Spitzer operations: scheduling the out years

William A. Mahoney[a], Mark J. Effertz[b], Mark E. Fisher[b], Lisa J. Garcia[a], Joseph C. Hunt, Jr.[c], Vincent Mannings[a], Douglas B. McElroy[a], and Elena Scire[a]
[a]California Institute of Technology, MS 314-6, 1200 E. California Blvd., Pasadena, CA, USA, 91125; [b]Lockheed Martin Space Systems, 12257 S. Wadsworth Blvd., Littleton, CO, USA, 80127; [c]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, USA, 91109

ABSTRACT

Spitzer Warm Mission operations have remained robust and exceptionally efficient since the cryogenic mission ended in mid-2009. The distance to the observatory now exceeds 1 AU, making telecommunications increasingly difficult; however, analysis has shown that two-way communication could be maintained through at least 2017 with minimal loss in observing efficiency. The science program continues to emphasize the characterization of exoplanets, time domain studies, and deep surveys, all of which can impose interesting scheduling constraints. Recent changes have significantly improved on-board data compression, which both enables certain high volume observations and reduces Spitzer's demand for competitive Deep Space Network resources.

Keywords: Spitzer, spacecraft operations, observation scheduling

1. INTRODUCTION

The Spitzer Space Telescope[1], launched on 25 August 2003, is the last of NASA's four Great Observatories. It was developed for infrared astronomy using a cryogenically cooled 85 cm primary mirror and three instruments sensitive from 3.6 to 160 μm. While the spacecraft operates at roughly room temperature, the detector arrays and the telescope mirrors were maintained at cryogenic temperatures through a combination of radiative cooling, a superfluid helium bath, and helium boil-off gas while helium remained. After the helium was exhausted on 15 May 2009 radiative cooling alone has kept the mirror and cryostat temperatures stabilized at about 26 K, sufficiently cold for observations with the Infrared Array Camera (IRAC) at 3.6 μm and 4.5 μm. At these wavelengths, the background-limited performance is virtually undiminished from the cryogenic phase of operations. IRAC uses two 256×256 pixel indium antimonide (InSb) arrays covering a 5×5 arc-minute field-of-view. The instrument provides extraordinary stability with the possibility of uninterrupted, staring observations in excess of 70 hours. IRAC has been on continuously for nearly three years since Warm Mission science observations began on 28 July 2009. A NASA review recently approved operations through the end of September 2014 with the expectation that operations will be extended for an additional two years. Spitzer is in an Earth-trailing orbit at a current distance of 1.07 AU. The observatory systems remain fully redundant while the operations teams continue to push performance to limits well beyond the original requirements. Despite the increasing distance and changes in the solar pitch angle required for Earth communications, detailed analyses have demonstrated that the observatory could operate safely and efficiently through at least January 2017.

Mission operations are being carried out by teams from the Spitzer Science Center (SSC) at Caltech, the Jet Propulsion Laboratory, and Lockheed Martin Space Systems in Denver, Colorado. The spacecraft operates autonomously, executing sequences of observations and spacecraft activities typically packaged and uplinked in one-week segments with ground contracts typically once per day. Observational efficiency has been excellent, averaging over 90% throughout the Warm Mission with scientific observations being executed at a rate exceeding 7800 hours/year.

2. OBSERVATORY OPERATIONS

2.1 Spitzer and the Challenge of Aging

Spitzer launched in August 2003 with a mission requirement of 2 ½ years and a mission goal of 5 years. Nine years after launch, the spacecraft and its hardware components continue to be robust. As with any aging spacecraft, unique

Observatory Operations: Strategies, Processes, and Systems IV, edited by
Alison B. Peck, Robert L. Seaman, Fernando Comeron, Proc. of SPIE Vol. 8448,
84481Z · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.926584

challenges arise as hardware degrades or fails. Spitzer has a fault detection and protection system that can autonomously swap to redundant hardware if needed. This system is designed to protect against sudden faults and failures that require immediate action. Reliance on this system to detect faults is of last resort. Instead, disciplined telemetry trending and analysis must be sustained throughout the lifetime of the mission. Carefully monitoring the health of the spacecraft becomes even more important as it ages. The earlier an issue is identified, the more options are usually available to respond. Early detection can become challenging as staffing is reduced to keep costs down during extended missions.

RCS Thruster Degradation: Four reaction wheels provide the control actuation for the pointing control system (PCS). Reaction wheel momentum is removed when the observatory's angular momentum exceeds a configurable limit. Momentum is removed by the reaction control system (RCS) using six nitrogen cold gas thrusters covering the three rotational axes in the positive and negative directions. Desaturation opportunities are generally scheduled twice a day.

In mid 2009, telemetry trending showed that when Thruster 6 was in use, it would first apply the expected thrust, but later it would exhibit irregular reductions in performance. The most probable cause for this behavior was a fracture in the solenoid coil that is used to open the thruster valve. As the coil heats up when current is applied, the fracture is exacerbated by thermal expansion causing an intermittent open circuit. When the circuit is open, the valve closes. The project decided to swap to the redundant thruster string and it has performed nominally.

Although the primary thruster string is degraded, steps are being taken to make it a fully functioning back-up. Since the momentum is fixed in the inertial frame the key is to schedule desaturation events at specific attitudes. Desaturation opportunities already occur every time there is downlink. For every Earthpoint downlink, an additional "anti-Earthpoint" desaturation opportunity would be scheduled so that only one of the two desaturation opportunities would require the degraded thruster. Adding the "anti-Earthpoint" desaturation opportunity would reduce the efficiency of science observations by about 20 minutes a day for additional slewing. The spacecraft and scheduling teams have already created the tools and techniques to rapidly implement this strategy should it become necessary.

IRU Degradation: Spitzer's pointing capabilities have far exceeded their original design requirements[2,3]. It is now possible to place a star within a 0.3" $\times$ 0.3" region and maintain that position to better than ~0.1" for at least 12 hours. The IRAC team and the science community are taking advantage of this capability to significantly improve the measurements of exoplanet eclipse depths. Spitzer employs a Kearfott Inertial Reference Unit (IRU) that contains two spinning mass gyros. There are two IRUs: the primary unit (IRU1) which was in use for the vast majority of the mission and the redundant unit (IRU2) which, until mid-2011, had been used only used briefly in flight and otherwise had remained powered off. To maintain optimal performance, IRU calibrations are being performed every three weeks.

