TECHNICAL REPORT

Title: Planning observing calendars in order to optimize the radiometric accuracy of observations		Doc #: JWST-STScI-000719, SM–12 Date: October 21, 2005 Rev: Baseline
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1.0 Abstract

The Science Operations Center requirement to schedule JWST so as to achieve a radiometric signal to noise ratio within 5% of best achievable is here studied using schedules of a subset of the Science Operations Design Reference Mission created with JWST Mission Simulator and Spike. We find that the requirement is readily achieved while simultaneously optimizing accumulation of angular momentum.

2.0 Introduction

A goal of the S&OC is to schedule and execute observations in a manner that provides scientific data of the highest quality. Of course, this goal is pursued taking into account the operational constraints and restrictions of JWST, each observer's scheduling requirements, and the goal to minimize use of propellant. A measure of the quality of scientific data is the ratio of radiometric signal and noise, S/N. Possible additional measures of the quality of scientific data include image sharpness and image stability, but these will not be considered here.

The signal S is the measured response of JWST to the incident photon flux from a target, *i.e.* the rate of accumulation of signal electrons in a scientific detector. The noise N is the standard deviation of the measured signal, which is caused by statistical variance of the target and background signals, which are simultaneously sensed by each detector pixel. Sources of background signals are the Zodiacal Light, stray light from the observatory thermal emission, stray light from diffuse celestial emission, stray light from the Earth and Moon, and detector dark current and read noise. Furthermore, flat field calibration error contributes to the variance of the background signals.

The target signal is normally unaffected by the date an observation is executed, but some background signals, which contribute noise, are so affected. The detector backgrounds and some observatory thermal backgrounds do not vary significantly, but the Zodiacal Light, scattered stray light, and scattered thermal observatory emission do vary. The proportion of the non-variable and variable backgrounds depends upon the instrumental configuration, in particular the optical bandwidth and wavelength. For example, the non-variable detector background generally dominates spectroscopic observations (spectral resolution $\lambda/\Delta\lambda$ = R ~ 1000), which therefore cannot be optimized. The noise of broadband imagery of faint targets is dominated by Zodiacal Light or, scattered light, which may be optimized. Bright targets are normally dominated by photon noise of the signal; these can't be optimized and are not a concern.

The extent to which the S/N of an observation may be optimized depends upon the potential range of background signal, considering all times when the observation may be executed. For example, the yearly range of brightness of the Zodiacal Light decreases from high to low ecliptic latitude targets, which is illustrated in Figure 1. In this example, the exposure time for a NIR (2 µm) background–limited broadband image varies as a function of date by as much as a factor 1.5× (for observations at longer wavelengths, this factor can be as great as 3.0, as shown in Figure 2). As can be seen in the figures, the potential to optimize observations of low ecliptic latitude targets is generally greater. However, the backgrounds of tightly constrained observations may not vary significantly because the change in the background will usually be very small during the narrow constraint window. Some examples are observations at a specific orientation and observations with narrow science time windows. In principle, the S&OC can optimize the

