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On-Orbit Data and Validation of Astra's ACE Electric Propulsion System

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ABSTRACT

The first ACE propulsion system reached orbit on July 1st 2021 as part of Spaceflight's demonstration of the Sherpa-LTE all-electric Orbital Transfer Vehicle (OTV). We are now able to share on-orbit data and have successfully verified the on-orbit performance of the ACE propulsion system, using xenon propellent.

The mission objective was to lower altitude and use on-orbit data to derive performance, correlating the propulsion system's performance to ground test data. The demonstration consisted of activating the propulsion system for 5-minute durations at a total input power of 340 W into the Power Processing Unit (PPU). Altitude change and propellant usage were used to derive thrust and total specific impulse.

On-orbit performance is compared to ground test data in Table 1. Averaged performance is within one standard deviation of ground test data. Astra considers this a validation of system performance, as well as the ground test facilities used to test propulsion systems. On-orbit thrust has a large standard deviation as a result of the limited data sampling rate and measurement errors, rather than variability in thruster performance. Figure 1 shows the thruster operating on-orbit. The Astra team gratefully acknowledges the support of Spaceflight, Inc., the U.S. Air Force, and Defense Innovation Unit (DIU) without which this mission would not have been possible.

Table 1: Ground test data compared to on-orbit

	Ground	Observed
Thruster power (W)	320	320.5 ± 2.2
Thrust (mN)	20.6	22.4 ± 5.5
Isp steady state (sec)	1325 at 320W 1410 at 380W	N/A because burns are 5 mins
Isp 5-min thrust (sec)	1087	1108 ± 77
System effic. (%)	94 ± 1	94 ± 1

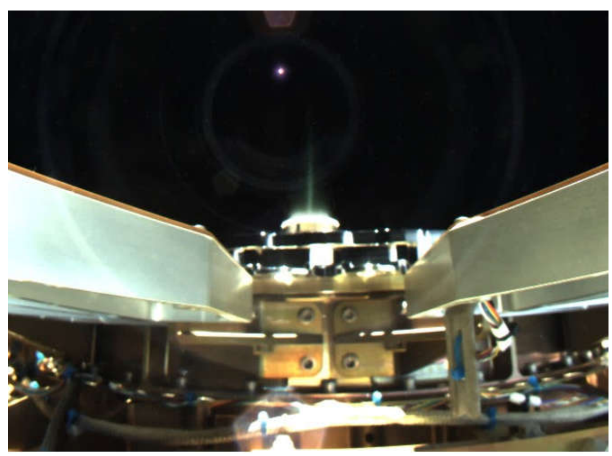

Figure 1: ACE thruster operating on-orbit[1]

INTRODUCTION

The ACE propulsion system was entirely designed, built, and tested by Apollo Fusion (now Astra). The system has been extensively tested on the ground but had not been demonstrated on-orbit until Spaceflight's Sherpa-LTE1 SXRS-5 mission.

The integration, testing, and qualification of a propulsion module has inherent difficulties that go beyond demonstrating individual subsystems. These include testing the full propulsion module in a flight-like configuration, spacecraft integration, module level environmental testing to meet launch environment, range safety, and Department of Transport requirements for shipping and launching a pressurized system. Spaceflight's Sherpa-LTE1 mission gave Astra the opportunity to demonstrate the process to successfully deliver, launch, and operate an integrated propulsion module in orbit.

The purpose of the Sherpa-LTE1 demonstration was to quickly demonstrate on-orbit performance of ACE. The propulsion module went from concept to hardware delivery in 6 months. To work fast, Sherpa's battery and power systems were under-sized for a 400 W propulsion system. It was determined that a maximum of 5-minute thrust durations could be used to complete the mission at 340 W to the PPU, allowing for system demonstration and slow de-orbiting of the satellite. The data from this demonstration mission has verified that on-orbit performance matches ground test data and validated the testing methods and facilities used by Astra.

