Solar Sail Attitude Control System for the NASA Near Earth Asteroid Scout Mission

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An Attitude Control System (ACS) has been developed for the NASA Near Earth Asteroid (NEA) Scout mission. The spacecraft is a 6U cubesat with an eighty-six square meter solar sail for primary propulsion. NEA Scout is a secondary payload on the Space Launch System (SLS) Exploration Mission 1. After a two-year journey, it will rendezvous with an asteroid and conduct science imaging. The ACS is composed of three actuating systems: Reaction Wheels (RW), an Active Mass Translator (AMT), and a Reaction Control System (RCS). The reaction wheels allow fine pointing for science, communication, and trajectory guidance. The AMT manages the reaction wheels’ momentum in pitch and yaw axis by shifting the spacecraft center of mass to change the solar torque. The roll momentum is managed by the RCS, but propellant-less alternatives are also explored. The RCS also performs the initial de-tumble, Trajectory Correction Maneuvers (TCM), and safe-mode attitude control. The NEA Scout ACS meets mission requirements including attitude holds, slews, optical navigation, and science with margin and including flexible body effects. This ACS is applicable to other potential missions with a smaller volume than traditional deep space missions.

Key Words: Solar Sail, Attitude Control, Momentum Management

Nomenclature

- $G_k$: Flexible Modal Gain per Axis
- $I_e$: Inertia per Axis
- $K_{de}$: Derivative Gain
- $K_{ie}$: Integral Gain
- $K_{pe}$: Proportional Gain
- $\omega_{o}$: Low Pass Cut-off Frequency
- $\alpha$: Down-Shift Factor
- $\delta$: Percent Flexible Modal Damping
- $\theta_e$: Attitude error (arbitrary coord. frame)
- $\omega_e$: Ang. Rate error (arbitrary coord. frame)
- $\omega_s$: Flexible Modal Frequency
- $\omega_b$: Ang. Rate about body x-axis
- $\omega_y$: Ang. Rate about body y-axis
- $Nm$: Newton-meters

1. Introduction

A solar sail presents unique challenges for achieving stable attitude control for a deep space mission due to the relatively high solar disturbance torque and the presence of low frequency flexible body effects.1-5) The ACS designed for NEA Scout allows for a wide range of spacecraft attitude control capabilities for the different phases of the NEA Scout mission. Early in the mission prior to solar sail deployment, primary control is performed by the RCS for major spacecraft activities. The RCS provides the high torques needed for de-tumble shortly after deployment from the launch vehicle and for attitude hold during the TCM, which is required to clean up navigational dispersions from the SLS deployment trajectory. The TCM is performed by using two RCS axial cold-gas thrusters. The RW control system is the primary ACS for control after the solar sail is deployed. Control axes, shown in Figure 1, are roll (sail normal) and off-roll pitch/yaw axes. Once the desired attitude is achieved using RW control, the AMT autonomously moves part of the spacecraft’s mass, shifting the Center of Mass (CM) until the pitch and yaw solar torques are trimmed.

For momentum management control, the AMT is used to actively manage RW momentum buildup in the pitch and yaw axes by periodically shifting the CM of the spacecraft. RW momentum buildup due to the solar sail roll, or “windmill” torque around the sail normal axis, is managed separately using RCS pulsing or trimming the sail roll angle when possible. The roll axis momentum desaturation can be successfully managed with propellant because it is roughly three orders of magnitude smaller than the pitch and yaw torques. Alternatively, the control of sail attitude for roll momentum management is also explored. Throughout the duration of the mission, the RCS serves as a secondary ACS that can be employed for attitude recovery maneuvers resulting from various off-nominal conditions, including a loss of RW control.
NEA Scout also has sensors for attitude determination, including three coarse sun sensors, a star tracker, and an IMU. The sun sensors are critical for sun-pointing that immediately follows de-tumbling. Initially, the ACS’s onboard sun ephemeris cannot be used due to a lack of accurate time reference onboard the spacecraft. Also, the star-tracker may be “blinded” after de-tumble if the sun is in the star-tracker’s field of view. Thus the sun sensors are critical to detumbling the spacecraft. After these early critical operations, sun sensors are only used for backup in case of star tracker failure and for safe modes. The star tracker provides accurate attitude data at low body rates, and is the primary sensor for the majority of the mission, particularly after the sail is deployed. Due to the high moment of inertia and mission requirements, the body rates will nominally remain below 0.1 deg/sec. The IMU provides critical body rate measurements during de-tumble and the initial sun-pointing slew, and is used more heavily prior to sail deploy when relatively high maneuver rates are possible. After sail deploy, the IMU serves as a secondary source of rate data because it is relatively noisy compared to the star tracker at low rates.

