The WISE satellite development: managing the risks and the opportunities

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ABSTRACT

NASA's Wide-field Infrared Survey Explorer (WISE) MIDEX mission is surveying the entire sky in four infrared bands from 3.4 to 22 micrometers. The WISE instrument consists of a 40 cm telescope, a solid hydrogen cryostat, a scan mirror mechanism, and four 1K x1K infrared detectors. The WISE spacecraft bus provides communication, data handling, and avionics including instrument pointing. A Delta 7920 successfully launched WISE into a Sun-synchronous polar orbit on December 14, 2009. WISE was competitively selected by NASA as a Medium cost Explorer mission (MIDEX) in 2002. MIDEX missions are led by the Principal Investigator who delegates day-to-day management to the Project Manager. Given the tight cost cap and relatively short development schedule, NASA chose to extend the development period one year with an option to cancel the mission if certain criteria were not met. To meet this and other challenges, the WISE management team had to learn to work seamlessly across institutional lines and to recognize risks and opportunities in order to develop the flight hardware within the project resources. In spite of significant technical issues, the WISE satellite was delivered on budget and on schedule. This paper describes our management approach and risk posture, technical issues, and critical decisions made.

Keywords: WISE, MIDEX, Management, Risk Management, Cryogenic Mission, Infrared

1. INTRODUCTION

Managing the development and delivery of a cost-constrained space satellite, using contractors for hardware development or in an "out-of-house mode", is a challenge that requires the dedicated efforts of many people, coordination across many organizations and extensive attention to resource allocations and expenditures. The following example cases from the development of WISE explores three successes of management of such out-of-house projects: 1) A seamless organizational environment amongst contractors engenders a system-level point-of-view and a commitment to joint ownership, 2) team efficiency is maximized by minimizing the time without a plan, and 3) managed risks create opportunities – once a clear understanding of risk types is attained.

For orientation the following is a short description of the WISE satellite.[1,2] The WISE mission is to complete a survey of the entire sky in four infrared bands between 3.4 to 22 micrometers. The WISE satellite is composed of two elements: 1) the instrument payload developed by Space Dynamics Laboratory (SDL) and 2) the spacecraft bus developed by Ball Aerospace and Technologies Corporation (BATC) and is shown in Figure 1. Project management was performed by Jet Propulsion Laboratory (JPL). The optics train is an f/3.375 system consisting of a 40-cm five-mirror anastigmatic telescope, which is followed by a single axis scan mirror operating in the pupil, which is followed by an imaging optics module and beamsplitter assembly, and finally four 1K x1K detectors (two HgCdTe and two Si:As). Each detector has a unique bandpass filter mounted over the detector substrate. The entire optical system is cooled via a 2-stage solid hydrogen cryostat, which maintains the Si:As detector at about 7K, and the HgCdTe at about 32K, for the ten month mission duration. The spacecraft is 3-axis stabilized and provides attitude control and jitter control by using a combination of 4 reaction wheels, magnetic torque rods, two Ball CT-633 star trackers, an inertial measurement unit , Sun sensors, and magnetometers. No propulsion is used on the WISE satellite. The electronics is based upon a RAD750 single board computer and SW developed by previous BATC programs modified for the specific needs of WISE – such as providing Earth avoidance. A fixed solar panel provides over 500 watts of power. During sun eclipse, a 20 amp-hour lithium-ion battery provides flight system power. Science data and flight system telemetry are stored on a 96GB flash memory card for later transmission to earth. Finally, a fixed high gain antenna is used to transmit data to the Tracking and Data Relay Satellite System (TDRSS).

