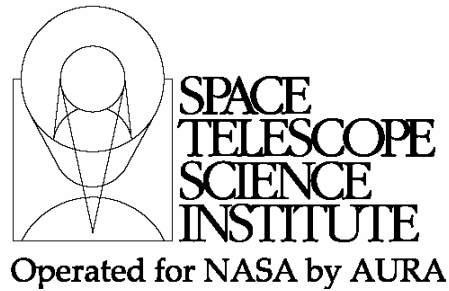




TECHNICAL REPORT



Title: Using Spacecraft Roll to Control JWST Momentum Buildup		Doc #: JWST-STScI-000729, SM-12
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1.0 Abstract

We have investigated the use of an algorithm that, for each visit in a JWST schedule, assigns an off normal roll within a limited roll range to control the JWST angular momentum accumulation and the impact to the angular momentum profile caused by visit failures when using this algorithm. We also studied the ability of the algorithm to manage the accumulated angular momentum using three different recently released torque tables.

We find using the JMS_071205 mission schedule, the SolarTorque_SimpleOptimized torque table, and a 2° off normal roll limit produces a factor of 3 lower mean momentum per momentum dump than that found assigning normal rolls to all the visits. Using a 2° off normal roll limit allowed 92% of the momentum dumps to occur at a level less than 29 Nms which would allow the momentum management to be robust against single visit failures. However, two momentum unloads significantly exceeded the dump momentum limit of 40 Nms and were caused by a large number of Same Orient link set that would have required rebuilding the schedule to avoid the large momentum gain.

We conclude that using off normal assignment algorithms in short term scheduling should be part of any strategy to limit momentum dumps on JWST.

If schedules can be created using a momentum dump limit sufficiently lower than the maximum that can be stored in the RWA, this is likely to be an effective strategy for preventing unplanned momentum dumps and allows the timeline to be robust against single visit failures.

Long duration Same Orient link sets will have to be managed in the JWST Long Range Plan to avoid clusters of the link sets from overwhelming the ability of the scheduling system to manage the angular momentum accumulation.

The Sep05_PS2 torque table was found to be problematic because of the 3° roll bias. It required the use of a 5° roll limit in order to maintain the mean momentum per dump just below the momentum dump limit of 123 Nms. Many visits (33%) were assigned a -5° roll which then constrains the visits so they cannot execute earlier than planned. Thus with visit failures, gaps will appear in the executing timeline. This indicates a roll symmetry requirement may be needed on the solar torque tables.

2.0 Introduction

An earlier study showed that actively adjusting the spacecraft roll or time ordering visits with fixed orientation in a JWST timeline was very effective in reducing the angular momentum accumulation for JWST (Kinzel, 2005). However, that study had several shortcomings: the simulated visits were all uniform in duration (1 day), the simulated targets were uniformly distributed across the Field of Regard, the allowed maximum assigned off normal roll limit for any particular visit was the maximum observatory off normal roll ($\pm 5^\circ$), and no visit link sets were implemented. In this study, we use various Design Reference Missions, and Mission Schedules created enforcing visit restrictions and timing links to investigate our ability to manage angular momentum accumulation using a smaller range of assigned off normal roll limits and determine the impact to the angular momentum profile if a visit fails and the subsequent visits execute at times earlier than that planned. We also investigate the ability of the algorithm to manage the accumulated angular momentum using three different recently released torque tables.

This study only used the assigned roll as a free parameter as it has been demonstrated that in the absence of tight timing constraints, proper time ordering of fixed orientation visits produces the same reduction the angular momentum accumulation as assigning particular roll angles (Kinzel 2005). We have assumed momentum dumps can occur no closer than 22 days and that the dump momentum limit is either 40 Nms or 123 Nms depending upon which torque table is being used.

3.0 Design Reference Missions and Mission Schedules

As the spacecraft design is evolving so are the Programs specified in the Design Reference Mission (DRM) and the software used to plan and schedule the observations, the NGST Mission Scheduler (NMS) and the JWST Mission Scheduler (JMS). Several Mission Schedules were used to establish the applicability of the roll assignment algorithm described in this report. The description of the DRMs and the software capabilities are below.

Mission Schedule	Number of Scheduled Visits	Total Visit Duration [Days]	Description
NMS V3.6b	1032	1653	Original ASWG DRM
JMS_1.3	1235	1948.9	Scheduler uses S/N for scheduling.
JMS_061505	3852	599.2	First cut at updated SO-DRM programs, released as JMS 1.4. Includes identification of Same Orient link set visits in its output.
JMS_071205	3487	569.3	Latest updated SODRM, not publicly released. More Same Orient link sets implemented.

Table 1 Summary of Mission Schedules used in the study.

NMS_V3.6b

This DRM was based upon the science requirements as developed by the Ad Hoc Science Working Group and was also originally based upon an 8m telescope. This set of observations contains many long observations, some as long as 60 days. NMS had the ability to break these long observations into smaller pieces (20 days in this case) that could be scheduled independently. In addition, NMS did not take into account any orientation restrictions on the observations. NMS produced schedules using a simple greedy scheduling algorithm. Since even a 20 day observation could violate observatory orientation constraints, the momentum analysis code used for this study was given the ability to break these longer visits (20 days) into shorter pieces (1 day duration) to allow independent assignment of valid observatory orientations. No timing links were implemented in the ASWG DRM or NMS. Each visit's duration was dependent upon the exposure time which was calculated from the specified observation parameters (target pointing, S/N, target brightness, wavelength, and band pass) and the scheduled time of year. During the scheduling process, NMS attempted to minimize the required exposure time for each visit.

JMS_1.3

The DRM is basically the same as NMS_V3.6b. However, some observations that could not originally schedule were fixed, the long visits have been split into visits of shorter durations, and the DRM visits were converted into fixed duration exposure times consistent with the original observation parameters. The JMS scheduler schedules observations by maximizing the visit S/N not by minimizing exposure times.

JMS_061505

This is the first incarnation of the Science Operations DRM (SO-DRM) (Petro 2005) and is much more representative of the type of visits that are expected for JWST, that is, visits are of reasonable size (mean duration ~8 hours), and timing and orient links have been implemented. Versions of the software JMS 1.4 and after also now output flags that indicate if a visit is part of an orient link set. This information was used in the momentum analysis code to identify visits in Same Orient Link Sets and assign the orientation of the visits appropriately. The JMS scheduling algorithm was modified to randomize visit scheduling so that visits were not always placed in their earliest available spot.

This SO-DRM and Mission Schedule version was released as JMS 1.4.

JMS_071205

This Mission Schedule was created using the JMS 1.4 scheduler. This proposal pool had more programs updated including additional Same Orient link sets. This mission schedule has many Same Orient link sets scheduled near the start of the schedule. This Mission schedule is currently not released.