In July 2011, two consecutive out of family IRU1 calibrations occurred. Concurrent with those calibrations, the IRAC team was validating new observational techniques which also demonstrated a minor degradation in pointing stability[2]. Further investigation showed that the current draw for one of the spinning mass gyros for IRU1 had increased noise. The small change was difficult to identify in the trending since the gyro motor current is noisy even when performing nominally. However, the emerging trend was apparent with a moving 100 sample smoothing which was performed on the raw dataset. Ultimately there was no way to definitively determine root cause of the IRU degradation. The age of IRU1 coupled with its almost constant use for 8 years pointed to mechanical wear, possibly introducing debris into the lubricant. Additionally, it is possible that there has been a change in the properties of the lubricant itself. While IRU1 was still performing within specifications, its performance no longer met the new pointing stability requirements for long staring observations. Thus the project decided to swap to IRU2 in August 2011 and measurements over the subsequent several months demonstrated that its performance equaled that of IRU1 prior to its degradation. Science observations were interrupted for less than 1 week to perform the swap and to calibrate IRU2.

The degradation of IRU1 and swap to IRU2 illustrates several important lessons that can be applied to any spacecraft. The first is that it is critical to have vigilant trending and analysis of spacecraft telemetry. In this case, both the spacecraft and IRAC teams observed the degradation early, well before anything was actually broken. If this degradation had not been caught, many long duration exoplanet observations would have been degraded or scientifically worthless despite the fact that IRU1 was within specification. The rapid swap and short calibration time can be directly attributed to preapproved contingency procedures and flight products. Contingency procedures should be routinely revisited and updated throughout the entire mission to maintain crisp responses. The final lesson future missions should consider is the possibility of using redundant hardware to achieve optimal performance, particularly in extended missions. IRU1, the primary hardware, is still robust and meets original design requirements. Since Spitzer is in its extended mission, the project decided to be more aggressive and maintain the greatest capability for science observations.

2.2 Pushing Spitzer to its Operational Limits

The Earth-trailing solar orbit (Figure 1) greatly reduced Spitzer's size, cost, and engineering complexity, compared to its original Earth orbiting concept[4]. As its distance increases, the geometry of Spitzer, Earth, and the sun, coupled with a non-articulated antenna and solar panel will create difficult engineering trades across multiple subsystems.

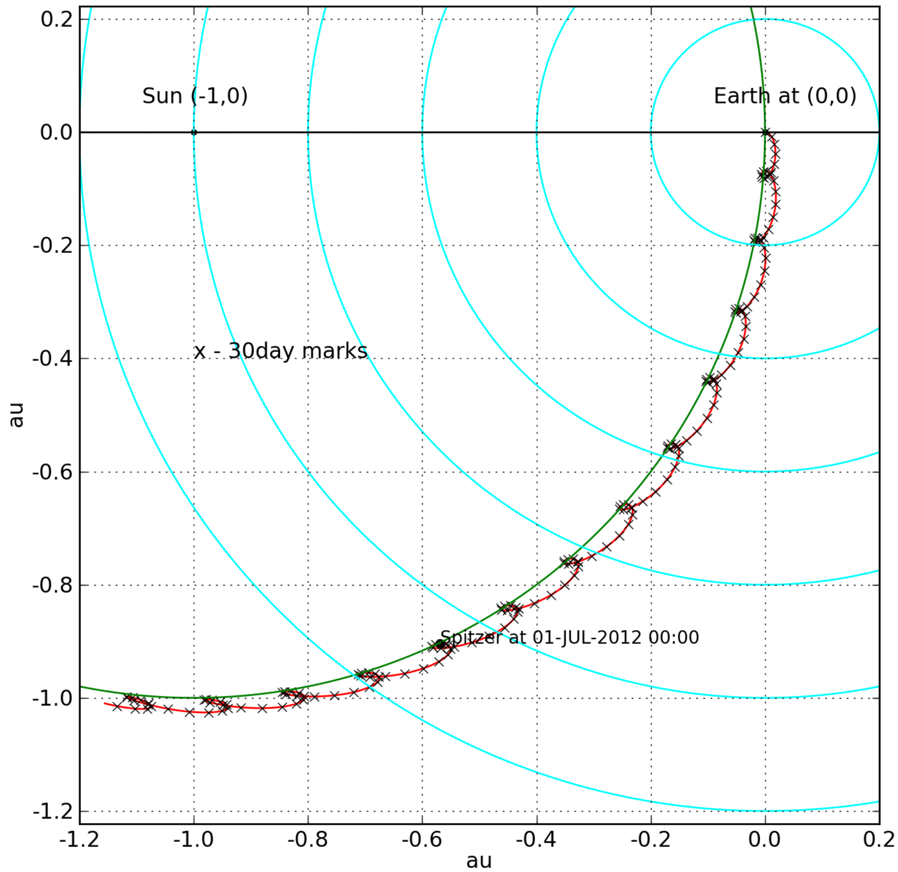

Figure 1. Spitzer orbit from launch on 25 August 2003 through January 2017: blue arcs are the range from Earth in 0.2 AU (Astronomical Unit) increments; the green arc represents 1.0 AU from Sun

The telecommunication, thermal, and power subsystems have the greatest interdependencies in the out years. In order to point the high gain antenna (HGA) towards Earth to downlink data, more and more of the spacecraft bus will need to be exposed to direct sunlight (Figure 2) causing more heat input into a very sensitive thermal system. The solar array output will continue to slowly decline due to normal aging. Lower power output will constrain the amount of time Spitzer can maintain large off-sun angles for the ever increasing angle when the HGA is pointed at Earth for downlinks.

Untangling this web of interdependencies can be achieved by identifying key, mission-changing modes of operation. Spitzer's extended mission cannot be flown with one set of operational constraints that will last for the remainder of the mission. Instead there are distinct points during the extended mission where the way the observatory operates will have to fundamentally change. Many of these new modes are without precedent and will push Spitzer far past its original design constraints.

Warm Mission Operations Today: As of today the extended mission has not required any significant changes in the way the observatory conducts its day-to-day operations. The spacecraft is constrained by an operational pointing zone

(OPZ) that thermally protects the telescope assembly behind the solar panel and also maintains a power positive attitude. The OPZ has remained unchanged since launch and covers ~35% of the sky. The telescope boresight cannot pitch more than 7.5° towards the sun and the bottom of the spacecraft (where the HGA is located) cannot pitch more than 30° towards the sun. Roll is constrained to ±2º about the boresight axis and yaw is unconstrained. Both science and spacecraft engineering data are currently downlinked approximately once a day for about 1 ½ hours via NASA's Deep Space Network (DSN).

