1.0 Abstract

We have performed momentum management analysis of various JWST schedules created using the JWST Mission Simulator and an enhanced Science and Operations Design Reference Mission. This study used the latest available torque tables and investigated three modes of Visit orientation assignment used to manage the momentum accumulation. In addition, the conditional scheduling of momentum unloads, and performing partial momentum unloads when possible was also investigated. Assuming one failed reaction wheel and the worst case torque tables, we find that the number of momentum unload activities per Station Keeping interval violates the existing Science & Operations Center requirement that limits the number of momentum unloads to two per interval. It was found that 65% of the Station Keeping intervals had three or more Momentum Unloads. This required a change in the Orbit Determination method used to one less sensitive to multiple orbit perturbations.

We also find that the roll optimization of scheduled visits and the conditional scheduling of partial Momentum Unloads provide a reduction of the stored momentum to be unloaded, a reduction of the number of Momentum Unloads, and a reduction of the time required to perform the Momentum Unloads as compared to un-optimized schedules.

It is recommended that the Optimize Last Visit orientation assignment mode, partial Momentum Unloads, and the conditional scheduling of Momentum Unloads should be implemented. In addition, the Observatory design is being changed substantially at the time of this study and may change again in the future. It is recommended the study be repeated at each major Observatory design milestone,
2.0 Introduction

This study extends the previous work reported in Kinzel (2005A) and Kinzel (2005B) and was done in support of the JWST Momentum Management Working Group. Several changes and enhancements from the previous analysis were implemented:

The Science Operations Design Reference Mission (SODRM) fidelity was enhanced including a manual implementation of relative orient constrained observations. Multiple schedules were produced by using different selections of SODRM proposals to allow momentum unload statistics to be gathered.

GSFC Flight Dynamics Facility (FDF) provided a new JWST ephemeris when the one used in the earlier studies was discovered to be out of date.

This study used the latest available torque tables which were generated including a variation of the parameters used to calculate the torques. In particular, NGST determined the calculated torques were most sensitive to the assumed position of the Center of Gravity (CG).

The earlier studies accessed the torque tables using spacecraft roll. That is, roll about the OTE boresight. However, the torque tables are provided as a function of sun roll and sun pitch. This caused the roll torques in particular to be slightly underestimated at large negative pitch angles in the earlier studies. This study uses sun roll and sun pitch to access the torque tables.

The momentum management simulation was enhanced. Previously, Momentum Unloads (MU) were scheduled when the accumulated momentum would exceed the Reaction Wheel Assemblies (RWA) momentum storage capacity limit. In this study, we simulated expected normal operations. That is, an orbit Station Keeping (SK) maneuver will occur between Visits roughly every 22 days. A MU is scheduled just before the SK maneuver. Between the SK maneuvers, MUs are inserted into the timeline before a Visit whenever the accumulated momentum at the end of the Visit would exceed the assumed RWA capacity limit.

Finally a set of metrics were developed including the mean momentum unloaded per 22 days and the mean time between momentum unloads to allow comparisons between the various momentum management techniques and torque tables.

3.0 Coordinate Systems

3.1 Spacecraft Coordinates

Figure 3-1 is Figure 3-10 from the Observatory Specification Document. The allowed Sun Pitch is -45° to 5° and the allowed Sun Roll is ±5°.
3.2 Position angle, and Roll

It is expected many JWST observations will have a specified orientation to align a science instrument aperture with an extended target or to control the direction of a spectrum’s dispersion. The Position Angle (PA) defines the orientation of the observatory (Figure 3-2). The PA is the angle between the North and the S3 vectors projected on the sky at the target position when the observatory vector S1 is pointing at the target. East from North is defined as positive.
Normal roll is defined as when the Sun Roll or Roll is zero. Since Normal Roll is defined with respect to the sun, it is not in an inertial frame and the observatory orientation for Normal Roll is a function of time. A visit is defined to be scheduled at Normal roll when the selected orientation produces Normal Roll at the mid time of the visit. Roll is defined as the normal orientation minus the scheduled orientation. Roll can also be defined using the sun unit vector:

\[
Roll = \arctan\left(\frac{-y_S}{z_S}\right)
\]

