APPL

WIRE
Case Study

WIRE Case Study

Introduction

The goal of the WIRE mission was to give new insight into the formation of galaxies, like galaxy NGC 4414 pictured here, and how the universe evolved.

Disaster. The Wide-Field Infrared Explorer (WIRE) mission was meant to study the formation and evolution of galaxies. Its telescope was so delicate it had to be sealed inside a solid hydrogen cryostat. But when, shortly after launch, a digital error ejected the cryostat's cover prematurely, hydrogen discharged with a force that sent the Small Explorer craft tumbling wildly through space.

The mission was lost. The subsequent investigation identified several opportunities, in review and testing, to have caught the fatal design error. Why did we not? James Barrowman's report offers several explanations, including lack of communication across Space Flight Centers, lack of vigilance, even when deviating from full system testing, and insufficient peer reviews.

Responses to the report, solicited from senior managers involved in the development of WIRE, offer competing theories. William Townsend sees particular fault in a complex management structure and misapplication of the Faster, Better, Cheaper mandate. Ken Ledbetter generally agrees, citing "too many players in the game." Jim Watzin, on the other hand, feels technical and inter-organizational excuses mask the real problem: individuals who wouldn't allow others to see their work.

WIRE Failure Case Study

by James S. Barrowman

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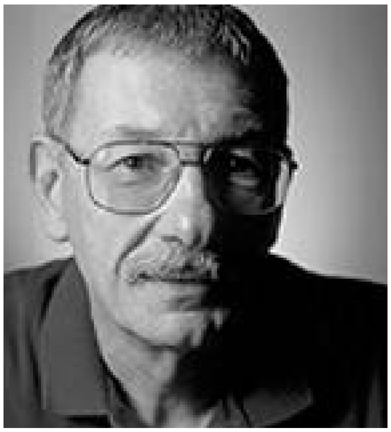


James Barrowman served as a project and program manager at the Goddard Space Flight Center for 22 years, managing Attached Shuttle and Space Station Payloads, the Explorers Program, and the Hubble Space Telescope Program. He was awarded NASA's Outstanding Leadership Medal and twice awarded NASA's Exceptional Service Medal, as well as the GSFC Award of Merit. He has been President of the National Association of Rocketry. Jim was the Explorers Program Manager at the time of the WIRE launch.

The Wide-Field Infrared Explorer (WIRE) mission was designed to study the formation and evolution of galaxies by surveying the sky in the infrared wavelength band for four months. Its instrument was a 30-centimeter telescope feeding Silicon/Arsenic detectors, all encased in a cryostat filled with solid hydrogen. The telescope aperture was sealed on the ground and during launch by a cryostat closeout cover. The spacecraft was a three-axis stabilized Small Explorer (SMEX) bus combining standard SMEX architecture and components with new technologies, such as a composite structure and Gallium Arsenide solar arrays.

The mission failed soon after launch on March 4, 1999 when the cover on the telescope/cryostat ejected prematurely. The uncontrolled heating of the cooler caused the loss of the solid hydrogen cryogen. The cryogen vented. The moment on the satellite caused by the venting overcame the torque authority of the magnetic torquer bars employed to stabilize the satellite. The satellite spun out of control. The WIRE Mishap Investigation found the root cause of the mission loss to be a digital logic error in the instrument pyro control electronics. The variable turn-on characteristics of the Field Programmable Gate Array (FPGA) used in the pyro control circuitry were not adequately considered in the electronics design. The FPGA application for the WIRE instrument did not account for the finite time it takes the FPGA to ramp up at turn-on and establish a stable configuration. That ramp-up time is a function of the time since the device was last powered down, since capacitors internal to the FPGA bleed off their charge. The details of the design issue can be found in the NASAAlert number NA-046-V via http://epims.gsfc.nasa.gov.

