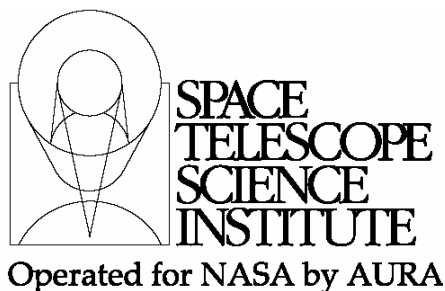




TECHNICAL REPORT



Title: Planning to minimize angular momentum	Doc #: JWST-STScI-000755, SM-12 Date: October 25, 2005 Rev: -
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1.0 Abstract

Solar radiation pressure on the JWST sunshield causes momentum to accumulate in the spacecraft's reaction wheel assemblies, which, however, have limited capacity to store that accumulated momentum. We report here the effectiveness of minimizing the accumulated angular momentum by several methods for planning and scheduling the observing calendar. We have considered four techniques to identify intervals of time when the magnitude of the angular momentum for observations of a scientific target is minimal and two criteria for selecting specific times within those intervals. Our experiments, using observations from the Science Operations Design Reference Mission, demonstrate the benefit of using a planning preference for earliest times of low torque in order to reduce the accumulated angular momentum, as compared to an unmanaged schedule. Furthermore, our study finds that constraining visits to earliest times that avoid high torque provides no significant benefit. However, we find that either a planning preference for minimum torque, or 50% constraint windows will reduce the accumulated angular momentum if, rather than scheduling at earliest times, observations are schedule at random times consistent with minimizing torque.

2.0 Introduction

During recent development of designs for the flight and ground elements, attention has been focused on the significant torque exerted by solar radiation pressure on the JWST sunshield. That torque causes angular momentum to be accumulated in Reaction Wheel Assemblies (RWA) that is unloaded by firing thrusters once, or twice every 22 days in synchronism with station keeping activities. Thereby solar radiation causes the expenditure of the consumable reaction mass, which will eventually end the science mission. Some attitudes of the observatory and some directions of the boresight within the Optical Telescope Element's field of regard (FOR) will produce solar torques that will exceed the capacity of the RWAs sooner than allowed by orbit tracking

requirements. Thus, operational restrictions may be necessary in order to meet those requirements and in order to enable an extended science mission.

Operational procedures can be imposed in the planning and scheduling process, in order to assure that benign attitudes of the observatory are considered when meeting the scientific requirements of each observation. Any, some, or all of several options might be used to manage the accumulated angular momentum in the RWAs. They include:

- 1) no active management, but simple verification
- 2) constraining the attitude to avoid attitudes that cause the greatest torque
- 3) planning observations preferentially to minimize the torque
- 4) scheduling observations that torque the observatory in opposition to the RWA momentum
- 5) rolling the observatory to minimize the torque
- 6) rolling the observatory to counteract the RWA momentum.

The purpose of this study is to evaluate whether the two planning approaches, items nos. 1 and 2, and a scheduling approach, item no. 3, from the preceding list can effectively manage accumulation of angular momentum. The no-management approach (item no. 1) has been previously evaluated for a schedule prepared with JWST Mission Simulator (JMS) for the Science Operations Design Reference Mission (SO-DRM) and found to be unsuccessful (Petro *et al.* 2005a). But, that study used a now-outdated sunshield design and its torque function and will be re-evaluated here. Furthermore, we consider the effects on the accumulation of angular momentum of observer-specified scheduling restrictions and of two prescriptions selecting when to schedule observations.

3.0 Methodology

We evaluate the effectiveness of three planning methodologies by directly applying them to simulated JWST science programs and comparing the results to schedules prepared without management of the angular momentum. The methodologies are comprised of one preference function and two implementations of a constraint function¹. The preference and constraint functions are computed by using JMS to evaluate torque on JWST, as described below. The simulated science programs are taken from the SO-DRM, as described below (§ 3.3). The visits are scheduled by Spike, as described below. In particular, either of two general criteria were used to form each schedule according to when within the set of all dates satisfying a particular momentum minimization criterion an observation is scheduled: *i*) at the earliest time, or *ii*) at a time selected randomly from a uniform distribution. The cumulative angular momentum for the scheduled activities is computed with JMS.