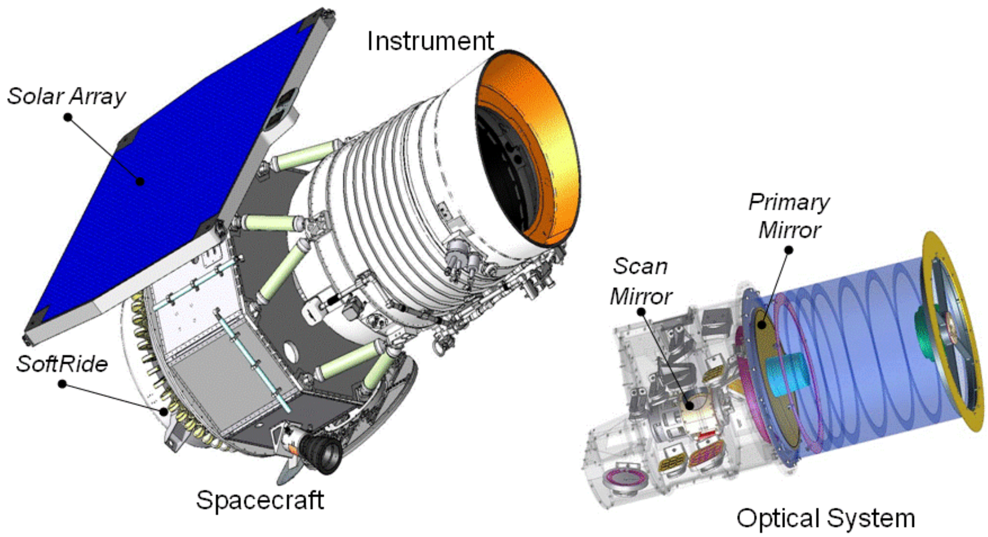

Figure 1: The WISE satellite. The left-hand image shows the spacecraft in gray and the instrument mounted on top via a set of eight bi-pods. The view shows the solar array on the spacecraft. The right-hand image shows the optical instrument without focal planes as if seen with "x-ray" vision. The gold telescope primary mirror is about mid-way down the structure.

2. SATELLITE MANAGEMENT

2.1. Satellite development organization—developing an one for all and all for one attitude

The WISE project organization for hardware development (Ref. Figure 2) was consistent with JPL practices and clearly defined the lines of authority. Each contractor had a single point-of-contact for technical direction. The definition of the contractors' roles and task scope was also facilitated by the intentional effort to keep the interfaces between the instrument and bus as simple as possible. These simple interfaces enabled the payload and spacecraft bus to be developed and tested on independent paths until very late in the schedule, thus allowing each contractor to control-their-own-destiny and time to manage their own problems, independently. As a counter balance to this independent development approach, the project flowed selected satellite system responsibilities to BATC and SDL. BATC was tasked to develop the satellite structural models and SDL was tasked to develop the satellite external thermal models. These system-level responsibilities acted as positive forcing functions for the contractors to think system-wide and eliminated the duplication of effort at JPL.

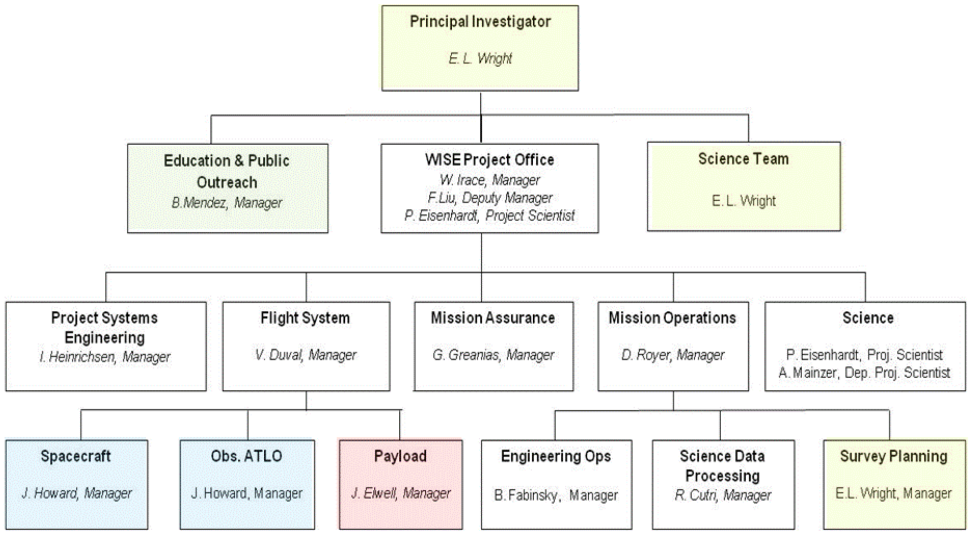

Figure 2: WISE organization chart: White boxes are JPL responsibilities, yellow are UCLA, green is UC Berkeley, Blue is BATC, and Red is SDL.