The Roll and Sun Roll are related by

\[
Roll = \arctan\left(\frac{\tan(SunRoll)}{\cos(SunPitch)}\right)
\]

### 3.3 Rotating Libration Point (RLP)

The RLP coordinate frame is typically used in spacecraft missions to one of the Sun-Earth Libration Points. For JWST it is defined with respect to the Sun-Earth L2 point (Figure 3-3). The x axis is defined outward along the sunline to L2. The y axis is perpendicular to x in the ecliptic plane in the direction of the Earth’s motion about the Sun. The positive z axis is pointing towards the North ecliptic pole. In Figure 3-3 the ecliptic is in the plane of the paper and the positive z axis is towards the reader.
Figure 3-3  The RLP coordinate frame (not to scale).

4.0 Torque Tables

The Torque Tables were provided by Northrop Grumman Space Technology (NGST). Each torque table is composed of 3 sub tables providing the Roll (S1), Pitch (S2), and Yaw (S3) torques modeled by NGST at 5° intervals in sun pitch and 2.5° intervals in sun roll.

Starting with the June 1, 2006 torque tables, NGST included sensitivity analysis by a variation of the parameters used to calculate the torques. Three Cases were generated

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nominal</td>
</tr>
<tr>
<td>2</td>
<td>(Nominal + RSS)<em>MUF</em>margin</td>
</tr>
<tr>
<td>3</td>
<td>(Nominal - RSS)<em>MUF</em>margin</td>
</tr>
</tbody>
</table>

Table 4-1: Torque Table Case descriptions.

where the Model Uncertainty Factor (MUF) was 1.5 and the margin was 1.25.

Up to 27 derived torque tables were generated from the permutations of these torque table components. The derived torque tables were identified using a nomenclature of a C and three numerals (CRPY) where C is the Case followed by a Roll, Pitch, and Yaw numeral indicating which Case for a particular spacecraft axis was used. For example, C323 indicates the roll and yaw torques used were taken from the –RSS table and the pitch torque was taken from the +RSS table.

Two sets of torque tables named Pass 1 (June 1, 2006) and Pass 2 (November/December, 2006) were analyzed. The Pass 2 tables differed from Pass1 by using an updated sunshield model and description of the observatory mass distribution to calculate the torques. In addition, the Pass 2 torque tables included an additional variation of parameters by assuming the Center of Gravity uncertainty along the y (S2) axis (CGy) varied from 30 to 75 mm.

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- 5 -
5.0 Generating Randomized SO-DRM mission schedules

The mission schedules are created by the JWST Mission Simulator (JMS; Petro 2001) from observations defined in the Science Operations Design Reference Mission (SODRM; Petro, 2005). The SODRM contains about 1.6 years of observations. About 50% of the duration is contained in visits with constrained orientations. This number includes NIRSPEC visits that were orient unconstrained during the JMS schedule generation and were then assumed fixed at the JMS assigned orientation.

The SODRM was modified to increase its fidelity for this study, as follows.

- All parallel (non-pointed) visits were removed. These were being scheduled by JMS as prime visits. During normal operations these activities would occur in parallel with the prime visit activities and not impact the observing timeline.

- JMS does not support Orient Link requirements (relative constraints between visits) currently specified in the SODRM. ORIENT AT <position angle> records were added that were consistent with the specified Orient Links and allowed the visits to schedule. However, this hard codes the visit orientations and reduces the scheduling flexibility of these visits.

- Several visits, each much longer than one day, were split into shorter visits. Orient and timing constraints were added to the new visits to maintain the original observing intent of the long visit. A handful of ~1.3 day long visits still exist in this modified SODRM.

It was desired to create many different schedules to enable modeling the momentum accumulation and collect momentum unload statistics. However, JMS produces the same schedule when the input visit set is the same. In addition, the JMS “randomization” qualifier was unusable because it caused very long run times. The input to JMS was varied by generating ten SODRM subsets that were created by randomly removing 80 to 120 days of observations from the SODRM. The process removed whole large proposals from the SODRM to avoid breaking linked visit sets.

Each SODRM visit set was input to JMS to create 11 initial schedules (10 subsets, one set with all the proposals). For each schedule, after about day 400, large gaps (days long) would appear in the schedules as JMS had difficulty packing the remaining visits. The long gaps were avoided in the analysis by truncating each schedule at the end time of the first visit greater than 400 days from the start of the schedule.

