FUSE Planning and Scheduling Under One Wheel Attitude Control

Alice F. Berman[a], Humberto M. Calvani[a], James R. Caplinger[a,b], Thomas Civeit[a,c] and Mark Kochte[a,b]

[a]Department of Physics and Astronomy, The Johns Hopkins University
3400 North Charles Street, Baltimore, MD 21218 USA
[b]Computer Science Corporation, 7700 Hubble Drive, Lanham-Seabrook, MD 20706
[c]Centre National d'Etudes Spatiales, 2 place Maurice Quentin, 75039 Paris Cedex 1, France

{aberman | calvani | caplingr | civeit | kochte}@pha.jhu.edu

Abstract

Since its launch into low-Earth orbit in June 1999, the mission of the Far Ultraviolet Spectroscopic Explorer (FUSE) has been to obtain high resolution far ultraviolet (905-1187 Å) spectra of a wide variety of astronomical sources. In late 2001, two of FUSE's four reaction wheels failed, compromising the ability to control spacecraft pointing. The FUSE Project adapted by developing a two-wheel attitude control system. In December 2004, FUSE lost the use of a third reaction wheel, leaving only one functioning reaction wheel. This interrupted all scientific observations with FUSE until a new one-wheel attitude control system was developed, uploaded, and tested in 2005. Regular scientific operations resumed in November 2005. In this paper, we explain FUSE's new operational constraints with a one-wheel attitude control system and their effect on the planning and scheduling process. We discuss how the FUSE Mission Planning software tools continue to be upgraded to work in this environment, and we describe how planning and scheduling decision-making strategies are evolving. FUSE can currently access about one-quarter of the sky, and scheduling efficiency continues to improve as on-orbit experience grows and software tools and processes are further refined.

Introduction

Overview of the FUSE Mission

The Far Ultraviolet Spectroscopic Explorer (FUSE) was launched into low-earth orbit on 24 June 1999 aboard a Delta II rocket. FUSE's orbit is roughly circular, with an inclination of 25° to the equator and a height of 765 km.

The purpose of the FUSE mission is to obtain high resolution spectra of a wide variety of astronomical objects over the far ultraviolet spectral region (905 - 1187Å) for the Principal Investigator team and Guest Investigators (GIs). FUSE is a three-axis stabilized satellite that requires arc second pointing stability. Now into the fourth year of its Extended Mission, approximately 4,200 science observations (totaling 57 million seconds of exposure time) of 2,500 unique objects have been obtained. As of June 2006, 373 scientific papers have been published in peer reviewed journals.

Full details about the FUSE mission, including the scientific objectives and the design of the instruments, can be found in Moos et al. (2000).

All satellite command and control functions, including Mission Planning, are performed at The Johns Hopkins University in Baltimore, Maryland. Communication with the satellite is performed with a Low Earth Orbit Terminal (LEO-T) ground station at the University of Puerto Rico at Mayaguez (UPRM), which provides 6-7 daily contacts of approximately 10 minutes each. Additional contact opportunities (for command uploads and real-time telemetry monitoring only) are provided by the NASA Tracking and Data Relay Satellite System (TDRSS), with typically one TDRSS pass every other orbit. Detailed science observing plans are generated and uplinked in advance and are performed autonomously onboard.

Guest Investigators propose to use FUSE through a yearly NASA peer-reviewed process. For the current Cycle 7, NASA granted 5.5 million seconds (Msec) to 47 total GI programs. There are presently two categories of GI observing programs: standard and survey. Standard programs are intended to be executed in their entirety. Survey programs, however, provide the opportunity for observations of a particular object class to be performed but without the requirement that any specific target be observed during the Cycle. Therefore, they provide a set of unrestricted targets for additional scheduling flexibility. In Cycle 7, 13 survey programs were accepted for 3.2 Msec.

The Role of the FUSE Mission Planning Team

The FUSE Mission Planning (MP) Team is responsible for all aspects of science operations planning, from initial processing of observing proposals to generation of detailed sequences of onboard activities. Proposal processing involves reviewing all new observing programs and

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translating the scientific requirements of each observation into functional requirements before scheduling. In addition, a number of validity and safety checks are performed before the relevant data are ingested into the MP database.

The MP Team is also responsible for long-range (twelve month) planning and short-term (one week) scheduling of all scientific and calibration activities onboard FUSE. Separate processes and software tools have been used for these historically distinct activities. For instance, long-range planning is performed using a FUSE-specific version of the Spike scheduling software developed at the Space Telescope Science Institute (STScI). Short-term scheduling tools have been written by FUSE MP personnel. Due to challenges with one-wheel operations and changes in the scheduling constraints, however, some of the long-range and short-term planning activities are beginning to overlap, thus changing some of our strategies and tools.

Evolution of FUSE Planning and Scheduling Constraints: Post-launch to Two-wheel Operations

Before introducing FUSE's new one-wheel attitude control system (ACS), it is useful to briefly explain FUSE's operational constraints and summarize how they evolved from launch through the two-wheel operations phase.