¹ Preference and constraint functions are similar in that both limit the valid places on an observing calendar for a visit. A constraint prevents scheduling a visit at some places and allowing all others. A preference also can disallow some places, but distinguishes the desirability of scheduling in the remaining places.

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3.1 Design Reference Mission

Two pools of visits are selected from the SO-DRM (v1.0, 28-Jan-2005; Petro 2005.) The duration of the visits in the first pool is 1.0 yr (*i.e.*, it matches the duration of the observing calendar) and the second oversubscribes the calendar by 20%. The process of selecting these visits is to randomly select them from the SO-DRM, requiring only that complete sets of linked visits be selected together. For this study, five subset DRMs were selected for each of the two nominal values of oversubscription and those ten were scheduled using JMS v1.4. As found in a study (Petro *et al.* 2005b) of the relationship between pool oversubscription and utilization of the observing calendar (*i.e.*, the fraction of the calendar with scheduled activities,) the utilization of each of the nominally equivalent mission schedules differed. The two DRMs selected for use in this study represent the median utilization of the five mission schedules of the same nominal DRM over-subscription. Thus, these two selected DRMs are “typical” of the 1.0-year and 1.2-yr DRMs.

3.2 Torque Preference and Constraint Functions

JMS computes time-sampled “torque” function for each visit in a Phase II program DRM. The torque is a function of time and is typically sampled at 100 uniformly spaced times per year. The visit “torque” is based upon the target coordinates, fixed orientation during the visit, and the assumption that nominal roll is attained at the mid-time of the visit. The value returned is the magnitude of the angular momentum accumulated during the visit. JMS uses tables of torque as a function of the off-nominal roll angle and Sun pitch angle. These tables are provided by the prime contractor, Northrop Grumman Corporation (NGC.) JMS v1.4 is used for this study, including the torque function that was released with it. Examples of this function for off-nominal roll angles of interest are shown in Figure 1.

The planning preference function for a visit is $p(t) = (T_{max} - T)/(T_{max} - T_{min})$, where T is the magnitude of the torque. It is a function of time and in this study is formed from the angular function illustrated in Figure 1. T_{min} and T_{max} are the yearly minimum and maximum values of that function for the visit. The preference p is bounded by the values 0 (not preferred) and 1 (preferred.) This function is only defined for times when the visit target is in the FOR, and is set to 0 otherwise. A parameterized constraint function $C_f(t)$ is formed from a preference function by setting it to 1 for that fraction f of the non-zero portion of the preference function of greatest value and setting the remainder to 0.

