National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

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Communication Aberration

When NASA launched the Hubble Space Telescope in 1990, astronomers boasted that Hubble would probe the universe to a degree unparalleled by earthbound observatories, and the images it would capture would be of unrivaled quality. Hubble has fulfilled these claims, and the telescope is presently credited with providing data for more than 6,000 published scholarly articles. Fortunately, Hubble's past and current successes now overshadow the debacle in which it was mired during its early years. After Hubble's Wide Field Planetary Camera recorded its first photograph, a voracious press clamored for weeks to see the result. They were met with disappointment. The picture - a severely blurred image of a star cluster in the Carina constellation - fell far short of the crystal representation everyone expected, and a difficult truth became strikingly evident: the telescope was flawed.

BACKGROUND

Optics

The Hubble Space Telescope (HST, Figure 1) has an optical design based on Isaac Newton's reflecting telescope. When light enters the aperture, it bounces from a concave primary mirror to a small secondary mirror that directs the light toward the focal plane (Figure 2). Unlike the Hubble, many reflecting telescopes are built with spherical mirrors because they are easy to fabricate and test for proper curvature. However, such mirrors are prone to spherical aberration, meaning they fail to direct incoming light to a single focal point, resulting in a blurred image (Figure 3). The shape of HST's primary and secondary mirrors is designed to be hyperbolic, eliminating aberration and substantially improving technical performance. Aspheric mirrors such as the ones in HST are much more difficult to fabricate and test than spherical ones and must be crafted with extreme precision.

Mirror Fabrication and Null Testing

Technicians fabricate aspheric mirrors by placing glass discs through repetitive polishing cycles that gradually wear away material until the disc conforms to the desired shape. At several intervals during the polishing procedure, technicians check the mirror for proper curvature by conducting a null test. Null testing requires a null corrector and an interferometer. Null correctors have many variations, but they are simply lenses used to compensate for the mirror's asphericity, i.e., the lenses create an optical template that allows technicians to compare the mirror with a projection of its desired shape. Interferometers allow technicians to analyze the mirror's curvature by producing results known as interferograms that show discrepancies between the mirror being tested and the projected optical template.

Figure 1: Hubble's vantage point in low-earth orbit allows it to collect a wider range of wavelengths than ground-based telescopes, and the images it captures are free from the atmosphere's distorting effects.

Reflective Null Corrector

One drawback of the commonly used refractive null corrector is the difficulty of performing unambiguous tests to determine that the corrector is producing the appropriate optical template. Furthermore, lenses used in the null corrector can contain variations and imperfections within the glass, limiting lens accuracy. To address these issues, Perkin-Elmer (now Raytheon Danbury) eliminated the large lenses typically used and developed a reflective null corrector (RNC) that used two mirrors and a small field lens to project the image of the calculated curve. Using these elements, Perkin-Elmer would be able to predict the shape of the optical template simply by knowing the dimensions of the mirrors, the dimensions of the field lens, and the spacing between the three pieces.

Optical Systems Failure on Hubble Cripples Data Collection

Proximate Causes:

- Manufacturer of primary mirror polishes mirror into the wrong shape
- Light rays falling on mirror's surface converge at multiple focal points, causing images to blur

Underlying Issues:

- Poor risk identification and mitigation
- Inadequate communication
- Insufficient test validation
- Distraction