ACE PROPULSION SYSTEM OVERVIEW

A qualification and a flight propulsion module were built. The described propulsion module is a fully fueled and tested integrated Electric Propulsion (EP) system, consisting of:

- Spacecraft panel - The propulsion system was integrated onto one of Spaceflight's spacecraft panels, for ease of installation into the final spacecraft.
- Propellent tank - 3-liter composite overwrapped pressure vessel (COPV) for xenon storage.
- Feed system - Consisting of two high pressure inhibits, designed to regulate propellent flow to the thruster. As the schedule was short, an engineering model (EM) feed system was up screened and used, which had the same components and functionality as future flight systems, but a different form factor (breadboard layout).
- Fill/drain valve - Consisting of two high pressure inhibits, used to manually fill the propellent tank.
- Thruster - Hall-effect thruster, using permanent magnets and instant start cathode, shown in Figure 2.
- Power Processing Unit (PPU) – Rad Hard electronics to control thruster and feed system.

Figure 2: ACE thruster and PPU[2]

Figure 3 and Figure 4 and show the qualification module and the flight module respectively (mounted to a vibration table as part of testing).

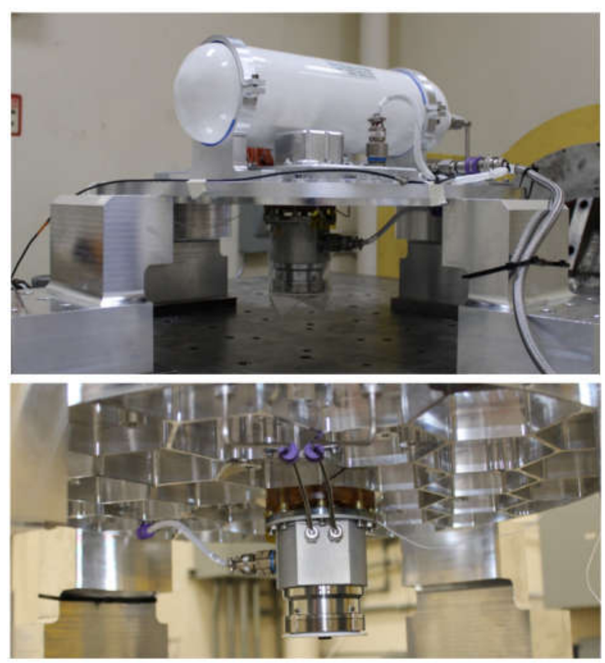

Figure 3: Qualification module

Figure 4: Flight module before MLI blanket

Piping and Instrumentation Diagram (P&ID)

Figure 5 shows the P&ID diagram for the pneumatic system. The system is designed to have two high pressure inhibits:

- Fill/drain valve:
    - Closed with actuation nut,
    - Capped.
- Feed system high pressure propellent management system:
    - High pressure normally closed solenoid valve (S1),
    - High pressure latching valve (L1).

All components meet the Maximum Expected Operating Pressure (MEOP), proof (1.5 x MEOP), and burst (2.5 x MEOP) pressures. After assembly, the full system was proof tested and helium leak tested at MEOP.

