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Comparison of Various Parachute Deployment Systems for Full Rocket Recovery of Sounding Rockets

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Abstract

Besides recovering a rocket for just the flight data, one can opt to recover the entire rocket, including the tank and engine. This can be done for public relation reasons, but also with full rocket reusability in mind. This article describes three concepts using parachutes to recover a sounding rocket in its entirety. As a reference design, a Stratos III-like vehicle, developed by Delft Aerospace Rocket Engineering (DARE) is chosen.

The concepts described are a separation of nose cone and tank with two separate recovery systems, separation of nose cone and tank with one single recovery system, and full rocket recovery without rocket separation. For each of the concepts, a system breakdown is given including mass, reliability and performance estimations.

The article continues by explaining the various methods for parachute deployment that can be used. An overview of the advantages and disadvantage of the various systems is given here. Finally, the article provides a recommendation of when to use which deployment system, linking back to the concepts discussed before.

1. Introduction

When designing a sounding rocket one is faced with the question of what to recover. The reasons for recovering rocket hardware can vary per mission but can include post-flight forensic analysis, payload recovery or safety requirements on landing location of parts of the rocket. Delft Aerospace Rocket Engineering (DARE) is a student society that focuses on creating sounding rockets for educational and research purposes. Within DARE multiple concepts have been designed to recover the entire rocket with each their advantages and disadvantages. Over the past 18 years these different concepts have been developed within the society and several have been proven in flight.

To compare the different concepts, a reference mission is used. This reference mission is based on the Stratos III sounding rocket by DARE, but is compared to multiple other missions. The various concepts are compared based op on the systems mass, but also redundancy and reliability are discussed. As all three discussed concepts have been flown within DARE, this experience is discussed.
To recover the rocket it is important to deploy the parachutes in a controlled manner. To achieve this, there are multiple deployment systems available. For each of these systems the working principle is described together with the advantages and disadvantages. As with the recovery concepts, the experience of DARE is also taken into account.

2. Mission overview Introduction

Recovering a sounding rocket can be done in several ways. When designing a rocket, one must make an important choice: whether to recover the entire rocket or to only to recover the nose cone section. The former is desirable when reusability is a requirement. Table 1 is a collection of reference missions and relevant missions from DARE. It is clear that together, the engine and propellant tank are significantly heavier than the nose cone section. The decision to design for full rocket recovery thus has a large effect on the recovery system.

Table 1: Sounding rocket mass breakdown

Vehicle (Company)	Apogee [km]	Post separation mass ratio	Total Dry Mass [kg]	Total Wet Mass [kg]	Remarks
Stratos II+ (DARE)	21	15 : 60	75	185	
Stratos III (DARE)	80 [1]	15 : 90	105	330	Broken up in flight
Stratos IV (DARE)	100+ [1]	15 : 87	102	328	To fly in summer 2020
REXUS 4 (REXUS/BEXUS)[3]	175	152.3 : 400 (111) + 598 (Unknown)	Unknown	1175.3	Two stage rocket
Heros 3 (HyEnD)[6,7]	32.3	Na : Na	75	161	
CanSat v7 (DARE)	1	0.5 : 11.5	12	16	
Redstone (NASA)	200	1000 : Unknown	29937		
Nexo II (CopSub)[16]	12.6	5.9 : 172.1	178	292	
SIR (SpaceForest)[5]	150	Na : Na	425	950	

For this article, the only viable option is assumed to be a parachute recovery system. Options such as inflatables, deployable decelerators and engine burns are discarded. As such, the parachutes must be supersonic capable. The reference vehicle is the following sounding rocket shown in Figure 1 and has the following properties:

- Empty mass = 100 kg
- Nose Cone : Engine (empty) = 20:80 kg
- Engine (empty) : Engine (full) = 80:330 kg
- Mass separation system = 3 kg
- Total Length = 8 m
  - Nose cone = 1.5 m
  - Engine = 6.5 m
- Required landing velocity (water) = 20 m/s
- Velocity at apogee = 340 m/s
- Nose cone - Aerodynamically unstable

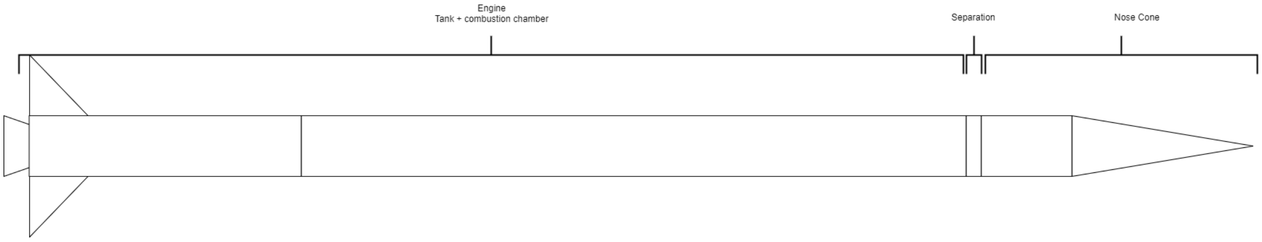

Figure 1: Schematic of the reference rocket

The trajectories are calculated using the, by DARE developed, Parachute Simulation tool (ParSim).[13] When plotting the trajectories of the rocket, it is assumed that the sounding rocket is stable. This means that, after separation, the tank + engine section has a stable orientation. The nose cone is assumed to be aerodynamically unstable and is calculated using a 90 deg angle of attack. The nose cone is assumed to spin with about 2 Hz during the re-entry. The results can be seen Figure 2 and Figure 3. Here it can be seen that the nose cone's maximum velocity is significantly lower than the velocity of the tank. It can be assumed that the unseparated rocket follows the same trajectory as only the tank.

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[1] Predicted values

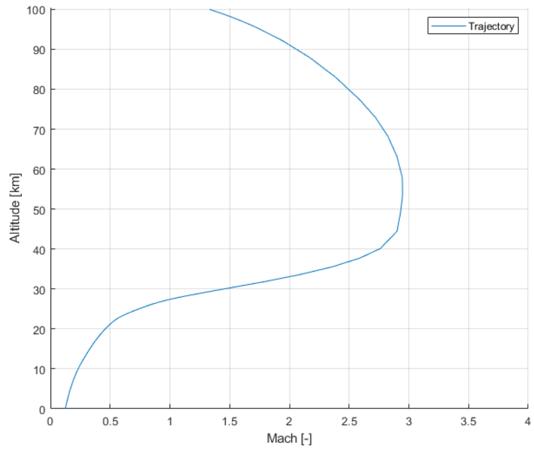

Figure 2: Trajectory of the nose cone

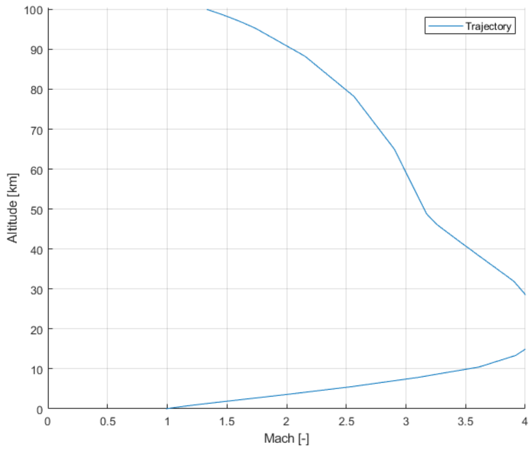

Figure 3: Trajectory of the tank

3. Concepts

Three concepts for full rocket recovery are identified and worked out. These concepts can be found in Figure 4 and Table 2.