The ACS must also point the sail for thrusting during the mission. However, as is typical of low-thrust trajectory guidance, the sail angles change relatively slowly (on the order of a degree or two per day) and the sail pointing for thrust guidance is the least challenging requirement that the ACS must meet.

The momentum management system must meet a unique requirement of trimming a relatively large solar disturbance torque caused by sail optical properties and shape. The untrimmed solar disturbance torques in the pitch and yaw axes are on the order of micro-Nm, but the AMT is capable of trimming those torques down to tens of nano-Nm. The AMT is unable to trim the residual “windmill” torque about the roll (sail normal) axis, so roll momentum is managed by the RCS. Residual roll torque is on the order of tens of nano-Nm, and requires approximately one thruster firing per day. Due to the small amount of roll torque, the propellant expenditure for roll desaturation is small, and the total propellant expended is within mission margins. This propellant usage can be further reduced by rolling the sail to reduce or eliminate the residual solar roll torque during phases of the mission where the sun incidence angle is high enough. This is discussed in more detail in Section 4.

The RCS faces challenges from having a small volume as well as only having four thrusters available for attitude control. There are a total of six thrusters, but two are axial thrusters used only for the TCM. The RCS must also be maintained at a minimum propellant temperature of 6 C. The RCS unit has built-in heaters to maintain the propellant temperature. Furthermore, the RCS unit is in front of the sail, so it will be sun-facing throughout the majority of the mission.

Maintaining the minimum propellant temperature is not a concern for most of the mission except during the initial de-tumble, which is performed shortly after NEA Scout is deployed. Before deployment from the SLS and during de-tumble, the RCS propellant temperature may be suboptimal. At this condition, the RCS will operate less efficiently. Since NEA Scout is a secondary payload, it cannot control its thermal state until it is powered up, which cannot occur until after deployment. Moreover, the arrays will be in their stowed position and cannot be pointed at the sun until after the spacecraft is de-tumbled. Since battery power and propellant temperature states are unknown at deployment, we must carry some contingency plans for spacecraft de-tumble in case the temperature of the RCS is too low.

Fig. 1. NEA-Scout (a) sail stowed, (b) sail deployed

2. Background

NEA Scout’s primary science objective is to survey at least one Near Earth Asteroid within 2.5 years of launch and return high-fidelity images of the asteroid to Earth.6,7 Currently, the target asteroid is 1991 VG, although this may change due to launch delays or other changes to the primary SLS mission.

During the approach to the asteroid, NEA Scout must perform a series of optical navigation measurements using the science camera to refine the ephemeris knowledge of the asteroid. The optical navigation pointing requirements must be met while accounting for flexible body effects and the capabilities of the ACS actuators and sensors. The ACS must also support science pointing, but the optical navigation requirements are the most difficult to meet and envelope the requirements for science pointing.

NEA Scout must also periodically slew to point at the Earth for communications once outside a certain range, requiring a large slew to a high sun incidence angle. The solar arrays may be as much as 70 degrees away from direct sun-pointing during Earth communications. This drives a requirement to slew to Earth at the fastest rate feasible to preserve power and reduce the time spent in high sun incidence angles. During these long slews, the AMT is critical to managing the reaction wheel momentum.

3. Control System Design and Results

3.1. Reaction Wheel Control Allocation

The reaction wheel hardware is composed of four reaction wheels with 0.015 N-m-s capacity each, provided by Blue Canyon and arranged in pyramidal fashion with spin axis 60 degrees off the roll (sail normal) body axis and a 45 degree clock from pitch/yaw body axis. This arrangement allows for redundancy in case one of the reaction wheels fails. The reaction wheels use an allocation algorithm that distributes the commanded torque from the controller, given in the three body axes, among the four reaction wheels using an allocation...
algorithm based on a Moore–Penrose pseudo inverse. In case of a single reaction wheel failure, the spacecraft remains controllable while a new allocation matrix can be uploaded from the ground.

3.2. Reaction Wheel Control Feedback Loop Architecture

The reaction wheel control feedback control loop, Figure 2, is composed of a star tracker sensor for attitude and rate sensor, a low pass filter, an Attitude Kalman Filter, a Proportional Integral and Derivative (PID) control, and the spacecraft plant model. At low body rates, below 0.1 deg/sec, the star tracker derived body rates provide less noise and no drift compared with the IMU. When the solar sail is deployed, the maximum slew rates are set to 0.04 deg/sec. As a contingency, if the star tracker becomes unavailable, the IMU will serve as a backup.

