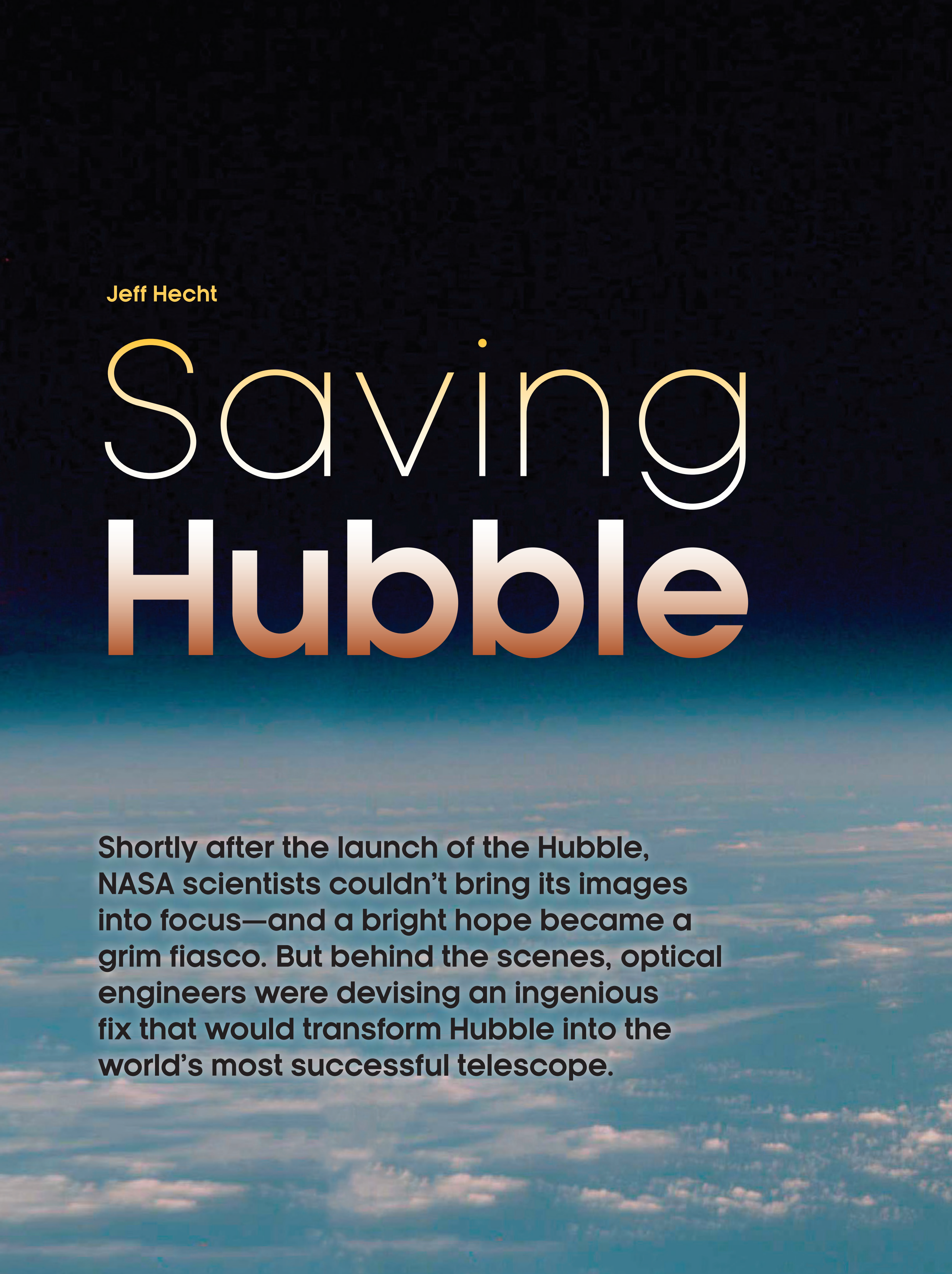

Jeff Hecht

Saving Hubble

Shortly after the launch of the Hubble, NASA scientists couldn't bring its images into focus—and a bright hope became a grim fiasco. But behind the scenes, optical engineers were devising an ingenious fix that would transform Hubble into the world's most successful telescope.

