Operational Experiences in Planning and Reconstructing Aqua Inclination Maneuvers

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ABSTRACT

As the lead satellite in NASA's growing Earth Observing System (EOS) PM constellation, it is increasingly critical that Aqua maintain its various orbit requirements. The two of interest for this paper are maintaining an orbit inclination that provides for a consistent mean local time and a semi-major Axis (SMA) that allows for ground track repeatability. Maneuvers to adjust the orbit inclination involve several flight dynamics constraints and complexities which make planning such maneuvers challenging. In particular, coupling between the orbital and attitude degrees of freedom lead to changes in SMA when changes in inclination are effected. A long term mission mean local time trend analysis was performed in order to determine the size and placement of the required inclination maneuvers. Following this analysis, detailed modeling of each burn and its various segments was performed to determine its effects on the immediate orbit state. Data gathered from an inclination slew test of the spacecraft and first inclination maneuver uncovered discrepancies in the modeling method that were investigated and resolved. The new modeling techniques were applied and validated during the second spacecraft inclination maneuver. These improvements should position Aqua to successfully complete a series of inclination maneuvers in the fall of 2004. The following paper presents the events and results related to the first two Aqua inclination maneuvers.

1. INTRODUCTION

Aqua, launched on May 4, 2002, is an Earth Observing System (EOS) mission taking part in a multi-disciplinary study of the Earth's atmosphere, oceans, and land surfaces and their relationships to climate change. EOS Aqua will help provide answers to global environmental changes with an emphasis on the water cycle. Science gathered from the mission will allow scientists to assess long-term climate change, the reasons (natural and human related) for the change, and develop models for future long-term forecasting.

1.1 Constellation Considerations

Aqua is the first of six spacecraft that will eventually create a science mission constellation called the PM-train to more thoroughly collect Earth science data. Once in orbit, all members in the constellation must coordinate inclination maneuvers to maintain relative Mean Local Time (MLT) requirements. Not only must the maneuvers be coordinated, inclination maneuvers for each spacecraft in the PM-train must be performed with high fidelity and accuracy. To ease operations for the other missions in the PM-train, Aqua performed its first inclination burn (fall 2003) and its second inclination burn (spring 2004) while alone in orbit. The first burn served as a data point for the second, and experience from both will help in planning future maneuvers.

1.2 Orbit Details

Aqua orbits the Earth in a sun-synchronous 705 km altitude orbit and follows a 16 day repeat ground track on the World Reference System (WRS)-2, a grid fixed to the earth consisting of 233 evenly spaced paths originally developed for the Landsat series. At each descending node, Aqua must pass within ±20 km of a WRS path to maintain ground track error requirements. Aqua must maintain a 13:30 to 13:45 GMT (Greenwich Mean Time) MLT at each ascending node. Inclination maneuvers are required to maintain Aqua's MLT constraint because normal orbit perturbations cause an inclination drift. Each inclination maneuver is accompanied by a change in Semi-Major Axis (SMA) because the maneuver is executed normal to the orbit plane, and small uncertainties in the direction of the effective thrust can lead to large relative uncertainties in the size and direction of the corresponding changes in SMA. The cumulative uncertainty in SMA change during a series of several maneuvers could result in Aqua violating the required WRS constraint. Therefore, it is necessary to accurately model the amount of change to avoid such errors.

2. INCLINATION OPERATIONS OVERVIEW

2.1 Spacecraft Details

The Aqua spacecraft is equipped with four primary thrusters and four redundant back-ups. All thrusters point roughly in the anti-velocity direction (-X in the Body Coordinate System) during normal operations and are responsible for both attitude and orbit change maneuvers. Because Aqua uses just four thrusters for all maneuvers, they are aligned to maximize their capability to perform all functions given the location of the spacecraft center of mass (Figure 1). These alignments result in a significant effective thruster cant in the X-Y plane such that any maneuver operation will require the target attitude to be adjusted by this effective cant angle. Currently this value is calculated to be +14.35° in yaw. So for example, to align the effective thrust normal to the orbit plane Aqua would slew -75.65° in yaw.