All of the mission schedules were constructed without regard to momentum management issues. The torque table SolarTorques_Simple_Optimized (April 2004) with a 40 Nms dump momentum limit was used for all momentum calculations in this study except in section 7.0

4.0 The Angular Momentum Management Algorithm

The NMS and JMS schedules provide a visit start and end time. This time interval includes a fixed duration (45 minutes) slew time and 15 minute slew settling time. The angular momentum accumulation calculation does not model slew motion and assumes JWST is at the target attitude during the entire visit time interval. In addition, any gap time in the schedule is ignored. That is, only time inside of a visit's start and end time is used to accumulate momentum and is also used to accumulate wall clock time. This is motivated by the assumption that gaps in operational unexecuted Observation Plans (OPs) will be minimal. Finally it was also assumed that the momentum unload activities were instantaneous.

Starting with the first visit in a JWST Mission Schedule, and for each visit in the schedule, the orientation of the visit was adjusted over the allowed roll range to find the minimum in the total accumulated observatory angular momentum up to the end time of the visit being adjusted. Visits contained in a Same Orient link set were set to the V3 Position Angle (PA) at the middle of the range defined by the Normal PA at the start of the earliest visit and the end time of the latest visit in the scheduled link set. The orientations of the visits in each link set were then fixed. This was done to simplify the roll assignment algorithm since several of the link sets spanned multiple days and had non link set visits interspersed inside the Same Orient link set time span. Before the start of each Visit, the time from the last momentum dump is determined. If the duration is greater than or equal to 22 days, a momentum dump is executed. The accumulated angular momentum just before the dump is recorded. We did not perform a momentum dump when the accumulated momentum violated the dump limit inside of the 22 day interval. This was done to determine the accumulated angular momentum at the end of each ~22 day interval.

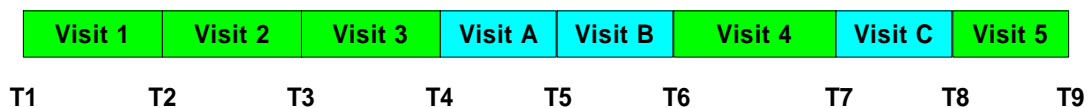


Figure 4-1 Example Mission Timeline.

A usage example of the orient assignment algorithm is given based upon Figure 4-1. The orientations of Visit 1, 2, and 3 were adjusted sequentially to minimize the total accumulated observatory angular momentum at times T2, T3, and T4 respectively. Visits A, B, and C are part of a SAME ORIENT link set. The middle of the orientation range defined by the Normal V3 position angles at times T4 and T8 and the link set's target pointing was used as the orientation for the link set. The orientation for Visits A and B are set and their contribution to the total angular momentum was calculated. Then, Visit 4 has its roll adjusted to minimize the total angular momentum accumulated up to time T7. Then again, the orientation for Visit C is set and its contribution to the total angular

momentum was calculated. The process then continues for visits remaining in the timeline.

5.0 Restricting Allowed Off Normal Roll Assignment

One of the issues with the previous momentum study (Kinzel 2005) is that the assigned off normal roll for each visit could be as large as the maximum allowed observatory roll. This roll assignment can cause individual visits to be scheduled at the minus roll limit which means no flexibility is available for these visits to execute at an earlier time in the event an earlier visit failed. These visit failure events will open gaps (no activity) in the executing time line. A histogram of the assigned off normal roll for the JMS_071205 mission schedule using an off normal roll limit of 5° is shown in Figure 5-1

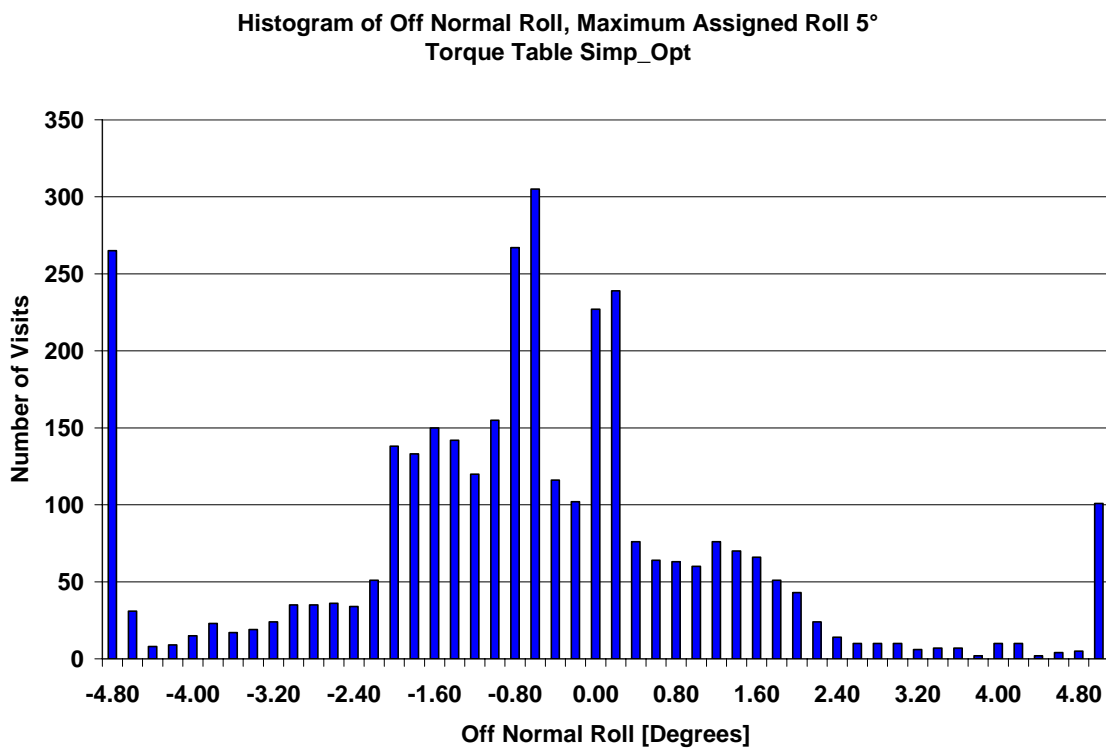


Figure 5-1 Histogram of assigned rolls using roll limits of $\pm 5^\circ$.

Ignoring the large number of rolls at -5° , the peak in the histogram is roughly centered about an off normal roll of -1° . This is consistent with the known roll bias in the torque table used in the analysis. Now note the large number of visits with assignment of rolls in the -5° bin. Visits with targets at high ecliptic latitudes scheduled at this roll would be unable to execute earlier than scheduled because they would violate the observatory roll limit. Thus if an earlier visit failed, a gap in observatory activities would occur before this visit during OP execution.

