Hubble Error: Time, Money and Millionths of an inch

By Robert S. Capers and Eric Lipton

Executive Overview

Space exploration has had some serious setbacks. One of the most often mentioned is the Hubble Space Telescope. The drama of that fiasco is a human and organizational tapestry perhaps more complex than the technology involved. The account that follows is excerpted from a Pulitzer Prize-winning series.

On a chilly autumn day in 1978, in an upstate New York factory town Bud Rigby stared at the glass that would dominate his life for the next three years. The stocky man ran his thick fingers gently along the smooth face of what looked like a round, transparent waffle. The sheer size of it thrilled him--eight feet in diameter with a two-foot hole in the center. No one had ever tried what Rigby's employer, the Perkin-Elmer Corporation of Connecticut, expected him to do. He was to use a new technology to turn the one-ton slab from the Corning Glass Works into the finest mirror in the world—the heart of a space telescope. Rigby would have to make sure his team shaved off just the right amount of glass. The difference would be measured in millionths of an inch—and in the millions of dollars in this and other government contracts.

The enormous expectations for the space telescope, perhaps the most complex scientific instrument ever made, rested largely on Rigby's mirror. It would need a curve so fine, a surface so sublimely smooth that it could capture and focus light that had traveled billions of years—light that had left the farthest reaches of the universe even before the stars had formed. The space telescope's minor would have to be so perfect that if its surface were the size of the Atlantic Ocean, no wave could be higher than three inches. On the ground, telescopes couldn't take advantage of such quality because the light that reaches them is already degraded by the earth's atmosphere. So their minors always had been made with a good degree of handicraft, shaped roughly by machine, then polished to their final form by opticians whose work fell somewhere between science and art.

To make the space telescope's main mirror, as well as its 12.5-inch secondary minor, Perkin-Elmer devised a system at its Danbury plant that substantially advanced the science. Lying on a bed of 134 titanium nails to simulate the gravity-free environment of space, the glass would be polished by a spinning abrasive pad attached to a swiveling arm. For the first time, computers would control the speed, pressure and direction of the arm. After polishing runs lasting from six to seventy hours, the mirror would be trundled on rails to an adjacent room so Rigby's team could determine how much closer they had come to the desired shape. For that purpose, the company's top scientists had designed an optical measuring system so precise that they used it only in the middle of the night when there were no vibrations from tractor-trailers rumbling down Route 7 outside the plant. The system, consisting of an instrument called a null corrector and a special camera, was so sensitive the company had to pull out the speed bumps in the parking lot. They even had to shut down the air conditioners when they used it.

The trouble was, NASA designed the schedule and the funding for the program as though space minors this smooth were built all the time. The telescope could be finished on time and on budget only if no problems occurred. Even without problems, Rigby knew, his crew would have to put in some long hours to make the mirror's scheduled delivery in early 1980. When the $1.5

billion Hubble Space Telescope finally was launched in April 1990 and the tenable truth about its misshapen mirror was revealed, these men would be blamed for a fundamental error.

Unkind Cuts

At the Corning factory, little things were already going wrong. The minor was designed like a sandwich, with two 2-inch-thick plates fused to an interior of glass slats arranged in an egg-crate pattern ten inches thick. Inspecting the slats as the mirror was being assembled, another Perkin-Elmer man—David Burch, responsible for quality control—stepped carefully along a wooden board next to the glass. Suddenly the board broke. An alert Corning worker lunged for Burch's shirt and swung him away, keeping him from crashing down into the middle of the slats. Burch sliced his hand on the glass but didn't damage the minor. Then, after the mirror's several parts had been joined in a 3,600-degree furnace, the workers discovered that the round outside band of the glass had fused in several places to the slats inside. This could cause dangerously uneven stresses in the minor, especially during launch: For fourteen precious weeks, Corning technicians tried to cut out the fused glass without harming the surface. Instead of fixing the problem, however, they created a new one, leaving straight-edged grooves where they had cut. Rigby sweated; straight edges could cause cracks that could quickly spread. When the glass finally was trucked in December 1978 to the Perkin-Elmer plant in Wilton for preliminary grinding, Rigby's technicians used acid to eat away at the edges, leaving the glass round. They then used a dental tool to cut out the fused places in the glass. The work was successful, but it delayed the start of polishing.

One spring day in 1979, an inspector halted the grinding. He had discovered a tiny cluster of fissures, a flaw that looked like a quarter-inch-wide teacup. Small, but it could ruin the mirror if not removed. It came to be called the Teacup Affair. First, Perkin-Elmer and NASA engineers argued vehemently for two weeks. Some wanted to go in from the side of the minor, then drill up and under the crack. Rigby, who could out shout just about everyone, was in this camp. He was anxious about leaving a blemish. 'I did not want to cut the face of the mirror,' he said. But drilling from the side would leave glass dust inside the hollow center of the minor. That wouldn't hurt the mirror, but the dust might escape in space and interfere with the performance of the telescope's instruments.

Drilling in from the top and removing a core of glass, including the crack, was risky as well. But it seemed to be the better choice. So Rigby held his breath as an engineer lowered a drilling tool onto the surface of the minor and slowly dug a hole in the glass. "It was like brain surgery," he said. The delicate job was a success; the hole would not go away but it wouldn't affect the mirror's performance. However, the Teacup Affair had cost Rigby another six weeks. A year had been allowed for the rough grinding in Wilton. The mirror had been scheduled for delivery to the Danbury plant for fine polishing in early September 1979; it didn't arrive until late May 1980.