The WISE project manager actively implemented a culture of broad and open communication between the satellite contractors, JPL, and the WISE scientists.[3] Each month he held a senior management meeting that included the participation of the contractor managers and system engineers. The meeting had a face-to-face format and the location rotated among all the participants' home facilities. The meeting was a forum for discussion of issues that affected the entire WISE mission. A standing agenda item was the review of the financial status, which included discussion of requests for additional funding from the project reserves (i.e., liens). Although the project manager and principal investigator held final decision authority, this review of liens allowed all parties to express their opinion (pro or con) on how project reserves should be spent and engendered a climate of shared ownership of reserves. In other words, giving the contractors more insight into and participation in the overall financial status of the project than was typical, resulted in an atmosphere of mutual commitment to get the job done within the allocated resources, rather than a perhaps more typical experience where each contractor tries to maximize their piece of the reserve pie without consideration of the impact to the overall project. The WISE contractors gained such a strong feeling of reserve ownership that at times they even argued against their own liens! One final benefit of the meeting was that it enabled the WISE team to get to know each other better and thereby increased trust. Clearly defined interfaces and scope with open communication and shared information led to a common vision for the development of the WISE satellite.

2.2. Planning and team efficiency—lessons in making lemonade

The early phases of the WISE development suffered from multiple NASA imposed changes in implementation and funding profile. Although WISE proposed and was selected to be launched on a Taurus launch vehicle, NASA directed the project to switch to launch on a Delta II rocket mid-way through Phase B (at the time of the system requirements review).Since the Delta had significantly greater launch capacity than what WISE required, NASA desired WISE to find another satellite with which to co-manifest (i.e., share the launch). Rockets are very expensive and it is understandable that NASA would want to maximize the return on investment, but given its complex and hazardous cryogenic launch operations, WISE appeared to be a particularly poor mission to try to co-manifest. The WISE team did like the idea of a Delta launch (the vehicle has a significantly longer launch history than Taurus), with the co-manifest requirement we had been given a very large lemon of a problem. Rather than waste time arguing with NASA that WISE would be difficult to co-manifest, the project directed that we quickly create a plan assuming co-manifest, which started with reviewing all the potential co-manifest partners and at the same time continue work on the long lead procurements of detectors and optics. This meant the contractor teams could still make progress in areas unaffected by the change in launch vehicle, i.e., maintain efficiency. In fact a potential co-manifest partner was identified and good faith cost estimates and schedules were generated assuming the co-manifest. However, these cost estimates showed that between satellite re-designs, a more complex co-manifest payload attach fitting (PAF), the additional time that WISE waited for the other mission to ship to the launch site, and the longer launch operation needed to simultaneously ready two satellites for launch it would actually cost NASA more than the two separate launches. NASA correctly directed both missions to return to separate launches with WISE staying on the Delta II. Unfortunately, the co-manifest partner project was later cancelled. For the pain of having to try an implementation approach that would not work, we suddenly gained enormous mass margins.

Even though WISE made good progress after the decision to not co-manifest, in 2005 and 2006 NASA was forced to cut our funding in half, half way through each year. Each funding cut gave the project a lemon of a problem. After each cut the senior management team quickly put together a re-plan that in general favored continuing development as much as possible of the higher risk payload and slowing down development of the bus. The open participation of the contractors in these re-plans enabled each team to understand the full scope of the issues and to have ownership of the solution. However, given that the absolute level of funding in these two years was reduced the entire project slowed down and launch was slipped a total of 16 months to November 1, 2009 with the bus schedule showing upwards of eight months schedule margin. Even in adversity, by quickly developing new plans, the project was able to continue to make progress and maximize the efficiency of the team.