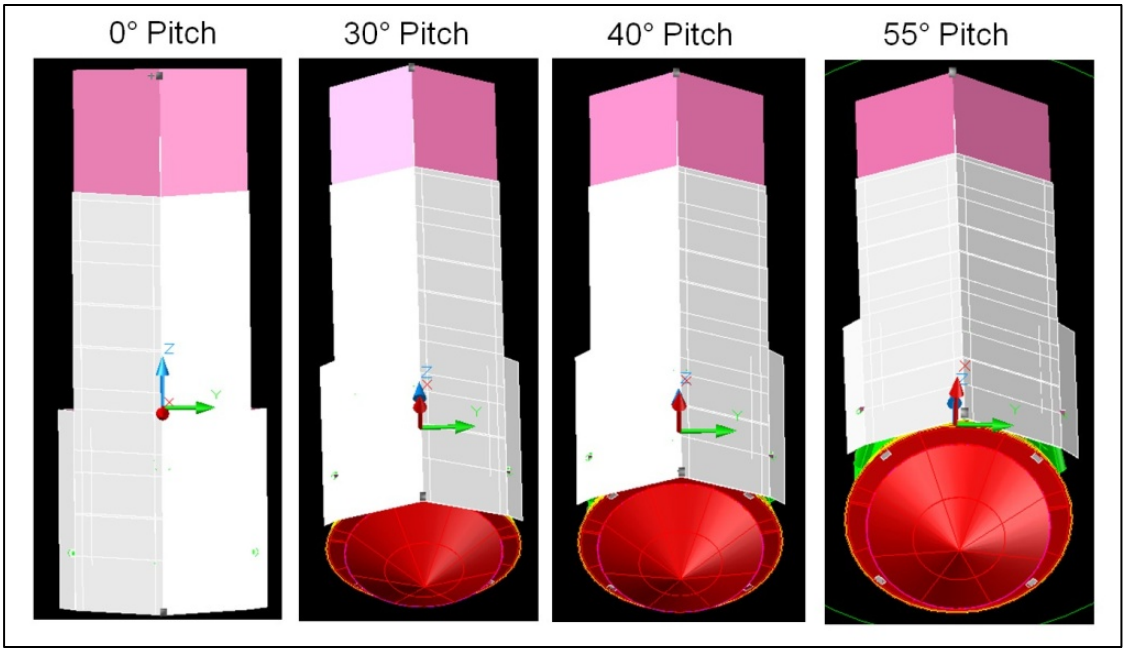

Figure 2. HGA/spacecraft bus sun exposure at the increasingly large pitch angles required for communication: 30° in 2013, 40° in 2015, and 55° in 2020.

Thus far operational enhancements and mitigations in the warm mission have primarily focused on minimizing downlink durations and the frequency of downlinks. In addition to keeping data rates as high as possible, a significant effort has been made to reduce the amount of data that is downlinked to the ground. These efforts have focused on improving compression performance of the IRAC data that dominate the total playback volumes. Spitzer uses a Rice compression algorithm. The IRAC array data are stored as unsigned integers with small positive and negative values for the shorter integration times. The resulting data thus form a bimodal distribution of very small and very large integers that compresses poorly, if at all. To combat this issue, the array data are now biased by a fixed negative value, largely removing the bimodal distribution and improving compression significantly. When averaged over many weeks, the change reduces data volumes by about 10%, however, for certain modes the improvement exceeds a factor of two, enabling observations previously infeasible. In parallel, the least significant bit is dropped for certain frame times. This modification reduces average data volumes by ~15% with a very modest (<1%) increase in image noise.

Extending the OPZ: In late 2013, spacecraft operational constraints must change for the mission to continue. At this time the geometry between Spitzer, Earth, and the sun would cause a violation of the current OPZ when the spacecraft attempts to point the HGA towards Earth for downlink. Considering the narrow beam-width of the HGA, if the OPZ is left unchanged downlinks would not be possible after the 30° limit was reached. Therefore when this limit is reached the OPZ will be expanded to 38° in pitch for downlinks only. All other OPZ constraints will remain unchanged and all science observations shall remain inside the original OPZ constraints.

Expanding the OPZ for downlinks creates new thermal and power concerns that the spacecraft has not experienced in flight. During the initial in-flight checkout, there was a 24 hour IRAC test at 30° pitch. The thermal model and in-flight performance data correlated well. Additional analysis has been done using the thermal model for pitch angles up to 45°. Based on the model, the spacecraft should be able to remain Earth-pointed and operate within thermally allowable limits at pitch angles up to 45° for up to 4 hours. Since the thermal model has not been correlated with flight data at these angles there is significant uncertainty in this analysis. The pitch angle necessary for Earthpoint will change in small increments as the mission progresses, therefore the thermal model can be correlated with progressively higher angle data. The thermal analysis cannot predict higher order effects, particularly those that could affect the telescope performance. For example, earlier in the mission a cycling heater was identified as the cause of a periodic wobble in long duration observations[2]. A reduction in the cycling thresholds reduced the wobble by about a factor of two.

The greater HGA pitch angles also affect power generation from the solar arrays. Thus far, the solar arrays have provided enough power at all OPZ-allowable attitudes to rarely discharge the battery. The average load is 11 A and the maximum load is about 12.5 A (Figure 3). Currently the arrays produce about 14-12.5 A. In late 2013, the solar array output is predicted to decline to 13.5-12 A and there will be more frequent and deeper discharging of the battery. The greatest power strain will be at Earth pointing attitudes because the pitch angle between Spitzer and the sun is at its maximum. Downlinking data at 550 kps will require approximately 3 hours of Earth pointing every day, if data volumes remain as they are now. Battery recharging will occur during nominal science observations that generally place the observatory in a power positive attitude.

