Hubble: The Case of the Single-Point Failure

The technical glitch in Hubble's mirror has been found; what remains to be identified are the managerial problems that led to it

NOW THAT NASA OFFICIALS have zeroed in on the cause of the optical flaw in the $1.6 billion Hubble Space Telescope, the question everyone is asking is, How could it have happened? How could a mistake this huge have gone undetected—or more precisely, ignored? The answer seems to lie in a combination of managerial laxness and technological hubris that is just now coming to light.

The final word on the technical problem was revealed on 9 August. As the telescope's 2.4-meter primary mirror was being polished in 1980 and 1981, explained NASA officials, an unrecognized 1-millimeter error in the structure of a device used to monitor the process caused technicians to give the mirror an exquisitely smooth surface with a grossly inaccurate shape. The result is the "spherical aberration" that now bathes the stars in fuzz whenever Hubble tries to look at them.

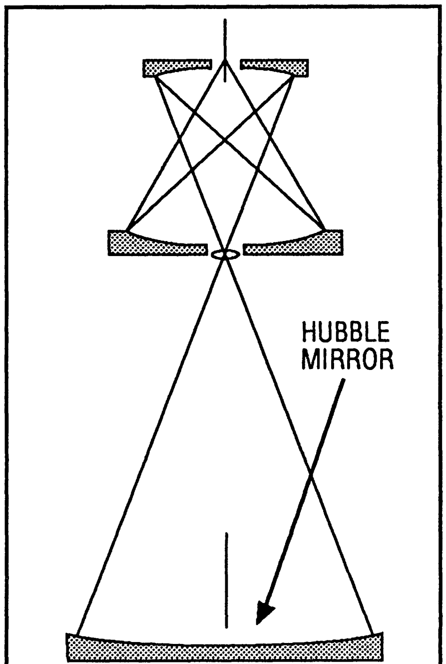
Out in the broader space science community, however, people are less interested in the specifics of the problem than in asking some very tough questions. Why was the most fundamental component of the telescope—its primary mirror—manufactured with just one testing device? Why were there no cross checks? And worse, why did mirror technicians ignore the results of the one independent test they *did* do? That test was performed in May 1981 at the Danbury, Connecticut, plant of the telescope's prime optical contractor, Perkin-Elmer (now renamed Hughes-Danbury Optical Systems after a 1989 takeover). It showed clear evidence of the very flaw that shocked the astronomical community in the summer of 1990, after Hubble was launched. And yet, Perkin-Elmer technicians seem to have convinced themselves that the result was incorrect and irrelevant.

"It was a *gross* error," says a baffled William Fastie, a Johns Hopkins University physicist who regularly reviewed Perkin-Elmer's optical work as one of the project's designated telescope scientists. "If we'd seen anything like that result it would have rung all sorts of alarm bells. But they didn't tell us anything about it."

"All of us feel horrible," agrees Rice University astronomer C. Robert O'Dell, who served as the project's chief scientist from 1977 to 1983. "We keep searching our souls: Could we have done something differently?"

Perhaps so, he says, but remember what things were like in 1981. The project was in deep trouble on almost every front, he says. And nowhere was it deeper than at Perkin-Elmer. The Fine Guidance Sensors were a prime example: designed to keep the telescope pointed toward celestial targets with ultrahigh precision, they were so far behind schedule that people were beginning to wonder if they could ever be made to work—much less be ready for a launch date that was then scheduled for early 1985. And in the meantime Perkin-Elmer's costs were hemorrhaging, to the fury of NASA project managers who were desperately trying to control them.

In that climate, says O'Dell, the mirror-polishing program actually seemed like a haven of relative peace and tranquillity. Not only had the company already made any number of mirrors for intelligence satellites, but the art of mirror-making had been established for more than a century.



Precision without accuracy. *Perkin-Elmer's reflective null should have measured the mirror surface to less than a nanometer. But one of its two mirrors was misplaced.*

As with any other telescope mirror, the basic idea was to hollow out one face of the Hubble mirror into a shallow dish, and then put it through cycle after cycle of polish and test, polish and test. The polishing device would be a standard one—essentially just a mechanized version of the rag and polishing compound people use to put a shine on the family silver. And the testing device would be similar to the standard "null corrector"—essentially just a light that shines onto the polished mirror face through a set of lenses. The beams that come bouncing back from the mirror face would allow the technicians to map out rough spots and errors in the curvature for further polishing.