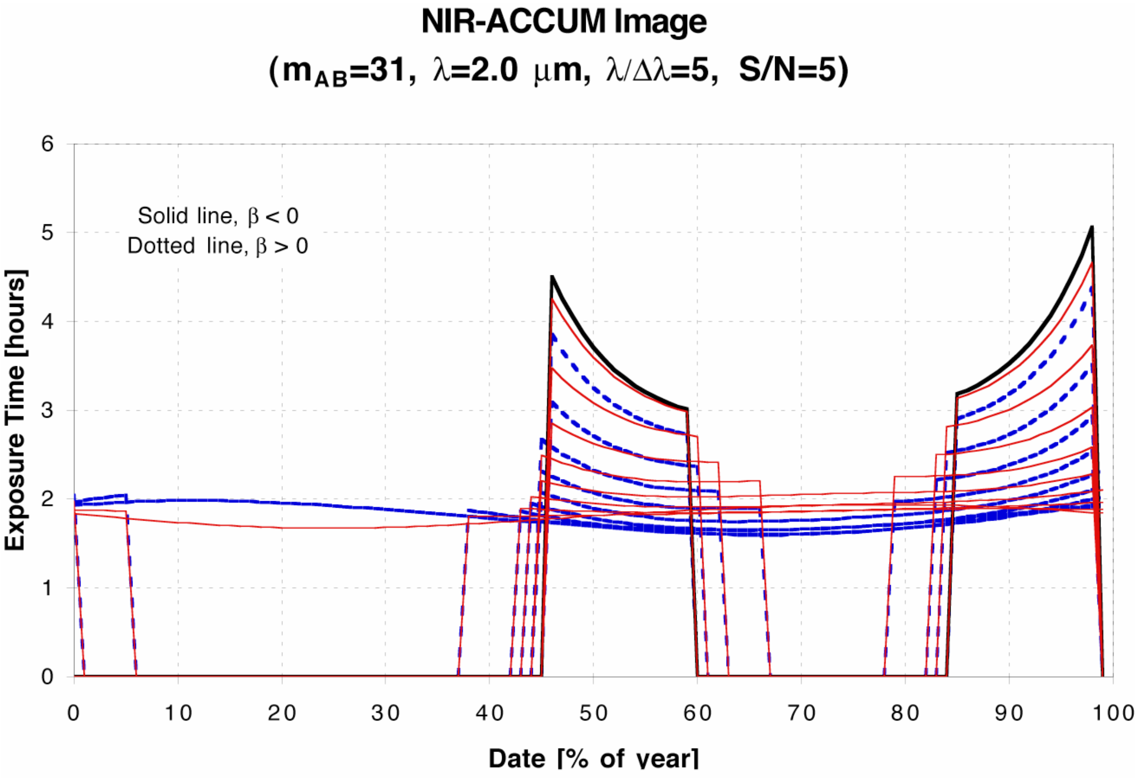

Figure 1: Variation of the exposure time required to obtain a fixed S/N. For a set of targets in 10º increments of ecliptic latitude β in the range β = -90˚ → +90˚ the exposure time required to achieve S/N = 5 is presented. The exposure time for each target varies as a function of date, shown here as the percent age of year.

S/N by appropriate scheduling in so far as the noise of observations is dominated by significantly variable sources of background.

