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On the Development of Spacecraft Operating Modes for a Deep Space CubeSat

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In contrast to technology demonstration missions, very small spacecraft (also known as CubeSats) conducting a science experiment often require multiple carefully designed operating modes. These modes are typically driven by power and communications budgets, and by the specific requirements of the science payload itself. The design constraints levied on these operating modes become more stringent for CubeSats operating beyond low Earth orbit, as all of the attendant subsystem budgets become stretched even further. This paper will discuss the design of the operating modes for the BioSentinel spacecraft, a six cube CubeSat that will be deployed into an Earth-leading, heliocentric orbit after tip-off from the Space Launch System. The nature of the science payload, combined with the challenging subsystem constraints that are typical of CubeSats, necessitates the design of multiple distinct spacecraft operating modes to ensure mission success.

I. Introduction

Since their inception in the early 2000s, the vast majority of CubeSat missions have been fairly simple, either demonstrating specific technologies or performing straightforward tasks such as taking a single picture. However, as the community of CubeSat developers has grown and the underlying enabling technologies have matured, these very small spacecraft have seen a drastic increase in capability. Attendant with this growth in capability has been a growth in the complexity of the operating modes necessary to ensure mission success. The stringent power and communications budgets associated with spacecraft adhering to the CubeSat standard leads to many operational challenges that larger spacecraft are not concerned with, such as the need to duty cycle radios or GPS units to stay power-positive.[1] These challenges are amplified when operating beyond low Earth orbit (LEO), where operations and communications becomes even more difficult. This paper will describe the development of the operating modes for the six cube (6U) BioSentinel spacecraft, currently under development at NASA Ames Research Center. BioSentinel will operate in an Earth-leading, heliocentric orbit, and will conduct the first biological experiment beyond LEO since the Apollo era. The combination of an advanced science payload, a full suite of standard spacecraft subsystems, and the requirement to function beyond LEO makes BioSentinel the most complex CubeSat NASA Ames has built to date, and this complexity is reflected in the nature of the operating modes.

For the purposes of this work, a CubeSat (also known as a nanosatellite) will refer to any spacecraft that weighs 14 kg or less. These spacecraft adhere to the CubeSat standard,[2] whereby a 10 cm × 10 cm × 10 cm cube comprises one unit of volume, abbreviated as 1U. Traditional CubeSats are restricted to being no more than 3U in total volume, with an overall size of 10 cm × 10 cm × 30 cm. This volume constraint allows the spacecraft to be compatible with the various deployment mechanisms that are available, such as the Cal Poly P-POD[3] or the UTIAS/SFL X-POD.[4] NASA Ames has a rich history of building 3U CubeSats to research topics in fundamental space biology, such as the GeneSat-1, O/OREOS, and PharmaSat spacecraft.[5] More recently, NASA Ames developed a fleet of eight 1.5U CubeSats for the Edison Demonstration of SmallSat Networks (EDSN) mission, which will demonstrate multi-point science operations in LEO.[1]

BioSentinel is unique among NASA Ames CubeSat missions in that it will be the first actively controlled 6U spacecraft designed to operate beyond LEO. BioSentinel will launch as a secondary payload on the first

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flight of the Space Launch System (SLS), currently scheduled to occur sometime in 2018. During this first test of SLS the rocket will place the Orion Multi-Purpose Crew Vehicle on a trans-lunar injection trajectory, and then will perform a divert maneuver. Following the divert maneuver BioSentinel will be ejected from its dispenser into an Earth-leading, heliocentric orbit. The science objective of BioSentinel is to study the impact of the deep space radiation environment on genetically modified yeast cells, building upon past NASA Ames space biology missions such as PharmaSat. While the science payload itself does not impose stringent attitude pointing requirements, it will be necessary to detumble the spacecraft after tip-off and to point a patch antenna back towards the Earth. These attitude control operations, combined with the thermal requirements that are imposed in order to protect the biological payload, give rise to the unique requirements for the spacecraft operating modes.

The remainder of this paper is organized as follows. First, the BioSentinel mission will be described in greater detail in Section II, and the basic operating requirements of the spacecraft will be summarized. Additional design details about the spacecraft, with an emphasis on the attitude determination and control system, will be presented in Section III. Next, the speific operating modes that arise from the mission requirements will be outlined in Section IV. A discussion of these operating modes will be given in Section V, and then the paper will offer some concluding remarks in Section VI.

