Execution of the Spitzer in-orbit checkout and science verification plan
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ABSTRACT

The Spitzer Space Telescope is an 85-cm telescope with three cryogenically cooled instruments. Following launch, the observatory was initialized and commissioned for science operations during the in-orbit checkout (IOC) and science verification (SV) phases, carried out over a total of 98.3 days. The execution of the IOC/SV mission plan progressively established Spitzer capabilities taking into consideration thermal, cryogenic, optical, pointing, communications, and operational designs and constraints. The plan was carried out with high efficiency, making effective use of cryogen-limited flight time. One key component to the success of the plan was the pre-launch allocation of schedule reserve in the timeline of IOC/SV activities, and how it was used in flight both to cover activity redesign and growth due to continually improving spacecraft and instrument knowledge, and to recover from anomalies. This paper describes the adaptive system design and evolution, implementation, and lessons learned from IOC/SV operations. It is hoped that this information will provide guidance to future missions with similar engineering challenges.

Keywords: Spitzer Space Telescope, SIRTF, IOC, calibration, checkout, operations

1. INTRODUCTION

The Spitzer Space Telescope, the fourth and final of NASA's great observatories and a cornerstone of NASA's origins program, was launched 25 August 2003 into an earth-trailing solar orbit (Gallagher, Irace, and Werner 2004; Kwok et al. 2004). The observatory is designed to probe and explore the universe in the infrared. Prior to the primary science mission, the observatory was initialized, characterized, calibrated, and commissioned during a two-phased operations approach: the in-orbit checkout (IOC) phase and the science verification (SV) phase. The objectives of the IOC phase, completed in 62.7 days, were to bring the facility on-line safely and expeditiously, verify the functionality of the instruments, telescope, and spacecraft, and demonstrate that the facility met level-1 requirements. The objectives of the SV phase, completed in the following 35.6 days, were to characterize observatory in-orbit performance, demonstrate observatory capability for autonomous operations, demonstrate the readiness of ground systems software, processes, and staffing for routine operations, and carry out early release observations intended primarily for public affairs purposes.

High-efficiency operations are extremely important for the Spitzer mission, whose lifetime is cryogen-limited. The IOC/SV operations were designed to accommodate the distributed organizational structure's ability to support a complex cryogenic flight system. Many checkout activities were inter-dependent, and therefore the operations concept and ground data system had to provide the flexibility required for a short turn-around environment. This paper describes the adaptive operations system design, implementation, and lessons learned from IOC/SV operations. It is hoped that this information will provide guidance to future missions with similar engineering challenges.

1.1 Mission Overview

The Spitzer Space Telescope (Figure 1) consists of a cryo-telescope assembly (CTA), spacecraft (S/C), and three science instruments (SIs): the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS), and the Multiband Imaging Photometer (MIPS). The SIs collectively operate over a wavelength range of 3 \textmu m to 180 \textmu m, and each consists of a cold assembly mounted in the cryostat and warm electronics mounted in the S/C bus. The CTA has an outer shell that radiates to cold space in the anti-sun direction, and is shielded from the sun by the solar panel assembly. The CTA outer shell surrounds a series of thermal shields, the 85-cm telescope, the cryostat, and the cold instruments. The S/C bus contains the subsystems required for housekeeping and control engineering: telecommunications, reaction control, pointing control, command and data handling, power, and fault protection. Because pointing control is so critical, a pointing calibration reference sensor (PCRS) is provided to calibrate the reference frame between the SIs and the externally mounted star tracker used by the pointing control subsystem (PCS). The PCRS is located in the cold focal plane and operates in the visible (0.5 \textmu m).
Unlike the conventional cold launch architecture in which the telescope, science instruments, and superfluid liquid helium tank are surrounded with a vacuum shell, Spitzer implemented a warm launch architecture in which the vacuum shell surrounds only the instrument chamber and the helium tank. This creative approach enabled significant size and mass reduction with a smaller vacuum chamber and lower cryogen consumption rate. The cryogen consumption is dominated by the instrument’s heat input in the helium bath, because the parasitic heat input is intercepted by the cooling power of the effluent helium vapor by thermally connecting the helium vent line to key cryostat components. The telescope is attached to the top of the vapor-cooled cryostat vacuum shell. The telescope was launched warm, and cooled on orbit over a period of 45 days to its operating temperature of 5.6 K.

