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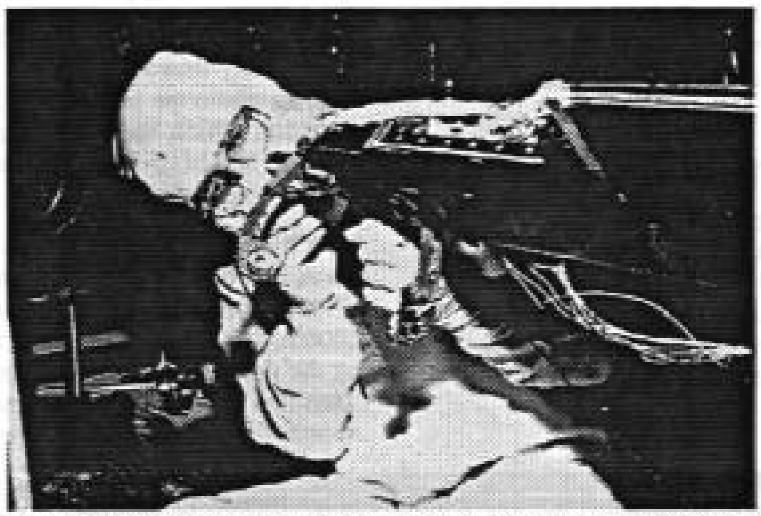
# NASA's Optical Verification Program

NASA did not rely on a single test or testing device to verify the two optical instruments designed to correct the Hubble Space Telescope's flawed vision. At every level—from component manufacturing to subsystem and instrument assembly—NASA conducted exhaustive and sophisticated tests to make sure each piece of equipment performed as specified.

NASA approached the correction of Hubble's nearsightedness as would an optometrist. The agency first diagnosed the telescope's vision problem, determined a prescription to fix the ailment and monitored the development of corrective optics to make sure the telescope's sight would be restored to the fullest extent possible.



*The Corrective Optics Space Telescope Axial Replacement (COSTAR) is an assembly of mechanical arms equipped with corrective mirrors that focus and rout light to three other instruments aboard Hubble. Optics specialists thoroughly tested every component and subsystem to make sure COSTAR would work as designed once on orbit.*

As further precautions, the agency directed its contractors to develop highly accurate equipment to test the optics packages, and established an independent panel of experts charged with verifying both the accuracy of the corrective optics—the Wide Field and Planetary Camera 2 (WFPC2) and the Corrective Optics Space Telescope Axial Replacement (COSTAR)—and the equipment used to test them.

That panel, the Independent Verification Team (IVT), reported to the Goddard Space Flight Center Engineering Directorate and ultimately found that the instruments performed within specifications. Before signing off on the corrective optics, the team tested each instrument with a device called the Aberrated Beam Analyzer (ABA).

Both sets of corrective optics also underwent at the Goddard Space Flight Center a "glint" test to make sure they did not contain reflective surfaces that would interfere with light gathering and a "confocality" test to make sure they both could focus in the same focal plane.

The months-long testing program involved many specialists across the country, who spent thousands of hours developing and testing WFPC2, built by the Jet Propulsion Laboratory (JPL) and COSTAR, built by Ball Aerospace. Because engineers performed so many tests at so many levels along the way, it would be difficult to list them all.

For example, Tinsley Laboratories, which manufactured the coin-sized mirrors fitted into both instruments, performed three independent verification tests. Other instrument components also underwent the same level of scrutiny.

The European Space Agency (ESA), meanwhile, provided a refurbished structural and thermal model of one of the telescope's instruments—the

Faint Object Camera—to help Ball test how well COSTAR focused light streaming into a Hubble-like instrument. In addition, the Space Telescope Science Institute independently provided staff experts and computer support in the verification and alignment of both optical instruments.

Though the effort was complex, the philosophy guiding the testing was straightforward: All test results would be analyzed by optical science experts who would not be under pressure to overlook discordant data.

