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FLIGHT EXPERIENCE AND LESSONS LEARNED FROM BIOSENTINEL: A 6U DEEP SPACE CUBESAT

Jesse Fusco[*], Terry Stevenson,[†] and Robert Nakamura[‡]

This paper reviews the flight experiences of the BioSentinel propulsion and Attitude Determination and Control System (ADCS) teams. BioSentinel, a 6U CubeSat, launched as a secondary aboard the Space Launch System (SLS) maiden flight in November of 2022 and is now operating in an Earth-trailing heliocentric orbit. The creation and performance of a novel approach to gyro bias estimation in the spacecraft's Sun safe controller is discussed in detail. Furthermore, the development and in-flight experience with the spacecraft's propulsion system is discussed. Finally, an angular momentum management approach is described to address a propulsion system valve failure.

INTRODUCTION

BioSentinel launched as a secondary payload aboard the Space Launch System's inaugural and historic Artemis I flight on November 16, 2022. BioSentinel not only carries a biology experiment into deep space for the first time in 50 years, but farther than ever before. The budding yeast, *Saccharomyces cerevisiae*, serves as an analog to human cells to test the biological response to deep space radiation. Additionally, the 6U CubeSat form factor includes technologies newly developed or adapted for operations beyond Earth orbit, providing the maiden deep-space voyage to evaluate their flight performance[1]. The on-going mission continues to be a pathfinder for future deep space CubeSats.

This paper starts with an overview of the mission and the spacecraft, with a particular focus on the design of the Attitude Determination and Control System (ADCS) and the propulsion system, as well as some of the unique challenges to operating a CubeSat in deep space. A novel gyro bias estimation technique for use in safe mode is described and flight data is shown to validate the approach. A mission summary is then presented, focusing on several important mission events, as well as anomalies encountered and their resolution. Finally, a propulsion system valve failure is discussed along with the resulting changes made to spacecraft momentum management and a new momentum prediction tool to enable those changes.

SPACECRAFT DESIGN

The BioSentinel spacecraft's design started with two simplifying operational aspects derived from its science payloads (the BioSensor and a conventional radiation sensor). First, the deep space trajectory required to investigate the radiation environment away from Earth's protection was designed to enter a relatively stable heliocentric orbit after a lunar fly-by. This trajectory implies that

[*] BioSentinel Mission Operations Manager and ADCS Lead, NASA ARC - REE, N-213 Moffett Field, CA
[†] BioSentinel Flight Director and Propulsion Lead, KBR Wyle Inc, N-213 Moffett Field, CA
[‡] BioSentinel Flight Director and Fault Management Lead, NASA ARC - REE, N-213 Moffett Field, CA

the Sun-Spacecraft-Earth angle is close to 90° throughout the science and extended phases of the mission. Second, the science payloads place no restrictions on attitude pointing. Therefore, the mission nominally orients the spacecraft with the solar arrays (-X face) pointed toward the Sun and only slews away if necessary to point a communication antenna toward Earth. To minimize the angle change during that slew and maximize power available, Figure 1 shows how the low and medium gain antennas were placed on opposite faces (-Y and +Y faces respectively), both 90° from the solar panels to match the Sun-Earth geometry. Additionally, the single star tracker camera completes the triad (-Z face) to ensure it is typically clear of any bright objects for all operations.

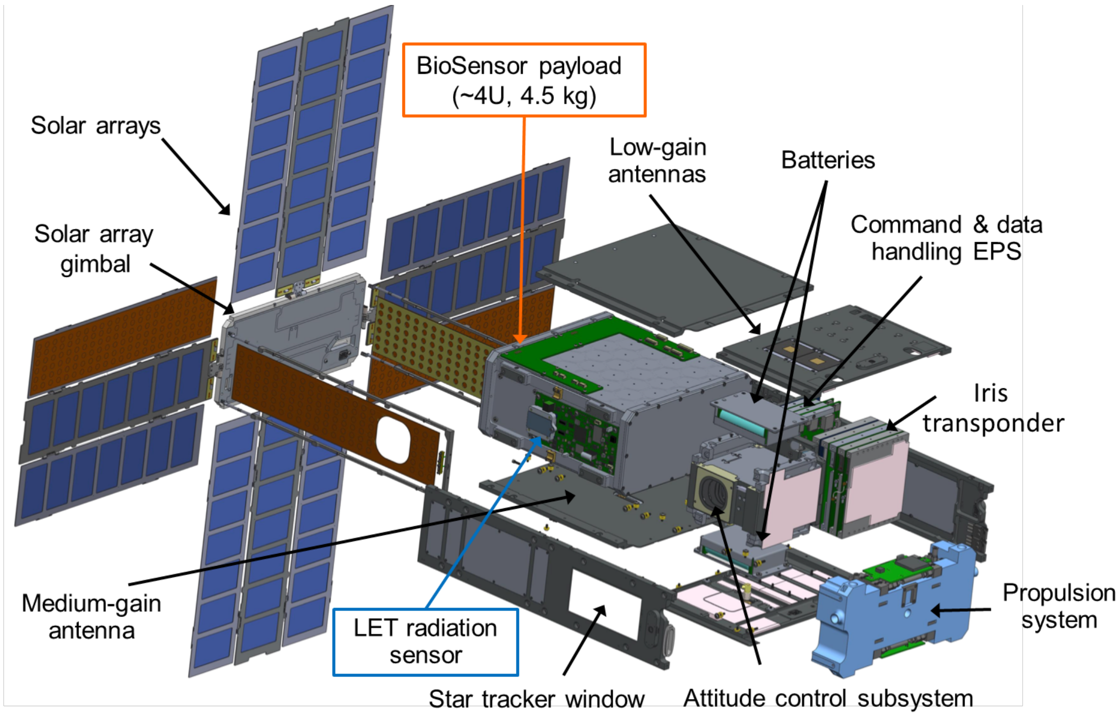

Figure 1. Spacecraft Components - Exploded View.

The spacecraft was also designed to accommodate the many constraints inherent in its status as a secondary payload, with as much flexibility and subsystem margin as possible within a small volume. There was a large amount of uncertainty in the deployment from the launch vehicle in terms of timing, tip-off rates, force magnitude, and direction. These uncertainties, then amplified by a lunar fly-by, meant possible trajectories ranged from no lunar eclipse, to eclipses long enough to negatively affect the science payload and spacecraft hardware, to lunar impacts, or even cases with a retrograde hyperbolic orbit returning to Earth[7] (impact avoidance discussed in the mission highlights section).

The thermal design analysis indicated not just healthy margins during nominal Sun pointing attitudes, but also survival through the longest possible lunar eclipse, which was also the design case for the battery system. Degradation of the battery system was also a consideration as the launch date was repeatedly delayed. The solar array system is composed of two deployable panels and a technology demonstration of two gimbaled panels, and was not only sized for possible degradation by the end of mission, but possible trajectories taking the spacecraft further from the Sun. As an additional demonstration, the Electronic Power Subsystem (EPS) was designed from scratch with all COTS components to prove their performance in a deep space environment. The ADCS design uses the star tracker for inertial attitude measurements, an Inertial Measurement Unit (IMU) for rate measurement, and three reaction wheels for attitude control. Not pictured in Figure 1 are five two-axis Sun sensors, with one located on each spacecraft face except +X. Finally, the cold gas propulsion system was placed on the extreme aft (+X) side of the spacecraft, giving the highest possible moment arm and torque. While forced into an extremely small volume, it contains two propellant tanks, valve driving electronics, and seven thrusters.