![Fig. 2. Reaction wheel feedback control loop](image)

3.3. Reaction Wheel Control Requirements

The RW control shall meet the control stability margins in frequency domain as well as the mission requirements, evaluated in time domain. Control stability margin requirements are 6dB gain and 30 deg. phase, including flex contributions from the sail and booms. Mission requirements include optical navigation, (for asteroid detection and trajectory characterization) science, and communications pointing.

A communication pointing requirement of 1 deg. is needed once outside the earth–lunar phase of the mission. However, this requirement is bounded by the science and optical navigation requirement of 0.5 degrees of attitude error. Besides pointing attitude error, there are pointing stability requirements for optical navigation and science, aimed at keeping the science camera steady during imaging periods and optical navigation. The constraining mission requirements driving the reaction wheel control design are summarized below:

- Pointing attitude error of 0.5 deg.
- A maximum attitude error of 130 arcsec during a 60 sec. period
- A maximum attitude error of 13 arcsec during a 0.7 sec. period

Where error is defined as the difference between the commanded attitude and true attitude.

3.4. Reaction Wheel Frequency Domain Control Stability

The PID control gains, proportional $K_p$, derivative $K_d$ and integral $K_i$, and the low pass filter, order and cut-off frequency, are designed to meet control stability margins and mission requirements. The solar sail flexible dynamics posed a challenge since the natural frequencies of the sail and bus are low and close to the typical control bandwidth. The sail and bus free-free boundary condition have first mode frequencies of: 0.67Hz for the roll axis, 1.4Hz for the pitch axis and 1.2Hz for the yaw axis. However, a 0.7 uncertainty factor, $\alpha$, is applied to the sail and bus natural frequencies that represents a 30% down shift to 0.47Hz in roll, 1.02Hz in pitch, and 0.85Hz in yaw. The uncertainty factor is applied since the frequencies are derived from analysis only, and validation using modal testing of the deployed sail would be impractical under earth gravity loads. Only the first modes are evaluated since higher modes will have lower gain and will be strongly attenuated by the control system. Also, modal damping is assumed conservatively to be 0.1%. To remove the low flexible sail frequencies from the control bandwidth and attenuate sensor noise, a fourth order low pass filter, with cut-off frequency of 0.1 Hz, is used. The control open loop block diagram is shown in Figure 3, with parameters summarized in Table 1, and depicts the low pass filter, the PID, and the spacecraft plant model, which includes rigid and flexible body dynamics on a per axis, $k$, basis.

![Fig. 3. Open loop block diagram](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value Per Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$ (rad/sec)</td>
<td>2(\pi)0.1, 2(\pi)0.1, 2(\pi)0.1</td>
</tr>
<tr>
<td>$K_p$</td>
<td>0.011, 0.012, 0.002</td>
</tr>
<tr>
<td>$K_d$</td>
<td>1.479, 1.530, 0.804</td>
</tr>
<tr>
<td>$K_i$</td>
<td>0.133, 0.138, 0.008</td>
</tr>
<tr>
<td>$J_k$ (kg m$^2$)</td>
<td>15.975, 16.525, 32.217</td>
</tr>
<tr>
<td>$G_k$</td>
<td>0.770, 0.531, 1.340</td>
</tr>
<tr>
<td>$\omega_o$(rad/sec)</td>
<td>2(\pi)a1.45, 2(\pi)a1.21, 2(\pi)a0.67</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.1, 0.1, 0.1</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.7, 0.7, 0.7</td>
</tr>
</tbody>
</table>

The rigid body dynamics are represented by the principal moment of inertia of the spacecraft and added to the flexible dynamics. The flex dynamics assume a second order behavior with a flexible modal gain $G_k$, which results from the multiplication of sensor and actuator rotational
mass-normalized eigenvectors per axis \( k=1,2,3 \) for \( x, y, z \) axis, respectively. The Bode plot of the discretized open loop is shown in Figure 4 for the roll axis. The bode plot shows the system bandwidth to be approximately 0.067 \( \text{Hz} \) and the first flexible sail roll mode peak response at 0.47 \( \text{Hz} \) with the uncertainty factor applied. The system minimum stability margins for the open loop roll axis are 16\( \text{dB} \) in gain and 67 deg of phase, well above the requirements. Similarly, Table 2 summarizes stability margins for the pitch and yaw axes as well. All axes meet the minimum stability margins of 6\( \text{dB} \) in gain and 30 deg. in phase.

