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The design and development of an electromechanical drogue parachute line release mechanism for level 3 high-power amateur rockets

by

Marie House

An undergraduate honors thesis submitted in partial fulfillment of the
requirements for the degree of
Bachelor of Science
in
University Honors
and
Mechanical Engineering

Thesis Adviser

Robert Paxton

Portland State University

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Abstract

This research has developed a viable drogue parachute release system sufficient for recovering level 3 amateur rockets. The system is based on the simple mechanics of combining two lever arms and a 2 to 1 pulley interaction to create a 200:1 force reduction between the weight applied to the system and the force required to release it. A linear actuator retracts a release cord, triggering the three rings that hold the system together to unfurl from one another and separate the drogue parachute from the payload. Three variations of the concept were prototyped and tested primarily for the required pull force to actuate. The results demonstrated that for any set the force should never exceed 4 lbf. Parachute testing was also completed to prove that most of the energy change during the drogue parachute deployment is absorbed by the actual parachute and not the release system's hardware. This system will be integrated into the Portland State Aerospace Society (PSAS) rocket, scheduled to launch in July 2019.

~ Dedication ~

I am ever grateful for the love and patience of my little man with cheeks of tan...my 12lb forever-baby with a tail, Reggie. I will now have time to be the coolest dog mom in the park.

I would also like to dedicate this work to the person who prioritized me when I prioritized my work. To my loving partner, James. You kept me fed and helped with my laundry more than I care to admit. Thank you for your unwavering support, please keep cooking.

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First and foremost, thank you Robert Paxton for taking on this thesis as the advisor. The advisor is just as important as the student, and I am so grateful that we were able to stay aligned throughout the whole process. Your time and support have been the difference in my success.

Thank you to Alan Hurley for all of your time spent manufacturing the various prototypes and working with me to test them..time and time again. We persevered through broken sensors and prototypes, but the pain will be worth the success when this system is able to save a falling rocket.

Thank you as well to the Portland State Aerospace Society (PSAS), and specifically Andrew Greenberg, for your support throughout this project and long before. My history with PSAS stretches almost five years and I owe much of my growth as a professional and individual to my experiences with the team.

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1 Introduction

This paper serves two purposes: primarily, this research is meant to benefit the Portland State Aerospace Society (PSAS) in their race to reach 100 kilometers to win the Base 11 Space Challenge [1,2]. The second goal, consequently, of this research is to benefit the community of high-power amateur rocketry that is generally associated with university level rockets. At higher apogees, one of the subsystems greatly affected is the rocket's recovery system. Atmospheric pressure and temperature decrease as altitude rises, which can have negative consequences on the various mechanisms that make up the system. As well, the vibration and G-forces increase and are spread over longer periods of time due to the increased thrust and time to apogee, which can lead to parts jamming or vibrating loose. With this in mind, my research will attempt to develop a non-consumable line release mechanism that is reliable for level 3 amateur rocket recovery systems. The line release mechanism finalized during this study will be used in the recovery system of the PSAS Launch Vehicle 3.1 (LV3.1) rocket, scheduled for launch in July 2019.

1.1 Project Motivation

PSAS is a university group that has been building and flying high powered amateur rockets for over 20 years. Using an evolutionary process, they have flown four generations of rockets totaling 13 separate launches. Every subsystem within the rocket, including parts of the recovery system, have been consistently improved throughout the lifetime of each model.

The PSAS recovery system started out by using explosive powder to separate both the nose cone from the body of the rocket and to sever the line that connects the body to the drogue parachute. Discussed in section 2, a gunpowder ring separated the nose cone from the main body and a pyrotechnic line cutter assembly severed the drogue parachute and deployed the main parachute [3,4]. The main parachute was stored within the main body of the rocket and the drogue was exposed after the nose cone separated. A surgical tubing assembly was also created and drawn in tension during assembly, acting as a slingshot to separate the nose cone from the body of the rocket.

Eventually, the gunpowder separation ring was replaced by an entirely electromechanical system, the Electromechanical Nose Cone Separation Ring (eNSR) [5]. This was an improvement over the explosive design because it eliminated the use of consumable components (i.e. the explosives) and allowed both parachutes to be stored within the nose cone of the rocket. Storing the parachutes within the nose cone and the electronics at the top of the main body is more advantageous because it shifts the center of gravity closer to the front of the rocket. This is very important for stability during

flight [6]. However, it adds a significant level of complication to the recovery system since, once the nose cone has been separated, almost all components are exposed to the open air currents flowing around the rocket - especially the undeployed main parachute. Also, the nose cone must now eject far enough from the rest of the rocket to clear the stack of parachutes contained within itself.

Before its first launch, the eNSR was put through one redesign for assembly and manufacture improvements. The surgical tubing assembly was also improved to accommodate the new system. Although successfully flight tested using a plane to mimic a fall from apogee, the system was crushed during its first launch due to a catastrophic failure mid-flight. This has led to the formation of the current senior design team to develop the next generation drogue parachute deployment subsystem (a.k.a. nose cone separation subsystem).

Throughout every other subsystems' modernization, the line cutters used to detach the drogue parachute were never changed. This became an issue when the previous design team began to have trouble with system's performance and were unable to easily follow manufacturing and assembly documentation. When set up according to instruction, the assemblies were not cutting through the same line that was always used in the past. Documentation was scarce and the team struggled to fix the cutting heads, ultimately making new sets. This, too, proved to be a challenge due to the lack of documentation and skills and precision required to manufacture the heads. Thus, upon the demise of last rocket, the need for a new drogue parachute release system was born.

1.2 Amateur Rocketry Classifications

High-power amateur rockets may have enough thrust to reach space, but they are still considered sounding rockets because they do not have the horizontal trajectory to stay in space like an orbital rocket. High-power rockets do, however, have significantly more power than model rockets and require special certifications at distinct levels in order to fly [7]. This is important for flying university level rockets, such as the PSAS rocket which requires a level 3 certification.

The three different certification levels are dictated by the thrust capabilities of the motors. At the base of high power amateur rocketry stand class H motors with 160 N-s of total impulse. Launching with this size motor requires the first level of Tripoli or NAR certification. Level 2 certifications are required after 640 N-s, and level 3 is required from 5120 N-s (1,151 lbf-s) to 40,960 N-s (9208 lbf-s). Level 4 is reserved for classes of motors that are not normal to university level work and are therefore not included in the scope of this discussion. Table 1 lists the motors within the outlined levels and their corresponding impulse for metric and standard units.