Already Rigby was nine months behind schedule and the hard stuff hadn't even begun—and he was fully aware what delays in the mirror polishing meant. While Perkin-Elmer and Lockheed Missiles and Space Co. held the major contracts, thousands of people in dozens of companies and laboratories around the world were building parts of the space telescope. NASA wrote a schedule to coordinate all their work. Each bottleneck would have a ripple effect, would cost money. One engineering team might have to sit idle, collecting paychecks, waiting for another team to deliver its job. A delay in the mirror would delay assembly of the forty-three-foot-long telescope, delay installation of the scientific instruments, and delay Lockheed's work putting together the twelve-ton satellite. Ultimately, it would postpone the optimistic launch date of

December 1983. Second thoughts and double checking were luxuries this program could not afford.

Lowballed

From the start, Perkin-Elmer was operating without any flexibility because the company had underbid the telescope contract. With its considerable space experience, Perkin-Elmer desperately wanted the business and the reputation it would gain by building the telescope. NASA, although confident about the company's technical expertise, admitted to some concerns about Perkin-Elmer's ability to plan and manage such a complex project. In addition, the company's competitor, Eastman Kodak Company, had proposed two major testing procedures to catch any flaws in the mirror. Kodak proposed to make two main minors using different equipment and then to test each minor with the instruments used to make the other, choosing the better of the two for the telescope. Kodak also proposed testing the telescope's main mirror and its smaller, secondary mirror together before launch. Perkin-Elmer proposed no such testing. However, Perkin-Elmer said it could do the job for $70 million, $35.5 million less than Kodak. For public consumption, the company argued, and NASA concurred, that much of the needed technology already was in hand. But many later described the bid as a partnership in deception by NASA and the company's managers. Perkin-Elmer "had to lie to get the contract. NASA had to lie to get the money," said one key company official. "It was a fable to start with."

Like other government agencies, NASA had winked at underbidding. Richard C. Babish, a former Perkin-Elmer technical director, recalls going to meetings at which U.S. officials would coach corporate officers on winning contracts. The government man would stand up and talk about the game, Babish said, warning that if the company sent a realistic estimate, "Congress will say no. Once the project was approved, the official would explain, the companies could demand more money for unforeseen technical challenges. Yet, by the time work began on the space telescope, Congress no longer was willing to give NASA extra money. In turn, the space agency's top managers became unsympathetic to Perkin-Elmer's pleas, threatening to cancel the project if it didn't stay within budget.

When Donald Fordyce became Perkin-Elmer's telescope project manager in 1982, he found no money budgeted for whole areas of scheduled work. The company wasn't trying to hide the overruns and contract changes that increased its cost, Fordyce felt. Perkin-Elmer had gone to NASA earlier to say that the costs of the contract had quadrupled to $272 million. NASA refused to accept the new figure. The company "just kind of felt snake bit," Fordyce said. "That was the word that was used around the plant. It was like, 'Gee whiz, this program is snake bit. You can't get it done.' "So corners were cut. "You know the thing to do every time you get in trouble with money is kill the spares, cut that other piece of test equipment, then pare yourself down to the point where you're just hanging on by a thread," Fordyce said.

Sleeping on the job

In Danbury, Rigby eventually had to put the mirror polishers on back-to-back ten-hour shifts. Rigby tried to be forthright about the time he would need to do the work, but whenever he sent a schedule to management it was cut in half before it even reached NASA. The crew would polish for days, then move the mirror to the testing room to find out how well they had done. Then they would get a new set of computer instructions and start the next run. Under pressure from Perkin-Elmer and NASA, Daniel J. McCarthy, Rigby's boss, said he was "forever bugging him" to move faster. Rigby protected his mirror and his crew as best he could. “I don’t think he ever did anything except the way he thought it should be done, schedule or otherwise,” McCarthy said.

The aura of the project added to the pressure. In scheduling the hourly workers, Rigby tried to make sure they did not work too many weekends in a row or too many late nights. But he drove himself hard, coming in at 6:30 a.m. and often not leaving until 10 p.m., sometimes later. He couldn’t smoke in the polishing room but managed to go through two packs of Kool menthols a day anyway, largely by smoking in his office. He’d rarely go two hours before chewing one of the antacid tablets he kept in his shirt pocket or taking a swig of Maalox from the bottle in his desk drawer to soothe the ulcer in his esophagus. Rigby would often call the master optician, Wilhelm R. Geissler, to his office to talk about the polishing. After a few of these sessions took place at 2 a.m., Geissler figured it would be easier to sleep at the plant than to go home. He brought in a cot and set it up in a trailer in the parking lot.

Opticians traditionally did their work with a kind of black magic, even rubbing their thumbs along a lens or minor to apply the finishing touch. But unlike other Old World opticians in the industry, Geissler fully embraced the idea that on this mirror, he would rely on computers to tell him how to polish. This reliance on machines—coupled perhaps with fatigue—exacted a price from the mirror. One morning, Geissler punched the wrong numbers into the computer, hitting “1.0” instead of “0.1.” To everyone’s horror, the whirring polishing tool began digging a groove near the inside edge of the mirror. It could have been much worse. A technician watched the mirror constantly during the hours it was polished, keeping his finger on a kill switch on a long electrical cord that ran to the motor. The job was mind numbing, but the technician on duty acted instantly when the polishing tool ran amok. The motor cut off, preventing the arm from leaving a deep scar. The groove was smoothed over somewhat in later polishing runs, but Geissler’s mark would never go away completely.

The Fatal Flaw

What no one knew was that there was a much more serious flaw in the project, and it had been there since the beginning of the fine polishing in Danbury. The flaw was introduced in mid-1980 when technicians assembled that precision piece of optical testing equipment, the null corrector. The cylindrical device, a little taller than a beer keg, consisted of two small mirrors and a small lens. Null correctors had been used before, but Perkin-Elmer’s elegantly simple new design could provide unprecedented accuracy, measuring surface smoothness to a fraction of the wavelength of light, a few millionths of an inch.