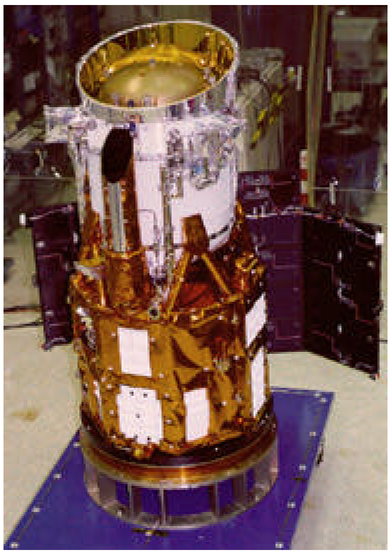
The Investigation Board identified two potential opportunities during the WIRE development cycle to catch the fatal design error in the instrument pyro electronics. The first, and most effective, opportunity was in the design review process. The second, more elusive, opportunity was during the test program.

Mission development activities for the WIRE mission were delegated through three layers of organizations. One NASA Center had overall mission responsibility. A second NASA Center was responsible for the instrument development. The instrument electronics, including the pyro control electronics, was contracted to a third organization. This organizational approach was intended to capitalize on the respective strengths of the organizations. Unfortunately, it also provided the opportunity for communications to be impeded. This, in turn, compromised the degree to which the appropriate level of insight was provided into the instrument electronics design. The project office and the instrument management organization were not able to resolve the level of insight needed for the instrument. Because the instrument was managed by another NASA Center, the project office was encouraged by senior management not to press the insight issue out of respect for the capabilities of the sister center.

The pyro electronics design lagged behind the core instrument design and, therefore, did not benefit from the regular instrument design reviews. Late in the build phase, there was a turnover of instrument managers. There was no overlap between the managers, and the instrument development center had not captured key development information, or provided it to the new manager. While the new instrument manager focused on getting the cryostat delivered, the need for a make-up peer review of the instrument electronics was lost in the transition and did not take place. The WIRE Mishap Investigation Board cited the absence of this review as a significant contributing cause to the WIRE failure.

The WIRE failure root cause was not caught during instrument or integrated systems testing. Because it was impractical to conduct live pyro firing tests in the all-up observatory configuration, the mission team devised a series of piecemeal tests to verify the pyro system. A complete end-to-end test in the instrument itself, blowing the cover using the pyro box and flight harness, was completed before instrument delivery. After instrument delivery, it was not safe to open the cover or the secondary vent; so all instrument testing was done with a pyro test box, all the way to the end of the harness, right at the pyros. While using live pyros at spacecraft level was considered, the instrument team did not have extra pyros for this purpose, and they felt that they had tested exhaustively at the instrument system level, and testing on the flight instrument in atmosphere would damage it.

WIRE Failure Case Study



The Assembled WIRE Spacecraft

A significant contributor to the failure of the testing was the poor fidelity of the pyro test box. The design of the test box focused more on verifying that pyros received proper current when they were supposed to fire, with little consideration given to verifying that the pyros did not receive current when they were not supposed to fire. The inability to perform complete end-to-end testing should have been a signal to systems engineering and project management to review in greater depth the pyro electronics design, test interfaces, simulations, and test anomalies.

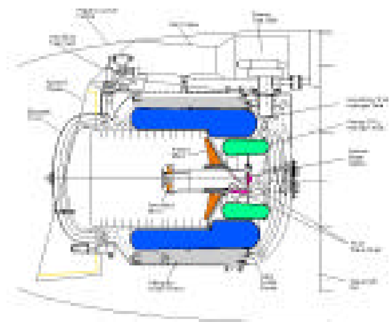
Apparently, the symptoms of the FPGA misapplication did exhibit themselves at least once during testing. However, they weren't recognized as a design problem because they were not there again when the circuit was immediately retested, due to the dependence of the FPGA ramp-up behavior on the time since last power removal. The system was energized every day, so the FPGA internal capacitance never had a chance to bleed off. Prior to launch, this part of the satellite circuitry was off for about two weeks.

A contributory design issue was the placement of the cryogenic vent. The vent itself followed good design practice and had a "T" fitting at the end to eliminate thrust from the venting of the cryogen. Because the thermal loads were much greater than expected, the vent rate was much higher and more forceful than anticipated. Unfortunately, the vent was close enough to another structure that the higher level of venting was deflected by that structure and induced a thrust and moment on the spacecraft that sent it tumbling.

The detailed vent design was never reviewed because it was not done until after the cryostat was built and delivered. The potential impingement problem was noticed by the project systems engineer when the instrument was delivered; but, based on low expected vent rates, the project office decided that it was not prudent to pursue a change four months before launch.