Details of the baseline schedules are given in Table 5-1.
Table 5-1: Details of the baseline schedules.

These baseline schedules were used as input to the angular momentum calculation and management process.

6.0 Creation of the Momentum Profiles

The creation of the momentum profiles is an attempt to simulate normal scheduling operations. That is, interlaced with the JWST science activities, a station keeping (SK) maneuver is required roughly every 22 days, a momentum unload (MU) is scheduled in the day before each SK maneuver to ensure the RWAs have enough usable capacity to handle the SK maneuver, and a MU is scheduled whenever the modeled stored momentum reaches a predefined limit in the schedule. The JMS mission schedules did not contain MU or SK activities. The simulation process would use a baseline schedule for input and on-the-fly; insert the MU or SK activities into the timeline.

Each simulation starts with zero momentum. Starting with the first visit in the simulation and for each subsequent visit in the baseline schedule used for input, the accumulated vector angular momentum for the visit is calculated, transformed from the spacecraft frame to the ECI frame, and then added to a running accumulated momentum total.

Each JMS schedule provides a visit start and end time and a visit target attitude. This time interval includes an assumed fixed duration 45 minute slew time and 15 minute slew settling time. The angular momentum accumulation calculation does not model slew

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motion between targets and assumes JWST is at the visit target attitude during the entire time interval.

The vector torque is integrated using a trapezoid rule over the time interval of the visit, in the spacecraft frame, to produce the accumulated vector angular momentum. The position of the sun is recomputed for each step in the integration. The instantaneous torques are found using the Sun’s pitch and roll with respect to the spacecraft and a linear interpolation between points in the provided torque tables.

It is also assumed each simulation starts with a SK maneuver. The later SK maneuvers are assumed to occur in the schedule between visits at the first visit break greater than 22 days from previous SK maneuver.

The simulations assume a MU is scheduled just before the expected time of a SK maneuver. In addition, a MU is scheduled whenever the momentum contribution from the next visit plus the current accumulated momentum exceeds a specified RSS momentum limit.

The simulations do not model the time required or the attitude changes required for the SK maneuvers or the MUs. Currently it is expected a full MU will take about 4.5 hours and a SK maneuver will take about 2 hours.

For each baseline schedule and set of input parameters (torque table, MU limit, visit orientation assignment mode, etc.) two momentum profiles were created. This was accomplished by shifting the momentum accumulation pattern with respect to the visits by assuming the start of the momentum accumulation and the first SK maneuver occurred on day zero of the baseline schedule and also at the end time of the first visit in the schedule greater than day 11.

The first 50 days of two sample momentum profiles is shown in Figure 6-1. The profiles were generated from the baseline schedule 11 and starting the momentum accumulation on day 0 or roughly day 11. Each symbol indicates the RSS stored angular momentum at the start of each visit. Discontinuities in the slope of the momentum profiles are caused by changes in the spacecraft attitude or the scheduling of a MU. For this example, a MU limit of 70 Nms and the Pass 1 torque table C333 (See section 10.1.) was used.
Figure 6-1: The first fifty days of two example momentum profiles.

7.0 Visit Orientation Assignment Modes

An earlier study (Kinzel, 2005) determined that adjusting the assigned orientation of visits in a schedule or reordering the visits in a schedule could be effective in reducing the amount of accumulated momentum. In this study, only adjusting the visit orientations using simple algorithms was used. JMS assigned Normal Roll for visits with unrestricted orientation. In the baseline schedules, visits were marked to indicate if the orientation could be adjusted by the momentum management process. During the simulations, visit orientations were assigned using 3 modes and a specified maximum adjusted off normal roll.

7.1 JMS Position Angle (JPA)

This mode uses the Position Angles assigned by JMS. This mode is used as a baseline for comparison with the other momentum management orientation assignment methods.

7.2 Optimize Last Visit (OLV)

In this mode the process steps through the visits in a schedule and adjusts the orientation of the current visit (if it can be adjusted) to minimize accumulated RSS momentum up through the visit being adjusted.

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Figure 7-1: Example Mission Timeline.