To test the telescope minor, light from a laser would be sent through the null corrector and then bounced off the glass. The light then would pass back through the null corrector, creating a pattern of black and white lines. That interference pattern would be photographed; working with a computer, the scientists would analyze the photograph to determine where the minor needed more polishing. When the minor was exactly the correct shape, the light pattern seen in the photographs would be an evenly spaced series of straight lines. Perkin-Elmer had to retool the null corrector after making a five-foot mirror to prove to NASA that the company was up to the job. Company managers were pushing the null corrector technicians to do the adjustments quickly. Rigby’s crew needed the null to get going on the fine polishing of the telescope’s big mirror.

Lucian A. Montagnino, a meticulous, 42-year-old engineer, was responsible for seeing that the retooling was done right. For the telescope mirror, Montagnino’s crew spent several weeks making the tiny adjustments in the space between the null corrector’s two internal mirrors. They had only a few days left for the final adjustment: the distance between the lower of the mirrors and the lens. Special rods had been manufactured to measure the spaces. The rods were made of Invar, a material that doesn't expand or contract in heat or cold. They had been measured and cut, then shipped to an independent laboratory that certified their lengths. But using the rods was not simple. Because an error of even the width of a human hair would make the mirror the wrong shape, a special microscope and a laser were used to make the measurements. And the harried technicians made a mistake. To set the distance between the lens and the mirror the technicians eased a measuring rod into place and looked through the microscope at the end of the rod. They had to bounce the laser beam precisely off the tip, through a hole in a tiny cap on the rod. The cap was coated with special paint so there would be no reflection unless the laser was aimed at the right spot. But one little spot of paint had worn off. Unknown to the technicians, the laser was set to bounce off that worn spot.

Maybe if they hadn't been so rushed they would have recognized the problem. Because when they tried to set the null corrector's lens where the laser said to put it, something was wrong. The way the null corrector was built, the lens wouldn't go down far enough without adding something to the bracket that held the lens in place. Under normal circumstances, this design anomaly might have triggered an engineering inquiry; but the deadline was upon them. There was no time for an inquiry. There wasn't even time to ask the machine shop to custom-make spacers for the bracket. The technicians grabbed three household washers, the kind you could find in any hardware store for twenty cents. They flattened the washers and put them into the $1 million null corrector. The technicians moved the lens 1.3 millimeters lower than it was supposed to go. Charles Robert, the engineer who shimmed the lens with the washers, doesn't remember much discussion about it, just the pressure to finish up the job.

The designer himself, Abe Offner, is surprised that he was not consulted. "These things are made so they would not need washers. I would have expected any questions to be referred to me," he says. But only the technical crew was in the room. Because there was so much other work going on, company and NASA quality control inspectors rarely visited the lab where the null adjustments were done. As the technicians moved the null corrector atop the measuring tower in Danbury, they handled it "like the crown jewels," Rigby remembers. But once it was up there, no one was going to be able to recheck the spacing between its mirrors and lens. For the next eleven months, Rigby and his crew would rely entirely on the null corrector to tell them whether the mirror was getting closer to the desired shape. It was as if they were cutting and measuring with a thirteen-inch ruler they thought was a foot long. During that time, there would be ample evidence of a flaw. It would be staring them all in the face—tacked up on the walls in Rigby's office, distributed among the opticians and engineers, entered in the official logbooks. Questions were raised, but they were never answered. There was no time. Rigby was no expert on null correctors. He relied on Montagnino for that. And Montagnino said to trust him and his device.

Bringing in a Skeptic

The people trying to finish the mirror destined for the Hubble Space Telescope didn't exactly welcome Roderic M. Scott, an optical designer. Less than a year since his retirement, he was back at Perkin-Elmer's Danbury plant, as a part-time consultant who functioned as a troubleshooter. Some company officials thought Scott's day was past.

At 65, Scott was an unrepentant skeptic. If you told Scott it was a nice day. "He would say, 'Why do you say that? Is there a reason for that?' joked Babish.

Scott had no reason to believe anything was wrong with the system, but one thing bothered him. The minor makers relied entirely on the null corrector, not only to measure the progress of shaping the mirror, but also to test the finished glass. So he tried to sell the mirror makers some "fire insurance," an independent test of the mirror. The project team, however, regarded Scott as something of a company relic whose frequent inquisitive visits cost too much time.

Whatever the reasons, Scott and other scientists felt the company now paid too much attention to management and too little to science. Profit had become an end in itself, not something that was necessary only so scientists could poke around and make interesting and important discoveries. And the space telescope program seemed to be taking the new emphasis on management to extremes. In part, this was because NASA, too, had changed. The space agency was being funded much less generously than during the glory days of Apollo and it had lost many of its best people. But it hadn't scaled back its ambitions to fit its budget. The changes at the company and NASA made the space telescope project a troubled partnership from the start, with both partners primed to compromise on science for the sake of budgets and schedules.

Best and Brightest

Company folklore held that Perkin-Elmer began in 1937 with a handshake on the steps of the Harvard library when Richard S. Perkin and a fellow amateur stargazer. Charles W. Elmer were attending a world conference of astronomers. Perkin was a 30-year-old Wall Street stockbroker. Elmer, 64, a former court reporter, had made his money in the stenography supply business. Sharing a fascination with telescopes, they agreed to invest $5,000 each. Their friendly hands-on style set the tone at their new company, which grew quickly, supplying the military with optics for bombsights, periscopes, and aerial reconnaissance cameras. Perkin-Elmer attracted the best and brightest with its entrepreneurial philosophy about research, similar to that of many companies that grew up during and after World War II. As one employee characterized it later, "It might be said that we invent solutions and then go in search of problems they can solve." A scientist could propose an interesting idea in the afternoon and come in the next morning to find a laboratory with equipment and a secretary waiting.