COMMUNICATIONS OVERVIEW

The Deep Space Network (DSN) provides the interface for RF communications. During the first few days, scheduling was accomplished with the Multiple-Spacecraft Per Aperture (MSPA) time sharing scheme in conjunction with the other nine CubeSat secondaries on Artemis I. However, as distances increased, dedicated time slots are now scheduled to manage spacecraft activities and ensure all data is downlinked to the ground. Several characteristics of BioSentinel's extremely compact communication system drive flight operations. First, lacking a hybrid coupler, only one set of antennas can be used at a time, forcing operators to choose either the side of the spacecraft with the transmit Medium Gain Antenna (MGA) or the transmit Low Gain Antenna (LGA), along with the corresponding receive LGA. Thermal limitations and high-power dissipation in the transmit amplifier are also major drivers, preventing continuous transmission with the radio for longer than approximately three hours. Finally, power margins and the corresponding link budget limit the data rates available as the spacecraft travels further away from Earth.

When in pointing mode, operations are quite simple as on-board command sequences can orient the active antenna directly toward Earth and power on/off the transmitter at scheduled times to match DSN tracks. However, safe mode faces several additional challenges. As there is no active command sequence or onboard ephemeris knowledge, a constant rotation about the Sun vector sweeps the active antenna set through the entire sky to ensure communication availability with the spacecraft for 50% of the rotation, but this also limits the time before the signal is lost as the antenna will rotate away from Earth eventually. Additionally, to manage the thermal limitations while also providing autonomous periods of telemetry transmission, the spacecraft power-cycles the transmitter on for roughly 25% of the time and off the other 75%, although it is always commands receptive. The rotation rate and transmitter duty cycle duration are purposefully mismatched so that the transmitter is on for different portions of each rotation.

To accomplish safe mode communications with this design, operators wait for BioSentinel's allocated command time, command the spacecraft (in the blind typically) to enable the transmitter and disable the duty cycling for one hour. Since the active receive antenna could be pointed in the wrong direction, the command is resent every two minutes until a signal is detected. Once DSN can lock on to an RF signal, the operations team evaluates if the signal to noise received on the ground is sufficient, and a command is sent to stop the spacecraft's rotation for one hour before resuming. Automatic one-hour timers before resuming the duty cycle and rotation were established as a safety net. Since consistent communication was not guaranteed (especially in safe mode), a commitment was made to never leave the spacecraft in a non-optimal position. The timers prevented the transmitter from overheating, or the spacecraft rotation stopped but pointing the wrong way, or the rotation stopped for too long causing angular momentum to accumulate more rapidly. This method has proven to be successful, allowing for the safe recovery back into nominal pointing mode throughout the mission.

ATTITUDE DETERMINATION AND CONTROL SYSTEM

The BioSentinel Attitude Determination and Control System (ADCS) is composed of four autonomous control modes summarized in Figure 2: nominal pointing mode, momentum management mode, rate reduction mode, and a Sun safe mode. The star tracker and IMU measurements are fused in an extended Kalman filter to provide attitude and rotation-rate feedback in the standard operating control modes for the Nominal Pointing Controller and Momentum Management Controller. The Rate Reduction Controller simply closes the loop between the IMU and propulsion system to detumble the spacecraft post separation or in the event of an anomaly.

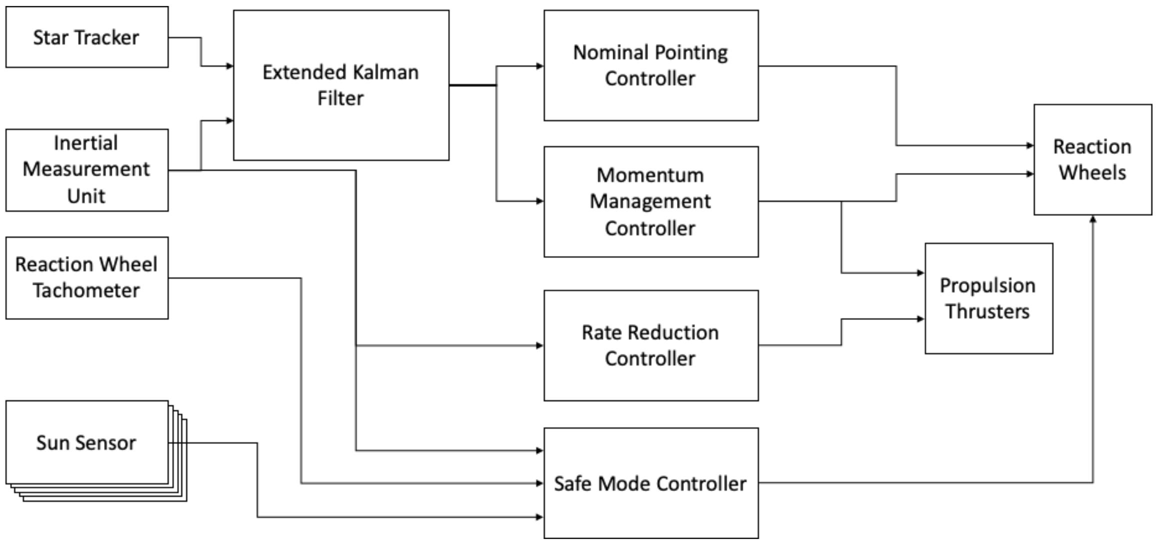

Figure 2. ADCS Controller Overview.

The BioSentinel Sun Safe Mode is a minimum hardware control mode designed to orient the spacecraft such that it is power positive, thermally safe, and available for communication with ground controllers. The first two are accomplished by simply pointing the solar panels directly at the Sun. The spacecraft then rolls about the Sun vector to sweep the low gain antenna around the sky and prevent excessive momentum buildup in the reaction wheels from solar radiation pressure (or any body-fixed torque such as a propellent leak).

Safe Mode Controller

The BioSentinel controller design methodology and architecture builds on the Lunar and Dust Environment Explorer (LADEE) safe mode controller[2]. The BioSentinel safe mode had two unique requirements that its LADEE predecessor did not. First, it required much more precise rate control over the Sun vector spin rate due to the limited communication windows with DSN and the lack of omnidirectional antenna coverage. Second, to facilitate safe mode recovery with the hemispherical coverage from a single low gain antenna, the spacecraft is required to stop rotating with that antenna aligned with Earth. Both requirements pushed the safe mode design to incorporate a gyroscope bias estimation mechanism. This technique (described in detail in the following section) imposed further control accuracy requirements on the controller and necessitated the addition of an integrator (compared to the LADEE safe mode design, which was just a proportional derivative (PD) controller).

Figure 3 shows a functional block diagram of the BioSentinel safe mode controller. Attitude error in the controller uses a common technique for Sun pointing controllers[2,3,4], and is calculated using:

