Spitzer Space Telescope In-Orbit Checkout and Science Verification Operations

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Introduction

Spitzer Space Telescope, the fourth and final of NASA's great observatories, and the first mission in NASA's Origins Program was launched 25 August 2003 into an Earth-trailing solar orbit. The observatory was designed to probe and explore the universe in the infrared. Before science data could be acquired, however, the observatory had to be initialized, characterized, calibrated, and commissioned. A two phased operations approach was defined to complete this work. These phases were identified as In-Orbit Checkout (IOC) and Science Verification (SV). Because the observatory lifetime is cryogen-limited these operations had to be highly efficient. The IOC/SV operations design accommodated a pre-defined distributed organizational structure and 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 and evolution, implementation, and lessons-learned from the completion of IOC/SV.

Mission Overview

The Spitzer observatory (Figure 1) consists of a cryo-telescope assembly (CTA), spacecraft (S/C), and three science instruments: the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS), and the Multiband Imaging Photometer (MIPS). The science instruments collectively operate over the wavelength range 3 μm to 180 μm, and each consists of a cold assembly mounted in the cryostat and warm electronics mounted in the Spacecraft 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.

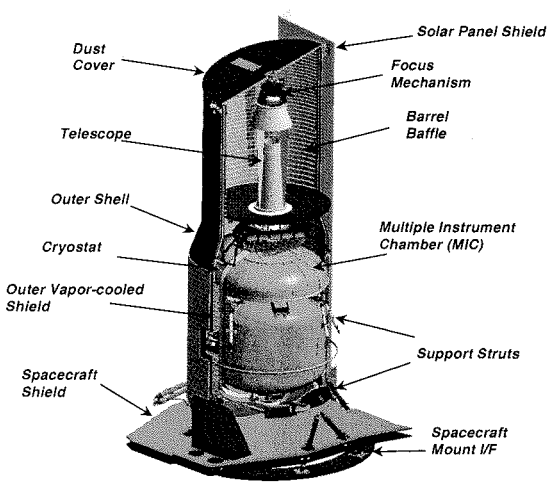

Figure 1 – Spitzer Observatory

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. 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 earth trailing solar orbit also eliminates the need for station-keeping maneuvers.

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. The telescope is attached to the top of the vapor-cooled cryostat vacuum shell. With the telescope launched warm, it was expected to take approximately 45 days to cool to the operating temperature of 5.6 K. Effluent helium vapor from the cryostat is used to keep the telescope cold.

The mission was designed for easy operability with the heliocentric orbit providing no eclipses or occultations, excellent sky access and visibility (sun angle between 80° and 120°), and continuous viewing of the ecliptic poles. To reduce operations complexity, only one instrument operates at any time.

Flight Operations Organization

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 2 shows the organizational structure.

The Replan Team was added to the list of operational teams because the strategies needed throughout IOC and SV were too unique to have a common design with nominal operations. System Engineering had to provide a quick response ground system that could meet the challenges laid out by the onboard IOC/SV Mission Plan.

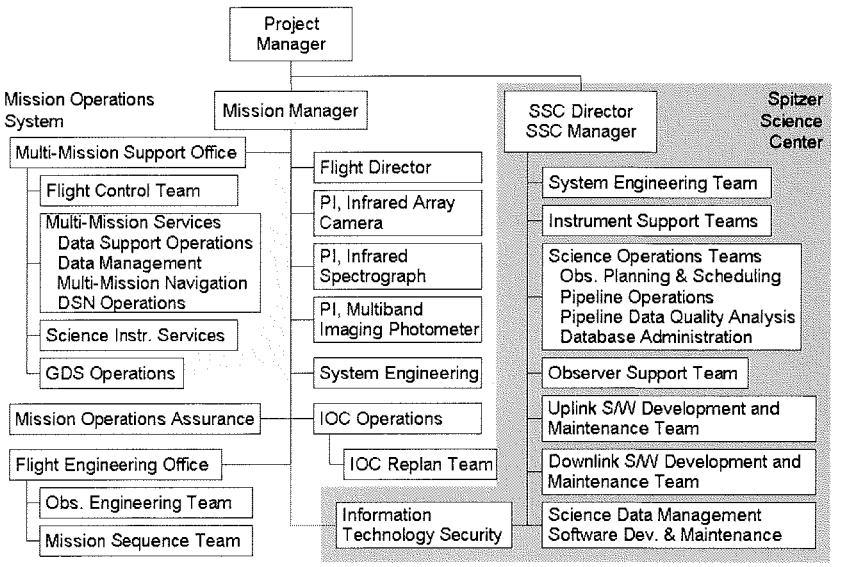

Figure 2 – Spitzer Project Organization

Definition of IOC and SV

The IOC phase, nominally planned for the first 60 days after launch, was dedicated to bringing the Facility on-line safely and expeditiously verifying the functionality of the instruments, telescope, and spacecraft, and demonstrating the Observatory meets level 1 requirements. The SV phase, nominally planned for the 30 days following IOC, was dedicated to characterizing Observatory in-orbit performance, demonstrating Observatory capability for autonomous operations, conducting early release observations, commissioning

