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Understanding Maneuver Uncertainties during Inclination Maneuvers of the Aqua Spacecraft[†]

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Abstract

During the Fall 2006 inclination campaign for the Aqua spacecraft it was discovered that there was significant uncertainty in the prediction of the semi-major axis change during a maneuver. The low atmospheric drag environment at the time of the maneuvers amplified the effects of this uncertainty leading to a potential violation of the spacecraft ground-track requirements. In order to understand the uncertainty, a Monte Carlo simulation was developed to characterize the expected semi-major axis change uncertainty given the observed behavior of the spacecraft propulsion and attitude control systems during a maneuver. This expected uncertainty was then used to develop new analysis tools to ensure that future inclination maneuver plans will meet ground-track control requirements in the presence of the error.

I. Introduction

The earth Observing System (EOS) Aqua mission orbit is in a sun-synchronous orbit with a 16-day repeating ground track. The mean local time (MLT) of the sun-synchronous orbit is required to remain between 13:30 and 13:45 at each ascending node. The ground track must be maintained to within ±10 km of the World Reference System – 2 (WRS-2) grid. A unique combination of ideal SMA and inclination values allow the orbit to meet both the sun-synchronous and repeating orbit conditions simultaneously. This is because both sun-synchronous and repeating orbits are derived from special conditions placed on the rate of change of the right ascension of the ascending node, which is in turn a function of SMA and inclination. Therefore, changes to either element value due to perturbations on the orbit cause changes in both the sun-synchronous and repeating properties of the mission orbit. Changes in MLT are predominantly driven by changes in inclination due to luni-solar perturbations on the orbit, while changes in the period are predominantly driven by changes in the SMA due to atmospheric drag. Aqua routinely corrects for these perturbations using inclination corrections maneuvers and ground track correction maneuvers, respectively. During the inclination adjustments, the SMA of the orbit must also be corrected due to the inclination/ideal-SMA coupling. Additionally, Aqua is only capable of performing posigrade ground track maneuvers, meaning the +10 km limit on the WRS-2 control box is the only controllable limit. Orbit maneuvers are therefore designed such that the orbit shall never violate the -10 km limit.

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Due to thermal, power, and instrument constraints, Aqua is required to complete inclination maneuvers within one spacecraft night of approximately 33 minutes. Because the reaction wheels do not provide enough control authority to perform the attitude maneuvers within this allotted time, the yaw slews to the burn attitude must be performed on thrusters. The yaw slew rate using thrusters then dictates that the maximum inclination burn duration is approximately 10 minutes. This limitation means that large inclination changes have to be broken into a series of smaller maneuvers to achieve the final desired orbit change. Additionally, when Aqua slews on thrusters to perform an inclination maneuver, the pulsing of the attitude thrusters during the slews imparts SMA changes. The SMA change is positive during both slews, so the inclination maneuver is intentionally performed at an offset yaw angle to remove the anticipated accrued SMA during the main burn. A full description of Aqua's maneuver capabilities and limitations is provided in Reference 1.

During the fall of 2006, a series of six inclination maneuvers was planned to control the Aqua MLT. During the execution of the first four maneuvers in this series, the expected SMA performance from the maneuver sequence was not achieved. This resulted in a potential violation of the uncontrollable -10 km WRS-2 limit if further inclination changes occurred without reduction in the SMA. Therefore, mission management decided to waive-off the remaining two maneuvers and investigate the causes of the variations in SMA performance.

An investigation was undertaken to understand what had led to the unexpected observed SMA performance and potential WRS-2 violation. In addition, a more robust methodology for future maneuver planning was required to account for the problem. This paper details this investigation and the new techniques developed to plan maneuvers in the presence of uncertainty. Past inclination maneuver performance, which was used as the basis for the planning of the Fall 2006 series, is discussed. The differences in the operational and orbital environments between 2004 and 2006 and their effects on SMA control are highlighted. The performance of the inclination maneuvers is statistically characterized using Monte Carlo methods and these statistics are used to develop new, non-deterministic methods for analyzing future inclination maneuvers.

II. Historical Inclination Maneuver Planning Model and Methodology

An inclination maneuver consists of three segments: slew-out, inclination burn, and slew-back as shown in Figure 1. The entire maneuver sequence must be completed during orbit night due spacecraft constraints such as instrument lighting. The slew-out is a thruster based attitude maneuver that yaws the spacecraft from its operational attitude of 0,0,0 Yaw-Pitch-Roll (YPR) in the Local-Vertical-Local-Horizontal (LVLH) coordinate system to the inclination burn attitude. The inclination burn segment is dedicated to the out-of-plane orbit change. The slew-back is another thruster-based attitude maneuver that returns the spacecraft from the burn attitude to its operational attitude.

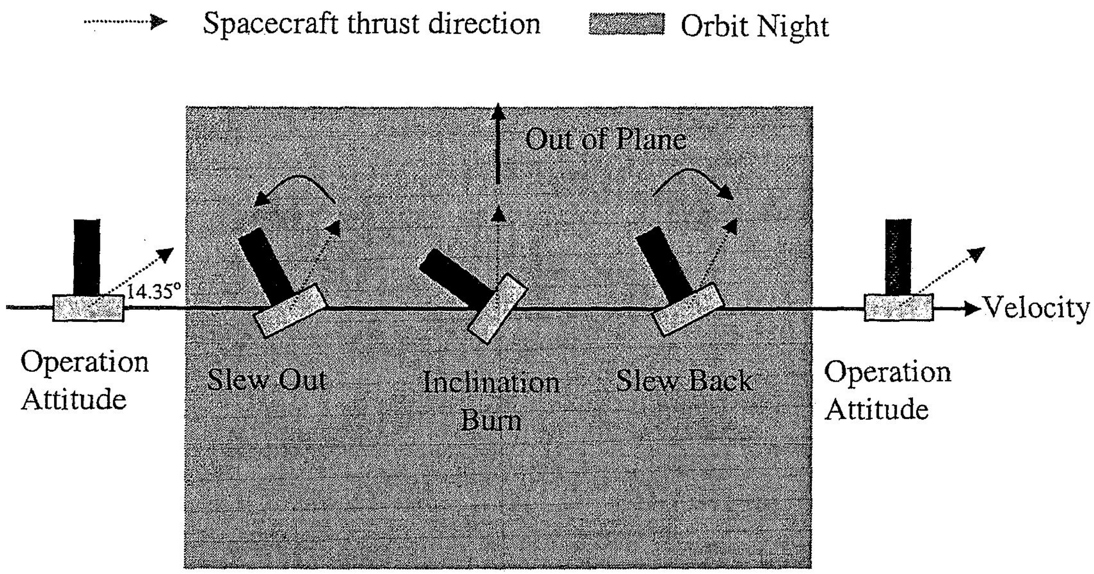

Figure 1. Inclination maneuver sequence.