Interestingly, even though its planned scientific mission was a failure, the WIRE spacecraft was recovered by the mission controllers and completed a number of asteroseismology investigations for the Office of Space Science as well as acting as a technology test bed for several advanced technology projects.

WIRE Failure Case Study



A cutaway of the WIRE Cryostat

Lessons Learned

There are six key lessons learned from the WIRE failure:

1. The proper application of Field Programmable Gate Arrays.

- A thorough discussion of FPGA application design guidelines can be found at http://klabs.org.
- Beyond FPGAs, project engineers should have an awareness of the unique initialization characteristics of all modern digital devices.

2. The importance of proper peer reviews of critical mission subsystems and components.

Two considerations need to be addressed about peer reviews.

- A clear definition assures uniform understanding of peer reviews:

  An Engineering Peer Review (EPR) is a focused, in-depth, independent technical review that supports the evolving design and development of a product subsystem or lower level of assembly. The purpose of an EPR is to add value and reduce risk through expert knowledge infusion, confirmation of approach, and specific recommendations. Reviewers should come from bodies both internal and external to the performing organization to provide maximum value through exposure to outside practices and lessons learned. An EPR provides a penetrating examination of design, analysis, manufacturing, integration, test and operational details, drawings, processes, and data, as appropriate.

  The Project Manager (PM) should define and implement a set of Engineering Peer Reviews for the hardware/software subsystems of the system commensurate with the scope, complexity, and acceptable risk of the mission. The mission system should be systematically and comprehensively peer reviewed at the individual subsystem level, and at component ("box") and even lower assembly levels, as appropriate. Multiple peer reviews should be conducted, as appropriate, over the lifecycle of each subsystem and component, with content consistent with the evolving design and development.

EPR's should also be used for the focused evaluation of concepts, designs, plans, and processes associated with combinations of subsystems and system functions that cross traditional subsystem or discipline boundaries. Examples include maneuver planning and execution; fault detection and correction; the end-to-end data path from detection to data archiving and distribution; or solutions to address, for example, pointing, thermal or contamination constraints.

- Project managers must assure people with the proper expertise are involved in the peer reviews. If the organization responsible for the peer review doesn't have appropriate expertise available, the responsible NASA Center should be prepared to provide it.

3. The importance of effective closed-loop tracking of system and peer review action items.

- Most projects, including the SMEX Project, do have a closed-loop action item tracking process. This lesson learned re-emphasizes that project managers must be diligent in assuring such a closed-loop process is in place, functioning properly, and not weakened by outside influences.

4. Greater care is necessary when managing a project across major organizational boundaries.

- Miscommunications and conflicts are much harder to resolve.
- Project managers must be able to turn to senior management to help ensure that inter-organizational conflicts are resolved.

5. Extra vigilance is required when deviating from full system end-to-end testing.

- System-level testing must be thorough. Deviating from full end-to-end system testing is inadvisable, and extra attention to planning, test procedures, equipment, and resolving anomalies is required when doing so.

6. System designs must consider both nominal and off-nominal situations.

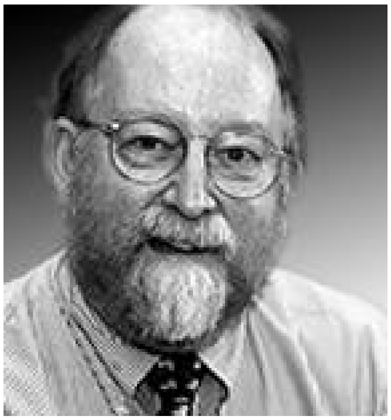
- A thorough Failure Modes and Effects Criticality Analysis (FMECA) is an excellent tool for identifying potential dangers.

Responses

We solicited responses to this case from senior managers at the major units of NASA that were involved in the development of the WIRE mission. All commentators are familiar with the WIRE mission failure. As well as extensive, high-level management experience, they provide personal insight to the case study.

Response #1

by Bill Townsend



William Townsend is Deputy Director of NASA's Goddard Space Flight Center. Townsend's previous positions include acting Associate Administrator of the Office of Mission to Planet Earth, Deputy Director of the Earth Science and Applications Division, Chief of the Flight Programs Branch in that division, and Program Manager for the TOPEX/Poseidon and NSCAT programs.