Classical and FUSE-specific scheduling constraints. As a low-earth orbiting satellite, FUSE's general planning and scheduling constraints are:

- Sun avoidance: FUSE's solar restriction is referred to as the Beta (β) angle, which is measured from the anti-Sun position to FUSE's boresight (long axis). All observations must be performed when the β angle is in the range $30° < \beta < 115°$.

- Moon avoidance: No observations are performed within 10° of the Moon. Since targets with $|\text{declination}| < 50°$ are not currently observed, the Moon constraint is not applicable at this time.

- Ram avoidance: The Ram vector points in the direction of instantaneous spacecraft motion. After launch, no observations were performed within 20° of the Ram angle in order to protect FUSE's mirrors against damage from residual atomic oxygen. After several successful in-orbit tests, this restriction was lowered to 10° in 2003. The Ram constraint was dropped in 2005 due to the Sun activity being at solar minimum state, which greatly reduces the density of the residual atmosphere at the FUSE altitude.

- South Atlantic Anomaly (SAA) avoidance: The SAA is the portion of the Earth's inner Van Allen belt which dips closest to the Earth. Due to the intensity and frequency of charged particles, FUSE cannot perform target acquisitions or take astronomical data during its nine daily passages through the SAA. The science detectors' high voltage (HV) is reduced to a lower level for the duration of the passage (typically 30 minutes).

- Spacecraft roll constraint: Early in the mission, spacecraft roll offsets were constrained to ±2.5° from nominal roll, due to thermal issues. By late 2005, the roll constraint was relaxed such that observations could be performed at orientations within -10° to +20° of spacecraft nominal roll. Currently, observations are performed within ±25° from the spacecraft nominal roll.

The above constraints are applied to all observations and have been in place since launch. In previous cycles, observers also requested certain target-specific constraints such as ROLL (absolute position angle), EPHEMERIS (for targets with periodic variability), and MONITOR (for observations which require exact spacing). Some of these observations from previous cycles still remain in the FUSE scheduling pool. However, except for a few special cases, these special requirements are no longer permitted as of Cycle 7, since they overly constrain the schedule.

Calvani et al. (2004) described the original Spike scheduling software and how it was upgraded shortly after FUSE's launch to take into account Beta/pole constraints and hemisphere crossing campaigns.

Beta/pole constraints. During the in-orbit checkout period (June – November 1999), measurements showed that large changes in Beta and pole angles caused misalignments of the mirrors (Sahnow et al. 2000). (The pole angle is the angle between FUSE's orbit pole and the target being observed.) The motions can be minimized if additional constraints are placed on changes in Beta and pole angle between observations. A Criteria Scheduler (utilizing a weighting and scoring function) was added to Spike in 2001 to optimize Beta and pole constraints. See Calvani et al. (2004) for full details regarding how Beta and pole constraints are handled.

Hemisphere campaigns. Because targets in opposite hemispheres generally have different Beta angles, switching between hemispheres also contributed to channel misalignment. Prior to launch, a hemisphere-crossing constraint was not considered. Observations of targets in both hemispheres were completely mixed based on scheduling efficiency and other drivers.

In early 2001, FUSE Spike was upgraded with a new hemisphere Campaign Scheduler algorithm. Tunable by the user, the Campaign Scheduler automated the grouping of observations into North and South hemisphere observing campaigns, typically lasting 2-4 weeks each.

Torque authority constraint in two-wheel mode. With the loss of two reaction wheels at the end of 2001, it became necessary to include a new constraint into planning and scheduling due to the gravity-gradient disturbance torque by the Earth on the satellite.

The Earth's gravitational field produces the largest external force on FUSE, decreasing as $1/r^2$, where r is the distance from the geocenter. Although FUSE is only about five meters long (and not spherical), the variation of the gravitational force over the dimensions of the satellite is non-negligible. It produces a net torque on the satellite which tends to rotate the satellite to align the boresight (long axis) radially outward from the Earth. A gravity-gradient torque on FUSE can be as large as 5 milliNewton meters (mNm), but it is minimized when FUSE is pointed towards one of its two orbit poles because the distances from the Earth to the two ends of the satellite are equal. However, due to FUSE’s shape, gravity-gradient forces never zero out. To counteract gravity-gradient torques, the original onboard ACS applied an equal but opposite torque using its reaction wheels. When FUSE's reaction wheels (pitch, yaw, roll, plus redundant skew) were all operational, these adjustments were performed autonomously and were never considered during the planning and scheduling process. (Note: FUSE’s skew wheel is mounted at an equidistant angle to the three primary wheels.) The four wheels provided all control torques. If momentum built up in the wheels, the three Magnetic Torquer Bars (MTBs) would be used to shed excess wheel momentum. The MTBs are mounted parallel to each of the spacecraft's three main body axes (pitch, yaw, roll) and were initially designed only for unloading excess momentum from the reaction wheels.