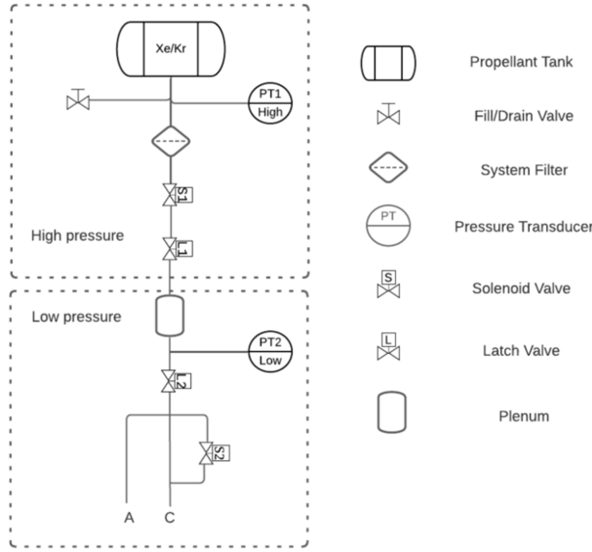

Figure 5: Simplified P&ID of the pneumatic system

Xenon is metered into a plenum volume by pulsing the high-pressure valves, and a down stream orifice flow split is used to control flow rates to the anode and cathode. An additional valve (S2) is used to give additional ignition flow to the cathode at startup.

Electrical and Software Design and Operation

The ACE PPU is a robust, single PCB design that controls the hardware required to run the ACE thruster. The PPU allows the spacecraft to send a single command to ignite and the run the thruster and checks if the system is in a safe state before executing this command.

The PPU uses a combination of rad hard parts and COTS parts that have been radiation tested and de-rated to applicable MIL or ECSS standards. All electrical returns are grounded to the spacecraft single point ground by the spacecraft electrical power subsystem. The system is designed to function with either RS-485 or RS-422, and the communications interface is galvanically isolated.

The system software (and associated processor hardware) continuously scrubs for bit errors in memory due to radiation effects. The processor and associated voltage regulators implement brownout protection. The system has several "health checks" which monitor PPU conditions. Health checks have an upper and lower boundary and are not allowed to exceed those thresholds (eg, Bus voltage, thruster temperature, discharge converter output Current, etc). When a health check is triggered, it will shut down thruster-related subsystems, and raise a fault flag. The spacecraft can query the type of fault and must explicitly acknowledge and clear all fault conditions before the thruster can be turned on again.

All health check boundaries, as well as operating conditions, are configurable by the spacecraft passing configuration parameters to the PPU, and do not require flashing new firmware. This was tested in flight, reconfiguring the low voltage cutoff to better suit the mission.

As part of development testing, Astra ran end-to-end integrated system tests with Spaceflight and components from their satellite bus. A thruster was operated as part of a propulsion module for representative durations with a flight like power management system, on-board computer, harnessing, and telemetry commands. These tests are critical for de-risking areas such as inrush transients (which can vary based on the design of power management systems) and allow for stress testing the system in different conditions. These integrated tests allowed both sides to lock down the ignition sequences and CONOPS on the ground, which allowed smooth thruster operation in space.

ACCEPTANCE AND QUAL TESTING

The propulsion module for the Sherpa-LTE1 mission contains potentially hazardous high-pressure components and must survive the launch environment. Vibration and shock testing of a qualification module (Figure 3 and Figure 6) as well as vibration testing of the flight module (Figure 4) was performed to ensure structural stability of the module during the launch environment. Pressure and leakage testing before and after dynamics testing were used to demonstrate that the high-pressure system had not been compromised. Visual inspections and full system function tests were also performed.

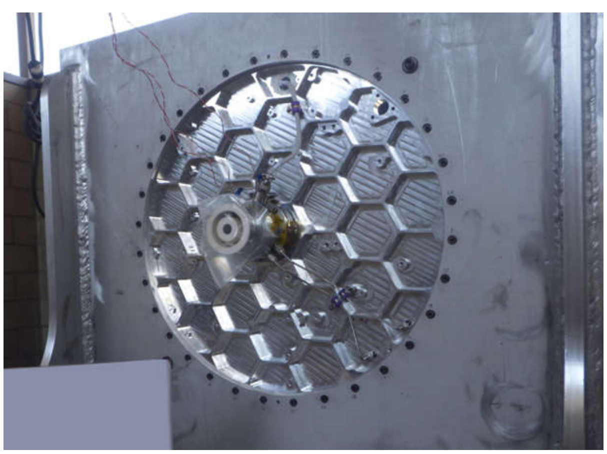

Figure 6: Qualification module shock test setup

Before integration into the propulsion module and module level qualification and acceptance tests, the PPU undergoes thermal vacuum cycles and burn-in.