instrument Astronomical Observing Templates and ensuring the ground systems software, processes, and staffing were sufficient to commission the Facility for routine operations

IOC/SV Ground Operations Expectations and Strategy

Ground operations during IOC and SV were expected to be 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 scheduled through both phases. Rescheduling and re-sequencing had to be flexible and rapid to maximize the productive use of flight time.

Because IOC and SV were event-driven, a real-time communications strategy was chosen. The uplink sequences were transmitted using the "Load & Go" strategy with time between events spent with the spacecraft antenna pointed toward earth. Since there was 100% DSN coverage, events were shifted as needed. Once the observations were complete a ground command was sent to downlink the data.

On-Board Activities in IOC/SV

Ground operations were driven by the IOC/SV time-ordered listing (TOL) of on-board activities. Figure 3 shows some highlights from the IOC/SV timeline. The first week of IOC was dedicated to successfully completing the mission critical events – ejecting the telescope dust cover and opening the cryostat aperture door. During the telescope cooldown period the infrared background noise diminished, and

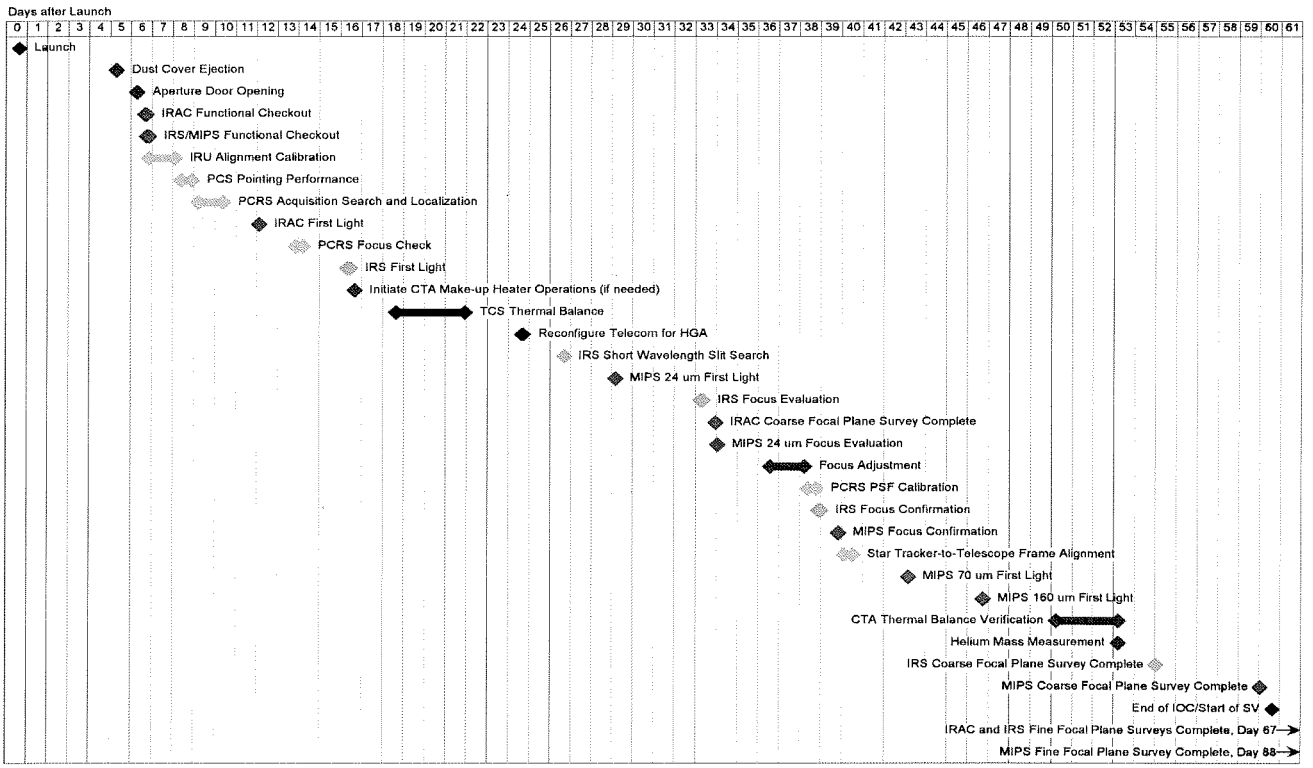

Figure 3 – IOC/SV Timeline Overview

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.

