MAINTAINING AURA'S ORBIT REQUIREMENTS WHILE PERFORMING ORBIT MAINTENANCE MANEUVERS CONTAINING AN ORBIT NORMAL DELTA-V COMPONENT

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The Earth Observing System (EOS) Afternoon Constellation consists of five member missions (GCOM-W1, Aqua, CALIPSO, CloudSat, and Aura), each of which maintain a frozen, sun-synchronous orbit with a 16-day repeating ground track that follows the Worldwide Reference System-2 (WRS-2). Under nominal science operations for Aura, the propulsion system is oriented such that the resultant thrust vector is aligned 13.493 degrees away from the velocity vector along the yaw axis. When performing orbit maintenance maneuvers, the spacecraft performs a yaw slew to align the thrust vector in the appropriate direction. A new Drag Make Up (DMU) maneuver operations scheme has been implemented for Aura alleviating the need for the 13.493 degree yaw slew. The focus of this investigation is to assess the impact that no-slew DMU maneuver operations will have on Aura's Mean Local Time (MLT) which drives the required along track separation between Aura and the constellation members, as well as Aura's frozen orbit properties, eccentricity and argument of perigee. Seven maneuver strategies were analyzed to determine the best operational approach. A mirror pole strategy, with maneuvers alternating at the North and South poles, was implemented operationally to minimize impact to the MLT. Additional analysis determined that the mirror pole strategy could be further modified to include frozen orbit maneuvers and thus maintain both MLT and the frozen orbit properties under no-slew operations.

Keywords: *Aura, Earth Observing System (EOS), Afternoon Constellation, Mean Local Time, Frozen Orbit*

1. Introduction

The Afternoon Constellation consists of five member missions (GCOM-W1, Aqua, CALIPSO, CloudSat, and Aura) with OCO-2 joining the constellation in July 2014. These missions each maintain a frozen, sun-synchronous orbit with a 16-day repeating ground track that follows the Worldwide Reference System-2 (WRS-2). Figure 1 provides a representation of the Afternoon constellation members and their location within the constellation while Tab. 1 outlines the orbit properties and requirements for Aura.

To maintain the orbit described above, each mission must maintain its Mean Local Time (MLT) of equator crossings to ensure consistent lighting conditions on Earth's surface for each orbit. Additionally, missions must also maintain a defined ground track to ensure repeatable data collection. Perturbations to inclination and semi-major axis (SMA) cause changes to the sun-synchronous and repeating ground track properties of the orbit. Changes in MLT are predominately driven by luni-solar perturbations acting on the inclination of the orbit while changes in the repeating ground track property are driven by changes in the SMA from atmospheric drag. Each constellation member routinely performs annual Inclination Adjust

Maneuvers (IAM) and periodic Drag Make Up (DMU) maneuvers in order to compensate for these perturbations, respectively.

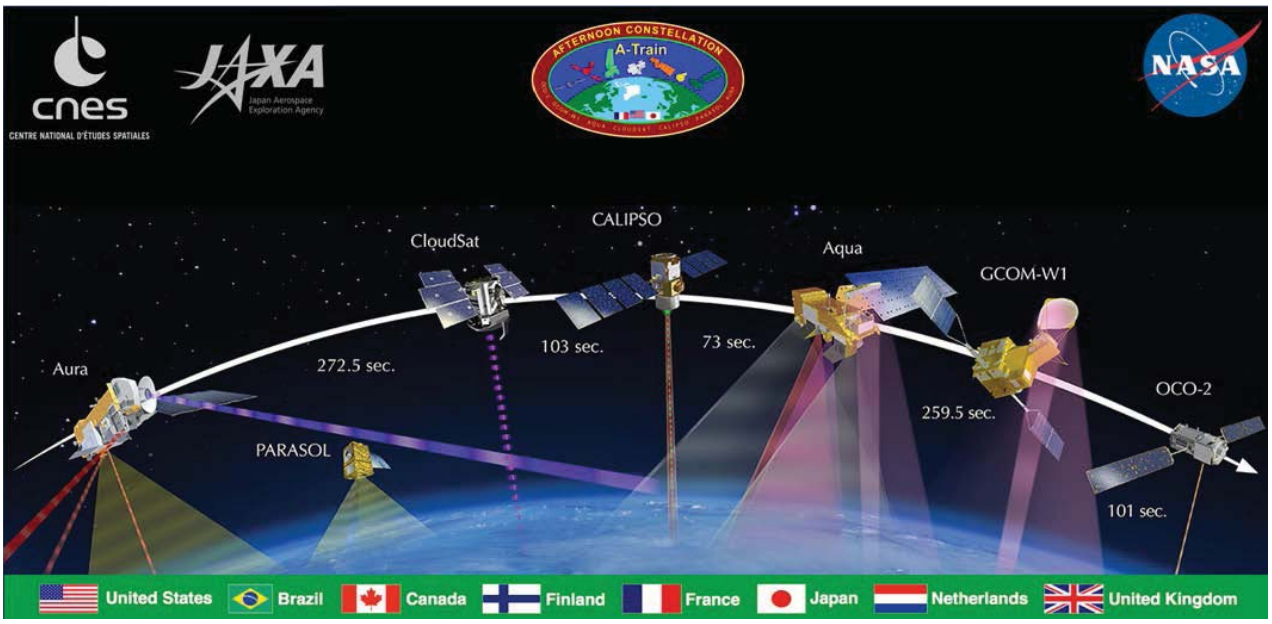


Figure 1. A visual representation of the Afternoon constellation showing each member's along track phasing relative to Aqua.

Table 1. Orbit Properties and Missions Requirements for Aura [1].

Orbital Element	**Value**
WRS-2 Ground Track	18 +/- 20 km mission requirement 18 +/- 10 km operational requirement
Mean Local Time Aura	13:30:00 to 14:00:00 8.5 minutes +/- 15 seconds w.r.t Aqua
Mean Local Time Aqua	13:35:00 to 13:36:30
Semi-major Axis	7077.7 km +/- 0.3 km
Inclination	98.2 +/- 0.15 degrees
Argument of Perigee	90 +/- 20 degrees
Eccentricity	0.0012 +/- 0.0004

1.1 Drag Make-up Maneuvers (DMUs)

Under nominal science operations for Aura, the propulsion system is oriented such that the resultant thrust vector is offset 13.493 degrees from the velocity vector in the yaw plane. For DMU maneuvers, the spacecraft performs a 13.493 degree yaw slew to apply the delta-V purely in the velocity direction to maximize maneuver efficiency. The maneuver is performed at an argument of latitude which best maintains the frozen orbit properties (argument of perigee and eccentricity). The argument of latitude varies for subsequent maneuvers because of the natural

movement of the eccentricity vector caused by Earth's odd numbered, harmonic gravitational coefficients. The argument of perigee and eccentricity are coupled together and evolve in a 116 day period cycle about the ideal values [2]. The frequency of DMU maneuvers is primarily a function of the drag environment. High solar flux conditions require more frequent DMU maneuvers to make up for the accelerated SMA decay caused by increased atmospheric density.

A new DMU maneuver operations scheme has been operationally utilized on the Aura satellite, alleviating the need for the 13.493 degree yaw slew. Removing this yaw slew results in a number of improvements to spacecraft operations and science acquisition including simplifying spacecraft commanding, minimizing required communications coverage during maneuvers, reducing the number of required man hours for the Flight Operations Team (FOT) when executing the maneuver, and reducing the amount of science data collection loss per maneuver. Man hours are reduced for the FOT because slewing the spacecraft requires additional time and contacts. By removing this portion of the maneuver, there is also simplification when planning for and executing Debris Avoidance Maneuvers (DAMs). Additionally, there are improvements in maneuver predictions and performance as removing the slew minimizes slew-induced attitude errors before, during, and after the maneuver.

1.2 Inclination Adjust Maneuvers (IAMs)

Aura, along with the rest of the Afternoon Constellation members, reference Aqua's MLT profile as the anchor for the constellation. Each mission is required to maintain a MLT separation from Aqua which creates a desired along track separation necessary to facilitate mission safety and science coordination. Table 2 outlines the along-track separation and WRS-2 ground track requirements for each mission.

Table 2. Mission requirements for the Afternoon constellation. Aqua acts as the reference mission for the Afternoon constellation. All of the along-track separation values are relative to Aqua. Negative sign indicates the spacecraft flies ahead of Aqua [1].

Mission	Along-track separation at Equator (seconds relative to Aqua)	WRS-2 Ground Track Error (km)
OCO-2	-317.5 +/- 43 seconds	0 +/- 20 km
GCOM-W1	-259.5 +/- 43 seconds	0 +/- 20 km
Aqua	Reference Mission	0 +/- 20 km
CALIPSO	73 +/- 21.5 seconds	43 +/- 10 km
CloudSat	176 +/- 21.5 seconds	45.3 +/- 10 km
Aura	484 +/- 21.5 seconds	18 +/- 20 km

Prior to Aura's annual Inclination Adjust Maneuver (IAM) series, the flight dynamics teams for each mission plan their annual IAM schedule based on Aqua's nominal IAM plan and predicted MLT profile in order to maintain the required along-track separation. Under current operations, the annual inclination series is the only opportunity in which a deliberate change in inclination is made to Aura's orbit. This approach gives the constellation members the ability to plan their own maneuver series in order to maintain the along-track separation requirements. Under the proposed no-slew DMU maneuver scheme, the 13.493 degree yaw offset from the velocity vector will add a small out-of-plane delta-v component. This small out-of-plane delta-v component will add a combination of inclination or right ascension of the ascending node (RAAN) change based on the maneuver location.