One of the purposes of this study was to determine if actively setting the observatory roll to manage the observatory angular momentum using smaller off normal roll limits would

still be effective. The four mission schedules described in Section 3.0 were analyzed using off normal roll limits of 0° (normal roll), 0.5°, 1°, 2°, 3°, 4°, 5° during the roll assignment process. The accumulated angular momentum and the number of required momentum dumps were calculated and recorded. The mean accumulated angular momentum at the time of each dump using a ~22 day dump interval as a function of the allowed off nominal roll limit for the four mission schedules are shown in Figure 5-2.

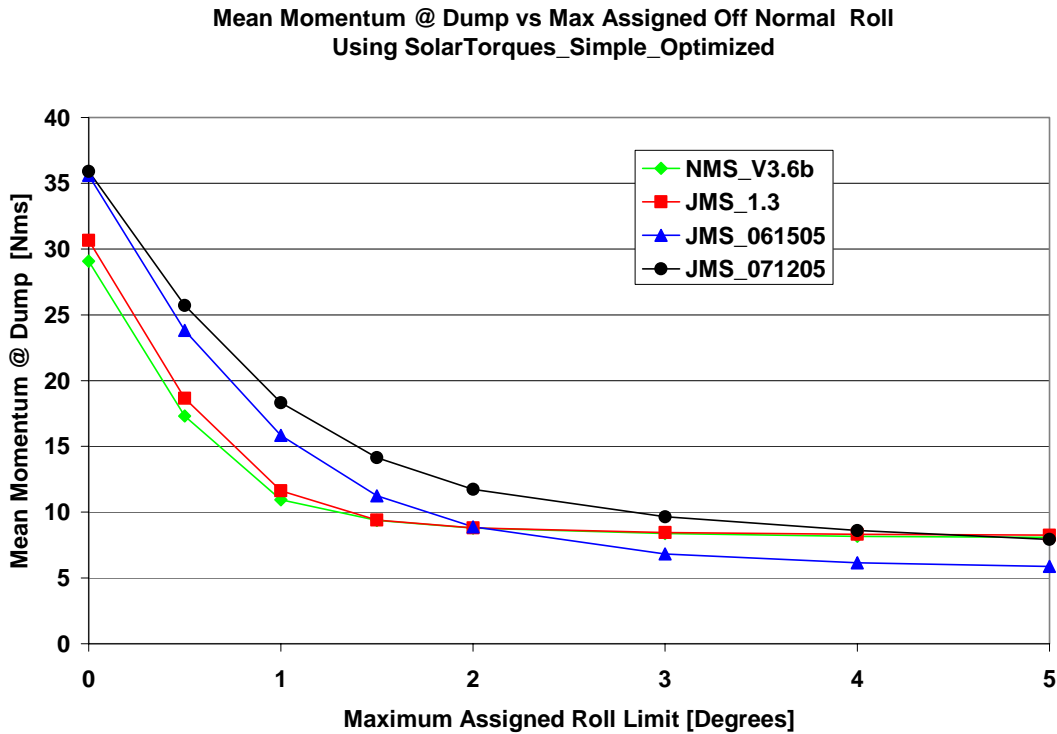


Figure 5-2 Comparison of the Mean Momentum at Dump versus Maximum Assigned Roll limits for different Mission Schedules

All of the Mission Schedules analyzed, show the same basic trend that using an assigned off normal roll limit greater than 2° gives little further reduction in the mean accumulated momentum at the time of the dumps. Using an assigned roll limit of 2° produces a minimum of a factor of 3 reduction in the mean accumulated momentum for all of the mission schedules studied.

Using an assigned roll limit of 2° the momentum profiles for the 4 mission schedules were generated. For each profile, the accumulated momentum for the dumps was placed in rank order and the cumulative percentage of dumps was plotted as a function of accumulated angular momentum (Figure 5-3). The summary statistics for each mission schedule are shown in Table 2.

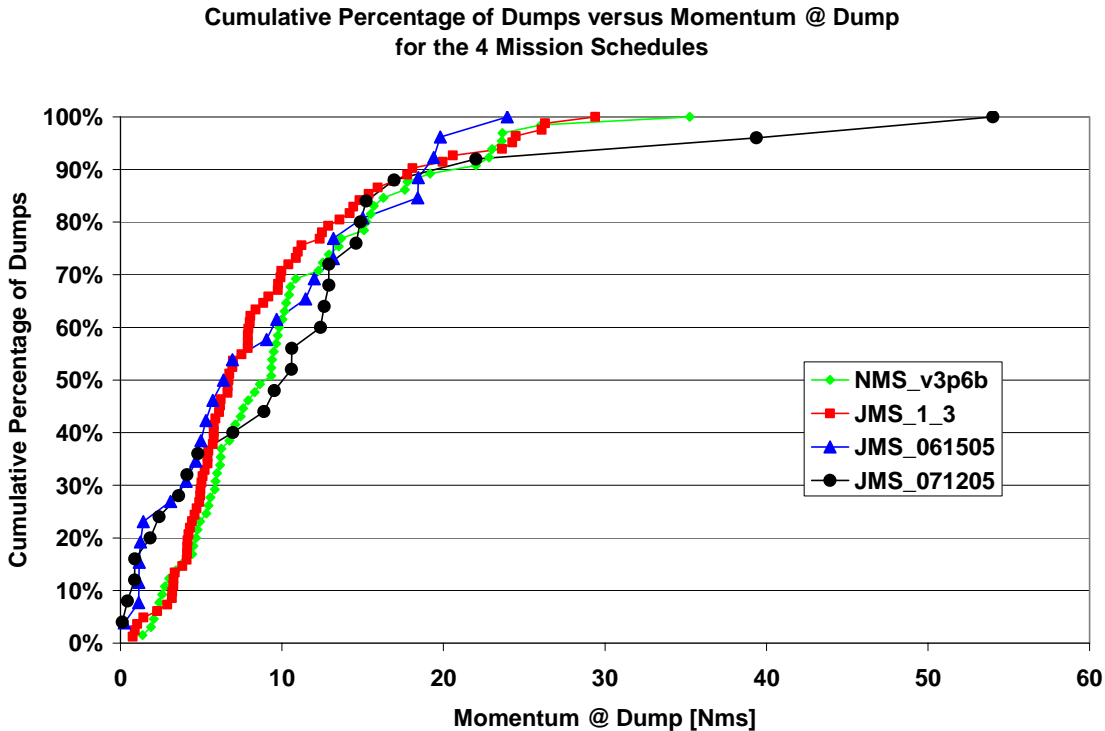


Figure 5-3 The cumulative percentage of momentum dumps versus the accumulated angular momentum, using a maximum off nominal roll limit of 2° for the various Mission Schedules.