Hubble against
Earth’s horizon.

NASA

When the Hubble Space Telescope launched from the shuttle *Discovery* in April 1990, it carried with it the hopes and dreams of astronomers everywhere. The state-of-the-art NASA instrument was expected to show scientists their clearest view ever of the cosmos.

It was the culmination of a 25-year effort that had begun with a 1965 proposal from a panel headed by astronomer Lyman Spitzer Jr. After many iterations, the plan to build a large space telescope was approved by the U.S. Congress in 1977, with a launch scheduled for 1983. However, that date was delayed for seven years due to shifting government priorities and the 1986 *Challenger* explosion.

So when Hubble's time finally came, expectations were high among both scientists and the public.

The bad news started rolling in right away ...

Its Strehl ratio was **only 0.15**, far from the **optically perfect 1.0**.

In public disgrace

Radiation from the Van Allen belts knocked out the guidance system's electronic memory for up to 10 minutes of every 98-min. orbit. The solar arrays shook as they warmed in sunlight and cooled in the dark, making pointing difficult. Worst of all, fine-tuning the optics did not bring starlight to the sharp focus expected in the vacuum of space. An analysis of the light surrounding the star images revealed that the telescope optics had suffered from a root-mean-square (RMS) spherical aberration of 275 nm. Disheartened officials announced the problem on 21 June.

Yet Hubble's design gave NASA hope for recovery. The telescope's instruments were packaged in modules designed for in-space replacement—although nobody had expected the optics would need to be fixed.

NASA named a panel of experts led by Lew Allen, director of the Jet Propulsion Laboratory (JPL), to find the cause of the optical systems' failure and determine why it had not been spotted before launch. Duncan Moore, then the director of the Institute of Optics at the University of Rochester, headed the Hubble Independent Optical Review Panel; he was charged with diagnosing the optical problem and designing repairs.

Comparing images from the Wide Field Planetary Camera and the Faint Object Camera confirmed that the problem was spherical aberration in the Ritchey-Chrétien telescope at the heart of Hubble. This resulted in images no better than those produced by a high-elevation ground telescope. Its Strehl ratio was only 0.15, far from the optically perfect 1.0.

What was the source of the aberration? Only limited tests were possible in space, but test equipment and records were available, mostly at the Danbury, Conn., plant where the Perkin-Elmer Corp. had fabricated the primary mirror and polished it to its final shape. Among the hardware was a back-up primary mirror, made and finished to its final shape by Eastman Kodak, but not polished. Tests of the back-up showed that it met optical specifications, so the error had not been in design; thus, it must have been in fabrication and testing.

Meanwhile, Moore's group found spherical aberration both on and off axis in Hubble images, showing the figure of the primary was in error. However, they did not see the coma expected from serious errors on the secondary. That left NASA in the embarrassing position of having launched a flawed primary when a perfect back-up was available. Swapping mirrors was not feasible in space.

Forensic optics

Investigators pored through NASA and Perkin-Elmer documents on design, fabrication and testing of the primary. Perkin-Elmer tests found that the primary mirror was within tolerance after it was polished and coated in 1981. Records also revealed that the complete optical system had never been tested end-to-end after assembly.

The rationale was that realistic simulation of the space environment is very difficult and expensive. For Hubble, it would have required $100 million to construct a huge special-purpose vacuum chamber. With the telescope already over budget, such testing had seemed a luxury when measurements had shown the component optics to be perfect. That decision looked much worse in hindsight.

The Moore panel sent expert optical trouble-shooters to the Danbury plant. Perkin-Elmer had sold the division to Hughes Aircraft in 1989, but test equipment

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Hubble's primary mirror being ground at Perkin-Elmer (1979).