Spitzer was launched from Cape Kennedy on a Delta 7920H launch vehicle and injected into an escape trajectory, resulting in a heliocentric orbit in which the observatory moves around the sun in roughly the same orbit as the earth (Kwok et al. 2004). The observatory slowly drifts away from the earth at an average rate of 0.12 AU/year. This orbit eliminates the effect of heat input from the earth, allowing the unique cryogenic design to achieve an expected mission lifetime of 5 years using 335 liters of superfluid helium. The average cold instrument power dissipation is 2.9 mW for IRAC, 2.3 mW for IRS, and 1.7 mW for MIPS. The detector bath temperature is 1.4 K, and the steady state outer shell temperature is 34 K. To maintain the telescope at its lowest operating temperature of 5.6 K, 5.2 mW of cryostat power dissipation is required to produce enough effluent helium vapor; a heater in the helium bath is used to make up the difference between the 5.2 mW and the cold power dissipation produced by MIPS, which requires a 5.6 K telescope to achieve maximum sensitivity. The other two instruments place less severe requirements on the telescope temperature.

The mission was designed for easy operability. To reduce operations complexity, only one instrument operates at any time. The heliocentric orbit provides an efficient observing environment, with no eclipses or occultations, excellent sky access and visibility (sun angle between 80° and 120°), continuous viewing of the ecliptic poles, and no need for station-keeping maneuvers. The drawback of this orbit, however, is that the maximum data rate drops as the observatory drifts away from the earth.

1.2 On-Board Activities in IOC/SV

Ground operations were driven by the IOC/SV timeline of all on-board activities. The first week of IOC was dedicated to successfully completing the mission critical events—launch and ascent, opening the cryostat vent line valves, initial attitude acquisition, initial communications acquisition, ejecting the telescope dust cover, and opening the cryostat aperture door. During the telescope cooldown period the infrared background noise diminished, and observations became possible at longer wavelengths. Some activities were carried out with a warm telescope, including initial functional checks and background monitoring of the cooling telescope. As the telescope approached the appropriate temperature for each instrument, first light observations were executed. The watershed event was the adjustment of telescope focus. Once this major milestone was complete, and the telescope reached its stable operating temperature of 5.5 K, each science instrument carried out its set of detailed characterization activities. Highlights of the pre-launch timeline are shown in Figure 2. Pre-launch planning and details of IOC/SV activities are described by Miles & Kwok (2002).

1.3 Campaigns

A campaign is defined as a period of continuous operation of a single instrument. The campaigns are typically short (a few hours) early in IOC and increase to as long as 3 days by the end of SV. The use of campaigns limits the number of instrument-to-instrument transitions, reduces the inefficiencies from the latency time required for the SI warm electronics to reach thermal stability, and consolidates the time that any particular science team is on real-time duty. Campaigns include activities such as uplink/downlink, instrument startup & shutdown, and routine PCS/spacecraft activities, as well as a set of unique instrument activities. In the early planning stages, each campaign was allocated 20% margin over the initial time estimate. By the time of launch, the campaigns had grown to consume most of the 20% margin, and many
Figure 2: Highlights of the pre-launch IOC timeline went over, requiring a reallocation of the timeline. One problem was that campaign durations were systematically underestimated due to inaccurate slew modeling.

As launch approached, one hour of reserve time was inserted between each pair of campaigns in the timeline. In a few places an additional 6-hour gap between campaigns was added. This reserve time gave more flexibility to make quick changes, by limiting rework due to the “domino effect” on subsequent campaigns. In addition, all celestial targets were required to be visible for three weeks following the planned start of the campaign, minimizing the chance that schedule delays would cause major rework.