$$\theta = \hat{S} \times \hat{S}_{cmd} \tag{1}$$

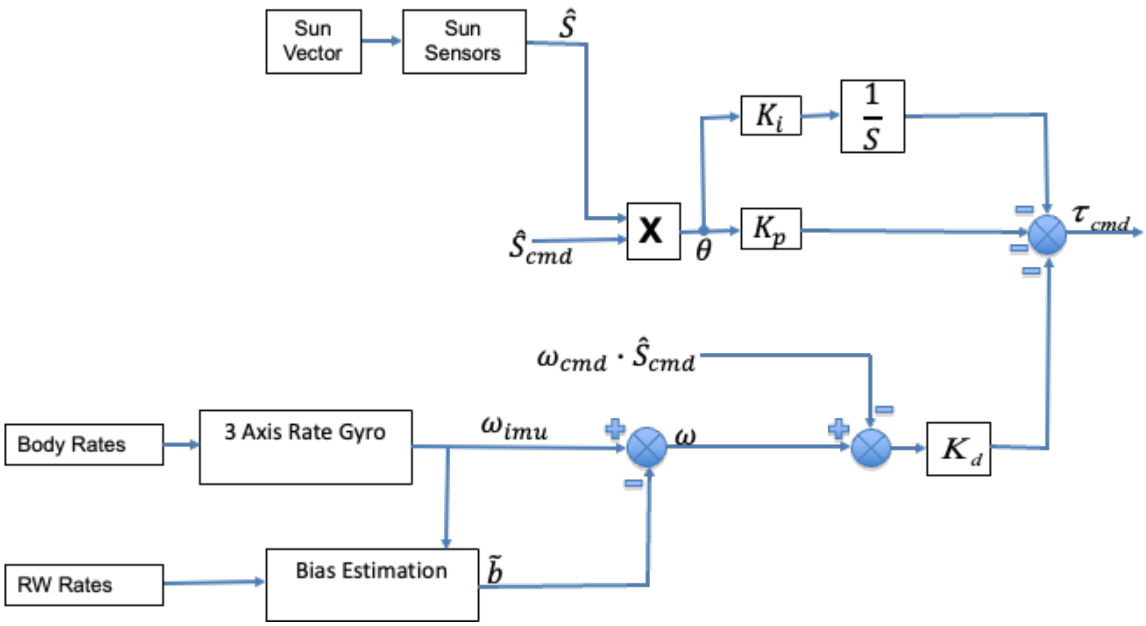

Figure 3. BioSentinel Safe Mode Controller Functional Block Diagram.

Proportional and integral gains are then applied to the attitude error θ to generate commanded restorative torques to the reaction wheels, τ_{cmd}. Note, τ_{cmd} is the commanded torque to the reaction wheel rotor and is therefore the opposite of the torque applied to the spacecraft. Protection against integrator windup is implemented by enforcing a saturation limit of one-tenth the available reaction wheel torque and by holding the integrator in reset with attitude errors above 25°. Rotation about the Sun vector at the scaler rate, ω_{cmd}, is accomplished by generating a commanded body rate, $\omega_{cmd} \cdot \hat{S}_{cmd}$. Where, ω_{cmd} is nominally set to a fixed rate of one revolution every 30 minutes, providing communication windows of about 15 minutes while the spacecraft is spinning due to the hemispherical low gain antenna coverage. During recovery from safe mode to the spacecraft's nominal pointing mode, longer communication windows are required, and the mission operations team sets ω_{cmd} to zero once communication and sufficient radio power levels are observed.

Bias Estimation Technique

The BioSentinel safe mode required an accurate estimate of the gyroscope bias to maintain the correct rotation rate (which was potentially as high or higher than the commanded spin rate) and enable communication with Earth. The safe mode design adapted techniques used by the Solar Dynamics Observatory (SDO)[4] to make this estimate. Where the SDO design was attempting to replace the use of gyroscopes in their safehold mode with reaction wheel tachometer measurements, the BioSentinel design uses these measurements to reconstruct true body rate about the Sun vector, which is nominally aligned with the spacecraft body *X* axis. This approach leverages the fact that in the absence of disturbances, system momentum (the sum of momentum stored in the body and the reaction wheel array) is conserved in both magnitude and direction in inertial space. To maintain Sun vector alignment while spinning about the Sun vector, the attitude loop applies *Y* and *Z* axis torques which tracks the movement of the reaction wheel momentum vector in the body frame. This provides a measurement of the rotation $\tilde{\omega}_x$ of the body frame relative to inertial space. $\tilde{\omega}_x$ can be calculated from reaction wheel momentum projected into the plane normal to the rotation vector[4] (*YZ* in the case of the target rotation vector being *X*), as shown in Equation (2) and Figure 4.

$$\widetilde{\omega}_x = \sin^{-1}\left(\frac{\|H_{yz}(t_k)\times H_{yz}(t_{k-n})\|}{\|H_{yz}(t_{k-n})\|\|H_{yz}(t_k)\|}\right)\frac{1}{\Delta t} \tag{2}$$

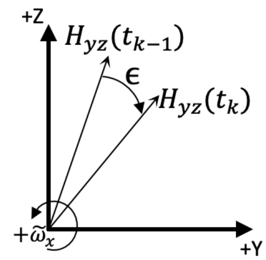

Figure 4. X-axis Rate from YZ Reaction Wheel Momentum Change.

Where H_{yz} is the reaction wheel momentum projected into the YZ plane, t_k is the current measurement, and t_{k-n} is the sample from *n* samples ago. The selection of *n* and Δt was a tuning exercise where longer times between samples allowed better resolution at lower rotation rates.

The estimated gyro bias, *b*, is then computed as:

$$b = \omega_{x,imu} - \widetilde{\omega}_x \tag{3}$$

Which is then filtered through a first order low pass filter with a cutoff frequency of .001 Hz, to produce the estimated gyro bias, $\tilde{b}$.

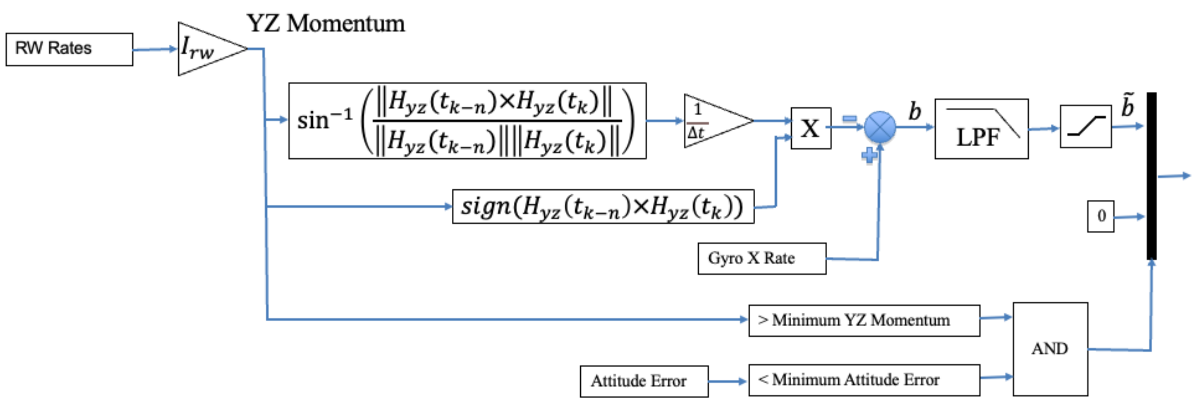

Figure 5. Bias Estimation Functional Block Diagram.

As shown in Figure 5, several conditions must be met for the estimated bias to be used, otherwise zero is output. The bias estimate is disabled until the attitude error with the target Sun vector drops below a fixed threshold, as the momentum in the reaction wheels does not track the inertial frame until the closed loop system has reached steady state. Additionally, the bias measurement becomes inaccurate as $\|H_{yz}\|$ approaches zero, and another safety is implemented to disable the bias estimation if the *YZ* momentum is below a threshold. As accurate bias estimation was critical for communication with the spacecraft in safe mode, when momentum is insufficient to perform the bias estimation, the propulsion system is used to autonomously add momentum to the YZ plane with a single thruster pulse.

Bias Estimation Flight Performance

After initial boot up, BioSentinel has only transitioned to safe mode eight times during the mission (with the vast majority occurring in the first few months), and the safe mode controller has worked as designed in each instance. In flight, the BioSentinel mission operations team checks that the Kalman filter bias estimates used in nominal pointing agree with the safe mode estimated bias estimate as part of the transition out of safe mode into nominal pointing. As the Kalman filter is nominally disabled in safe mode and only enabled during the transition, there is very little flight data with both bias estimation sources enabled. However, the flight software does compute an implied body rate from each subsequent star tracker measured quaternion onboard. This value, ω_{st}, was then used to compute an independent estimate of the gyro bias by:

$$ST\ Derived\ Bias = \omega_{st} - \omega_{imu} \tag{4}$$

Figure 6 shows a comparison of the star tracker derived bias (red dashed line, labeled ST Derived) and the safe mode estimated bias using the techniques described in the previous sections (blue line, labeled H_{rw}Derived). Note, the star tracker derived bias had a short windowed moving average filter applied to clean up some excessive noise spikes. This subset of data is consistent with the safe mode performance observed throughout the mission and shows that this bias estimation technique tracks the true gyro bias.