### Table 2: Stability margins per axis

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Margin (dB)</td>
<td>10.7</td>
<td>10.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Phase Margin (deg)</td>
<td>50.4</td>
<td>49.5</td>
<td>67.4</td>
</tr>
</tbody>
</table>

#### 3.5. Reaction Wheel Time Domain Results

The frequency domain analysis proved stability of the control system, but the time domain results shown below will prove the ability of NEA Scout to meet the mission requirements. The time domain analysis includes a high fidelity spacecraft plant model including sail flexible dynamics, AMT motion with the associated changes to spacecraft mass properties, and reaction wheel dynamics with static and coupled imbalances. Also, the time domain results include star tracker and IMU sensor modeling, which use noise parameters derived from in-house testing. The first ACS mission requirement is to be able to meet a 1 degree pointing error for communication and a 0.5 degree mission science/optical navigation pointing error. Figure 5 shows the attitude error during a ninety degree slew, with maximum slew rate of 0.04 degrees per second.

[Fig. 5. Attitude pointing error]

The dashed black lines indicate the beginning and end of the slew maneuver, while the green dashed lines indicate that the maximum slew rate was achieved after a ramp period. Throughout the slew maneuver the attitude error remains below 0.2 degrees. Furthermore, during the subsequent attitude hold condition, the attitude error becomes less than 0.1 degrees, well below the required 0.5 degrees denoted by the red dashed line. The attitude error analysis includes modeling of the AMT dynamics which constantly seek new equilibrium positions during slew and hold conditions.

The second mission requirement is to have a pointing stability of 13 arc seconds during a period of 0.7 seconds, which guarantees small drift of the target object across image pixels. Figure 6 shows the achieved pointing stability for the 0.7 seconds intervals, which represents the maximum attitude change during a 0.7 second time window. Pointing stability is affected by both low frequency and high frequency dynamics. These dynamics are usually referred to as drift and jitter, the terminology used in the results below. With the exception of an initial transient peak right at the start of the slew maneuver, the 0.7 second pointing stability remains below 4 arc seconds during the slew maneuver and remains below 1 arc second during attitude hold, which is well below the 13 arc second requirement.

[Fig. 6. Pointing stability for 0.7 seconds duration]

A third mission requirement states that a pointing stability of 130 arc seconds during a period of 60 seconds shall be met. This requirement is an optical navigation constraint which is only needed for the initial capture of the asteroid to help refine its orbit determination. The initial capture requires a series of images taken during a 60 second period. Figure 7 shows the pointing stability during 60 second intervals during a 90 degree slew maneuver and subsequent attitude hold. However,
this requirement will only be needed during an attitude hold condition. After the attitude slew, the pointing stability quickly drops below 50 arc seconds and stabilizes around 10 arc seconds for the remainder of the time, well below the required 130 arc seconds.

3.6. Reaction Control System (RCS)

NEA Scout uses a cold gas RCS to control the spacecraft’s attitude at various times during the mission. Specifically, the RCS has five responsibilities:

- Initial spacecraft de-tumble
- Initial sun-pointing and attitude hold
- Trajectory Correction Maneuver (TCM)
- Reaction wheel momentum desaturation
- Safe mode operation

NEA Scout will be ejected from SLS with some residual angular rates (up to 10 degrees per second on each body axis). The spacecraft power state will be somewhat uncertain, as the vehicle could be in storage for up to one year prior to SLS launch. Therefore, the first and second operations are to null the spacecraft angular rates and point toward the sun to charge the batteries. After achieving a net-positive charge state, the reaction wheels will take over as the primary actuator for the spacecraft.

While the reaction wheels are the primary actuator, attitude control is handed over to the RCS at certain phases of the mission. One example is during the TCM. This maneuver is performed to target a desired lunar flyby, and occurs shortly after ejection from SLS. Here, the axial jets will fire continuously to provide the necessary delta-V, while the RCS jets maintain the spacecraft’s attitude during the maneuver. Attitude control is performed by the RCS jets during the TCM because the torques are too high for the reaction wheels. Additionally the RCS is used to desaturate the reaction wheels as needed throughout the mission as detailed in Section 4.