NASA Marshall Space Flight Center

and records had been untouched since the optics were shipped in 1984 to Lockheed Missiles and Space in California for assembly of the Hubble spacecraft.

"The place looked like a crime scene," recalled Mark Kahan of Optical Research Associates (ORA, now Synopsys). Federal marshals had secured all Hubble-related files and gathered the paper files in a cafeteria. "It was a scary process," said Kahan, whose job was to sort through the records to deduce what had happened, why, and how that information could help repair Hubble.

The stakes were high for NASA management. Critics howled about the misfigured mirror and talked about scrapping Hubble. The agency desperately needed an affordable way to fix it. Kahan also had personal stakes. He knew people at Perkin-Elmer and realized that mistakes on crucial tests could end careers.

Another ORA optical specialist, William Wetherell, focused on the equipment used to test the main mirror. The crucial device used to figure the primary was a null corrector, an optical assembly designed to generate a wavefront to serve as an optical template for interferometric measurements of the mirror shape. The mirror is polished to match the wavefront; when that happens, tests produce a characteristic fringe pattern.

The standard design used in the 1970s was a refractive null corrector, in which a plano-convex lens focused light from a point source through a three-element field lens onto the mirror being tested. Its performance depended crucially on both the positioning and the optical properties of the lenses. That worried Perkin-Elmer managers because it was difficult to verify that the refractive null corrector was producing the desired optical template for the mirror.

To avoid that problem in fabricating a 1.5-m test mirror for NASA, Perkin-Elmer engineers designed a novel reflective null corrector with a single field lens and a pair of spherical mirrors instead of the usual single mirror. That design offered an important advantage: It had fewer surfaces and on paper was more accurately testable. The shape of the optical template it produced could be calculated from the dimensions of the mirrors and field lens, as well as the refractive index of the lens and the spacing of the optical elements. Optical-element spacing had to be within 10 µm to meet specifications, but optical metrology achieved that for a prototype mirror. That result, and an aggressively low bid of \$69 million, helped Perkin-Elmer win the Hubble contract in 1977.

The reflective null corrector was modified in 1980 to test the larger Hubble primary during figuring, polishing and coating—a process that was completed in December 1981. Then it sat in place atop the Hubble test tower until the trouble-shooters arrived eight years later.