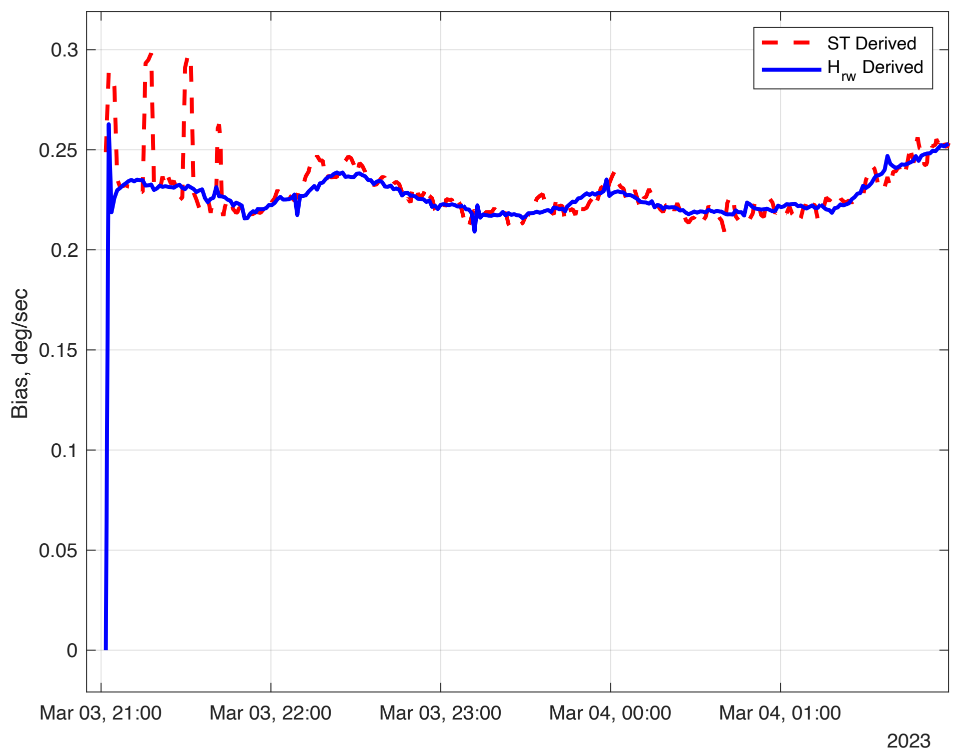

Figure 6. Bias Estimation In-Flight Performance.

PROPULSION SYSTEM

As a consequence of being a deep-space mission outside of Earth's magnetic field, BioSentinel cannot rely on the typical CubeSat combination of reaction wheels and magnetic torque rods for attitude control; instead requiring a propulsion system. This system was developed at the Georgia Institute of Technology, based on design heritage from the Bevo-2 and Prox-1 missions[5]. The requirements evolved during the design process, but ultimately the propulsion system was designed for three roles.

First was detumbling the spacecraft after initial deployment, as well as upon safe mode entry if system momentum is high. Artemis I provided relatively high maximum tip-off rates (10°/s each axis), and there was a potential for these rates to exceed the angular momentum capacity of the reaction wheels. The propulsion system was designed to reduce the body rates sufficiently to allow the wheels to capture the remaining angular momentum and begin nominal wheel control.

Second was the regular unloading of the reaction wheels, which slowly accumulate angular momentum from solar radiation pressure (SRP). When the propellant tank was sized, the spacecraft had an asymmetric arrangement of three solar panels, which resulted in a large offset between the center of radiation pressure and the center of mass. The spacecraft ultimately used a symmetric four-panel arrangement with a smaller SRP torque, which required less frequent momentum unloading. The flight propulsion system was already assembled when this change was made, so it was not redesigned, leading to a rather high propellant margin of 73%.

The final role was a small delta-V capability originally added to the propulsion system as a technology demonstration for future missions. However, after spacecraft delivery, the Artemis I launch schedule and trajectory now included a high possibility of lunar impact for the secondary payloads. The propellant margin was reallocated to provide up to ~4.2 m/s for a trajectory correction maneuver. Ultimately, BioSentinel's deployed trajectory was safely above the lunar surface, so this maneuver was not required, and the technology demonstration is currently planned at the end of the extended mission.

Design Approach

The most restrictive requirement on the propulsion system was its maximum volume envelope; the entire system including nozzles and driving electronics could only occupy a 4 cm thick section of the spacecraft's 1x2U face, for a total size extent of 4 x 10.6 x 20.9 cm. This volume was also shared with a ground support equipment connector, some structural elements, and two Sun sensors, leading to an oddly shaped volume not well suited for a pressure vessel. For this reason, the propulsion system was built around a single piece of 3D-printed composite that contained the propellant tanks, nozzles, and most of the fluid piping. The use of 3D printing allowed much more efficient use of the available volume via nonstandard tank geometry. Metal manifolds face-sealed to this printed structure provided interface points for valves and sensors.

Cold gas was selected due to the relatively low total impulse requirement. This also reduced the cost and complexity of the propulsion system (relative to a combustion system) as well as the risk it could pose to the primary payload, which was a significant consideration for Artemis I. R-236fa (1,1,1,3,3,3 hexafluoropropane) was chosen as the propellant primarily due to its high density and low storage pressure. A high-density propellant was necessary given the restrictive volume available for propellant storage.

Most of the propellant is stored in the "main tank" as a saturated liquid/vapor mixture due to the high density of that state. The propellant is expanded into a smaller vapor-only tank called the plenum, and from there is fed to the nozzles via the thruster valves. As the thrusters are fired, the plenum is depleted, and it must be periodically refilled from the main tank. This two-tank arrangement is designed to prevent liquid droplets from being ingested into the nozzles, which would make performance unpredictable. The plenum is kept in a vapor-only state by restricting its refills from the main tank to maintain pressure below the propellant's saturation pressure at the current plenum temperature. Figure 7 shows a schematic of the propellant tanks, valves, and nozzles.

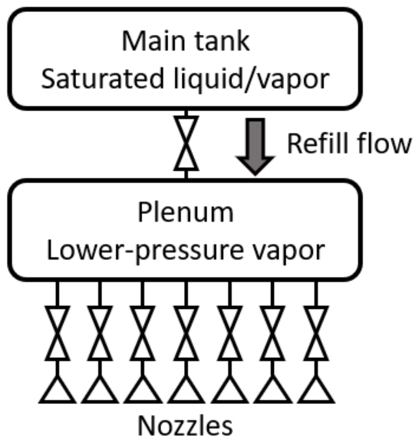

Figure 7. Schematic of Propellant Tanks, Valves, and Nozzles.

Seven thrusters are used to provide 3-axis attitude control as well as single axis delta-V. Figure 8 shows the flight propulsion system prior to integration, with five of the seven nozzles visible at the bottom of the image. The nozzle arrangement gives independent control of each rotation axis, but does not have full redundancy, so the loss of any one thruster would reduce the system to 2-axis control. This risk was understood and accepted during the design process, since sufficient volume was not available for full redundancy.

