Return To Sender: Lessons Learned From Rocket Lab's First Recovery Mission

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ABSTRACT

On November 20th, 2020, Rocket Lab successfully re-entered the first stage of its Electron launch vehicle, successfully demonstrating a soft water landing under parachute. The 'Return to Sender' mission was a major milestone in Rocket Lab's program to make the Electron rocket a reusable launch vehicle for small satellites. The mission followed a robust test program in early 2020 and late 2019 that spanned parachute testing, mid-air helicopter capture tests, and the guided re-entry of two Electron vehicles on prior commercial missions.

This paper discusses the lessons learned from the ground-breaking mission and explores the development of Electron's reusability systems and processes, with a focus on the innovative systems that enabled Electron to survive the extreme heat of re-entry without propulsive support. The paper also explores recent developments in Rocket Lab's recovery program, including advances in heat shielding and refined processes for mid-air helicopter recovery to minimize contamination by avoiding saltwater immersion. The paper will also examine the potential reusability has to reduce launch costs for small satellites, while increasing launch frequency and availability.

INTRODUCTION

Rocket Lab is a leading end-to-end space company delivering frequent, reliable, and affordable small satellite launch services, with 100+ small satellites deployed to space across 17 orbital launches of its small launch vehicle Electron (Figure 1). To further increase launch cadence to meet the market demand, Rocket Lab is developing new systems, technology, and infrastructure to make Electron the world's first orbital-class reusable small launch vehicle.

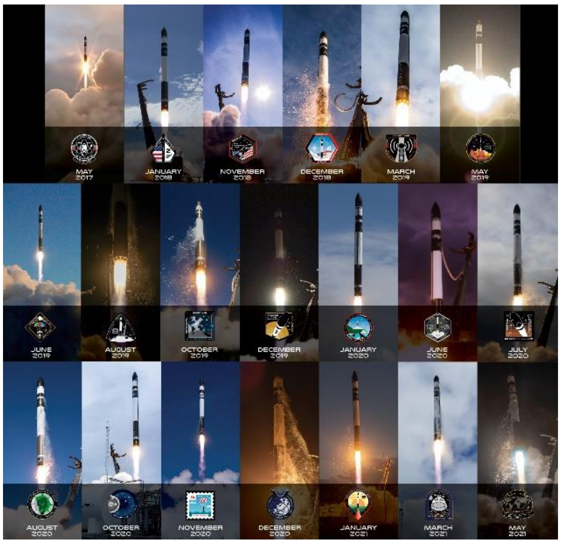

Figure 1: Electron launch vehicles in flight.

The plan to recover and reuse Electron's first stages involves eliminating the need to build a new first booster for every mission, thereby increasing launch frequency and enabling small satellites to access space more frequently and reliably. By recovering, refurbishing and re-flying Electron's first stage, Rocket Lab aims to reduce production timelines and drive the company closer to its ultimate goal of launching every week to meet market demand.

Rocket Lab's reusability plans for Electron were announced in August 2019 and will be implemented in two phases. The first phase involves returning Electron's first stage to Earth under a parachute for a soft water landing, to then be retrieved and returned to Rocket Lab's Production Complex for analysis. The second phase builds on the progress made in the recovery program by returning Electron's first stage to Earth under a parachute for mid-air capture by helicopter, before the stage is transported back to Rocket Lab's Production Complex for analysis, refurbishment, and relaunch.

Experimental instrumentation carried on Rocket Lab's seventh and eighth Electron launches, in June and August 2019 respectively, provided flight data that informed the company's first guided, full-telemetry re-entry of the Electron launch vehicle's first stage post-launch during its tenth Electron mission in December 2019. Recovery instrumentation on-board this flight included guidance and navigation hardware, including S-band telemetry and on-board flight computer systems, to live-gather data during the first stage's atmospheric re-entry, as well as a reaction control system to orient the booster. Separately, Rocket

Lab also conducted a mid-air recovery test in March 2020 that saw an Electron first stage test article successfully dropped from a helicopter over open ocean, its parachute successfully deploy, and a second helicopter successfully capture the descending stage at around 5,000 ft using a specially-designed grappling hook to snag the parachute's drogue line and deliver it safely back to land. Following the success of these early tests, Rocket Lab conducted its first recovery of a flown booster during its sixteenth Electron launch in November that same year.