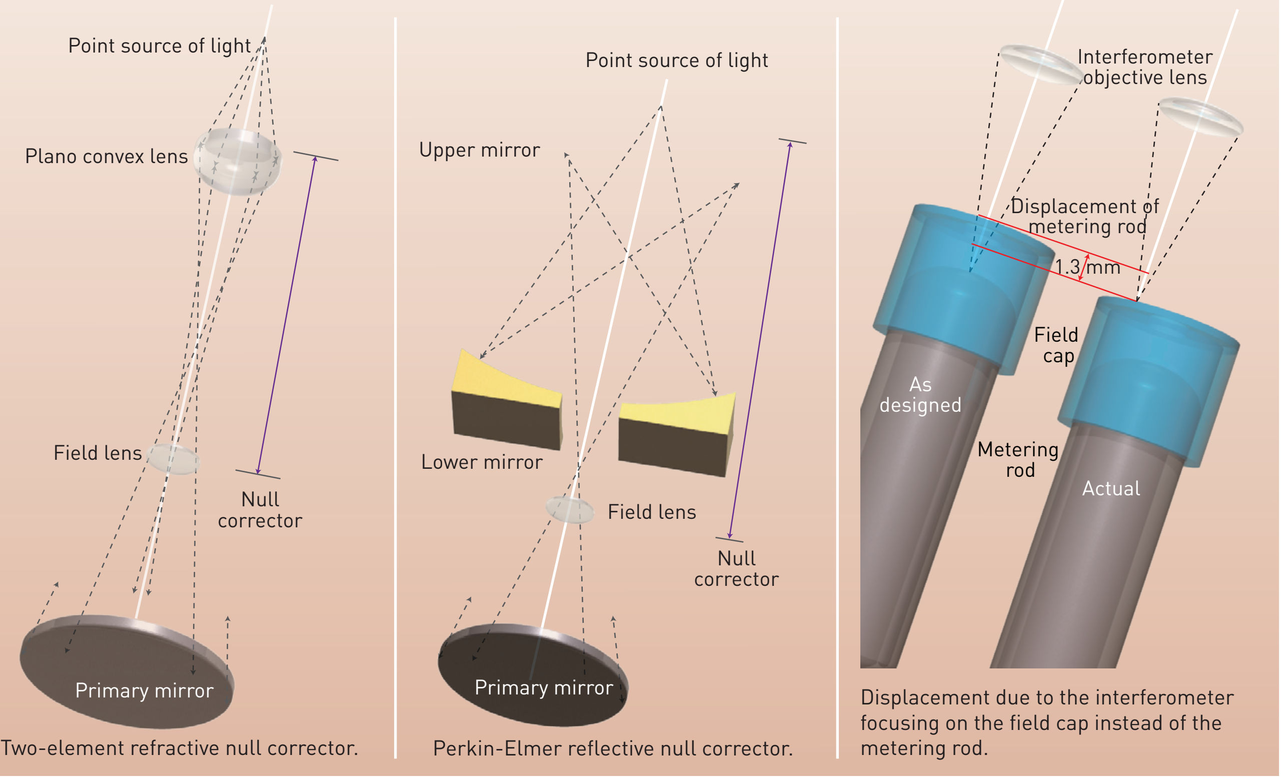
The reflective null corrector could not perform all needed measurements, so the team at Perkin-Elmer used a refractive null corrector for initial figuring and polishing of the primary. They reserved the reflective null corrector, expected to be more accurate, for final mirror polishing. They also used an inverse null corrector to simulate a perfect mirror so they could check that the reflective null did not change during its measurements of the primary.

Federal marshals had **secured all Hubble-related files** and gathered the paper files in a cafeteria.

Perkin-Elmer's tests with the reflective null corrector showed the primary mirror exceeded NASA specifications. But 1981 data from the refractive null corrector in the old files told a different story. "We found spherical aberration roughly equal to what was found on station," says Kahan. The test results didn't match those taken with the reflective null at the same stage in the fabrication process even when test-equipment tolerances were considered. Standard procedure is to repeat the tests until the problem is identified, but documents showed the Perkin-Elmer test engineers decided the less-precise refractive null had to be wrong.

Trouble-shooters in 1990 first tested the refractive null, which they found to be accurate to within 0.02 wave RMS. That pointed to an error in the reflective null corrector. On 22 July, they put the inverse null corrector in the primary-mirror test tower with the reflective null and produced interferograms showing spherical aberration, which were virtually identical to those taken with the same setup in 1982. This bolstered the case against the reflective null corrector.

The crucial test equipment



Two-element refractive null corrector.

Perkin-Elmer reflective null corrector.

Displacement due to the interferometer focusing on the field cap instead of the metering rod.

Phil Saunders/Adapted from NASA, Hubble Space Telescope Optical Systems Failure Report

Examination of the reflective null ruled out the two causes of the problems that initially seemed most likely: installing the field lens backwards or using glass with the wrong refractive index. While incorrect spacing of the optical elements initially had seemed unlikely, new measurements revealed that the field lens was about 1.3 mm too far below the lower mirror. This, the Allen panel found, accounted for the observed spherical aberration. In other words, Perkin-Elmer had fabricated the main mirror perfectly, but to the wrong shape.