The focus of this investigation is to assess the impact no-slew DMU maneuver operations will have on Aura's frozen orbit properties and to assess the ability to preserve the required MLT separation between Aqua and the constellation member. Following the successful implementation of no-slew maneuvers for the Aura satellite, it is likely that Aqua will perform operational DMUs as no-slew. Additional concerns for Aqua's MLT as the reference mission in the Afternoon Constellation led to Aura as the choice for operational testing.

2. Effects of Out-of-Plane Acceleration on the Orbital Elements

Under no-slew operations, a small out-of-plane delta-v component will be introduced due to the 13.493 degree yaw offset of the thrust vector from the velocity vector. Gauss's form of Lagrange's planetary equations of motion for nonconservative forces describes the impact to the orbital elements due to any combination of accelerations in the RSW frame [3]. In the *RSW* system, the *R* axis is parallel to the position vector. Along-track displacements are normal to the position vector along the *S* axis. The *W* axis points in the instantaneous direction of the angular momentum vector.

$$\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}}\left(e\sin(v)F_R + \frac{p}{r}rF_S\right) \tag{1}$$

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}\left(\sin(v)F_R + \left(\cos(v) + \frac{e+\cos(v)}{1+e\cos(v)}r\right)F_S\right) \tag{2}$$

$$\frac{di}{dt} = \frac{r}{na^2\sqrt{1-e^2}}F_w\cos(v) \tag{3}$$

$$\frac{d\Omega}{dt} = \frac{r}{na^2\sqrt{1-e^2}}F_W\frac{\sin(v)}{\sin(i)} \tag{4}$$

$$\frac{d\omega}{dt} = \frac{\sqrt{1-e^2}}{na^2e}\left\{-\cos(v)F_R + \sin(v)\left(1+\frac{r}{p}\right)F_s\right\} - \frac{r\cot(i)\sin(v)F_w}{h} \tag{5}$$

$$\frac{dM_o}{dt} = \frac{1}{na^2e}\{(p\cos(v) - 2er)F_R - (p + r)\sin(v)F_S\} \quad (6)$$

Three of the equations contain an out-of-plane acceleration component (F_w): inclination (Eq. 3), right ascension (Eq. 4), and argument of perigee (Eq. 5). Argument of perigee contains all three acceleration components; effects on the argument of perigee will not be studied in depth analytically, but rather via simulations. As expected, inclination and right ascension are only a function of the out-of-plane component of acceleration. In fact, Eq. 3 and 4 are identical except for the argument of latitude component (v) (the *sin(i)* component in the denominator for the right ascension equation merely acts as a scaling factor). The relationship between inclination and right ascension is essentially a unit circle with inclination change on the x-axis, right ascension change on the y-axis, and the argument of latitude (v) as the angle measured from the x-axis.

The propulsion system is oriented such that any out-of-plane delta-v component will be oriented along the F_w vector. Combining the thruster orientation with the unit circle relationship between inclination and right ascension, a simple understanding of the effects on the orbit plane based on the location of the maneuver (argument of latitude) can be established. Maneuvering at the nodes produces pure delta-i while maneuvering at the poles produces pure delta-RAAN. All other maneuver locations produce a combination of both inclination and right ascension change. Additionally, deleterious effects to the argument of perigee, and therefore the frozen orbit, will be driven by the F_w acceleration component.

3. Constellation Flying

3.1 Sun-Synchronous Orbits

As part of the Afternoon constellation, each member is required to maintain a sun-synchronous orbit. Maintaining a sun-synchronous orbit is beneficial to science data as the lighting conditions on the Earth's surface are nearly the same for every orbit. By definition, a satellite in a sun-synchronous orbit maintains the same angle relative to the Sun-Earth vector with noon defined as the day side.

In order to maintain a constant MLT, the time rate of change of the right ascension must match the rate of the secondary body around its primary. For the Sun-Earth system, this rate is 360 degrees per one Earth year. For classical two body mechanics, the right ascension is fixed once the orbit plane is established; however, the Earth is not a perfect sphere. The J2 zonal coefficient is the prime perturbation that affects the right ascension of the orbit plane. Equation 7 governs the time rate of change of the right ascension due to Earth's bulge at the equator [4].

$$\frac{d\Omega}{dt} = \frac{-3nR_e^2J_2}{2p^2}\cos(i) \quad (7)$$

For a sun-synchronous orbit, the above equation must equal 360 degrees per one Earth year. Equation 7 is a relationship between Earth's physical characteristics (Earth's oblateness coefficient, J2, and radius) and the orbital elements of the spacecraft (inclination and semi-major

axis). The semi-major axis required to stay on the WRS-2 path is fixed at 7077 km. With the semi-major axis fixed, the only free variable remaining is inclination. Based on Eq. 7, the inclination must be fixed at 98.2 degrees in order to maintain a sun-synchronous orbit. Slight variations in the inclination are enough to alter the time rate of change of the ascending node, thus affecting the MLT.

3.2 Separation Requirements

In order to ensure safety and coordinate science between missions, each member of the constellation flies within a control box defined by their MLT constraint and ground track error constraint on the WRS-2 path. Aqua acts as the reference mission for the constellation. As such, all separation requirements are relative to Aqua and measured at the equator. Table 2 from the introduction lists the along-track separation and ground track error requirements for each member. In order to maintain these requirements, there are two methods for adjusting the along track separation: MLT control and ground track error control. MLT control is performed through maintenance of the inclination through the Spring IAM series in order to achieve a proper time rate of change for the right ascension while ground track error control is performed through semi-major axis maintenance with DMU maneuvers. The Spring IAM series occurs around the Vernal Equinox, for maximum efficiency, with 3+ maneuvers planned each year.

Every 1 km of ground track error is equivalent to 2.156 seconds of along track separation at the equator. Converting between ground track and along track separation in seconds is a simple conversion; Earth's rotation (86400 seconds / 360 degrees) times Earth's circumference (360 degrees / 40075 km) equals 2.156 seconds of along track separation at the equator per km of ground track error.

MLT is measured between 0 and 24 hours, with noon defined as the day side of the Sun-Earth line and midnight as the night side. When using this hourly definition, separation in terms of meal local time difference is a one-to-one relationship with along track separation at the equator. As an example, two missions that fly exactly on the WRS-2 path (ground track error equal to zero) but with a mean local time difference of one minute equates to 60 seconds of along track separation at the equator.

In addition to flying within their defined control boxes, each mission must meet a +/- two second MLT prediction requirement between each Spring IAM series. In other words, the MLT prediction must be within +/- 2 seconds of the definitive MLT after one year. This requirement is especially important for Aqua as it acts as the anchor mission for the constellation and all separation requirements are based off of Aqua's MLT. Aura's MLT, referenced to Aqua, is 8.5 minutes +/- 15 seconds.

3.3 Complications Due to No-Slew DMU Maneuver Operations

The EOS Flight Dynamics System (EOS FDS) for Aqua is responsible for generating and delivering a long predicted Aqua ephemeris that models the upcoming predicted IAM series to the other constellation members. This occurs after the completion of the IAM series. The flight dynamics teams for each mission will use the predicted Aqua ephemeris as a baseline for

modeling their own IAM series in order to meet the along-track separation requirements. This is true for Aura as well; its yearly IAMs are synchronized with Aqua's. Both Aqua and Aura have similar lifetime simulations used to plan the IAM series, each modified according to the particular satellite constraints.

When producing the Aqua and Aura long term prediction ephemeris, all DMU maneuvers are performed through a simple logic loop that maintains the ground track error within 0 to 10 km while maneuvering at the location that best maintains the frozen orbit parameters. Under nominal slewed operations, the location and date of the DMU maneuvers would never have an impact to the MLT profile as all of the delta-v is directed along the velocity vector. In other words, the predicted ephemeris is immune to differences between a predicted DMU maneuver schedule and the actual maneuver dates in regards to predicting the MLT profile for the year. This benefit allows the remaining constellation members to accurately plan their own IAM series in order to meet the mission along-track separation requirements.

Problems occur when using the current targeting logic used to generate the predicted Aura ephemeris under no-slew DMU operations. The variability in actual versus predicted maneuver dates and locations could cause a violation of the +/- two second MLT prediction accuracy requirement. The maneuver dates and locations when compared to the prediction will be different due to a variety of circumstances: actual solar flux conditions compared to the Schatten Mean Nominal solar flux model used in predictions will shift the maneuvers dates, movements of maneuvers for operational convenience (such as avoiding holidays, weekends, and inclement weather conditions), unexpected RMMs due to close approaches with debris objects, and movement of the maneuver location due to TDRS and ground station contact scheduling. This variability makes it difficult for the other constellation members to maintain a constant MLT separation from Aura as the potential delta-i induced during each DMU maneuver will alter the time rate of change of the right ascension. This will cause Aura to drift relative to the other constellation members.