After FUSE lost the use of the pitch and yaw reaction wheels in late 2001, Orbital Sciences Corporation (OSC), which built the spacecraft bus and developed the original attitude control system, redesigned the ACS to utilize the MTBs to perform a new function: provide attitude control on the third axis. The MTBs can generate a magnetic dipole moment, and the resulting torque generated is perpendicular to the geomagnetic field. The magnetic torque is denoted $\boldsymbol{\mu} \times \mathbf{B}$, where $\boldsymbol{\mu}$ is the dipole moment and $\mathbf{B}$ is the geomagnetic field. The magnetic torque is used to offset the gravity-gradient torque. Unfortunately, the amount of torque that can be generated by the MTBs (approximately 2-6 mNm) is at best 10% that of the reaction wheels (Roberts et al. 2004).

Integrating magnetic torque into the onboard ACS led to the additional scheduling constraint of torque authority (TA). Torque authority is the margin of control provided by the reaction wheels plus MTBs to compensate for gravity-gradient torques on the spacecraft. Approximately seven weeks after the loss of the pitch and yaw wheels, the FUSE ACS was modified to include MTB control. The Mission Planning tools were upgraded to compute and use torque authority *windows* for scheduling. TA windows are visibility periods during which the reaction wheels and MTBs can provide sufficient torque authority to overcome the predicted gravity-gradient torques. Under the two-wheel ACS, targets were scheduled only during windows when predicted pointing errors (also called theta errors) were 5° or less.

After adding TA window constraints to planning and scheduling, FUSE’s overall sky visibility initially decreased. Some regions at mid-range declinations had very short windows, and some areas of the sky became inaccessible. However, visibility was greatly improved after the operational spacecraft roll tolerance was relaxed to ±25° from nominal roll. The orientation of **B** relative to the MTBs changes at different roll offsets, thus changing the start time and length of scheduling windows.

Additional improvements were made to the planning and scheduling tools to optimize scheduling opportunities and more accurately predict periods of poor TA. With these improvements, FUSE, with a two-wheel ACS, re-achieved full sky coverage in April 2004.

Torque Authority and Wheel Momentum Constraints in One-Wheel Mode

With the failure of the roll wheel in late 2004, FUSE lost the ability to control another axis. All primary axis wheels (pitch, yaw, and roll) are now inoperative. Attempts to restart the stopped wheels were unsuccessful. Because the remaining skew wheel is mounted to the spacecraft differently than the primary wheels, the manufacturers assert the skew wheel is not in danger of failing before the end of the mission. However, in order to resume scientific operations, a new one-wheel attitude control system was required.

In early 2005, OSC modified the onboard ACS again to change the job of the MTBs to provide control on *two* axes. But the MTBs also have to continue their job of unloading excess momentum on the sole functioning skew wheel. The momentum on the skew wheel cannot exceed ±21 Newton-meter-seconds (Nms), which corresponds to a wheel speed of approximately ±6,500 revolutions per minute. Once the wheel speed limit is reached, excess wheel momentum is transferred to the body of the satellite, and attitude control is lost.

In the two-wheel environment, the switching between control and momentum management tasks worked smoothly and autonomously onboard by the MTBs. Now with only one functioning reaction wheel, the MTBs must provide control on two axes and also unload excess skew wheel momentum. While unloading momentum, the amount of control on the other axes is decreased. The optimal situation from the standpoint of torque authority is to have the spacecraft oriented such that the skew axis is closely aligned to **B**. This limitation must be considered during the scheduling process and has become the primary planning and scheduling restriction (Kruk 2006). As will be described below, judicious selection and ordering of observations by the MP Team is now the principal strategy to manage wheel momentum.

Figure 1 shows the current amount of sky visibility (in non-contiguous days) available to FUSE over the course of one year at all allowable spacecraft roll offsets (±25° relative to nominal roll). To be counted, windows must contain at least 3 orbits of torque authority with theta errors ≤ 5°. The best visibility windows near the poles are in FUSE's Continuous Viewing Zones (CVZs), where pointings are not impacted by Earth occultations. Currently, only targets with |declination| > 50° are observed because they have relatively unconstrained TA windows over the course of an entire observing cycle.

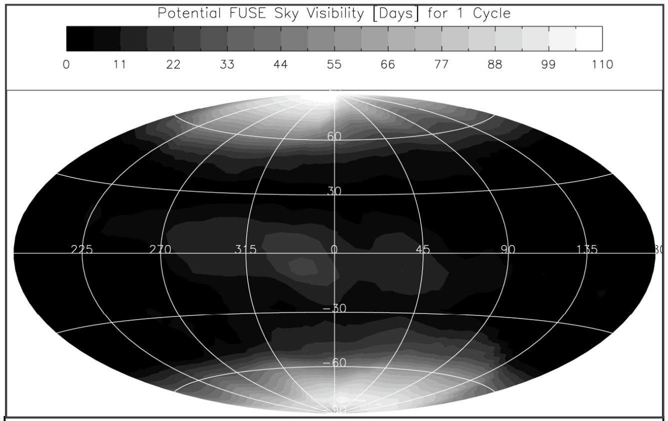

Figure 1: FUSE sky visibility plot for one year. The shading corresponds to the number of non-contiguous days of schedulability at all allowable spacecraft roll.