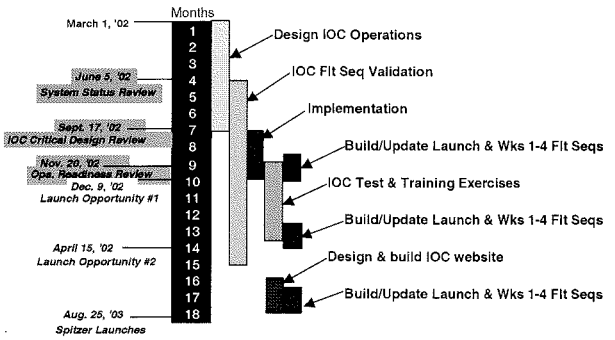

Figure 4 – IOC/SV Operations Development Timeline

Design and Development of Ground Operations

The design and development of IOC ground operations started only 9 months from the first planned launch (December '02). Figure 4 shows the development timeline as it occurred. An IOC Working Group was formed and met twice a week to develop the unique processes and validate them against realistic scenarios. A Critical Design Review was held in September to review the IOC/SV operations design, and details were provided in a written IOC/SV Operations Plan.

Two months later the Operational Readiness Review was held. IOC operations were declared "yellow". In December '02 the launch slipped to April'03, allowing 4 months to be spent performing training exercises including tabletops and rehearsals of the two complex ground processes (Focus Adjust and Focal Plane Survey). In addition, there were eight replan training exercises that allowed the Replan Team to practice making quick changes to the timeline. No end-to-end training exercise was performed due to resources spent on late flight software updates. The launch delay to August'03 provided a window of opportunity to build and test an IOC/SV status website and to complete an initial build of all sequences through IOC.

As the ground plans were being developed, the science and engineering campaigns were built and validated through the Operations Software Test Lab. The campaign durations tended to grow beyond the original 20% design margin allocated. Control over time allocation was enhanced by adding strategically placed reserve time in the timeline, and reallocating the reserve time as needed using the standard configuration control process. By August 2003 the planned

Pre-Launch	Pre-focus IOC	Focus	Post-focus IOC	SV	Totals
	(days)				
Duration	36.56	1.88	23.56	30.00	92.00
CTA	0.21	0.13	3.07	0.00	3.41
IRAC	7.37	0.35	4.77	7.06	19.55
IRS	3.28	0.00	4.29	7.31	14.88
MIPS	0.92	0.00	3.55	8.50	12.97
PCS	10.01	0.36	3.09	1.86	15.33
SC	2.94	0.00	0.13	0.02	3.08
Ground	0.41	1.02	0.19	0.08	1.71
Total Activities	25.14	1.87	19.08	24.83	70.92
Margin/Reserve	11.42	0.01	4.48	5.17	21.08
Efficiency	69%	99%	81%	83%	77%

Figure 5 Pre-Launch IOC/SV Time Allocations

IOC duration was 62 days and the SV duration was 30 days. Figure 5 shows how the time was allocated in IOC and SV.

IOC/SV Processes

The processes developed for the nominal science operations phase were not able to support IOC/SV due to inter-dependencies 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.

IOC 20-Day Sequence Development Process provided the capability to update campaigns (activity groupings) as well as the background sequence.

IOC 3-Day Update Process allowed teams to change a campaign sequence within 3 days of start of execution providing the update does not require re-simulation.

IOC Rapid Turn-around (24 hour) Process allowed a late update to a limited set of instrument parameters to flight sequences expected to execute within the next day.