This paper summarizes the early successes of Rocket Lab's Electron reusability program and the innovative technology and systems developed and successfully implemented for Rocket Lab's first Electron recovery mission.

ELECTRON LAUNCH VEHICLE

Electron is Rocket Lab's small launch vehicle (Figure 2) designed for rapid manufacture and launch to meet the dedicated launch needs of the small satellite market. As of the date this paper was submitted on 01 June 2021, Electron has delivered 104 small satellites to low Earth orbit for private, commercial, educational, and government enterprise.

Figure 2: Electron Launch Vehicle

With a lift capacity of up to 300 kg (661 lbs.), Electron nominally delivers up to 200 kg payloads to a 500 km sun-synchronous orbit. Orbital delivery across Electron's 20 missions ranges from 430km to 1,200 km circular orbits. Rocket Lab primarily launches Electron from its privately-owned orbital launch site Launch Complex 1 in New Zealand (Figure 3) where it is licensed to launch up to 120 times a year, but the company also offers responsive launch capability on home soil from its second site Launch Complex 2 at the Mid-Atlantic Regional Spaceport at Wallops Flight Facility in Virginia, USA

Figure 3: Electron on the pad at Rocket Lab Launch Complex 1, Mahia, New Zealand.

Electron's design incorporates Rocket Lab's in-house designed and manufactured Rutherford engine with the innovative use of electrical systems and carbon composite materials. The Electron launch vehicle dimensions and specifications are outlined in Table 1.

Table 1: Electron Launch Vehicle Dimensions and Specifications

Length	17m
Diameter	1.2m
Stages	2+ Kick Stage
Vehicle Mass (Lift-off)	13,000 kg
Nominal Payload Mass	200 kg (Sun-Synchronous Orbit)
Payload Diameter	1.08 m
Propulsion – Stage 1	9x Rutherford Engines (Lox/Kerosene)
Propulsion – Stage 2	1x Rutherford Engine (Lox/Kerosene)
Material/Structure	Carbon Fiber Composite
Launch Site Locations	Mahia, New Zealand Wallops Island, Virginia

THE ARGUMENT FOR REUSABILITY

Rocket Lab's Electron reusability program was established on the foundational basis of eliminating the need to build a new first stage for every mission. Rocket Lab utilizes additive techniques like 3D-printing and carbon-composite structures to manufacture a complete Electron launch vehicle once every 30 days. However, manufacture of the launch vehicle's first stage consumes 40% of the company's labour hours and represents ~50% of the cost of Electron manufacture.

While Rocket Lab continues to scale its manufacturing capability, time, cost, resource availability, and material supply are all considerable constraints. Transitioning Electron from a fully expendable launch vehicle to a reusable one by recovering, refurbishing, and re-flying its first stage targets significant reductions in time and labour.

THE CHALLENGES OF REUSABILITY

Atmospheric re-entry

During launch, the first stage of Electron accelerates to a speed of approximately 8,400km/h and an altitude of 71km before Main Engine Cut Off (MECO) and separation. Electron encounters decreasing atmospheric density as it ascends and accelerates. The fairing at the top of the vehicle, encasing the payload during launch, is covered with a thick layer of thermally protective material, referred to as Thermal Protection System or TPS. The fairing TPS shields the payload from aerodynamic heating during ascent, while additional regions of TPS around critical areas of the vehicle provide protection to vulnerable components, including the powerpack that houses the engines and batteries.

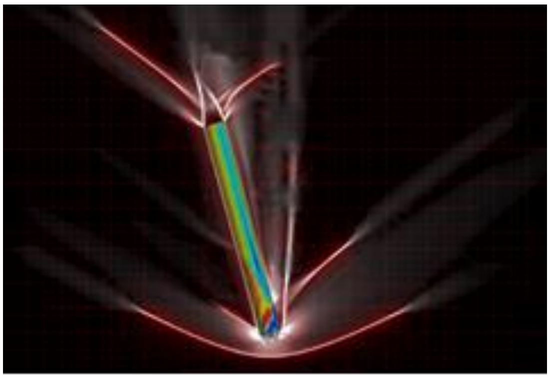

Figure 4: Visual depiction of thermal and shock loads on Electron first stage during atmospheric re-entry.

