EXECUTIVE SUMMARY

The Hubble Space Telescope (HST) was launched aboard the Space Shuttle Discovery on April 24, 1990. During checkout on orbit, it was discovered that the telescope could not be properly focused because of a flaw in the optics. The HST Project Manager announced this failure on June 21, 1990. Both of the high-resolution imaging cameras (the Wide Field/Planetary Camera and the Faint Object Camera) showed the same characteristic distortion, called spherical aberration, that must have originated in the primary mirror, the secondary mirror, or both.

The National Aeronautics and Space Administration (NASA) Associate Administrator for the Office of Space Science and Applications then formed the Hubble Space Telescope Optical Systems Board of Investigation on July 2, 1990, to determine the cause of the flaw in the telescope, how it occurred, and why it was not detected before launch. The Board conducted its investigation to include interviews with personnel involved in the fabrication and test of the telescope, review of documentation, and analysis and test of the equipment used in the fabrication of the telescope's mirrors. The information in this report is based exclusively on the analyses and tests requested by the Board, the testimony given to the Board, and the documentation found during this investigation.

Continued analysis of images transmitted from the telescope indicated that most, if not all, of the problem lies in the primary mirror. The Board's investigation of the manufacture of the mirror proved that the mirror was made in the wrong shape, being too much flattened away from the mirror's center (a 0.4-wave rms wavefront error at 632.8 nm). The error is ten times larger than the specified tolerance.

The primary mirror is a disc of glass 2.4 m in diameter, whose polished front surface is coated with a very thin layer of aluminum. When glass is polished, small amounts of material are worn away, so by selectively polishing different parts of a mirror, the shape is altered. During the manufacture of all telescope mirrors there are many repetitive cycles in which the surface is tested by reflecting light from it; the surface is then selectively polished to correct any errors in its shape. The error in the HST's mirror occurred because the optical test used in this process was not set up correctly; thus the surface was polished into the wrong shape.

The primary mirror was manufactured by the Perkin-Elmer Corporation, now Hughes Danbury Optical Systems, Inc., which was the contractor for the Optical Telescope Assembly. The critical optics used as a template in shaping the mirror, the reflective null corrector (RNC), consisted of two small mirrors and a lens. The

RNC was designed and built by the Perkin-Elmer Corporation for the HST Project. This unit had been preserved by the manufacturer exactly as it was during the manufacture of the mirror. When the Board measured the RNC, the lens was incorrectly spaced from the mirrors. Calculations of the effect of such displacement on the primary mirror show that the measured amount, 1.3 mm, accounts in detail for the amount and character of the observed image blurring.

No verification of the reflective null corrector's dimensions was carried out by Perkin-Elmer after the original assembly. There were, however, clear indications of the problem from auxiliary optical tests made at the time, the results of which have been studied by the Board. A special optical unit called an inverse null corrector, designed to mimic the reflection from a perfect primary mirror, was built and used to align the apparatus; when so used, it clearly showed the error in the reflective null corrector. A second null corrector, made only with lenses, was used to measure the vertex radius of the finished primary mirror. It, too, clearly showed the error in the primary mirror. Both indicators of error were discounted at the time as being themselves flawed.

The Perkin-Elmer plan for fabricating the primary mirror placed complete reliance on the reflective null corrector as the only test to be used in both manufacturing and verifying the mirror's surface with the required precision. NASA understood and accepted this plan. This methodology should have alerted NASA management to the fragility of the process and the possibility of gross error, that is, a mistake in the process, and the need for continued care and consideration of independent measurements.

The design of the telescope and the measuring instruments was performed well by skilled optical scientists. However, the fabrication was the responsibility of the Optical Operations Division at the Perkin-Elmer Corporation (P-E), which was insulated from review or technical supervision. The P-E design scientists, management, and Technical Advisory Group, as well as NASA management and NASA review activities, all failed to follow the fabrication process with reasonable diligence and, according to testimony, were unaware that discrepant data existed, although the data were of concern to some members of P-E's Optical Operations Division. Reliance on a single test method was a process which was clearly vulnerable to simple error. Such errors had been seen in other telescope programs, yet no independent tests were planned, although some simple tests to protect against major error were considered and rejected. During the critical time period, there was great concern about cost and schedule, which further inhibited consideration of independent tests.

The most unfortunate aspect of this HST optical system failure, however, is that the data revealing these errors were available from time to time in the fabrication process, but were not recognized and fully investigated at the time. Reviews were inadequate, both internally and externally, and the engineers and scientists who were qualified to analyze the test data did not do so in sufficient detail. Competitive, organizational, cost, and schedule pressures were all factors in limiting full exposure of all the test information to qualified reviewers.

INTRODUCTION

The rough grinding operation for the Hubble Space Telescope began in December 1978, at the Perkin-Elmer Corporation, in Wilton, Connecticut. The mirror was then transferred to Perkin-Elmer in Danbury, Connecticut, now Hughes Danbury Optical Systems, Inc. (HDOS), where polishing was completed in April 1981, and the mirror was accepted as ready for reflective coating. The final post-coating test was made in February 1982.

Approximately two months after launch, on June 21, 1990, the Hubble Space Telescope Project Manager announced that there was a major flaw in one or both of the mirrors in the Optical Telescope Assembly. Dr. Lennard Fisk, Associate Administrator for the Office of Space Science and Applications, in accordance with the procedures of the HST Contingency Plan, established the Hubble Space Telescope Optical Systems Board of Investigation to determine the relevant facts. A copy of the Board's charter, incorporated in a letter of authorization to the Chairman, and a list of the members of the Board are presented in Appendix A of this report.

The Board, in accordance with its charter, impounded all relevant documentation and equipment at the HDOS facility. With the assistance of HDOS personnel and NASA HST Project and Program management, the Board reviewed documents, interviewed personnel, and analyzed and tested the equipment used during the fabrication of the mirrors.

The first meeting of the Board was held in Washington, DC on July 5 and 6, 1990, and the subsequent meetings were held at HDOS. A summary of all the Board meetings and attendees can be found in Appendix B.

The investigation was quickly directed to the fabrication and testing of the primary mirror. The test equipment used during the final shaping and polishing of the primary mirror was found in 1990 in essentially the same configuration as it had been when used in 1980 through 1982.

Another investigating body, the Independent Optical Review Panel, was formed by the HST Project to examine the on-orbit data and recommend actions to maximize the scientific utility of the HST. One of the principal concerns of the Independent Optical Review Panel is the impact of the spherical aberration discovered in the HST primary mirror. The results and findings of the HST Optical Systems Board of Investigation will undoubtedly assist the Independent Optical Review Panel in its work. (An early report of the Panel's findings is included in Appendix B.)

This report of the Board's investigation describes the results of the analysis and test of the equipment used during fabrication and sets forth the conclusions which can be drawn. It is difficult to reconstruct the exact events of the time, particularly since the status of the documentation is poor. It is also difficult to consider fairly the pressures of the time in question when cost and schedule were issues of crisis proportions. Therefore, the Board's judgments clearly benefit from hindsight, with the clear knowledge that an error occurred and should not have occurred.

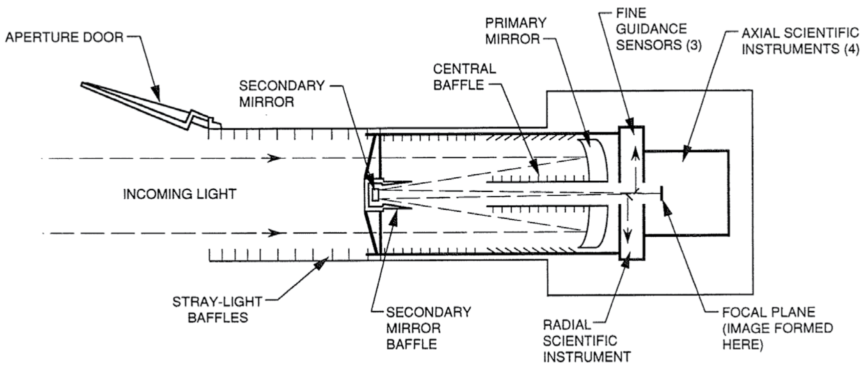


Figure 2-1. Optical Telescope Assembly.

THE HUBBLE SPACE TELESCOPE MISSION

The HST was designed to be the first of the great space observatories. It was launched aboard the Space Shuttle and placed in an Earth orbit approximately 607 kilometers in altitude. The expected life of the telescope is about 15 years, with instrument changeouts every 3 to 5 years.

The goal of the mission is to extend our knowledge of the universe. A space-based telescope has the advantage of being in an environment free of the turbulence and absorption of the Earth's atmosphere. Prior to this mission, astronomical telescopes in space, such as the Einstein Observatory (HEAO-2) and the Infrared Astronomical Satellite (IRAS), had been designed to explore new wavelength bands not transmitted through the atmosphere. The HST was the first space telescope designed to overcome the blurring of images caused by the atmosphere. The inherent resolution of a precisely made telescope is in proportion to its diameter, and the large 2.4-m aperture of HST promised images ten times sharper than the best images from the ground.

At the heart of the Optical Telescope Assembly (OTA) is a 2.4-m Ritchey-Chretien telescope with a focal ratio of f/24. The optical range of the HST extends from 1,100 to 11,000 angstroms, and the performance quality in the ultraviolet is unique. Figure 2-1 illustrates the OTA.
from 1,100 to 11,000 angstroms, and the performance quality in the ultraviolet is unique. Figure 2-1 illustrates the OTA.

Eight instrument packages are attached to the HST: two cameras (Wide Field/Planetary Camera and Faint Object Camera), two spectrographs (Faint Object Spectrograph and High-Resolution Spectrograph), one photometer (High-Speed Photometer), and three fine guidance sensors. Each fine guidance sensor package also contains a wavefront sensor. Table 2-1 lists the HST and scientific instrument specifications.

Table 2-1. HST scientific instrument specifications.