2. IOC/SV MISSION PLAN

The design of the IOC/SV mission plan was dominated by two unique features of the Spitzer mission: the heliocentric orbit that affects the thermal design and the communications strategy, and the warm launch architecture whereby the telescope is outside the cryostat and radiatively cools in deep space. The key challenges of Spitzer are optical, cryogenic, and pointing control performance, which have dependencies on the performance of the three instruments, and vice versa. In addition, the mission and science operations teams faced the challenge of operating a new space observatory while safely establishing autonomous operations under very tight timing constraints. The IOC/SV mission plan progressively established Spitzer capabilities during the IOC/SV phases, taking into consideration thermal, cryogenic, optical, communications, celestial mechanics, and operational designs and constraints. The mission plan provided the ground operations team with an implementation baseline. However, realities quickly intervened making changes necessary, therefore the timeline, operations processes, and staff had to be flexible to respond to anomalies that required deviation from the plan.

2.1 Telescope Cooldown

Due to the warm launch design, the telescope required 45 days to cool down to its operating temperature of 5.6 K. During this cooldown period the infrared background noise diminished, and observations became possible at increasingly
longer wavelengths. The SIs performed their unique set of tests: first IRAC, then IRS, and finally MIPS. Some activities could be carried out with a warm telescope, including initial functional checks to demonstrate that the instrument survived launch, and warm background monitoring. As the telescope approached the operating temperature for each instrument, first light observations were executed. After reaching stable operating temperature, each SI carried out its set of detailed characterizations. During the cooldown, activities were scheduled as soon as their temperature constraint allowed, unless driven by another constraint, such as pointing performance or image quality.

The key temperature-driven activities were those allowing MIPS to assess image quality before the decision to adjust focus could be made. At \( L + 21.8 \) days, the cryostat make-up heater was activated to accelerate the boiloff of helium so that the telescope could reach the necessary operating temperature in time to support MIPS focus evaluation. Telescope cooldown was managed by use of the make-up heat to drive the telescope to the desired cool-down profile. Once the telescope reached 5.6 K, the cryostat make-up heat was adjusted as needed to keep telescope temperature less than 5.6 K for the duration of IOC and SV. Lawrence (2004) and Finley, Hopkins, & Schweickart (2004) describe this process in detail.

2.2 Focus Assessment and Adjustment
Focus assessment and adjustment activities began as soon as each of the three SIs and the PCRS could take images, continued through the adjustment of the focus mechanism, and concluded with the final focus assessment for each of the three SIs and the PCRS. IRAC and PCRS took images at first light, and roughly every two days thereafter during cooldown to measure and monitor the telescope focus as the telescope cooled. IRS and MIPS took data in their short wavelength channels as soon as the thermal background permitted. The results were used to verify parfocality, agree on a focus target position, and then to adjust the telescope to that target focus. For discussions of the focus assessment and adjustment process, see Gehrz et al. (2004) and Hoffmann et al. (2004). The planned number of focus mechanism actuations was three, however, only two moves were needed.

2.3 Focal Plane Survey
The focal plane survey (FPS) is comprised of a set of activities for each of the three SIs and the PCRS that are distributed throughout the IOC and SV periods. The purpose of the focal plane survey is to determine the mapping of celestial coordinates to pixel coordinates for each focal plane array, and relate those to the star tracker. A diagram of the locations of the fields of view in the focal plane is shown in Figure 3.

The telescope pointing frame (TPF) is defined to be the boresight of the telescope, and is determined by a combination of ground measurements of the position of the telescope boresight relative to the PCRS arrays combined with on-orbit measurements of the PCRS and the star tracker. The TPF measurement strategy began with PCRS acquisition search and localization, and then a series of telescope pointing frame calibration measurements to achieve the required star tracker-to-PCRS frame alignment accuracy. Periodic star tracker-to-PCRS alignment calibrations were executed every 8 to 10 hours to maintain alignment in the face of thermo-mechanical drifts, which are small than 1 arcsec on this timescale.

The approach for the focal plane survey is to execute a series of coarse surveys for each array, followed by a series of fine surveys. The coarse surveys have relaxed requirements, so that they are not driven by the need to change focus or to have a stable, cold telescope, but they provide enough pointing capability to proceed with other early activities. Once the telescope is focused and the focal plane is stable, a series of fine surveys are executed. The fine surveys provide the ultimate pointing capability for each array. The coarse survey and fine survey strategies and procedures are similar, except
that the coarse surveys typically require fewer iterations. Bayard et al. (2004) discuss the details of the focal plane survey process.