4. Proposed Maneuver Schemes

To solve the challenges that come with no-slew DMU maneuvers for Aqua and Aura, an alteration to the current maneuver strategy is necessary. The first approach is to maintain the current maneuver approach while introducing the no-slew concept. This scenario suffers from a crucial complication; the amount of delta-i and delta-RAAN achieved each DMU maneuver becomes uncertain. The variability in the argument of latitude necessary to maintain a frozen orbit and the varying frequency of maneuvers required to maintain the operational ground track due to changing atmospheric conditions leads to long term uncertainty in MLT predictions. This unpredictability complicates the other constellation members' ability to accurately plan their Spring IAM series to meet the MLT separation requirements. While MLT may be deleteriously affected, the nominal maneuver scheme does adequately maintain frozen orbit requirements over the spacecraft lifetime.

An alternative maneuver approach attempts to compensate for the drawback of MLT uncertainty by limiting to maneuvers near the poles where there is insignificant net change to the inclination. While the effect to the inclination (or MLT drift rate) is reduced, maneuvering near the poles

causes an instantaneous change to the right ascension of the ascending node (MLT). At first, this instantaneous change in RAAN is not detrimental to the MLT separation between Aura and the constellation members; however, as more DMU maneuvers are performed to deal with atmospheric drag, the change in RAAN can compound and become a significant factor. To compensate for the changes in RAAN, one could modify this approach by performing the subsequent DMU maneuver on the opposite side of the orbit when compared to the previous DMU maneuver (i.e. "mirror pole strategy"). Mirror pole maneuvers will cancel the achieved delta-i and correct the instantaneous RAAN change resulting in little to no net change to the MLT rate and no net change to the MLT, thus allowing the constellation members the ability to accurately plan their Spring IAM series in order to maintain the required MLT separation. This maneuver scheme, however, neglects to maintain the frozen orbit properties. Additionally, other considerations, such as the feasibility of performing DMU maneuvers over the North and South pole, due to contact limitations, must be further explored.

Both the current maneuver strategy and the mirror pole strategy succeed in either minimizing affects to the frozen orbit requirements or the MLT while simultaneously increasing detrimental effects to the other. Long term drift to the frozen orbit parameters becomes increasingly difficult to correct over time, implying that short term corrections are needed. The MLT, important for science and mission safety, can be reset each year but cannot be neglected when planning DMUs without affecting the Afternoon Constellation members during the yearly IAM series. In order to maintain all mission requirements, a third maneuver scheme, which will be some combination of both frozen orbit and MLT maintaining (mirror pole) maneuvers, is needed.

5. Analyzing Maneuver Strategies which Minimize MLT Effects

The current strategy of maneuvering in the location that minimizes the impact to the frozen orbit properties needs to be adjusted to incorporate the effects of out-of-plane delta-v induced from no-slew operations. The overall goal of the modified strategy should be to minimize the effects on the MLT by controlling the delta-i achieved from each DMU in order to reduce the uncertainty in Aura's future MLT profile. Once the MLT can be maintained, further study of how to balance the effects to MLT with those of a frozen orbit, can be considered.

From the investigation of Eq. 1-6, maneuvering at the north or south pole (argument of latitude equal to 90 or 270 degrees, respectively) will achieve this goal as all of the out-of-plane delta-v will go into delta-RAAN instead of delta-i. Placing the out-of-plane component into delta-RAAN will have no effect on the time rate of change of the right ascension as Eq. 7 is only a function of semi-major axis and inclination.

To see the effects on the orbital elements and MLT through various maneuver strategies, a reference scenario was generated that maintains the current maneuver ideology (maintaining the yaw slew and performing the maneuver in the location that maintains the frozen orbit properties). Seven different no-slew DMU scenarios were modeled: maneuvering at the location that best maintains the frozen orbit properties (one scenario), maneuvering only at the north or south pole (two scenarios), maneuvering only at the ascending or descending node (two scenarios), and alternating maneuvers between the poles or between the nodes (two scenarios). Figures 2-7 show

the difference in the orbital elements and MLT when compared to the reference slewed DMU simulation over a 10.5 month period between successive Spring IAM series. All DMU maneuvers are modeled as finite maneuvers centered about their respective locations.

The first insight from Fig. 2 and 4 is the confirmation of the conclusion reached from studying Lagrange's planetary equations of motion for nonconservative forces; maneuvering at the poles results in all delta-RAAN while maneuvering at the nodes produces all delta-i. Further insight into the problem is gained when studying Fig. 7. The initial concern that the accumulated delta-i achieved throughout the year from no-slew operations could violate the +/- two second MLT prediction requirements is confirmed. The two scenarios in which all DMUs are performed at either node deviate from +/- two seconds of the reference scenarios within 6 months. As shown in Tab. 3, the other five scenarios all maintain a MLT difference within +/- two seconds of the reference scenario. The three scenarios with maneuvers occurring at the poles provide the best results, as expected. All of the MLT difference is due to the instantaneous plane change when maneuvering at the poles. The mirror poles strategy provides the best results as the RAAN change from the previous maneuver is canceled out. This canceling effect is evident in Fig. 4 and 5 as the right ascension difference over the year roughly averages zero.

Table 3. Mean local time difference after 10.5 months between the seven no-slew scenarios and the reference slewed DMU scenario. The polar strategies provide the best results with mirror strategy producing almost zero MLT difference.

Maneuver Location (Argument of Latitude)	Mean Local Time Difference (seconds)
North Pole (90°)	+ 0.225
South Pole (270°)	- 0.380
Mirror Poles (90°/270°)	- 0.035
Ascending Node (0°)	+ 5.364
Descending Node (180°)	- 5.494
Mirror Nodes (0°/180°)	- 0.914
Frozen Orbit Maintenance (various)	- 0.374

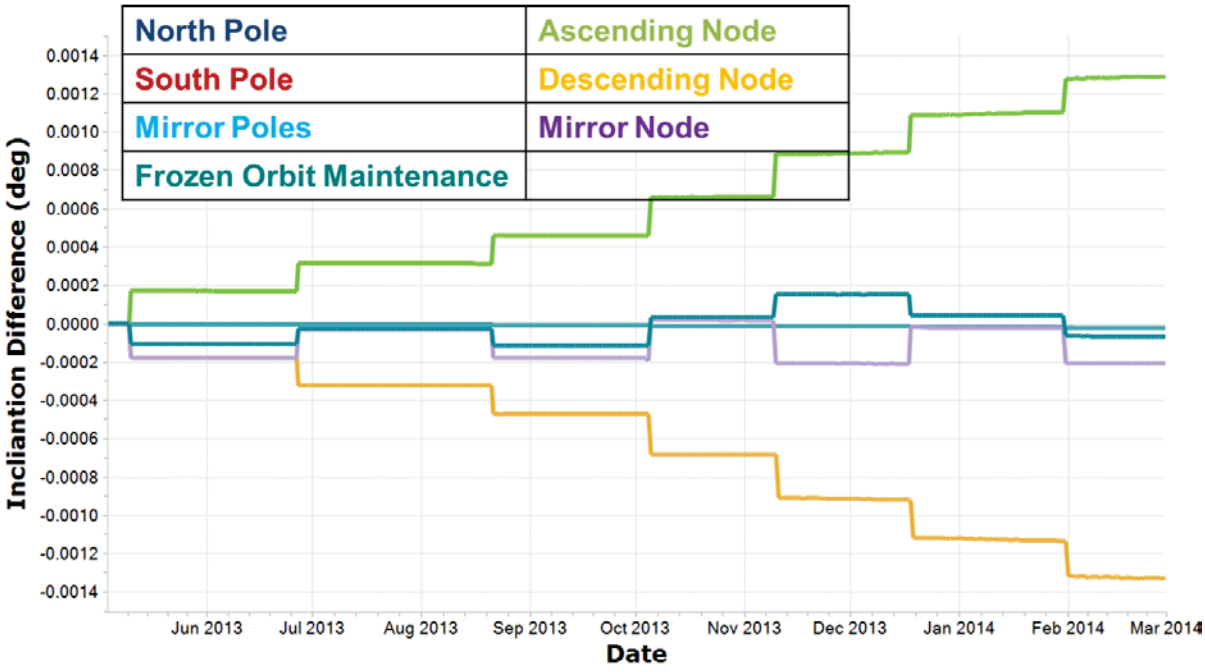


Figure 2. Inclination difference between the seven no-slew strategies and the reference slewed DMU approach. It is evident that maneuvering at the nodes produces pure inclination change while maneuvering at the poles produces zero inclination change.