Hubble Space Telescope	
Weight	11,500 kg
Length	13 m
Diameter	4.2 m at widest
Optical System	Ritchey-Chretien design Cassegrain telescope
Optical Length	57.6 m folded to 6.4 m
Primary Mirror	2.4 m in diameter
Secondary Mirror	0.3 m in diameter
Field of View	See instruments and sensors below
Pointing Accuracy	0.007 arcsec for 24 hr
Magnitude Range	5–29 m_V
Wavelength Range	1,100–11,000 angstroms
Angular Resolution	0.1 arcsec at 6,328 angstroms
Orbit	611 km (330 nmi) inclined 28.5° from equator
Orbit Time	94 minutes per orbit
Mission	15 years
Faint Object Camera	
Weight	315 kg
Dimensions	0.9 x 0.9 x 2.2 m
Principal Investigator	F. D. Macchetto, European Space Agency (ESA)
Contractor	ESA (Dornier, Matra Corp.)
Optical Modes	f/96, f/48
Field of View	11.2, 22 $arcsec^2$
Magnitude Range	5–28 m_V
Wavelength Range	1,150–6,500 angstroms
Wide Field/Planetary Camera	
Weight	268 kg
Dimensions	Camera: 1 x 1.3 x 0.5 m Radiator: 0.8 x 2.2 m
Principal Investigator	J. A. Westphal, California Institute of Technology
Contractor	Jet Propulsion Laboratory
Optical Modes	f/12.9 (WF); f/30 (P)
Field of View	160, 66 $arcsec^2$
Magnitude Range	9–28 m_V
Wavelength Range	1,150–11,000 angstroms
GSFC High-Resolution Spectrograph	
Weight	315 kg
Dimensions	0.9 x 0.9 x 2.2 m
Principal Investigator	J. C. Brandt, NASA/Goddard Space Flight Center
Contractor	Ball Aerospace
Apertures	2 $arcsec^2$ target, 0.25 $arcsec^2$ science
Resolution	2,000–100,000
Magnitude Range	17–11 m_V
Wavelength Range	1,050–3,200 angstroms

Table 2-1. HST scientific instrument specifications (continued).

Faint Object Spectrograph	
Weight	306 kg
Dimensions	0.9 x 0.9 x 2.2 m
Principal Investigator	R. J. Harms, NASA/Ames Research Center
Contractor	Martin Marietta Corporation
Apertures	0.1–4.3 $arcsec^2$
Resolution	250, 1,300
Magnitude Range	19–26 m_V
Wavelength Range	1,100–8,000 angstroms
High-Speed Photometer	
Weight	270 kg
Dimensions	0.9 x 0.9 x 2.2 m
Principal Investigator	R. Bless, University of Wisconsin
Contractor	University of Wisconsin
Apertures	0.4, 1.0, 10.0 $arcsec^2$
Resolution	Filter-defined
Magnitude Range	$<24\ m_V$
Wavelength Range	1,200–7,500 angstroms
Fine Guidance Sensors	
Weight	218 kg
Dimensions	0.5 x 1 x 1.6 m
Contractor	Perkin-Elmer Corporation
Astrometric Modes	Stationary and moving target, scan
Precision	0.002 $arcsec^2$
Measurement Speed	10 stars in 10 minutes
Field of View	Access: 60 $arcmin^2$ Detect: 5 $arcsec^2$
Magnitude Range	4–18.5 m_V
Wavelength Range	4,670–7,000 angstroms

PROGRAM HISTORY AND MANAGEMENT

A. RESPONSIBILITIES

The HST program is the result of a cooperative effort between NASA and the European Space Agency, private contractors, and astronomers worldwide. The management responsibilities included design, development, launch, and daily operations of the telescope. The NASA Centers and prime contractors involved in the development of the HST, and their interrelationships, are listed in Figure 3-1.

At NASA Headquarters, the director of the Astrophysics Division, who reports to the NASA Associate Administrator for the Office of Space Science and Applications, has overall authority for the HST Project. He assigned the NASA HST Program Manager to ensure that NASA policies and Project goals are maintained and to administer the schedule and budget. Overall science policy is the responsibility of the HST Program Scientist.

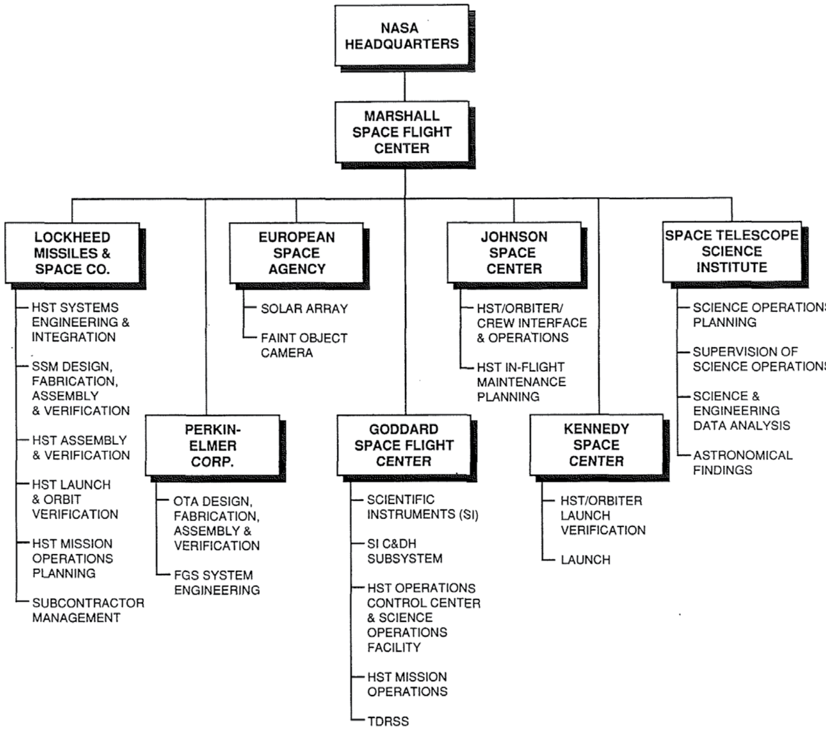
Marshall Space Flight Center (MSFC) was assigned as lead center for the HST Project management and tasked with the development of the telescope flight hardware and the general checkout phase after deployment. Responsibility for meeting the technical performance goals and for managing the program within budget and schedule was also with MSFC. Figure 3-2 is the MSFC organization chart for the HST.

The other NASA Center with a major involvement in the Project is the Goddard Space Flight Center (GSFC), which was responsible for verifying the performance of the science instruments. GSFC also controls the daily operations of the HST. On October 16, 1990, the responsibility for the HST Project (except for the optical system failure questions) was transferred from MSFC to GSFC.

The two prime contractors for the Project were Lockheed Missiles and Space Company, Inc. (LMSC) and the Perkin-Elmer Corporation (P-E). LMSC developed the Support Systems Module (SSM) and supervised many subcontracts; P-E designed and developed the OTA, including the fabrication of the primary and secondary mirrors. P-E was also responsible for verification testing and delivery of the OTA to LMSC, where the OTA was integrated with the other subsystems. In addition to the OTA, P-E developed the fine guidance sensors and wavefront sensors used in the HST.

Before P-E was selected as the OTA prime contractor, the company was asked to design and build a smaller hyperbolic mirror in order to demonstrate their technical capability. A 1.5-m mirror was successfully designed, fabricated, and tested using the new technologies that would be used for the larger 2.4-m HST primary mirror. After a competitive bid process, P-E was awarded the HST contract, based in part on their successful demonstration of the 1.5-m mirror and on other factors, including their proposed fine guidance sensors.

Because NASA considered the quality of the primary mirror to be a major challenge, it directed P-E to subcontract with the Eastman Kodak Company to fabricate a second primary mirror. The fabrication and test methods used at



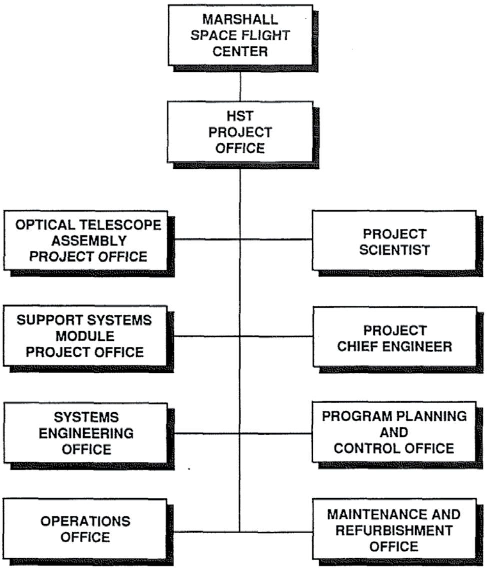
INFORMATION PROVIDED BY LOCKHEED MISSILES AND SPACE COMPANY, INC.

Figure 3-1. Hubble Space Telescope responsibilities.

Eastman Kodak and P-E were entirely different. It was the responsibility of NASA to review the final specifications of the mirrors and to choose the best one for flight. The P-E primary and secondary mirrors were selected.

B. ENVIRONMENT

During 1981 and continuing through early 1982, the HST program was beset by many difficulties. The estimated cost of the P-E contract had increased several-fold and the schedule had slipped substantially. The fine guidance sensors were having serious technical problems, and the severity of the challenge to keep the mirrors sufficiently free from contamination to meet the specifications in ultraviolet light was just being recognized. The program was threatened with cancellation, and management ability was questioned. All these factors appear to have contributed to a situation where NASA and P-E management were likely to be distracted from supervision of mirror fabrication.



MSFC RESPONSIBILITIES

- HST DEVELOPMENT LEAD CENTER
- TOTAL PROJECT MANAGEMENT
- OTA DEVELOPMENT
- SSM DEVELOPMENT
- HST INTEGRATION AND VERIFICATION
- ORBITAL VERIFICATION OPERATIONS
- MAINTENANCE AND REFURBISHMENT PLANNING

INFORMATION PROVIDED BY LOCKHEED MISSILES AND SPACE COMPANY, INC.

Figure 3-2. MSFC's Hubble Space Telescope responsibilities.

OPTICAL TELESCOPE ASSEMBLY

A. HST OPTICAL DESIGN

The Optical Telescope Assembly in the Hubble Space Telescope is a two-mirror reflecting telescope very similar to most Earth-based telescopes built in the last 75 years. These two-mirror telescopes are generally referred to as Cassegrain telescopes, after the French cleric who first published the design. The OTA is a special type of Cassegrain telescope called a Ritchey-Chretien (R-C) that has better optical performance over a larger format in the image plane. The mirrors in the R-C are slightly more aspheric (have a greater departure from a pure spherical shape) than in the Cassegrain type, but both types of telescopes are quite common. The primary mirror in the OTA, the one in which the error exists, is a 2.4-m diameter concave hyperboloid. The 0.3-m diameter secondary mirror is a convex hyperboloid. This makes the OTA a little less than half the size of the Hale telescope on Mt. Palomar.

B. OPTICAL TESTING

Spherical mirrors are easy to make and to test, but such mirrors do not produce good-quality images. The aspheric mirrors used in Cassegrain or R-C telescopes can produce theoretically perfect images, but their aspheric shape makes them difficult to test. Because the two mirrors in the OTA are hyperboloids or aspheric mirrors, special test optics are needed to guarantee that the mirrors are the correct shape. These special test optics, called null correctors, generate test reference wavefronts that make the aspheric mirror look spherical to the optician. The null correctors achieve this effect by projecting an optical template of the desired aspheric shape that can be designed to be accurate to better than 25 nanometers.