A usage example of the OLV orient assignment algorithm is given using Figure 7-1. The orientations of visit 1, 2, and 3 are sequentially adjusted to minimize the total accumulated observatory angular momentum at times T2, T3, and T4 respectively. Visits A, B, and C have observer specified orientation requirements and are fixed at their specified orientation. The accumulated angular momentum for visits A and B is calculated and each is added to the total angular momentum. Then, visit 4 has its orientation adjusted to minimize the total angular momentum accumulated up to time T7. Then again, the contribution to the total angular momentum for fixed orientation visit C is calculated. The process then continues for visits remaining in the timeline.

The assigned orientation for each visit is dependent upon the torque table used and the total accumulated momentum at the start of the visit.

7.3 Optimize Over Interval (OOI)

The OOI method is similar to the OLV method. Referring to Figure 7-1 again, assume T1 through T9 span the time between two SK maneuvers. In the OOI mode, the visits’ orientations are again sequentially adjusted. However now, starting with the orientation assigned by JMS, each visit’s orientation is varied to minimize the total accumulated momentum at time T9. Since the momentum at time T9 is dependent upon the orientation assigned to all the visits in the interval, this process was repeated 9 more times to allow the orientation assignments to converge for each visit.
7.4 Example Momentum Profiles

Figure 7-2: Example momentum profiles using the JPA, OLV, and OOI roll assignment modes.

Figure 7-2 shows three momentum profiles generated using the Pass 1 nominal (C111) torque table, the different roll assignment modes, the momentum accumulation offset of 0 days, always performing an MU just before the SK maneuver, and the baseline schedule 11. The momentum profiles start with zero momentum at time zero. Momentum Unloads occur roughly on day 22, 44, 66, 88, and 110 just before an expected SK maneuver. Most SK intervals in the JPA profile have increasing stored momentum up until the time the SK MU occurs. However, note that the accumulated RSS momentum can be reduced by the contribution of later visits scheduled at appropriate attitudes. The OLV mode tends to keep the total momentum low except for the intervals at days 5 to 10 and days 113 to 120 when a series of fixed orient visits are scheduled. The OOI mode succeeded in having zero momentum at the SK times without using a MU. However, in most of the SK intervals, the accumulated momentum peaked roughly in the center of each SK interval well above the OLV momentum profile. This caused problems once non-nominal torque tables were used in that multiple MUs could occur in the middle of an SK interval, but the algorithm would continue to adjust visits early in the interval in an attempt to minimize the momentum at the end of the interval. This was impossible since the MUs removed any contribution of the earlier visits to the momentum at the end of the interval. For this reason, the OOI mode was not used in the Pass 2 analysis.
8.0 Momentum Unload Variations

A JWST momentum unload is accomplished by slewing to an optimal attitude and slowing the wheel speeds of particular RWAs. The torque produced by changing the wheel speeds is balanced by a torque produced by thruster firing.

During this study, several algorithms for unloading the momentum were investigated.

8.1 Types of Momentum Unloads

In general, because of the positioning of the thrusters, two unique attitudes are required to completely unload the angular momentum stored in the RWAs. One attitude allows the stored momentum in the RLP YZ directions to be unloaded and the second attitude allows the stored momentum in the RLP X direction to be unloaded. Most of the time required to perform a MU is contained in the slew times. Thus, unloading momentum at two attitudes nearly doubles the time needed to unload the momentum at a single attitude. In addition, unloading the stored momentum in the RLP X direction perturbs the JWST orbit much more than unloading the stored momentum in the RLP YZ directions. For Pass 2 analysis, the possible reductions in the time required and the orbit perturbations motivated restricting whether the RLP X momentum is unloaded during a MU and comparing it to the unrestricted case. The labels ZERO and RLP_YZ are used to indicate the two cases:

ZERO – in this case, the RWAs were unloaded to zero when ever a MU was scheduled.

RLP_YZ – in this case, the momentum components in the RLP YZ directions are unloaded to zero whenever a MU was scheduled. If the remaining RLP X momentum is greater than 20% of the specified MU limit, then the RLP X component is also unloaded.

