Hubble's Corrective Mirrors: Pushing the Optics Envelope

The Hubble Repair Mission provides important lessons in engineering management and project oversight. The following article describes how one NASA subcontractor succeeds.

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Editor's note: This article replaces the "Engineering" and "How To" columns which appear in OPN.

By definition, there could be no ready made precedent for correcting the flawed vision of the Hubble Space Telescope. To ensure Hubble would perform as originally intended required advances in metrology and fabrication.

Tinsley Laboratories produced two sets of corrective optics for the December 1993 repair mission. One set, produced under contract with the Jet Propulsion Laboratory, was Hubble's new Wide Field/Planetary Camera II (WFPC II). The second set, comprised of 10 mirrors, was installed in the Corrective Optics Space Telescope Axial Replacement (COSTAR), the innovative instrument developed by Ball Aerospace of Boulder, Colo.

Work began on COSTAR after the completion and delivery of the WFPC II optics. The COSTAR concept posed special considerations: the very small size of the mirrors, the high precision of the specifications, and a narrow time for completing the project.

Tinsley received the COSTAR order in June 1991. Our immediate priorities were to lay out the phases of the work and to select the teams, made up of people inside and outside the company, who would carry out on a strict timetable the various tasks assigned them. Tinsley's Robert Kestner was named program manager because of his extensive experience on previous programs involving the design, manufacture, and testing of high precision components and sub-systems. Jack Pinkham was named lead optical specialist because of his extensive experience in the fabrication of optics highly difficult to make.

The COSTAR program was divided into three primary assignments: optical metrology design, fabrication of metrology, and fabrication of the mirrors.

The first team concentrated on null lens design, tolerance, analysis, and quality verification. Here we drew on the talents of two support groups: Optical Research Associates (ORA) of Pasadena, Calif. and Phase Shift Technology of Tucson, Ariz. We called on ORA many times in the past for program support. Phase Shift worked with us on interferometry hardware and custom software, an area in which we had called on them before.

The COSTAR optics consist of five pairs of mirrors designed to "pick-off" light from Hubble's primary mirror and relay the light into one of three optical instruments. These are the Faint Object Camera and the Faint Object Spectrograph, and the Goddard High Resolution Spectrometer. Figure 1 shows the COSTAR corrective principle.

The initial program phase involved designing the optical tests that were to be used for the aspheric COSTAR Corrective Optics Fabrication. We worked closely with ORA on this phase. Two independent approaches were developed for testing the aspheric mirrors: 1) a computer generated hologram (CGH) null test, and 2) a combination of refractive optics with software null residual error compensation. The CGH null test became the principal test instrument. The second test was used mainly as an independent backup test after the aspheric mirrors had been completed.