Following separation, stage one continues to coast in an upward trajectory before arcing over and accelerating under gravity back towards the ocean. As it descends and accelerates, stage one reaches speeds of around Mach 8 (eight times the speed of sound) and experiences a rapid growth in dynamic pressure and temperature as the air compresses and shocks down at the leading edge of the stage. At its maximum, the differential pressures and temperatures encountered can reach 120 kPa (1.2 atmospheres) and 2400 °C - nearly 1000 °C higher than the melting temperature of steel. At Rocket Lab, this environment is referred to as the Wall.

Limited mass margins

To make Electron recoverable and re-usable, the challenge is to turn a vehicle designed with tight margins and for a single, expendable use into one capable of withstanding the searing heat and crushing pressure during re-entry, then decelerate in a controlled manner to a velocity where it could splashdown intact or be captured during descent. These tight margins and single use design mean that mass and volume are at a premium, while the structure is designed for particular load cases and directions.

After careful analysis and evaluation of options, the approach selected was to turn the vehicle end-over-end after separation so that it enters engine first, and develop a recovery system to be housed in the interstage to provide communication, control, and deceleration of the stage to safe conditions for splashdown and retrieval.

Program Development

The road to recovery of Electron began with a fast-track programme to develop a compact, robust data acquisition system modelled on the 'Black-Box' flight recorder installed in commercial aircraft. Known as BRUTUS (Blackbox Recorder and Useful Telemetry Upload System), the aim of this unit was to gather data following separation and provide critical information on the environment experienced during re-entry. Packaged as a 2U device, BRUTUS was deployed using a modified Maxwell Cubesat deployer. Successfully developed and tested within just three months during early 2019, BRUTUS was flown on Electron's seventh and eighth flights in June 2019 and August 2019 respectively.

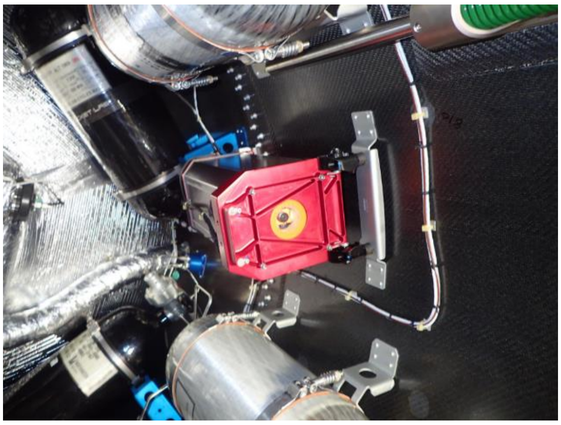

Figure 5: BRUTUS installed for Flight 7.

Following these missions, the team set the ambitious goal of implementing a control and communication system on the first stage to provide re-orientation and controlled re-entry of the stage and telemetry of data to ensure information on the environment and vehicle performance was received. Building from existing hardware designs already used elsewhere on the vehicle, Rocket Lab was able to quickly implement a solution which was successfully flown for the first time on Flight 10 in December 2019 (Figure 6), and again on Flight 11 in January 2020. This system re-oriented the stage following separation and controlled the stage attitude to ensure an engines-first, low Angle of Attack (AoA) entry and provided video, acceleration, pressure, temperature and positional data through the re-entry and descent of the stage. Beyond expectations, the telemetry system was able to keep transmitting and providing data all the way to impact with the ocean, providing vital information for the next phase of the programme – controlled descent.

Figure 6: Electron lift-off for Flight 10.

During the initial announcement about making Electron re-usable, the approach of mid-air recovery by helicopter was proposed as a method for catching the stage during terminal descent and avoiding splashdown in the ocean. A rapid programme was developed to investigate and demonstrate the feasibility of Mid-Air Recovery (MAR), using a scaled test article, custom parachute, and the company's Bell 429 helicopter (Figure 7).

Figure 7: Depiction of Mid-Air Recovery by helicopter.

A capture hook was designed and developed, and the concept of operations (CONOPS) for approaching and snagging the parachute devised. Following the successes of Flights 10 and 11, a helicopter demonstration test was conducted in early March 2020 and successfully demonstrated the viability of the method along with the criticality of timing, visibility, and weather.

Figure 8: Mid-Air Recovery Test, March 2020.

Figure 9: Mid-Air Recovery Test, March 2020.