8.2 Conditional Momentum Unloads

The Pass 1 analysis showed there were SK intervals where a limit triggered MU occurred a few days before the SK maneuver. Then the SK MU would occur. This might have caused a bias in the mean time between MUs so the concept of conditional SK MUs was implemented for Pass 2. The labels ALWAYS and SKIP are used to indicate the two cases:

ALWAYS – The MU just before the SK maneuver was always scheduled.

SKIP – The MU just before the SK maneuver only occurred if the RSS stored momentum was greater than 20% of the specified MU limit. (That is, the MU could be skipped.)

9.0 Output

9.1 Momentum Profiles

Each momentum profile contain the visit information from the input schedule: the start and end time, RA, Dec, orientation, orientation adjustability flag, and the visit ID. For each visit, the profile also contains the starting and ending stored accumulated momentum vector components and magnitudes calculated during the simulation process. If the visit orientation was changed during the momentum management process, the new

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value is represented in the profile. The Pass 1 momentum profiles were delivered to GSFC Flight Dynamics Facility (FDF) for an independent check of the momentum calculations.

9.2 Momentum Unload Statistics

Each set of input parameters (torque table, MU limit, visit orientation assignment mode, etc.) to the momentum profile creation process produced 22 momentum profiles. These were created from the 11 baseline schedules and the 2 momentum accumulation starting points (at day 1 and day 11). This allowed the creation of the following momentum unload statistics for each input parameter set.

- The number of MUs per SK interval. - This was used during the Pass 1 activities to determine the number of invalid SK intervals
- The mean time between MUs. - This allows computation of the MU activities impact to the observatory efficiency.
- Mean momentum unloaded per 22 days. - This allows the relative comparison of the MU propellant usage between the different cases. It is calculated by summing the RSS momentum for each MU, dividing by the sum of all the MU intervals, and scaling by 22 days.

For the Pass 2 simulations, the number of full MUs and the number of RLP_YZ MUs per input set were also recorded. This allowed a more accurate observatory efficiency estimate to be generated.

9.3 Momentum Unload Data

This is a summary file generated from a particular Momentum Profile, which lists the time and the starting and ending stored vector momentum for each momentum unload in the profile. The vectors are in the RLP frame defined at the time of the MU.

10.0 Results

10.1 Pass 1 Scheduling and MU frequency

The Pass 1 momentum profiles were created using the Pass 1 derived torque tables, assuming full momentum unloads, and always performing an MU just before the SK maneuver.

4158 Momentum Profiles were created based upon the permutations of

- 11 "baseline" schedules
- 2 MU starting offsets (0 or 11 days)
- 27 derived torque table cases (the permutations of all the sub tables)
- 3 roll assignment modes
- 3 maximum assigned off normal rolls (3°, 4°, or 5°).

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For the Pass 1 analysis, FDF was using the “batch” orbit determination method. The time 1 day to 22 days prior to a SK maneuver was used to track JWST and determine its orbit. Any interval between two SK maneuvers that had 2 or more in track MUs had a lower probability of obtaining an orbital solution. These intervals were classed as “bad”. The MU statistics showing the number of in track MUs per SK interval are shown in Table 10-1.

<table>
<thead>
<tr>
<th>MU Limit</th>
<th>Max Roll 4 Deg</th>
<th>Number of intervals containing this number of in track MUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nms</td>
<td>Nms</td>
<td>0</td>
</tr>
<tr>
<td>70 JPA</td>
<td>1.8 70.0 59.1</td>
<td>126</td>
</tr>
<tr>
<td>70 JPA</td>
<td>2.0 70.0 58.6</td>
<td>21</td>
</tr>
<tr>
<td>70 JPA</td>
<td>2.1 70.0 56.9</td>
<td>99</td>
</tr>
<tr>
<td>70 JPA</td>
<td>2.3 70.0 57.2</td>
<td>110</td>
</tr>
<tr>
<td>70 JPA</td>
<td>2.5 70.0 56.8</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 10-1: Example MU statistics for the maximum 4° assigned roll cases showing the number of MUs for the SK intervals. SK intervals with 2 or more in track MUs violate the FDF requirement and are marked in red.

