Spitzer observatory operations — increasing efficiency in mission operations

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ABSTRACT

This paper explores the how's and why's of the Spitzer Mission Operations System's (MOS) success, efficiency, and affordability in comparison to other observatory-class missions. MOS exploits today's flight, ground, and operations capabilities, embraces automation, and balances both risk and cost. With operational efficiency as the primary goal, MOS maintains a strong control process by translating lessons learned into efficiency improvements, thereby enabling the MOS processes, teams, and procedures to rapidly evolve from concept (through thorough validation) into in-flight implementation. Operational teaming, planning, and execution are designed to enable re-use. Mission changes, unforeseen events, and continuous improvement have often times forced us to learn to fly anew. Collaborative spacecraft operations and remote science and instrument teams have become well integrated, and worked together to improve and optimize each human, machine, and software-system element. Adaptation to tighter spacecraft margins has facilitated continuous operational improvements via automated and autonomous software coupled with improved human analysis. Based upon what we now know and what we need to improve, adapt, or fix, the projected mission lifetime continues to grow—as does the opportunity for numerous scientific discoveries.

Keywords: Operational Efficiency, Observatory, Spitzer, Mission Operations

1. INTRODUCTION

The Spitzer Space Telescope was launched on 25 August 2003, into an Earth-trailing solar orbit to make infrared astronomical observations from space. After its 60-day In-Orbit Checkout (IOC) and 30-day Science Verification (SV) period, the mission began nominal operations. Spitzer's lifetime is directly related to the amount of liquid helium on board—once the helium runs out, the primary mission ends. The requirement for the primary mission duration was two and a half years from the start of nominal operations, with a goal of 5 years. We currently project that we will exceed the 5-year goal, see Fig. 1.

The Spitzer MOS differs greatly from those of planetary missions—there is no cruise period to allow for deferred development. Therefore, the MOS and Ground Data System (GDS) had to be ready to support all aspects of the mission at launch. For Spitzer, all post-launch mission-critical events happen in hours or days after launch, rather than months or years. In addition, Spitzer's heliocentric (rather than geocentric) orbit provides the MOS with more opportunity to contribute to the overall efficiency of the Observatory, because of the minimal spacecraft pointing constraints. We have achieved efficiencies of more than 90%, which is more than double any other great observatory, and with fewer personnel.

We were able to take advantage of multimission heritage software processes and procedures that required only minor changes to support Spitzer. Two examples of this type of multimission software are JPL's Advanced Multimission Operations System, (AMMOS) and Lockheed's Spacecraft Performance Analysis System (SPAS). By utilizing these systems, we were able to focus more on system-Level testing and training and thus able to rely on the unit testing and training performed by the multimission organizations. Although some of the software processes and procedures that were developed specifically for Spitzer required more time in testing and training, the number of such special-purpose items was limited. A couple of examples are the packet acknowledgement process (PAP) and solar-flare contingency procedures.