2.4 Communications
The spacecraft communicates with the Deep Space Network (DSN) using either a high gain antenna (HGA) or a low gain antenna (LGA). During IOC and part of SV, the DSN provided nearly continuous coverage. Dust cover ejection and aperture door opening (mission critical events) were covered by two stations for redundancy.

The LGA allows a maximum data rate of 88 kbps with a very broad antenna pattern, until L+24 days when it drops to 44 kbps. The HGA allows a maximum data rate of 2.2 Mbps with a narrow antenna pattern. The LGA is used during safemode, and during the early portion of IOC when pointing the HGA to earth would violate the sun constraints due to the early sun-observatory-earth geometry. Spitzer was first able to acquire HGA link on day 20.

2.5 Routine Activities
Several periodic engineering activities are routinely performed on the observatory. A periodic inertial reference unit alignment calibration and update was performed every 24 h ± 2 h. After a few months of on-orbit experience, the update frequency was changed to once per two weeks.

The periodic PCRS-to-star tracker alignment filter update maintains knowledge of the star tracker-to-telescope frame alignment in the presence of thermal and mechanical drift. With a star on one of the PCRS detectors, the on-board alignment filter updates the star tracker-to-telescope alignment estimate. PCRS-to-star tracker calibrations are scheduled every 8 hours ± 2 hours. Again, based on on-orbit experiences the interval was lengthened to ~12 hours.

The on-board ephemeris file is updated every 2 weeks, and flight software diagnostics are carried out on a daily and weekly basis.

2.6 Ground System Checkout
In addition to the flight system, the capabilities of the ground system were demonstrated during IOC and SV. This included demonstrations of sustained autonomous operations and pipeline data processing capabilities as well as investigations into optimal observing strategies (Dodd et al. 2004).

2.7 IOC/SV Ground Operations
Ground operations during IOC and SV were intense compared to nominal operations. Many on-board activities were dependent on the results of precursor activities. Some activities could be carried out early with a warm telescope, while others had to wait for the telescope to cool down. Many engineering calibrations with periodicity requirements had to be maintained in the schedule. Rescheduling and resequencing had to be flexible and rapid to maximize the productive use of flight time and cryogen usage. The challenge was to determine how much flexibility was needed in IOC operations, given the workforce constraints. Flexibility and the ability to make activity modifications quickly had to be infused into the operations design to complete the work in the allotted 90 days. An IOC operations implementation plan was developed to assure that ground operations processes would be in place to capture and analyze engineering and science data obtained during this intense mission phase. In many cases, the interval between on-orbit activities was set by the amount of time required to analyze the results of the first activity before executing the follow-on.

2.8 IOC/SV Ground Operations Strategy
Because IOC and SV were event-driven, a real-time communications strategy was chosen. The uplink sequences were transmitted using the "load and go" approach with relative-time sequencing. Time between events was spent with the spacecraft antenna pointed toward earth to monitor observatory conditions. Since there was 100% DSN coverage, events were shifted as needed. Once the observations were complete a ground command was sent to play back the data. A campaign is built as a single command sequence, so campaigns are single events for the purposes of timeline planning.
2.9 Organizational Structure

The Spitzer flight operations organization has two components—the mission operations system (MOS), where the engineering functions are performed, and the Spitzer Science Center at Caltech, where the science operations are performed. The MOS is a distributed system with the teams at the Jet Propulsion Laboratory, Lockheed Martin in Denver, and distributed principal investigator (PI) sites. Figure 4 shows the organizational structure.

2.10 Replan Team

The replan team was an IOC/SV-only operational team. Since the strategies needed throughout IOC and SV were unique, and limited the ability to have a common design with nominal operations, the replan team supported the rest of the ground system by providing quick-response system engineering services, incorporating requests for new or modified activities in the timeline, and maintaining the integrity of the mission plan while maximizing observatory efficiency. There were 7 people on the replan team to accommodate 7 days per week coverage during IOC/SV.