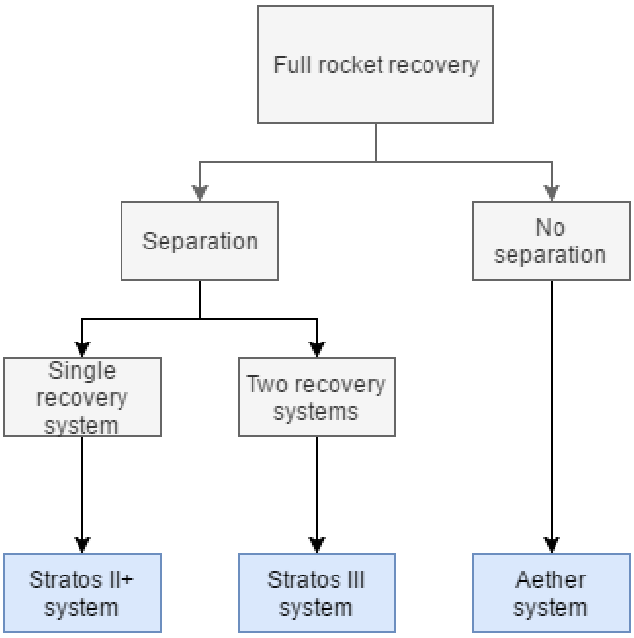

Figure 4: Concepts for full sounding rocket recovery

Table 2: Concept comparison

Parameter	Concept 1	Concept 2	Concept 3
DARE reference mission	Stratos II+	Aether	Stratos III
Separation	Yes	No	Yes
Nr of drogue parachutes	1	1	1-2
Nr of main parachutes	1	1	2

3.1 Concept 1

The first concept discussed is the recovery of the full vehicle with a single recovery system while splitting up the rocket in an engine and nosecone section. DARE used this system with partial success in the Stratos II+ rocket. In this concept, the rocket is split into two parts at or around apogee, while still staying tethered to each other. The rocket is then recovered by a single recovery system consisting of two or more parachutes. During the ascent, the engine of the Stratos II+ rocket and nosecone were held together by a double clampband system as can be seen in Figure 5. At apogee, the first clampband deployed which detached the engine section and nosecone module from each other. Both these sections were connected to the drogue parachute which was deployed by spring at the same moment. When the vehicle reached an altitude of 1000m, the second clampband released allowing the main parachute to be deployed, bringing the vehicle down to a safe landing velocity.

The key advantage of this concept is the limited complexity of the system. Only one recovery system is needed and thus also only one deployment mechanism (per parachute). The second advantage of this concept is that the overall mass of the recovery system will be lighter compared to two separate systems. Even though the size of the individual parachutes and suspension lines will be larger due to the increase in to be recovered mass, only one storage container and one deployment mechanism are required, which can lead to a lower overall system mass. Another advantage is that the parachutes are ejected axially instead of radially. This means that no hatches or openings are needed that potentially weaken the structural rigidity.

A disadvantage is that the parachute material, suspension lines, links and stitches will have to be able to handle higher inflation loads due to the increased mass. This can be compensated by dividing the loads over several smaller parachutes and clustering them together. Alternatively, reefing can be used to decrease the parachute inflation loads. Another disadvantage is that two items will be hanging from the parachute and interacting with the lines, each other and the atmosphere. Modelling this behaviour becomes much more complicated when compared to a single body hanging from a parachute. Besides issues in modelling, there is a significant risk of entanglement of the parachute lines.

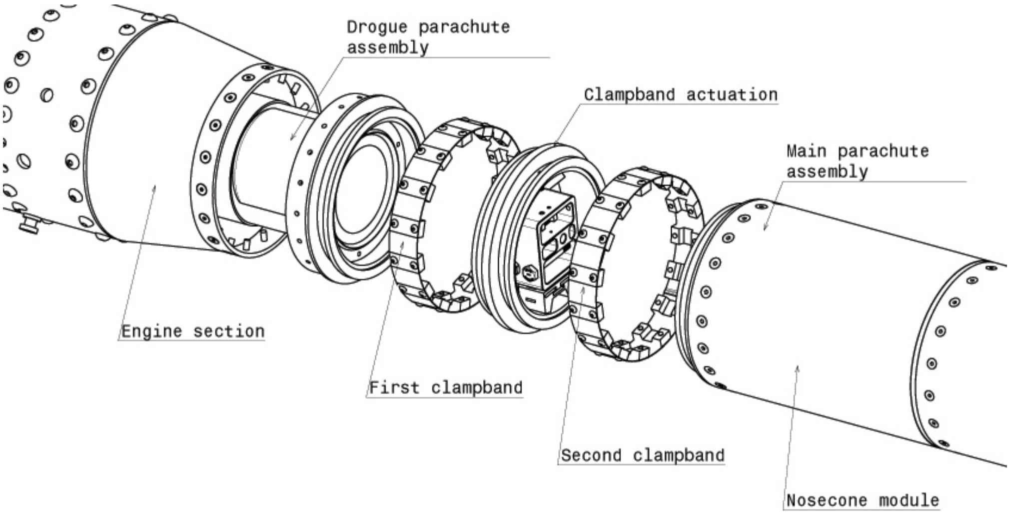

Figure 5: Schematic overview of the recovery system of Stratos II+ integrated in the rocket

This system was flown on board the Stratos II+ sounding rocket, launched in 2015. However, during the flight, this system did not function as expected as the drogue parachute tore off as inflation loads were higher than expected. One of the contributing factors was the apogee, which was lower than initially expected. The failure of the drogue parachute led to the loss of the tank section of the rocket. As the nose cone was aerodynamically unstable, it entered into a flat spin, which allowed the main parachute to be opened inside its envelope leading to the safe recovery of the flight data.

3.2 Concept 2

Concept 2 is a concept where the drogue is deployed from the side of the rocket after which it trails behind the rocket. This system was developed for the not yet flown Aether mission. Aether is a supersonic test platform for DARE that allows for low-cost testing. In this concept, the rocket is stable during descent with its nose down. To avoid impact with the fins, a high-velocity parachute mortar ejection is required to get sufficient clearance between the drogue parachute and the fins. To keep the rocket in a stable position during drogue flight, a connection point is needed to attach the drogue line to the aft end of the engine section. This connection point is released upon main parachute deployment. A connection between the drogue and main parachutes then pulls out the main parachute. A schematic overview can be seen in Figure 6.

