1.0 Abstract

The JWST Mission Simulator schedule of the science program of the Science Operations–Design Reference Mission and the calculated angular momentum stored in the JWST Reaction Wheel Assemblies is presented. The magnitude of the accumulated angular momentum exceeds limits for the full complement (6) of Reaction Wheel Assemblies during many of the simulated thruster firing cycles (either 11–day intervals, or 22–day intervals). This failure is not surprising because this mission schedule was generated without attempting to minimize the accumulation of angular momentum. The need for management of angular momentum by the Ground Segment is indicated by this study, which will require further development.

2.0 Introduction

Solar radiation pressure on the JWST sunshield applies a torque on the observatory because the center of pressure is displaced from the center of mass. The magnitude and direction of the torque varies significantly according to the attitude (quantified by the pitch and roll angles) of the observatory. For an observation of a given scientific target, pitch (the angle between the line of sight and the direction of the Sun) is a function of the time when that observation is executed and roll about the line of sight will depend upon the scientific requirements for the orientation of the field of view of the scientific instrument (SI), availability of guide stars, and the direction of the Sun at the time of observation. Thus, the solar torque on the observatory depends significantly on the scientific operation of the observatory as expressed in the mission schedule of observations and the orientation requirements.

The JWST Reaction Wheel Assemblies (RWA) counteract the solar torque on the observatory and consequently they accumulate angular momentum. The maximum angular velocity of an RWA is limited such that the maximum magnitude of the angular momentum stored by six RWAs is 40 N–m–s, or four RWAs may store 24 N–m–s. When the accumulated RWA angular momentum reaches these limits, the JWST cold–gas
reaction thrusters are operated to unload the angular momentum stored in the RWAs. But, firing the thrusters also perturbs the L2 Lissajous orbit of JWST, which then requires an extended interval of unperturbed tracking in order to measure. Operation of JWST is restricted such that no more than 40 N•m•s (6–RWA operations), or 24 N•m•s (4–RWA operations) is accumulated in the RWAs no more than twice per 22–day station keeping cycle. The operations restrictions on station keeping and momentum management are more fully described in the Mission Operations Concept Document (Stanley et al.) and by Baggett (2004).

Early operations concepts for the Next Generation Space Telescope (since renamed JWST) assumed that scientific operations would be unconstrained by solar torque because: i) the capacity of the RWAs would provide generous margin and ii) onboard, event–driven autonomous operations would manage angular momentum without significant impact to other operations. Understanding of the design of JWST has matured since those early concepts and the possibility that the ground segment must manage the RWA angular momentum has been identified. Kinzel (2004) has shown that angular momentum rapidly exceeds the 40 N•m•s limit at observatory attitudes that meet all other operational requirements. However, such extreme cases may not obtain in typical science operations. Therefore, Kinzel (2004) also analyzed the angular momentum of two mission schedules of the Ad Hoc Science Working Group Design Reference Mission, as prepared by the NGST Mission Simulator (the precursor of the JWST Mission Simulator, JMS) and JMS. However, although the scientific objectives of the ASWG DRM are representative of JWST scientific objectives, the observing programs were not designed to meet operational requirements. To overcome that deficit, the Science Operations Design Reference Mission (SO–DRM) has been developed (Petro 2005).

The purpose of this memorandum is to present an analysis of the RWA total angular momentum for a high–fidelity mission schedule of the SO–DRM. The analysis demonstrates the failure of this non–optimal schedule to meet the RWA requirements. In the following section brief descriptions of the salient characteristics of the SO–DRM and the mission schedule of the SO–DRM are presented. The analysis of the RWA angular momentum is presented in the following section.

3.0 Mission Schedule of the Science Operations Design Reference Mission

The SO–DRM is a nominal 1–year (1.5 year total visit duration as implemented) program of scientific, scientific instrument calibration, and observatory maintenance activities. It is comprised of 49 primary mode observing programs, each of which identifies its scientific goals, targets, instruments, and observing requirements. The Phase II program specifications of each observation meet the operational limitations of the JWST mission to a level of detail sufficient to meet the requirements of studies such as the present analysis of angular momentum. The activities comprising an observation of a single target are organized as a visit. A visit is comprised of the following kinds of activities: exposing the detector, instrument set up, attitude control set up, and all telescope motions (including large angle slews, changes of FOV, and intra–FOV dithers.) Only one SI is used in primary mode during a visit. The SO–DRM is comprised of 4,066 such visits, the
duration of which range from 0.8 hr to 290 hr, with only approximately a half–dozen exceeding one day. In the present version of the SO–DRM visits longer than 1 day are used to simulate the effects of observations that must be conducted at a fixed orientation of the observatory\(^1\). Scientifically required linkages between visits are implemented, as are time–constrained windows. The latter constraint is used to simulate the scheduling effects of scientifically constrained orientation of the SI field of view (FOV.) The SO–DRM and mission schedule have been presented in detail elsewhere (Petro 2005 and references therein).