The only real complication on Hubble was that, to take advantage of the airless clarity of space, the mirror would have to be closer to absolute perfection than any telescope mirror before it. NASA's specification was that the hills and valleys on its surface should be no higher than $1/65$ the wavelength of a helium-neon laser (632.8 nanometers).

To accomplish this feat, the Perkin-Elmer engineers decided to build the most precisely crafted null corrector ever. Instead of directing light at the Hubble surface using lenses, which might have subtle inhomogeneities, the device employed a pair of carefully calibrated mirrors; thus the name "reflective null." Instead of using ordinary light, moreover, it used lasers. Its physical dimensions were adjusted to a tolerance of micrometers. And in the end it seemed capable of measuring the Hubble mirror surface to better than one one-thousandth of a wavelength.

The Hubble mirror arrived in Danbury for final polishing in 1979, after having been roughed into shape at Perkin-Elmer's plant in nearby Wilton, Connecticut. An initial evaluation with the reflective null indicated that the surface had about half a wavelength of spherical aberration overall—not too bad, considering that the rough-grinding process was only supposed to get the surface accurate to within one wavelength. There was only one minor-seeming worry: this spherical aberration hadn't been visible at Wilton when the mirror was tested with a conventional "refractive null," which used lenses instead of mirrors. As it happens, this less-sophisticated refractive null had a design that made it potentially accurate to $1/100$ of a wavelength. But no one had ever bothered to measure its true accuracy, since the rough-grinding process it was intended for didn't seem to require very much precision. Probably it was just a little off.

The Perkin-Elmer team therefore went ahead and polished out the spherical aberration as seen by their super-accurate reflective null, finishing the job to NASA's satisfaction in April 1981. Then, in May 1981, they brought the conventional refractive null in from Wilton to do a final double check on the mirror's focal length. (For technical reasons, it was still considered more accurate for that purpose, although not for testing the overall shape of the mirror.) The test patterns from the refractive null showed that the focal length was fine—and that the mirror surface contained about $1/4$ wavelength of spherical aberration. But of course, that was only to be expected from such a relatively crude testing device. The Perkin-Elmer technicians certified to NASA that the Hubble mirror was within specifications and put away the photographic record of the May 1981 test in the project files.

These photographs were apparently never looked at again until after Hubble's spherical aberration was discovered this past June. The existence of the May 1981 test result was first reported on 22 July by the *Hartford Courant*. The photographs themselves were reviewed on 25–26 July during a visit to Danbury by NASA's official investigation committee, chaired by JPL director Lew Allen. Even then, it was all too apparent what had happened. In spite of everything, that "crude," conventional refractive null was correct, and that lovingly constructed, high-tech reflective null was wrong. The surface error that Hubble astronomers now have to live with when they look at the stars is indeed about $1/4$ wavelength.

What the Allen committee will say about this in its final report remains to be seen. However, astronomers experienced in making ground-based telescopes say they are appalled that NASA and Perkin-Elmer would rely on one single test. "I always insisted on three independent tests," says JPL's Aden Meinel, who made the 2.5-meter mirror of the Carnegie Institution's Las Campanas telescope in 1968. The Hartmann test, the knife-edge test—there are any number of simple and inexpensive experiments that could have seen the spherical aberration that now exists in Hubble, says Meinel. They may not have been able to measure $1/65$ of a wavelength, but they certainly could have served as sanity checks.

So why didn't the Perkin-Elmer team incorporate multiple mirror tests in the program? And why didn't NASA insist on them? Until the Allen committee makes its final report, Hughes/Perkin-Elmer employees are under strict orders to make no public comments about Hubble whatsoever. NASA's Hubble veterans, however, point to several reasons. For one thing, they say, extra tests would have taken extra time and money, both of which were in very short supply in 1981—especially at Perkin-Elmer. For another, NASA officials and Perkin-Elmer technicians alike were so obsessed with meeting that $1/65$ wavelength challenge that they simply never thought in terms of sanity checks. "The point is that we didn't *do* crude tests," says Max Rosenthal, who oversaw the Perkin-Elmer contract as manager of the Optical Telescope Assembly at NASA's Marshall Space Flight Center.