The records did not reveal exactly what went wrong, but by mid-September 1990 the Allen panel had worked out the likely cause, with key evidence coming from Hughes-Danbury staff working for the panel. Originally used to test a 1.5-m test mirror, the reflective null had to be modified for the 2.4-m Hubble primary, and Perkin-Elmer used custom-made invar metering rods with rounded ends to accurately space the field lens. To make their optical measurements from the right point and to protect the invar rod, technicians had mounted a black cap with a small central hole over the rounded end.

What they didn't notice was that a chip had flaked off the black paint and they mistakenly measured distance to the exposed metal glint rather than to the spacing rod. Trying to correct the spacing to that point, they inserted washers at the field lens, causing a 1.3-mm error in spacing between the field lens and the lower mirror.

The washers were inserted in May 1980, and the NASA investigators who dug through the mountains of paperwork found that the refractive null showed aberrations then. Tests with the inverse null corrector showed aberrations in August, when polishing began. A refractive null test in April 1981, at the end of polishing, still indicated aberration.

On 19 May, an internal Perkin-Elmer review suggested a "sanity check" for an incorrect null. Testing manager Lucian Montagnino tried to pin down the discrepancy, and every month from May 1981 to March 1982 he reminded Hubble optics manufacturing manager Bud Rigby of the need to certify the reflective null. But it never happened.

With NASA unwilling to pay Perkin-Elmer more than their $69 million contract, Perkin-Elmer deputy program manager Robert W. Jones closed the primary mirror project in March 1982. In 1990, he and two higher-level managers told NASA investigators that they didn't know about the measurement discrepancies. NASA sued for damages and later recovered $25 million from Perkin-Elmer and Hughes in an out-of-court settlement.

The Things It Carried ...

The Hubble Space Telescope carried five scientific instruments when it first launched:

NASA/Amanda Diller

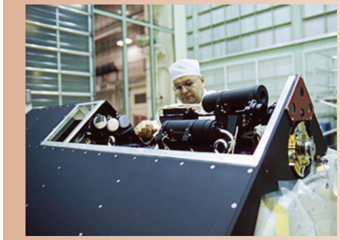
Wide-field and planetary camera

WFPC held two cameras that each had four 800 x 800 pixel CCDs to cover a contiguous field of view.

Wikimedia commons

Goddard high-resolution spectrograph

This instrument was designed to take spectral observations of astrophysical sources from 1,150 to 3,200 Å.



Courtesy of University of Wisconsin-Madison

High-speed photometer

It could be used in UV, visible light and near IR at a rate of one measurement per 10 μs.