The Aqua spacecraft propulsion system consists of four asymmetrically-aligned thrusters located on the –X face of the spacecraft that provide both attitude and orbit control. This design results in a high degree of coupling between attitude maneuvers and the spacecraft orbit because the thrusters are aligned to maximize their capability to perform all required functions given the location of the spacecraft center-of-mass. During attitude maneuvers, combinations of the four thrusters are fired to provide the necessary rotational torque. However, due to the thruster locations, the thruster firings to perform attitude maneuvers result in perturbations to the spacecraft orbit. The resultant thrust vector is -14.35 degrees away from the +X axis of the spacecraft, which must be compensated for by slewing to burn attitude prior to orbit maintenance maneuvers. As attitude errors accumulate during an orbit adjust maneuver, the thrusters are modulated, or off-pulsed, to maintain the proper attitude. The ratio of the amount of time a thruster actually fires to the commanded burn duration is termed the "duty cycle" of the thruster. The actual duty cycles for any given maneuver will depend on the accumulated attitude errors during the maneuver. Attitude errors are in turn a function of the environmental torques on the spacecraft as well as initial conditions of the attitude.

The ideal inclination burn attitude that puts the thrust vector entirely out-of-plane has a yaw angle of -75.65 degrees due to the thrust vector offset. However, due to the asymmetric thrusters, the slew-out and slew-back portions of the maneuver contribute a significant amount of positive energy increase to the orbit as seen in Figure 2. Therefore, the commanded yaw angle of the inclination maneuver is increased to compensate for the expected combined energy increase during the slew out and slew back. By selecting an appropriate yaw angle, the net SMA change from the entire sequence should be controllable, allowing the maneuvers to be designed to achieve both inclination change and the new ideal SMA required by the new inclination.

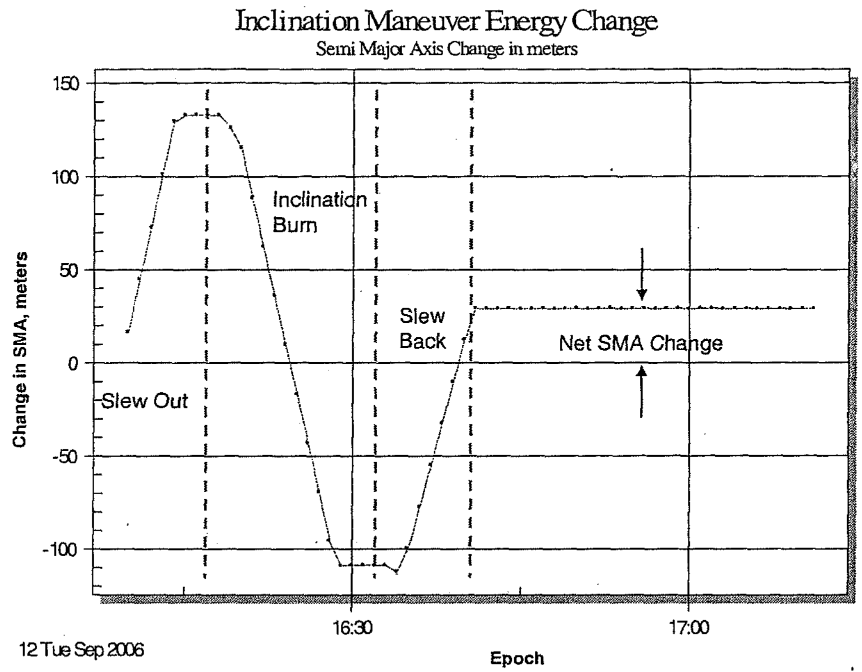

Figure 2. Semi major axis change during slew out, inclination burn, and slew back.

The inclination maneuver sequence is modeled in the Flight Dynamics System (FDS) software as a separate finite propulsive maneuver for each of the three segments. Each segment has unique values for thruster duty cycles for thrusters 1-4, for maneuver duration, and for maneuver thrust scale factors. Additionally, the averaged roll, pitch, and yaw attitude errors are added to the commanded attitude for the inclination burn. The duty cycles and attitude errors used in maneuver planning are averages of previous inclination maneuvers. Assuming the historical average performance of the propulsion and attitude control systems is representative, the only remaining variable under the control of the maneuver designer is the commanded yaw angle. This commanded yaw angle is used to control the variation in the SMA during the inclination maneuver by determining how much of the thrust vector is normal to the orbit plane. This model has been used for all inclination maneuvers for Aqua as well as the Aura spacecraft, which is built on the same spacecraft bus and has virtually identical flight code. Post-maneuver reconstruction is performed using the same models but with observed telemetry values used for the maneuver duty cycles and attitude errors.

The basis for the methodology and performance modeling of the 2006 inclination series was the performance of a similar series in August/September of 2004. The same tools and methodology used during the 2004 series were used in the planning and reconstruction of the 2006 series. The inclination and SMA performances for maneuvers 3 – 7 which constituted the 2004 series are shown in Figure 3 and Figure 4. Figure 3 shows that the actual inclination change was less than 3% in error from the predicted change. The small difference between the predicted and actual inclination change suggests that the maneuver model adequately predicts this portion of the maneuver. The SMA performance error is shown in Figure 4, which shows variation from the expected. The yaw angles chosen for the 2004 inclination series were designed to deliver approximately zero change in SMA, with the exception of the third maneuver. Due to the drag environment during the fall of 2004, the third maneuver was designed to deliver an increase in SMA of approximately 44 meters to prevent a violation of the top of the WRS-2 control box. The observed SMA error, which is between 4 and 16 meters per maneuver, can have a significant effect on the WRS-2 Error evolution. However, the high drag environment of 2004 served as the primary mechanism for the reduction in SMA required by the inclination change. As a result, the variations in the SMA performance had little effect on the overall WRS-2 Error evolution during the 2004 maneuver sequence. The importance of drag as a "damping" factor on the WRS-2 Error evolutions will be discussed later.