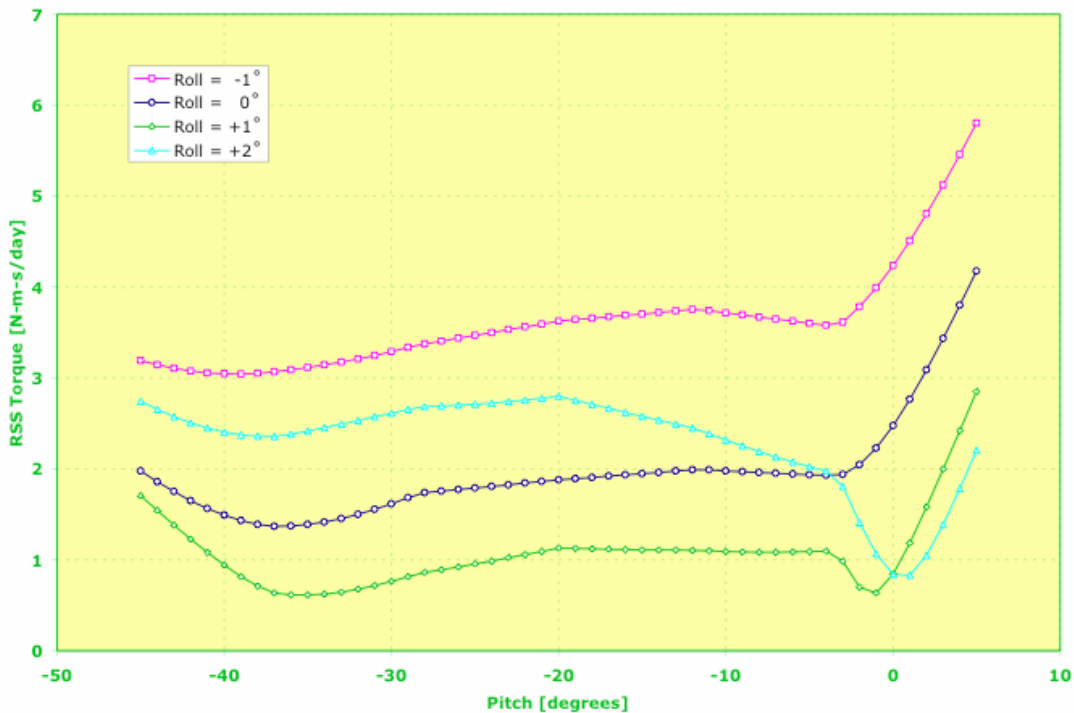


Figure 1 • Solar Torque on JWST The torque on JWST is presented for attitudes of JWST of interest. The torque is a function of the Solar pitch and is parameterized by the value of off-nominal roll. Note that the torque is not minimized at nominal roll.

3.3 Spike Scheduling

In this study, the Spike Constraint Satisfaction Problems (CSP) scheduler assigns visits to 0.025-day bins using a multi-pass process, taking into account preferences and constraints as appropriate for the selected scheduling mode. For this momentum management study, four modes were tried. First, in order to minimize torque, a preference function that is inversely proportion to torque is used. Second, without preferences, scheduling constraint windows may be created for each visit that contain only the 80% of the unconstrained target time (as limited by the field of regard and user-specified time constraint windows.) The third mode takes the same approach, but uses 50% of the available target time. Fourth, the schedule can be created without using either of the three management modes. For any of these four modes, visits are placed first on a 2-year calendar. Then visits are sought that can be shifted from the second to first year in order to occupy contiguous bins. Only the first-year schedule is reported.

As a consequence of assigning one, and only one, visit to each bin, some bins are only partially used. This artifact increases the gaps in the schedule, or equivalently reduces the utilization of the observing calendar. The number of bins assigned to a visit is $\text{ceiling}(L_{\text{visit}} / L_{\text{bin}})$, where L is the duration of a visit, or bin. Therefore, on-average, each visit on the schedule has associated with it a gap equal to the duration of a one-half

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schedule bin. The total gap in a schedule will be $N_{\text{visit}} \times T_{\text{bin}}/2$, which in this study is equal to $0.0125 N_{\text{visit}}$ day, where N_{visit} is the number of visits scheduled on the observing calendar.

Each of the two DRMs (1.0 yr and 1.2 yr) is scheduled both with user-specified scheduling requirements (as specified in the SO-DRM) and without those requirements. The user-specified scheduling requirements implemented in Spike are TIMECONSTR, GROUPWITHIN, AFTER, SAME ORIENT, and ORIENT FROM.

As previously noted, either of two general criteria were used to form each schedule according to when within the set of all dates satisfying a particular momentum minimization criterion an observation is scheduled: *i*) at the earliest time, or *ii*) at a time selected randomly from a uniform distribution.

Each schedule is created twice, differing by a Monte Carlo selection of scheduling order. Examination of the results showed very small differences between each of the two runs. Therefore, they are averaged in the results presented here.