Finally, and perhaps most important, the Space Telescope project was in such disarray at the time that no one who knew the right questions to ask ever really had a chance to see what was going on. Throughout this entire period, for example, NASA had precisely three representatives working full time at Danbury—none of them experienced opticians. Since Perkin-Elmer was also a major contractor for classified intelligence satellites, the Pentagon had insisted on that limit for national security reasons.

Meanwhile, the astronomical community was represented at Perkin-Elmer by two designated "telescope scientists," Johns Hopkins' Fastie and Daniel Schroeder of Beloit College in Wisconsin. Both men are highly regarded optical experts and certainly would have known what questions to ask. But they were only occasional visitors who relied on briefings by the Perkin-Elmer staff. And in any case, like the NASA representatives, they spent most of their time worrying about acute crises such as the Fine Guidance Sensors.

Then at a still higher level, chief scientist O'Dell and the astronomers on his science advisory panel were spending roughly 25 hours per day on budget battles—defending Hubble against NASA higher-ups who keep talking about sacrificing some of the telescope's scientific performance to keep the burgeoning costs under control. "I found myself reacting to crises instead of trying to do the job right," says O'Dell.

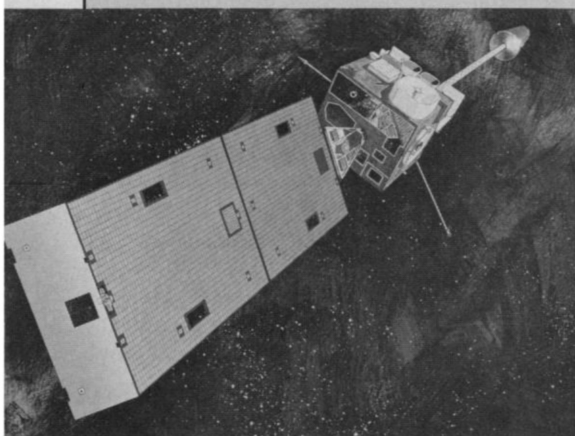
So are there any lessons to be learned from all this? Yes—and they seem to be the same lessons that were learned from another NASA disaster. "At the end of any process,it's always been NASA's policy to do a cross check to *prove* that it's right" says Fastie. The first exception to that policy seems to have been the O-rings that destroyed Challenger, he says, "and now the second is Hubble."

■ M. MITCHELL WALDROP

Mirror, Mirror, in the Sky . . .

National Aeronautics and Space Administration officials have ample reason to wince at the word "mirror" these days. But when it comes to the problematic mirrors being developed for the GOES-NEXT weather satellites, which are scheduled for launch in February 1992, they seem to have little to apologize for.

As the name suggests, GOES-NEXT is an advanced version of the GOES-series satellites that circle Earth once per day in the 35,700-kilometer high geostationary orbit and that send back the globe-spanning cloudscapes seen on the evening news. They are being designed and built by Ford Aerospace under contract to NASA, which in turn is acting on behalf of the National Oceanic and Atmospheric Administration.


Ford Aerospace

Clear vision? *NASA hopes to fix GOES-NEXT's mirror by 1992.*

The mirrors in question are a pair of flat, 12-inch by 20-inch ovals designed to bounce Earthlight into the spacecraft's cameras. The problem, first reported in the *New York Times*, was discovered in early August when Ford Aerospace and its subcontractors ran a new, advanced computer model suggesting that the mirrors would warp when exposed to sunlight. Earlier computer models had shown no indication of the problem whatsoever, says a Ford spokesman.

Be that as it may, NASA project managers immediately announced the potential flaw and formed a task force to find a solution. No one can yet say what the cost or schedule impact is going to be. But it seems safe to say that if GOES-NEXT ever does have a mirror problem in orbit, it won't be because NASA failed to pay attention to it on the ground.

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