While TA windows were the primary driver for two-wheel planning and scheduling, there is more to consider with the one-wheel ACS. To maintain continuous spacecraft stability and autonomous operation, it is also necessary to order the observations in such a way to keep the skew wheel speed within its operating limits. As will be seen below, new MP tools have been created to accomplish this task.

Hemisphere crossings. To move the spacecraft from one pole pointing to the other, a suitable trajectory must be found with the precise starting wheel momentum at the planned slew start time. Whereas hemisphere crossing slews were automated and generally uncomplicated with the two-wheel ACS, they have proved much more challenging with the one-wheel attitude control system. The MP Team must first simulate many possible slew trajectories in order to find precisely timed and positioned slews which provide the satellite with sufficient control torque to complete the maneuver safely. This is primarily a manual process now, but work is underway to automate these steps. In addition, the slews must be scheduled and monitored in real-time. Because of the considerable resources required to perform hemisphere-crossing slews, it is preferable to minimize their occurrence, unless the hemisphere transition is driven by high priority science or observations with very limited visibility.

LVLH. If control of the satellite is lost during slews or static pointings, it may be necessary to transition to Inertial Hold or to a completely non-inertial safe configuration called Local Vertical Local Horizontal (LVLH). In LVLH, FUSE's boresight is continuously pointed towards the nadir, and the pitch axis is kept perpendicular to the orbit plane. The solar arrays are continuously adjusted to point at the Sun. It is possible to maintain attitude control in LVLH without the use of any reaction wheels. However, transitioning into and out of LVLH can be complicated. For instance, if the satellite points too closely to the Sun, the baffle doors may close. The baffle doors were not designed for frequent use. Also, manual effort is required in real-time for recovery from LVLH. For these reasons, every effort is made to avoid entering LVLH.

Long-Range Planning: Strategy and Tools

The purpose of building a Long Range Plan (LRP) is to assign observations into weekly bins covering a one-year time period. This provides information on the overall distribution of observations, flags scheduling problems or conflicts, and manages approved special scheduling requirements such as roll offsets and ephemeris constraints. The LRP is regenerated, manually reviewed, and optimized approximately every three weeks.

Prior to launch, Spike was designed to produce a stable long-range plan that could be baselined for most of an observing cycle. The original scheduling algorithms focused on arranging the observations primarily by time and priorities, filling the earliest bins first.

As discussed by Calvani et al. (2004), the Spike long-range scheduling software now uses pre-computed torque authority windows for long-range planning. The TA windows are computed by MP software, ingested into Spike, and treated as an absolute constraint (i.e., like Beta and Moon constraints) by Spike's Criteria Scheduler. At this time, however, Spike has no mechanism to minimize the net change in wheel momentum as a function of time.

Figure 2 illustrates the interplay between torque authority and change in wheel momentum over one orbit. The plot provides a snapshot of the fraction of sky (in one hemisphere) over which the spacecraft has torque authority. In this particular timeframe, there is a relatively large area on the sky where FUSE can point with sufficient torque authority. The torque authority contours (or TACOs) are outlined in white. The background of grey bands corresponds to the predicted changes in wheel momentum (Nms/orbit) over the sky. These values are computed by averaging over the next 3 orbits. Thus, the dark grey bands represent areas on the sky where pointing FUSE for one orbit would result in a positive change in wheel momentum; the light grey bands correspond to negative change in wheel momentum. The intensity of the bands denotes how rapidly the momentum will change. The morphology of the TACOs changes tremendously over the course of FUSE's orbital precession cycle (~60 days).

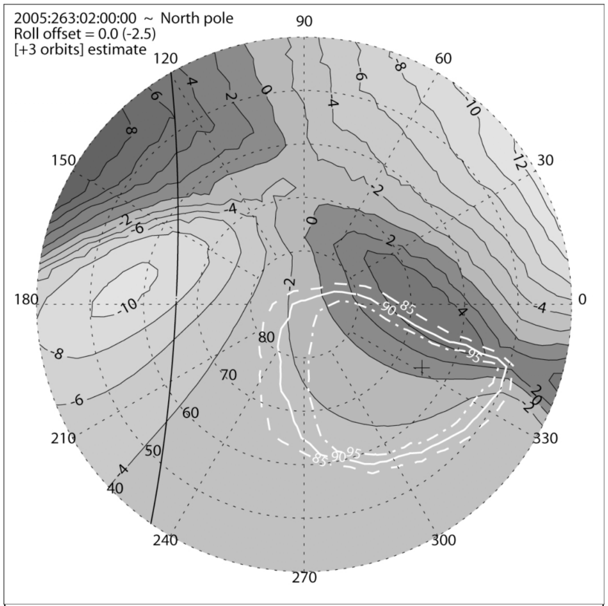

Figure 2: Sky visibility on 2005:263 (20 Sept. 2005) near North orbit pole (cross symbol). The white contours mark areas of 85% (outer-dashed), 90% (middle), and 95% (inner) torque authority. Predicted wheel momentum bands are denoted by dark shades of grey (positive change) and light shades of grey (negative change). The slightly curved, vertical dark line marks the Beta angle limit.