3. IOC/SV OPERATIONS DESIGN AND DEVELOPMENT

The IOC/SV design was documented in the IOC/SV implementation plan. This document defined the following IOC strategies:

1. 24/7 ground antenna coverage for ground commanding/receipt of data;
2. Instrument/engineering sequences built in relative time to reduce sequence rebuilds due to start time changes;
3. Real-time commanding (load and go) of all sequences and playbacks to provide maximum flexibility;
4. Telescope cooldown managed by using make-up heat to drive the telescope to the desired cool-down profile;
5. Focus adjust to refocus telescope in three moves (if needed) supported by a team of experts with a substantial amount of pre-launch planning;
6. Focal plane survey throughout IOC/SV to continually increase instrument pointing accuracy by updating a configuration file used by the on-board attitude control software;
7. Periodic PCS calibrations;
8. Operational support teams operated primarily on prime shift, except for the flight control team which worked around the clock, and instrument teams who were on-shift when their data was received on the ground;
9. Background master sequence loads would be 1-2 weeks in duration with the instrument campaigns loaded into the sequence engines as “load and go” sequences;
10. Simulation of all unique IOC activities on the operations software test lab (OSTL) before on-board execution.

The difficult question to determine when developing the IOC operations concept was how much flexibility, robustness, and quickness in response was needed. The decision was to be as flexible as possible, while working most of the teams 7 days a week, prime-shift only (except for the flight control team and instrument teams). The replan front end would be quick and flexible, giving the teams downstream as much time as reasonable to do their work. The IOC operations de-
sign started by walking through the timeline to understand the plan, an then determine what nominal processes could be used and what unique new processes would need to be developed. The goal was to transition to nominal processes prior to completing IOC/SV, thus validating that the nominal processes worked prior to the start of the science mission.

IOC sequences were built by the Spitzer Science Center instrument team members and science planners, integrated into sequences by the JPL mission sequence team, then validated on the operations software test lab (OSTL) at Lockheed Martin. This was a difficult task in the distributed environment, especially since the OSTL was being heavily used by the assembly, test, and launch operations team prior to launch. Sequence validation took longer than expected (11 months), however, it turned out to be very important to the fidelity of the timeline as these sequences grew significantly.

Training exercises were carried out, including tabletops and rehearsals of the two complex ground processes, focus adjust and focal plane survey. A series of 8 replan training exercises allowed the replan team to practice making quick changes to the timeline. A launch delay provided an opportunity to build and test an IOC/SV status website and to complete an initial build of all sequences through the end of IOC. SV sequences were built after launch. There were 32 changes made to the IOC/SV timeline from the time it went under configuration management (in April 2002) to launch.

3.1 Transition from IOC to SV

One of the big challenges was to transition between the real-time IOC operations environment to the nominal operations mode, where the observatory operates autonomously for one week at a time with two planned 1-hour downlinks per day. This operational transition was to occur in SV, approximately two weeks after completing IOC. The transition strategy employed was to sequence the last three SV loads (about a week in duration) using the nominal operations methodology, but leave a 12-hour gap following each load to accommodate late-breaking real-time activities required to complete SV. This approach worked extremely well with some MIPS SV spillover into the nominal science phase.

In addition, responsibility for instrument operations was transferred from the principal investigator team for each SI to the respective science center instrument support team when IOCs and requirements were met. The transfer was assessed and approved via a transition review. The three science instruments transitioned at different times, and the on-board sequence operations and ground team transitions were independent of each other.

3.2 IOC Uplink Strategy

Spitzer's nominal uplink strategy consists of a 30-day sequence generation cycle. The master sequences are 7 days in duration and absolute-timed. Slave sequence durations are campaign-dependent and are relative-timed. There is one 1-hour DSN pass per day with 25 minutes allocated to uplink. Meeting schedules are planned during nominal work hours.