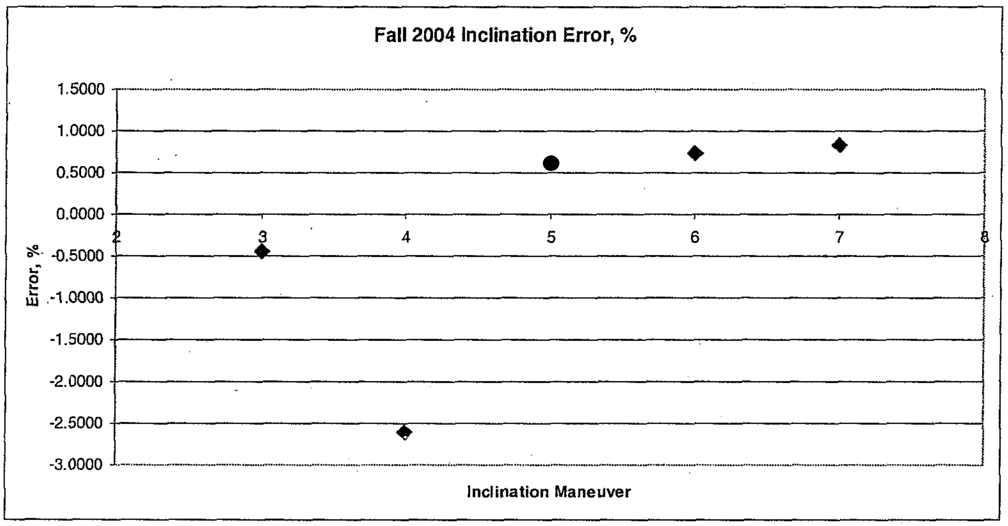

Figure 3. Fall 2004 inclination performance.

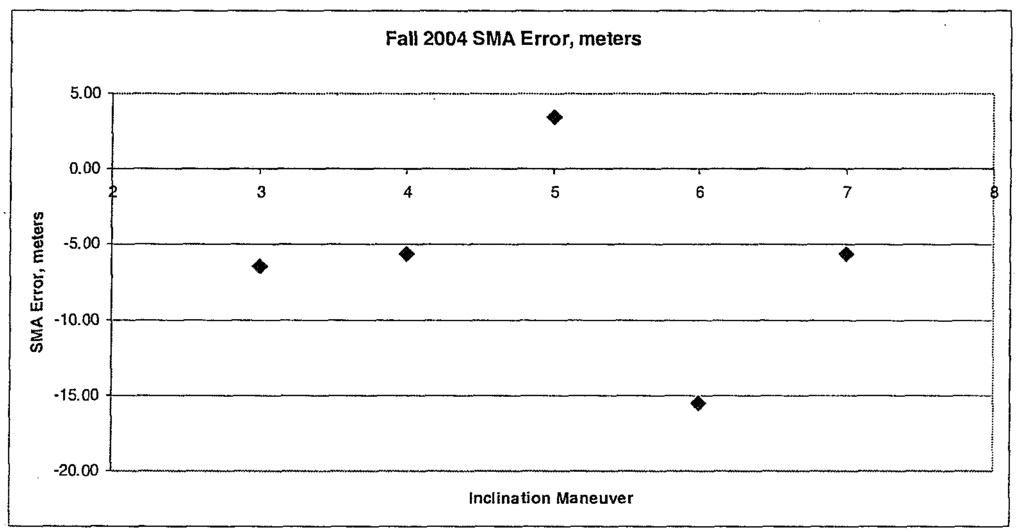

Figure 4. Fall 2004 semi major axis performance.

III. Fall 2006 Maneuver Planning

The following assumptions, based on past inclination maneuver performance and experience, were used in planning the 2006 inclination maneuver series:

1. It is desirable to minimize variations in the maneuver parameters from those used in the 2004 inclination series. Specifically, yaw angles used for the 2006 maneuvers should be "in family" with those used in 2004.
2. Similar performance of the spacecraft's propulsion system will result in similar effects on the spacecraft's orbital trajectory. Specifically, average propulsion system parameters can be used to choose commanded yaw angles that will result in specific SMA performance.
3. The tools and methodology used in 2004 are sufficient for the 2006 inclination time period.

The Fall 2006 inclination maneuver plan resulting from using the 2004 planning process and the above assumptions is shown in Table 1. Six maneuvers were planned. Each maneuver used the commanded yaw angle of -82.9 degrees to deliver approximately –0.011 degrees of inclination change and an SMA change of approximately -10 meters as seen in Figure 5. The expected WRS-2 Error evolution is shown in Figure 12 for the entire maneuver series. This maneuver plan, along with the predicted drag environment, was expected to remove more SMA than required and force the WRS-2 Error trend toward the upper/controllable +10 km limit as seen in Figure 5. A Drag Make Up (DMU) maneuver could then be performed shortly after the inclination series.

Inc #	Day of Week	Date	Day of Year	Slew Out Time	Inc Start Time	Slew Back Time	Δi deg	Inc ΔV m/s
8	Tue	22-Aug-06	234	15:52:34	16:02:29	16:17:41	-0.0108	1.438
9	Tue	29-Aug-06	241	15:58:11	16:08:06	16:23:18	-0.0108	1.429
10	Thu	7-Sep-06	250	15:51:11	16:01:06	16:16:18	-0.0107	1.420
11	Tue	12-Sep-06	255	16:09:13	16:19:08	16:34:20	-0.0107	1.411
12	Tue	19-Sep-06	262	16:14:37	16:24:32	16:39:44	-0.0106	1.403
13	Tue	26-Sep-06	269	16:19:56	16:29:51	16:45:03	-0.0105	1.394

Table 1. Inclination maneuver plan for Fall 2006.

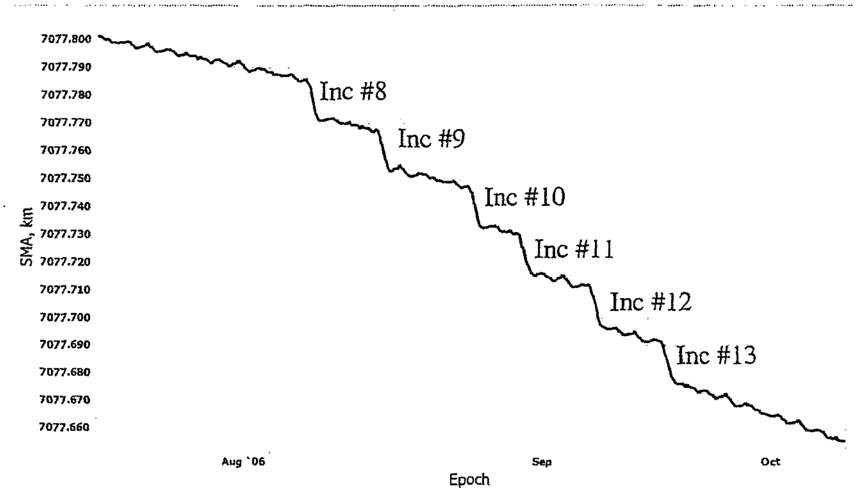

Figure 5. Fall 2006 inclination maneuver series expected SMA change.