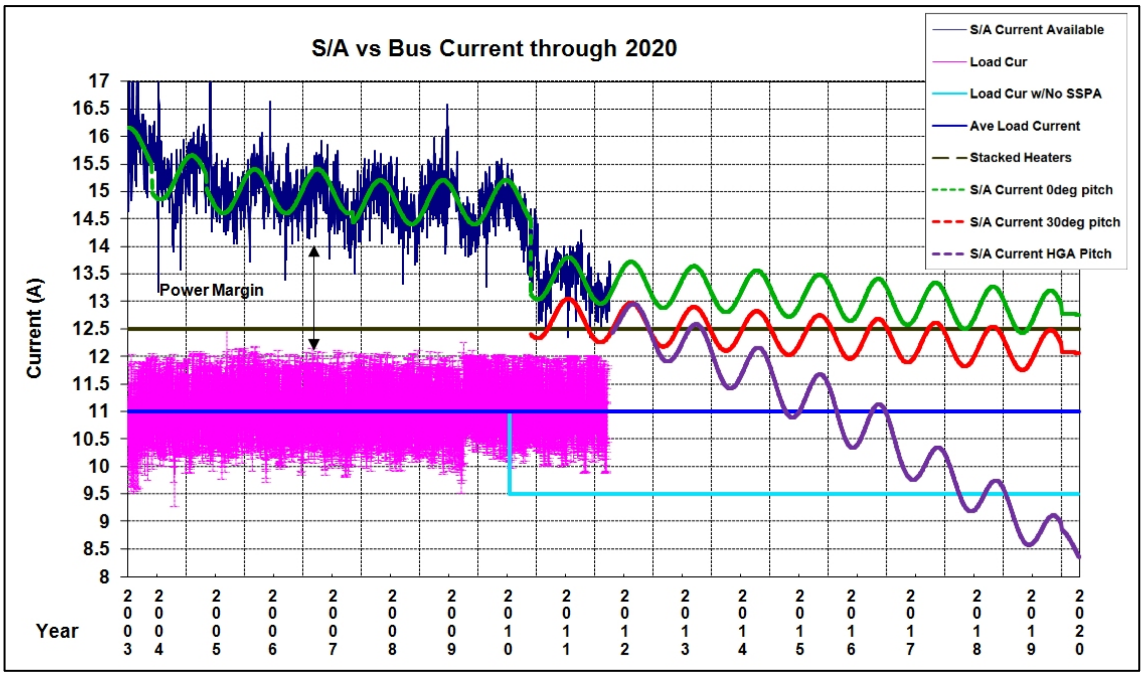

Figure 3. Solar array output and spacecraft load. Science observations are constrained to 0-30° pitch. Earthpoint pitch angle increases in time, therefore solar array output will decline at these larger angles. Note: in late 2010 the solar array output dropped 6% due to a micro-meteorite impact.

Changing Safe and Standby Mode: If a problem is detected, Spitzer's fault detection and protection system can autonomously place the spacecraft into two different modes depending on severity of the fault. Both modes terminate the executing on-board sequence. Standby mode returns the spacecraft to Earthpoint on the HGA, while Safe mode places the observatory in an attitude where the solar panels are normal to the sun and uses two low gain antennas (LGA) to communicate with the ground. In 2014, both of these configurations will no longer be supportable if they and their subsequent ground responses remain unchanged.

Standby mode is the less severe response by fault protection. Once the spacecraft is Earth pointed, data are downlinked at 44 kbps on the HGA for quick diagnosis of the anomaly. In 2013 pointing the HGA towards Earth will pitch the spacecraft beyond 30°. This will be potentially a power negative attitude and may be thermally unviable as well. If the spacecraft loads are in excess of the solar array output, the battery will slowly be discharged. In addition, there may be solar heating of the bus beyond thermal limits. In either case fault detection will eventually send the spacecraft to Safe mode. The Standby mode response will eventually be reconfigured to move to the spacecraft to an Earthpoint LGA attitude that will place the solar arrays normal to the sun. This attitude, much like Safe mode, will be both power positive and thermally protected but allow the spacecraft to remain in Normal mode.

Safe mode places the observatory into a power positive attitude. Data are transmitted over two LGAs. In 2014 the signal strength for the LGAs will be too weak to support 40 bps data downlink, the lowest data rate that Spitzer can produce. The signal may be too weak to detect data, but it is still strong enough to know the spacecraft is in Safe mode and to infer the health of certain subsystems based on the carrier signal's characteristics. Once it is known the Spitzer is in Safe mode, the ground will command an Earthpoint attitude that will allow use of the HGA. The spacecraft team will then diagnose the anomaly, while actively managing the batteries' state of charge and thermal status.

2015 and Beyond: As Spitzer continues to trail farther from Earth, the HGA to Sun pitch angle will also increase. In 2015 the pitch angle will cross the expanded 38° OPZ limit and the OPZ will have to be widened again; by 2020 the pitch angle will be up to 45°. In these out years, both power and thermal will be the primary limiting factors on whether the mission can continue. The greater the pitch angle, the more heat is inputted to the spacecraft bus and the less power is produced by the solar arrays while off the sun. Both factors will have to be actively managed.

There are few options to mitigate the increased thermal input of the sun into the unshaded HGA and spacecraft bus. The downlink rate on the HGA will remain at 550 kbps and the only mechanism for briefer total downlink time is by reduction of data volume which could limit certain science programs. If the temperature variations in the bus become too great in magnitude, the frequency of downlinks could be increased but with shorter durations. This approach would require greater DSN resources in a contentious environment and it would put more stress on the operations staff.

Active management of the batteries will have to be employed in the out years. The larger HGA Earthpoint pitch angles will force the system to discharge the batteries more deeply to maintain power equilibrium when at Earthpoint. The batteries will need to be recharged between downlinks. Up to this point, science observations were allowed to point the observatory anywhere within the original OPZ and there was enough excess trickle charge to fill the batteries. In the out years this may not be adequate. Science observations could be constrained to smaller pitch angles to produce more output from the arrays, but this approach would add significant burden to the scheduling team. Another option is to power off the 15 W solid-state power amplifier (SSPA) that is only used during data downlinks. This would be a change from the original mission design and have to be carefully considered.

Besides thermal and power, no subsystems have any specific limitations in the out years. The only direct consumable on Spitzer is nitrogen gas for RCS thrusters and there is 10 kg out of original 15.5 kg still available. Aging hardware is always a concern in extended missions, but the spacecraft remains fully redundant and ready to continue its mission.

3. TELECOMMUNICATIONS

3.1 Complications from increasing distance

Perhaps the biggest challenge for scheduling the warm mission is obtaining sufficient DSN coverage to support a demanding observational suite. As Spitzer recedes from Earth, the strength of its transmitted signal continues to decrease. Spitzer's relatively high data rate and weak signal now dictate use of the three DSN 70-meter antennas (Goldstone, California; Canberra, Australia; and Madrid, Spain) for downlinking data. The 70-meter antennas are generally arrayed with a 34-meter antenna to boost performance. However, competition for time with other projects, especially Mars projects when that planet is in the same region of sky as Spitzer, often makes it difficult to obtain the desired allocations of 1 track/day with at least one scheduled during the prime working shift. The maximum downlink rate is now 1.1 Mbps which requires a 70m/34m array at elevation angles above 40° but even under the best conditions the maximum rate will drop to 550 kbps by Fall 2012 (Table 1). As the rates are reduced, the downlink durations will need to increase proportionally somewhat reducing the overall efficiency.