The mission schedule of the SO–DRM is comprised of all 4,066 visits on a 2–year (730 day) calendar. The total duration of the visits is 531 days, with the last visit ending at mission day 643. During all visits the telescope line of sight remains within the 50˚ annular field of regard. All visits meet the linkage and time–constraint requirements specified by the program authors. Approximately 54% of the visits have linkage and/or time–constrained scheduling windows.

The mission schedule of the SO–DRM is illustrated in Figures 1 and 2 (which are Figures 2 and 3 of Petro 2005.) Figure 1 demonstrates that the duration of visits early in the schedule tend to be long and conversely those late in the schedule are short. As shown in Figure 2, the first gap between visits occurs at day 480 and only after day 574 do gaps generally exceed 1 day in duration. Therefore, in the analysis of angular momentum presented here only the first 574 days of the mission schedule are considered, which comprises 3934 (97%) of the full SO–DRM.

\(^1\) When orientation constraints are implemented in the scheduling system, then these long visits will be expressed as a set of 1–day visits linked with a SAME ORIENTATION scheduling requirement.
Calendar utilization remains above the mission requirement (95%) until day 550, at which time only 4% of the pool of SO–DRM visits remains to be executed, as shown in Figure 3 (Figure 4, Petro 2005). In Figure 3 the “utilization” at any given time is the fraction of the calendar preceding that time that is used for scheduled activities.
The algorithm that achieves successful placement of all 4,066 visits of the SO–DRM onto the calendar and that achieves the required high utilization is a two-step greedy algorithm. In the first step all timing link sets and visits are ranked in order of estimated difficulty of placement. For example, sets with a large number of visits are placed at the head of the rank, as are long-duration visits or sets. In the second step the sets and visits are placed by rank on the calendar at the “best” available place. The “best” place is taken to be the earliest time that is consistent with the target visibility, user-supplied constraints, and visits previously placed on the calendar. The objective of this preference is to reduce both gaps between visits and the span of calendar required to complete the science program. Of importance for the interpretation of the results presented below, no account of the angular momentum is taken in the process of placing visits on the calendar. Nor, was a “repair” step used to improve the schedule in any way.

![Utilization of the calendar](image)

**Figure 3** Utilization of the calendar. Utilization is the fraction of the calendar containing useful activities. The scheduling pool is the set of visits remaining to be placed on the calendar, quantified by the duration of those visits.

### 4.0 RWA Angular Momentum

The magnitude of the cumulative angular momentum stored in the RWAs for the SO–DRM mission schedule is modeled by JMS using tables computed by the prime contractor (Northrup Grumman Corporation) of torque as functions of telescope pitch and roll (L. Meza 2004). The torque is expressed in a Cartesian vehicle coordinate system \( V_1-V_2-V_3 \) (\( V_1 \) along boresight, \( V_2-V_3 \) tangent to primary mirror vertex). The pitch and roll rotations are defined by Meza and Tung (2003). Their mathematical model of
observatory torque used an 8–boom sunshield and other design parameters as known in August, 2004. JMS computes the accumulation of angular momentum during a visit on the assumption that the inertial attitude of the observatory is fixed during that visit such that nominal roll is attained at the mid–point of the visit. Note that, as described above, each visit contains overhead to account for the average duration of the slew between targets. JMS did not model the slew quaternion, nor the angular momentum accumulated along that unknown path. JMS does approximate the momentum accumulated during a slew by using the target directions at the endpoints of the slew and the slew duration. JMS tracks and reports the cumulative vector angular momentum in an inertial coordinate system by summing the momentum accumulated during each visit. Momentum unloads are not simulated, but JMS does report the run of accumulated momentum for use in external simulation and analysis (see discussion below). Major slews between targets are not modeled in JMS, other than to take into account the time required for such slews. As noted above, the present version of JMS does not apply user–specified orientation restrictions for a visit, or set of visits.

Before considering the timeline of angular momentum, the effect of calendar placement is considered as illustrated in Figure 4. As shown, torque is greatest at the start (and end) of the visibility window for each target (except the target at ecliptic latitude $\beta = 90^\circ$). This is significant because, as noted above, the JMS scheduling algorithm attempts to schedule each target early in its window of visibility, thereby tending to maximize (not optimize) the angular momentum. The 8–hour interval for accumulation of angular momentum used in the illustration approximates the average duration of a visit in the SO–DRM, 7.5 hr.
Figure 4 Solar radiation pressure torque on JWST. Torque is indicated by the change in RWA angular momentum in an 8-hour interval. Torque depends upon target direction and when the observation is executed. Only when a target is within the 50° annular field of regard is the torque computed. The torque for 6 targets is illustrated, all with ecliptic longitude $\lambda = 0^\circ$ for a range of ecliptic latitude $\beta = 0^\circ \rightarrow 90^\circ$.