The example shows many SK intervals with too many MUs. In some optimized roll cases, some SK intervals had as many as 6 in-track MUs. Any SK intervals that had two or more in track MUs were classed as “bad”. The percentage of bad intervals as a
function of the torque table, orientation assignment mode, and maximum assigned off normal roll are shown in Figure 10-1

![Graph showing percentage of bad SK intervals for different torque tables, roll assignment modes, and maximum assigned off normal roll.](https://example.com/graph.png)

**Figure 10-1** Graph comparing the number of “bad” Station Keeping intervals between the different torque tables, roll assignment mode, and maximum assigned off normal roll.

The nominal torque table (C111) had zero bad SK intervals for all roll assignment modes. The OLV mode usually provided about 5 percentage points fewer bad SK intervals than the OOI mode. Increasing the maximum assigned off normal roll decreases the number of bad SK intervals. However, even using an assigned 5° maximum roll limit, the best non-nominal torque table (C233) produces at least 40% bad SK intervals. The worst case torque table (C333) produces over 65% bad SK intervals even with either roll optimization.

The other MU statistics for the nominal torque table and the 4 worst case non-nominal torque tables are presented in Table 10-2.
The data also show that in many cases the minimum interval between two MUs is much less than a day and is at best about 3.5 days. It was determined this is caused by a limit

The data also show that in many cases the minimum interval between two MUs is much less than a day and is at best about 3.5 days. It was determined this is caused by a limit

Using the nominal torque table (C111) the OOI mode is about 35% better than the OLV mode when comparing the mean momentum unload per 22 days. However, an examination of the non-nominal torque tables finds the mean momentum unloaded per 22 days is nearly identical between the OOI mode and OLV modes. As explained in section 7.4, the OOI algorithm doesn't work effectively with in track MUs.

The data also show that in many cases the minimum interval between two MUs is much less than a day and is at best about 3.5 days. It was determined this is caused by a limit triggered MU occurring shortly before the MU before the SK maneuver. This was the motivation for performing conditional MUs (the SKIP option) that were used in the Pass 2 analysis.

### 10.2 Pass 2 Scheduling and MU frequency

The momentum profiles were created using the Pass 2 torque tables and a maximum assigned off normal roll of 4°. The OOI orient assignment mode was not used in this analysis because of its poor performance with multiple in track MUs.

8316 Momentum Profiles were created based upon the permutations of

- 11 "baseline" schedules
- 2 MU starting offsets (0 or 11 days)
- 5 Torque Tables (generated using a CG y uncertainty of 30, 40, 50, 60, or 75 mm)
- 27 derived torque table cases (the permutations of all the sub torque tables)

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To verify that this is the current version.
• 2 roll assignment modes (JPA and OLV)
• 2 momentum unload types (ZERO MU with ALWAYS unloading before a SK and RLP_YZ MUs with conditional unloading before each SK, SKIP).
<table>
<thead>
<tr>
<th>Line #</th>
<th>Limit [Nms]</th>
<th>Case</th>
<th>CGy Unc [mm]</th>
<th>Roll Opt Mode</th>
<th>MU Type</th>
<th>MU [Nms]</th>
<th>MU Interval [Days]</th>
<th>Number of intervals containing this number of MUs</th>
<th># Full MU</th>
<th># YZ MU</th>
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</thead>
<tbody>
<tr>
<td>1</td>
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<td>JPA</td>
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<td>YZ_RLP</td>
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<td>70.00</td>
<td>59.26</td>
<td>13.32</td>
<td>217.95</td>
</tr>
<tr>
<td>13</td>
<td>70</td>
<td>333</td>
<td>50</td>
<td>OLV</td>
<td>YZ_RLP</td>
<td>4.20</td>
<td>70.00</td>
<td>59.25</td>
<td>13.47</td>
<td>231.13</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
<td>333</td>
<td>60</td>
<td>OLV</td>
<td>YZ_RLP</td>
<td>7.23</td>
<td>69.99</td>
<td>59.76</td>
<td>13.01</td>
<td>247.42</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>333</td>
<td>75</td>
<td>OLV</td>
<td>YZ_RLP</td>
<td>8.81</td>
<td>69.99</td>
<td>60.05</td>
<td>12.93</td>
<td>273.37</td>
</tr>
<tr>
<td>16</td>
<td>70</td>
<td>333</td>
<td>75</td>
<td>OLV</td>
<td>ZERO</td>
<td>1.79</td>
<td>70.00</td>
<td>59.21</td>
<td>14.56</td>
<td>267.44</td>
</tr>
</tbody>
</table>

Table 10-3: The MU statistics for the nominal and worst non-nominal torque tables and the four roll assignment mode and MU type combinations.