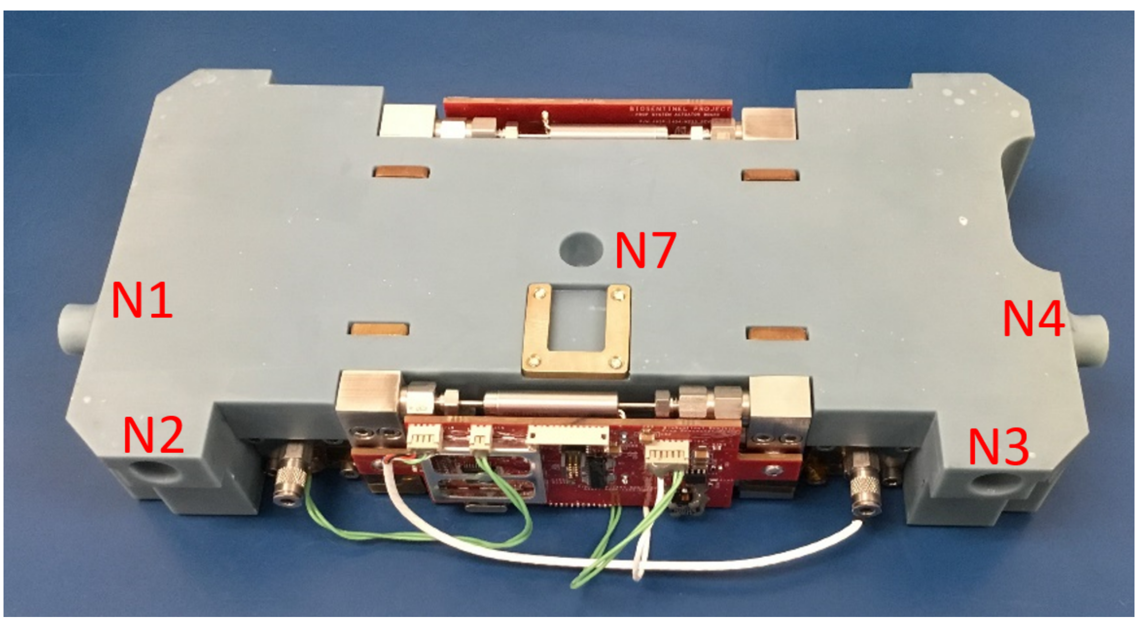

Figure 8. BioSentinel Propulsion System, Pre-Integration, with Five of Seven Nozzles Indicated. Light Blue/Gray Component is 3D-Printed Composite.

The propulsion system was tested to characterize leak rate, thrust, minimum impulse bit, and specific impulse[6]. Proof pressure testing, random vibration, and thermal vacuum testing were also conducted at the subsystem level to reduce the risk of encountering unexpected propulsion issues during full system testing. End-to-end detumble testing was also done at the system level to confirm that motion of the spacecraft resulted in firing of the appropriate thrusters. The use of nontoxic and nonflammable propellant allowed more extensive testing to be conducted at the system level with propellant loaded, making for more flight-like testing.

Propulsion System Performance

The propulsion system has been in operation in flight for over a year and has accomplished its role in detumbling the spacecraft and managing angular momentum accumulation throughout the mission. A total of 464 thruster pulses have been performed across 29 momentum unloadings, with a nominal cadence during routine operations of one unloading per 2-3 weeks. Thanks to the wave-off of the delta-V and the new momentum management scheme, such unloadings are far less frequent than originally planned, and only 12 grams (out of 200 grams) of propellant have been consumed, leaving a large amount of margin for extended mission operations and a delta-V demonstration. A few anomalies have occurred within the subsystem (described in following sections) but otherwise performance has been stable throughout the year of operation and in agreement with ground testing. There has been no indication of degradation of any functioning valve or of excessive filter loading. Torque estimation has allowed the propellant leak rate to be upper bounded at 200µg per hour, with no leaks detectable from ADCS or propulsion telemetry.

MISSION HIGHLIGHTS

To date, the spacecraft has completed the commissioning and nominal science phases and has entered an extended mission phase, traveling over 27 million kilometers from earth, collecting over 9,700 hours of radiation data, and operating for over a year in space. There were, however, several adventurous moments during the journey.

Deployment and Detumble

Although the BioSentinel team was able to promptly acquire signal on its first ground contact, initial telemetry from the spacecraft uncovered that the vehicle was tumbling rapidly after separation from the launch vehicle. The propulsion system should have executed a detumble maneuver in the first minutes of operation, but had not done so, and the high deployment rotation rate saturated the reaction wheels, leaving the ADCS subsystem unable to stabilize the attitude in a power positive direction. The spacecraft's batteries were depleting, and the off-Sun pointing was beginning to cause thermal issues as parts of the spacecraft were illuminated that were not intended to be. Fortunately, the extensive mission simulations conducted between spacecraft delivery and launch had discovered this anomaly possibility.

As discussed in the propulsion design section, to maintain plenum pressure, the plenum must be periodically refilled from the main tank. Two modes were developed for controlling this refill: a 'closed-loop' mode that refilled the plenum to a specified percentage of the main tank pressure, and a timer-based 'dead reckoning' mode in which refilling was performed at regular intervals, regardless of pressure data. Rapid bias drift and general unreliability of the pressure sensors during ground testing led to the decision to only use the timer-based mode. The closed-loop mode was abandoned and not included in further testing, so otherwise-important safety features were not added, such as a backup timeout. Although unplanned to use, this mode was left in the propulsion system software and still commandable.

During initial deployment and detumble, the propulsion system was configured to use the closed-loop refilling mode rather than the timer-based mode. Unfortunately, between delivery and launch the pressure sensors experienced significant bias drift, with the plenum pressure sensor biased low relative to the main tank sensor, which was the exact situation that could cause closed-loop filling to lock up. Meaning that the closed loop refilling mode attempted to refill the plenum continuously and ignored impulse commands until the spacecraft's automated fault management system exited the detumble mode.

This misconfiguration was only discovered after spacecraft delivery, too late to change flight software, but a response plan was developed and tested. Because this risk was well understood, anomaly investigation after the first contact was brief and conclusive. However, the MSPA scheme discussed above meant that BioSentinel was only slated for downlink and would not have had an uplink pass available before the batteries depleted. The NEAScout team, a sister payload on Artemis I, generously yielded some of their allotted command time despite anomalies of their own, allowing the BioSentinel team to send commands in the blind to reconfigure the propulsion system into the dead reckoning mode and restart the detumble. While the first command attempt was not received by the tumbling spacecraft, the second attempt was successful, reducing rates sufficiently to begin nominal attitude control.

Lunar Flyby

With the full range of possible trajectories not realized until the final months leading up to launch[7] (specifically the >50% possibility of lunar impact for many launch dates), some last-minute operation plans and procedures were generated to support an ad-hoc delta-V in the first days of the mission to avoid a lunar impact.

No specific mode had been designed into the system to support such an activity, thus attitude control during the delta-V would need to be accomplished with the reaction wheels, not with thrusters. The first issue to tackle in this endeavor was that the propulsion system plenum had to be consistently refilled throughout the maneuver. To impart maximum delta-V, analysis showed a 1:1 ratio of thrust to refill was necessary. The on-board command sequence would fire the delta-V thruster for one second, followed by refilling the plenum for one second, and repeat. Then, because a large thrust to center of mass offset was possible (and never measured since the maneuver was unplanned), it was expected that momentum would rapidly accumulate in the reaction wheels. Therefore, a consistent one revolution per three-minute rotation about the thrust vector would be commanded to even out this offset torque. Even with this rotation applied, analysis showed the spacecraft could accumulate momentum about the thrust vector and required pausing the maneuver to unload momentum after every full rotation to maintain margins.

There were a wide range of possible thrust vectors required depending on exact deployment details that would not be available in advance. Many of these required pointing the solar arrays away from the Sun, making the spacecraft power negative throughout the maneuver. However, the rotation about the thrust vector also had the effect of only pointing the LGA (with its hemispherical gain pattern) at Earth half of the time. Since telemetry would only be intermittently available anyway, the transmitter would be powered off while not Earth-pointed to conserve battery power. Thus, the battery supply was sufficient for a maximum maneuver duration of about 40 minutes, with roughly half this time dedicated to thrust and half to momentum unloading; if longer was necessary then the spacecraft would have to point towards the Sun to recharge for two hours before continuing.