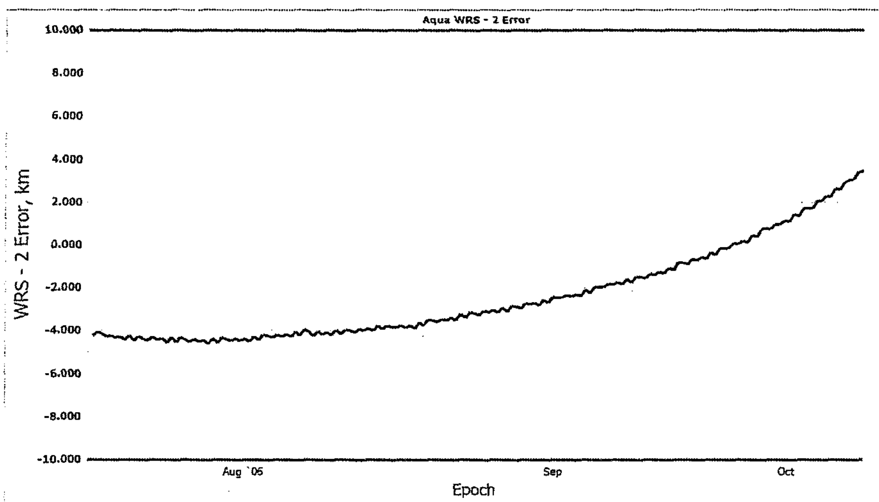

Figure 6. Fall 2006 inclination maneuver plan effects on WRS-2 evolution.

IV. 2006 Inclination Maneuver Performance

The first four maneuvers of the 2006 inclination series (maneuvers 8 – 11) were performed as planned according to Table 1. The inclination performance was within the expected 3% error as seen in Figure 7; however, the SMA performance was not as expected. The achieved versus expected SMA performance is shown in Figure 8 and the SMA history is shown in Figure 9.

The first maneuver, Inclination #8, used the commanded yaw angle of -82.94 degrees. This yaw angle slightly over-performed based on historical performance, removing more SMA than expected (-19 vs. -10 meters). Inclination #9 was therefore planned with a small reduction in yaw angle to -82.89 degrees. This maneuver resulted in a positive 5 meter SMA change as opposed to the planned -5 meter change. Between maneuver #9 and #10 the planning duty cycles and scale factors were updated to average in the values from maneuvers #8 and #9. These updated planning parameters resulted in the commanded yaw angle of -82.75 degrees being used to deliver an expected -11 meter SMA change. However, the slew duty cycles were larger than the average values resulting in a nearly 0 SMA change. The fourth maneuver was therefore planned with a yaw angle of -83 degrees to give an expected -17 meter SMA change. However, the slew duty cycles again increased resulting in a positive SMA change for maneuver #11.

The required SMA change over the entire inclination series was approximately -100 meters. The original plan was designed for each of the 6 maneuvers to remove approximately 10 meters of SMA. The predicted drag environment was expected to remove an additional 30 to 40 meters of SMA. By the end of the fourth maneuver, the SMA had only been decreased by approximately 35 meters, much of which was due to the first maneuver of the series and drag. The resulting WRS-2 Error evolution is shown in Figure 10. Comparing the actual trend with the expected trend from Figure 6 shows that the actual maneuver performance never established a WRS-2 Error trend toward the top, controllable limit. In fact, Figure 10 shows that a trend toward the uncontrollable -10 km limit was established.

Analysis following inclination maneuver #11 showed that any further reduction in inclination without a reduction in SMA would lead to a violation of the -10 km WRS-2 limit. At this point, mission management made the decision to halt the current maneuver series until analysis could be completed that would indicate why these maneuvers didn't yield the expected SMA change and how planning of future maneuvers could be done differently to correctly model the expected change.

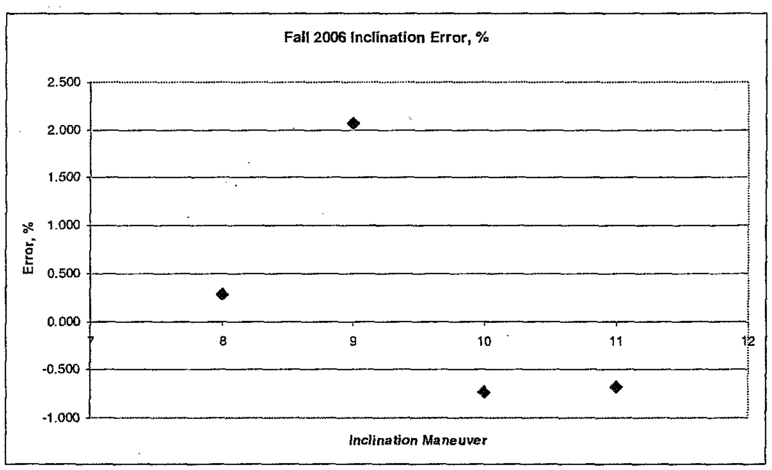

Figure 7. Fall 2006 inclination performance.

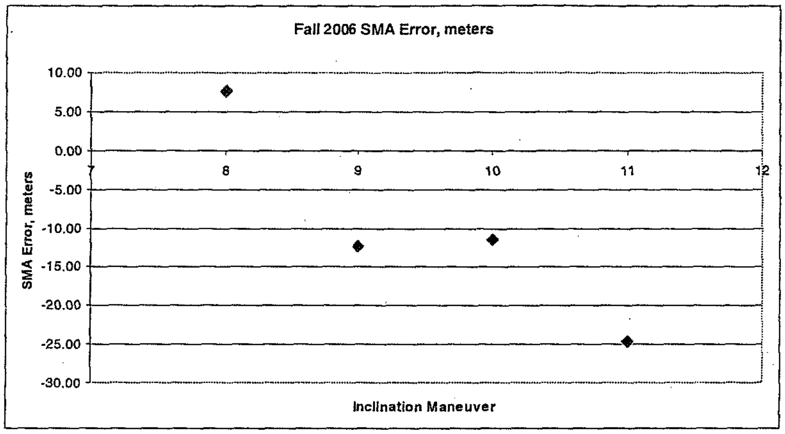

Figure 8. Fall 2006 observed SMA change.