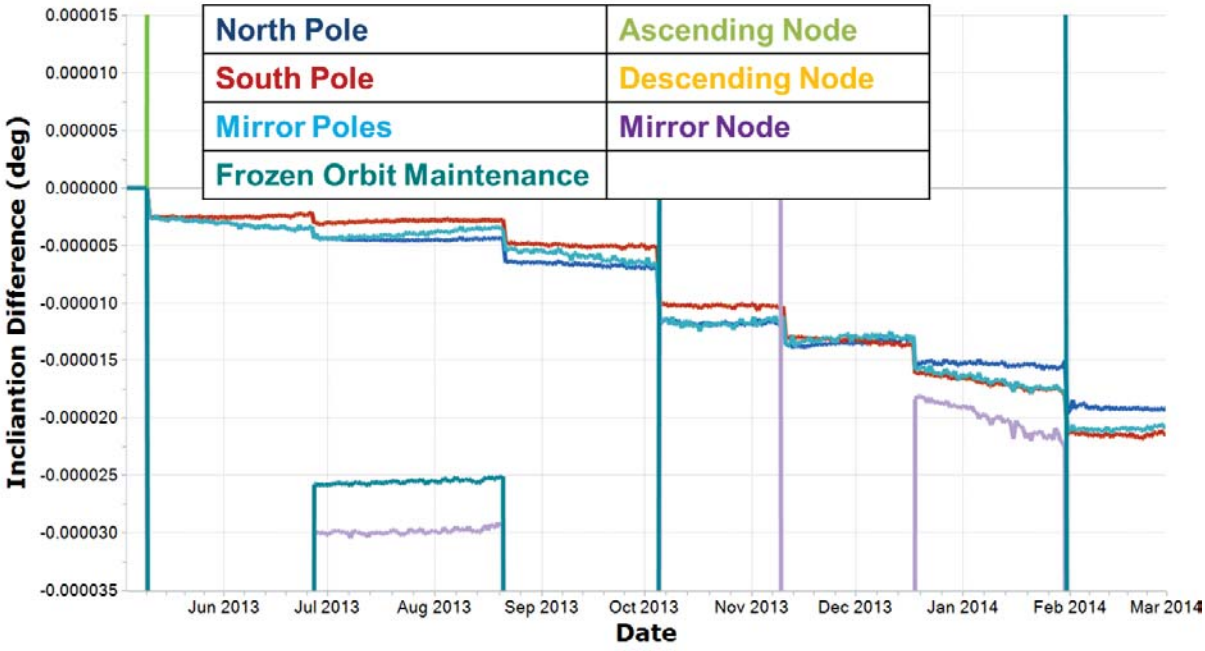


Figure 3. Zoomed in view of the inclination change between the seven no-slew strategies and the slewed reference scenario. The zoomed in view highlights the negligible inclination change achieved when maneuvering at the poles. The magnitude is one to two orders of magnitude lower than maneuvers at the nodes.

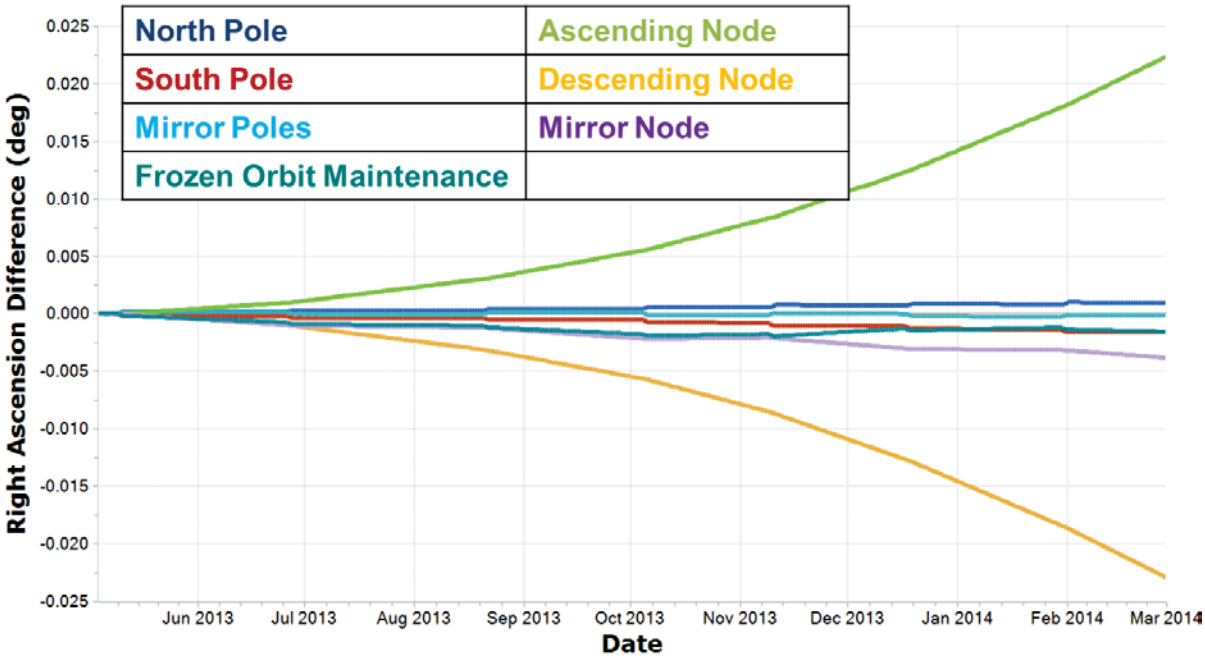


Figure 4. This figure shows the difference in right ascension between the seven no-slew scenarios and the reference slewed scenario. As expected, maneuvering at the poles produces instantaneous RAAN change while the poles produce no RAAN change. The RAAN change present for the node cases is due to the achieved inclination change (evident in Fig. 2) affecting the MLT drift rate.

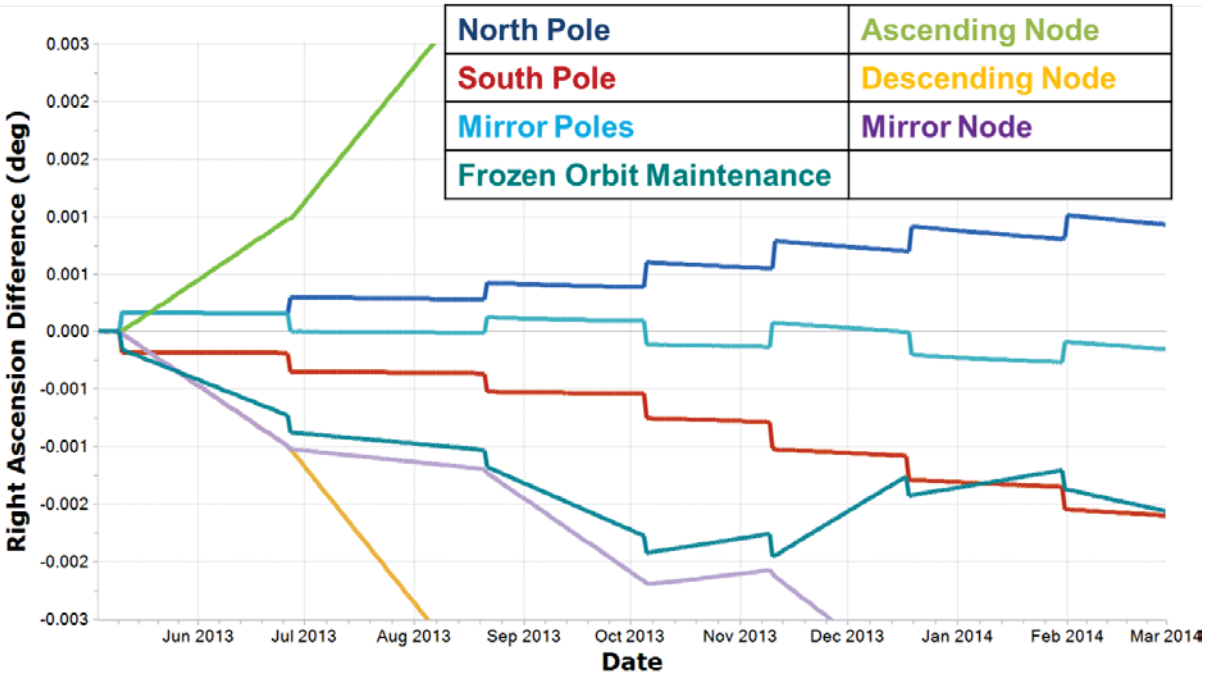


Figure 5. The above figure provides a zoomed in view of the right ascension change. The instantaneous RAAN changes for the polar strategies are more pronounced in this zoomed in view. In addition, the zero net change in RAAN is apparent for the mirror poles strategy.