Table 1. Motor class and impulse for the first three levels of Tripoli/NAR certifications [8].

Class	Total Impulse (N·s)	Total Impulse (lbf·s)	US Requirement
H	160.01–320	36.01–71.9	Level 1 Certification required from Tripoli or NAR.
I	320.01–640	71.9–144	
J	640.01–1,280	144.01–288	Level 2 Certification required from Tripoli or NAR.
K	1,280.01–2,560	288.01–576	
L	2,560.01–5,120	576.01–1,151	
M	5,120.01–10,240	1,151.01–2,302	Level 3 Certification required from Tripoli or NAR.
N	10,240.01–20,560	2,302.01–4,604	
O	20,560.01–40,960	4,604.01–9,208	
P	40,960–81,920	9,210–18,400	FAA/AST Permit or License required.
Q	81,920–163,840	18,400–36,800	
R	163,840–327,680	36,800–73,700	
S	327,680–655,360	73,700–147,000	Largest motor used by amateurs.

1.3 Recovery for a Level 3 Rocket

A dual deployment parachute recovery system is the strategy used by PSAS to recover their level 3 rockets, and therefore is what was adopted for this research. As Figure 1 shows, this breaks the task into two separate subsystems: the drogue parachute deployment and main parachute deployment (a.k.a. drogue parachute release). Immediately after apogee, a drogue parachute is deployed followed by a main parachute much later in the rocket's descent. The purpose of the drogue parachute is to reduce both the shock force experienced during deployment and the radius of landing. The principle behind the system is to catch the falling rocket with a smaller area, reducing the drag force acquired in the opposite direction of travel and effectively

reducing the initial shock force applied to the system. A drogue parachute is smaller than the main parachute, often manufactured out of more durable materials, and is released first after apogee. Since the surface area of the parachute is smaller, the rocket also falls faster which leaves less time for it to drift radially.

Figure 1. Example of a dual deployment parachute recovery system [9]. The example is shown with the drogue parachute remaining attached; however, for the actual application the drogue parachute will be completely detached.

When the rocket is relatively close (approximately 1000 ft) to the ground, the drogue parachute is released from its anchor and the main parachute is simultaneously deployed. There is an option to either release the drogue parachute entirely from the rocket or to leave it attached to the main parachute as it deploys and takes control. Again, since this project is researched and designed to integrate into the PSAS rocket, the drogue release system will be such that it completely detaches from the rocket. The line of the drogue parachute will be worked into the packaging of the main parachute by the PSAS recovery team so that when the drogue parachute separates, it functions as the actuator to deploy the main parachute.

1.4 Current PSAS recovery system requirements

The Solidworks CAD model of the PSAS Launch Vehicle 3 (LV3) rendered in Figure 2 is the rocket that the system resulting from this research will recover. The rocket has a 6.6 inch diameter and stands 11.6 feet tall. It is designed as a modular carbon fiber

airframe, connected using aluminum rings clamped together. The recovery system will be stored partially in the nose cone of the rocket and partially within its own miniature module made almost entirely of aluminum. The final drogue parachute release system that is developed from this research will primarily be housed within the mini aluminum module.

Figure 2. Launch Vehicle 3 (LV3). Solidworks model made by the 2016 PSAS Airframe team.

After successfully deploying the drogue parachute, the main parachute deployment is most important. For a two-parachute system, such as the one in Figure 1 above, this is triggered by the release of the drogue parachute. Once the drogue parachute is released from the payload, the upward drag force pulls it away as the payload experiences downward acceleration due to gravity. For the current PSAS rocket, the drogue parachute is prescribed to completely detach and consequently pull a cup housing the main parachute away with it.

The system that releases the drogue parachute must be packaged alongside the nose cone separation system and the main parachute anchor. The actuator itself and the electronics to run it can sit above or below (or partially recessed) the plate they are mounted to. There is an option to mount a steel bar below the plate for anchoring the parachutes as well.

The ultimate intent of this design is to integrate it into the recovery system of the PSAS Launch Vehicle 4 (LV4) rocket, which is competing in the Base 11 Space Challenge, a race to reach 100 km [2]. Thus, the project requirements are set at a minimum of withstanding the environments during a level 3 rocket launch, with a stretch goal to create a system that can handle LV4.

1.5 Proposed Development Plan

This project will begin with a literature review of prior work specific to rocketry and designs of similar applications. Using the initial research and knowledge accumulated through practice, conceptual designs will be developed and graded based on design criteria that has been adopted from the PSAS recovery system team. Once a design has been chosen, variations of the concept will be prototyped and tested. This will assess the validity of the design with regard to the design criteria and it will highlight areas of improvement for the final design. The final design will include the necessary drawings and bill of materials (Appendix A) to manufacture the system as well as the standard operating procedure (Appendix B) that will describe the assembly and actuation of the system.

2 Prior Work

2.1 Discourse Community

Since this research will be integrated into the PSAS rocket, the primary sources of my discourse community come from amateur rocketry. Level 3 rockets are also the most commonly constructed among university level teams. There are two professional institutes that are significantly relevant within my research as well: the Institute of Electrical and Electronics Engineers (IEEE) and the American Institute of Aeronautics and Astronautics (AIAA). They publish several journals that host topics similar to mine. This research will actually be incorporated into a submission the PSAS recovery system team for presentation at the 70th International Astronautical Congress sponsored by AIAA (Washington DC, October 2019).

2.2 Prior Work within Amateur Rocketry

2.2.1 *Traditional Recovery Systems*

Previously, PSAS has used line cutters actuated by gunpowder to release the drogue parachute [3], effectively deploying the main parachute by pulling its container away with the drogue parachute. This is a thoroughly practiced method commonly found in amateur rocketry as far back as 1956 [9-12]. Another method uses a spring to initially hold down and then release the drogue parachute when the drag force reaches a state of equilibrium [13]. However, there are many designs that argue against the use of pyrotechnics and springs for high altitude applications because their properties change with such increased apogees [14]. Although tried-and-true, gunpowder methods lack a level of robustness that is required for high powered flights. The properties of the gunpowder and its resulting combustion change with dramatic increases in altitude, making the system unpredictable. As well, the various systems require fresh gunpowder after each run, leaving the resulting fresh assembly untested until it flies again. Many designs also call for the use of a timer for the pyrotechnic actuation [13]; this is ill advised because location is not solely dependent on time when dealing with a bluff body. Therefore, it is preferred to track position directly using sensors, such as the ones incorporated within the PSAS avionics module.