Mission Schedule	NMS_v3p6b	JMS_1.3	JMS_061505	JMS_071205
Max	35.2	29.4	24.0	54.0
Mean	10.2	9.1	8.9	11.7
Min	1.4	0.8	0.2	0.1

Table 2 The maximum, mean, and minimum accumulated momentum [Nms] for each of the mission schedules.

As the observation descriptions become more realistic and the planning and scheduling software obtains higher fidelity (mission schedule NMS_v3.6b to mission schedule JMS_071205), the difficulty of momentum management becomes more apparent. This is seen in Figure 5-2 as the mean momentum per dump for JMS_071205 was greater than or equal to the mean momentum per dump for the other mission schedules at all rolls limits. Mission schedule JMS_071205 also produced the largest momentum dumps as shown in Figure 5-3. Since mission schedule JMS_071205 currently best represents expected reality, we will use it in the analysis for the remainder of this section and the next.

A histogram of the assigned off normal rolls for the JMS_071205 mission schedule using an off normal roll limit of 2° is shown in Figure 5-4.

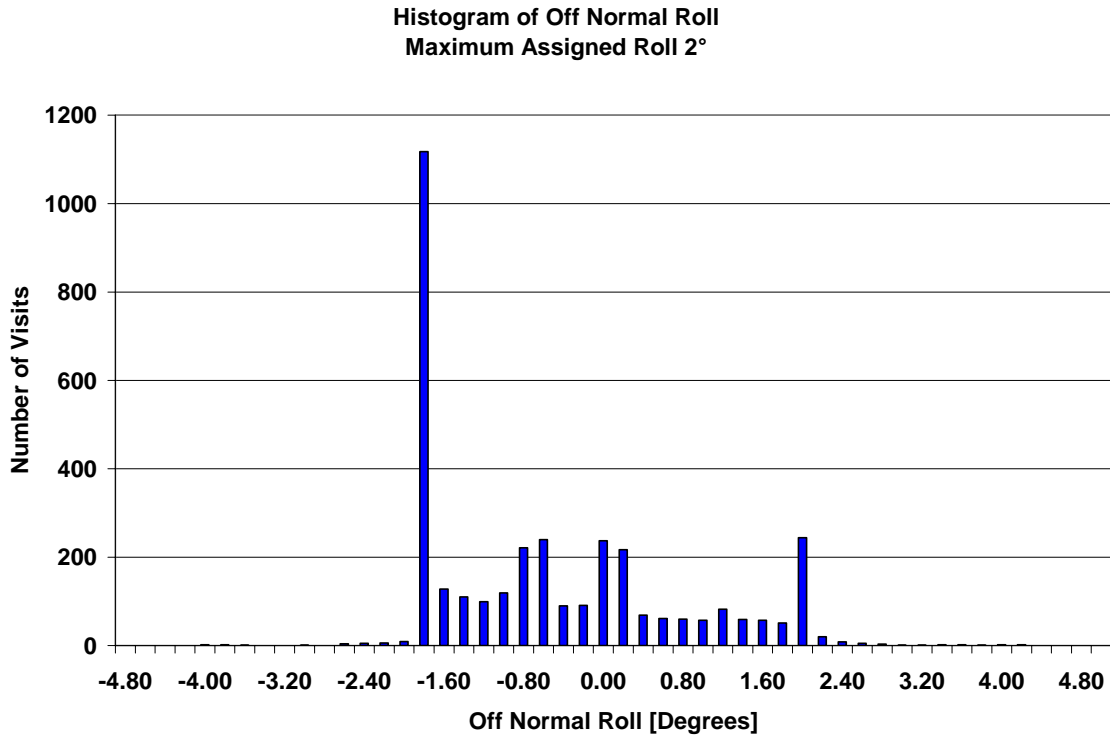


Figure 5-4 Histogram of assigned rolls using a roll limits of $\pm 2^\circ$.

Visits in the mission schedule that have off normal rolls outside of the $\pm 2^\circ$ roll limit belong to Same Orient Link Sets that spanned more than 4 days. The large number of visit roll assignments in the off normal roll bin of -2° is again caused by the roll bias (minimum roll torque at an off nominal roll of about -1°) in the torque table used. However, the assignment of a -2° off normal roll will still allow these visits with high ecliptic latitude targets to execute up to roughly three days earlier than planned without violating the observatory roll limit.

6.0 Visit Failures and the Momentum Profile

Visit failures will be the principle reason for departures from the planned JWST timeline. Therefore, it is important to investigate the effect of visit failures on momentum management. (Science instrument safings or vehicle safings will impact the executing time line. Because they can eliminate a large number of observations, they will commonly require the operations staff to reestablish the observing timeline and the momentum management.) In this study, we only examine the impact to the momentum management caused by random visit failures such as guide star or target acquisition failures and the subsequent shifting of the executing timeline caused by these failures. We assume a small visit failure rate ($< 2\%$) which implies the probability of two or more visits failing in a week (the nominal OP update interval) is less than 11% (assumes 28 visits per week and a binomial probability). Thus we will only examine impacts to the momentum profile caused single visit failures. We can bound the amount of time visits will execute early by examining the visit size distribution in the SO-DRM. Figure 6-1 indicates that in this version of the SO-DRM, 95% of the visits, including the slew time

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(counting Same Orient link sets as a single visit), are less than 16 hours (0.67 days) in duration.