After a thorough investigation by the MP Team and STScI software engineers, it was determined that a large-scale overhaul to Spike to add wheel momentum calculations would be too time consuming and cost prohibitive in this late stage of FUSE's Extended Mission. However, a number of other valuable Spike modifications were recently conceived which will improve Spike and the LRP process. Specifically, the following Spike upgrades are now under development:

- Allow the LRP Planner to apply one (larger) oversubscription factor to the first four bins and another to the rest of the LRP. The first month of the new LRP is used by Planners to generate the next set of short-term schedules. These bins should contain a larger number of potential science targets for maximum scheduling flexibility.

- Apply a tunable (typically 20%) adjustment factor on requested observation times. Frequently, an observation becomes unschedulable because Spike deems it too lengthy to fit in its visibility window. Since MP policy is to allow a 20% reduction in requested exposure time, more observations will be scheduled satisfactorily if Spike also applies this adjustment when filling LRP bins.

- Prohibit observations when FUSE's orbit pole is within a specified distance of the Beta exclusion zones. When the orbit pole is close to the Beta limit, a significant portion of the TACO may be unavailable for scheduling.

After the Spike software produces an LRP, there are several manual steps that must be performed before the LRP is released. The first step is to review all unschedulable observations and, if possible, manually assign them to suitable bins. If the observations cannot be scheduled, the scheduling issues must be worked out with the GI.

The next manual LRP task is to review Spike's timing of hemisphere campaigns. Since Spike incorporates TA window information and rules about observations' priorities, it generally performs a satisfactory job of planning hemisphere campaigns. However, it is beneficial to inspect the predicted TA trends, and use this information for planning guidance while generating hemisphere campaigns which optimize the TA ratio variations.

Figure 3 shows the predicted percentage of torque authority vs. time for observing at the Northern and Southern orbit poles (assuming roll offset = 0). Fourier analysis shows that the periodicity is approximately 50 days, and there is an offset between North and South hemispheres.

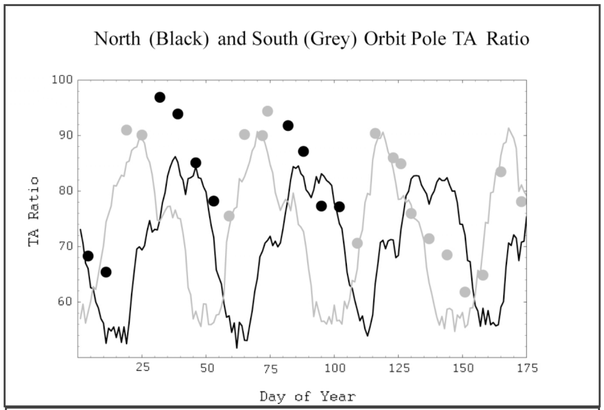

Figure 2: Percentage of time per day with TA at the North (black curve) and South (grey curve) orbit poles over the first half of 2006. The dots represent the actual percentage of time of TA per entire scheduled MPS.

Although target positions can be automatically included on TACO plots (like Figure 2), they only provide a snapshot of the portion of sky over which the spacecraft has torque authority. A significantly better method to examine targets' TA and momentum change characteristics (over time and at different roll offsets) is provided by daily target plots as shown in Figure 4.

By examining these plots over the seven days of a bin, the LRP Planner can ensure an optimal set of targets for wheel momentum management. For example, if Spike scheduled too many targets in a bin that drive momentum positive (dark grey bars), the Planner can balance the bin by manually adding targets that drive the momentum negative (light grey bars). The LRP Planner makes this assessment and correction for only the first four bins. As will be seen in the next section, these daily TA/momentum plots are also crucial to short-term scheduling. Thus, these plots have become a hybrid tool used for both the long-term and short-term scheduling processes.

Short-Term Scheduling: Strategy and Tools

At the short-term scheduling level, the MP Team prepares detailed one-week observing instructions for the spacecraft to execute autonomously. The short-term scheduling software computes target visibility, constraints, theta errors, and wheel momentum. The Mission Planning Schedule (MPS) is the final output product, and it specifies the start time and duration of every activity (e.g., slews, target acquisitions, exposures) and event (e.g., SAA passes, Earth occultations) associated with each observation.