2.2.2 *Shape Memory Alloy Releases*

Several recovery system designs that are non-consumable use a thermal technique that incorporates a Shape Memory Alloy (SMA) wire as the trigger for release [16-18]. In general, SMA actuators work by heating the wire to an activation temperature, which then causes it to contract or change shape as it undergoes a phase transformation during the heating process. Of particular interest, SMA can be actuated by running a

current through the wire to induce ohmic (or Joule) heating [19]. Using this method, the wire can be heated using current from a battery consequently actuating the release mechanism. The resistive property of SMA wire also changes significantly during the phase change and actuation of the SMA [20]. Therefore, a circuit may be controlled by monitoring the wire resistance and cutting off the current after the resistance indicated that the wire had changed phases and the device has actuated. For parachute recovery applications, this phenomenon has been used in conjunction with a separation nut to release parachute lines [16,18]. These systems are capable of having a reliable design and incorporating “in-situ” reset. The principal of “in-situ” is creating a system that can be reset without replacing any components and breaking no electrical connections [16].

2.2.3 *Designed by PSAS*

As an alternative, the aforementioned eNSR was also used for inspiration. Shown in Figure 3, the system utilizes a brushless DC motor attached to a threaded guide rod to pull back a clamp, releasing the nose cone. The clamp is circular shaped so that when it is in place it is clamping directly to the inner flange of the nose cone module ring. This clamp is then released at apogee by rotating the threaded rod backwards off of the flange. This system also incorporates “in-situ” reset; by driving the motor forward and back the system is put into its locked and unlocked positions.

Figure 3. Assembled eNSR for LV3.0. The motor is located at the back of the anchor rail and the guide rod is threaded into the carriage at the front of the rail with the clamp attached to the outermost ends of the carriage.

2.3 Prior Work within Similar Applications

2.3.1 Three Ring Personal Parachute Release

Researching other parachute release mechanisms lead to another, more frequent application: skydiving [21]. The Three Ring release system, shown in Figure 4, is a very popular reserve parachute deployment (i.e. main parachute release) device. Originally invented by Bill Booth in 1979 [22], the system uses mechanical advantage to reduce the pull force required for actuation. In Booth's design, each ring pairing is a lever arm that provides a 10:1 force reduction, coupled with a 2 to 1 pulley interaction through the retaining loop - totaling a 100:1 force reduction if manufactured and assembled as theorized. The nylon retaining loop is kept in place by a wire release cord, which is pulled out to cause the smaller of the three rings to unfurl and detach from the largest ring. Figure 5 demonstrates the system in its locked state and its released state.

Figure 4. Three Ring Parachute Release [23]. Main components are called out with arrow indicators. It is important to note that the nylon retaining loop first passes through the smallest ring, then behind and through the grommet to be retained until release.

Figure 5. Locked and released stages of a typical three ring release (Acodered / CC BY-SA 3.0).

The original design has been popularized as a refined “mini set” which reduces the overall size of the system but increases the pull force required for actuation [24]. Another set changes the design of the middle ring to maintain the smaller size but gain length (i.e. force reduction) by changing the shape of the ring to be an oval [25]. Regardless, the force to actuate is small but it is designed to withstand the shock from catching a falling person.

2.3.2 Locking Plunger Socket Wrenches

A similar concept, found even more commonly, is that applied to socket wrenches (Figure 6) [26]. Using a spring force, the plunger retains a socket head even against high forces. When the plunger is depressed, the ball falls into the groove shown which releases the socket head.

Figure 6. Depressible, ball-bearing plunger design for socket wrenches. Highlighted in green is the area of interest for this research; the shape of the plunger, the size ratios between the ball and the overlap within the socket and the ball and the wall thicknesses.

This invention can be useful by replacing the socket head with the line of the drogue parachute and the push button with a solenoid. The ball bearing and housing should be able to withstand the force of the drogue parachute deployment and the availability of a solenoid with enough pull force to move the plunger is reasonable to expect.

3 Concept Development and Evaluation

3.1 Conceptual Designs

Three initial concept designs were developed from the prior work research. The first was designed to use SMA wire as the actuator and mimic the plunger of a socket wrench. The second concept replaced the SMA wire with a DC motor and a threaded rod; and the last conceptual design applied the three ring system used by skydivers. These designs are detailed below and evaluated based on criteria set by the PSAS recovery team.

3.1.1 SMA Wire Activated Plunger

Depicted in Figure 7, the SMA wire was designed to be formed into a spring and captured by the housing. A bias spring would be used to keep the plunger in its closed position until actuated. When the SMA spring is heated, it would retract into its closed spring shape, pulling the plunger along with it. This allows the set of ball bearings to fall into the indent of the plunger and release a sleeve (not shown). The system is shown with only two balls, but it is possible for there to be up to four if the force applied during shock needs to be further reduced. Once the system is deployed and the wire cools, the bias spring would pull the plunger back into place. The benefits of this design are its ease of manufacturing, orientation of application, and simplicity. Only three parts would need to be machined: the sleeve, housing, and plunger. The remaining required parts are all commercial off-the-shelf (COTS) parts. When integrated with the rest of the rocket, this design would sit vertically, saving space for other components.

Figure 7. SMA and Bias Spring Controlled Plunger Design

One disadvantage of this design is the need for a very specific standard operating procedure (SOP) regarding the purchase and creation of the SMA spring. Furthermore, after trying to source the material for prototyping, it became clear that there are few distributors that work with small customers, such as university groups, and can provide enough documentation to provide confidence in the consistency and capabilities of their products. The procedure for training the wire into different shapes must be consistent in order to achieve the same results. The person creating the spring in the future would need access to a thermal chamber that can reach temperatures of 900 °C and have the capability to immediately quench the spring after heat treating.

3.1.2 DC Motor Activated Plunger

For the second concept, annotated in Figure 8, the SMA wire spring and bias spring were replaced with a motor and threaded rod. The threaded rod replaced both the SMA and bias spring since it is a rigid connection (i.e. the plunger cannot move without twisting the threaded rod). When the rod is turned by the motor (not shown), it threads into the plunger. This pulls the plunger downward since the motor would be rigidly mounted and the housing is being pulled in the opposite direction by the parachute.

