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CAPSTONE: Recovery & Operations of a Tumbling Small Satellite in Deep Space

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ABSTRACT

The Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) satellite, deployed in July 2022, experienced a thruster anomaly in September 2022 during its Ballistic Lunar Transfer (BLT) into the Earth-Moon L2 Near Rectilinear Halo Orbit (NRHO). CAPSTONE's primary mission objective to achieve and maintain NRHO serves to validate the cislunar CONOPS contemplated for NASA's Lunar Gateway. Terran Orbital designed and built CAPSTONE, and serves as the operator of the on-orbit spacecraft. Advanced Space owns and operates the CAPSTONE payload and its software on behalf of NASA, as well as performs mission navigation and maneuver design.

This 12U+ lunar nanosatellite contains a pump-fed hydrazine propulsion system from Stellar Exploration, enabling all orbital maneuvers and momentum management for the mission. The CAPSTONE mission is funded by the NASA Space Technology Mission Directorate (STMD) through the Small Spacecraft Technology program, and by the Human Exploration and Operations Mission Directorate (HEOMD) through the Advanced Exploration Systems program.

This paper will examine the timeline, innovation, and steps taken by the spacecraft team to recover the vehicle from the thruster anomaly and the resulting high-rate tumble. The high-rate tumble was induced by a valve which became stuck open at the conclusion of Trajectory Correction Maneuver 3 (TCM-3). The timeline discussion includes initial autonomous fault recovery, the evolution of the state of the vehicle, and the recovery actions taken by a small, agile engineering team. The off-nominal attitude and thermal state was determined from a limited data set, requiring the largest assets in NASA's Deep Space Network (DSN) to support communications with the vehicle.

Once a determination was made that the hydrazine propellant was freezing, an assessment was made on the minimum amount of heat required to thaw propellant without placing the spacecraft in a power-negative state. The integrated spacecraft team performed root cause analysis and incrementally tested the propulsion system to recommission it in the face of an anomalous thruster valve. The recommissioning approach eventually lead to the development of a new propulsive state machine and Guidance Navigation and Control (GNC) thruster controller for detumbling.

After recovering 3-axis attitude control, power and thermal stability, and establishing nominal communications, significant development and testing was required to ensure the vehicle could operate in the presence of a continued thruster anomaly. This effort enabled CAPSTONE to execute future propulsive maneuvers with an open thruster valve. The resultant updates were tested on Terran Orbital's Hardware-in-the-Loop (HITL) platform in partnership with Stellar Exploration. A comparison of GNC subsystem requirements will be presented pre-and post-anomaly, based on the resulting capability and restrictions of the propulsion system to meet mission objectives.

Ultimately, the spacecraft was successfully recovered from body rates exceeding 120 deg/s, allowing the CAPSTONE spacecraft to continue its mission, including successful insertion into NRHO in November 2022. An examination of the lessons learned for future deep space small satellite missions is also discussed herein.

Mission Overview

At the intersection of new space small satellites and the global interest in pursuing cislunar exploration and operations, the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission serves as a rapid, low-cost CubeSat solution to supporting future NASA Lunar Gateway program objectives. Compact within a single 12U+ form factor, the CAPSTONE spacecraft contains both its methods of travelling and remaining in a Near Rectilinear Halo Orbit (NRHO) about the L2 Earth-Moon Lagrange point, as well as methods for communicating with Earth via the Deep Space Network and other cislunar spacecraft. Deployed by its launch vehicle on July 4, 2022, CAPSTONE achieved its insertion into NRHO on November 13, 2022 after completing six Trajectory Correction Maneuvers (TCMs) executed along its low-energy ballistic lunar trajectory. Since NRHO is the target orbit of the Lunar Gateway platform, CAPSTONE is able to validate and demonstrate continued navigation and station keeping in this unique environment[1].

Developed by Terran Orbital on behalf of Advanced Space, the CAPSTONE spacecraft has already accomplished many of its mission goals, including stable operations in NRHO since November 2022, survival during lunar eclipses greater than 70 minutes in duration, and processing navigation information through communications with the Lunar Reconnaissance Orbiter (LRO) using an S-band radio and on-orbit computation by the CAPS payload board. Ground-to-space communications, as well as the generation of navigation data through Doppler measurements and two-way ranging, are made possible by use of the Deep Space Network (DSN).

The CAPSTONE program includes three primary mission objectives: to validate and demonstrate NRHO and dynamic Earth-Moon operations, inform future lunar exploration requirements, and to incorporate Advanced Space's CAPS technology into operations. As the CAPSTONE mission progresses, the spacecraft will continue to fulfill these primary mission objectives, as well as demonstrate additional functionality such as one-way ranging and further on-orbit navigation processing[2,3].

Vehicle System Architecture

The CAPSTONE 12U+ spacecraft includes a radio tower extending the vehicle from a traditional 12U form factor and deployable tri-fold solar panels providing 120 W of peak power. The spacecraft design includes redundant Terran Orbital (TO) flight computers, a TO rad-tolerant watchdog, and a suite of redundant TO sensors and actuators. The CAPSTONE sensor suite also includes 2x COTS IMUs that each include a gyro and accelerometer, 2x TO Coarse Sensor modules that include redundant coarse sun sensors and magnetometers, and 2x TO Star Trackers. CAPSTONE is equipped with 4x TO 55 mNms nano reaction wheels in a pyramid configuration for attitude control, and the Stellar Exploration Propulsion System with 8x thrusters for momentum management and orbital maneuvers. A render of the CAPSTONE spacecraft is provided in Figure 1.