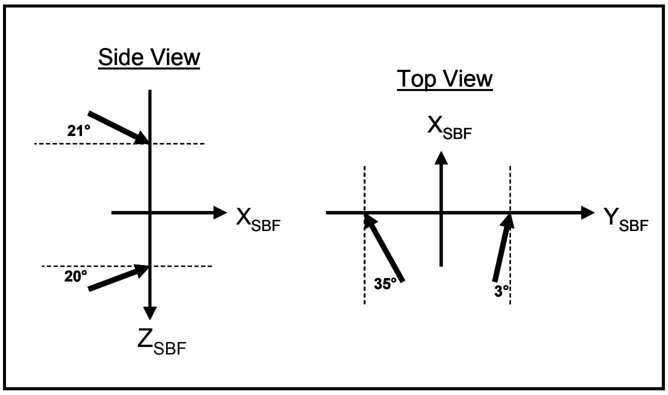

Fig. 1: Aqua thruster arrangement and orientations in both the spacecraft X-Z and X-Y planes

2.2 Operational Constraints

To achieve maximum inclination change, the Aqua spacecraft must be rotated, in yaw, roughly normal to the orbit plane when the thrust is applied. Operationally, this means the spacecraft must slew out to the target attitude, hold the attitude for the duration of the inclination burn, and slew back to the nominal science attitude. Due to thermal, power, and science instrument constraints, it is a requirement that the entire maneuver be performed within one spacecraft night of approximately 33-35 minutes. Because of this, the yaw slews had to be performed on thrusters rather than reaction wheels because the rates achievable on wheels are insufficient to complete the maneuver in one orbit night [1].

Furthermore, in order to maximize efficiency, the burn should be centered on the orbit node, in this case the descending node. This consideration dictates that the burn be performed at a seasonal equinox (spring or fall) in order to center spacecraft night on the descending node.

2.3 Maneuver Uncertainties

Orbit change maneuvers operate with a +/- 3° attitude control deadband in an off-pulse mode. The thrusters fire to change the orbit but off-pulse to control the attitude to within 3° of the target value. For typical short duration orbit raising maneuvers, this degree of attitude uncertainty is easily acceptable. However, inclination maneuvers can be quite long and are at much larger slew angles, so the effects of such attitude uncertainties can be significant. Inclination maneuvers consist primarily of out-of-plane thrusting, but attitude uncertainties can place some thrusting in the orbit plane, resulting in SMA effects and therefore ground track error maintenance problems. Further complicating ground track maintenance is future drag prediction and its effect on ground track error.

2.4 Maneuver Modeling

With an understanding of the details and complexities of Aqua's inclination maneuvers, simulations could be performed to aid in planning.

All planning simulations were run using FreeFlyer® 5.4, a commercial off the shelf (COTS) tool developed by a.i. solutions, Inc. for spacecraft mission design and operations. The orbital analysis projects used for this inclination maneuver were created by a.i. solutions, Inc. and are now used to support mission operations.

These analysis projects take into account the following user inputs in order to execute an inclination maneuver and then predict the resulting SMA and inclination changes, and the WRS ground track error trend:

- Thruster Duty cycles
- JRNOAA solar flux file (Jacchia-Roberts drag model)
- Current spacecraft state (including mass, area)
- Spacecraft Coefficient of Drag (C_d)
- Full Propulsion system in blowdown mode

The inclination maneuvers were modelled as three separate sequential burns: slew out, inclination burn, and slew back, each at a fixed attitude. The duration of the first segment was modeled as the difference between the time of the first thruster firing and the time when half the desired slew angle was achieved. The duration of the second segment was modeled as the difference between the time the first segment ended and the time when half the return slew angle was achieved. The duration of the third segment was modeled as the time difference between the end of the second segment and the final thruster firing. To begin the planning process Northrop Grumman Space Technologies (NGST), the spacecraft manufacturer, provided inclination adjust maneuver simulation results which consisted of: elapsed time, expected thruster on-times, accumulated on-times of thrusters and roll, pitch, and yaw of the spacecraft [2]. Using the thruster on-times from the NGST simulation, duty cycles were determined for the four thrusters for the three segments above. The accumulated thruster on-times of each segment were divided by the duration of that segment to yield the corresponding duty cycle.

When updated spacecraft state and atmospheric modeling data was needed, up-to-date data were acquired from various institutional sources. A current Aqua state file was acquired from the Earth Science Mission Operations (ESMO) web site [3]. The Flight Dynamics Facility (FDF) updated the Coefficient of Drag (C_d) value and uploaded a daily and weekly JRNOAA solar flux prediction onto their Product Center [4]. Initial indications were that the uncertainty in atmospheric drag (JRNOAA data and C_d) would prove to be a driving factor in the way Aqua reacted to the SMA change incurred by the inclination maneuvers.