C. NULL CORRECTORS AND OPTICS

The convex secondary mirror of the OTA was tested in a geometrically perfect null test with what is called a Hindle Shell test, a modification of the classic Hindle Sphere test. Because hyperboloids have the property of perfectly imaging rays from one focus into the other focus, the Hindle Shell null corrector is used to physically implement this test. The Hindle test of the OTA secondary was carried out precisely as planned, and the shape of this mirror met specification. The aspheric shape of the secondary mirror was verified through the use of two independent tests during fabrication of the component.

In the manufacture of prior telescopes, refractive null correctors (RvNCs), such as the one shown in Figure 4-1, were used. The combination of the two precisely made and spaced lenses produces the desired optical template of the concave aspheric mirror.

Carrying out an unambiguous and accurate test to determine whether a null corrector is producing the correct optical template is a known difficulty. For the HST program, Perkin-Elmer concluded that an RvNC would not yield sufficient precision for testing the figure of the primary mirror, and as a result, a new and novel reflective null corrector (RNC) was designed. As shown in Figure 4-2, the Perkin-Elmer RNC consists of two spherical mirrors and one small field lens. (The more common RNC design contains only a single mirror and a field lens.) In the P-E design, the shape of the optical template could be precisely predicted simply by knowing the manufactured dimensions of the two mirrors and the lens, including the lens material, and the spacings of the three optical elements. Perkin-Elmer planned to certify the RNC with great care, and they did not plan to do any independent testing of the mirror.

The RNC was designed to provide easy access to all the optical surfaces in the null corrector in order to measure these spacings at any time. The spacing between the two spherical mirrors can be measured by determining the distance between the centers of curvature of the two mirrors. This measurement is done interferometrically, using a known metering rod of the desired length. In a similar manner, the field lens spacing can be measured relative to the center of curvature of the lower mirror. The spacings need to be correct to 10 μm to meet specifications.

This ability to measure the optical element spacings at any time is something that is not possible with a traditional RvNC, made up of all lenses and no mirrors. The novel RNC that answered some of the misgivings about the RvNC approach was one of the factors leading to the award of the HST contract to Perkin-Elmer.

As a check on the position of the Coaxial Reference Interferometer (CORI) used with the RNC, an inverse null corrector (INC) was designed. When swung under the RNC, the INC would simulate a perfect mirror, just as a perfect primary mirror would appear with straight fringes when viewed through the RNC (Figure 4-3).

Although not considered as a backup or additional check of the optical template produced by the RNC, an RvNC was built to test the OTA primary during early stages of polishing and was again used to test the primary mirror during a measurement of the vertex radius of curvature or "power" of the primary mirror. The RvNC had to be used for this radius measurement because the RNC had to have central holes in the two mirrors (just as the primary had a hole) to let the light through. Because of the holes in the RNC mirrors, it was not possible to see the location of the vertex of the primary mirror.

"White-light" fringes were used as an initial setup procedure to align the reference test plate (i.e., the calibrated mirror inserted into the hole of the primary mirror) for the vertex radius measurement. This measurement was extremely sensitive to vibration, and the fringes could not be captured on film because of the short duration and faintness of the images. Several observers were required to witness that the fringes were seen. When this test was accomplished, a helium-neon (He-Ne) laser replaced the white-light source in order to take photographs (interferograms) by which to make the vertex radius measurement.

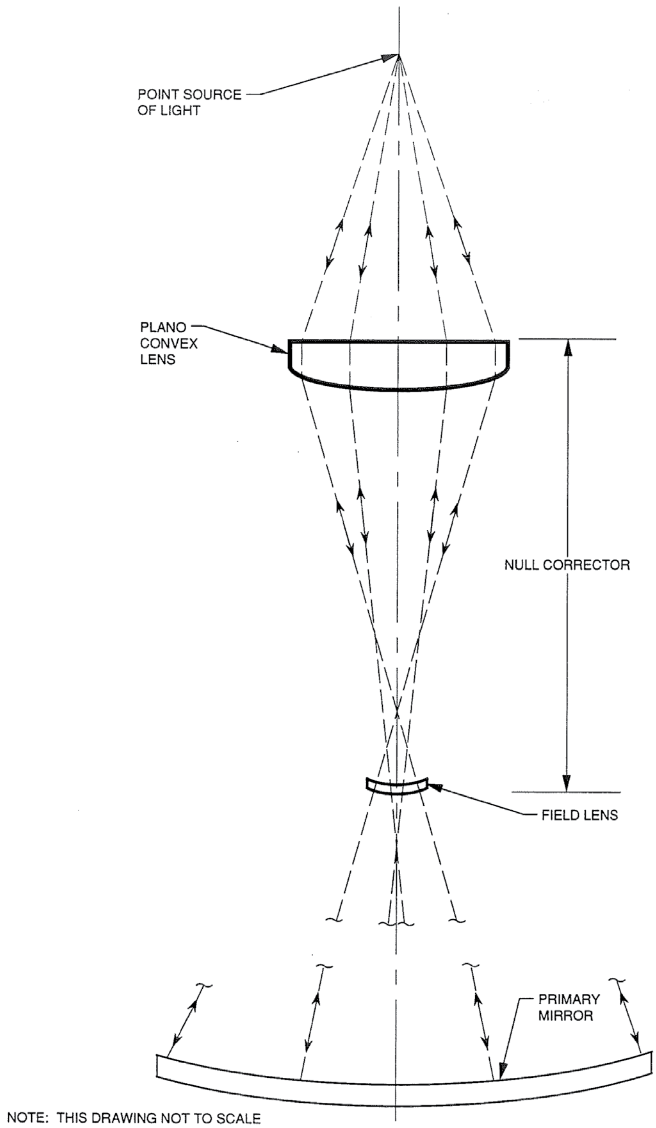


Figure 4-1. Two-element refractive null corrector.

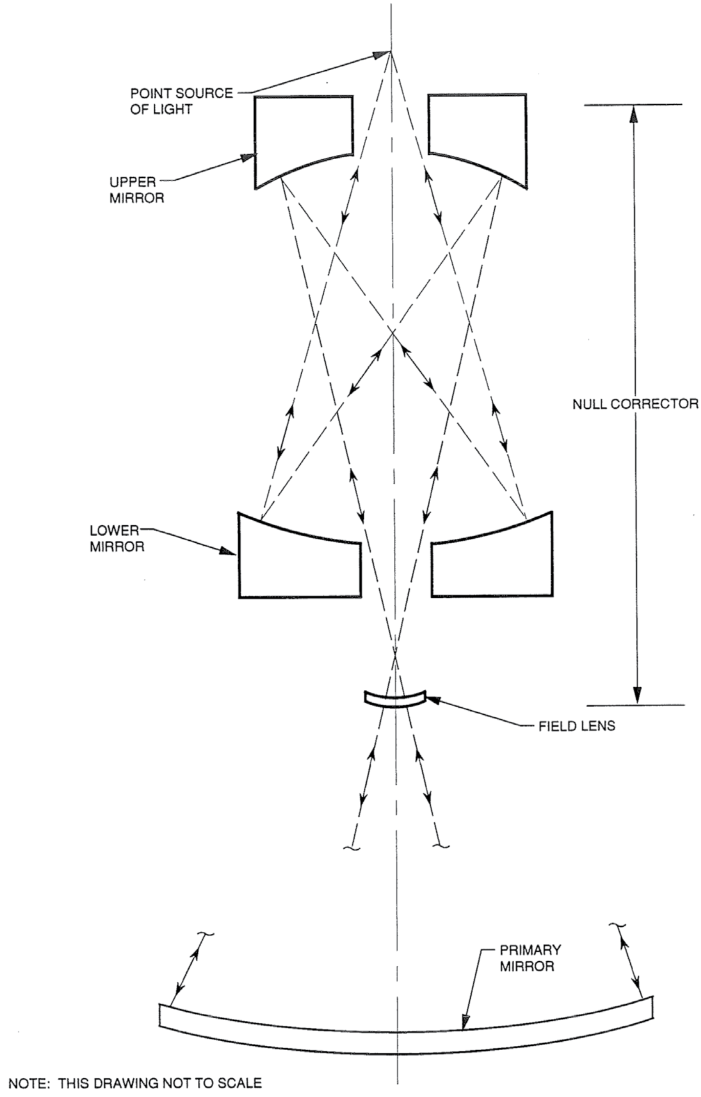
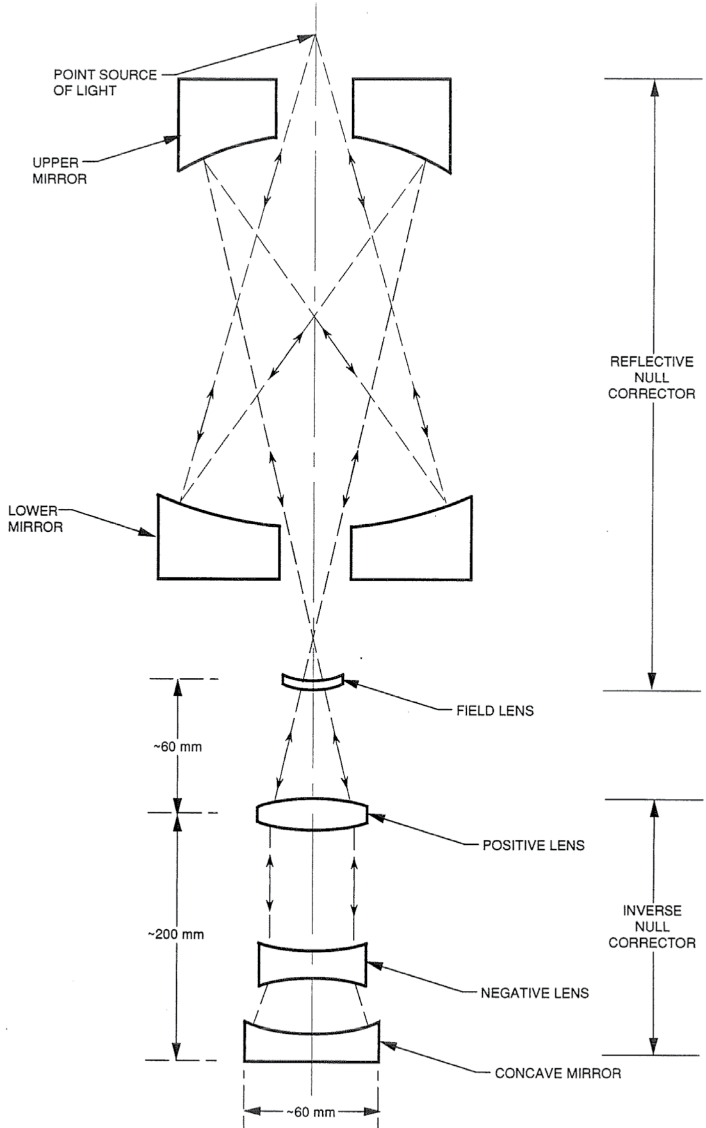


Figure 4-2. Reflective null corrector.



NOTE: THIS DRAWING NOT TO SCALE

Figure 4-3. Inverse null corrector inserted below the reflective null corrector.