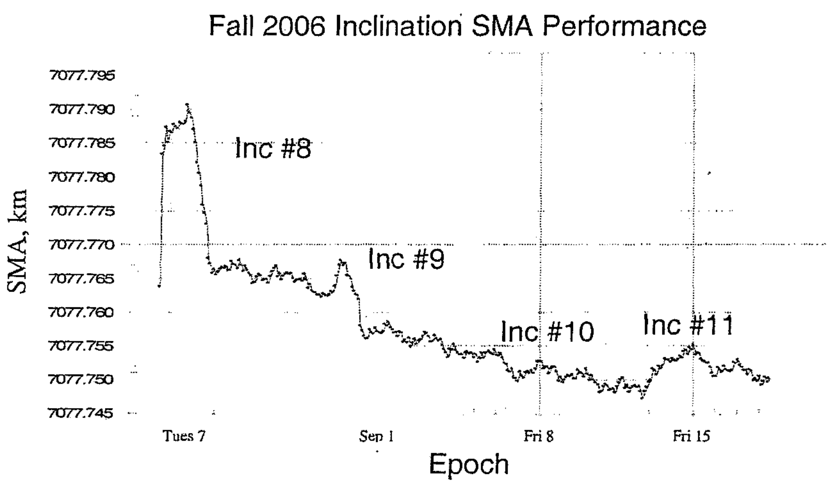

Figure 9. Fall 2006 SMA history.

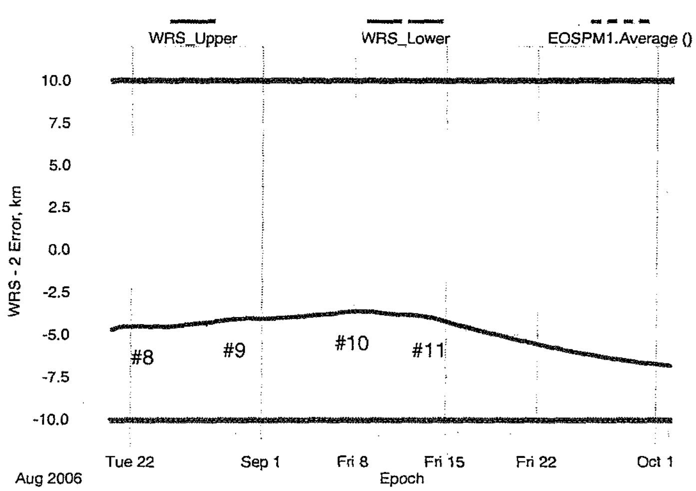

Figure 10. Fall 2006 WRS-2 Error.

V. Operational Differences Between 2004 and 2006 Maneuvers

Several fundamental differences in the orbital environments and operational plans existed between the 2004 and 2006 inclination series. The first step in analyzing the unexpected SMA changes was to investigate these differences to assess their impact on the 2006 maneuver performance.

The primary difference in the orbital environment between the 2004 and 2006 inclination series was drag. The average solar flux level during the 2004 inclination series is characterized by a F10.7 value of 101. The average solar flux level during the 2006 inclination series was significantly lower and is characterized by an F10.7 value of 77. To investigate the effect of the drag environment on the WRS-2 control during inclination maneuvers, two trajectories were propagated using the actual 2006 inclination maneuver performance with different drag models. The higher drag propagation used the Harris Priester drag model with a flux level of 100 which is typical of the drag environment during the 2004 inclination maneuvers. The lower drag model used the Harris Priester drag model with a flux level of 75 which is typical of the drag environment during the 2006 inclination maneuvers. The results are shown in Figure 11 and Figure 12.

The SMA profile shown in Figure 11 demonstrates that the higher drag environment of 2004 removes over twice as much SMA as the low drag environment of 2006. As stated previously, the high drag environment of 2004 was the primary mechanism for removal of SMA during those inclination maneuvers. The fourth maneuver of that series actually required SMA to be put back into the trajectory to compensate for energy loss. The effect of the different drag profiles on the WRS-2 Error is seen in Figure 12. The low drag environment curve shows the actual performance during 2006. In this case, because the actual SMA is greater than the ideal SMA the WRS-2 error curve trends toward the uncontrollable – 10 km limit. In the high drag case, the SMA has been decreased below the ideal SMA due to the high drag and the WRS-2 Error is trending toward the controllable + 10 km limit.

During the 2004 inclination series, the higher drag environment was the dominant factor in the evolution of the SMA and hence the WRS-2 Error. The variations in SMA performance that were observed in the 2004 maneuvers and their effects on WRS-2 Error were "damped" by this dominant drag environment. With the lower drag environment in 2006, the variations in SMA had a greater effect on the WRS-2 Error evolution. Therefore, it is reasonable to state that when the WRS-2 Error evolution is not dominated by drag, variations in the SMA performance will have an increased effect and must be considered in the overall maneuver plan.

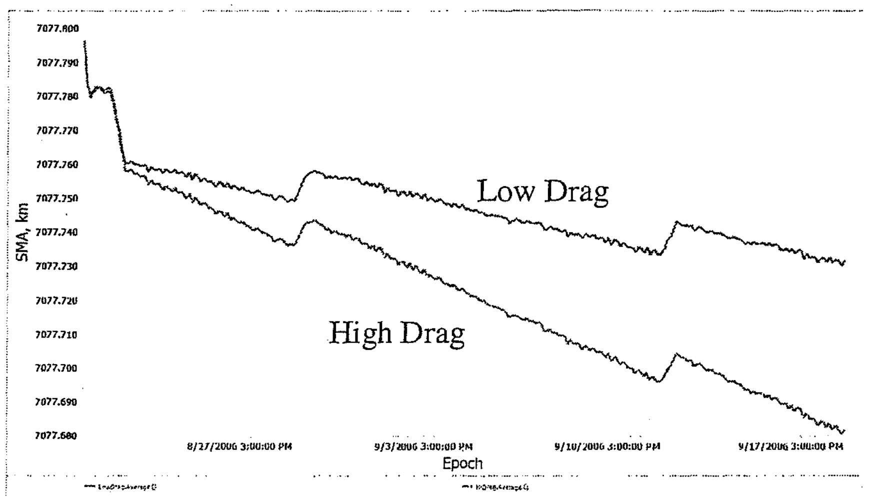

Figure 11. Semi Major Axis history for low and high drag environments.