II. The BioSentinel Mission

The objective of the BioSentinel mission is to assist in mitigating risks to humans during future long-term space exploration missions beyond LEO. This will be achieved by studying the impact of the deep space radiation environment on genetically modified yeast cells. Specifically, BioSentinel will utilize the monocellular eukaryotic organism *Saccharomyces cerevisiae* (yeast) to report DNA double-strand-break (DSB) events that result from ambient space radiation. Yeast was selected due to its similarity to cells in higher organisms, the well-established history of strains engineered to measure DSB repair, and the spaceflight heritage from past NASA Ames missions. DSB repair is strikingly similar at the protein level from yeast to humans, and BioSentinel will provide critical information about what impact deep space radiation may have on future manned missions. BioSentinel will also include physical radiation sensors based on the TimePix sensor, as implemented by the RadWorks group at NASA's Johnson Space Center. This sensor records individual radiation events, including estimates of linear energy transfer (LET) values. Radiation dose and LET data will be compared directly to the rate of DSB-and-repair events as indicated by *S. cerevisiae* cell population numbers.

The yeast cells are dehydrated prior to launch, and then are rehydrated and kept alive in deep space using a microfluidics system and heaters. The payload container itself is maintained at 1 atm pressure throughout the mission life, and the overall size of the science payload is approximately 4U (10cm x 20cm x 20cm). The reaction of the yeast cells to the deep space radiation environment is monitored using optical measurements inside the payload container. The yeast is cultured in multiple independent culture microwells, which are built into a 96 well plate, depicted in Figure 1 below. Optical measurements are performed using LEDs shining through the culture wells, allowing for measurement of DSB-triggered cell growth and metabolism. It is noteworthy that unlike many deep space missions, there are no specific pointing requirements levied on the spacecraft by the science payload. This experiment simply requires access to the deep space environment, as opposed to being pointed in a specific direction to take measurements.

All spacecraft bus subsystems, including command and data handling (C&DH), communications, attitude determination and control, and power management must occupy no more than 2U of volume in order to conform to the volume restrictions of the spacecraft dispenser. As can be seen in Figure 2, these subsystems occupy the "rear" portion of the spacecraft, including a thruster subsystem placed in a small 10cm x 20cm x 3cm volume on the rear end cap. A thin slice of volume on the front of the spacecraft is allocated for sun sensors and for the gimbal for the deployable solar arrays. The nature of the Earth-leading, heliocentric orbit that BioSentinel will occupy is such that for the majority of the mission it will be necessary to slew the spacecraft up to 90 degrees in order to establish a communications link with the Deep Space Network (DSN). This slew maneuver will be undertaken using a suite of three reaction wheels integrated within the spacecraft. These reaction wheels will also have to account for the effects of a solar radiation pressure torque, and current estimates are that the wheels will saturate approximately every three days. Furthermore, early estimates for the tip-off conditions from SLS indicate that the reaction wheels may also saturate during detumble. Given the deep space operating environment, both spacecraft detumble and reaction wheel momentum

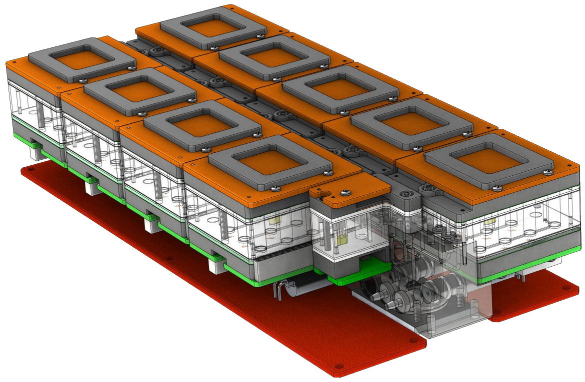

Figure 1 – Artist's depiction of the BioSentinel science experiment payload, in which colonies of yeast cells must be kept alive in deep space.

management over the 12 month nominal operating life must be accomplished using a thruster system, as opposed to magnetic torque rods.

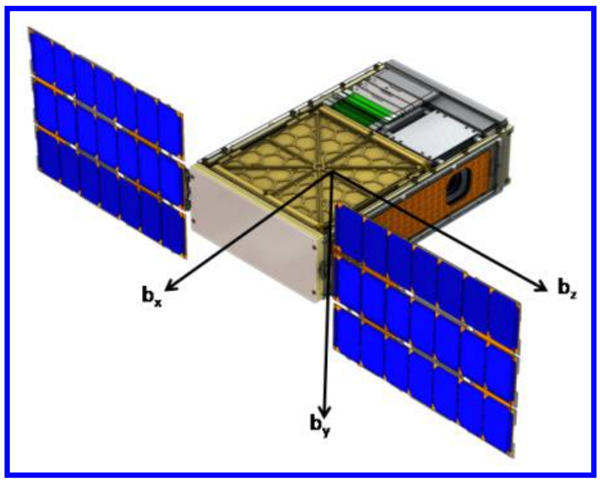

Figure 2 – Artist's depiction of the BioSentinel spacecraft, shown with solar panels deployed and one side panel removed.