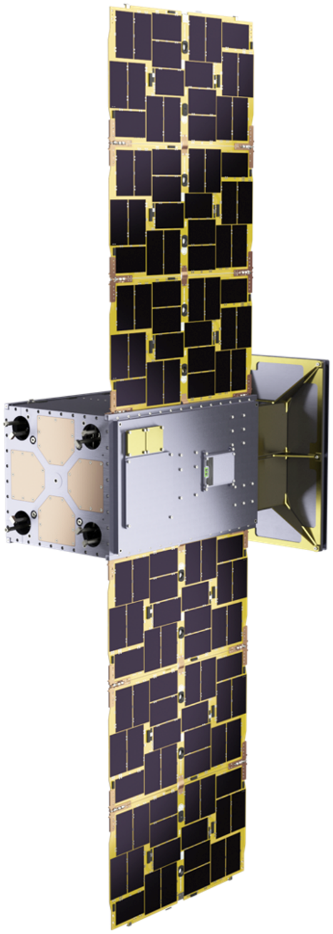


Figure 1: CAPSTONE spacecraft in a deployed configuration.

The Stellar Exploration propulsion system is a mono-propellant pump-fed hydrazine system with ~3 kg of propellant and is capable of delivering more than 200 m/s of ΔV and throttling between 40 mN to 250 mN of thrust. The system contains four translational and four rotational thrusters oriented to provide 3-axis attitude control and ΔV maneuverability with single thruster-out redundancy. Thrust and torque vector mappings for the eight thrusters are detailed in Figure 2 and Figure 3. The Stellar Exploration propulsion system provides all propulsive capability required for the CAPSTONE mission, including Trajectory Correction Maneuvers (TCMs) ranging in ΔV from 1 to 20 m/s, Orbital Maintenance Maneuvers (OMMs) ranging in ΔV from 6 to 60 cm/s, and momentum management maneuvers.

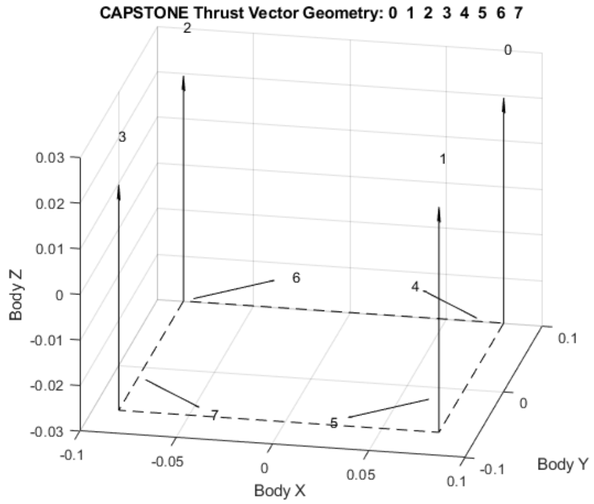


Figure 2: Thrust Vector Geometry

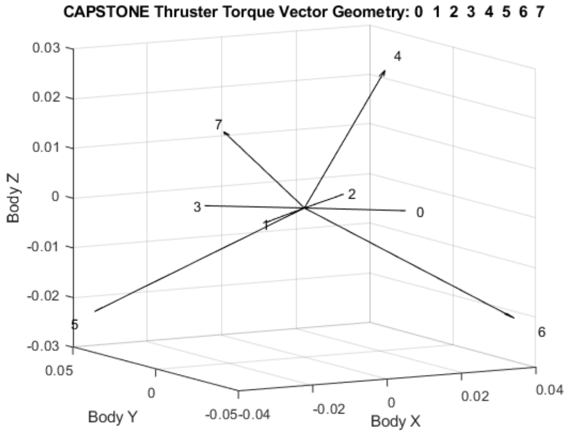


Figure 3: Torque Vector Geometry

Terran Orbital software architecture employs an application-based system on a Linux-based operating system, where each application pertains to a unique subsystem. The vehicle executive state machine, fault protection, and scheduling is managed by the 'Executive' application. For CAPSTONE, the state machine includes nominal, safe, propulsive, and payload states, as seen in Figure 4. The Fault Detection Isolation and Recovery (FDIR) system enables monitoring of telemetry in real time and autonomous responses to detected faults, including state transitions.

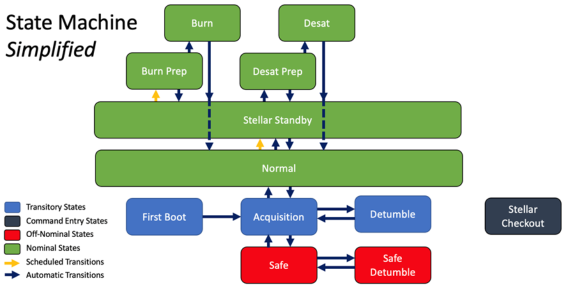


Figure 4: CAPSTONE Vehicle State Machine

The Attitude Determination and Control System (ADCS) also employs its own 'GNC state machine' including coarse and fine pointing states for sun, earth, and propulsive maneuvers. These states, and their transitions, are shown in Figure 5. Additionally, the ADCS application has its own FDIR to monitor ADCS specific health telemetry at higher frequencies.