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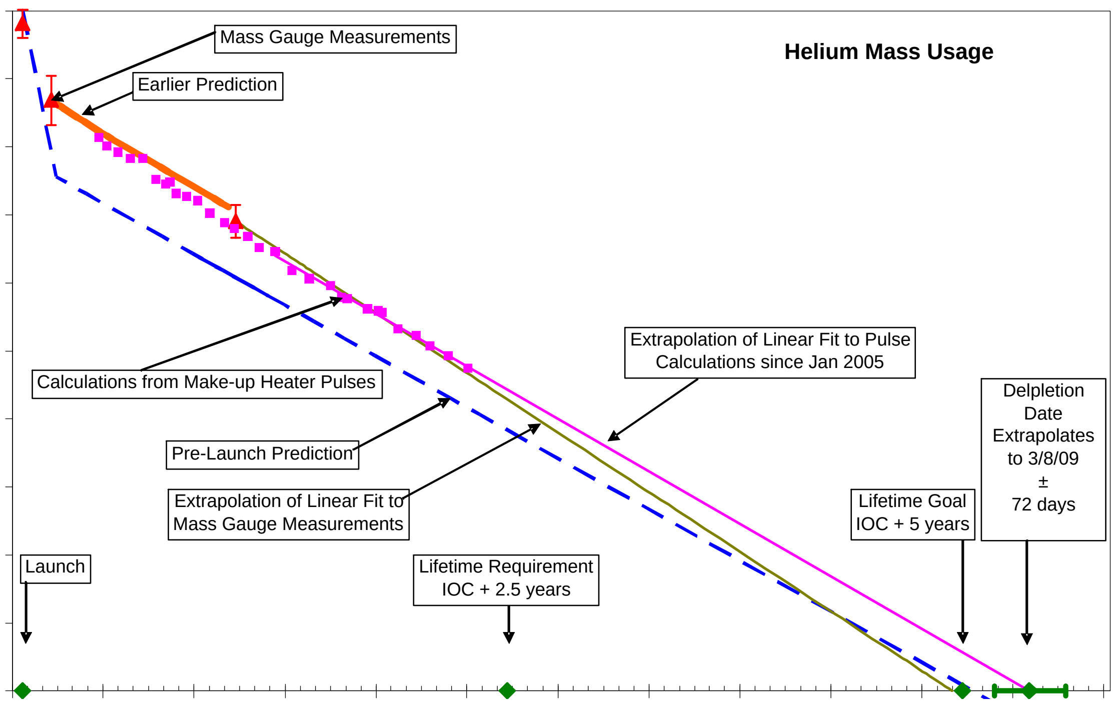

Fig. 1 Historical and projected usage of Helium by the Spitzer Space Telescope.

Similar to our success in the reuse of software processes and procedures, we also benefited from having experienced development and operations personnel who joined the project early (starting around the Critical Design Review) and stayed on well beyond launch into nominal operations. We streamlined and reorganized the MOS after the start of nominal operations, but the continuity was maintained by retaining key personnel, even if in new roles.

Within the context of this paper, we consider the facility to include both the flight and ground segments, since the observatory is composed of both the spacecraft and the science instruments. Spitzer uses a two-pass sequence-development process—we always have three sequences in different phases of development in addition to the sequence that is being executed on the Observatory. Our sequences are always 1-week long and the downlink products go through preliminary processing before being delivered, within 12 hours of receipt, to the Spitzer Science Center (SSC).

This paper explores the lessons learned and how and why MOS has become successful, efficient and affordable, when compared to other observatory-class missions.

2. IMPROVING EFFICIENCIES POST-LAUNCH

Many of the efficiency gains can be attributed to the Spitzer's adaptable operations organization. The pre-launch, launch, and IOC/SV periods were focused on building and operating the baseline system and identifying areas for later improvement. Pre-launch domain experts were then transitioned from development to operations to facilitate a more integrated post-launch operational team. During the IOC/SV period, the Project (including MOS) validated that Spitzer had met its level-one requirements. Starting with IOC/SV and continuing through Nominal Operations, we have identified lessons learned and opportunities for improvement. The most important of these were quickly implemented during IOC/SV, based on flight experience. Now, during Nominal Operations, we are implementing the remainder. Various working groups continue to look at ways of improving our efficiency in operating the facility.

MOS improvements can be grouped into three categories:

1) Operations System (processes, procedures and interfaces)

2) Ground Data System

3) Flight System

Improvements in these areas had three primary goals:

1) Manage mission risks and consequences to increase reliability and robustness
2) Automate routine tasks/duties to minimize personnel required for MOS
3) Increase overall observatory efficiency

Throughout the paper, the improvements discussed are cross-referenced to the goals they support.

3. OPERATIONS SYSTEM

The continued focus of Spitzer Operations is operational excellence through better characterization, testing, and utilization of key mission resources. We use regularly scheduled staff, working group, and team meetings to coordinate activities, check status, and effect change among geographically distributed operations teams at Jet Propulsion Laboratory (JPL), Lockheed Martin Space Systems Company (LMSSC), and SSC to stay on plan. Although these meetings are often routine in nature, they play a key role in keeping the lines of communication open and the teams sharp and ready for action (similar to a fire station). Gains in MOS efficiencies can more specifically be credited to the MOS Design Team (MOSDT), Uplink Working Group (UWG), Downlink Working Group (DWG), or the GDS Working Group (GDSWG) meetings.