Spitzer's X-band telecommunication system is fully redundant and has operated without issue. Throughout the mission, Spitzer has used a single 15-W solid-state power amplifier (SSPA) for data transmission. While the observatory has the capability of transmission powered by dual SSPAs, the risks and complications involved make it highly unlikely that this mode will ever be implemented.

Downlink Rate	20° Elevation		30° Elevation		40° Elevation	
	Single 70m	70m/34m Array	Single 70m	70m/34m Array	Single 70m	70m/34m Array
2.2 Mbps	2008 Oct 28	2008 Dec 5	2009 Jan 13	2009 Sep 30	-	-
1.65 Mbps	2009 Oct 13	2009 Nov 29	2010 Jan 14	2010 Oct 17	-	-
1.1 Mbps	2010 Dec 31	2011 Oct 3	2011 Nov 30	2012 Jan 27	2012 Feb 6	2012 Nov 17
550 kbps	2016 Jan 8	2016 Dec 27	2017 Dec 29	2019 Jan 2	2019 Jan 19	Beyond 2020
275 kbps	Beyond 2020	Beyond 2020	Beyond 2020	Beyond 2020	Beyond 2020	Beyond 2020

Table 1: Cutoff dates for downlinks at the allowed rates as a function of elevation angle. The rates are listed for both a standalone 70-meter DSN antenna and a 70-meter/34-meter array under normal weather conditions. A two antenna 34m-array can receive data at 275 kbps through 2014 depending on the configuration and elevation angle.

Scheduling DSN resources to maximize the downlink bandwidth presents several challenges for the Mission Operation System (MOS) uplink process, e.g. the elevation angles throughout the tracking pass, the number and types of antennas scheduled, and the equipment configuration dictated by the data coding scheme. The telecommunication link margin for each antenna configuration is predetermined based on the spacecraft orbit. This process allows predicts to be generated several years out. By generating telecom predicts the science planning can be optimized and DSN downlinks can be managed with real-time commands to ensure the continuity of data transmission when the link margin changes because of either station or weather issues. For maximum telecom link margin the spacecraft is capable of being configured to transmit data with two different convolutional coding rates. Convolutional coding is a type of channel coding that adds patterns of redundancy to the data in order to improve the signal-to-noise ratio (SNR), depending on the data rate. However, this requires that the DSN antenna is correctly configured to decode the data. As the project continues with the warm mission phase new DSN scheduling requirements are generated to ensure resource allocation planning is in sync with the telecom predicts for science planning. Although the emphasis has been on maximizing the downlink efficiency, adequate time must be scheduled to uplink and validate command products as the round-trip light time increases.

3.2 DSN availability

The Spitzer mission science planning process has allowed the project to be single fault tolerant in the usage of DSN support. This means that if a ground anomaly or another mission in critical need of a DSN antenna results in a missed DSN track, the science data and the functionality of the observatory will not be impaired or at risk. To date Spitzer has received 100% of the required DSN allocations. Because the planning of science sequence is at least 30 days ahead of the execution, mapping the exact science to the allocation has allowed the project the ability to return a percentage of the allocations not required for sequence execution.

3.3 Dealing with Anomalies

Most ground or spacecraft anomalies are handled with mature procedures, however, the procedure dealing with space weather has evolved. The space environment includes various solar and cosmic phenomena that affect spacecraft operations and lifetime. Solar and extrasolar cosmic rays are constantly present in space. Galactic cosmic ray fluxes are highest by approximately 25% during solar minimum when the Sun ejects little solar material. Solar proton events result from powerful solar flares with fast coronal mass ejections (CMEs). In the cryogenic mission phase, Spitzer experienced space weather events at the trailing edge of the solar cycle peak. The biggest impact was experienced during the solar storms of October 2003 and January 2005 where the spacecraft solar array experienced an approximately 5% loss in power. The net result was within the Solar Array operating margin of 26% with no impact to meeting the mission power requirement. During that time the response procedure was based on the GOES (Geostationary Operational Environmental Satellites) data that was more relevant to Spitzer. Currently Spitzer is beyond 1 AU making the GOES data not relevant. After the launch of Stereo B in 2006 a new procedure incorporated alerts from the Goddard Space Weather Center based on data from multiple spacecraft. These alerts are based on predicted CMEs and solar flares and they provide the expected time that the leading edge of the CME will arrive at Spitzer. The Spitzer project coordinated with Goddard to add the spacecraft ephemeris to the visualization tool that provides a graphical illustration of the CME. If the event is expected to impact Spitzer based on the model predicts, degraded data can occasionally be directly correlated. The Flight Control team uses this information to annotate logs, plots, and trending data such as the Mass Memory Card (MMC) soft scrub errors. In addition notification is sent to the Spacecraft and Instrument teams for trending and data analysis. Use of this procedure during the March 2012 solar flare identified degraded engineering data and lost science and calibration data totaling about 70 hours, most of which is being rescheduled. Damage to observatory hardware cannot be mitigated by powering down systems in anticipation of a CME hitting Spitzer, thus the observatory will remain operational but may experience lost science.

3.4 General Operations Process changes

We continually improve uplink and downlink processes as the mission progresses from launch through extended operations. Lessons learned are incorporated and, in fact, re-engineering processes can be thought of as a method to eliminate unforeseen design inefficiencies that are often revealed in the operations phase of a mission. At the start of the primary mission, the MOS tools used for sequence scheduling and review consisted of paper schedules, and email and fax-based communications. As the mission progressed, web based communication tools were introduced to JPL and the MOS. The Sequence Tracker is a web-based tool that provides a calendar view of deliverables and events associated with the progression from initiation to execution of an activity sequence. The tool serves as a central location for project members with sequence product interfaces to post status as well as track a given sequence related activity. With the implementation of a web-based uplink summary tool hundreds, if not thousands, of paper products that required manual manipulation for retrieval are now replaced by an electronic search. This supports rapid response for mission operations. Before the process update, a hardcopy of the uplink summary was distributed, and when remote teams' signatures were required, it was transmitted via fax. After all required signatures were collected, it was faxed back to JPL for final approval.