III. Spacecraft Design Details

Due to the fact that the biological payload does not need the spacecraft to be in any specific orientation, the pointing requirements levied upon the spacecraft are quite loose. The ADCS must keep the solar panels oriented towards the sun and periodically point the medium gain antenna (MGA) at the Earth. Both of these activities require no better than 5 degrees of pointing accuracy. However, coarse attitude determination methods employed in LEO that leverage a magnetic field or Earth vector measurement cannot be used in this environment; a star tracker is necessary for 3-axis attitude determination. BioSentinel will also utilize sun sensors for attitude determination when the star tracker is not enabled and a gyro for rate information. For control, the spacecraft has 3 mutually orthogonal reaction wheels and 6 thrusters. The wheels will control the attitude of the spacecraft while the thrusters will be responsible for removing momentum from the system. To tie together the various sensors and actuators on BioSentinel, NASA Ames software will process and filter the sensor data and commanded control inputs to the actuators. A diagram of all of the elements of the BioSentinel ADCS is depicted in Figure 3.

Prior to designing the different operating modes, it is necessary to define the three reference frames applied to mission: the inertial frame, an orbit frame, and the body frame. The inertial frame is centered at the barycenter of the solar system and defined at the J2000 epoch. The orbit frame resembles a local-vertical, local-horizontal frame normally applied to an Earth orbit. The unit vector representation of the

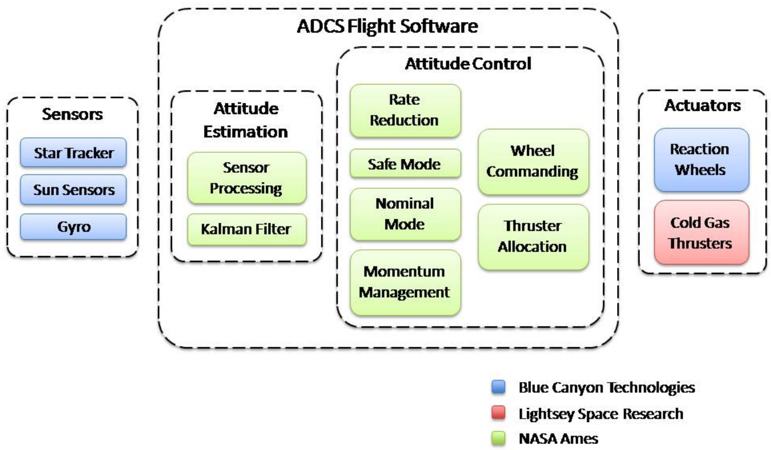

Figure 3 – A block diagram representation of the attitude determination and control subsystem for the BioSentinel spacecraft.

vector from the origin of the inertial frame to the spacecraft ($\bar{r}$) is the X-axis of the orbit frame; the cross product between the X-axis and the velocity ($\bar{V}$) direction becomes the Z-axis; and the Y-axis completes the right-handed coordinate system. A brief derivation of the orbit frame is given below as:

$$\hat{i} = \frac{\bar{r}}{\|\bar{r}\|} \tag{1}$$

$$\hat{k} = \frac{\bar{r} \times \bar{V}}{\|\bar{r} \times \bar{V}\|} \tag{2}$$

$$\hat{j} = \hat{k} \times \hat{i} \tag{3}$$

Using the above definitions of the orbit frame unit vectors, one can construct the rotation matrix ${}^{I}R^{O}$ from the orbit frame to the inertial frame as

$${}^{I}R^{O} = \begin{bmatrix} \hat{i}_x & \hat{j}_x & \hat{k}_x \\ \hat{i}_y & \hat{j}_y & \hat{k}_y \\ \hat{i}_z & \hat{j}_z & \hat{k}_z \end{bmatrix} \tag{4}$$

Finally, the body frame is fixed to the spacecraft such that the nominal sun pointing axis is the body X-axis (as shown in Figure 2). For the following analyses, it is assumed that the body axes coincide with the spacecraft principal axes. A sketch of the relationship between the orbit frame and the inertial frame can be seen in Figure 4.

IV. Spacecraft Operating Modes

The remainder of this paper will focus on two main operating modes: a nominal operating mode and safe mode. At the beginning of the mission, after tip-off from SLS, the ADCS will first need to drive the spacecraft from an unknown initial angular velocity to below a pre-determined threshold. A conservative estimate for the initial tip-off rate from the launch vehicle is 10 deg/sec, which generates enough momentum to saturate the reaction wheels. Therefore, the ADCS will utilize the onboard thrusters to remove body rates below a given threshold that will serve as a thruster deadband to avoid chatter. After detumbling the spacecraft, the ADCS will then move into nominal mode, which includes science operations and communication with the Earth. If necessary, the ADCS will also transition into a safe operating mode, which is designed to protect the spacecraft while ensuring a communication link with Earth can be established.