The regularly scheduled meetings are:

1) Status and Coordination Meetings (Weekly - coordination and reporting by all mission elements to stay on plan and/or coordinate critical science driven changes; all elements of the project, including those not directly related to operations, are represented)
2) Change Control Board (Weekly - approval of all system upgrades, fixes and changes to operational configuration controlled system and test beds)
3) Observatory schedule approval (Weekly - initial approval for sequences; key to facility resource allocation, including data volume and mass memory card prediction)
4) Sequence reviews (Weekly - review different phases of sequence development and approve changes to sequence content)
5) Command conference (Weekly – final approval to uplink commands, load sequences)
6) Anomaly Response Team Meetings (As required from anomaly detection to resolution – to initiate anomaly recovery from major anomalies)
7) MOSDT, UWG, and DWG (Weekly - to design, analyze, propose and prioritize efficiency improvements and cross-organizational activities affecting on-going operations)
8) Flight Engineering Team Meetings (Weekly or as-required - review of science, engineering, instrument, and operational changes to ensure that Observatory system integrity, operational performance and science delivery are not compromised)
9) GDSWG Meetings (Weekly - to coordinate the implementation, integration and testing of ground segment hardware and software, including remote and on-site installations)

These meetings are an integral part of the daily operations process flow to ensure that operational processes and teams are routinely re-examined for possible lessons-learned corrections, and risk mitigation, as well as opportunities for process and operations automation, continuous improvements, or obsolescence. The Spitzer MOS uses these meetings to discuss issues and problems, and as a means of both upward and downward communication throughout the MOS.

To date, the annual Science efficiency achieved is 92.0%, far exceeding the 90% goal (see Fig. 2). This level of efficiency has been made possible because of the SSC observation efficiencies and the MOS improvements discussed in the following paragraphs. Utilizing an integrated Spitzer Operational Process Flow, as illustrated in Fig. 3, has resulted in successfully developing and uplinking more than 5,200 commands/files to the Observatory, and yielding a science and engineering data return of more than 500 gigabytes.