Wikimedia commons

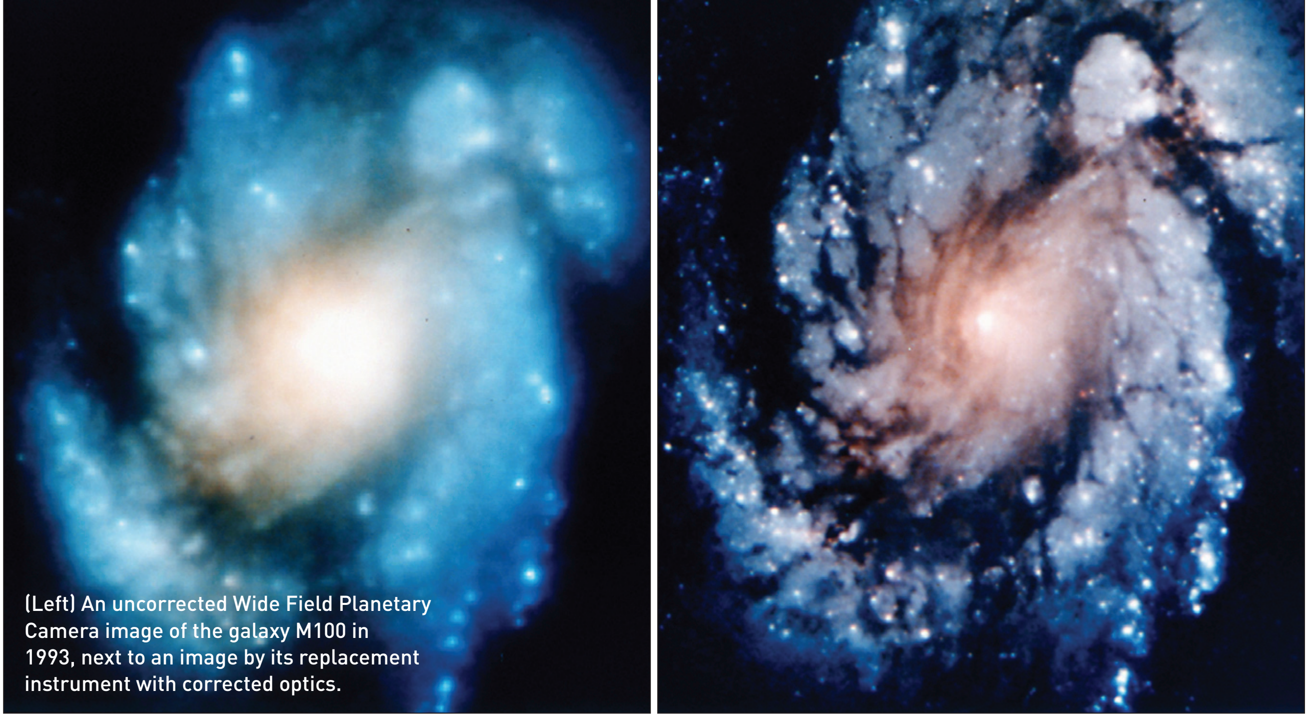
Faint object camera

This piece of equipment was designed to view faint UV light from 115 to 650 nm.

Wikimedia commons

Faint object spectrograph

FOS used blue and red digicon detectors and had a resolving power of about 1,300 over 115 nm to 850 nm.



(Left) An uncorrected Wide Field Planetary Camera image of the galaxy M100 in 1993, next to an image by its replacement instrument with corrected optics.

NASA

Prescribing corrective optics

The plan to save Hubble began as soon as aberration was recognized, although it took several more months to pin down the optical errors tightly enough to compensate for them.

The first plan was to build the corrective optics into a new generation of instruments. JPL was already building a new Wide Field Planetary Camera (WFPC) for the 1993 service mission. It was a relatively straightforward process because the needed correction could be figured onto the camera's secondary mirror, where Hubble focused light.

> **"It's fixed beyond our wildest expectations,"** said program scientist Ed Weiler.

However, that would have left the four instruments along Hubble's axis uncorrected, so Holland Ford and Robert Brown of the Space Telescope Science Institute (STSI) figured out how to fix them with their strategy team. The task was tougher than fixing WFPC because new optics had to be added to serve the axial instruments.

In the end, Ford recalls, they picked "two simple but genius ideas" suggested by James Crocker of STSI. He proposed sacrificing one axial instrument to make room for a module holding pairs of corrective mirrors. Once the module was installed, an optical bench would slip out and rods would slide one pair of corrective mirrors into the optical path to each of the other three instruments.

Crocker later said he got the idea of sliding the little mirrors on rods from a fancy shower in the hotel where he had stayed during a meeting. By November, they had sketched out the design of COSTAR (for Corrective Optics Space Telescope Axial Replacement) and decided it would replace the High-Speed Photometer, a first-generation axial instrument rendered almost useless by Hubble's vibration problem.

Murk Bottema, a veteran designer of space instruments at Ball Aerospace, did the design work on the aspheric COSTAR mirrors, which had to be precisely positioned to bring the three remaining axial instruments into focus. Investigators spent months more determining the main mirror's flaws, so the 10- to 30-mm mirrors could provide exact corrections.

The COSTAR might sound simple, but it took a total of 5,300 parts to slide the six small mirrors in place so that they could focus exactly onto the three remaining axial instruments. Specifications called for the aspheric surfaces to be accurate within 6 nm of Ball's design and smooth to within 1 nm, better than Hubble's main mirror. Tinsley Optics took the job. The company created surfaces that were accurate to within 3 nm and smooth to within 0.5 nm.