Early in the mission, there were very few short-term scheduling drivers. As with Spike, however, the short-term scheduling tools were upgraded shortly after launch to include predictive Focal Plane Assembly (FPA) and mirror motions in order to minimize the thermal effects on the alignment of the optics between observations. More substantial changes were incorporated in 2002 to support the two-wheel attitude control system. See Roberts et al. (2004) for more details regarding FUSE's two-wheel operations.

Once the short-term Planner receives the pool of observations for the next MPS, s/he assembles a one-week timeline of observations which meets the following goals:

- Schedule as many high priority and standard science targets as possible. Schedule at least 80% of the requested exposure time, preferably pad the observation by 20%.
- Maximize torque authority; i.e., schedule targets when predicted theta errors are less than 5°.
- Minimize skew wheel momentum. Although the actual hardware limit is 21 Nms, the MP Team uses a planning limit of ±14 Nms as a safety margin, since the actual momentum may deviate from the predicted value.

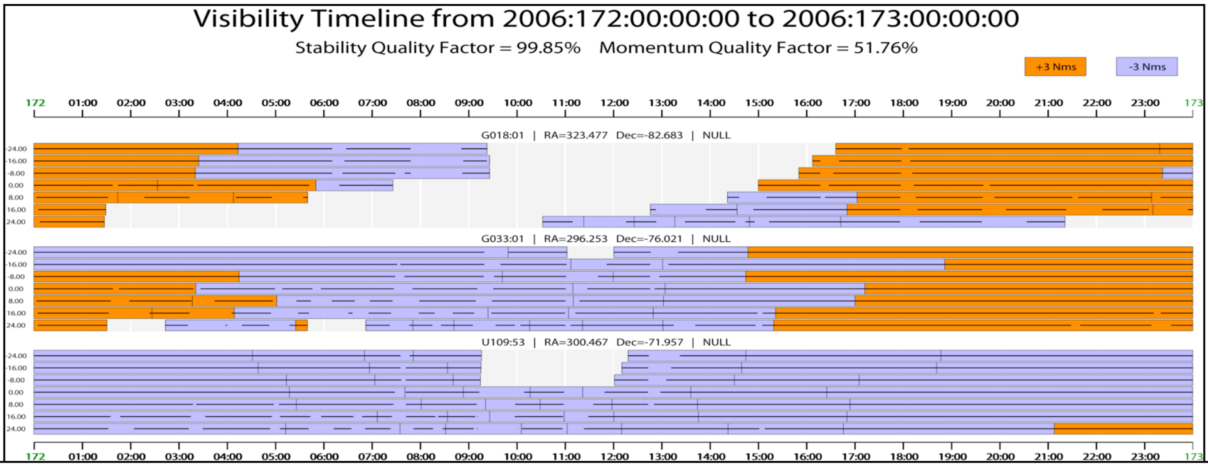

Figure 4: Daily TA and momentum change plot. Broad bars mark intervals when predicted theta errors are less than 5°; heavy lines within bars indicated when predicted theta errors less than 30 arc min. Length of each bar shows predicted interval over which momentum will increase (dark grey) or decrease (light grey) by 3 Nms.

The short-term scheduling tool does not have the capability to order the observations for the MPS; the short-term Planner inputs the exact ordering to the scheduling tool. To decide on the ordering, the MP Team uses separate tools to assess TA and momentum changes over the timeframe of the MPS. Daily TA and momentum plots, like the one shown in Figure 4, are critical to understanding the nature of torque authority and wheel momentum changes over short timescales. These plots are the main tool used to decide the order of observations in an MPS.

The short-term scheduling tools provide feedback if any observations or slews would be unsafe or if the momentum limit would be reached. If these errors are predicted to occur, the Planner has several options to correct the schedule. For example, the Planner can try applying a spacecraft roll offset (up to ±25°) to the observation to improve torque authority or change wheel momentum. Also, the Planner can rearrange the order of observations. The Planner iterates with the software until a safe schedule is produced. Preparing a one-week MPS generally takes 4-5 days to complete.

To fully assess the safety and feasibility of a completed MPS, the entire schedule is tested before it is compiled into commands and up linked to the satellite. The MP tool *mpssim* computes the theta errors and wheel momentum changes over the course of the whole MPS. The Planner plots and reviews these values before finalizing the MPS.

Figure 5 shows a comparison of predicted momentum with actual telemetry from completed observations. There is generally satisfactory agreement between predicted values and actual values.