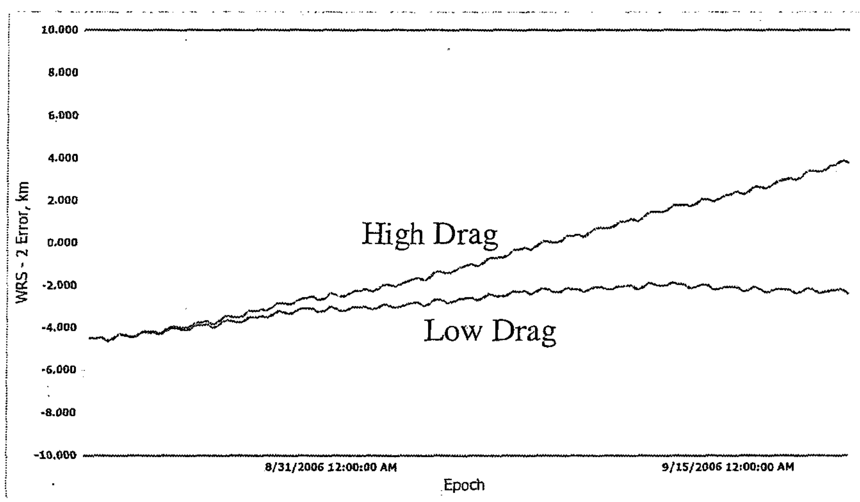

Figure 12. WRS-2 Error performance for low and high drag environments.

Also, between the 2004 and 2006 maneuver campaigns the WRS-2 error limits for Aqua were reduced from +/- 20 km to +/- 10 km. This reduction in ground track control requirements was implemented to accommodate the addition of CloudSat and Calipso to the Afternoon Constellation. While the control limit reduction has no direct impact on the spacecraft maneuver performance, it did reduce the margin for errors in ground track performance. With a larger control box, larger negative WRS-2 Error rates could have been tolerated without violating the lower limit. However, because the smaller control box was in place, any additional negative rate after maneuver #11 would have resulted in a violation of the – 10 km limit.

In light of the SMA and WRS-2 performance issues observed in the first four inclination maneuvers of the 2006 series, an effort was made to understand the effect of normal variations in the propulsion system on SMA and WRS-2 performance. The first efforts centered on trying to find a correlation between spacecraft propulsion system performance and commanded yaw angle, as it was hypothesized that a correlation may exist.

The achieved SMA change versus commanded yaw angle is shown in Figure 13. No direct correlation can be observed from this data. In fact, a single yaw angle of -82.65 degrees shows three distinct resulting changes in SMA. Additionally, no general trend can be established: increased yaw angles between maneuvers 10 and 9 show an increase in SMA, while increase in yaw angles between maneuvers 9 and 8 shows a decrease in SMA. The multiple SMA values at -82.65 degrees and the lack of a definite trend suggests that the resulting SMA change is not deterministic but has significant variations that must be understood.

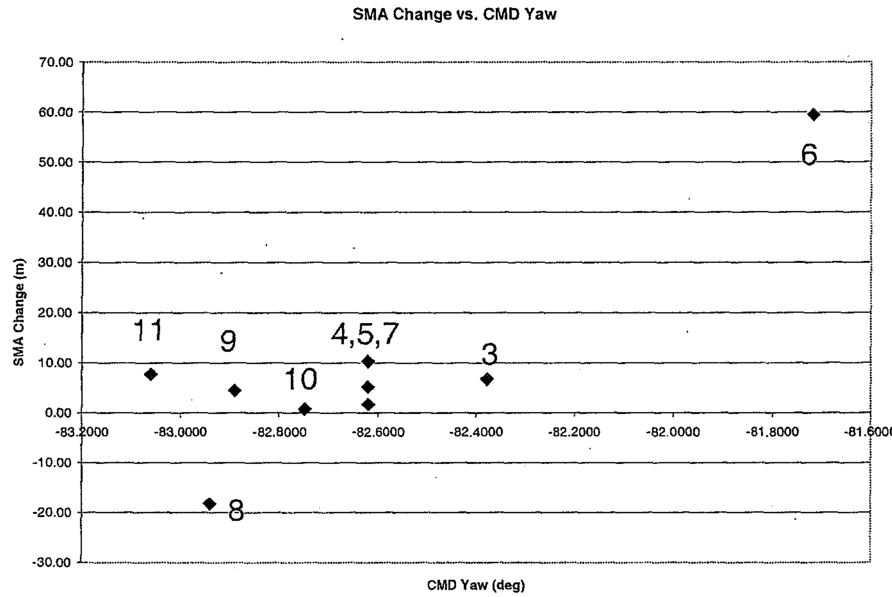

Figure 13. SMA performance versus commanded yaw angle.

To determine if the spacecraft was operating differently during the current inclination maneuvers as opposed to previous maneuvers, the maneuver parameters were evaluated statistically. The observed values along with the +/- 2 sigma values for the duty cycles, average attitude errors, and scale factors were analyzed. With the exception of the Thruster 4 duty cycle during maneuver 7 and the inclination maneuver scale factor for maneuver 8, all values are seen to be within the +/- 2 sigma variation. This consistency leads to the conclusion that the spacecraft propulsion system was performing essentially the same in the Fall 2006 inclination series as it did in previous inclination maneuvers and that none of the observed propulsion system parameters were unexpected. This conclusion was verified by the spacecraft Guidance, Navigation, and Control Systems Engineer.

VI. Monte Carlo Investigation of Spacecraft Performance

A search for a correlation between the maneuver performance and the commanded yaw angle did not yield any insight. Additionally, all the maneuver parameters coming from the spacecraft – duty cycles, attitude errors – appeared to be statistically similar from one maneuver series to the next. It was therefore reasonable to assume that the spacecraft propulsion system had been consistent over all inclination maneuvers. However, there appears to be normal variations in the spacecraft systems that drive the actual SMA change. Due to the low drag environment, these SMA variations were having amplified effects on the WRS-2 Error in the Fall of 2006.

To understand the effect of normal system performance variations on the resulting SMA change from an inclination maneuver, a Monte Carlo analysis was developed. The mean and standard deviation for the propulsion system parameters and attitude errors were determined based on past maneuver performance. The distributions on all the parameters were assumed to be Gaussian. For a given commanded yaw angle, a set of random realizations for all duty cycles, attitude errors, and scale factors were chosen and the maneuver planning script run as a single trial. The resulting SMA for each trial was computed. Trials were repeated with a new set of random inputs until convergence in the mean and standard deviation of the resulting SMA change was observed.