With some conservative estimates, it was predicted the propulsion system could impart roughly 0.85 m/s of delta-V with each 40-minute maneuver. As fate would have it, after all this intricate planning, the deployment from the launch vehicle put BioSentinel on a nominal trajectory with no impact expected and only a 36-minute eclipse – well within the system's capability. The delta-V maneuver was waved off, with the capability slated to be tested during the extended mission after science data collection has completed.

Commissioning

The rest of spacecraft commissioning went relatively smoothly and completed a week ahead of schedule. The solar arrays deployed nominally, high and medium comm rates worked well, and the medium gain antenna pattern was as expected from ground testing. The ADCS subsystem checked out flawlessly, and the payload reported nominal state-of-health telemetry.

A couple of issues arose during this time that included a stuck closed thruster valve (detailed later) and an inability to lock onto the lowest data rate (resolved as a mismatch in parameter settings with the ground antenna). The most intrusive issues were several software bugs that led to the spacecraft rebooting itself a total of five times and culminated with an in-flight FSW patch[1].

The transition to science phase was kicked off on December 6, 2022, with the first of four biology experiments that would be run. Unfortunately, results were inconclusive, and the focus of the science mission shifted to the radiation detector. The radiation detector continues to record cumulative radiation dosage and has characterized several significant solar events with data being shared with both the bioscience and heliophysics communities[1].

Liquid Accumulation in Plenum

In the first weeks of the mission, some thruster firings were producing larger impulses than expected, a possible symptom of saturated liquid propellant in the plenum. The $+X$ face of the spacecraft where the propulsion system is located is always directed away from the Sun and is thus the coldest part of the spacecraft. The subsystem has roughly a 20°C thermal gradient along the X direction, warmer on its interior face adjacent to the comm system and coldest where it is exposed to space. To prevent liquid from condensing in the plenum, its pressure must be maintained below the saturation pressure of the coldest interior face, an issue complicated by the unreliable pressure sensors and lack of a temperature sensor in that precise location. Initially, the plenum was refilled too much and allowed liquid to condense on the cold face of the plenum. Liquid droplets were then sucked into the thruster feed lines during long firings.

Once discovered, unloading maneuvers were modified to use a larger number of shorter firings on the order of 50 milliseconds each, spaced at least 30 seconds apart. These shorter pulses do not allow enough time for liquid droplets to move from the cold face to the thruster valve inlets before the valve closes. However, the use of short, spaced-out pulses increases the time required to carry out an unloading maneuver. In total, these short pulses were used for six unloading maneuvers, at which point the plenum propellant had depleted enough that the liquid was no longer present. Refilling has since resumed at a lower cadence, maintaining the plenum pressure at a low enough level to prevent further accumulation.

A more reliable solution to this problem would be to heat the plenum sufficiently such that the coldest interior wall of the plenum is consistently hotter than the propellant temperature in the main tank. This prevents any condensation in the plenum regardless of how much refilling is done. A similar propulsion system developed for the Starling mission and launched in July 2023 uses this approach (a lesson learned from BioSentinel) and has not yet encountered issues with liquid accumulation.

Thruster 5 Failure

During the propulsion system checkout, the team determined the thruster 5 valve was stuck closed, delivering no detectable thrust. Review of the telemetry showed that the thruster was non-functional earlier during the successful detumble since a tumbling spacecraft does not need full 3-axis control simply to null its rates. Repeated attempts to actuate the valve were unsuccessful, despite nominal current and voltage readings, indicating a mechanical rather than an electrical failure. With some adjustments to the momentum management plan (described in the next section), the failure was judged to be non-mission-ending. However, the team decided that continuing to command the stuck valve was too risky. Depending on the failure mode, a mechanically stuck valve that is successfully actuated could become stuck open, a much more severe anomaly that would likely have ended the mission by making the propulsion system unusable. To avoid this, further attempts to free it have been delayed until the decommissioning phase.

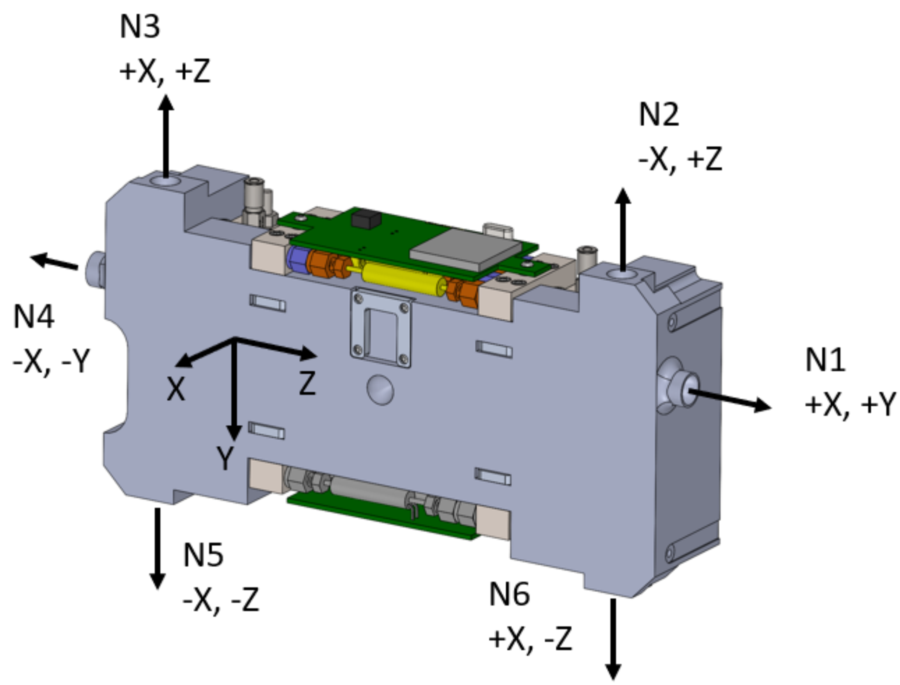

Figure 9. Nozzle Numbering, Spacecraft Body Axes, and resulting Torque Directions.

The loss of one thruster meant that the system could no longer deliver complete 3-axis control. Without valve 5, angular momentum could not be reduced about the body -X and -Z axes at the same time. Each could be individually reduced, but only by increasing the other, so if both axes had high positive momentum accumulated, it could not be unloaded. Thruster 5 (N5 in Figure 9) is the only way to reduce momentum about both the -X and -Z axis simultaneously, no other combination of thrusters can achieve this.

This thruster failure necessitated a change in the momentum management plan. The baseline plan was that the spacecraft would autonomously unload momentum whenever the magnitude exceeded a certain threshold. This approach relies on the ability to control momentum in all body axes, and with one thruster out, it was possible for it to encounter a situation where it would continuously attempt to command thruster 5 until it timed out – an undesired action as previously mentioned.

The team considered two approaches to address the issue. One was to command the spacecraft into an attitude in which the current momentum vector could be unloaded with the remaining thrusters (i.e. an attitude in which X and Z momentum are not both positive). However, this would likely have to be done out of ground contact since this attitude could not be guaranteed to be both a good comm attitude and a power-positive one. The second, and ultimately selected approach, was to modify the attitude of the spacecraft in between ground contacts to take advantage of the SRP and then manually command thrusters to desaturate the wheels while avoiding the failed valve.