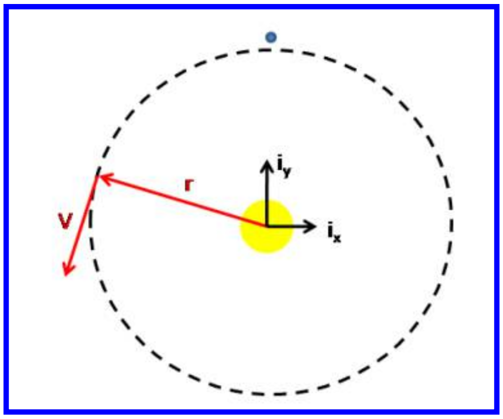

Figure 4 – The Orbit frame is designed as a function of the position vector from BioSentinel to the sun $\bar{r}$ and the spacecraft velocity vector $\bar{V}$.

IV.A. Nominal Mode

The ADCS nominal mode consists of keeping the solar panels pointed at the sun and slewing the spacecraft so that the MGA points towards Earth during ground communication. These two activities pose relatively loose pointing requirements; attitude control in nominal mode must be capable of maintaining the spacecraft attitude within ± 5 degrees of the desired pointing vector. Although the pointing requirement is lenient, the ADCS will leverage an extended Kalman filter to estimate gyro bias and incorporate the sun sensor inputs into the attitude solution for instances when the star tracker input becomes invalid. Simulation results from the six-state multiplicative extended Kalman filter (MEKF) are shown in Figures 5 and 6. Note that between 15 and 25 minutes into the simulation there is a simulated star tracker anomaly in which the star tracker input becomes unavailable.

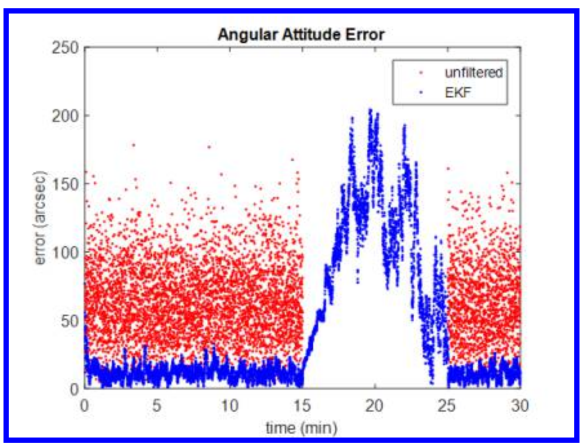

Figure 5 – Attitude knowledge error as a function of time for the six-state MEKF, including a simulated star tracker anomaly.

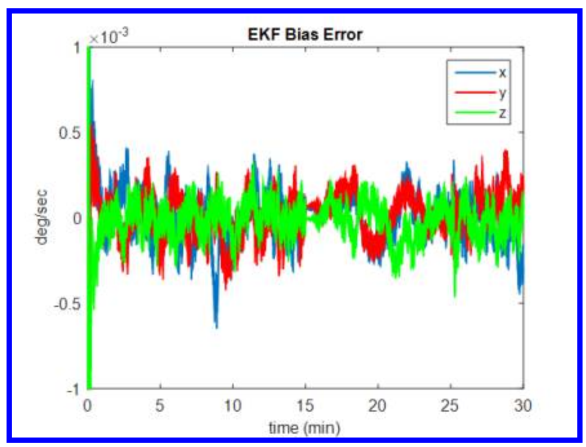

Figure 6 – Gyro bias estimate as a function of time for the six-state MEKF used on BioSentinel.

When the spacecraft is not communicating with the ground, it will align the body frame with the orbit frame. This attitude orients the smallest spacecraft face towards the sun to minimize thermal impact. Alignment with the orbit frame corresponds to a zero gimbal angle on the solar arrays and places the MGA boresight in the orbit plane and normal to the sun vector. During a communications activity, the ADCS will slew about the spacecraft Z-axis and point the MGA towards Earth while simultaneously gimbaling the solar arrays to stay facing the sun. The solar arrays cannot leave their sun pointing orientation during communications because a typical communication pass will last up to four hours. This pointing strategy is illustrated in Figure 7.

The controller used to achieve the pointing strategy described above is a simple proportional-derivative, quaternion feedback control law, as suggested in Reference 6. The gains are tuned in a linear model to

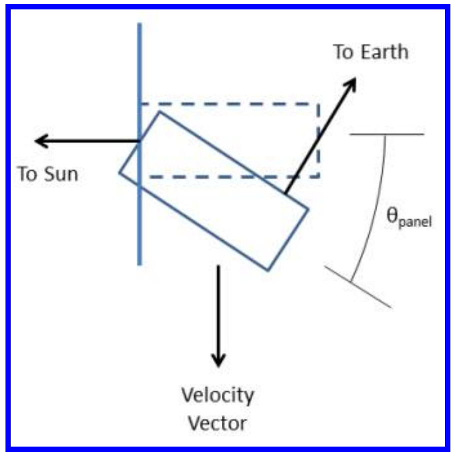

Figure 7 – Geometry of the nominal operating mode used by the BioSentinel spacecraft.

achieve a bandwidth sufficiently lower than the first structural mode and to ensure adequate gain and phase margins. Figure 8 demonstrates a simulated maneuver that points the MGA towards Earth.