Beginning in 2007, the WISE funding stabilized and the satellite development was progressing very nearly on plan. Then in February 2008 disaster struck. A high fidelity flight-like instrument payload simulator called the thermal-mass dynamic simulator (TMDS) which implemented the payload fiberglass tube support structure and external thermal properties failed during structural vibration testing (Ref. Figure 3). One of the fiberglass tubes had failed and these tubes. were from the same flight lot as the ones in the $20M flight cryostat that was nearing delivery to SDL. The failure called into question the flight worthiness of the cryostat and hence the satellite. The project had another lemon of a problem. As the payload structural engineers started investigation into the failure, the senior management team started to re-plan. The question was how could the spacecraft bus development continue without the TMDS which was needed to for the structural verification test. We needed to separate the TMDS problem from the spacecraft development. Here's when the team realized that the eight months of bus schedule margin really was lemonade. The decision was made to consume reserves and BATC's schedule margin and have BATC develop an instrument mass simulator (IMS) that would be used for the satellite structural verification (Ref. Figure 4). On a parallel path, the root cause of the TMDS failure pointed toward an error in the analysis of the fiberglass which resulted in weaker than expected tubes, the decision was made to use some of our enormous satellite mass margin to incorporate a SoftRide into the satellite and lessen the launch loads on the flight cryostat enabling it to fly as is (Ref. Figure 1). (Rebuilding the cryostat was not an option given the large cost and 20 months time needed.) So, as an outgrowth of the project aggressively working prior lemons into lemonade, the project was able to recover from a potentially mission cancelling failure without additional funding or launch slip.

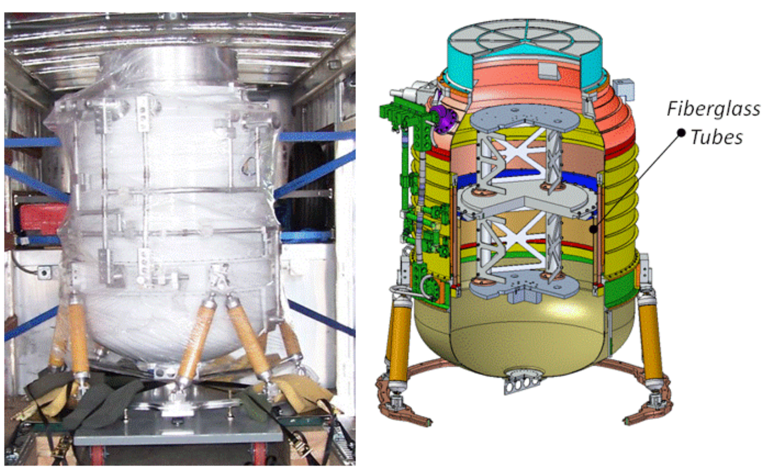

Figure 3: The thermal mass dynamic simulator (TMDS). The right-hand cut away image shows the optical mass simulator (grey) mounted on the concentric set of fiberglass support tubes which run just inside the TMDS outer shell (yellow).

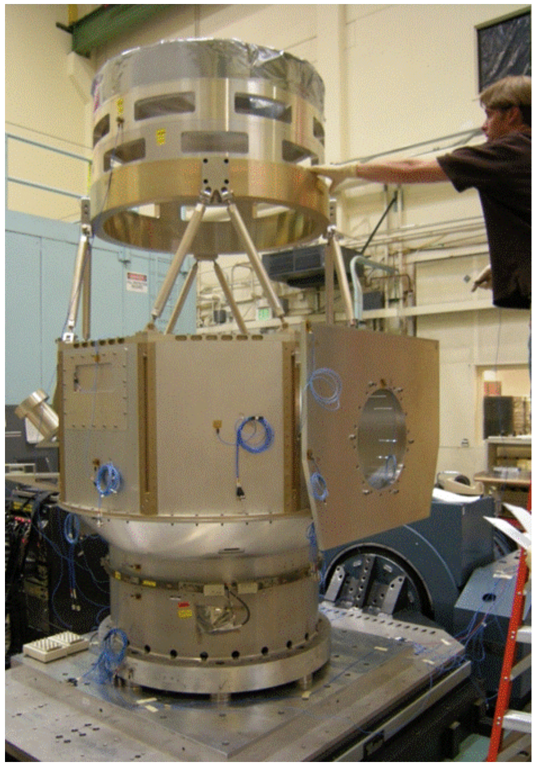

Figure 4: Structural testing with the instrument mass simulator. The bus structure includes mass simulators for the solar arrays and other assemblies and electronics boxes.