D. POLISHING

During the polishing of the OTA mirrors, the Hindle test was performed on the secondary mirror, and its surface was polished until it looked like a pure sphere to about 0.012-wave rms wavefront error at 632.8 nm. This meant that the surface was the correct hyperboloid to this same quality, a quality better than that specified in the contract.

The backup OTA primary mirror was polished at Eastman Kodak Company using both a refractive and a reflective null corrector of a completely different design from the Perkin-Elmer version. This mirror matched the templates of the two null correctors to better than 0.014-wave rms wavefront error at 632.8 nm, and the Board has every reason to believe it is the correct hyperboloidal shape.

The primary mirror now flying in the HST was polished using the Perkin-Elmer RNC as a guide or template. Again, the fit to the template was better than 0.014-wave rms wavefront error at 632.8 nm, better than the contract specification for the accuracy of the mirror. Unfortunately, as has been subsequently learned, there was an error in the template produced by the RNC, thus making the primary mirror the wrong shape.

E. FINAL TESTS

An end-to-end test of the OTA would have been very expensive to perform at the level of accuracy specified for the telescope. The test would have cost on the order of what the OTA itself cost, because a flat or plano mirror would have been needed. To test the flat mirror by a single interferogram would have required a spherical mirror about 15 percent larger than the flat mirror. Thus the test could have required two additional mirrors as large as or larger than the OTA primary.

In hindsight, a much less severe test could have been done to check for a gross error such as did occur. The belief at the time was that if the two mirrors had each exceeded their individual specifications, only a test at the level of accuracy of the individual mirrors would have been meaningful. Such a test would have been very hard to justify because of cost.

Actually, an end-to-end test was done over a 0.3-m diameter aperture to ensure that the assembled telescope focused where it should. There was no attempt to use this test as a check on the figure of the primary mirror, apparently because it was believed that the fraction of the mirror tested was too small to give reliable results and also because the OTA was mounted horizontally and the distortion due to gravity was significant.

THE FAILURE

The Level I specification for the HST is to achieve 70 percent encircled energy in a circle of 0.1-arcsecond radius and to meet a Rayleigh criterion (i.e., image resolution of two objects) of at least 0.1 arcsecond. Early in the checkout phase of the mission, it was discovered that the telescope did not meet the above requirement. Instead, the telescope focused 70 percent encircled energy into a 0.7-arcsecond radius. Figure 5-1 is a plot of the encircled energy percentage versus radius in arcseconds for both the specified HST performance and the actual performance.

The problem was initially detected when the "first light" images from both the Wide Field/Planetary Camera and the Faint Object Camera were analyzed and major defects were detected. Computer simulation of these images indicated that 0.5-wave rms wavefront spherical aberration at 547 nm existed in the telescope and not in the instruments. Further verification of the spherical aberration problem came from the wavefront sensors.

Both on-axis and off-axis data were analyzed in order to determine whether the primary mirror or the secondary mirror, or perhaps both mirrors, were flawed. Data taken by the wavefront sensors, the Wide Field/Planetary Camera, and the Faint Object Camera indicated a significant spherical aberration wavefront error. Although some coma appeared in the off-axis results taken by the fine guidance sensors, the amount of coma was small and the conclusion was reached that the primary source of image spreading is spherical aberration of the primary mirror.

Spherical aberration distorts a point source image (e.g., a distant star) by broadening the image and surrounding it with concentric diffraction rings. This broadening effect prevents distant, closely spaced objects from being separated in the image. A tutorial on spherical and coma aberration is given in Appendix C.

IDENTIFICATION OF THE FAILURE

A. ONBOARD DATA

The first step in focusing the HST requires the onboard pointing control system (PCS) to position the telescope at a known pattern of stars that are imaged into the three fine guidance sensors (FGS). Once this pattern of stars is locked onto by the FGS, the secondary mirror is moved along the axis of symmetry in order both to ensure that the mirror is moving in the correct direction and to obtain an accurate estimate of where the best focus is located. It was a NASA policy that first light images would not be recorded until after the best focus had been obtained using the FGS.

Several problems occurred early in the checkout phase. The PCS was hindered by the thermal environment at the terminator (where the HST passes from Earth shadow to sunlight and vice versa), which induced a mechanical distortion in the solar array structure, in turn causing pointing difficulties. In addition, the HST's star trackers executed several improper star acquisitions, causing the telescope to be pointed in the wrong direction; only three of the first 16 star acquisitions were successful. Both these effects severely complicated the focusing activity.

After a position for the secondary mirror was selected for first light, the Wide Field/Planetary Camera (WF/PC) recorded its first image. The initial image analysis indicated significant defects. Since the secondary mirror had only been moved along the axis of symmetry, it was still believed at the time that corrections could be made by tilting or decentering the mirror to improve the focus.

The next portion of the checkout involved using the wavefront sensors (WFS), which are more sensitive than the FGS, to precisely analyze the errors in the optical wavefront. Deviations from a perfect incoming shape could then be precisely determined and quantified. Such deviations can take on any geometrical shape and are classified as alignment errors or optical aberrations such as astigmatism, spherical aberration, and coma.

The secondary mirror was again moved along the axis of symmetry, and the wavefront was analyzed by the WFS. At the same time, star images were made with the WF/PC. Both the WFS and the WF/PC indicated that a large amount of spherical aberration was present. Subsequent calibration tests indicated that the spherical aberration was not internal to the WF/PC.

Corrections to the imaging defects due to misalignment were attempted by tilting and decentering the secondary mirror, but these adjustments did not improve the wavefront or the image quality. Further analysis and computer simulation of the WF/PC images indicated that 0.5-wave rms wavefront spherical aberration at 547 nm (equivalent to 0.43-wave rms wavefront error at 632.8 nm) existed in the telescope (Figure 6-1). When interferograms taken by the WFS also indicated severe spherical aberration, the HST Project Manager was notified, and the Contingency Plan was put into effect.

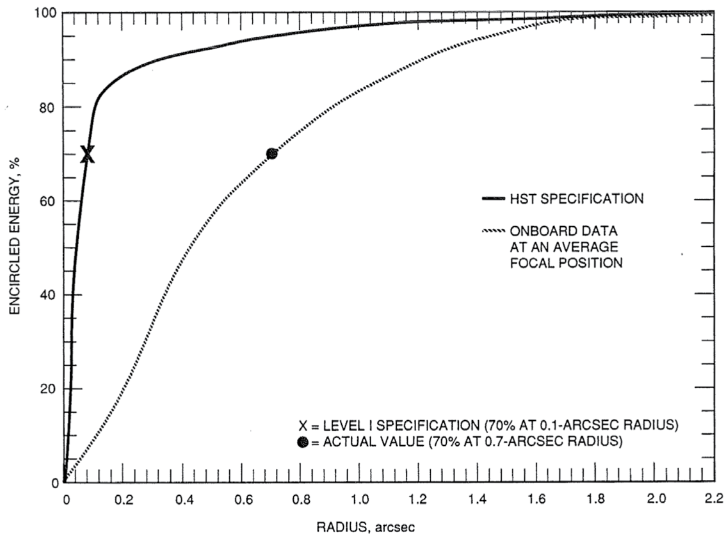


Figure 5-1. Encircled energy versus arcsecond radius of image produced by the HST.

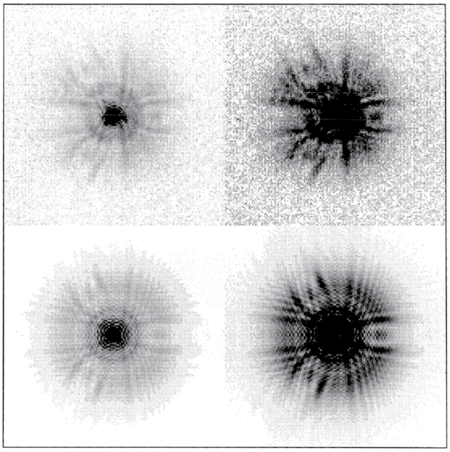
At this point, the activity began centering on determining which mirror, or perhaps both mirrors, had the incorrect shape. Error in the primary mirror would exhibit spherical aberration both along the axis of symmetry, where the WF/PC is located, and off-axis, where the FGS, WFS, and Faint Object Camera are located. If the secondary mirror were flawed, there should have been a large amount of coma in addition to the spherical aberration. No significant amount of coma was detected and, consequently, it was decided that most of the error resided in the primary mirror.

The NASA Administrator directed the MSFC Project Office to establish an Independent Optical Review Panel to further investigate the problem and recommend follow-on actions. Shortly thereafter, the Hubble Space Telescope Optical Systems Board of Investigation was formed to determine the technical facts behind the failure.

B. SOURCES OF ERROR

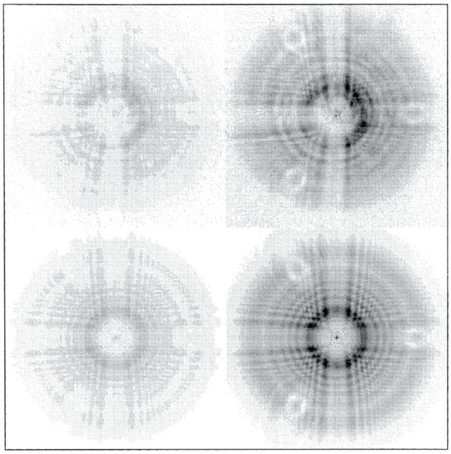
The HST investigation indicated some inconsistencies in the primary mirror's test data. The historical test data showed that the primary mirror appeared to have spherical aberration when tested against the refractive null corrector, which was used to test the vertex radius of the primary mirror. At the time of the fabrication, P-E believed (without independent verification) that some level of error may have existed in the RvNC. An analysis conducted by the Board verified that the RvNC was accurate to better than 0.02 wave rms.

The final test data for the primary mirror, obtained using the reflective null corrector, indicated that the mirror exceeded the specifications. The Board found interferograms relating to the RvNC test (found in Appendix D), which indicated a surface-figure error of about the right magnitude and sign to explain the errors existing in the operational telescope. Since a perfectly polished mirror would have shown no error on either null corrector, it was evident to the Board that an error actually existed in the RNC.



(a) Recorded image of the PC5 star taken on June 14, 1990, with a 0-μm inside focus.

Figure 6-1. Planetary Camera images versus computer simulations. The images in the top frames were taken with the Planetary Camera; those in the bottom frames are computer simulations created using an optical model with 0.5-wave rms wavefront error at 547 nm.



(b) Recorded image of the PC5 star taken on June 21, 1990, with a -300-μm inside focus.

Figure 6-1 (continued). The images in both (a) and (b) show a linear-intensity display on the left, and a logarithmic ("stretched") image display on the right. The focal position denotes the position of the secondary mirror. (Data were supplied by Dr. Jon Holtzman.)