Figure 8. Motor Driven Plunger Design

One of the main benefits of this design is that it uses traditional components that are readily available with various specifications. Using a motor also enables the system to apply more pull force to the plunger with more precise control as well.

3.1.3 Three Ring Release Design

The three ring design was applied largely the way it is presented in Booth's patent; however, the system had to be automated. To do this, a motor was implemented to pull on the release cord. Both a DC motor and a linear actuator were considered for this application. The DC motor is desirable for its ability to retract large lengths within a small volume by winding around its shaft. On the other hand, the linear actuator is easier to implement vertically, which is more space saving. For the DC motor application, a string would be attached to a spindle at the end of the motor shaft and to the end of the release cord. The string would be wound by the motor to pull the release cord through the retaining loop. For the linear actuator that was selected, it is possible to loop the release cord directly to the actuator, through a hole at the end of its shaft.

As shown in Figure 9, the green webbing at the base of the design would be attached to the body of the rocket and the middle blue webbing would be attached to the drogue parachute. When the system is triggered, the smaller two of the three rings fly away with the drogue parachute and the base ring stays attached to the rocket.

Figure 9. Three Ring Release Design

It is suggested that the success of this system is sensitive to manufacturing [27], but after further research it is still unclear exactly what dimensions of the system are most critical. My hypothesis is that the ring spacing and perhaps the retaining loop placement for the yellow cord are the most important. Also, to note, there is currently a PSAS member that is capable of manufacturing the system from prior experience, but this will not always be the case. Therefore, there must be detailed drawings that a future PSAS member can follow if this design is carried through.

3.2 Design Criteria

The following criteria, in order of importance, were selected by the PSAS recovery team to evaluate their concept designs and are consequently the basis for this evaluation as well.

3.2.1 *Vibration Resistance*

There are small but intense vibrations from the Mach forces during ascent that can vibrate hardware and other components loose. All sensors and/or mechanics for the system must be chosen with vibration resistance in mind. Most importantly, components should not be able to vibrate into a jammed position and sensors should be robust enough to maintain their calibration throughout the extreme motion.

3.2.2 *Accidental Actuation*

Whatever method of actuation chosen, it is important that it not be possible to release the drogue parachute accidentally. Strategies such as designing over-center and with lost motion can easily accomplish this [28,29]. The system must also be strong enough to withstand the shock force applied when the drogue parachute deploys and inflates. Theoretically, the unfurling and inflation of the parachute should absorb most of the change in kinetic energy at the time of deployment but the speed at deployment can vary greatly [30].

3.2.3 *Simplicity*

Simplicity is defined by the complexity of the final assembly - how many parts could break or malfunction. The less parts, especially less moving parts, the better the design. Any electronics used to control the system should be easy to debug and operate. The final concept should be relatively intuitive for others who will work with the system in the future. Longevity and durability are also evaluated through simplicity. If parts need to be replaced often, that complicates the design.

3.2.4 *Ease of Assembly*

The system will ultimately be passed down to a future team, so it is important that the final assembly and operation of the design be easy to understand and carry out. The recovery system is a critical aspect of flight, so it is important that the success of the operation not depend on any assembly step that is commonly forgotten or easy to perform incorrectly. It is likely that the drogue parachute release will be assembled on-site, too. This means that extra tools, especially unique tools, required for assembly should be avoided; and that assembly should be possible in adverse environments.

3.2.5 *Commercial-off-the-shelf (COTS) Parts*

Designing with COTS parts rather than for custom manufacturing is important for simplicity, availability and consistency of parts, and potentially the overall cost of the project. Although not always possible, a design that incorporates more COTS parts than custom will be considered more favorable. It is also important that the COTS part not be too unique; that there be several variations that would allow for improvements to the prototype for the final design. Also, that the manufacturer be reputable and will likely continue to be in business.

3.2.6 *Internal Space Saving*

Since the drogue parachute release is housed alongside the nose cone separation system and the main parachute anchor, the surface area available is best described by cutting a pie into equal thirds. That being said, the less room that the line release system takes up, the more space available for the rest of recovery which is very desirable. It is also safer for each system the more isolated it is. A more compact system will likely weigh less as well.

3.2.7 *Lightweight*

Although one of the described advantages of the current recovery system is that weight is brought to the front of the rocket, it is still an overall goal for the rocket to be as lightweight as possible. Efficiency of a design is partially dependent on the overall weight - the more compact, the lighter, and thus the more efficient.

3.3 **Concept Evaluation Matrix**

Each of the criteria outlined above were also given a weighting factor of 1-5, where a factor of five signifies that the criteria is extremely important and a factor of one indicates relatively low importance. The weight applied to each criteria is listed in the second column of Table 2 which outlines the concept evaluation results. The three conceptual designs were reviewed with the PSAS recovery team to establish overall scores for each. The weighted totals are listed along the bottom of the table.

Table 2. Concept Evaluation Matrix for the Drogue Parachute Separation Design

Criteria	Wt.	SMA Plunger	SMA Plunger Weighted	Screw and DC Motor	Screw and DC Motor Weighted	Three Ring Release	Three Ring Release Weighted
Vibration Resistance	5	4	20	5	25	4	20
Accidental Actuation	5	4	20	4	20	2	10
Simplicity	4	2	8	4	16	4	16
Ease of Assembly	3	3	9	3	9	4	12
COTS parts (use and availability)	3	2	6	3	6	5	15
Internally Space Saving	2	4	8	2	8	5	10
Lightweight	2	2	4	1	2	5	10
Total			75		86		93

The Three Ring Release concept scored highest primarily due to the COTS parts use, space saving and lightweight design. The one criteria that raised concern, however, was accidental actuation. Without prior hands-on knowledge of the ring release system, it is unknown how well the yellow cord stays positioned through the retaining ring. If actuation cannot be well controlled, then the system will not be deemed reliable enough for flight. Since the connection on either side of the release is a fabric loop, and there is no way that the fabric can vibrate loose, vibration resistance is negligible.

3.4 Final Design Prototyping

To further develop the three ring release concept, three different prototypes were created. The top prototype shown in Figure 10 is modeled directly after the original Bill Booth “Three Ring Release” design. It is composed of larger rings (No. 10, No. 2, and No. 3 sized rings) than what is typically called a “mini ring” set. The prototype featured at the bottom of Figure 10 is intended to reflect the typical mini design, made from a No. 8, No. 3, and No. 4 sized ring. The ring set in the middle is a simplification of the general concept. The theory behind the three ring design can be applied to any number of rings, dependent on the desired force reduction. Therefore, a large two ring set was created in an attempt to measure the actual force reduction added by an additional ring.