Qualification module - Qualification test flow:

- Proof pressure test
- Helium leakage test
- Functional test (including thruster operation)
- Vibration tests
- Shock test
- Helium leakage test
- Proof pressure test
- Functional test (inc, thruster operation)
- Disassembly and inspection

Flight module - Acceptance test flow:

- Proof pressure test
- Helium leakage test
- Functional test (including thruster operation)
- Vibration test
- Helium leakage test
- Functional test (including thruster operation)
- Fill and ship

Dynamics Test Levels and Acceptance Criteria

Test levels were a combination of launch vehicle requirements for shock and NASA GEVS levels for vibration testing.[3,4] Leakage tests and full system functional tests were performed pre- and post-environmental testing to ensure no degradation in function or performance.

During vibration tests, the major resonances were measured pre- and post-test to assess if anything failed. ECSS-E-ST-10-03 was used to determine if resonance changes were acceptable, using thresholds as follows:[5]

- 5% in frequency, and
- 20% in amplitude.

The tank was pressurized pre-vibration testing and measured post-test to verify that valves had not opened or chattered during the dynamics tests.

The qualification module was shock tested, with the shock spectrum tuned using a representative mass model to ensure that:

- A minimum of 50% of the SRS response met or exceeded the nominal test specification.
- A minimum of 80% of the SRS response was contained between -3 dB and +6 dB of the nominal test specification.
- 100% of the SRS response was contained between -6 dB and +9 dB of the nominal test specification.

As shown in Figure 7, the module was over tested in the high frequency range, which was considered acceptable.

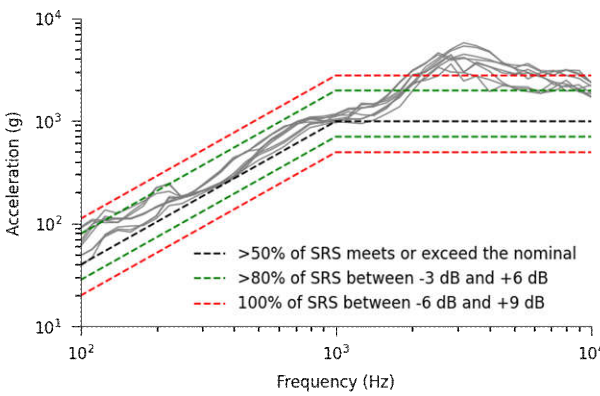

Figure 7: All shock spectra in all axes for the qualification module test. All shocks met or exceeded the required test levels.

Final Functional Test, Tank Fill, and Shipment

Full system hot fire tests were performed pre- and post-dynamics testing. Prior to shipping, the tank was filled with xenon propellant. The ACE propulsion module was operated with a filled tank to get baseline data for comparison on-orbit, shown in Figure 8.

The final wet mass of the system was measured prior to packaging, crating, and shipping, shown in Figure 9.