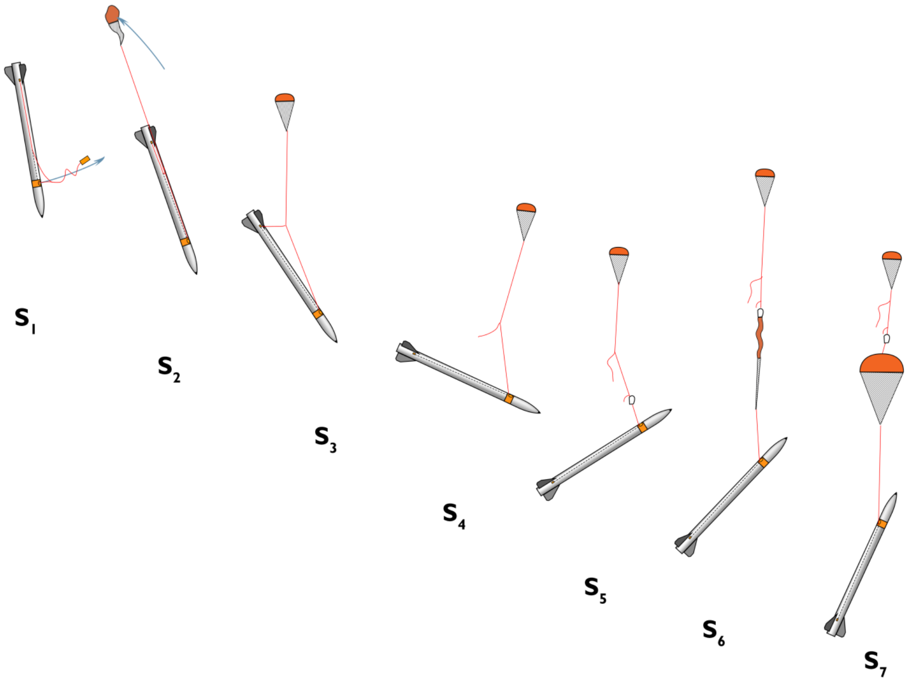

Figure 6: Concept 2 in a schematic overview

One of the main advantages is that in this concept, the parachute is deployed from the side of the rocket. This eliminates the need for a separation system. It also means that the parachute loads can be guided through the main structure. Furthermore, the trailing drogue parachute keeps the vehicle stable in case of supersonic recovery. Finally, the landing happens in an engine down configuration where the engine can be used to absorb the impact from landing and keeping the electronics' data safe.

One of the drawbacks of this system is that the drogue parachute might impact on the rocket. This could cause the failure of the drogue parachute if the fins cut through the parachute. If a hatch is used to deploy the parachute radially, this weakens the stiffness of the rocket, which is critical during ascent. Furthermore, because the rocket is kept in one piece, the load of the parachutes has to be guided in the structure which likely creates a significant moment next to the axial loads. Finally, the drogue is attached at the aft of the rocket, and it is released when deploying the main parachute. This means the rocket will have to reorient itself during flight. This will cause a swinging motion which, if not handled correctly, could end up entangling the rocket with the parachute.

3.3 Concept 3

The third concept uses separate recovery systems for two sections that separate at apogee. The two recovery systems operate independently from each other. Splitting up the rocket with separate recovery systems allows each section to be recovered at a different landing velocity. This is desirable when both elements have different reliability or landing velocity requirements.
This system was used in the Stratos III mission[14] where the recovery of the tank was fully discarded after the conceptual design phase. An overview of the Stratos III nose cone recovery system can be seen in Figure 7.
Another advantage is that the payload section can be designed to be aerodynamically unstable. An unstable section tumbles during re-entry, which decreases the ballistic coefficient, which in term decreases the parachute inflation loads. The use of two separate recovery systems also reduces the risk of entanglement or collision between the two rocket sections after separation. As the parachutes are deployed a certain time after separation, a parachute deployment system is required that can contain the parachutes during flight and deploy on command.

A disadvantage of this system is that this system requires a large volume. For Stratos III, a cylinder of 28 cm diameter and 30 cm length was needed for recovery of a ~ 20 kg mass. The additional volume of a recovery system for the ~ 80 kg tank section would have been much more significant. As the rocket was constraint by the 28cm diameter, the added recovery section would be quite long.

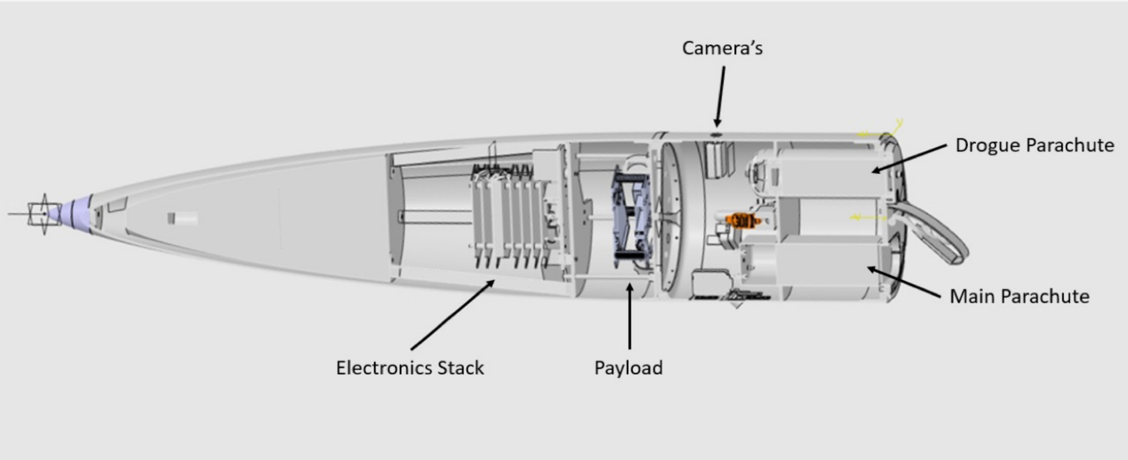

Figure 7: Schematic overview of the recovery system of Stratos III

4. Preliminary Design - Parachute mass

The mass of the parachute systems in each concept can be determined as a function of the parachute diameter, which can be seen in Figure 8 (application I) and Figure 9 (type II). For ballutes the material choice has a significant impact on the parachute mass, as can be seen in Figure 10. Since the ballute will be deployed in low dynamic pressure conditions, an inflation aid is required. Depending on the ballute size and the gas choice this can range from 20% to 50% of the ballute mass[4].[9] In Knacke[12] it can be found that the mass of a parachute deployment system is approximately half the total subsystem mass.