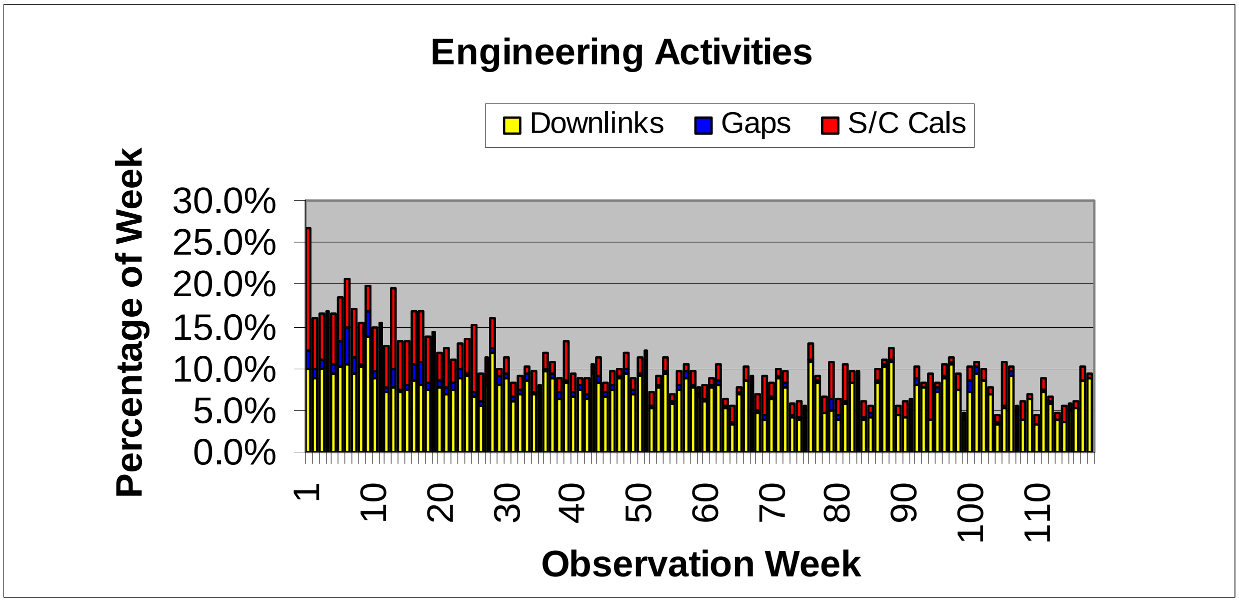

Fig.2 Spitzer non-science activities per week (goal is 10% or less).

Changes to the operational process flow are carefully analyzed to ensure that the end-to-end process yields the predicted improvement. Changes to the Observatory are rigorously tested on the ground before being uploaded. This MOS environment has enabled the effective collaboration and analysis of safe mode and recovery (including identifying lessons-learned) in a timely fashion. This is possible because of the extensive anomaly/contingency procedures that were developed pre launch, and that are enhanced post launch

The following is a list of Operations Systems improvements:

1) Reduced the number of iterations to produce a sequence from three passes to two. This was achieved through changes in SSC S/W and procedures, as well as MOS increasing parallelism. We now allow for the simultaneous repair of sequence problems and science content changes. (Goal 2)

2) Identified common uplink-product improvements and made checks earlier in the sequence process, e.g., making sure the bore sight calibrations are done on alternating sides of the hardware. (Goal 1)

3) Improved teams' interactions in processing the downlink, minimizing the personnel required, and increasing reliability. This was achieved by implementing a Data Products Working Group to track downlink products and the implementation of the Post-Pass Data Processing web page. (Goal 2)

4) Actively managed usage of Mass Memory Card (MMC). This was achieved by incorporating two additional checks into the schedule approval process. (Goal 1)

   a. Verified that if there is a missed pass during the sequence, the MMC will not fill. If the MMC fills, the fault protection will place the observatory in Standby mode and two days of observations would be lost.

   b. Verified that if there is a missed pass, the data can be retransmitted within six passes. This avoids the problem of the data perpetually backing up.

5) Off loaded commanding requiring on console Mission Manager approval to the Observatory Engineering Team (OET) and the Flight Control Team (FCT). This contributes to fewer personnel to run operations. (Goal 2)

6) Improved Target-of-Opportunity (ToO) Planning. We have a requirement to respond to high-impact ToOs by changing the sequence on the observatory within 48 hours. We found it necessary not only to have a generic operations process, but to also analyze each of the approved ToO observations and make plans for