4.0 Results for “Earliest Time” Scheduling

We first considered comparison of the four momentum minimization methodologies for “earliest time” scheduling because it is generally recognized to provide benefits to both observers and to science operations personnel. The results of the four Spike scheduling methods are illustrated in Figures 2a and 2b for the 1.2-yr subset of the SO-DRM. In these two figures we consider two methods to characterize the performance of the four minimization methodologies. In Figure 2a we present the run of accumulated angular momentum without considering unloading angular momentum from the RWAs. This is operationally unrealistic and so in Figure 2b we consider the angular momentum accumulated during a sequence of 22-day intervals that begin on the first day of the mission and at the beginning of each of which the angular momentum is set to 0. For each of the four methodologies (unmanaged, preference for low torque, 80% constraint window, and 50% constraint window), one of the two Monte Carlo runs is presented. The results presented Figures 2a and 2b suggest that the preference planning method obtains superior results, although the 22-day evaluation presented in Figure 2b does not provide nearly so clear a discriminant as does the 1-year accumulation presented in Figure 2a. However, a 1-year accumulation of angular momentum is an unrealistic representation of the expected operation of JWST, whereas the 22-accumulations are, at least, a good first approximation.

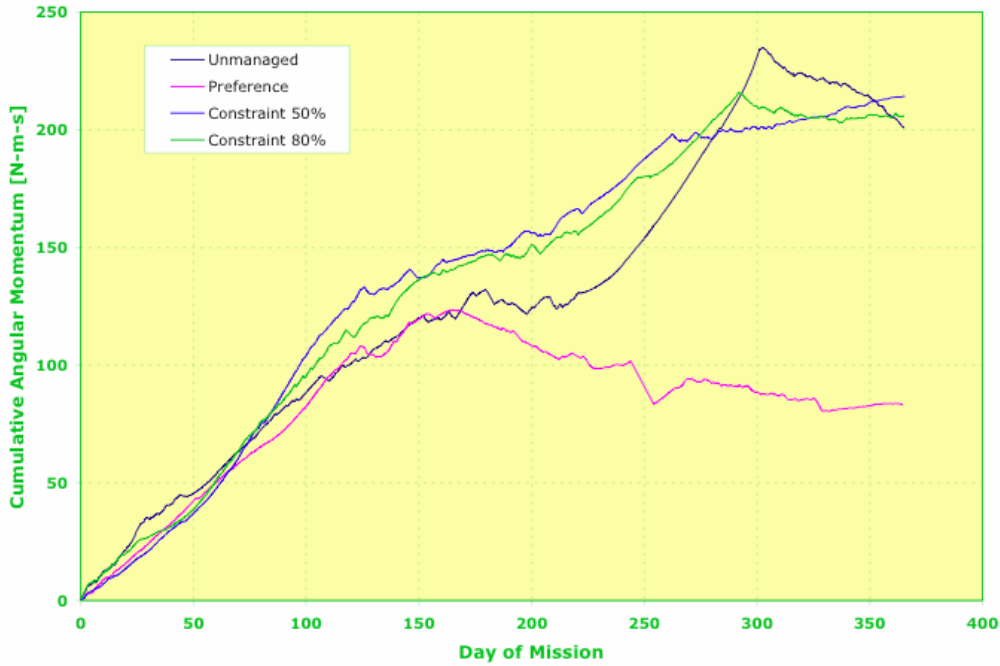


Figure 2a • Accumulated Angular Momentum The run of accumulated RWA angular momentum for a 1-yr schedule of activities chosen from a 1.2-yr subset of the SO-DRM is shown for schedules prepared by Spike with four momentum optimization methods: unmanaged (*i.e.*, none), maximum preference, constraint to the 80% window with least torque, and with 50% window.