## The Diagnosis

NASA's optical verification program began with the Lew Allen Board of Investigation, established to determine the cause of the telescope's mirror flaw, how it occurred and why it was not detected before launch. It concluded in late 1990 that Hughes Danbury Optical Systems, Inc. (formerly Perkin-Elmer Corp.) had relied exclusively on a single testing device called the null corrector.

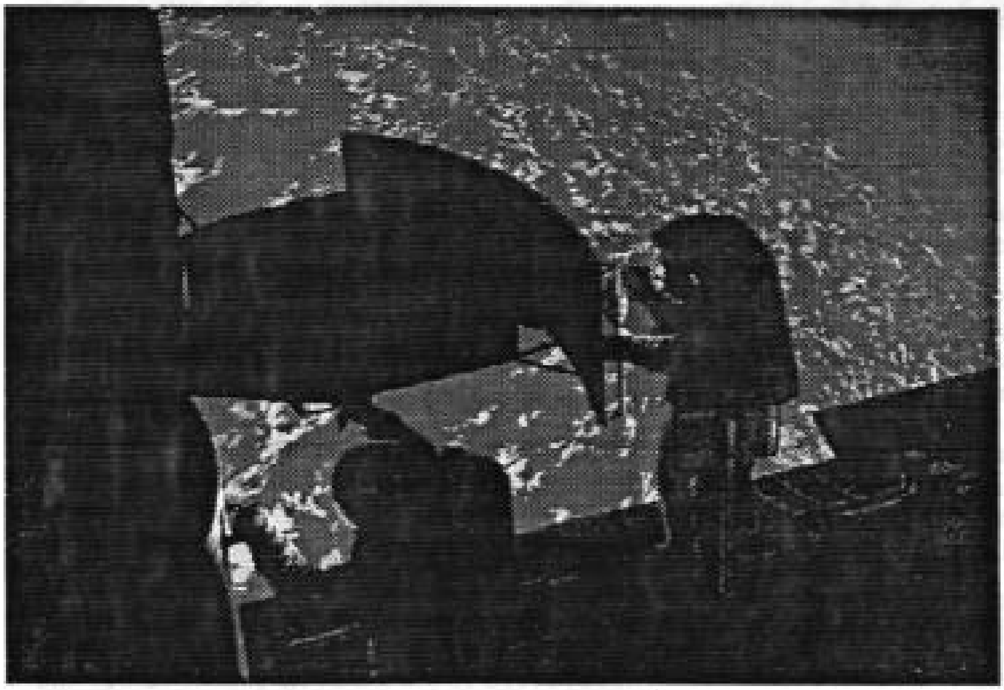
This cylindrical device, which was a little larger than a barrel, consisted of two mirrors and a lens. To test the telescope's mirror, laser light was sent through the null corrector and bounced off the telescope mirror. The light then passed back through the null corrector to create a pattern of black and white lines, called an interferogram. Those lines told technicians whether the mirror was correctly shaped.

Unfortunately, technicians had not properly assembled the device, incorrectly positioning one optical element by 1.3 millimeters. Consequently, technicians, using the null corrector as their guide, ground the mirror to the wrong figure. In the end, the mirror—the largest astronomical mirror ever to be launched in space—was too flat at the edge by an amount equal to 1/50 the width of a human hair—a big error in optical terms.

To find an optical prescription that would correct the telescope's flawed vision, NASA established another panel, the Hubble Independent Optical Review Panel (HIORP), and asked Duncan Moore, director of the University of Rochester's Institute of Optics, to chair it. NASA charged it with finding a prescription that would correct Hubble's focusing problem.