2.5 Yaw Demonstration

Since inclination maneuvers require Aqua to operate in an off-nominal attitude, a test maneuver, called the yaw demonstration, was performed to gather data and assess the Aqua spacecraft's ability to successfully perform this function entirely on thrusters, while maintaining ground track and MLT requirements. The yaw demonstration was operationally identical to a typical inclination maneuver except that no inclination burn was performed and no inclination change was affected.

In August 2003 Aqua successfully slewed out to a representative inclination burn attitude, held that attitude and returned. There were some unexplained discrepancies between the predicted maneuver data and actual orbit results, but the differences were not large enough to warrant further investigation. Immediately following the demonstration, analysis for the inclination maneuver began.

3. THE FIRST INCLINATION MANEUVER

3.1 Planning

The first inclination maneuver was planned and executed in the Fall of 2003 based on experience gained from the yaw demonstration. To mitigate the change in SMA, estimated spacecraft pointing errors and drag uncertainties were used to predict the spacecraft ground track over time. Because of the large differences in WRS Ground Track Turnaround points due to daily atmospheric changes, the WRS turnaround for the inclination maneuver was targeted to -15km rather than -20km to provide more room for error. To determine the worst case yaw angles possible, the ±3° attitude control deadband was applied to the nominal slew attitude, creating two bounding cases (Fig. 2).

NGST provided new simulation data for a -80° nominal slew angle and a ten minute burn with adjustments to their simulation model to account for additional thrust impingement observed in the yaw demonstration. Similar to the yaw demonstration, the inclination maneuver was modeled as three parts: slew out, ten minute inclination burn, and slew back. The thruster on-times from NGST were used to determine the duty cycles for the four dual thruster modules (DTM-1 through DTM-4) used to perform the maneuver sequence (Table 1). The duty cycles were determined as before (see Maneuver Modeling) but used 600 seconds duration for the inclination burn duty cycles computation.

Table 1: Modeled Duty Cycles for -80° slew with a 10-minute inclination burn

	DTM1	**DTM2**	**DTM3**	**DTM4**
Slew Out: 262.50 sec				
Total On-time	19.5174	27.5354	0.0000	28.8973
Duty Cycle	0.0744	0.1049	0.0000	0.1101
Inc. Burn: 600 sec				
Total On-time	463.7034	467.1122	232.5928	264.2899
Duty Cycle	0.7728	0.7785	0.3877	0.4405
Slew Back: 382.50 sec				
Total On-time	36.1463	14.5198	17.5237	8.3746
Duty Cycle	0.0945	0.0380	0.0458	0.0219

October 7th was chosen as the date to perform the first maneuver because of favourable predicted ground track error trends. Slew angles were then targeted using the procedure outlined above and yielded a -79.2° nominal slew angle for the maneuver (Fig. 2).

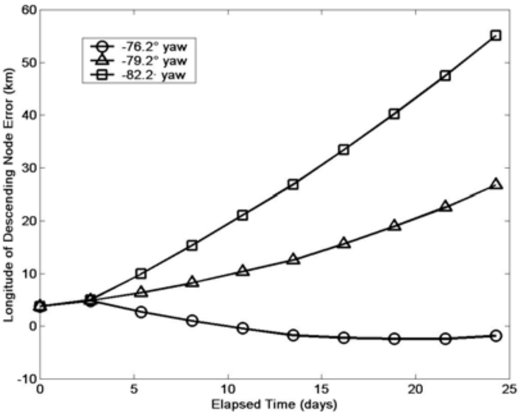

Fig. 2: October 7, 2003 -79.2° nominal slew with ±3° slew deadband. All plots are within ground track requirements.

To account for the thrust uncertainty revealed in the yaw demonstration, two more cases were also examined: -10% thrusting was simulated on the absolute maximum slew angle (-82.2°) and +10% thrusting on absolute minimum slew angle (-76.2°). These cases served to bound all possible ground track error trends and proved they are all safely above the lower end of the control box, with a -13 km turnaround for the absolute worst case, and allow ample time for a DMU (Drag Make-up) maneuver to be planned and executed prior to an upper boundary violation. A DMU is a maneuver designed to compensate for orbit altitude lost due to atmospheric drag.