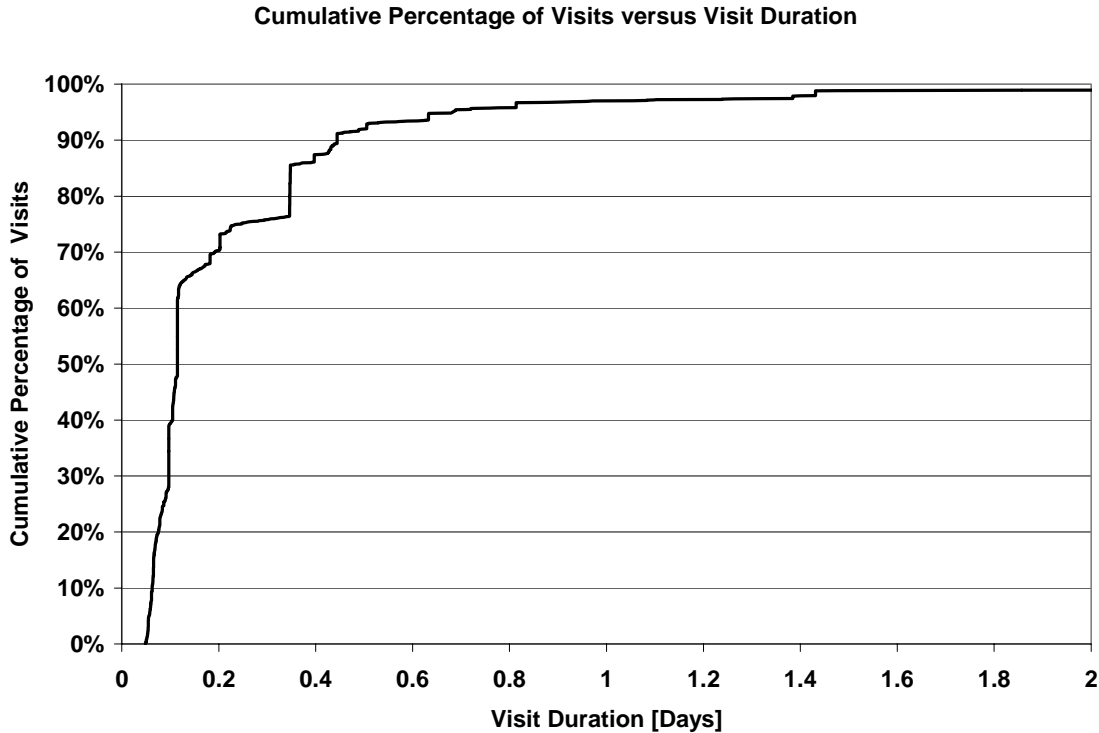


Figure 6-1 Cumulative percentage of visits versus the visit duration for visits in JMS_071205.

The algorithm used to determine the change in the momentum is explained using Figure 6-2 for the case of visits executing 0.67 days earlier than planned and determining the momentum change ~3 days later. For each visit in the mission schedule using the start time of this visit, find the first visit later in the schedule whose end time is greater than 3.0 days and less than 3.5 days. In the example, these are visits 1 to 5. We assume a momentum dump is planned to occur just after visit 5, constrained so it cannot execute early. Determine the vector magnitude of $\mathbf{M2} - \mathbf{M1}$. Shift the assumed start and end times of each visit in the interval 0.67 days earlier and calculate the momentum accumulation again. Find the vector magnitude of $\mathbf{M4} - \mathbf{M3}$. Note, as the visits execute early the visit orientation was kept fixed at its assigned value as that is what will occur on board JWST during execution. In addition, the observatory stays at the same orientation between the end of visit 5 and the start of the momentum dump. The momentum code also accumulated momentum during this time.

The change in the momentum is then $|\mathbf{M4} - \mathbf{M3}| - |\mathbf{M2} - \mathbf{M1}|$.



Figure 6-2 A Visit Sequence execution assuming 0.67 Day early execution.

Note too that all visits inclusively between the first and last visit all had to be executable at the earlier start time. If they were not, the momentum change for that particular starting visit was not recorded. The rationale being that the scheduling algorithm did not try to schedule visits away from a constraint boundary and the primary reason why the visit cannot execute early is because they were scheduled at or near their earliest possible start time in the mission schedule. When visits cannot execute early, the original momentum profile is maintained but a gap is produced in the observatory activities. In addition, modeling and tracking the visits that could not execute at an earlier time would have significantly complicated the code simulating the earlier execution.

Starting with the first visit in the Mission Schedule, the visits were assumed to execute 0.67 days earlier than planned and the momentum change was determined 3 to 3.5 days and 7 to 7.5 days later than the starting visit's start time. For each case the momentum changes were placed in rank order and the cumulative fractional number of visits as a function of the momentum change was calculated. The results are shown in Figure 6-3.

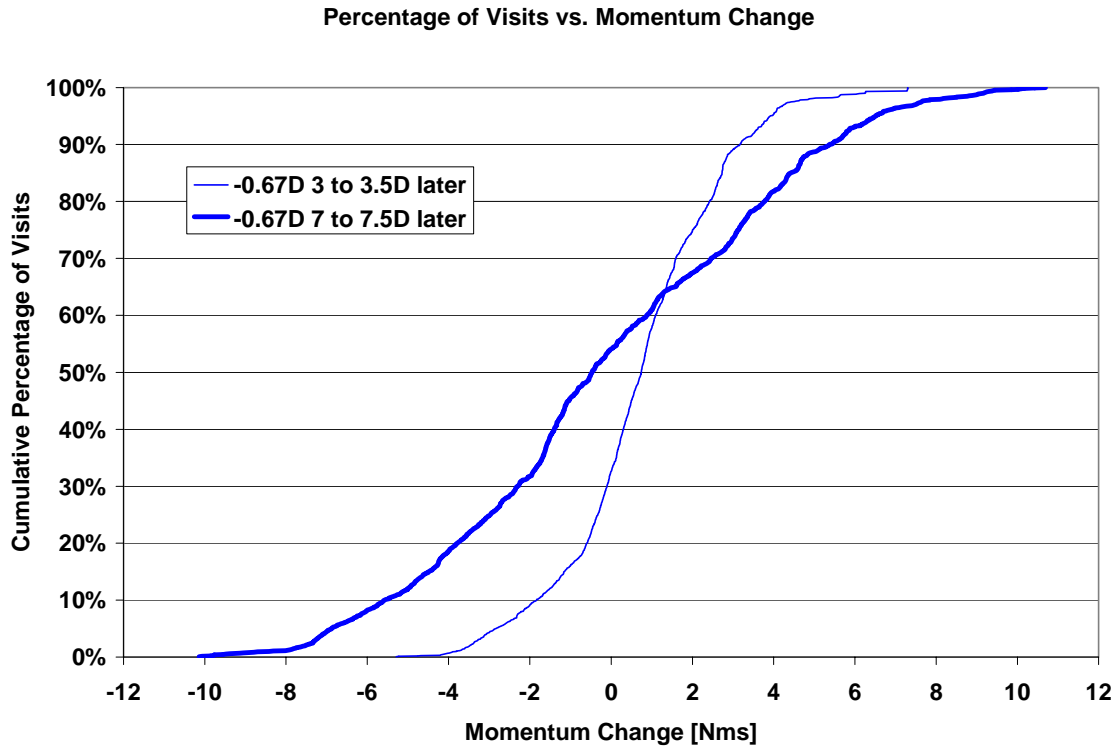


Figure 6-3 Cumulative Percentage of Visits versus the Amount of Momentum Change

The negative momentum changes are caused by the Same Orient Link Sets. That is, the accumulated momentum was smaller when the visits executed earlier than planned. The reason for this is the visits in these link sets were set to roughly the Normal roll at the mid time of the link set. When an early execution is simulated, the assigned orientation of the link set visits is closer to an off normal roll of -1° , thus closer to the minimum in the roll torque creating a lower value for the accumulated momentum. The figure indicates for 95% of the visit failures, the maximum increase in the momentum is 10.7 Nms after 7 days or 7.3 Nms after 3 days. Thus assuming the Simp_Opt torque table represents the observatory architecture, if we plan the momentum dumps every 22 days using a 29.3 Nms dump limit, then for 95% of single visit failures, even if a failure occurs a week before a planned momentum dump the planned momentum dump will occur before the momentum dump limit of 40 Nms is reached. For the JMS_071205 mission schedule, this would be possible for 92% of the momentum dumps, Figure 5-3. However, also note that two momentum unloads significantly exceeded the dump momentum limit of 40 Nms and would have required rebuilding the schedule to avoid the large momentum gain.