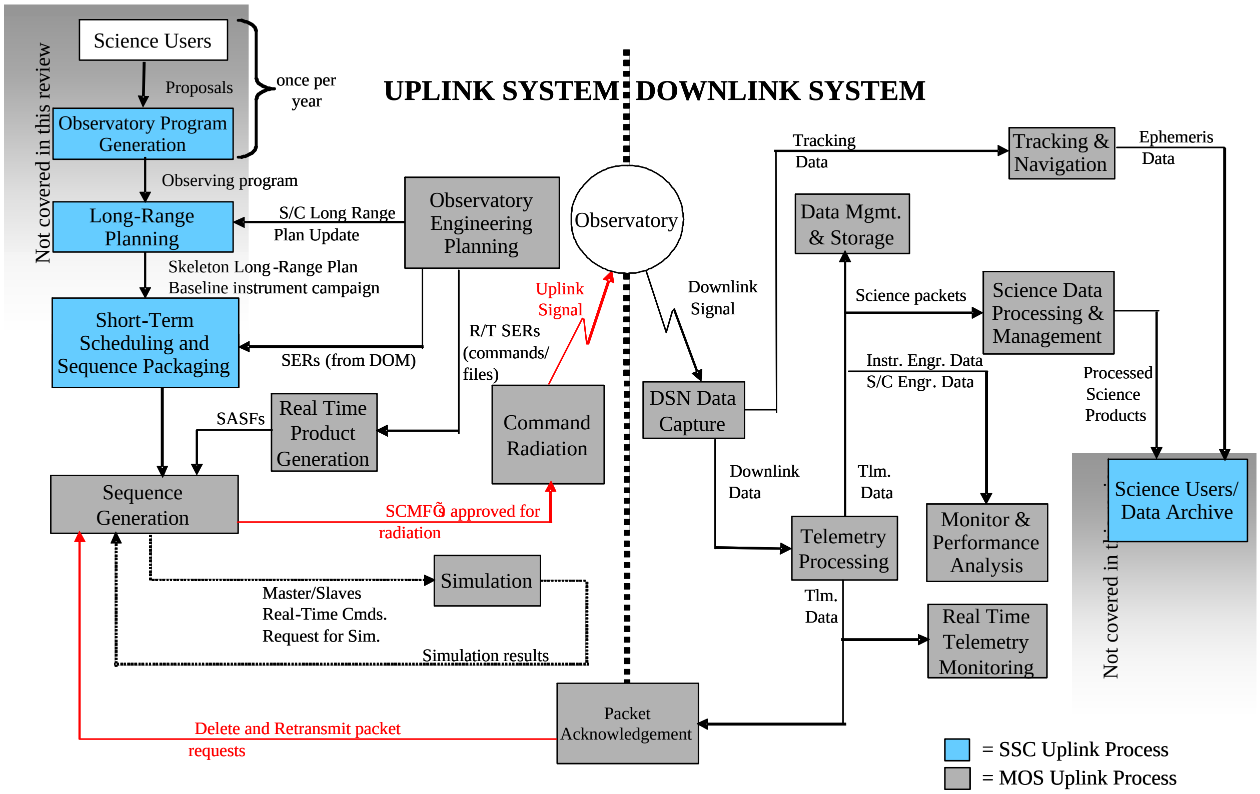

Fig.3 Spitzer high-level uplink and downlink system diagram.

each, individually. The important differences included the number and spacing of repeat observations (typically spaced over a few days to weeks), and which science instruments were called for. The time relative to our sequence construction cycle at which the go for the ToO was given was also important. Since each of our sequences is 1-week long, we outlined separate strategies for each approved ToO observation for each day of the week to minimize sequencing work, uplink time, and disruption to our baseline sequencing activities. This allowed us to accommodate ToOs with no increase in MOS personnel. (Goals 1 and 3)

7) Improved single-failure analysis of missed-pass scenarios. In conjunction with the changes to PAP and the creation of the MMC Prediction Tool (MPT), we analyzed many single failures in the data downlink and acknowledgement system. These were either failure to uplink acknowledgement and retransmission commands, failure to receive all the data transmitted by the spacecraft, or both. Each of the scenarios includes plans for data acknowledgement and retransmission: 1) to avoid filling the MMC; 2) to start the retransmission of data right away; and 3) to clear the backlogs of data as soon as possible. (Goal 1)

8) Implemented an MMC fill-avoidance flight software change. At the start of each observation, this change makes sure there is enough room on the MMC for the data that will be generated. If there is not enough room, the observation is skipped. This change in flight software will require changes to the MMC analysis and approval described above in items 4 and 7. Once this patch is in place, we can collect more data because we have reduced the consequences of a missed uplink or downlink. Instead of filling the MMC, we will skip observations. (Goal 1)

4. GROUND DATA SYSTEM

Traditionally, GDS designs have evolved after the flight system designs, rather than in conjunction with them. This held true for Spitzer's pre-launch development. But now during post-launch, the GDS is an integral part of the Spitzer Facility and is being system engineered and integrated concurrently with the flight segment. The improvements in the GDS post-launch primarily involve automating tasks and increasing reliability and robustness. The GDS has two components that may be changed to accomplish this: 1) Hardware and 2) Software. Both have been modified for Spitzer to contribute to accomplishing all three primary goals.