Meanwhile, NASA tried to find some good news from Hubble despite its optical flaws. One achievement was recording Pluto and its moon as widely separated objects rather than blurry spots that appeared in ground photos. Aberration scattered light across the background of these images. NASA tried to enhance them, but could not recover the faint galaxies obscured by the stray light. Astronomers complained bitterly.

Hubble continued to experience technical and organizational failures. The telescope was shut down in May

1991 because part of its main computer memory failed. The following month, a second gyroscope malfunctioned, leaving only one spare. Power-supply problems hobbled the Goddard High Resolution Spectrometer instrument in July. In early 1992, veteran astronaut Richard Truly was forced out as a NASA administrator. The first Hubble servicing mission had to repair reputations as well as hardware.

Choreography in space

NASA planners had envisioned Hubble service missions as an orderly process of replacing old instrument modules with better ones. They had not expected the cascade of problems that surfaced after launch. In the spring of 1992, NASA picked veteran astronaut Story Musgrave to head the complicated first Hubble service mission.

Repairs in space need to be carefully choreographed, and the work is cumbersome and tiring. Musgrave was an expert; he had helped develop NASA space suits and worked on space servicing techniques since 1976. He knew work in space had to be planned far in advance, so he rehearsed in simulation tanks. That August, well over a year before the planned Hubble repair, fellow astronauts Tom Akers, Kathy Thornton and Jeff Hoffman joined Musgrave's mission team.

The group faced new complications. Previous spacewalks had been largely in sunlight, so space suits had been designed to avoid overheating. But Hubble had to be kept out of the sun to prevent outgassing from the black insulation that absorbed stray light. After Musgrave suffered frostbite while spending hours in a space suit testing tools and procedures in a vacuum chamber, NASA had to redesign the mission and adjust the suits to keep astronauts warmer.

NASA scheduled five spacewalks for the 2-13 December 1993 repair mission, the most on any shuttle mission. The long list of tasks started with replacing the wobbly solar arrays and defective gyros, and installing COSTAR and the second WFPC. Thanks to careful planning, the astronauts completed their work with only minor glitches. When they were done, they had clocked 35 hours and 28 minutes in space.

After a few weeks of re-commissioning, Hubble was working well for the first time. "It's fixed beyond our wildest expectations," said program scientist Ed Weiler. The difference was obvious in pictures. The Faint Object Camera showed Pluto and Charon crystal-clear with COSTAR in place on 21 February 1994. The light scattered by spherical aberration was gone; Hubble's Strehl ratio is now estimated at 0.90 at 500 nm and 0.98 at 1,200 nm.


A clear view of Pluto and its moon, Charon, via the Hubble Faint Object Camera after COSTAR was installed.

Dr. R. Albrecht, ESA/ESO Space Telescope European Coordinating Facility; NASA

Soon Hubble became a favorite with both astronomers and the public. The National Aeronautic Association gave the recovery team its 1993 Robert J. Collier trophy, "for outstanding leadership, intrepidity and the renewal of public faith in America's space program ..."

Hubble has far exceeded its planned 15-year lifetime. In 2005, after its fourth service mission, it discovered two previously unknown 100-km moons of Pluto. The decision to ground the shuttle in 2009 made the 2009 upgrade the Hubble's last, and allowed it to spot a smaller fourth moon in 2011 and a fifth in July 2012. That little moon, as yet unnamed, was only 10 to 25 km across, yet it clearly appears beside Pluto, says its discoverer, Mark Showalter of the SETI Institute. "I'm still struck by just what an amazing instrument Hubble is," he said.

The telescope is expected to continue functioning until 2014. At that point, its successor, the James Webb Telescope, should be nearing completion and preparing for a 2018 launch. OPN

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