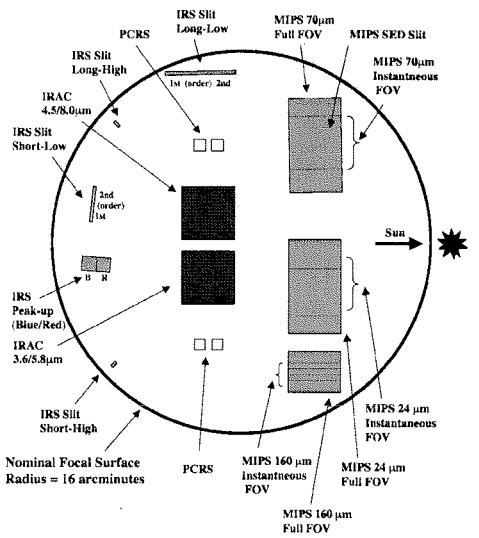

Figure 6 – Nominal Field-of-View Locations Projected on the Sky

Focal Plane Survey (FPS) Process was singled out as its own process because of its complex inter-dependent activities (on-board and ground) that continued throughout IOC/SV. The goal of the FPS was to map the pixel coordinates of each instrument focal plane reference frame (shown in Figure 6). There are 23 prime frames and 56 relative frames maintained in the on-board frame table. The FPS was iterative in order to beat down the errors to meet the pointing accuracy requirements for each aperture. Fifteen frame table updates (FTUs) were initially planned; seventeen were performed in IOC/SV.

Focus Adjust Process was a short process that required a series of ground activities (analysis and decisions) in order to achieve the best focus for all the instruments. This process was repeated until the Observatory met the image quality requirements. Focus assessment was carried out by a series of IRAC and PCRS observations scheduled roughly every two days starting at L+11 days, leading up to the focus adjustment event. The images were analyzed on the ground, and focus changes were tracked as the telescope cooled. IRS and MIPS focus assessment images were taken a few days prior to the actual focus adjustment because these two instruments observe at longer wavelengths and needed a colder telescope. They were also less sensitive to focus errors. Armed with data from all three science instruments and the PCRS, the best common focus position was determined and then the focus

adjustment was made. The focus adjust was planned as a series of three moves, each followed by an IRAC image to monitor the change.

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 in the middle of each load to accommodate any new real-time activities required to complete SV. This worked overall with some MIPS SV spillover into the nominal science phase.

Other ground operations transitions occurred here also. Responsibility for instrument operations from each Principal Investigator Team was transferred to the respective Science Center Instrument Support Team Lead when IOC requirements were met (via a transition review). The three instruments transitioned at different times. The on-board sequence operations and team ground transitions were independent of each other.

Observatory Anomalies during IOC

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 duration (from planned) Observatory 'cool-down' causing a minor delay in the start of MIPS campaigns, Safemode/Standby mode entries, and a period of 'Stand-Down' due to solar storm activities. Highlights are described below.

1st Safe Mode Entry: 8/25/03 – After launch and initial Deep Space Network (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 recovery from safe mode. Safing lasted 14 hours. The two mission critical events (dust cover eject and aperture door open) were performed during this safe mode entry.

2nd Safe Mode Entry: 8/27/03 -The observatory entered safe mode 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 safe mode to carry out both the dust cover ejection and aperture door opening.

Standby Mode Entry #1: 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 management issue 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 flares from the solar storm of the century. Another 2 days was spent carrying out solar storm recovery procedures for the science instruments.

3rd Safe Mode Entry: 11/12/03 – The observatory entered safe mode 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.

Timeline Changes During Flight

The Replan Team accepted 62 change requests post-launch and incorporated them into 33 different versions of the IOC timeline. Many more activities were added and only a few were reduced and or deleted. Figure 7 shows how the instrument campaigns unfolded in flight. The blue diamonds show the pre-launch planned time of each campaign, the green squares show the actual time the campaigns were executed, and the pink triangles show the delay in flight execution of each campaign relative to the pre-

