Lessons learned in extended-extended Spitzer Space Telescope operations

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ABSTRACT

The Spitzer Space Telescope is executing the ninth year of extended operations beyond its 5.5-year prime mission. The project anticipated a maximum extended mission of about four years when the first mission extension was proposed. The robustness of the observatory hardware and the creativity of the project engineers and scientists in overcoming hurdles to operations has enabled a substantially longer mission lifetime. This has led to more challenges with an aging ground-system due to resource reductions and decisions made early in the extended mission based on a shorter planned lifetime. We provide an overview of the extended mission phases, challenges met in maintaining and enhancing the science productivity, and what we would have done differently if the extended mission was planned from the start to be nearly twice as long as the prime mission.

Keywords: Spitzer Space Telescope, operations, extended mission, space telescopes

1. INTRODUCTION

The Spitzer Space Telescope[1] was launched in 2003 as NASA's Great Observatory for Infrared Astronomy. Extended operations began July 28, 2009 after successful completion of the five and a half year prime mission. No formal plans for extended operations were made prior to launch though it was expected that Spitzer could continue to operate with the two shortest wavelengths of the InfraRed Array Camera (IRAC)[2] after the depletion of the cryogen. The project began putting serious effort into defining the extended mission in 2006. When it was formally proposed for the first time in 2008, the project expected a maximum extended lifetime of another four years. In our 2010 SPIE paper[3] we confidently stated:

> "Science operations for the warm mission, operating the IRAC 3.6 and 4.5 micron channels, began July 28, 2009 and can continue through December 2013 (if funded) using our new warm operations model."

Spitzer operations are currently funded through November 2019. Due to the ingenuity of the engineering and science staff, and continued support from NASA and the science community, the observatory has been able to continue executing new and exciting science far beyond our wildest expectations.

In retrospect, specific plans for the extended mission that were made prior to launch would not have been particularly useful, other than additional instrument testing at different temperatures, due to the substantial changes in the scientific landscape during the prime mission years. For example, the evolution of the study of exoplanets, the Kepler and K2 missions, and the installation of the Wide Field Camera 3 on the Hubble Space Telescope all helped open major areas of science with Spitzer in its extended mission that were not part of the prime mission plan. In addition to changes in the scientific landscape, the NASA Astrophysics Division initiated a regular cadence of Senior Reviews for all operating astrophysics mission. Spitzer participated in the Senior Review every two years from 2008 – 2016. The Senior Review cadence, along with the project's uncertainty from a technical standpoint of how long the observatory could successfully operate, made planning beyond a two-year horizon difficult. We discuss below lessons learned in our nine years of extended operations.

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2. HAVE A PLAN

2.1 New Plans

There were no formal level 1 requirements for the extended mission but the project developed five principles that we have continued to use to guide decisions. They have served the project well.

1. **Don't do anything stupid.** This was already the primary mission rule during prime mission operations and it has proved invaluable in evaluating options.
2. **Maximize the scientific return of the mission.** Spitzer exists to do the highest quality science possible. We didn't want to continue operating the observatory if the science program wasn't first rate.
3. **Spitzer is a community observatory.** As the fourth of NASA's Great Observatories, Spitzer has always executed a community driven science program. The selected observations are peer-reviewed and recommended by the astronomical community.
4. **Minimize the risk to the health and safety of the observatory.** Changes in mission operations introduced for the warm mission should not add substantial risk to the health and safety of the observatory.
5. **Accept additional risk to science.** While we did not want to make changes that risked losing the observatory, we did make changes that could have negative impact on science. These would be manifested primarily in terms of scheduling efficiency. We accepted reduced mission and science operations staffing levels that would lead to slower recoveries from anomalies, fewer late changes to schedules, fewer high-impact scheduling opportunities and less direct user support.

2.2 Old Plans

Though Spitzer came up with new principals for approaching extended operations, the mission remains viable and successful due to three important rules that were carried forward from the prime mission.