Perkin and Elmer stayed close to the work. Perkin sometimes called staff meetings in the barn behind his New Canaan home, inviting participants afterward to gaze through the twenty-four-inch telescope in his backyard observatory. At work he would wander through the shops asking whether he could join in discussions. He had built his own telescope as a boy in Brooklyn, and he insisted that top people such as Scott personally supervise manufacturing. During his final years with the company, Elmer couldn't stay out of the room where they polished telescope mirrors. Someone brought in a rocking chair and Scott would see him sitting there in the afternoon, dozing while the machines hummed.

In the 1950s and '6Os, work on the Stratoscope program, a precursor to the space telescope that proved the technology and value of high-altitude observation, exemplified the culture of the company. Stratoscope II, first launched in 1963, was the most advanced airborne telescope of its time. After its thirty-six-inch mirror, was ground to the approximate shape by machines, an optician finished the polishing by hand. Perkin-Elmer's technicians worked under the direction of the Princeton University astronomers who would be using Stratoscope. They would say. "Make it as good as you can. When we run out of money, we'll quit."

Waking from a Dream

For NASA, the 1960s had been a space scientist's dream, a time when children followed every launch with transistor radios pressed to their ears. President Kennedy had vowed to put a man on the moon before the decade was over, rallying Congress and the public to pay to do the job right. NASA's budget more than tripled in four years. Apollo 11 lifted off for the moon in July 1969, on time and on budget. Yet soon after that first moon landing, the government cut NASA adrift. Its budget plunged to a third of its peak as the space agency searched for a new, defining mission.

Astronomers convinced NASA of the space telescope's value, that it would enable them to study quasars and other exotic celestial objects better and to measure more accurately the distances to galaxies, which would help determine the age—and future—of the universe. But with an estimated price tag of 5700 million, the idea had to compete against plans for the space shuttle and for planetary probes. Three months after Neil Armstrong stepped on the moon, NASA dropped plans for intermediate space telescopes intended to reduce the technical challenges. It was the first step in a decade-long effort to cut the telescope program by squeezing the budget, deferring spending, reducing staff, making design compromises and eliminating tests and spare parts. "In most programs, you go through stages where you look for fat. It's not necessarily an unhealthy thing." says Robert W. Smith of the Smithsonian Institution, author of a 1989 book on the Hubble's troubled history. On the telescope program, "There really wasn't that much to cut, so you weren't just cutting out the fat."

In 1969 Perkin-Elmer was celebrating more than thirty years of growing success as a maker of telescopes and other advanced optics and scientific instruments, but rapid growth was revolutionizing the corporate culture. Elmer had died in 19S4. Perkin-Elmer had sold stock to the public for the first time in 1960. Perkin had stepped aside as chief executive officer in 1961. He stayed on as chairman, thrilled at the company's success but troubled that, with more than 3.000 employees, he no longer knew everyone's name. In 1964 the company got a new chief executive officer in Chester W. Nimitz, Jr., a retired admiral like his famous father. Nimitz set Perkin-Elmer on a new course, reorganizing it to accommodate the purchases of new commercial businesses and the marketing of an invention that soon would be the biggest money maker in its history. By May 1969, when Perkin fell ill on an airliner over Ireland and died in a Limerick hospital, the old days were really gone.

Beating the World

Thanks largely to Micralign, a business that created microlithography equipment needed for electronic miniaturization, sales and profits at Perkin-Elmer tripled between 1976 and 1980. But with all of the growth and diversification, the management style of Perkin and Elmer seemed obsolete. In the old days, projects like the Stratoscope aerial observatory had been paid for by the government but run by scientists. Open-ended research programs, such as the Air Force contract that eventually led to Micralign, were common. No more. Now the government itself ran the programs, and it seemed that scientists had less and less say.

Nimitz began filling management positions with outsiders, including a retired submarine commander, instead of scientists. The company sent accountants and salesmen off to business schools for crash courses. When they returned, they all talked about a new way to organize a corporation. It was called "matrix management." Previously, when scientists won a contract, they would organize their own task forces. They would consult upper management, but the process was informal. Now managers decided who worked on what, shifting employees from job to job, depending on which project had the most pressing schedule problem or the most commercial promise. In effect, people now had two bosses. Many of those working on the Hubble mirror, for example, were employed by the Optical Operations division. But they reported to Bud Rigby, who was in the Electro-Optical division. And Rigby reported on the mirror to the director of yet another division. Optical Technology.

Although the new system helped the company save money by making its workforce more flexible, it also widened the rift between science and management. The scientists felt the managers no longer shared their goals. And many believed the system left people with less pride in their work and less responsibility for the product. “It relegated the technical people to clerk-typists,” Rigby said. Managers thought scientists lacked the training to run increasingly large and complex programs. But the new system squelched the scientific initiative and independence that had characterized Perkin-Elmer in its early days.

Compromising on Science

With its lofty goals and shrinking budget. NASA too was forced to relax the rigor with which it had done science programs since the space agency was founded in 1958. In the space agency’s official view, computer simulations, good design and careful supervision could overcome the need for prototypes or full-scale tests of the space telescope.

That wasn’t the way NASA used to do big projects. For the Skylab space station program in the 1970s, for example. NASA built an entire backup module at a cost of nearly SI billion. The agency also built test mock-ups so engineers could make their mistakes early. The backup now sits in the National Air and Space Museum in Washington.