A fault-tree analysis of the RNC and the manufacturing data indicated three reasonable possibilities for the error:

(1) The field lens was inserted backward.
(2) The index of refraction of the field lens was incorrect (i.e., the wrong glass was used).
(3) The optical elements were incorrectly spaced (a circumstance that seemed highly unlikely because of the method used to set the lens spacings).

It was possible to be so specific because spherical aberration is a symmetric error and can only be produced by a longitudinal spacing error. A more extensive analysis to cover other, less viable causes of spherical aberration was halted once the Board agreed on the cause of the on-orbit spherical aberration.

The Board decided that no tests were to be performed on the null correctors that might in any way disturb their present condition, because the null correctors were the only direct links by which to determine the actual shape of the primary mirror in orbit. This precise shape data would be needed if the telescope were to be fixed or brought back to the originally specified image quality.

Under this restriction, the RNC could not be moved from its place at the top of the test tower, nor could it be adjusted or disassembled. By design, the RNC had access ports in its sides so that it was possible to get at the various optical elements in order to make the necessary measurements.

The first test performed on the RNC was to insert the INC and take an interferogram on July 22, 1990. This interferogram was analyzed and compared with a previous interferogram taken with the INC in place. (This latter interferogram was found in a notebook of a P-E employee and was dated June 22, 1982.) Comparison of these two interferograms (Figure 6-2) shows virtually identical results, clearly indicating the existence of spherical aberration. These INC interferograms are corroborated by the RvNC interferograms, which also show spherical aberration (as discussed in Appendix D, Figure D-2). The combination of these interferograms led the Board to conclude that the CORI/RNC assembly is now essentially in the same state of operation as it was at the time the final measurements were made on the primary mirror.

Unverifiable testimony raised the possibility of a waiver having been granted for an optical spacing error in the INC. During the current investigation, an error in the design calculations was discovered that produced a small amount of spherical aberration in the INC. An analysis of the "as-built" INC conducted for the investigation showed that the instrument had an accuracy to better than 0.14 wave. The amount of spherical aberration introduced by the INC error is only a small amount compared to the amount of spherical aberration actually measured.

The first possibility of error in the RNC involved the field lens. Measurements were made and it was determined that the field lens was not put into the RNC assembly backwards.

The next test was to measure the effective focal length of the field lens to verify that the correct material had been used. The actual measurement determined the magnification of the field lens and verified that the correct glass had been used. Two spare lenses from the same lot were also measured for figure and focal length, and the measurements confirmed the results on the installed field lens.

Since the index was not in error, plans were made to measure the spacing of the field lens to the lower mirror in the RNC. This measurement could not be made as it was originally, because the metering rod used at the time of initial assembly was too long to fit in the assembled RNC and interferometer unit.

The RNC was designed such that high-precision (1-µm) measurements of the optical elements could be taken at any time. In the case of the 1.5-m prototype mirror, the metering rods could be positioned within the RNC to perform the spacing measurements. For the 2.4-m design, the spacing between the optics was greater and therefore the metering rods needed to be lengthened. The longest rod was lengthened in such a way that it could only be inserted in one piece and, consequently, a reverification of this spacing could not be made with this rod since disassembly of the RNC would be required. In principle, a new rod could have been designed in two pieces that would have allowed a remeasurement of the distance from the field lens to the center of curvature of the lower mirror.

The optical element spacing was measured in 1990 by shining collimated light up through the field lens using a Zygo interferometer as the source, and by placing a flat mirror at the focus of the field lens (a distance of about 0.55 m above the lens). The correct position of the mirror was determined by using the interferometer to find the best focus (Figure 6-3). The distance from the flat mirror was then measured down to the vertex of the lower mirror using a fixture in the mirror hole for a reference. This measurement showed that the field lens was about 1.3 mm too far from the lower mirror. Both the direction and the magnitude of the spacing error correctly explained the spherical aberration observed in the HST image data. The spacings of the other optical elements in the RNC were measured and were found to be correct.

In addition to the optical test used to detect the field-lens spacing error, a direct physical measurement was made from the field lens to the vertex of the lower mirror (Figure 6-4). A lightweight spacing rod and a new vertex plug were made. The results verified the previously measured spacing error to ±0.1 mm. More accurate measurements of the displacement error will be done at a later time, as this information is necessary for an accurate determination of a prescription for the recovery optics.

When the field lens position error (FLPE) is taken into account and applied in correcting the data taken with the RNC, it results in a mirror shape that would account for most of the error observed in the HST images. Also, the interferograms taken with the RvNC were reprocessed and corrected for the as-built data available for the RvNC. This independent set of data yields a mirror shape very close in value to the RNC/FLPE data. These data led the Board to conclude that the predominant source of error had been found and was caused by the field lens position error. (See Appendix E for the HST performance based on the as-built data.)

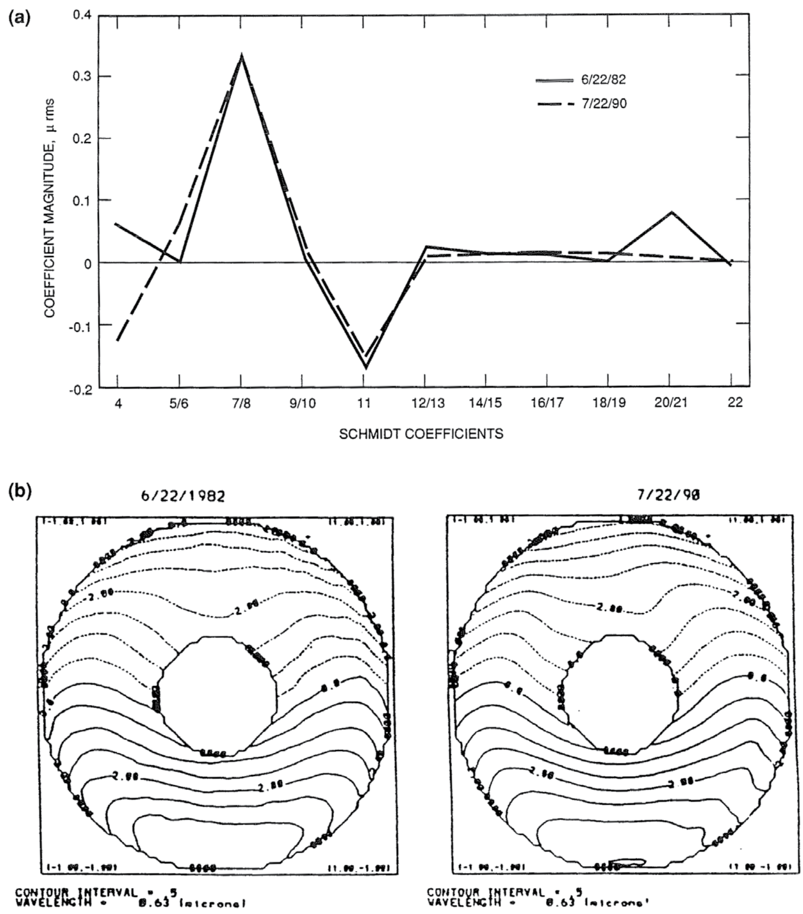


Figure 6-2. Comparison of 1982 and 1990 inverse null corrector data. (a) The coefficients which define the magnitude of various distortions to the wavefront were measured by the INC when it was inserted in front of the RNC in 1982 and in 1990. (b) The coefficient data were extracted from these plots of the interferograms.

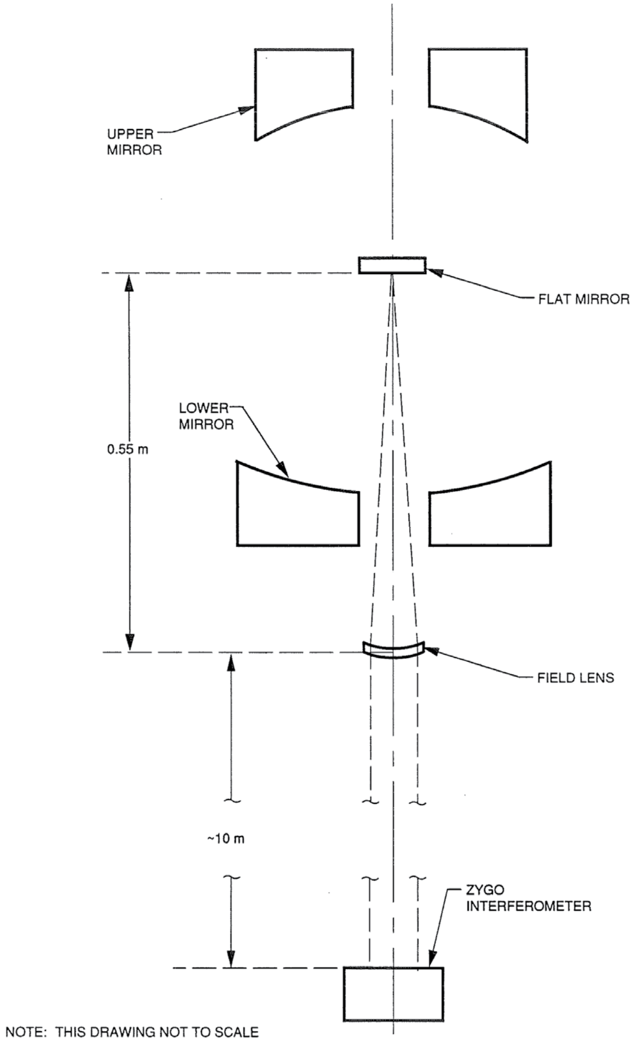


Figure 6-3. The 1990 spacing measurement between the field lens and the lower mirror of the reflective null corrector, using an optical test.

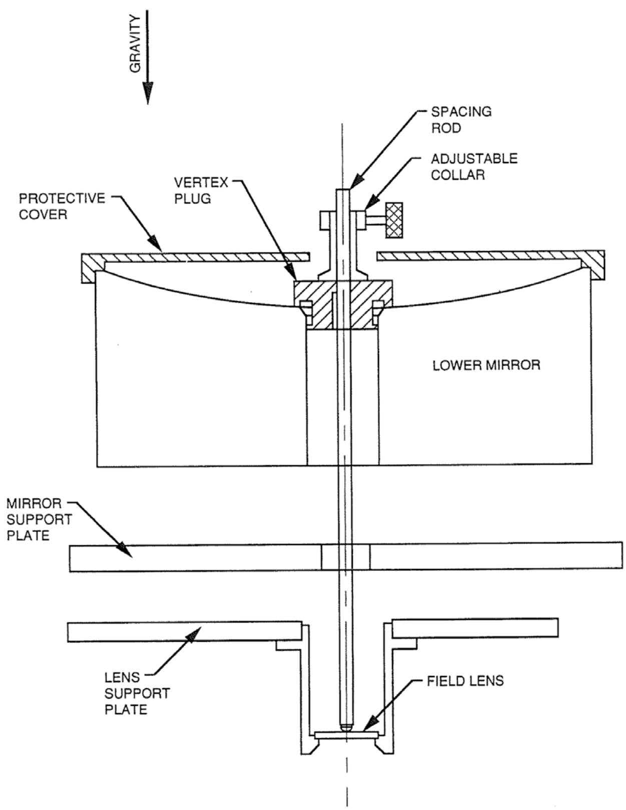


Figure 6-4. The 1990 spacing measurement between the lower mirror vertex and the field lens of the reflective null corrector, using a mechanical technique.