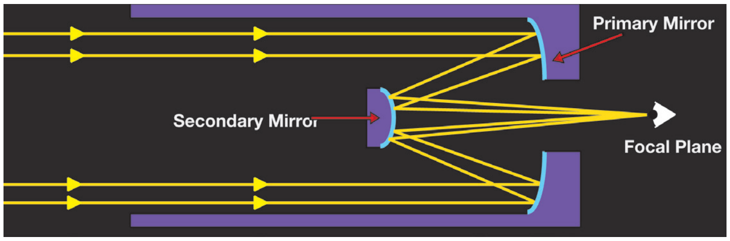

Figure 2: Light path through a reflecting telescope

Sample Mirror Fabrication

Before choosing a prime contractor to design and develop the optical telescope assembly (OTA), NASA tasked the two major competitors, Perkin-Elmer and Eastman Kodak, to fabricate and test a smaller version of the 2.4-meter primary mirror to demonstrate technical competency. Eastman Kodak fabricated and tested the sample mirror using conventional methods. Perkin-Elmer used a new computerized device called a Draper-style polisher to polish the mirror. The company then tested the mirror's curvature with the RNC. In its proposal, Perkin-Elmer stated that the RNC would serve as the principal testing device for the primary mirror. Perkin-Elmer did not plan to test the RNC independently; instead it would depend on careful certification of the components and precise assembly of the apparatus.

NASA, attracted by Perkin-Elmer's elegant plan of predicting the optical template based on RNC element spacing, its low projected contract costs, and its matrix organization, awarded the firm with the prime contract for the OTA in 1978. However, according to the HST Optical Systems Failure Report, NASA directed Perkin-Elmer to subcontract Eastman Kodak to fabricate and test a backup primary mirror. When both mirrors were complete, NASA would review each mirror's specifications and choose the best one for flight.

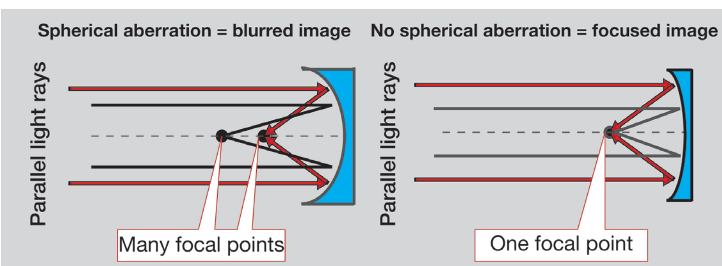

Figure 3: The diagram on the left depicts a spherical mirror directing light rays to several points of focus. The aspheric mirror depicted on the right eliminates spherical aberration by directing light rays to a single focal point.

WHAT HAPPENED?

Null Corrector Adjustments

After completing shape testing on the small sample mirror, Perkin-Elmer needed to re-space the optical elements and replace the field lens in the RNC to create the correct optical template for the primary mirror. Since accurate spacing was critical to the project's success, the technician used a metal measuring rod (called a B Rod) to ensure correct spacing between the lower mirror and the field lens. The B Rod had a field cap attached that prevented the rod from moving laterally. The field cap was coated with non-reflective material because the technician would later use an interferometer to shine light through a hole in the field cap. The light would reflect off of the end of the B Rod and back into the interferometer. The resulting measurement would verify that field lens placement matched calculations.

According to the HST Optical Systems Failure Report, some of the non-reflective material coating the field cap's exterior had chipped off. When the technician measured the spacing, the interferometer's beam reflected off of the field cap instead of the B Rod, resulting in an erroneous reading (Figure 4). Therefore, when the technician attempted to position the field lens based on the reading, the lens would not fit. Pressed for time and assured of the RNC's infallibility, the technician added washers to each of three bolts that held the field lens retainer in place. This forced the lens to fit and altered the prescribed spacing by 1.3 mm – a colossal deviation in a device whose measurements depended on precision up to millionths of an inch. Nevertheless, the technician chose not to inform RNC designers, metrology experts, or managers of the alteration. Generating a non-conformance report to document the change should have been standard procedure, but investigators later found no evidence that such a report had ever existed.

Vertex Tests and Discrepant Data

Rough grinding for the primary mirror took place at Perkin-Elmer's Wilton, CT plant in 1978. The company then transported the glass to its Danbury facility where it planned to polish the mirror to perfection. This shaping and polishing process would continue until May 1981. The launch date, originally slated for 1983, was rescheduled several times as NASA and its contractors wrestled with unforeseen difficulties in balancing the telescope's technical requirements and budgetary constraints.