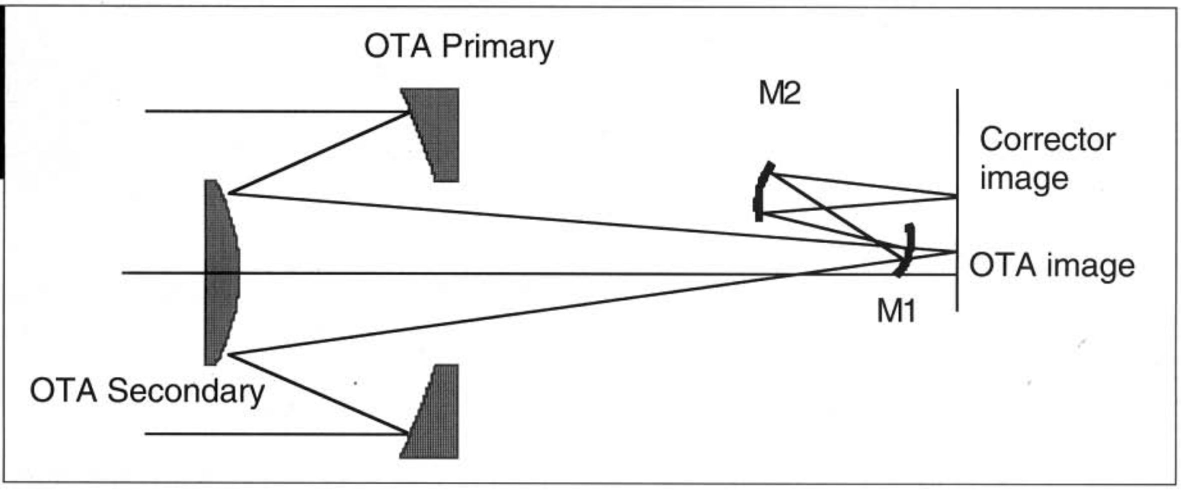

Figure 1. COSTAR Corrector Principle

The CGH test was chosen as the principal fabrication test because it could be more accurately calibrated than the refractive null test (layout shown in Fig. 2). The test consists of a custom unequal path phase measuring interferometer, designed to minimize sources of coherent noise that could downgrade testing accuracy. The CGH was placed in the imaging arm. The distance measuring interferometer (DMI) provided accurate radius control and near absolute axial positioning of the mirror in the test. The allowable error of the COSTAR aspheric mirrors, including test errors, was 0.01λ rms (λ=632.8 nm). The error budget allocation for the CGH test was established at 0.005λ rms. This allowed 0.0087λ rms error to be allocated to the mirror surface fabrication (based on the root sum of squares error budget approach). The test proved to be highly repeatable, allowing the COSTAR mirrors to be polished to a 0.0025λ rms match to the test null.

Our refractive backup test included cylinder lenses required to test the astigmatic nature of the aspheric mirrors. The residual test error budget for the refractive null test was 0.007λ rms, leaving a surface fabrication allowance of 0.0071λ rms. A test setup constructed to map the wavefront error of the cylindrical lenses used a tilted spherical mirror to cancel the astigmatism caused by the cylinders.

METROLOGY FABRICATION PHASE

ORA began a detailed design and sensitivity analysis of the CGH null test design. CODE V model of the CGH optical test was used to define the CGH prescription.

We had previously used the CGH test on a technology development program for the Air Force Rome Laboratory. Steve Arnold of APA Optics, who worked with us on the Rome program, was called on to fabricate the CGH elements for COSTAR. The CGHs were designed to minimize the test effects of errors in their fabrication and incorporated optical test alignment patterns required to verify the placement of fiducial reticles on the back of the COSTAR mirrors.

Numerous test design discussions were held between Tinsley and ORA, and between Tinsley and Ball Aerospace. Ball Aerospace's COSTAR Team also made monthly visits to monitor and review our progress. NASA's Goddard Space Flight Center assigned their independent verification team to examine every aspect of the optical test design and implementation.

ON-TIME DELIVERY

The schedule for the fabrication of the COSTAR optics was critical, as the optics had to be completed, integrated by Ball Aerospace into the instrument package, and delivered to Goddard to meet a planned launch window. Tinsley received a contract in late June 1991. The required delivery of the mirrors was March 1992. This allowed nine months to implement state-of-the-art metrology and to fabricate the spherical and anamorphic aspheric surfaces to demanding tolerances.

The first tasks included in our detailed program plan centered on metrology design and implementation. The metrology optical design study began in July 1991 and was largely complete in October. In August, mechanical design and fabrication of various pieces of metrology hardware began. As the optical design progressed, fabrication of null test elements and hardware was begun. The basic interferometer was completed in October and the CGH elements by mid-November.

Construction of the backup test began in September and was complete in December. This test was used after the first of the aspheric mirrors had been completed in early January of 1992.

Due to the small size and high

quality of the COSTAR aspheres, further improvements were needed in our technology for on-time delivery of the optics. In particular, adjustments were required to accurately map the surface error measured by the CGH test onto the physical surface of the mirror on the computerized polishing machine.

We took several steps to reduce the risk of late delivery. Diagnostic CGH elements were designed and fabricated so that potential problems with the CGH test could be determined. Several spare COSTAR mirror elements were also fabricated. Risk reduction geometry samples were prepared before geometry on the actual parts was performed. Vacuum deposited fiducial marks were required on the back side of the mirrors.