The following is a list of GDS improvements:

1) Improved uplink tools to provide increased efficiency and robustness. This was achieved by modifying both hardware and software for sequence generation. The sequence software was optimized by only outputting changes to the Observatory's state rather than the complete state each time. We also upgraded the hardware platform from Sun Ultra 60s to Sun Sunblade 2500s. This combination of these changes effectively doubled the sequence-generation speed—important for anomalies support, and to produce ToO products quickly. (Goal 1)

2) Implemented changes to automate verification of sequence loads. This was achieved by creating a program to compare the cyclic redundancy codes (CRCs) in the uplink products to the CRCs in telemetry. During IOC/SV all sequence CRCs were checked manually in real time. Once normal operations began manual checking was no longer possible, since IRAC sequences could contain tens to hundreds of CRCs to be checked in a short period of time. The CRC check software can verify a sequence module load two orders of magnitude faster than the manual check. This allows the FCT to attend to other functions, and uplink more commands in one Deep Space Network (DSN) track. (Goal 2)

3) Implemented changes to verify downlink integrity. This was achieved by creating a program to verify that the real-time transfer frames received at the DSN were contiguous. Since Spitzer data is downlinked at 2.2 Mbps, the data must be separated into a real-time vs. playback stream. However, DSN monitor data cannot verify the integrity of the downlink data. The only way the downlink data could be verified for integrity at the packet level was when the Packet Acknowledgment Process (PAP) was run. Because this is done after the tracking pass is complete, we needed a way to verify that the data being received at the DSN and JPL was good, before the pass was over. The track frames program analyzes both real-time and playback data to ensure the telemetry data is contiguous. Every time a real-time frame is dropped or received out of order, this tool gives the FCT a visual and audible alarm. (Goal 1)

4) Implemented an intermediate data record (IDR) check tool to verify receipt of transfer frames at JPL. The DSN provides web page reports on how many transfer frames it has received for a given time range. This tool can also be used to make sure we have a complete copy of the data before proceeding with the rest of our ground processing. The tool ensures against otherwise undetectable GDS anomalies between the DSN and JPL. (Goal 1)

5) Improved the time-accountability reporting of science observations. The Activity Accountability Report software (AAR) compares the actual start and stop time with the predicted times. In addition to confirming the accuracy of our observation models, it indicates whether observations were truncated or skipped. We were able to identify, track, and resolve at least one systematic error that caused multiple truncations via this software. (Goals 1 and 3)

6) Improved packet acknowledgement and retransmission. The Packet Acknowledgement Process (PAP) software builds commands to delete packets that we have received on the ground from the MMC, and to retransmit those we have missed. We have made several bug fixes and improvements to it during operations. The improvements would enable us to manage several failure scenarios that we had not anticipated at pre-launch. (Goal 1)

7) Created MMC tracking and prediction capability. The MPT compares the predicted data volumes to the actual data volumes. It assesses how well we predict data volumes, and tracks the effects of anomalies on the downlink system. Spitzer's two-phase downlink system operates by downlinking data during one pass and then deleting it from the MMC via PAP commands during the next. This makes prediction and management difficult. The MPT can predict if and when we will fill the MMC and helps us decide on the best recovery strategy. (Goals 1 and 3)

8) Reduced the time it takes to process telemetry on the ground. This was achieved in four ways. (Goals 1 and 2)

a. Dedicate two machines only for Spitzer. Although Spitzer uses multimission software, we do not use multimission hardware. This allows Spitzer telemetry processing to be run unencumbered.

b. Increase hardware platform of both machines (from Sun Ultra 80s to Sun Sunfires), which allowed telemetry processing to double in speed.

c. Upgraded our system that reconstructs the lowest-level science data products from the raw packets.

d. Upgraded to faster CPUs and turned off the RAID real-time mirroring in favor of daily synchronization. This processing includes data decompression and assembly of packets into uncalibrated image frames or the equivalent (called data-collection events or DCEs).