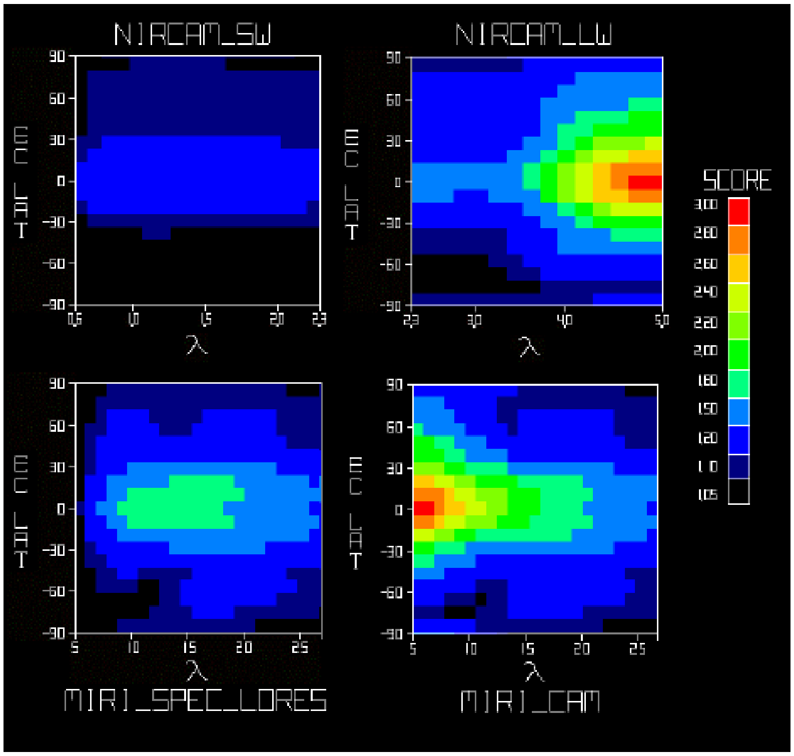

Figure 2. Dependence of exposure time on wavelength of observations and target ecliptic latitude. Each panel represents the ratio of longest to shortest exposure time required to achieve a particular S/N as a function of wavelength and latitude. Only imaging observations of faint targets at low ecliptic latitude ($|\beta| \leq 30^\circ$) in the 4 – 20 μm waveband are significantly sensitive to yearly variation of the background (*i.e.*, the ratio of longest to shortest exposure time required to achieve a particular S/N is greater than 2.0).

The goal of optimizing the quality of scientific data is quantified in a requirement on the S&OC. That requirement is, quoting from *Science and Operations Center Element Requirements Document, Requirements Baseline* (JWST-RQMT-002032 = JWST-STScI-CI--0046 = SM-01; December 15, 2004):

> The PPS shall schedule JWST Observations to achieve a time-weighted mean S/N within 5% (TBR) of the optimum time-weighted mean S/N with respect to background and stray light over a one-year period. [SOC-1868]
>
> Note: the time-weighted mean S/N, S/N(mean), is defined as follows:
>
> S/N(mean) = (∑(obs) T(obs) S/N(obs)) / ∑(obs) T(obs)

> where T(obs) and S/N(obs) are the total duration and signal-to-noise ratio of an individual observation. The optimum is the highest possible mean S/N for the set of observations being scheduled.

In order to implement this requirement, the PPS will compute the S/N as a function of time for each exposure in a one–year plan. The target signal will be estimated using the target brightness and the instrument configuration specified by the user in the Phase 2 program and models of the observatory response. The backgrounds (as listed above) will be estimated from the target direction, models of the backgrounds, the spacecraft ephemeris, and other observatory characteristics. The S/N of each exposure will be evaluated only for times that meet mission and user–specified constraints, which is named the S/N Function (SF). For an exposure, the duration of an observation is the exposure time, which does not vary according to when it is executed.

For each exposure, the optimum S/N is the maximum value of its SF, which is evaluated without regard to other exposures:

$$(S/N)_{opt} = \Sigma\, t_{exp}\, SF(t_{opt}) \,/\, \Sigma\, t_{exp}$$

where the sums are over all exposures in a one–year calendar. The S/N of a short term schedule is computed similarly, replacing the optimum SF for each exposure with the evaluated the SF at the scheduled time (t_{sched}):

$$(S/N)_{wgt} = \Sigma\, t_{exp}\, SF(t_{sched}) \,/\, \Sigma\, t_{exp}$$

As explained above, for some observations (spectroscopic, tightly time–constrained, *etc.*) the worst–case value of the SF does not deviate significantly from the optimum value, SF_{opt}. However, as found by Speck (2004) for some kinds of exposures, the worst–case range of exposure time required to achieve a fixed S/N is approximately a factor of three.

Therefore, for background noise-limited observations typical of the JWST science program, the worst–case range of S/N for fixed exposure time is approximately a factor 1.7. Without planning, $(S/N)_{wgt}$ for a one–year program comprised of a typical mixture of sensitive and insensitive observations would likely fall short of $(S/N)_{opt}$ by more than the S&OC requirement, 5% (TBR). Because a large fraction (~50%) of the one–year program is expected to be comprised of insensitive observations (high ecliptic latitude targets, 5%; spectroscopic observations, 30%; and special scheduling requirements, >20%) and because the predominant variation of the SF for the remainder occurs on a 1-year timescale, long–range planning will be used to optimize the S/N of the schedule.