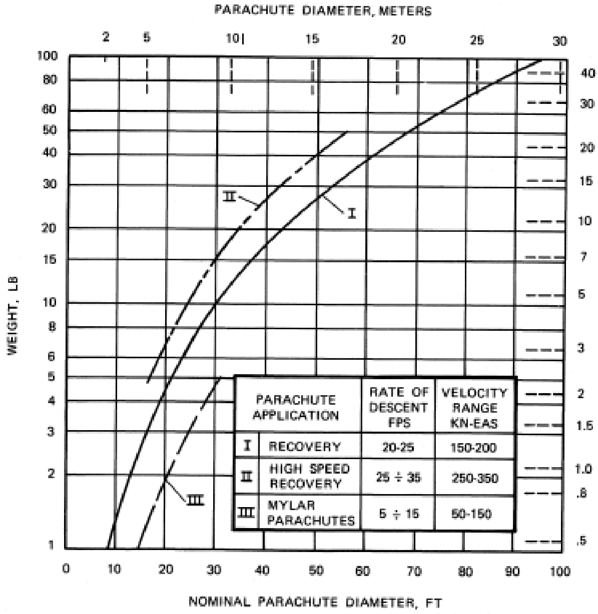

Figure 8: Mass of a nylon main descent parachute[12]

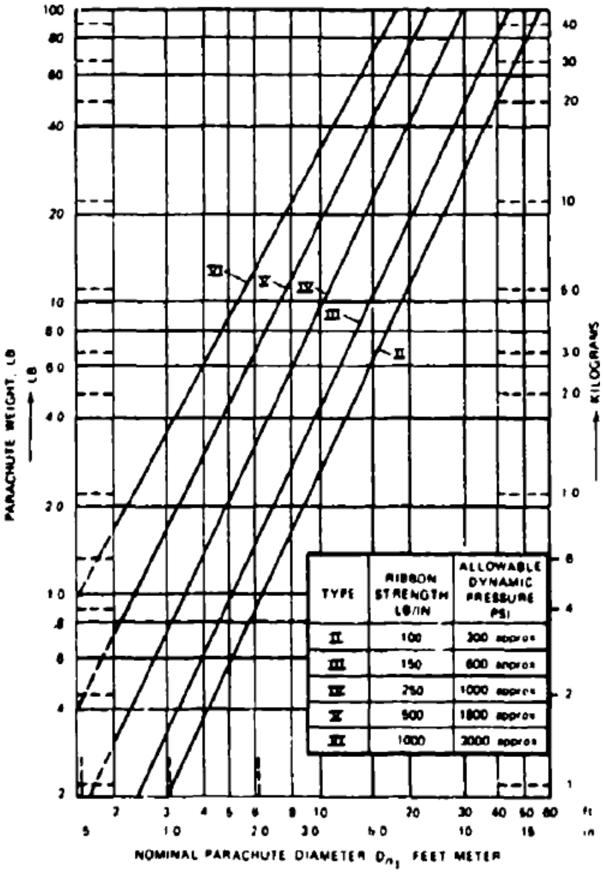

Figure 9: Mass of a ribbon parachute[12]

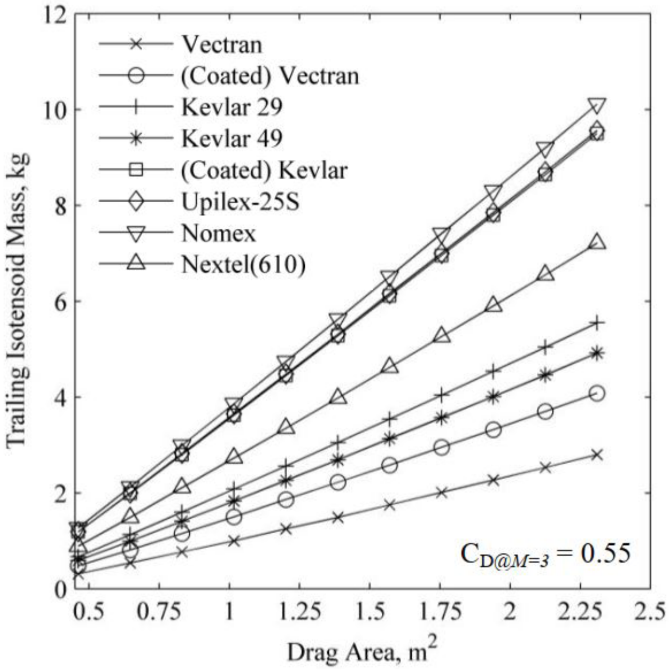

Figure 10: Mass of a ballute[8]

The diameter of the parachute can be determined using the following force equilibrium:

$$F_{gravity} = F_{parachute} \tag{1}$$

$$M_{stage} g_0 = \frac{1}{2} V_{Landing}^2 \rho C_D A_{parachute} \tag{2}$$

$$A_{parachute} = \frac{2 M_{stage} g_0}{V_{Landing}^2 \rho C_D} \tag{3}$$

Given the requirements of the reference sounding rocket mission, the parachute systems can be chosen and their masses can be determined. A deployment altitude of 3 km has been chosen for the final descent parachute to ensure a successful recovery is still possible in all scenarios, whilst limiting the drift. The different parachutes together with their performance can be found in Table 3. Here the C_D is determined using the projected area of the parachute and has been found empirically during wind tunnel testing by DARE.

Table 3: Comparison of chosen parachutes

Type of parachute	Function	Drag coefficient	Mass estimate	Mach range
Supersonic ribbon	Drogue and Main	0.3	Figure 9	0 - 3.0
Ballute	Drogue	0.3	Figure 10	0 - 10
Subsonic parachute	Main	0.55	Figure 8	0 - 0.3

For each of the three concepts a preliminary parachute system can be selected.

4.1 Concept 1

With this concept the sections should separate in lower air density (above 60 km). When separating during descent in thicker atmosphere, the risk of collision increases significantly. After separation the parachute should be deployed directly to also avoid collision between the two sections. The only parachute able to inflate with a very low air density is the ballute, using a gas inflation system. This is combined with a subsonic main parachute for the final descent. Kevlar is taken as material for a lower limit mass estimate, since Vectran is not estimated to withstand the thermal loads the ballute would encounter.
Area ballute parachute: 0.9 m^2. Mass ballute: 1.5-2.0 kg. Mass gas inflation system: 1.0 kg.
Area subsonic main parachute: 7.28 m^2. Mass main parachute: 0.6 kg.

4.2 Concept 2

With this concept there are two possibilities; a supersonic main parachute or a supersonic drogue in combination with a subsonic main parachute. When looking at the trajectory of the vehicle in Figure 3, it is seen that the vehicle has a very high descent velocity.
The use of a single supersonic parachute (area of 13.34 m^2) would be possible between 3-7.5 km altitude, resulting in high inflation loads due to the high dynamic pressures and a large area. A smaller drogue parachute can be deployed around these altitudes, slowing down the vehicle to allow for a subsonic main parachute deployment. The advantage of this drogue parachute is that it can tilt the body, thus increasing the body drag significantly. When only taking the parachute drag into account, the drogue parachute has an area of 0.9 m^2. The body drag can be a significant portion

of the total drag which will decrease the drogue area, depending on the angle of attack. To determine this a stability analysis needs to be made of the vehicle in which the attachment point of the drogue parachute can be altered to reach the desired angle of attack. The drogue parachute deployment can be more violent when the angle of attack is adjusted heavily due to drogue deployment.
Area supersonic ribbon drogue parachute: 0.9 m^2. Mass drogue parachute: 1.3 kg.
Area subsonic main parachute: 7.28 m^2. Mass main parachute: 0.6 kg.