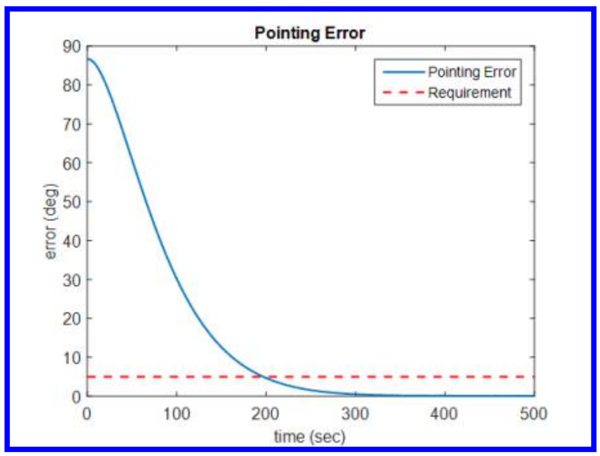

Figure 8 – Pointing error as a function of time for a pointing manuever undertaken during nominal spacecraft operations.

Alignment with the orbit frame will minimize the nominal offset between spacecraft center of mass and center of pressure, thus minimizing the effect of solar torque and thus momentum accumulation. However, the long duration of the communications passes will enlarge this offset and allow for a more rapid accumulation of momentum. The ADCS will autonomously make use of the cold gas thruster to manage momentum when the wheels exceed a given threshold. The reaction wheels will maintain the spacecraft attitude while the thrusters provide the external torque to unload the wheels. The ADCS will feed wheel momentum data to a proportional-integral controller to determine the necessary external torque for momentum management. Once the torque is computed, a thruster allocation algorithm will solve for the optimal combination of thruster outputs to achieve the commanded torque. The momentum management controller is disabled once the reaction wheel speeds have reduced below a certain threshold. During momentum management thruster firings the reaction wheels will still be used to maintain the orientation of the spacecraft. A different gain set is required to accomodate the increased external disturbance from the thrusters. Simulated results for reaction wheel momentum being reduced and the attendant pointing error can be seen in Figures 9 and 10 below. Note that the pointing error briefly exceeds the 5 degree pointing requirement during this simulation. This is acceptable because momentum management never occurs during communications with the Earth, which is the motivation for the pointing requirement.

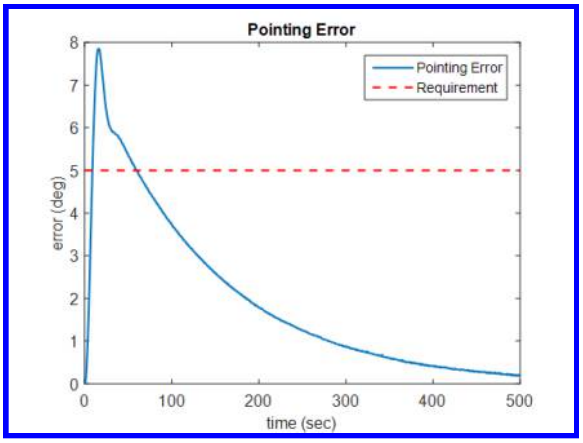

Figure 9 – Pointing error resulting from a momentum dump operation during nominal mode.

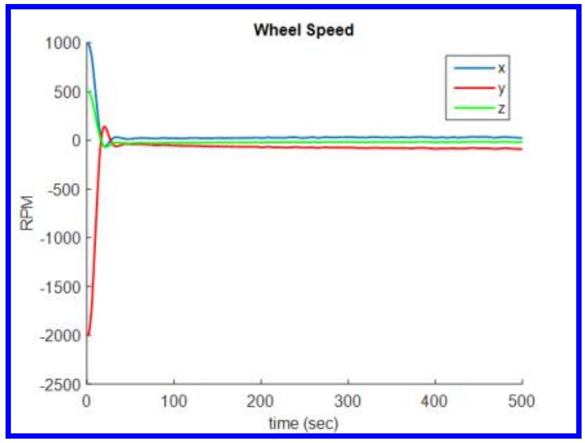

Figure 10 – Wheel speed as a function of time during a momentum dump operation.