Late in the polishing process, Perkin-Elmer measured the primary mirror's center of curvature using a refractive null corrector and an inverse null corrector. The resulting interferograms had wavy lines – outcomes that contradicted the interferograms from the RNC (Figure 5). However, because the optics fabrication group at Perkin-Elmer considered the refractive and inverse null correctors to be less accurate than the RNC, it discounted the data and did not attempt to resolve the discrepancy. In a report to Congress, William Colvin, NASA's Inspector General, indicated that those results "concerned Perkin-Elmer managers, but they did not disclose the results or their concerns outside of the optics fabrication group . . . to our best determination, Perkin-Elmer did not share the discrepant results of the vertex test with NASA."

After the mirror was attached to its 3-point flight mount, it was tested many times with a refractive null corrector. Each time, results disclosed an error. Engineers postulated that the error could be at-

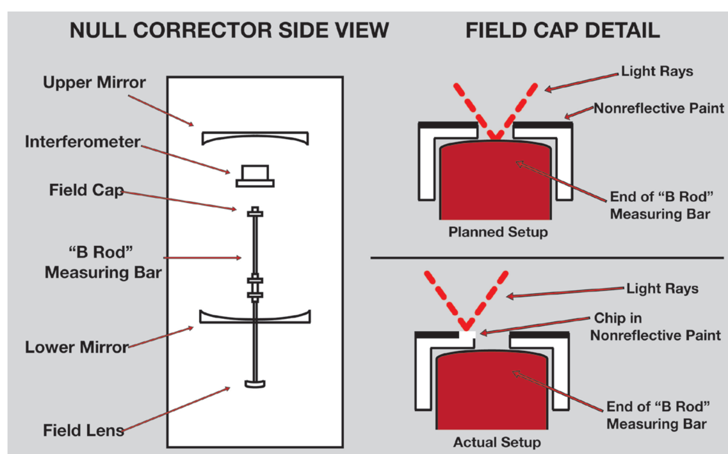

Figure 4: The RNC was designed to allow scientists to predict an optical template based on RNC element spacing, but damage to the field cap caused an erroneous reading that led technicians to make unauthorized adjustments to the RNC.

tributed to a sag in the mirror caused by Earth's gravity. Each time the mirror had been tested before, it had been lying flat on a 'bed of nails' to simulate zero g conditions. Engineers calculated that the error in the null test corresponded to the error induced by the sag from gravity. Investigators later discovered that this calculation was wrong, but no further steps to resolve the test outcomes had been taken.

Launch and Letdown

When Perkin-Elmer finished the OTA, RNC tests indicated the mirror exceeded NASA's requirements. The next step would be to integrate the OTA with the support systems module. The telescope would then be ready to launch in the second half of 1986. But in January of that year, NASA grounded the Shuttle fleet in the wake of the Challenger disaster, delaying Hubble's launch four more years. Finally, on May 21, 1990, the telescope opened its aperture for first light. Back on Earth, an impatient press relentlessly demanded to see photographs. They waited weeks for an answer. When NASA finally called a press conference in June 1990, it had no spectacular images to present, and its news was the antithesis of all expectation: despite the thousands of hours and billions of dollars invested, the telescope suffered from the most basic of errors – the primary mirror was the wrong shape. Its curvature differed from the calculated shape by 1/50 the width of a strand of human hair, enough to introduce spherical aberration. The images were blurred, and the distant wonders it was supposed to catalogue would remain out of reach a while longer. NASA scientist Ed Weiler summarized the problem succinctly: "the Hubble is comparable to a very good ground telescope on a very good night, but it's not better than the best."

PROXIMATE CAUSE

NASA established the Allen Commission to investigate, and the findings implicated the 1.3 mm misplacement of the field lens. The misplacement caused the RNC to project the wrong optical template. Then, the computerized polisher, which shaped the mirror based on the RNC's output, polished the mirror into a hyperbola that was slightly too flat near the edges. The incorrectly shaped mirror failed to direct incoming light to a single focal point, blurring each image before it reached the camera.