Atmospheric solar flux variations between 100 and 200 were observed during analysis for the yaw demonstration. To capture all ground track possibilities, the Harris-Priester atmospheric drag model was used with flux values from HP-75 (low flux) to HP-250 (high flux). Table 2 shows that the only lower bound ground track violation occurred for HP-75 flux and the smallest slew angle case. An immediate DMU is necessary for all HP-250 cases. For realistic flux levels, the analysis predicted that Aqua would remain within its ground track control box.

Table 2: HP Flux Values for the nominal -79.2° slew and its deadband were plotted to find the lowest ground track turnaround. Aqua violates the ground track box only for the HP 75 (low drag) case and an immediate DMU is necessary at HP Flux of 250 (denotes immediate DMU).*

	Ground Track Turnarounds (km) for Harris Priester F 10.7 cm Flux Values						
Angle	75	100	125	150	175	200	250*
-76.2°	>-**20**	-15	-4.5	4	8	12	19
-79.2°	3.5	4	5.5	6	8	11.5	19
-82.2°	3	4	5	6.5	8	11.5	19

3.2 Execution and Reconstruction

On October 7th, 2003 Aqua slewed out to -78°, performed a 600 second burn, and completed the slew back. The 31:21 minute total duration for the maneuver fulfilled the spacecraft requirements for the maneuver to occur within a single spacecraft night.

The Aqua spacecraft achieved a -0.1207° inclination change, a 0.24% difference from the expected -0.1210° change. Thruster observations revealed the thrusters fired less than the NGST simulation expected (-5 to -33% per segment) (Table 3) with Thruster Two (DTM2) showing the largest differences.

Table 3: Percent Difference between Actual Observed Duty Cycles and NGST Simulation Duty Cycles

Duty Cycle Percent Difference (Actual Vs. Predicted)				
Segment	**DTM1**	**DTM2**	**DTM3**	**DTM4**
Slew Out	3.5%	-16.2%	0	-8.3%
Inclination Burn	-10.8%	-5.6%	-3.0%	-1.1%
Slew Back	-0.3%	-33.0%	-1.2%	-22.3%

However, while the pre-maneuver predicted SMA change was 24 meters and the post maneuver reconstructed SMA change was twice this value, the actual SMA change was significantly larger at 155 meters (Table 4).

Table 4: Predicted and Actual Changes in SMA. The actual SMA change from ephemeris comparisons yields 155m of SMA in the positive direction.

Method Used	**SMA Change (m)**
FreeFlyer® *Predicted* SMA Change w/ NGST simulation data	24
FreeFlyer® *Predicted* SMA Change Analysis Model w/ *actual* telemetry data (from carryout file)	56
Actual Post-maneuver Orbit Determination (OD)	155

The modeling discrepancy presented in Table 4 of approximately three times is very significant, and would impact planning of an inclination maneuver sequence unfavorably. The causes of this discrepancy were immediately investigated and must be resolved to within a very small tolerance.

3.3 Simple Error Sources

The following simple possibilities were immediately examined and ruled out as causes of the difference between the SMA determined by reconstruction and by orbit determination: SMA change calculation, tank pressure uncertainty, thruster performance uncertainty, and erroneous post burn orbit determination.

The method used to calculate the SMA change for these longer duration maneuvers takes into account the natural orbit osculations that occur over such durations. The method compares a post burn orbit evolution to a "no-burn" orbit evolution at the same time. Figure 3 shows this method applied to the inclination burn and clearly illustrates that the large SMA change difference observed is real and not an artifact of comparison.

Uncertainty in measurement of the tank pressure prompted the team to reconstruct using nominal and ±1.6 psi tank pressures (the granularity of the tank pressure transducer) and resulted in no significant effect (~0.5%) on SMA.

Given that the SMA change observed was higher than modelled, the thrust levels were increased from 0.82lbf, the actual pressure modelling dictated, to 0.9lbf, the maximum value physically possible. This increase did not account for the 100m SMA change difference.

Finally, the observed change in SMA remained consistent over several increasingly accurate orbit determination (OD) solutions and prior operational experience suggested that the OD solutions were highly accurate, thereby ruling out OD errors.