1. **Test what you fly and fly what you test.**

Test what you fly and fly what you test has enabled the Spitzer Operations (Mission, Spacecraft, and Science) to apply end-to-end testing, analysis, and execution of pivotal engineering changes required to sustain operations far beyond its design limits. While Spitzer's earth trailing orbit allows for very long uninterrupted observations, the geometry of the orbit with respect to earth also creates the biggest engineering challenges. The high-gain antenna required for communication with earth is fixed on the bottom of the observatory, therefore to communicate with earth requires repointing the observatory. The design limit for the maximum earth-point pitch angle was 30 degrees but in 2018 operations required a maximum earth-point pitch angle of 48.4 degrees, and is expected to reach to 52 degrees in 2019. Enabling this required complex modifications of the fault-protection flight software, procedures for downlinks and observing strategies to maintain efficient science operations while managing the power and thermal state of the observatory. Every configuration modification required testing on the Flight system test-beds, thorough review of the analysis, and check-out by mission, flight, science operations and IRAC instrument teams to determine if any operational changes to processes and procedures would be necessary prior to execution of the proposed changes.

Any new commanding sequence that we plan to run on the observatory is first run on the engineering test beds. This provides the confidence necessary to make critical changes to the flight software that have been required to extend the mission. Without the test beds it is highly unlikely the Spitzer mission would still be operating.

2. **Adhere to processes and procedures, making changes only when necessary.**

We reviewed all of our nominal scheduling and review procedures prior to the end of the prime mission and determined that the benefits of any major changes did not outweigh the additional risk. We have deviated from our nominal scheduling process to support important science programs that required it, i.e. microlensing surveys, but we have done this by accelerating steps in the process, not skipping them.

3. **Rehearse, train, and retrain staffing to be prepared for anomaly recovery and the unknown.**

The Spitzer observatory has been extremely robust with only one anomaly in 2016, due to a communications glitch that did not resolve itself quickly enough, during the entire extended mission. While having rare anomalies is the desired situation for any space observatory, it also means that no one is in practice for the recovery. Particularly as staff turnover, and new people join the project, having training and discussions every year or two about the process is very valuable.

3. ENGAGE WITH YOUR COMMUNITY

The most obvious way to reduce costs as we entered extended operations was to reduce the number of programs supported by the Spitzer Science Center (SSC). With the same number of hours per year available for science this means we needed a smaller number of larger programs. We initially presented plans to the Spitzer User's Panel and Oversight Committee suggesting that we call for "Exploration Science" programs with a minimum size of 1000 hours. We formed a steering committee of eight external scientists from multiple disciplines and asked them to form teams to write white papers describing what they would do with > 1000 hour proposals. We then scheduled a community workshop entitled "Science Opportunities with the Spitzer Warm Mission" in June 2007 where the steering committee presented their white papers and the community discussed them and provided feedback. In addition, we asked the workshop attendees to answer the following questions:

- What are the most important science drivers for a warm Spitzer mission?
- What should be the duration of the warm mission?
- What public 'HDF-style' program should be prepared for the cryo/warm transition period?
- What is the appropriate balance between smaller and larger programs?
- Are ToOs an important component of the warm mission? If yes, at what level?
- Should any science programs be specifically solicited for the warm mission?
- Are there any 'huge' (> 5000 hours) projects that should be done? If yes, how should they be selected and organized?
- How does the community participate in science of big projects if not part of the executing teams?
- Can most of the review process be done remotely instead of bringing 100 people to Pasadena annually for a week?
- Should the review of observing proposals and archival/theory proposals be held at the same time or 6 months out of phase?

The results from the Workshop were substantial and provided the primary structure for the extended mission science program model. Every team that presented a white paper proposed ideas for exciting science, much of which couldn't be done in the prime mission because during the regular TAC process getting > 1000 hours of time would have been impossible. The community strongly recommended continuing to execute peer-reviewed science selected from proposals, as opposed to having a large HDF-like program ready when the cryogen ran out. They embraced the Exploration Science concept but also strongly recommended that we maintain the ability to select and execute small programs. Based specifically on feedback from the extrasolar planet community we reduced the minimum size for exploration science proposals from 1000 to 500 hours. There was no justification for changing the annual nature of the proposal process but no strong feeling against trying to make it less expensive by doing more of it remotely instead of all as an in-person review. Though the Spitzer project provided suggested overall plans and changes the community had a substantial impact on the details of how the warm mission operations actually look. The proceedings[4] of the workshop were published and made available to the entire astronomical community.