In a bid to save money and to make the telescope and the space shuttle more attractive to Congress, NASA was packaging the two programs. Using the shuttle to launch and maintain the telescope, rather than putting it atop an unmanned rocket, would mean that if they overlooked something because of a lack of ground testing, they might be able to fix it in orbit. And telescope maintenance was one answer to skeptics who questioned the need for a shuttle. But when the shuttle proved to be too expensive and unreliable to be counted on for routine maintenance of the space telescope, no more testing was built into the project. Instead. NASA simply cut the number of telescope components that could be replaced in orbit.

Many of the astronomers involved in the space telescope project disliked the shuttle link because it meant scientific compromise. The shuttle could not place the telescope in an orbit any higher than 380 miles, meaning Earth would block part of the sky from the telescope’s view. In 1975, NASA decided the diameter of the telescope mirror would have to shrink from ten feet to eight feet to save money and to make the telescope fit into the shuttle’s cargo compartment. That would cut by one-third the amount of light captured by the telescope, reducing its ability’ to study faint objects.

Packaging the shuttle with the space telescope was not the only compromise made for the sake of politics. NASA did the same thing in deciding which of its field centers should run the space telescope program. Both the Marshall Space Flight Center in Alabama and the Goddard Space Flight Center in Maryland knew the space telescope program was important, and they competed hotly for the project. In May 1972, NASA headquarters split the project, giving Marshall responsibility for the telescope’s optics and structure and Goddard responsibility for the science instruments. Although the solution kept both centers busy, the division resulted in friction that lingered throughout the program. “No one really felt like they had the authority to go in and direct all other elements of the program to conform.” said James C. Welch, who became NASA’s Hubble program manager in 1983.

No Sign Off

NASA’s stripped-down posture shifted an unusual amount of responsibility to the people the agency sent to Danbury to observe the work—Carl Fuller for instance, a cantankerous Southerner. Fuller had spent most of his career as a NASA engineer, testing the docking mechanism on Skylab, for example, or the million-gallon liquid oxygen tanks for the Saturn V rocket. But for the first time in his career as a NASA quality-assurance specialist, his bosses told him to ignore the quality of one job—the mirror.

During the making of the mirror, there were only three space agency engineers in Danbury, compared with more than twenty at a project NASA considered comparable—construction of the Saturn boosters at Rockwell International Corporation in the 1960s. Money was one reason. Another was that, just down the corridor from the polishing room, Perkin-Elmer still was doing classified work for the Defense Department. High-ranking NASA officials say the Pentagon was nervous about having outsiders running around the plant and talked the space agency into limiting the number of people it had there. Company officials worried that manufacturing secrets could fall into the hands of competitors. They sometimes discouraged their own workers from publishing scientific papers about polishing techniques. Fuller’s supervisors told him to worry only about the mirror’s safety, not whether it was being made correctly. Safety had been a concern ever since 1968, when four Perkin-E1mer technicians had tripped over a two-by-four and dropped a $1 million mirror for an earlier satellite. A mechanical engineer by training, Fuller also was told he did not have the expertise to understand optical testing. He was baffled. He was no optical scientist but had planned, as usual, to bring in experts to help him. Fuller fought with his supervisors to regain quality-control responsibility for the mirror. His superiors told him that NASA’s separate engineering division was taking over that role. But Danny D. Johnston, the NASA resident engineer on the program, says he never was told to assume Fuller’s responsibilities for the minor. So he didn’t. Johnston continued to concentrate on designs and documents, rather than watching the actual work.

NASA required that one of its quality assurance officials give final approval to each piece of equipment destined for space. Of all the approval documents on the thousands of parts that went into one of the most complicated scientific instruments ever assembled, only one is known to lack a signature from the quality office. Fuller just wouldn’t sign off on the main mirror.

Without Fuller looking over the shoulders of the mirror makers, NASA managers were going to have an even harder time seeing warning signs. Already it was widely believed that accurate information didn’t flow far at NASA’s Marshall Space Flight Center in Huntsville, Alabama. Marshall’s director, William R. Lucas, had a reputation for disliking bad news, which discouraged Perkin-Elmer managers and other NASA officials from raising concerns. The quarterly briefings held in Huntsville turned into chances to tell Lucas what he wanted to hear, say many Perkin-Elmer and NASA officials. Years later, after investigating the 1986 explosion of the space shuttle Challenger, the Rogers Commission would criticize Marshall managers for failing to raise concerns, saying this weakness contributed to the disaster.

During the polishing of the telescope mirror, Perkin-Elmer’s managers didn’t step into the void left by NASA. The company cut corners on quality assurance. too, and the pressure got to Burch, who was Fuller's quality-control counterpart at the company. Trying to perform a crushing number of tasks under a budget and staff level that he said was "worse then any other project we had of any size," Burch suffered two heart attacks. The first came in 1982, after the mirror was finished and during an exhaustive NASA audit. Burch recovered from the two heart attacks, but he had to be replaced on the program.

Company managers, confident of the abilities of the mirror makers, say they paid little attention to the mirror work beyond pushing the workers to hurry up. They had other things to worry about. In the early 1980s, Perkin-Elmer suffered its first sustained decline in sales and profits in twenty-seven years. The recession and the strength of the dollar abroad hurt. Further damage was done as American and, later, Japanese companies ate away at Perkin-Elmer's edge in microchip machines.

Some say the company tried to respond by diverting resources to its Micralign division. "Compared to what we were doing on the space telescope, this was far larger in total scale and many, many times larger in terms of profits," said Peter B. Mumola, vice president for applied science and technology. "The space telescope was nice and it would make great magazine covers in the future, but it was not looked at at the time as the top priority."