9) Improved the Mission Support Area (MSA) robustness and reliability. This was achieved by changing from a dumb central disk array to a smart RAID system. The old disk array would take two hours to recover and all client workstations had to be rebooted. With the new system the recovery is less than fifteen minutes, and the client workstations need not be rebooted. (Goal 1)

10) Implemented antenna arraying. As Spitzer moves farther away from Earth over the course of its mission, we must use larger ground antennas to support our 2.2 Mbps downlink rate. Since there are fewer larger antennas, we found it useful to add the capability to our MOS to use arrays of smaller antennas. Antenna arraying is a supported capability of the DSN, but we had to change some of our procedures and ground software to accommodate it. (Goals 1 and 3)

11) Improved data volume prediction. At the beginning of flight, we would only estimate the volume of science data and not explicitly account for the volume of engineering data recorded to the MMC. However, once we started to vary the time between DSN passes, about either twelve or twenty-four hours, this introduced errors into our analysis of if we were in danger of filling the MMC and of the amount of time needed to downlink the data. First, we measured the average rate at which engineering data is generated, and added that engineering data volume into the total predicted data volume. Then, we did an analysis on the accuracy of the science data volume predictions. That analysis revealed some systematic errors in those predictions. We added some controls at various points in the prediction process. Those allow us to remove most of the systematic error. Then, what remains is just the inherent error due to uncertainty in the on-board data compression. (Goals 1 and 3)

12) Optimized track time utilization. We have two requirements on the duration of our DSN passes. First, the amount of time available for uplink must be forty minutes during the day (prime shift at JPL) and thirty minute during the night. When we have one pass per day, it is always a daytime pass. Second, the amount of time available for downlink must be sufficient to accommodate the predicted amount of data volume. At the beginning of each pass, the observatory remains at Earth-point for about seven minutes before starting to downlink the data. This is to allow the DSN station to establish communications. However, the vast majority of the time, the link is established very quickly. So, we have arranged to always establish the connection at the beginning of the seven minutes, and count those seven minutes as part of the uplink time. That then reduces the minimum downlink time that we must allow. Even with that reduction, on low-data-volume days, we do not need that minimum time to downlink all the data. But, reducing the minimum has increased our efficiency by reducing the overall amount of slack in the our DSN passes. (Goal 3)

5. FLIGHT SYSTEM

The Flight System is being system engineered and integrated concurrently with the ground segment. The improvements in the Flight System post launch primarily increased reliability and robustness, and science efficiency. The Flight System has three components that may be changed to accomplish this: 1) Configuration files 2) Flight Software, and 3) Sequencing. All three components have been used for Spitzer to contribute to accomplishing all three primary goals.

In accordance with “test what you fly” and “fly what you test” practices, Spitzer has made extensive use of (Operations) Spacecraft Test Laboratories (O/STL). These test beds provide proper fidelity and have been utilized to support more than 1500 formal and thousands more informal test activities. From the Observatory perspective, testing has ranged from simple configuration file updates to validation of long duration calibrations and science activities. Every significant science sequence has been validated in the O/STL using the high fidelity Combined Electronics (CE) Multi-band Imaging Photometer for Spitzer (MIPS), Infrared Spectrograph (IRS) or Infrared Array Camera (IRAC) engineering units. The true value of the O/STL has been in rapid response anomaly resolution and recovery, having been successfully utilized in support of eleven Observatory anomalies.

The following is a list of Flight System improvements:

1) Reduced bore sight calibration frequencies. Spitzer must perform a boresight calibration periodically to maintain pointing accuracy. Reducing these calibrations saved five hours of spacecraft calibration time per week. Analysis of absolute pointing performance enabled a change to extend the interval between calibrations to 12 hours, which has allowed science observations to run longer without being interrupted every 8 hours by pseudo-SER activities. (Goal 3)

2) Reduced Inertial Reference Unit (IRU) calibration frequencies. The IRU is part of the Pointing Control System (PCS) and must be calibrated regularly to maintain pointing accuracy. Reducing IRU calibrations saved 16 hours per month. Trending of the Gyro Calibration Filter (GCF) and all IRU calibration post-processing indicated a slow drift rate in the GCF absolute scale factors and misalignment matrix elements. This enabled reducing the frequency of IRU calibrations to once every three weeks, resulting in 13 additional hours per year to perform science operations. This equates to a 2.5% reduction in time away from science activities. (Goal 3)