To accommodate the unique needs of IOC/SV, an IOC uplink strategy was formulated. The sequence generation cycle, while 30 days for the nominal mission, was shortened to 15 days for IOC. The faster cycle was aided by generating and verifying all 8 IOC loads (a load is about a week of activities) in the OSTL prior to launch. The on-board master/slave sequence strategy was also altered to allow more flexibility. The IOC uplink strategy generated a dummy master 2-3 weeks in duration and all activities were built in the form of load and go sequences to provide maximum flexibility for start times and parameter updates.

3.3 IOC Downlink Strategy

Spitzer had nearly continuous ground antenna coverage for the duration of IOC/SV, so downlinks could be scheduled at the convenience of the campaign designers. The data pipeline was expedited to make sure that the science teams received their data in a timely manner, since many of the results could/would have an impact on near-term planned and unplanned activities.

3.4 IOC-Unique Meetings

IOC decisions were required to be made in a rapid manner to accommodate necessary adjustments to the IOC plan. To insure communications between distributed teams two meetings were added to the Spitzer meeting schedule for IOC:

- IOC replan meeting. This meeting was scheduled in the morning 7 days a week for the purpose of reviewing change requests and agreeing on a strategy for developing a new IOC/SV timeline, as required.
• IOC tag-up meeting. This meeting was scheduled in the afternoon 7 days a week for the purpose of reviewing the new IOC/SV timeline and receiving formal approval for its implementation.

These and most other meetings during this period were held as teleconferences so that team members from across the country could participate efficiently.

3.5 IOC/SV Processes

The processes developed for the nominal science operations phase were not able to support IOC/SV due to interdependencies of on-board campaigns as a function of telescope temperature, and the flexibility needed to make quick changes to the timeline. Thus the following unique processes were developed to complete the IOC tasks.

The following unique ground processes were developed for IOC/SV:

• IOC 15-day sequence development process – This is the nominal IOC sequence development process.

• IOC 3-day update process – This process was created to accommodate changes in the timeline such as block or activity substitution, re-ordering of campaigns, modifications of sequences (including changes in targets), and addition of activities within 3 days of receipt of the request, provided that the update does not require re-simulation on the OSTL.

• IOC rapid turn-around process – This process provides for late update to flight sequences of a limited set of instrument parameters for execution within the next day. In general, the need for the rapid turn-around process was identified well before its actual use so that the operations teams were prepared in advance for these events.

• Focal plane survey process – Based on engineering analysis from an activity, determine updated field-of-view offsets on the telescope focal plane. Build and test the frame table that defines the on-board instrument pointing frames. Fifteen frame table updates were initially planned; seventeen were performed in IOC/SV.

• Focus adjust process – This process includes image quality assessment of the three instruments and the P CRS, followed by determination of the amount and manner to move focus, and then focus confirmation.

• IOC replan process – This process allowed for anyone on the team to initiate or modify an activity in the timeline. The change requests were submitted via a web-based form. Requests were discussed in the morning IOC replan meeting, to afford everyone on the team an understanding of the pending changes. The replan team led discussion of all the issues associated with the change, and affected parties had an opportunity to provide inputs. During the day, the changes were worked in detail and implemented into the timeline. The results were presented at the afternoon IOC tag-up meeting, and a request was made for formal approval to baseline the new IOC/SV timeline. The IOC/SV timeline was maintained under rigorous configuration control. The replan process was usually completed within a day, although some complex issues spanned more than one day.

3.6 IOC/SV Replan Tools

The IOC/SV timeline, including all constraints and dependencies, was maintained using Microsoft Project. The timeline data were exported to Microsoft Excel format for dissemination to the teams, since the Project format was cumbersome to view, and only a few individuals maintained use licenses. MS Excel also allowed the inclusion of useful calculations such as multiple time formats, as well as several worksheets with FPS process flow and timing information that would automatically update following an import of data from MS Project. Because the very complex FPS process was intricately laced throughout the IOC/SV period, the spreadsheets allowed us to view the process and seamlessly maintain workforce and shift plans as the timeline evolved. Neither MS Project nor MS Excel had an option that provided good overall visualization due to the extensive and detailed nature of the timeline, therefore a visual version of the timeline was created using Adobe illustrator. An example of a segment of the visual IOC timeline is shown in Figure 5. Although it was very popular, maintaining the visual timeline was a labor-intensive process, and therefore updates were limited. A fourth program, called Activity Plan Generator (APGEN), was utilized to do rules checking on the Excel timeline, i.e., ensure that periodic calibrations were scheduled appropriately, and that a ground station was available for scheduled downlinks. APGEN is a program developed at JPL by the Advanced Multi-Mission Operations System (AMMOS).
4. FLIGHT OPERATIONS EXPERIENCE