Turn up the Radio

This left only Scott, the company's old-time scientist, to ask the hard questions. A few years after Perkin's death in 1969, at the request of the new managers, Scott had left the corporate headquarters in Norwalk to become technical director in Danbury. Scott soon asked to be put on half time, and at 64 he retired a year early, planning to spend more time sailing at his summer place in Maine. As a consultant, Scott thought his role was "to keep people honest technically." But the polishing room crew rejected his recommendation for a relatively inexpensive independent test on the mirror. The leading argument was that his test was too crude, that although it could catch a gross error, it couldn't check to the nearly perfect standards the mirror required. Whenever Scott knocked on the door of the polishing room, the technicians would groan to themselves. Yes, he was a brilliant guy, but he had nothing to do with the program. He would talk too much and ask too many questions. Geissler, the chief optician, recalls, "They would tell me, 'Hey, Rod is out there. Don't let him in. Turn up the radio.'"

Clues to a Flaw

Albert F. Slomba, a 43-year-old senior optical engineer, spread the poster-sized pictures, called interferograms, on his desk and frowned, "This is a little strange," he said to himself. He looked again. No mistake. The pictures said there was something wrong with the big mirror that would become part of the Hubble Space Telescope. Slomba just knew that couldn't be right. He picked up his two-foot-square sheets and walked down the hall to see Montagnino, who was in charge of testing the mirror, measuring its progress toward perfection. Printed on Slomba's sheets were round pictures that looked something like closeups of a zebra's hide. Slomba's specialty was using light in metrology, the science of precision measurements, and he was one of the best. Studying the patterns of black and white lines, he saw evidence of a shaping error known as a spherical aberration. With such a flaw, a mirror couldn't properly focus light. The patterns he carried hadn't come from the null corrector that the mirror makers had been using all along. These were from a second, much less accurate null corrector that had been brought in for another purpose. Together, Slomba knew, he and Montagnino would come up with a good reason for the curious result.

Of the key tasks in the Hubble Space Telescope project, none received less outside scrutiny than the testing of the mirror. Montagnino ran the show like a dictator, Tight control was essential, he thought. Metrology was excruciatingly delicate work, requiring careful records. He had developed a work ethic based on rigor and detail. If the design was perfect and the methods carefully set, the way to prevent an error was to control every movement. And that meant no random strolls through his lab, no second-guessing by outsiders. Montagnino controlled records of the work with an "almost obsessive" zeal, said Burch. It was his niche in life and he used whatever advantage or leverage he could" to keep other people out, Burch said. "He absolutely was an extremely dominant force." The company photo lab that processed the interferograms was not allowed even to keep copies of the prints it made, Burch said. He described this as unprecedented. Many of those who dealt with Montagnino felt the same way Burch did. No one doubted Montagnino's technical abilities, but some worried that he was too isolated and defensive. He argued bitterly with Scott. "If anybody questioned anything, he took it as a personal affront," Scott said. "I was insulting his intelligence."

They used to tell a joke about Montagnino, according to one company official. It was said that Montagnino stopped going to baseball games because he couldn't handle it whenever the catcher walked out to the pitcher's mound. He thought someone was talking about him.

Montagnino now says there was no prohibition on copies of interferograms, but that anyone who wanted one had to go through channels, "You don't just distribute them like you hand out cookies," he says.

Slomba laid the interferogram on the desk in Montagnino's office. No one expected to use the second null corrector to judge the 94.5-inch mirror's shape. The less accurate instrument had been mounted over the completed mirror on May 26, 1981, to determine the center of curvature. That test couldn't be done by the main null corrector, Still, Slomba, who had been brought in to do the curvature test himself, thought it was important that the wavy patterns differed so radically from the nice straight lines generated by the other instrument. "We had a discussion about why these fringes looked the way they did," he said. They reviewed the design of the second null, looking for something that could produce such an erroneous reading. Nothing. "Lou mentioned that he was concerned about it," Slomba said. But Montagnino gave Slomba a tutorial on the two null correctors. The refractive null corrector, the one that was giving them the troubling pattern of lines, was much less precise. It was made of lenses instead of mirrors and could not be counted on to produce a mirror as smooth as was needed for the space telescope.

Montagnino had great faith in the main, reflective null. He had supervised its construction, its use on the five-foot demonstration mirror built for NASA, and its readjustment for the eight-foot space telescope mirror. Montagnino now says he didn't know that the technicians who assembled the reflective null had shimmed the instrument's lens with washers. That might have been a clue that they had made a measuring error. No one caught the technicians' mistake and no one knew the null corrector had been giving inaccurate readings for nearly a year. So Slomba had no reason to doubt Montagnino's reliance on the main instrument.

"All the rationales came up," Slomba said. "We kicked it around for the better part of an hour. I think he covered all the bases and offered a decent explanation of it." Slomba said he and Montagnino considered other ways to check the reflective null. Each knew that lack of time and money would interfere with any unplanned tests. Montagnino took comfort in knowing that there would be a thorough review of all design and assembly documents and test results once the mirror was coated in a few months. That would resolve any remaining questions, they agreed.

Montagnino's confidence rubbed off on Rigby, the man in charge of the mirror polishing. Rigby was technically Montagnino's supervisor on this project, but he was no expert in metrology. When told about the puzzling discrepancy, Rigby trusted Montagnino's explanation that the reflective null corrector couldn't be a problem. Montagnino, Slomba, and Rigby were so sure there was no problem that they never formally raised the issue outside the polishing room. Scientific advisers such as Scott never were told, despite their misgivings about the lack of independent testing on the mirror.

During the project, Scott said, "I went to Montagr.ino several times and said, 'Look, Bub, you'd better buy some fire insurance. I know that other people had problems with null correctors that were made with great care and exactitude.' And he'd say, 'I don't need that,' " Montagnino says now that he had no problem with the idea of more testing, but that Scott's particular plan was inadequate. In fact, he says he proposed two tests, including a test of the Perkin-Elmer mirror with Kodak's null corrector. They were rejected because of cost concerns, he says.