The results of the Monte Carlo analysis are shown in Figure 14 and Figure 15. The mean SMA change versus commanded yaw angle shows an intuitive linear behavior. The standard deviation of the change in SMA is between 12 and 13 meters as seen in Figure 15. These results support the uncertainty observed during Aqua inclination maneuvers. For example, the yaw angle -86.2 degrees has been used three times and resulted in SMA changes from 1.75 meters to 10.35 meters, as shown in **Error! Reference source not found.**. This is consistent with the results shown in Figure 14 and Figure 15, where this yaw angle should result in a mean SMA change of about 7 meters with a standard deviation of approximately 11.9 meters.

Additionally, during the Fall 2006 inclination series the commanded yaw angles used were -82.75 to -83.06 degrees. These yaw angles are seen to have a mean SMA of nearly zero and a standard deviation of around 12 meters. In fact, taking the mean and standard deviation of the SMA change from the -83.06 meter case and assuming a Gaussian distribution, there is an approximate 40% chance for this maneuver to deliver a positive SMA, even though the expected SMA change was negative. In light of these results, it should not have been unexpected that Inclination Maneuvers #7 - #11 gave positive SMA changes at the yaw angles that were used.

The initial assumption used in the planning of the 2006 maneuver series that the average spacecraft parameters from previous maneuvers could be used to determine a specific SMA change was erroneous. The Monte Carlo analysis has shown that the performance envelope of the spacecraft leads to variable SMA performance that should be statistically characterized. This understanding of the characteristics of the SMA performance at various commanded yaw angles will therefore be used to analyze future inclination maneuvers.

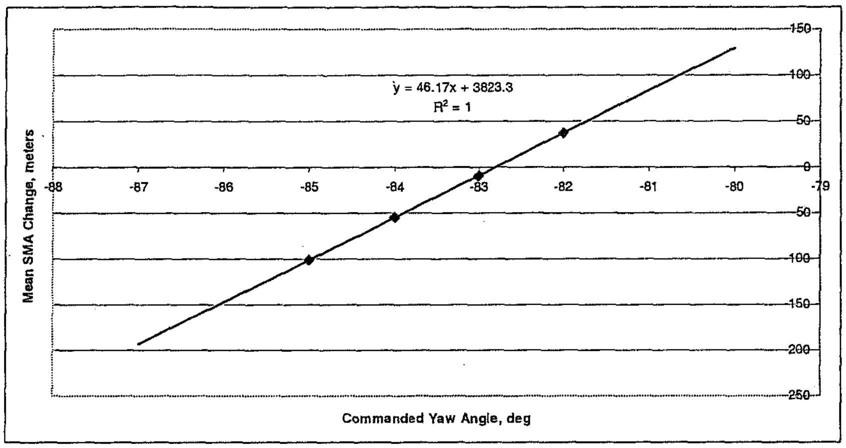

Figure 14. Mean SMA change versus commanded yaw angle from Monte Carlo analysis.

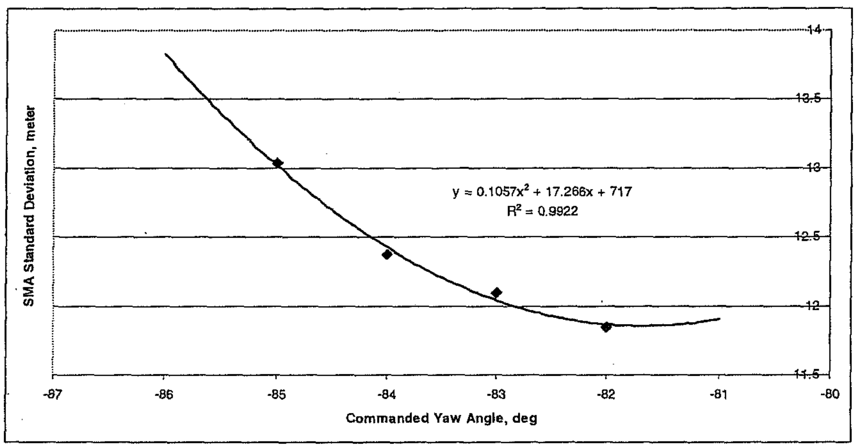

Figure 15. Standard Deviation of SMA change versus commanded yaw angle from Monte Carlo analysis.

VII. Updated Maneuver Planning Technique

The new insight into the statistical performance of Aqua at various commanded yaw angles will be used to plan future Aqua inclination maneuvers. Instead of analyzing only the expected SMA change and its effect on the WRS-2 Error, the 3-sigma predicted SMA change will be used to bound the planned maneuver size. This methodology is demonstrated in Figure 16. The initial maneuver, #12, is planned such that the $+3\sigma$ performance does not lead to a violation of the -10 km limit and the -3σ performance does not lead to a violation of the +10 km limit prior to the next planned maneuver. Additionally, it is demonstrated that the following maneuver, #13, can also be planned to correct the $+3\sigma$ performance. With this new technique, future inclination maneuvers can be designed to maintain the +/- 10 km WRS-2 Error control box with a high degree of confidence.

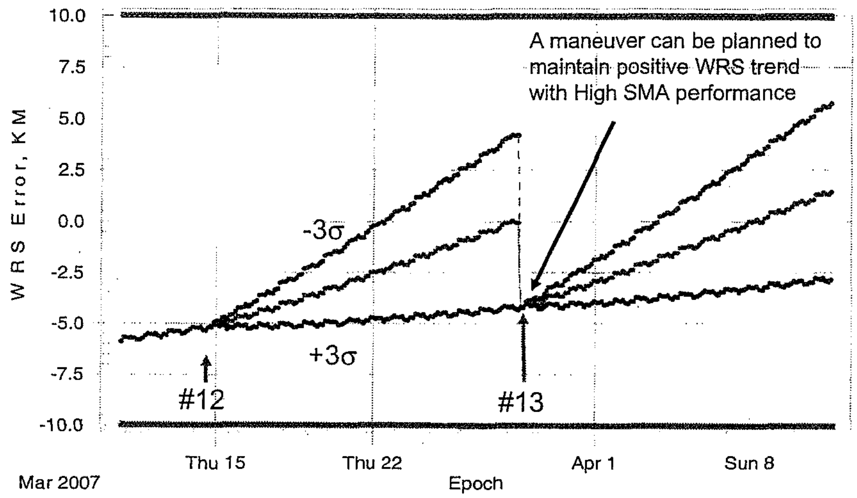

Figure 16. 3 – sigma bounding of maneuver performance.