4.3 Concept 3

With this concept the sections are evaluated separately. For the nose cone a single subsonic main parachute is sufficient when looking at the trajectory in Figure 2. The main parachute of the nose cone would be 1.45 m^2.
For the tank again the choice is present between a single supersonic main parachute versus the combination of a small supersonic drogue parachute in combination with a subsonic main. The same reasoning applies as in concept 2.
Area supersonic ribbon drogue parachute tank: 0.7 m^2. Mass drogue parachute: 1.1 kg.
Area subsonic main parachute tank: 5.8 m^2. Mass main parachute: 0.5 kg.
Area subsonic main parachute nose cone: 1.45 m^2. Mass main parachute: 0.1 kg.

4.4 Comparison of concepts

The different masses of each parachute system are gathered in Table 4.

Table 4: Mass overview of the three concepts

Parameter	Concept 1	Concept 2	Concept 3
Drogue parachute mass [kg]	3.0	1.3	1.1
Main parachute mass [kg]	0.6	0.6	0.6
Drogue deployment system mass [kg]	3.0	1.3	1.1
Main deployment system mass [kg]	0.6	0.6	0.6
Separation system mass [kg]	3.0	-	3.0
Total mass [kg]	10.2	3.8	6.4

There is an additional structural mass for concept 1 to reinforce the structure to allow for radial deployment (see subsection 3.1). There is also additional structural mass for concept 3 due to the additional section for the second recovery system (see subsection 3.3). These mass penalties depend on the structural design of the rocket.
Aside this, high parachute inflation loads can be a driving design factor for the surrounding structure. An overview of all these influences on the structural mass can be seen in Table 5. The inflation loads are calculated using the Parachute Simulation tool (ParSim).[13] Here it can be seen that the lightest option from Table 4, concept 2, currently has significant higher inflation loads than the other concepts. It should be noted that, as mentioned in subsection 4.2, the drogue parachute can be smaller due to the additional body drag, depending on the angle of attack. The reduction in size also reduces the inflation load.

Table 5: Overview of the three concepts

Parameter	Concept 1	Concept 2	Concept 3
Drogue inflation force [kN]	6	53	0; 32 [2]
Main inflation force [kN]	20	25	2; 16[2]
Additional structural mass	-	Reinforcement needed for radial deployment	Larger recovery bay is needed

5. Deployment Systems Overview

Deployment time and reliability are often the key factors to select a parachute deployment system. Vehicles with high ballistic coefficient require low deployment times and vice versa. The deployment time should be chosen such that suspension lines stay in tension throughout the unfurling of the parachute.
The rate of rotation (spinning) of the vehicle can significantly impact the desired deployment time as well, to prevent entangling with the rocket. For concept 3 of the reference mission, the predicted rotation of 2 Hz of the nose cone

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[2] force is given in Nosecone;Tank inflation loads

requires the deployment time to be 0.125 seconds to ensure that the parachute is unfurled before 0.25 rotations.
The shorter the deployment time, the higher reaction loads. From a structural point of view, it is desirable to select the longest possible deployment time. Low deployment times also lead to higher system weight due to higher ejection velocity requirements.
In deployment systems, a division can be made between forced ejection and extraction (pulling) to deploy the parachute. Forced ejection leads to higher reaction loads of the deployment system. Ejection vs. extraction influences other aspects of the design as well, like the parachute bag. This, however, is not considered in the conceptual design.
An overview of the deployment systems contemplated in this article can be seen in Table 6. Here different qualities of the systems are displayed.

Table 6: Comparison of parachute deployment systems

Deployment system	Ejection Velocity	Reaction Load	System Weight	Heritage
Aerodynamic	Low	Low	Low	Amateur sounding rocket
Spring	Low	Low	Medium	Amateur sounding rocket
Mortar	High	High	High	Apollo, Mars 2020
Slug Gun	High	Medium	High	Ejection seats
Tractor Rocket	High	Low	Medium	Ejection seats, spin stabilisation

5.1 Aerodynamic

One of the simplest ways of deployment is the use of a drogue parachute which creates drag to pull the main parachute out of the rocket. To prevent pulling out the main parachute at the moment the drogue parachute inflates, a release mechanism has to be included. The drogue parachute is attached to the release mechanism during the drogue parachute flight phase and is released upon command. A connecting line between the drogue parachute and the main parachute ensures that the parachute is pulled out of its container. The drogue parachute also acts as a pilot chute, ensuring line stretch before canopy inflation.

This can be an advantageous system, especially when a drogue parachute is already present before the main parachute deployment. The most considerable benefit of this deployment system is that the release mechanism can be small, lightweight and relatively simple, therefore making the additional mass and volume needed for deployment very low. Various release mechanisms such as pyrotechnic bolts, wire cutters, bolt cutters and pulling pins can be used. This wide range allows for varying use in different missions since it can comply to requirements with a different focus such as mass, availability and actuation signal.

However, there are some difficulties to this deployment mechanism, which vary in importance for different mission applications. The load of the drogue parachute needs to be held by an attachment point, which also needs to be released. This can be a complex issue depending on the release mechanism used. For instance, a bolt cutter that cuts through a load carrying bolt can do this, while a pulling pin mechanism can possibly not hold a substantial drogue load itself. A different system needs to be used, which either lowers the drogue load on the release actuator or the release mechanism shouldn't be load bearing. An example of this is a 3-ring system which is often used in skydiving. This system can take up high loads while the to be removed cable only carries low loads.
Next to this the main parachute has to be contained in its canister until the moment of deployment. In case the drogue parachute delivers a high drag force, this containment mechanism can be more rigid, for instance, a permanently attached chord or thread. In this case a considerable force is used to pull out the parachute which safeguards against an accidental early deployment. When the drogue doesn't deliver much drag force however, weaker configurations need to be used, such as rubber bands. This increases the risk of it getting loose during the flight and thus an early deployment of the main parachute. If this is the case it needs to be considered to add a rigid containment on the parachute container which is released by a separate actuator. This adds mass and complexity. In some design cases, it might be possible to combine the release mechanism of the drogue with the release mechanism of the parachute container, which would be a best-case scenario.
Next to this system entirely relies on the proper functioning of the drogue parachute system. In case of a drogue parachute failure, it might not be possible for the main parachute to deploy. In missions where the success depends on the deployment of the main parachute using this deployment system leads to an increase in single points of failure.

This concept is used in the Aether rocket, where a cold gas parachute mortar deploys a Hemisflo ribbon drogue parachute which is attached to a pyrotechnic bolt. This pyrotechnic bolt releases the drogue parachute upon deployment command. Then it pulls on looped wires (passive containment system) and deploys the main parachute.

5.2 Springs

The simplest active method of parachute deployment is the spring based systems. These systems rely on a compressed spring that is placed at the bottom the parachute canister that on command releases the potential, pushing the parachute into the free stream. The main advantage of this over aerodynamic deployment is that it allows for more reliable deployment as it will enable the parachute to still be ejected even if the flow conditions are not ideal. For instance when the parachute canister is in the wake of the vehicle.