This approach disables autonomous momentum management and requires operators to manually run the desaturation procedures approximately every 2-3 weeks. In a scenario where the spacecraft is out of contact with the ground for a longer period (such as a long government shutdown), angular momentum would continue to accumulate in the reaction wheels. Eventually, the system momentum would reach the threshold to trigger an autonomous transition to safe mode. At that point, reaction wheel control would cease, and the spacecraft would perform a detumble, just as it did after deployment. By its nature, detumble allows the spacecraft to rotate freely until momentum is reduced to a safe level, so even with one thruster out it can successfully complete by tumbling into an attitude where the failed thruster is not required. This is a non-ideal way of reducing momentum as it leaves the spacecraft in safe mode but is present as a backup.

Sun Pointing Attitude Adjustment

To address the thruster failure, two actions were added by the mission operations team. The first of which is to perform momentum desaturations via ground command to prevent the failed valve from being actuated and potentially damaging the seal. The second and more challenging action to solve the loss of full three-axis momentum control, is to command a biased attitude such that SRP induced momentum always accumulates in a way that can be unloaded with the remaining thrusters, taking advantage of the loose pointing requirements for the mission when not in communication with the ground.

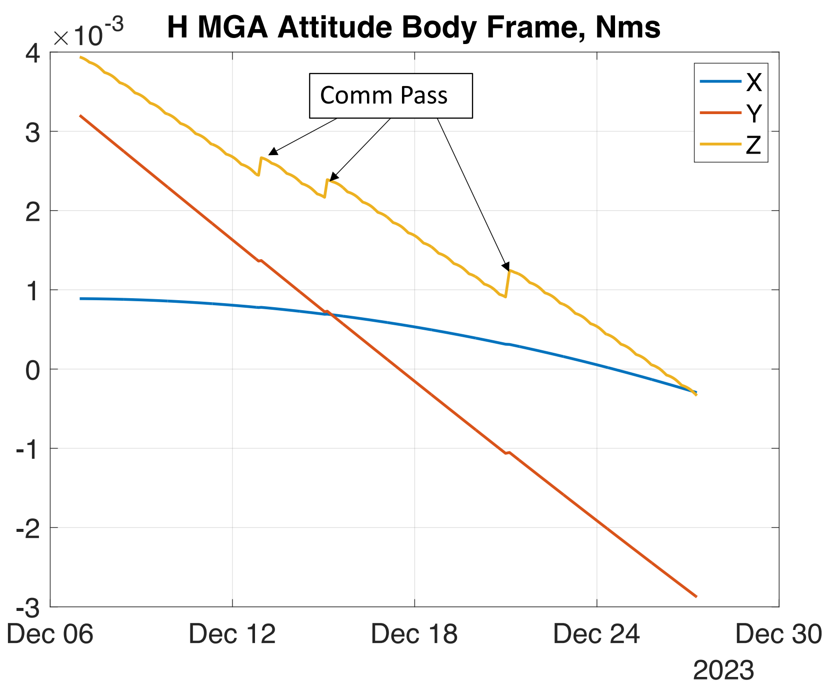

Figure 10. Momentum Accumulation with Attitude Bias.

When BioSentinel is operating nominally (not in safe mode) it orients the vehicle X axis towards the Sun to maximize power generation when not in contact with the ground. This attitude must simply keep the spacecraft power positive and thermal safe. These requirements are sufficiently flexible that the attitude can be adjusted slightly to apply a bias torque in the opposite polarity of the relatively strong +Z momentum accumulated when pointing the MGA toward the Earth during ground contacts. Figure 10 shows the effect of the Sun pointing attitude adjustment of just over 1°, resulting in negative torques being applied in all three axes. This approach allows momentum desaturations to always apply a positive torque in all three axes, which does not require use of the failed thruster. This attitude offset has been updated as higher fidelity torque models have been produced (see Momentum Prediction section), and as the cadence of communication passes has lowered. Ideally, the *Z*-axis momentum accumulated during communication passes would be completely negated while Sun-pointing, but in practice, the operations team has always erred on the side of keeping the *Z*-axis momentum negative to allow for variances in the communication passes due to Deep Space Network scheduling. Note, the *X* and *Y* momentum is mostly a parasitic result of having to accumulate a negative *Z* axis torque when Sun-pointing.

The coordinate frame used in Figure 10 is a quasi-inertial frame that is aligned with the spacecraft body axes during ground contacts. This frame was chosen for visualizing momentum accumulation since the propulsion system constraints are body-fixed, and momentum management occurs during ground contacts.

Momentum Prediction

The combination of using the solar radiation pressure as a torque actuator and the need to schedule ground commanded momentum desaturations drove the operations team to develop accurate momentum predictions with models of the solar radiation pressure torque at various Sun angles. Initial efforts to characterize the SRP torques began during the spacecraft's design phase to size actuators and budget propellent. This initial effort used spectral properties of the TDRS-05 spacecraft[8,9] and estimates (and later measurements) of the BioSentinel spacecraft inertial properties. Figure 11 shows how these pre-flight estimates (τ_{predict}) were very much in family with the model built up (τ_{observed}) from in-flight observations described below.

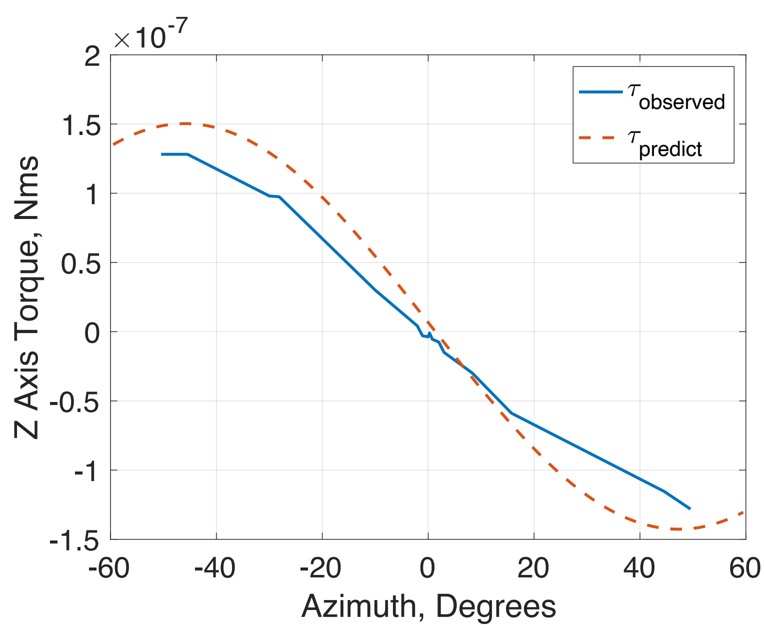

Figure 11. Pre-Flight and In-Flight Z Axis SRP Torques vs Sun Azimuth.

When referencing azimuth and elevation, azimuth is the angle about the *Z* axis of the Sun vector's projection into the *XY* plane, with 0° azimuth being defined as the *XY* axis projection being aligned with the -*X* axis. In operations, the Sun is always maintained in the *XY* plane, with no Z component and 0° elevation.

A dictionary was developed that mapped 3-axis torque to various Sun azimuth angles, with the *Z* axis value of that dictionary shown in Figure 11. This dictionary started with the predicted value and has been refined by integrating several months of flight data, with emphasis around the Sun pointing attitude at 0° azimuth. The Sun azimuth in the MGA Earth pointed attitude continues to change as the spacecraft gets further and further from Earth in its heliocentric orbit, allowing the team to continue to develop a higher fidelity lookup table of the SRP torques for the entire range of Sun angles. Performance of this tool is shown in Figure 12, with the predicted momentum growth (dotted lines) and measured momentum changes (circle for each data point) during a 12-day period in early December 2023. The tool is generally tasked with predicting momentum for a duration of about 14 days, the current cadence between propulsive momentum management maneuvers.