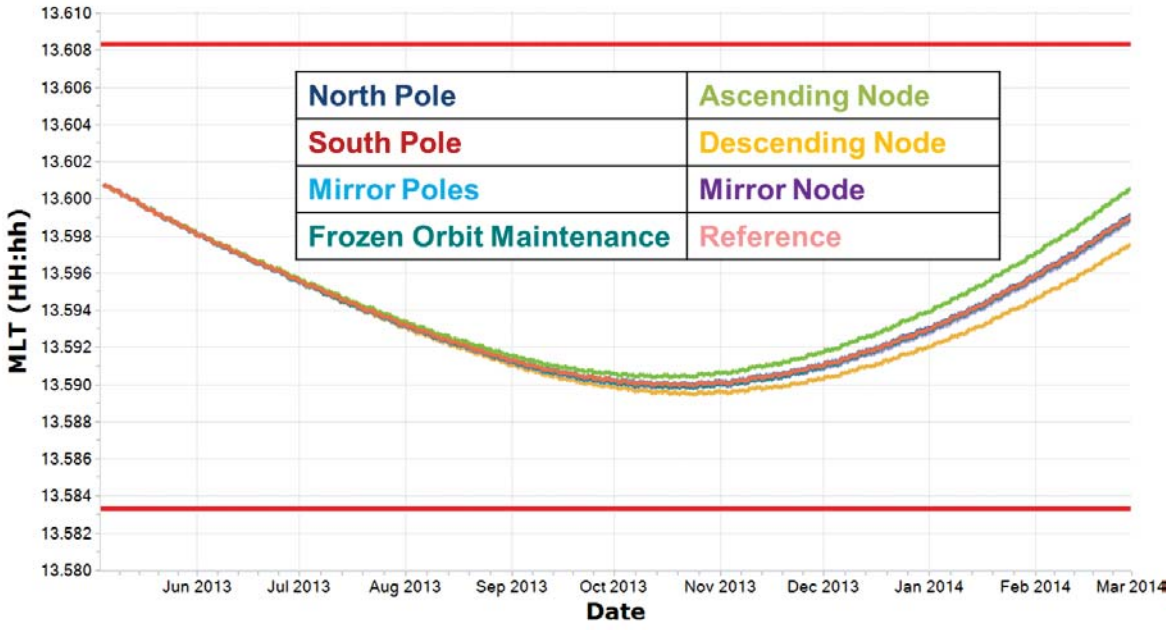


Figure 6. The MLT profiles for the seven strategies and reference scenario over a 10.5 month period. The horizontal red lines highlight the mission requirements for Aura. Clearly, the node strategies deviate from the reference scenario (pink) the most. The polar strategies are almost indistinguishable from the reference scenario.

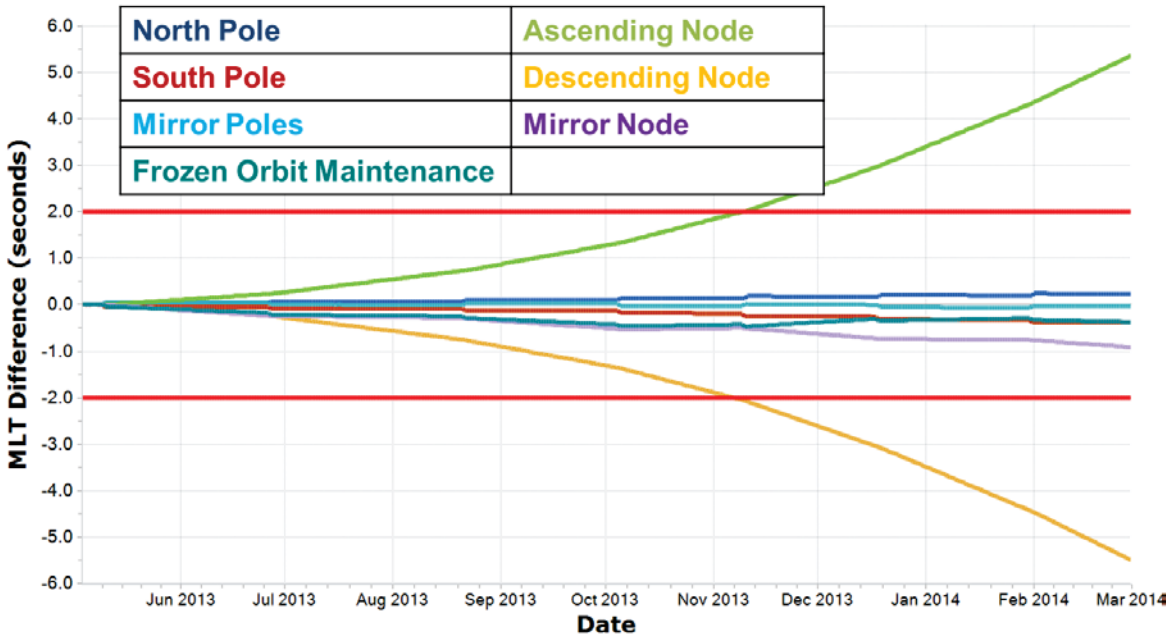


Figure 7. This figure provides a quantitative comparison of the MLT difference between the seven no-slew scenarios and the reference slewed scenario. The horizontal red lines mark the +/- two second prediction requirement. The node strategies violate the +/- two second prediction within seven months. The polar strategies provide the smallest MLT difference, each within +/- one second.

The mirror nodes strategy also provides a scenario that passes the +/- two second MLT prediction requirement. Under the mirror nodes strategy, each maneuver produces a small amount of inclination change that affects the time rate of change of the right ascension. By alternating maneuvers between the nodes, the achieved delta-i is essentially canceled out; however, the right ascension has time to drift between maneuvers before the inclination change has been canceled. The "success" of this strategy is its reliance upon solar flux conditions. During solar minimum, the time between DMU maneuvers is larger and therefore the MLT has more time to drift from the ideal before the inclination is returned to its ideal value during the subsequent maneuver. During solar max DMU maneuvers occur more frequently, thus shortening the amount of time the inclination change affects the right ascension rate. For this analysis, the simulation was run during solar max of solar cycle 24 (2013-2014) in which a DMU is predicted to occur about once a month [5]. This timing essentially represents a best case scenario for the mirror nodes strategy, which is already more than twice the frozen orbit strategy MLT error.

The frozen orbit maintenance strategy passes the +/- two second requirement as well. At first glance, this scenario seems like the best choice as it involves the least amount of change to the current maneuvering strategy while maintaining the +/- two second requirement. The largest flaw with this scenario is its lack of predictability. The algorithm that selects the optimal maneuver location based on frozen orbit maintenance just happens to select maneuver locations that successfully maintains Aura's MLT. Historically, maneuvers have ranged between an argument of latitude of 140 and 360 degrees but have occurred outside of this range as well. The unpredictability in this strategy is especially evident in Fig. 5 as the amount of right ascension change has no predictable pattern. It is possible that in order to maintain the frozen orbit throughout a year the maneuver location will need to be near the nodes, which was shown to be detrimental to the MLT prediction requirements. The unpredictable nature of this strategy is reason enough to discard it as predictability is an essential factor in constellation flying, and especially important in future implementation on Aqua as the constellation anchor.

In summary, this year long simulation demonstrates that maneuvering at the poles provides the best method for maintaining Aura's MLT profile as the out-of-plane energy is put into changing the right ascension instead of the inclination. In order to take the benefits of this pole strategy to the extremes, alternating DMU maneuvers between the poles provides virtually no change in MLT compared to the reference as the effects on the right ascension from a pair of maneuvers is essentially zero.

5. Frozen Orbit Implications and Modification to the Mirror Pole Strategy

Under slewed DMU maneuver operations, the maneuver is performed in the location that best maintains the frozen orbit properties. When switching to no-slew operations using the mirror poles strategies, the freedom to maneuver in the location that best maintains the frozen orbit property is lost. The analysis presented in Section 5 shows how MLT considerations now dictate the maneuver location. Figures 8 and 9 show the impact to the frozen orbit properties (argument of perigee and eccentricity) over the course of a four year simulation. The horizontal red lines

represent the mission requirements (argument of perigee = 90 +/- 20 degrees and eccentricity = 0.0012 +/- 0.0004).

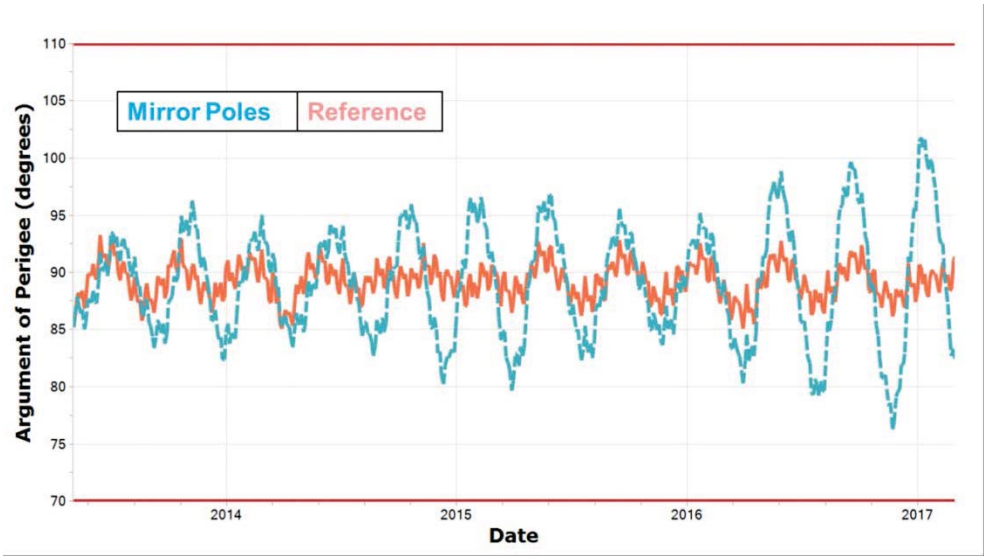


Figure 8. The argument of perigee for the mirror poles strategy and the reference slewed scenario over a four year simulation. The reference scenario maintains a tight oscillation around 90 degrees as the maneuver location is selected to maintain this tight behavior. The amplitude of the mirror poles strategy continues to compound over the four year simulation.