A spring system usually consists of a spring attached to the base of the canister with a platform placed on top of it. The spring is then compressed, and the parachute put on top of the platform. The system is then secured with a lid. The parachute is pushed against the lid which is later released either through the use of some mechanical release mechanism or else a pyrotechnic system. Once the lid is released the spring's potential energy accelerates the parachute, pushing it out of the canister. An example of a spring deployment system can be Figure 11.

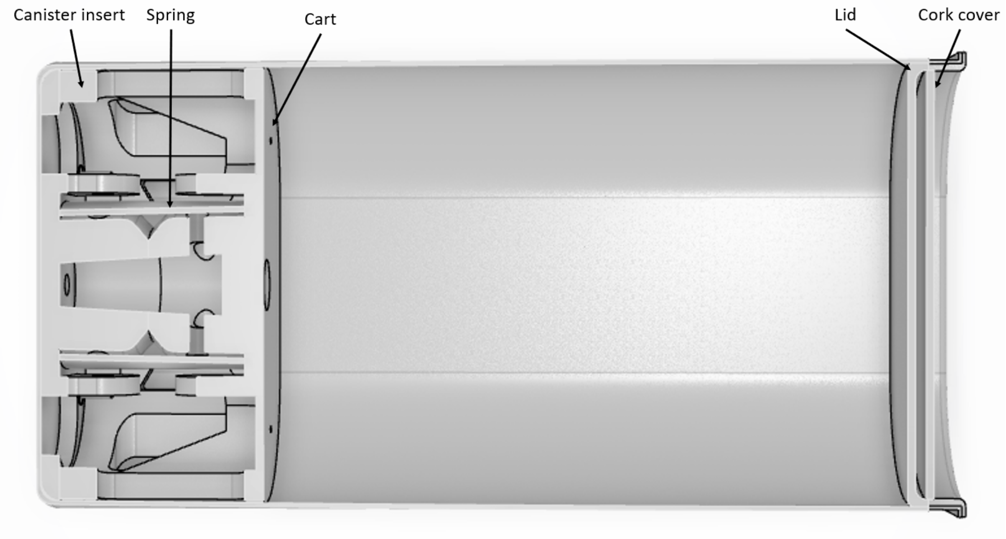

Figure 11: Diagram of the Stratos III main canister and deployment mechanism

The main advantages of this spring system are that it is a relatively simple system which does not have the complexity of feed systems or pyrotechnic components that are present in other deployment systems. This gives it fewer points failure but perhaps, more importantly, allows it to be tested repeatedly without requiring the extensive safety procedures that are needed for testing with pressurised or pyrotechnic systems. Although the Stratos system used pyrotechnic cutters, it could be tested using scissors to actuate it. This also means the mechanical functionality could be tested in isolation of the actuation method. Furthermore, no drogue parachute is required; thus, the recovery system can rely solely on the main parachute.

This system does, however, have some significant drawbacks. High power springs have considerable mass, making them difficult to implement in lightweight rocket structures. This means that systems are limited in terms of ejection force, making them unsuitable for high Mach number deployment. Another significant drawback is that is it difficult to make a spring system that can be compressed after integration. This means spring systems are inherently dangerous as they are always in an armed state. The safety risk of this system then depends mostly on the maximum damage an accidental spring deployment can cause.

The Stratos system indicated in Figure 11 used a single spring below a 3D printed cart. This cart was then pushed against the main parachute that was then in turn held in place by a 3D printed lid. This lid is held down by an aramid wire that is stretched over it and then cut by two Cypress wire cutters which release the lid on command and deploying the parachute.

5.3 Parachute deployment mortar

5.3.1 General Concept

Parachute mortars work by accelerating a parachute out of a tube using a pressurised gas. This principle can be utilised to deploy parachutes reliably with high velocities. This is especially important when the deployment time of the parachute has to be minimised as in aircraft spin recovery[15] or when rocket parts are expected to be tumbling during recovery. In general, the mortar deployment system will have requirements on a minimum deployment velocity, a maximum kickback force and a maximum internal pressure.

The gas used to accelerate the parachute can either be contained in a tank (cold gas), or generated by a chemical reaction (hot gas), which is often done by burning a solid propellant. These two concepts are treated separately in the following sections. A schematic of a general parachute mortar can be seen in Figure 12. The parachute sits on top of a sabot, that seals the plenum. When the gas flows into the plenum below the sabot, the sabot starts moving and compresses the parachute. The parachute then exerts a force on the fixed lid. The lid is attached using shear bolts, which are designed to shear when the predetermined pressure in the system is reached. The sabot then accelerates the parachute out of the tube. The ejection velocity can be determined by varying the length of the tube and the pressure at which the bolts shear.

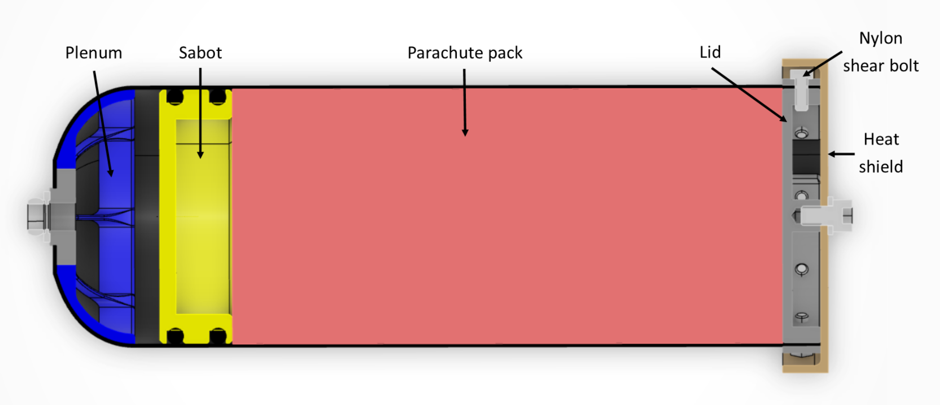

Figure 12: Cross section of a mortar developed in DARE showing all of its components

5.3.2 Cold gas parachute mortar

The first concept uses compressed, cold gases to accelerate the sabot and parachute. The advantage of a cold gas mortar is that all essential parts are readily available, and one does not rely on reactive chemicals or explosives. For the design of a cold gas system, there are two main design choices: the gas storage and the gas release, while the selection of the gas itself often is directly bound to the choice of storage. A disadvantage that all cold gas mortars share is the feed system. The feed system is susceptible to leaks, is heavy and takes space. The first choice is the storage of the gas. This can either be commercially off-the-shelf or self-made, refillable tanks. The advantage of the latter is that they can be manufactured to the exact required volume, and one is free in the choice of gas. However, the design and manufacturing of lightweight tanks are not always trivial, and especially for smaller systems, it might not be worth it and or feasible to do so. An alternative is off-the-shelf cartridges like the ones used for whipped cream dispensers or bike tire pumps. They are readily available, come in a variety of sizes and often contain CO_2 and N_2O in a liquid state. Their most significant disadvantage is that one only has a limited choice of available gases. This comes with a high density, but also substantial heat losses when the gases change state. Due to that, they are better suited for smaller or amateur gas deployment systems.