4. SCIENCE PROGRAM AND SCHEDULING CHALLENGES

4.1 Science Program

All observational programs are selected via the peer review process, primarily through an annual Call for Proposals (CP). The Spitzer Cycle 9 CP was issued by the Spitzer Science Center (SSC) 1 May 2012 with proposals due at the SSC later this year. The latest cycle solicits proposals from the international scientific community in three categories: (a) Exploration Science (>500 hours), (b) regular general observer (GO), both large (100-500 hours) and small (<100 hours), and (c) snapshot (100-500 hours). The snapshot category was initiated and designed largely to facilitate scheduling. The Astronomical Observing Requests (AORs) must have no constraints, employ modes with low data volumes, and have a maximum duration of about one hour. While several previous snapshot programs have been executed in their entirety, each program must be designed to yield useful scientific results if only 50% of the observations are executed[5]. The CP discusses both technical and scheduling limitations and indicates ways a program can be designed to ease scheduling difficulties without limiting the scope of the science objectives.

The warm mission science program will continue to emphasize the characterization of exoplanets and investigation of the distant universe.

Exoplanets: One of Spitzer's unique capabilities is its ability to obtain long, uninterrupted (up to ~70 hours) staring observations with high-precision photometry (28 ppm/1 sigma has been achieved for the measurement of exoplanet eclipse depths[6]) that enables both finding and characterizing transiting exoplanets. An immediate goal is finding or confirming an Earth-size planet orbiting in the habitable zone of a nearby star. As part of Cycle 7 Spitzer spent 21 consecutive days, interrupted only by a downlink and limited calibrations every three days, staring at the nearby M-dwarf star GJ1214 in search of an Earth-like planet. For Cycle 8, over 2000 hours of high priority observing time was awarded to the characterization of transiting exoplanets discovered by other facilities, including the Kepler observatory (Table 2). Additional time was awarded as part of the Director's Discretionary Time (DDT) process.

High Redshift Universe: Spitzer is uniquely suited to measure the age and stellar mass of distant galaxies ($z > 7$) to address such questions as when and how the first galaxies formed and what was responsible for the re-ionization of the Universe.

Other areas of research conducted during the warm mission have included a precise determination of the Hubble constant, confirmation and characterization of cold brown dwarfs, time domain astronomy including investigation of the mechanisms driving the time-variability of young stellar object (YSO) circumstellar disks and variability of active galactic nuclei (AGN), and completion of a map of the Galactic plane (GLIMPSE; see Table 2). Many of these investigations include coordinated observations with other facilities, both ground- and space-based.

PID	Science Category	PI Institution	Title	Co-Is	Hours
80025	nearby galaxies	Liese van Zee *University of Indiana*	Stellar Distributions in Dark Matter Halos: Looking Over the Edge	7	**1005**
80057	high-z galaxies	Giovanni Fazio *Smithsonian Astrophysical Obs.*	Spitzer Very Deep Survey of the HST/CANDELS Fields	12	**1182**
80096	high-z clusters	S. Adam Stanford *U. C. Davis*	SPT-Spitzer Deep Field	33	**766**
80100	high-z galaxies	Casey Papovich *Texas A&M*	Spitzer-HETDEX Exploratory Large Area (SHELA) Survey	28	**526**
80072	nearby galaxies	Brent Tully *University of Hawaii*	Cosmic Flows	7	**200**
80040	YSOs	John Stauffer *Spitzer Science Center*	YSOVAR II: Mapping YSO Inner Disk Structure in NGC 2264 with Simultaneous Spitzer and CoRoT Time Series Photometry	40	**630**
80073	exoplanets	Heather Knutson *California Institute of Technology*	Life on the Edge: Planetary Atmospheres in Extreme Environments	12	**596**
80117	exoplanets	David Charbonneau *Harvard University*	Validating the First Habitable-Zone Planet Candidates Identified by the NASA Kepler Mission	13	**600**
80179	brown dwarfs	Stanimir Metchev *SUNY Stony Brook*	Weather on Other Worlds: A Survey of Cloud-Induced Variability in Brown Dwarfs	9	**873**
80016	exoplanets	Jessica Krick *Spitzer Science Center*	Comparative Atmospheric Study of Exoplanets	13	**619**
80074	galactic structure	Barbara Whitney *University of Wisconsin*	Deep GLIMPSE: Exploring the Far Side of the Galaxy	51	**600**

Table 2. Priority 1 and 2 Exploration Science (ES) programs approved for Spitzer Cycle 8 grouped into extragalactic (top) and Galactic (bottom) studies. These programs were allocated nearly 7600 hours of observing time.

In Cycle 9, the maximum DDT hours has been increased from 5% to 10% of the total executed. This time is used to address unanticipated phenomena, including medium- and high-impact ToOs (see Tyler et al.[7]). However, because of reduced project resources, no more than 1 or 2 high-impact ToOs can be accommodated per year. For Cycle 9, the increased DDT allocation will enable the possibility of carrying out new deep field observations that include participation by all three remaining Great Observatories: Chandra, HST, and Spitzer.

In Cycle 9, snapshot programs will be assigned priority 2 whereas all others selected will be given priority 1, meaning the snapshot AORs will be scheduled only after the available priority 1 observations have been scheduled or to facilitate scheduling difficult programs. Until the recent NASA Senior Review extended Spitzer operations through September 2014, there was a distinct possibility the Cycle 8 would have been the final one. Thus the selection process included three levels of prioritization to allow maximum flexibility in completing the mission, consistent with the desires of the Timeline Allocation Committee (TAC). The Cycle 8 allocations included over 10,000 hours of priority 1 and 2 observations along with over 2000 hours of priority 3, much of which will be executed. While the goal remains to schedule the higher priority observations first, this is not always possible because of significant peaks and valleys in the visibility of the approved programs. Historically during the spring and fall of each year, there is a relative lack of available AORs largely because the lengthy survey programs tend to observe regions not visible when the inner Galactic plane is in the OPZ. Also, the valleys tend to be self-perpetuating as the pool of available AORs in the spring, for example, will be nearly emptied leaving little remaining six months later when the same fields are next visible to Spitzer.

In transitioning to Cycle 9, remaining Cycle 8 priority 1 and 2 programs will be completed, however, no priority 3 AORs will be executed after 2012. It is expected that 8000 to 9000 hours of observations will be selected in Cycle 9 to be executed by the end of March 2014. A Cycle 10 CP will solicit proposals for completion of the currently approved mission. As has been the case throughout the warm mission, the average size of the selected programs will be larger than during the cryogenic mission but fewer will be selected to reduce the cost of management. However, this change has little affect on scheduling.

4.2 Observatory Planning and Scheduling Team (OPST)

The warm mission is being run much the same as the prime cryogenic mission except that IRAC is now on continuously and observing only at 3.6 μm and 4.5 μm. All the basic operations teams, processes, and tools remain the same.