The replanning of IOC activities worked extremely well. The replan team consisted of engineers with talents that were unique and complementary. The training exercises demonstrated that the replan team worked well together and that everyone had a "can do" attitude. As time progressed, the team became more efficient to the point where one request came in at 2 PM, was implemented into the timeline, and went through the change board at 3 PM. The campaign was tested in the OSTL in the late afternoon, and was executed on the spacecraft that night.

The 3-day update process also worked well. The instrument teams planned their sequence of campaigns well enough that they had time, within the limitations of this process, to evaluate instrument data, determine what changes would be necessary in upcoming campaigns, and fold those changes into the campaign sequences. The IOC rapid turnaround process was only used a couple of times by the MIPS team, with advance preparation as indicated above.

The telescope cooldown followed the nominal pre-launch prediction pretty well. The nature of the cold telescope's thermal emission is such that even a small (~1 K) temperature change could produce a major change in the infrared background at long wavelengths. Thus the actual cooldown profile required some adjustments to the timeline, but there was no need for major replans due to on-orbit performance in this area. The focus adjust process proceeded according to plan, except that only two focus moves were performed to meet the requirement, while three moves were planned.

The most complex activity during IOC/SV, the focal plane survey, represented the single greatest risk to the integrity of the IOC/SV timeline. Overall it went very smoothly, and proceeded largely according to plan. As campaigns moved later in the timeline, the focal plane survey ground data processing and analysis time were squeezed and often had to be performed during second and third shifts or weekends. A few days prior to each frame table update the focal plane survey system engineer reviewed the frame table update schedule, which was maintained as an automated worksheet in the MS Excel timeline. This worksheet kept track of allocated times for data processing, data analysis, and generation of a new frame table update product. Between email and meetings, the focal plane survey system engineer received revised up-

Figure 5. Sample of the visual IOC timeline covering days 30 to 45
dates to these time allocations and predictions. Original data analysis time allocations were quite conservative, providing built-in margin that could be used to achieve schedule flexibility. However, the time required to review an updated frame table was often longer than originally planned.

4.1 Observatory Anomalies During IOC

Although the overall IOC operations went extremely well, the observatory had its share of minor anomalies that hindered the progress of IOC. These events included a longer observatory 'cool-down' duration than planned, forcing a minor delay in the start of two MIPS campaigns, multiple safemode/standby mode entries, and a stand-down period due to solar storm activity.

First safemode entry: 8/25/03 – After launch and initial DSN acquisition, the spacecraft went into safemode. The star tracker failed to acquire a valid position within a timeout period. The conclusion was that the star tracker was turned on too early, and was confused by stray light from the nearby earth and/or the contamination cloud that persisted for a short period following ascent. Once these conditions passed, the star tracker was able to acquire autonomously. No actions were required, other than the nominal safemode recovery procedure. Safing lasted 14 hours.

Second safemode Entry: 8/27/03 – The observatory entered safemode during the momentum management checkout due to higher than expected drag torque on reaction wheel #2. Safing lasted 4 days. The Project decided to stay in safemode to carry out two mission critical events, dust cover ejection and aperture door opening.

First standby mode entry: 10/23/03 – The observatory suddenly entered standby mode during the execution of the MIPS-J campaign. Standby entry was caused by a global variable corruption due to interrupting tasks in the MIPS flight software. The observatory was in standby mode for 10.5 hours.

Solar storm stand down: 10/28/03 – The observatory had to stand down for 2.4 days to protect against solar flare radiation from the solar storm of the (still young) century. Another 2 days was spent carrying out solar storm recovery procedures for the science instruments.