3. RISK MANAGEMENT

3.1. Managed risks create opportunities—look beyond the process

WISE implemented a risk management program consistent with JPL requirements and the NASA's mission risk classification (Class C) which defines a set of looser risk criteria and allows for example, the mission to fly essentially single string. The risk management policy established for WISE was: 1) To identify and fully mitigate risks to personnel safety, 2) To identify and mitigate to Low mission risks, i.e., risk to achievement of Level 1 performance requirements, 3) To identify and mitigate to Low programmatic risks, i.e., risks to project completion within the cost cap and other programmatic commitments, and 4) to reduce to minimum/acceptable levels risks which cannot be reduced to Low risks. The Project Manager was responsible for risk management and he created a project level risk list that was maintained by the him. On approximately monthly intervals, the senior management team would review the risk list, update progress on mitigations, assign any needed additional mitigation actions, and discuss potential additions to the risk list. Each contractor followed its own internal risk management process and potentially significant risks were forwarded to the project level risk meetings for discussion on inclusion on the project-level risk list.

So, on paper the WISE risk management process appeared to be a fairly typical process. The difference came with how we a rated risk and then how we handled mitigation of Mission Risks vs. Programmatice Risks. Overall the project did a good job in rating the risks, so that risks rated Low received lower priority and less mitigation, which saved the project both time and money. Effort for mitigation of Mission Risk was always to reduce the level of risk and was never knowingly to allow mission risk to increase. Converesly, sometimes Programmatic Risk was allowed to increase for a period of time if ultimately the risk could be mitigated to a lower level. An example of this short term acceptance of higher programmatic risk was a decision to defer testing of an item to a higher level of assembly in order to maintain schedule. In other words, we accepted a higher programmatic risk of a cost/schedule overrun in the future if a problem was reveled in the higher level test in order to maintain the current cost/schedule. Of course the devil was in the details in making these risk decisions. The following sections provide specific examples of risk decisions from the WISE satellite development (both mission and programmatic) to help illuminate how to create opportunity by managing risk.

3.2. Limited satellite redundancy—sometimes you need a belt and suspenders

At the mission preliminary design review, we presented a fully single string WISE spacecraft, while the instrument had redundant scan mirror electronics, redundant cryostat vent valve actuators, redundant cover release actuators, and graceful degradation of performance where each detector output had a separate, independent signal chain (a total of 40 signal chains!). The review board correctly noted the implementation of redundancy was somewhat out-of-balance between the instrument and spacecraft and the project should look for high value areas that could be made redundant on the bus. So the project took a more critical look at how mission risk could be reduced by the addition of targeted redundancy in the spacecraft bus. Additionally, we still had large mass margin so we did not need to limit our thinking due to resource limitations. WISE attitude and basic pointing of the instrument for science observations is controlled by the spacecraft. The spacecraft also keeps the sun and earth out of the WISE instrument which runs at 17K. Unintentional viewing of the sun would damage or destroy the WISE optics, so the spacecraft attitude control and determination subsystem (ADCS) performance was critical to the accomplishment of the WISE mission (Level 1 requirements). Two high value low implementation risk modifications to the ADCS were found. The first was the addition of a second star tracker and the second was the addition of a fourth reaction wheel. The inherited WISE software already assumed two trackers and four wheels, so there adding the additional hardware was not a large impact to flight software development. Other changes were increased solar array size, increased battery size, and adding support at BATC and JPL to develop and test a sensible fault protection response system. So, the policy for continuous effort to reduce mission risk gave us the opportunity to add targeted high value redundancy and enhancements to the spacecraft.