Furthermore, ADCS has an additional 'burn state machine' to prepare for and execute propulsive maneuvers, detailed in Figure 6.

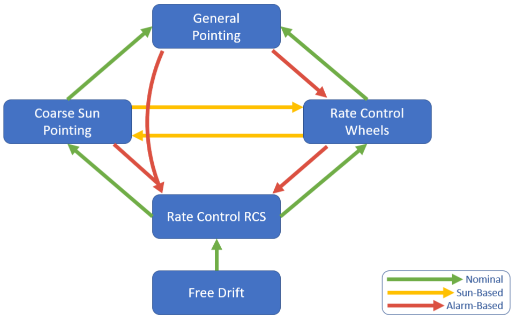


Figure 5: CAPSTONE GNC State Machine

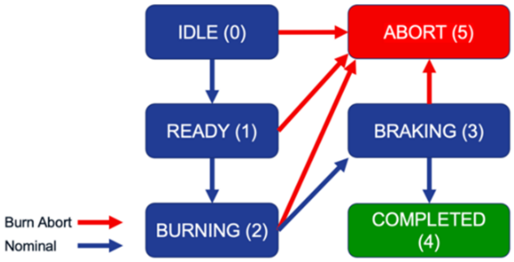


Figure 6: CAPSTONE ADCS Burn State Machine

Finally, the propulsive subsystem has its own ‘propulsive state machines’ to guide operation, commanding, and timing of the Stellar Propulsion System. Like the previously mentioned state machines, the propulsive application has its own FDIR to protect against faults specific to the Stellar Propulsion System.

The Executive, GNC, Burn, and Stellar Propulsion state machines are interdependent and were developed and tested thoroughly in conjunction on a Hardware-in-the-Loop (HITL) platform specifically for the CAPSTONE program. Each state machine controls a different portion of a maneuver with hand offs between phases to successfully execute propulsive maneuvers.

Mission Propulsive Maneuvers

For each maneuver, after performing CAPSTONE’s orbit determination and maneuver design, the Advanced Space Flight Dynamics team delivers maneuver design parameters to the Terran Orbital GNC team for validation of expected execution and performance in simulation. Data products from these simulations are delivered back to Advanced Space and a maneuver design evaluation meeting is held between the Terran Orbital GNC and Mission Operations teams and the Advanced Space program team to determine a Go/No Go decision.

After each Maneuver Assesment Meeting, the Terran Orbital Mission Operations Center (MOC) converts the maneuver design into a command sequence, schedules the maneuver, and monitors the burn preparation, then gathers and reviews pre- and post-burn telemetry to verify the health of the spacecraft and all subsystems. Early maneuver designs were tested on the HITL platform prior to on-orbit execution to verify proper hardware execution of command sequences.

While most maneuvers take place during ground contact windows, the required maneuver attitude often causes the vehicle to slew away from Earth-pointing, resulting in the execution of the maneuver occuring while out of contact with the MOC. Prior to any maneuver, the spacecraft is scheduled to return to Earth-pointing after the maneuver completes and a sufficient recharging period has elapsed.

Any time the propulsion system is exercised, it may increase the momentum of the spacecraft during the maneuver or via outgassing after completion. When the ADCS software determines a maneuver has reached its commanded ΔV, the ADCS controller will first “brake” by re-activating reaction wheels and pulsing thrusters to reduce the momentum stored in the reaction wheels. Independent of any trajectory correction maneuver and depending on the GNC state and the level of momentum, the spacecraft architecture contains autonomy to perform a desaturation maneuver to reduce the momentum stored in the vehicle.

TCM-3

During a nominal DSN track on September 8, 2022, the MOC observed the CAPSTONE spacecraft preparing for the pre-scheduled 2.28 m/s TCM-3 burn, including the planned slew away from a downlink attitude to the burn attitude, starting the expected loss of signal (LOS) period while the maneuver executes. The ground expected acquisition of signal (AOS) approximately 5-10 minutes after completion of the maneuver. Following the expected AOS + 5 mins, the ground commanded a contingency request for beacons resulting only in observation of an oscillating carrier signal as communicated verbally by the DSN station operator. With the help of the DSN, MOC, and Advanced Space’s NAV teams, the spacecraft operations team began to track carrier power over time. Figure 7 was delivered to the MOC showing the amplitude and frequency of the oscillating signal. The approximate 6-7 second period of the peak-to-peak carrier signal strength over time implied that if the vehicle was spinning, the spin rate could be on the order of $2\pi/6$, or 60 degrees per second. CAPSTONE’s reaction wheel assembly maximum momentum storage could only accommodate a maximum spin rate of approximately 10 degrees per second.

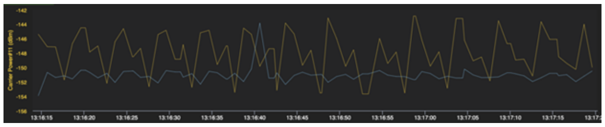


Figure 7: SNR after reaquiring signal after TCM-3.

This conclusion led the team to declare a spacecraft emergency with the DSN and request additional antennas and tracking time on the DSN network. The MOC attempted to command the spacecraft to a lower telemetry data rate, which resulted in a measurable corresponding increase in carrier signal strength. The observed increase in signal strength implied that the spacecraft could receive commands, because the transmit capability of DSN 34-m dishes gives significant uplink link budget margin. However, since carrier lock could not be achieved, the ground suspected spacecraft attitude must have been severely unfavorable for Earth-pointed communications and telemetry decoding.