Long–range planning will optimize S/N by assigning observations to Plan Windows that maximize S/N. The preference function for this purpose will be SF. This function will be computed for all visits using the time–weighted combination of SF of the individual exposures composing the visit. SF will be sampled at sufficient time resolution to represent its variation. The model of backgrounds will be sufficiently accurate to identify best scheduling times, ~20% (TBR). The target signal will be computed using the Phase 2 program information for target brightness and instrument configuration, and a throughput model of JWST. The PPS will report the LRP $(S/N)_{opt}$ and $(S/N)_{wgt}$. It will also report these quantities for each visit in addition to the maximum value, $(S/N)_{max}$.

3.0 Scheduling Experiments

In order to assess the feasibility of achieving the required radiometric S/N of a year of JWST observations, we carried out four scheduling experiments using visits from a typical 1.2–year subset of the 1.7–year SO–DRM. These experiments were conducted using JMS and Spike in order to implement the procedures described in the *Introduction*. JMS was used to compute for each visit its:

i) duration (based upon a model of operational overheads),

ii) the JWST angular momentum accumulated, and

iii) the exposure time weighted S/N (for external targets).

Spike was used to schedule the visits on a 1–year calendar using visit planning preferences based upon the visit S/N and angular momentum functions. The four scheduling experiments used all combinations of S/N and angular momentum as preferences:

i) no preference for optimizing either S/N, or angular momentum accumulation,

ii) preference to maximize S/N,

iii) preference to minimize angular momentum accumulation, and

iv) equal preference to optimize S/N and angular momentum accumulation.

We evaluated each of the four schedules in terms of achieving the best possible S/N and the angular momentum accumulated. The achieved S/N of the 1–year schedule is defined, in analogy with the time–weighted visit S/N, as the weighted average of the S/N of each visit as date it was scheduled on the calendar, where the exposure time of each visit is the weight of that visit. The best achievable S/N for the calendar is defined to be the weighted average of the maximum achievable S/N of the visits. Only feasible dates for each visit are taken into account as limited by mission constraints and observer–specified special scheduling requirements (*e.g.*, orientation, or a restricted interval of time.)

Before presenting the results of the scheduling experiments, we present in Figures 3 – 5 some characteristics of the S/N and torque of target observing visits. In Figure 3 the yearly variation of S/N and torque is presented for a target at the first point of Aires observed with a NIRCam F444W broadband image. Of particular interest, the torque for two designs of the sunshield is presented. The older design, from September 2004, indicates that torque and S/N cannot be simultaneously optimized. For this older design, torque is minimized on DOM 108, at which time S/N is mid-way between the minimum and maximum values and when S/N is minimized on DOM 130, the value of torque is twice its minimum value. With the newer design, from April 2005, simultaneous optimization can be achieved to a good and useful approximation. For this design when S/N is minimized on DOM 130, the value of torque is within 10% of the minimum value.