Fig. 8. NEA Scout ACS Hardware

The RCS unit is shown in Figures 8 and 9. The unit is approximately 2U of volume on NEA Scout and contains 1.25kg of propellant when full. The propellant is refrigerant R236fa. A conceptual image of the RCS unit is shown in Figure 9. The four circular features at the corners represent the RCS jets, and arrows are used to show the direction of thrust for each jet. The RCS jets are oriented so that firing any pair creates torque about one of the spacecraft body axes. For example, opening jets 1 and 2 create a positive y-axis torque, and jets 2 and 4 create a positive z-axis torque. The two circular features in the center of the RCS unit are the axial jets, with force components along the negative z-axis (into the page).

Fig. 9. NEA Scout RCS Layout

NEA Scout uses simple logic known as a phase-plane control system for the RCS. This type of control is sometimes referred to as a Schmitt Trigger or a bang-off-bang controller. A phase-plane controller is best described visually as shown in Figure 10. The figure depicts a Cartesian coordinate frame with the attitude error on the x-axis, and angular rate error on the y-axis. The red lines on the plot denote the switching lines, while the grey inner-region denotes the quiescent region, or deadband. In this logic, each body axis has a separate phase-plane, and the angular rate error and attitude error are evaluated for each vehicle body axis. If the values are outside the deadband, a pair of RCS jets are commanded to open, driving the system back toward the quiescent region.

Fig. 10. RCS Phase-Plane Control Diagram

A theoretical system trajectory is shown in Figure 10 depicted with blue arrows. At $t_o$, the rate and attitude errors
are outside the deadband, so a pair of RCS jets are opened. This drives the state into the 4th quadrant of the phase-plane until reaching the upper switching line. At this point, the jets are closed and the system is quiescent. But because the angular rate error is non-zero, the system’s attitude error drifts across the deadband until reaching the lower switching line. The system follows a stair case along the lower switching line caused by opening and closing the jets. This effect is the result of a digital (non-continuous) control system. Once the angular rate error is positive, the attitude drifts back across the phase plane toward the upper switching line. If there are no disturbance torques on the vehicle, this system will continue to encircle the origin of the phase-plane as is partially shown in the figure.

A plot of the RCS performance is shown in Figure 11. This plot provides the simulated results of the spacecraft’s angular rates during the initial detumble. As shown, the vehicle is initially rotating at ten degrees per second about each body axis. The RCS then de-tumbles the spacecraft within 25 seconds.

![Figure 11. Simulated results of the initial de-tumble.](image)

4. Momentum Control System Design and Results

The Momentum Management System (MMS) maintains margins on the reaction wheel speeds so they can perform all attitude holds and slews required for operations. The system monitors the momentum of the four reaction wheels, projected into the three dimensions of the body axes. The MMS controls the body axis momentum using primarily the AMT and/or the RCS. Roll axis momentum may also be controlled by rolling the sail to adjust the roll axis component of the solar torque.

The controller can receive a momentum bias command to increase margins of reaction wheels before slews, allowing the reaction wheels to achieve bias speeds before the start of the slew. During slews, the commanded spacecraft rate and estimated inertia are used to calculate a momentum bias that corresponds to the reaction wheel momentum required to execute the slew. This allows the MMS to provide the wheels with the margin they need during a slew, and minimize the momentum error at the conclusion of a slew.

The combination of the external momentum bias and slew momentum bias provide a total momentum bias, from which the reaction wheel momentum is subtracted to produce a control error to command either the AMT or RCS actuators.

Before sail deployment, the RCS is used for momentum management of all three axes. After sail deployment, the AMT is used to control the in-plane (X and Y) momentum by shifting the center of mass to produce solar torques. Roll (Z) axis momentum is controlled either by the RCS or rolling the sail to trim the in-plane solar torque. These three methods are discussed in more detail below.

4.1. Active Mass Translator (AMT)

The primary actuator for X and Y momentum management is the AMT, which moves part of the cubesat bus in two dimensions in a plane parallel to the sail in order to shift the center of mass (CM) relative to the center of pressure (CP). To achieve this planar motion of the spacecraft bus, an actuated translating table was custom designed for NEA Scout. 1) Using a two-dimensional translation of the CM was once explored by NASA’s New Millennium Program Space Technology 7 (ST7). 12,13) However, ST7 opted for a two-axis gimbaled control boom connecting the sail center and the spacecraft bus instead of a planar translation of the bus as implemented here.

As depicted in Figure 12, the Momentum Management System for the AMT uses a Proportional-Integral (PI) controller on the reaction wheel momentum projected into the X and Y (in-plane) body axes.