Additional carrier signal power changes indicated that the spacecraft had spun up further likely due to an event powering off the reaction wheels, resulting in momentum being transferred from the wheels into spacecraft body rotation.

Approximately 24 hours after TCM-3, the team was able to reserve antenna time from a DSN 70-m dish asset that was allocated on an emergency basis. The additional gain of the 70-m dish enabled telemetry lock with a low data rate and with a low signal strength just above the available margin, allowing the decoding of limited beacon frames from the spacecraft. Telemetry confirmed that the spacecraft was spinning at a high rate and the momentum in the system was much greater than its storage capability.

The spacecraft was tumbling in a flat spin about the solar array normal axis. Telemetry also indicated the vehicle was in a severely power negative orientation, resulting in repeated instances of full vehicle shutdowns. If the battery voltage is below its hardware threshold and power in the system is too low to maintain system operations, the modules powered by system voltage are disconnected from the batteries, allowing all solar input power to only charge the batteries. This is referred to as a “dead-bus” event. After a minimum voltage is reached through solar charging, the vehicle automatically powers back on.

Based on reconstruction of the power input to solar arrays and SNR observed by the ground, it was determined that the spacecraft’s spin attitude resulted in the downlink antenna off-pointed by more than 90 degrees from Earth and the solar array normal off-pointed by about 75 degrees from the Sun. This orientation resulted in a large surface area of the bus pointed at deep space and a limited amount of solar flux heat in, a less favorable thermal attitude with minimal power input from solar arrays, and limited heat dissipation due to frequent dead-bus events.

The temperature of the vehicle slowly decreased by 20 °C across most subsystems while the spacecraft was tumbling, from a nominal 10 °C to approximately -10 °C. The hydrazine propellant, which freezes at 2 °C, dropped in temperature with the bus. It was determined in later analysis that the propellant began to freeze after about one day without thermal control, because the temperature of tank wall thermistors suddenly rose back up to 2 °C and remained flat due to the latent heat of freezing. This temperature rise due to the latent heat energy released in the transition from a fluid to a solid is shown in Figure 8. Propellant slowly continued to freeze for 35 hours before there was sufficient power available to utilize heaters.

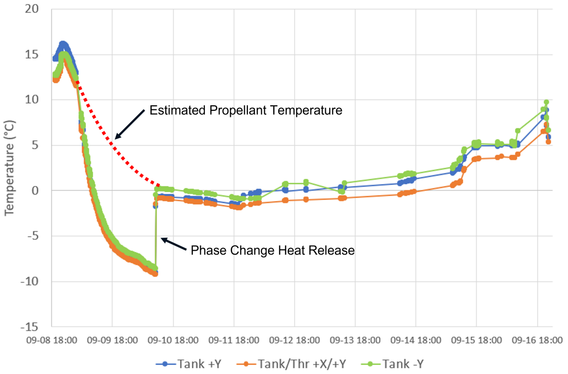


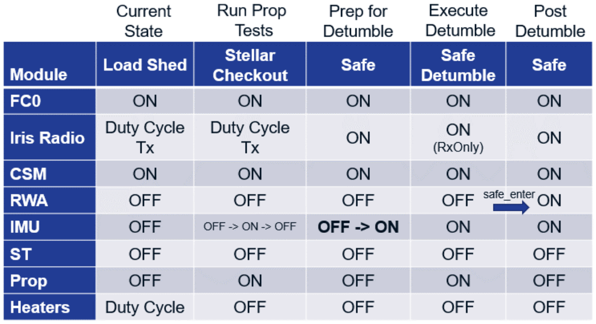
Figure 8: Propellant temperature while freezing.

The initial recovery effort had two main objectives:

1. Stabilize the vehicle health to enable consistent communication and prevent further dead-bus events.

2. Review the limited data on the vehicle to understand the root cause of the anomaly.

The peak solar array power generation in the off-nominal attitude state was determined to be just over 20 W. However, over the following days, the sun would precess with respect to CAPSTONE’s inertial spin, slowly decreasing the angle to sun and allowing the arrays to increase power generation to about 25 W. In a nominal radio receive-only mode with no heater consumption, the spacecraft in Safe mode consumes 18 W of power. A road map was laid out of possible power states to balance goals of safely warming the bus and gathering data about the current spacecraft health and anomaly reconstruction.



	Current State	Run Prop Tests	Prep for Detumble	Execute Detumble	Post Detumble
Module	**Load Shed**	**Stellar Checkout**	**Safe**	**Safe Detumble**	**Safe**
FC0	ON	ON	ON	ON	ON
Iris Radio	Duty Cycle Tx	Duty Cycle Tx	ON	ON (RxOnly)	ON
CSM	ON	ON	ON	ON	ON
RWA	OFF	OFF	OFF	OFF	safe_enter → ON
IMU	OFF	OFF -> ON -> OFF	**OFF -> ON**	ON	ON
ST	OFF	OFF	OFF	OFF	OFF
Prop	OFF	ON	OFF	ON	OFF
Heaters	Duty Cycle	OFF	OFF	OFF	OFF

Figure 9: Vehicle power states needed to detumble.