Figure 10. Ring Release Prototypes. Each square on the grid is equivalent to one inch in real life. From top to bottom: Large Ring Set, Two Ring Set, and Small Ring Set. (Photo credit: Alan Hurley)

For all of the prototype designs, the grommet location was changed from the body of the main webbing to a separate piece of webbing out in front of the ring set. This removed the hole in the main webbing line that takes away from the overall integrity. Guide rails were also sewn in place on either side of the assembly to help facilitate the movement of the release cord. The given names for each of the prototypes and their ring sizes are listed in Table 3.

Table 3. Ring Set Parameters. Inner and outer diameters specified along with their typical manufacturing part name.

Set	Ring	ID	OD
Large Ring Set	No. 10	1 23/32"	1 3/4"
	No. 2	1 19/64"	1 43/64"
	No. 3	7/8"	1 15/64"
Two Ring Set	No. 2	1 19/64"	1 43/64"
	No. 3	7/8"	1 15/64"
Small Ring Set	No. 8	1 9/32"	1 3/4"
	No. 3	7/8"	1 15/64"
	No. 4	17/32"	51/64"

4 Prototype Testing

Testing was completed in three phases. The first phase was concerned with the pull force to actuate the release systems. This was measured as the force required to pull a discrete length of the yellow cord through the white retaining loop to release the system, which was held under tension from an applied load equivalent to the anticipated weight of the rocket. The second phase of testing was used to determine the motor selection by validating and comparing torque capabilities. The third phase completed a test external to the ring systems, using the drogue parachute. Discussed in Section 4.1 below, the shock force experienced by the ring system during the drogue parachute deployment was measured as a “sanity” check for the maximum anticipated force to be applied to the ring system. The goal was to test the “worst case scenario”, defined by full drogue parachute inflation after four seconds of free fall. Four seconds is the longest expected time after apogee until the parachute is fully deployed. This anticipates a full second after apogee until the nose cone separation begins and three seconds from then for parachute to inflate.

4.1 Parachute Testing Apparatus

Depicted in Figure 11, a 300 kg S-bar load cell was attached to the roof rack of a vehicle using two eye bolts, several carabiners, and a small amount of 200 lb strength line. The 200 lb line was to ensure that no damage could be done to the roof rack. Not shown, is the drogue parachute that is attached to the other end of the last carabiner in the assembly line. A camera was also attached to the roof to take footage of the drogue parachute as it deployed.

Figure 11. Parachute Testing Apparatus. Several break-away lines were used with carabiners to connect the vehicle and the drogue parachute to the eye bolts at either end of the load cell.

4.2 Actuation Force Testing Apparatus

Shown in Figure 12, a bucket of concrete was hooked to one end of each ring release design while the other end of the design was looped over another eye hook at the top of the apparatus. An extending line was used on the bottom end of the assembly to reduce the distance from the floor to the base of the concrete bucket and make it easier to access the tension gauge during each test. The main frame of the apparatus was made of 2 x 4 ft wooden beams combined with two sawhorse brackets. The frame stands approximately five feet tall and three feet wide. Pads were placed below the weight to cushion the impact when the weight falls at the end of each run.

Figure 12. Ring Release Testing Apparatus

The concrete weight was made of an 80 pound bag of mix, which over approximates the weight of the PSAS LV3 rocket. The mix was poured into a bucket with an eye hook anchored at the top for attaching the ring releases for each run. A 40 kg tensiometer (load cell) with hooks at either end was used to measure the pull force required to actuate. This meant crimping one end of the wire release cord to make a loop for the tension gauge to hook on to. The other end of the gauge was pulled by hand to actuate each run. The release cord was started in the same position and pulled through the nylon retaining loop in approximately three seconds for each run.

4.3 Shock Force Measurement

As other tests were being developed, a particular verification became of interest to gain confidence in the hardware choices for the final system as well as the necessary testing parameters for the dynamic tests described in the next section. As mentioned previously [30], most of the shock experienced during drogue parachute deployment is theoretically absorbed by the parachute inflating; which implies force imparted on the hardware connecting the parachute to the payload (i.e. the ring release system) is of the same order of magnitude as the weight of the rocket. To prove this, a deployment test was developed using a larger strain gauge and a car driving at various speeds.

An Arduino with an SD card attached was used to log the data during testing. The parachute was folded using the “z-fold” technique [31] that will be employed during launch; and deployed from the window once the car reached the test speed.

4.4 Actuation Force Measurement

The actuation force was measured for straight pull and angled pull tests. For each test the ring design was set up according to the assembly procedure (Appendix B), then the smaller ring side of the assembly was looped over the eye hook in the top member of the apparatus frame and the concrete weight was hooked onto the largest ring side.

The straight pull tests were designed to evaluate the difference in required pull force to actuate between each of the three prototypes. This pull force translates to the required strength of the motor that will pull the release cord. The “straight pull” was defined by pulling the release cord as parallel to the main webbing as possible. The hypothesis was that the large ring design will require the least force to actuate, while the two ring design will likely require the most applied force. The small ring design should require more force than the large set; however, it is uncertain how it will compare to the two ring set.

The angled pull settings are depicted in Figure 13. The tests were guided by pulling in line with the scribed angles, designed to mimic some of the possible angles of the motor relative to the release cord due to off-center mounting within the actual rocket. The more the system is mounted away from the center axis of the rocket, the more the payload will tilt during descent. The pull angle was offset at 20, 30, and 40 degrees, measured from in-line with the main webbing were tested. It was decided that 10 degrees would not provide useful results and was probably encompassed through human error during the straight tests anyways. Furthermore, 45 degrees or more was determined unrealistic based purely on the required force balance to obtain such an angle. The hypothesis is that the required force to pull the release cord will also increase as the angle of the ring release is increased.

Figure 13. Angled Pull Force Measurement Gauge

4.5 Stall Torque Measurement

Using the same tension gauge as the actuation force measurements, a DC motor and linear actuator (Figure 14) were tested to verify their stall torque. The stall torque is primarily determined by the stall current, which is the amount of current produced when the motor has too much back pressure on it restricting the shaft from turning. The force measured at this point is the maximum available pull force during actuation. The test was purely observational since the objective was to verify that it was considerably (3-5 times) greater than the force required to actuate the release cord. A spindle was 3D printed for the shaft of the DC motor and a string was attached between the spindle and end of the release cord. The linear actuator came with a clevis end that the release cord could loop through and then be crimped around.