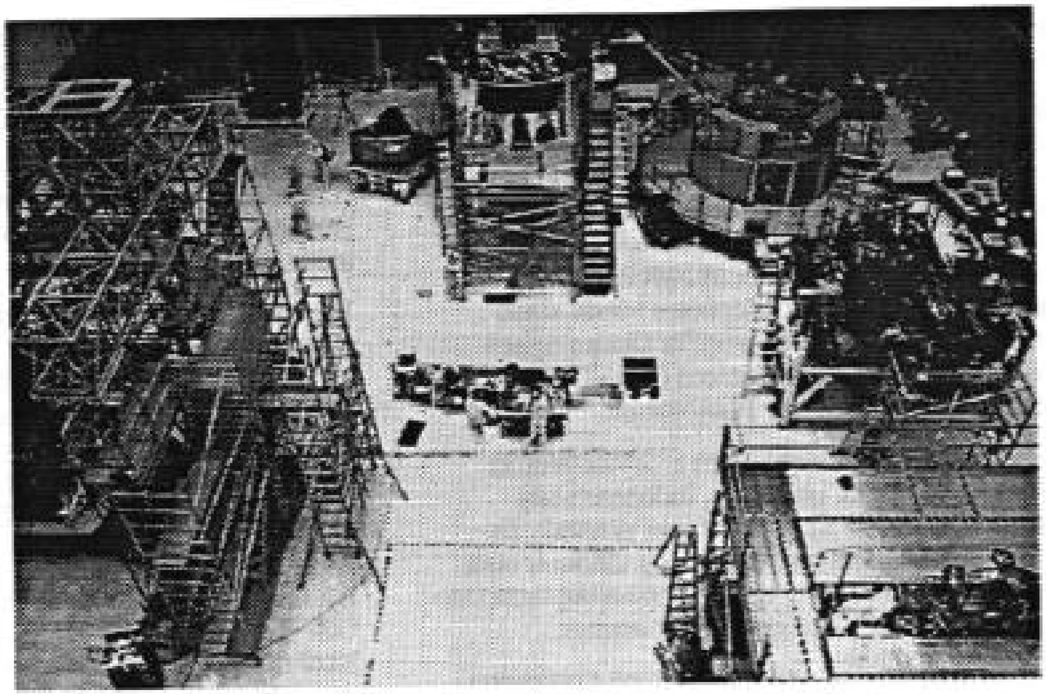
The panel relied on information that came from two primary sources: the data transmitted by the orbiting telescope and Perkin Elmer's null corrector, which had been untouched for nearly 10 years in a high-security area of the company's Danbury, CT, plant.

After months of analyzing the data using computers and other techniques, the board prescribed a "conic constant" that would describe Hubble's incorrectly shaped mirror. In addition to checking the data and the null corrector, the board examined the possibility that technicians had incorrectly ground Hubble's secondary mirror.



*This artist's rendition shows the installation of the Wide Field and Planetary Camera (WFPC2), which contains corrective optics and replaces the original camera. Engineers and scientists spend many, many hours checking and rechecking the instrument's optical performance.*

*For months, technicians tested and calibrated instruments and other components in this Goddard Space Flight Center cleanroom to make sure the equipment will work as designed in space.*



However, it determined conclusively that the secondary was built within specification.

## The Optical Prescription

***Wide Field and Planetary Camera 2***

The Wide Field and Planetary Camera 2 (WFPC2), pronounced Wiffpick for short, is designed to take visible and ultraviolet light images of celestial objects. In 1984, long before NASA discovered the spherical aberration, JPL engineers and scientists had decided to upgrade the original flight-spare instrument and install it on the first servicing mission. The instrument was some two years away from completion when NASA discovered the spherical aberration. With that discovery, WFPC2's design had to be slightly reconfigured.

To compensate for the mirror defect, engineers recognized almost immediately that a fix, at least for WFPC, would be relatively straightforward. The instrument contained a set of convex mirrors about a centimeter in diameter that relayed images to instrument detectors. Therefore, a defect in the Hubble primary mirror could be compensated for by introducing an equal but opposite defect on these small mirrors.