Bus Stabilization and Emergency Operations

During the pre-launch design phase, Safe mode was configured to include an automatic sequence of events that would command the spacecraft to occasionally transmit basic telemetry at low data rates (beaconing). The original intention of this design was based on an expectation that in a Safe mode scenario, the vehicle could still manage momentum with adequate torque authority, while in a coarse pointing state. Planning that the spacecraft would be in a coarse sun pointing attitude while in its Safe mode, the transmit sequence was designed to alternate use of the two low gain transmit antennas, on opposite spacecraft body faces, increasing the probability that the vehicle's signal could be detected from Earth despite a variable Sun-Probe-Earth angle. However, the vehicle state in Safe mode at the time of the TCM-3 anomaly did not match the designed use case of that mode, and therefore needed to be modified.

Because the attitude state of the spacecraft was known and fixed during this anomaly resolution period, Safe mode was modified into a "load shed" power state by manually powering off additional modules including reaction wheels, IMUs, star trackers, and manually disabling heater protection at typical set points. This modified load shed state relied on the ground to open loop manage vehicle operations, removing autonomy from the system in this extreme fault case.

Maintaining a consistent communication link was a priority while the remaining spacecraft power available was divided between managing propulsion system and battery system temperatures. This minimal power state maximized power available for heaters and for a limited transmit cadence from the radio. Since the spacecraft could not nominally slew to Earth for a scheduled downlink track, a modified Safe behavior was implemented to allow a telemetry beacon duty cycle of 6 minutes of transmitting, 62 minute wait, repeat – a change from the preconfigured 20 minute transmit/wait periods. Lowering the duty cycle from 50% to <10% would ensure the spacecraft remained transmitting on a predictable basis to monitor for further anomalies, allowing the DSN to make contact as track time could be allocated, while maintaining a power positive energy budget. In addition, the telemetry beacon cycle was configured to only use the optimal antenna for the geometry of anomaly, rather than switching between the two available low gain antennas. The propulsion tank heater was activated on a duty cycle with the goal of bringing the propulsion tank above +5 °C, nominally set at +7 °C, so that a new propulsive maneuver could be executed after a period of heating. The battery heaters were enabled and set to 0 °C, nominally set at +5 °C, to preserve battery health and optimize battery charging.

During this minimal power state time, communications focused on gathering thermal data to inform thermal models for recovery and anomaly back-orbit data. With key sensors powered off, insight into real-time vehicle momentum and body rates was removed from telemetry, requiring operations to rely on signal detection as indication of spacecraft attitude. This phase of recovery operations continued for a week.

A correlated thermal model was used in conjunction with flight telemetry to estimate the total heat flow out of tank during the 35 hours the bus was losing heat and propellant was freezing, and that was used to determine the mass of frozen propellant. Thawing the propellant took significantly longer than the time freezing because the heaters had to overcome the additional heat loss from the propellant to the abnormally cold spacecraft. The time to thaw the frozen propellant was based on the total heater power supplied minus the heat loss to the spacecraft, which resulted in about a 6-day period. Propellant was considered fully thawed on September 16. The goal for this phase was to maintain propulsion system temperatures above 5 °C for more than 12 hours, ensuring the hydrazine was fully fluid.

As an aside, frozen propellant was identified as a pre-mission risk while in lunar eclipse. After a TVAC thermal balance and model correlation, the team identified a more conductive heat path from the tank to the spacecraft structure than previously expected. As a result, radiator area on the -Z face of the spacecraft was removed to ensure tank heaters had positive thermal control authority. This change may have saved the mission because the heaters were much more efficient at thawing propellant than in the previous case.

The ground was able to downlink only limited data surrounding the initial anomaly, but the data set was sufficient to understand the sequence of events that led to the anomalous state of the vehicle. Telemetry shows that the vehicle prepared for and executed the TCM-3 maneuver nominally. The maneuver completed and the ADCS Burn state machine transitioned to BRAKING(3) to reduce any latent momentum imparted on the vehicle during the maneuver. Towards the end of the braking duration, a rapid increase in momentum was observed. The burn abort alarm triggered immediately halting the vehicle at approximately 12 deg/s of rotation and

195 mNms of momentum. Following this abort, the Executive state machine reacted to the high body rates and transitioned the vehicle to detumble with thrusters to reduce the momentum. During the pressurization of the system, lasting 10 seconds, and the detumble itself, lasting about 50 seconds, momentum and body rates continued to grow until the vehicle hit the “insane rate alarm.” Once the insane rate alarm was tripped, ADCS inhibited all GNC state transitions and locked itself into “Free Drift” at an approximate body rate of 68 deg/s and over 1215 mNms of momentum. Based on the direction of the increase in body rates, it was suspected that either thruster 3 or thruster 5 was stuck open.

It was a known and intentional design decision to allow the Executive state machine to attempt a detumble despite the burn abort alarm being high. In the majority of expected burn abort cases, the vehicle could be in an off-nominal momentum state, with rates too high to be controlled on wheels alone, but the propulsion system functional. This would allow the vehicle to reduce momentum in the system to regain pointing control, allowing CAPSTONE to make ground contact and operators to investigate and resolve the anomaly. The “thruster stuck open” fault case remained a known risk where few traditional mitigations were available for a small, low-cost technology demonstration satellite like CAPSTONE. One possible response to a valve anomaly is to further actuate the valve to “shock” it open or closed.