7.0 The Impact of Torque Table Roll Bias

The Observatory design continues to evolve as more is learned about the properties of the telescope and its operation. Periodically, new torque tables have been released. Given the “piling up” of roll assignments at the roll limit on the side of zero roll containing the torque roll bias (Figure 5-1), this implies that large torque biases may be problematic and need to be investigated. Three of the recently released torque tables were analyzed and are summarized in Table 3.

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Torque Table Excel file name	Brief Name	Description
SolarTorque_Simple_Optimized.xls	SimpOpt	Used with 40 Nms momentum dump limit. Roughly 1° roll for minimum roll torque.
SolarTorqueTable050725.xls	072505	Used with 123 Nms momentum dump limit. Roughly 1° roll for minimum roll torque.
SolarTorques_Sept2005_PrelimScale2.xls	Sep05_PS2	Used with 123 Nms momentum dump limit. Roughly 3° roll for minimum roll torque.

Table 3 Summary of Torque Tables used in the analysis.

The body roll where the roll torque is zero as a function of body pitch angle for the three torque tables is shown in Figure 7-1. All of the torque tables analyzed have a roll bias of about 1° or 3°.

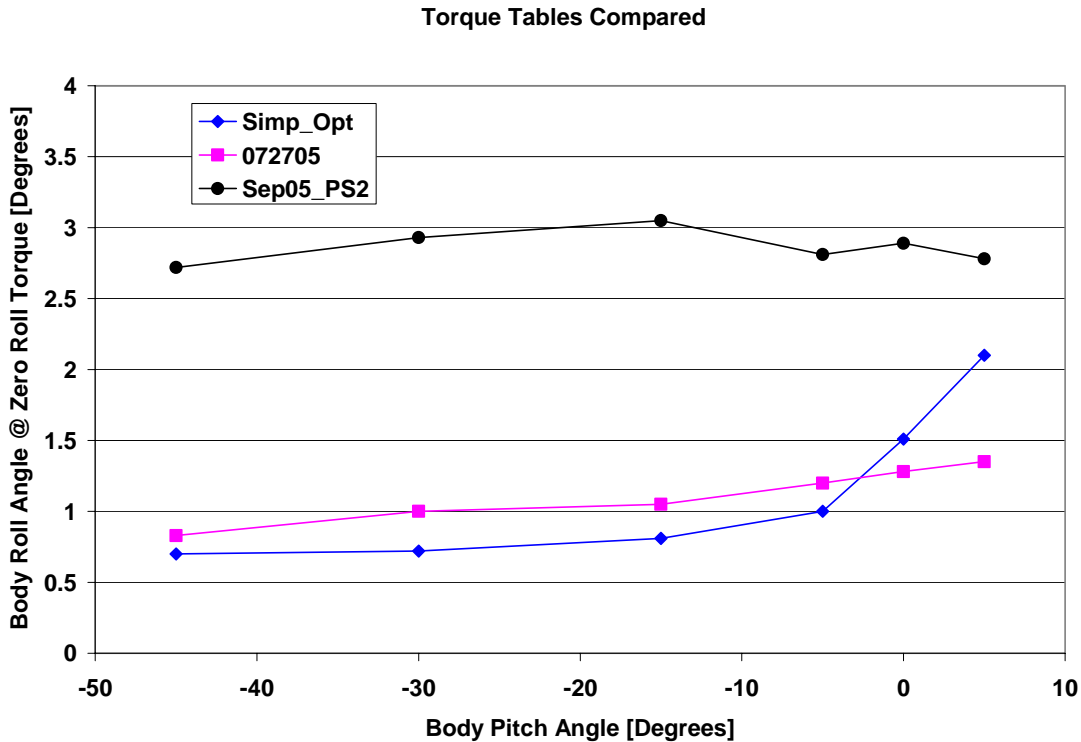


Figure 7-1 Body roll angle at zero roll torque versus body pitch angle for the three torque tables.

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The mean accumulated angular momentum at the time of each dump using a ~22 day dump interval as a function of the allowed off nominal roll limit for the three torque tables are shown in Figure 7-2

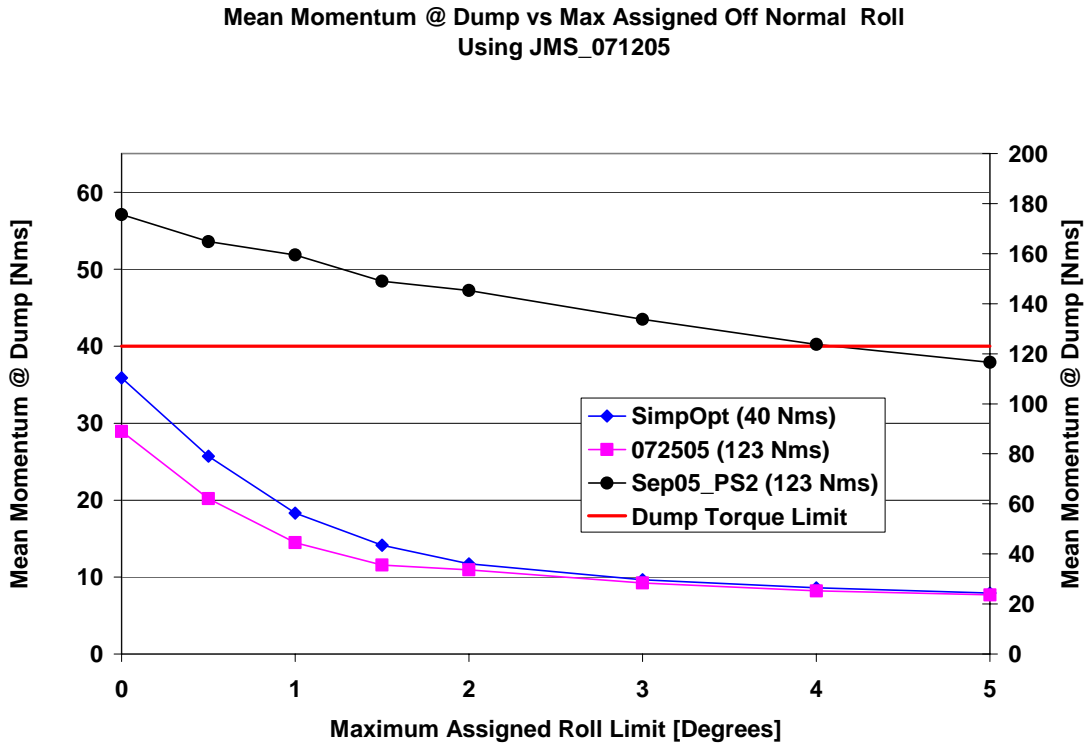


Figure 7-2 Mean momentum at dump versus maximum assigned roll limit for different torque tables.