This methodology can also be extended to an entire series of maneuvers. Following the wave-off of the final two maneuvers of the Fall 2006 series, four additional maneuvers were required in the spring of 2007 to meet mission requirements. Figure 17 shows the WRS-2 Error evolutions for three possible trajectories for the Spring 2007 series: the expected performance as well as +/-3 sigma performance. Each of the four maneuvers is included for each trajectory, and the associated commanded yaw angle is annotated on the plot. Currently, the spacecraft is limited to commanded yaw angles less than 85 degrees. While it may not be reasonable to expect consistent +/- 3 sigma performance over a series of four maneuvers, this plot verified that entire maneuver sequences could be planned using acceptable commanded yaw attitudes in the presence of such large errors.

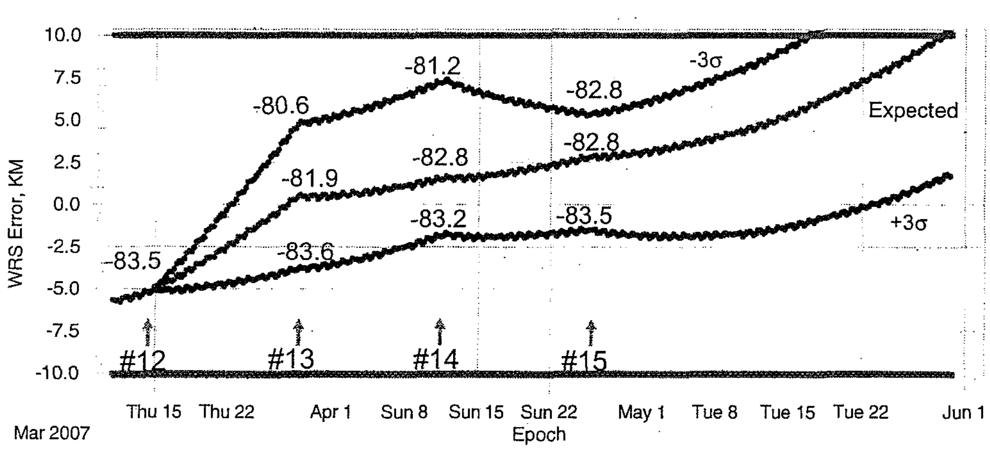

Figure 17. Spring 2007 3 – sigma bounding of entire maneuver sequence.

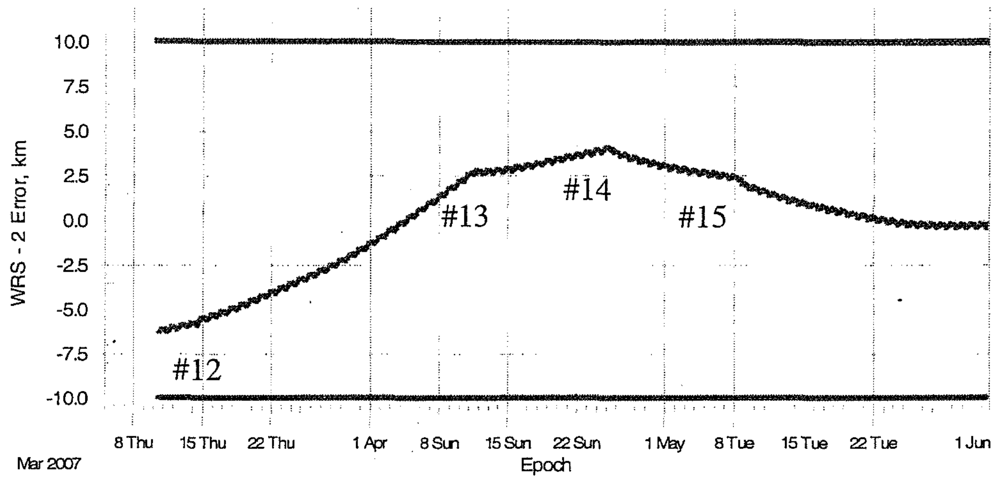

Figure 18. Spring 2007 actual WRS-2 Error.

The actual WRS-2 Error evolution during the four maneuvers of the Spring 2007 sequence is shown in Figure 18. Due to a ground system problem, the original date for maneuver #13 was pushed back from March 28th to April 11th. Given the WRS-2 Error rate established after maneuver #12 and the additional time due to the delay, the remaining maneuvers had to be replanned from what is shown in Figure 17. However, using the techniques of bounding the maneuver performance and ensuring that the next maneuver could compensate for any +/- 3 sigma performance, the WRS-2 Error was maintained within limits at all times.

VIII. Summary

The Fall 2006 Inclination Maneuvers were halted after 4 of 6 planned maneuvers were performed because the maneuvers did not achieve the expected change in SMA. The variable SMA performance led to a potential violation of the -10 km WRS-2 Error control box. The maneuver performance was extensively analyzed, including statistically using a Monte Carlo technique. Analysis comparing the 2004 and 2006 maneuvers indicated that:

1. The spacecraft propulsion system performed within expectations when compared to previous inclination maneuvers. In particular, the duty cycles, attitude errors, and maneuver scale factors from the Fall 2006 maneuvers were statistically similar to previous maneuvers.
2. The low drag environment during the Fall 2006 maneuvers amplified the effect of resulting SMA variations on the WRS-2 Error trend. A higher drag environment would have "damped out" these errors and would have reduced the potential for violation of the -10 km WRS-2 Error limit.

A lesson learned is that the system errors should be statistically analyzed when their source is not fully understood to ensure that all possible outcomes are accounted for. Using average values from previous maneuvers is not sufficient to prevent undesirable outcomes. Monte Carlo analysis has shown that for Aqua there is a statistical performance envelope of the resulting SMA change for a given yaw angle. The analysis confirms actual maneuver performance observed during the Fall 2006 inclination maneuvers. Future inclination maneuvers plans must take into account the statistical SMA performance. The +/- 3 sigma SMA variations should be used to bound the WRS-2 Error trend to ensure the control box will not be violated with a high degree of confidence. This more robust method was successfully used to plan the Spring 2007 inclination series.

This analysis determined how to compensate for the uncertainty in the maneuver performance of the Aqua spacecraft in the maneuver planning process. It should be noted that this analysis deals with the symptom of uncertain performance, but makes no attempt to determine the underlying cause of the uncertainty. Further analysis of the spacecraft systems is required to determine the cause of the observed uncertainty.

References

1. Rand, David, Lauri Newman and Kevin Work, "Inclination Adjust Maneuver Planning And Execution For The Earth Science Afternoon Constellation", AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, August 7-11, 2005.