3.3. Trading a RAID for a FMC—sometimes you need to go for the bird in the field

WISE proposed a redundant array of independent disks (RAID) as a relatively inexpensive large (160GB) mass memory storage unit for science data. Although, this technology had real flight heritage, the assemblies were mechanically complex. A RAID was comprised of two counter rotating stacks of memory disks that had to be mounted in a pressurized box; counter-rotating to cancel the momentum in a micro gravity environment and pressurized to provide the one atmosphere environment required for the disks to operate. Of course, there had to be cabling into and out of the pressurized box to allow power and data in and to get the data back out. Overall, the RAID was a difficult technology with which to work and had a broad range of reliability estimates. So an alternative to the RAID was explored as part of our effort to reduce mission risk in the spacecraft. The search revealed a flash memory-based mass memory card (FMC) that had been developed for the International Space Station but had not flown. (Yes, this is the same flash memory technology as the "stick" you carry around with your computer.) A developmental unit had been through qualification testing. The FMC was attractive since it was entirely solid state with no moving parts and no need for pressurized boxes. The cons were that it had no flight heritage and there were questions regarding how much ionizing radiation the flash memory chips could handle and whether there were lifetime issues with the number of "reads" that could be put on the chips. Working with the FMC vendor, SEAKR, the radiation and lifetime questions were satisfactorily addressed for WISE and sufficient residual flight lot flash memory chips were available at SEAKR to build a 96GB FMC for WISE. This was just big enough to meet the memory requirements for the mission. So the decision came down to do we stick with a proven but still risky technology or move an unproven but robust technology. After lengthy senior management team discussions the decision was made to switch to the FMC. Several key points tipped the decision to the FMC. First SEAKR was a very motivated vendor and had provided very high quality responses to our questions and with BATC had developed a nicely detailed development plan. Second, given the capability of the SEAKR engineers, BATC reduced its level of support system engineering for the FMC making the FMC more affordable. Third, SEAKR agreed to a firm fixed price contract which provided some containment of the programmatic risk. So the potential reduction in mission risk (by switching to a high reliability technology), outweighed the increased programmatic risk associated with developing and testing the FMC for flight. Once again we had created the opportunity to decrease mission risk. In the end, the FMC was delivered in an acceptable time-frame and has performed without problem during testing on the ground and while in operation on-orbit.

3.4. EMI/EMC testing vs instrument performance—all things happen in good time

High sensitivity, low noise detectors (such as those onWISE) have a susceptibility for picking up additional noise through conducted and/or radiated electromagnetic emissions from elsewhere in the satellite. Good electro-magnetic interference and compatibility (EMI/EMC) performance must be designed-in at the beginning of a project as there are limited fixes that can be made to reduce emissions or decrease susceptibility of a set of electronics after fabrication. Ultimately WISE instrument performance was dependent on good EMI/EMC design. To help review and design the detector noise rejection approach, we brought in appropriate experts from the Spitzer instruments development. In situations like this, projects will develop test plans that will expose problems at the lowest level of integration possible and the proposed WISE test plan for EMI/EMC testing provided for a set of tests from lower to higher levels of satellite integration. In broad outline, the plan was to first test the integrated payload electronics boxes, then test again at the integrated spacecraft with the TMDS level, and finally test the integrated satellite with the flight instrument cold. When the TMDS failed, any schedule for the EMI/EMC test with the TMDS was consumed by the recovery from the failure. Now the decision before the project was to either stretch the schedule and perform the TMDS level EMC/EMI test or eliminate the test and only perform the final integrated satellite test. This is really a decision of programmatic risk not mission risk, since the full-up integrated satellite test was still in the plan and any problems with detector noise pick-up would be exposed then. EMI/EMC testing is an art that is highly dependent on the actual configuration of the hardware. In talking with the EMI/EMC experts, they shared that in their experience subtle problems are often not revealed in lower level testing and only come to light at the highest level of integration in the most flight-like configuration. Given this experience, the project decided to forego the TMDS-level EMI/EMC test and accept the higher programmatic risk of waiting to test and confirm good detector performance at the most flight-like integrated satellite level with the instrument cold. As the project manager put it, even if we had seen an indication of a detector noise problem in the TMDS level test, we would have probably waited for the full-up test to confirm that there was a problem. By accepting increased programmatic risk, we created the opportunity to maintain the project cost and schedule. Indeed, the lowest detector noisesseen during any system test were those measured during the full-up integrated satellite EMI/EMC test with the instrument cold. Figure 5 shows the WISE satellite in the EMI/EMC chamber in preparation for testing.