I remember well the early call I got that March morning from Jim Watzin, the WIRE Project Manager, shortly after the successful launch of WIRE. It was my first such call after having been the GSFC Deputy Director for a year, and having overseen five successful launches up to that point. At the time of the call it still wasn't clear what had happened, but I understood that we had a problem. So, I made the obligatory call to Al Diaz, the GSFC Center Director. That was a call I didn't want to have to make, but he needed to know, even if everything ended up OK. As we now know, that was not to be the case.

A number of us assembled at Goddard on Saturday morning to go over the status of WIRE and to discuss our options. It was clear at the time of that meeting that we had lost the instrument due to the solid hydrogen cryogen having boiled off, sending the spacecraft into a tumble. But we didn't know why. So, the immediate task was to recover the spacecraft from the tumble and then assess the situation to see if there was any understanding that we were missing. We ***were*** able to recover from the tumble. Unfortunately, the rest of the news continued to be bad: there was no doubt at this point that the mission—as originally envisioned at least—was lost. While we were able to use the spacecraft as a sort of flying test bed, the fact that WIRE would not be able to study the formation and evolution of galaxies by conducting an all-sky survey in the infrared band had sunk in, and we were immensely disappointed.

So, what went wrong? It took excellent detective work by the Investigation Board, coupled with some equally excellent work in the lab at Utah State University to replicate the problem, and find that it was a failure to properly design and test the FPGA (Field Programmable Gate Array) circuit in the pyro control circuitry. It had caused the telescope cover to be blown away, letting the sun stare down the telescope's bore sight and boil off the solid hydrogen. Could it have been avoided? Yes. Should we have caught it in the test program? Also, yes. This should never have happened.

Why did it happen? I imagine that others associated with the project will have their own views, but it is my belief that we pushed the faster, better, cheaper paradigm too hard, such that key corners were cut too closely. This, coupled

Response #1

The WIRE Cryostat

with the organizational complexity of WIRE, where it wasn't always crystal clear who was in charge of what, pretty much put WIRE on the slab right from the get-go.

With regard to faster, better, cheaper: one should not assume, because of the WIRE failure or any other failure or extreme difficulty during development or testing, that FBC is not a good paradigm in which to operate. It has been applied well on many missions. The problem, in my opinion, is that the assumption has occasionally been that faster and cheaper are the dominant terms in this paradigm. However, to be successful, better needs to be on the same level as faster and cheaper. Additionally, better, faster, cheaper, does not mean that failure is acceptable. To be successful in this mode, one must not throw out the baby with the bath water. The basic tenets of good design and engineering management practices must be retained, including specifically, such things as high-quality up-front peer reviews; good parts selection, done in balance with the need to hold cost down while at the same time producing a quality product; selective use of engineering test units, when new/difficult designs are being pursued, so that the problems can be ferreted out prior to entering system level integration and test; and perhaps most of all, a serious test program, to where you are before you enter the launch campaign. Unfortunately for WIRE, many of these steps were omitted, in the interest of faster and cheaper, but with insufficient regard for better.

The second major issue was the complex management structure employed during the development of WIRE. GSFC had overall mission management responsibility, JPL had responsibility for the instrument development, and Utah State was the implementing organization for the instrument. Unfortunately, there wasn't as much oversight of Utah State's instrument development process by either JPL or GSFC as there should have been. To understand this, one needs to understand two aspects of this situation. First, our mandate was "insight, not oversight." Everyone was being told to back off and let the implementing organization do its thing with only minimal interference. Like faster, better, cheaper, this guidance was sometimes interpreted in a way that ignored many of the tenets of good management. Sometimes the interpretation of this was do nothing; what "insight" really meant was to

Response #1

not check everything independently, but together, to arrive at a consensus solution. Secondly, WIRE had two NASA centers working on it, one (JPL) reporting to the other (GSFC). Given that either center could have adequately done any of the jobs, professional courtesy dictated neither get in the way of the other. While this was a noble gesture, it did create considerable confusion as to who was in charge of what. Taken together—that is, practicing "insight" in an organizationally confused environment—meant that Utah State got to do things without the checks and balances which are always needed to help folks get out of the forest.