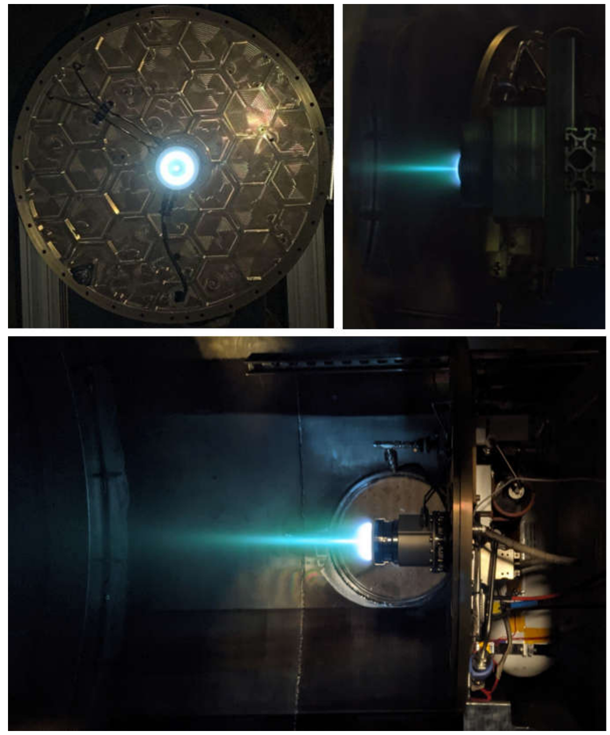

Figure 8: Flight propulsion module operating before MLI install.

Figure 9: Propulsion module in clean ESD bags inside shipping container.

EVALUATION OF ON-ORBIT DATA

The operating plan for Sherpa-LTE1 was to run the ACE propulsion system for 5-minute durations to deorbit the satellite. This served as a safe and effective way to demonstrate on-orbit performance. 5-minute durations were based on battery sizing of the spacecraft. For future missions larger batteries and solar panels would be required, however 5 minutes was considered adequate for a demonstration mission. As a result of battery limitations, the power to the propulsion system was limited to 340 W, rather than the nominal 400 W, to allow longer burns without depleting the battery. The reduced system power corresponded to 320 W to the thruster instead of the normal 380 W being delivered to the thruster.

The flight module was operated on the ground to get representative operating data which could be compared to on-orbit operations. On-orbit data was sampled at a frequency of one point per second.

Due to limited capacity to downlink data, data has only been downloaded for 54 thruster activations, after this, the frequency of data downlinks was reduced. Of the 54 activations:

- 16 GPS data sets were at a sampling rate suitable to evaluate on-orbit thrust, and
- 26 data sets from the PPU were suitable to resolve flow rates and estimate on-orbit Isp, as well as PPU temperatures and efficiencies.

There was an initial checkout phase of the thruster and propulsion system before regular operations. During regular operations the system has activated every time with no failed activation attempts. Figure 10 shows an on-orbit photograph of the ACE thruster operating on the Sherpa-LTE1 OTV.

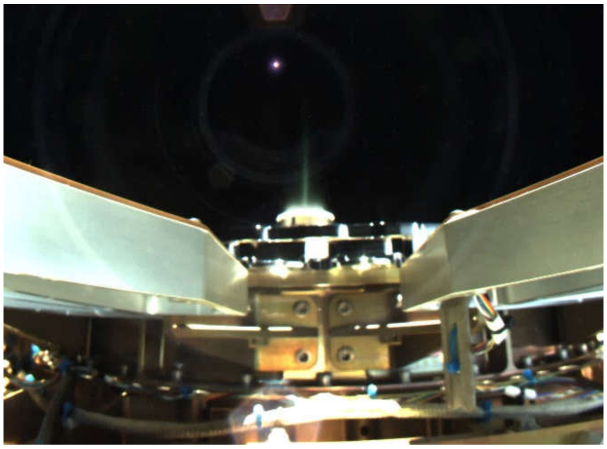

Figure 10: ACE thruster operating on-orbit[1]

Observed On-Orbit Thrust

The observed thrust on-orbit was calculated using Sherpa's GPS data. Semi-major axis values were taken at the same point along the orbit pre- and post-maneuver. The difference between pre- and post-maneuver altitude is considered the altitude change and used to calculate thrust for the maneuver.

As a result of low frequency of GPS data (polled every 1 s), and the relatively small change in altitude from 5-minute thruster operations, the measurement error is 30 - 40% of the altitude change. As such, it is not possible to get high accuracy thrust estimates from individual maneuvers, but the average of multiple measurements should be representative. 16 complete GPS data sets were used to calculate on-orbit thrust and compared to average ground test data.