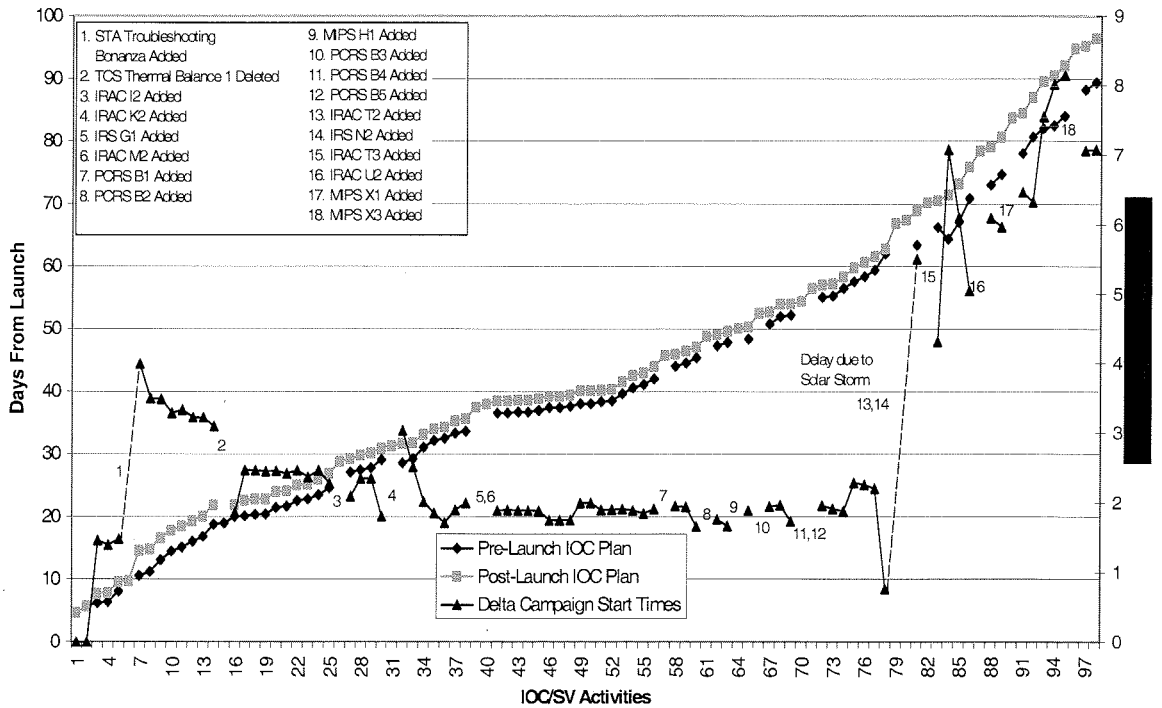

Figure 7 – IOC/SV Activities Plotted Against Time of Execution on the Left, and Delay Relative to Pre-Launch Plan on the Right

launch plan.

A summary of flight statistics is shown in Figure 8. A comparison of Figure 8 to Figure 5 shows reserve time scheduled in the pre-launch plan was needed and used effectively in flight.

IOC Ground Operations

The replanning of IOC activities worked well. The Replan Team consisted of engineers on the project with

talents that were unique to each other, but complementary. The training exercises showed that the Replan Team worked well together and everyone had a "can do" attitude. As time progressed, the team became more efficient to the point where one request came in at 2 p.m., was implemented into the timeline, and went through the change board at 3 p.m. The campaign was tested in the testbed in the late afternoon, and was executed on the spacecraft that night.

Flight Stats	Pre-focus IOC	Focus	Post-focus IOC	SV	Totals
	(days)				
Duration	38.46	1.90	22.38	35.54	98.29
CTA	0.24	0.05	2.99	0.00	3.28
IRAC	8.37	0.36	5.29	7.92	21.94
IRS	3.25	0.00	4.72	10.12	18.09
MIPS	0.95	0.00	4.16	10.98	16.09
PCS	11.51	0.92	3.67	2.40	18.50
SC	2.08	0.25	0.12	0.06	2.50
Ground	0.74	0.32	0.19	0.14	1.39
Total Activities	27.14	1.90	21.14	31.62	81.80
Idle Time	11.32	0.01	1.24	3.92	16.49
Efficiency	71%	100%	94%	89%	83%

Figure 8 – Flight Time Statistics

The 3-Day Update Process also worked well. The Instrument Teams usually knew in advance the effects of data on future campaigns such that the 3 day turnaround was responsive enough.

The IOC Rapid Turnaround Process was only used a couple of times by the MIPS Team.

The Focus Adjust Process proceeded according to plan, except that two focus mechanism moves were performed to meet the requirement, where three moves were planned.

The Focal Plane Survey was by far the most complex activity during IOC/SV, and 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 Plan Survey ground data processing and analysis time were squeezed and often had to be performed during 2nd shift or weekends. A few days prior to each Frame Table Update the Focal Plane Survey System Engineer would review the Frame Table Update schedule spreadsheet which 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 could get revised updates to time allocations and predictions. Original data analysis time allocations were quite conservative, providing built-in margin that could be used to achieve schedule flexibility. Generally, instrument analysis time could have been shorter but the time required to review an updated frame table was often longer than originally planned.

IOC/SV Development Challenges

Challenge #1 was developing IOC ground operations starting 9 months prior to launch with only an on-board plan in place.