The timeline of total accumulated angular momentum for the SO-DRM mission schedule is shown in Figure 5. Unloading the angular momentum of the RWAs is not modeled in this figure, but instead momentum is allowed to accumulate throughout the mission. The noteworthy features of the schedule are the rapid increase during the first 30 days of the mission, the slow increase until the end of the first year, and the rapid increase until day 550. As noted above, the analysis reported below uses the first 571 days of the mission schedule.
The total angular momentum accumulated during the first 572 days of the mission (corresponding to 52 11–day or 26 22–day thruster cycles) is 954 N·m·s (Figure 5). If the 40 N·m·s limit were reached in each of the first 52 11–day cycles of the SO–DRM schedule, the total would be 2.2× greater (2,080 N·m·s). But, if the 40 N·m·s limit applies to a 22–day cycle, then the accumulated total is 92% of that limit.

Momentum unloading for the mission schedule is considered here in an approximate manner. In this approximation, the angular momentum is set to 0 according to a steady cadence. Two alternative scenarios for operation of the thrusters are considered: an 11–day interval between firings (one that immediately precedes the station keeping maneuver and one at the mid–point of the 22–day tracking interval) and a 22–day interval. The run of the magnitude of the angular momentum between simulated thruster firings for the two scenarios are shown in Figures 6 and 7. The success of the schedule may be assessed by counting the number of thruster cycles during which a violation of the 40 N·m·s or 24 N·m·s operational limit occurred. A quick assessment can be made from a visual examination of Figures 6 and 7, which shows that for some thruster cycles either limit is exceeded, and for others it is not. The statistics are that for the first 52 11–day thruster firing cycles represented in the SO–DRM mission schedule, the 6–RWA limit is exceeded 11 times and the 4–RWA limit 32 times. In other words, the 6–RWA limit is exceeded for 21% of the cycles and the 4–RWA limit for 62%. The magnitude of the worst exceedance of the 6–RWA limit is 62%, but is 170% of the 4–RWA limit. Considering the 22–day thruster cycle, the 6–RWA limit is exceeded during 54% of the cycles and the 4–RWA limit is exceeded for 88% of the cycles.
Figure 6 Cumulative total RWA angular momentum during an 11–day thruster firing cycle. The phase is 0 at the start of the 2–year SO–DRM schedule and the angular momentum is set to 0 at the start of each cycle. The symbols represent the angular momentum at the end of each of the 4,066 SO–DRM target/SI visits. The limits on total angular momentum for 6−RWA and 4−RWA operations are indicated by the horizontal lines at 40 N−m−s and 24 N−m−s respectively.

An alternative momentum unloading procedure could, in some circumstances better meet the 40 N−m−s limits. If the execution of the schedule may be trusted, then one possibility is to condition the RWAs for the start of the next 11–day cycle such that the momentum accumulated during that net cycle remains within limits, rather than setting the angular momentum to 0. As noted in the preceding paragraph, the worst exceedance of the 6−RWA operational limit is 62%. Therefore, if the thrusters were fired such that the angular momentum of the RWA were in the opposite sense, but of 62% magnitude for that accumulated during the next cycle, then the net after that next cycle would be at the limit. Such effective doubling of the usable capacity of the RWAs will also double the mass of thruster gas required to unload the momentum, which may be undesirable. In any case, for the present schedule of the SO–DRM, such operation cannot maintain the RWAs within the 4−RWA limit on total 11–day angular momentum because the worst–case exceeds the requirements by more than the 4−RWA capacity (i.e., 170% as shown in Figure 6.)
Another alternative is to optimize the accumulated angular momentum as a part of the planning process, a procedure not employed in the present study. Consideration of the dependence of angular momentum on schedule place, as shown in Figure 4, suggests that a 2x reduction in the target “visibility” window would eliminate the times when the torque is greater than \( \sim 1.5 \times \) the minimum torque, could substantially reduced the accumulated angular momentum from the values found in this study. The implementation of this optimization need not enforce a hard constraint, but rather could consider low torque as a preference in the second step of the greedy algorithm described above, rather than the presently implemented preference for early execution. Scheduling presents yet other opportunities to optimize the accumulation of angular during a thruster firing cycle. For example, targets can be selected so that direction of the torque is offsetting. Or, targets may be schedule at times of off-nominal roll to achieve a desired offsetting torque. However, limited availability of guide stars for some targets will limit the possible orientations and opportunities to apply offsetting torques. These, and other options, require development and study, taking into account all the complexities of the JWST mission.

5.0 Conclusions

Scheduling the SO–DRM to meet scientific and the mission schedule utilization requirements, but without taking into account solar torque fails to meet angular momentum limits for either 6-RWA operations, or 4–RWA operations. The exceedance of
the 6–RWA angular momentum limit is 62% in the worst 11–day case and 170% in the worst 22–day case. The 6–RWA limit is exceed for 21% of the 11–day thruster cycles and the 4–RWA limit for 62%. The percentages for the 22–day cycle are 54% and 88%, respectively. In order to meet the operational requirements, a momentum management strategy that employs planning and scheduling techniques will be necessary.

6.0 References