The second design choice is the gas release mechanism. One option is the use of electrically actuated solenoid valves. They are very reliable and exist in many variants. However, the higher the pressure in the storage tank, the more power it needs to actuate. This can have a significant impact on the power budget, especially for smaller rockets. Solenoid valves are often restricted by orifice area and size. Another disadvantage is that the compressed gases (especially liquid CO_2) can damage the seals of the valve, which leads to leaks and pressure losses. If a solenoid valve is being used in combination with an off-the-shelf cartridge, the cartridge first also has to be punctured and connected.

An alternative to solenoid valves are other mechanical, servo or spring actuated mechanisms. Furthermore, pyrotechnic valves can be used to release the gas. Systems of this type are especially common with cartridge holders. Two of these systems are shown in Figure 13 and Figure 14.

5.3.3 Hot gas parachute mortar

The second concept uses hot gas from a chemical reaction to pressurise the system. At first glance, the hot gas system seems very desirable over its cold gas counterpart. It eliminates the need for complex feed systems and consists of fewer moving parts. While in general, these statements are true, a load of difficulties come along with the use of pyrotechnics. A cold gas system uses pre-pressurised gas in a tank, while a hot gas system uses a chemical reaction. To understand the different styles of hot gas production, the system requirements must first be explored.

Figure 13: Servo actuated *"Hawk"*[2]

Figure 14: Pyrotechnic actuated *"Peregrine Raptor"*[2]

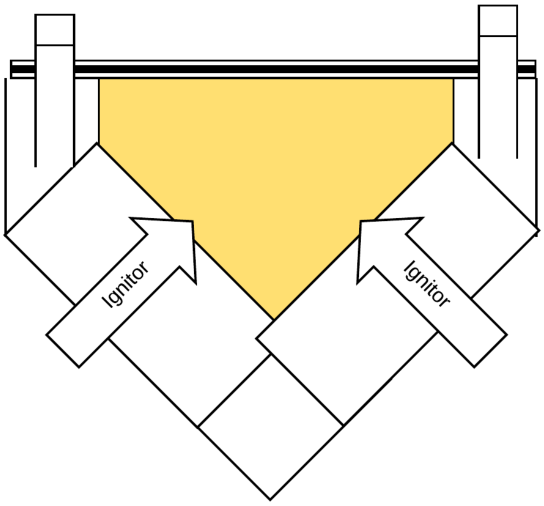

Figure 15: Gas generator with redundant ignitors

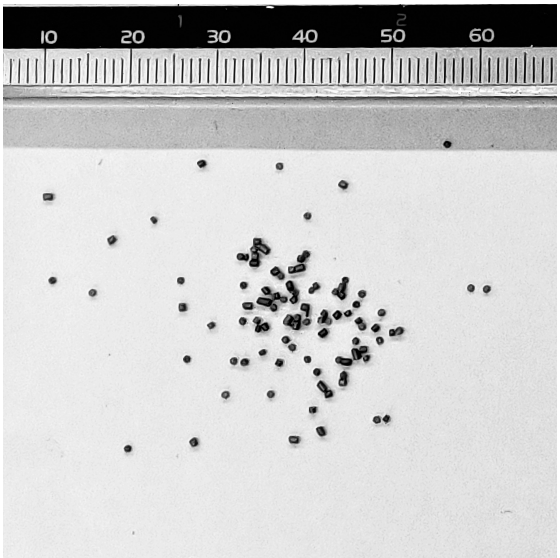

Figure 16: Nitrocellulose pellets

The complexity of the hot gas system comes in when maximising exit velocity for a minimum internal pressure and kickback force. In an ideal case, the pressure is constant throughout the motion of the sabot. This keeps the kickback force at a minimum while maximising exit velocity. This is easier to achieve with regulated cold gas systems as more gas can be added throughout the firing.

In comparison to the ideal case where the pressure is constant over the motion of the sabot, a simple hot gas system produces all of its gas instantaneous. This means a higher peak pressure is required to obtain the same exit velocity, thus creating a higher kickback and an overall heavier structure. The development of such a system is much easier but much less elegant compared to the ideal system. Burning all the pyrotechnics as fast as possible means the gas generator can be straightforward, as shown in Figure 15.

On the other hand, to create the ideal system, the gas needs to be generated with a specific pressure-time profile. What this entails is developing something that resembles a small solid rocket motor. Not only is this difficult in and of itself, but the burn rate must also still be extremely high to account for the fast actuation of the deployment system.

Due to the difficulties of creating a constant pressure mortar DARE has spent its resources developing the high peak pressure mortar with a pseudo instant ignition. While its pseudo instant ignition may be much simpler, achieving reliable ignition in different flight profiles is still a challenge. To accomplish this, a part was designed to house the ignitors and the pyrotechnics also known as a 'gas generator' as this part replaces the feed system and tank of the cold gas parachute mortar.

Nitrocellulose has been the pyrotechnic of choice in DARE for the hot gas parachute mortar. It was chosen due to its extremely high burn rate, low residue and low combustion temperature. Nitrocellulose can be found in the form of small pellets, the shape can be seen in Figure 16. The problem with having pyrotechnics in the form of lose pellets is that to sustain a combustion reaction the pellets need to be close enough to each other. To keep the nitrocellulose from spreading out during flight it is held in place by a mesh this, in turn, is constrained by a retainer ring. The assembly can be seen in Figure 17 and Figure 18. To ensure ignition, this particular design keeps the ignitors pressed up against the nitrocellulose.

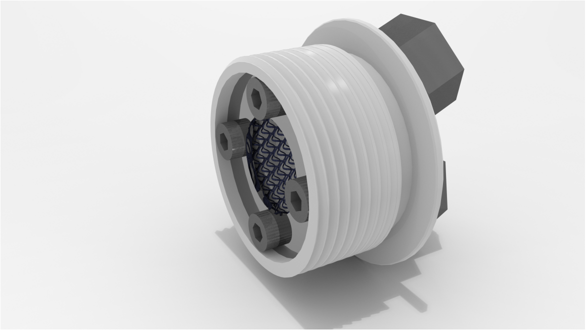

Figure 17: Render of the Stratos gas generator

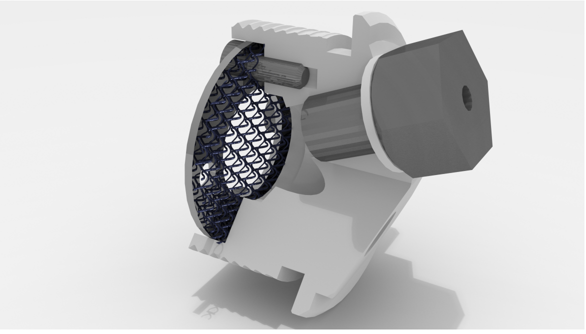

Figure 18: Section view of the Stratos gas generator

The main advantage of the hot gas deployment device is the lack of a feed system. This reduces both weight and volume while making the system less complex since it has fewer moving parts. Furthermore, as the system has lower power requirements, it is also easier to actuate and requires less effort from the electronics while also being cheaper because no expensive valves are needed.