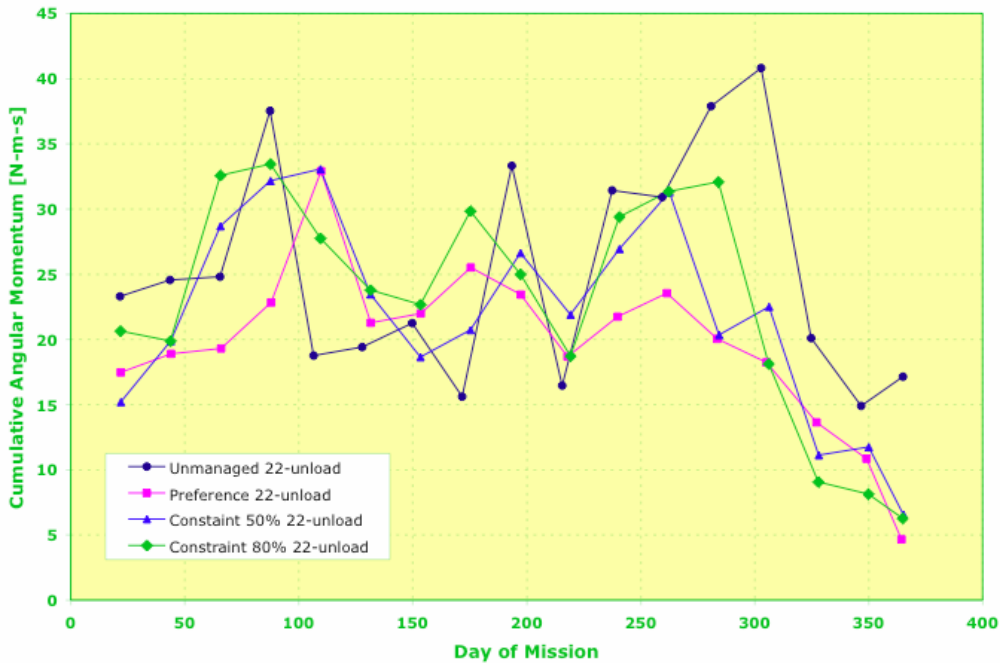


Figure 2b • Accumulated Angular Momentum The run of accumulated RWA angular momentum for a 1-yr schedule of activities chosen from a 1.2-yr subset of the SO-DRM is shown for schedules prepared by Spike with four momentum optimization methods: unmanaged (*i.e.*, none), maximum preference, constraint to the 80% window with least torque, and with 50% window.

In order to better assess the benefit of managing the magnitude of torque during planning, a quantitative evaluation of the sixteen kinds of scheduling trials is presented in Table 1. The results are categorized according to which of the four methods described above is used to manage the accumulation of angular momentum (Column 1) and whether user-specified scheduling requirements constrain scheduling (Column 2.) The success achieved with each schedule is gauged by three different measures: *i*) the maximum cumulative angular momentum during the 1-year schedule (Column 3), *ii*) the number of 22-day intervals during which the accumulated angular momentum exceeds 24 N-m-s (Column 5), and *iii*) the average angular momentum accumulated during the 22-day intervals (Column 6). The efficacy of each of the three active angular momentum management methods is shown by whether it achieves lower angular momentum than the corresponding unmanaged schedule. For each schedule this “benefit” is quantified by expressing the maximum angular momentum as a percentage of the maximum angular momentum of the analogous unmanaged schedule (Column4).

Table 1 • Evaluations of Cumulative Angular Momentum Performance¹

Planning Management	User Sched. Reqts.?	Maximum Momentum [N-m-s]	Benefit [%]	N(> 24 N-m-s)	Average 22-day Momentum [N-m-s]
<i>1.0-yr DRM</i>					
NoPref	N	210	N/A	7	22.9
Pref	N	128	61	2	18.5
Cons80	N	241	115	7	22.1
Cons50	N	231	110	9	21.9
NoPref	Y	229	N/A	7	24.5
Pref	Y	129	56	2	18.2
Cons80	Y	229	100	8	22.9
Cons50	Y	221	97	7	22.2
<i>1.2-yr DRM</i>					
NoPref	N	168	N/A	5	22.3
Pref	N	115	68	3	20.2
Cons80	N	229	136	6	22.5
Cons50	N	232	138	8	22.5
NoPref	Y	234	N/A	8	25.0
Pref	Y	123	53	2	19.7
Cons80	Y	213	91	5	22.4
Cons50	Y	216	92	6	21.8

¹All results are for a 1-yr observing calendar scheduled with activities drawn from either the 1.0-yr or, the 1.2-yr subsets of the SO-DRM.

As noted from the graphical representations in Figures 2a and 2b, the planning preference produces better results for the 1.2-year DRM with observer-specified scheduling

restrictions. The planning preference method also outperforms the other three methods for the other three cases (1.2-year DRM without scheduling restrictions; and 1.0-year DRM and with, or without scheduling restrictions).