HOW THE ERROR OCCURRED

A. INTRODUCTION

It has been established that the field lens was approximately 1.3 mm too far from the lower mirror of the RNC, which was used to figure the primary mirror. The RNC and its associated interferometer were found in the test chamber, unused and unchanged since the completion of the HST program. The RNC was measured in situ, and there is high confidence that the spacing error existed during the fabrication and test of the HST primary mirror. The cause of the spacing error, on the other hand, becomes a matter of conjecture, because the records necessary to reproduce what actually happened were not found. The scenario given below reproduces the events and provides a rationale of how the spacing error occurred. This scenario was simulated in the laboratory under the guidance of the Board and is the most likely cause of the error.

B. METERING ROD MEASUREMENTS

At the beginning of the program to build the 2.4-m Hubble primary mirror, P-E modified the RNC that had been used in building a 1.5-m mirror prototype. This modification required adding a new field lens and respacing the optical elements to create the correct shape for the larger mirror. Figure 7-1 is a schematic of this RNC, including the positions of the metering rods used to set the optics.

There were three metering rods (labeled A, B, and C) made of Invar, a metal with a small temperature expansion coefficient. The ends of the metering rods were rounded and polished because the very precise positioning of the optics in the RNC used an interferometer, rather than a mechanical measurement. This procedure involved auto-reflecting a focused beam of light off the end of a rod and observing an interference pattern from the beam that came back on itself. Centering the light beam on the rod end was essential for the measurement. To prevent the metering rod from being misaligned laterally with respect to the interferometer axis, P-E decided to attach "field caps" to one end of the rod (Figures 7-2 and 7-3). The field caps were fitted over the rod ends and had a small aperture in the center to ensure centering of the rod on the beam. The top surface of the field cap was covered with nonreflecting material; however, some of this material had, apparently inadvertently, broken away from a small area around the field cap aperture. It appears that the operator obtained reflection from the field cap where the nonreflecting material was absent, rather than the rod end, causing the 1.3-mm misspacing. A test performed in 1990 with the equipment showed that it was quite easy, even probable, to make this error with the configuration used. Figure 7-4 indicates how the displacement error occurred by reflecting light off the field cap, rather than the rod end, as designed. Figure 7-5 is a photograph of the field cap and shows the specular region around the aperture. (In this photograph, the broken-away coating appears darker than the surrounding region.)

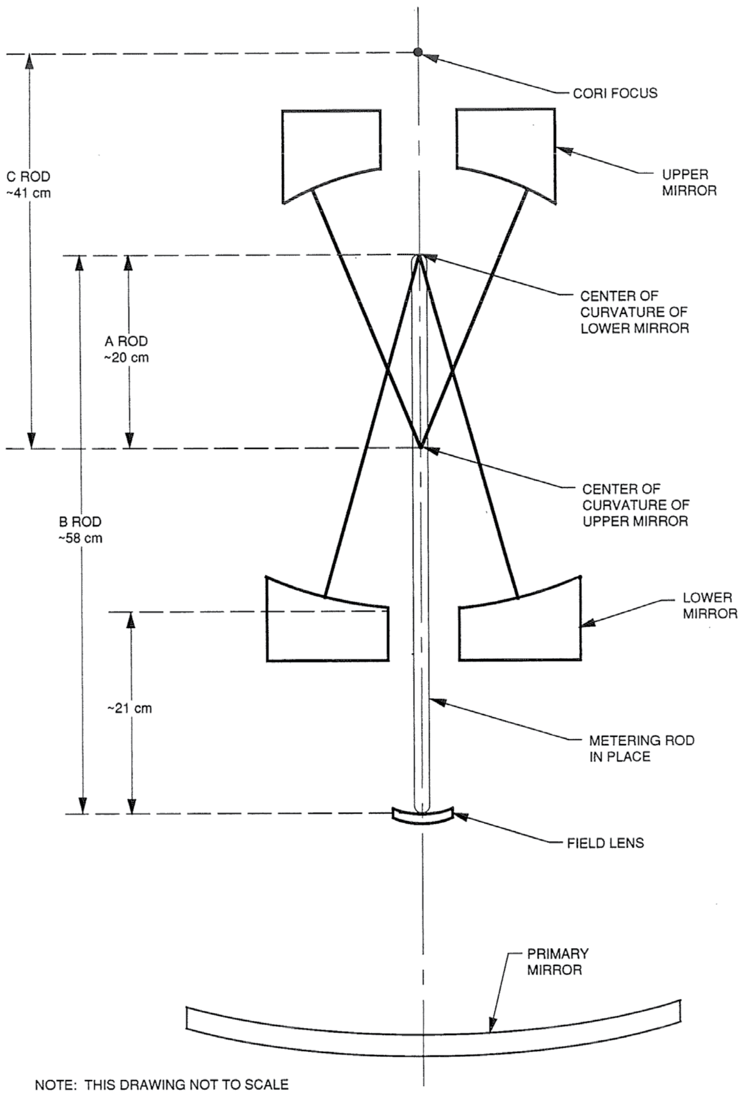


Figure 7-1. Position of metering rods used to space optical elements in the reflective null corrector.

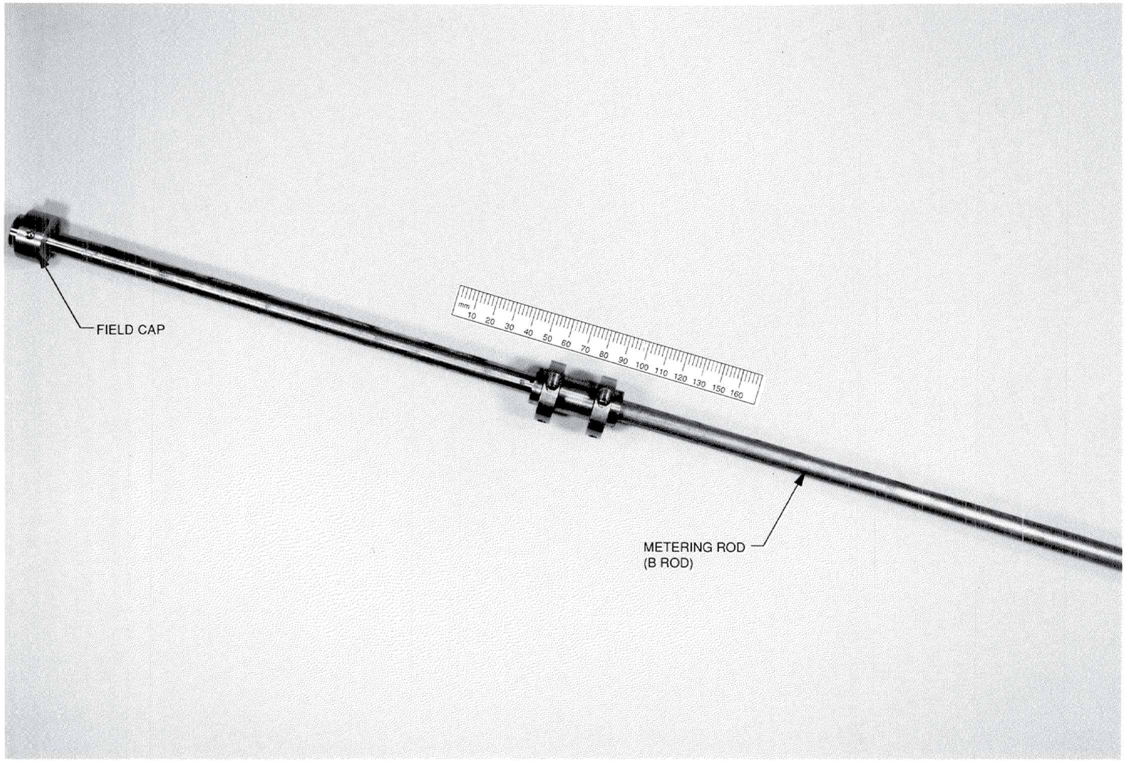


Figure 7-2. Metering rod (B rod) used to space the field lens and the center of curvature of the lower mirror in the reflective null corrector.

With one end of the metering rod presumably located at the center of curvature of the lower RNC mirror, the field lens was then brought up to the end of rod B, but there was no adjustment left in the screws used for this positioning. More adjustment room was made by inserting spacers between the field lens and the lower mirror mounting plate. The adjustment mechanism was found not to be staked. Staking, i.e., securing the mechanism to prevent inadvertent movement, was a specified procedure. The final location of the field lens was then set with the addition of the spacers. As a result, the field lens was about 1.3 mm too far from its correct position relative to the lower mirror.

QUALITY ASSURANCE OBSERVATIONS

The error in the HST has brought the role of quality assurance (QA) into question, since the problem remained undiscovered before launch. From an examination of the evidence, it is clear that there were specific QA requirements in the contract for the building of the OTA and that an "OTA Product Assurance Plan" was written and released in 1978 by Perkin-Elmer. Less clear are the contract's data retention requirements and to which aspects of the P-E hardware they applied. While the OTA Product Assurance Plan did not specifically refer to testing of the RNC, the plan did set forth detailed requirements in regard to validation and engineering sign-off that would have ensured that the RNC would be adequately designed and tested. If this QA plan had been rigorously applied, it is probable that the HST error would never have occurred. At the very least, it would have been much easier to reconstruct what had happened if a complete record of the fabrication of the test equipment and mirrors had been retained.

Review of the existing documentation indicates that the QA function relating to the metrology of the primary mirror was inadequately staffed. Defense Contract Administration Services (DCAS), now Defense Contract Management Command (DCMC), personnel were not added to the Project's staff until after the primary mirror was completed. Both the MSFC and the P-E QA personnel were excluded from key areas and at critical times. This decision was made by P-E engineering management with the concurrence of the MSFC Project Office. The result of this decision was that an informed and independent evaluation of the assembly and manufacturing area was not done.

In addition, the P-E QA personnel reported to the OTA Project Manager rather than to someone independent of immediate Project pressures. This may also explain why QA personnel were apparently denied access to metrology areas where they could have hindered the data-taking and analysis process.