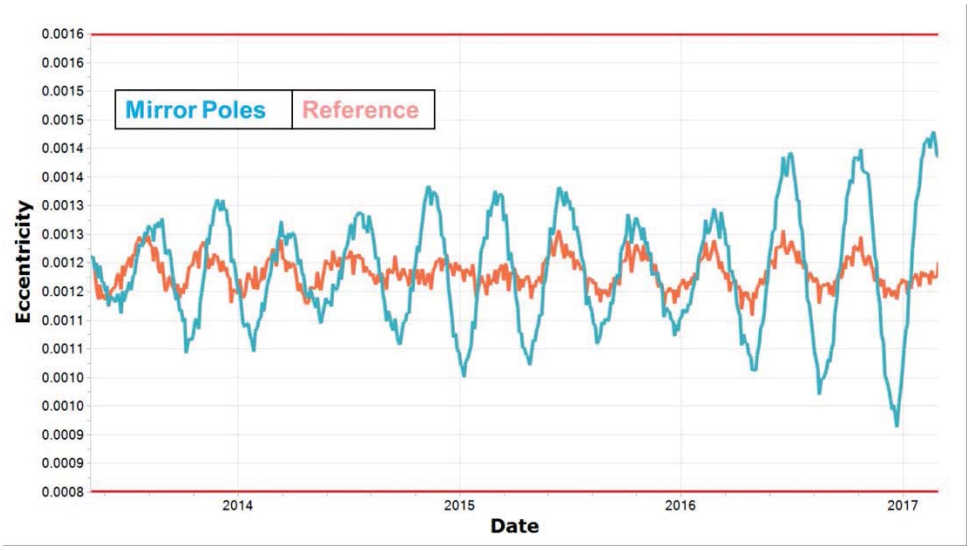


Figure 9. The eccentricity for the mirror poles strategy and reference slew scenario over a four year simulation. The same behavior found in the argument of perigee plot is evident in the eccentricity plot; the reference scenario maintains a tight oscillation about the ideal value (0.0012) while the amplitude for the mirror poles strategy continues to increase.

Clearly the frozen orbit parameters are maintained within their requirements; however, there is a noticeable compounding effect. The 116 day period of coupled frozen orbit properties remains intact but the amplitude of oscillation continues to grow. There are three primary concerns with

this behavior: violation of mission requirements, detrimental effects to the science data, and impact to mission safety. First, current lifetime estimates indicate that Aura has enough fuel to maintain its MLT until 2022, and Aqua until 2020. Although changes in MLT can become more apparent in the short term, the longer term frozen orbit effects could become problematic over the lifetime of the mission. Additionally, the compounding effects within the first four years could be enough to disturb the science data. By the end of the four year simulation, the eccentricity extremes reach 0.0009 and 0.0014. This corresponds to a difference of approximately 3 km at apogee and perigee at the extreme eccentricities. A discussion with the scientists would need to occur to determine if these altitude variations are detrimental to science collection. Global altitude variations due to geographic features can be more pronounced than effects from larger eccentricity amplitudes and therefore it is possible that this concern can be ignored. Third, the impact of having the argument of perigee oscillate between 75 and 105 degrees has not been assessed in regard to mission safety; specifically, along-track separation at the orbit plane intersection instead of at the equator.

At this point in the study, no-slew maneuvers were implemented operationally on Aura. Three eight-second demonstration maneuvers were performed followed by six burns of varying sizes from 14.5 to 38.5 seconds. The operational no-slew maneuvers provided the opportunity to gather definitive data which was then used to hone the maneuver predictions. Based on the operational data, it was shown that the elimination of the slew reduced all pre-maneuver attitude thruster firings. Additionally, the maneuver thruster firing data has indicated that maneuvers larger than 17.75 to 21.5 seconds are susceptible to post-maneuver firings. A finer threshold will be determined as more data is collected, as well as increased accuracy predictions for all maneuver sizes. Table 4 below provides the results of the nine no-slew DMUs used in this study. The reduction in attitude errors, which further reduces the pre- and post-maneuver thruster firings, increases the accuracy of the maneuver predictions.

Table 4. Aura no-slew maneuver results. Maneuver prediction accuracy is based on the relative error of the SMA prediction.

Maneuver	Date	Duration (seconds)	Predicted SMA Change (meters)	Achieved SMA Change (meters)	Percent Error
DMU#43	7/19/12	8.00	55.30	47.10	14.8 Cold[1]
DMU#46	10/4/12	8.00	46.80	46.71	0.2 Cold
DMU#49	11/14/12	8.00	47.10	45.51	3.4 Cold
DMU#50	12/20/12	14.50	84.83	84.05	0.9 Cold
DMU#51	1/16/13	33.00	194.49	200.59	3.1 Hot
DMU#52	4/3/13	38.50	228.27	240.30	5.3 Hot
DMU#53	5/22/13	25.00	148.80	146.10	1.8 Cold
DMU#54	6/26/13	17.50	103.25	98.89	4.2 Cold
DMU#55	8/1/13	21.50	127.58	124.15	2.7 Cold

[1] DMU#43 prediction was based on slewed maneuver data causing the maneuver to be 14.8 percent cold. Subsequent maneuvers used only no-slew maneuver data.

Following the operational no-slew maneuvers, the lifetime simulations run in section 5 were further modified to include the operational no-slew thruster duty cycle and thrust scale factor (TSF) data. New maneuver scenarios were created and analyzed over a four year period. The reference scenario, which modeled all maneuvers as slewed and planned for frozen orbit maintenance, was compared to four others: all mirror pole maneuvers, all frozen orbit maneuvers, and two hybrid schemes, frozen orbit maneuvers with one mirror pole pair, or with two mirror pole pairs. The first two schemes bound the problem; all mirror pole pairs will have the largest effect on the frozen orbit while all frozen orbit maneuvers will have the largest effect on the MLT. The goal was to find the right balance in the hybrid maneuver scheme to maintain both requirements.

The hybrid maneuver schemes were set up in the simulation to model mirror pole maneuvers, in pairs, directly following the completion of the Spring IAM series. This minimizes the time that any small inclination change can propagate before the next IAM series. At some to-be determined point in the year, these schemes switch to frozen orbit maneuvers. Based on the simulation which used the April 2013 Schatten Mean Nominal solar flux predictions, either one or two mirror pole maneuver pairs could be performed each year before the switch. The data collected from the four year simulation is shown in the tables and plots that follow. Tables 5 and 6 show the maximum difference in frozen orbit properties over the four year study. Figures 10-14 plot the frozen orbit, argument of perigee vs. eccentricity over four years, with the graph limits as the operational requirements defined in Tab 1. Figure 15 plots the eccentricity over four years, while Fig. 16 shows the deviation in eccentricity from the reference slew scenario.

Table 5. This table shows the maximum eccentricity for each maneuver scheme in comparison to the eccentricity requirement of .0012 (1.2E-3)

Plan	Max Eccentricity Difference (1 Year)	Max Eccentricity Difference (4 Years)
All Slew	4.59E-05	6.25E-05
All Mirror Pole	9.76E-05	1.47E-04
All Frozen Orbit	4.01E-05	5.69E-05
One Mirror Pole Pair	6.34E-05	8.06E-05
Two Mirror Pole Pairs	9.76E-05	1.20E04

Table 6. This table shows the maximum argument of perigee difference for each maneuver scheme in comparison to the argument of perigee requirement of 90 degrees.