In Figure 11, the black line shows average thruster performance as a function of power, from ground test data. The gray points show observed on-orbit thrust. The red point shows the average of on-orbit thrust measurements with one standard deviation.

The mean on-orbit thrust is within one standard deviation of the expected value. Astra considers this validation of thrust and ground test facilities.

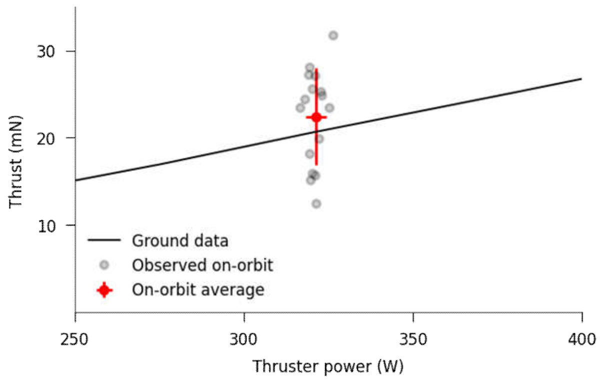

Figure 11: Comparison of ground thrust and observed on-orbit thrust. For clarity, measurement error bars on observed data have been excluded.

Observed On-Orbit Propellent Use and Isp

Isp is calculated using average gas flow rates and thrust measurements. Due to the high thrust measurement error, averaged ground measurements of thrust were used to calculate Isp.

The flow rate used for a maneuver can be calculated by using either the tank pressure sensor or the feed system regulation pressure sensor. Both sensors have a 3% full scale error. As such, for each thruster activation the tank pressure sensor cannot resolve the change in pressure (each activation uses less than 3% of the propellant). Later in life the total change in tank pressure can be used to estimate the total propellent used by many thruster activations. For each individual thruster activation, the propellent regulator's pressure sensor was used to calculate the total gas flowing through the system.

26 complete PPU telemetry data sets were used to calculate on-orbit Isp and compared to average ground test data.

As a result of activation losses (some propellant flows during activation but does not produce thrust until the thruster turns on), the Isp for a maneuver is dependent on the maneuver duration. Longer maneuvers have higher Isp. The black line Figure 12 shows the impact of activation losses on Isp. Note, due to schedule constraints, the feed system used for the Sherpa demonstration is an early EM and has higher activation losses compared to optimized production designs.

In Figure 12 the black line shows expected Isp as a function of maneuver duration. The grey points show observed on-orbit Isp for the 5-minute maneuvers. The red point shows the average of on-orbit Isp with one standard deviation.

The mean on-orbit Isp is within one standard deviation of the expected value. Astra considers this validation of Isp, and ground test facilities.

PPU Thermal Performance and Efficiency

Figure 13 shows that on-orbit PPU temperature increases match those from ground testing. Temperature was recorded around the hottest part of the board, at the discharge converter.

The total system electrical efficiency was verified as 94 ± 1% when operating at 340 W, accounting for housekeeping circuits, feed system power, and circuit efficiency. Accounting for power dissipation in the valves and feed system, the PPU's electrical efficiency is higher. Note, the PPU is optimized for a peak efficiency of 95% at 400 W, and Astra considers 94% suitable at this off nominal power.

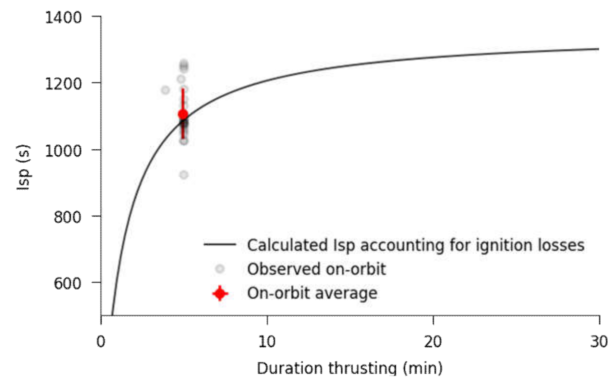

Figure 12: Comparison of ground Isp, as a function of burn duration, compared to values observed on-orbit. For clarity, measurement error bars on observed data have been excluded. Note, the feed system used for the Sherpa demonstration is an early EM and has high ignition losses compared to optimized production designs.