The relative force thrust of the 0.25 N thrusters required to enable the mission’s high ΔV trajectory correction maneuvers can quickly place the vehicle into a momentum state that is uncontrollable on wheels. This makes the detection and response of a stuck open thruster event challenging to catch quickly. In the context of this anomaly, within only eight seconds of the thruster stuck open event, the momentum state had increased to over 180 mNms and body rates to 11 deg/s. The pump fed hydrazine propulsion system operation contains initial transients accumulating to up to a few degrees per second. Any body rate alarm threshold needs to comfortably accommodate nominal body rates plus initial transients with some margin, further increasing the challenge of detecting a stuck open thruster event.

Path to Detumble

Based on a FMECA analysis and extensive discussion with the Stellar Exploration propulsion team, the approach was to incrementally exercise the propulsion system and state machine to verify propulsion system health. This was essentially a re-commission of the propulsion system after both the initial anomaly and the hydrazine partial freeze event. The first component to exercise was the electric pump, placing it in the “Arm” and then “Prime” state, demonstrating propellant flow through the pump, recirculation valve, and back into the propellant tank. This verified electrical health of the system, health of the pump itself, ability of the Propellant Management Device (PMD) to absorb and feed propellant to the pump while the spacecraft experienced high body rates, and ability to maintain pressure upstream of the primary valve. This exercise was performed nominally, validating the health of the electric pump and initial health of the propulsion system, a testament to the robustness of the Stellar Exploration system, depicted in Figure 10.

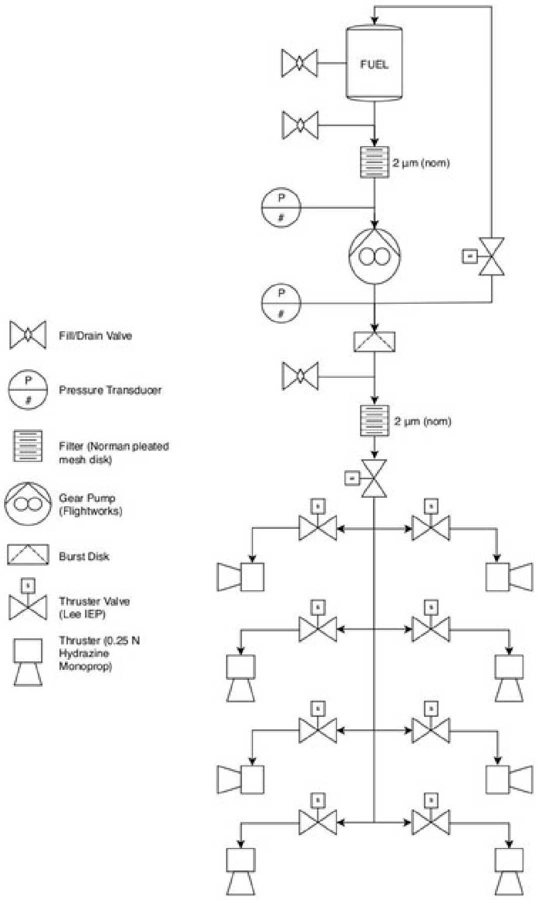


Figure 10: Stellar Exploration Piping and Instrumentation Diagram.

In propulsion system development and ground testing, it had been seen by Stellar Exploration that valves could occasionally remain open despite being commanded closed. A subsequent open and close command would then succeed in closing the valve. Evacuate sequences dedicated to quickly and repeatedly toggling each valve while the system remains unpressurized were developed for commissioning for the purpose of evacuating the lines prior to rupturing the burst disk. During these tests, the primary upstream valve is open, but the pump is not actuated so the system does not pressurize, but some propellant vapor did vent to vacuum through the stuck open valve. This sequence was exercised twice on-orbit and actuation of the valves appeared nominal in telemetry but no further determination of the true valve state could be made until the system was pressurized.

To verify the result of the evacuate sequences' attempt to unstick the valve, the standard pre-maneuver "pressurize" command sequence was commanded on September 23, two weeks after the initial anomaly. The pressurize phase nominally times out after 10 seconds. During this time, operators observed the body rates further increase from 68 deg/s to 103 deg/s, indicating the valve remained stuck open. Following this experiment, the CAPSTONE team decided to pursue avenues to detumble the vehicle despite the stuck open thruster rather than spend additional time and resources to continue to attempt to close the valve.

Following this decision, development began on updating the detumble controller.

The generic CAPSTONE ADCS detumble state uses basic rate guidance and a simple Proportional ("P") controller using measured body rates from the gyro for feedback. The rate controller was not designed to require rejection of a steady state disturbance which is what allowed the vehicle to spin up during the initial detumble attempt. Adding an integrator term to the controller to reject steady state disturbances was the obvious choice, however that would require new ADCS code to be written, tested, uploaded, and patched onto the vehicle while the vehicle remained in an off-pointed and unfavorable power configuration. Instead, the GNC team utilized an existing filter on the rate controller error with configurable parameters, saving significant design and review time. On Saturday September 24 the GNC team first updated the existing rate controller to become "passthrough" and then configured the rate filter to act as a PI controller itself. This new rate "controller" was then simulated with the current (pre-pressurization test) thrust estimates for each thruster and succeeded in detumbling the vehicles for both thruster 3 and thruster 5 disturbance force cases.