![Figure 12. Diagram of AMT X and Y momentum management controller](image)

A second order low pass filter smoothes the reaction wheel momentum measurements. The much noisier reaction wheel torque measurement is smoothed with a fourth order filter. This delays the torque measurement, but because it is used as a threshold to check for equilibrium and not in the feedback control signal, this does not degrade performance.

The AMT controller for each axis activates when the momentum reaches a threshold and deactivates when both the momentum and torque fall within deadbands, meaning that the wheel momentum has been desaturated and the solar torque has been trimmed out. The system actuates the AMT during and after slew maneuvers, but otherwise the AMT only moves once approximately every 12 hours during an attitude hold. The AMT will move throughout a slew maneuver and approximately one hour afterwards to remove residual momentum errors and achieve equilibrium.
Figure 13 shows the AMT position, reaction wheel speeds and reaction wheel torques during two consecutive 90-degree slews that go from -45 deg sun incidence to 45 deg sun incidence and back again. The first slew occurs at 100 seconds while the second slew occurs at 5000 seconds (1 hour 23 minutes). The MMS continuously adjusts the AMT position during the slews to minimize the momentum error while preventing the reaction wheels from saturating. To limit the total cycles on the AMT, the AMT is only commanded to a new position every 100 seconds.

4.2 RCS Momentum Management

While the vehicle is under reaction wheel control, the MMS will monitor the reaction momentum in all three spacecraft body axes. If any axis exceeds a threshold, a command will be sent to the RCS to deliver a torque on the specified axis and in the direction to reduce the momentum until a deadband is reached. Whichever axis has the highest momentum error will be desaturated first. The thresholds for the pitch and yaw (X and Y) axes are set much higher than for the AMT, so that the RCS serves as a backup, and will not fire under normal circumstances. The RCS momentum management deadbands are set large enough to accommodate the minimum angular momentum bit size of the RCS, which depends on the minimum RCS pulse duration, thrust, and orientation.

Before sail deployment, the RCS will perform all reaction wheel momentum management. The solar torques are minimal so that propellant consumption will be small. After sail deployment, RCS will manage the roll (Z) momentum.

4.3 Roll Control

Figure 14 shows the residual torque about the sail normal (Z) axis when the AMT is in a trim position for a range of sun incidence and roll angles. The residual roll torque will be gradually absorbed by the reaction wheels until it reaches a pre-determined threshold which triggers RCS to desaturate the accumulated Z momentum. However, the roll torque varies with roll angle when the sun incidence is greater than 0 degrees. Above 20 degrees sun incidence, the roll torque variation with roll angle will cross zero, allowing it to be trimmed and managed purely with roll attitude. During portions of the mission when the sun incidence angle is less than 20 degrees, RCS will be used for Z-axis momentum management. A worst-case estimate of $1 \times 10^{-7}$ Nm roll torque for the entire 2.5 year mission duration (not including times when roll control is available) results in a propellant consumption of 240 grams. RCS will also be used as a backup to the AMT for momentum management control of all body axes.

The roll angle can be controlled from the ground by adding a roll angle to the commanded quaternion based on the observed roll axis momentum growth at different roll attitudes. Also, it may be managed autonomously onboard using a controller to monitor the Z momentum accumulation and generate a roll command that is added to the commanded attitude quaternion sent to the guidance controller. Autonomous roll control is under development.
Alternatively, roll control may be passive. If there is a zero-crossing in the roll torque, which is the case for sun incidence angles larger than 20 degrees, then the spacecraft will start to roll and oscillate about the equilibrium point. These stable equilibria correspond to points where the torque is zero and the slope is negative. Two of these points are shown in Figure 14 at roll angles zero and 180 degrees. Over long periods of time, the roll oscillations will decay due to structural damping, a process that could be sped up with an additional energy sink, similar to a nutation damper for roll. This passive roll control alternative is currently being explored and would have the benefit of not using RCS propellant for Z momentum desaturation.

5. Conclusions

The NEA Scout Guidance and Control team has designed an ACS to meet all mission requirements before and after the sail is deployed. The reaction wheel control system slews the sailcraft, meets science pointing stability requirements.

All the above requirements are met with restrictive volume and mass constraints from the 6U configuration of the sailcraft and also while subject to flexible body effects from an 86 square meter sail. The inclusion of the AMT for momentum management will be a first for solar sails, and is a novel configuration for using a shift in center of mass for momentum management.

Overall, the NEA Scout ACS provides a robust control system that provides a model for future solar sail missions as well as future small sat missions.

Acknowledgments

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