Check with the JWST SOCCER Database at: [http://soccer.stsci.edu/DmsProdAgile/PLMServlet](http://soccer.stsci.edu/DmsProdAgile/PLMServlet) To verify that this is the current version.
<table>
<thead>
<tr>
<th>Line #</th>
<th>Limit [Nms]</th>
<th>Case</th>
<th>CGy Uncert [mm]</th>
<th>Opt Mode</th>
<th>MUs [Nms]</th>
<th>MU Interval [Days]</th>
<th>Number of intervals containing this number of MUs</th>
<th>#</th>
<th>Full MU</th>
<th># YZ MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>333</td>
<td>50</td>
<td>OLV</td>
<td>7.22</td>
<td>50.00</td>
<td>42.09</td>
<td>8.76</td>
<td>242.69</td>
<td>0.51 18.4 3.82 0 20 51 48 50 48 51 32 19 12 10 11 1</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>333</td>
<td>50</td>
<td>OLV</td>
<td>6.82</td>
<td>59.99</td>
<td>51.06</td>
<td>10.72</td>
<td>237.31</td>
<td>0.49 22.3 4.73 1 47 62 62 63 52 35 14 7 10 0 0 0</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>333</td>
<td>50</td>
<td>OLV</td>
<td>4.20</td>
<td>70.00</td>
<td>59.25</td>
<td>13.47</td>
<td>231.13</td>
<td>0.51 23.0 5.64 0 55 69 67 66 40 14 15 5 0 0 0 0</td>
</tr>
</tbody>
</table>

Table 10-4: The MU statistics for the MU limit variation cases.
The C333 Torque Table cases produced the shortest mean MU interval for all values of the CG y uncertainty. These are highlighted by the red box in Table 10-3. Out of the 22 momentum profiles for each CGy uncertainty; the baseline schedule 11 with a 00 day MU offset had the shortest mean MU interval. These worst case momentum profiles were used to produce the MU files for SK analysis. Additional momentum profiles were generated using the C333 torque table with a CGy uncertainty of 50 mm, the RLP_YZ MU type, and 2 MU limits of 50 and 60 Nms. The MU statistics for these cases are grouped for comparison with the corresponding case using a MU limit of 70 Nms in Table 10-4. The MU files for the baseline schedule 11 with a 00 day MU offset were produced for SK analysis.

10.3 Roll optimization OLV versus JPA

<table>
<thead>
<tr>
<th>Case</th>
<th>Percentage Change</th>
<th>Percentage YZ MUs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MU / 22days # MUs</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>-44.8% 0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>333</td>
<td>-14.0% 0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Table 10-5: OLV versus JPA roll optimization

Table 10-5 presents a summary comparison of the momentum unload statistics for the OLV versus JPA roll optimizations and the momentum unload type ZERO presented in Table 10-2. In the case of the nominal torque table (C111), roll optimization reduced the mean momentum unloaded per 22 days by almost 50%. Using the worst case torque table (C333, CGy=75mm), the reduction is 14%. The smaller reduction is caused by the 4° roll bias of the C333 torque table impacting the ability of the optimization algorithm to manage the momentum. The momentum unload type ZERO always scheduled a MU before each SK maneuver so the number of MUs did not change between the two roll optimization modes.

10.4 MU Variation Comparison

<table>
<thead>
<tr>
<th>Case</th>
<th>Percentage Change</th>
<th>Percentage YZ MUs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MU / 22days # MUs</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>-3.1% -69.5% 78.9%</td>
<td></td>
</tr>
<tr>
<td>333</td>
<td>2.2% -3.5% 17.6%</td>
<td></td>
</tr>
</tbody>
</table>

Table 10-6: RLP_YZ/SKIP versus ZERO/ALWAYS momentum unload types.