Two of the torque tables analyzed (SimpOpt and 072505), show the same basic trend, that is, a rapid decrease in the mean momentum with increasing roll limit until when using an assigned off normal roll limit greater than 2° gives little further reduction in the mean accumulated momentum at the time of the dumps, even though the scale in the torque in the two tables is different by a factor of ~3. However, the torque table Sep05_PS2 shows more of a linear decrease of the mean momentum and for most of the roll limit range, the mean momentum accumulation is larger than the momentum dump limit of 123 Nms.

Histograms of the assigned off normal rolls for the JMS_071205 mission schedule using an off normal roll limit of 5° for each of the three torque tables are shown in Figure 7-3, Figure 7-4, and Figure 7-5.

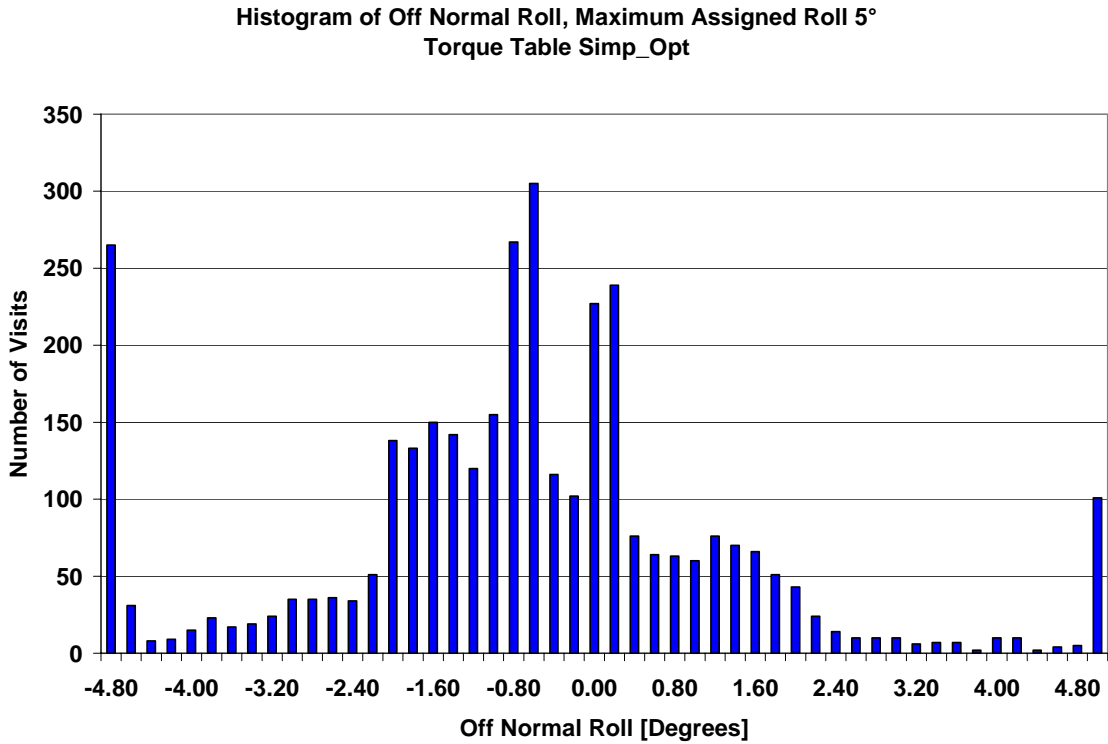


Figure 7-3 Histogram of Off Normal Roll assignments for torque table Simp_Opt.