UNDERLYING ISSUES

Managerial Failures

The Allen Commission attributed the technical shortcomings to management errors, both at Perkin-Elmer and at Marshall Space Flight Center (MSFC), which had been assigned as project lead. The errors in configuring the RNC took place at a time when the HST project was beset with financial difficulties and faced significant political and schedule pressures. These problems distracted managers at NASA as well as at Perkin-Elmer, and supervisors neglected to oversee work on the primary mirror. Escalating costs and delayed timetables overwhelmed managers to the point that they failed to identify and mitigate risk, enforce quality assurance procedures, and maintain good communication within the project. These shortcomings led to a breakdown in the design process where individuals on different levels made decisions based solely upon the unverified assumption that the RNC could not be wrong.

Risk Identification and Mitigation

In its proposal, Perkin-Elmer clearly stated it would rely exclusively upon the RNC to determine the primary mirror's curvature. Hence, the mirror's performance would rest on RNC component tests and precise assembly. Before accepting the proposal, NASA should have recognized that such a process was susceptible to error and demanded independent validation of the RNC. The Allen Commission further asserted that a formal procedure such as a fault-tree analysis might have called attention to the risk of using an incorrectly configured RNC.

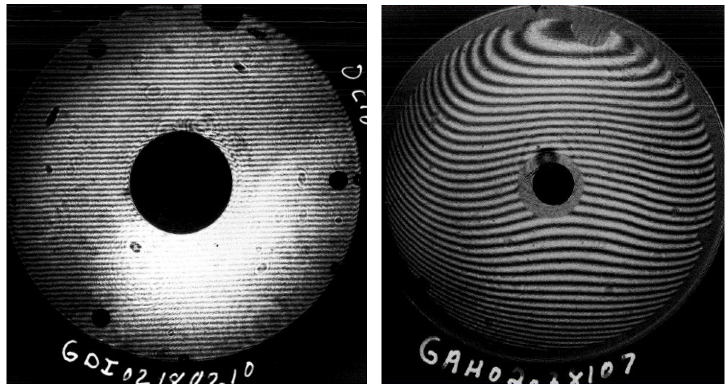

Figure 5: The interferogram on the left came from the RNC. The straight lines indicate no interference, meaning the mirror matches the optical template. The interferogram on the right came from the inverse null corrector. The wavy lines indicate interference resulting from errors in the shape of the mirror.

Although many managers did not appear to have considered the risk of an error in the RNC, a few employees at Perkin-Elmer did. On May 21, 1981, a technical advisory board made up of a group of Perkin-Elmer's senior scientists advised the firm's vice president to perform independent tests on the primary mirror "to uncover some gross error such as an incorrect null corrector." However, once the advisory group identified the risk, the vice president chose not to follow its mitigation strategy, presumably due to cost and schedule. The independent tests were never performed.

This decision proved costly when Perkin-Elmer's optics fabrication group discovered and discounted the data that contradicted the RNC's results. Employees assumed the flaw was not in the mirror or in the RNC, but in the refractive and inverse null correctors. If the group had taken time to resolve the discrepancies between the tests and determined the source of the error, they almost certainly would have identified the mistake.

Inadequate Communication

The official mishap investigation board reported that throughout its duration, the HST project experienced cost and schedule issues of "crisis proportions." These pressures, inevitably, were imparted to contractors. Possibly believing issues further increasing costs or delaying schedules could instigate contention, contractors began reporting only the risks they thought were real. Because the discrepant test results were thought to be inaccurate anyway, Perkin Elmer excluded them from its report.