Scott says that when he brought up the Kodak test, he was vilified by others at Perkin-Elmer. "I was a traitor to the cause," Scott said. "I had absolutely gone bonkers. Invite our competitor in here, when our null corrector was so much better?" Paul Schwindt, NASA's resident manager in Danbury, says he too hoped the Kodak test would be done, but NASA rejected the idea. Mumola also had misgivings about the self-contained nature of the null testing. "Lou's position was. 'We do this all the time,' " Mumola said. Montagnino would say. "It requires an enormous amount of care and attention to detail. It is not slap-it-together-and trust-it-to-work." But to Mumola, "It seemed to be somewhat of a theological argument as opposed to a technical one." No one else had a chance to pass judgment on the odd interferogram. Eventually it was attached to a Perkin-Elmer report on the mirror, seen by company and some NASA officials, but the spherical aberration, visible only on the outside portion of the pattern, had been cropped out. That may have been done because the pattern originally had been intended to show only the mirror's center of curvature, and you didn't need the whole picture to see it.

A Third Clue

The May 1981 test that Slomba and Montagnino had discussed was the third clue that something was wrong with the mirror. The discrepancy between the two nulls first was seen at the end of the preliminary grinding in 1980, but it was dismissed because the mirror still was very rough. And a third optical instrument used for aligning the measuring equipment showed the spherical aberration more than two dozen times. The technicians, however, paid little attention because the device wasn't meant to test the shape of the glass.

Only days before the refractive null corrector produced the May 26 interference pattern that worried Slomba, Perkin-Elmer missed another opportunity to discover the flaw in the mirror. To mark the end of the polishing, a group of senior Perkin-Elmer scientists met as a technical advisory committee to review data from the project. The scientists, Scott among them, listened to a presentation from Montagnino and discussed the big glass. None of them had any reason to doubt that the mirror was anything but perfect. But on May 21 they issued a memorandum urging a number of final actions. Number three on the list of five said an independent test of some kind should be performed on the mirror: "The purpose of this test would be to uncover some gross error such as an incorrect null corrector". One of the committee members, Robert E. Hulnagel, now says, it was simply that queasy feeling that you ought to check it somehow. It's based on horse sense.

The committee's recommendations went to John D. Rehnberg, who was head of the division that held the space telescope contract. Rehnberg says he does not remember the recommendations. In any case, the consensus among company officials was that there was no need for such a test, he says. Some thought that was just another way of saying there wasn't enough money. "If Perkin was alive, he would have insisted on a test, even if it had come out of his own pocket," says Robert Och, an optician who worked on the Hubble's 12.5-inch secondary mirror. After the pressure, all the rush, the finished mirror then sat around for several months while Perkin-Elmer finished installing the specially made coating chamber needed to apply a perfectly even layer of reflective aluminum to the face of the glass. "We didn't really have to go as fast as we did," said Geissler, the chief optician. And the final review Rigby and Montagnino had waited for—the one that would carefully check the various devices and resolve the discrepancies—never happened.

A Final Opportunity

After the mirror was trucked to Perkin-Elmer's Wilton plant and coated in December 1981, technicians started assembling the documents they would need. Then they were told to stop. Perkin-Elmer was shutting their project down. Montagnino and others from the polishing team seethed. They stormed to the management offices in protest. Montagnino describes the meeting as "very heated. Lots of bad words" were exchanged, "and we were told, 'You're off it, at the risk of your jobs.' "The orders came from Kent H. Meserve, the project manager, and his deputy, Robert Jones. To Meserve, it was just one more demand for time and money he wasn't able to fulfill; and in this case, it didn't seem necessary, "We had the mirrors, they were done, they had been coated, they had been accepted," he said. The crew wanted to do weeks' worth of additional work and "we did not have the funding. We needed their talents on something else."

Rigby also fought for the final review. "But recognizing the situation that everyone was under at the time, I did not put my life on the line and say I would quit or resign if [don't get it," he said. "The authority and responsibility of the fabrication team was usurped," Montagnino says now. "Did we believe the thing was right? Yes, we believed it was right." he says. The mirror was so rough when the original discrepancy surfaced in 1980 that the results were not considered seriously. The connection between that discrepancy and the aberration shown by the third optical instrument was never made, although Montagnino says, "In hindsight, we probably should have questioned it more. It was just common sense to conduct a review," Montagnino says, "like checking your parachute" before jumping out of an airplane.

By the time the mirror was finished in late 1981, the scheduled launch of the space telescope had slipped from 1983 to 1985, and it was in danger of slipping further. The mirror was only one of three parts of Perkin-Elmer's Hubble contract, and in some ways the other two projects were more demanding. Work was proceeding slowly on the graphite epoxy structure that would hold the telescope's two mirrors and on the fine guidance sensors that would keep the telescope steady with unprecedented precision. That work had to be completed before the telescope could be shipped to Lockheed Missiles and Space Company in Sunnyvale, California, where the telescope and five scientific instruments had to be assembled into a satellite that could be launched on the space shuttle.

When Perkin-Elmer fell seriously behind schedule in 1981, the company told NASA it needed to put more people to work on the project. But that would have cost money, and NASA said no. Then NASA finally realized in 1982 that the space telescope was not going to be finished without a major infusion of people and money. The space agency moved more than twenty program managers from the Marshall Space Flight Center in Huntsville, Alabama, to Danbury. The agency told Perkin-Elmer to hire about 200 more people. The company, at the urging of

NASA, had gone to the outside for a new telescope manager, hiring Fordyce to replace Meserve. “I did not know how much trouble they were in. They were in a hell of a lot more trouble than I thoughts” Fordyce said. “It was very obvious that we were not going to meet the schedule that was there with the manpower we had.”