For representative subset DRMs with user-specified scheduling requirements, only the planning preference method reduces the angular momentum for the “Earliest Time” prescription. For the 1.0-yr subset of the SO-DRM, the angular momentum is 61% of the unmanaged value and for the 1.2-yr subset of the SO-DRM it is 52%. The 80% and 50% constraint windows actually yield results similar to those of the unmanaged schedule: improvement as great as 9% and worsening by as much as 15%, depending upon case. Comparing the three scheduling modes, it is clear that the constraint method has not yielded a significant benefit. However, the planning preference has succeeded in reducing the accumulated angular momentum by factors in the range 1.5 to 1.9.

However, do secondary factors determine these results? As noted in §3.3, by binning the observing calendar Spike introduces gaps into the schedule. Because the accumulated angular momentum depends in part on the number of scheduled visits, as well as on which visits are scheduled and when they are scheduled, the utilization of the schedule influences the conclusions drawn above. The schedules used in this study are comprised of between 2,100 and 2,500 visits. The binning gap introduced is expected to be in the range 26 – 31 days, which is a significant fraction (~8%) of the duration of the calendar. To assess whether the maximum angular momentum is correlated with the utilization, *i.e.*, whether it is primarily a by-product of the utilization, the correlation diagram is presented in Figure 3. As can be seen, no correlation is found between the utilization of

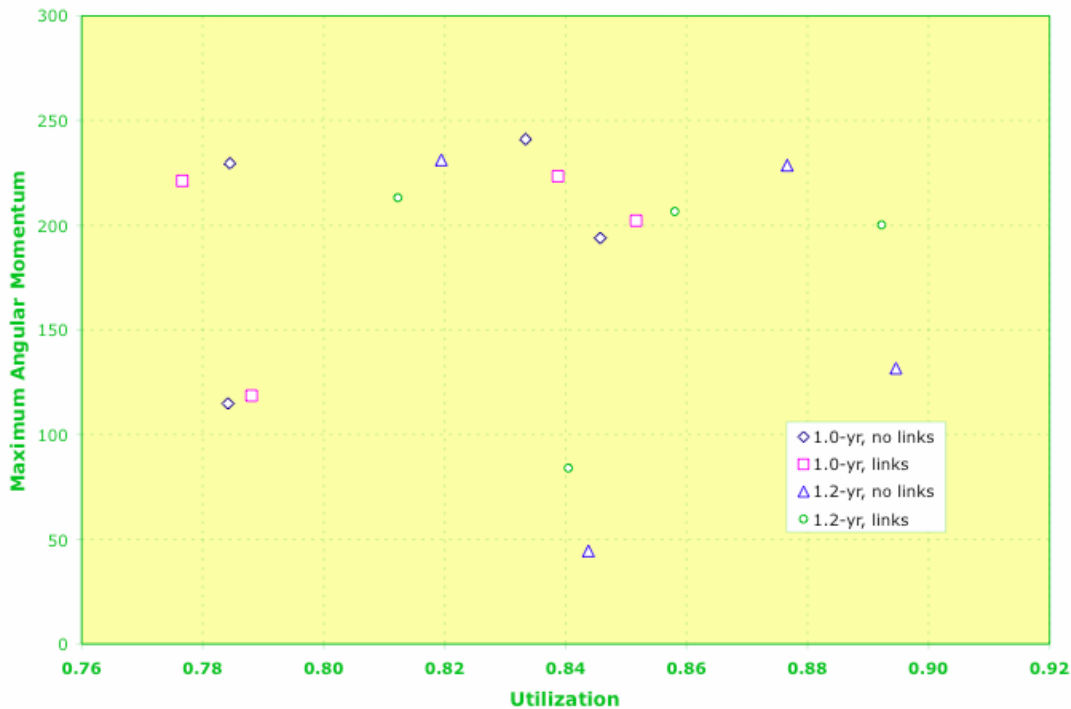


Figure 3 • Utilization and Angular Momentum For each of the four DRM kinds identified in the legend, four scheduling methods were employed. Each of the sixteen schedules is represented by its utilization and the maximum value of the accumulated angular momentum.

the calendar, which is determined by the Spike scheduling algorithm, and the measure of success of the momentum management algorithms, the maximum angular momentum.