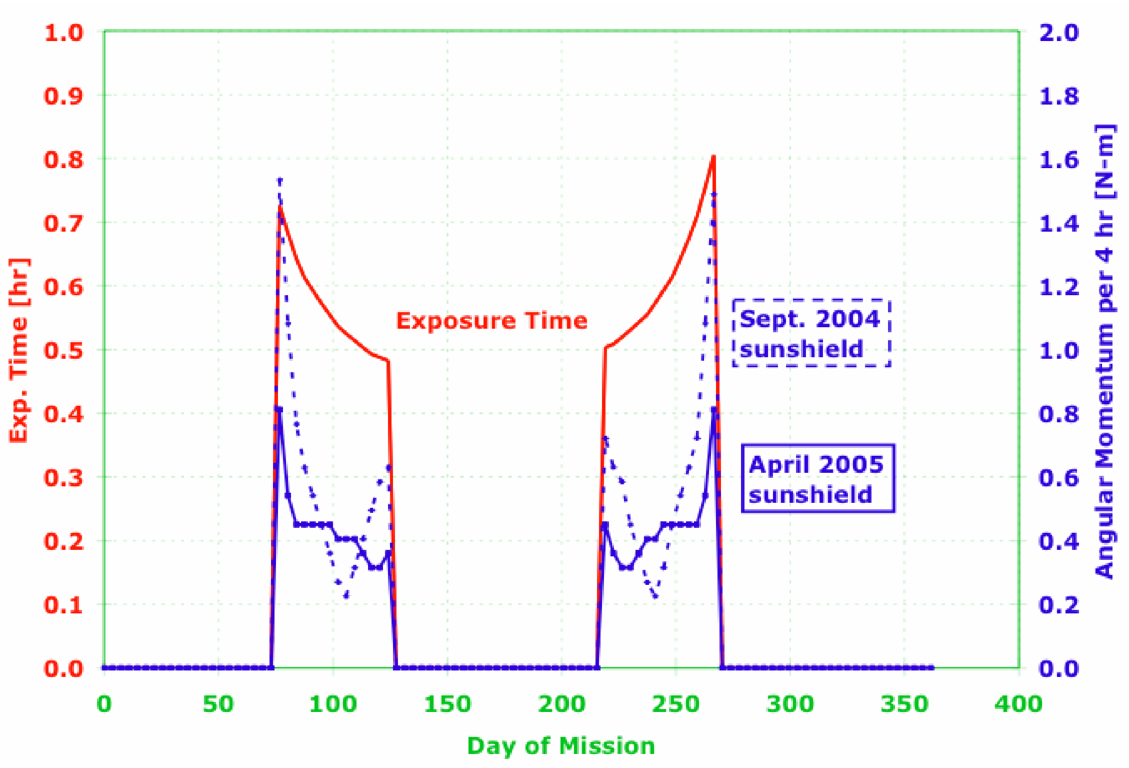

Figure 3. Tradeoff between science and JWST propellant. The time required to obtain radiometric S/N = 5 in a NIR detection of a m_{AB} = 28 target at the first point of Aires is represent as a function of time by the red curve. For the same target, the solar torque is indicated by the two blue curves (representing the angular momentum accumulated in the RWA in a nominal 4-hour interval.) The September 2004 design of the sunshield is represented by the dashed curve and the April 2005 design by the solid curve.

To demonstrate that co–optimization for the newer design is not restricted to the ecliptic plane target, we present in Figure 4 the S/N and torque functions for four targets spanning the range of equatorial to polar ecliptic latitudes. The possibility for effective co–optimization for each of these targets can be noted.