Building on the success of Flights 10 and 11, design and development of the Main Descent System (MDS) commenced. A three-stage parachute system was designed, using a mortar-deployed supersonic pilot parachute to extract a larger supersonic stabilising drogue parachute, which in turn extracts a subsonic reefed Ringsail main parachute (Figure

10) sized to provide a terminal velocity of 10 m/s for splashdown of the stage.

Figure 10: Rocket Lab Ringsail main chute.

The entire system was designed in house, with only the manufacture of the parachutes outsourced. In order to mitigate the inflation loads of the parachute to a level the vehicle could tolerate, a single stage reefing system was implemented, constraining the parachute to an initial area of 5% of the full open area then disreefing after a nominal delay of 10 s. Even with the reefing, the initial inflation and subsequent disreefing of the main parachute provide a double 60 kN shock load to the vehicle; to withstand this, the interstage was reinforced and a bespoke parachute attachment and release mechanism developed. To deploy the drogue, a cold-gas mortar powered by residual Nitrogen from the RCS was designed and developed. When triggered, the mortar ejects a supersonic pilot parachute through the wake of the stage, immediately extracting the larger drogue which provides stabilisation of the vehicle from Mach 1.5 down to around Mach 0.3. A comprehensive lab test programme was conducted to characterise, tune, and qualify the mortar, but for the parachute system it was necessary to perform a drop test to verify packing, extraction, inflation, reefing level, and disreef of the main parachute.

In August 2020, just five months after commencement of the MDS design, a drop test campaign comprising two tests over two consecutive days was conducted at the Rocket Lab Launch Complex-1 facility in Mahia (Figure 11). Using a full flight-weight drop test vehicle, the qualification pilot, drogue, and main parachutes were tested at flight-representative conditions for the main parachute deployment, providing evidence and confidence that the system met the requirements and had the required performance and design robustness to proceed to flight.

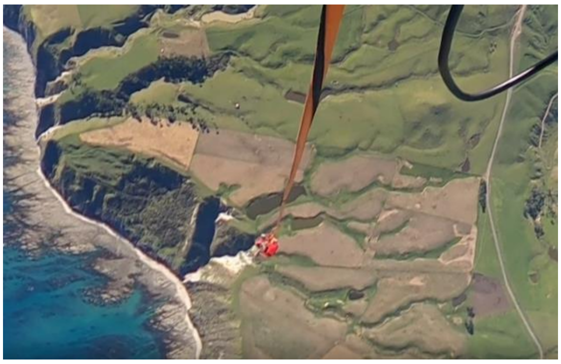

Figure 11: Drop test, Mahia New Zealand, August 2020

The final piece of the puzzle before attempting to recover a first stage following an operational flight was the tracking and recovery of the stage following splashdown. From Flight 10 and Flight 11, there was a high level of confidence in the telemetry system and the ability to track the descending stage to the water; however due to safety considerations and the need to position the recovery vessel outside the hazard zone for any off-nominal events, a system to provide position updates following splashdown was required. A combination of trackers, GPS asset tags, and optical strobes were implemented to provide the solution. Going into the flight, the biggest unknown was the condition of the stage following entry and splashdown, and the level of challenge that finding, securing, and recovering the stage from the Southern Ocean would present.

First Recovery Attempt

The 16th Electron flight launched on November 20th 2020. Following a nominal ascent and separation, Stage 1 re-oriented and re-entered as planned, deploying the pilot, drogue, and then main parachute to slow the vehicle to an impact velocity of just under 10 m/s. Comparison of measured flight data to performance models for the parachute system indicated very good agreement.

Figure 12: Electron Launch Vehicle for Flight 16.

The recovery team stationed approximately 10 nautical miles away proceeded to approach, inspect, secure, and retrieve the stage, arriving at the splashdown location approximately 1.5 hours after splashdown. On arrival, the stage was found to be in very good condition, with expected thermal damage around the powerpack and engines in keeping with predictions from before flight.