At this time, uncertainty still existed about exactly which thruster was stuck open. The initial values for the disturbance thrust were estimated based on the observed increase in body rate during the initial detumble that spun the vehicle up. However, this had the existing detumble controller fighting the disturbance in addition to lack of higher rate data causing the team to underestimate the magnitude of the stuck open thruster's force. Based on the observed torque and the momentum arms of thrusters 3 and 5, the team concluded that either thruster 3 was close to being stuck fully open, or thruster 5 was stuck approximately 40% open. At this time thruster 5 was the leading suspect as a near fully stuck open valve was considered unlikely.

The following day, Sunday September 25, upon after reviewing Friday's pressurization test data the simulated thrust values were updated to match observed behavior of the flight vehicle. The simulated vehicle no longer had the torque authority to detumble despite the updated PI thruster controller to fight the steady state disturbance.

On Monday September 26, the GNC team devised a method of altering the existing thruster allocation controller into potentially finding some extra torque authority. The existing thruster allocator works by finding the minimum set of thrusters that enclose a torque request by the attitude controller. This means to satisfy any torque request, the thruster allocator will select the best three thrusters that enclose the torque request and duty cycle them proportionally.

To nominally oppose the stuck open thruster disturbance, thrusters 0, 2, and 7 were selected to fire, but as previously described did not have enough force/torque authority to overcome the disturbance. Using the configurability of the GNC code, it was possible extend this set of best three and force a fourth thruster to be fired whenever another, preconfigured, thruster was fired. Thruster 6 was the optimal candidate, as it contains opposite torque components of the stuck open thruster in the X/Y axes, and was chosen to be "glued" to thruster 0. Once thruster 6 (THR6) was added and glued to thruster 0, the net torque of the four thrusters was large enough to overcome the stuck open thruster disturbance. However, the tradeoff to this action was torquing the vehicle even further in Z. In summary, the result of this is any time the attitude controller would request a torque that the thruster allocator would choose to fire thruster 0, it will always duplicate that force and send it to thruster 6. This essentially allows the allocator to map four thrusters instead of the nominal three for a given torque request.

Table 1 includes a list of the torque vectors for each thruster on the vehicle. To determine a torque response, one can sum a set of three thrusters, in this case thrusters 0, 2, and 7, to find the resultant torque. In the context of a stuck open THR3 or THR5, the resultant opposing torque vector,

$$\tau_{027} = [-0.002, -0.0423, 0.0236] Nm \tag{1}$$

would increase the body rate in the Z axis and still fail to create a net torque in the X axis. By adding in THR6, the new resultant torque vector becomes

$$\tau_{0627} = [0.0414, -0.0879, 0.0001] Nm. \tag{2}$$

This new net torque vector appropriately opposes the components of THR3 or THR5 allowing the vehicle to overcome the disturbance of either thruster and decrease net body rates.

Table 1: Thruster Torque Per Body Axis

THR #	X [Nm]	Y [Nm]	Z [Nm]
0	0.0207	-0.0213	0
1	-0.0208	-0.0213	0
2	0.0207	0.0202	0
3	-0.0208	0.0202	0
4	0.0434	0.0434	0.0243
5	-0.0434	0.0434	-0.0243
6	0.0434	-0.0434	-0.0235
7	-0.0434	-0.0434	0.0236

The simulation was reconfigured and scenarios were ran that successfully detumbled the vehicle with the updated force estimates using this methodology. Following this, a series of Monte Carlo simulations were kicked off with varying stressing initial rates and thruster disturbance force values and 100% of cases were successful in detumbling while utilizing the updated filter "PI controller" and "THR6 Glued" configuration, as seen in Figure 11. The worst cases used no more than 100 grams of propellant, and the nominal flight-like case was estimated to use approximately 20-40 g of propellant. At this time in the mission, it was estimated that approximately 1.7 kg of propellant remained in the tank, sufficient budget for many years beyond CAPSTONE's nominal mission lifetime. The path forward to detumbling was now known, and work began on creating the Executive state machine updates, testing, and patching to finalize the sequence of events and additional safeguards during the detumble event.

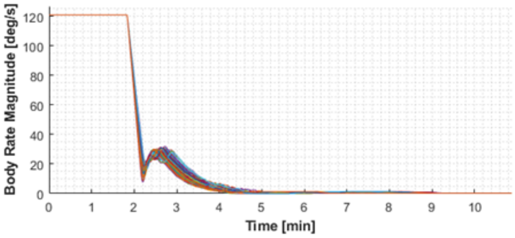


Figure 11: Monte Carlo results for 4-thruster detumble.

The CAPSTONE Hardware-in-the-Loop (HITL) test platform contains real hardware and a truth simulator to emulate a flight-like environment in real time. CAPSTONE's HITL includes a flight computer, 4x reaction wheels, and a Stellar Propulsion Controller (SPC) EDU. The SPC EDU was invaluable in enabling testing of the on-board propulsion system, because it includes a replica of electronics, a pump, and valves. The valve states are measured and input into the real time simulation, allowing modelling of the stuck open thruster during all phases of the propulsion system operation for testing. The simulated truth model was updated to ingest pressurization states such that while the system is pressurized it would generate a corresponding disturbance force to the stuck open thruster. The updated ADCS configurations and Executive timing were applied onto HITL to allow testing for all nominal propulsive system cases and the detumble itself.