Sequences continue to be built and executed in 1-week segments and SIRPASS (see below) remains the primary tool for scheduling. The responsibility for scheduling observatory activities has been assigned to the SSC and is carried out by OPST. The team's primary responsibilities involve long range planning during which provisional slots are defined for the more difficult and highly constrained observations and short term scheduling when the detailed weekly sequences are designed, reviewed, and prepared for execution on the observatory[8]. OPST consists of one long-range planner and four schedulers with each spending approximately half-time building every fourth week of operational activities. This staffing level is down from a peak of about six full-time members during the cryogenic phase of operations. Since the development of a one week segment generally involves an intense effort for about two weeks of the four-week cycle, the other duties (largely unrelated to OPST activities) of each scheduler tend to smooth out an otherwise uneven level of work. Having four individuals also provides adequate flexibility in responding to anomalies and covering personnel outages. It also allows time for supporting occasional component validation tests, block changes, and testing new versions of the scheduling tools.

Long Range Planning: Many of the programs selected for the warm mission involve complex and sometimes conflicting constraints. There has been an increased emphasis on exoplanet observations that usually have a very narrow window for their start in order to capture the transit/eclipse with a sufficient but not unnecessarily long baseline on each side, typically about one hour. Time variability studies have also become more popular. These tend to involve numerous observations of a given target spread throughout their corresponding visibility window.

Proposals submitted in response to the CP are given a cursory review by the SSC. For those that appear most challenging, the SSC performs a technical and scheduling feasibility study and provides the results to the Timeline Allocation Committee (TAC) to assist in its review. Once the selected programs are known, OPST examines those with special requirements. Examples include the 21-day observation of GJ1214 and a 30-day investigation of time variable objects in the star-forming region NGC2264 that occupied almost the entire month of December 2011. Other challenging programs have included investigations of Cepheid variables, observations involving very high data volumes, and large maps that must be executed over short time periods. For unique observations, especially the long exoplanet observations, OPST must negotiate with the JPL DSN schedulers several months in advance to obtain tracks consistent with the observation and with spacecraft requirements.

Short Term Scheduling: The general outline of activities determined by long range planning is used to build the detailed sequences of spacecraft activities which typically span about one week of operations (see Mahoney et al.[8]). The primary tool used by OPST members to build the weekly sequences remains SIRPASS (Spitzer Integrated Resource Planning and Scheduling System), a user interactive application that provides the scheduler a platform for developing the schedule, assessing numerous scheduling options and requirements, and providing a number of reports, many of which flag scheduling errors. While reasonably stable, SIRPASS continues to require maintenance to assure compatibility with institutional processes and interfaces and to accommodate changes in requirements. For example, the OPZ will need to be expanded to allow the observatory to return to Earthpoint for communication on the high-gain antenna (HGA) starting in November 2013 and the thruster 6 mitigation strategy may need to be implemented.

The detailed development of a given week of operations starts approximately 6 weeks before execution begins on the observatory. Because of the reduced staffing level and because the sequences are more highly correlated than during the cryogenic mission when three instruments were operated somewhat independently, one week has been added to this schedule for the warm mission phase. The added week provides schedulers with sufficient time to assure compatible interfaces between consecutive weeks and to hand off pools of science observations that are nearly the same.

4.3 Scheduling challenges

Highly constrained observations continue to pose significant scheduling challenges. In addition to an increasing number of exoplanet observations, many with durations in excess of 24 hours, there has been more interest in time-variability studies that can consist of more than 100 highly constrained observations of each of numerous sources. Also, the sheer number of AORs approved for Warm Mission observations greatly exceeds the number for a comparable period in the cryogenic mission that can significantly complicate scheduling and monitoring activities and can occasionally overwhelm the processing tools. As during the cryogenic mission, latent images from bright sources must be addressed to assure they will not degrade subsequent observations, including IRAC calibrations.

Managing on-board data volumes continues to be a significant scheduling driver, especially given Spitzer's increasing demands on DSN resources. The duration of tracking passes has increased to accommodate the reduced data transmission rate dictated by the increasing distance to Spitzer. The data collection rate for IRAC can vary by well over an order of magnitude, depending on the observing mode and the integration times. Extended maps such as the GLIMPSE Galactic plane survey (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire) and brighter exoplanet observations tend to use short integration times with correspondingly higher data volumes. The high-volume AORs in such maps must often be interleaved with low-volume AORs to avoid filling the on-board memory. Conversely, during periods of low data volume observations, an occasional DSN track can be dropped to both improve the Spitzer efficiency and to release the DSN antennas for use by other projects. The planning and scheduling of observations must also account, as well as possible, for periods of reduced DSN coverage such as during early August 2012 when the Mars Science Laboratory (MSL) will require extensive coverage for its approach and landing. However, even during this period, the Spitzer project has obtained sufficient DSN allocations to enable uninterrupted scheduling of low-volume observations. During this period and all others, OPST must design the schedule such that the bandwidth for data playback for each pass is within limits and that the risk of filling the MMC as could be caused by a missed pass (e.g. weather or antenna problems) is properly mitigated.

Despite the scheduling challenges, the Spitzer observational efficiency has remained exceptionally high. Figure 4 shows weekly averages of the fractional time spent on various activities. Plotted from the bottom up they are (a) science observations, (b) instrument calibrations, and (c) initial slews to the science target. These three together define the efficiency that has averaged well over 90% for the warm mission to date. This will drop by about 2-3% late in 2012 when the maximum supportable downlink rate will drop to 550 kbps and the average downlink interval will increase to about 3 hours. Conversely, the operational teams are continuously looking for ways to improve efficiency. For example, the IRAC team has recently reviewed the requirements for routine instrument calibrations and has concluded some are unnecessary, saving roughly an hour per week for additional science observations.