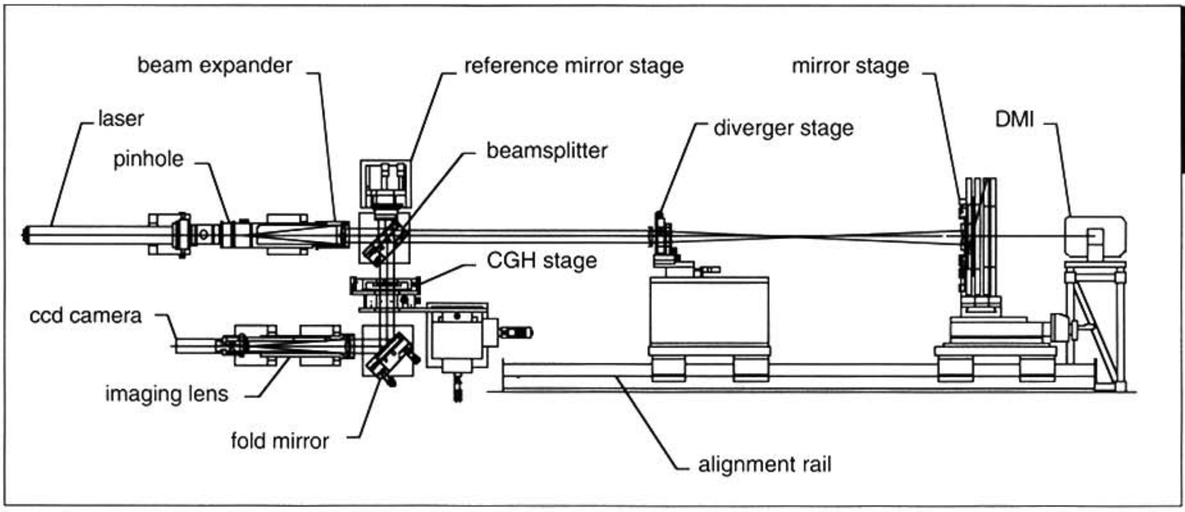

Figure 2. CGH Test Layout

The surface figures of the spherical mirrors were evaluated using a Zygo Mark II interferometer fitted with a PST phase modulating adapter. The Zygo interferometer system errors were mapped and removed during the analysis of the phase data. The required spherical mirror tolerance was 0.01λ rms. The error of the fabricated mirrors was typically 0.005λ rms.

The surface roughness of all mirrors, spherical or aspheric, was specified as 10Å rms at spatial wavelengths less than 1 mm. The surface roughness of the spherical mirror was measured on a Chapman MP2000 profilometer. The actual measured surface roughness was less than 5Å rms in all cases.

The fabrication of the anamorphic aspheric mirrors began in late August 1991. The mirrors were initially processed spherical, then polished to a rough aspheric accuracy (λ/2) using a precision surface profilometer to measure the surface and provide feedback to the CCOS polishing machines. Optical testing of the mirrors began in November 1991. The first set of five mirrors was completed by March 1992, the second set by May.

The Hubble Program taught us an important management lesson—the overwhelming advantages of an extended organization. We drew on our own people, specialists outside the company we had come to know well, and the resources of our own customers. The indispensable value of open, frank, and frequent communications across the board was proven time and again in the speedy solution of outstanding problems. Our technology developed incrementally over time. It was our guide to untried areas of testing and fabrication essential to success.

We also benefited from a significant intangible: the strong sense of mission that permeated the extended organization. Everyone involved was determined that the Hubble objectives would be accomplished.

ACKNOWLEDGMENTS

The making of the COSTAR optics is a tribute to the people of our company and to several other organizations who supported us throughout the whole program including ORA, Phase Shift Technology, and APA. We consider Ball Aerospace's COSTAR a masterpiece of innovative technology. JPL had the primary responsibility for WF/PC II, a major innovation of its own. We are grateful to Ball Aerospace, JPL, and NASA for their constant support and encouragement.

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