A second crucial communication breakdown occurred when the technician failed to notify others of the washer modification even though it deviated from the planned setup. If the technician had documented the alteration or alerted supervisors of the change, the knowledge may have led metrology experts to take steps that would have allowed them to identify the error. The culture at Perkin-Elmer at the time, however, made it easy to forego communication protocols. Perkin-Elmer allowed the division where the mirror was fabricated to operate in a closed-door environment, restricting communication and preventing problems from being reviewed. This situation stemmed in part from the fact that while Perkin-Elmer was shaping Hubble's primary mirror, it was also fabricating spy satellite mirrors for the DoD. Because of the ongoing military contracts, the Pentagon sought to limit NASA's penetration of Perkin-Elmer, thereby reducing the risk of exposing technological secrets. DoD only allowed 15 people to obtain both appropriate security clearance and USAF permission to enter the facility. Unfortunately, of the SMA personnel who were on site, no one had enough technical background in optics to realize the depth of the problems that were occurring with Hubble's mirror.

To complicate matters, Perkin-Elmer opted not to allow its own quality assurance team into the work area at critical times during the mirror's production, fearing its presence would inhibit data collection and analysis. Furthermore, the quality assurance personnel that eventually evaluated the mirror had limited expertise in optics and reported to the same mangers they were supposed to be monitoring. Such circumstances left lapses in production processes, such as poor communication and poor management, unchecked.

Distraction

In addition to the challenge of polishing a perfectly shaped mirror for the Hubble, Perkin-Elmer wrestled with the problem of designing a fine guidance system (FGS) that would meet Hubble's stringent pointing and control requirements. MSFC described the requirement this way: "if the telescope were in Washington D.C., it could focus on a dime in Boston and not stray from the width of coin." Center labs worked with Perkin-Elmer on the FGS, and NASA managers, rather than pressing for problems related to the mirror, focused efforts, questions, and analyses at the FGS. Hence, NASA managers paid little attention to the mirror, making it easy for Perkin-Elmer to rationalize discrepant test results and gloss over other concerns.

Figure 6: HST recorded the left image prior to the servicing mission that corrected the optical systems. HST recorded the right image after repairs.

AFTERMATH

Perkin-Elmer settled a lawsuit with NASA in which the contractor paid $25 million for witholding test results. In 1993, NASA launched a repair mission that became an astounding success. After astronauts installed new optics to compensate for the error, Hubble exceeded its original performance specifications by 50% (Figure 6). Hubble has now been orbiting Earth for more than two decades, making it one of the longest and most successful science missions to date.

FOR FUTURE NASA MISSIONS

In an industry dominated by engineering and in an Agency endeavoring to expand technology's limits, scientific emphasis can sometimes overrule social contexts. In a discussion concerning Hubble's failure, Dr. Charles Pellerin, former director of astrophysics at NASA, stated that NASA's leaders must also possess "soft skills" to enhance team-building and better identify managerial shortcomings before they result in broken team interfaces and technical mistakes, as they did during the HST project.

NASA's official Optical Systems Failure Report listed key lessons to take away from the HST mishap, and the first of these was to understand the accuracy of critical measurements. In particular, project managers must identify equipment that critically impacts flight hardware quality and reliability. The RNC was not classified as flight hardware equipment, so it did not undergo the same documentation or review that it would have if it had been properly classified. Maintaining rigorous documentation such as this became an additional lesson learned from the HST mishap. Project managers carry the responsibility of ensuring that any documentation that covers design, development, fabrication, and testing is properly prepared, indexed, and maintained. This allows verification that the hardware meets quality standards. The third lesson stated in the report called project managers to ensure clear assignment of responsibility to QA and engineering. These lines became blurred during the HST project in part because QA lacked an independent reporting path to top management and in part because managers lacked clarity as to what QA could and could not do. Finally, project and program managers should always remember the mission during crisis. Under schedule and budget pressure, managers may disregard evidence of threats to mission success in the name of efficiency. Managers must not allow these distractions to inhibit sound reasoning, judgment, and decision-making.

Questions for Discussion

- When faced with mounting cost and schedule pressures, how does your team avoid compromising quality?
- Have you identified positive or negative social factors that could be affecting your team's performance?
- What are some of the strategies you have learned in terms of assessing and managing team social contexts?

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