As part of the preparation for each successive Senior Review we have presented tentative plans to our Science User Panel and Oversight Committees, as well as reaching out to current investigators, and used their feedback to help craft the science case for the proposal. The annual proposal calls are the primary mechanism for evolving the science and while our process for selecting proposals has evolved, selecting the most compelling current science remains the driving force for the mission.

4. LISTEN TO YOUR STAFF

In addition to getting feedback from the external science community, input from your science and engineering staff are critical in identifying and implementing potential changes to operations that might enhance the science program and/or extend the operational lifetime of the mission. The science and mission operations teams have worked closely to further improve the observatory operations and the science data analysis, in particular to support one of Spitzer's key science strengths – the characterization of exoplanets. Over 30% of the time allocated in extended mission has been devoted to science requiring high-precision relative photometry, including exoplanet characterization and investigations of cloud cover and weather for brown dwarfs. Spitzer observations typically reach noise levels within 20% of the photon-noise limit in the unbinned time series. Precisions of 100 ppm are routinely reached, and precisions of 30 ppm can been achieved[5]. Spitzer's excellent photometric precision enables a wide range of exoplanet science including validation of planet candidates, refinement of transit ephemerides, transit timing variations, measuring planetary radii, characterizing atmospheric composition and thermal lapse rates, and determining the day–night atmospheric temperature difference.

Spitzer is in an earth-trailing solar orbit and continues to drift further away from the earth every year. The rate at which data can be downlinked is now 550 kbps, due the increased distance from the earth, compared to 2.2 Mbps during the bulk of the prime mission. The amount of data that can be stored on the mass memory card on board is also limited. For its primary full-array observing mode, IRAC nominally takes data in both the 3.6 and 4.5-micron channels. Data taking for one channel can be turned off for observations where the second channel is not scientifically useful and data volume is an issue. The IRAC and Observatory Engineering Teams have designed and implemented two different modifications in the data compression strategies that lead to 20-40% improvements in the data compression. These enable longer staring observations of bright targets using short exposure times, as well as larger area shallow surveys. We have recently made an update to the default telemetry modulation index which extends support for 7 months for the 550 kbps downlink rate with a standalone 70 meter antenna.

The original expected lifetime for extended operations of four years was based on the fact that Spitzer would not be able to recover from an anomaly beyond 2013 utilizing the strategy from the prime mission. This was due to Spitzer's continually increasing distance from the Earth. To extend the mission lifetime the Observatory Engineering Team developed several creative adaptations for flight operations:

1. Disabling some of the fault protection when the observatory is pointed at the earth for communication;
2. A new strategy for getting to an earth-point attitude that keeps the observatory safe if an anomaly occurs during the process;
3. Inventing a new Carrier-only Safe and Stand-by Mode Recovery with automated Smart Sequences which was successfully executed during recovery from a November 2016 Standby Mode anomaly.

Without the continued efforts of the spacecraft and mission operations teams, Spitzer would have ceased operating many years ago. To keep the people working behind the scenes up-to-date on the science their work enables, the science staff regularly shares new science results with the entire operations staff.

5. PEOPLE ARE YOUR MOST IMPORTANT RESOURCE

This lesson is not unique to extended missions but becomes even more critical as staffing levels are dramatically reduced and the level of uncertainty about the future grows. The initial plans for extended Spitzer operations were based on a 50% reduction in the operations staff. The mission operates today with 80% fewer FTEs compared to the middle of the prime mission. Everyone wears more hats in extended operations. Retaining key expertise, training new staff, cross-training existing staff, and supporting people's careers all becomes more difficult but no less important. The primary management lessons learned are:

1. **Provide your staff with regular updates on the project status.**

   Even if nothing has changed, information voids have a tendency to be filled with rumors or gossip. An informed staff is an empowered staff that will spend more time doing their job and less time worrying about what they might not know.

2. **Tell people that they are valued and what their role is, regularly and individually.**

   The positive impact of talking to people individually about what they are doing and what their future role in the project is cannot be overestimated. And this isn't a 'review,' it is a conversation that should happen at least once a year. People who understand what the plan is and what their role is are much more likely to stay rather than think they need to leave because uncertainty about the future. When you have to tell people that their job is going to end, doing this with as much notice as possible is valuable, particularly for science staff. In our experience if people learn their job is going to end in a year they don't necessarily immediately find a new job and leave. Most people supporting extended missions are experts in what they do and feel a part of the mission. Scientists who want to apply for jobs that are advertised on the academic calendar schedule need to know if they should be applying this year for a job that starts next year. Again, if people know where they stand they will make better decision for themselves and for the project.