Figure 14. Motors Tested. DC motor with spindle (left) and linear actuator shown retracted (right).

5 Results and Discussion

The pull test and shock force results were very reflective of the hypotheses outlined in section 4.4; however, the calculated mechanical advantage of each system did not compare to the theorized 200:1 advantage. Granted, it is important to note, that even though the average force required for the Small and Two Ring sets is nearly double that of the Large Ring set, the maximum measured force from all of the pull tests is relatively small compared to the available power from the motors selected. The data collection from the shock force testing was limited but proved that the force applied to the system is on the same order of magnitude as the weight of the rocket. The raw data from the test results below are tabulated in Appendix 3.

5.1 Shock force effects

The shock force imparted on the ring release hardware was measured for various deployment speeds by replacing the release system with a load cell. It was discovered during this testing that the drogue parachute does not seem to inflate before 60 mph, therefore very few tests could be completed in the available range of speeds. The upper velocity boundary was dictated by the length of the roadway that the vehicle was driven on. Figure 15 displays the results from the parachute testing. Although the data becomes more scattered as the speed of the vehicle is increased, there still appears to be a positive relationship. More importantly, the forces detected by the load cell were all on the same order of magnitude as the weight of the rocket; rather than the magnitude of the total energy change during the parachute deployment. This means that testing the ring releases using a static weight equivalent to the anticipated rocket or more should be sufficient to cover the expected loads that the system might experience during flight. In other words, the shock force experienced during the drogue parachute deployment is not enough to warrant testing after shock loading the system.

Figure 15. Parachute Deployment Shock Force Results. The energy converted to the system hardware is small relative to the total energy change.

The upper speed boundary restricted any of the tests from actually reaching the velocity determined by the worst case scenario, but it is possible to attempt an extrapolation. For the purposes of this research, only the magnitude relative to the static weight of the rocket is critical.

5.2 Straight Pull Force Requirements

Figure 16 is a box-whisker plot of the maximum recorded force during each run for the straight pull tests. As expected, by comparing the mean measured forces it is evident that the Large ring set requires less force to actuate than the Small and Two ring sets. The ratio of the Small data to the Large data is approximately 1.9, suggesting that diametral reduction from the Large Ring set to the Small Ring set equates to almost doubling the required pull force. Calculating the ratio between the Large and Two Ring sets analyzes the effect of removing a ring from the system. The ratio of 0.47 indicates that removing a ring nearly doubles the required pull force as well. Comparing the Small and Two ring data by their mean ratio as well suggests that the systems have a similar effect on the required pull force since their ratio is 0.9.

Figure 16. Straight Pull Force Results. The plot uses the maximum recorded force from each run to compare the required pull force for each ring set.

The Small Ring set had the widest spread of significant data, while the Large Ring set seems to be the most controlled. This would make sense, given the warning from previous researchers that the small ring set is more sensitive to variation in construction [27]. The two ring set had the widest data spread overall, but several of the data points are outliers according to the “1.5 X IQR” rule [32]. The values calculated for the box plot constraints are tabulated below (Table 4). The minimum and maximum values are determined by subtracting and adding the interquartile range (Q3-Q1) from Q1 and Q3, respectively.

Table 4. Box Plot Results. The critical values to create a box-whisker plot for each prototype were recorded. Data points outside of the minimum and maximum values were considered outliers.

Ring Set	Minimum	Q1	Q3	Maximum	Median
Small	1.8	2.1	2.5	2.6	2.3
Large	0.9	1.125	1.275	1.4	1.2
Two Ring	2.3	2.4	2.5	2.6	2.45

Using the tools and time available, there is an appreciable amount of room for human error to consider. Although the release cord was positioned the same for each run, it was pulled by hand with a best attempt at finishing the run in three seconds at a constant speed. If the cord was pulled quicker at any point, the force would likely decrease due to the frictional force reduction between the nylon retaining loop and the release cord. It was also a challenge to consistently pull the release cord parallel with the webbing. If the cord were pulled at any small angle (<10 degrees), then the next test described in this paper will provide justification for the significance, if any, of this error.

5.3 Pull Angle Effects

To better understand the change in required pull force given the release system ends up mounted off-center with respect to the cross-sectional area of rocket body, the pull force was measured for three discrete angles. As the results show in Figure 17, the required pull force increased as the angle relative to the load application was increased. Again, the Large Ring set required less force than the other two prototypes and the Two Ring and Small Ring sets produced similar results.

Figure 17. Angled Pull Force Results. The angle was measured relative to inline with the webbing of the ring release (i.e. relative to perpendicular to the ground) to demonstrate the increase in pull force with increase in angle of pull.

Although the pull force to actuate increased with increases in pull angle, it is important to note that the magnitude of increase was relatively small. This provides more confidence that the final ring release system will be able to actuate under all foreseeable circumstances. There is the same human error to consider as the straight pull test; however, there is still a clear increasing trend in the data.

5.4 Stall Torque Results

The same tensiometer used for the pull force tests was also used to measure the force applied to the motors when the stall torque was achieved. No data was collected during this test since it was just important to verify that the motors could exceed the pull force requirements. Both motors surpassed the maximum pull force recorded in previous tests (3.38 lbf) with a factor of safety greater than 3. These results should guarantee that the motor is able to pull the release cord at any angle, and after any shock force is applied.

5.5 Additional discoveries

Originally, tubular webbing was planned for all connecting straps because it absorbs more shock force than flat webbing. During initial manufacturing, however, it was found that tubular style was too thick for a standard sewing machine by the time it was doubled over to create the top and bottom loops and to attach the two smallest rings of the system together. After reviewing the results from testing the drogue parachute and working with the ring release prototypes, it was decided that the material type could change for all parts. The test results proved that even if the drogue parachute deploys at the “worst case scenario”, the main webbing of the ring release should not see loads over 200 lbf. Additionally, by working with the ring release prototypes it became clear that the webbing used to attach the smallest ring does not see any significant loads, especially when compared to the main webbing. This is useful because the webbing is layered within several others so the thinner it can be, the easier it is to sew the stack together.