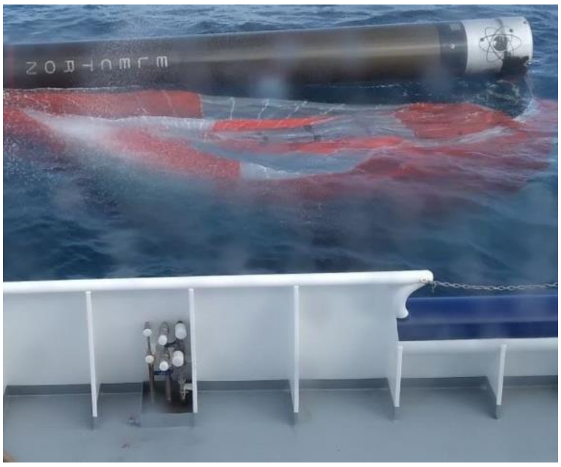

Figure 13: Electron after successful ocean splashdown for flight 16.

It should be noted that no change or augmentation of the powerpack heatshield or TPS was made for Flight 16 – the objective for this flight was to test and flight qualify the Main Descent System. As expected, retrieval of the stage proved challenging, with the team having to resort to using the crane of the recovery vessel to haul the stage onto deck after a number of other methods were tried without success. Once the stage was secured and equipment stowed, the recovery vessel returned to port for offload and transport of the stage back to Rocket Lab's Auckland Production Complex.

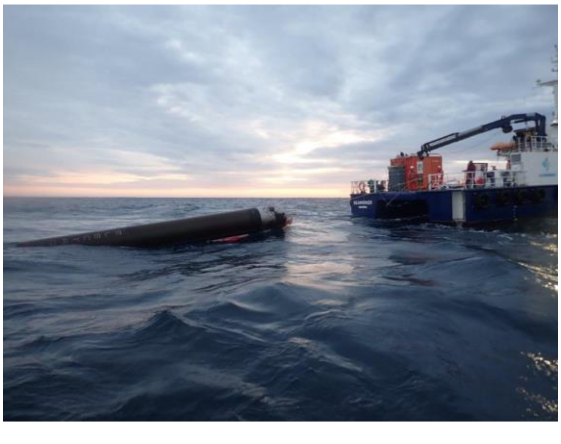

Figure 14: Electron during ocean recovery operations for Flight 16.

Lessons Learned

The experience gained getting to and achieving the first intact splashdown and recovery of Electron on Flight 16 yielded a number of valuable lessons and validated a number of decisions made during the development of the recovery system. The incremental approach adopted proved especially valuable, providing important data on the entry environment to inform the system design and allowing key items such as the control and telemetry system to be flight-tested and refined before the MDS flight on Flight 16.

Keeping designs and solutions as simple as possible and re-using or adapting existing hardware from Electron was a key enabler for the success and speed of development of the system. The recovery flight computer, IMU, Reaction Control System, telemetry system, and even the parachute attachment/release mechanism were all existing designs or featured key elements from existing designs. The mortar was a novel design, but used the N2 pressurant system already required for the RCS and existing flight qualified valves and regulators to minimize risk and development time.

Water operations and logistics presented a significant challenge, with sea-state and weather providing a variable that is present all the way through launch and recovery. The experience gained through the first recovery attempt for flight 16 provided a list of improvements to aid locating, securing and lifting the stage that have already been implemented and proven their worth with the successful recovery of the stage from the recent Flight 20 Running Out of Toes mission in May 2021. For Flight 20, in addition to vehicle changes, the approach for securing and lifting the stage was completely revised, with the design, development, and deployment of the ORCA (Ocean Retrieval and Capture Apparatus) to improve and derisk the water retrieval aspect of recovery.

The original decision to make Electron a composite, Carbon Fibre Reinforce Polymer (CFRP) structure was a great design choice and a key enabler for the success of the recovery programme to date. Backed up by an extraordinary team of fabricators, technicians, and engineers, CFRP is robust, light weight, and has good thermal and mechanical properties that have made the task of retro-fitting a recovery system to an existing vehicle design a smoother process than might have been expected.

Finally, the approach of incremental development and improvement towards the goal of recovery and re-use has worked very well for the company to date.

The development path so far has moved from controlling and characterising the re-entry through to the implementation of the GNC, RCS, and telemetry system for Flight 7, to getting the stage down intact through implementation of the MDS for Flight 16. The next steps, most recently implemented for Flight 20, are to improve the thermal protection and mitigate the re-entry environment, improve water retrieval (as this will always be required in the event of problems with dry recovery), and finally to implement a dry recovery solution – whether that be Mid Air Recovery via helicopter, or other methods currently under investigation and trade.