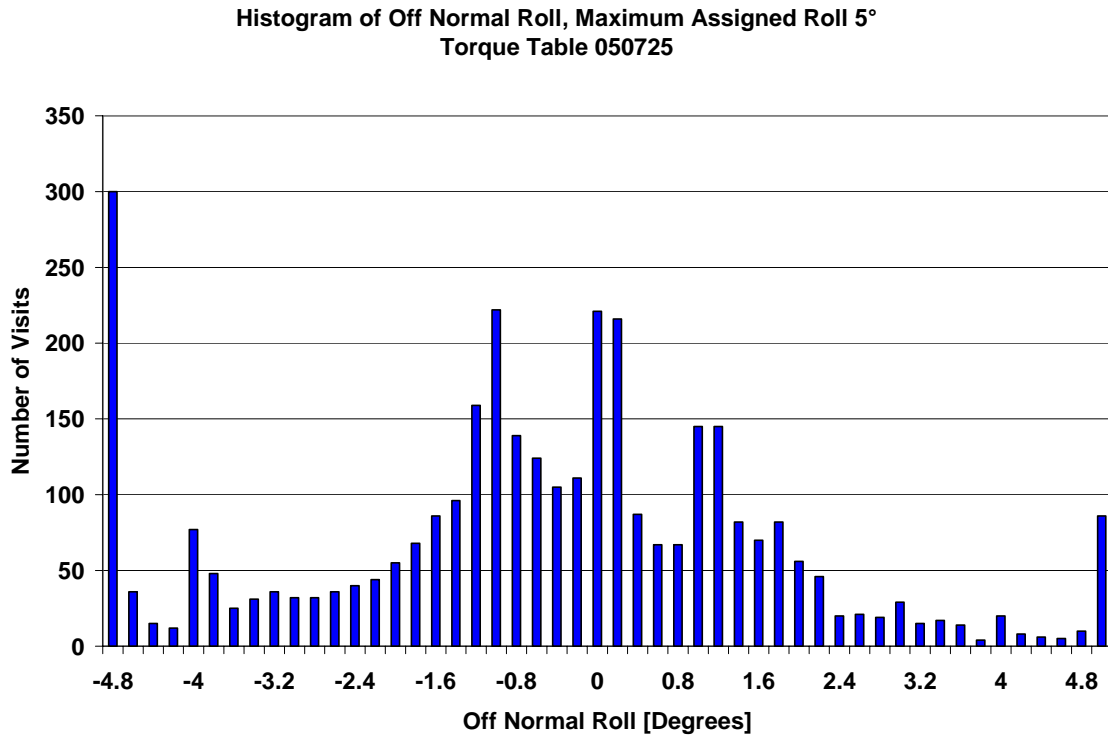


Figure 7-4 Histogram of Off Normal Roll assignments for torque table 050725.
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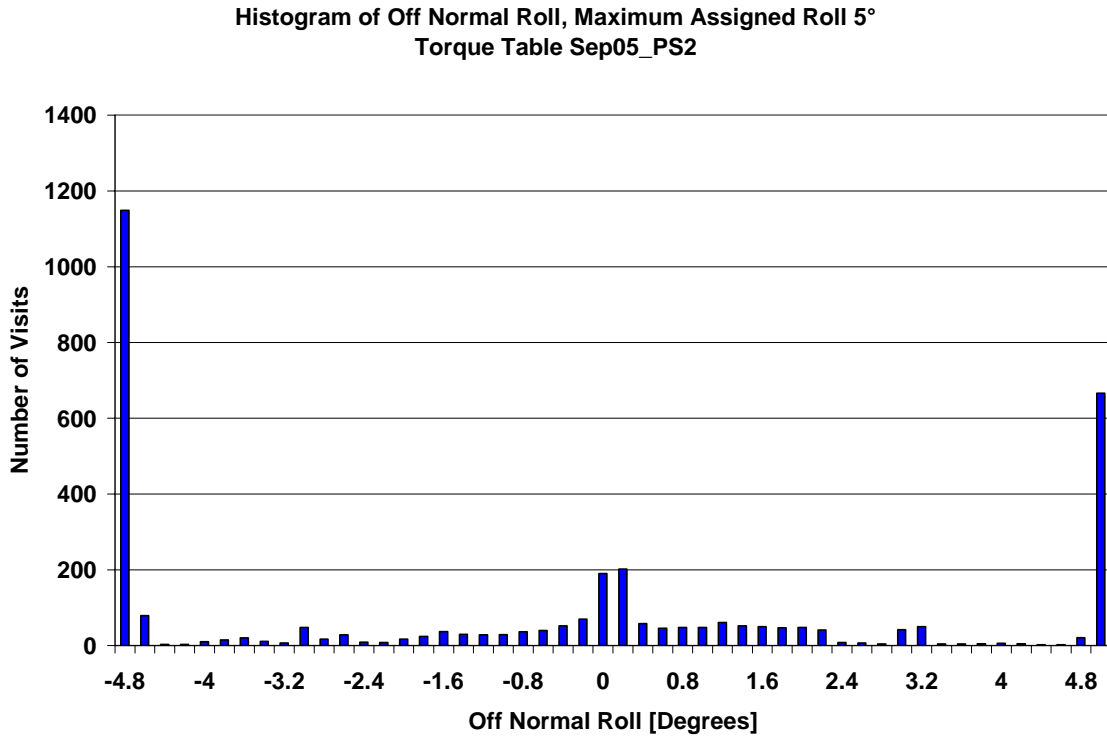


Figure 7-5 Histogram of Off Normal Roll assignments for torque table Sep05_PS2.

The histograms of the roll assignments using first two torque tables are quantitatively similar. They both show the concentration of assigned rolls in the $\pm 5^\circ$ bins with 10.5% and 11.1%, respectively, of the visits in those bins. However, again, the histogram for the Sep05_PS2 torque table is very different with 52.1% of the visit roll assignments occurring in the $\pm 5^\circ$ bins. This means that all of these visits in the -5° bin (33%) are scheduled at or near their earliest start time and will be unable to execute earlier in the event of a failed visit.

8.0 Conclusions

Actively using off normal roll assignments to manage the JWST momentum accumulation enables a significant reduction in the accumulated mean momentum over that obtained from a normal roll orientation assignment if the roll bias in the torque table is 1° or less. Using the JMS_071205 mission schedule, the SolarTorque_SimpleOptimized torque table, and a 2° off normal roll limit produces a factor of 3 lower mean momentum per dump than that found assigning normal rolls to all the visits. Using a 2° off normal roll limit allowed 92% of the momentum dumps to occur at a level less than 29 Nms which would allow the momentum management to be robust against single visit failures.

The Sep05_PS2 torque table is problematic because of the 3° roll bias. It required the use of a 5° roll limit in order to maintain the mean momentum just below the momentum dump limit of 123 Nms and may not provide unplanned momentum dump protection. In addition, because of the bias and the use of the 5° roll limit, many visits were assigned a -

5° roll which then disallows the visits to execute at a time earlier than planned. Thus with visit failures, gaps will appear in the executing timeline. This indicates a roll symmetry requirement may be needed on the solar torque tables.

If schedules can be created using a momentum dump limit sufficiently lower than the maximum that can be stored in the RWA, this is likely to be an effective strategy for preventing unplanned momentum dumps and allows the timeline to be robust against single visit failures.

Long duration Same Orient link sets will have to be managed in the JWST Long Range Plan to avoid clusters of the link sets from overwhelming the ability of the scheduling system to manage the angular momentum accumulation, such as found in the early part of the JMS_071205 mission schedule.

9.0 Future Work

The roll assignment algorithm used in this study was very simple and based upon the historical momentum accumulation. It may be possible to decrease the accumulated mean momentum further by using a historical and predictive momentum algorithm and also by developing a visit ordering algorithm for the fixed orientation visits. However, in reality, the slew time from target to target will vary. Thus during operations, the slew will be modeled with a reasonable level of fidelity. This implies that a simple visit reordering after the schedule is built algorithm, as used in Kinzel 2005, will not work as the visit reordering would change the slew profile and the duration of each visit. Thus the ordering of the visits will have to be part of the initial timeline construction and an algorithm will have to be developed that combines the visit ordering and visit roll assignment. In addition, a better orient assignment algorithm for visits in Same Orient link sets could be developed, but will need to be validated against visit failures.

Finally, as each new torque table is released, the ability of this process to manage the JWST angular momentum and the value used for the off normal roll limit will need to be reevaluated.

10.0 References

Kinzel, W. 2005, STSCI-JWST-TM 000540, Managing Angular Momentum Accumulation by Visit Sequencing and Visit Roll Selection

Petro, L & the SO-DRM Working Group 2004, STSCI-JWST-TM-2004-0011, Science utilization patterns of JWST

11.0 Definitions

Term	Definition
Astronomical Roll	Same as V3 Position Angle
Normal roll	The spacecraft roll when the sun is in the plane that is normal to the V2 vector and the half plane defined by the – V3 vector at the mid-time of the visit.

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Roll or space craft roll	The difference in the V3 position angle between the current S/C attitude and that at Normal roll.
V3 Position Angle	The angle at the target, measured eastward, between true north and the spacecraft V3 vector projected on the plane of the sky.