5.0 Results for “Random Time” Scheduling

The planning preference and constraint window methods allow considerable latitude in when an observation is scheduled. The “Earliest Time” prescription breaks that degeneracy and obtains the benefit of obtaining science data as early as feasible. However, this prescription could conceivably cause a net torque through a correlation of “early time” and observatory attitude. We have carried out scheduling experiments with the 1.2-year DRM containing observer-specified scheduling restrictions, using a “Random Time” prescription and the scheduling methodologies evaluated in the preceding section. These schedules represent one-fourth of the cases considered for the “Earliest Time” experiments, but they are the most representative portion thereof of expected science programs. Four schedules were prepared with these methodologies for both the “Earliest Time” and the “Random Time” prescriptions. These schedules were evaluated with a running 22-day maximum accumulated angular momentum filter (in distinction to the fixed-epoch 22-day evaluation presented in §4). The 22-day filter was evaluated each day of the 365-day schedule resulting in 343 values for each schedule. Those time series were characterized by the fraction of the 22-day intervals that exceeded a threshold value of accumulated angular momentum. These cumulative distribution functions are presented in Figures 4a and 4b.

The “Earliest Time” and “Random Time” prescriptions are readily distinguished in Figures 4a and 4b. For any given threshold value of accumulated angular momentum, the “Earliest Time” prescription produces a larger number of exceedances. The distribution functions of the four momentum optimization methodologies are more widely separated for the “Earliest Time” prescription than for the “Random Time” prescription. For both prescriptions, the “no-management” method produces the worst results. The “80% constraint window” method works best with “Earliest Time,” whereas the “50% constraint window” method is best with the “Random Time” prescription. Overall, the combination of “Random Time” and “50% constraint window” produced the best results, as judged from the distribution function of 22-day angular momentum accumulations.

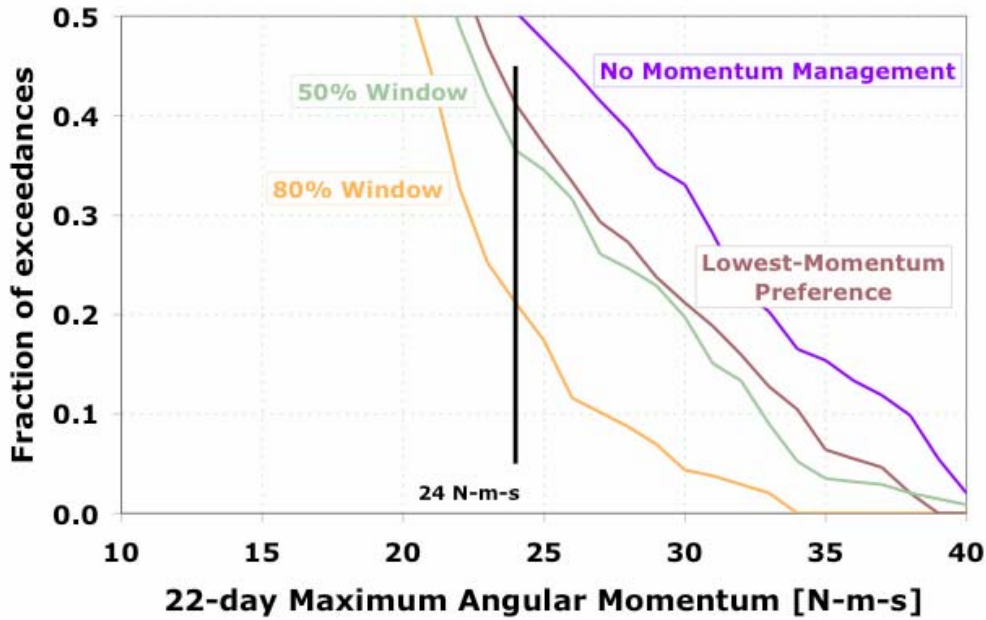


Figure 4a • Cumulative Distribution Function of 22-day Accumulated Angular Momentum – “Earliest Time” scheduling The fraction of 22-day intervals exceeding a threshold value of accumulated angular momentum as a function of the value of that threshold is shown for four optimization methods for forming with Spike a 1-yr schedule of activities chosen from a 1.2-yr subset of the SO-DRM: unmanaged (*i.e.*, none), preference for lowest torque, constraint to the 80% window with least torque, and with 50% window. Each observation is scheduled at the earliest time within the allowed set of times.