Table 10-6 presents a summary comparison of the momentum unload statistics for the RLP_YZ/SKIP versus ZERO/ALWAYS momentum unload types and the OLV orientation assignment mode presented in Table 10-3. In the case of the nominal torque table (C111), the RLP_YZ MU type slightly reduced the mean momentum unloaded per 22 days by 3%. Using the worst case torque table (C333, CGy=75mm), the mean momentum unloaded increased by 2%. In the case of the nominal torque table, the
RLP_YZ/SKIP momentum unload type reduced the number of momentum unloads by 70%. In addition, of the momentum unloads that were scheduled; almost 80% were the RLP_YZ type. The large roll bias of the worst case torque table again impacted the momentum management. The number of MUs dropped by less than 4% and less than 20% of the scheduled MUs were of the RLP_YZ type.

11.0 Conclusions

The requirement limiting the number of MUs to two per Station Keeping interval (~22 days) could not be met assuming one failed reaction wheel, the worst case non-nominal torque table, and SO-DRM roll optimized schedules. In the Pass 1 analysis, about 65% of the Station Keeping intervals contained three or more momentum unloads. In both Passes the mean MU interval was less than 5 days implying at least 4 MUs per interval on average. This requirement is based upon limitations of the “batch” Orbit Determination method; which is not the case with the sequential Orbit Determination method. Therefore, the sequential Orbit Determination method is required.

Using the worst case non-nominal torque tables both the OLV and OOI roll assignment modes provide a 19% to 20% reduction of the unloaded momentum compared to the un-optimized JPA mode. As described in section 7.47.0, the algorithm for the OOI roll assignment mode does not properly minimize momentum over the interval when non-nominal torque tables are used. In addition, it is more complex to implement than the OLV mode. Given these three facts, the OLV roll assignment mode is preferred.

The Pass 2 simulations, using the OLV roll assignment mode and the worst case non-nominal torque table also compared the scheduling of partial MUs and conditional MUs (RLP_YZ / SKIP) versus full MUs and always performing a pre-SK MU (ZERO / ALWAYS). The results indicate a ~4% reduction in the number of MUs required and allowed roughly 20% of the MUs to be the RLP_YZ type. Using the nominal torque table in the simulations produced larger changes in that the required number of MUs dropped by 70% and of those remaining MUs, nearly 80% are of the RLP_YZ type. In both comparisons the required amount of momentum unloaded changed by less than ~3%. Thus based upon the reduction of time needed to perform the MUs, the scheduling of partial MUs and conditional MUs (RLP_YZ / SKIP) is superior.

It is recommended that the OLV roll assignment mode, partial momentum unloads (RLP_YX), and conditional momentum unloads (SKIP) be implemented for JWST.

12.0 Future Work

The impact to the momentum profile caused by Visit failures needs to be investigated including the constraints imposed by Visit relative timing constraints.

Changing the scheduled start time of Visits with fixed orientations is effectively changing the roll (Kinzel 2005A). Since 50% of the Visits are expected to have orientation constraints, this will allow an additional option in managing the momentum accumulation and should be investigated.

The OOI roll optimization mode should continue to be investigated as it did show additional reduction in the unloaded momentum as compared to the OLV mode when using a nominal torque table.

Check with the JWST SOCCER Database at: http://soccer.stsci.edu/DmsProdAgile/PLMServlet
To verify that this is the current version.
This study assumed a maximum assigned off normal roll of 4°. For a nominal torque
table, a previous study (Kinzel 2005B) indicated little additional reduction in the
accumulated momentum occurred for maximum assigned off normal rolls larger than 2°.
Also, visits scheduled at large off normal rolls can cause gaps in the executing timeline in
the event of visit failures. The Observatory design is being changed substantially at the
time of this study. Thus at each major Observatory design milestone, the ability of the
momentum management process to manage the JWST angular momentum and the value
used for the maximum assigned off normal roll limit should be reevaluated.

13.0 References

Management Analysis”

Kinzel, W. M., 2005A, JWST-STScI-000713, SM-12, “Managing Angular Momentum
Accumulation by Visit Sequencing and Visit Roll Selection”

Kinzel, W. M., 2005B, JWST-STScI- 000729, “Using Spacecraft Roll to Control JWST
Momentum Buildup”


Mission (SO-DRM) Data Products”, Version 1.1 (S&OC-DRD OP-01), October 25,
2005.

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