IV.B. Safe Mode

Following anomalous events, the BioSentinel Fault Protection System will command the ADCS to enter safe mode. The goals of safe mode control include the following: staying power positive, ensuring communication with the ground, and preventing momentum accumulation. Due to the frequency of star tracker anomalies encountered on-orbit during previous missions,[7] the spacecraft safe mode must accomplish the safe mode goals without star tracker input. Absence of a star tracker attitude (with no prior three-axis attitude information) means that the only pieces of attitude state information the spacecraft will have are the sun vector and gyro measurements, which will be uncompensated for in terms of bias. Using this limited attitude knowledge, a safe mode configuration has been developed that makes use of the general orbit geometry and sun vector knowledge to infer the possible area on the attitude sphere in which the Earth resides.

Given that ground communication without relying on a star tracker is a main tenant of BioSentinel's safe mode, the spacecraft must be able orient the antenna towards Earth with only sun information. Obviously, Earth vector knowledge cannot be obtained from only sun vector information, but given the geometry of the orbit and the wide field of view of the spacecraft antenna, partial Earth position knowledge can be garnered and a communications link established. Figure 11 shows the angle between the sun vector and the Earth vector throughout the lifetime of the mission (an angle of 180 degrees corresponds to a configuration where BioSentinel is directly between the Earth and the sun). Current analysis shows that this angle never drops below approximately 80 degrees. As an additional point of reference, the orbit of the BioSentinel spaecraft is compared to that of the Earth after 550 days in orbit in Figure 12.

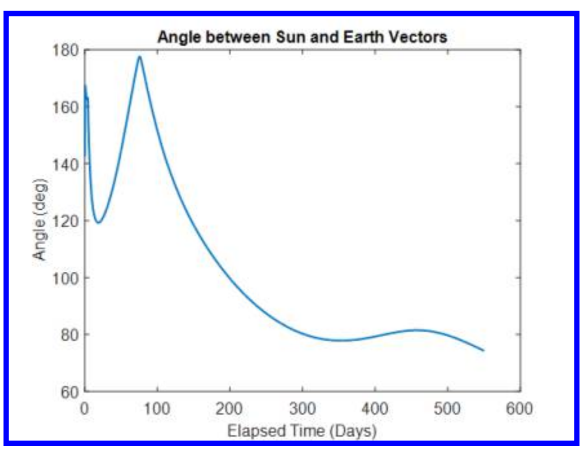

Figure 11 – Angle between the Earth and the Sun relative to the BioSentinel spacecraft over the life of the mission.

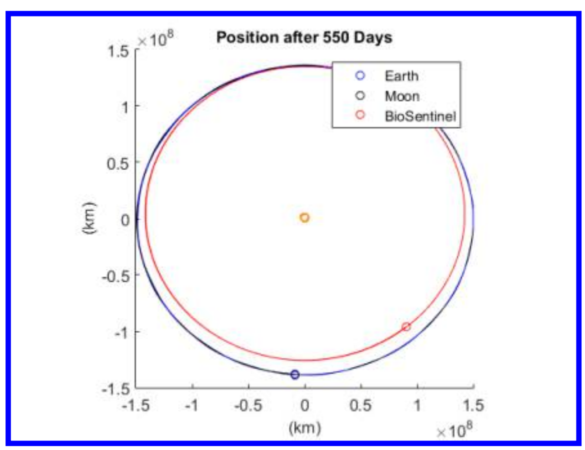

Figure 12 – BioSentinel orbit as compared to that of the Earth after 550 days of operation.

If the spacecraft has sun vector information, then the Earth must lie in a region denoted as the "Earth region" in the illustration in Figure 13. The safe mode pointing strategy consists of canting the spacecraft such that the MGA field of view (FOV) is oriented as shown in Figure 13, followed by a slow spin about the sun vector. This spin rotates the FOV of the MGA through the entire region of possible Earth locations, thus ensuring an opportunity for communication with the ground.