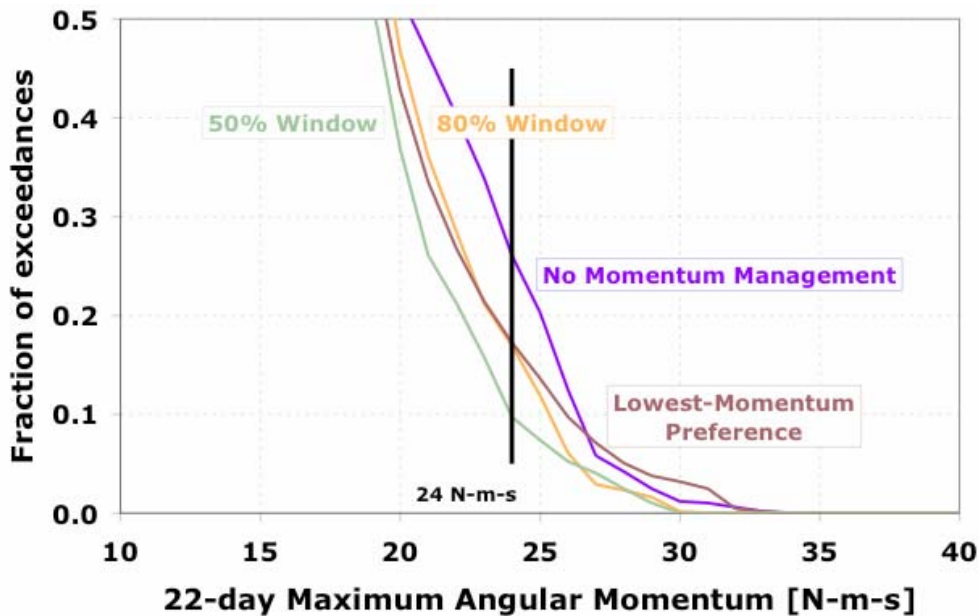


Figure 4b • Cumulative Distribution Function of 22-day Accumulated Angular Momentum – “Random Time” scheduling Same conditions as Figure 4a, but scheduling each observation at a random time within the allowed set of times.

6.0 Conclusions

According to the kind of evaluation applied, either of three planning and scheduling methodologies for minimizing accumulated angular momentum is the best. “Planning Preference” is best for “Earliest Time” prescription if evaluated for 1-year accumulations and for peak and average accumulation during one 22-day accumulation sequence. “80% Constraint Window” is best for “Earliest Time” prescription if evaluated for rolling 22-day accumulations. “50% Constraint Window” is best for “Random Time” if evaluated for rolling 22-day accumulations. The most striking effects found in this study are due to differences between the “Earliest Time” and “Random Time” prescriptions and in the evaluation of 1-year accumulation for the “Earliest Time” prescription. Further study of operational scenarios, sunshield designs, and planning and scheduling methodologies should be undertaken.

7.0 References

- Petro, L. 2005. *Science Operations Design Reference Mission* (JWST-STSCI-CI-0045, Rev. A, January 31, 2005).
- Petro, L., Kinzel, W., Ruml, W., Jones, D. and Rager, R. 2005a. *The angular momentum of JWST in a schedule of the Science Operations–Design Reference Mission* (STSCI-JWST-TM-000556, Rev. A., April 15, 2005).
- Petro, L., Stys, J., Rager, R., and Jones, D. 2005b. *An Empirical Study of the Effects of Proposal Over-subscription on Long-range observing schedules* (STSCI-JWST-TM-000644, Rev. A., July 8, 2005).