Plan	Max Argument of Perigee Difference (1 Year)	Max Argument of Perigee Difference (4 Years)
All Slew	1.9	3.12
All Mirror Pole	4.25	6.64
All Frozen Orbit	1.96	3.19
One Mirror Pole Pair	2.89	3.76
Two Mirror Pole Pairs	4.25	5.78

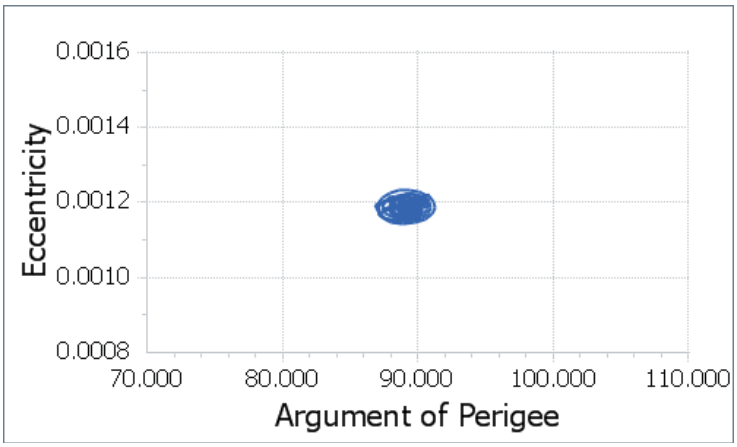


Figure 10. Frozen orbit (eccentricity, argument of perigee) for all no-slew frozen orbit maneuvers over four years.

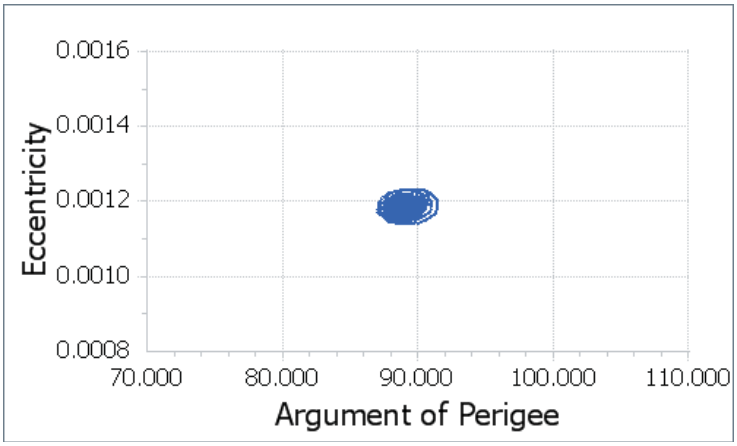


Figure 11. Frozen orbit (eccentricity, argument of perigee) for all slewed frozen orbit maneuvers over four years.

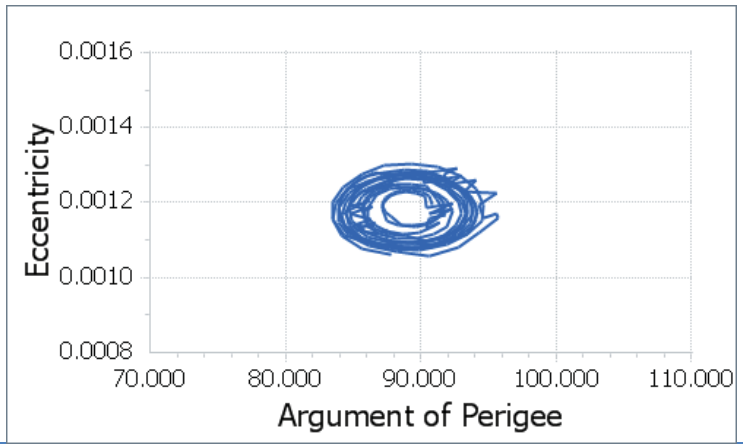


Figure 12. Frozen orbit (eccentricity, argument of perigee) for all no-slew mirror pole maneuvers over four years. The mirror pole strategy shows much larger deviations than the others, but still within operational constraints

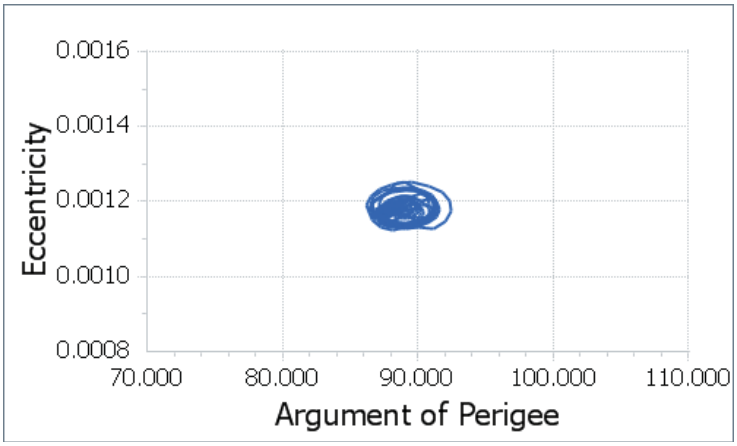


Figure 13. Frozen orbit (eccentricity, argument of perigee) for one mirror pole maneuver pair per year over four years.

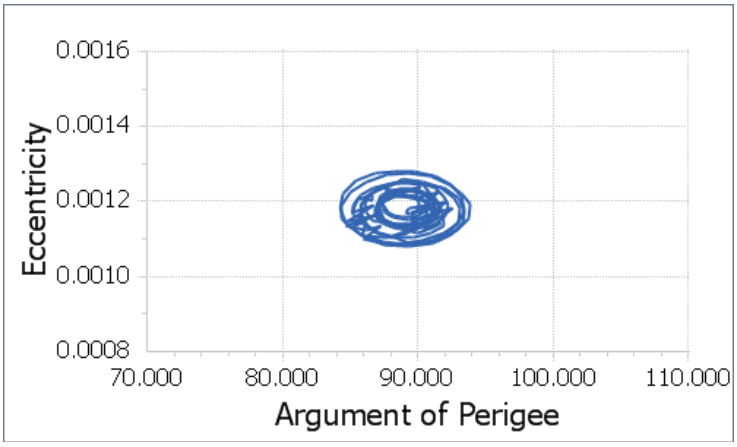


Figure 14. Frozen orbit (eccentricity, argument of perigee) for two mirror pole maneuver pairs per year over four years. The deviations in the frozen orbit are 30% larger for two mirror pole pairs than one pair.

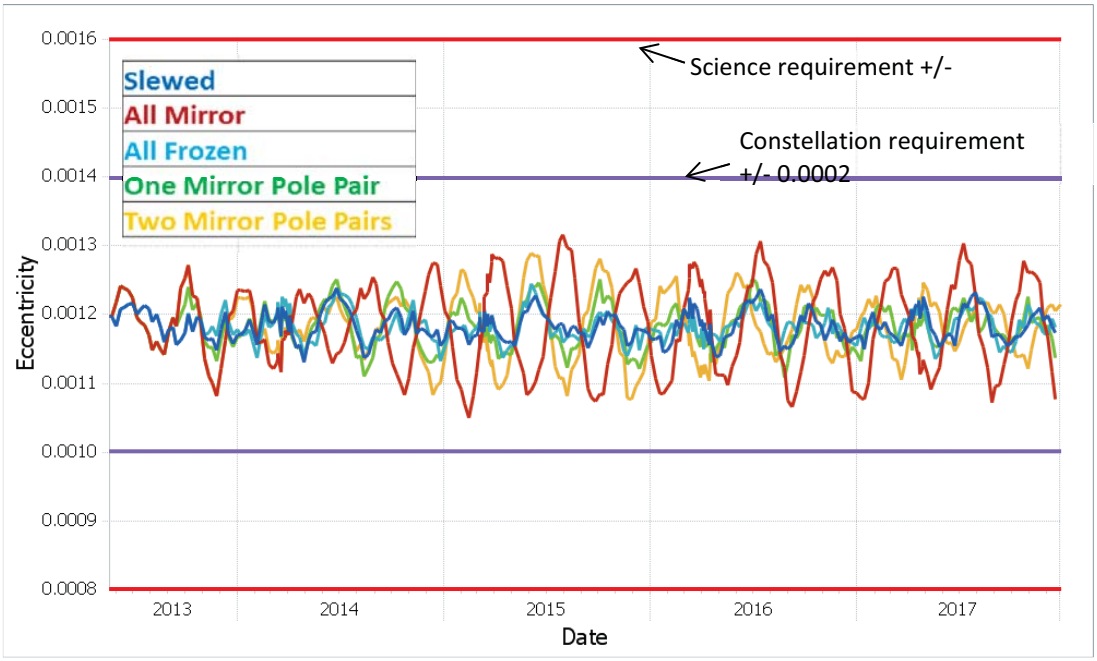
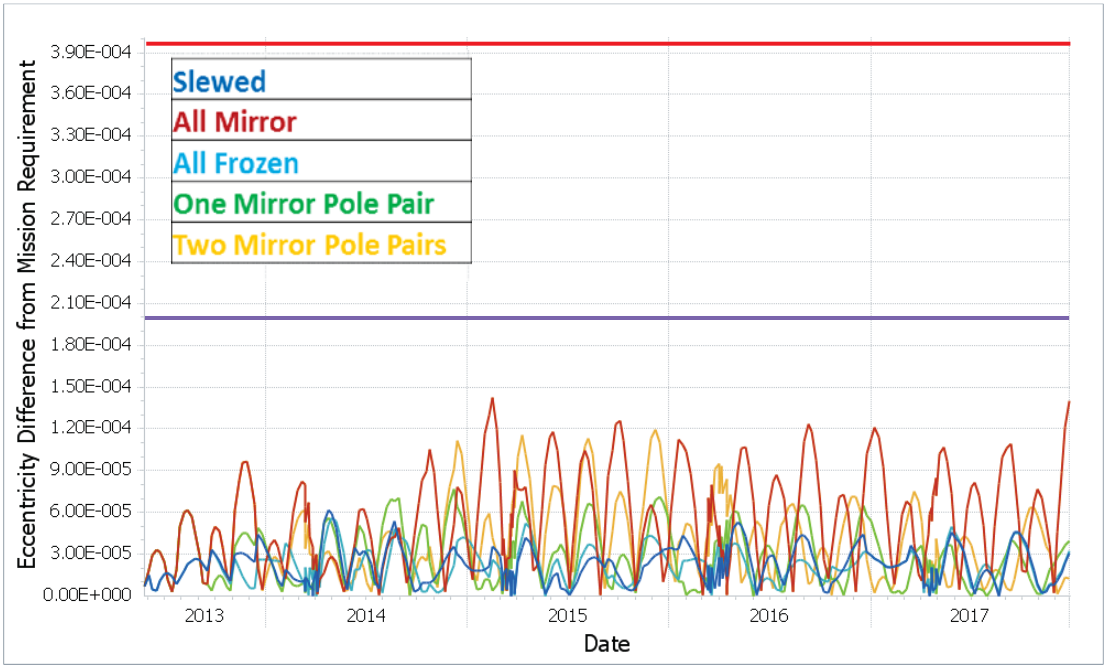