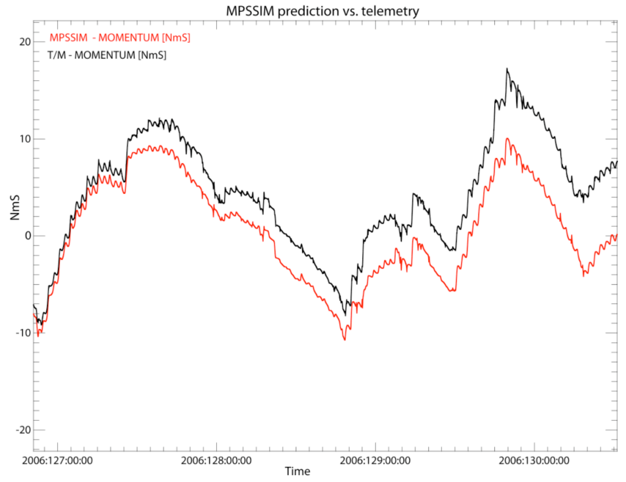

Figure 5: Predicted wheel momentum (black line) vs. actual value (grey line) over 4-day period.

While the goal is to construct an MPS with only peer-reviewed, NASA-approved science observations, the science targets in an individual bin or in the overall pool are often not adequate to fill up a weekly timeline because of their TA windows and/or the impact they have on skew wheel momentum (of which Spike has no insight).

As a result, the FUSE Project agreed to re-observe certain previously completed targets and make the data accessible immediately after they were obtained. In August 2005, the FUSE Project added 600 of these targets (all with |declination| > 50°) to the FUSE LRP.

In addition, the Project created a comprehensive set of 400 additional sky background observations to fill in apparent gaps on the sky. These observations (which point at blank portions of the sky) are extremely useful for wheel management flexibility. Furthermore, they provide the FUSE Project with two kinds of important scientific data. First, they provide necessary calibration of the relative sky background (scattered light) on the illuminated and non-illuminated portions of the detectors (Dixon et al. 2006a). Second, various FUSE observers are using the background data sets to look for diffuse emission from interstellar OVI, which represents hot (300,000 K) gas in the interstellar medium. More details can be obtained in Dixon et al. 2006b.

The Hybrid Dynamic Simulator

OSC's Hybrid Dynamic Simulator (HDS) is a standalone copy of their actual onboard ACS software. The HDS models the space environment and activities of the onboard subsystems. The HDS was developed for use by OSC for development and testing but was made available to the MP Team in 2005. The HDS can typically run 90 times faster than real-time, thus a one-week MPS takes several hours to simulate. However, due to the number of iterations required to finalize an MPS, the HDS is not a convenient short-term planning tool. Instead, the MP Team currently uses the HDS for three alternate purposes:

1. Comparing spacecraft performance to planned timelines. The MPS can be run through the HDS and the results compared to the actual telemetry values. This is most useful for assessing MP predictive tools.

2. Finding safe hemisphere crossing slews. As explained in the Introduction, all planned pole-to-pole maneuvers must be simulated beforehand to ensure there will be sufficient torque control during the slew.

3. Finding safe recovery slews from LVLH to the orbit pole. As with pole-to-pole maneuvers, taking the spacecraft out of LVLH mode and slewing back up to the pole is a manual process that must be simulated prior to execution.

Spacecraft Performance and Scheduling Efficiency

The FUSE Project resumed regular science operations on 1 November 2005. This section contains a discussion of current spacecraft performance and the efficiency of planned observations.

Pointing accuracy and stability. Before launch, the required spacecraft pointing accuracy was 1 arc second, and the required pointing stability was 0.5 arc second (Sahnow et al. 2000). After launch with 4 reaction wheels, the actual pointing stability was typically ~0.3 arc second (Moos et al. 2000). Under the two-wheel attitude control system, the stability was typically ~0.5 arc second (Sahnow et al. 2006), though with slow periodic drifts of a few arc sec under certain circumstances and occasional excursions of a few degrees. The CalFUSE data processing software was upgraded to compensate for most spacecraft drift. With only one functioning reaction wheel, pointing stability is still ~0.5 arc second during good TA windows (Sahnow et al. 2006). However, there are now longer time periods of reduced torque authority and larger pointing excursions up to 5°.

Scheduling and guiding efficiency. As mentioned previously, all FUSE observations are currently performed in and near the CVZs where the gravity-gradient torque is minimized. When observations are scheduled inside either CVZ, the only interruptions during the observation are for SAA passages, which typically last 30 minutes. Just outside the CVZ boundary, Earth occultations also interrupt observing for approximately 10 minutes per orbit. Without long Earth occultations, scheduling efficiency is currently quite high. Since November 2005, the average scheduling efficiency (percent science time vs. wall clock time) is 52% per month, which is greater than two-wheel operations (39%) and also the prime mission average (32%), when many observations of low declination (hard-occulted) targets were performed.

Guiding efficiency is a measure of the amount of exposure time achieved with the target in the aperture. As a result of more limited torque authority, FUSE's guiding efficiency has decreased under the one-wheel attitude control system. Since November 2005, the average guiding efficiency is 45% of the total amount of observing time scheduled per month. Figure 6 contains a monthly comparison of scheduling and guiding efficiency since November 2005.