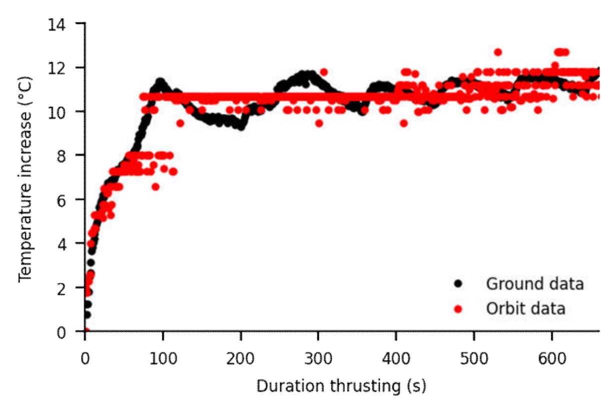

Figure 13: Increase in PPU temperature over the course of a thruster maneuver

SUMMARY OF GROUND AND ON-ORBIT DATA

Figure 14 summarizes the progress of de-orbiting the Sherpa-LTE1 Orbital Transfer Vehicle.

Table 2 and Figure 15 summarize thruster performance taken on the ground and on-orbit. System efficiency is the total efficiency, accounting for housekeeping circuits, feed system power, and circuit efficiency. All on-orbit data is within one standard deviation of ground test data. The data is considered suitable verification of the ACE propulsions system, and the ground test facilities used for qualification and acceptance testing.

Table 2: Average ground test data compared to observed on-orbit data.

	Ground	Observed
Thruster power (W)	320	320.5 ± 2.2
Thrust (mN)	20.6	22.4 ± 5.5
Isp steady state (sec)	1325 at 320W 1410 at 380W	N/A because burns are 5 mins
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System effic. (%)	94 ± 1	94 ± 1

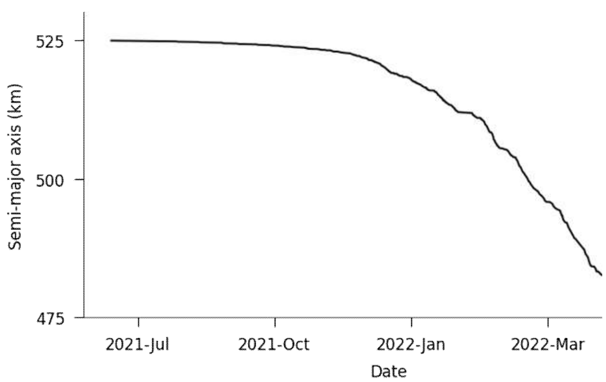

Figure 14: Sherpa change in altitude up to Apr 2022

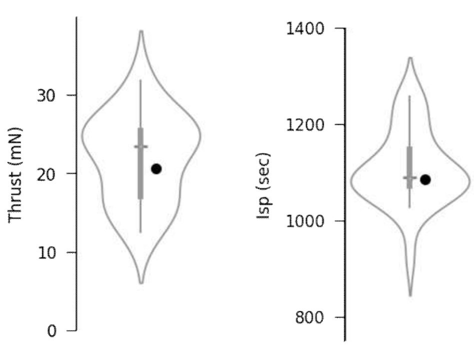

Figure 15: Violin plots comparing ground data (black) to on-orbit data (grey).

Acknowledgments

The Astra team gratefully acknowledges the support of Spaceflight, Inc., the U.S. Air Force, and Defense Innovation Unit (DIU) without which this mission would not have been possible.

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