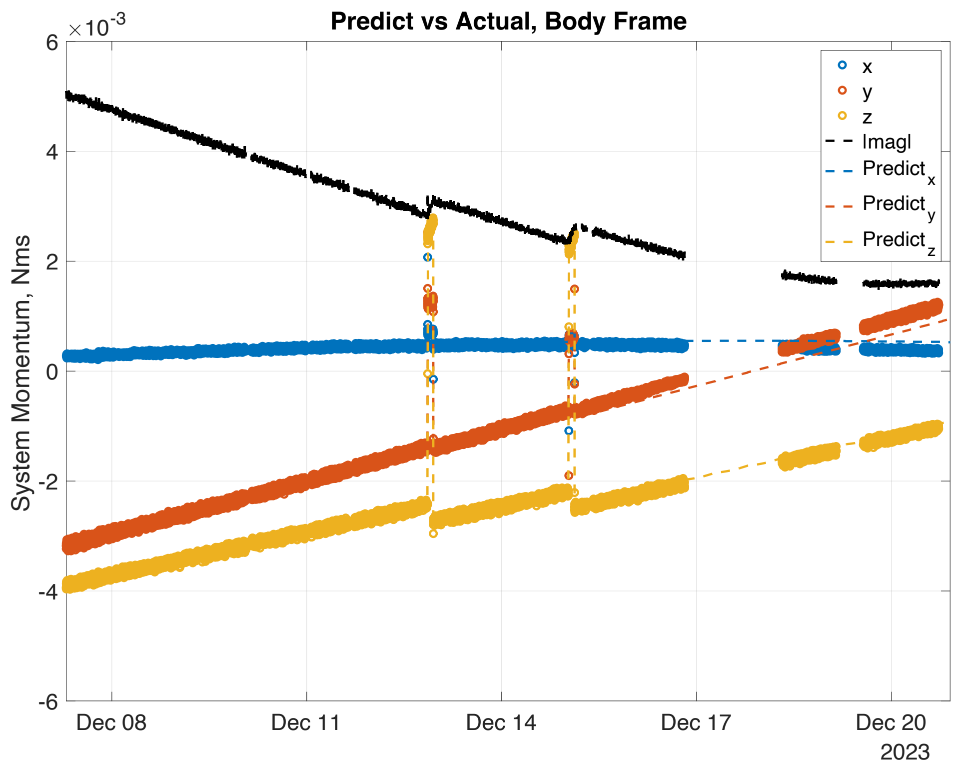

Figure 12. Performance of BioSentinel Momentum Prediction Tool.

Finally, an added benefit of being able to accurately predict momentum accumulation is the ability to preload momentum in the reaction wheels in the opposite direction, such that the momentum unloads for the first week before growing again the following week. Due to the minimum momentum constraints imposed by the safe mode bias estimation as described above, care must be taken to prevent momentum in the plane normal to the Sun from becoming too low over the course of the time between momentum management maneuvers.

Figure 13 illustrates the methodology used to prevent momentum from violating the safe mode bias estimation minimums, while still negatively preloading momentum. First, the tool described above generates $\vec{H}_{predict}$, which is then projected into the plane normal to the Sun. $\vec{H}_{preload}$ is then calculated as:

$$\vec{H}_{preload} = -k * \vec{H}_{predict} \tag{5}$$

Where k is a scalar usually set to about half of the reaction wheel momentum capacity. Two preload vectors are then computed that are normal to both $\vec{H}_{preload}$ and the Sun vector, $\hat{S}$.

$$\vec{H}_{sm,a} = \vec{H}_{preload} \times \hat{S} \tag{6}$$

$$\vec{H}_{sm,b} = \hat{S} \times \vec{H}_{preload} \tag{7}$$

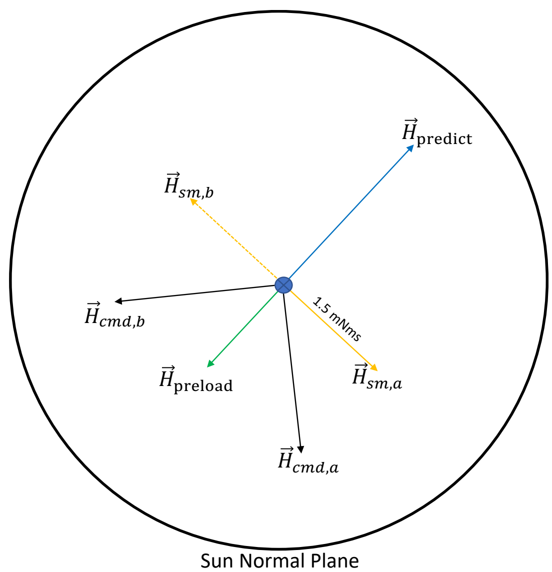

Figure 13. Momentum Preload Methodology.

$|\vec{H}_{sm,a}|$ and $|\vec{H}_{sm,b}|$ are scaled to a value (1.5mNms in this instance) that allows the safe mode bias estimation technique described above to function correctly in the event of an unexpected safe mode transition. The two candidate commands are then generated from the two $\vec{H}_{sm,a}$ and $\vec{H}_{sm,b}$ vectors as:

$$\vec{H}_{cmd,a} = \vec{H}_{sm,a} + \vec{H}_{preload} \tag{8}$$

$$\vec{H}_{cmd,b} = \vec{H}_{sm,b} + \vec{H}_{preload} \tag{9}$$

The two candidate commands are then reviewed, and the one requiring the least amount of momentum change, that is still achievable with the propulsion constraints, is selected. This preloading approach lengthens the time between momentum management maneuvers while ensuring that, if the spacecraft were to enter safe mode at any time between maneuvers, there would be sufficient momentum in the Sun-normal plane to allow gyro bias estimation.

CONCLUSION

The BioSentinel spacecraft and its radiation sensor have operated in deep space for over a year, collecting data on the interplanetary radiation environment. Since the completion of commissioning and the lunar flyby, spacecraft operations have become routine, with no major anomalies. The EPS has continued to operate without any errors, demonstrating the all-COTS design's success in deep space – a topic of great interest as the timeline continues into the extended mission. While there have been several flight processor resets, all of them have either been commanded or traced to root causes in flight software (i.e. no unexplained or radiation-driven resets), demonstrating the robustness of the design. Routine operations have also allowed for analysis of the nominal spacecraft performance. The extended processor "up" times even allowed for the discovery of a software counter rollover bug that only occurs every 106 days.

BioSentinel's novel approach to safe-mode gyro bias estimation was successfully employed and has been validated in-flight with star tracker measurements. This method has been used during the multiple safe mode periods throughout the mission and allows the spacecraft to precisely halt rotation to facilitate safe mode recovery. The miniature attitude control propulsion system has experienced anomalies but continues to serve the mission well as it unloads reaction wheel momentum to maintain attitude control. The propulsion system refilling has been tuned to eliminate liquid condensation in the plenum and momentum accumulation has been minimized by offsetting the Sun-pointing attitude to counter accumulation during Earth pointed comm sessions.

The radio transmitter has been determined to have an upper maximum of 2-3 hours on-time before reaching the thermal limit, depending on distance from the Sun and other on-board activities. As the distance from Earth slowly increases (over 27 million km and growing), the link margins have been continuing to decrease. It is expected that in the coming months, operators will be forced to decrease data rates and limit the amount of data downlinked during each DSN contact. These are two examples of issues that any CubeSat will face traveling away from Earth with the power and thermal limitations inherent to a small form factor.

The proud BioSentinel team and spacecraft seem to have overcome all anomalies as the successful CubeSat forges its path away from Earth.

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We extend a special thanks to the NEAScout team, a sister payload aboard Artemis I, for giving us the opportunity to save our mission by selflessly sharing their DSN allocation with BioSentinel during a critical period on mission-day 1.

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