A new budget and a new schedule were adopted. The value of Perkin-Elmer’s contract grew from $160.6 million to $350.8 million between 1982 and late 1984. And nearly forty years after it was conceived, the space telescope was named for Edwin P. Hubble, who in the 1930, proved there were galaxies beyond the Milky Way. The launch was put off until mid-1986. Tests and spare parts were restored to the program, but it was too late to put everything back. The mirror was finished, and no one seriously considered checking it. In late 1984, Perkin-Elmer shipped the telescope to Lockheed, which then spent two years installing the scientific instruments and assembling and testing the complete satellite.

Further Delays

In January 1986, NASA announced that the Hubble would be launched in October. But on Jan. 28, the *Challenger* exploded, killing the seven people aboard and halting the space shuttle program for more than 2V2 years. Storing the telescope at Lockheed—along with the continuing testing, safety checks and engineering work—cost NASA more than S7 million a month until shuttle flights resumed. The launch schedule was so congested then that a planned 1989 Hubble launch had to be postponed until 1990.

While the telescope and its makers waited for the day it would be carried into space, Perkin-Elmer struggled to regain its glory. In the early 1980s, the company had suffered its first sustained decline in sales and profits in twenty-seven years. Efforts to improve efficiency and to revive its microchip machine business continued, but by the late 1980s the news was mostly of layoffs. Between 1985 and 1989, over 1,000 of the more than 15,000 employees were let go. The company pulled back, concentrating on its core businesses of analytical instruments and science materials. One by one, divisions were sold off, including the microchip machine plant. Finally, even the optical division that had worked on the space telescope was gone. It was sold in December 1989 to Hughes Aircraft Company, a division of General Motors Corp., and it is now called Hughes Danbury Optical Systems, Inc. By 1990, Perkin-Elmer had gone from 15,000 employees to about 6,400.

The Launch

On the morning of April 24, 1990, several hundred people crowded around the two jumbo television screens in the cafeteria at Hughes Danbury Optical Systems, upstairs from where the mirrors had been built. Many of them had waited a decade for the countdown. They roared and applauded as the space shuttle Discovery lifted off with the Hubble Space Telescope in its cargo bay. But soon after the launch, scientists at the Space Telescope Science Institute in Baltimore recognized a problem in the data being transmitted by the telescope. For weeks they worked to understand it. It wasn’t a computer problem. It wasn’t that the two mirrors were misaligned. It wasn’t that gravity was distorting the glass. At the end of May, Christopher Burrows, a British physicist who was the institute’s chief telescope scientist, wrote a memorandum saying the problem could be explained only if the mirror were the wrong shape. Impossible, said many of his colleagues and the Danbury managers; but by mid-June, everyone came to agree with Burrows.

For all those involved with the space telescope, the news was sickening. “1 said, ‘Oh, my God, how could something like this happen?’ said Geissler, who had proudly watched the launch with his wife at Cape Canaveral, “There must be a mistake.” After the launch, Rehnberg had driven to Goddard Space Flight Center in Maryland with his wife to watch astronomers working with the telescope. “I thought, ‘we’re home free. Everything’s working fine. Everything is going to be super,’ Rehnberg said. Later, “When I got a call from the fellows; and they said, ‘Hey, we’ve got a problem,’ I absolutely was dumbfounded.”

Montagnino thought at first the mirror might have been bent somehow. “I had trouble believing the primary could be flawed,” Montagnino said, “I was very disturbed by it. It really hurt. It’s painful because all we had to do was complete all of the cross checks we had planned” and the flaw would have been found before the launch.

Scott blamed himself. In June, he had returned to Connecticut from his summer home in Maine and learned of the misshapen mirror. “I thought maybe I’d go to the moon. I was extremely depressed.” Scott, who had fought repeatedly for an independent test of the mirror, who had made a pest of himself with the polishing crew, still feels responsible. “I was hired to prevent things like that, to keep people honest technically.” he said, “It was obvious to me then that I had not put in enough effort to chase down all the observations and facts. What happened was a result of my laziness. I was unable to get to people like Montagnino and Slomba and get them to become honest and complete with me.” In his entire career, Scott said, “That was the one brush that’s tarred me.”

Rigby, who had retired a few months before the launch, so proud of his perfect minor, just couldn’t accept the news. “I just kept thinking it couldn’t be. It couldn’t be,” he said. When finally he had to believe it, he felt as though he’d wasted the best years of his career. In the end, Rigby admitted to himself that he’d always been carrying a tiny bit of doubt. “There was always a fear in my mind that if we did not make the null corrector right, we would have problems,” he said. “But I just built such faith in the null corrector over the years we had used it. I just felt it had to be right.”

The mirror, it turns out, isn’t the Hubble Space Telescope’s only problem. Scientists discovered that the solar power arrays manufactured by the European Space Agency shake every time the telescope passes from sunlight to darkness. The jitters sometimes knock the telescope’s sights off its targets. Despite that and other smaller problems, and even though the mirror flaw prevents the telescope from doing about half its intended work, the Hubble still sends back fine images of the planets and bright celestial objects, far better than those from any ground telescope. NASA plans during a 1993 space shuttle mission to install new optical devices to fix the telescope’s vision for the rest of its anticipated fifteen-year life. If the instruments, which will cost about $110 million, can be built on time and without serious technical difficulties, astronauts will take three six-hour space walks to install new solar panels and two phone-booth-sized devices with corrective optics. One of the two is an upgraded version of the telescope’s wide field/planetary camera, used primarily to search for planets around distant stars. The second device has tiny mirrors to restore the abilities of three of the telescope’s four other instruments—two spectrographs and a faint-object camera, The final instrument, a photometer, will have to be removed to make room for the new optics package.