The HIORP's job was to provide a value of that opposite defect, or the conic constant. But developing an optical fix also required that engineers make sure the instrument itself was aligned with excruciating precision. As a result, engineers and scientists decided early in the program to install remotely adjustable mirrors in the instrument's relay optics channels.

Their work was far from complete, however. Testing the new instrument would require an additional level of effort. When JPL built the first-generation WFPC, it tested the instrument with an optical simulator that fed light into the instrument the same way the actual telescope would supply images.

That testing device, called a "Stimulus," had to be redesigned and rebuilt to reproduce the aberrated images—a task that required nearly two years to complete. The reconfigured Stimulus, also independently tested and calibrated, became the ultimate gauge-block against which WFPC2 was tested.

***Corrective Optics Space Telescope Axial Replacement***

Correcting the light streaming into the telescope's other three instruments aboard the observatory—the Faint Object Camera, the Faint Object Spectrograph and the Goddard High Resolution Spectrograph—required a different approach.

The late Murk Bottema, a physicist and engineering consultant at Ball, devised the fastest, most practical plan. His solution involved inserting coin-sized mirrors behind the flawed primary mirror. These mirrors, inversely shaped according to the conic constant to correct the spherical aberration, would intercept and correct the light and bounce it directly into the apertures of the observatory's instruments.

How to install these mirrors became another engineering problem. Jim Crocker, an electrical engineer at the Space Telescope Science Institute in Baltimore, came up with the idea of building a compact assembly of small mirrors attached to mechanical arms that would unfold once installed on-orbit. This telephone booth-sized assembly, called the Corrective Optics Space Telescope Axial Replacement (COSTAR) would replace the High Speed Photometer.

Like WFPC2, however, such a device would require a series of intensive, independently verified tests to make sure it was properly focused and aligned—an especially difficult task since the instrument would be directing light into the apertures of three other instruments.

One testing device—the Refractive Aberration Simulator (RAS)—was built by Ball Aerospace to simulate as closely as possible the as-built performance of Hubble's optics and duplicate simulated star sources for each science instrument.

NASA required, however, that its alignment and performance be verified by independent means, including checks the IVT and ESA, which provided the structural thermal model of the Faint Object Camera (FOC). RAS was then attached to the Hubble Optical Mechanical Simulator (HOMS), which held COSTAR and FOC in a flight-like configuration, and Ball conducted its own in-house tests.

## The Monitors: Aberrated Beam Analyzer and the 'Sanity Check'

Quite independently of these efforts, the IVT—the engineering team tasked with verifying the optics packages and the equipment used to test them—developed a portable, compact instrument to non-invasively test WFPC2 and COSTAR at the contractor facilities. Called the Aberrated Beam Analyzer (ABA), the instrument was designed and developed jointly by a team of representatives from GSFC, Adaptive Optics Associates, Inc., Fairchild Space, and Swales and Associates, Inc. It measured wavefront and pupil parameters. And it, too, underwent extensive testing.

It took some 12 months to design, build and test the ABA. In late February 1993, the ABA was used at Ball and JPL to verify that the RAS and JPL Stimulus correctly simulated Hubble's aberrated vision. The team returned later to test COSTAR. All results were thoroughly examined and understood before the IVT signed off on both instruments.

By June 1993, both instruments were shipped to GSFC for further tests in the high-fidelity simulator of the Hubble instrument bay to make sure they were compatible with one another. The "sanity check" determined that neither instrument contained reflective surfaces that might scatter light. It also confirmed that the instruments could simultaneously focus on-orbit. However, the confocality testing produced results that seemed to dispute other verification tests. NASA found a flaw in the test set-up, which explained the discrepancies in the data. But to eliminate all doubt, it also directed that engineers take additional measurements of WFPC2. Those tests, conducted at Kennedy Space Center, confirmed the revised data from the GSFC test.

## Summary

The optical verification process took months to complete. All contractors, including the component manufacturers, conducted a minimum of two independent tests. In addition, the IVT also performed thorough checks during the verification process. NASA is ready for launch. ♦