3. **Have everyone be training their replacement, or at least identify candidates.**

Particularly with a small staff, transition planning is important. People will leave for new professional opportunities or personal reasons. This can be difficult for people with critical skill sets at any time in a mission but the issue is amplified in extended operations. Most people are 'the' domain expert for their job. In the prime mission there might have been a team to support that function but in extended operations it is more likely parts of a few people. Cross-training is critical.

6. PLAN FOR THE MISSION CONTINUING

One of the major lessons learned is that you should always plan to operate longer than your currently planned end date. This doesn't suggest being unrealistic. Anyone who operates a space mission knows it could end tomorrow because of an uncorrectable fault but space observatories are built to be robust. The marginal cost of continuing to operate is generally orders of magnitude smaller than replacing them, as long as they continue to be scientifically productive.

Extended operations is an exercise in doing more with less, and then figuring out how to do it again, and again. Always keeping in mind that the mission might last longer than the current funding profile will lead to better decisions about staffing, maintaining the ground system, and managing key external interfaces. A 2016 National Academy study[6] of the NASA Senior Review process noted the following:

> "Experience and knowledge gained during the prime phase typically result in lower costs for extended mission operations, but there may be counteractive effects that can create upward pressure on operational costs. After the first two Senior Reviews, most missions have implemented all (or almost all) practical steps to reduce costs. Further budget cuts often then result in disproportionate cuts to project funded science activities, increasing risks that science will be diminished or not performed at all."

The operations budget was reduced in each of five Senior Reviews and one of the trades made was to reduce software support to effectively nothing, assuming the mission could manage with that for 2-3 more years. That has made it very difficult to maintain software for 6+ years, let alone to make enhancements. The key lessons from the Spitzer experience can be summarized as follows:

1. **Freezing your operational software is impossible.**

Even if you don't make any enhancements or changes, which you will want to do to respond to new science cases, software must be updated to function as operating systems continue to be updated. Something else that wasn't anticipated was the substantial increase in cybersecurity mandates for anything connected to any network. Just having software on a dedicated flight network is no longer sufficient to protect it from attack. These are some of the most challenging unfunded mandates that have surfaced in just the past two years.

2. **If you don't update the software, you can't update the hardware.**

There are several parts of the operations system that we would like to move to Linux, but there are no resources to do that nor is the expertise still available within the project to do the transition. The way extended missions keep their older ground systems working is buying old computers and parts on eBay or taking surplus machines from other older missions that end.

3. If you utilize multi-mission software it will change and you want to be able to accept the newer versions.

This is related to item #1, that freezing software for more than 18 – 24 months just doesn't work. Spitzer stopped accepting updates for some of the multi-mission software utilized for sequencing, but then ran into issues when we tried to substantially increase the number of commands in each sequence, to support Microlensing surveys. It would have been much easier for the multi-mission software team to diagnose the issues if Spitzer was running the current version. Having let go of your dedicated software/hardware integration and test staff means that any required changes add more risk.

4. Your key external interfaces must evolve.

Spitzer requires the Deep Space Network (DSN) for communicating with the observatory and has been operating long enough that some of the equipment required is only used by Spitzer and Voyager. Not having absolute certainty about the mission lifetime makes it more difficult for other organizations to plan support and upgrade requirements. Along with providing regular updates to your staff it is crucial that external organizations get regular updates as well. This isn't just for their benefit. It will prevent the project getting notification of required services or equipment being discontinued "because you will no longer be operating." Regular and open communication is the answer, even when the update is "we don't know yet when we will know."

7. CONCLUSION: IT'S WORTH IT

On February 22, 2017, NASA announced to the world the Spitzer Space Telescope had revealed the first known system of seven Earth-size planets around a single star, TRAPPIST-1[7]. Besides being an incredible science result, the story and image were column 1, above the fold in the New York Times and later than day TRAPPIST-1 was the Google doodle. No one could have predicted that Spitzer's most impactful science result would come in the 14^{th} year of the mission, more than 8 years after completion of the prime mission. It was a wonderful reminder that while operating space observatories well past their prime mission lifetime can be difficult, they can and do still produce amazing science.

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