At the time of the primary mirror's polishing and testing, the quality reviews and audits conducted according to the QA Plan did not raise technical issues about the shortcomings of the test procedures prior to their implementation. The procedures did not provide criteria for the correct results of testing and thus did not provide guidance toward identifying unexpected out-of-limits behavior of the optical tests. In most cases, the expected results of the optical tests were not specified, and inexperienced personnel were not able to distinguish the presence of an unacceptable behavior of the tests. There was also no criterion given for the required experience of the observer approving passage of a milestone on the basis of test results. In hindsight, and with the knowledge there was a problem with the mirror, it is easy to see that various technical issues about the test procedures, such as the lack both of independent tests and of any correlation of the results of related tests, should have been questioned.

When the primary mirror was transferred from P-E Wilton to P-E Danbury at the beginning of Phase II of the contract, a DoD-classified project was ongoing at the Danbury site. Initially, DoD imposed a restriction on the number of NASA personnel who had access to the Danbury facility. However, this restriction was seen by the MSFC Project Manager as being too constraining and then was subsequently renegotiated with DoD. Unlimited access by NASA personnel was allowed after that time. The DoD project did not prohibit NASA QA from adequately monitoring the P-E activity.

The Optical Operations Division of P-E imposed its own access limitations to the Danbury metrology area where the RNC and INC were assembled. This area was secured by a cipher lock door, and only metrology engineers from the Wilton facility were allowed access. QA personnel from both NASA and P-E were not informed that this test equipment was being assembled and were aware of its existence only after the RNC assembly was moved to the OTA test chamber. No formal manufacturing-process paperwork on this activity was filed; consequently, the QA organization did not become involved.

Other evidence that QA did not play as full a role as outlined in the QA Plan is shown by the lack of, or even callouts for, QA signatures on several procedures relating to the primary mirror metrology. Similarly, it is perhaps because the P-E QA personnel reported through the Project management that there is no written evidence that QA ever protested being denied access either to the primary mirror test area during the actual testing or to the area where the data were being analyzed.

Finally, there is no evidence of QA records calling into question the discrepancies in the actual test data that seem so obvious in hindsight. No mention has been found in any records that the RNC could not be recalibrated in the same manner as when it was first assembled, or that the RNC/INC test showed spherical aberration when it should not have. Neither was any mention made that the vertex radius test with the RvNC showed spherical aberration in the finished primary mirror when it should have shown none. There was no formal and centralized information management system to retain and categorize the voluminous data that defined the HST.

The documentation describing the addition of the spacers under the field lens to achieve the apparent proper spacing of this element was never filed or has been lost in the intervening 10 years. This can be understood in part since the QA organization was not involved in this activity. A reference was made during the testimony that a Material Review Board was held on the spacer issue, but no documentation was found.

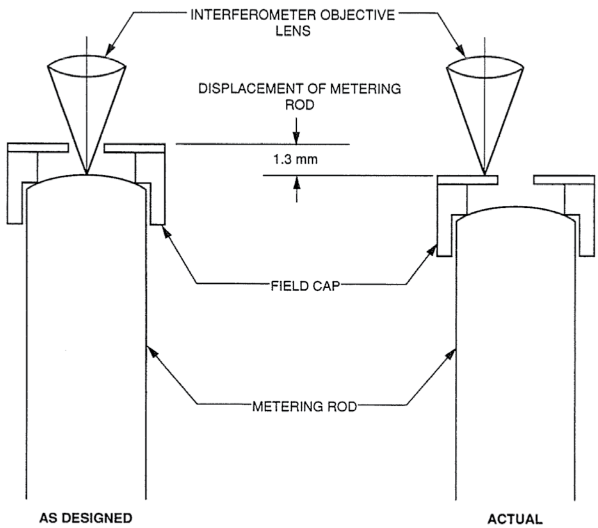


Figure 7-4. Displacement due to the interferometer focusing on the field cap instead of the metering rod.

What is clear from the error that occurred, and the evidence found, is that QA has a significant role to play in the avoidance of similar problems on future programs. For this to happen, however, the role of QA must be understood and seen as a positive factor by top management. QA organizations must be adequately staffed by fully qualified individuals, and these people must be given free access to all aspects of the project, from conceptualization through final delivery. They should have clear authority to stop work on projects where there are unresolved quality issues. They should also have an independent reporting path to top management to avoid the undue influences and schedule pressures being imposed by the program or the engineering organizations.

Further, thorough and well-cataloged documentation of all these aspects of the project must be maintained by the contractor and/or NASA for the duration of the mission. To do otherwise will make recovery of salvageable missions improbable or impossible.

Additional quality assurance information on the HST can be found in an extensive report, *SRM&QA Observations and Lessons Learned,* by George A. Rodney, Associate Administrator, Office of Safety and Mission Quality, National Aeronautics and Space Administration, dated October 1990.

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WHY THE ERROR WAS NOT DETECTED PRIOR TO FLIGHT

The explanations for why the HST error was not detected before launch can be separated into two categories: factual and judgmental. Based on the test plan that was in place at the time of the fabrication of the HST mirrors, the factual issues presented in this Chapter were events that should have warned the Project personnel of the existence of a problem. The judgmental issues that follow are conclusions based on the Board's own expertise.

A. FACTUAL STATEMENTS

1. Complete reliance was placed on the reflective null corrector (RNC) to determine the shape of the primary mirror. It was determined that the RNC would be certified only by accurate measurement of the elements and the spacings. Although test philosophy placed great emphasis on "certification" of the RNC, the Board could not find documentation that the RNC was certified. In spite of the total reliance on the RNC, no independent measurements were made of the optical-element spacings of the RNC to verify the values. Although the RNC was designed so that spacings could be rechecked without disassembly, the actual implementation did not permit such measurements, and no remeasurement of spacings was made after initial assembly.

2. The erroneous measurement of the spacing of the field lens of the RNC led to the need to install spacers to increase the separation of the field lens from the lower mirror. The bolts securing the field-lens basket were not staked, suggesting a lack of quality surveillance, since securing bolts was a common and easily observable inspection to conduct. These anomalies should have led to a Material Review Board (MRB) approval document and a thorough consideration of the cause. Although the NASA representative recalls approving such an MRB, no documentation was found.

3. After the RNC was assembled in the laboratory, an INC was set up below the RNC. The INC was intended to simulate a perfect mirror below the RNC so that any errors in the null corrector could be detected. The interferograms taken when using the INC to align the RNC/CORI indicated a spherical aberration pattern (see Figure D-3). The full RNC/CORI assembly was then moved to the top of the optical telescope assembly test chamber, and each time the primary mirror was tested the INC was used to check the alignment of the setup. As before, the same spherical aberration distortion was evident in the fringes. These aberration fringes could not be aligned out and were incorrectly attributed to the spacing errors in the lens system of the INC. Perkin-Elmer's Optical Operation Division believed that the INC was not reliable when, in fact, it was quite accurate enough to detect the gross error, and indeed did so.

4. The vertex radius measurement taken by the refractive null corrector (RvNC) indicated the presence of spherical aberration (see Figure D-2). This information was dismissed, as it was in the case for the INC, because the RvNC was believed to be less precise than the RNC and therefore not reliable. It has

been determined that the RvNC was easily accurate enough to detect the spherical aberration that existed, and its reliability should not have been discounted.

5. There were two other occasions when a careful analysis of the data might have revealed the problem:

a. The primary mirror was ground and polished to an approximate shape, about 1 wavelength rms, using the RvNC for the test. This took place at Perkin-Elmer's facility in Wilton, Connecticut. The mirror was then transferred to P-E's Danbury facility, where the RNC was the test instrument for final polishing. At the time of transfer, the interferograms obtained with the RvNC were compared with those obtained from the RNC, and the discrepancy could have been noted. However, the data and the circumstances of transfer are unclear, and the requirements for transfer appeared to be adequately met; therefore no concern was noted.

b. After the assembly of the OTA, tests were performed to assure proper focus position. Those tests were made with a 0.36-m telescope (subaperture test), and careful analysis of the data might have revealed the problem. However, the data were complicated by gravity sag because the OTA was mounted horizontally, and only the focus position was verified.

6. A range of feasible tests to verify the shape of the primary mirror were considered, but not carried out. Finally, no end-to-end tests were planned or implemented to verify the performance of the OTA.

B. JUDGMENTAL STATEMENTS

The following judgements are offered with the recognition that there were many distractions and crises during this period—cost, schedule, threat of cancellation, mirror contamination, possibility of mirror distortion caused by mount, etc. Nevertheless, the flaw occurred and, as can now be seen, these are factors that bear on that occurrence.

1. The proposal of P-E, accepted by NASA, to rely entirely on the RNC should have alerted knowledgeable people in P-E and NASA that special attention was required to certify the RNC; to the need for independent validation of the RNC and/or the primary mirror; and to the need to examine and review the test data for any indications of inconsistency. A project test plan that considered the various measurements, the possibilities of error in each, and the feasibility of independent checks should have been prepared by the implementing organization and externally reviewed.

2. The conclusion by P-E, accepted by NASA, that the RNC was the only device that would yield an accuracy of 0.01 wave rms at 632.8 nm led P-E to fail to consider any independent measurement which would yield less accuracy. In fact, such independent data were obtained incidental to other measurements and were rationalized away due to this mindset.

3. The HST development program was complex and challenging and there were many issues demanding management attention; the primary mirror was only one of these. Although the telescope was recognized as a particular challenge, with a primary mirror requiring unprecedented performance, there was a surprising lack of participation by optical experts with experience in the manufacture of large telescopes during the fabrication phase. The NASA Project management did not have the necessary expertise to critically monitor the optical activities of the program and to probe deeply enough into the adequacy and competence of the review process that was established to guard against technical errors. The record of reviews reveals no sensitivity to in-process data and no questioning of the test method.

4. The NASA Scientific Advisory Group did not have the depth of experience and skill to critically monitor the fabrication and test results of a large aspheric mirror. However, this Group should have recognized the criticality of the figure of the primary mirror and the fragility of the metrology approach, and these concerns should have impelled them to penetrate the process and ask for validation.

5. A highly competitive environment existed between Perkin-Elmer and the Eastman Kodak subcontractor. Although the manufacturing process and the method of measurement for the backup primary mirror were reviewed and approved by P-E, there was limited additional technical exchange of experience. NASA did not utilize the opportunity offered by this directed subcontract to validate, and gain confidence in, the P-E approach to the primary mirror manufacture.

6. Perkin-Elmer line management did not review or supervise their Optical Operations Division adequately. In fact, the management structure provided a strong block against communication between the people actually doing the job and higher level experts both within and outside of P-E.

7. The P-E Technical Advisory Group did not probe at all deeply into the optical manufacturing processes and, although they recognized the fragility of the measuring approach, they did not adequately assert their concerns or follow up with data reviews. This is particularly surprising since the members were aware of the history of manufacture of other Ritchey-Chretien telescopes, where spherical aberration was known to be a common problem.

8. The most capable optical scientists at P-E were involved closely with the production of the 1.5-m demonstration mirror and the design of the HST mirror and the test apparatus. However, fabrication of the HST mirror was the responsibility of the Optical Operations Division of P-E, which did not include optical design scientists and which did not use the skills external to the Division which were available at Perkin-Elmer.