After the Investigation Board finished its work, Larry Dumas, then Deputy Director of JPL, called me and said, "Bill, I just want you to know that JPL accepts full responsibility for the WIRE failure." My initial response was, "No, Larry, you've got it wrong. It was GSFC's responsibility to make the mission a success. We're the ones that screwed this up." By the end of our conversation we agreed that it was all of us that let this happen, and in particular, that it was management—Larry and I and others—that didn't provide the proper perspective for the changes in direction under better, faster, cheaper.

While it is extremely unfortunate that WIRE was a failure, the lessons learned have been tremendous, and there is no doubt in my mind that we (GSFC) are a vastly improved organization as a consequence. As I write, we have just conducted the 26th launch of a GSFC mission accomplished during my tenure as GSFC Deputy Director. We have had 20 launches since the WIRE failure, and I have not had to make another call to Al of the sort that I did on that morning in March of 1999. I hope I will never have to. Certainly, I feel that we have learned our WIRE lessons.

Response #2

by Jim Watzin

James Watzin is project manager for the ICESat Mission, a Pathfinder Earth Science mission. He also continues to lead the development of the Triana Mission. Watzin was one of the founders of the Small Explorer Project, back in 1988, and led the design and development of the initial three SMEX missions (SAMPEX, FAST, and SWAS). Jim was the project manager on the SMEX Project at the time of the WIRE failure.

As with any failure situation one can extract many lessons. The WIRE case study is no exception. But as this study plays out, one can lose sight of the fundamental issues in the multiplicity of technical matters that are discussed.

WIRE failed because people could not or would not communicate well with each other. Why this happened is somewhat rooted within the dynamics of institutional competition and the inevitable conflicts that arise therein. However, the WIRE communication difficulties, though masked by the resultant inter-organizational conflicts, were driven more by individuals who simply were uncomfortable allowing others to see their work. These folks feared oversight and criticism and hid behind the organizational boundaries in order to ensure their privacy. They felt more in control by doing so. But they lost so much. They lost the opportunity for thorough peer review (the first opportunity to catch the design defect) and in doing so they lost the entire mission. Yes, there may have been opportunities to catch this defect in test. But it is highly likely, that even with higher fidelity GSE, or even with full-up end-to-end testing, this defect may have escaped detection due to its subtle nature.

The organizational conflict that surfaced early in the mission development (the second opportunity to catch the defect before the conduct of the mission) was an indication that there could be problems and should have been a signal flare to upper management that the mission was at risk. The real lessons from this loss is that any team member that does not participate as a true team player should be excused, and that management should watch for signs of unnecessary conflict and act to understand it before more serious problems arise. Personnel management is usually a weakness of technical managers, but short of extraordinary good luck, it is one of the most important elements for any successful undertaking.

Response #3

by Kenneth Ledbetter

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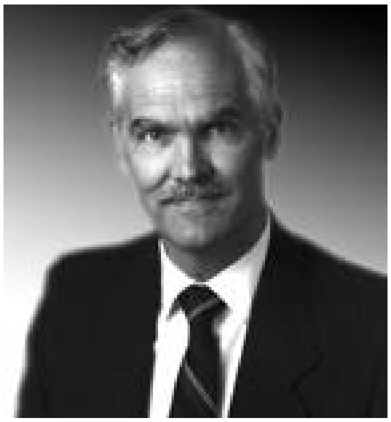

Kenneth W. Ledbetter oversees management of all flight program activities for NASA space science spacecraft as the Executive Director for Programs in the Office of Space Science at NASA Headquarters. During the WIRE development and flight, Ken was the Flight Programs Division Director in the Office of Space Science, with full responsibility for the Explorer Program and the WIRE mission.

The loss of the WIRE mission was a significant blow to the Office of Space Science. Certainly the loss of the WIRE mission data was significant in its own right, but even more significant was the impact on the Space Infra-Red Telescope Facility (SIRTF), the final Great Observatory, which was scheduled to launch a couple of years after WIRE and greatly utilize WIRE data in the planning of its data collection activities. WIRE was intended to be an infrared survey mission, which would locate the high priority infrared targets that would form the basis of subsequent detailed investigations by SIRTF. After the failure, the SIRTF Project was forced to re-design their baseline mission to accomplish the intended WIRE survey prior to beginning detailed target observations. On such a cryogenic mission, the time to conduct this survey will subtract from observations at the end of the SIRTF mission, since the lifetime is limited by cryogen depletion. Therefore the WIRE failure will lead to the effective shortening of the operational life of the infrared Great Observatory.