After one week of testing, on October 7, final approval was given by the spacecraft team to upload and apply all patches and configuration changes developed. The vehicle's sensors and actuators were powered back on and the vehicle's onboard autonomy was re-enabled to trigger and execute its detumble. During this time, the spacecraft was necessarily out of contact with the ground. Approximately 9 minutes after LOS, signal was observed briefly, followed a minute later by steady signal. Soon after, telemetry lock was achieved and the vehicle was in a coarse sun pointing mode with approximately 30 mNms of momentum. The CAPSTONE vehicle could resume nominal ground contact while sun pointing on reaction wheel control.

Prior to the detumble, current body rate norms were around 108 deg/s, and during the course of the detumble, body rates exceeded 120 deg/s during the pressurization phase. Ultimately the ADCS controller was able to fight the disturbance, and momentum decreased as the vehicle slowly detumbled over the 5-minute duration burn. Results comparing the expected performance from the HITL testing as well as the real flight results can be found in Figure 12.

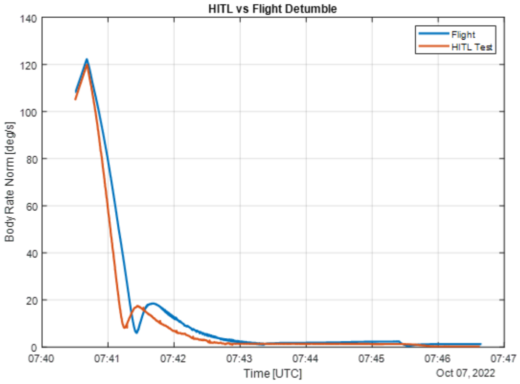


Figure 12: HITL and Flight Data of Body Rate Magnitude vs Time for CAPSTONE's Detumble.

The next steps were to perform a system ID on the propulsion system to understand exactly which thruster was stuck, evaluate the possibility of attempting further valve troubleshooting, and eventually investigating into the feasibility of maneuver execution with a stuck open thruster. It was determined that thruster 3 remained fully stuck open, producing approximately 0.25 N of force anytime the propulsion system is pressurized. All attempts to close the valve were unsuccessful.

CAPSTONE's maneuver design was updated to allow for maneuvers despite thruster 3's disturbance force. Thruster 3 was removed from the thruster allocator mapping and the number of translational thrusters "on" for maneuvers was reduced from four to two to include only thruster 3 and its opposite pair, thruster 0, because there would always be a constant force from thruster 3, whether commanded by the allocator or not. Additional significant updates were made to the Executive and Propulsion state machines to minimize time spent in the pressurization phase, reducing the overall disturbance before the maneuver begins. This reduced the overall momentum gained by the system during pressurization and lowers the initial transient seen by ADCS, allowing more accurate maneuver execution. Reduced pressurization time came at a minor cost of commanding and firing thrusters before reaching steady state pressure, however, this "loss" of performance under these circumstances is miniscule when compared to the error introduced by the pressurization disturbance from a stuck open thruster 3.

Lessons Learned

The CAPSTONE team experienced first-hand the challenges of deep space missions, pushing the limits of what a small satellite and small team are capable of, including changing mission objectives and requirements. CAPSTONE had experienced anomalies prior, unrelated to the propulsion system, and the program in flight needed to adapt for additional fault cases not originally in project scope.

Fast paced missions need to be flexible in schedule, technical risk management, and allocating available resources to the highest risks known at the time. Notably in the mission Integration & Test phase, the TVAC thermal balance data results revealed a more conductive heat path from the tank to the spacecraft structure than previously expected. The correlated thermal model and the ability and decision for the program to change the radiator properties before launch, along with highly configurable heater set points and duty cycles, enabled the team to restore the propulsion system to nominal operating temperature and recover the mission.

The ADCS application was developed with significant upfront effort for robust, generalized, and configurable code. This design architecture allowed significant time savings in flight anomaly response, particularly in developing confidence in results due to the lack of changes to the code base, resolving the issue with purely configuration parameter changes and zero updates to the ADCS source code. It is essential to keep track and maintain configuration as the mission progresses. An initial configuration for CAPSTONE's deployment and propulsive detumble required significantly more conservative values for alarms when compared to nominal propulsion operations. These initial requirements included body rates of 40 deg/s, but the configuration was never lowered once vehicle commissioning was completed. Updating the configuration after initial contact could have resulted in less extreme body rates during this anomaly, however, would not have prevented the issues encountered.

The CAPSTONE mission would continue on to execute TCM-4, NIM, ICM-1 and ICM-2, totaling 30.23 m/s of ΔV and 27.18 minutes of burn duration. CAPSTONE reached NRHO on November 13, 2022 and continues to operate in NRHO and perform its mission objectives, despite the challenges of the initial anomaly and its continued impacts. Furthermore, once reaching NRHO, additional work was performed to reduce the thrust allowing small ΔV maneuvers for OMMs, on the order of 6 cm/s ΔV and larger. Additionally, a sequence was developed that allowed the CAPSTONE team to utilize thruster 3 to manage its momentum on demand, in lieu of the planned and traditional desaturation maneuvers. Future publications may include analysis of the maneuver performance prior to and following the anomaly.

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Thanks to understanding friends and family for when we had to stay up all night to ensure CAPSTONE remains "Happy and Healthy." No thanks are given to the unlucky snacks that were consumed at inopportune times – let's just say we will not be eating any pie to celebrate CAPSTONE's future birthdays.

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