3) Eliminated Wide Angle Sun Sensor (WASS) calibrations. Performing Ground-based WASS recalibration in lieu of on-orbit cal saved 1.5 hours per month. While pursuing efficiency improvements, an unexpected bias was discovered in the output current of WASS-1 and WASS-2, which had previously been unaccounted for in the WASS modeling. A new method was developed to compensate for superimposed biases and scale factors in the WASS output. This new calibration method uses pitch and roll data collected during nominal science operations to improve WASS accuracy. This improvement resulted in approximately 21 hours a year to perform science operations, thus reducing the time away from science by 4%. (Goals 1 and 3)

4) Improved IRU calibrations. Performing 3-axis IRU calibration in place of more frequent single-axis calibrations improved schedule efficiency. Prior to launch, it was recognized that the single-axis IRU calibration, performed on a daily basis by ground command in IOC and via the master background sequence in the nominal science mission, could be made more efficient. Performing it daily was a burden on IOC timeline development and the operations team. The team re-engineered the event such that all three axis could be performed in one activity, and then executed once every three days. The new three-axis calibration became the IOC standard. It was then implemented in the nominal mission sequences to improve scheduling and science efficiency. (Goals 1 and 3)

5) Optimized slew performance. Implementing a change to the pointing control system maximum torque configuration, reducing the slewing time for short slews and saving on average 3 hours of time per week. Analysis indicated that by slightly decreasing the size of the OPZ, the maximum torque threshold could be increased from 0.21 to 0.4. Nm, which in turn decreased required, slew times by 25 to 30%. (Goal 3)

6) Improved utilization of downlink time. Performing MIPS Ge:Ga anneals during downlink passes saved 168 minutes per week during MIPS operation. MIPS Ge:Ga anneals do not require any specific pointing to be performed, therefore these anneals may be performed while downlinking data.

7) Improved MMC utilization. Implemented an MMC fill-avoidance test on-board the observatory before each science observation. If the test determines that there is not enough free space on the MMC, the observatory will skip the science observation and sit idle instead. The test takes into account the predicted data volume of the observation plus some margin, an estimate of the remaining engineering data to be recorded before the next downlink and the bare minimum amount of free space we want to allow. If we were to actually fill the MMC, the observatory stands a good chance of triggering a fault-protection response. This fill-avoidance test allows us to maintain our single-fault tolerance in the downlink system while collecting larger data volumes than in the nominal case. We sacrifice single-fault tolerance with respect to individual observations while maintaining single-fault tolerance with respect to filling the MMC. (Goal 3)

6. CONCLUSION

Since Spitzer's lifetime is directly related to amount of liquid helium on board, it is important that we maximize the amount of science we can obtain. We have already made great strides in maximizing efficiency which is reflected in our projection of exceeding our five year goal.

Spitzer is in a heliocentric orbit which allows the Spitzer MOS more opportunity to contribute to the overall efficiency of the Observatory. We have achieved efficiencies of more than 90%, which is more than double any other great observatory, and with fewer personnel.

This was accomplished by MOS improvements in the Operations System, the Ground Data System and the Flight System working in concert with each other to yield operational efficiency gains. The benefit of this is to the Science Community. Gains made in managing mission risks and consequences increases reliability and robustness, this will allow operations to run highly reliably with minimal down time. Embracing automation and autonomous capabilities streamlines operations and lowers the cost to obtain science data.

Because of these improvements and our flight experience, we believe the Observatory can provide science data beyond the cryogen life time. This extended mission will be an IRAC only mission for five years after the helium runs out. This extended mission will require running the Observatory at a far lower cost, but with the same amount of observing efficiency. Increasing overall observatory efficiency and lifetime allows for more science data to be taken. All of these factors combined leads to a new challenge in running the observatory more efficiently. This will lead to a better understanding of the universe.

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