9. The Optical Operations Division at P-E operated in a "closed-door" environment which permitted discrepant data to be discounted without review. During the testimony, it was indicated that some technical personnel in the Optical Operations Division were deeply concerned at the time that the discrepant optical data might indicate a flaw. There are no indications that these concerns were formally expressed outside this Division.

10. The quality assurance people at P-E, NASA, and DCAS (Defense Contract Administration Services, now Defense Contract Management Command) were not optical experts and, therefore, were not able to distinguish the presence of inconsistent data results from the optical tests. The DCAS people concentrated mainly on safety issues.

11. The basic product assurance requirements and formal review processes were procedurally adequate to raise critical issues in most safety, material, and handling matters, but not in optical matters.

12. The inability of P-E to provide the Board with vital archival data on the design and manufacture of the primary mirror is an indication of inadequate documentation practices, which hampered the Board in determining the source of the primary mirror error.

LESSONS LEARNED

A. IDENTIFY AND MITIGATE RISK

The Project Manager must make a deliberate effort to identify those aspects of the project where there is a risk of error with serious consequences for the mission. Upon recognizing the risks the manager must consider those actions which mitigate that risk.

In this case, the primary mirror fabrication task was identified as particularly challenging due to the stringent performance requirements. The contractor clearly specified in the proposal that total reliance would be placed on a single test instrument and that no optical performance tests would be made at higher levels of assembly. Therefore, OTA performance would be determined by component tests and great care in precision assembly. Although NASA accepted this proposal, the methodology should have alerted NASA management to the fragility of the process, the possibility of gross error (that is, a mistake in the process), and the need for continued care and consideration of independent tests.

The history of spherical aberration in the primary mirrors of Ritchey-Chretien telescopes was known to some of the optical scientists involved, but did not lead to specific recommendations early in the Project. Late in the Project an advisory group did call out the risk of gross error and suggested simple tests to check for such errors. This recommendation was not seriously considered, primarily due to total lack of concern that such a risk was reasonable, but also in view of cost and schedule problems.

Several methods of detecting the flaw were inherent in the testing, but Project management did not recognize the value of or need for independent tests. Project management was concerned about the performance specifications and directed a subcontract to Eastman Kodak Company for an alternate primary mirror. The Eastman Kodak mirror was fabricated and tested using quite different techniques. The mirror or the instrumentation could also have served as cross-checks for gross error. Such error checks were not made, again due to total lack of concern about the possibility of gross error. Project management failed to identify a significant risk and therefore failed to consider mitigating actions. A formal discipline such as fault-tree analysis might have assisted the manager in directing his attention to this risk.

B. MAINTAIN GOOD COMMUNICATION WITHIN THE PROJECT

While proper delegation of responsibility and authority is important, this delegation must not restrict communication such that problems are not subject to review. In this case, the Optical Operations Division of P-E was allowed to operate in an artisan, closed-door mode. The impermeability of this Division seems astounding. The optical designers at P-E did not learn how their designs were being implemented; e.g., if the designer of the null correctors had been following their use, the data from the INC and the RvNC likely would not have been discounted. The data indicating the flaw was of great concern to some members of the division. Testimony indicates that their concerns were addressed at the level of the head of metrology and the division manager, but were not discussed outside the division at all. There were individuals who were not satisfied by the decision to rely only on the RNC data and remained deeply concerned. Their concerns and the data which caused them did not seem to come to the attention of anyone external to the division. P-E management should have been sensitive and open to these concerns. The P-E Technical Advisory Group should have found out what was going on in the Division and insisted on reviewing in-process data. NASA Project management should have been aware that communications were failing with the Optical Operations Division.

Contributing to poor communications was an apparent philosophy at MSFC at the time to resolve issues at the lowest possible level and to consider problems that surfaced at reviews to be indications of bad management.

A culture must be developed in any project which encourages concerns to be expressed and which ensures that those concerns which deal with a potential risk to the mission cannot be disposed without appropriate review, a review which includes NASA project management.

C. UNDERSTAND ACCURACY OF CRITICAL MEASUREMENTS

The project manager must understand the accuracy of critical measurements. P-E concluded, based on design considerations, that the RNC was the only test device which could achieve the required precision. They stated that its performance could not be determined by optical test but would be determined by component and assembly measurements which could be made in situ.
P-E engineers regarded the RNC as "certified" and the INC and RvNC as "uncertified." The terms were not defined, and "certification" was not documented. P-E discounted evidence of spherical aberration from INC and RvNC measurements on the basis of "uncertified" status. In fact, the Board reviewed a recent as-built error analysis of both devices. The review showed the RvNC to be

accurate to 0.02 wave rms and the INC to 0.14 wave rms. This indicates that the INC is a factor of three more accurate than the error observed in the INC/RNC interferograms. While in-process data were not subject to external review, which is another lesson, the methodology of test instrument use was reviewed by P-E and NASA management. This review could and should have questioned the judgment not to use the INC or the RvNC as independent checks of the *accuracy* of the RNC even though the *precision* was not to specification. Project management must understand critical tests and measurement.

In addition, the project management must seriously consider the classification of test equipment that directly impacts the flight hardware. The RNC was classified as standard test equipment, which means that the RNC was not subject to the rigorous documentation and review requirements demanded of items classifed as flight hardware equipment. Under the contract, there were no Government regulations requiring that records for the RNC be maintained. Considering the importance placed on the RNC in the test program, management should have upgraded the level of classification of this equipment.

Key decisions, test results, and changes in plans and procedures must be adequately documented. In preparing such documentation, individuals are forced to review and explain inconsistencies in the test data. This also provides a communication link to those individuals who are responsible for overseeing the project.

D. ENSURE CLEAR ASSIGNMENT OF RESPONSIBILITY

Project managers must ensure clear assignment of responsibility to QA and Engineering. NASA QA personnel were not optical system experts. The Project relied upon P-E Engineering to establish test and fabrication procedures, and P-E or NASA QA generally verified that Engineering approved and certified accomplishment of procedures. However, at times, NASA management seemed to rely on QA to verify the adequacy of procedures and the fact that they were satisfactorily accomplished. This lack of clarity apparently led to incomplete documentation and may have contributed to faulty procedures. The project manager must know what QA can and cannot do, and when it is necessary to rely on engineering for verifying its own procedures, management should be alert to the need for independent checks.

Quality assurance, to be truly effective, must have an independent reporting path to top management.

E. REMEMBER THE MISSION DURING CRISIS

There will be a period of crisis in cost or schedule during most challenging projects. The project manager must be especially careful during such periods that the project does not become distracted and fail to give proper consideration to prudent action. At one point in the fabrication cycle of the primary mirror, an urgent recommendation for independent tests to check for gross error entered the system, but was apparently not acted upon. Again, at the completion of mirror polishing, the final review of data for a final report was abandoned and the team reassigned as a cost-cutting measure.

F. MAINTAIN RIGOROUS DOCUMENTATION

The project manager should ensure that documentation covering design, development, fabrication, and testing is rigorously prepared, indexed, and maintained. Because quality, at a minimum, consists in meeting requirements, it is not possible to determine whether the necessary quality is being achieved if the requirements are not set forth in sufficient detail and maintained in retrievable archival form. Adequate documentation also helps maintain a disciplined approach to fabrication and testing processes, especially with so complicated a project as the HST.

GLOSSARY

arcsec (arcsecond)	A wedge of angle, 1/3600th of one degree, in the 360-degree sphere that makes up the sky. An arcminute is 60 seconds; a degree is 60 minutes.
astigmatism	A defect of curvature that prevents sharp focusing and degrades the quality of an image.
axial	Along the optical axis of a telescope.
baffle	Structure that obstructs stray light from the incoming image (see Figure 2-1).
C&DH	command and data handling
Cassegrain	A type of two-mirror telescope that reflects or "folds" incoming light.
coma aberration	A type of aberration where the rays from a point source do not meet at one focus, but rather spread into a comet-shaped area (see Figure C-2).
concave	A mirror surface that bends outward to expand an image.
convex	A mirror surface that bends inward to concentrate an image.
CORI	Coaxial Reference Interferometer
DCAS	Defense Contract Administration Services, now DCMC
DCMC	Defense Contract Management Command, formerly DCAS
DoD	Department of Defense

Einstein Observatory	The High-Energy Astronomy Observatory (HEAO-2) managed by Marshall Space Flight Center.
EK	Eastman Kodak Company
FGS	fine guidance sensors
figure	The shape of an optical surface.
first light	When an instrument's shutter is first opened and light enters the instrument.
FLPE	field lens position error
FOC	Faint Object Camera
focal plane	The geometric plane where incoming light is focused by the telescope.
fringe pattern	The bright and dark alternating intensity pattern in an interferogram (see Figure D-1).
GSFC	Goddard Space Flight Center
HDOS	Hughes Danbury Optical Systems, Inc.
Hindle test	An arrangement for testing a convex hyperboloid by retroreflection; used to shape the Hubble Space Telescope's secondary mirror.
HST	Hubble Space Telescope
hyperboloidal	A slightly deeper curve, mathematically, than a parabola; the shape of the Hubble Space Telescope's primary mirror.
image plane	The geometric plane in the telescope where the image is reconstructed.
INC	inverse null corrector
interferogram	A photograph of an interfering light pattern; used to test the figures of the Hubble Space Telescope's mirrors.
JPL	Jet Propulsion Laboratory
knife-edge test	A simple, qualitative test to measure an optical figure.
LMSC	Lockheed Missiles and Space Company, Inc.
MRB	Material Review Board
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration

OOD	Optical Operations Division (at the Perkin-Elmer Corporation)
ORA	Optical Research Associates
OTA	Optical Telescope Assembly
PA	product assurance
PCS	pointing control system
P-E	Perkin-Elmer Corporation, now HDOS
QA	quality assurance
QC	quality control
radial	Perpendicular to the optical axis of a telescope; for example, instruments placed at a 90-degree angle from the optical axis of the Hubble Space Telescope.
R-C	Ritchey-Chretien—A type of Cassegrain telescope where both the primary and secondary mirrors are hyperboloidal to correct for image aberrations; the Hubble Space Telescope's Optical Telescope Assembly (see Figure 2-1).
rms	root mean square
RNC	reflective null corrector
RvNC	refractive null corrector
SAIC	Science Applications International Corporation
spectrum	The wavelength range of light in an image.
SRM&QA	safety, reliability, maintainability, and quality assurance
TDRSS	Tracking and Data Relay Satellite System
vertex radius test	A comparative measurement of the primary mirror's radius of curvature at its center.
wavefront	The surface composed of all the points just reached by a bundle of light rays from a source.
wavelength (wave)	The distance in a wave from any one point to the next point of corresponding phase (for example, the distance from one wave crest to the next is one wavelength).
WF/PC	Wide Field/Planetary Camera
WFS	wavefront sensors