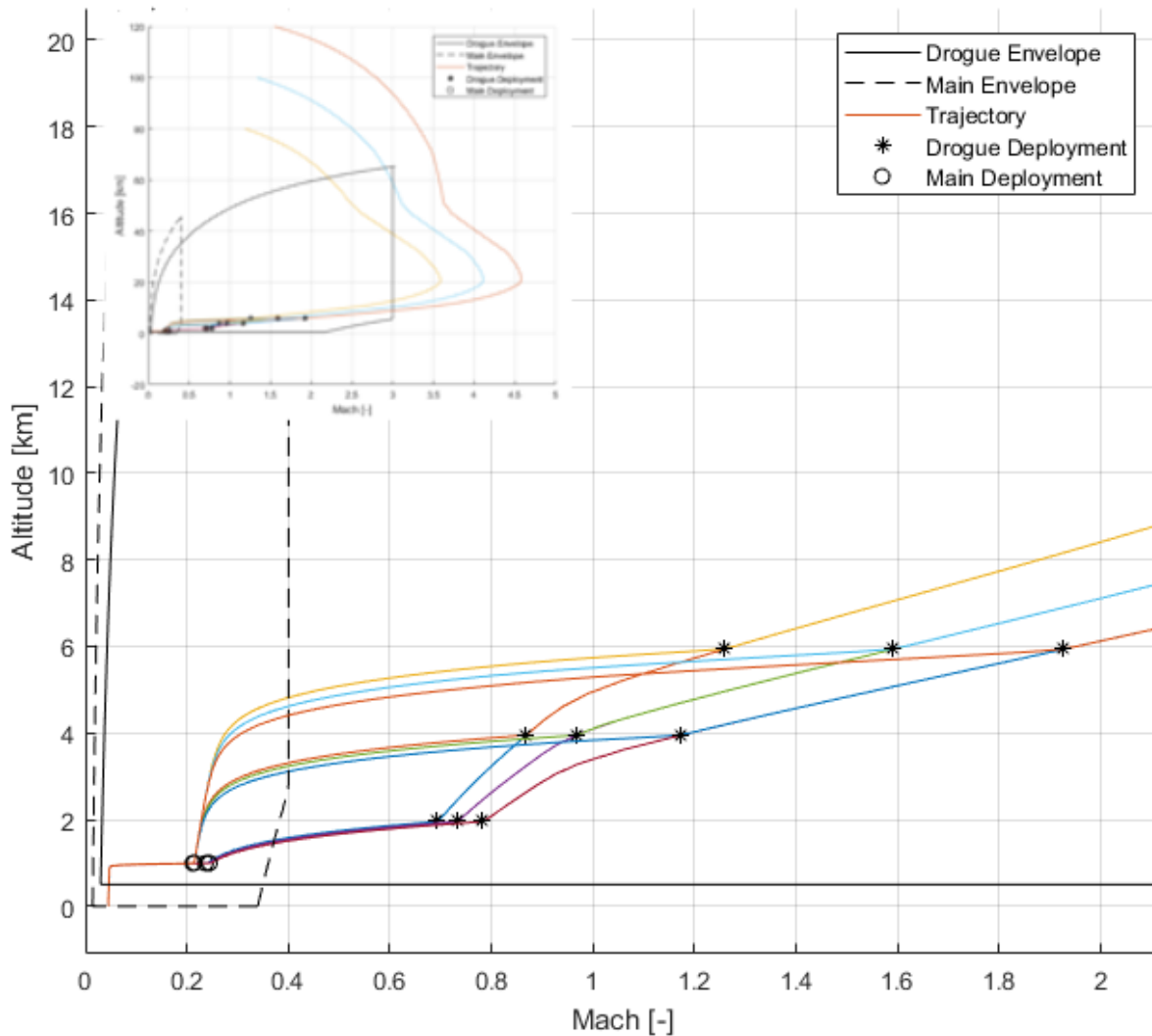American Institute of Aeronautics and Astronautics

Figure 18: Grid search results with a variation in the apogee altitude and drogue deployment altitude

The critical point is when the drogue parachute is deployed at 2000m and the main parachute is deployed at 1500m, as seen in Fig. 17. At this point the load is close to the structural limit of the main parachute attachment. All other deployment cases fall well in the system limits.