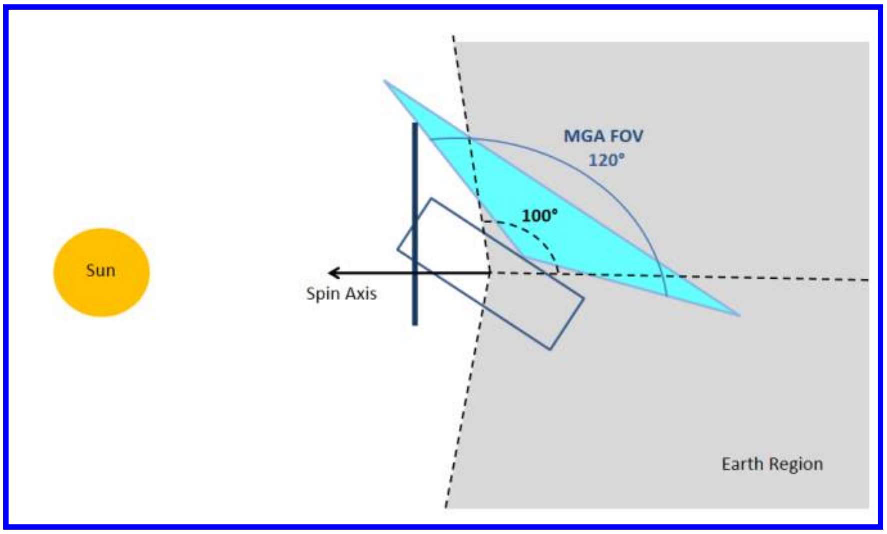

Figure 13 – Geometry of the BioSentinel safe mode.

In order to obtain the spinning safe mode described above, BioSentinel employs a two-axis controller that aligns the desired body axis with the sun and rotates the spacecraft at a given rate about this axis. The linear control law is given by:

$$\tau = k_P(\hat{s}_{est} \times \hat{s}_{com}) + k_D(\bar{\omega}_{est} - \bar{\omega}_{com}) \tag{5}$$

where the first term represents the error between the estimated and commanded sun vectors, $\hat{s}_{est}$ and $\hat{s}_{com}$, respectively. The second error term is the difference between the estimated spacecraft angular velocity $\bar{\omega}_{est}$ and the commanded spacecraft angular velocity $\bar{\omega}_{com}$. Note that k_P and k_D are user-tunable control gains. An example of pointing error and wheel speed during safe mode operations can be seen in Figures 14 and 15 below.

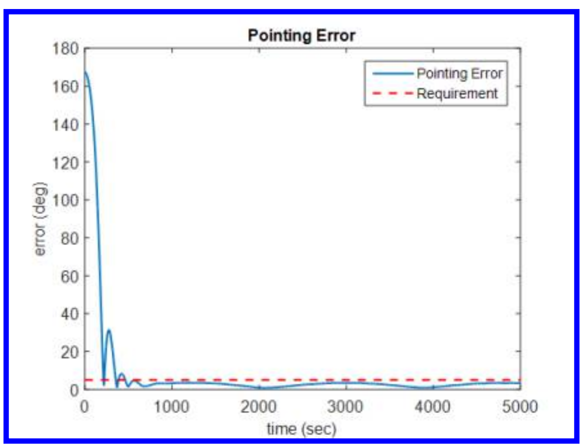

Figure 14 – Pointing error as a function of time using the safe mode controller.

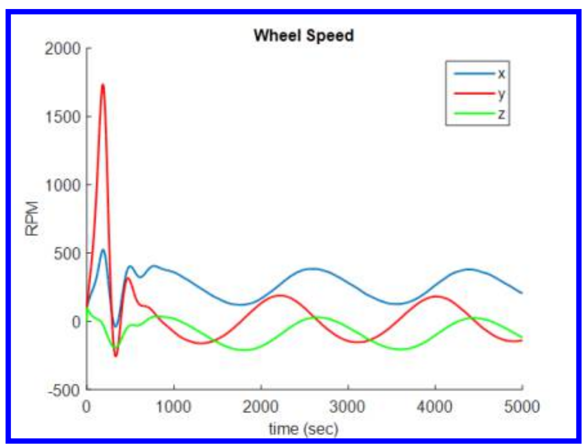

Figure 15 – Wheel speed as a function of time using the safe mode controller.

As can be seen above, since the spacecraft is spinning about the sun vector and solar torque is the only disturbance, the spin rates on each wheel fluctuate within certain bounds and the spacecraft momentum does not increase. The spinning nature of safe mode that allows for ground communication with only sun information also mitigates the accumulation of momentum.

To examine the robustness of the safe mode control scheme to uncertainties in the system, a Monte Carlo analysis was performed in which certain parameters were varied according to assumed statistical distributions. For this particular Monte Carlo, uncertainty was introduced to three categories of parameters: the physical characteristics of the system including moments of inertia, solar panel bending modes, and cold gas fuel slosh modes; sensor and actuator errors such as misalignments, biases, and scale factors; and initial conditions of the simulation such as initial attitude and body rates. Each Monte Carlo case is carried out until either the spacecraft reaches a steady state attitude or a maximum elapsed simulation time is reached. Results of the Monte Carlo study are plotted in Figure 16. Note that all of the 1000 cases converge to an error that is within the 5 degree safe mode pointing requirement. In the future, it will be important to perform a sensitivity analysis for each of the aforementioned parameters. Preliminary results indicate that gyro bias represents the largest sensitivity, due largely to the fact that in safe mode the bias can't be estimated. As a result, the controller has to accomodate for this error. As the derivative gain increases, the impact of this bias becomes greater.