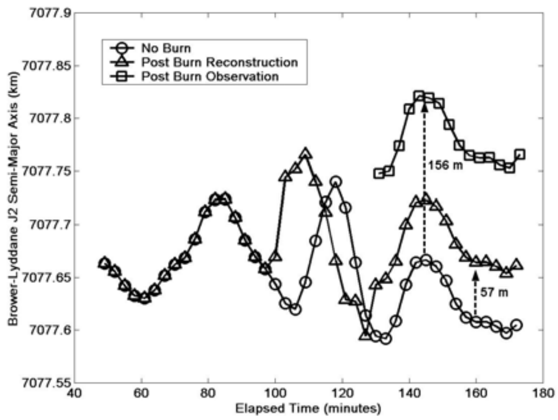

Fig. 3: FreeFlyer® plot showing differences between the reconstructed maneuver and post maneuver orbit determination

As a result of the unsolved inclination maneuver discrepancies, the Inclination Maneuver Working Group (IMWG) and the Goddard Space Flight Center (GSFC) Flight Dynamics Analysis Branch (FDAB) charged the Flight Dynamics Team [6] to look at less trivial possibilities to account for the errors observed.

3.4 Thruster Plume Impingement

After eliminating several possible causes, thruster plume impingement became the most promising candidate for further analysis. Aqua was known to have a small plume impingement present since launch, but it had never proven significant in maneuver planning. To determine the magnitude of the impingement effect, the following steps were performed:

1) A combined attitude and orbit analysis based on historical data to determine a likely combination of thruster performance and pointing to fit observed attitude and orbit behavior for the Aqua inclination maneuver.
2) Vary modelling parameters to achieve the observed change in SMA and inclination.
3) Apply these values to the yaw demonstration, first inclination maneuver, and the last two DMUs.
4) Repeat steps 1 through 3 until consistency is achieved or no further progress is made.

Using a similar method, D. Lorenz of SGT Inc. found new thrust scale factors and effective pointing for thrusters 1 and 2 (the only two thrusters physically capable of impinging on the spacecraft body) [7]. Using this data in the previously constructed analysis simulation, the following differences between the SMA change modeled in the reconstruction and observed by OD were obtained (Table 5):

Table 5: SMA Differences Using Data Fit to new Thrust Scale Factor Values

Case	SMA Difference vs. OD
Yaw Demonstration	9 m
Inclination Maneuver 1 (reconstructed)	1 m
Inclination Maneuver 1 (pre-maneuver predicted)	13 m

Clearly the modifications made to the propulsion model dramatically improved inclination maneuver prediction capabilities, indicating that impingement was in fact the un-modeled force and the source of the prediction discrepancy.

4. THE SECOND INCLINATION MANEUVER

The second inclination adjust maneuver was planned using data and experience gained from the first maneuver, with the goal of proving that Aqua could perform a series of similar inclination burns. In March 2004 Aqua successfully performed its second inclination adjust maneuver and validated the new modelling and planning techniques developed after the first inclination burn. The SMA change results were far better than previously achieved (Table 6).

Table 6: Predicted and Actual Changes in SMA. The actual SMA change from ephemeris comparisons yields 133m of SMA in the positive direction.

Method Used	SMA Change (m)
FreeFlyer® *Predicted* SMA Change – modelling	153
FreeFlyer® *Predicted* SMA Change using *actual* telemetry data	133
Actual Post-maneuver Orbit Determination (OD)	140

The second inclination adjust maneuver achieved an actual SMA change within 8.5% of the planned value, demonstrating the type of accuracy needed for Aqua to perform a series of such maneuvers in the fall of 2004.

5. CONCLUSIONS

The inclination adjust maneuvers performed by the EOS Aqua spacecraft have all been successful, but proved difficult to plan, and even more difficult to predict. Most difficult was prediction of the orbit SMA change and the resulting ground track error evolution. After addressing various possible causes, resolution came by analyzing a known thruster impingement in the context of a new maneuver regime and revising the propulsion model. The updated propulsion modeling was validated and has positioned the Aqua mission well to successfully perform inclination maneuvers in the future.

The current PM constellation goal is for Aqua to perform a series of inclination maneuvers prior to the launch of CloudSat and CALIPSO in March 2005 to reduce the amount of fuel used by these missions and maintain Aqua's MLT requirements for the next 3-4 years. There are several future burn opportunities in September of 2004 and the spring of 2005.

6. REMARKS

6.1 Acknowledgements

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