During manufacturing, the stitching used to attach the top and bottom webbing to the rings was discovered to be the weakest link in the assembly. The 80 lbf concrete weight was dropped from a height of roughly four feet which provided enough shock load to break the system. The assembly obviously broke at the stitching used to sew loops at either end. No deformation of the rings, testing apparatus, or other components was observed. This makes sense since the relative strength of the other loaded components are orders of magnitude greater. Even though the load applied to this system is significantly greater than in practice, it is important to know what the weakest link in the system is. Furthermore, the stitching pattern is a feature of the design that can be

controlled and improved so knowing that it is a failure mode provides an opportunity for improvement.

The sensitivity of the placement of the nylon retaining loop was also discovered during initial manufacturing. Incorrect stitching placement led to the scenario depicted in Figure 18, where the grommet, retaining loop, and smallest ring are able to balance the force of concrete weight below – even though the release cord has been pulled. This could be a possible failure mode in practice since the ability to further interfere with the system after pulling the release cord is impossible. If this failure mode occurred, the main parachute would never deploy, and the entire rocket would descend to the ground on the drogue parachute (falling approximately 100 ft/s).

Figure 18. Discovered Failure Mode. The smallest ring, retaining loop, and grommet are perfectly captured by one another, holding onto the 80 lb weight below *after* the release cord has been pulled.

To additionally help avoid the failure mode in Figure 18, the grommet webbing should be sewn with more slack. The webbing (shown in black) for the prototypes was made just to size, no slack in the line when the system is assembled. Part of the failure mode was the ability of the three components to be in complete tension at the same time. By adding slack to the webbing line, the grommet is considerably more likely to fall out or be pushed out of the way.

6 Conclusion

The three manufactured prototypes were tested to compare the required pull strength relative to one another by graphing the maximum standard pull force; they were also compared against themselves using the angled pull force results to gain an understanding of the change in required pull force when the motor is mounted off-center. The results from these tests demonstrated that for any set, even though the required force increases with pull angle, it should never exceed 4 lbf. The parachute testing proved that the force exerted on the system during drogue parachute deployment is equivalent to the weight of the rocket relative to the total energy change – most of which is absorbed by the parachute itself.

6.1 Final Design Specifications

After testing all three prototypes, the Small Ring set was chosen for the final design specification. Even though the Large set required half as much pull force, the stall torque measured for both motors was more than 10 pounds – therefore more than capable of pulling the release cord for any of the three prototypes, even with a factor-of-safety of 3. The Small was chosen over the Two Ring as well since it has a smaller overall width. Shown in Figure 19, the largest ring was also changed to a plain ring as opposed to the original that had a slot in the base for webbing. These choices significantly reduced the overall size of the assembly.

While testing the prototypes, the best orientation for the system was determined through repeated actuation and working with the PSAS recovery team. The goal while working with the team was to determine the most effective integration within the rest of the recovery system. It was decided that the side of the assembly with the nylon retaining loop will be attached to the rocket, and the side of the assembly with the singular largest ring will connect to the drogue parachute webbing. Actuating the system with the two smaller rings oriented on the bottom of the assembly is functionally beneficial as well, since it lessens the distance that the release cord must travel to reach the retaining loop.

Figure 19. Final Ring Release Design. Depicted in its locked state, the three rings are intertwined and captured with the nylon retaining loop (white) and the wire release cord (yellow).

Between the two motors tested, the linear actuator was chosen over the basic DC motor primarily because of its ability to integrate into the rest of the recovery system. It was easier to incorporate vertically (i.e. space saving), and the release cord could be directly attached to the motor. To use the DC motor, the release cord would need a flexible medium in between that could wrap around the shaft (or a spindle design over the shaft) in order to pull the cord downward. The linear actuator had a slightly higher stall torque, as well.

The stitching that creates each of the end loops and attaches the two largest rings to the assembly was increased in length and density to add strength (see Figure 20 for final design example). Mentioned previously, this was done after learning throughout manufacturing that the stitching is most likely the weakest link in the system. As well, two of the release cord guides added during manufacturing, sewn to the front webbing line that contains the grommet, were adopted for the final design. The guides, drawn in orange in Figure 19, are meant to help facilitate the travel of the yellow cord as it is pulled out as well as to keep it secure from “accidental actuation” during launch.

6.2 Ring Release Assembly Procedure

There are three different pieces that make up the total assembly. The largest ring in the set has a connecting loop of webbing sewn to it. Separate from those two pieces are the two smaller rings, retaining loop for the release cord, and piece of webbing containing the grommet. The third piece of the assembly is simply the crimped release cord. Figure 20 outlines the steps of the assembly procedure, and the official standard operating procedure (SOP) for the system is detailed in Appendix B.

Following Figure 20 backwards (right to left), the first step is to pass the middle ring through the largest ring and fold it back over onto itself. Next, the same instruction is followed for the smallest ring through the middle. As a last step, the nylon retaining loop is passed through the smallest ring, then through the grommet. At this point the release cord is passed through the guides and nylon loop to secure the assembly.

Figure 20. Ring Release Steps. Various stages of the system are depicted beginning with the locked position and ending with the full release. Stages 3 and 4 attempt to clearly depict the unfurling of the rings. (Photo credit: Alan Hurley)

6.3 Next Steps

With the final Bill of Materials complete (Appendix A), the PSAS recovery team will be able to complete the final system manufacturing and integration with the rest of the system architecture. Since this research was completed in conjunction with the development of the other new PSAS recovery subsystem, the final design should integrate effortlessly with the rest of the architecture. The current architecture design for the system integration is detailed in Figure 21.

Figure 21. PSAS Recovery System Integration Design. Labels 5 and 9 describe the components of the ring release system.

Once integration is complete, the entire recovery system will be dropped from a helicopter as a last validation test before it is cleared for launch. The electronics are put on timers since it is only the physical mechanics of the subsystems that are being tested. The first timer will activate the first stage of the recovery system, shown complete in the middle of Figure 22. This ejects the nose cone from the rocket body, effectively deploying the drogue parachute. This is the first time that the ring release is called into action. Shown with a green box below, the ring release is the only connection between the drogue parachute and the rocket body. When the ring release is actuated in the last stage, the drogue parachute will carry off the large ring section of the ring release system and deploy the main for landing.

Figure 22. Illustration of the Current Recovery Deployment Design.