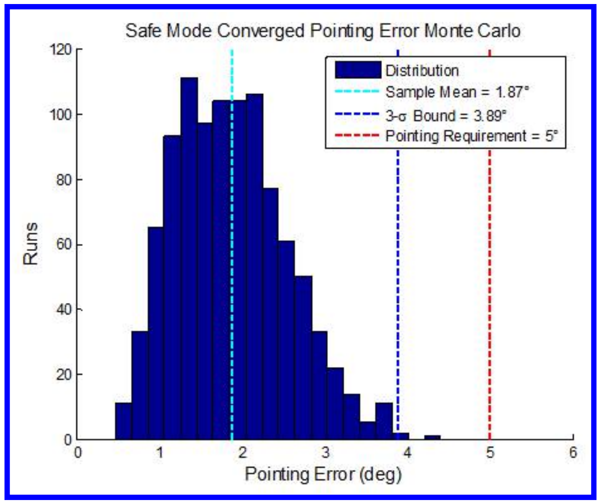

Figure 16 – Results from the Monte Carlo analysis carried out to study the robustness of the safe mode controller used for the BioSentinel mission.

V. Discussion

Given the complexity of the operating modes described above, it is worth revisting Figure 3, which provides a block diagram representation of the major elements of the BioSentinel ADCS. As called out in the legend in the bottom-right corner of this diagram, there are three different contributors to the BioSentinel ADCS: Blue Canyon Technologies of Boulder, Colorado, Lightsey Space Research of Atlanta, Georgia, and NASA Ames. While these vendors (and many other CubeSat ADCS vendors) offer complete ADCS or GNC solutions, the BioSentinel team felt that it was necessary for NASA Ames to be the final aggregator of all the software elements associated with the ADCS. The safe mode is clearly not typical to the LEO enviroment for which the vast majority of CubeSat ADCS systems are designed, and there has also not yet been an on-orbit demonstration of CubeSat-class ADCS elements interacting with a 3 degrees-of-freedom (DOF) cold gas system. The combination of sensors and acutators, along with the required operating modes, are unique among CubeSats, and for that reason it was decided that a combination of commerical elements and custom-made software was the best approach for the system.

While it does not strictly fall within the scope of this paper, it is worth noting that additional system efficiency will be achieved through the use of an optimized thruster allocation strategy.[8] Using this strategy, the optimal combination of thrusters is selected for each commanded control torque in a manner that minimizes the amount of propellant consumed. This is important because multiple pairs of thrusters are capable of effecting control about multiple axes of the spacecraft, and the minimum 12 month mission duration means it will be important to conserve fuel wherever possible. This allocation strategy will be applied throughout nominal operations, including detumble after tip-off from SLS. Note that momentum management will not be carried out during safe mode, as the primary goal of this operating mode is to ensure that communication with Earth is established while minimizing power consumption.

A unique feature of the BioSentinel spacecraft is that, unlike traditional CubeSats, the ADCS in general is not subject to single point failures. The combination of a 3-DOF thruster system and three mutually orthogonal reaction wheels means that even if one reaction wheel or one set of thrusters were to fail the spacecraft would still have full control authority. Similarly, the fairly loose pointing requirements for the mission mean that even when operating in safe mode it is still possible for the spacecraft to achieve its top level requirements: carry out the Double-Strand Break science experiment in a deep space environment, and transmit the results of that experiment back to ground controllers on Earth. Early on in the mission design process the team investigated orienting the spacecraft such that the solar radiation pressure acting on the solar panels would serve as a mechanism to remove momentum from the system. This approach is currently being used on-orbit by the Kepler mission following multiple reaction wheel failures.[9] The thruster system currently manifested for BioSentinel is one of the lower TRL components on the spacecraft, and in the event of a system-level failure of the thrusters it would be possible to dump reaction wheel momentum by periodically flipping the orientation of the spacecraft with respect to the sun line by 180 degrees. As a result of all of these factors, the BioSentinel design team is reasonably confident that the spacecraft will be robust to numerous failure modes on orbit.

VI. Conclusion

The BioSentinel mission represents an important step forward for scientific CubeSats, pushing the boundaries not only of the level of science being undertaken within the spacecraft but also in the complexity of the spacecraft bus subsystems. The demands of the operational concept for a deep space CubeSat necessitate a combination of traditional spacecraft operations (such as detumble) with more novel operational approaches, such as the safe mode described herein. The extreme power and mass budgets levied on this mission further complicate the operational approach. It is noteworthy that many of the results presented in this paper use realistic models of the sensors and actuators that have been baselined for BioSentinel, providing a higher degree of confidence in the simulation results. Further work will include additional refinement of flexible modes induced on the system from deployable solar panels and fuel slosh, and increased optimization of the thruster allocation algorithm used during detumble and momentum management.

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