3rd safemode Entry: 11/12/03 - The observatory entered safemode during execution of the IRAC-V campaign. Incorrect momentum check fault protection parameters were uplinked just prior to the event. The new parameters were based upon pre-launch analysis, not on the existing observatory configuration.

4.2 Timeline Changes During Flight

The replan team accepted 62 change requests after launch and incorporated them into 33 released updates to the IOC/SV timeline. Many activities were added and only a few were reduced or deleted. Figure 6 shows how the instrument campaigns unfolded in flight. The diamonds show the pre-launch planned time of each campaign, the squares show the actual time the campaigns were executed, and the triangles show the delay in flight execution of each campaign relative to the pre-launch plan.

A summary of flight time statistics is shown in Figure 7. The timeline is divided into a series of periods, as denoted at the top of each column. The first row of data shows the total duration of the specified period, and subsequent rows shows the time spent carrying out activities for the various observatory systems. The last three rows show the total time spent carrying out activities, the idle time, and the efficiency, which is the ratio of the two. A comparison of Figure 7 to Figure 2 shows that the reserve time scheduled in the pre-launch plan was needed and used effectively in flight.

4.3 Lessons Learned

1. At least 20 months needs to be provided to develop IOC/SV operations prior to launch and the experts who designed IOC should be retained for IOC operations.

2. Complex interleaved ground activities should be written as individual processes and have independent design reviews and readiness tests. Good systems engineering practices (i.e. checklists, process flow diagrams, and contingencies) should be applied. They can provide greater control and insight during operations.

3. Relative-time sequencing is the key to flexibility.
4. Reserve time should be distributed throughout a timeline in order to ensure that a complex, interleaved set of dependent activities is robust against unplanned anomalies. One hour of reserve was added behind every campaign and six hours weekly to allow the timeline to slip without having to extend the phase.

5. Tools must have a simple way to model dependencies, since the planning process must allow a rapid, frequent response to changes and anomalies. Use of the off-the-shelf software (i.e. Excel) allowed the replan team to focus on process design and timeline planning rather than tool design and testing. Excel is a flexible tool for passing data in human-readable form, and is useful for linking timeline information to schedules and diagrams.

6. Allow for frequent communication between teams and team members. The replan team required all disciplines to be able to recommend solutions at a rapid pace. The IOC/SV website with access to all important documentation, tools, forms, useful links, and daily status was one stop shopping for the distributed teams. A dedicated replan war-room was invaluable for maintaining focus, rapid communications, and a centralized organization.

7. Quick replanning allows for other teams downstream the standard amount of time to do their jobs.

Figure 6. IOC/SV Activities plotted against time of execution (left), and delay relative to pre-launch plan (right)

<table>
<thead>
<tr>
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Figure 7. IOC/SV as-flown timeline statistics
8. Test and training exercises provide invaluable experience. Spitzer performed eight replan training exercises prior to launch, starting simple and ending with more challenging situations. Tabletop training exercises were chosen to exercise the team's decision-making capabilities.

9. Phased transition from IOC to SV to nominal operations allows the team to get up to speed smoothly. We had team responsibilities changing as well as the change from relative time sequencing to absolute. Keep the IOC replan team on during transition.

10. Co-location, clear lines of authority and responsibility, and the fact that the key IOC team members had no other project responsibilities during that period were also key factors in the success of IOC/SV.

5. CONCLUSION

The IOC/SV plan was an aggressive program to bring the Spitzer Space Telescope online within programmatic constraints, built with an approach that mitigated risk to the schedule, and provided the necessary data calibrations and characterizations to make effective use of the observatory as soon as the primary science mission began 98.4 days after launch, only 8.4 days later than planned (note that 4.4 of those days were lost to the solar storm). The success of the IOC/SV activities allowed us to meet our pre-launch objective of having the early release observation press conference on December 18, 2004, less than four months after launch.

IOC/SV operations provided a significant and unique set of challenges. Proper design for the Observatory IOC and SV phases required a dedicated team of engineers and scientists. The operations strategy needed for the IOC/SV phases did not allow a common design with nominal operations.

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