Disadvantages of the hot gas deployment device are that the device may put higher load requirements on the plate housing the system and may end up at higher internal pressure than the cold gas deployment device. An top of this, sourcing pyrotechnics in another country when at the launch site may become an issue. Testing can be more difficult since the gas that is under pressure and becomes hot. The latter means that during the design of the parachute, special attention should be paid when deciding on the parachute material as heat might cause it to degrade.

5.4 Slug guns

A slug gun, also known as drogue gun, is the classical method of forced ejection for parachutes. It is a mechanically triggered pyrotechnic device which ejects a slug at a high velocity. The system is identical to the hot gas parachute mortar in principle where pressurised gases from a chemical reaction push mass out at high velocity. The slug is attached to the parachute bag using a line, as seen in Figure 19. Given its simplicity, it is an extremely reliable method of parachute deployment.

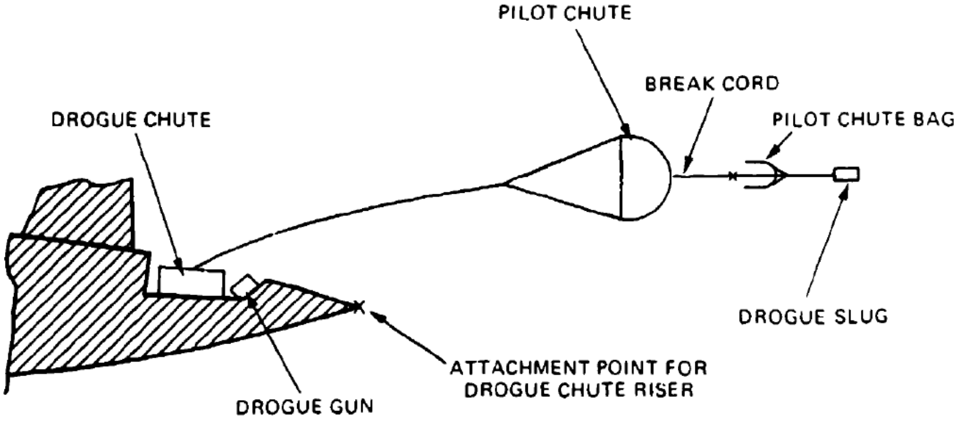

Figure 19: Slug Gun Parachute Deployment[12]

Slug guns are relatively heavy and have higher reaction loads than extraction systems such as tractor rockets.[10] However, the reaction loads of slug gun are often lower than those of a parachute mortar for the same parachute size.[1] Slug guns are only suitable for smaller parachutes, as the additional weight of the slug starts becoming considerably inefficient for larger parachutes. Therefore, slug guns are only used for pilot chutes and small drogue parachutes. This implies that slug guns are often used in combination in with aerodynamic extraction of larger parachutes. The maximum mass of a slug is recommended at 1 kg.[12]

They are typically used in aircraft ejection seats and spin recovery of aeroplanes to deploy pilot chutes at high-velocity.[1,11] They are capable of performing well at high dynamic pressures and spin rates. Their use in big rockets is limited because of their limited scalability for larger parachutes. DARE has not developed slug guns yet for a variety of reasons. The primary being the lack of available surface area on the Stratos III recovery plate for placement of an additional system. Additionally, there are safety concerns regarding the deployment of a dense slug at high velocities during testing. Lastly, given their better scalability, DARE chose to develop mortar systems instead.

5.5 Tractor rocket

A tractor rocket uses a solid propellant to pull the parachute out of the vehicle, a sketch of the system can be seen in Figure 1. The tractor rocket is generally a lightweight solution for deploying a parachute. It requires few supporting systems on the main vehicle and almost no reaction loads are created on the supporting structure. It also puts out a continues force over the deployment time; this means no pilot chute is needed to pull of the parachute bag. Finally, it is possible to achieve very high accelerations and thus fast deployment times. The disadvantages are that, due to its high velocity can be some frictional heating between the parachute bag and the parachute components and that the exhaust from the rocket needs to diverted in such a manner that it does not impact on the parachute bag.

DARE does not have experience with this method of deployment. However, it has not been taken into consideration when selecting deployment devices for projects such as Stratos due to its complexity of testing. The requirements of previous DARE missions did not require this system. Finally, the space in the Stratos sounding rockets was limited such that the addition of a rocket canister was not feasible.

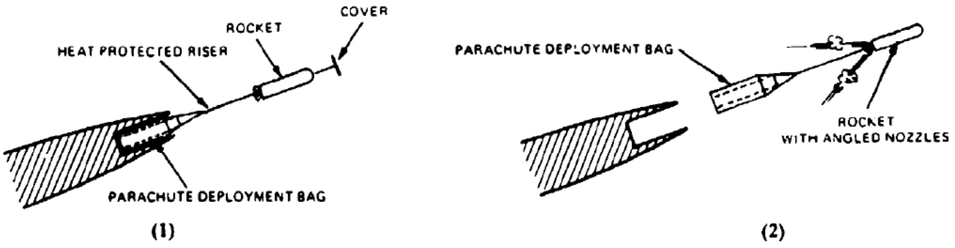

Figure 20: Tractor rocket schematic[12]

6. Conclusion

For the conceptual design of the recovery system, one must first select one of the three mentioned concepts. Based on this a general parachute configuration is gathered as seen in section 4. Concepts 1 is significantly higher in mass. Additionally, due to the entanglement risk, it is not advised to use concept 1 for full rocket recovery of sounding rockets. When a launch provider desires to recover the entire sounding rocket, it is recommended to do this in one piece, with two parachutes. Any form of making the rocket unstable to decrease the ballistic coefficient is advised. When the rocket is optionally fully recoverable, concept 3 is preferred as the user can choose to lower the requirements on the tank recovery or remove tank recovery as a whole.

In terms of the parachute deployment system, it is suggested to keep it as simple as possible. This means that for a second parachute, which has lower deployment requirements, an aerodynamic or spring deployment is almost always sufficient. When a faster deployment of the main parachute is required, one can investigate the parachute mortar. The choice of whether hot or cold gas is desirable depends on the experience and testing opportunities of the user. Only when the kick-back force of the main parachute mortar system is too high for the system then a tractor rocket solution is advised.

A parachute mortar is always advised for the drogue parachute as the nose cone is either unstable (concept 3) or sharp objects like the fins of the rocket need to be avoided (concept 2). For the drogue parachute, a slug gun system can also be considered when the drogue parachute is sufficiently small. In this case the slug can act as a pilot chute. This is mainly advantageous when the Mach number or dynamic pressure is too high for a standard pilot chute.

Aside this it is advised that during the design process the requirements on the recovery system and different deployment systems are clearly stated and traceable via for instance a requirements discovery tree, since different requirements form the initial selection of which systems are feasible. Additionally logistics and resources are to be taken into account, possibly included in the requirements overview as well, since they form a large constraint on the selection of deployment mechanisms.

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