Challenge #2 was allocating design margin in the timeline, while meeting programmatic schedule goals. The first validated campaigns showed that the original allocation of 20% was not enough.

Challenge #3 was determining the length of campaigns without accurate slew modeling. Slew times were not accurately known and estimates were too low. The flight software and models that were originally due

two years prior to launch came in 6 months prior to the December launch. Slew model accuracy was needed 18 months prior to launch.

Challenge #4 was maintaining a workable pre-launch sequence development schedule. One of the teams had difficulty delivering their sequence products.

Challenge #5 was determining how much flexibility was needed in IOC operations, given the workforce constraints. The flexibility and quick ground response were key drivers in the operations design.

Challenge #6 was getting enough testbed time to test the IOC flight sequences. This was because the flight software and ground software stabilized very late.

Challenge #7 was changing the complex IOC timeline with ground and flight constraints quickly and accurately. During development there was no time to develop new tools.

Challenge #8 was transitioning between real-time IOC operations to weeklong autonomous sequences.

Lessons Learned

Lesson #1: Commissioning a telescope is likely to involve several complex, interdependent processes. The planning process should be designed to make use of whatever tools are needed for the entire mission, and not just address the science planning needs alone.

Lesson #2: Tools must have a simple way to modeling dependencies. This is needed because the planning process must allow a rapid, frequent response to onboard sequence glitches. Use of the off-the-shelf software (i.e. EXCEL) allowed the IOC Team to focus on process design and timeline planning rather than tool design and testing. EXCEL is a fairly flexible tool for passing data in human-readable form, and is especially useful for linking timeline information to updateable schedules and diagrams. These can then be distributed along with the timeline to ensure rapid and accurate communication among operations personnel.

Lesson #3: 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 operations. For Spitzer, this proved invaluable.

Lesson #4: Margin should be distributed throughout a timeline in order to ensure that a complex, interleaved set of dependent activities is robust against unplanned anomalies.

Lesson #5: Complex interleaved ground activities should be written as individual processes and have independent design reviews and readiness tests. Good systems engineering practices should be applied to even the smallest processes (i.e. checklists, process flow diagrams, and contingencies). They can provide greater control and insight during operations.

Lesson #6: Have all participants in a process participate in testing, no matter how small their role appears to be. The Pointing Control Reference Sensor Team (PCRS) was not well integrated into Focal Plane Survey process design and testing. As a result several PCRS-related processes were modified during operations, and there were a few failures that might have been avoided with more rehearsals.

Plans/Approaches/Strategies That Made Spitzer IOC/SV Successful

- An IOC Working Group was the forum used to quickly design and develop IOC/SV operations. The IOC Architect, IOC Lead, Focal Plan Survey Lead and a few other members of the Working Group went on to become the Replan Team and work operations.
- A "top-down" approach was taken to designing IOC/SV operations. It allowed us to capture all level of details needed to design the ground system and MOS for IOC. Nominal processes were used where possible.
- We required science campaigns be built in "relative time" with viewing targets "in view" for three weeks. This maximized schedule flexibility allowing the timeline to shift with no additional rework.
- We strategically placed reserve in the timeline. Since the campaign estimates were poor, one hour of reserve was added behind every campaign and six hour chunks of reserve were added weekly to allow the timeline to slip without having to extend the phase.
- Eight replan training exercises were performed prior to launch, starting simple and ending with an extremely challenging situation to resolve. We were limited to tabletop format, due to the heavy load on the observatory and testbed.
- The Replan Team operated in a war-room a team member could be reached any time during scheduled work hours. Two meetings were scheduled per day, at 9 AM and 3 PM – providing frequent communication. The morning meeting was used to work changes and the afternoon was a "tag-up".
- A large focal survey graphic wall chart was used to show complete ground processing, and its relationship to the flight activities.
- The team could replan quickly allowing for other teams downstream the standard amount of time to do their jobs.
- The IOC website with access to all important documentation, tools, forms, useful links, and daily status was one stop shopping and worked well for communications with the distributed teams.

Conclusion/Final Statement:

IOC/SV operations turned out to be a significant and unique set of challenges. It was a bigger job than was anticipated. To develop a proper design for an Observatory IOC and SV phases requires a dedicated team of engineers and scientists. The strategy needed for operations throughout these phases was too unique to have a common design with nominal operations.

The Spitzer Flight Team completed IOC in 62.8 days and SV in 35.6 days. It was an amazing ride that led to the phenomenal images being released today.

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