WIRE was the fifth Small Explorer (SMEX) selected for implementation, chosen along with TRACE from the same Announcement of Opportunity, in the middle of the Faster, Better, Cheaper era. The TRACE mission has performed marvelously, returning detailed close-up images of activity at the sun's surface and astounding everyone with its capabilities and data return achievements. The two previous SMEX missions, FAST and SWAS, likewise resulted in amazingly successful missions, and both are still, today, returning scientific data well into their extended missions. These missions were achieved for a total cost, from design and development through prime mission operations, in the vicinity of $80M, and were generally single string spacecraft built to perform very focused science, usually with a single instrument. The WIRE failure withstanding, these missions have been returning very high science for the dollar.

Being an Explorer, responsibility for overall mission management for WIRE resided at GSFC, who also had responsibility for the spacecraft bus. Being a PI-class mission, proposed by a PI at JPL, the instrument development was wherever the PI proposed it to be, in this case at JPL, subcontracted to Utah State University. With Lockheed Martin developing the cryostat and Boeing

Response #3

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The WIRE telescope can be seen inside the cryostat assembly.

the detectors, there were a lot of players in the game. This should have been a flag to NASA Headquarters, and to GSFC, to pay special attention to the interfaces and intercommunication, but after all, it was only a Small Explorer, not pushing the state of the art in any technology. And we thought we knew how to build these simple spacecraft.

After launch, the WIRE instrument aperture cover was deployed prematurely and the cryogen was depleted in less than a day. A Failure Review Board determined that an instrument design flaw in the pyro initiation circuitry, designed, built, and tested by a subcontractor to JPL was the direct cause of the mission loss. It was also determined that JPL management failed to assure an appropriate peer review and adequate box-level testing of this key instrument subsystem. GSFC management did not validate the peer review process nor uncover the deficient test plan. Subsequent observatory-level testing at GSFC did not have the timing fidelity/resolution to detect this flaw. These errors resulted in a complete loss of the originally intended mission.

In 2000, the NASA Integrated Action Team (NIAT) studied the WIRE case along with the failures of the two Mars missions and the Spaced Shuttle wiring problems before releasing a 100-page report of its findings and recommendations. This report (Dec 2000) flagged shortcuts that were being taken in many cases under Faster, Better, Cheaper, and made numerous recommendations for preventing these types of failures. For one, it recommended a significant increase in Quality Assurance activity on all missions, particularly in the area of risk management, including the expanded use of fault trees and failure modes analyses. It requested careful examination of the use of selective functional redundancy in spacecraft design. It also discussed the importance of communication between project elements, particularly in the case of diversified projects. The NIAT recommendations have led to an increase in the amount of independent review to which a project is subjected before launch.

From the NASA Headquarters perspective, the Explorers Program, and the SMEX projects in particular, have achieved such an overall success that there has not been any significant change in the selection process or in the

Response #3

way the mission are overseen due to this particular failure. Certainly, Headquarters managers may be more inclined to ask questions at reviews and probe into the thoroughness with which the Program Office has conducted its oversight of a given project. But, in the end, these missions are (relatively) inexpensive because we want to maximize the number of flight opportunities we can offer to the science community. To control cost and maintain frequency, we are willing to accept some risk in this category of mission. The trick is to identify and manage the risk through appropriate mitigation activity, and to learn to recognize the border between acceptable risk and unacceptable risk. This isn't always easy to do.

Follow-Up

Here are some links that can provide you with more information on the WIRE mission:

WIRE INFO:
NASA Jet Propulsion Laboratory

NASA Goddard Space Flight Center

NASA Spacelink

NASA PROJECT MANAGEMENT:
Academy of Program and Project Leadership

(Image sources: NASA's Jet Propulsion Laboratory and NASA's Goddard Space Flight Center.)

What's Your Take?

In his comments to the WIRE mission report, Jim Watzin finds fault with individuals who did not want to let others see their work. Is institutional competition always/ever a threat to mission success? Share your experiences and discuss other hot topics in the WIRE Forum.