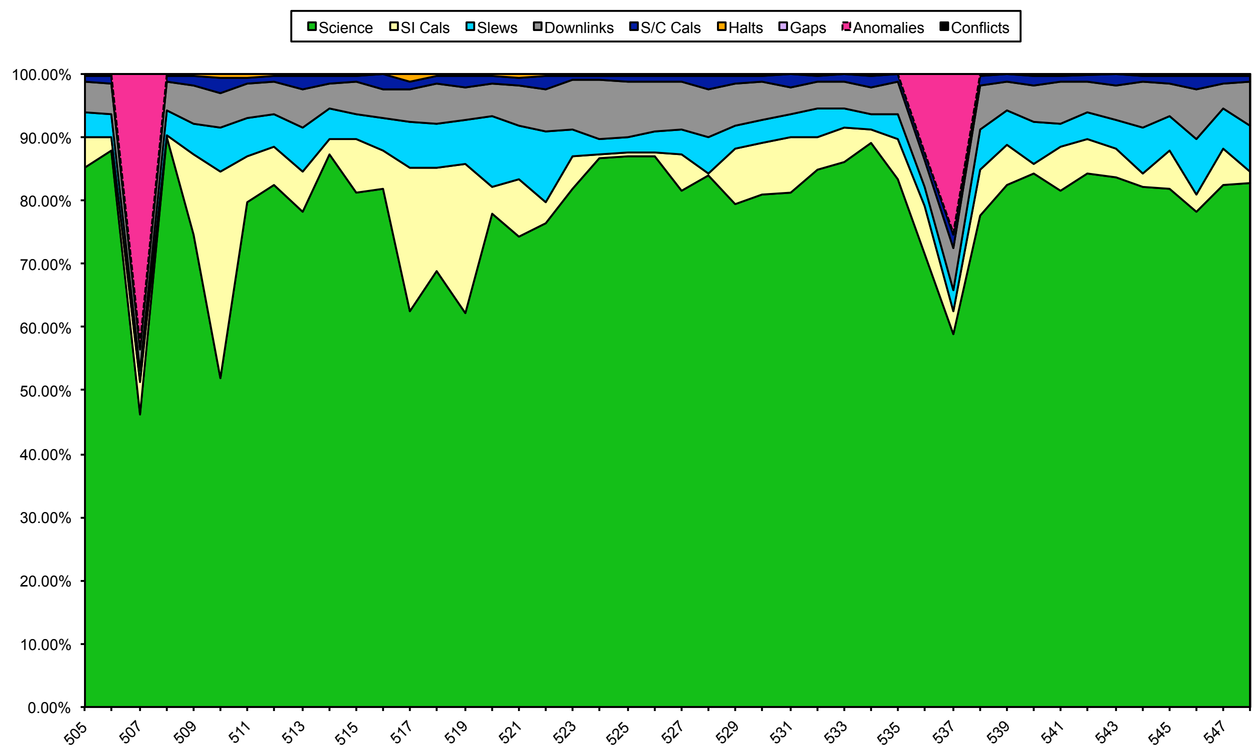

Figure 4: Weekly averages of fractional time spent on various activities during year 3 of the Warm Spitzer mission (2011 Jul 28 through 2012 May 31). The anomaly in week 507 corresponds to time lost during the swap to IRU 2 and the anomaly during weeks 536 and 537 corresponds to data lost because of the X1 solar flare in early March.

5. CONCLUDING COMMENTS

Following its launch on 23 August 2003, Spitzer completed nearly 5 ½ years of cryogenic operations prior to the exhaustion of helium in May 2009. Since then, the IRAC instrument, operating with its two shorter wavelength bands, has now completed nearly 3 years of Warm Mission operations. The scientific objectives for the Warm Mission are emphasizing the characterization of transiting exoplanets where eclipse depths accurate to 28 ppm have been achieved. The second primary goal involves the study of the distant ($z > 7$) Universe to address questions on the formation and evolution of galaxies and on the re-ionization of the Universe.

While the observatory remains healthy and fully redundant, backup systems are being used to maximize performance, especially precision pointing. Maintaining peak performance requires diligence on the part of the operations teams. This is especially challenging in the extended mission environment of increased demands and reduced resources and workforce. On the other hand, the operations teams continue to extend the observatory capabilities, especially in the areas of precision pointing and photometric stability, both of which are now required for optimal exoplanet observations.

The observatory is in an Earth-trailing orbit at a distance that now exceeds 1 AU. As it continues to recede, communication becomes more difficult and the downlink data rate will soon drop from a current maximum of 1.1 Mbps to 550 kbps. While this will not limit the scientific capabilities, it will place further demands on DSN resources, especially during highly contentious periods such as early August 2012 during the approach and landing of MSL on Mars. Furthermore, in order to point the HGA at Earth for downlinks after late 2012, the solar pitch angle will exceed the current limit and thus the limit will have to be expanded. While this will involve a complex relationship among thermal performance, power management, and communication, studies have demonstrated that the observatory could operate safely and efficiently until at least 2017.

An ambitious scientific program coupled with observatory limitations continues to present challenges for the scheduling team, particularly in the management of data volumes and honoring complex constraints. Nevertheless, efficiency remains exceptionally high, averaging over 90%. This is expected to drop only 2-3% when the maximum downlink rate drops to 550 kbps. During the cryogenic mission, over 36,000 hours of observations were executed. For the Warm Mission to date science observations have exceeded 22,000 hours and will approach 40,000 hours by the end of the currently approved mission in September 2014. An additional 2-year extension would add 15,000 hours of science.

Acknowledgment: The Spitzer Space Telescope is operated by the Jet Propulsion Laboratory and the California Institute of Technology, under National Aeronautics and Space Administration contract number 1407. The authors wish to thank Try Lam of the JPL Navigation Team for provided Figure 1 showing the Spitzer orbit.

REFERENCES

[1] Werner, M. W., el al. "The Spitzer Space Telescope Mission", ApJS, 154, 1 (2004).

[2] Grillmair, Carl J., et al. "Pointing effects and their consequences for Spitzer IRAC exoplanet observations", this meeting, paper 8448-47, submitted (2012).

[3] Ingalls, James G., et al. "Intra-pixel gain variations and high-precision photometry with the infrared array camera (IRAC)", this meeting, paper 8442-68, submitted (2012).

[4] Kwok, J. H. "A New Mission Concept for the Space Infrared Telescope Facility", in AAS/AIAA Astrodynamics Conference, Aug. 16-19, 1993, V. J. Modi et al. eds. (Adv. Astronaut. Sci. 85; San Diego; Univelt/AAS), 1401 (1993).

[5] Storrie-Lombardi, Lisa J., and Dodd, Suzanne R. "Spitzer Space Telescope: maximizing the science return in the extended mission phase", this meeting, paper 8448-46, submitted (2012).

[6] Demory, B-O, et al. "Detection of Thermal Emission from a Super-Earth", astro-ph 1205.1766 (2012)

[7] Tyler, S., et al. "Rapid replacement of Spitzer Space Telescope sequences: targets of opportunity and anomalies", Proc. SPIE 7016, 70161V (2008).

[8] Mahoney, W., et al. "Spitzer warm mission transition and operations", Proc. SPIE 7737, 77371W (2010).