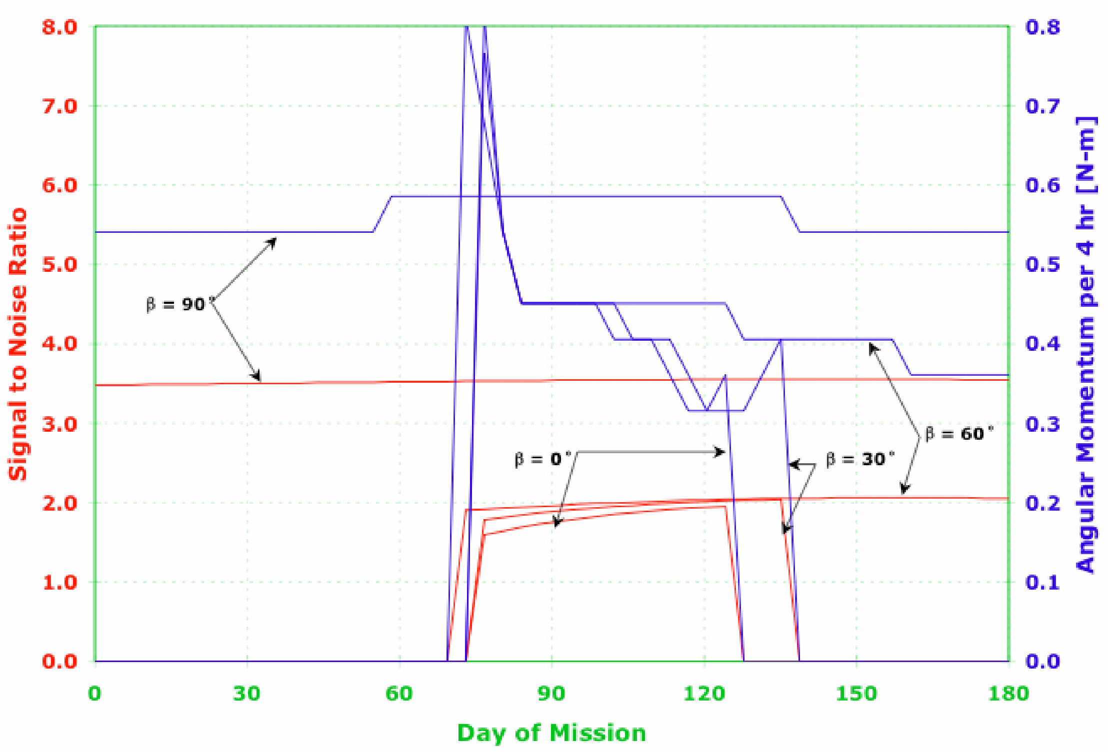

Figure 4. Tradeoff between science and JWST propellant. The radiometric S/N obtained in a fixed exposure time for a NIR detection of four $m_{AB} = 28$ targets at ecliptic latitudes β = 0˚, 30˚, 60˚, and 90˚ are represent as functions of time by the red curves. For the same targets, the solar torque on JWST for the April 2005 sunshield design is indicated by the blue curves (each representing the angular momentum accumulated in the RWA in a nominal 4-hour interval.).

The S/N of the yearly schedule is required to be within 5% of the best achievable value, whereas some the range of yearly variation of S/N for some JWST exposures is much larger, being $\approx \sqrt{3} \approx 1.7$, or a range of 70% (as noted in the *Introduction* and as can be judged from Figure 2.) However, in the *Introduction* we argued that such a large range may not be typical when considering all kinds of targets and Scientific Instruments. We consider in Figure 5 the yearly range of S/N for the visits comprising 1.2–year subset of the SO–DRM that we used in the present study. It is here seen that the yearly variation of S/N does approach a factor 1.7, as previously found. However, as can be judged from the figure, variations in the range 0 – 5% are most typical (comprising 54% of the visits) and for only a small fraction of visits does the variation exceed 25% (8% of the visits).