Following a successful drop test, the ring release system will be integrated into the PSAS LV3.1 rocket and launched during Summer 2019. Successful drogue parachute deployment and release during this event will prove that this system is a viable recovery solution for level 3 high-power rockets that use two-parachute recovery systems.

7 Future Work and Applications

As mentioned in Section 1.4, the hope is that the ring release system will eventually be integrated into the LV4 system architecture – and used to recover the rocket from space. Until that time, there are several different ways the ring release system may be iterated on and possibly improved.

The design was never tested against a model of itself. Three different designs were analyzed, but it was posed in prior research that the pull force of the release system is very sensitive to the construction. Therefore, it is strongly suggested that several models of the same design are made with relatively loose accuracy and then tested against one another to inspect any differences in pull force.

This is also just one configuration that works. It is possible that a stronger motor could be found that allows for smaller and/or few rings to be used in the design. Space turned out to be extremely limited in the overall assembly, so any reduction is useful for the entire recovery system.

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9 Appendix A – Bill of Materials

	Part Name	Vendor	Part Number	Unit Price	Qty	Unit	Mfg. Description
1	Ring - small	ParaGear	H3860B	\$6.50	1	each	NO. 3 STYLE RING
2	Ring - medium	ParaGear	H3840B	\$10.00	1	each	NO. 2 STYLE RING
3	Ring - large	ParaGear	H3880B	\$4.65	1	each	NO. 4 STYLE RING
4	Webbing - main	ParaGear	W9970	\$2.50	1	yard	YARD - TYPE 17 NYLON WEBBING (1", yellow)
5	Webbing - secondary	Joann Fabrics	18731636 26A	\$5.49	6	inch	Simplicity, Trim, ~ 3/4 in / 19.05 mm 9 ft / 2.74 m
6	Webbing - grommet	Joann Fabrics	14888341	\$5.99	4	inch	Offray 7/8"x21' Grosgrain Solid Ribbon
7	Webbing - guide	Joann Fabrics	14889463	\$7.99	3	inch	Offray 1.5"x21' Single Faced Satin Ribbon
8	Grommet	McMaster	9604K24	\$6.92	1	each	Fabric Grommets - with Washer, Brass, Trade Size 2, for 0.14" Material Thickness (pk of 50)
9	Crimp - release cord	McMaster	3896T3	\$10.60	1	each	Wire Rope Compression Sleeve for 1/8" Rope Diameter - Not for Lifting (pk of 50)
10	Yellow release cord	ParaGear	M5825	\$2.25	1	foot	YELLOW 3 RING RELEASE CABLE
11	White retaining loop	ParaGear	W9680	\$0.35	3	inch	YARD - TYPE IIA SLEEVING WHITE
12	Thread	Amazon	B00HVPT 65M	\$8.30	1	spool	Tex-70 Size 69 Nylon Thread - Black (color not important) - 1500 yard spool
13	Linear Actuator	Robot Shop	RB-Fir-165	\$90.00	1	each	P16 Linear Actuator, 50mm, 64:1, 12V w/ Potentiometer Feedback

10 Appendix B – Standard Operating Procedure (SOP)

This document describes the maintenance and assembly of the drogue parachute ring release system intended for the PSAS LV3.1 rocket.

Figure 1B. eRing Release Assembled

Maintenance

- It is good practice to keep the webbing lines out of the sunlight as much as possible to reduce UV exposure
- It is also good practice to exercise the webbing from time to time so that it does not become stiff and weak.
 - At the very least, exercise the webbing before launch.
 - Exercise by bending the webbing and moving it side to side
- Check the release cord for any kinks in the line or other obvious damage
- Check the retaining loop and guides for any fraying or other obvious damage

Assembly

1. Pieces of the assembly
 1. Large side
 1. Large ring
 2. Webbing
 2. Small side
 1. Medium ring
 2. Small ring
 3. Retaining loop
 4. Grommet (and grommet webbing)
 3. Release cord
2. At the end of this assembly procedure, the system should resemble Figure 1.

3. Working backwards (right to left) through the steps outlined in Figure 2, begin with the large and small sides.

Step 5 → 4: Slide the middle ring through the largest ring and fold it back over itself

Step 4 → 3: Slide the smallest ring through the middle ring and fold it back over itself

Step 3 → 2: Pass the retaining loop through the smallest ring

Fold the webbing flap containing the grommet of the rings and shown in Step 2

Step 2 → 1: Pass the retaining loop through the grommet and slide the release cord through the first guide, then the retaining loop, then the other guide.

4. That completes the eRing Release assembly!

* The ferrule (crimp) will not be on the release cord during assembly. The cord will be passed through the end of the linear actuator and then crimped into place.

Figure 2B. Ring Release Assembly Steps (labeled 1 through 5 for reference in this procedure)

11 Appendix C – Raw Data

Maximum Pull Force			
Run	Small	Large	2-Ring
1	2.4	1.2	3.1
2	2.2	1.2	2.4
3	1.8	0.9	2.2
4	2	1.1	2.4
5	1.9	1.3	2.6
6	2	1.2	3.6
7	2.5	1.4	2.3
8	2.6	1.3	2.5
9	2.1	0.9	2.2
10	2.6	1.3	2.4
11	2.3	1.2	2.4
12	2.2	1.2	2.4
13	2.6	1.2	2.5
14	2.4	1.2	2.5
15	2.3	1.2	2.5
16	2.1	1.2	2.3
17	2.2	1.1	2.5
18	2.3	1.1	2.4
19	2.5	1.3	2.6
20	2.5	1.2	2.5
Average	2.275	1.185	2.515
Small/Large	1.919831		
Small/Two	0.904573		

Angled Maximum Pull Force							Test angles:		20	30	40
Small				Large				2-Ring			
Run	20_s	30_s	40_s					Run	20_t	30_t	40_t
1	2.9	2.5	3					1	2.8	3	2.7
2	2.6	3	3.3					2	2.9	2.7	3.3
3	2.4	3	3.2					3	2.9	2.8	3.8
4	2.6	2.9	3.4					4	2.6	2.8	3.9
5	2.5	2.8	3.2					5	2.8	3	3.2
Avg	2.6	2.84	3.22	Avg	1.44	1.68	2.04	Avg	2.8	2.86	3.38

* Parachute data was collected through the PSAS recovery team. For raw data see <https://github.com/psas/lv3.0-recovery/tree/master/LV3.1/DCR>