V.   Conclusion

The Stratos recovery team was tasked with the development of a recovery system that is capable of safely recovering the Stratos III nose cone, housing the flight data. It was decided to discard the engine section and tank as their scientific value did not outweigh the added complexity and mass of the required recovery system. It was identified that a two stage recovery system would be required. A 0.2 m^2 Twaron® Hemisflo drogue parachute followed by a 2.0 m^2 cruciform main parachute will be used. The shape of the cruciform parachute was optimized by attaching its corners and introducing an aspect ratio of 0.7. The Hemisflo drogue parachute will be deployed using a cold gas deployment device to ensure clear separation of the parachute and the nose cone. This system results in a landing velocity below the required 20 m/s.

To ensure a successful recovery at all conditions, a grid search has been conducted. It showed that all foreseeable cases, the loads would stay below the structural limit load of 10 kN. This gives sufficient confidence that the recovery system shall work in the defined flight envelope.

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Appendix

Table 7: Detailed overview of the main parachute deployment system

Part	Dimension	Material	Weight
3-ring system	Width = 40 mm Height = 510 mm	Steel and nylon webbing	181 g
Wire cutters (4x)	Length = 66 mm Diameter = 8.5 mm	NA	4 x 20 g = 80 g
Main parachute canister	Height = 255 mm Width = 126 mm Length = 72 mm	Glass fiber	144 g
Cart insert	Length = 118 mm Width = 68 mm	Polylactide (PLA)	24 g
Spring	Free length = 205 mm Compressed length = 25 mm Diameter = 50 mm	Steel	55 g
Lid	Thickness = 16 mm Length = 120 mm Width = 70 mm	Polylactide (PLA)	21 g
Cover lid	Length = 114 mm Width = 64 mm	Cork	26 g
Wire clamp (2x)	Length = 73 mm Width = 10 mm Height = 10 mm	Aluminum	2 x 6.5 g = 13 g
Wire	Thickness = 2.5 mm Length = 200 mm	Twaron®	$\leq$ 1 g

Table 8: Detailed overview of the CGDD

Part	Dimension	Material	Weight
CGDD tube	Length = 235 mm Width = 83 mm Thickness = 1.5 mm	Carbon fiber	128 g
Sabot	Length = 23 mm Diameter = 79.9 mm	Pom	71 g
Lid CGDD	Length = 12 mm Diameter = 79.9 mm	Aluminum	70 g
Lid cover + M6 bolt	Length = 14 mm Diameter = 99 mm	Cork	21 g
Nylon bolts (6x)	M4 x 10	Nylon	$\leq$ 1 g

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Table 9: Detailed overview of the drogue parachute

Part	Dimension	Material	Weight
Canopy	Area = 0.2 m^2 Diameter = 500 mm Vent hole diameter = 100 mm	Twaron®	105 g
Parachute bag	Height = 130 mm Width = 100 mm Length = 60 mm	Paratex	42 g
Suspension lines (8x)	Length = 1000 mm Thickness = 2.5 mm	Technora®	12 x 7 g = 84 g
Riser	Length = 2780 mm Width = 16 mm Thickness = 6 mm	Technora®	240 g
Swivel	Height = 83 mm Width = 15 mm Length = 37 mm	NA	73 g
Ring	Diameter = 42 mm Thickness = 5 mm	Aluminum	7 g

Table 10: Detailed overview of the main parachute

Part	Dimension	Material	Weight
Canopy	A = 2 m^2	Low porous ripstop nylon	232 g
Parachute bag	Height = 180 mm Length = 100 mm Width = 50 mm	Paratex	70 g
Suspension lines	Length = 2160 mm Thickness = 3 mm	Spectra®	8 x 4 g = 32 g
Riser	Length = 1000 mm Width = 25 mm Thickness = 1 mm	Nylon	40 g
Swivel	Height = 83 mm Width = 15 mm Length = 37 mm	NA	73 g
Link	Height = 55 mm Length = 28 mm Width = 5 mm	Aluminum	32 g
Pilot chute	A = 0.33 m^2	Nylon	63 g
Soft link (2x)			2 x 4 g = 8 g
Bridle line (2x) hline	500 mm	Spectra®	2 g

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Acknowledgements

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