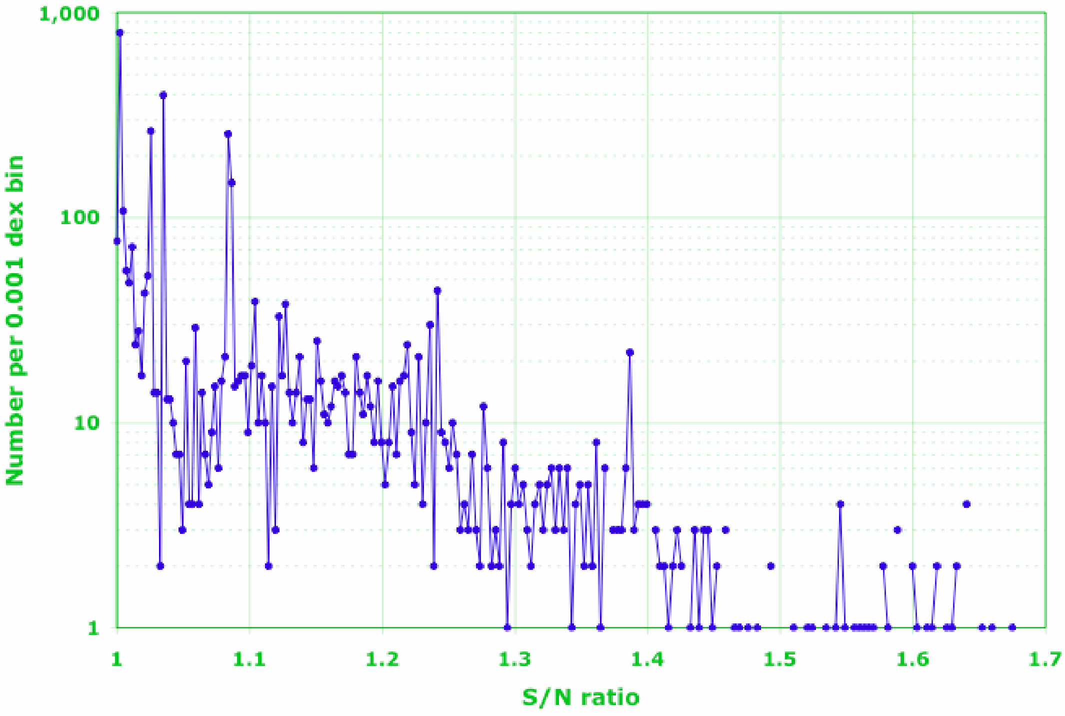

Figure 5. Sensitivity of achieved S/N of SO–DRM observations to scheduling. The ratio of the yearly maximum and minimum S/N for 3,798 visits of external targets in the SO–DRM lies in the range 1.0 – 1.7. A large value indicates that when the visit is scheduled will significantly affect the quality of the scientific data, whereas values near 1 indicate no potential significant effect of scheduling. The frequency of occurrence of these yearly ratios is represented by the blue points.

The results of the four scheduling experiments are presented in Table 1. The accumulation of angular momentum during possible 22–day orbit station keeping intervals was assessed by noting the maximum angular momentum accumulated within a rolling 22–day window, of which 343 such intervals during one year were considered. The schedule S/N was computed and compared to the best achievable S/N as described above in this section and in the *Introduction*. From these assessments, five independent measures are presented in Table 1:

i) The number of rolling 22–day intervals during which the maximum angular momentum exceeded 26 N-m-s (2nd column).

ii) As for the first item, but the number exceeding 40 N-m-s (3rd column).

iii) The maximum value of 22–day maximum angular momentum accumulated during any of the 343 intervals (4th column).

iv) The average of the rolling 22–day maximum angular momentum (5th column).

v) The schedule S/N as a percentage of best achievable angular momentum (6th column), or equivalently the deviation from best (7th column).

***Table 1* • Summary of S/N scheduling experiments**

Scheduling Experiment	**N(>26 N-m-s)**	**N(>40 N-m-s)**	**1-year max. mom. [N-m--s]**	**Avg. 22–day max. mom. [N-m-s]**	**S/N relative to best**	**S/N dev. from best**
No S/N or momentum preference	39	0	30	20.8	97.7%	2.3%
S/N preference	50	0	32	21.1	98.9%	1.1%
Momentum preference	15	0	29	19.4	98.4%	1.6%
S/N & momentum preference	8	0	27	19.4	98.5%	1.5%

Four of the five measures present very similar results for all four scheduling experiments, namely

i) the absence of any 22–day interval that exceeds the 6 RWA limit (40 N-m-s),

ii) the worst–case 22–day maximum accumulated angular momentum (in the range 27 – 32 N-m-s),

iii) the average maximum 22–day accumulated angular momentum (in the range 19.4 – 21.1 N-m-s), and

iv) deviation from best achievable S/N (in the range 1.1% – 2.3%).

Only the number of 22–day intervals with maximum accumulated angular momentum exceeding 26 N-m-s distinguishes the four methods. This measure varies from a low of 8 intervals (for co–optimization of S/N and angular momentum) to a high of 50 intervals (for S/N optimization).

4.0 Conclusions

The experiments using schedules of the SO-DRM prepared with JMS and Spike, as presented here, indicate that the S/N requirement can be met by any of the four scheduling methods, each of which presents similar performance in minimizing the accumulation of angular momentum.

5.0 References

Speck, S. *JWST Science Exposure Time Variability and its Impact on Science Scheduling,* STScI–JWST–R–2004–0002, 25 June 2004