Figure 15. The argument of perigee for the various maneuver strategies and reference slew scenario over a four year simulation. The all mirror pole maneuver strategy shows the most eccentricity deviation, with the other maneuver schemes more tightly controlled. The



spacecraft argument of perigee shows similar behavior over four years.

Figure 16. The argument of perigee for the various maneuver strategies and reference slew scenario over a four year simulation, plotted as the absolute difference from the mission requirement of .0012 (1.2E-3)

Based on the tables and figures, one can see that the mirror pole strategy on its own causes oscillation in the frozen orbit to grow over time. Over four years, performing all mirror pole pairs and performing two mirror maneuver pairs exhibit the most frozen orbit growthThe one mirror pole maneuver pair maneuver strategy maintains the frozen orbit parameters within 30% over four years. It would be helpful to continue this simulation further out in time as most of this simulation occurred during the predicted solar minimum. Solar minimum greatly reduces the need for DMU maneuvers and therefore reduces the effects of non-optimal maneuver locations on the spacecraft orbit. Figures 15 and 16 may imply that the eccentricity growth for the all mirror pole maneuver strategy is bounded, but there is no analytical reason to believe that this would be the case over a longer period of time.

Next, the Mean Local Time is compared in Tab. 7 below for each maneuver scheme over one year. The effects are limited to one year because the MLT is essentially reset each year during the IAM series.

Table 7. This table shows the maximum mean local time difference for each maneuver scheme in comparison to the nominal slewed maneuver scheme. The yearly mean local time requirement is +/- 2 seconds.

MLT Difference Compared to a Slewed Maneuver Strategy	
Plan	**MLT Difference (sec) over one year**
All Mirror Pole	0.20
All Frozen Orbit	0.24
One Mirror Pole Pair	0.03
Two Mirror Pole Pairs	0.05

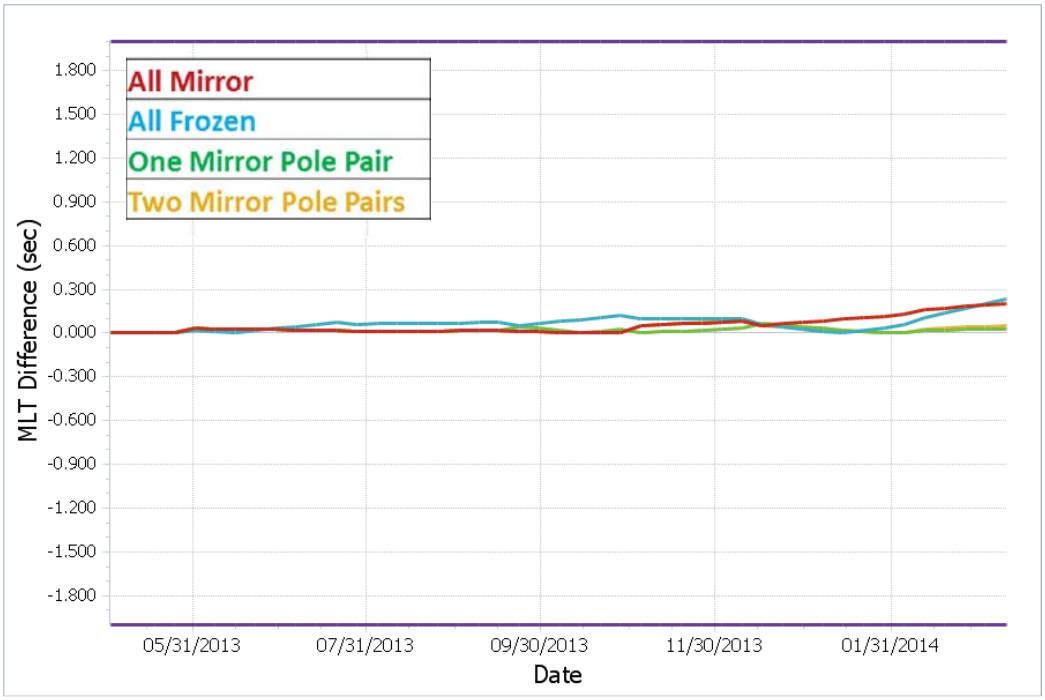


Figure 17. Absolute value of mean local time difference compared to the slewed reference strategy for each maneuver scheme over one year. Bounds represent +/- 2 second yearly mean local time requirement.

As shown, over one year the MLT difference over all maneuver schemes is tightly bound, predicted to be less than a .25 second deviation. There is not a significant amount of degradation of the MLT prediction for either hybrid maneuver strategy.

7. Conclusions

Modifications to the nominal DMU maneuver strategy are required in order to maintain the MLT prediction requirements under no-slew DMU operations. As shown, the maneuver location (argument of latitude) plays a key role in the effect on the orbital elements when introducing an out-of-plane delta-v component. DMU maneuvering at the poles produces pure delta-RAAN while maneuvering at the nodes produces pure delta-i. Slight variations in inclination will alter the time rate of change of the right ascension, thus altering the evolution and predictability of the MLT profile throughout the year. The potential for error in the MLT profile makes it difficult for other constellation members to plan their own IAM series in order to maintain along-track separation requirements. To prevent this unwanted alteration to the inclination, performing maneuvers alternating between the poles (instead of the location necessary to maintain frozen orbit properties) ensures zero inclination change from each maneuver with a zero net RAAN change after a pair of maneuvers.

While this strategy is successful in maintaining the MLT profiles and along-track separation requirements, further research determined that the long term effects on the frozen orbit properties were significant enough to warrant a modified mirror pole maneuver strategy. It was found that performing maneuvers at the poles for a given period after the Spring IAM series then switching the maneuver location to the argument of latitude that best maintains the frozen orbit properties

can be used to maintain both MLT and the frozen obit. Furthermore, the study finds that the MLT can be maintain by relatively few mirror pole pairs, with an insignificant difference between performing one or two pairs per year. Because the MLT can be reset each year during the IAM series, it would be more prudent to perform as many frozen orbit maneuvers as possible without broaching the +/-2 second MLT requirement; therefore, based on the current environmental predictions, performing one mirror pole pair per year will be sufficient to maintain both requirements.

Further study of the effects of solar minimum and maximum on this maneuver strategy will be important as the current solar cycle decreases in the solar minimum. Solar minimum will increase time between DMUs which in turn will increase the MLT deviation as the RAAN rate errors produced from an initial mirrored pole maneuver execution propagate over a longer period of time. Future work should also look at the effects of Risk Mitigation Maneuvers (RMMs) on both the frozen orbit and MLT. RMMs are most often performed in a location chosen to reduce current risk, generally from debris, and therefore could be detrimental to mission requirements under the no-slew strategy. Current analysis points to a small effect considering relatively few RMMs are executed each year. In addition, a longer term lifetime simulation, covering the entire remaining mission is warranted before implementing the no-slew hybrid maneuver strategy on Aqua.

8. References

[1] Earth Science Mission Operations Project, "Afternoon Constellation Operations Coordination Plan" 428-10-08 Revision 1, 2011.

[2] King-Hele, D.G., "Satellite Orbits in an Atmosphere: Theory and Application," Springer, 1987, pp. 127-132.

[3] Gurfil, P., "Modern Astrodynamics," Butterworth-Heinemann, 2006, pp. 15-17.

[4] Capderou, M., "Satellites: Orbits and Missions," Springer, 2005, pp. 59-90.

[5] Solar Physics, Marshall Space Flight Center, "Solar Cycle Prediction (Updated 2013/04/01)," http://solarscience.msfc.nasa.gov/predict.shtml, Accessed 02 Apr. 2013.