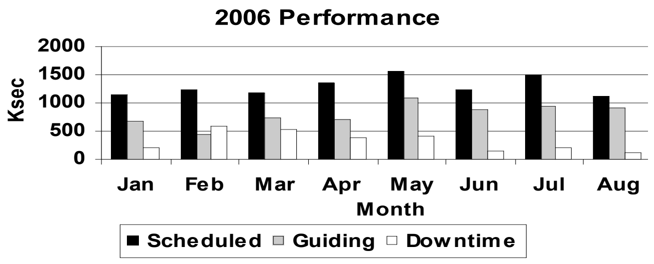

Figure 6: Amount of time (ksec) per month of observations scheduled, exposure time achieved guiding, and unplanned downtime (e.g., LVLH, momentum interventions) in 2006.

Whenever possible, observation times of prime science targets are increased (or padded) at MPS generation time to increase the chances of obtaining sufficient time on target. The amount of padding depends on the quality and length of TA windows and by how much the skew wheel momentum is predicted to change during the observation. Observations are often split into multiple pieces or visits to better accommodate TA and momentum constraints. A "successful" observation is one in which at least 80% of the observer's requested time is achieved. If an observation is missed or if less than 80% of the requested time is obtained, a redo observation for the remaining time is created and included in the next LRP run.

MPS timeline interventions. Due to differences between MP predictive tools and actual onboard performance, there are times when there is an offset between the predicted and actual wheel momentum values. Although an offset can remain stable for some time, if left unchecked, it may lead to large theta errors and/or skew wheel saturation. This may cause the slews and/or observations to become unsafe. If the ACS cannot cancel the resulting theta errors, the satellite would transition to a safe hold configuration, and manual intervention would be necessary to return FUSE to operational mode.

The Mission Operations Team (MOT) in the FUSE Satellite Control Center continuously monitors any offset between predicted and actual skew wheel momentum. If it appears that the offset may lead to wheel saturation within 12-18 hours, then a timeline intervention is performed, preferably during an "observatory" or background observation so that prime science is not lost.

There are currently two ways to adjust the onboard wheel speed in real-time. In the first method, the MOT aborts the currently executing observation and slews the spacecraft to a safe new pointing that is predicted to reduce the wheel speed within a few orbits. The timeline is rejoined when the actual wheel speed more closely agrees with the predicted value. This method has proven to be quite reliable. The disadvantage to this method, however, is that one or more real science observations may be missed during this intervention. The MOT currently performs about six timeline interruptions each month.

The second option is to change the onboard ACS automatic momentum unloading parameters to more aggressive values so that more time is spent unloading (rather than providing control) during the observation. The advantage to this method is that the observations executing are not interrupted. This method depends very highly on the angle between **B** and the skew wheel axis, with an angle greater than 80° preferred. However, when this angle is high, the TA is generally poor. Therefore, the momentum variation is more difficult to predict. Since less control is being applied during periods of aggressive unloading, there is generally more spacecraft drift during these periods.

LVLH downtime. The number of times FUSE has transitioned to LVLH after loss of control has decreased dramatically due to improvements in the ACS flight software, MP tools and from performing the real-time adjustments to manage the wheel speed. For example, in 2005, there was an average of 5 transitions to LVLH per month. There have only been a **total** of 4 unplanned transitions to LVLH in the first six months of 2006.

Summary and Future work

In the past 18 months, FUSE's two-wheel attitude control system was completely overhauled to operate with only one functioning reaction wheel. Magnetic Torquer Bars, which were originally designed only for shedding excess wheel momentum (in a four-wheel environment), now also supply the spacecraft with magnetic control torque on two axes. Pointing stability and accuracy are sufficient to perform important scientific observations. Guest Investigators continue to propose innovative new observations programs each year. As the FUSE Project gains more experience with this revolutionary new way of operating, predictive planning and scheduling tools will be upgraded and therefore scheduling and guiding efficiency will continue to improve.

In addition to the planned Spike improvements mentioned earlier, the following upgrades are being investigated now by the FUSE Project and Orbital Science Corporation engineers:

- New slew algorithm. OSC is currently developing a new onboard slew algorithm that would adjust the slew trajectory in real-time to minimize the control torque needed.
- Performing observations at 180° offsets from nominal roll. While this could provide different or better torque authority at difficult scheduling times, there may be significant thermal and/or guiding issues.
- Automating hemisphere crossing slews. Slewing from one orbital pole to the other is currently a resource-intensive task. Planning generally starts one month in advance and requires a day of observation downtime both before and after the pole-to-pole slew. Automation software is being developed now to search for the possible safe slews with minimal interaction from the FUSE team. Once this automation is in place, it will be possible for the Mission Planner to schedule pole-to-pole slews in the actual MPS a week or two in advance, instead of the month it currently requires. This will also reduce the required downtime of the telescope.
- Development of a tool to automatically replenish the observatory and background target pools before each LRP is generated. Creating new observations is currently a time-consuming, manual process. Automation will ensure a constant, optimal target pool required to satisfy wheel momentum and TA constraints.

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