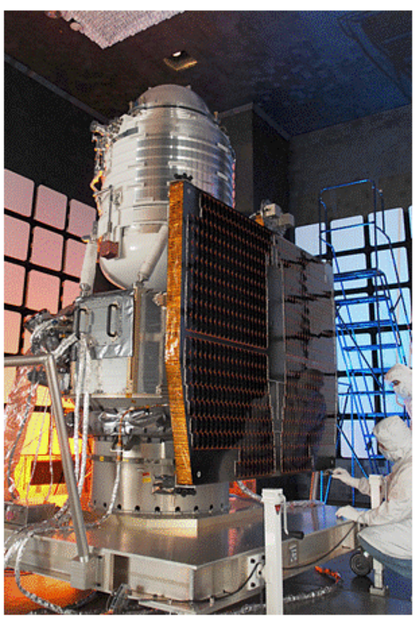

Figure 5: WISE in EMI/EMC chamber

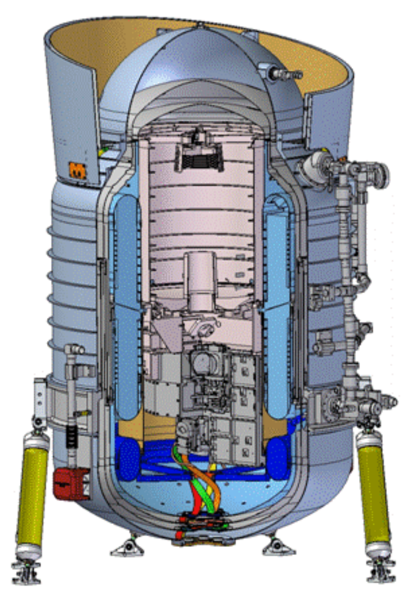

Figure 6: Cryostat cut-away showing H_2 tanks; Primary (dark blue) Secondary (light blue)

3.5. Improved cryostat venting—it is better to be safe than sorry

The payload is cooled by a two-stage solid hydrogen (H_2) cryostat, this means that the cryostat has two tanks holding frozen H_2 with the secondary tank (big one) providing thermal shielding for the primary tank (small one) (Ref. figure 6). The primary tank cools the Si:As detectors to about 7.8K and the secondary tank cools the rest of the instrument to about 17K. Over the course of the mission the H_2 sublimates into gas which needs to vent to space. This venting inputs a torque into the WISE satellite that must be offset by the spacecraft's ADCS. Not surprisingly, given the difference in their sizes, the vent torque from the secondary tank is much larger than the vent torque from the primary tank. The magnitude of the torque(s) is also dependent on the heat input into the instrument, so that erroneous pointing that allows additional heat from the earth or sun into the instrument aperture will increase the total momentum due to venting on the satellite. A prior heritage mission to WISE called the Wide-field infrared explorer (WIRE) suffered a mission ending run-away venting event that was initiated by additional heat entering the aperture of the instrument from the earth[4]. Given this past history, the WISE team was determined to ensure that such a mission failure would not happen to WISE. Early analysis indicated that the WISE ADCS could recover from torque induced through a simple open-ended vent pipe under most anomalous instrument heating conditions, but not a worst case scenario. Even though this worse case heating event was nearly a physical impossibility, the fact that WISE would likely not recover made the team nervous. Also during management discussions, it was noted that given the WIRE history, WISE would receive extensive NASA review of the cryostat vent implementation. Based on all these considerations, the project manager decided that even though the mission risk due to a run-away venting event was low, we needed to mitigate the venting risk to a level that enabled survival of the worst case scenario. Luckily, the Spitzer team had already designed and implemented a more robust venting approach that WISE was able to adapt and adopt. This required modification of the secondary tank vent to a T-shaped arrangement that included Spitzer-designed diffusing nozzles, so that the torque induced through one-side of the T was mostly cancelled by the torque from the other side of the T. This mission risk might have been mitigated to a lower level than strictly necessary, but sometimes it truly is better to be safe than sorry.

4. SUMMARY

This paper has provided some real-life examples of how the WISE satellite management team, comprised of members at different organizations, worked together to develop a system that was delivered essentially on-cost and on-budget. The contractors were not segregated, but had visibility into the all the WISE resources, which also gave them an understanding of the project's true status showing that a seamless organizational environment amongst contractors engenders a system-level point-of-view and a commitment to joint ownership. The contractors participated in developing re-plans, engendering a sense of ownership, rather than just having new plan imposed upon them. This also lead to creative ideas on keeping the project moving forward, so that team efficiency was maximized by minimizing the time without a plan. And finally, moving beyond the risk management process allows the team to create opportunities for enhancement or cost/schedule savings based on the type of risk.

5. ACKNOWLEDGMENTS

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